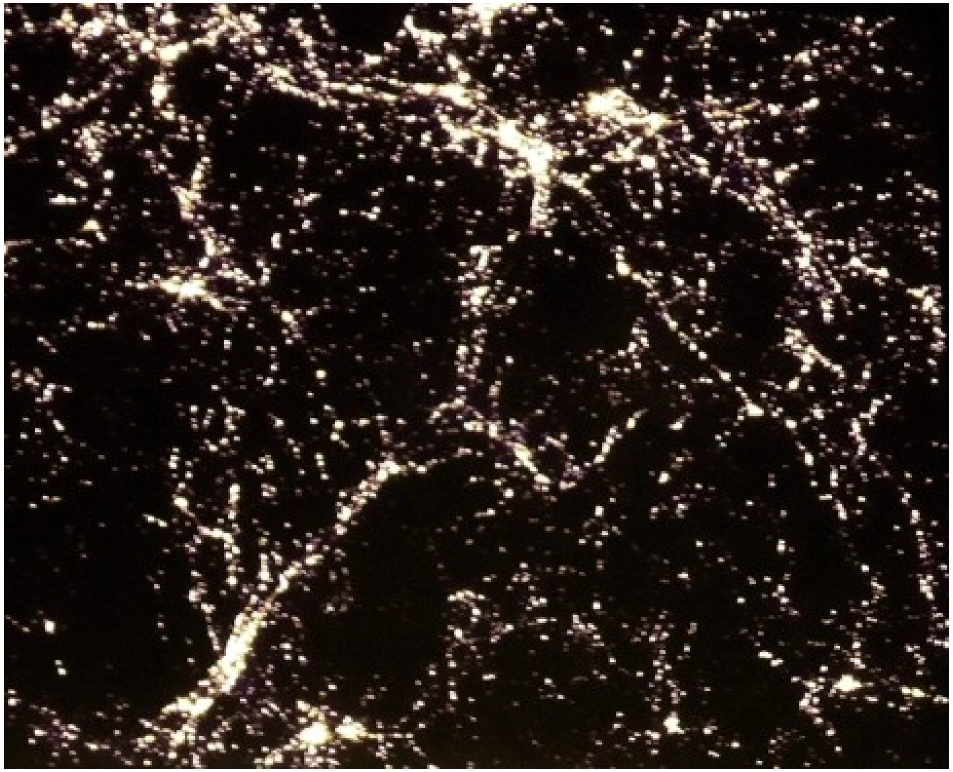
Dark Matter Mediators @ Colliders

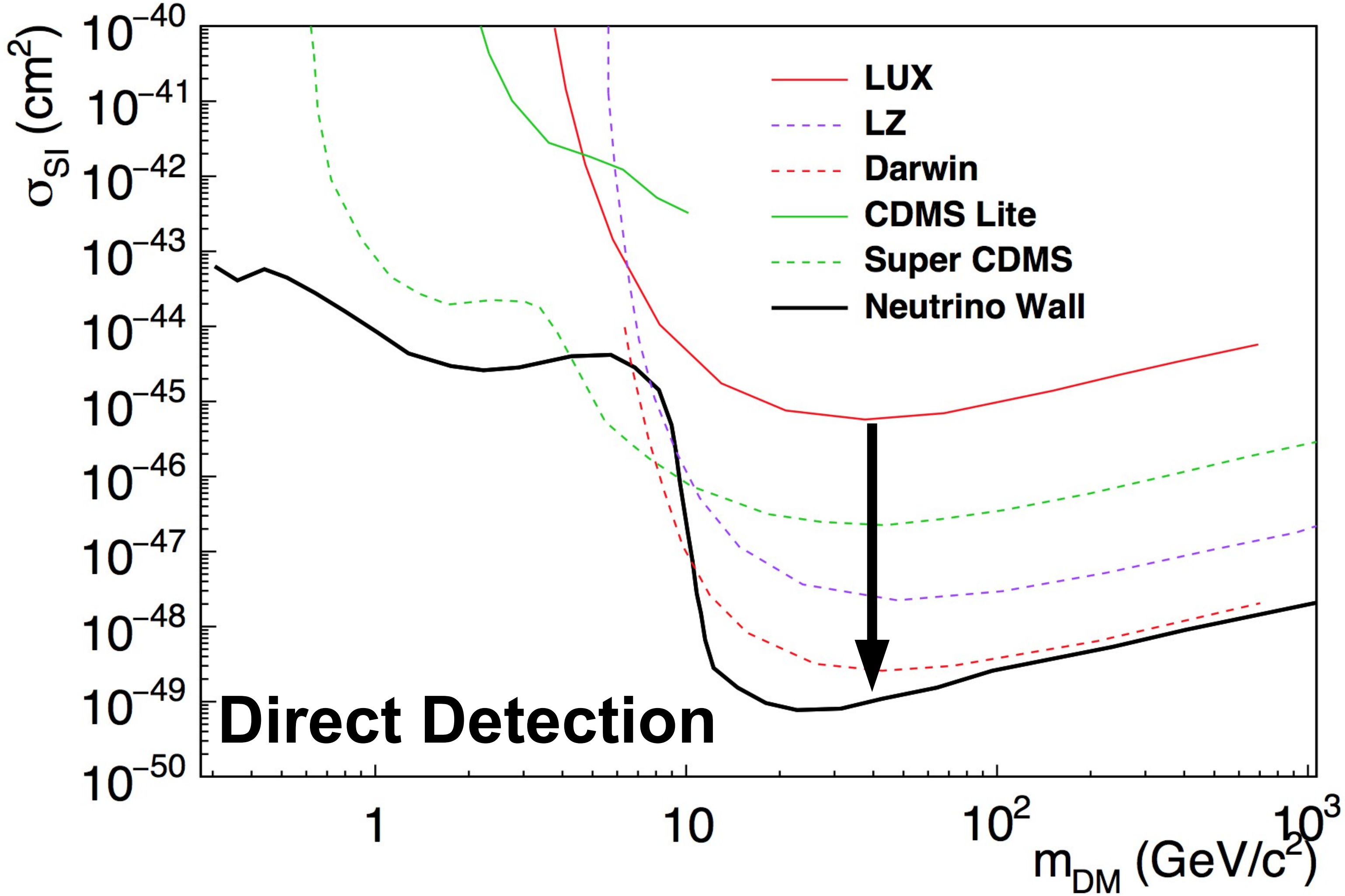


Phil Harris
(CERN)

CMS Compact Muon Solenoid

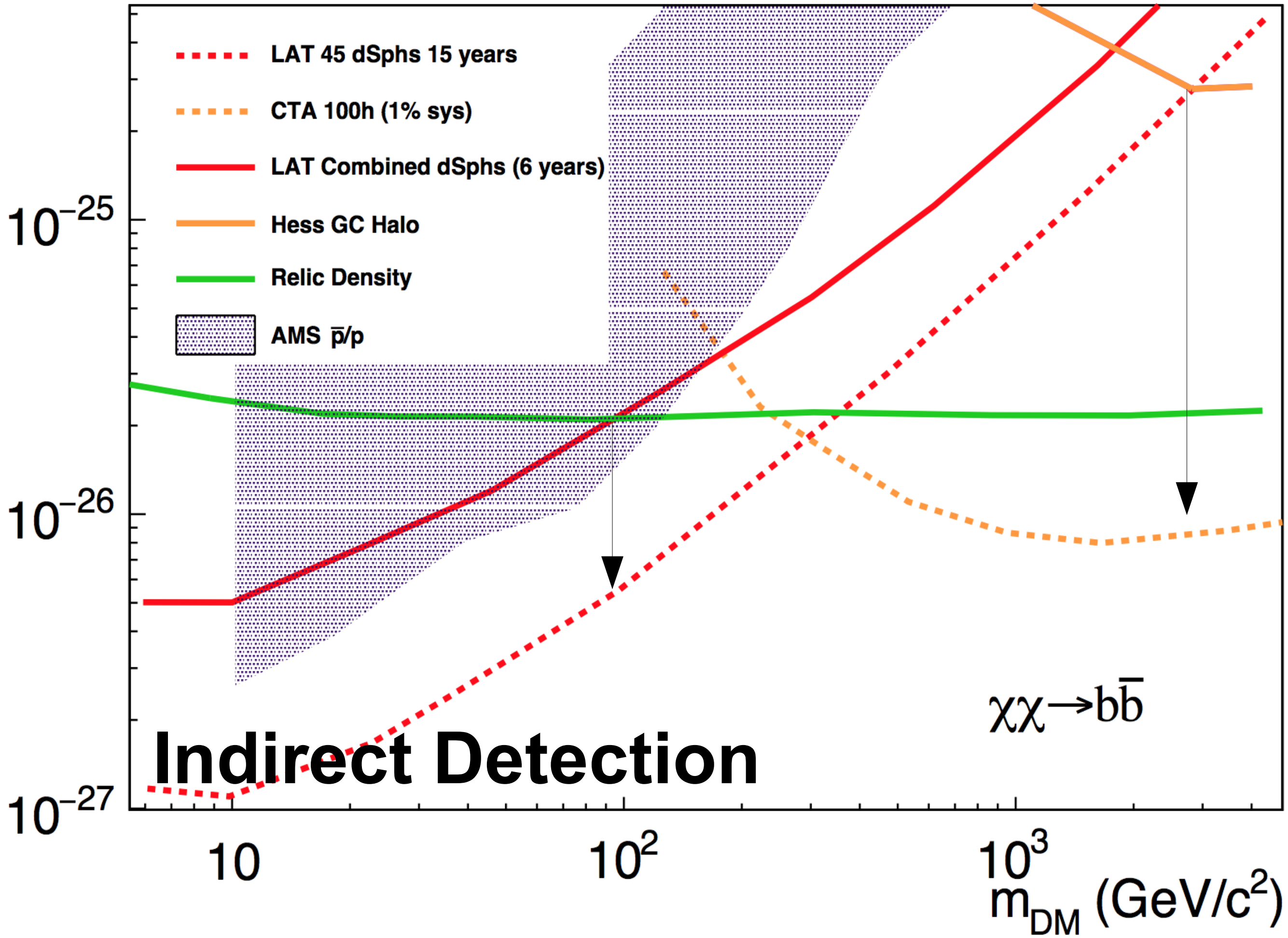
Dark Matter searches not @ collider

Dark matter searches not at colliders have clear benchmarks



Goal: get to the Neutrino background wall

Dark Matter searches not @ collider



Goal: get to the Relic density

Question:

- Whats the simplest way to present LHC results in the context of Dark Matter?

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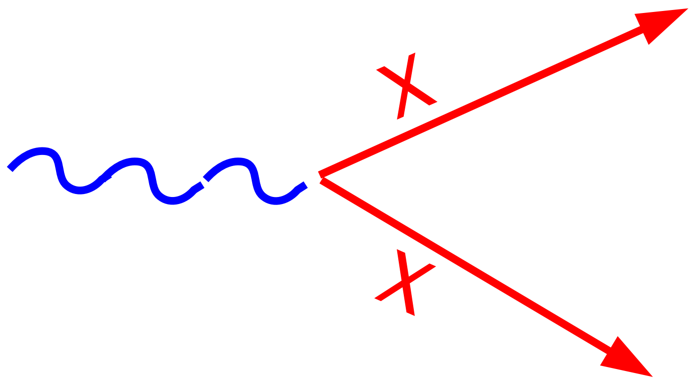
- Answer:
  - $\sigma_{\text{Invisible}}$



- Assumes dark matter coupling to standard model
  - $\mathcal{L} = g_{DM}\chi\bar{\chi}Y$ Mediator + SM interactions

Dark Matter

Adding Dark Matter

- What drives dark matter interaction is production
  - Take the approach that this is defined by the mediator

- $\mathcal{L}' = g_{DM}\chi\chi Y$

Z'^{μ} Spin 1

Uniform coupling to SM

$$\mathcal{L}' = \mathcal{L}' + g_{SM} Z'_{\mu}\bar{q}\gamma^{\mu}q$$

S Spin 0

Yukawa* couplings to SM

$$\mathcal{L}' = \mathcal{L}' + g_{SM} S\bar{q}q$$

Preserving Generality?

To compare with other (low energy) searches :
split by spin dependence

$$\mathcal{L} = g_{DM}\chi\chi Y$$

Spin 1

Z'^{μ} Vector

$$\mathcal{L} = \mathcal{L} + g_{SM} Z'_{\mu}\bar{q}\gamma^{\mu}q$$

γ^5

Z'^{μ} Axial-Vector

$$\mathcal{L} = \mathcal{L} + g_{SM} Z'_{\mu}\bar{q}\gamma^{\mu}\gamma^{5}q$$

Spin 0

S Scalar

$$\mathcal{L} = \mathcal{L} + g_{SM} S\bar{q}q$$

γ^5

P Pseudoscalar

$$\mathcal{L} = \mathcal{L} + g_{SM} P\bar{q}\gamma^{5}q$$

Strategy of searches in LHC does not change much

Interpretation agains Direct Detection/Indirect Changes a lot

Simplified Models 101

Vector

$$g_{\mathrm{DM}} Z'_\mu \bar{\chi}\gamma^\mu \chi$$

EWK style coupling
(equal to all quarks/leptons)

Axial vector

$$g_{\mathrm{DM}} Z''_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi$$

EWK style coupling
(equal to all quarks/leptons)

Scalar

$$g_{\mathrm{DM}} S\, \bar{\chi}\chi$$

Yukawa style coupling
(Mass based coupling)

Pseudoscalar

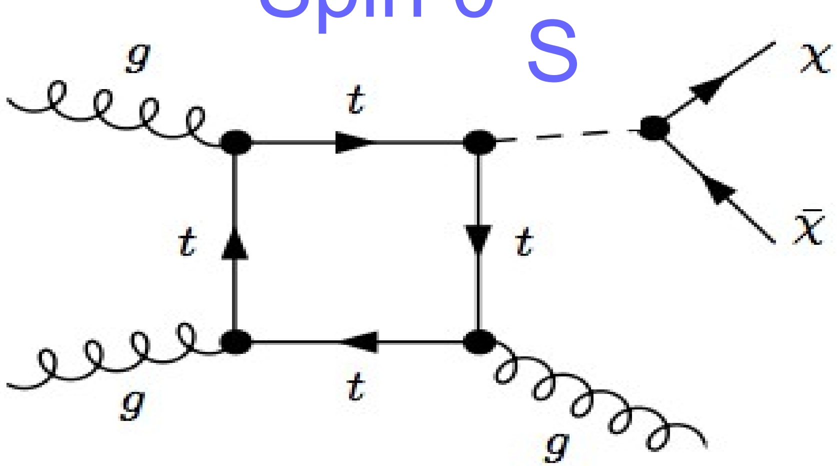
$$g_{\mathrm{DM}} P\, \bar{\chi}\gamma^5 \chi$$

Yukawa style coupling
(Mass based coupling)

Impact of the spin in production

- Couplings to SM force two different scenarios

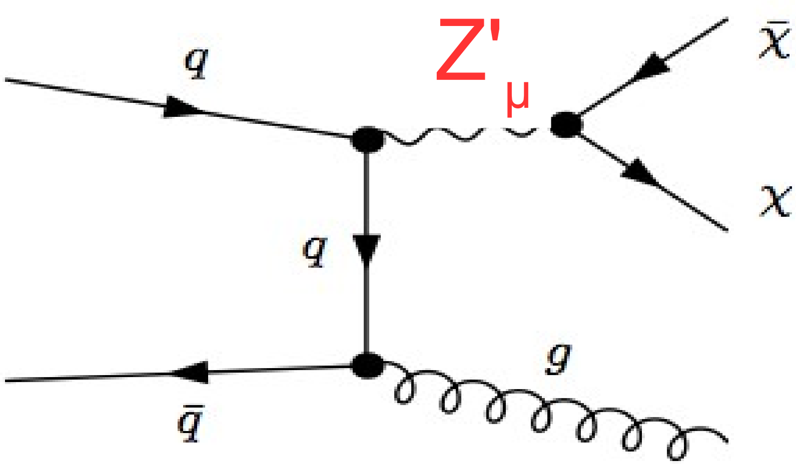
Spin 0



Yukawa coupling to quarks
Dominated by heavy quarks

Small cross sections :
Probe low masses or
Large couplings

Spin 1



Flavor universal to quarks
Dombined by light quark

Large cross sections :
Probe large masses or
Small couplings

Establishing a collider benchmark

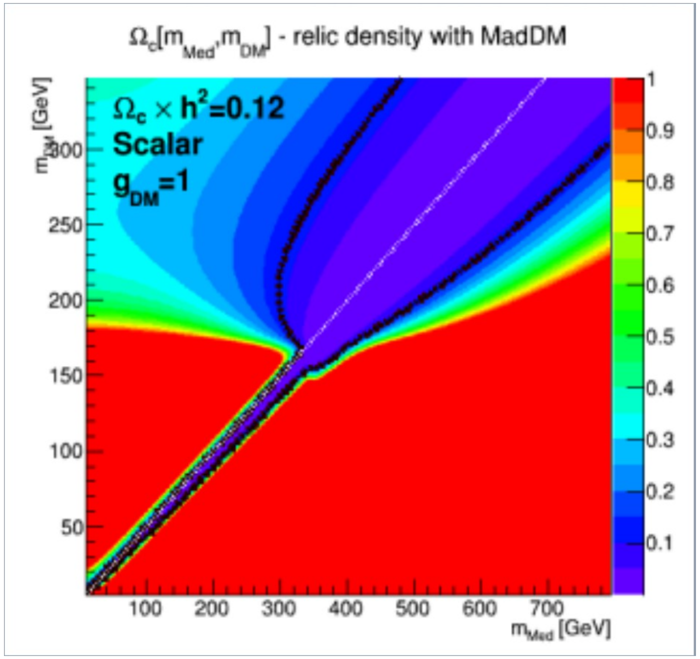
Relic Density??

Relic Density on Simplified Models

- Lets calculate relic density on simplified models
  - Calculation is performed with MadDM (2.0) MadDM

Acknowledge these models are simplified

All of our results come with caveats



However it still serves as a motivating benchmark

Note : I am experimentalist
Don't expect a strong theoretical motivation

Features of the relic density

- Considering form of the annihilation cross section

$$\sigma^{A}_{\mathrm{ann},s} \cdot v = \sum_q \frac{N_c^q g_{\mathrm{DM}}^2 g_q^2 \beta_q}{2\pi} \frac{m_q^2 \left(4m_{\mathrm{DM}}^2 - M_{\mathrm{med}}^2\right)^2}{M_{\mathrm{Med}}^4 \left[\left(M_{\mathrm{med}}^2 - 4m_{\mathrm{DM}}^2\right)^2 + M_{\mathrm{med}}^2 \Gamma_{\mathrm{med}}^2\right]}$$

$$\Gamma^{\chi\bar{\chi}}_{\mathrm{vector}} = \frac{g_{\mathrm{DM}}^2 M_{\mathrm{med}}}{12\pi} \left(1 - 4z_{\mathrm{DM}}\right)^{1/2} \left(1 + 2z_{\mathrm{DM}}\right),$$

$$z_i = m_i^2 / M_{\mathrm{med}}^2$$

Width a function of : $g^2{}_{SM}, g^2{}_{DM} m_{DM}$ *and* m_{MED}

For constant m_{DM}, m_{MED}, g_{DM} and $\langle\sigma v\rangle_{relic}$:

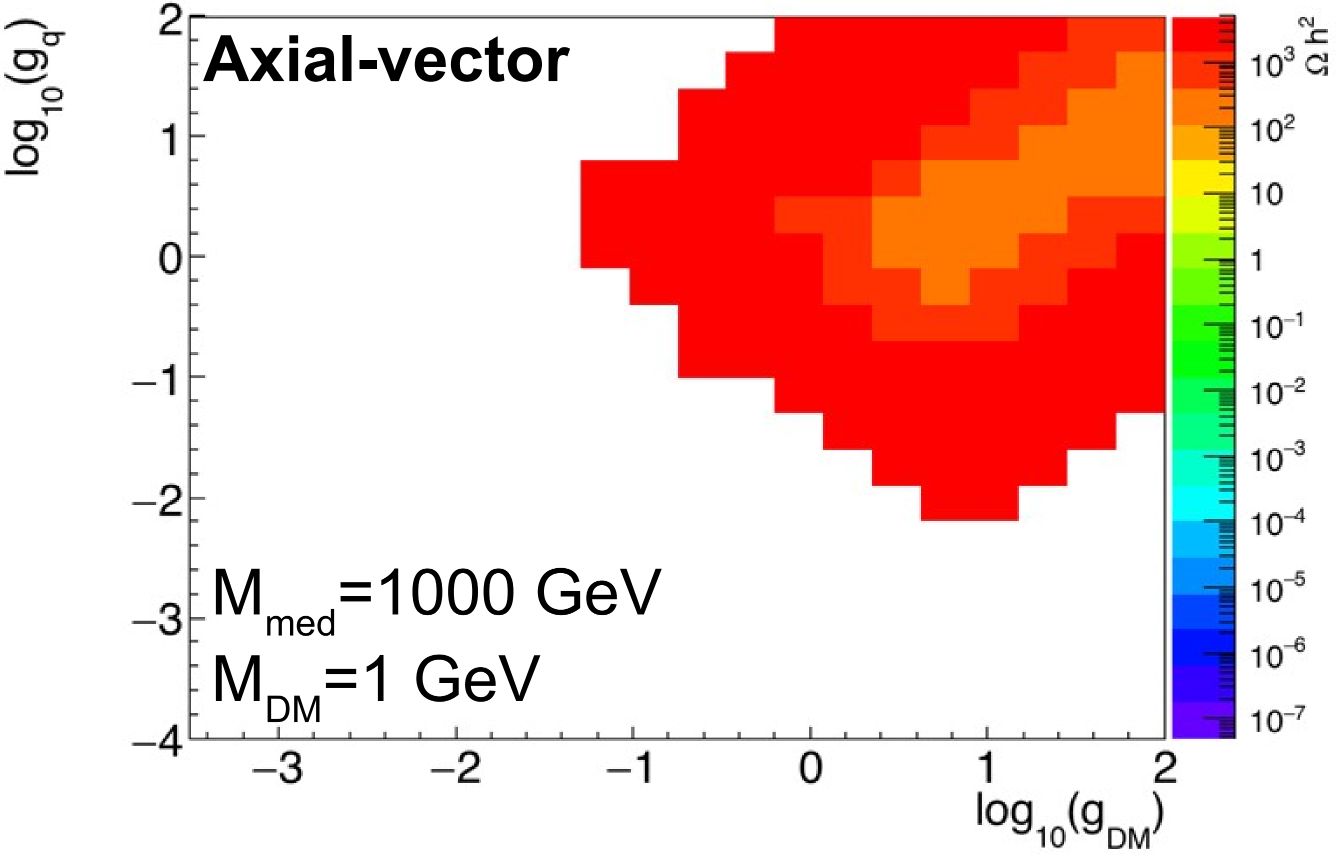
Above form is quadratic in g_{SM} for fixed relic

Yields two possible solutions for the relic density

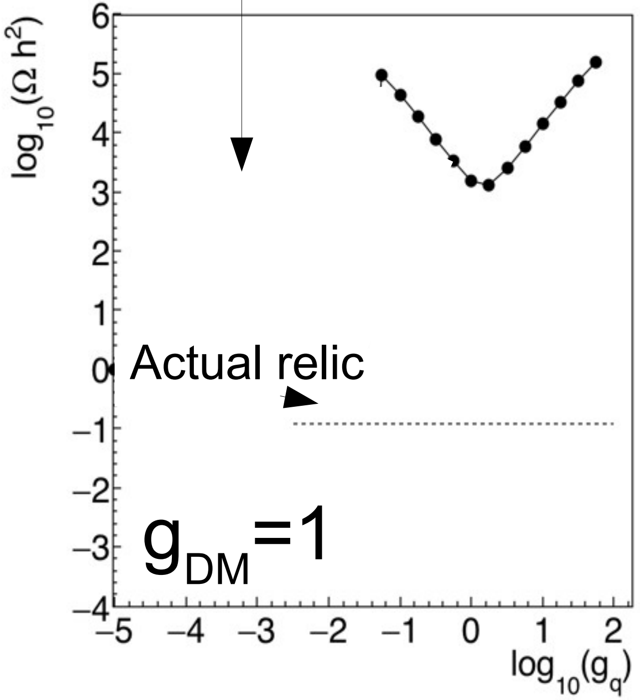
Arxiv:1703.05703

Solving for the relic

- We can numerically solve for the solution



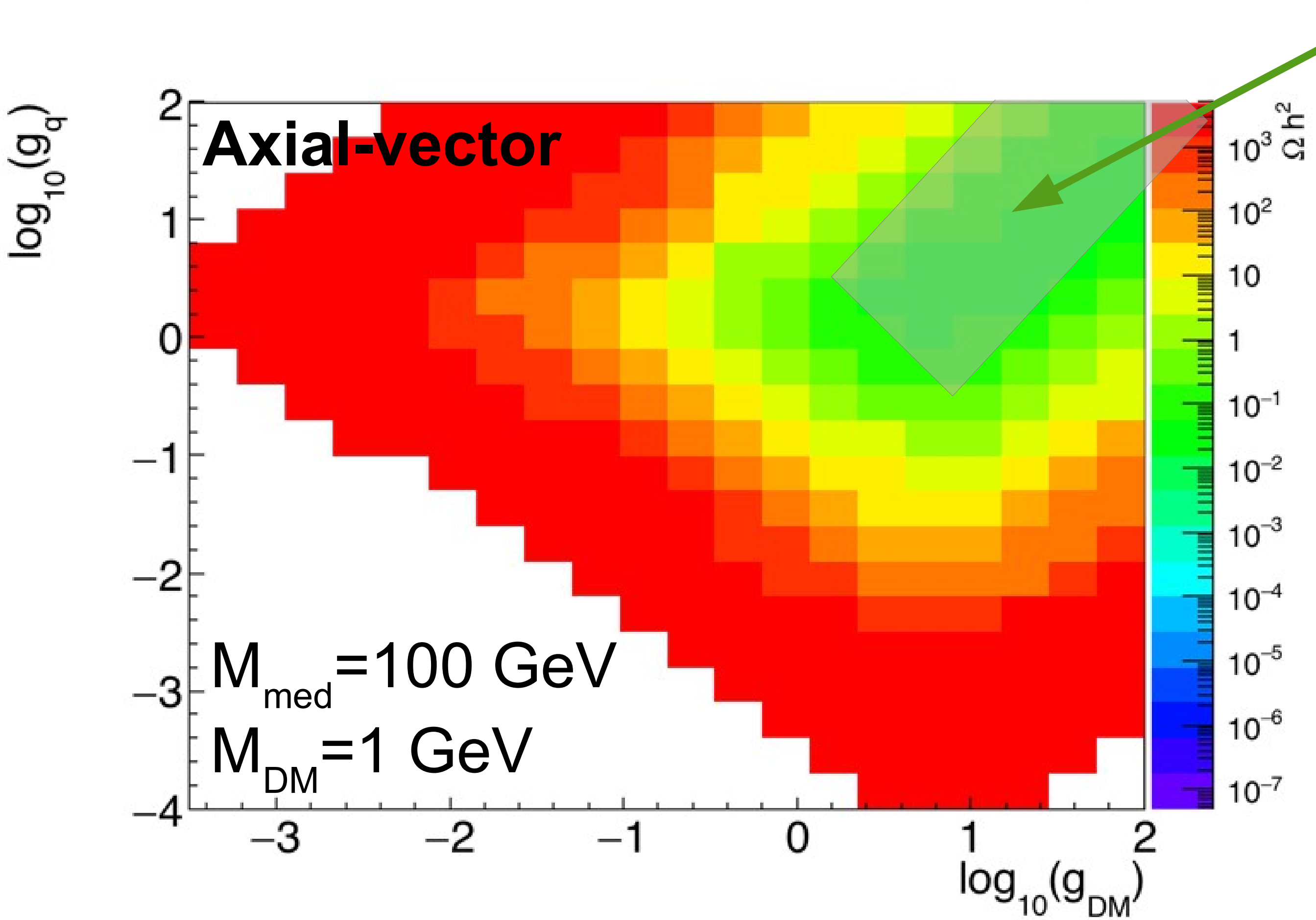
Fixing the DM coupling

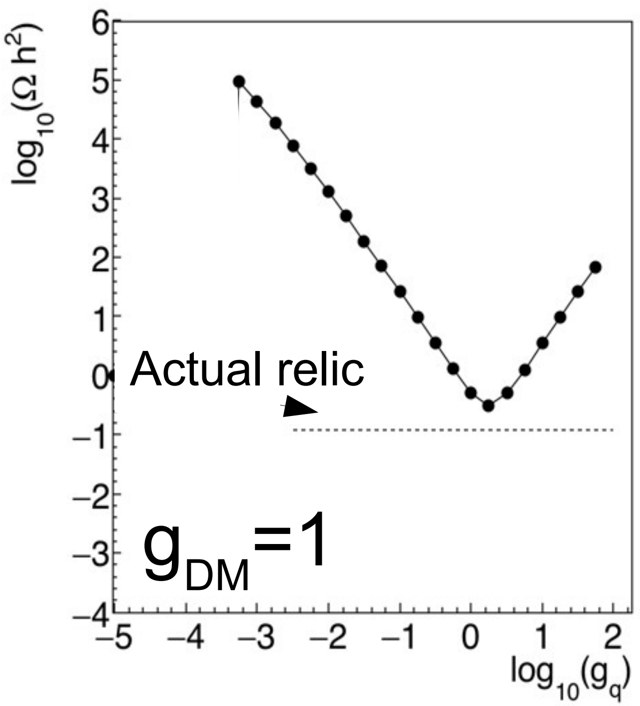


For a large mediator we have no allowed solution

Solving for the relic

- We can numerically solve for the solution



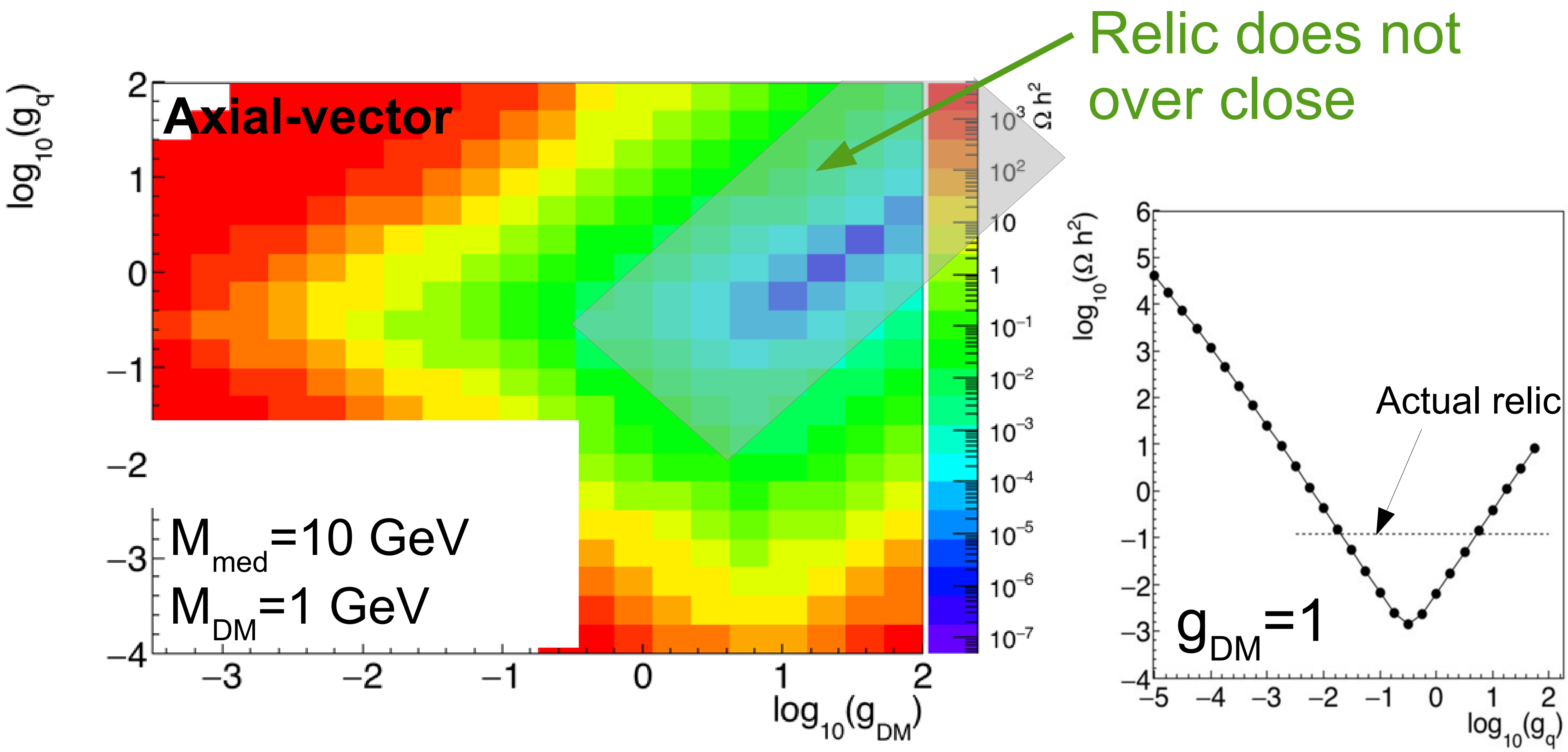


For smaller mediators allowed solution

Arxiv:1703.05703

Solving for the relic

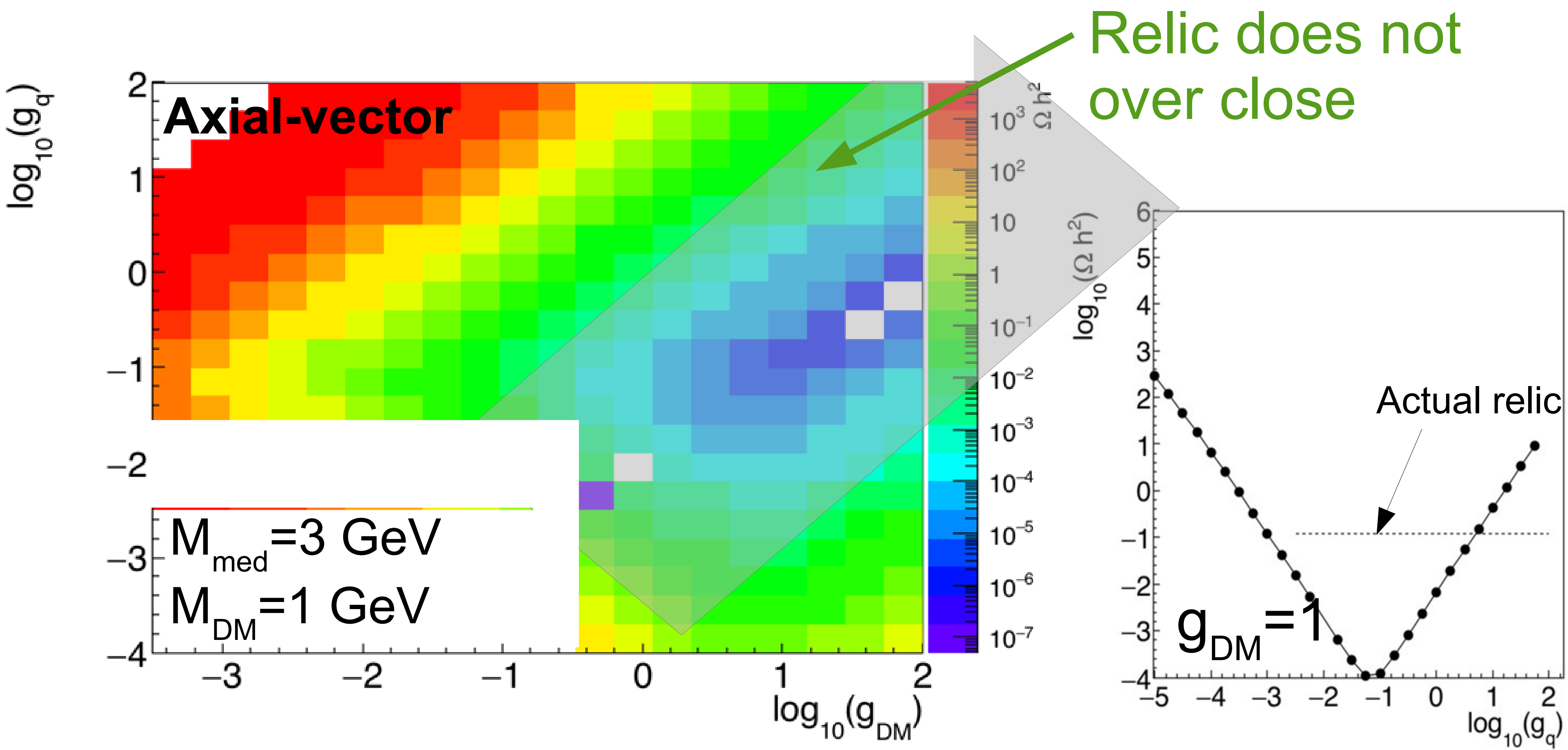
- We can numerically solve for the solution



Arxiv:1703.05703

Solving for the relic

- We can numerically solve for the solution

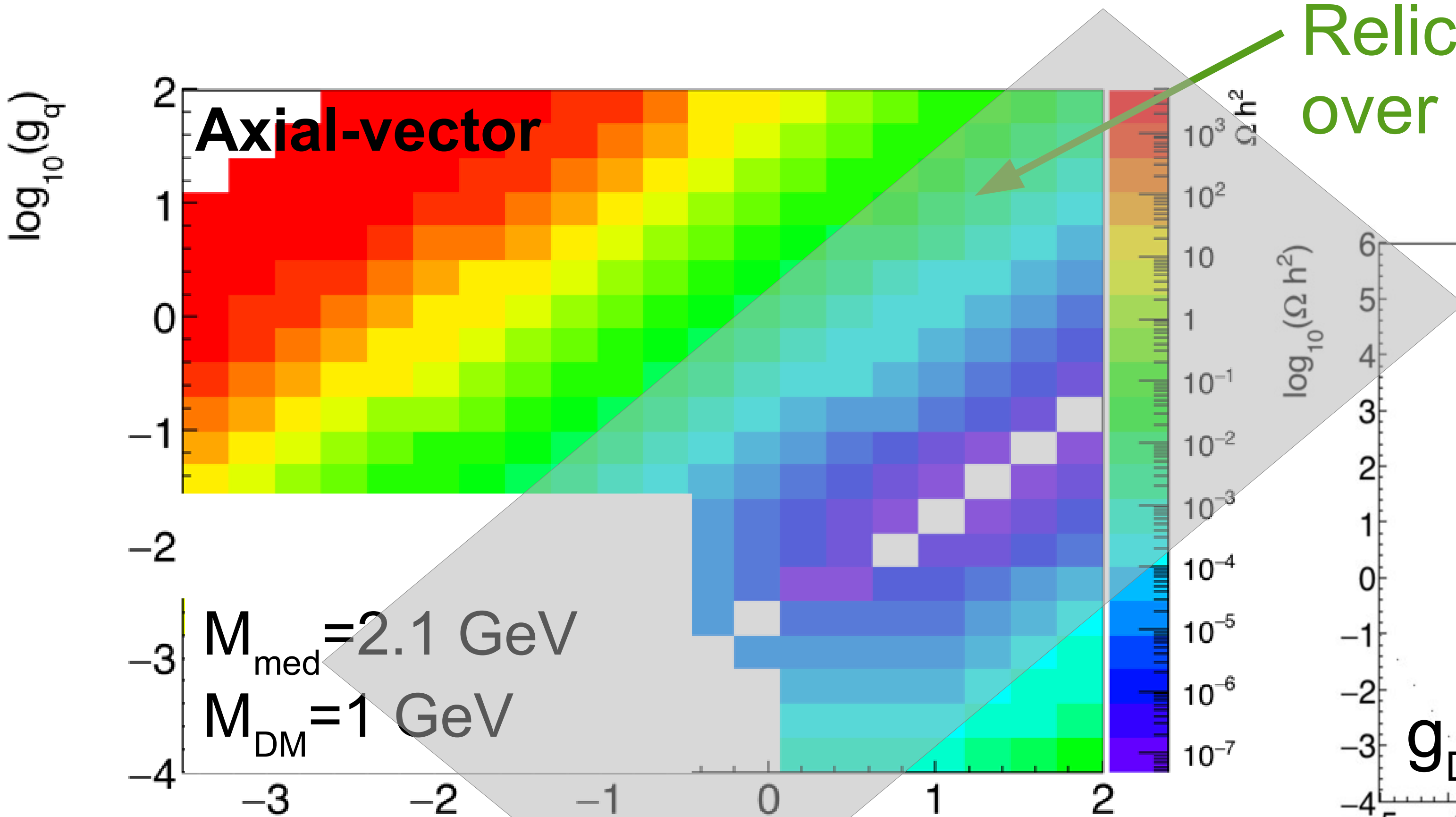


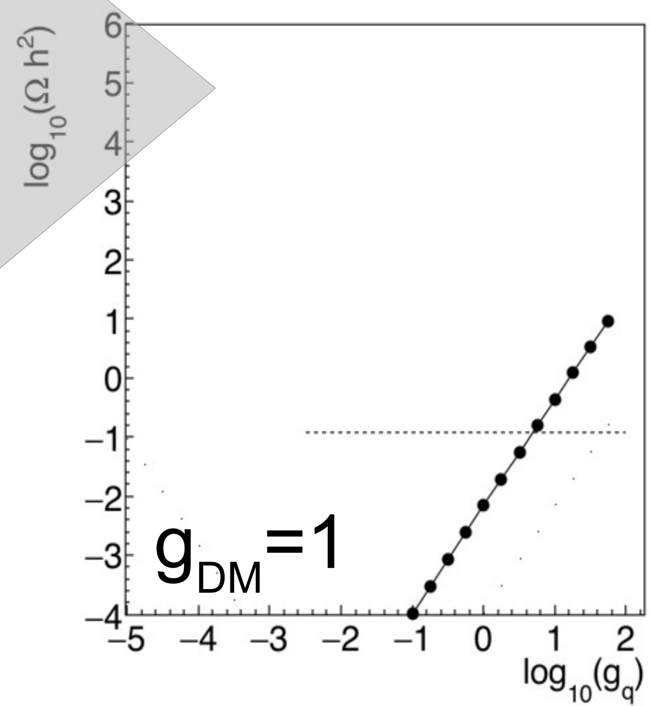
Arxiv:1703.05703

Solving for the relic

- We can numerically solve for the solution

Relic does not over close





Bounds are driven by $(g_q g_{DM})^2$

Arxiv:1703.05703

A common theme of DM talks

- For a constant value of:

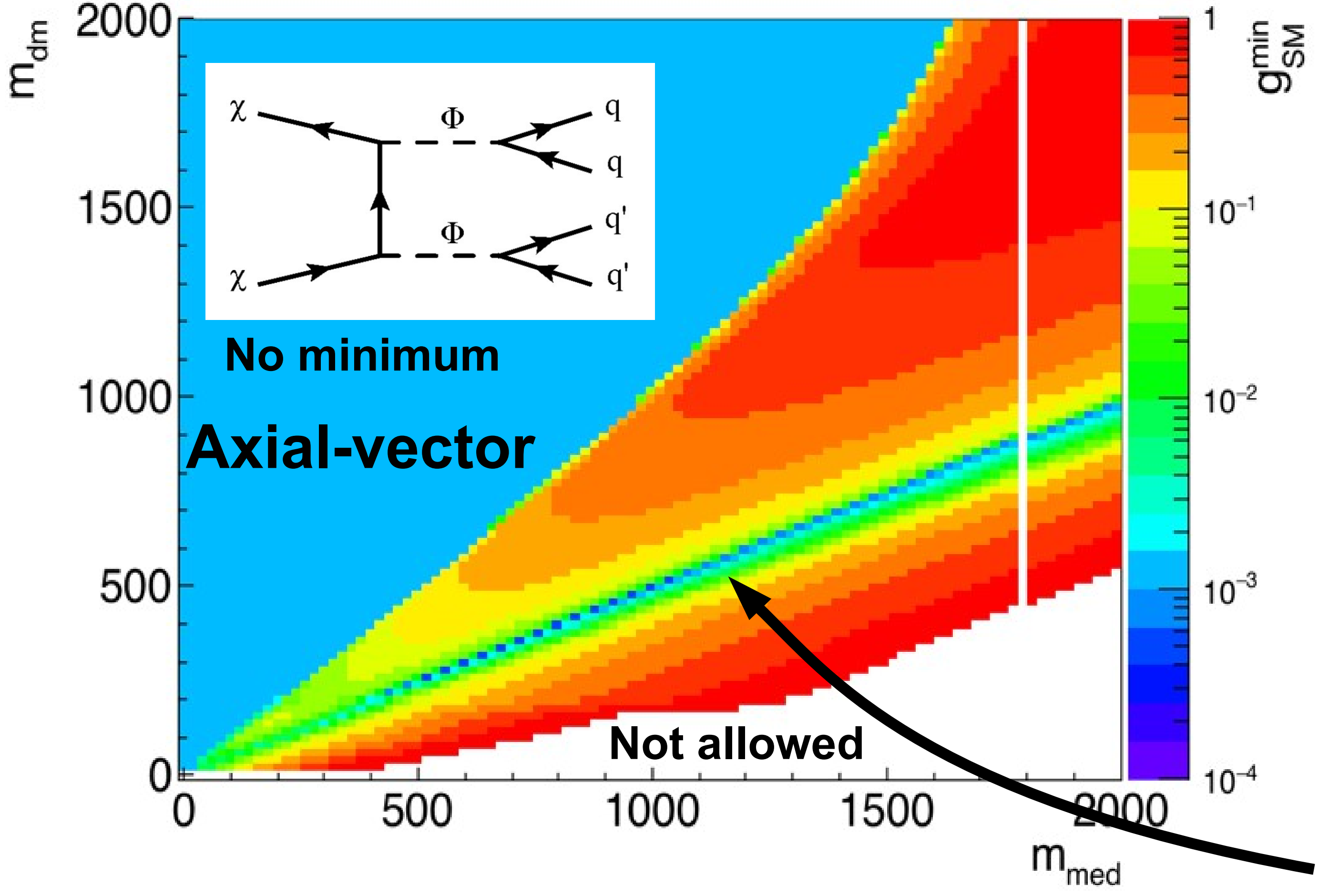
  - $(g_q g_{DM})^2 = C$

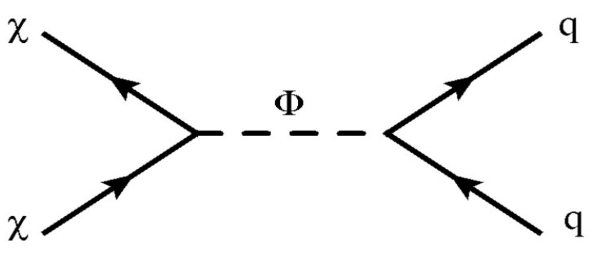
Set this to be large
still get right relic

Set this to be small
Weak coupling with the SM

Min couplings

- Can split the solution to the max and min coupling
  - In this case we fix $g_{DM}=1$ (product $g_q g_{DM}$ defines bound)





Min couplings

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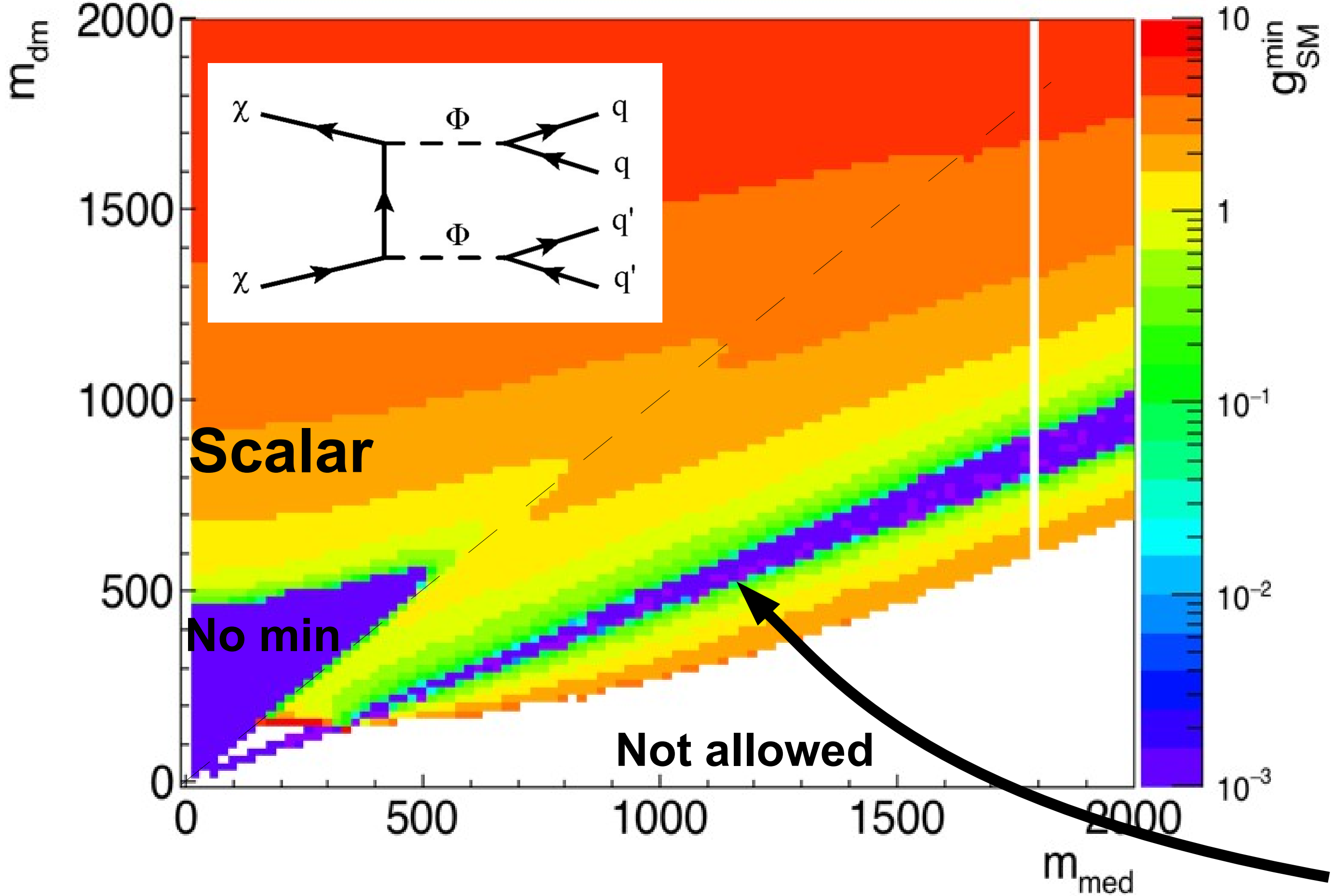
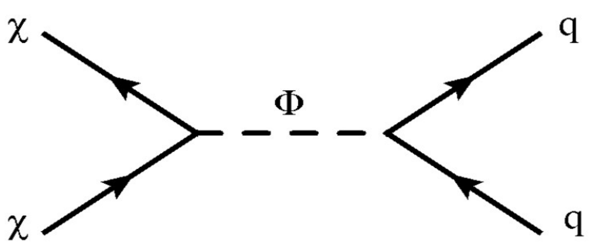
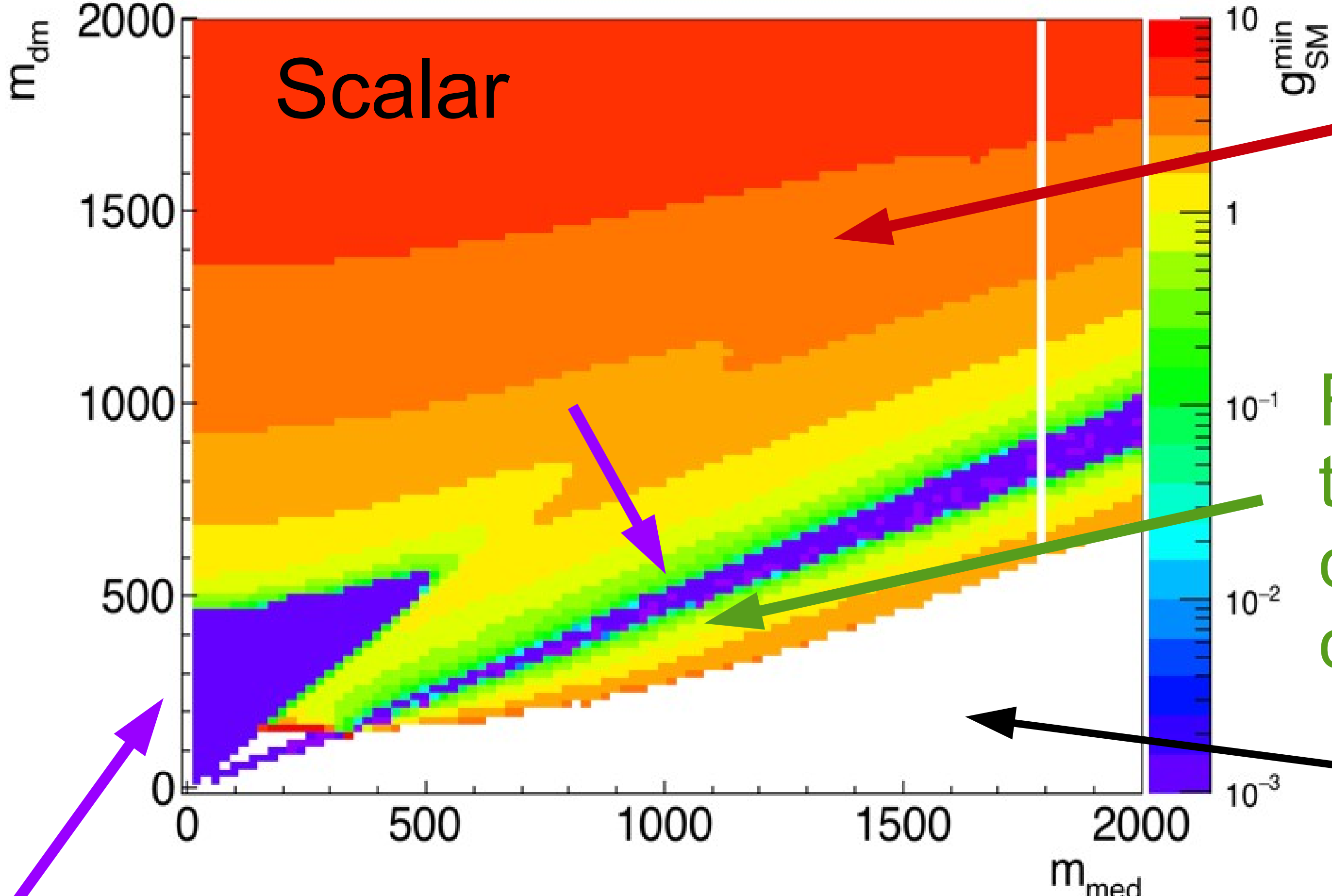




What do we conclude?

- What is driving the results is the coupling



Regions that generally overclose

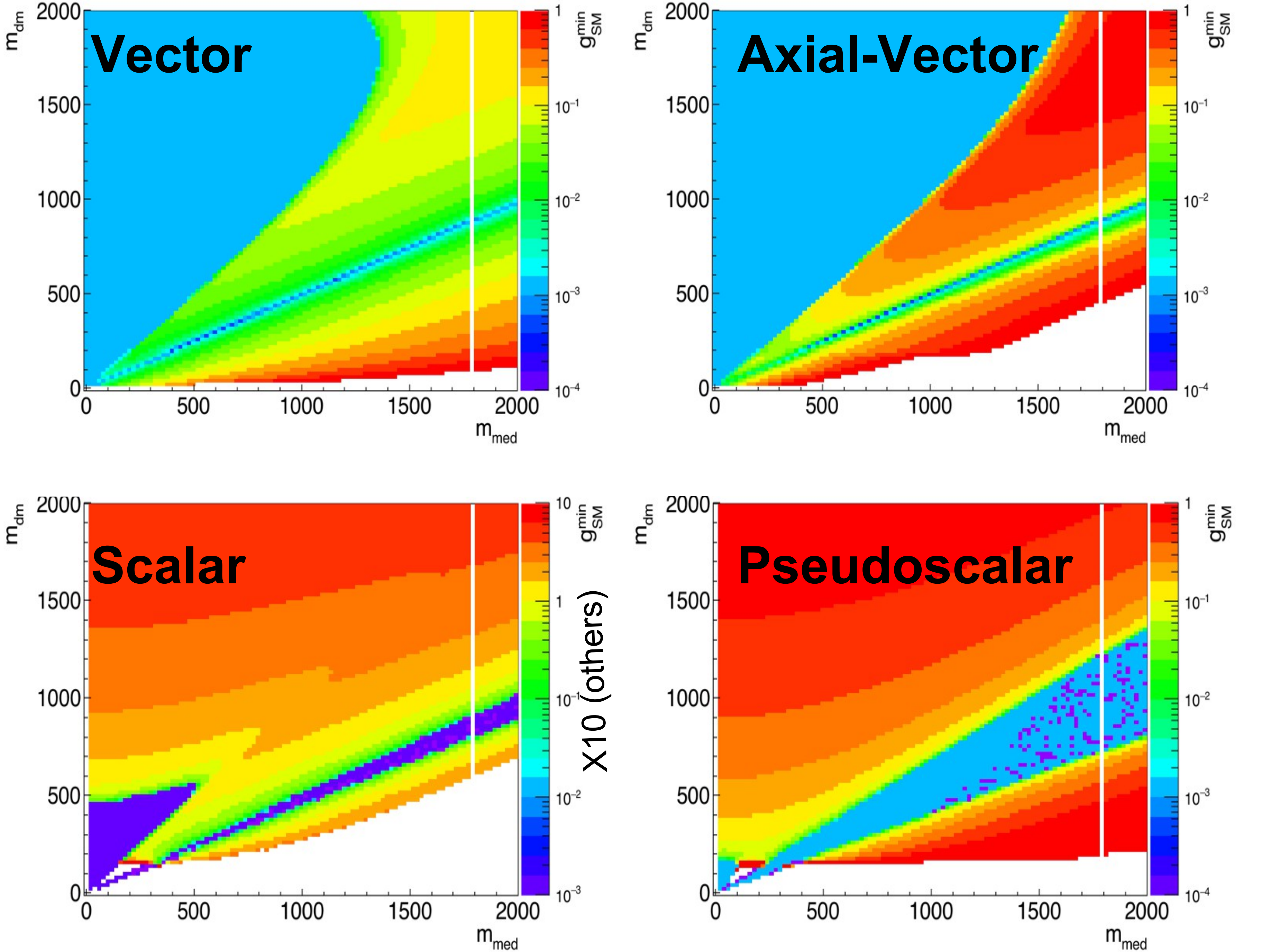
Regions we can try to probe with current or future colliders

Regions that are forbidden

Regions generally free Of relic constraints

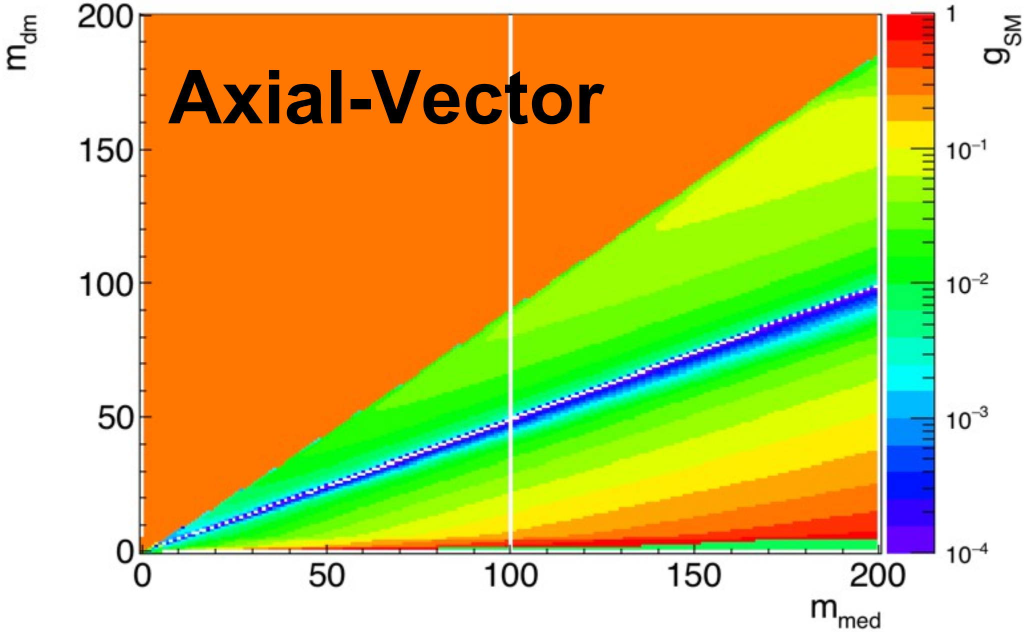
Aim for $0.1 < g_{SM} < 3$

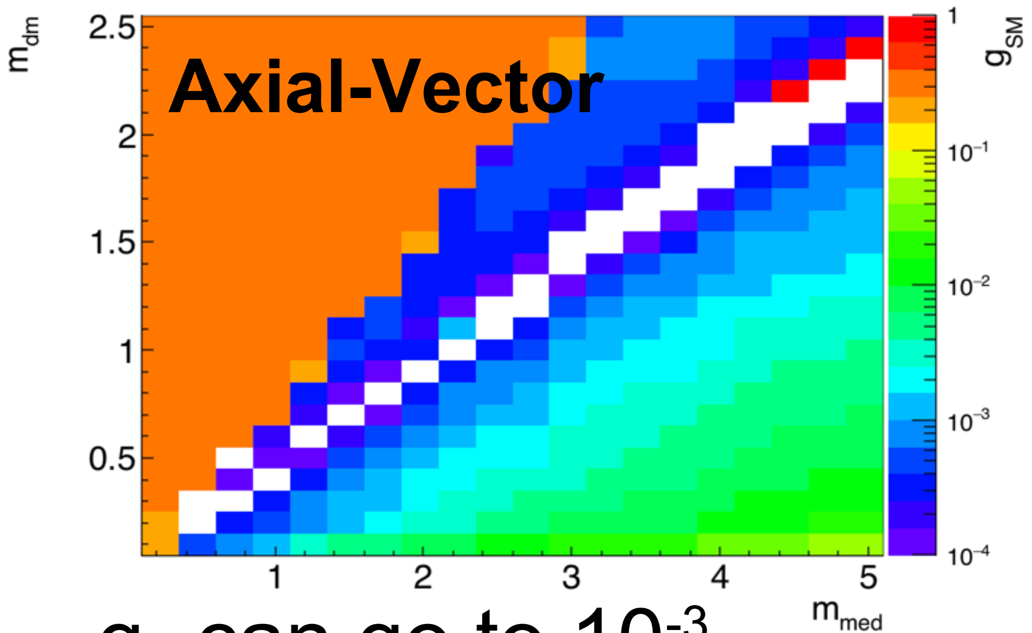
Min Couplings for all



What about at low mass?

- Coupling becomes a real challenge





g_q can go to 10^{-3}

At low masses we can have very small couplings

However we have more strategies

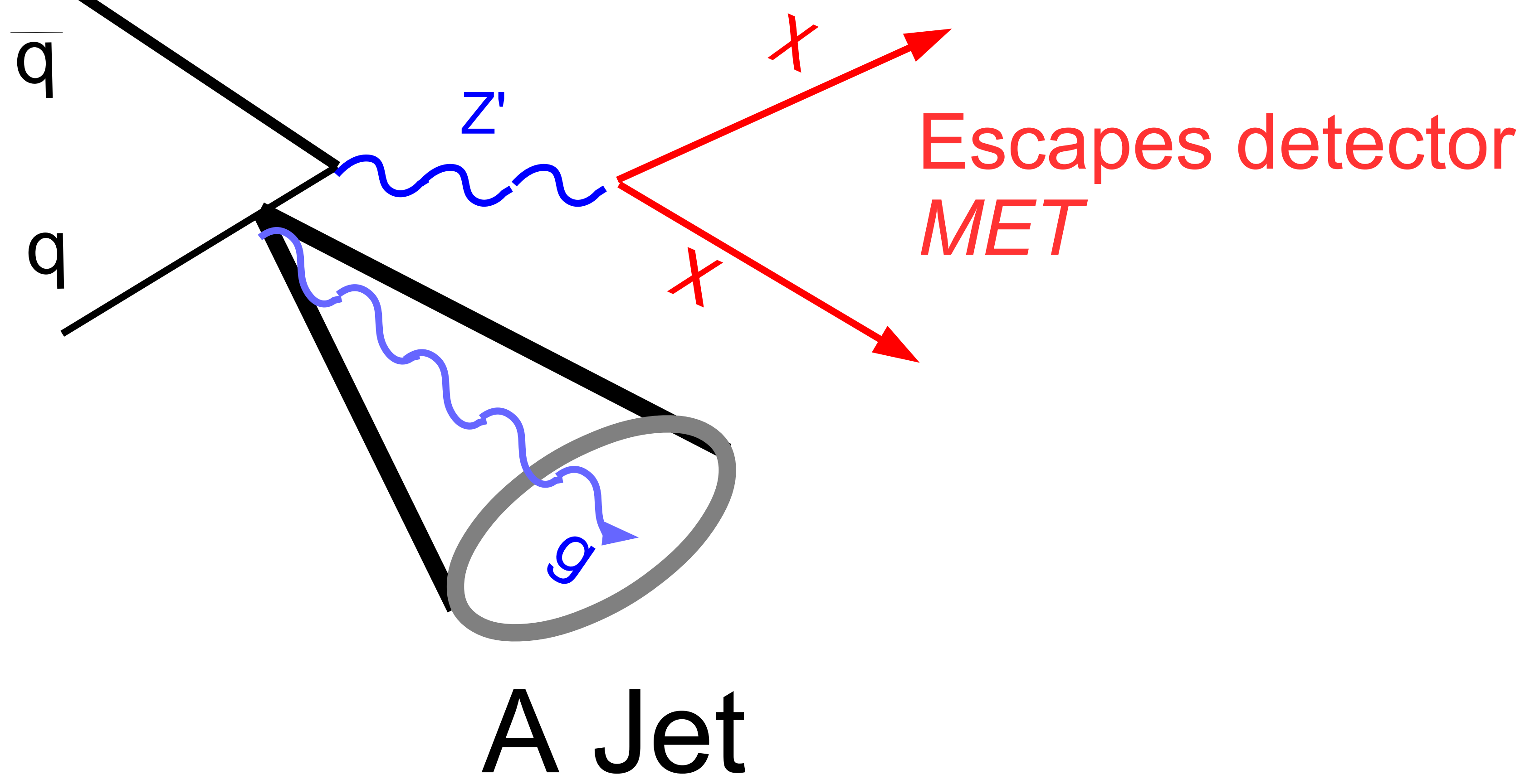
Summary Benchmarks

- Spin 1 :
  - Aim to probe couplings down 0.01 for m_{Med} > 100 GeV
  - For 10 < m_{Med} < 100 GeV aim to probe down to 10^{-3}
  - For m_{Med} < 10 GeV aim to probe coupling to 10^{-4}
- Spin 0 :
  - Aim to probe couplings down 0.1 for m_{Med} > 300 GeV
  - Try to cover m_{Med} < 300 by any means possible
- Covers most of the phase space

Collider Searches

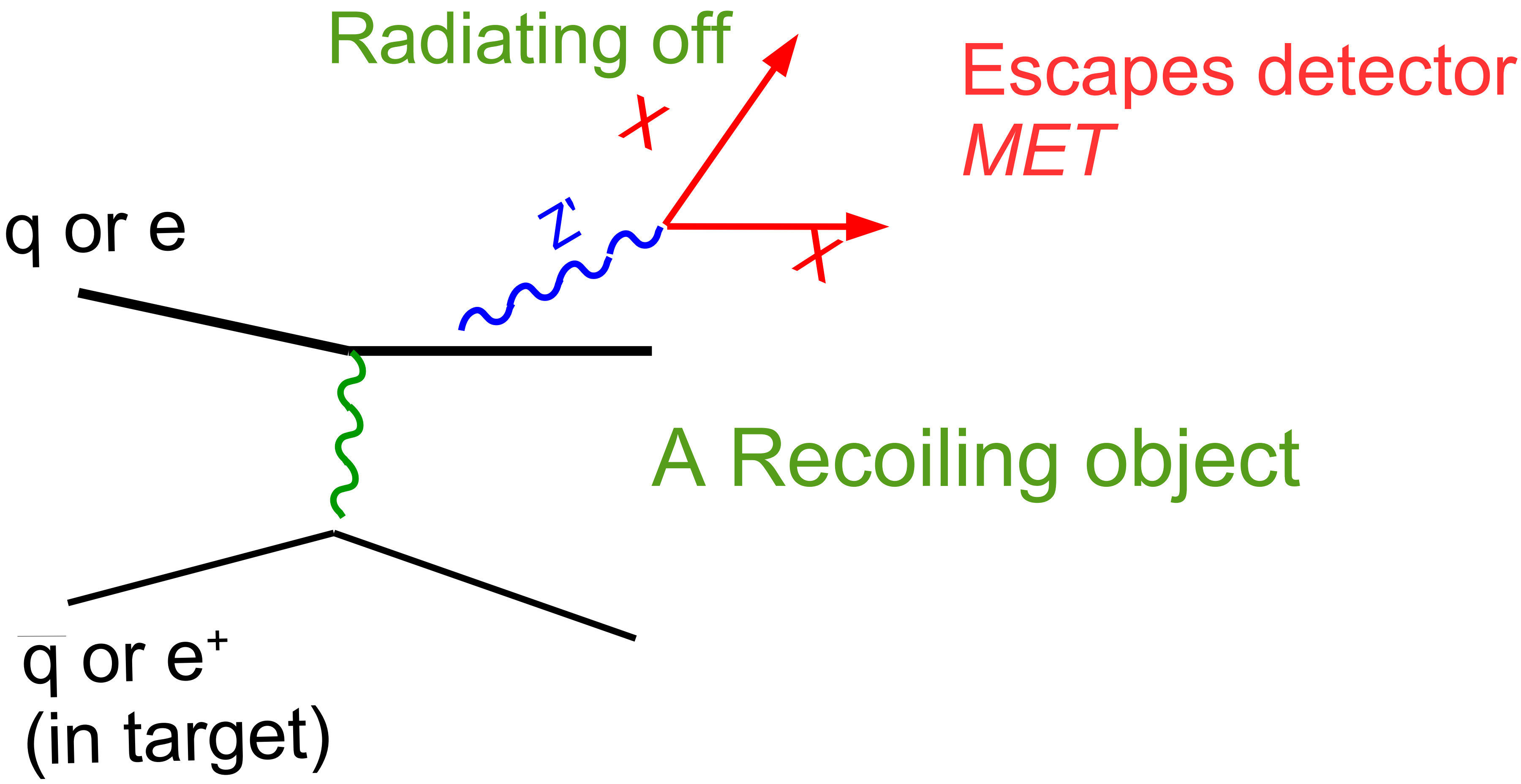
The Basic Monojet Search

Escaping detector gives us signatures of *MET*



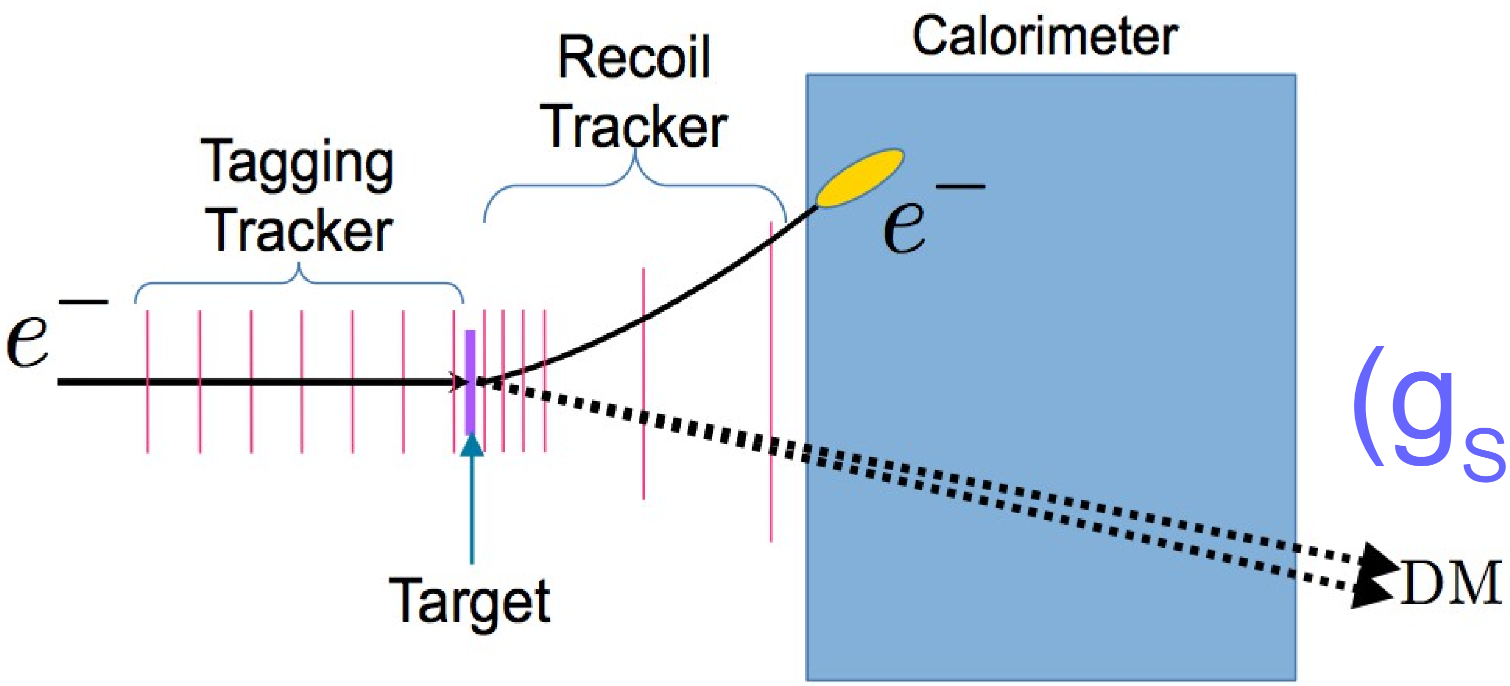
At Low masses

We still get *MET signatures but with other stuff*



@low mass aim is for low couplings

To probe small couplings you need very high rates
This is something we can do with a beam dump

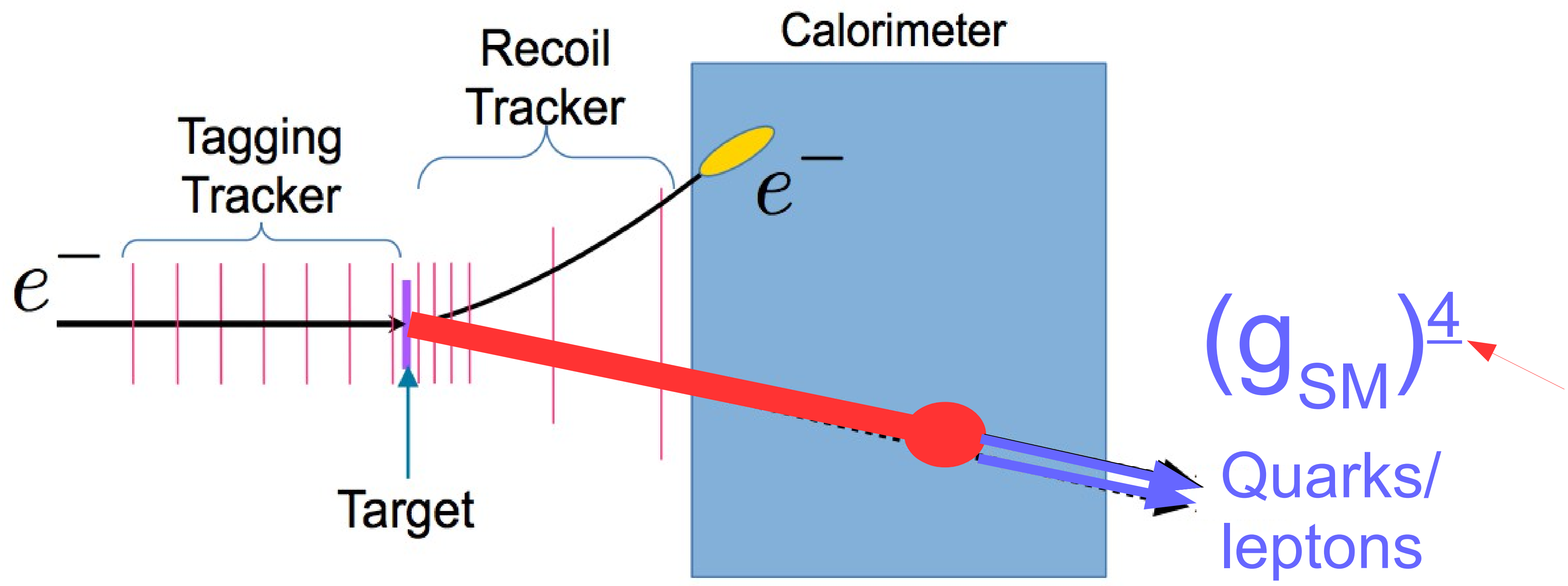


$(g_{SM} g_{DM})^2$

Now many experiments being made or proposed

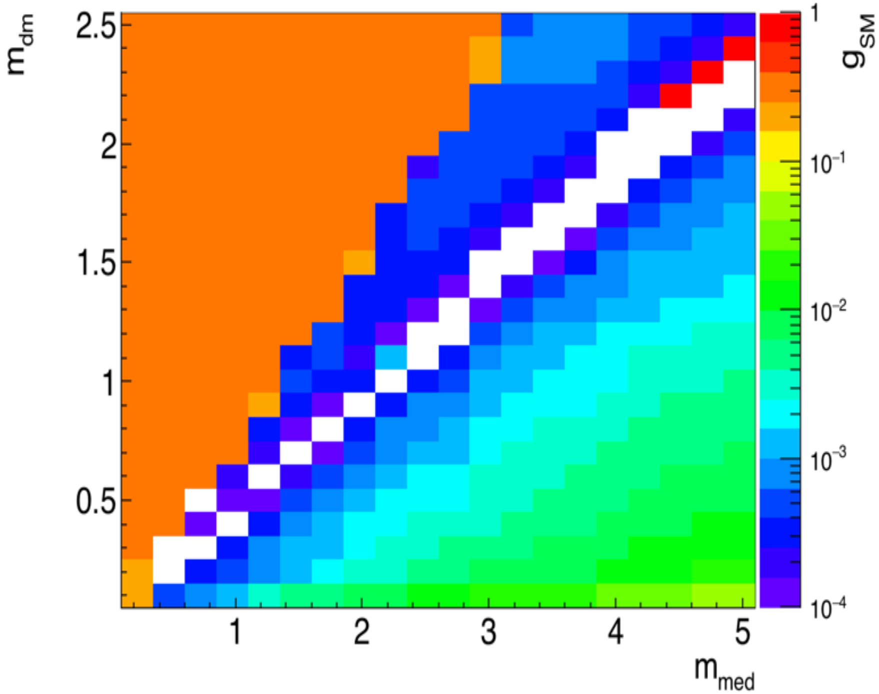
@low mass aim is for low couplings

To probe small couplings you need very high rates
This is something we can do with a beam dump



Alternative approach is to look for decays from dm
Suppressed if SM coupling is small

@low mass aim is for low couplings

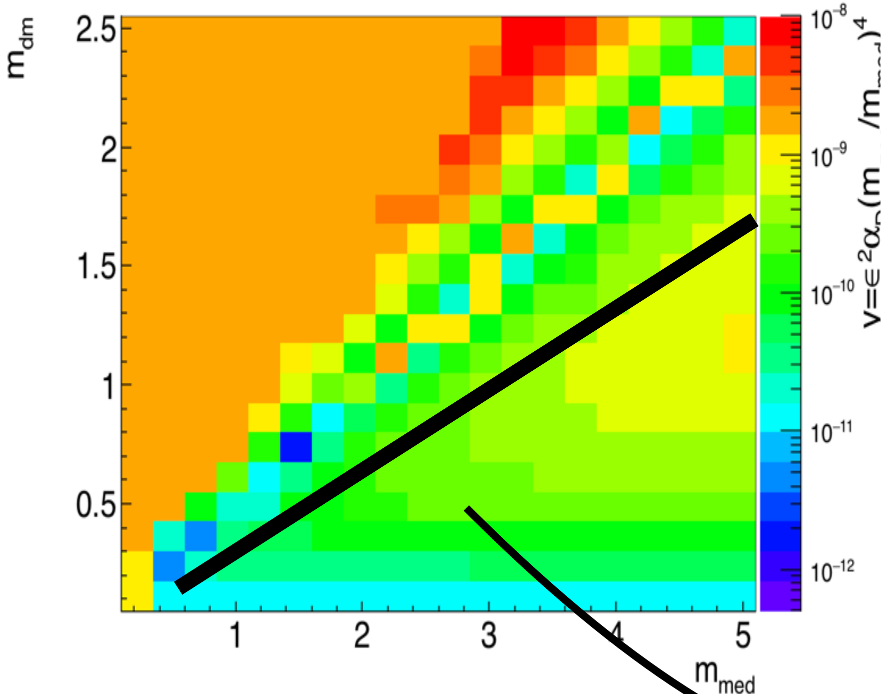


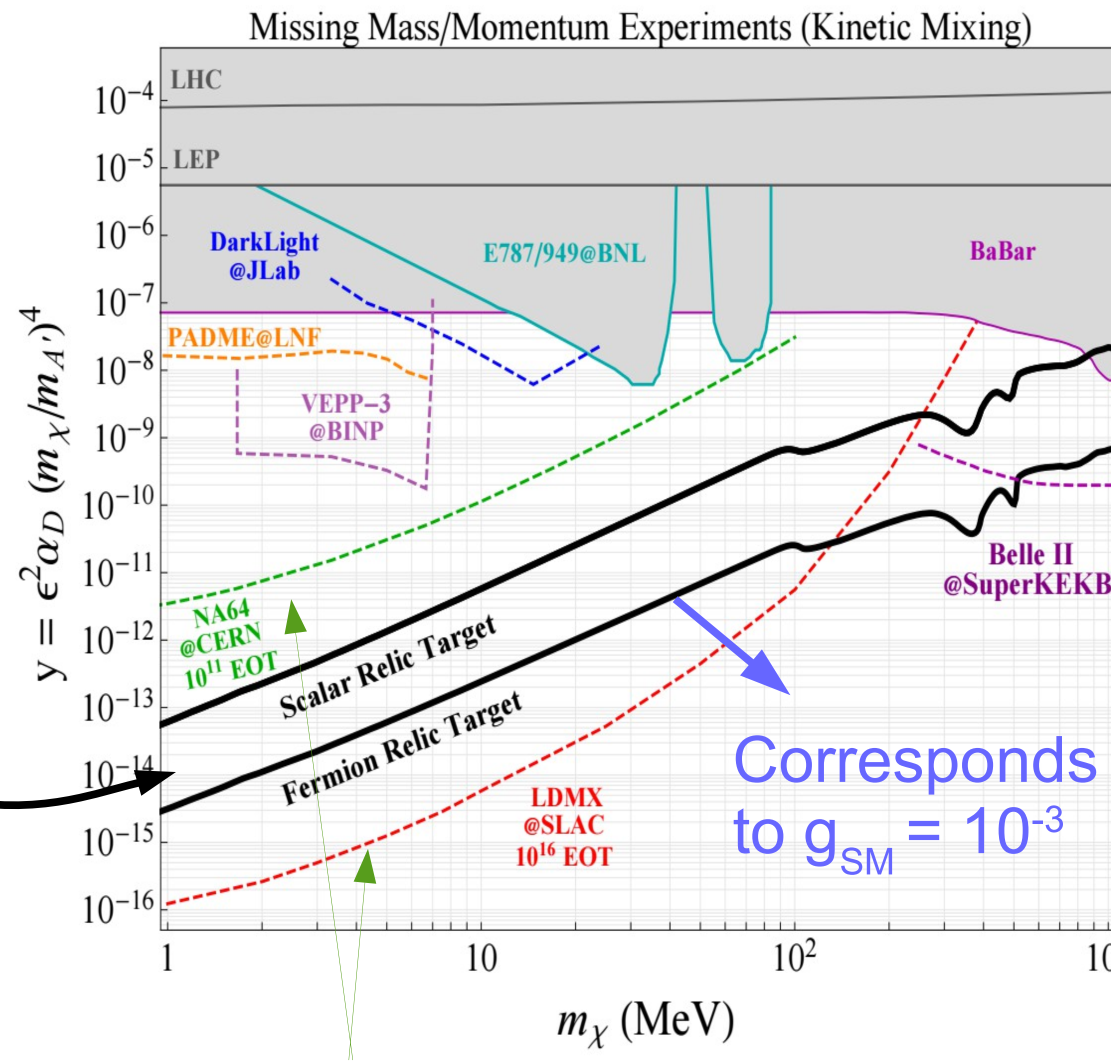
At low mass we want to probe the $g_{SM}=10^{-4}$ region

However, just to confuse everybody

Coupling units are changed : $\varepsilon^2\alpha_D(m_{DM}/m_{MED})^4$

@low mass aim is for low couplings





Consider a diagonal projection m_{DM}/m_{MED} = 1/3

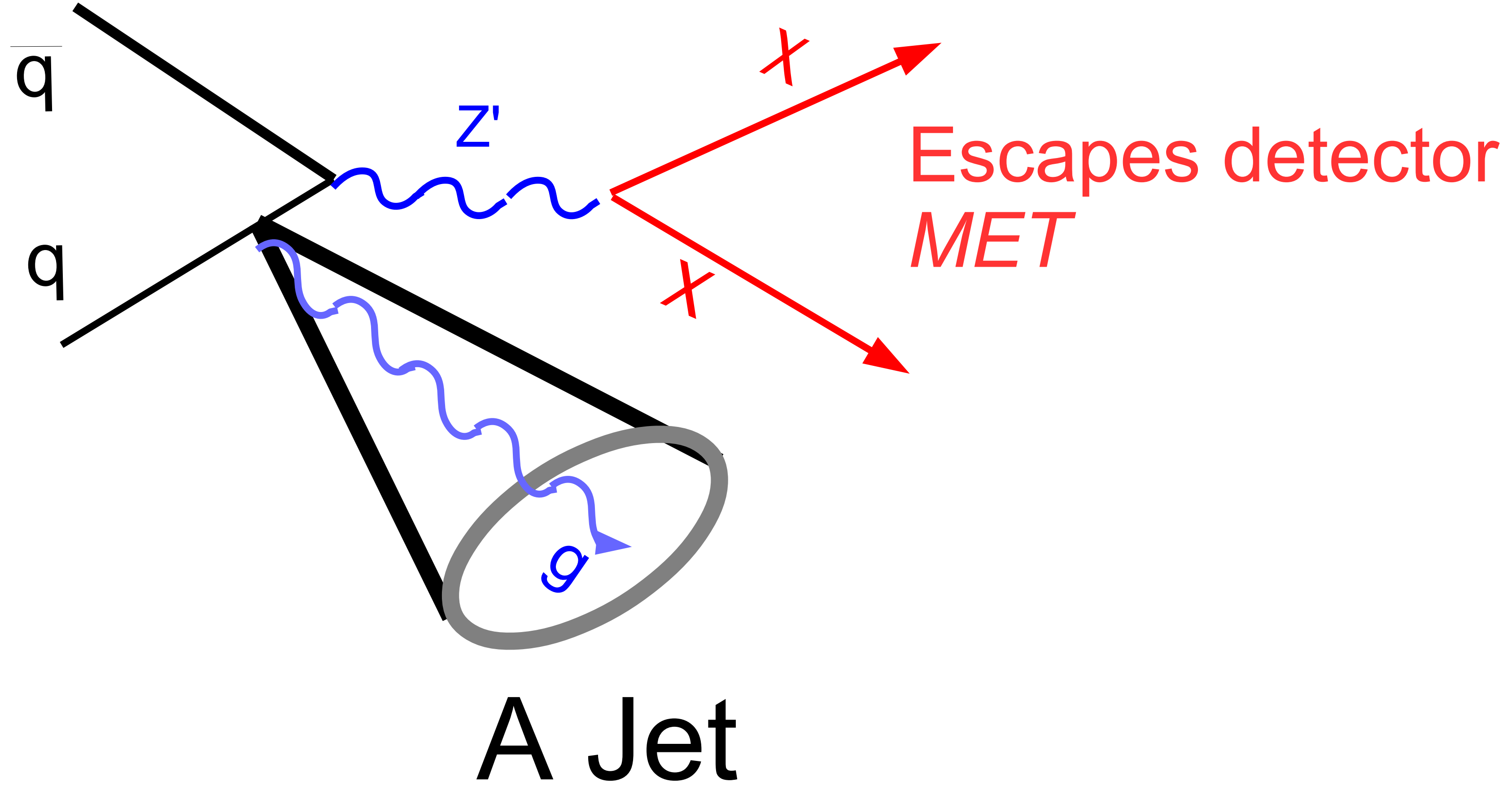
Corresponds to $g_{SM} = 10^{-3}$

Reach of a few proposed beam dump experiements

Can probe the interesting region

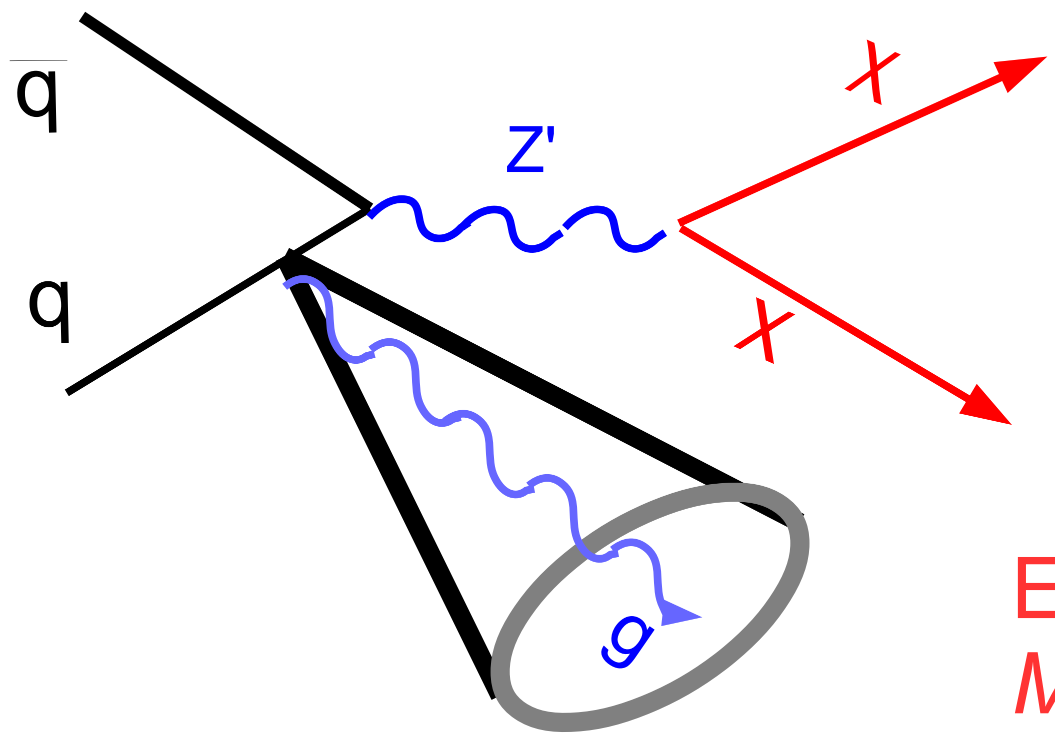
The Basic Monojet Search

Escaping detector gives us signatures of *MET*



Monojet search
Straddling SM and BSM

Searching for *MET*



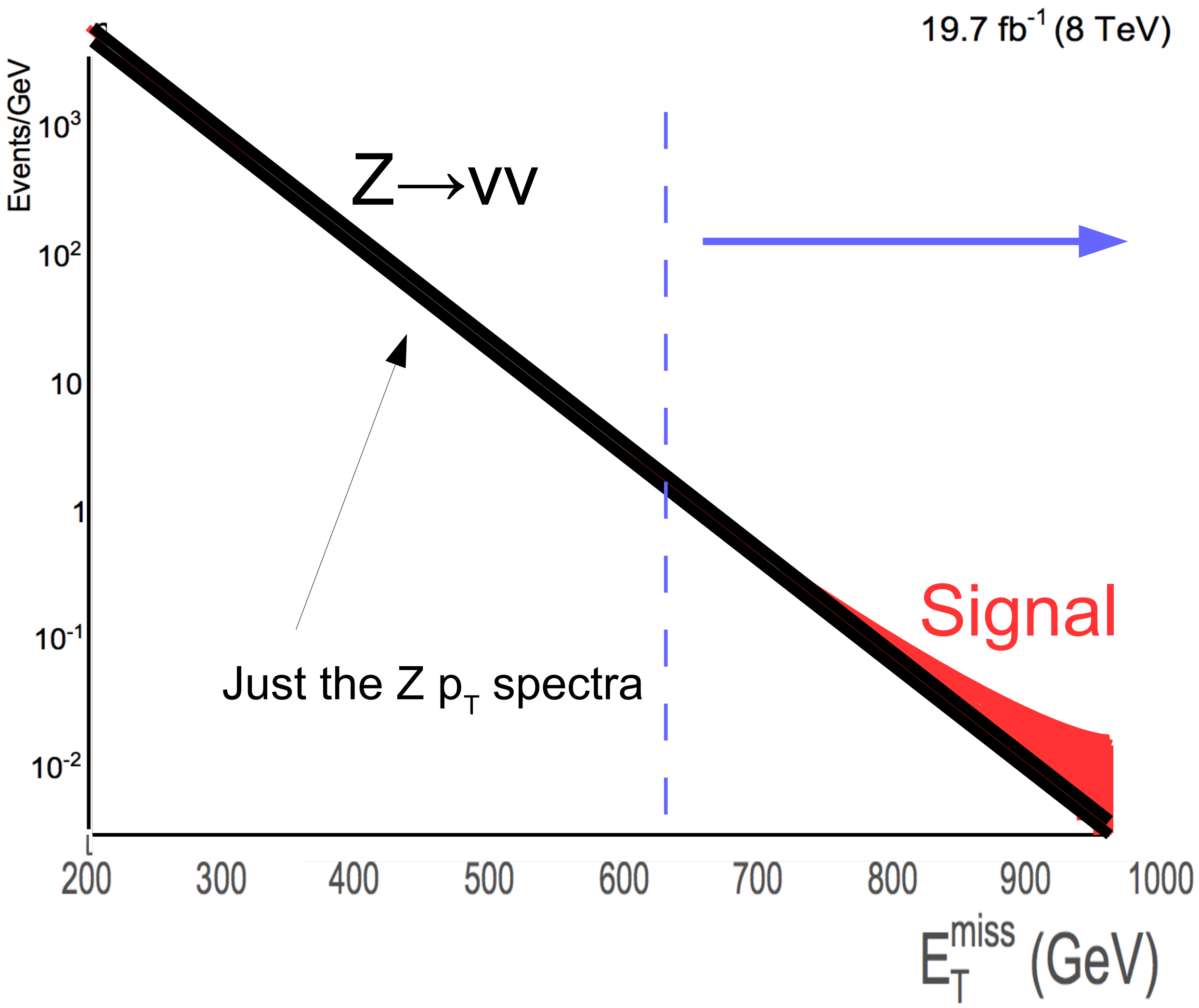
Escapes detector
MET

"To find nothing you have to reconstruct everything"[1]

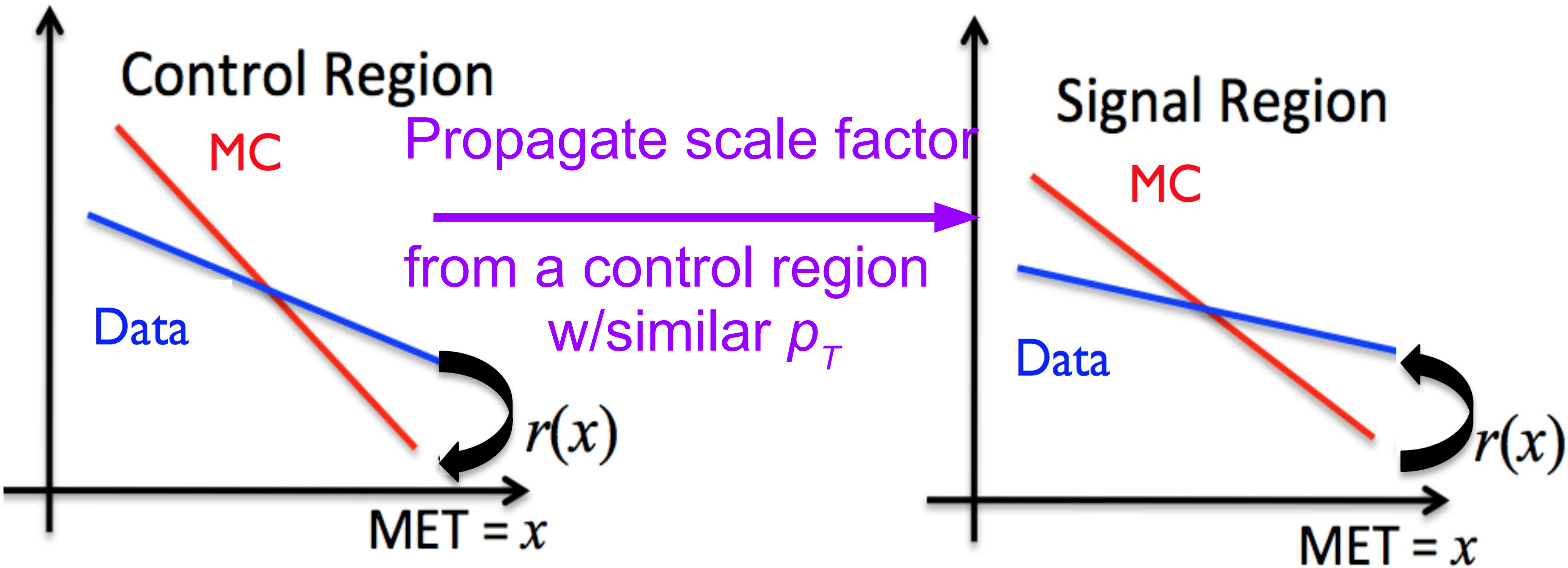
$-\Sigma_{All\ particles}\ p_T = MET_{(E_T^{Miss})}$

$-\text{Boson}\ p_T = MET_{(E_T^{Miss})}$

How do we search?



Strategy to fix agreement



Control: another decay of a Z boson

$Z \to \cancel{\mu\mu} \xrightarrow[\text{Remove}]{} Z \to \nu\nu$

hadronic recoil : Transverse sum of all particles in event excluding leptons/photons

CMS-EXO-16-037
CMS-EXO-16-010
CMS-EXO-12-055

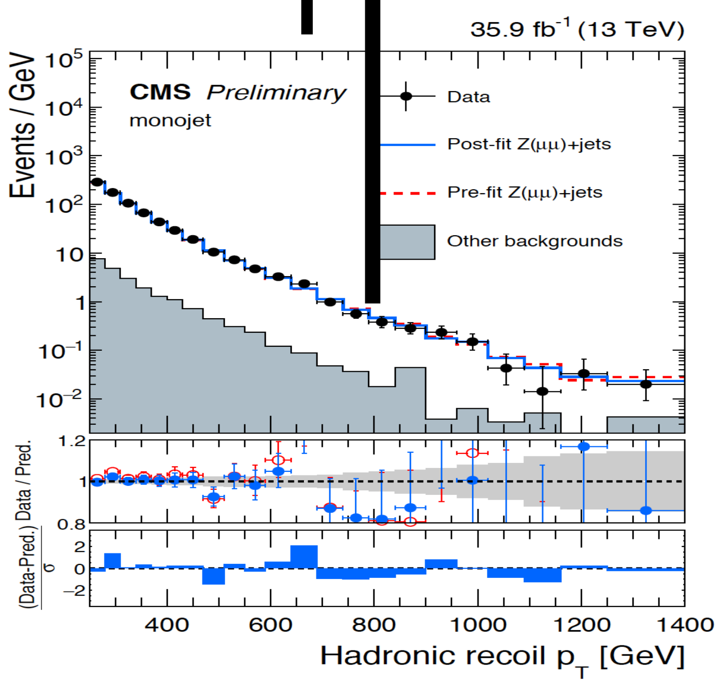
What is the transfer factor?

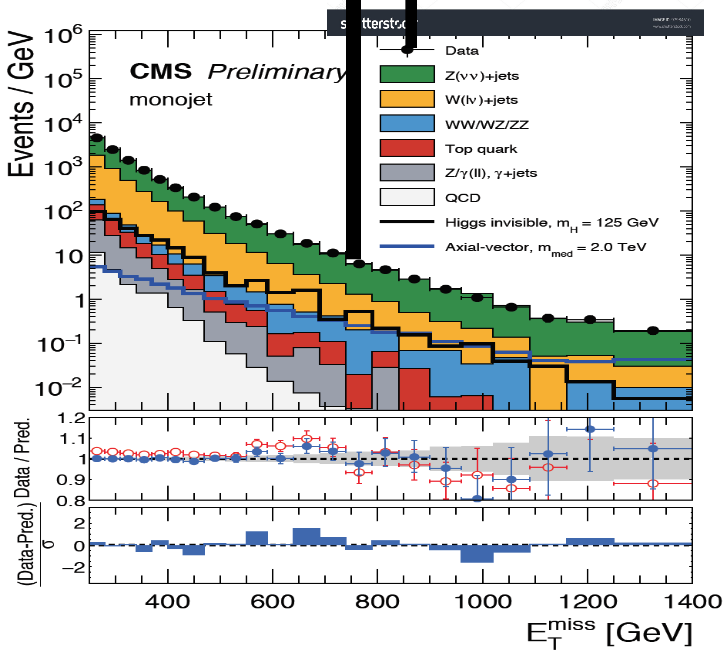
Propagate the data/MC agreement of the hadronic recoil
From a control region to a signal region

Control

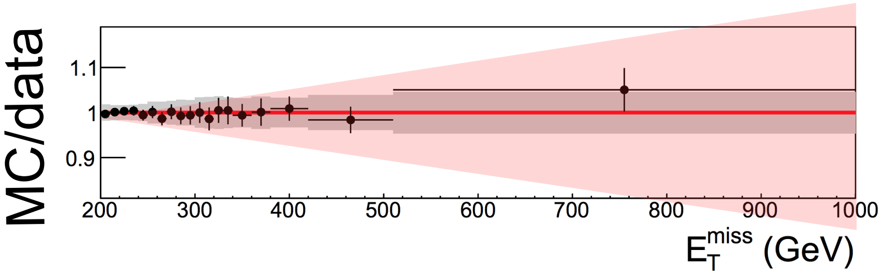
Signal

control bin welded to signal bin

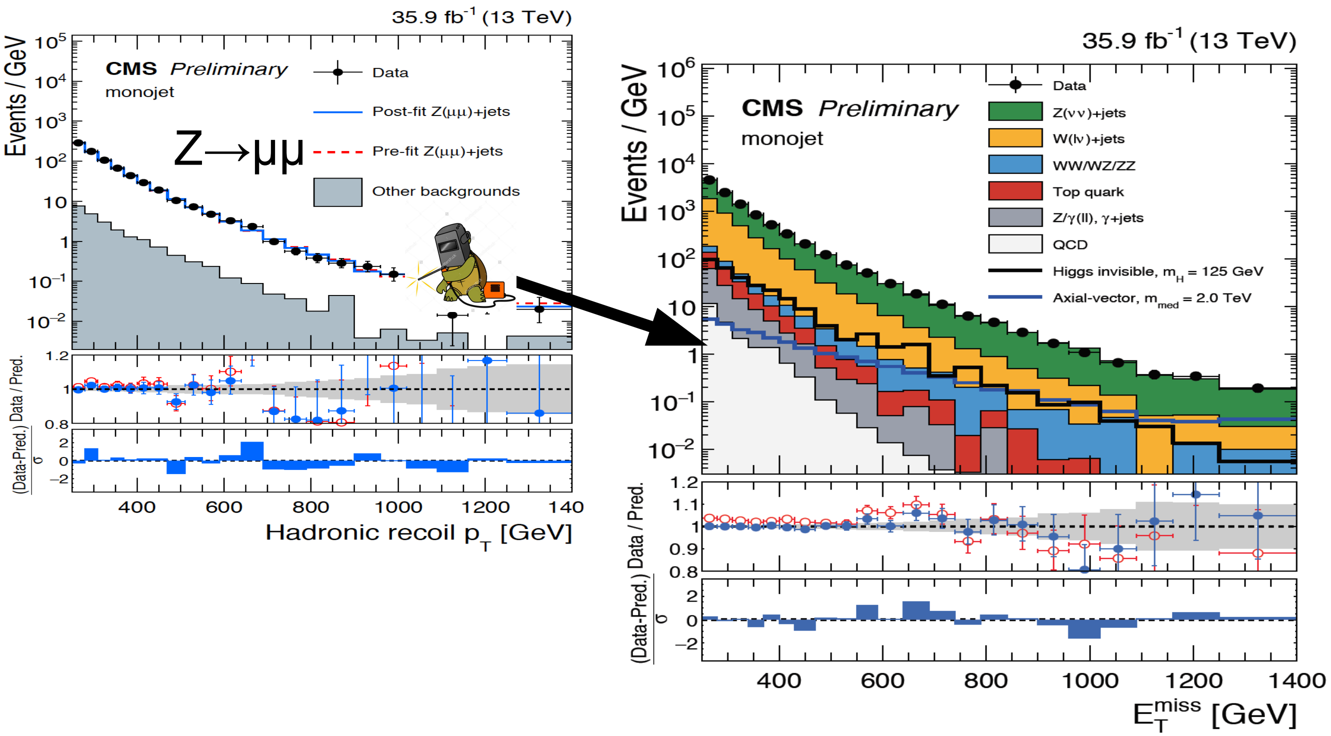




CMS-EXO-16-052



1 Control region
100% uncertainty @ 1 TeV



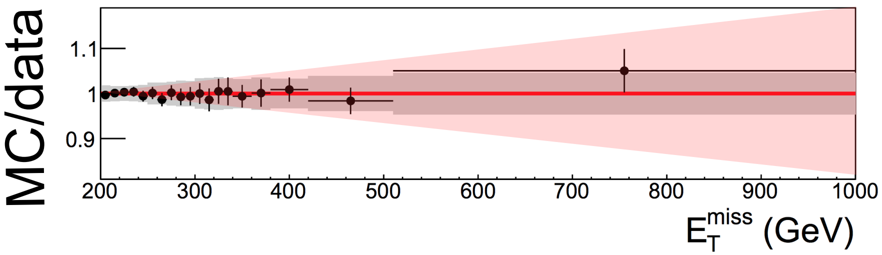
Control regions have less events than signal

$\sigma_{\mu\mu} = 0.1\ \sigma_{\nu\nu}$

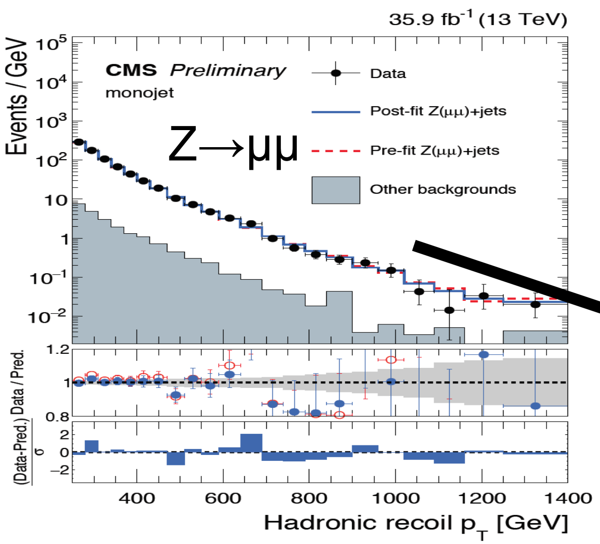
Statistical precision is 4x worse

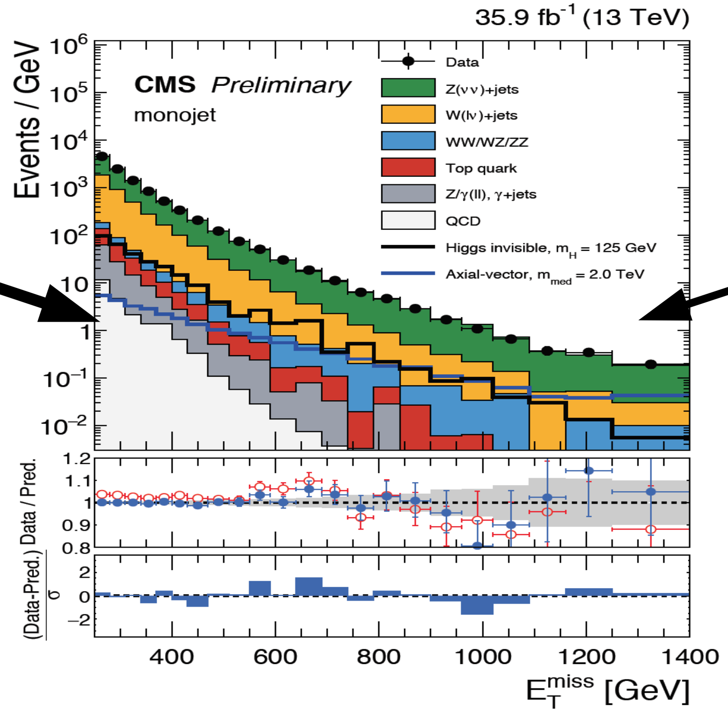
Not good enough!

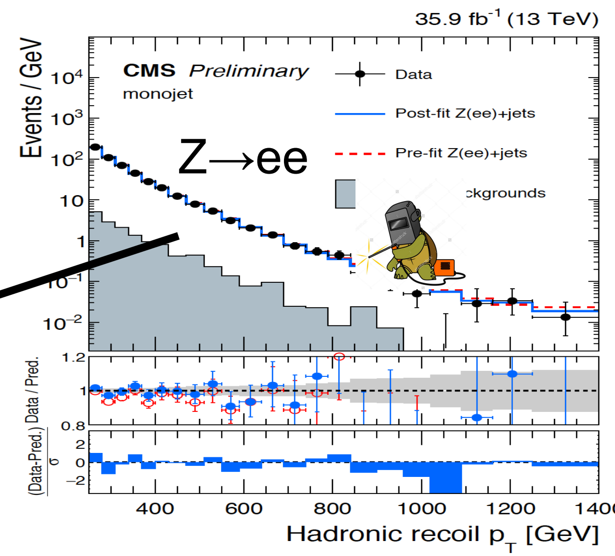
CMS-EXO-16-052



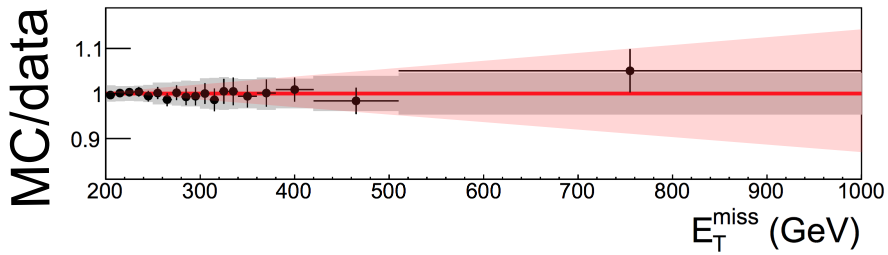
2 Control regions
60% uncertainty @ 1 TeV



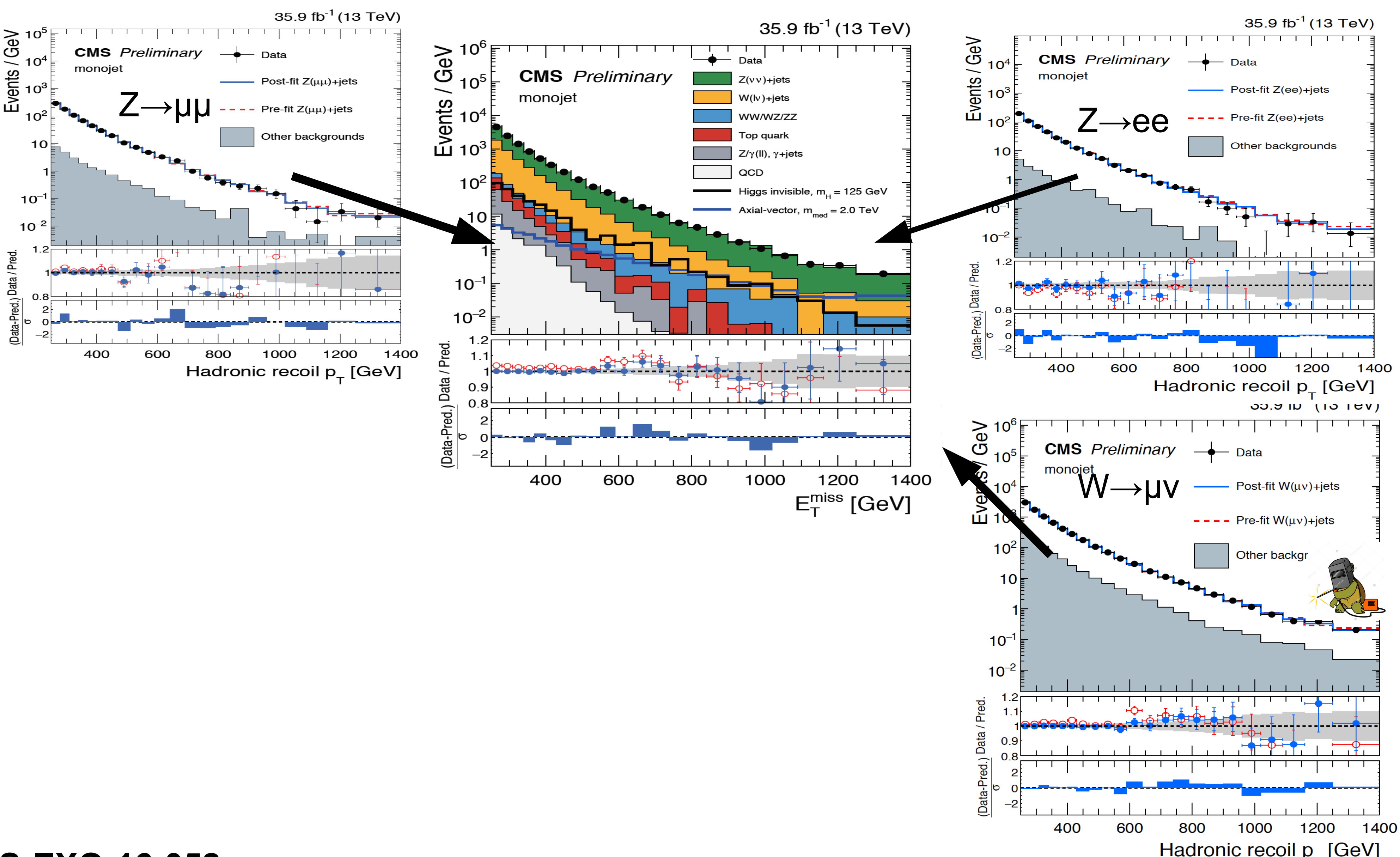




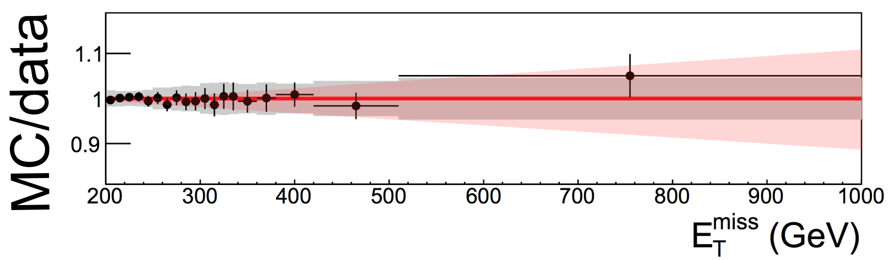
CMS-EXO-16-052



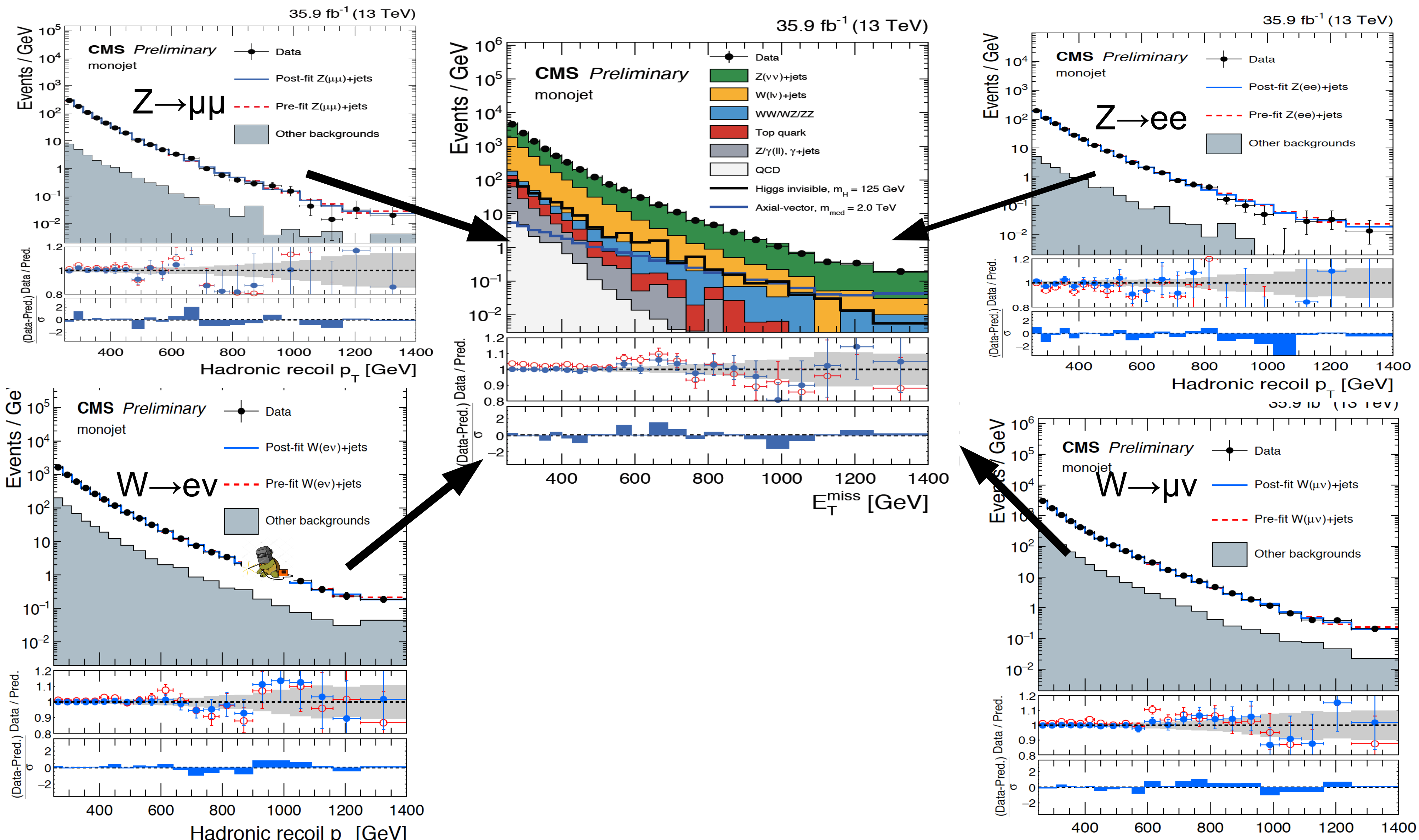
3 Control regions
40% uncertainty @ 1 TeV



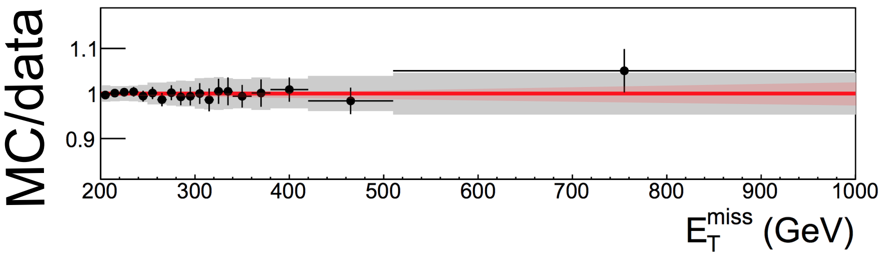
CMS-EXO-16-052



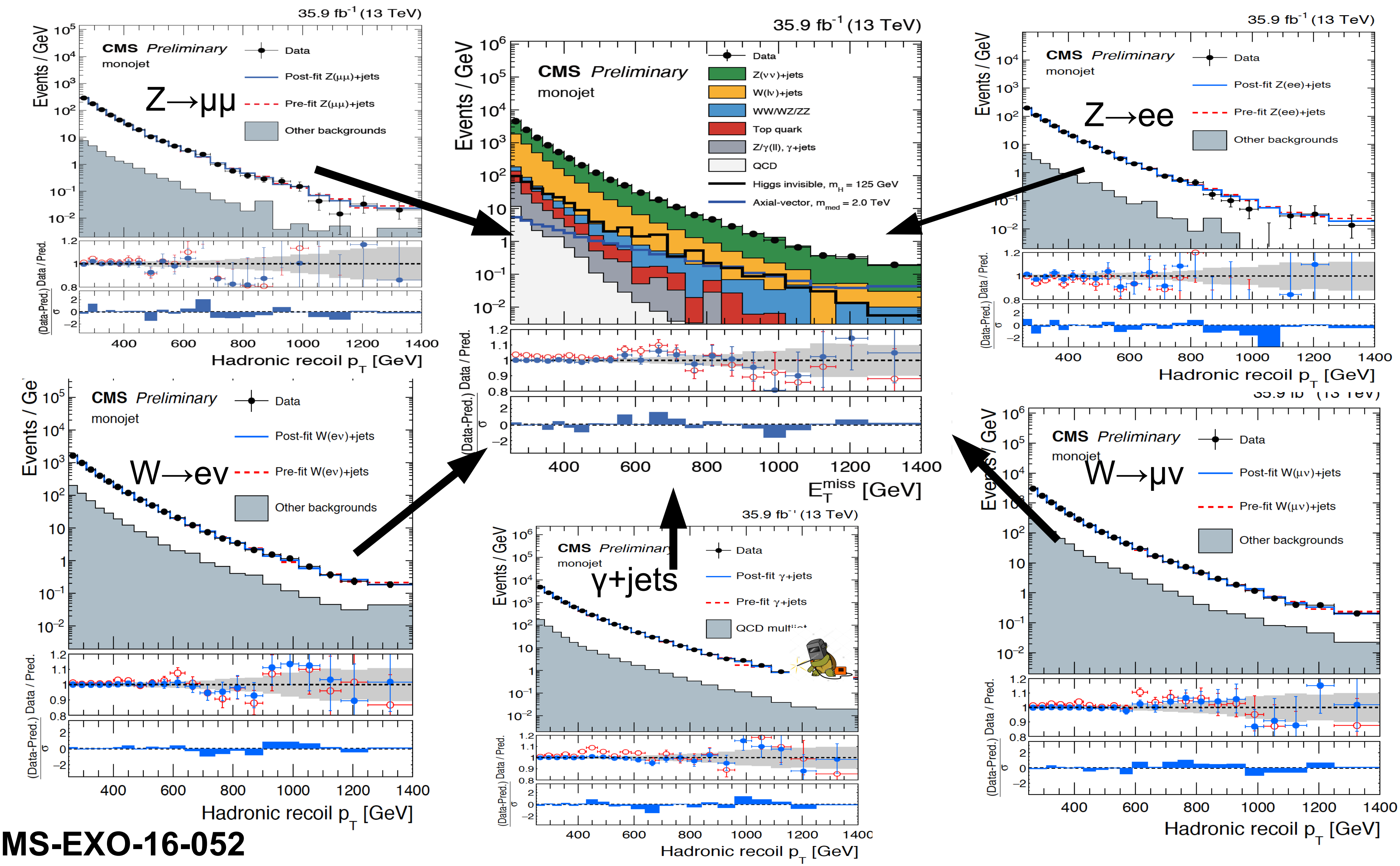
4 Control regions
30% uncertainty @ 1 TeV



CMS-EXO-16-052



5 Control regions
15% uncertainty @ 1 TeV

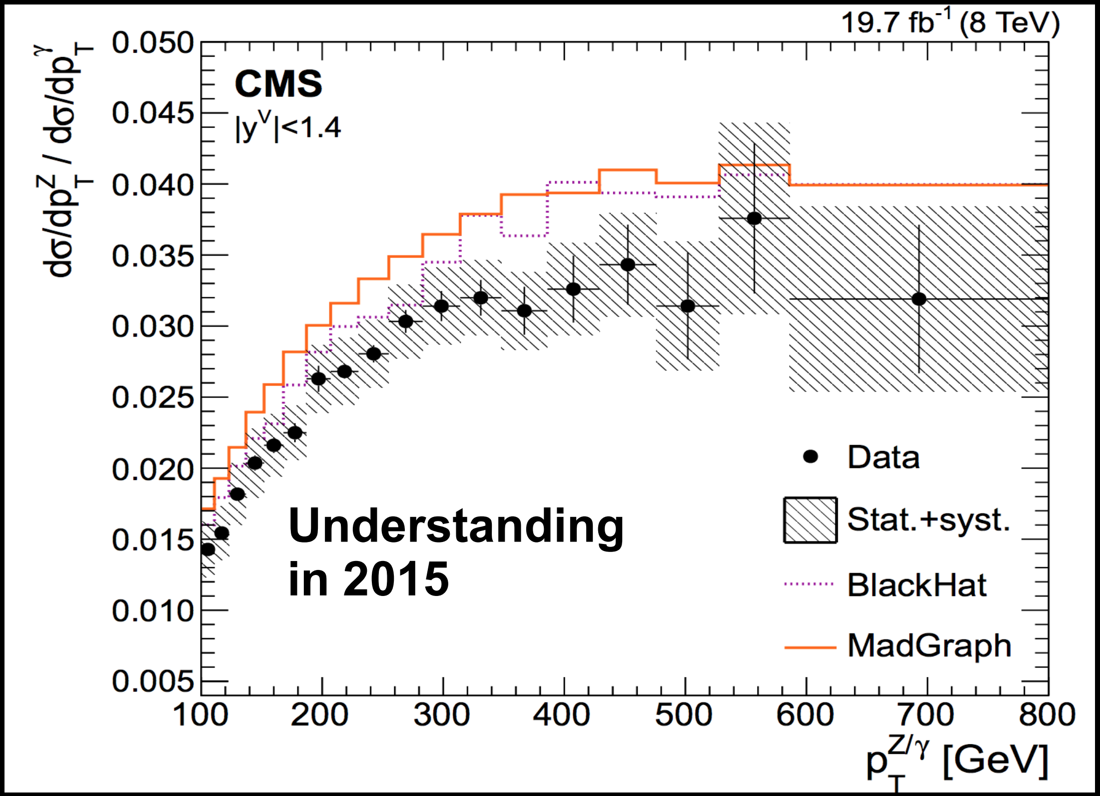


CMS-EXO-16-052

Can we really use all these regions?

CMS-EXO-12-055

Answer: Sort of.....



CMS-EXO-12-055

However we still have a problem!

Going from γ or $W \rightarrow Z$

Unc. $\longrightarrow \dfrac{d\sigma^{\gamma(W)}}{dp_T} \Big/ \dfrac{d\sigma^{Z}}{dp_T}$

Need to know the uncertainty on the ratios
@NNLO QCD @NLO EWK
This is not a light statement!

However we still have a problem!

Going from γ or W $\rightarrow$ Z

Unc. $\longrightarrow$ $\dfrac{d\sigma^{\gamma(W)}}{dp_T} \Big/ \dfrac{d\sigma^{Z}}{dp_T}$

Need to know the uncertainty on the ratios
@NNLO QCD @NLO EWK
This is not a light statement

Out last Monday

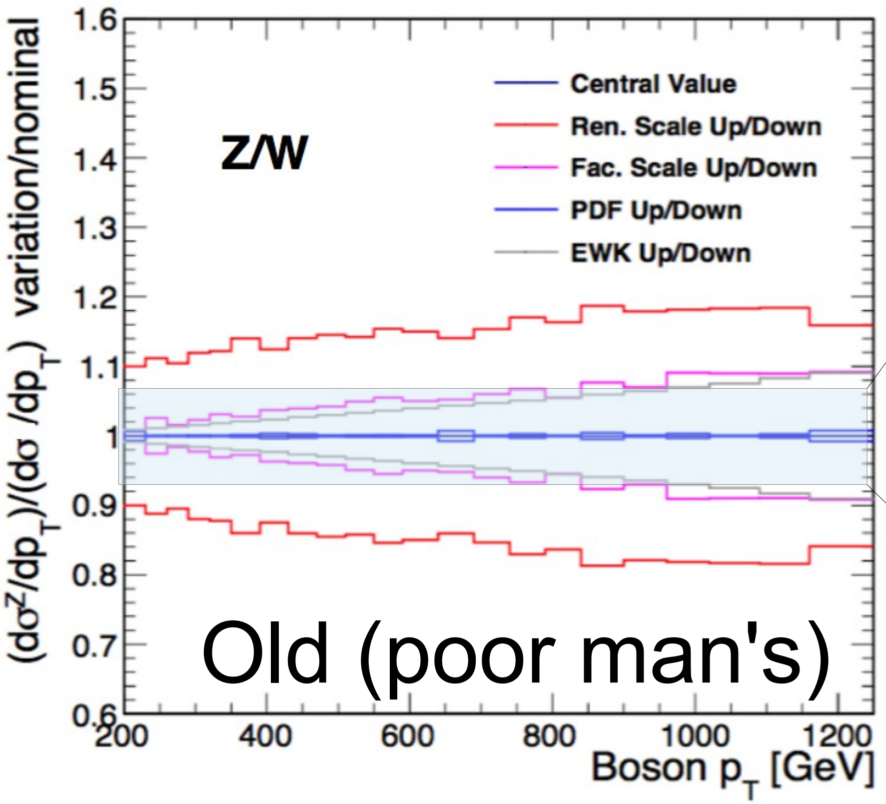
Arxiv:1705.04664

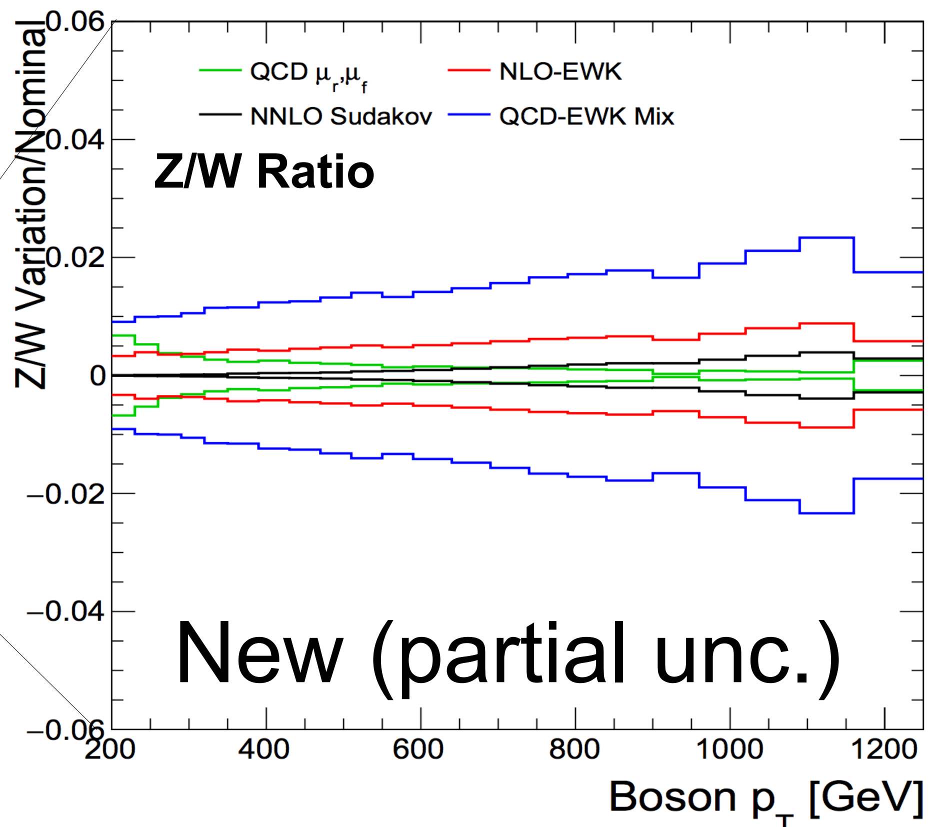
Precise predictions for V+jets dark matter backgrounds

J. M. Lindert[1], S. Pozzorini[2], R. Boughezal[3], J. M. Campbell[4], A. Denner[5], S. Dittmaier[6], A. Gehrmann-De Ridder[2,7], T. Gehrmann[2], N. Glover[1], A. Huss[7], S. Kallweit[8], P. Maierhöfer[6], M. L. Mangano[8], T.A. Morgan[1], A. Mück[9], F. Petriello[3,10], G. P. Salam*[8], M. Schönherr[2], and C. Williams[11]

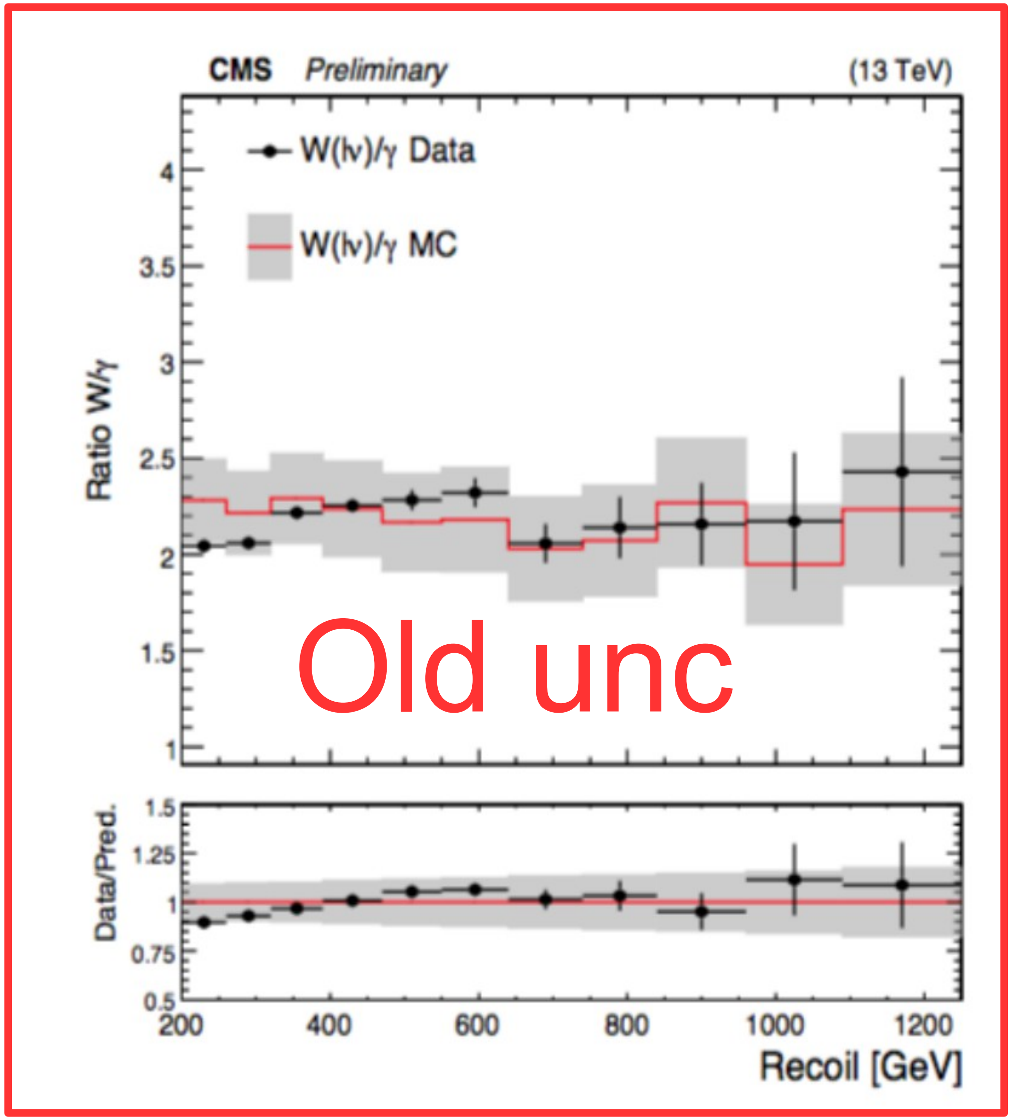
What did we get out of this?

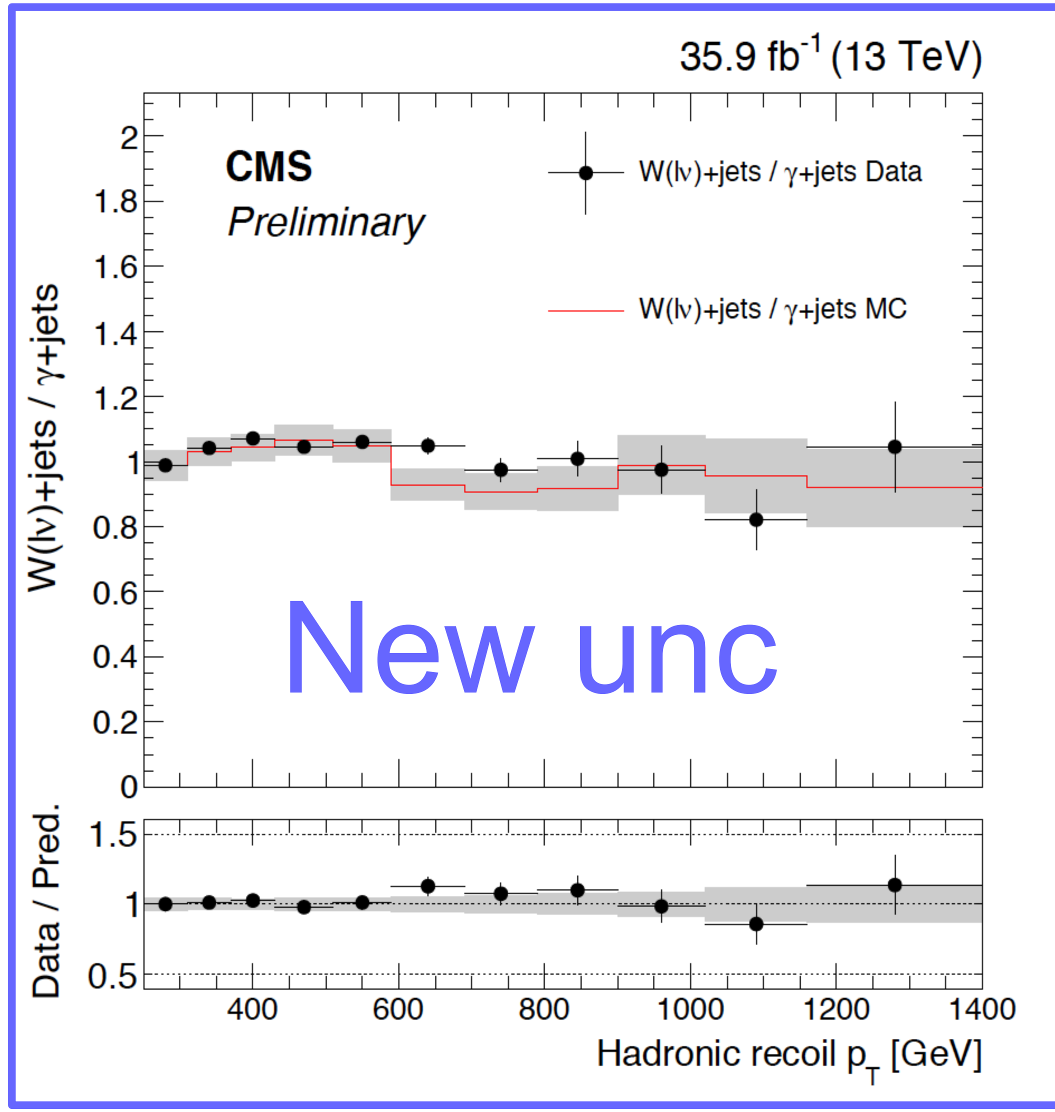
- Large reduction in theory uncertainties
  - Experimental effects of the same order
- Can now correlate unc. across boson p_T bins





Reducing these unc. by a 5x can give x2 improvement



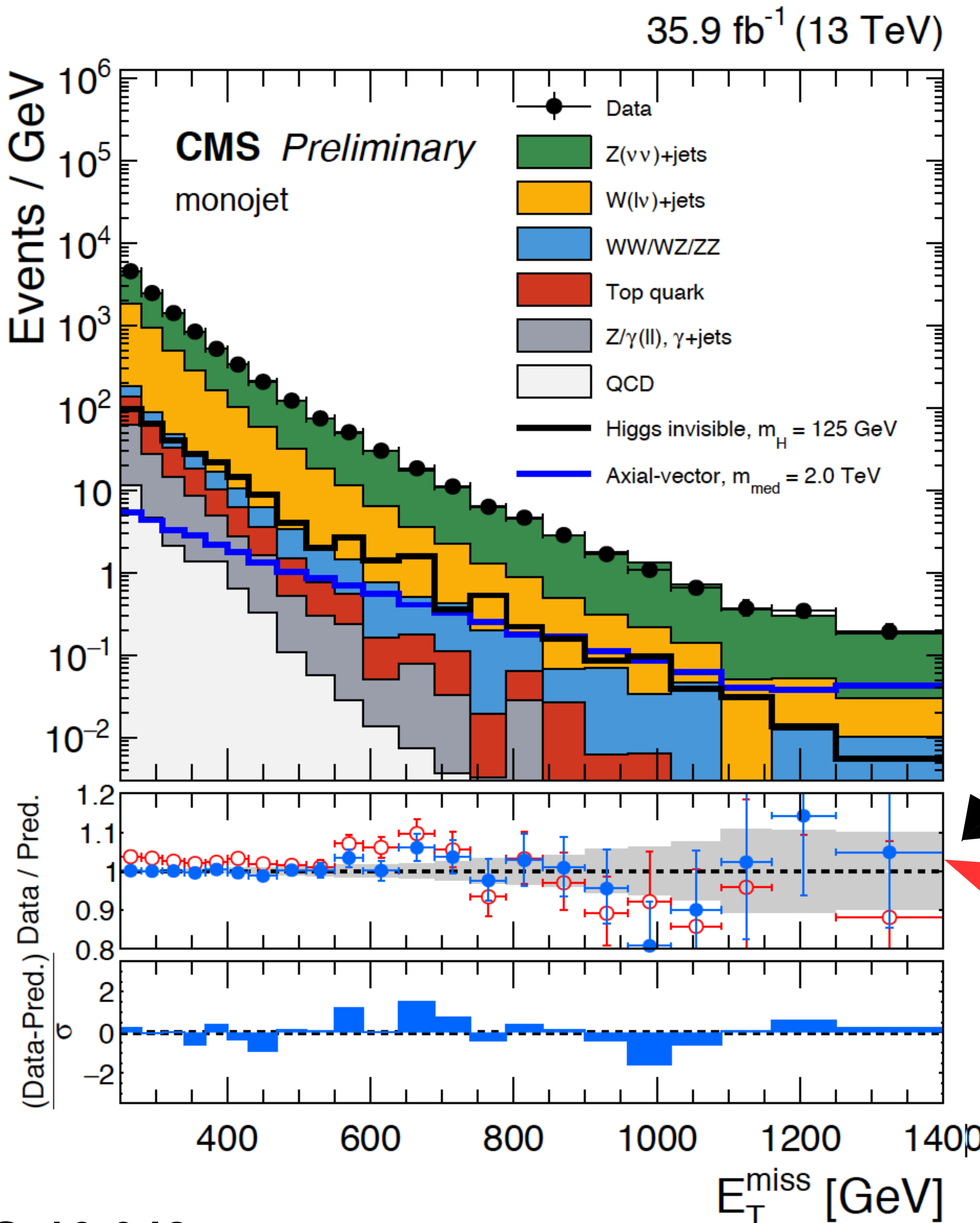


Uncertainties are considerably smaller

data constraints still better

EXO-16-048

Current Monojet Sensitivity



Uncertainty Now at 1% level

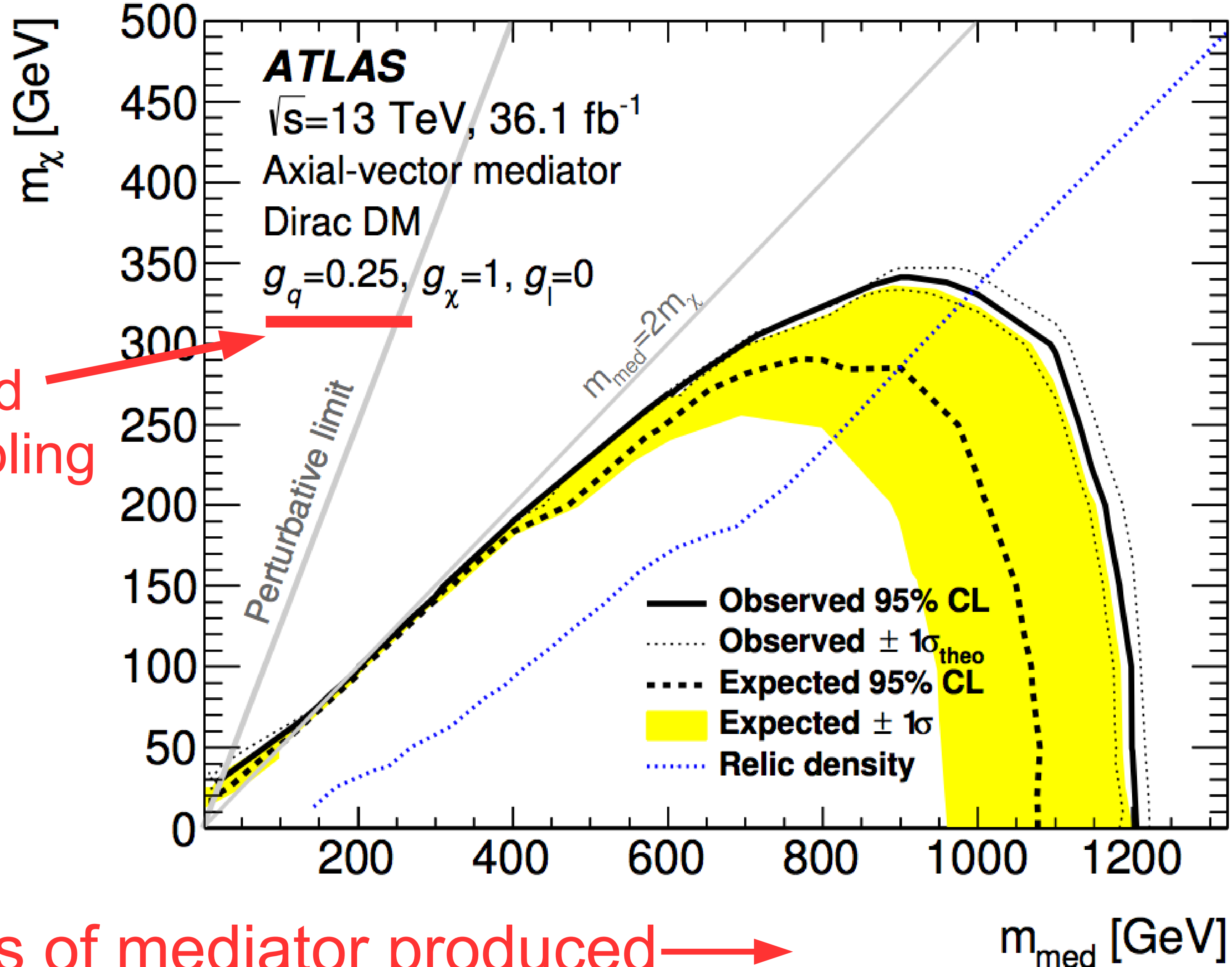
No excess

Almost no systematic wall

EXO-16-048

Pick a Model

Dark Matter Mass

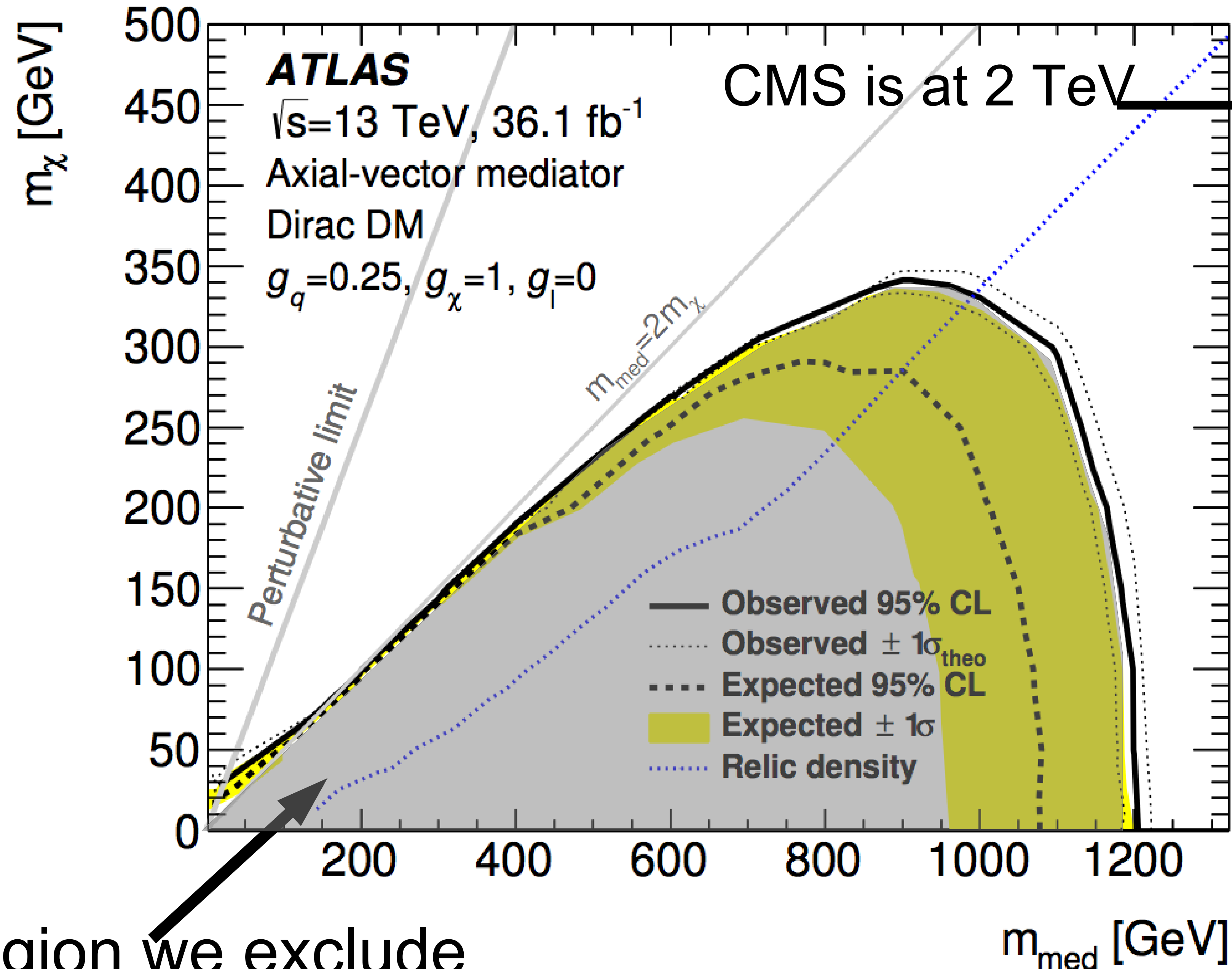


Fixed coupling

Mass of mediator produced

Arxiv:1704.03848

Understanding sensitivity



CMS is at 2 TeV

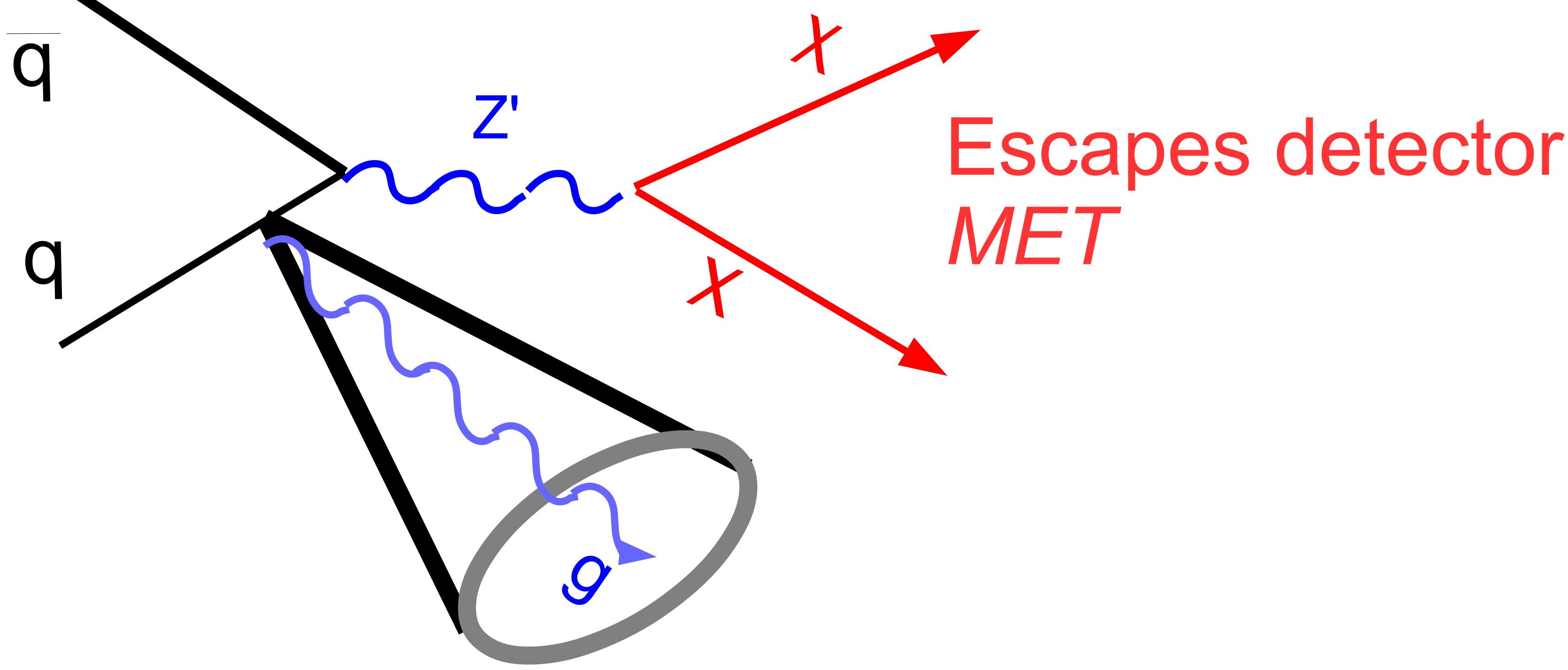
Region we exclude

Arxiv:1704.03848

Beyond Monojet

The Basic Monojet Search

Escaping detector gives us signatures of *MET*

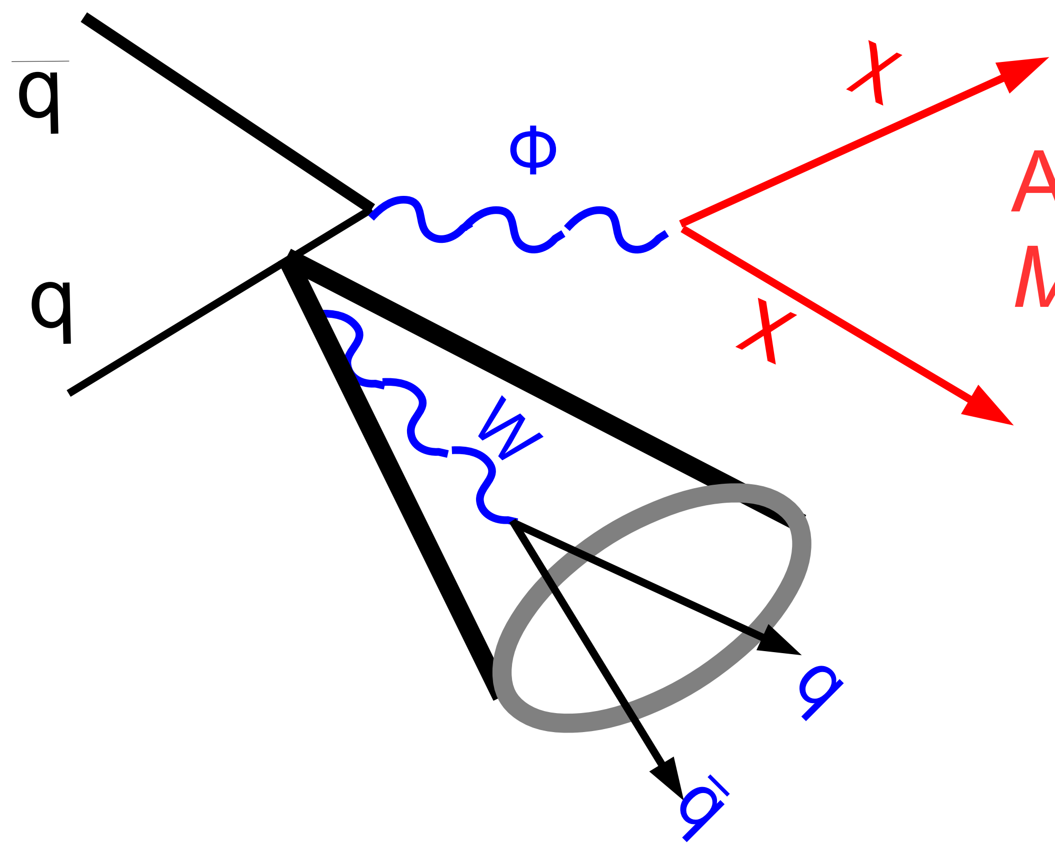


A Jet

How Do We Discriminate Models?

Mono-W

Monos : Vector,Axial,Higgs

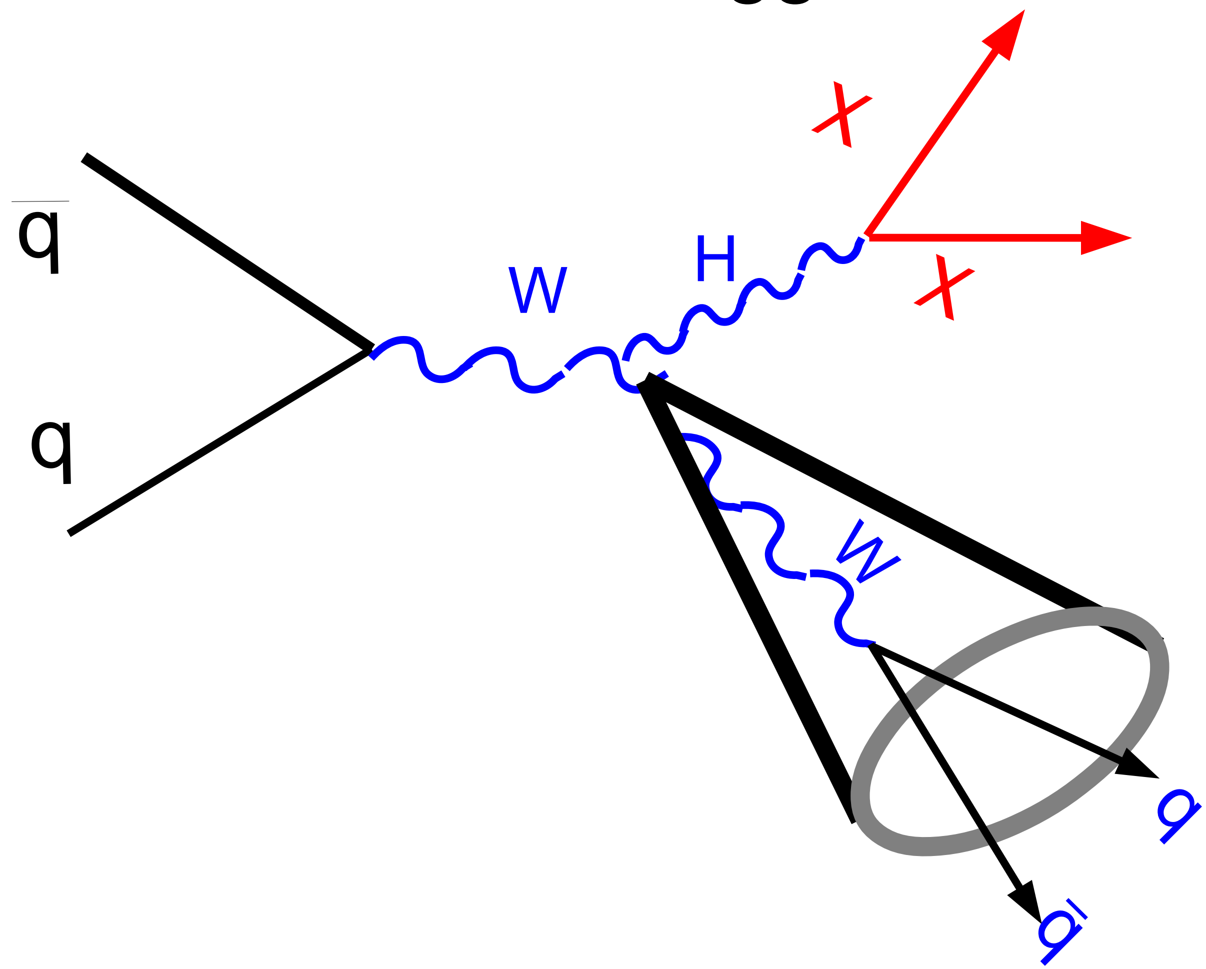


Again Escapes detector
MET

How Do We Discriminate Models?

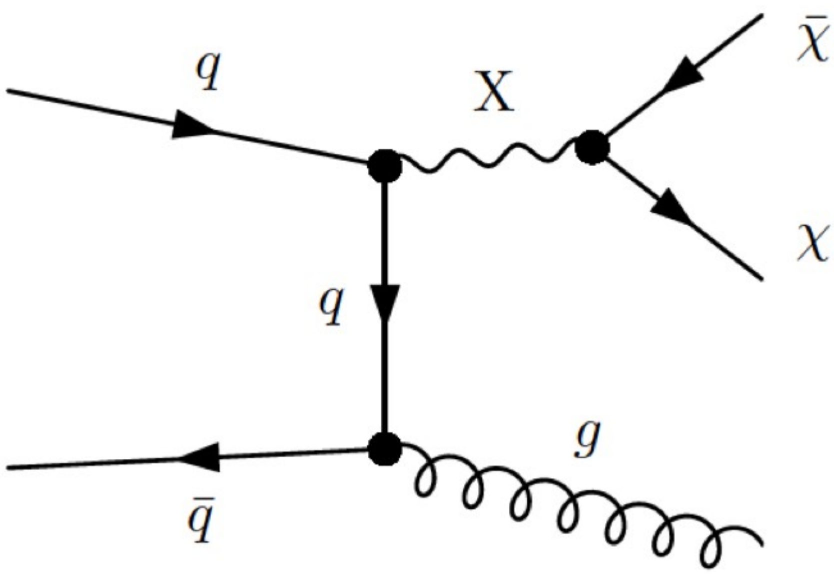
Mono-W

Monos : Vector,Axial,Higgs



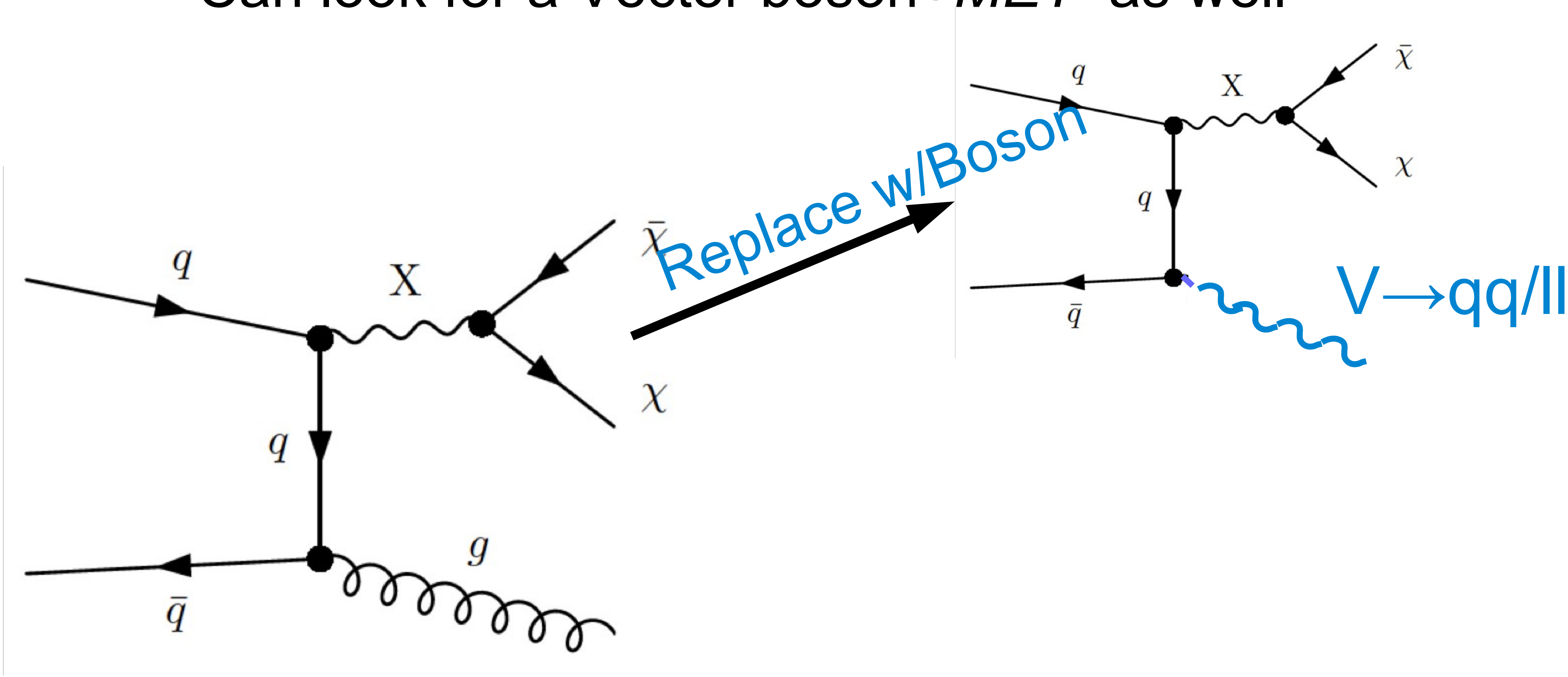
Spin 1 DM Searches

Spin 1 production on SM couplings for final state
Easily extend this to other final states



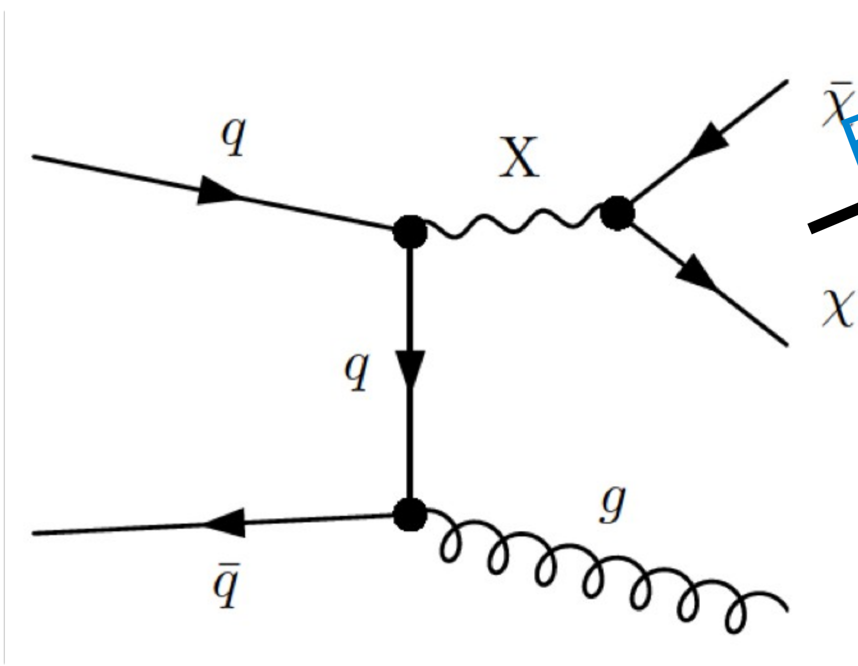
Spin 1 DM Searches

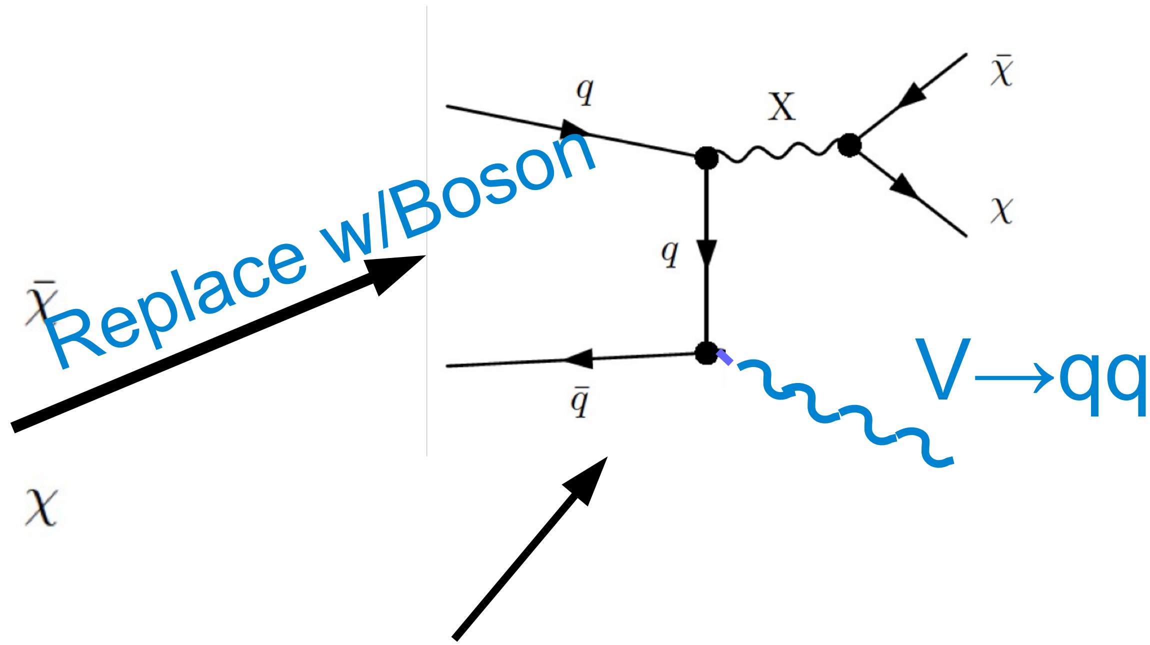
Can look for a Vector boson+*MET* as well



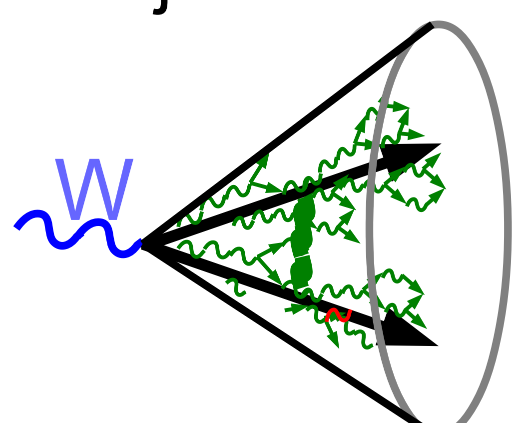
The split in simplified model terms

- With spin 1 can generate other final states :



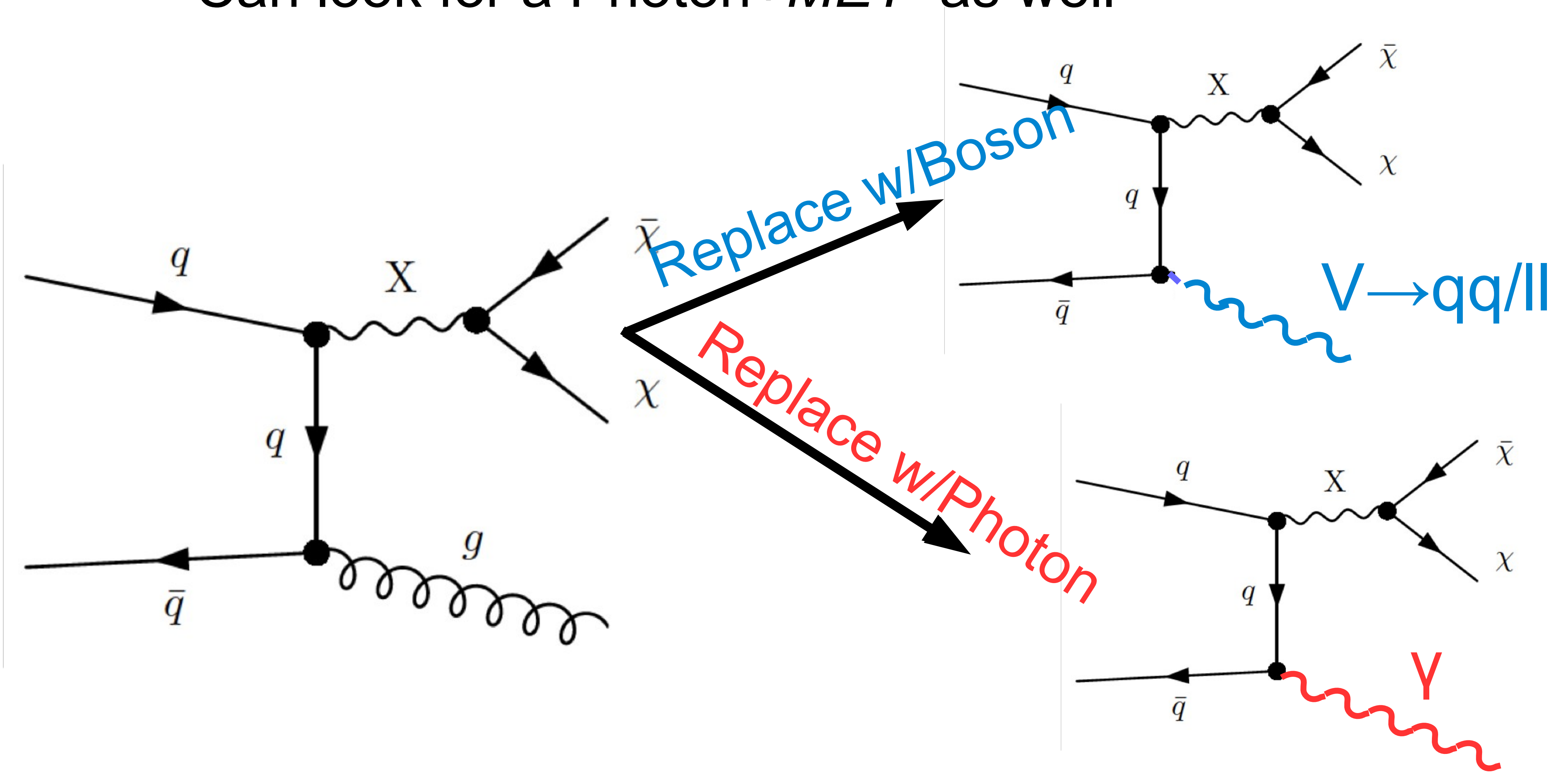


This is just a monojet



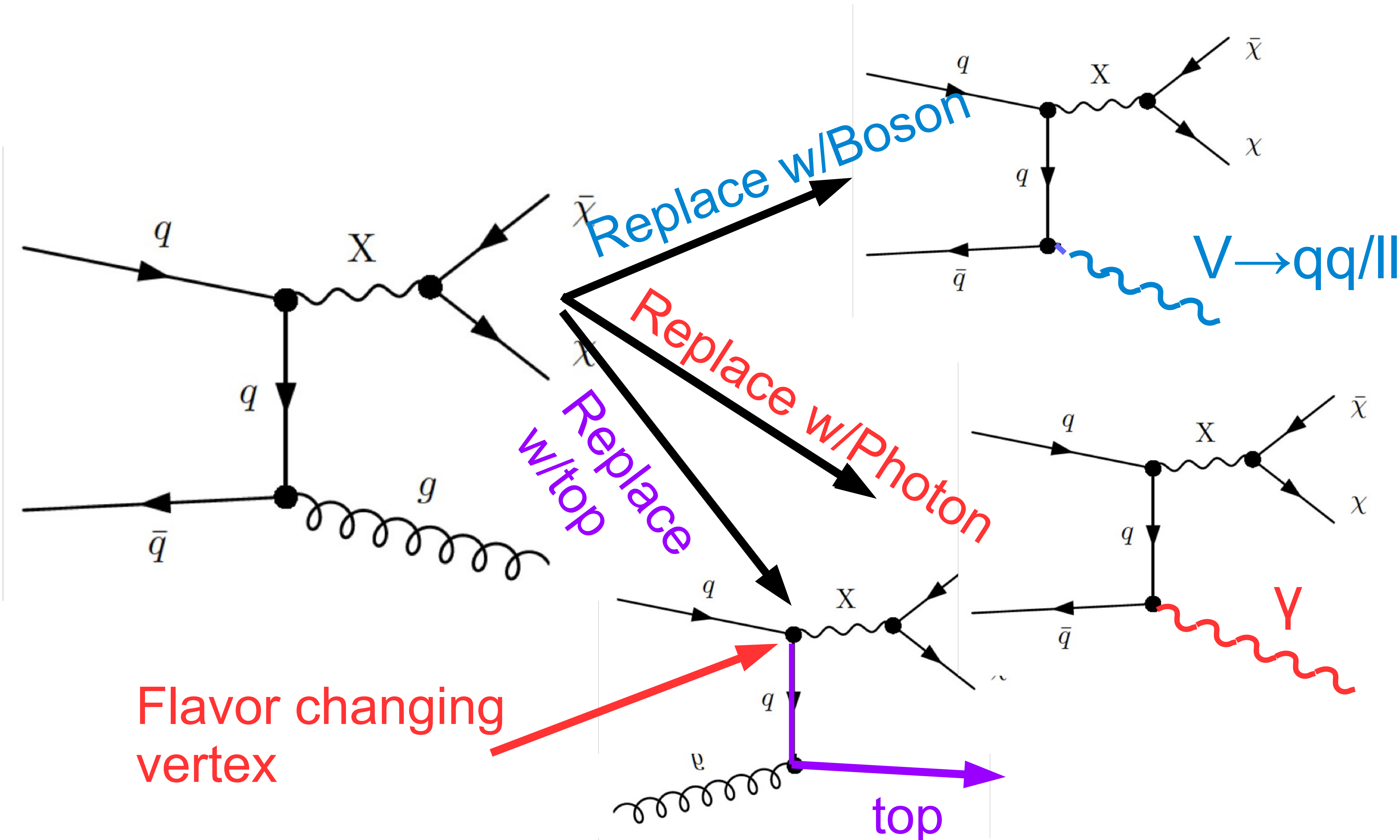
Spin 1 DM Searches

Can look for a Photon+*MET* as well



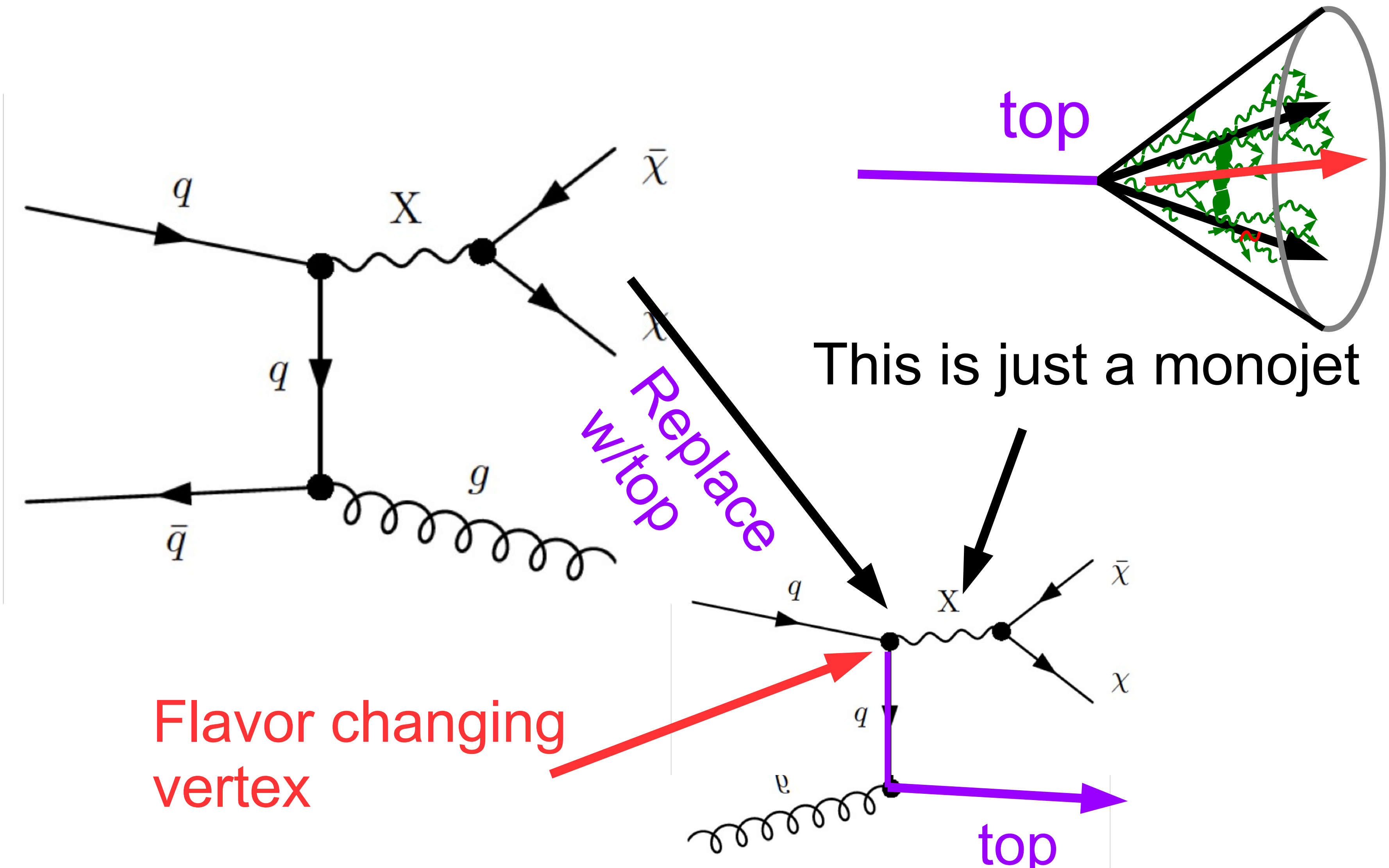
Spin 1 DM Searches

If vertex is flavor changing



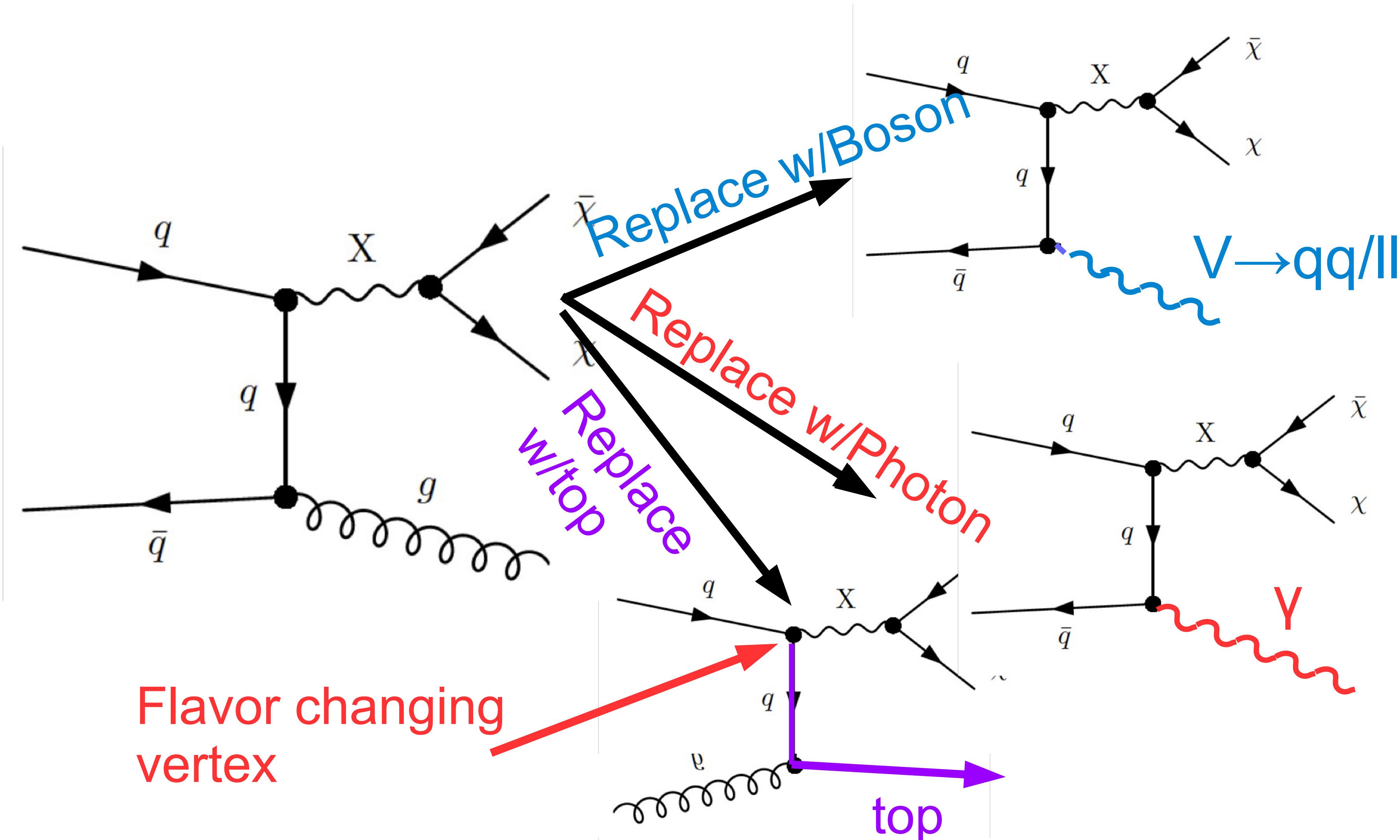
The split in simplified model terms

- With spin 1 can generate other final states :

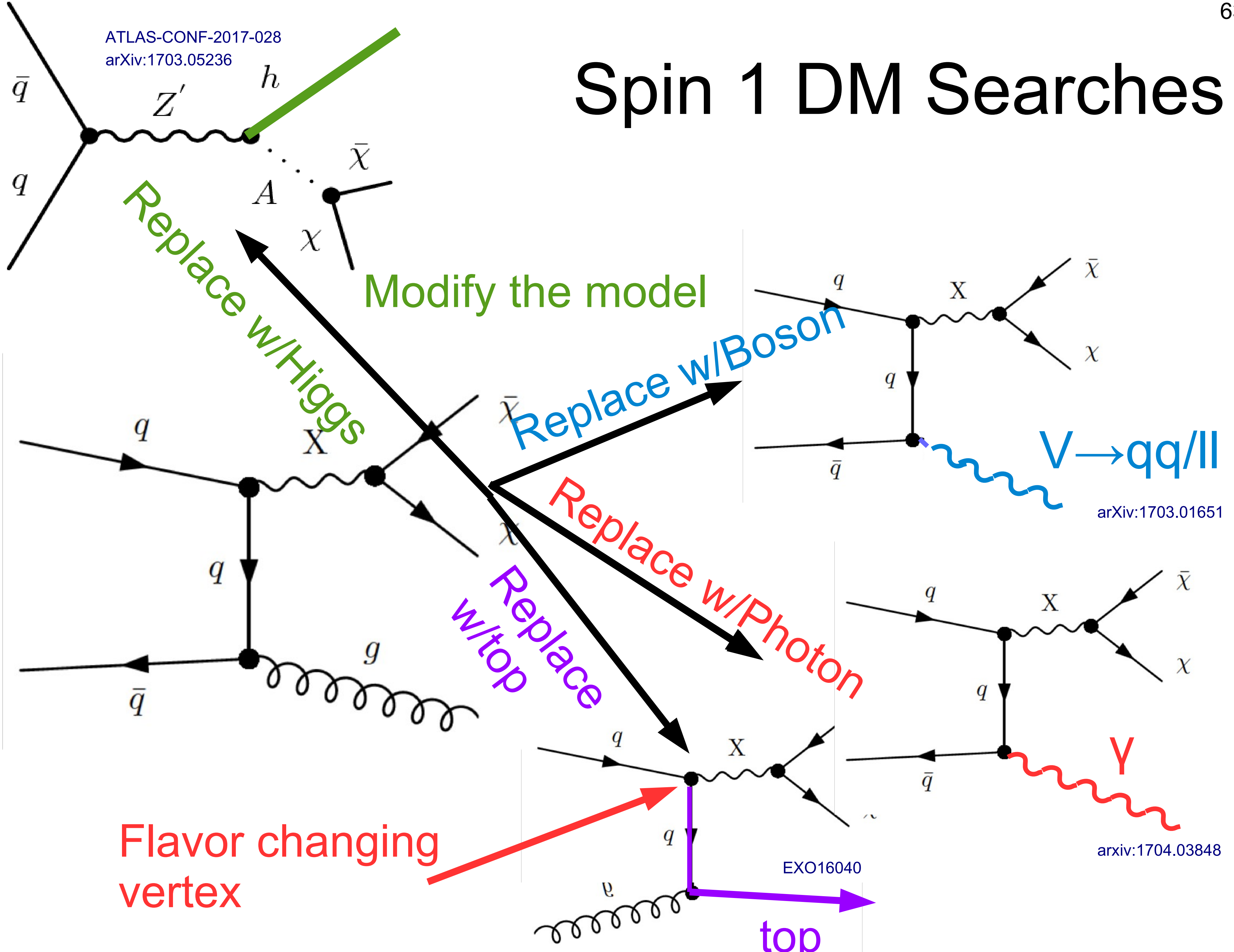


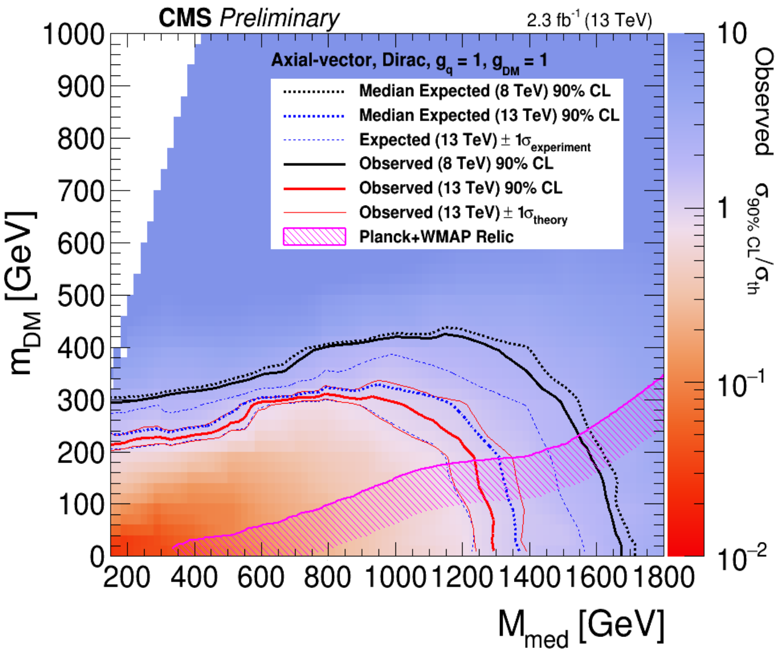
Spin 1 DM Searches

If vertex is flavor changing

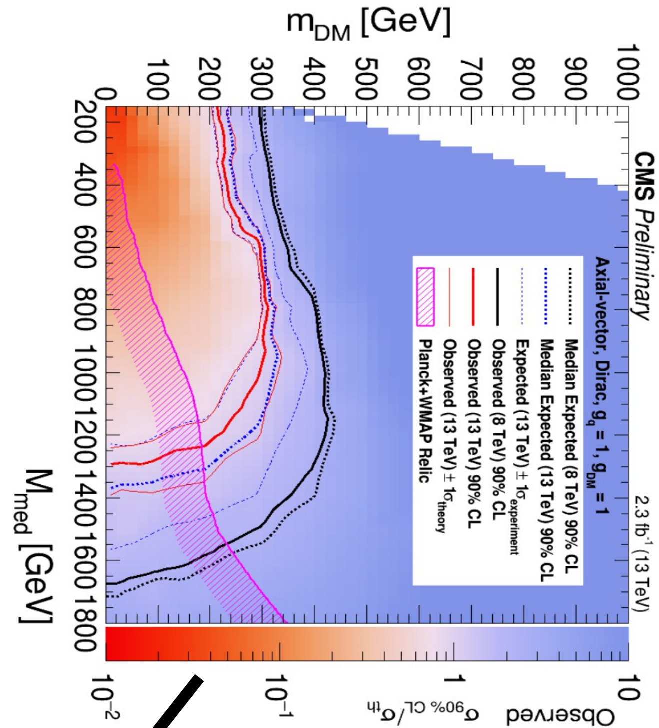


Spin 1 DM Searches



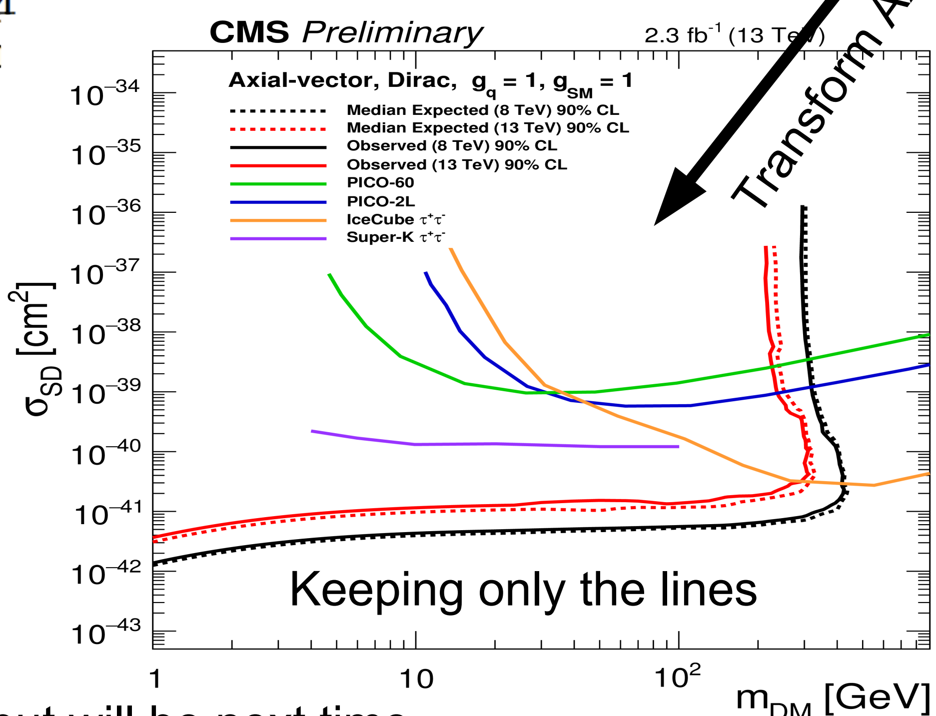


Rotate Plot



$$\sigma_{\mathrm{SI}} = \frac{f^2(g_q)\, g_{\mathrm{DM}}^2\, \mu_{n\chi}^2}{\pi M_{\mathrm{r}}^4}$$

Transform Axis



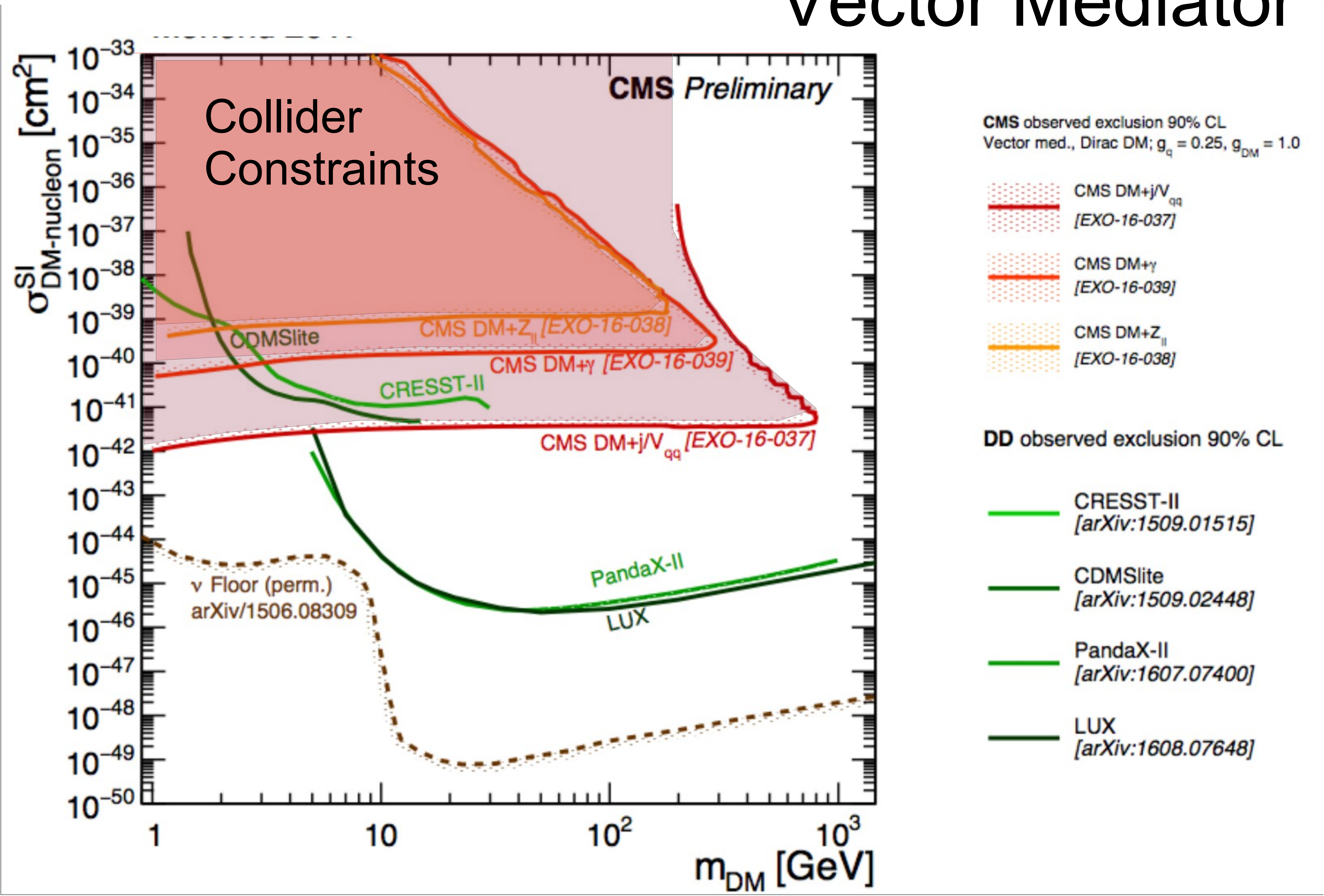
Now that search is cast in terms of mediator

No concerns in the translation
Fixed couplings

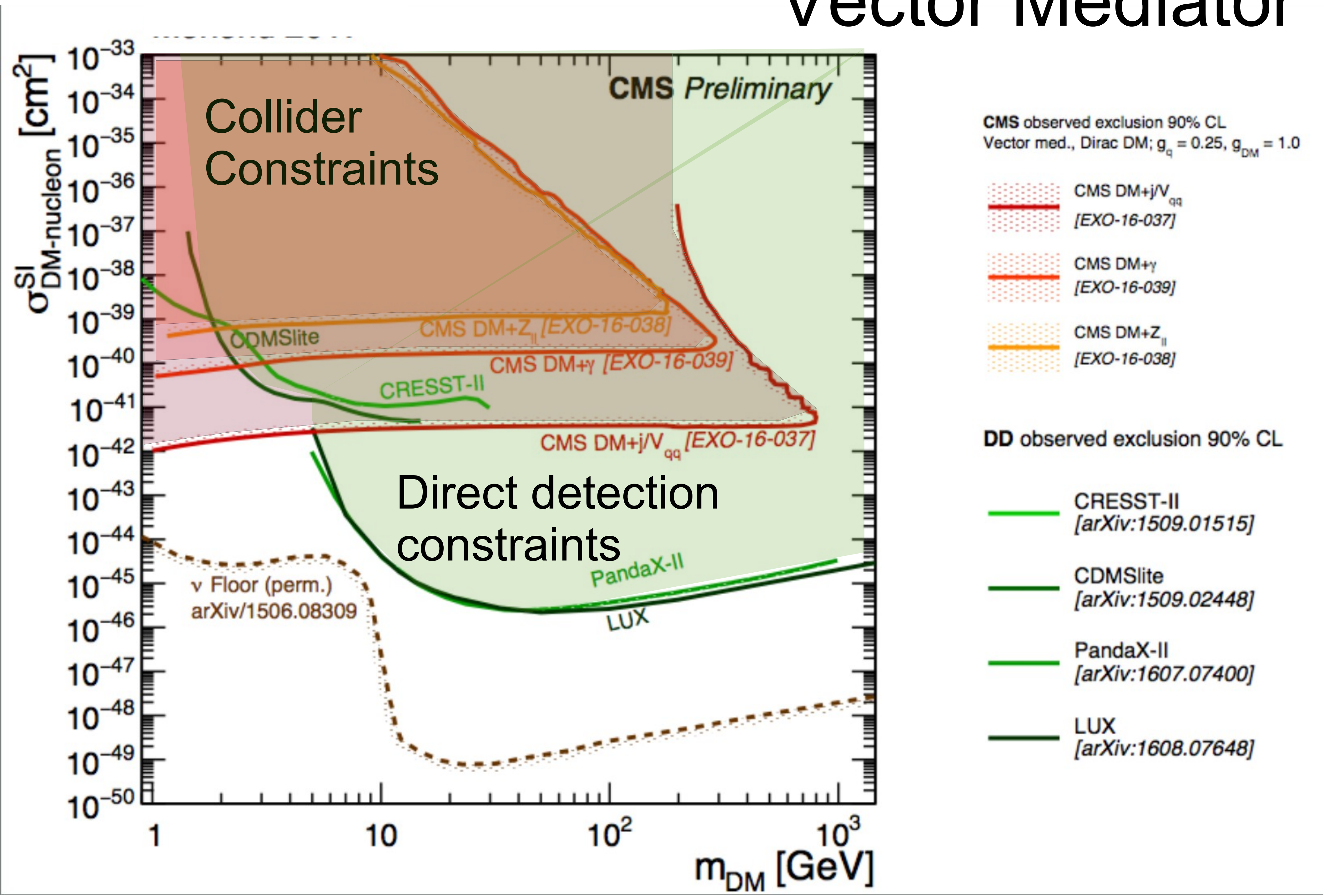
1605.04917

Note: scale not run, but will be next time

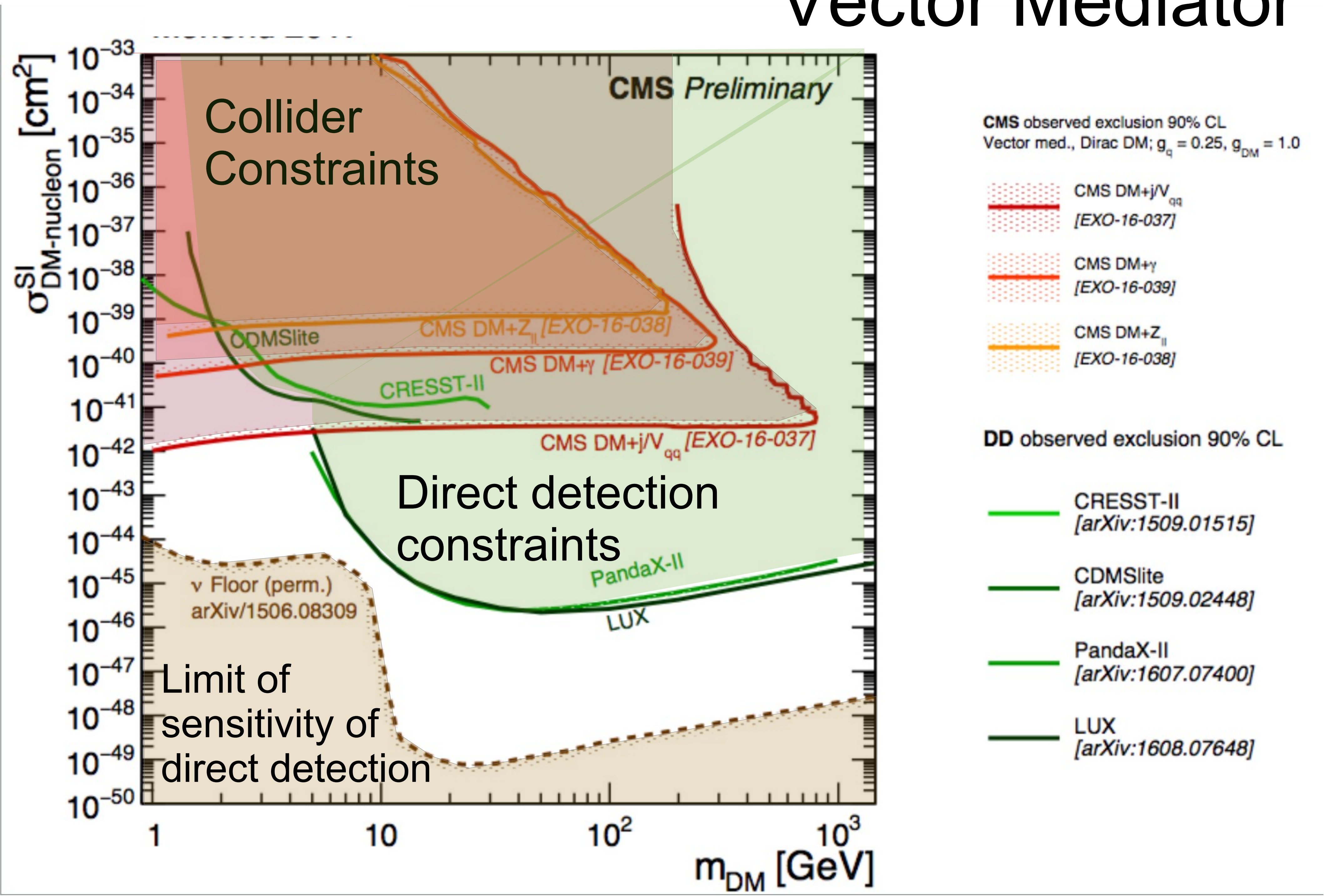
Vector Mediator



Vector Mediator



Vector Mediator



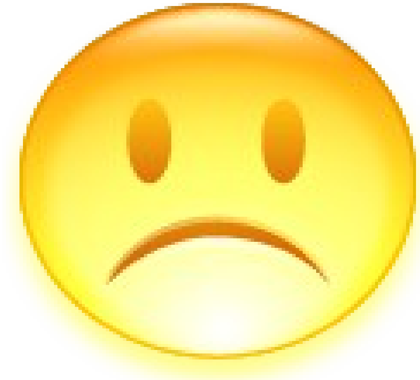
With Direct Detection

Vector(SI)

Spin independent

Extremely good

Axial(SD)



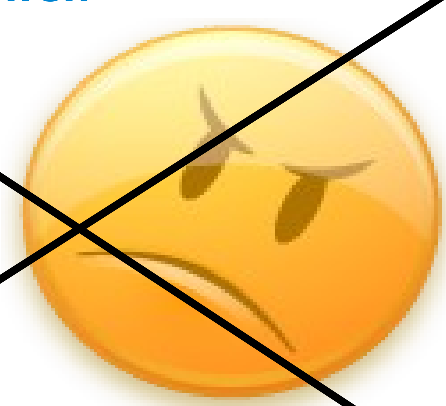
Spin dependent

Not so great

Scalar(SI)

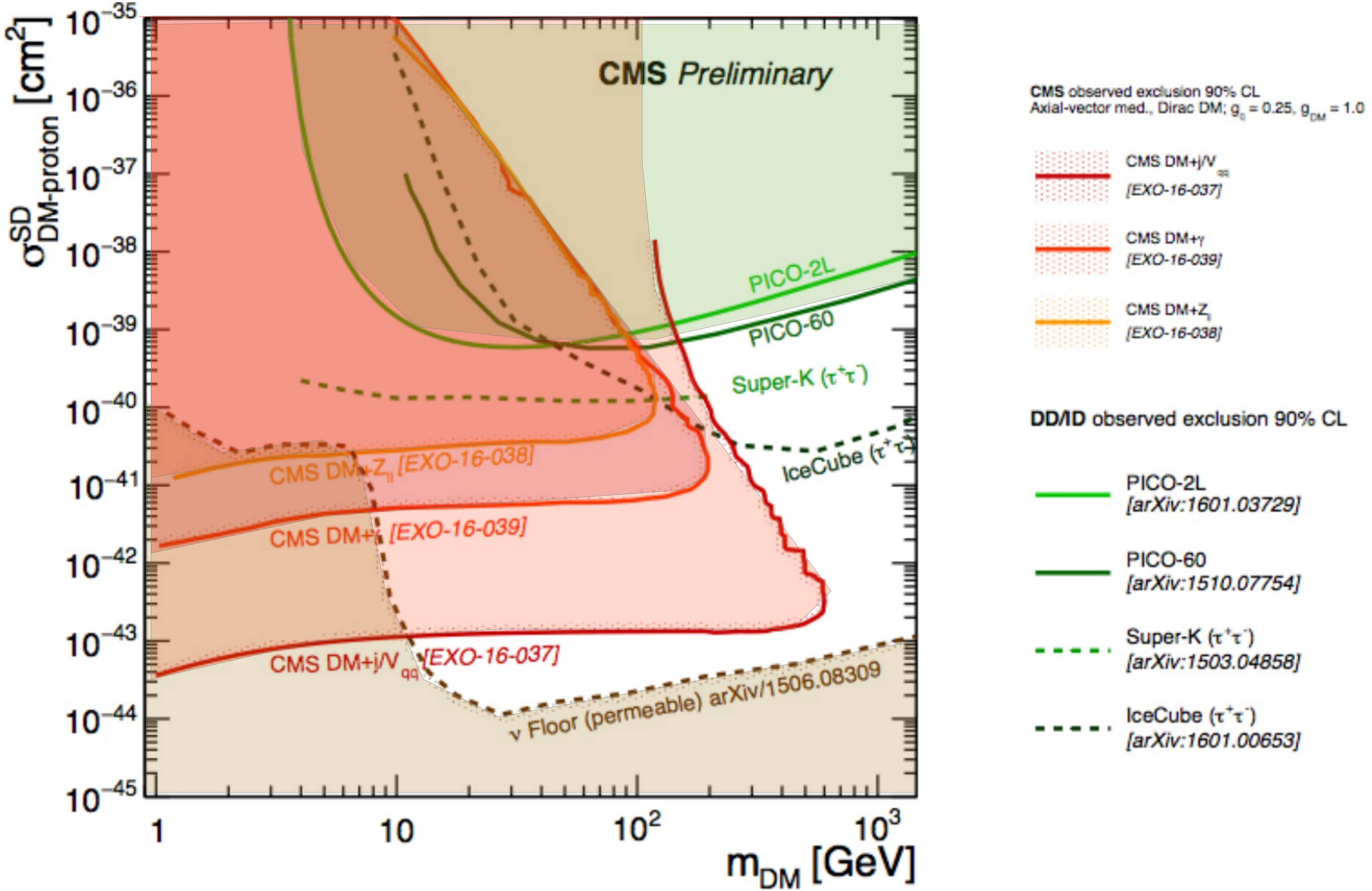
So-so
Spin independent

Pseudoscalar



Use indirect detection

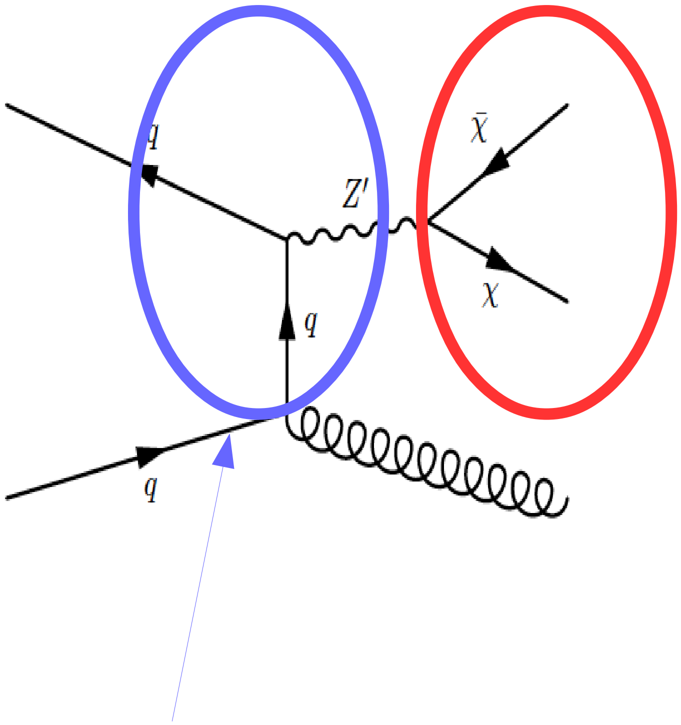
Axial Mediator



Beyond Invisible Searches

What else?

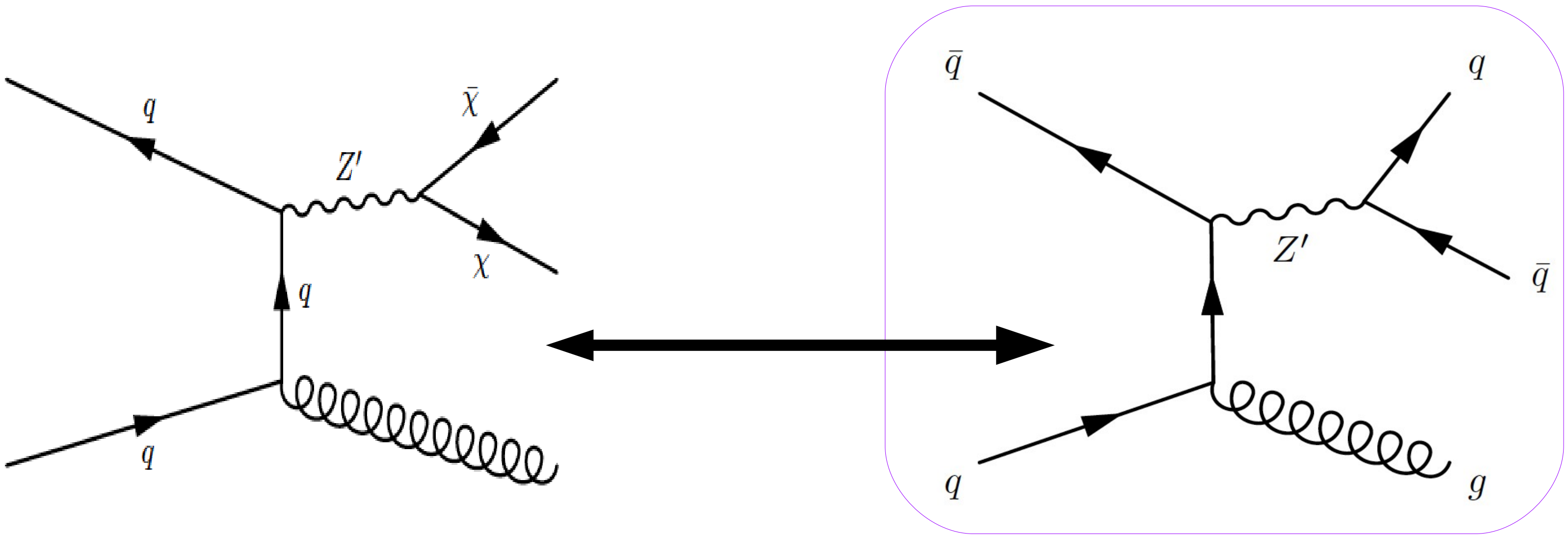
- Without loss of generality we also have dijets



Mediator is coupling to quarks and to Dark matter

What else?

- Without loss of generality we also have dijets

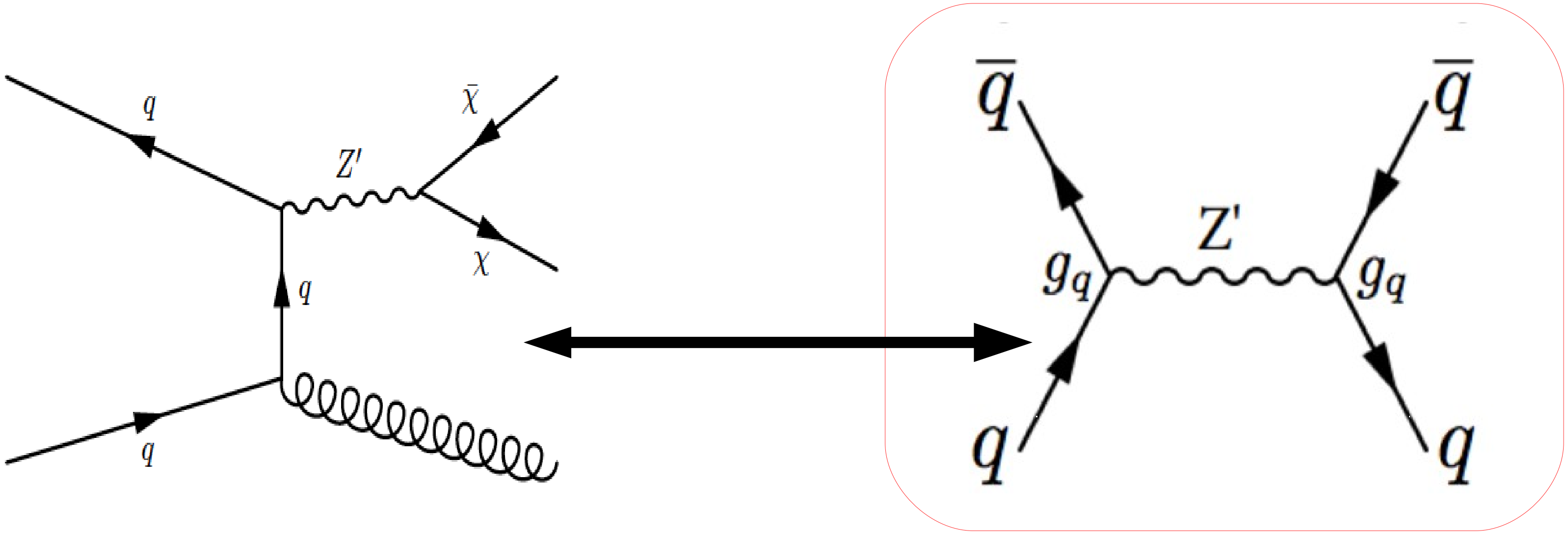


This is a dijet+ISR search

Mediator is coupling to quarks and to Dark matter
Mediator can decay to quarks

What else?

- Without loss of generality we also have dijets



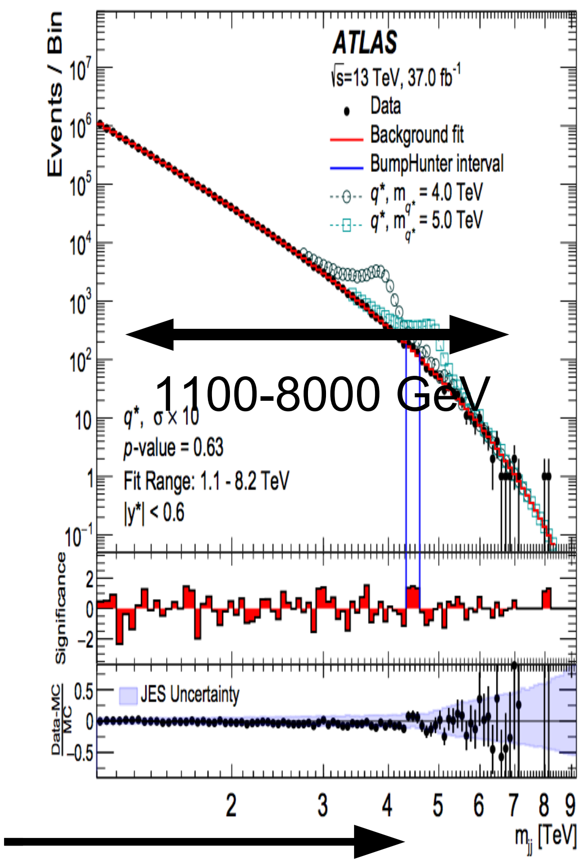
Can also just do a plain dijet search

When doing a dijet search don't need additional jet

BR(Z'→qq) ≈0.5BR(Z'→)

Probing the Mass range

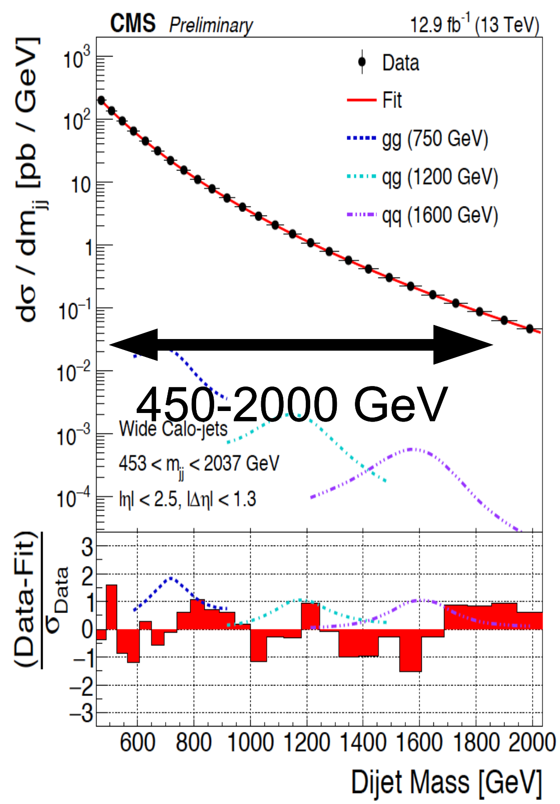
Like Monojet
we can expand to further regions
By tagging other objects

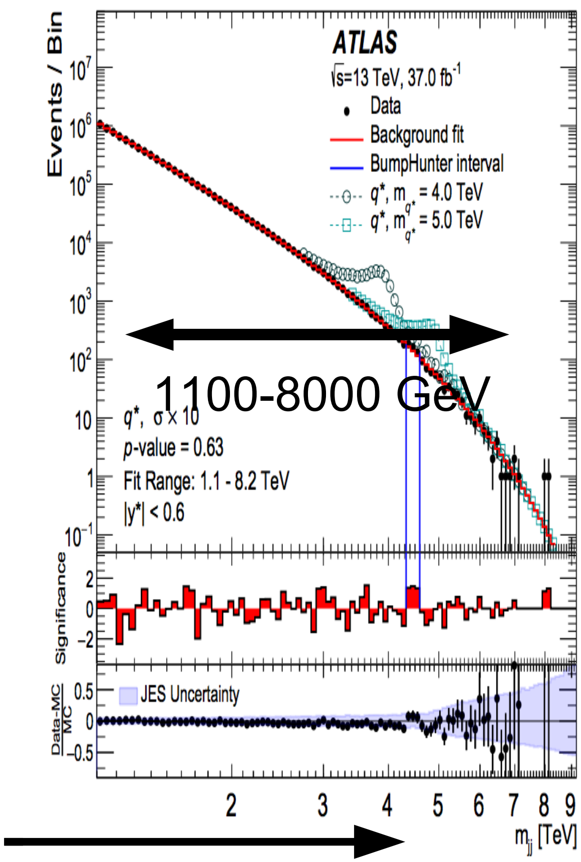


Standard jet triggers

No tag

Probing the Mass range



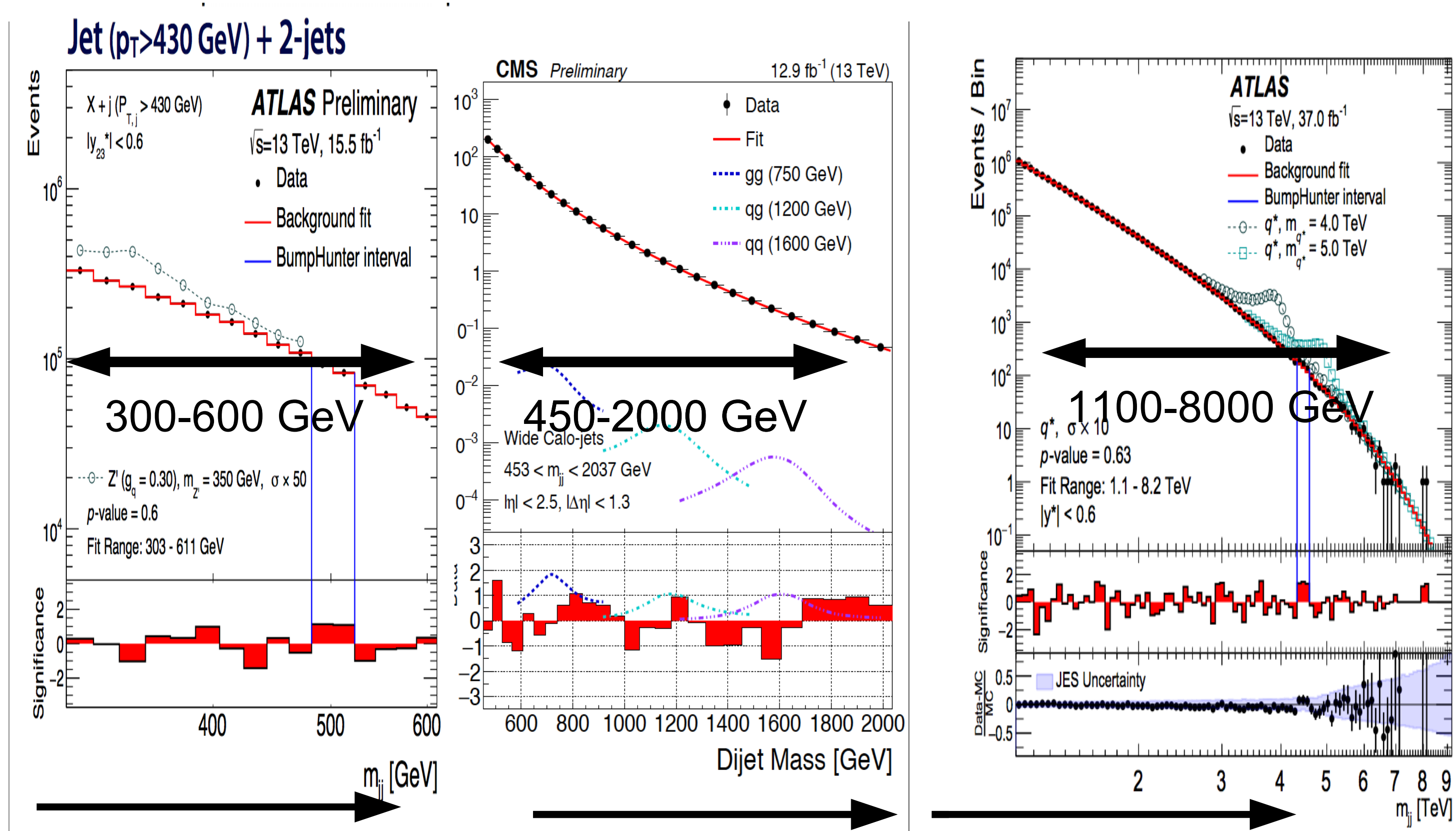


Trigger Level analysis

Standard jet triggers

Jets in trigger

Probing the Mass range



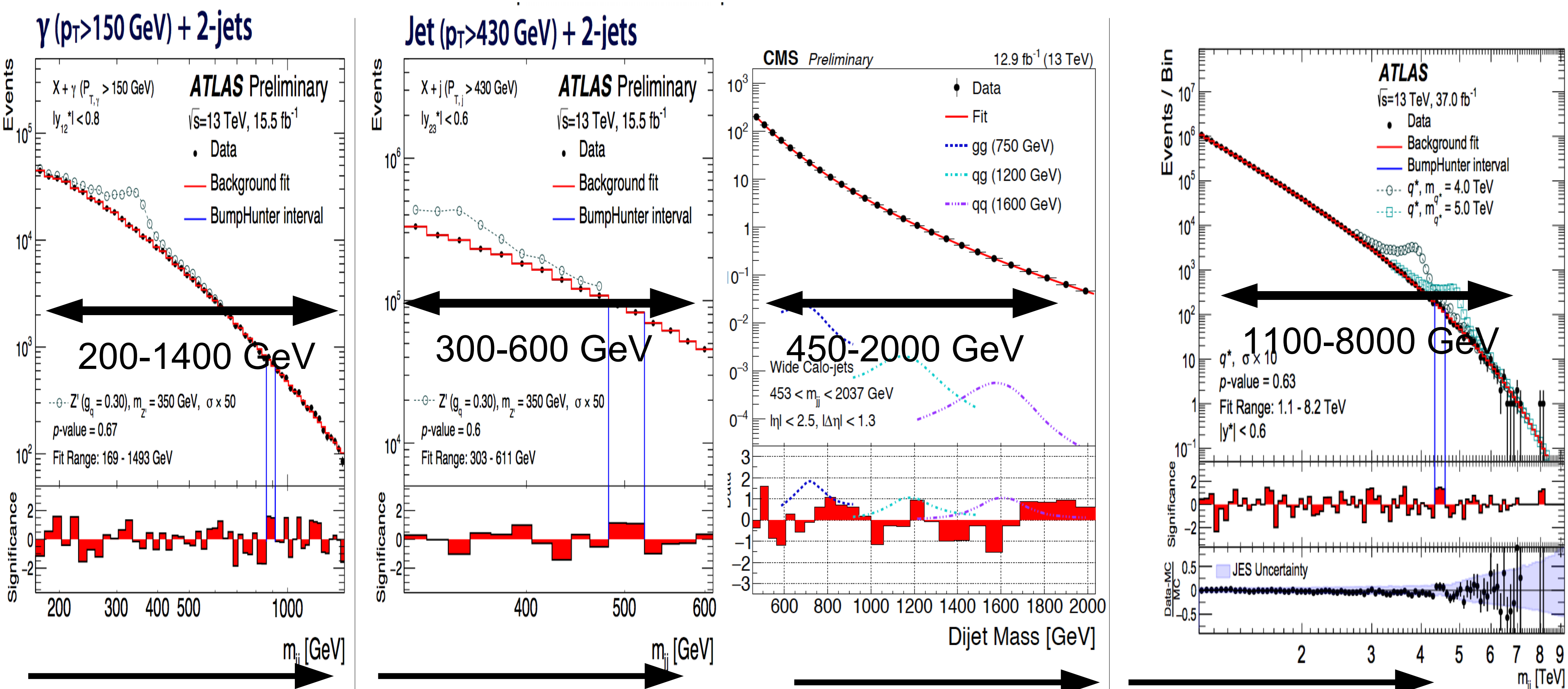
jj+j ISR analysis

Trigger Level analysis

Standard jet triggers

Additional jet (like monojet) ATLAS

Probing the Mass range



jj+γ ISR analysis

jj+j ISR analysis

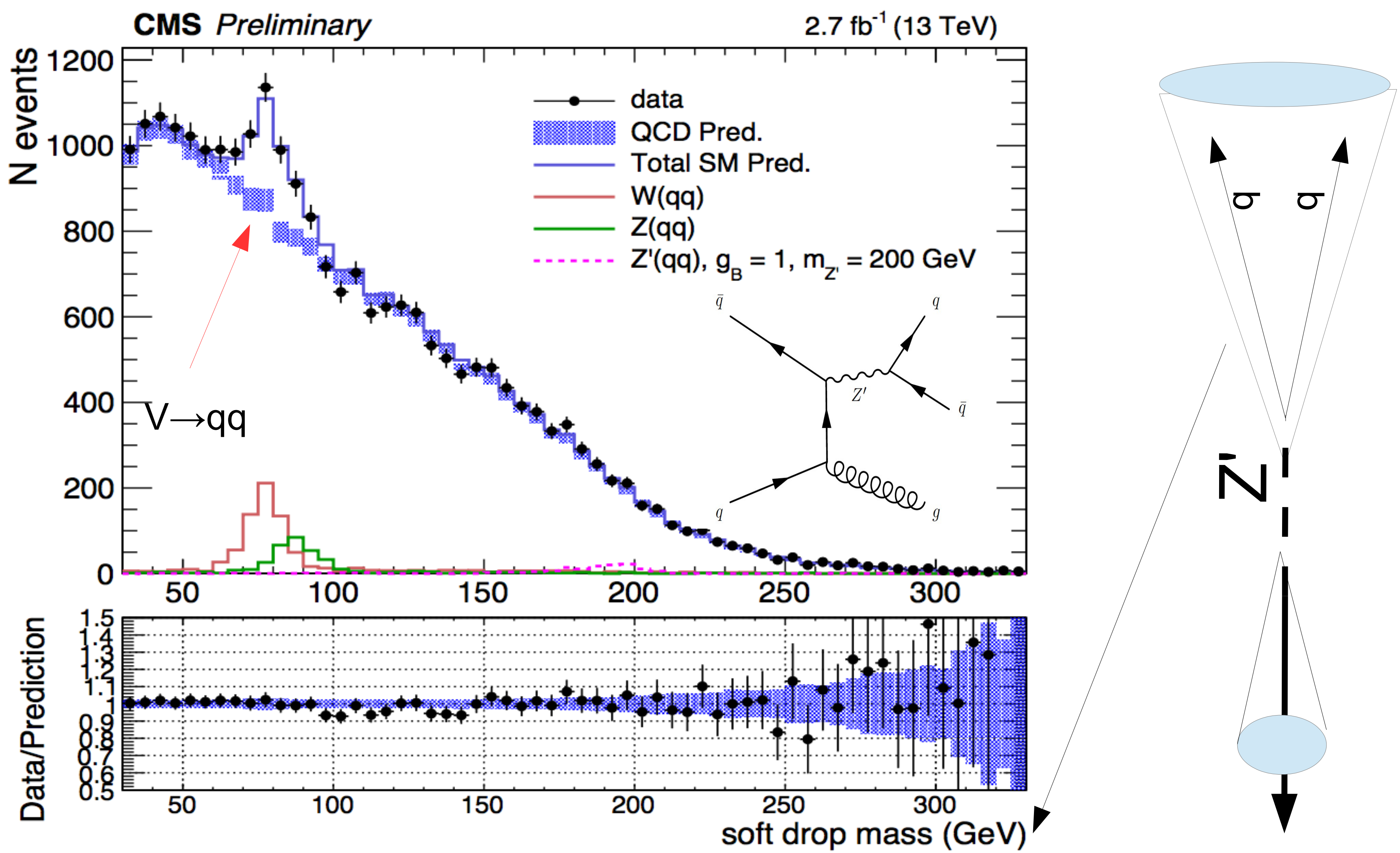
Trigger Level analysis

Standard jet triggers

Additional photon (like monophoton) ATLAS

EXO-16-030

Going all the way down



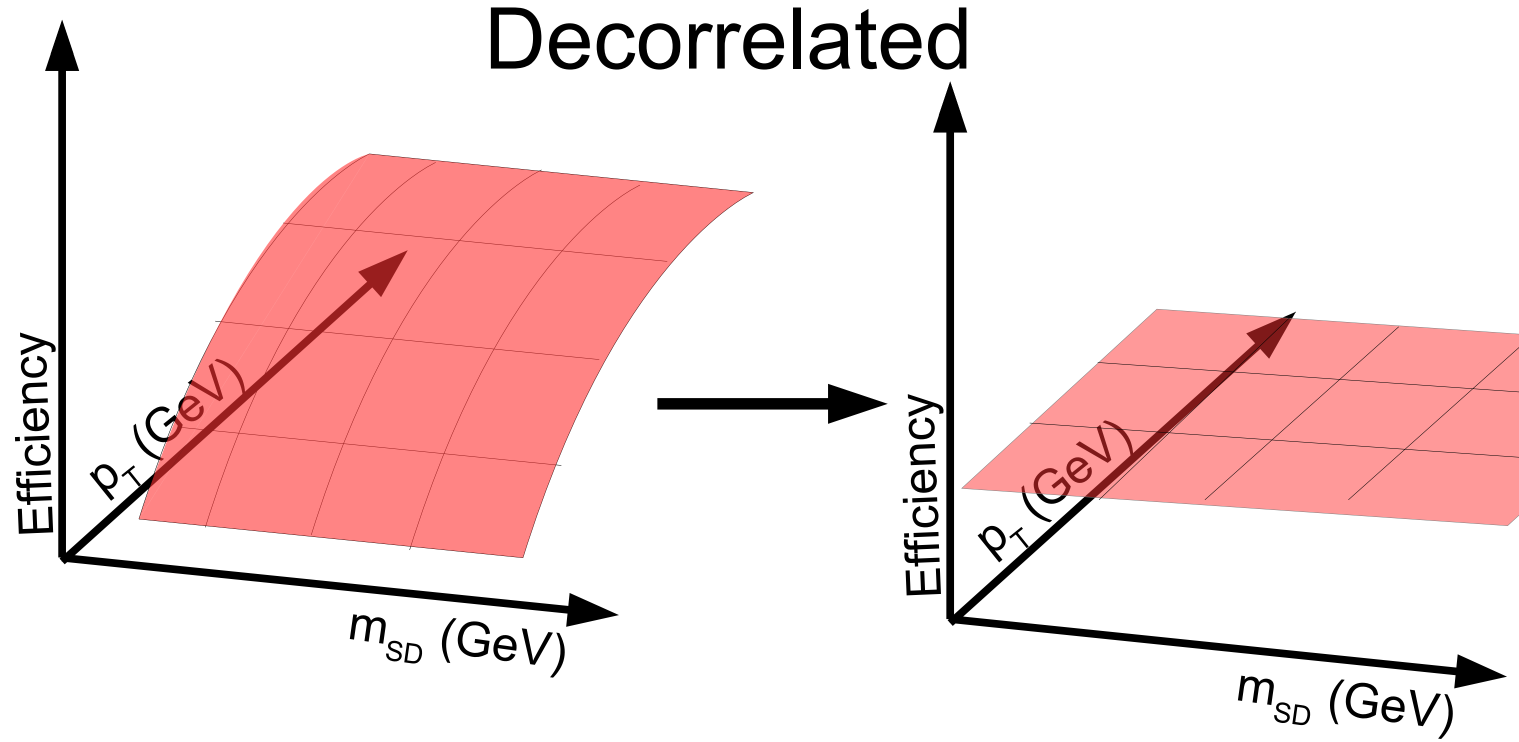
Fat jet + ISR

For this plot we invented a new substructure var

arXiv:1603.00027

Design a transfom to decorrelate against mass and p_T

Decorrelating avoid mass sculpting allows us to cut tighter

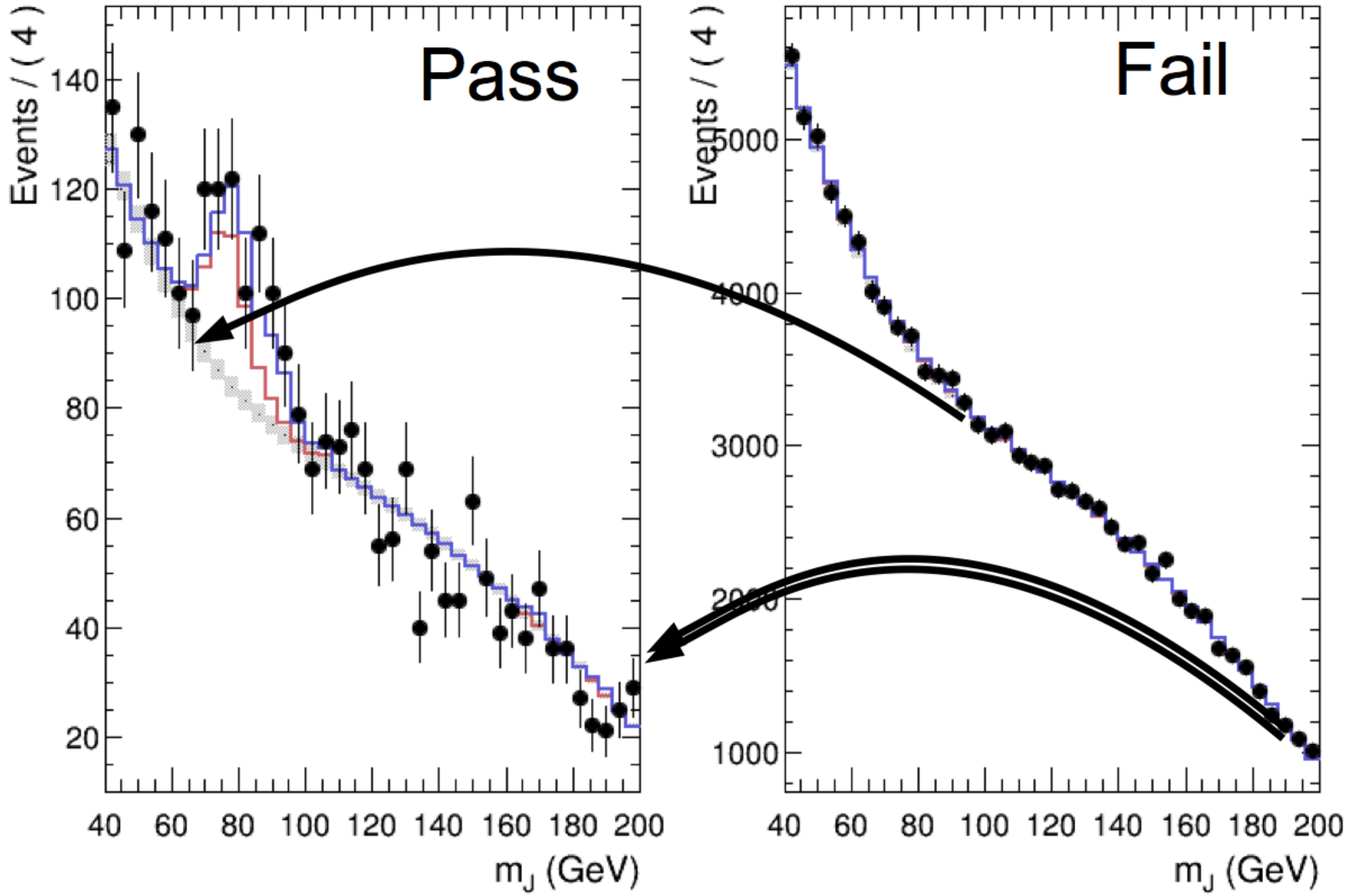


arXiv:1603.00027

Fit both Pass and Fail

Pass QCD = fail $\varepsilon(\rho,p_T)$

General Idea



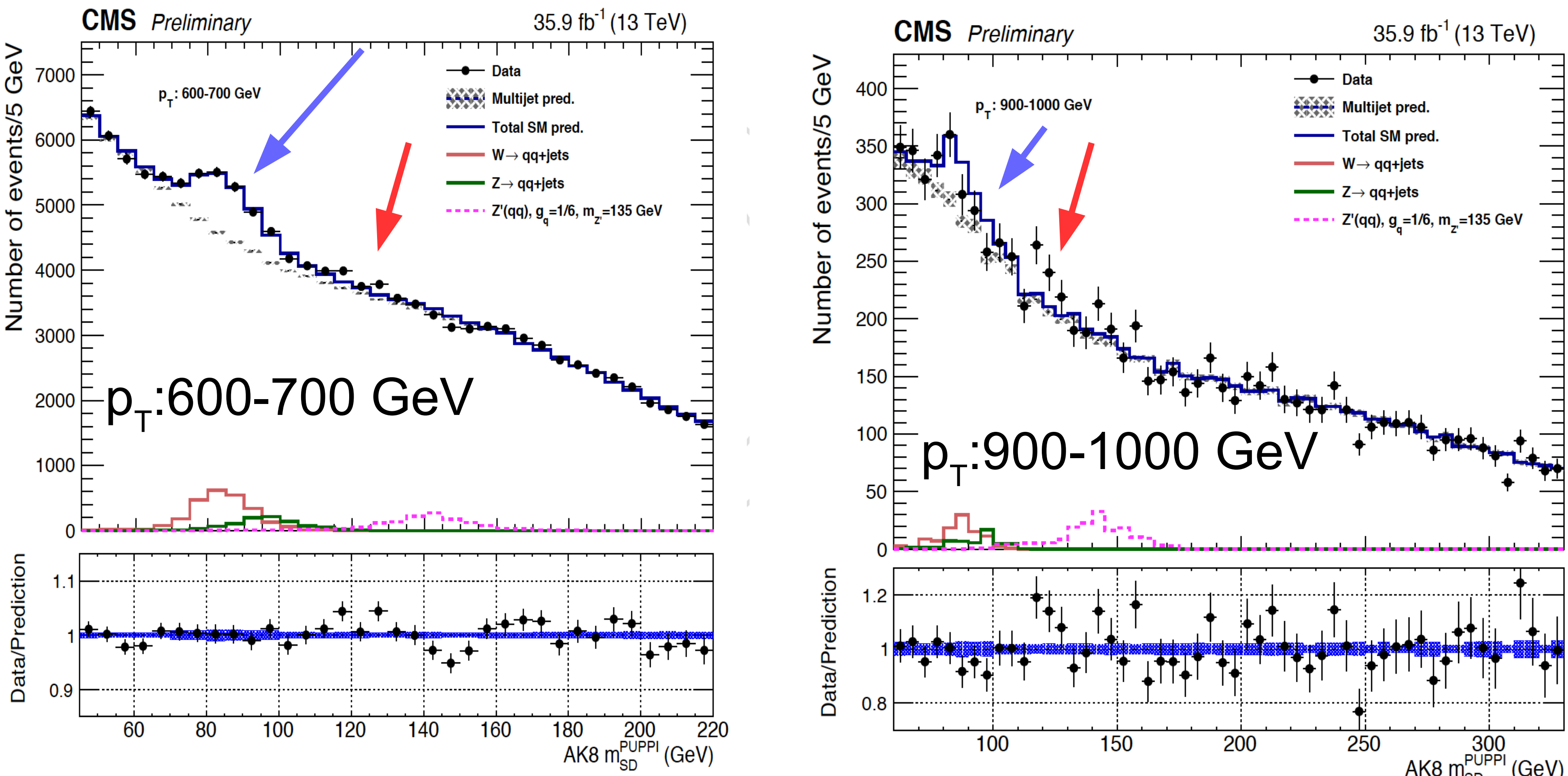
Fist iteration did this in two steps

Next iteration all in one fit (thanks to monojet technology)

$Bin_i^{Pass} = \varepsilon_0(1+a\ p_T+b\rho+c\rho^2+\ldots)\ Bin_i^{Fail}$ (add orders til f-test ok)

EXO-17-001

What we see



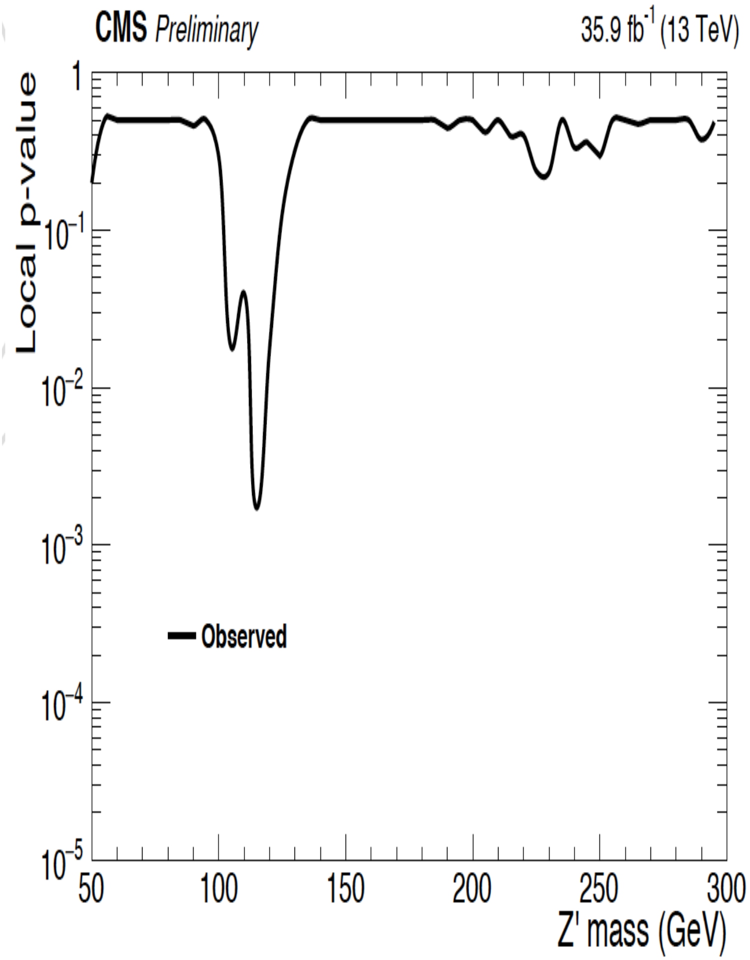
Nice W/Z→Jet peak

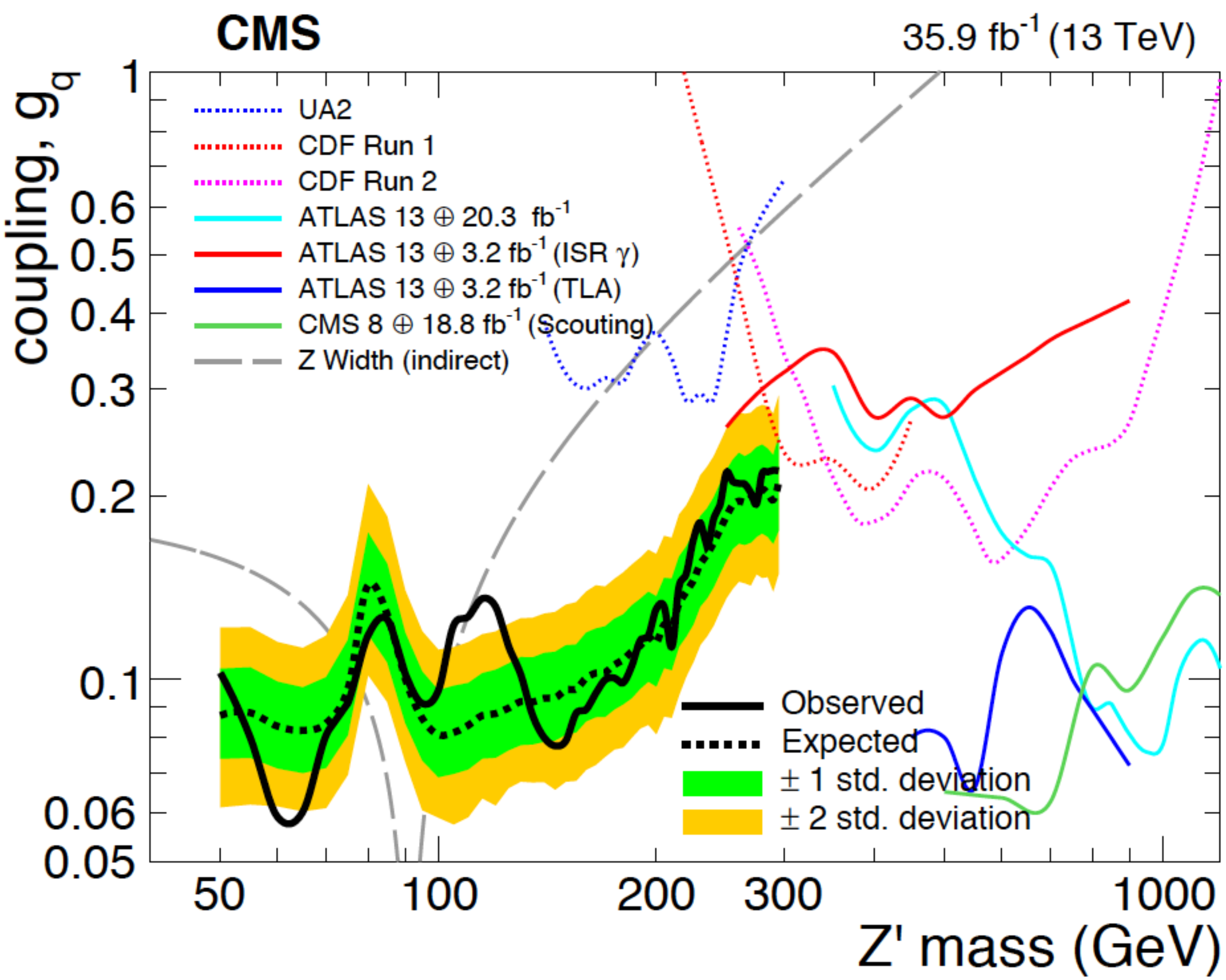
Excess present near 115-120 GeV

Precision level analysis

EXO-17-001

Combining



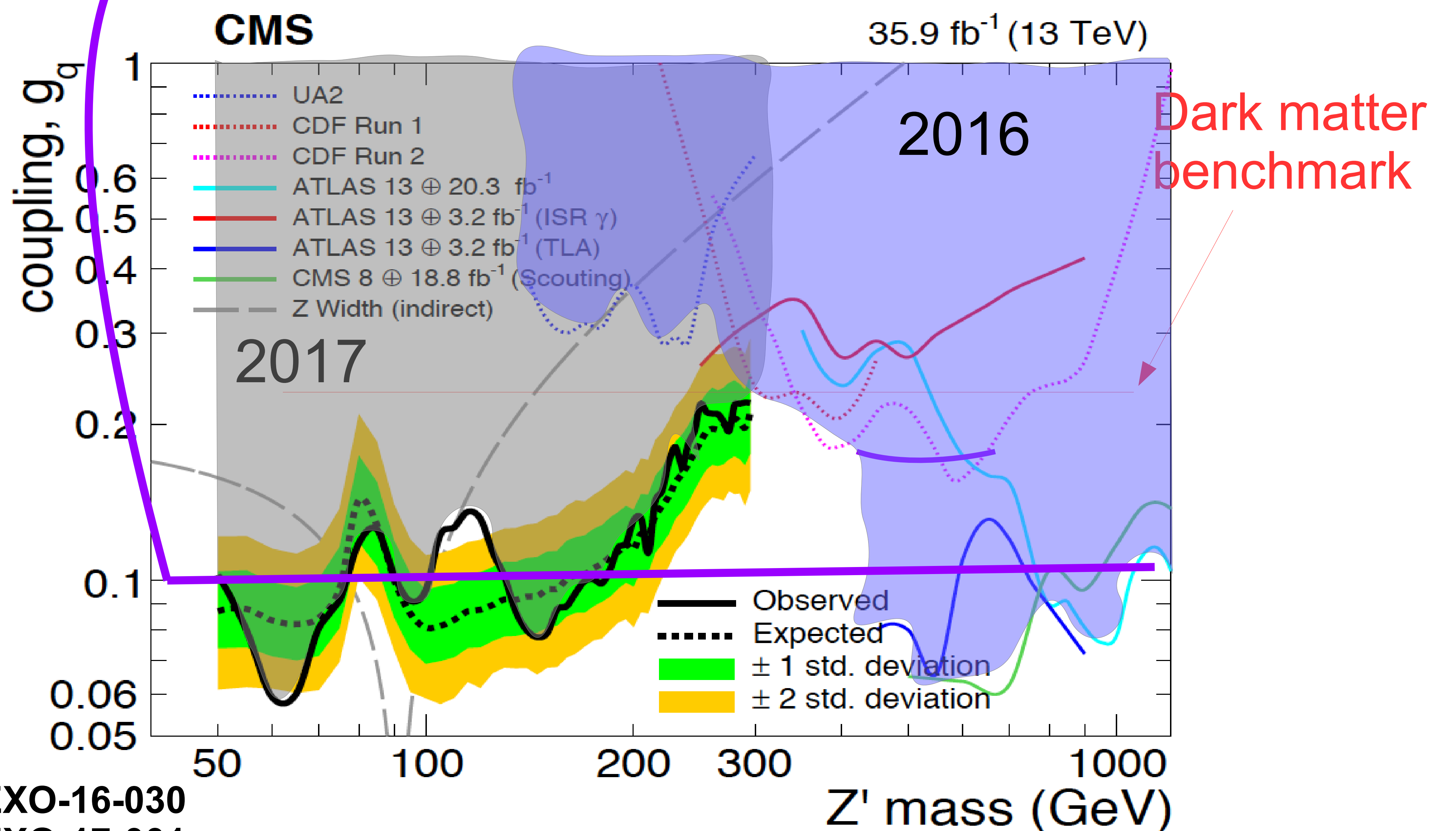


Excess with 2.9 (2.2 global) significance

Visible in last bin

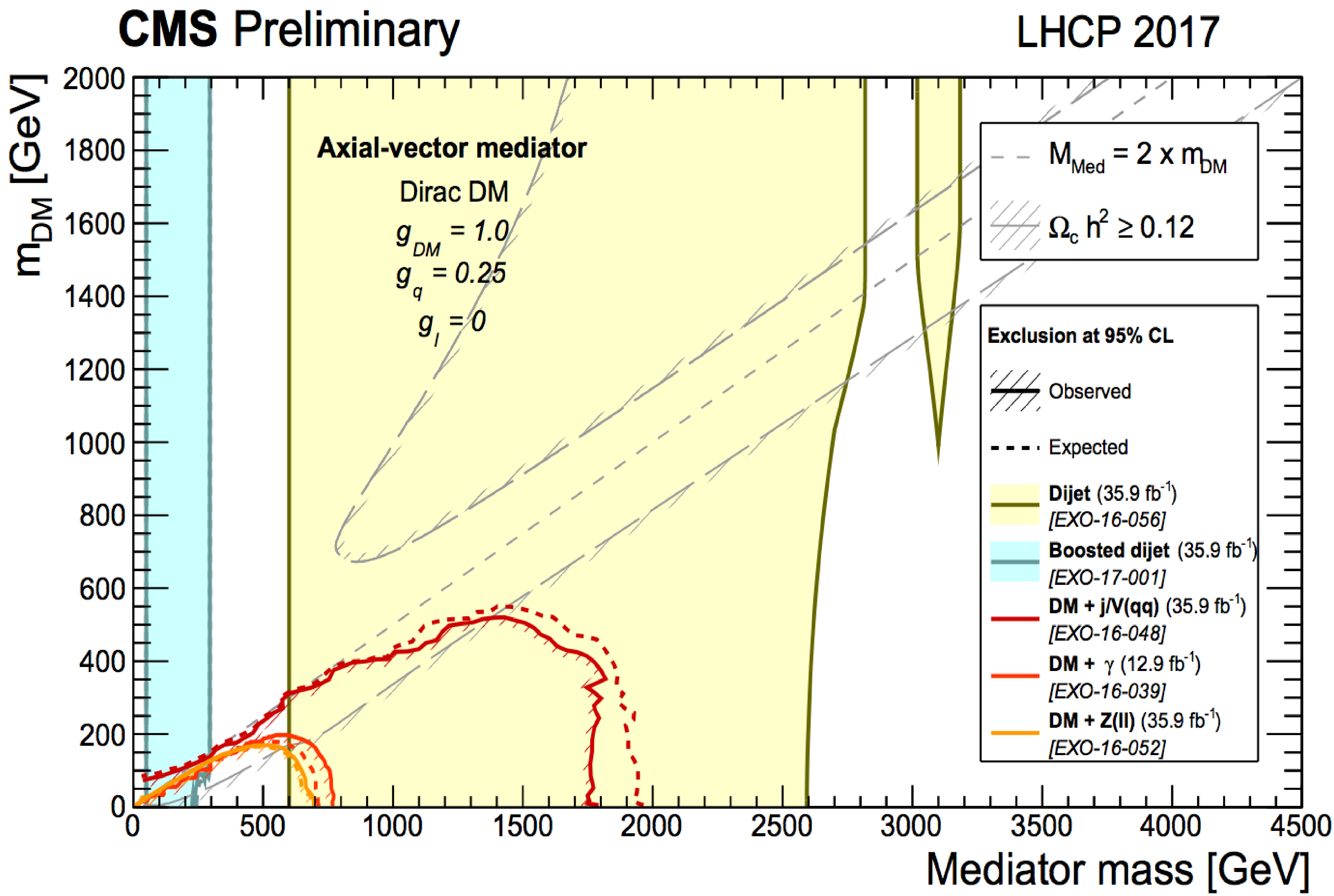
EXO-17-001

Interesting Region from earlier slides



EXO-16-030
EXO-17-001

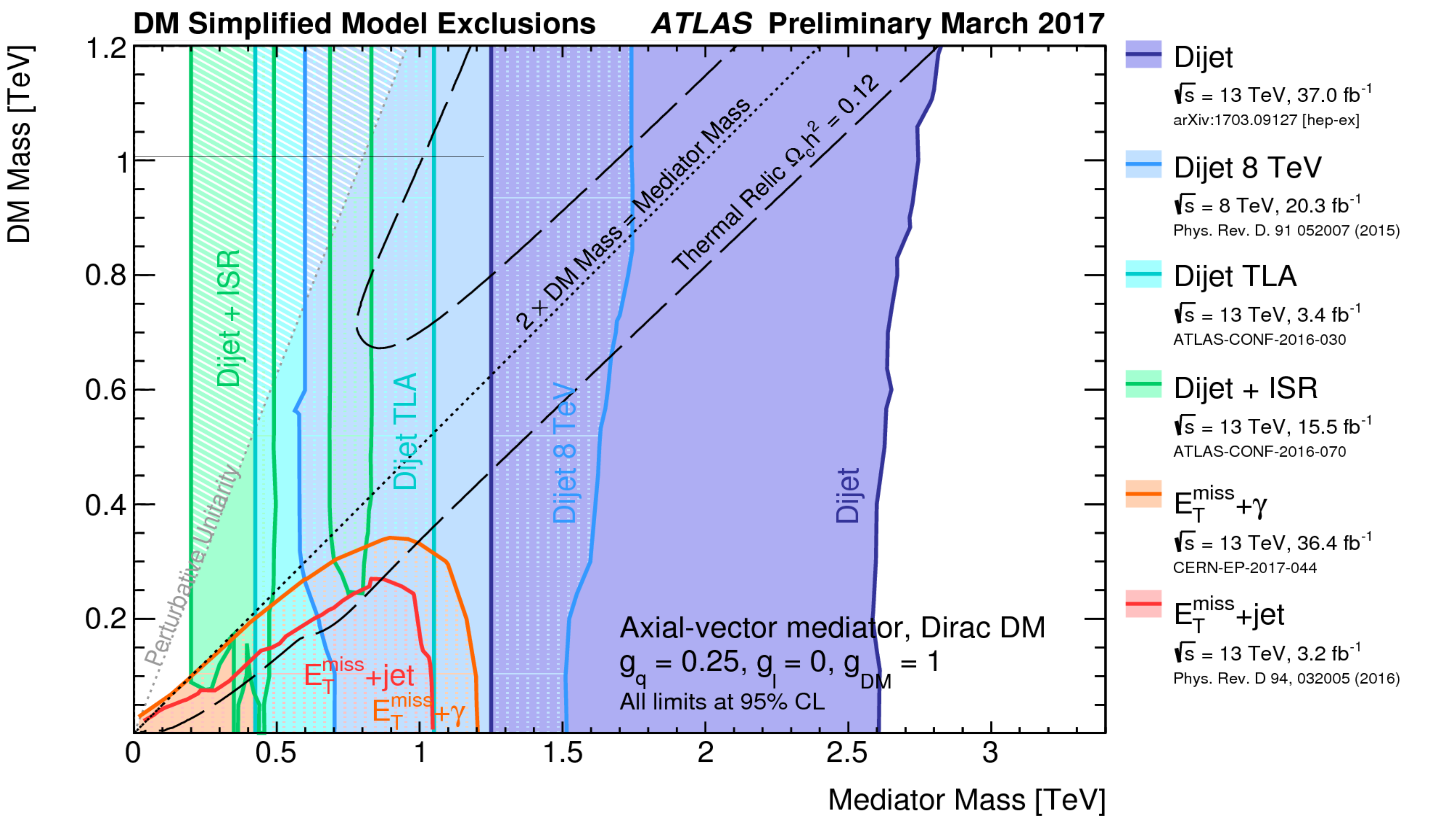
CMS



CMS-DP-2016-057

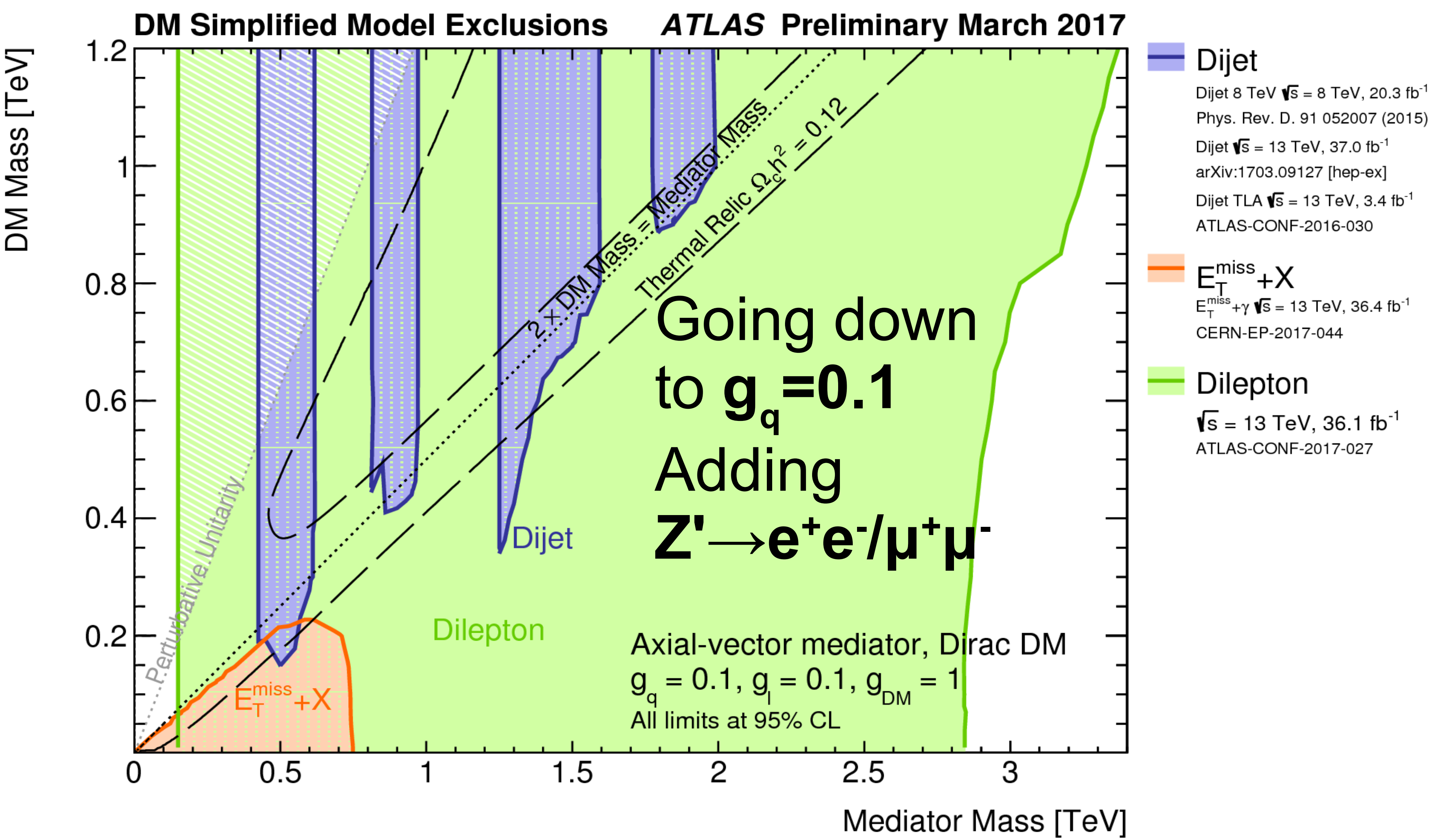
ATLAS Results : Split even further

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html#



Now with adding the leptons

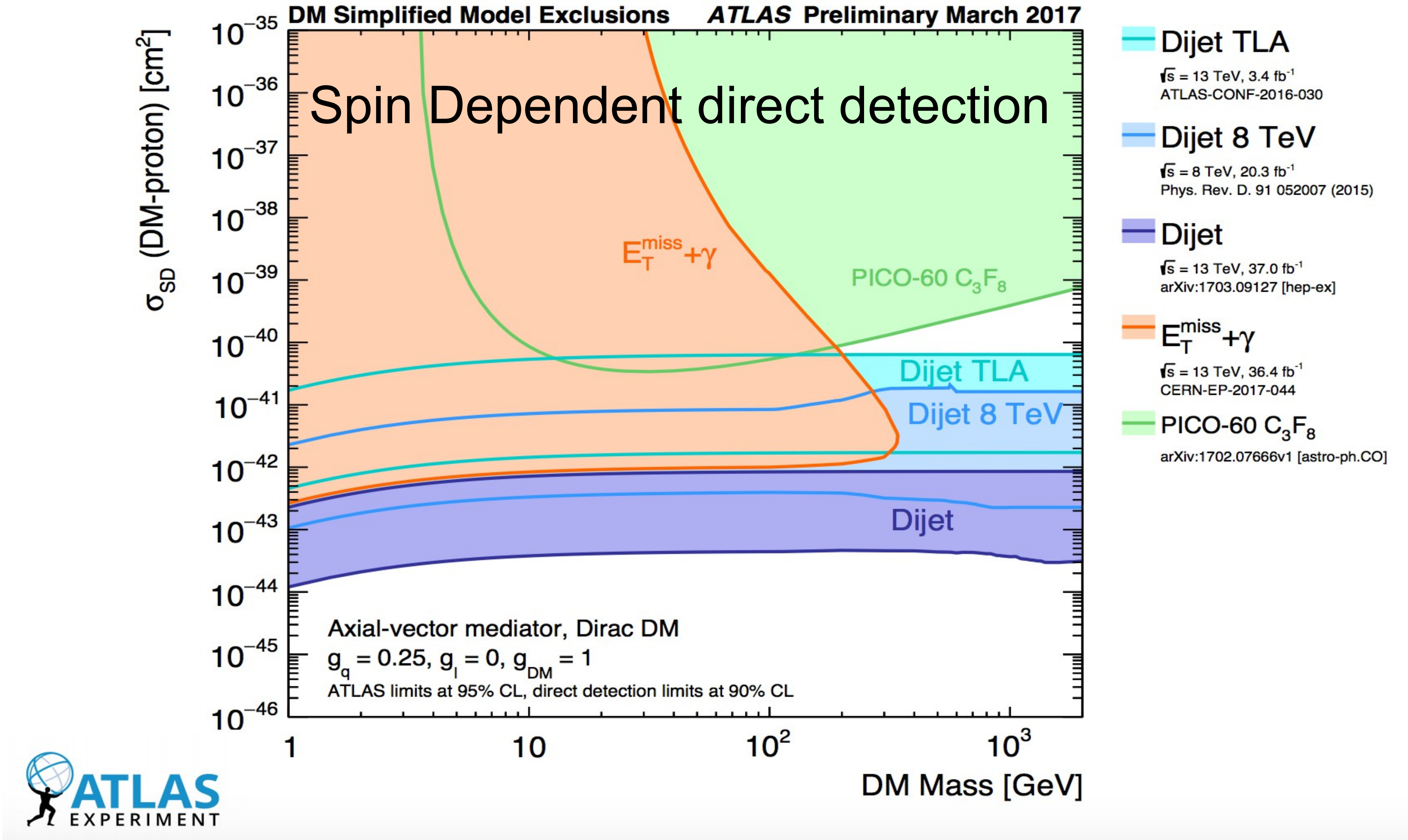
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html#



Going down to **g_q=0.1**

Adding **$Z' \rightarrow e^+e^-/\mu^+\mu^-$**

Direct Detection

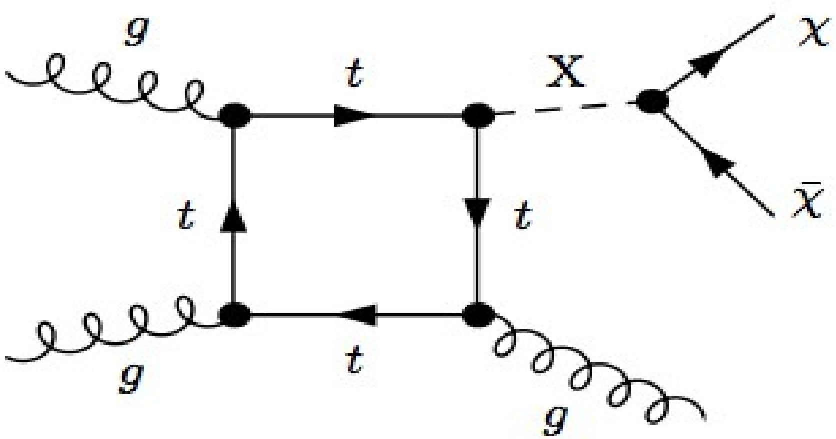


CMS-DP-2016-057

Spin 0

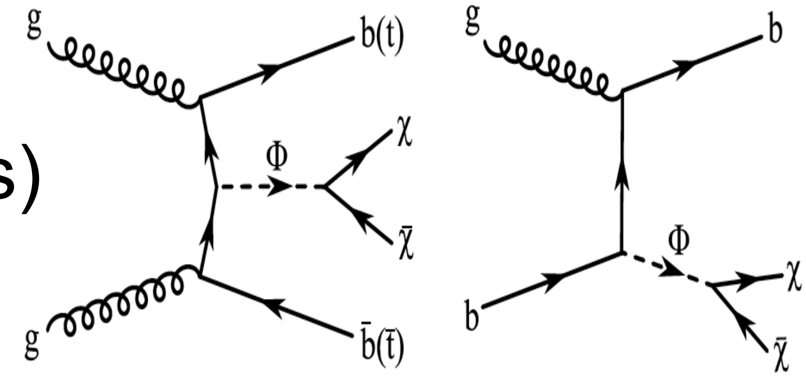
What can you do with Spin 0?

Basic production is gluon fusion
Amplitude is double for pseudoscalar mediator

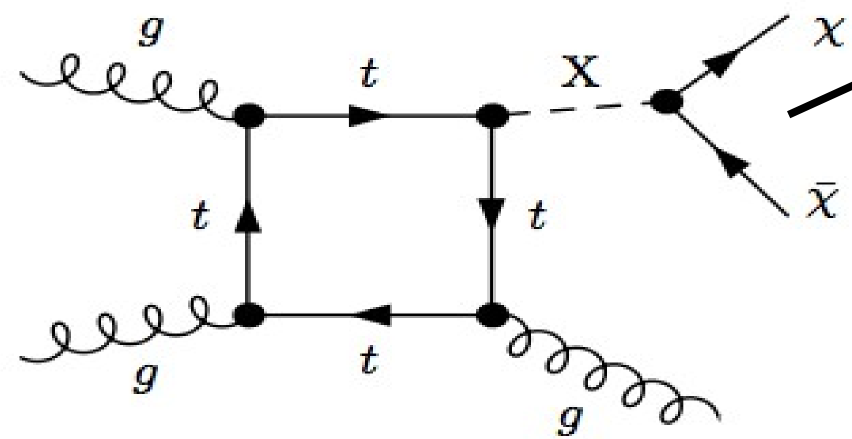


What can you do with Spin 0?

Heavy flavor channels
Can be added with (same couplings)

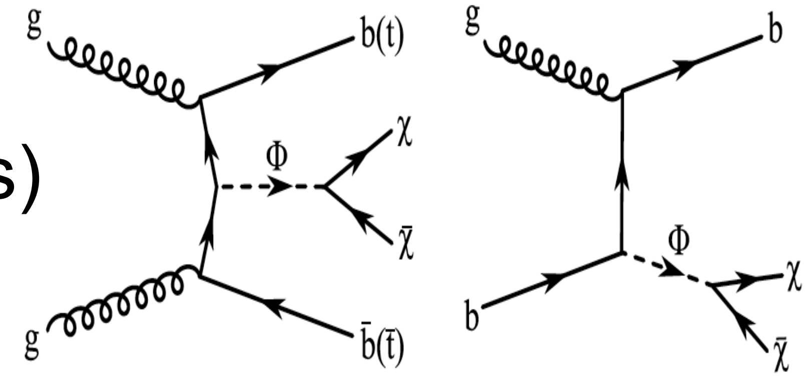


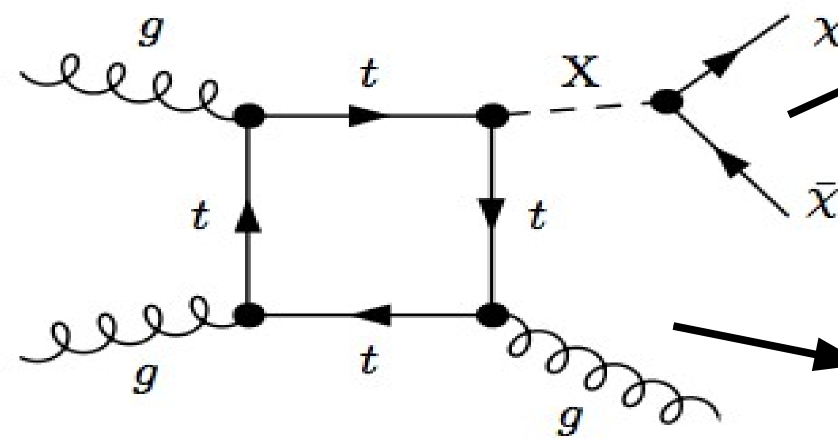
Heavy Flavor
final states



What can you do with Spin 0?

Heavy flavor channels
Can be added with (same couplings)

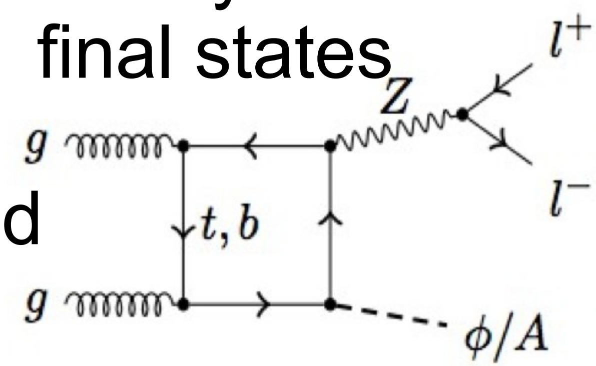




Heavy Flavor
final states

EXO16028

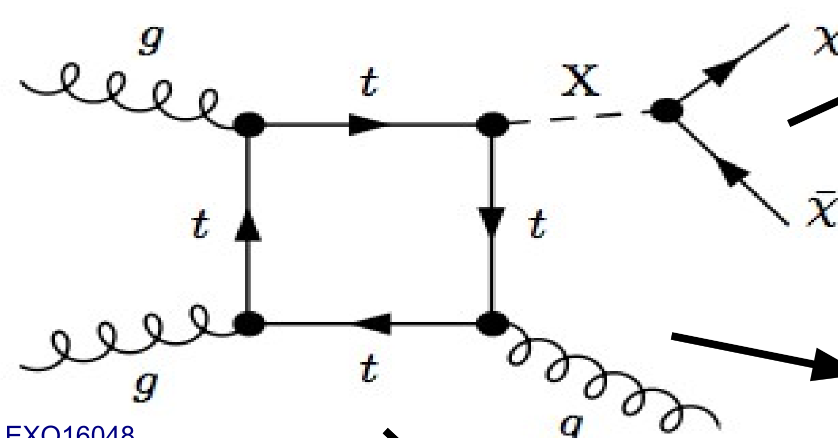
Loop induced
Z boson



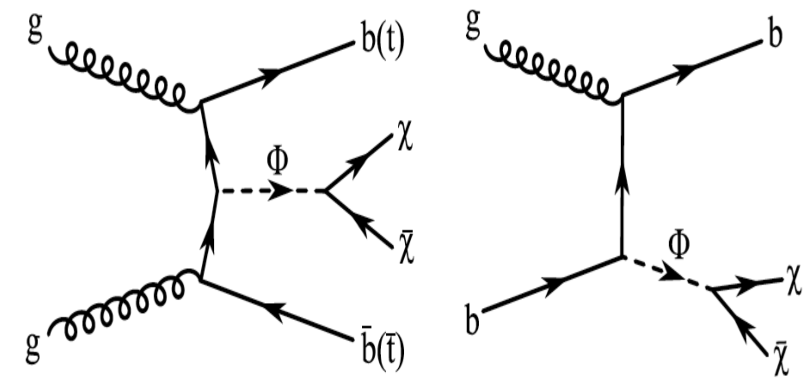
EXO16052

What can you do with Spin 0?

Big Assumption :
No mixing w/Higgs



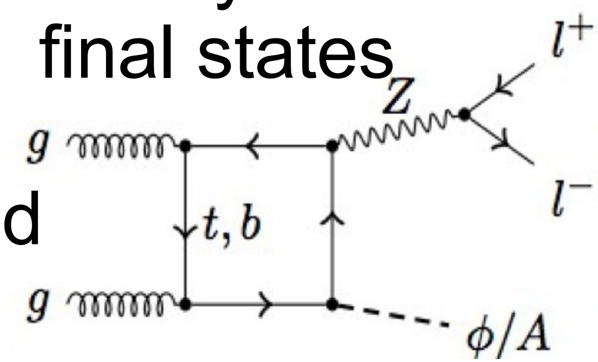
EXO16048



Heavy Flavor
final states

EXO16028

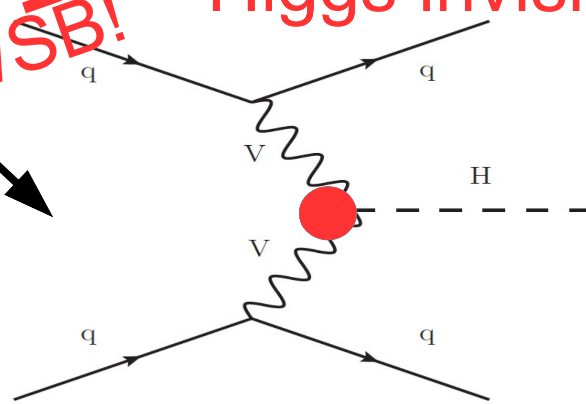
Loop induced
Z boson

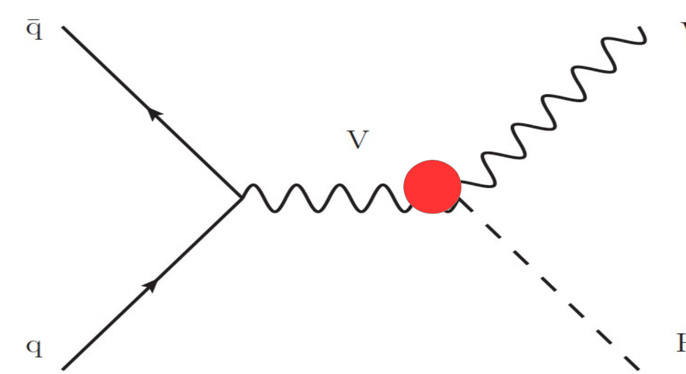


EXO16052

Applying EWSB!

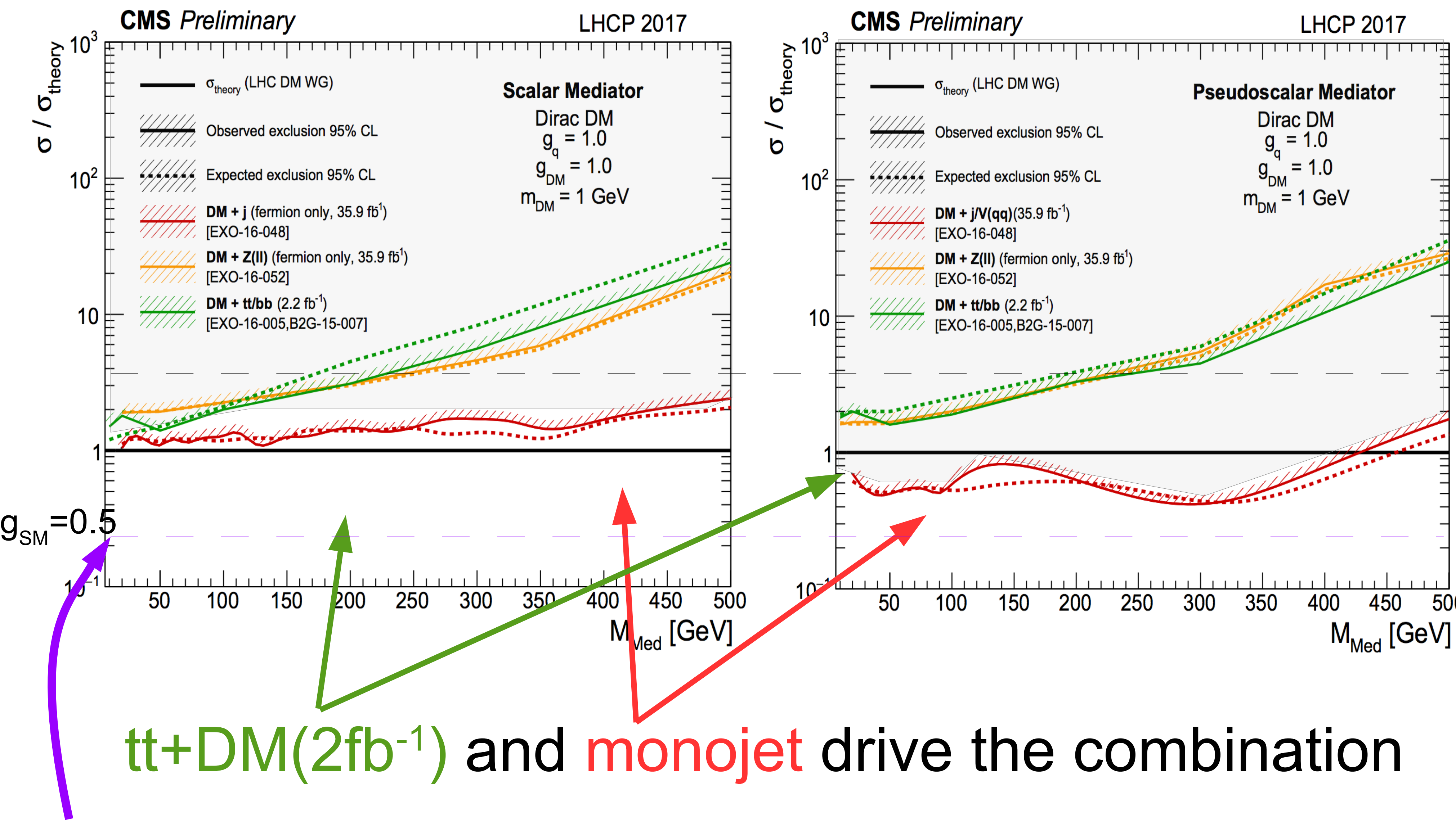
Higgs invisible or Scalar w/EWSB





No EWSB

Comparing all channels

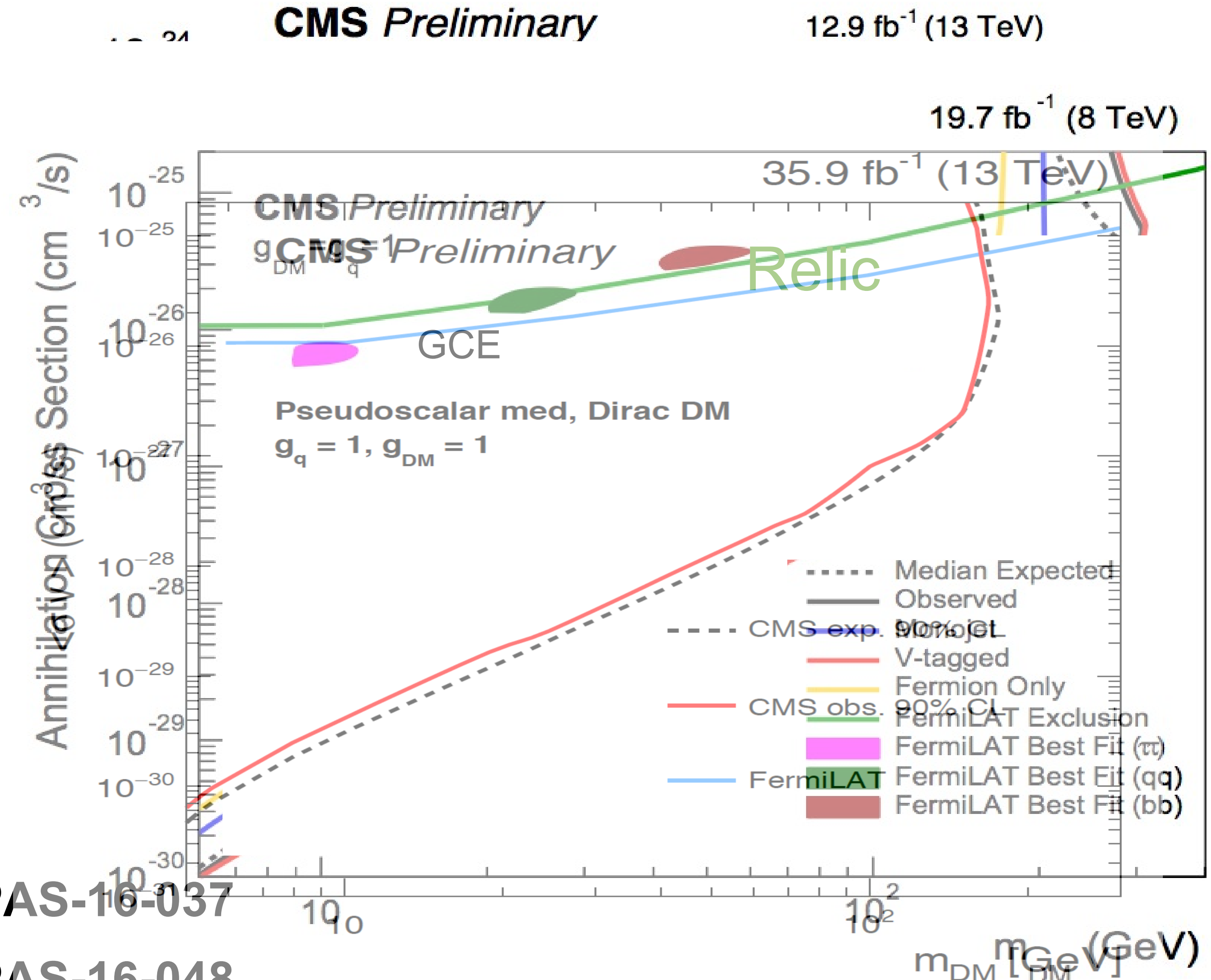


tt+DM(2fb^{-1}) and monojet drive the combination

Not far from an intermediate benchmark of g_{SM} = 0.5

Whats the impact?

No EWSB



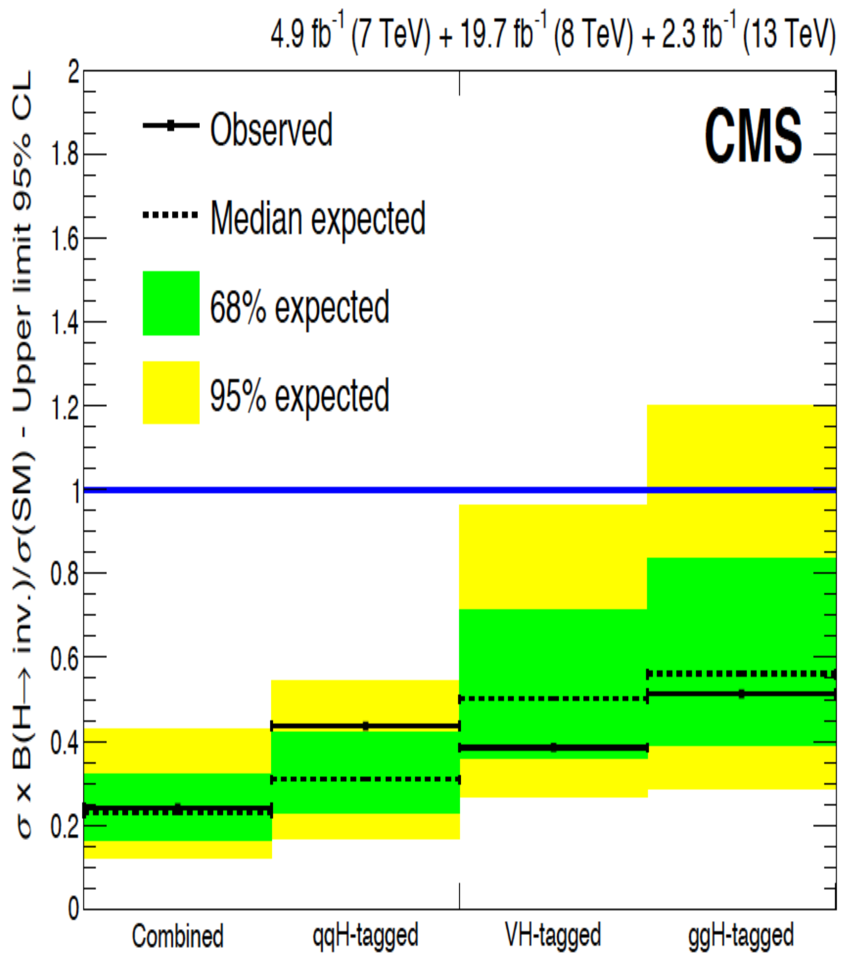
CMS-PAS-16-037

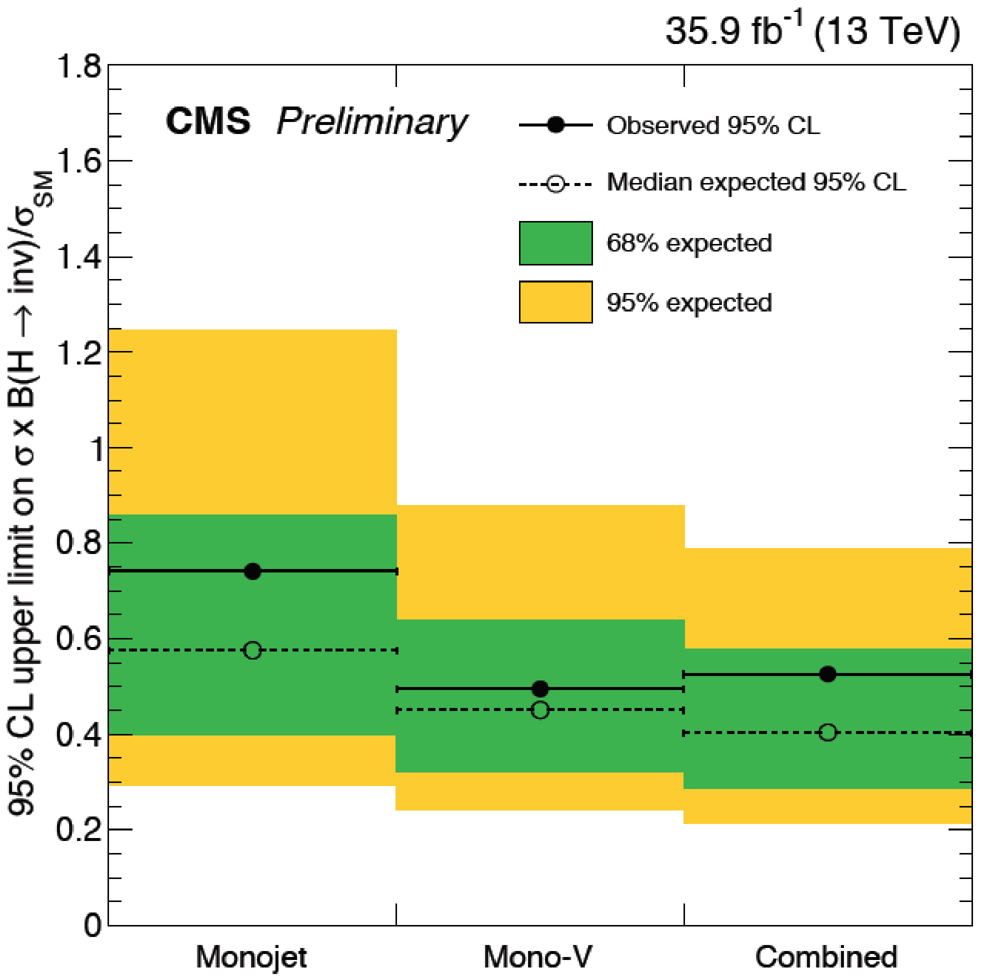
CMS-PAS-16-048

EWSB

At the Higgs mass

- This model is the same as Higgs invisible search

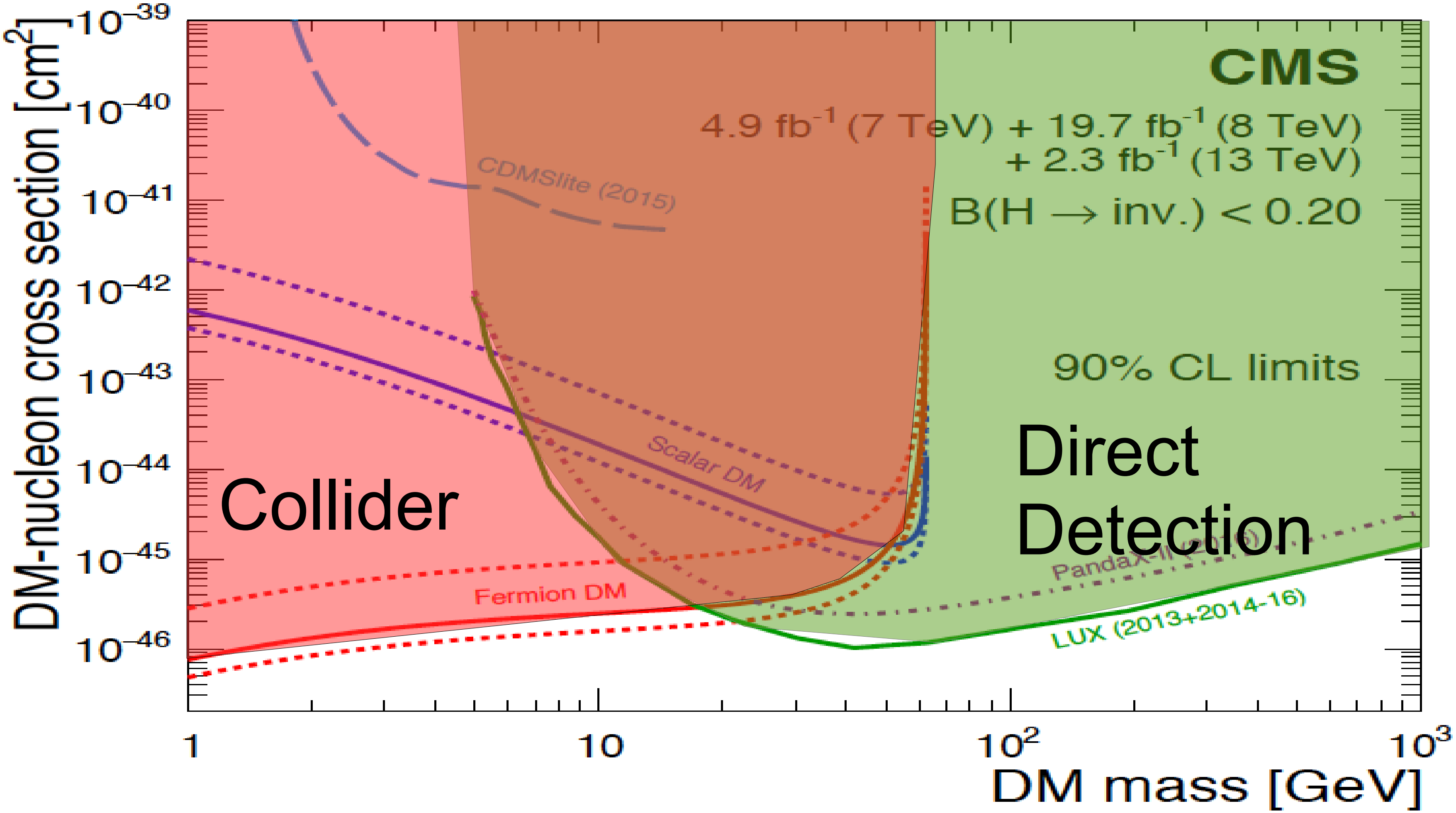




BR(H→Inv) < 24% (CMS) 25% (ATLAS)

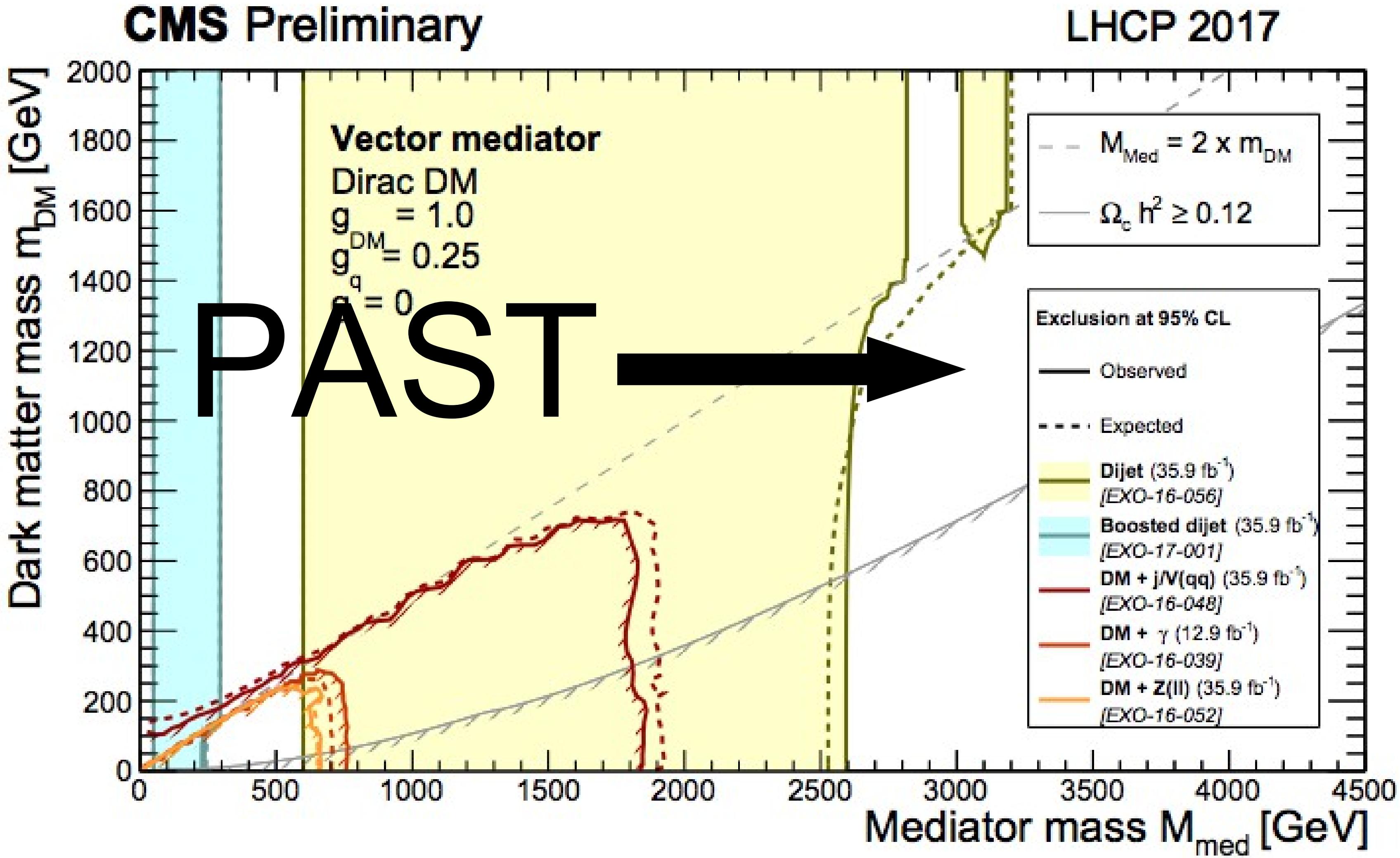
At the Higgs mass

- Higgs to invisible :
  - Direct detection and collider are head to head



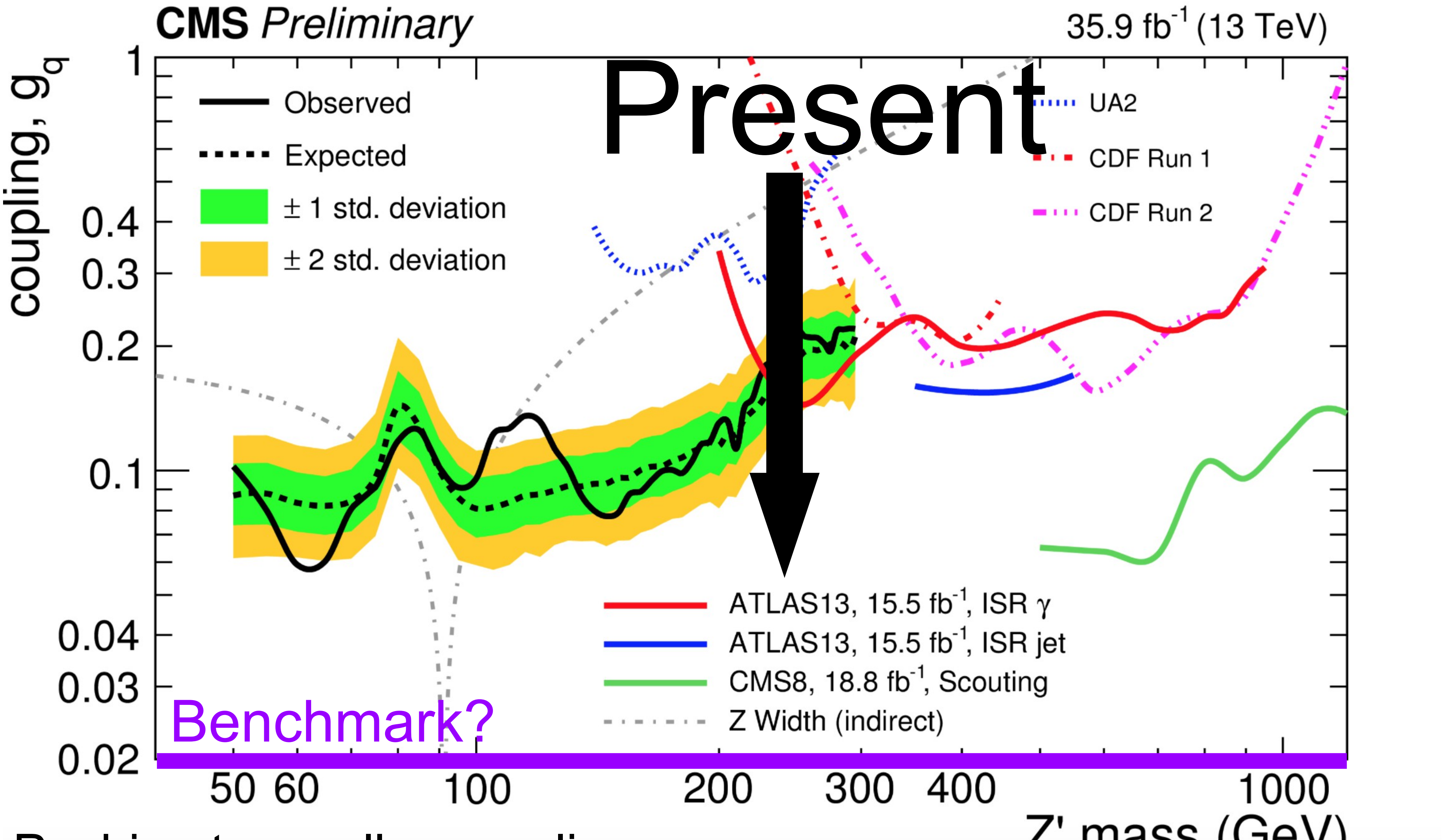
BR(H→Inv) < 24% (CMS) 25% (ATLAS)

Conclusions

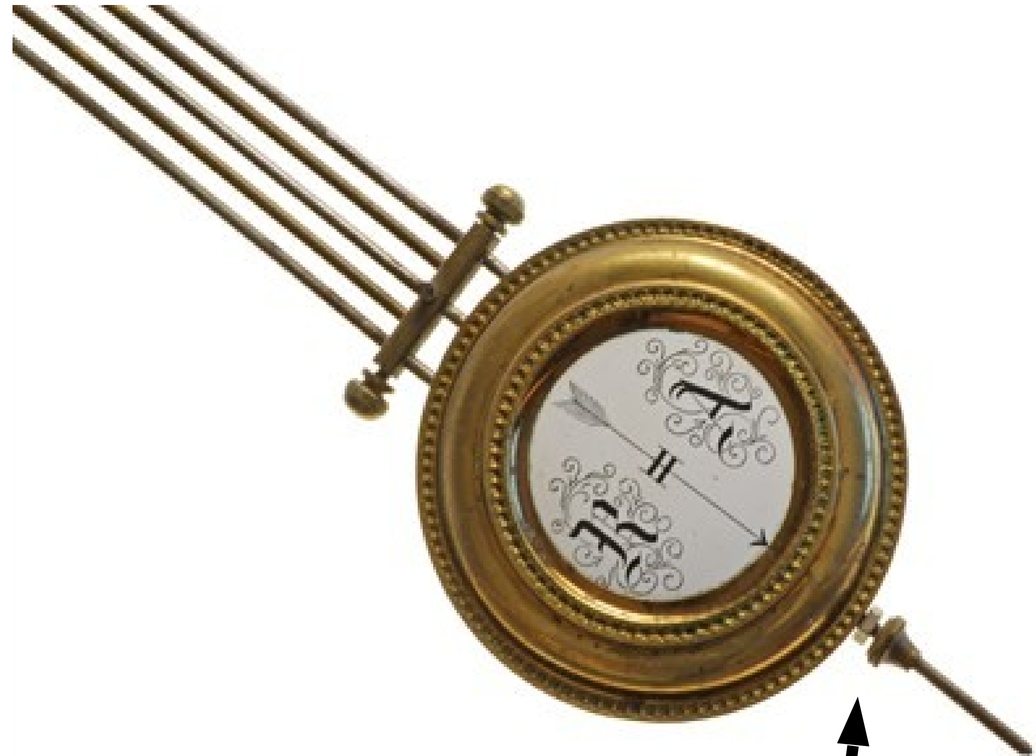


Pushing to higher masses

Conclusions



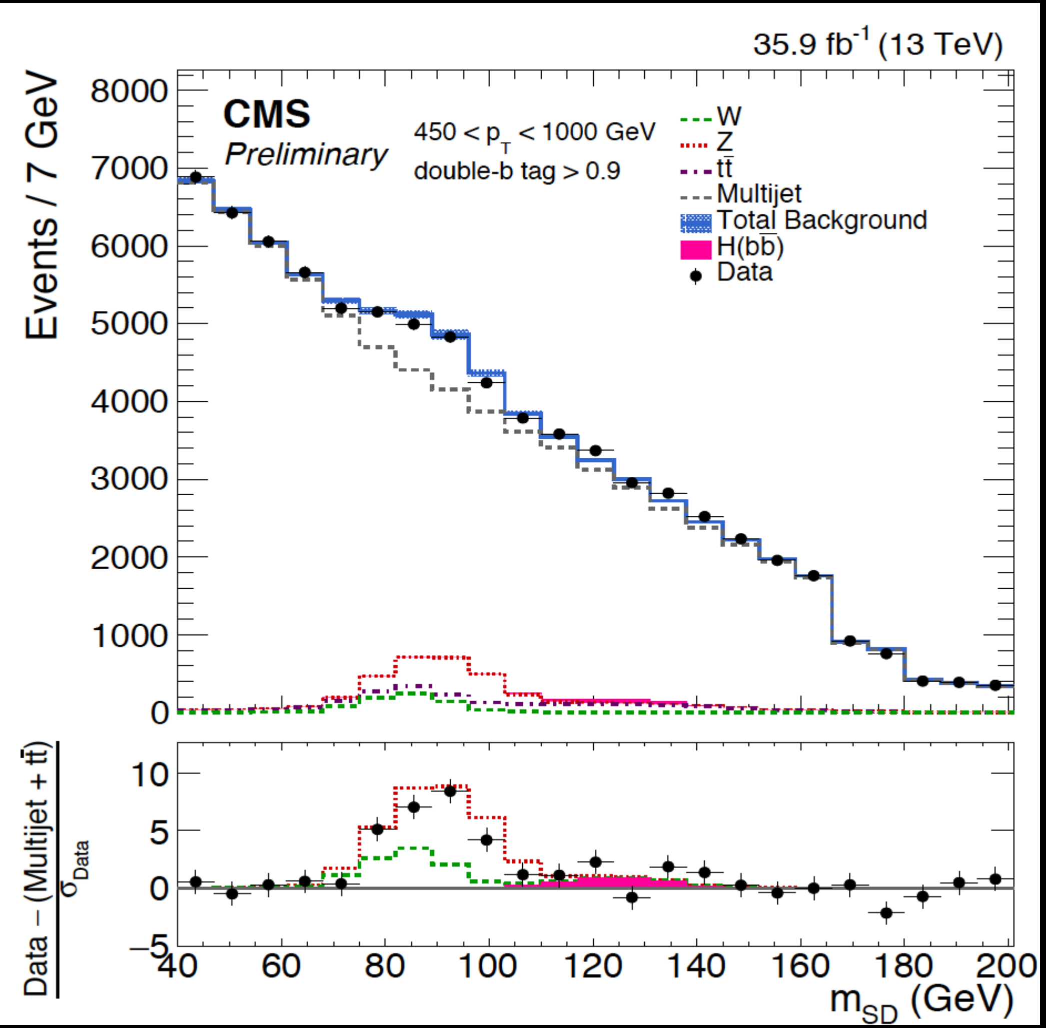
Pushing to smaller couplings



Forever

SM

BSM

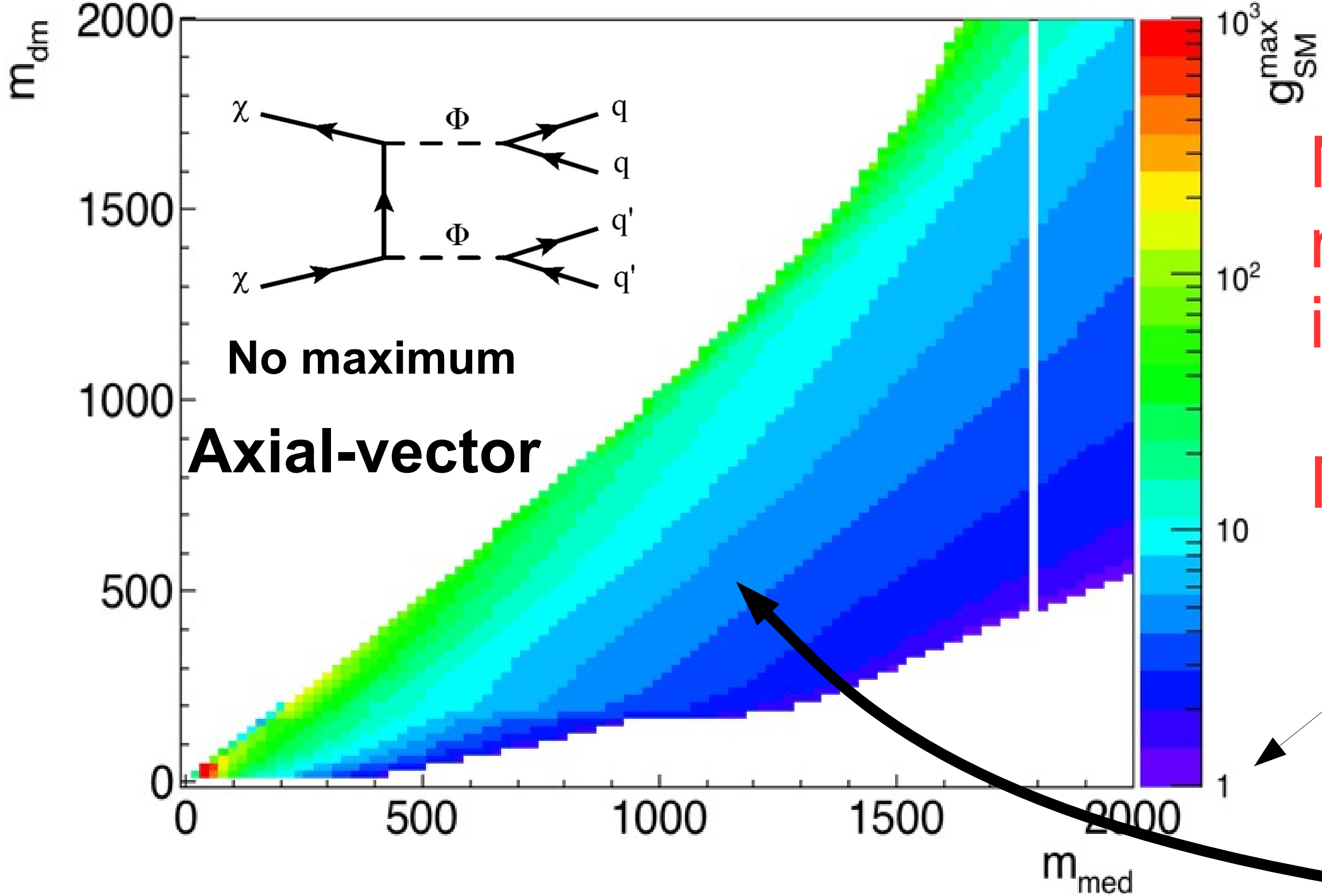


Thanks!

See Rainer Mankel's talk at Blois next week

Max couplings

- Now consider the maximum coupling
  - In this case we fix g_{DM}=1 (product $g_q g_{DM}$ defines bound)

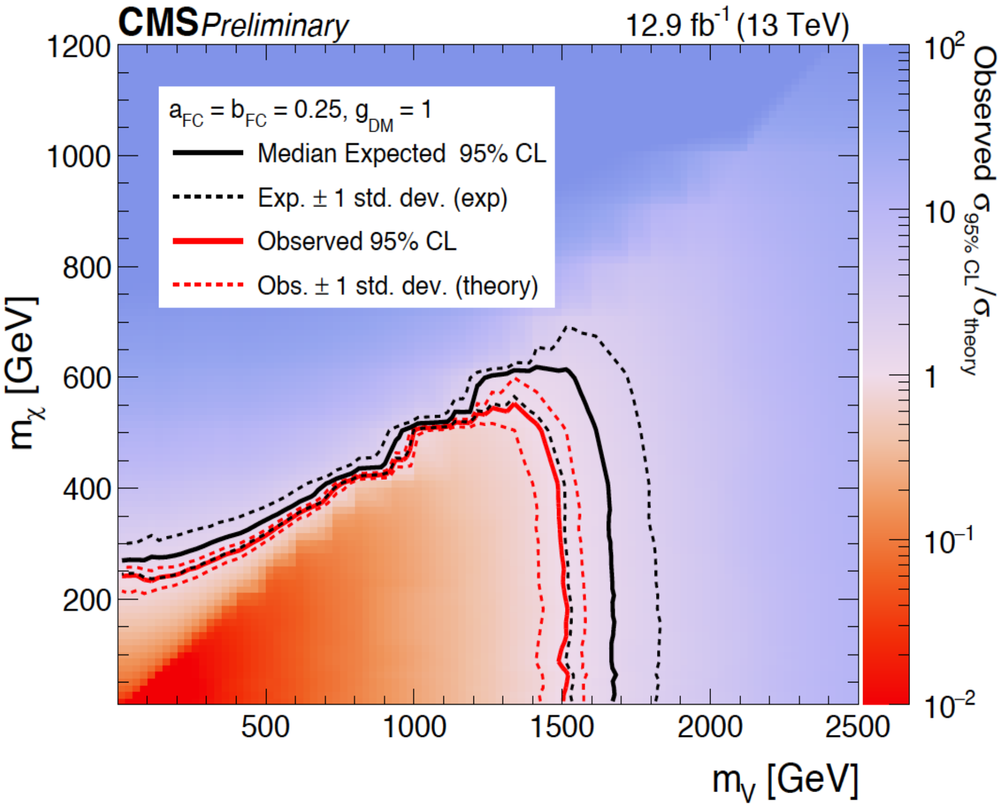


Note the
max allowed coupling
is very large

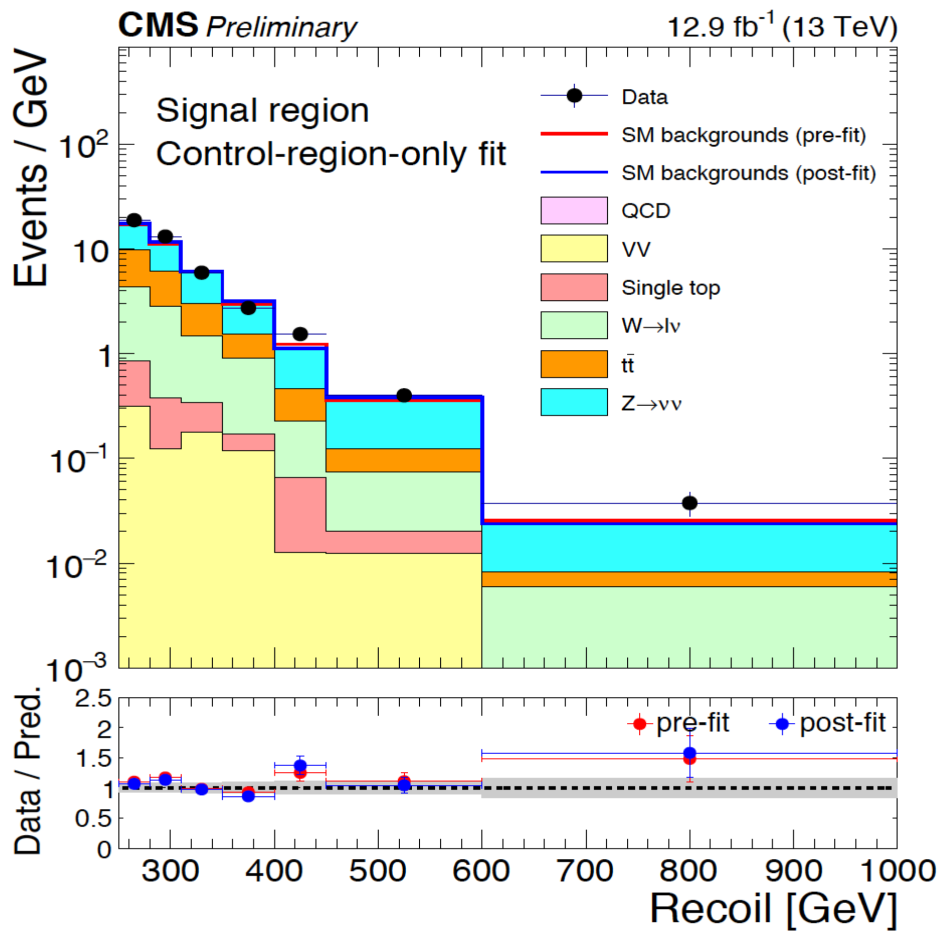
$\Gamma_{med}/M_{med} > 0.5$

Given coupling so large we will not focus on this upper bound

CMS Monotop



CMS Preliminary
12.9 fb^{-1} (13 TeV)
$a_{FC} = b_{FC} = 0.25$, $g_{DM} = 1$
Median Expected 95% CL
Exp. ± 1 std. dev. (exp)
Observed 95% CL
Obs. ± 1 std. dev. (theory)
m_χ [GeV]
m_V [GeV]
Observed $\sigma_{95\% CL}/\sigma_{theory}$



CMS Preliminary
12.9 fb^{-1} (13 TeV)
Signal region
Control-region-only fit
Data
SM backgrounds (pre-fit)
SM backgrounds (post-fit)
QCD
VV
Single top
W→lν
$t\bar{t}$
Z→νν
Events / GeV
pre-fit
post-fit
Data / Pred.
Recoil [GeV]

BRAND NEW

New Substructure Observables

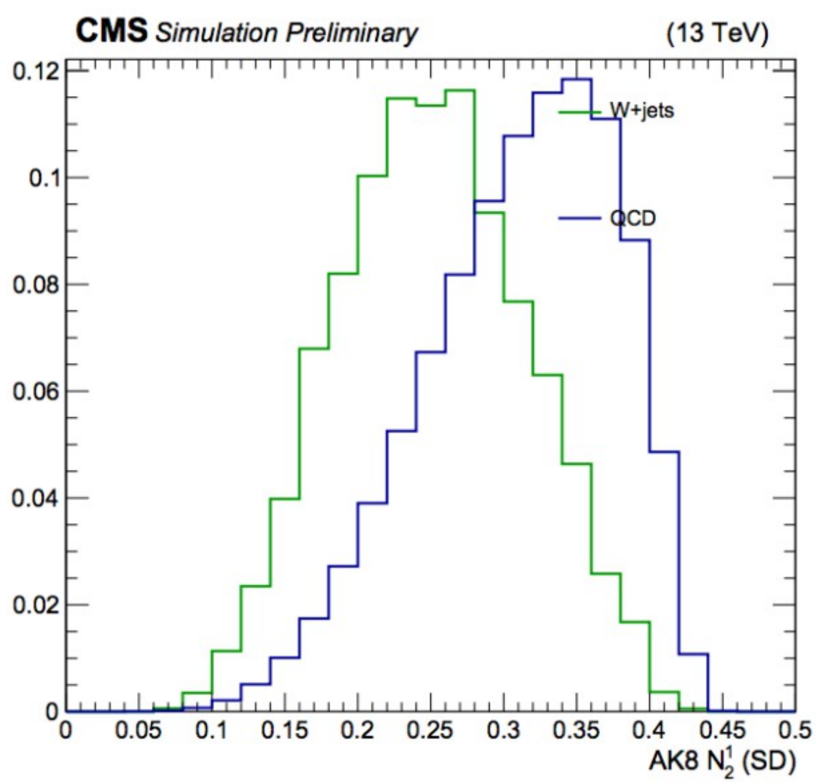
$$N_2(\beta) = \frac{{}_2e_3^{\beta}}{(e_2^{\beta})^2}$$

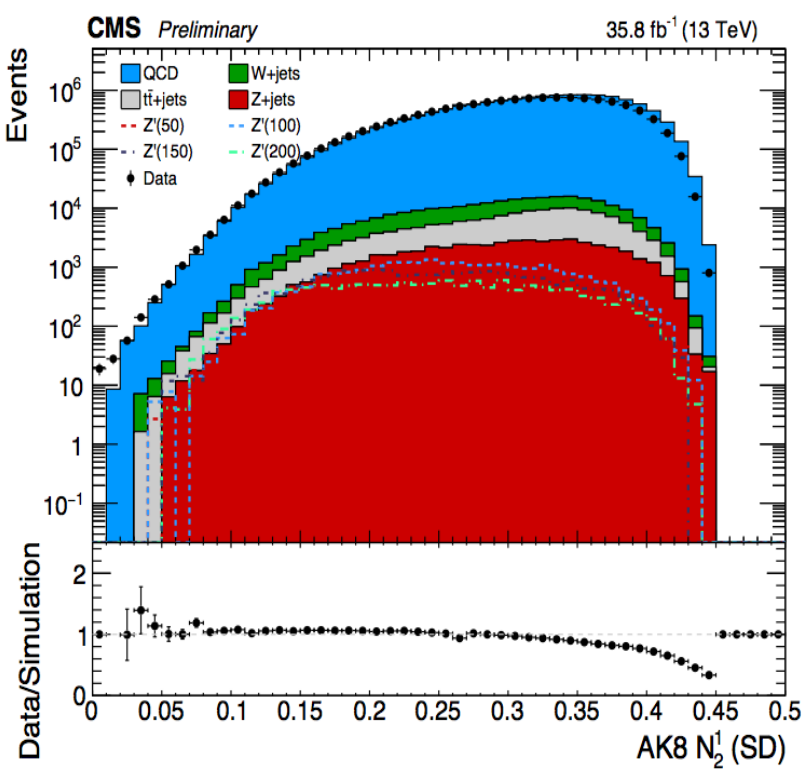
$${}_1e_2^{\beta} = e_2^{\beta} = \sum_{1 \le i < j \le n_J} z_i z_j \Delta R_{ij}^{\beta}$$

$${}_2e_3^{\beta} = \sum_{1 \le i < j < k \le n_J} z_i z_j z_k \min\{\Delta R_{ij}^{\beta}\Delta R_{ik}^{\beta}, \Delta R_{ij}^{\beta}\Delta R_{jk}^{\beta}, \Delta R_{ik}^{\beta}\Delta R_{jk}^{\beta}\}$$

$$z_i \equiv \frac{p_{Ti}}{\sum_{j \in \text{jet}} p_{Tj}}$$

Using AK8 PUPPI jets

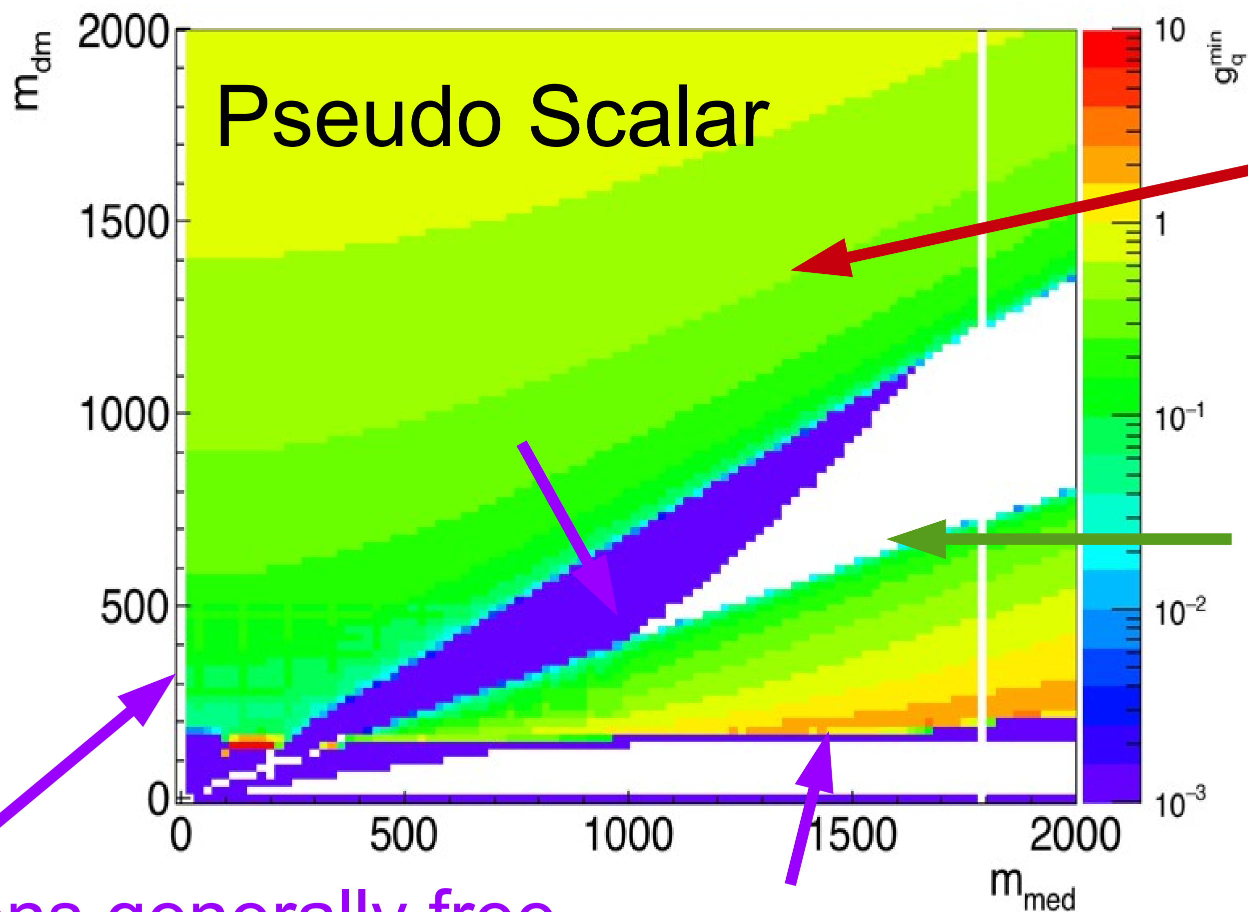




Arxiv/1609.07483

What do we conclude?

- For pseudoscalar we have looser constraints



Regions that generally overclose

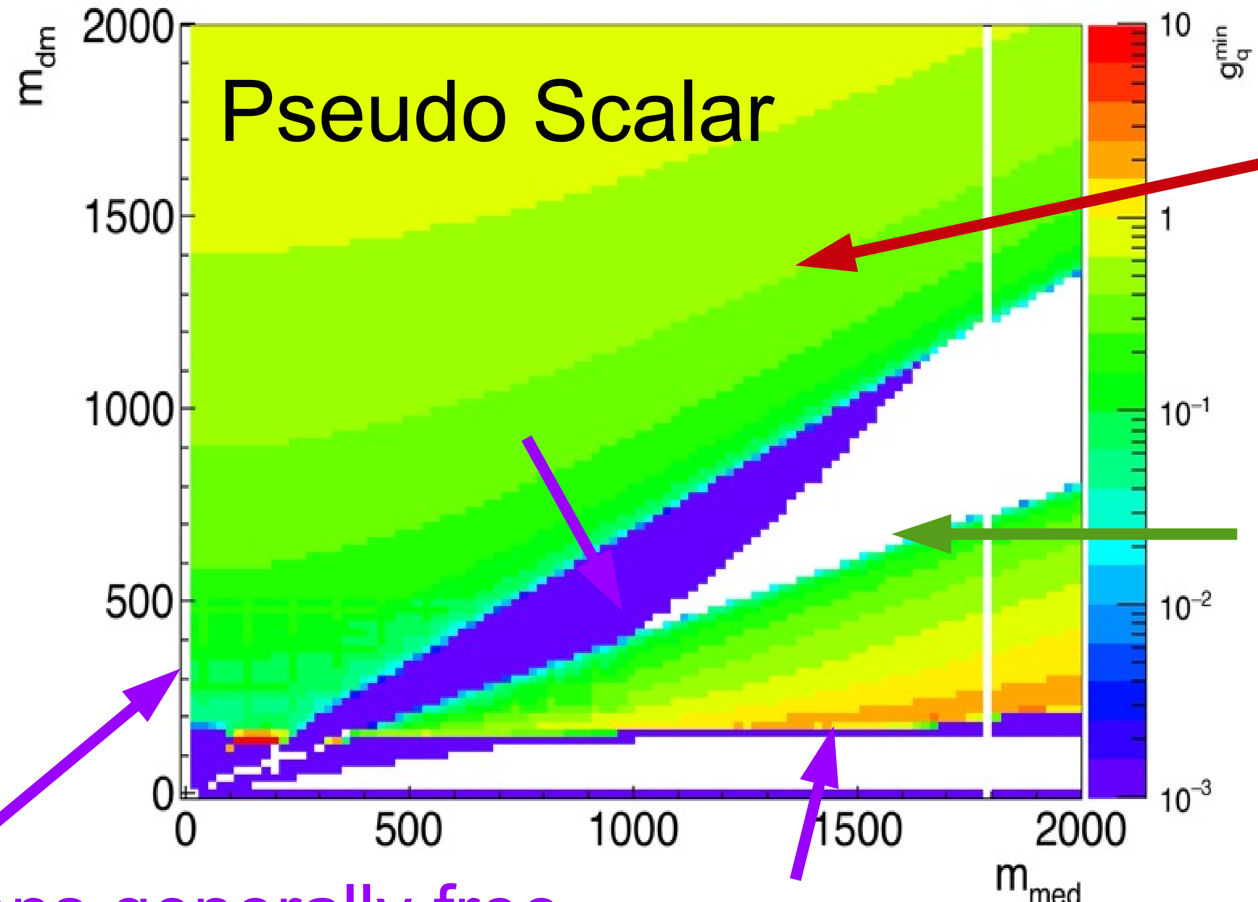
Regions we can try to probe with current or futrue colliders

Regions generally free
Of relic constraints

Aim for 0.1 < gq < 3

What do we conclude?

- What is driving the results is the coupling



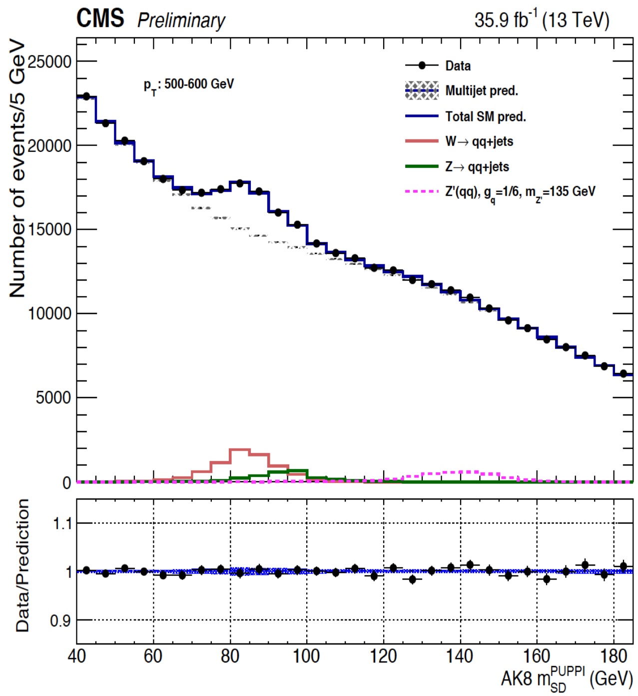
Regions that generally overclose

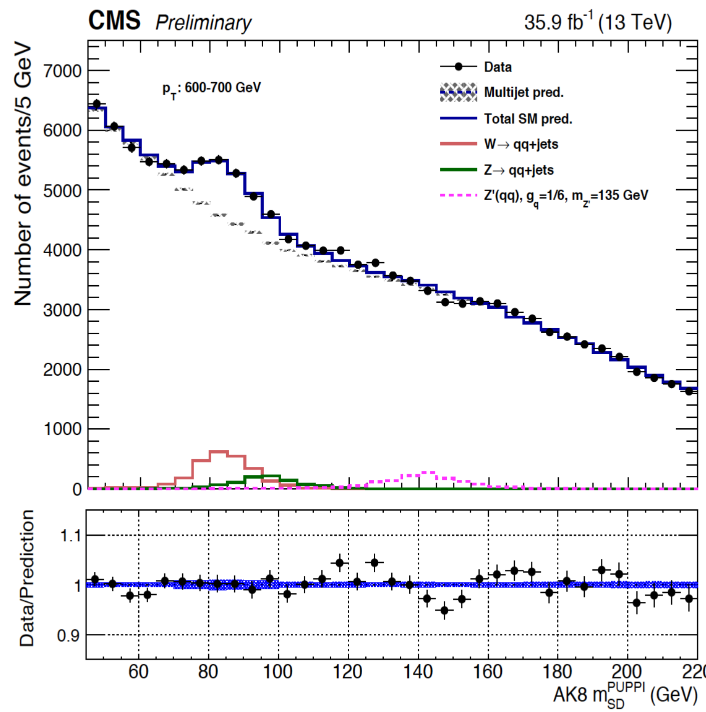
Regions we can try to probe with current or futrue colliders

Regions generally free
Of relic constraints

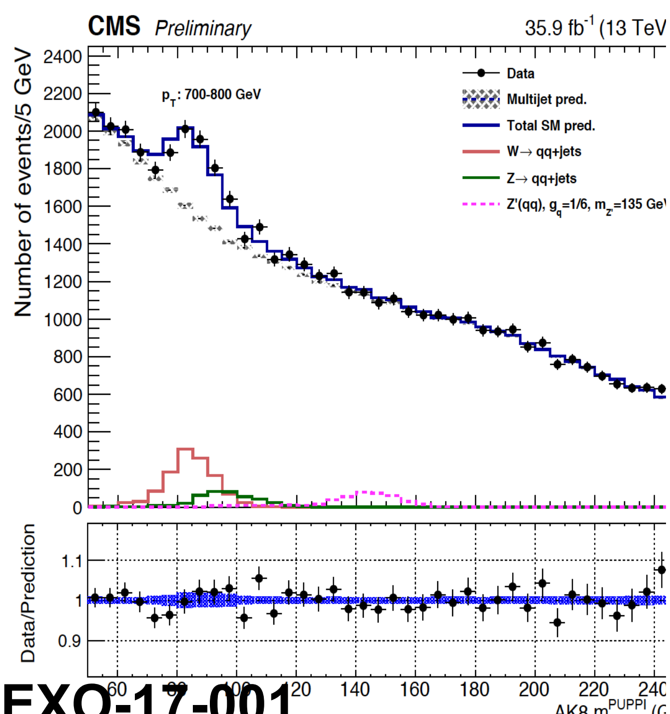
Aim for 0.1 < gq < 3

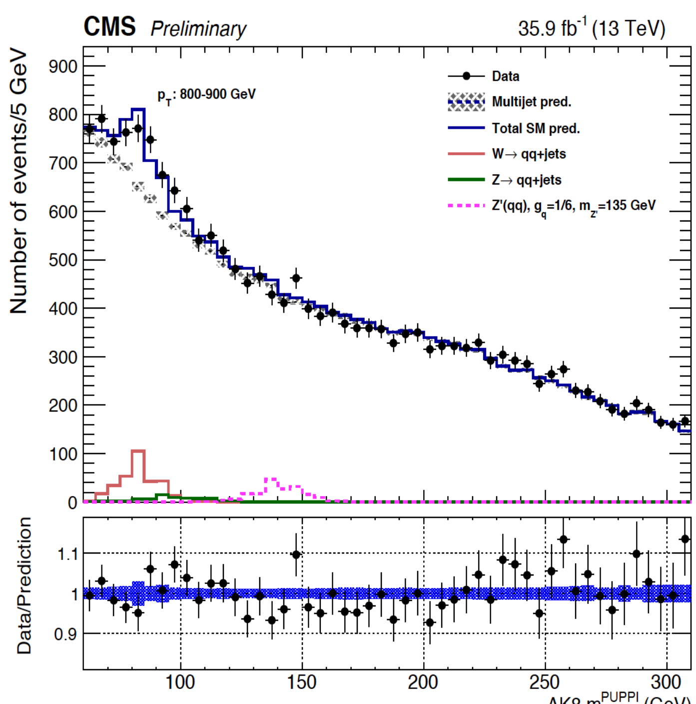
What we see

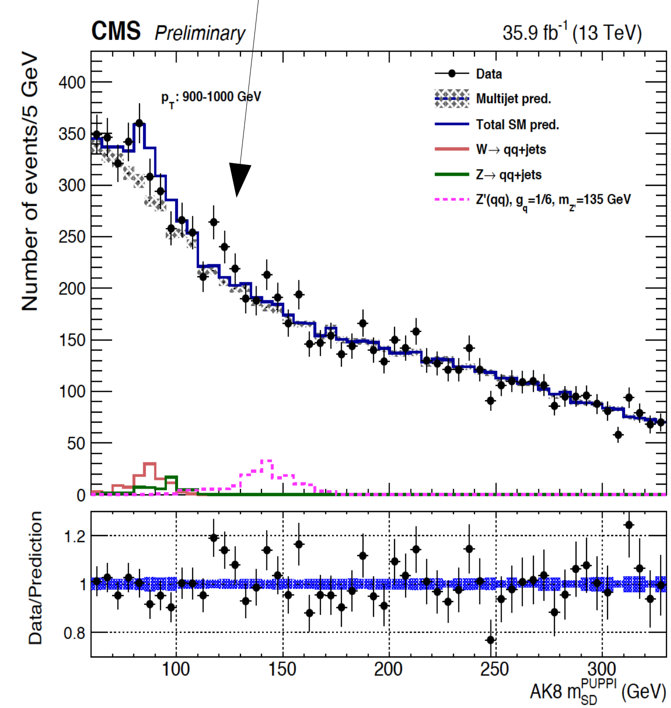




Excess present near 115-120

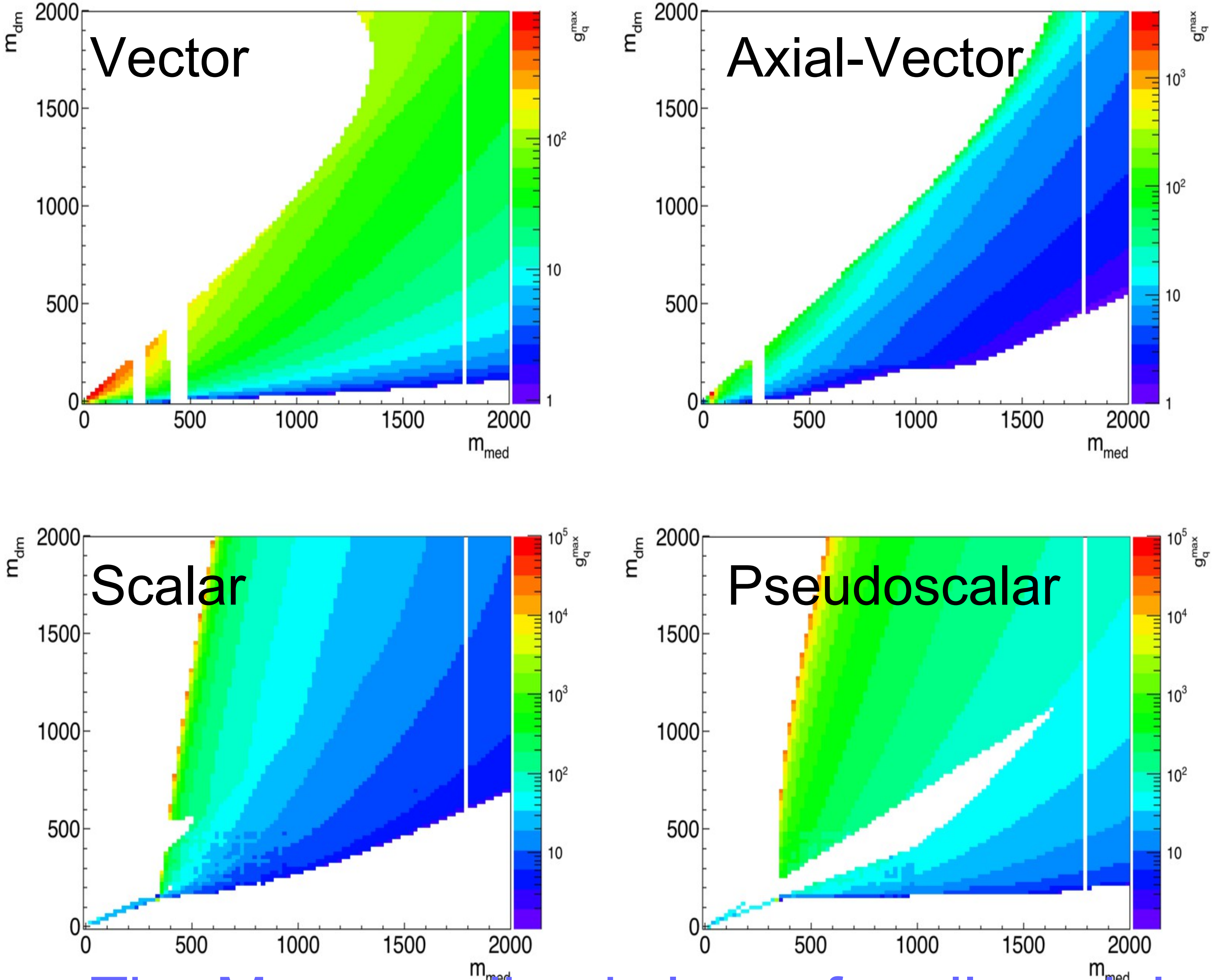






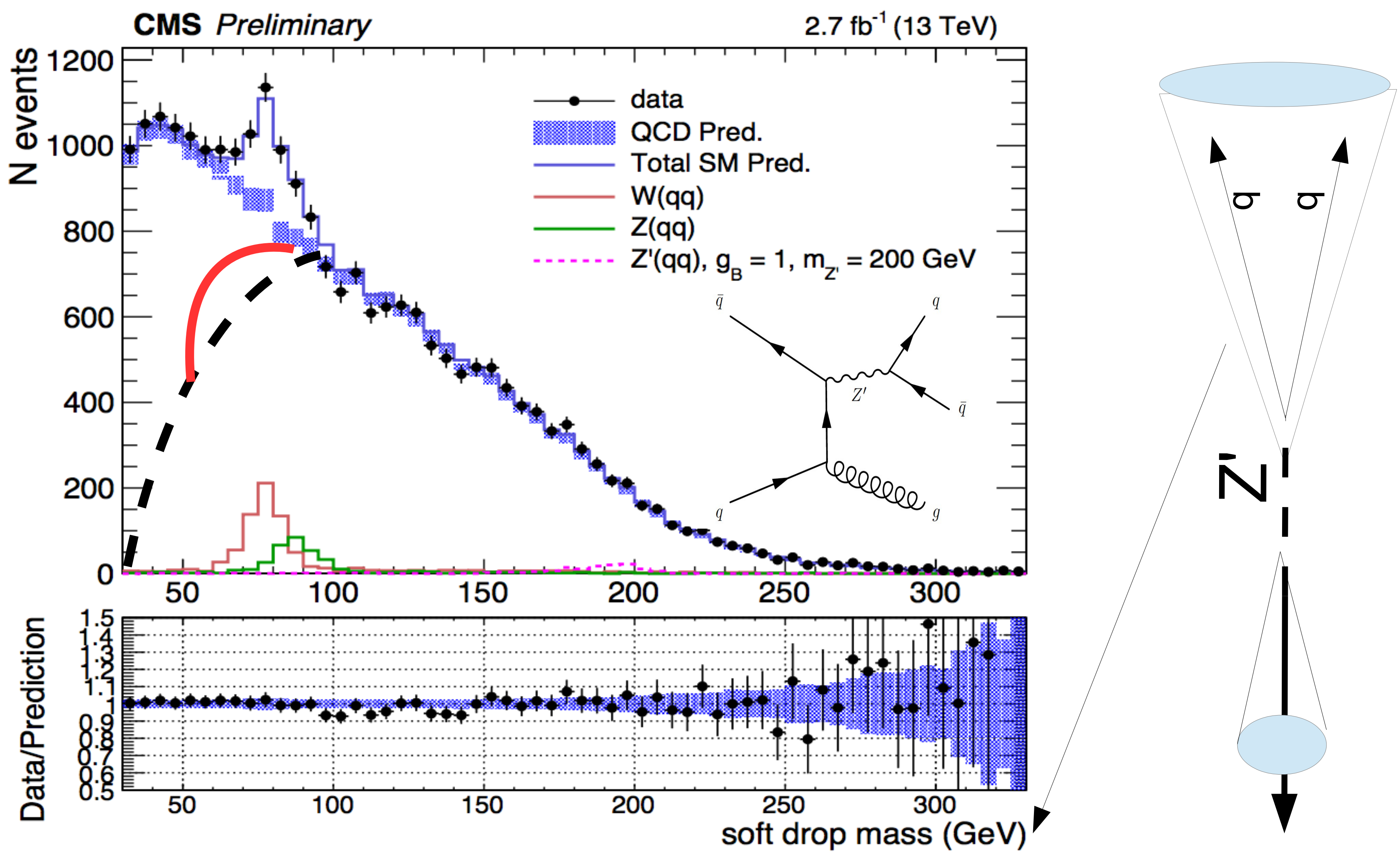
EXO-17-001

Max Couplings for all



The Max coupling is large for all models

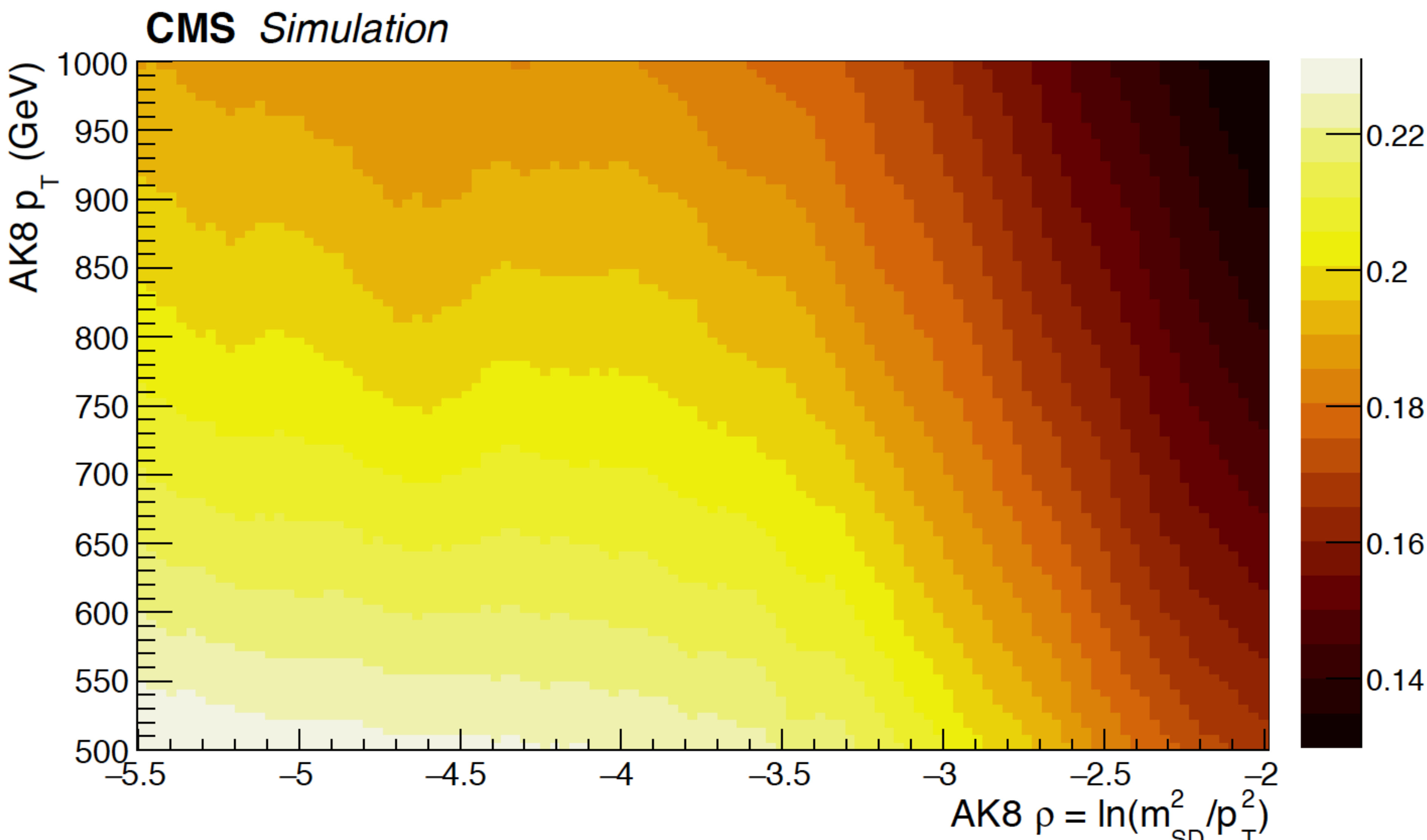
Going all the way down



Fat jet + ISR

arXiv:1603.00027

Full Decorrelation scheme

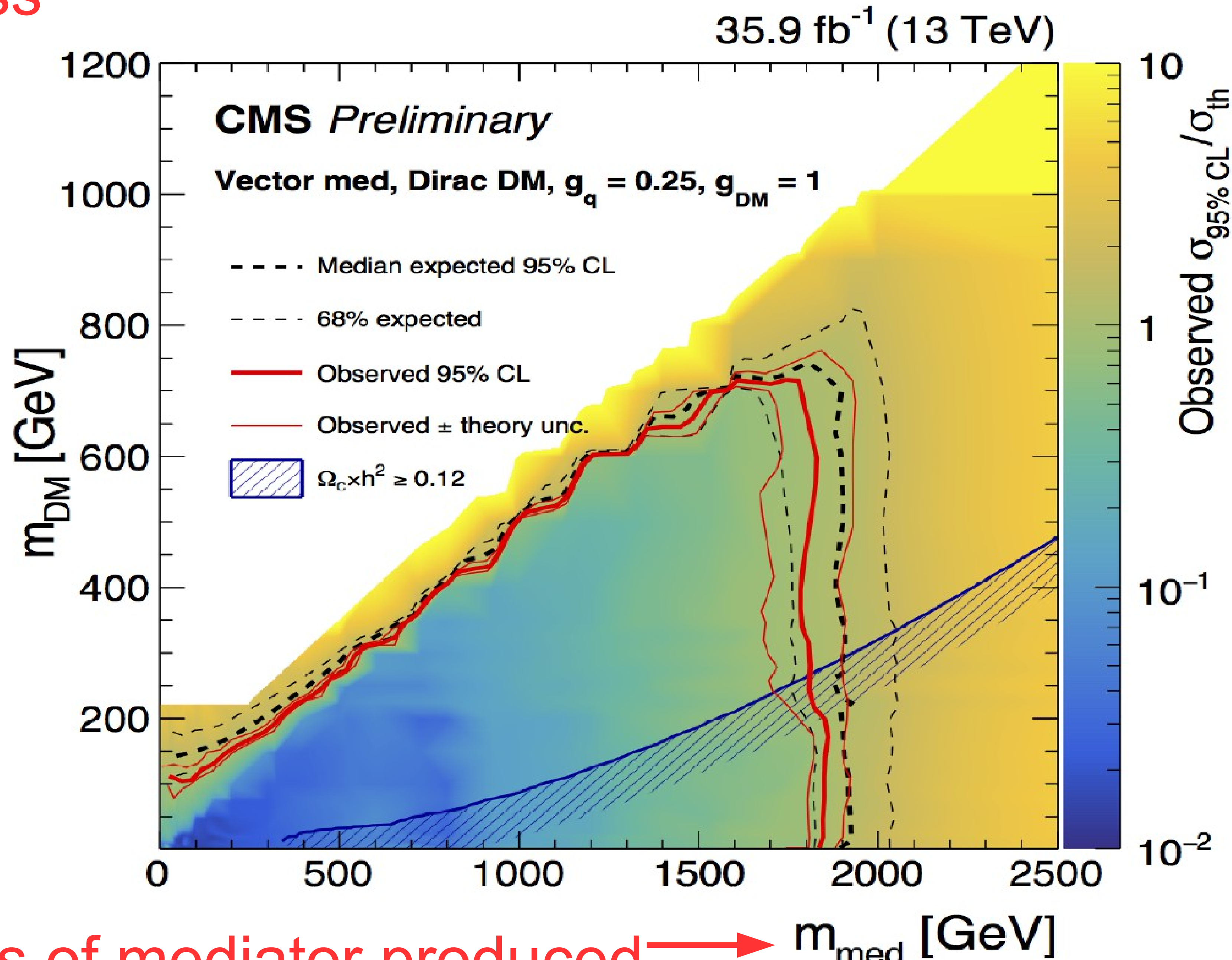


Use the k-Nearest Neighbor approach to determine N_2 cut

EXO-17-001

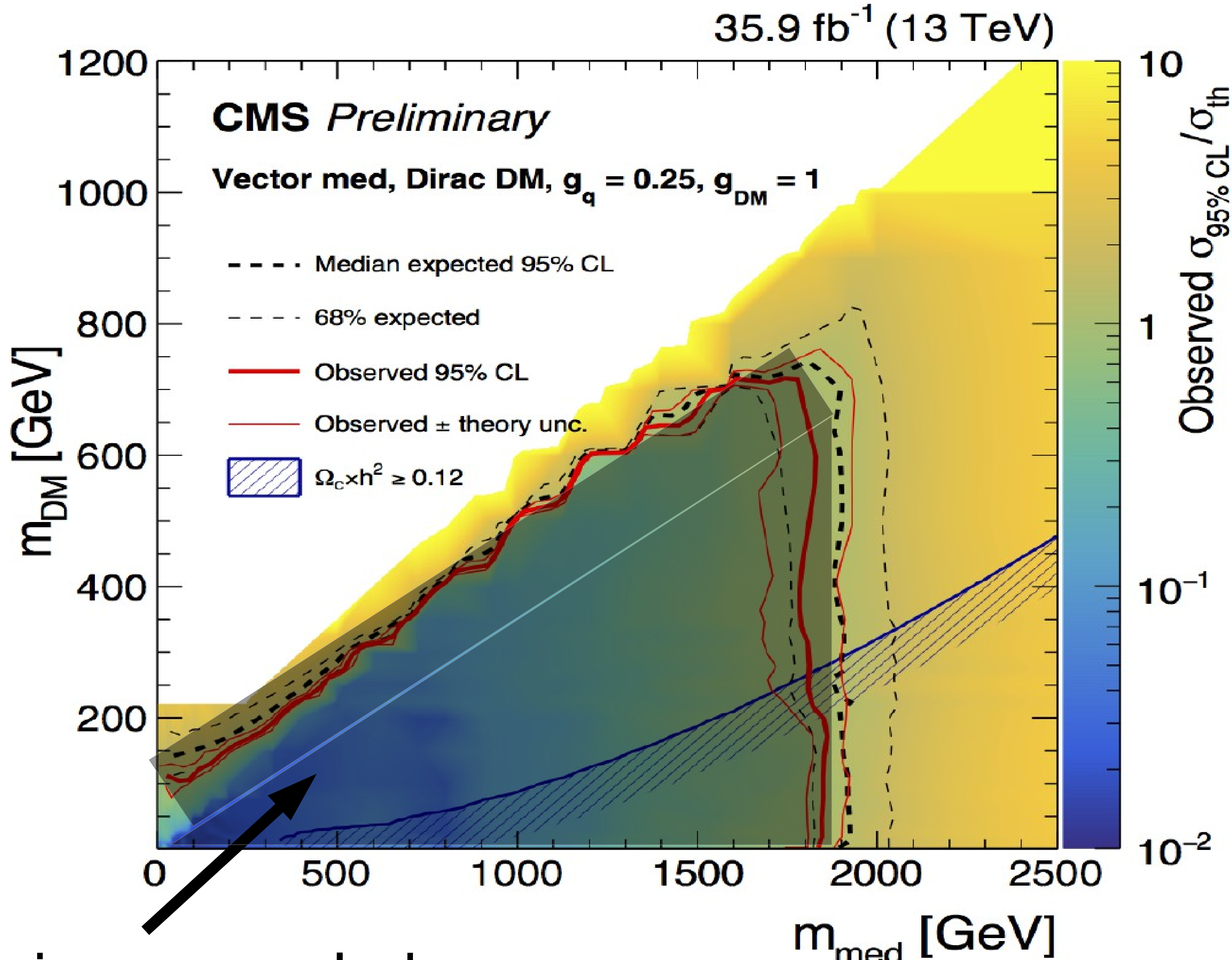
Pick a Model

Dark Matter Mass

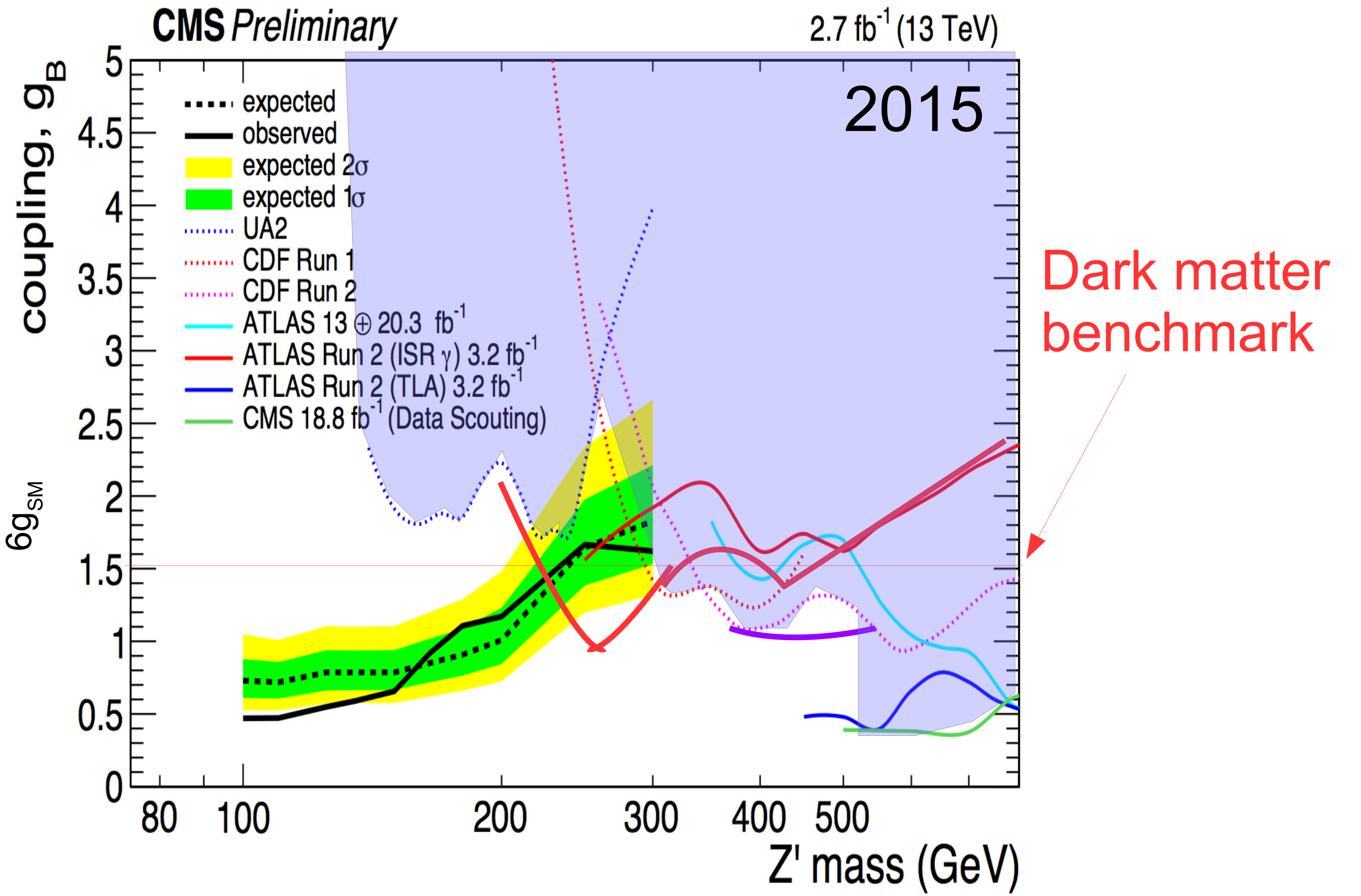


Mass of mediator produced

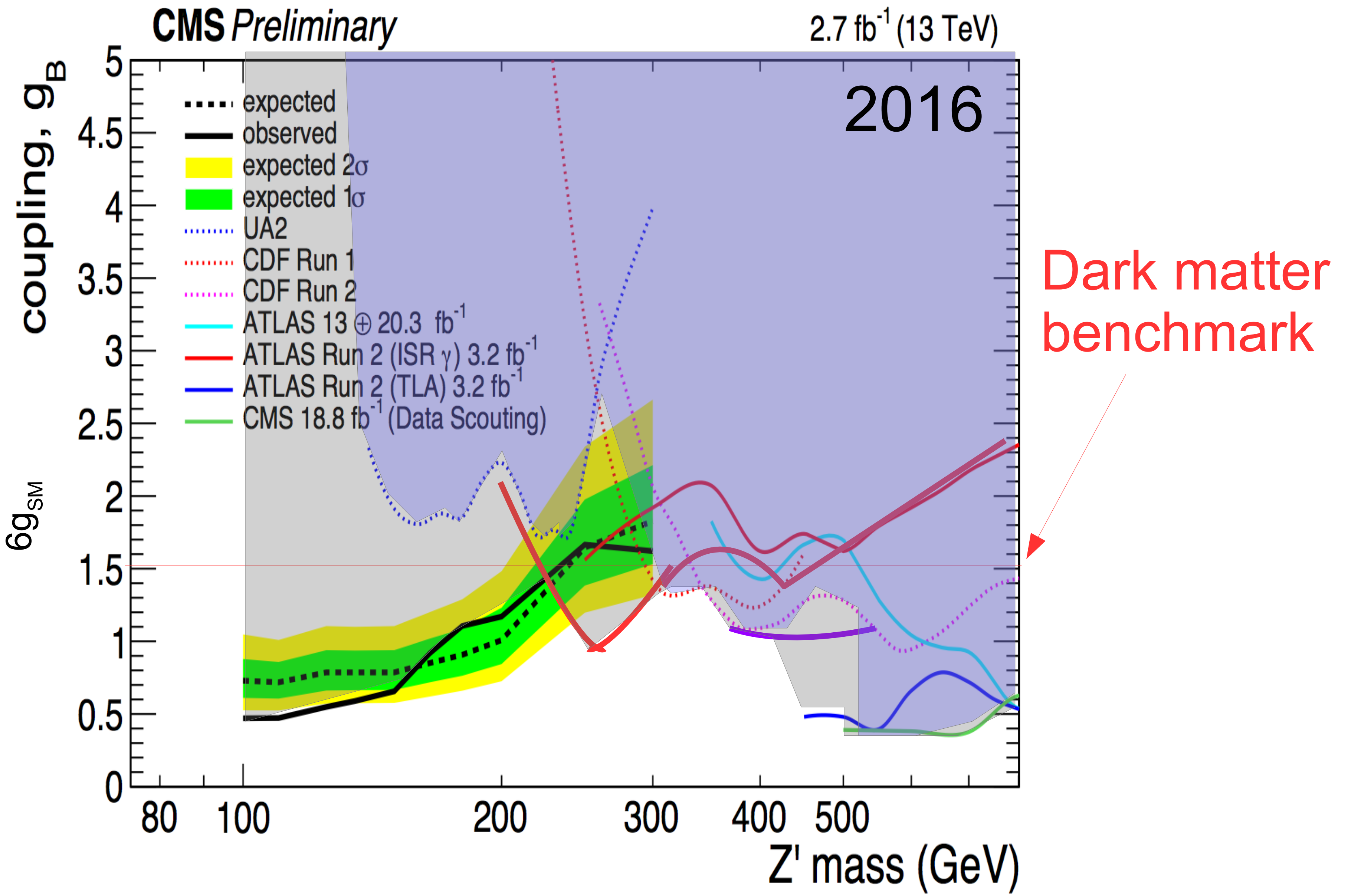
Understanding sensitivity



Region we exclude


CMS Preliminary
2.7 fb-1 (13 TeV)
2015
coupling, gB
6gSM
expected
observed
expected 2σ
expected 1σ
UA2
CDF Run 1
CDF Run 2
ATLAS 13 ⊕ 20.3 fb-1
ATLAS Run 2 (ISR γ) 3.2 fb-1
ATLAS Run 2 (TLA) 3.2 fb-1
CMS 18.8 fb-1 (Data Scouting)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
80
100
200
300
400
500
Z' mass (GeV)
Dark matter
benchmark

EXO-16-030



CMS Preliminary
2.7 fb^{-1} (13 TeV)
2016
expected
observed
expected 2σ
expected 1σ
UA2
CDF Run 1
CDF Run 2
ATLAS 13 ⊕ 20.3 fb^{-1}
ATLAS Run 2 (ISR γ) 3.2 fb^{-1}
ATLAS Run 2 (TLA) 3.2 fb^{-1}
CMS 18.8 fb^{-1} (Data Scouting)
coupling, g_B
$6g_{SM}$
Z' mass (GeV)
Dark matter benchmark

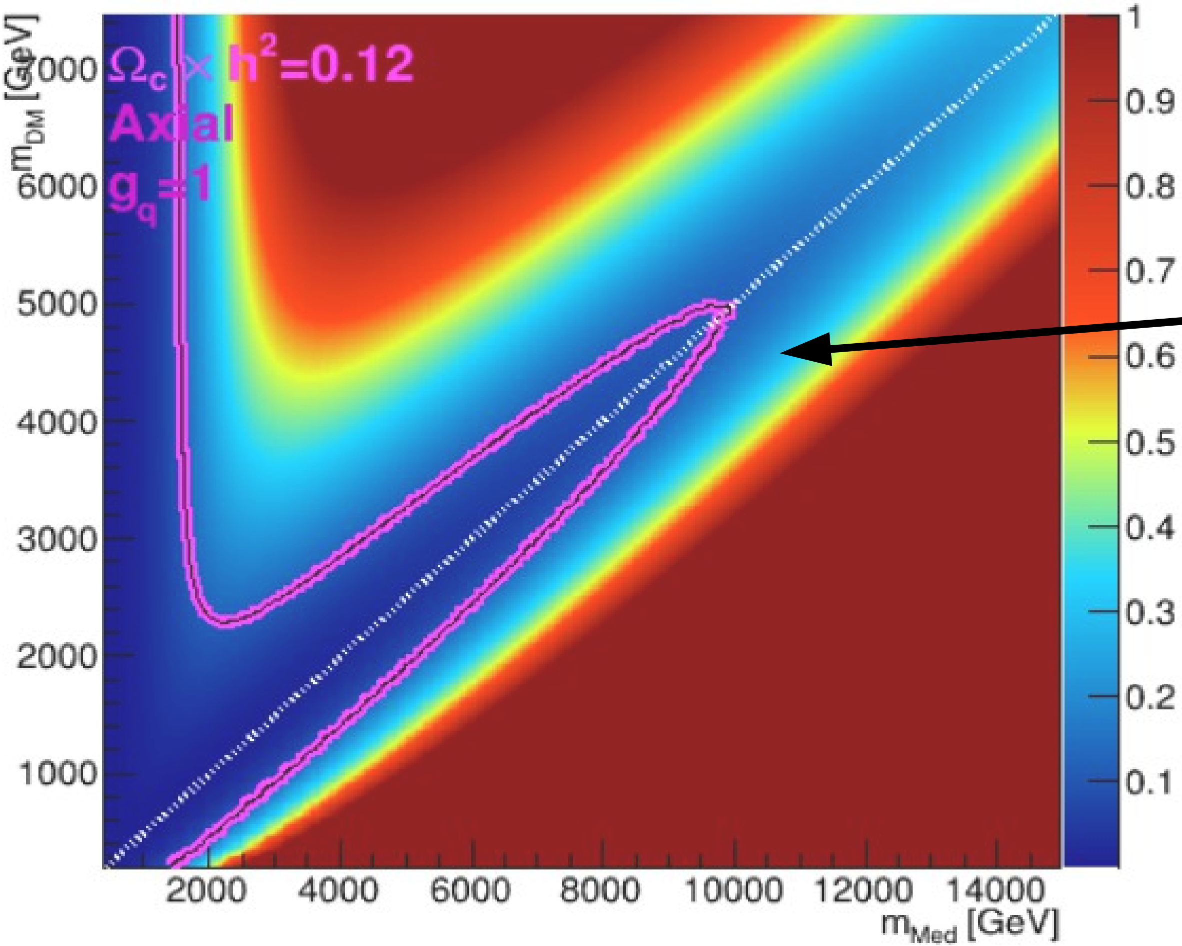
EXO-16-030

Outlook

Hep-ph/1603.08525
Hep-ph/1509.02904
ATL-PHYS-PUB-2015-004

Outlook

- Spin 1 :
  - Dijet and monojet will continue to push out the bounds
  - Have already crossed the neutrino wall

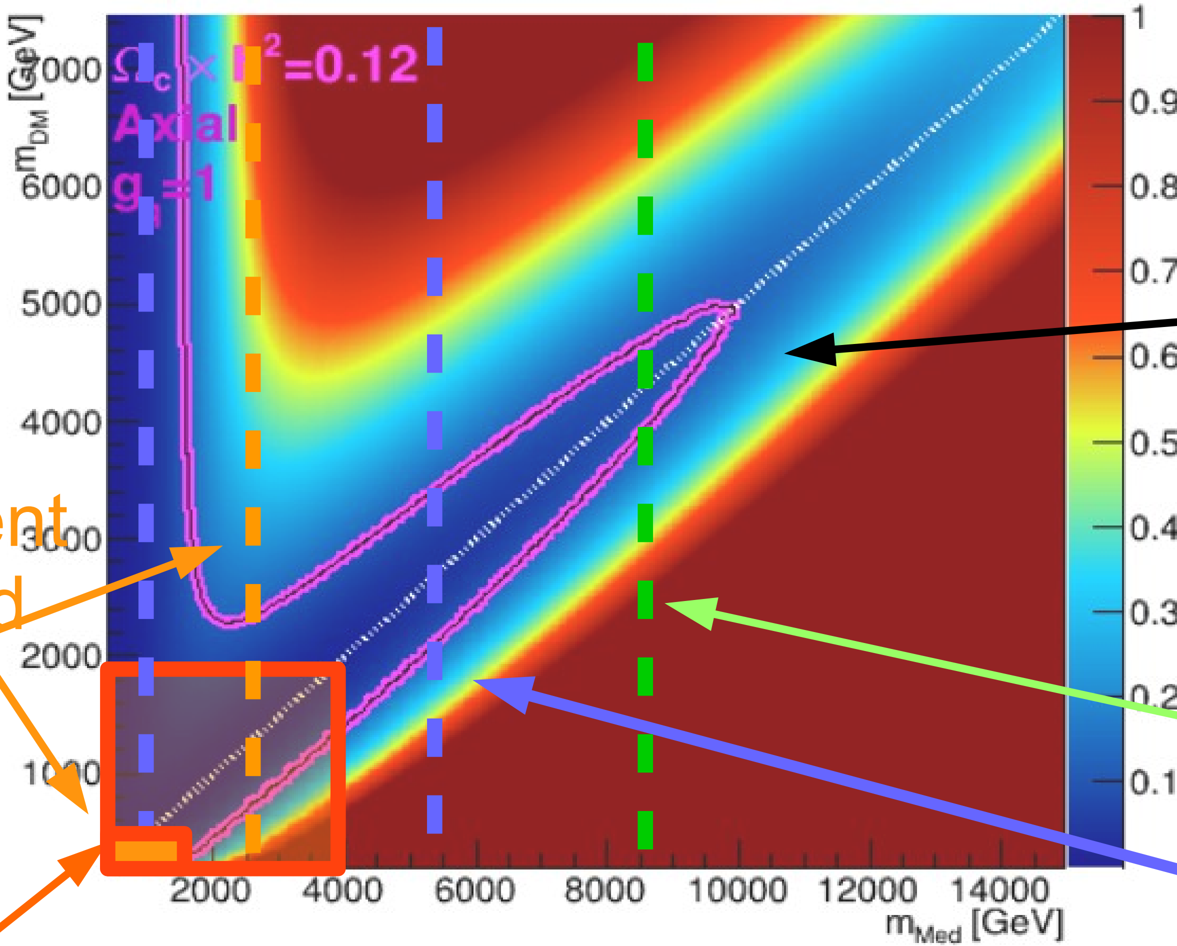


Mediator mass
Maxes out around
8-9 TeV

Hep-ph/1603.08525
Hep-ph/1509.02904
ATL-PHYS-PUB-2015-004

Outlook

- Spin 1 :
  - Dijet and monojet will continue to push out the bounds
  - Have already crossed the neutrino wall



Current bound

Mediator mass Maxes out around 8-9 TeV

Smaller for coupling g_q<1

Approximate Dilepton reach

Approximate dijet reach

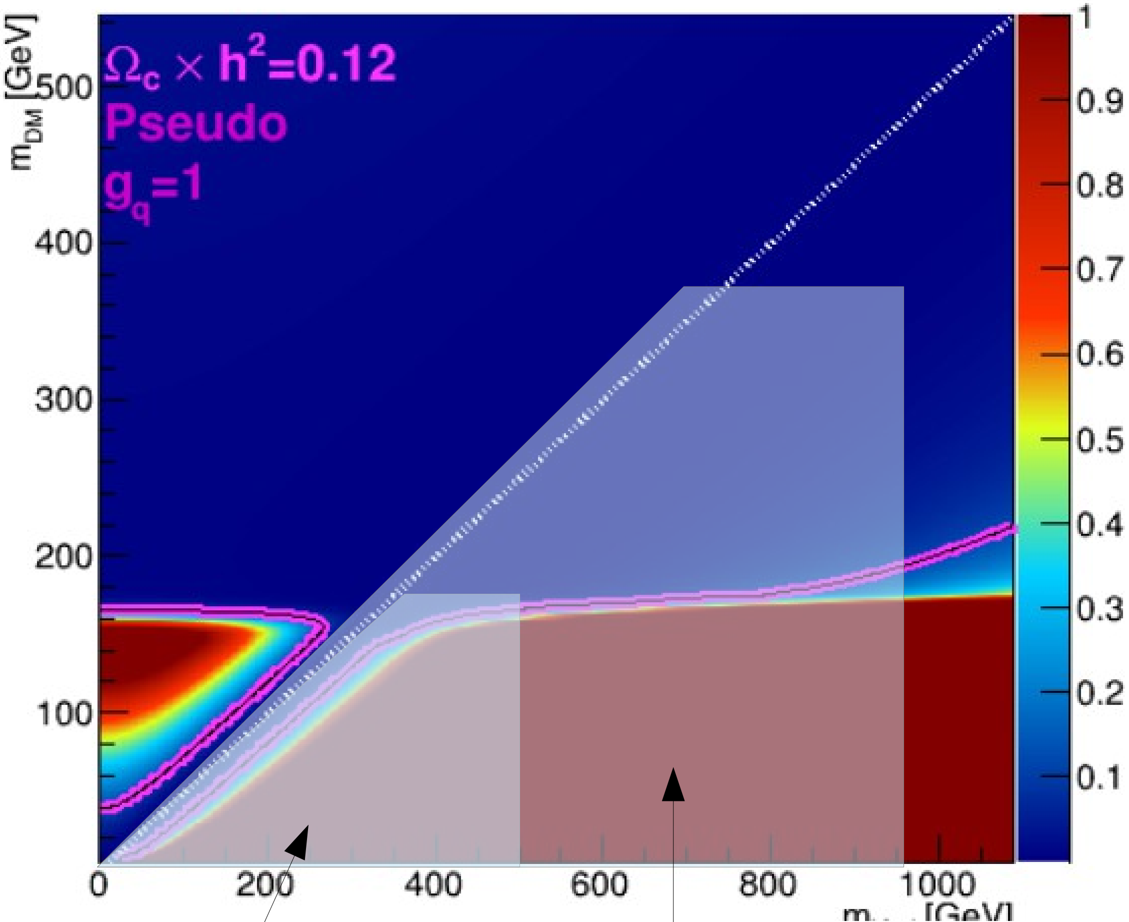
Approximate region monojet can probe

Hep-ph/1603.08525
Hep-ph/1509.02904
EXO-12-055
HIG-16-012

Outlook

- Spin 0 :
  - Just starting to probe interesting regions

Ω_c x h^2



Current monojet

Approx future

Current reach for Higgs-like Singlet Dominated by H→Inv
BR < 25%
Will get to < 5%

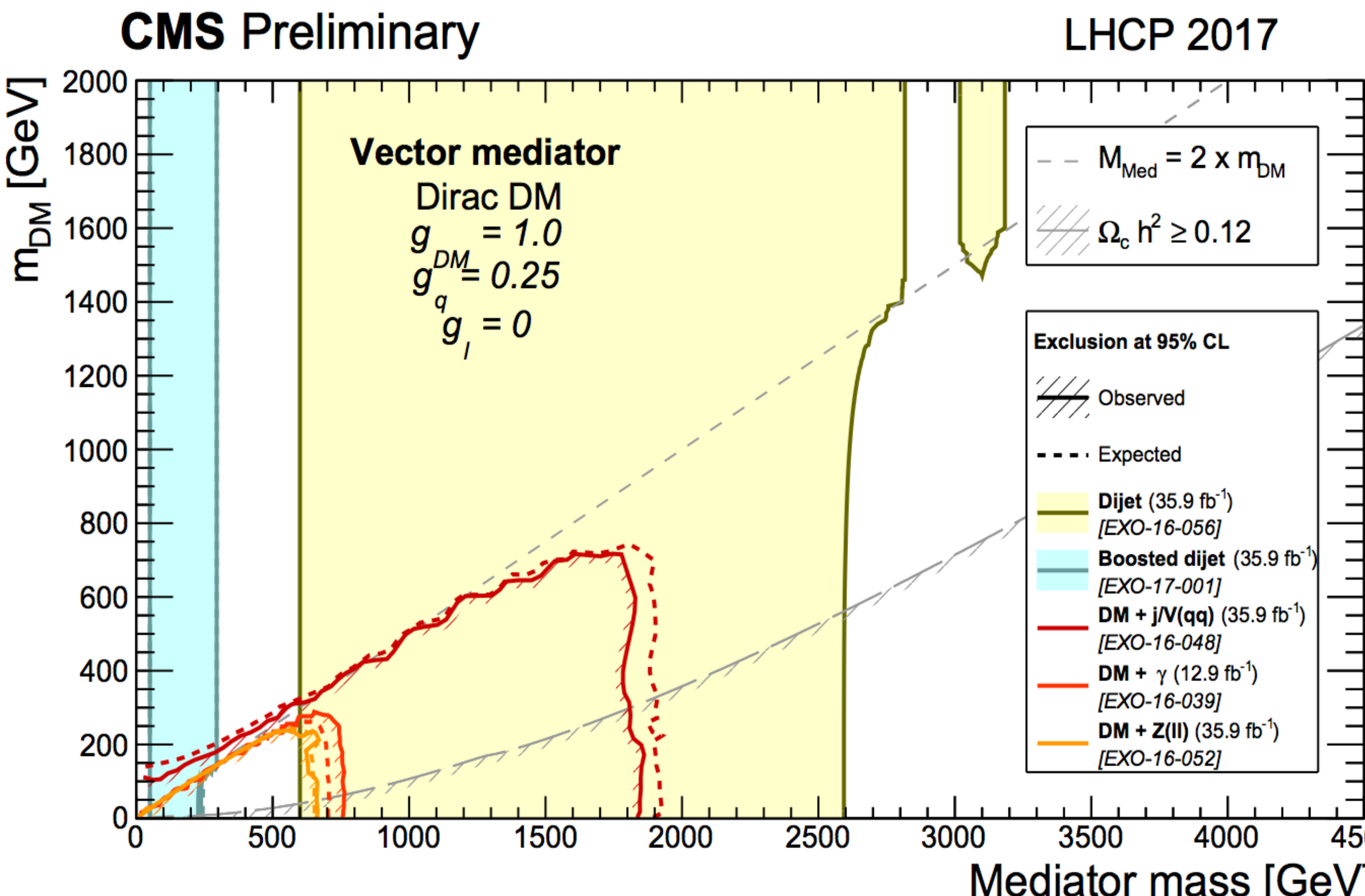
Heavy Flavor :
bb/tt+φ also excluding at low mass
Expect mono-Z too

Mediator Arms Race

CMS ATLAS

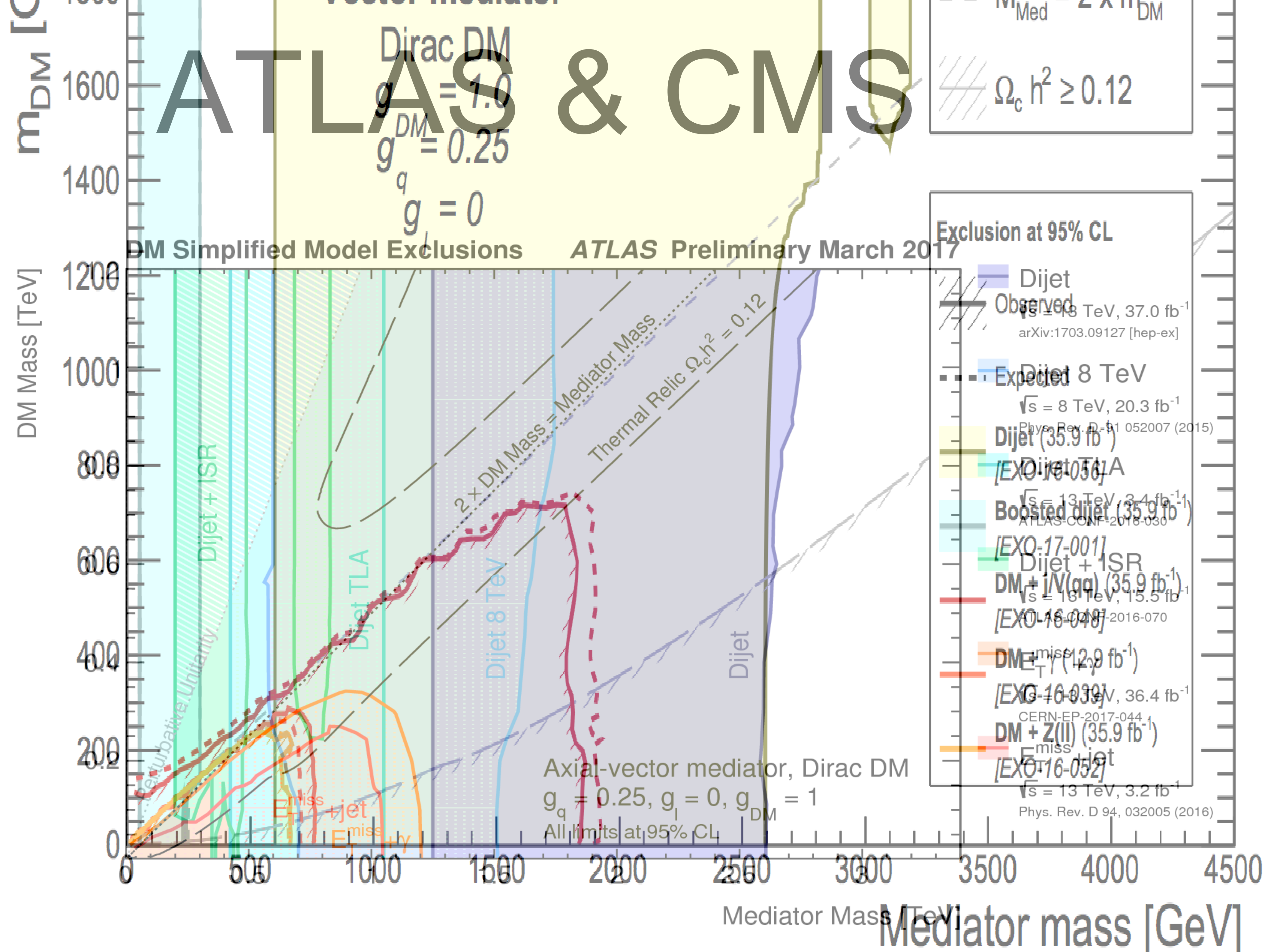
Who can cover the territory first?

CMS



CMS-DP-2016-057

ATLAS & CMS

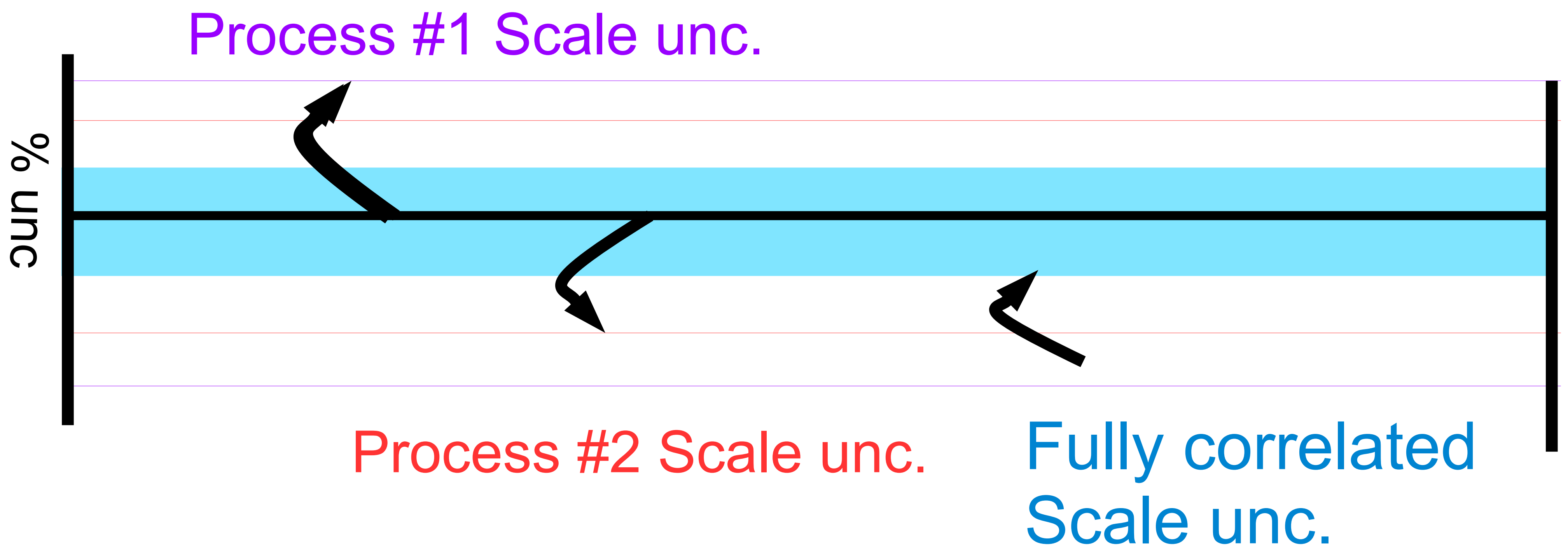


DM Simplified Model Exclusions
ATLAS Preliminary March 2017
Dirac DM
$g_{DM} = 1.0$
$g_q = 0.25$
$g_l = 0$
$\Omega_c h^2 \geq 0.12$
Exclusion at 95% CL
Dijet
Observed
$\sqrt{s}$ = 13 TeV, 37.0 fb^{-1}
arXiv:1703.09127 [hep-ex]
Expected
Dijet 8 TeV
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Phys. Rev. D 91 052007 (2015)
Dijet (35.9 fb^{-1})
[EXO-16-056]
Dijet TLA
$\sqrt{s}$ = 13 TeV, 3.4 fb^{-1}
ATLAS-CONF-2016-030
Boosted dijet (35.9 fb^{-1})
[EXO-17-001]
Dijet + ISR
$\sqrt{s}$ = 13 TeV, 15.5 fb^{-1}
ATLAS-CONF-2016-070
DM + j/V(qq) (35.9 fb^{-1})
[EXO-16-048]
$E_T^{miss}+\gamma$
$\sqrt{s}$ = 13 TeV, 36.4 fb^{-1}
CERN-EP-2017-044
DM + γ (12.9 fb^{-1})
[EXO-16-039]
DM + Z(ll) (35.9 fb^{-1})
[EXO-16-052]
E_T^{miss}+jet
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
Phys. Rev. D 94, 032005 (2016)
2 × DM Mass = Mediator Mass
Thermal Relic $\Omega_c h^2 = 0.12$
Perturbative Unitarity
Dijet + ISR
Dijet TLA
Dijet 8 TeV
Dijet
E_T^{miss}+jet
$E_T^{miss}+\gamma$
Axial-vector mediator, Dirac DM
$g_q = 0.25$, $g_l = 0$, $g_{DM} = 1$
All limits at 95% CL
DM Mass [TeV]
Mediator Mass [TeV]
m_{DM} [GeV]
Mediator mass [GeV]

However we still have a problem!

Unc. $\longrightarrow \dfrac{d\sigma^{\gamma}}{dp_T} \Big/ \dfrac{d\sigma^{Z}}{dp_T} = d\sigma^{\gamma}/d\sigma^{Z}(\mu)$

We don't know how to do scale uncertainties on ratios!



Uncertainty on ratio? How is it done?

Scale uncertainty on process #1

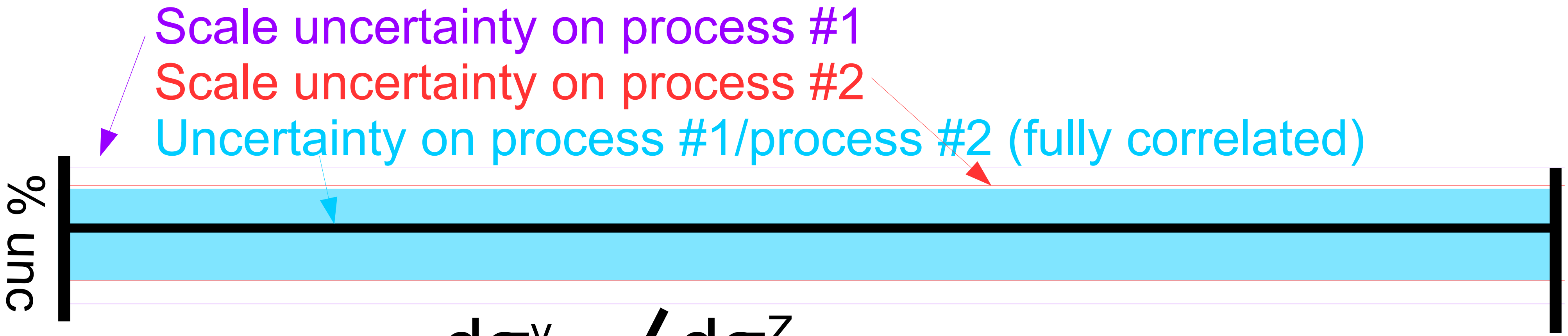
Scale uncertainty on process #2

Uncertainty on process #1/process #2 (fully correlated)

$$\text{Unc.} \longrightarrow \frac{d\sigma^{\gamma}}{dp_T} \Big/ \frac{d\sigma^{Z}}{dp_T} = d\sigma^{\gamma}/d\sigma^{Z}(\mu)$$

$$\begin{pmatrix} d\sigma^{\gamma}(+\sigma) \\ d\sigma^{Z}(+\sigma) \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} d\sigma^{\gamma}(\mu^{up})/d\sigma^{i}(\mu_0) \\ d\sigma^{Z}(\mu^{up})/d\sigma^{i}(\mu_0) \end{pmatrix}$$

Uncertainty on ratio? How is it done?



$$\text{Unc.} \longrightarrow \frac{d\sigma^{\gamma}}{dp_T} \Big/ \frac{d\sigma^{Z}}{dp_T} = d\sigma^{\gamma}/d\sigma^{Z}(\mu)$$

$$\begin{pmatrix} d\sigma^{\gamma}(+\sigma) \\ d\sigma^{Z}(+\sigma) \end{pmatrix} = \begin{pmatrix} 1 & C \\ C & 1 \end{pmatrix} \begin{pmatrix} d\sigma^{\gamma}(\mu^{up})/d\sigma^{i}(\mu_0) \\ d\sigma^{Z}(\mu^{up})/d\sigma^{i}(\mu_0) \end{pmatrix}$$

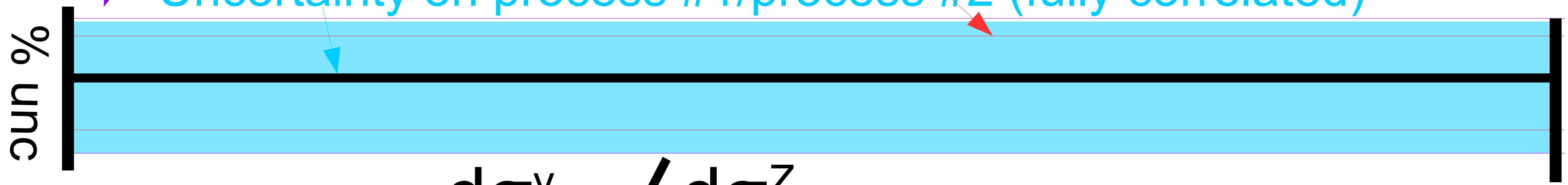
Adjust C until uncertainty is

Uncertainty on ratio? How is it done?

Scale uncertainty on process #1

Scale uncertainty on process #2

Uncertainty on process #1/process #2 (fully correlated)



$$\text{Unc.} \longrightarrow \frac{d\sigma^{\gamma}}{dp_T} \Big/ \frac{d\sigma^{Z}}{dp_T} = d\sigma^{\gamma}/d\sigma^{Z}(\mu)$$

$$\begin{pmatrix} d\sigma^{\gamma}(+\sigma) \\ d\sigma^{Z}(+\sigma) \end{pmatrix} = \begin{pmatrix} 1 & C \\ C & 1 \end{pmatrix} \begin{pmatrix} d\sigma^{\gamma}(\mu^{up})/d\sigma^{i}(\mu_0) \\ d\sigma^{Z}(\mu^{up})/d\sigma^{i}(\mu_0) \end{pmatrix}$$

Decorrelate scale unc. until its max of either process

$$\mathbf{d\sigma^{\gamma}/d\sigma^{Z}(+\sigma) < \max_i \left(d\sigma^{i}(\mu^{up})/d\sigma^{i}(\mu_0)\right)}$$

What is the previous unc?

Can we motivate this?

Unc. $\longrightarrow \dfrac{d\sigma^{\gamma}}{dp_T} \Big/ \dfrac{d\sigma^{Z}}{dp_T} = d\sigma^{\gamma}/d\sigma^{Z}(\mu)$

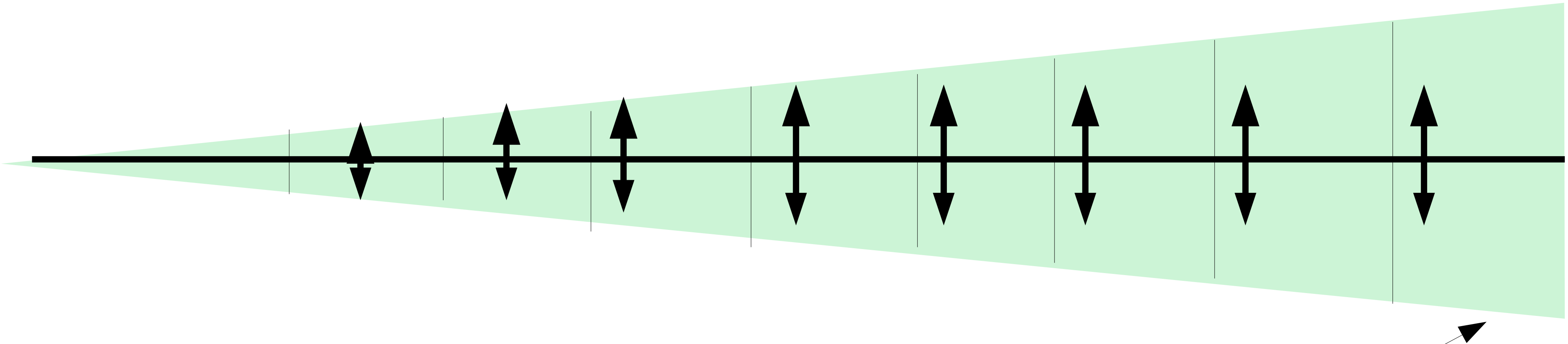
$$\begin{pmatrix} d\sigma^{\gamma}(+\sigma) \\ d\sigma^{Z}(+\sigma) \end{pmatrix} = \begin{pmatrix} 1 & C \\ C & 1 \end{pmatrix} \begin{pmatrix} d\sigma^{\gamma}(\mu^{up})/d\sigma^{i}(\mu_0) \\ d\sigma^{Z}(\mu^{up})/d\sigma^{i}(\mu_0) \end{pmatrix}$$

Makes Little Sense

What about EWK corr. uncertainty?

In light of being conservative :
Take the full correction

What about EWK corr. uncertainty?



In light of being conservative :
Take the full correction

Additionally de-correlated this per bin
Avoids low *MET* to high *MET* constraints

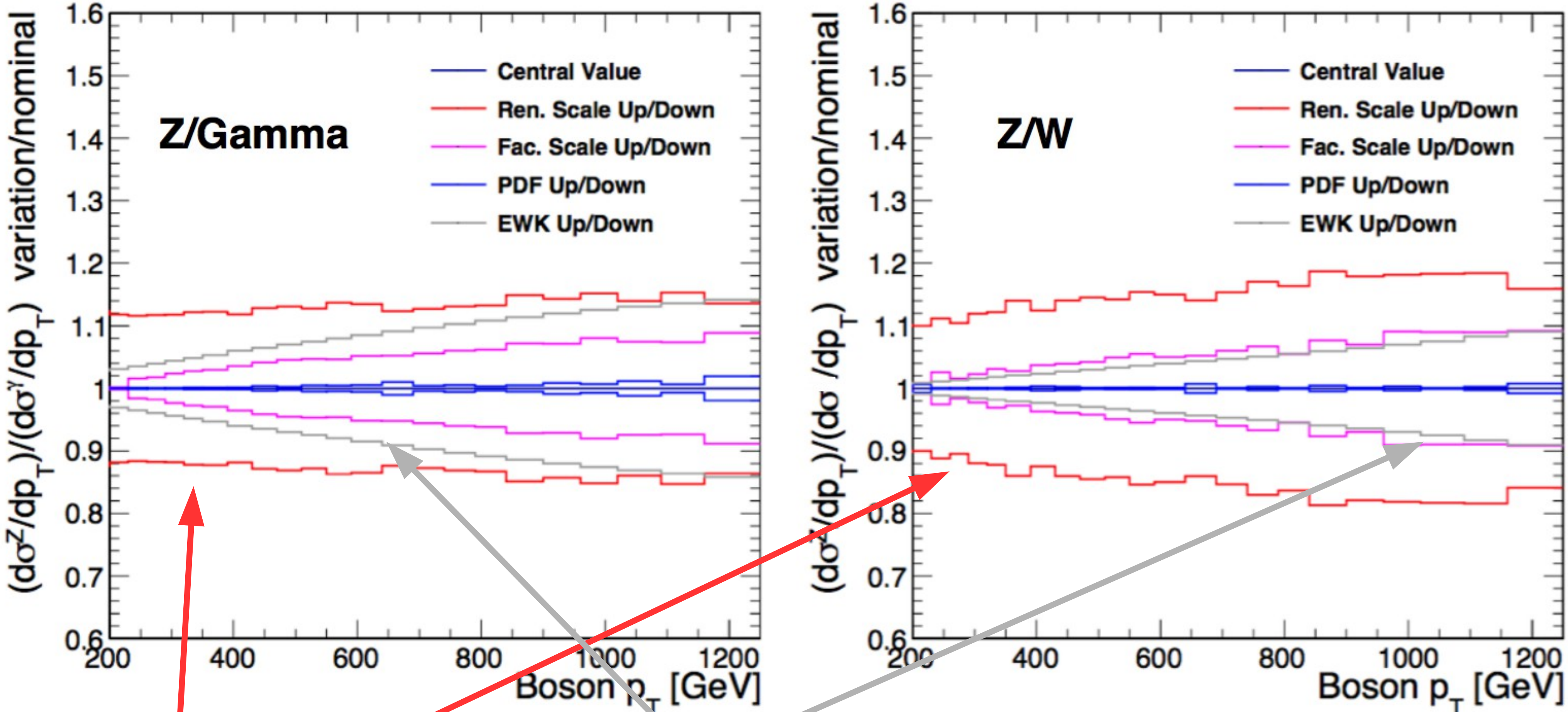
We were forced to do this by management!
This makes us too conservative

2015...
We are stuck

CMS-EXO-12-055

How do we propagate this in?

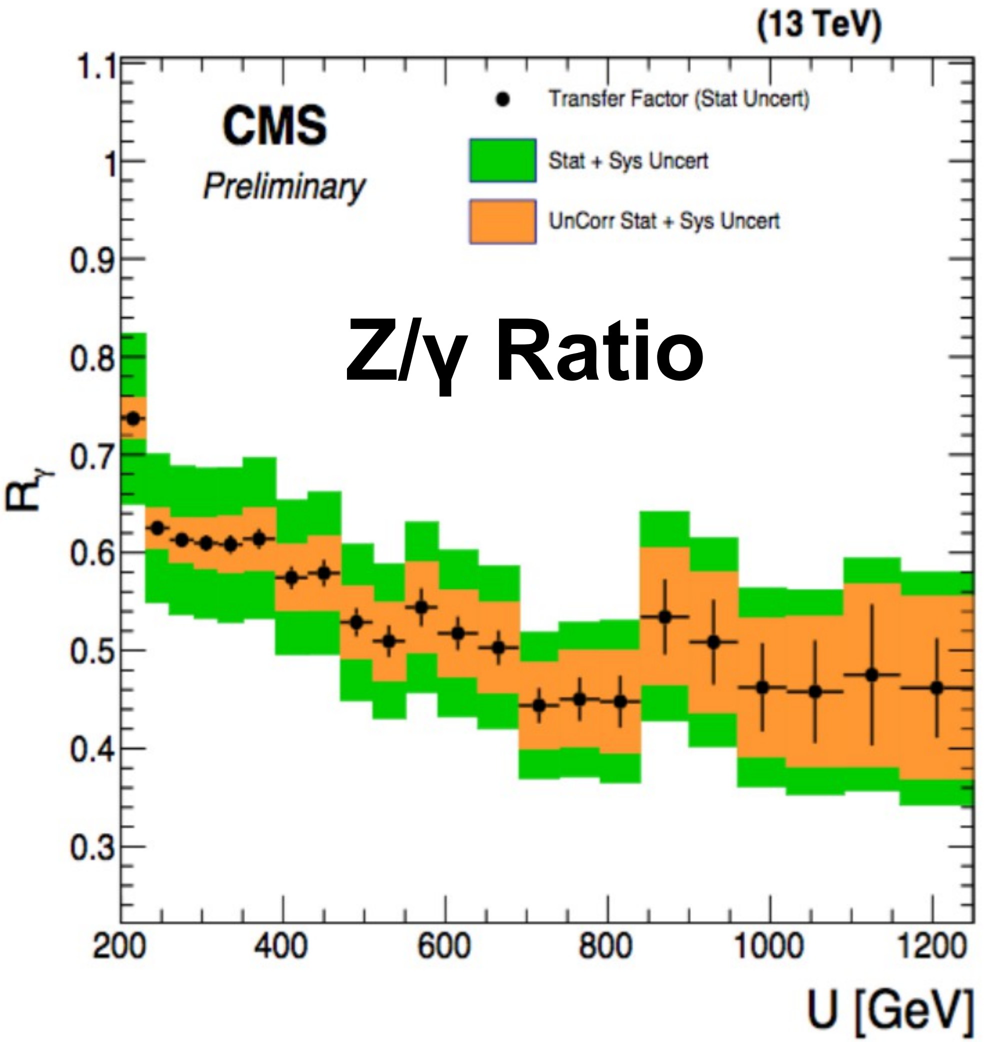
The actual uncertainties

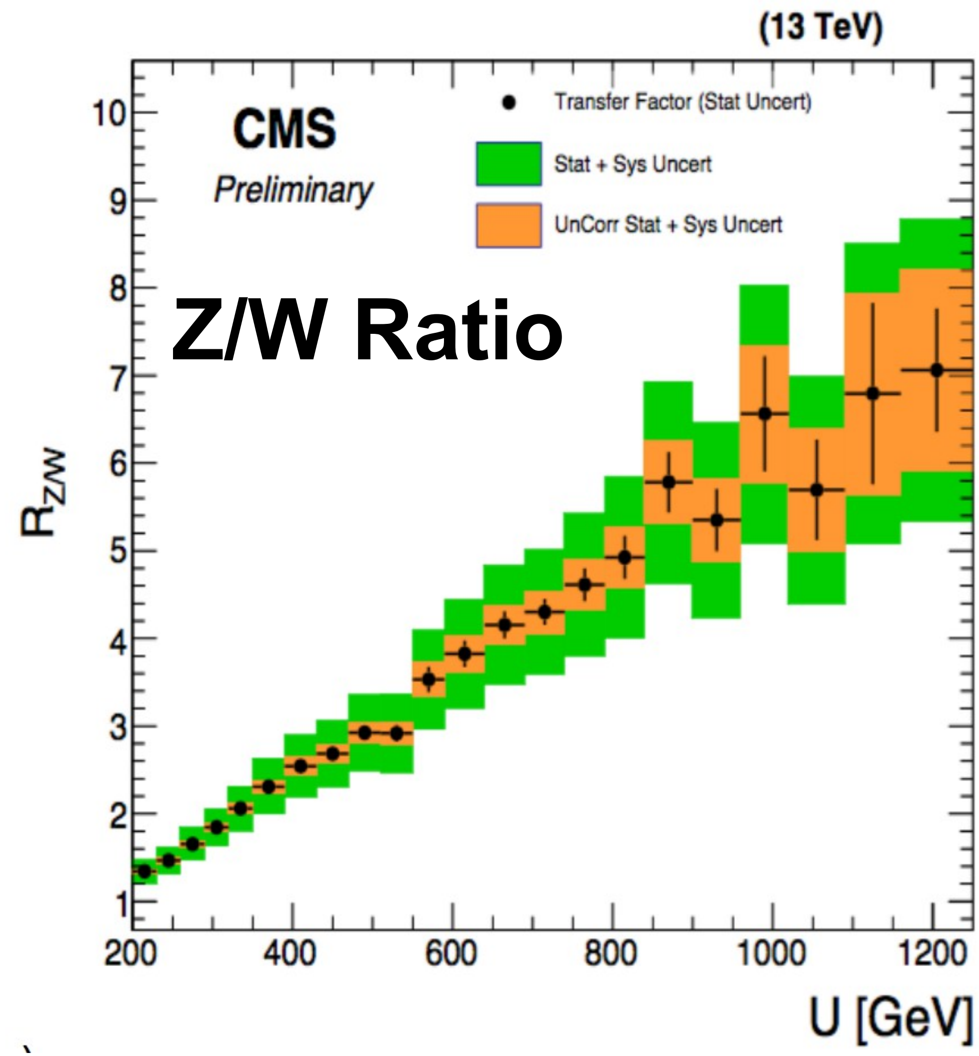


Correlated across boson p_T

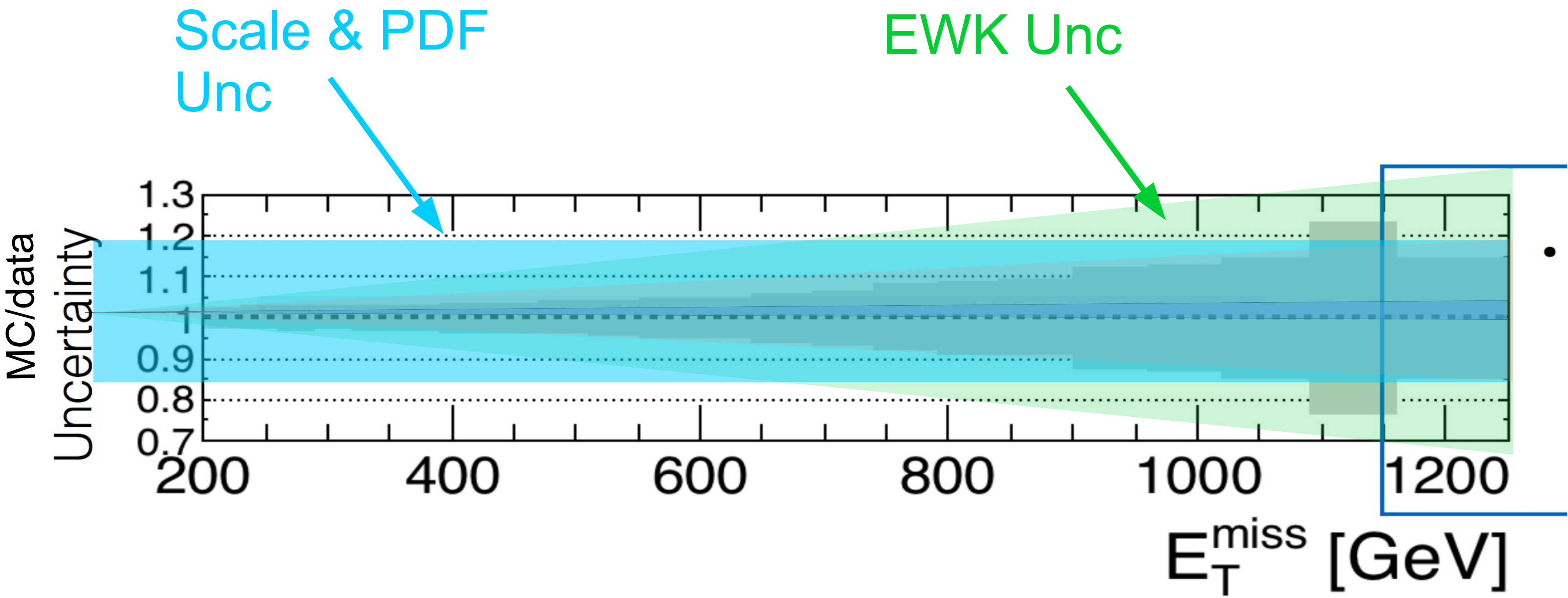
EWK: Since its not correlated dominant in tails

How exactly do they look?





What do the uncertainties look like?

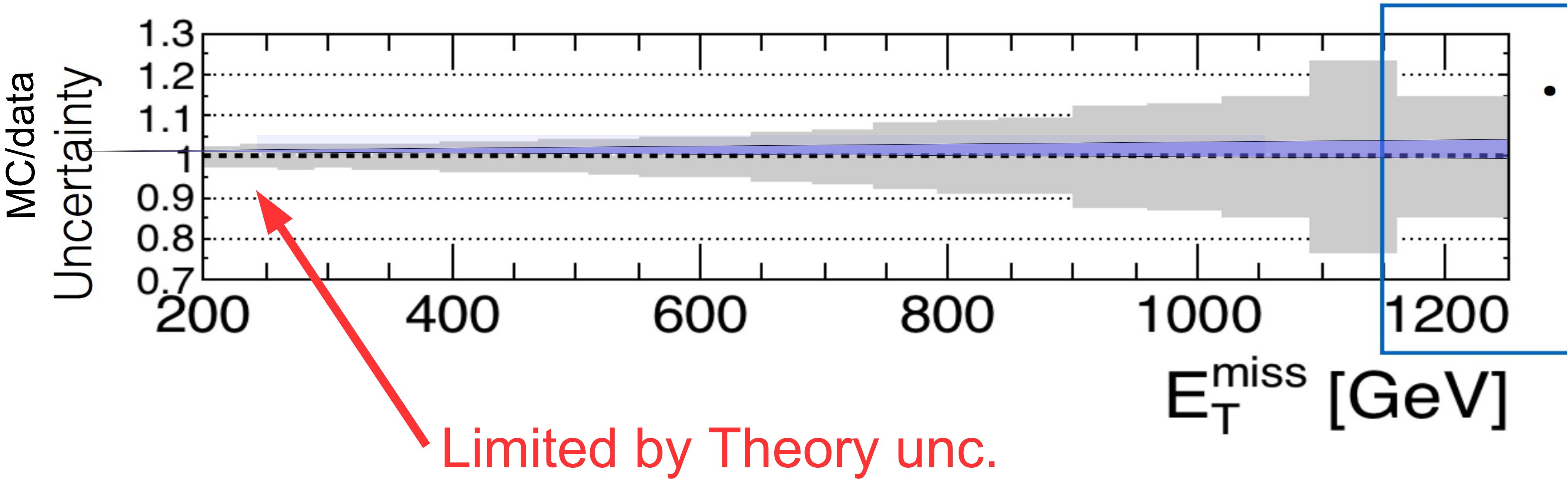


Updated unc still too large

CMS-EXO-12-055

Profiling them in the fit

Constraints after the fit

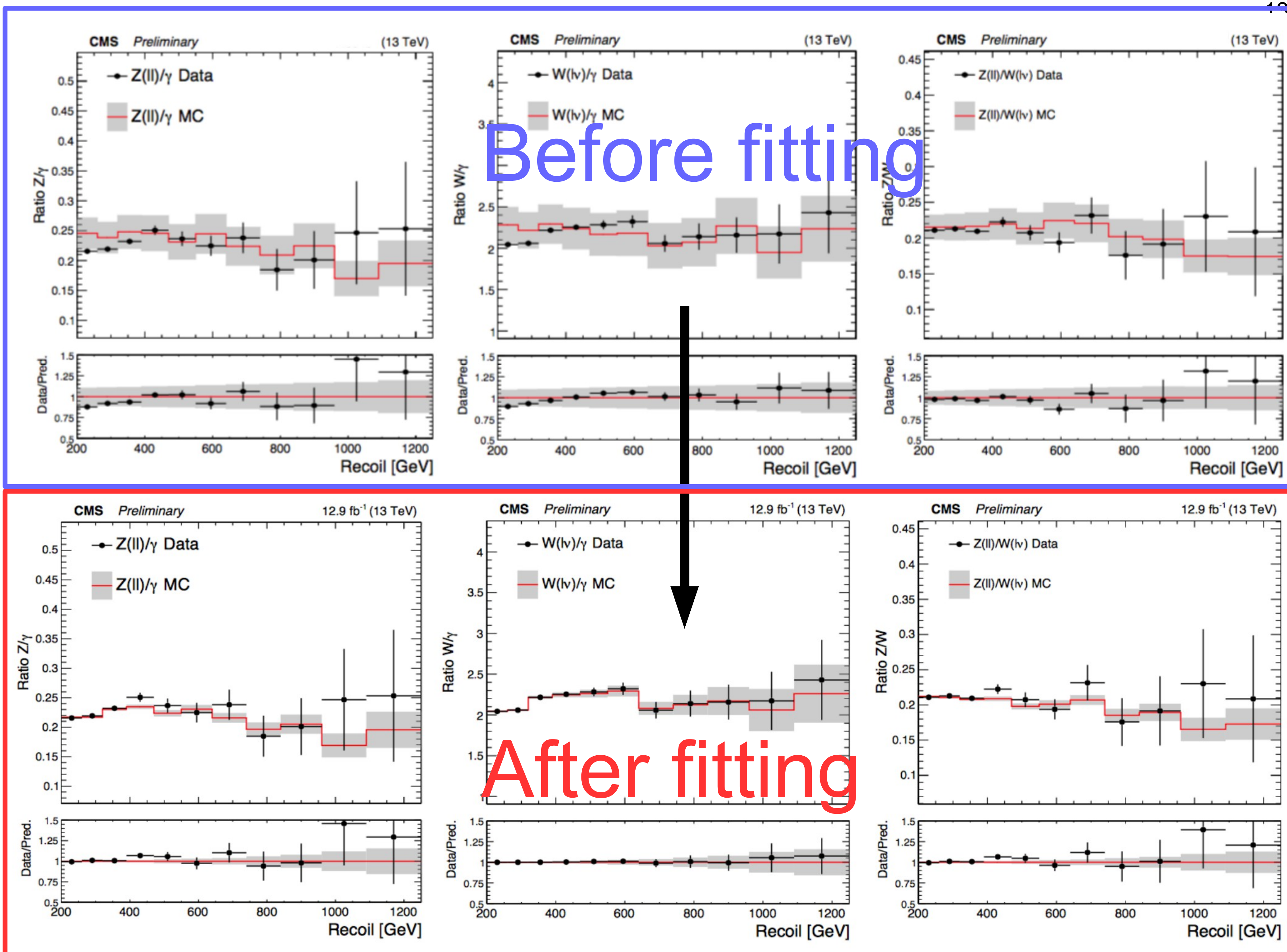


Still systematics limited @low *MET*

Not systematics limited @ high *MET*

→ Likely will *never* be

CMS-EXO-16-037

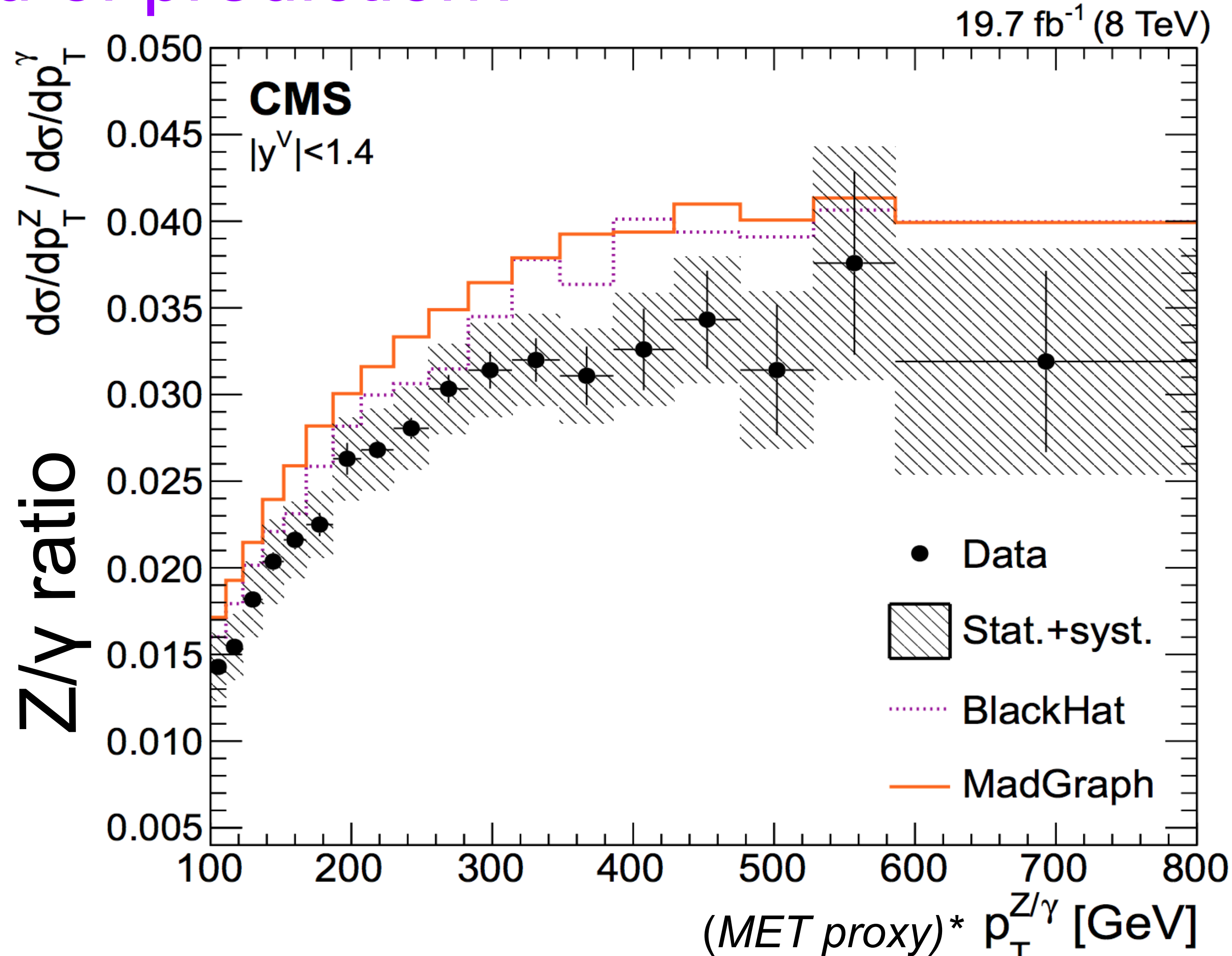

Before fitting
CMS Preliminary (13 TeV)
Z(ll)/γ Data
Z(ll)/γ MC
Ratio Z/γ
W(lν)/γ Data
W(lν)/γ MC
Ratio W/γ
Z(ll)/W(lν) Data
Z(ll)/W(lν) MC
Ratio Z/W
Data/Pred.
Recoil [GeV]
After fitting
CMS Preliminary 12.9 fb-1 (13 TeV)
Z(ll)/γ Data
Z(ll)/γ MC
Ratio Z/γ
W(lν)/γ Data
W(lν)/γ MC
Ratio W/γ
Z(ll)/W(lν) Data
Z(ll)/W(lν) MC
Ratio Z/W
Data/Pred.
Recoil [GeV]

2016:
A new hope

CMS-EXO-12-055

A mystery? Understanding Z/γ p_T

How are going to use photons for Z with this kind of prediction?



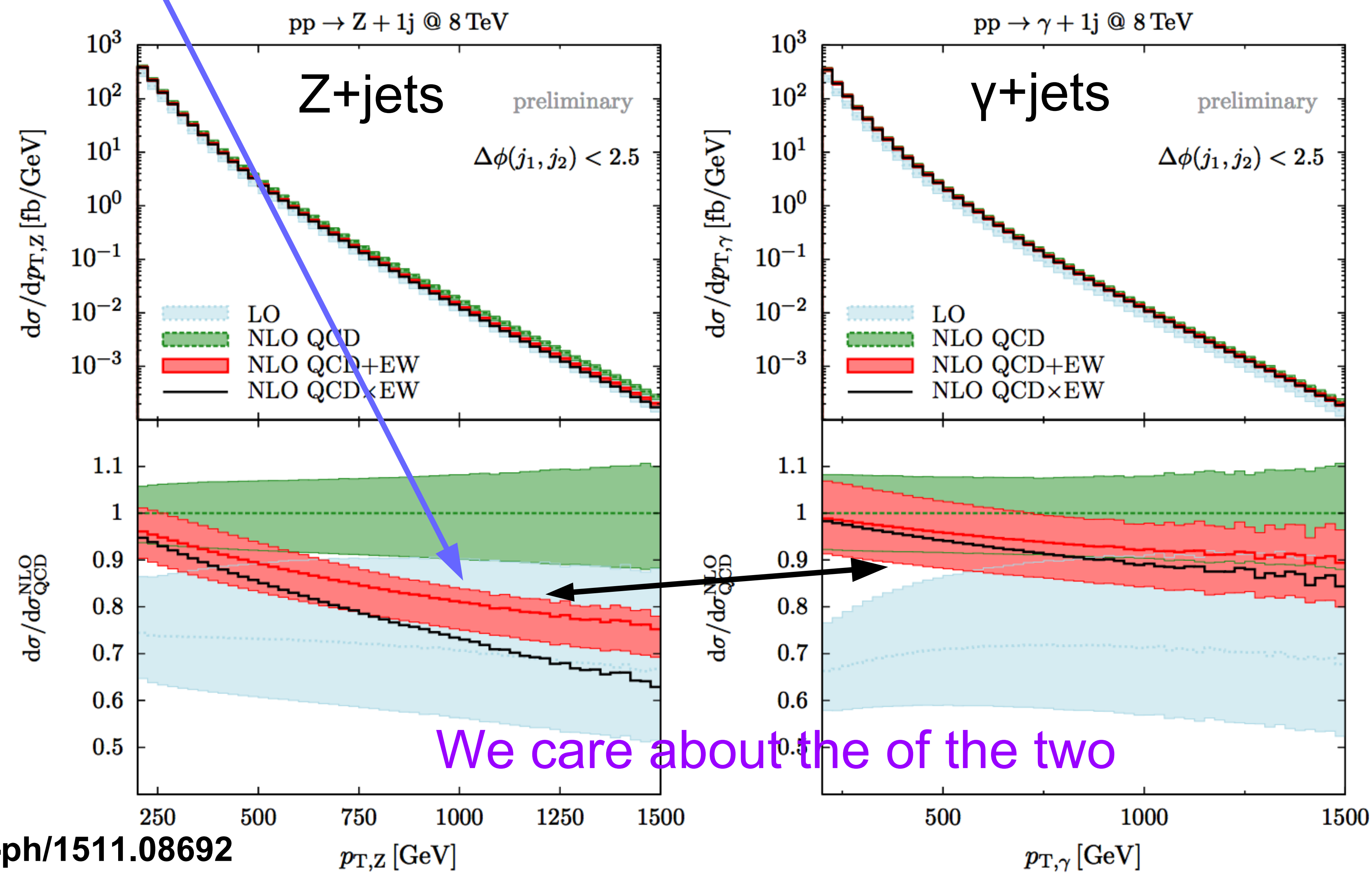
We need this to model the ratio perfectly to use it

CMS-SMP-14-005

2015

How do we fix this?

Impact of the electroweak corrections

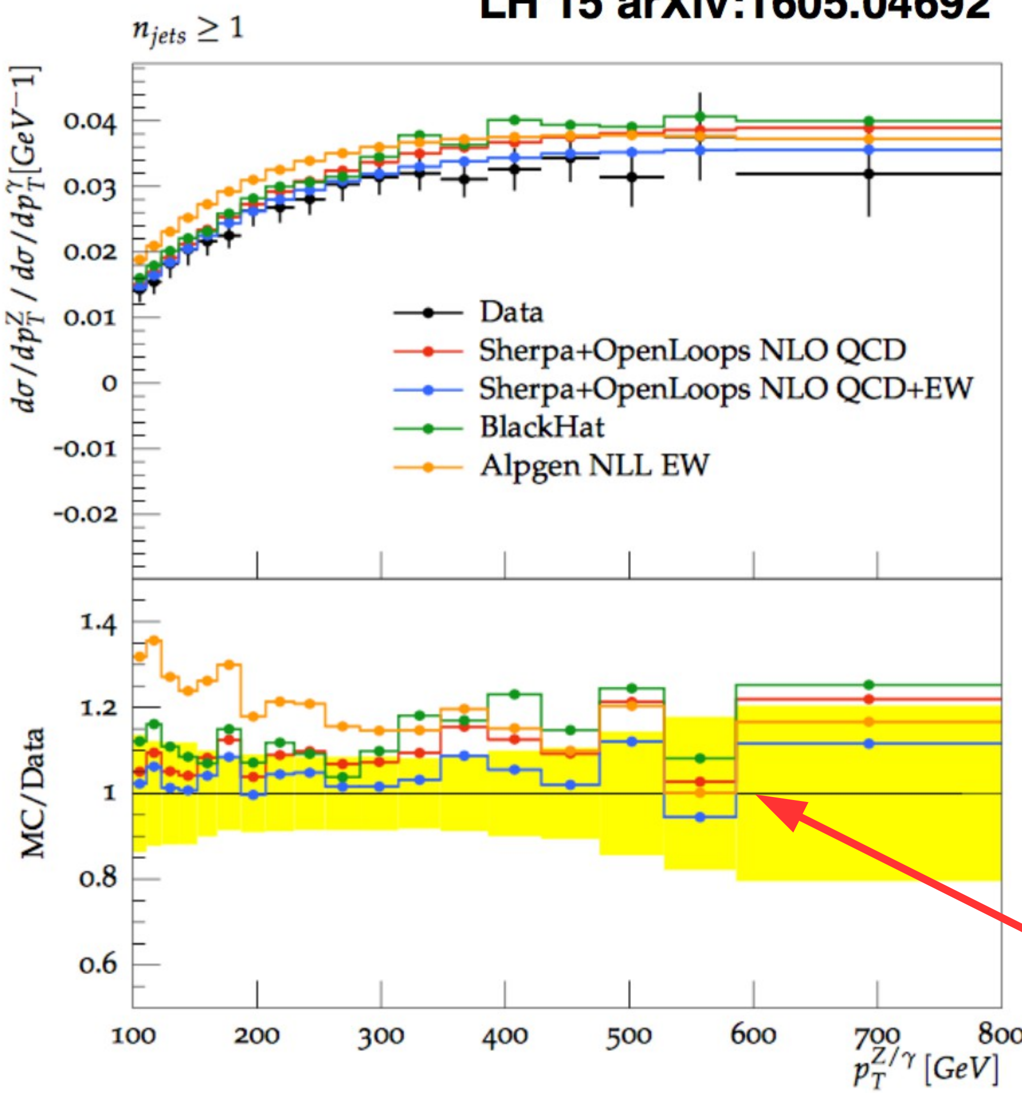


We care about the of the two

hep-ph/1511.08692
hep-ph/0508253

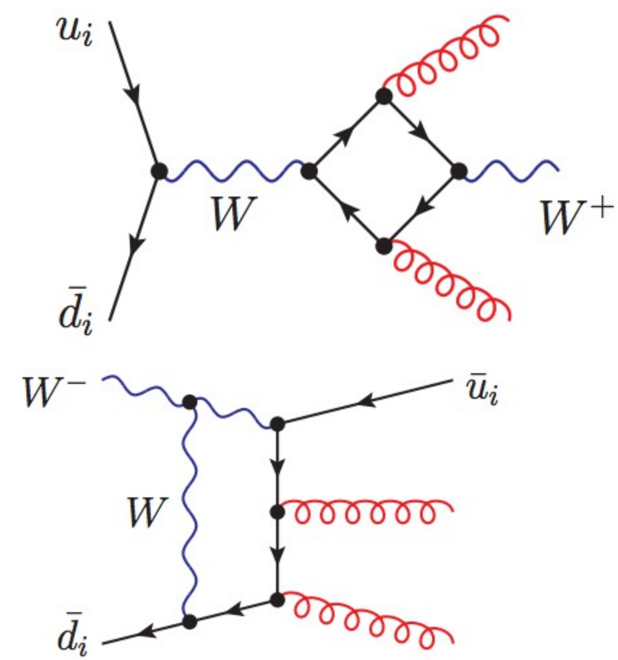
Solving the Mystery

LH'15 arXiv:1605.04692



CMS Z/gamma ratio (8 TeV) measurement compared to different generators

Some of the more heinous diagrams

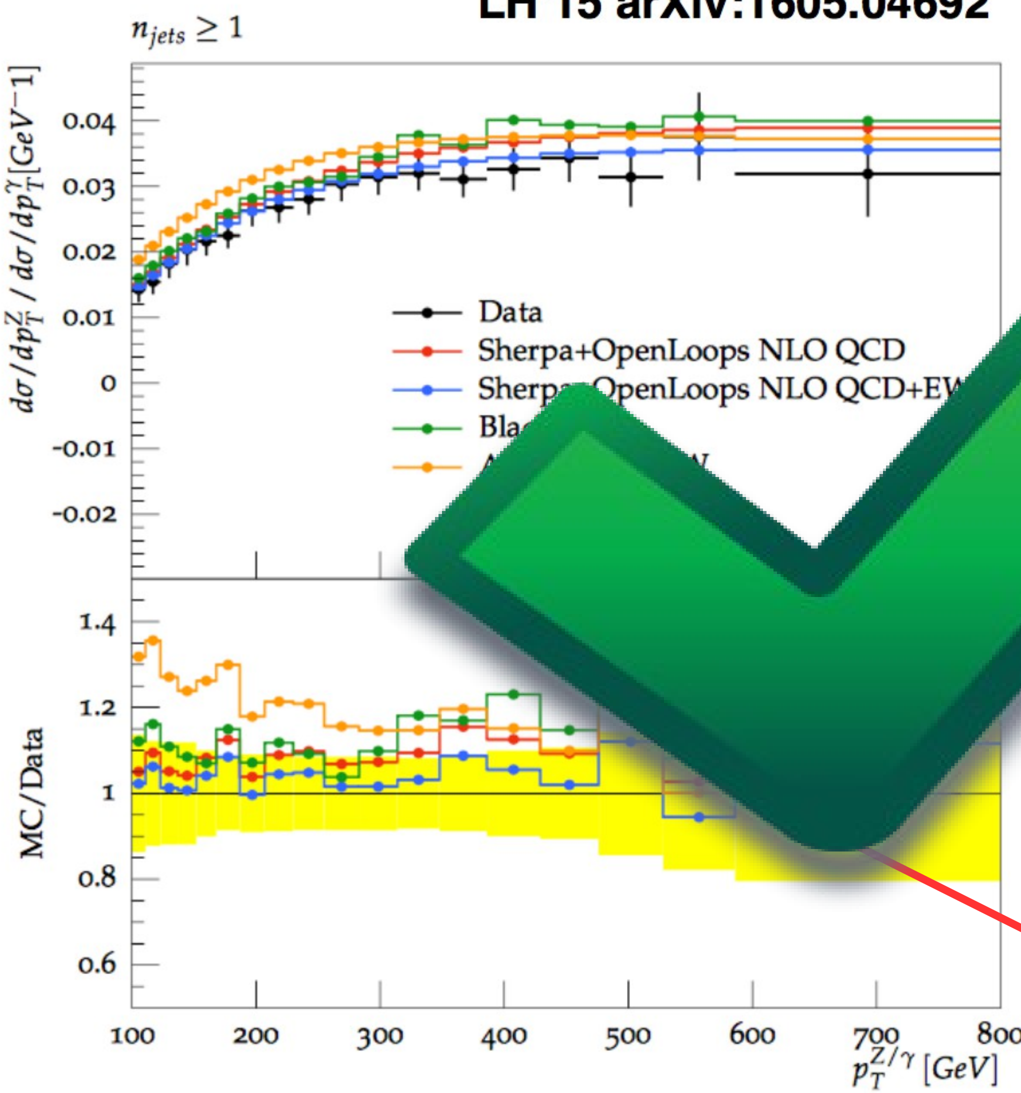


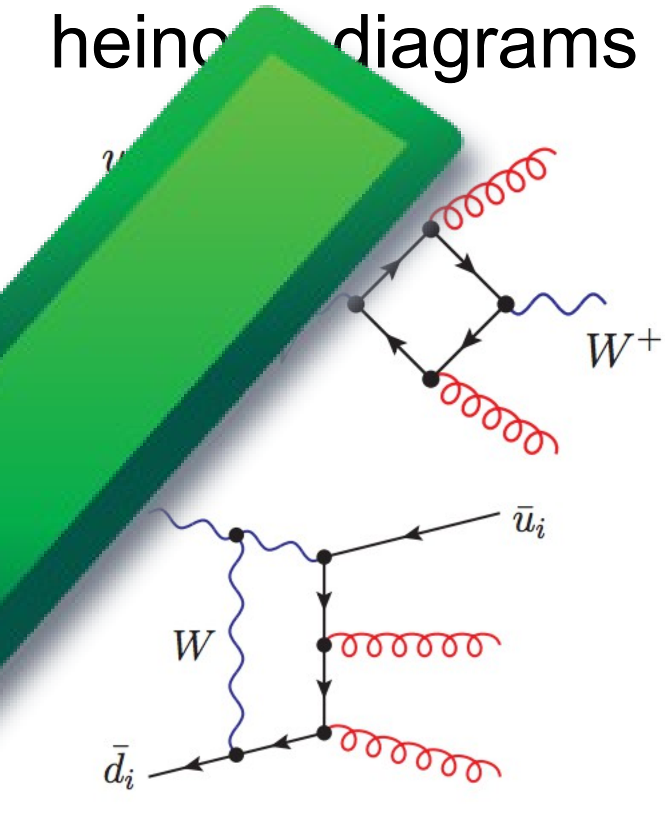
Adding the EWK corrections brings back agreement

Solving the Mystery

Some of the more heino diagrams

LH'15 arXiv:1605.04692





CMS Z/gamma ratio (8 TeV) measurement compared to different generators

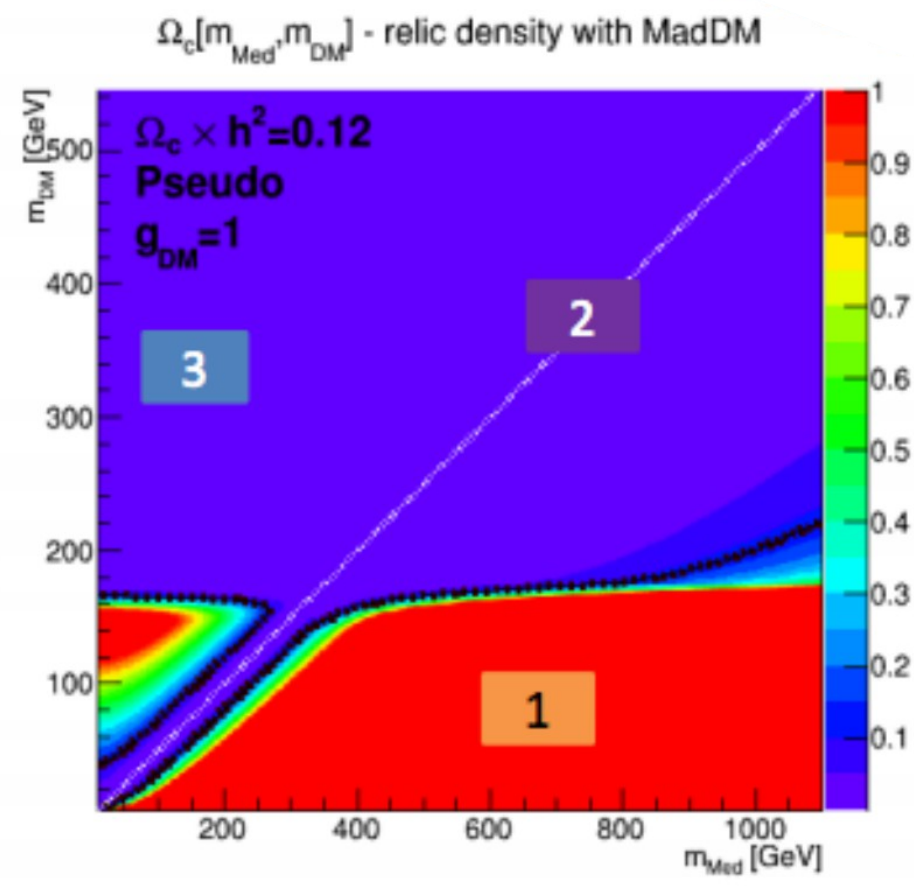
Adding the EWK corrections brings back agreement

2014...again!

CMS-EXO-12-055

Heuristic example to how it works

- [1] $m_\chi < m_t$→tight constraints
  - Suppression of the annihilation Process $\chi\chi \rightarrow Med \rightarrow SM$
- [2] $m_\Phi \sim 2 \cdot m_\chi$→weaker constraints
  - On-shell $\chi\chi \rightarrow Med$
- [3] $2 \cdot m_\chi > m_\Phi$→weaker constraints
  - Less suppressed annihilation $\chi\chi \rightarrow Med \rightarrow SM$



With Direct Detection

Vector(SI)

Spin independent

Extremely good

Axial(SD)

Spin dependent

Not so great

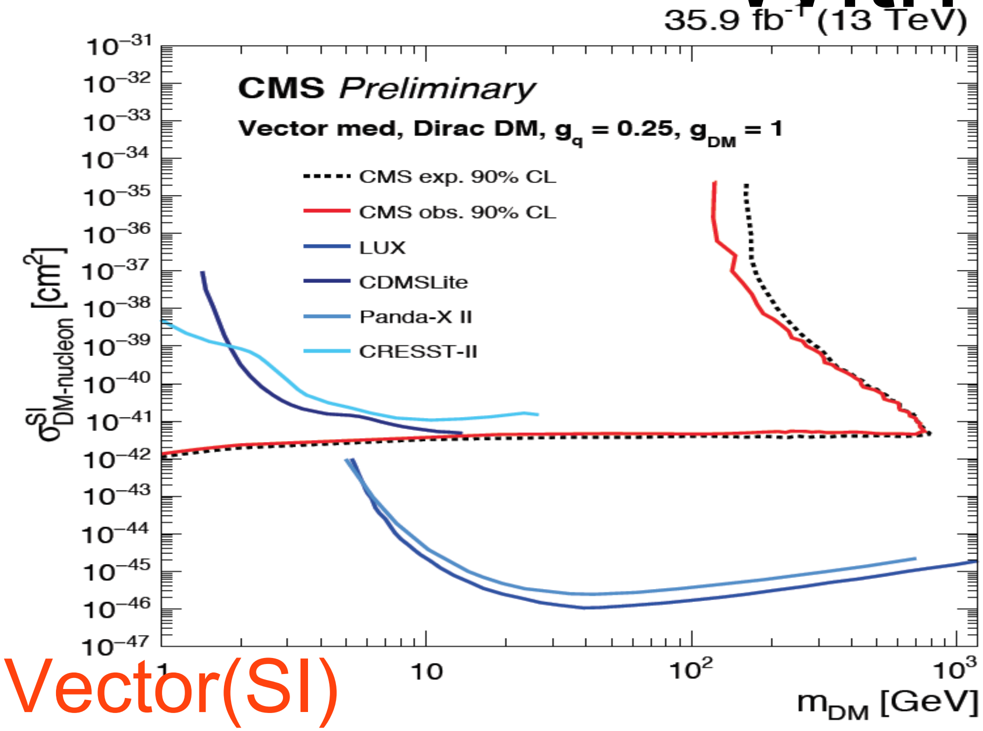
Scalar(SI)

So-so
Spin independent

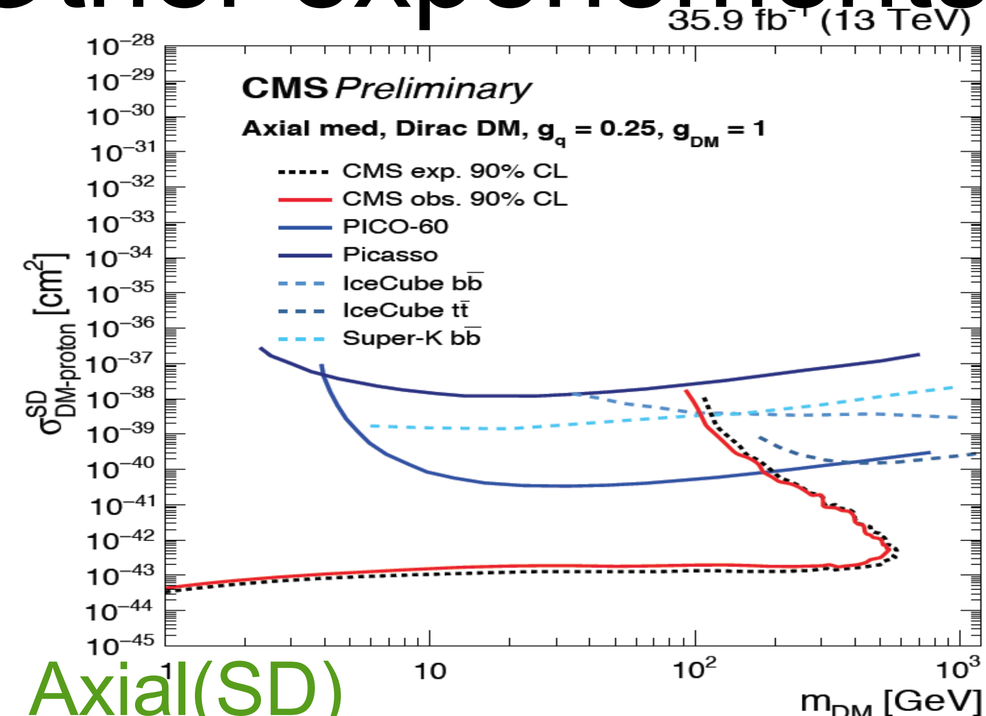
Pseudoscalar

Use indirect detection

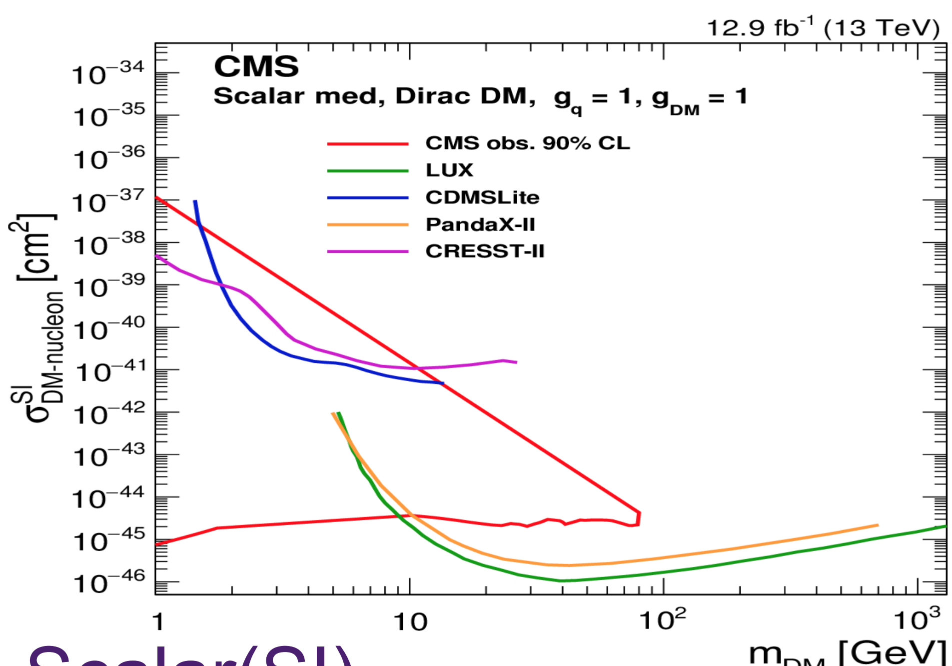
With Other experiements



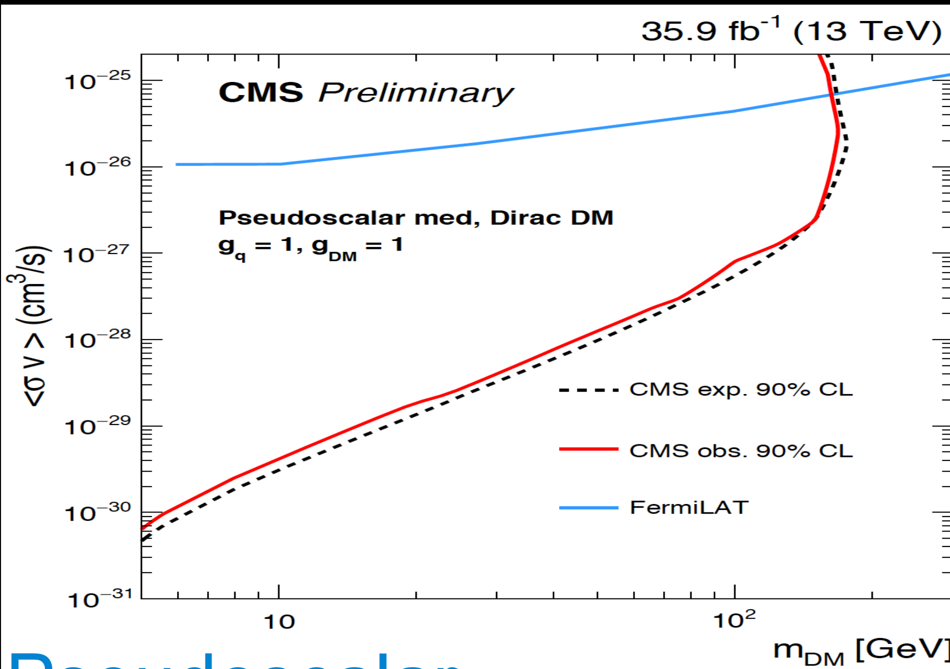
Vector(SI)



Axial(SD)

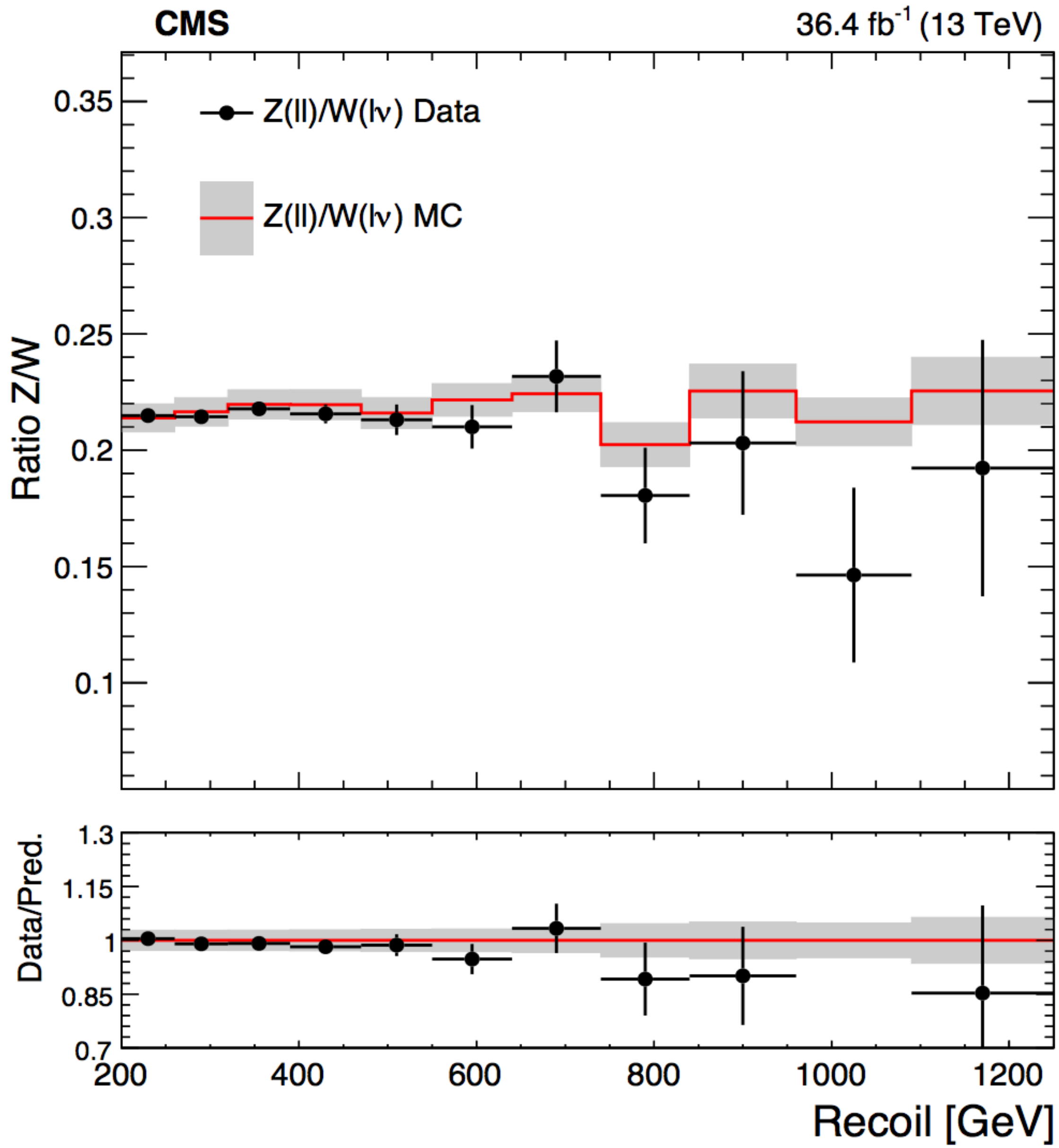


Scalar(SI)



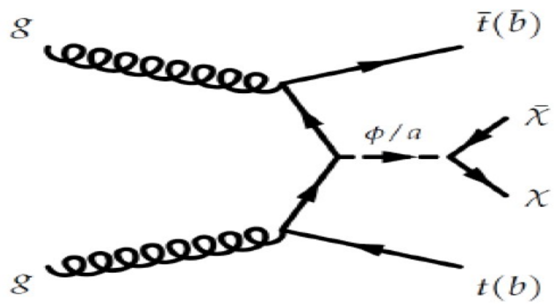
Pseudoscalar

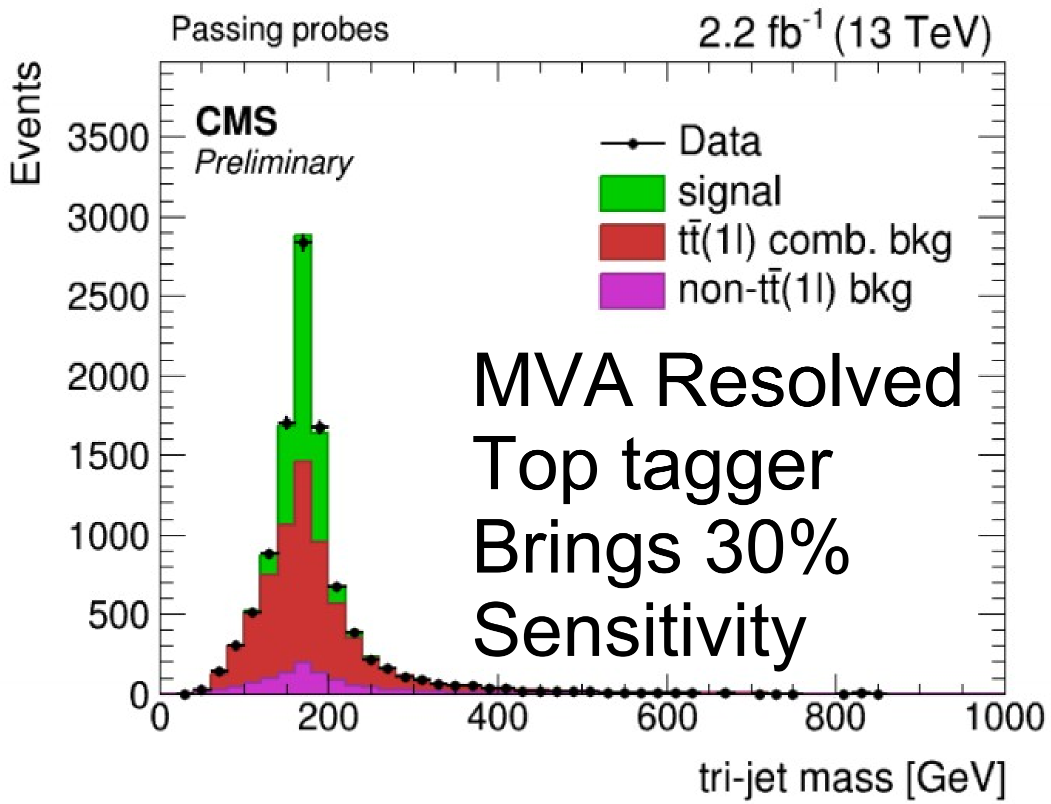
Can we really shrink unc?

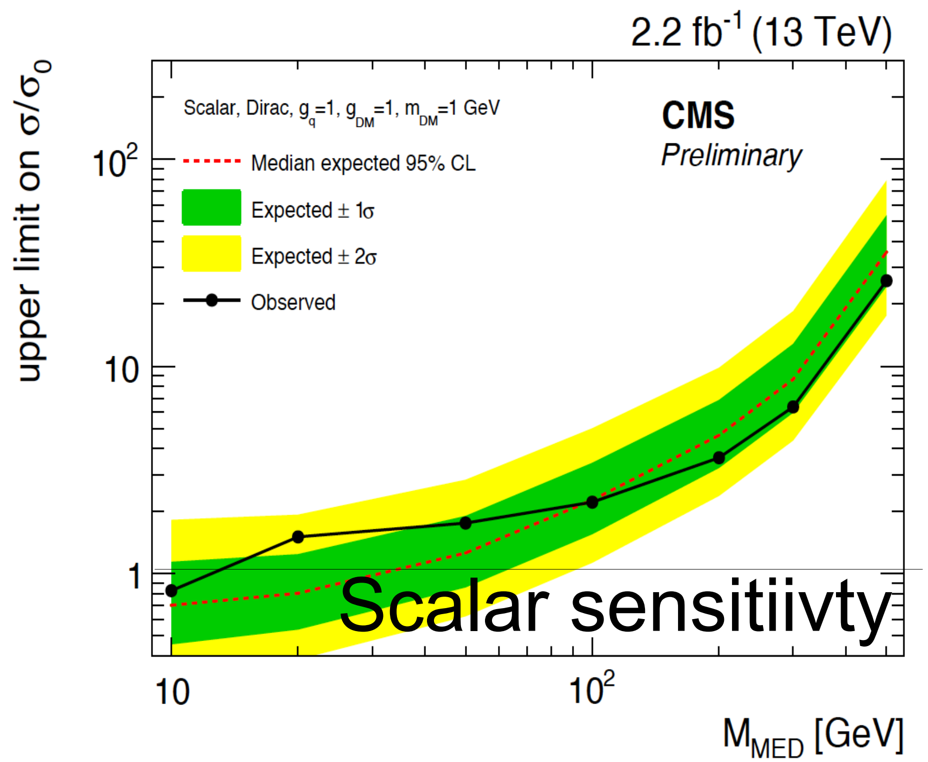


Total Luminosity : 2.3 fb^{-1} (2015)
Final State : tt+*MET*

tt+DM





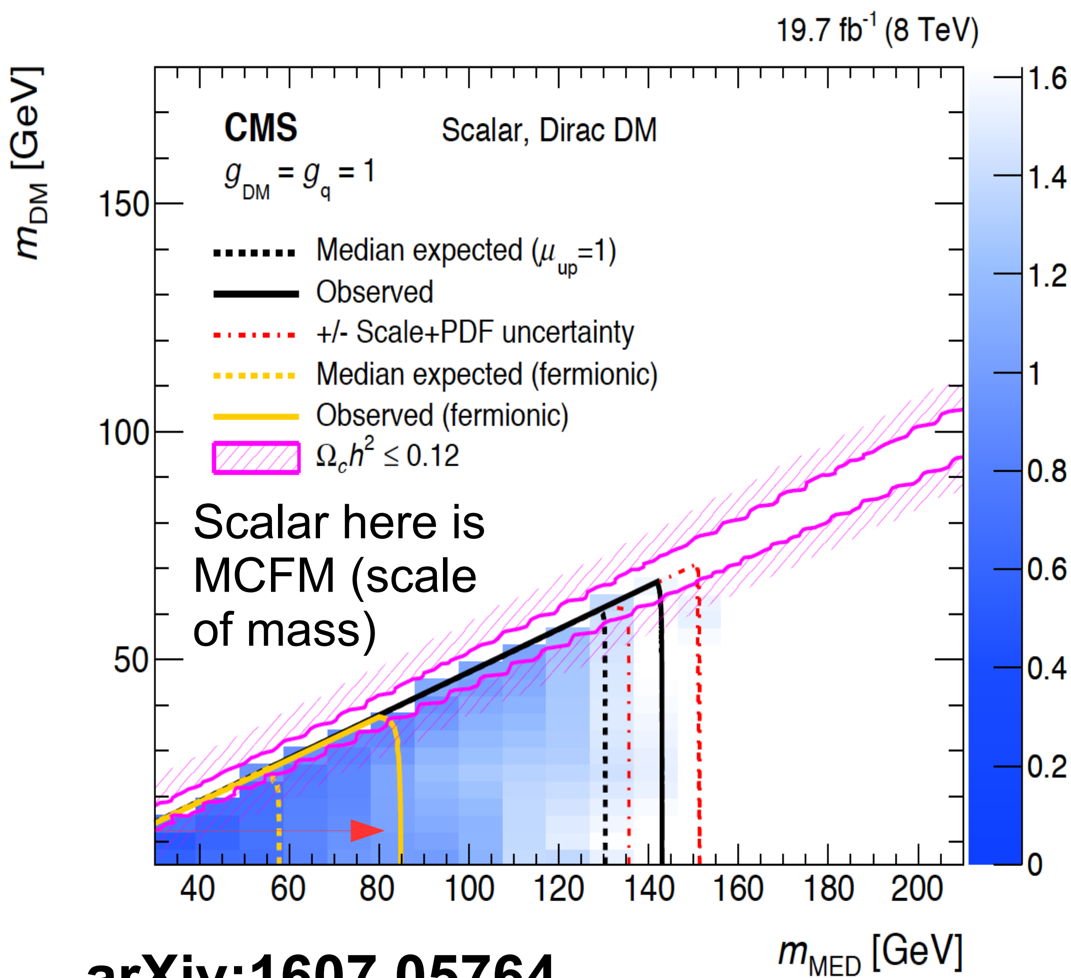


Sensitivity pushed to exclude Scalar mediator models

EXO-16-005

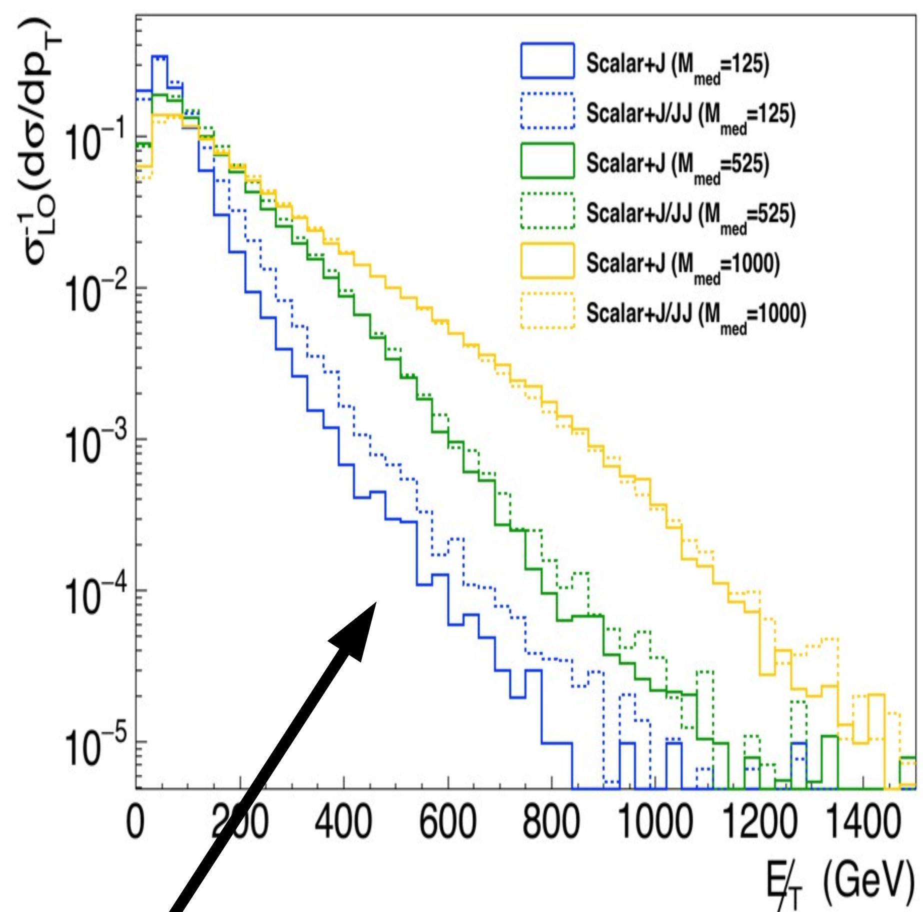
Comparing with Old results

- Exclusion for scalar up to 80 GeV



arXiv:1607.05764

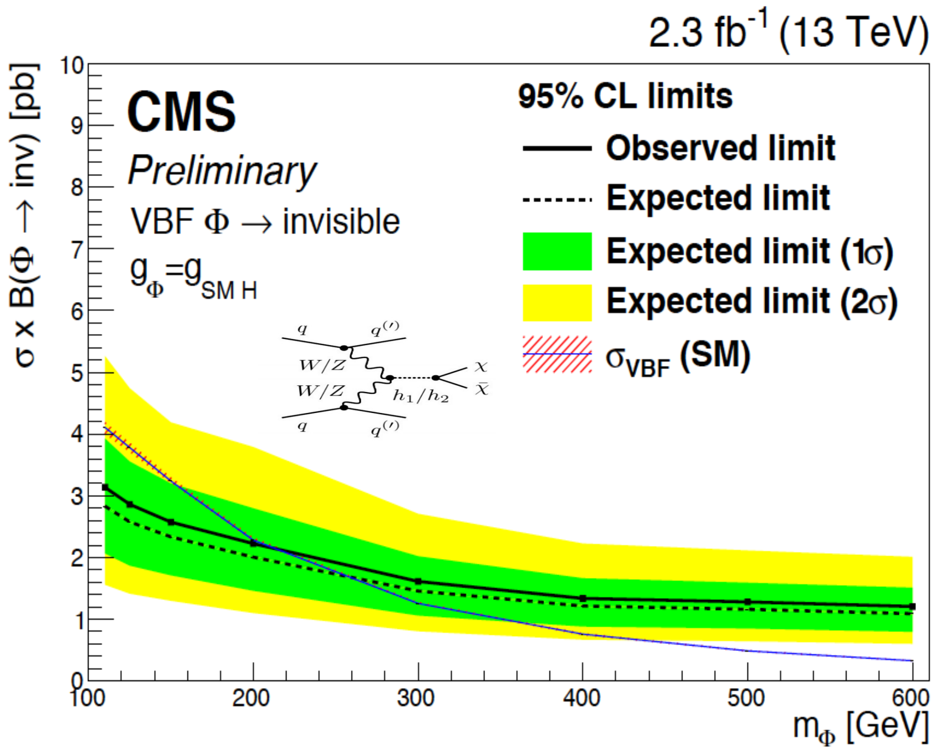
arXiv:1509.02904

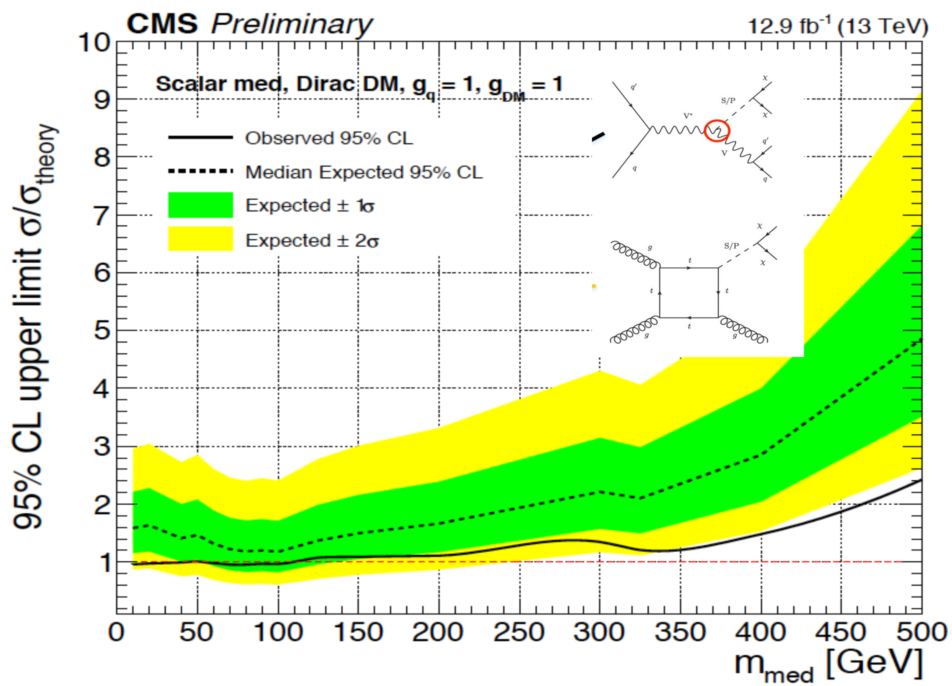


Expect the sensitivity to grow just by adding the 2 jet multiplicity back

Varying the mass

- When we vary the mass





Changing mass is a search for a different mediator

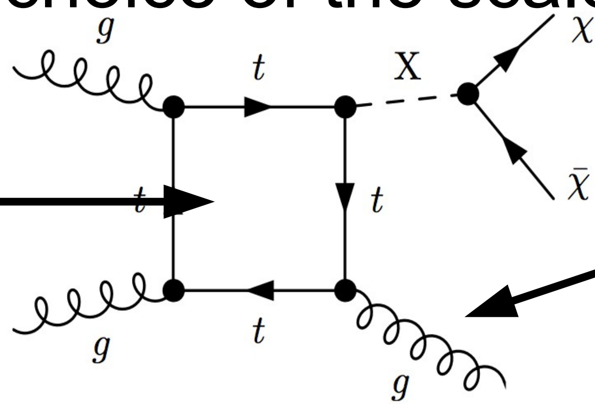
This state allows for combination of vector boson copuligns

Adding more jets

- Can split the signal models into 2 different sources
  - What is the choice of the scale?

Generate the two scales and compare

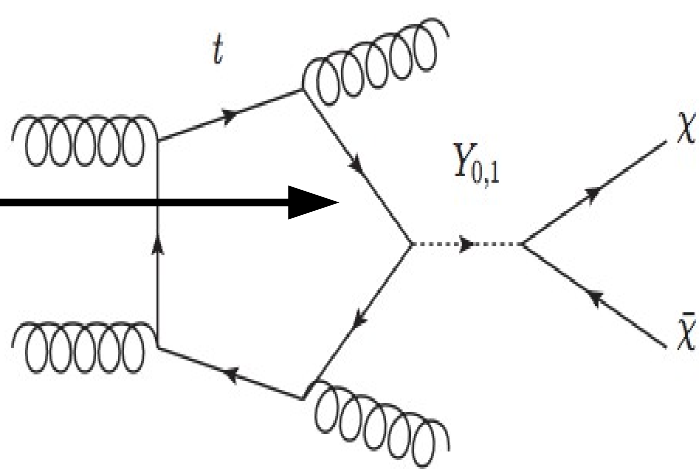
Inside the loop best motivated scale is Top mass



Outside the loop
Best motivated scale is the jet

  - What is the contribution from higher order effects?

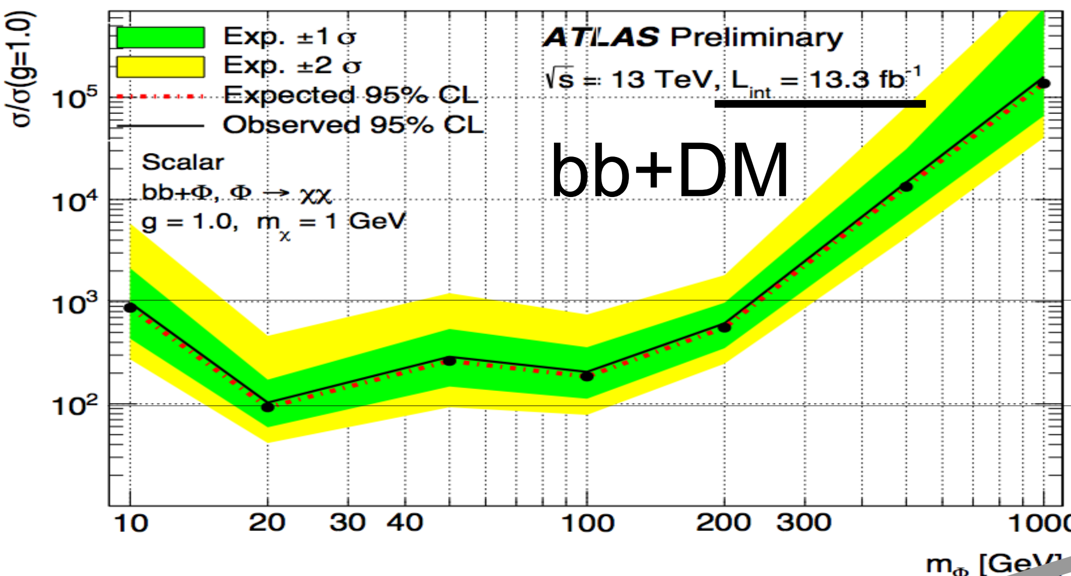
Diagrams like these add significant contribution



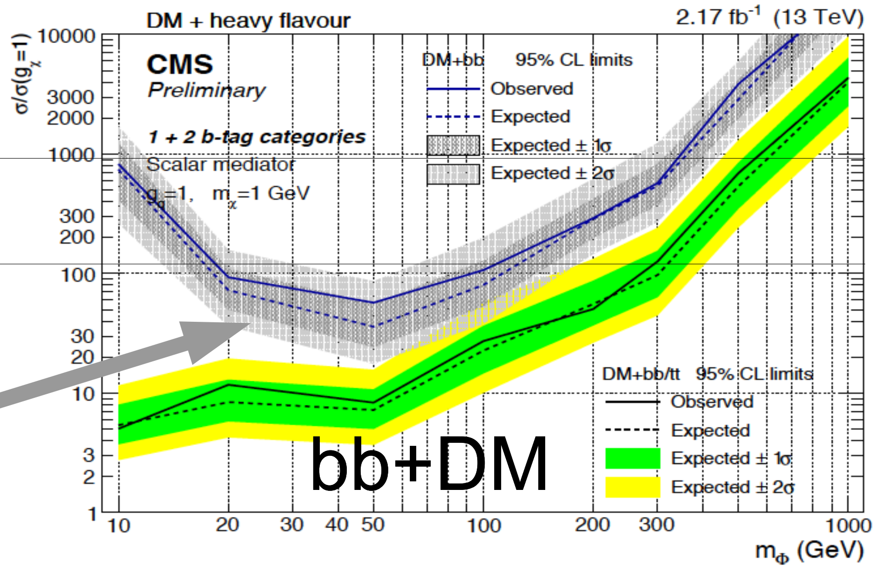
Generate the two jet diagrams and merge them with the one jet

We will soon take advantage of the 2[nd] jet

ATLAS vs CMS : Scalar HF results



ATLAS result 5x data



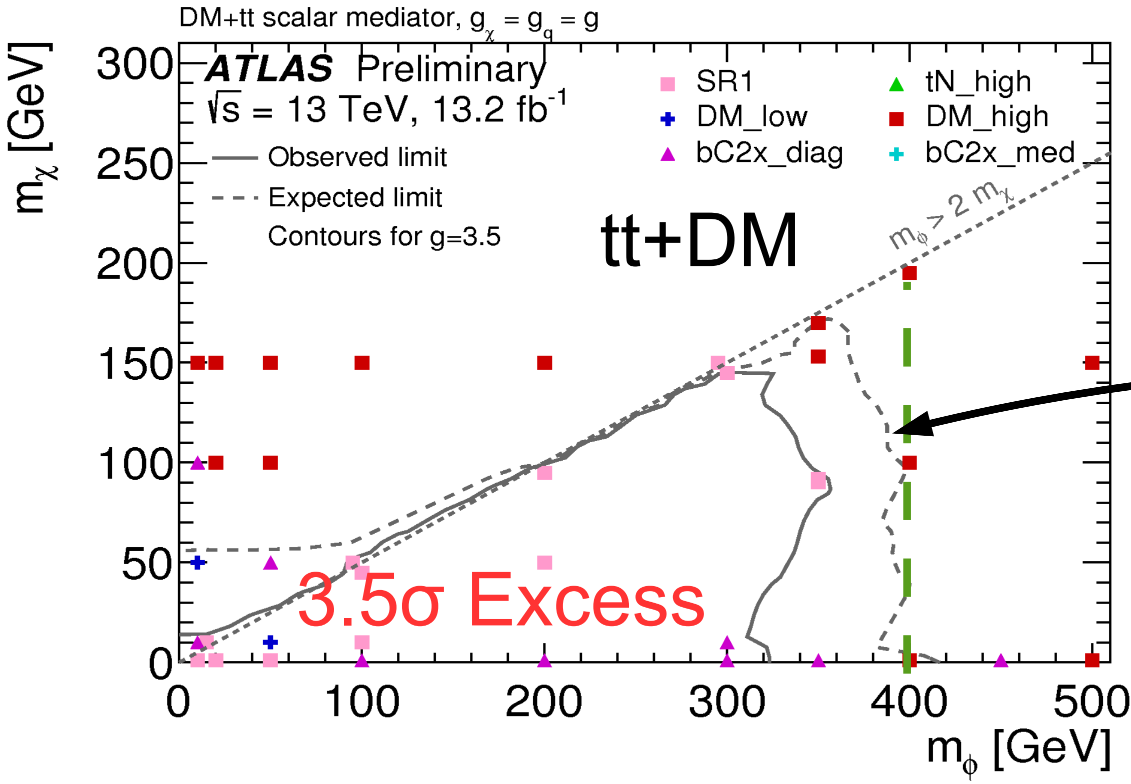
CMS results roughly the same
Even though 1/5 luminosity

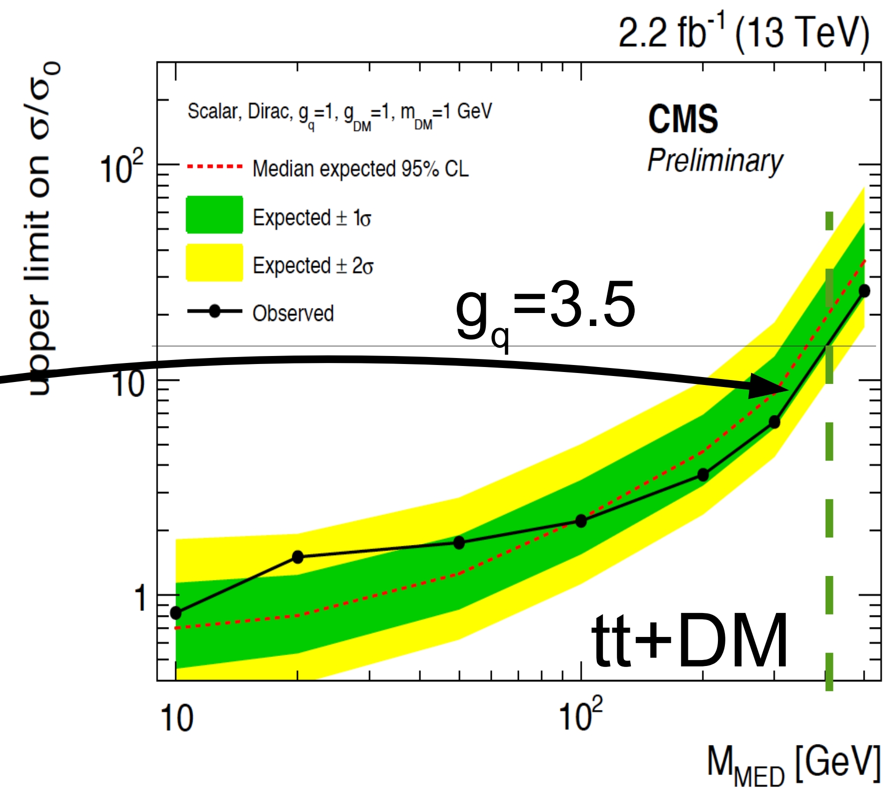
ATLAS neglects tt+DM and bb+DM combined interpretation

Neglects a potentially large contribution

B2G-15-007

ATLAS vs CMS : Scalar HF results





ATLAS result 5x data

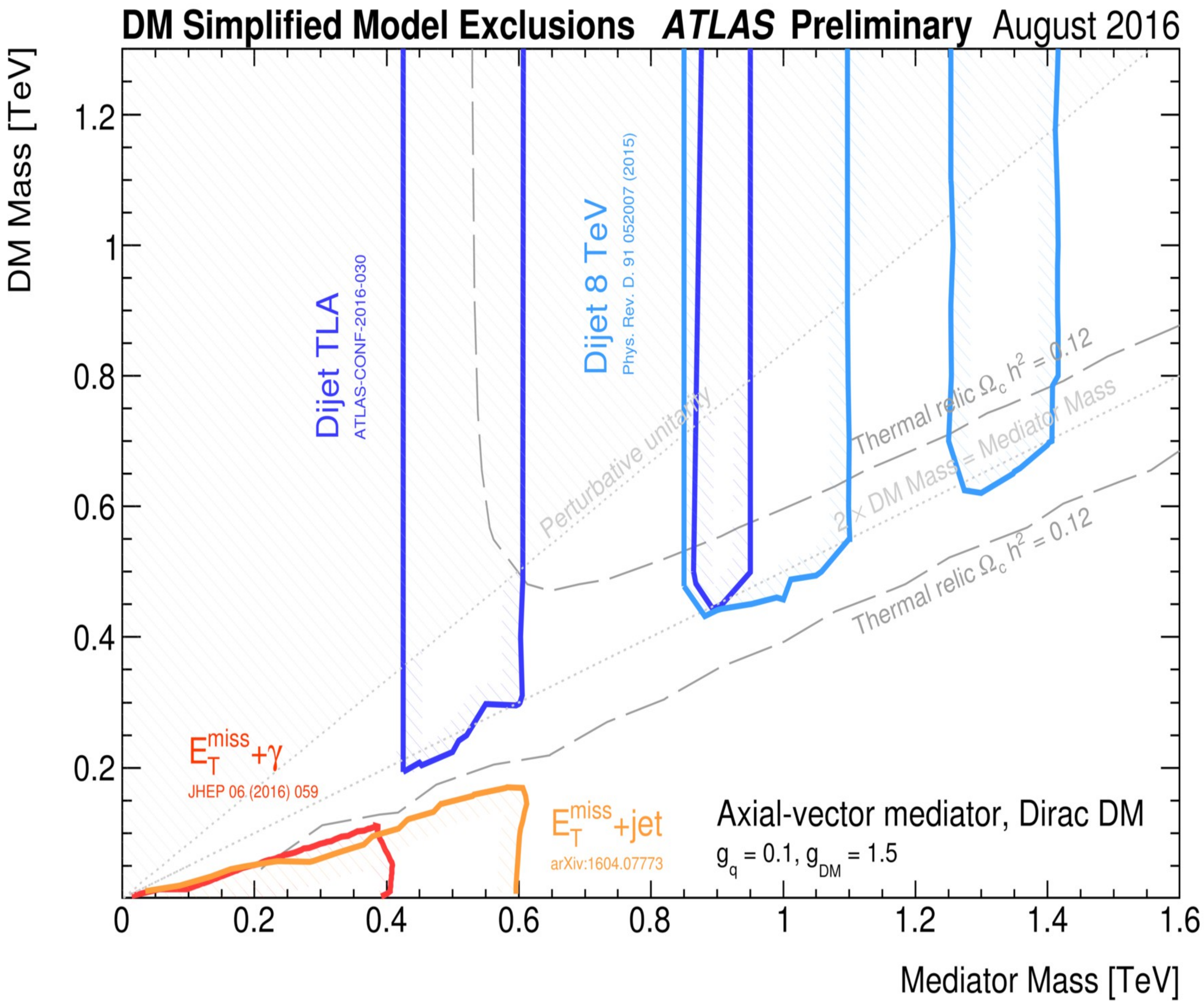
CMS results have roughly the same sensitivity

CMS excludes the tt+DM excess in ATLAS

EXO-16-005

ATLAS modified couplings

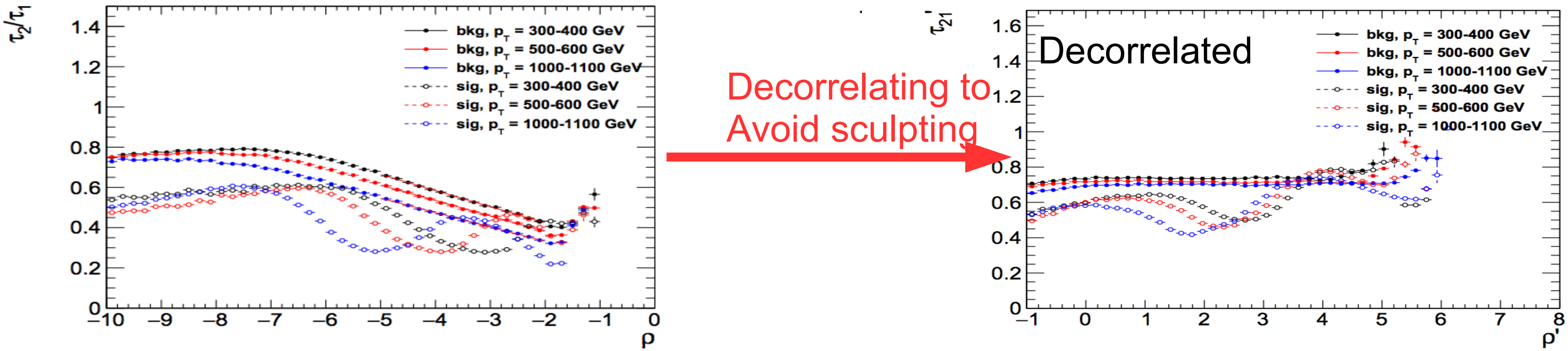
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html

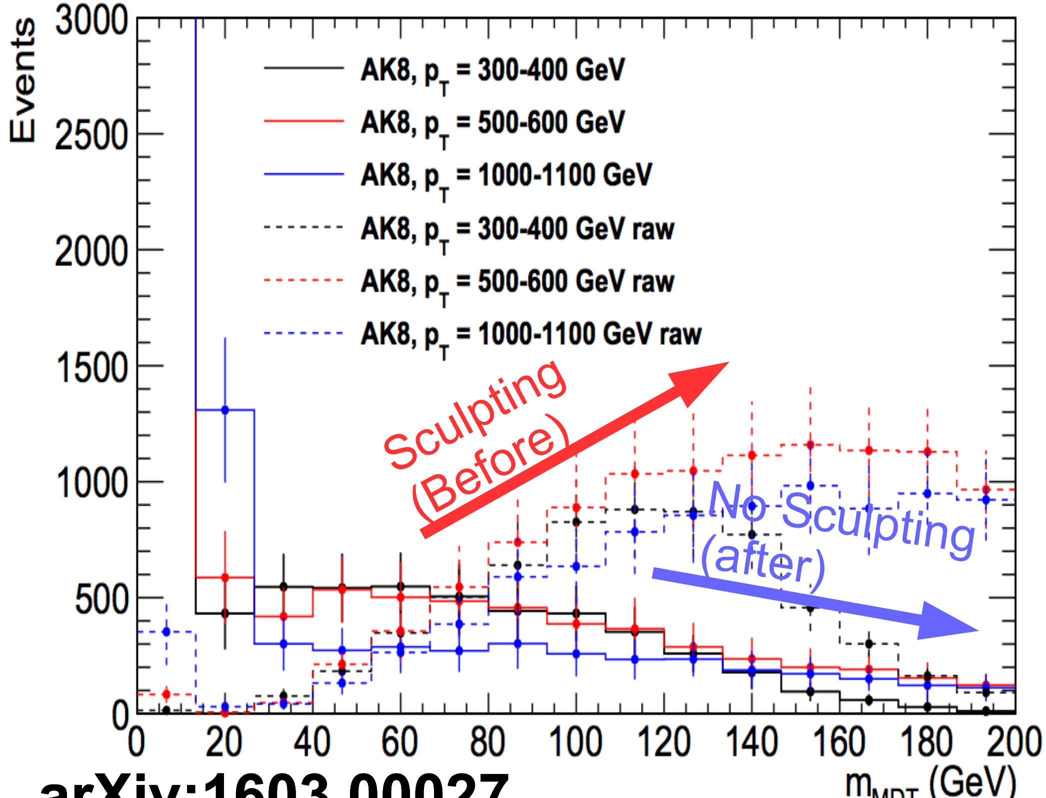


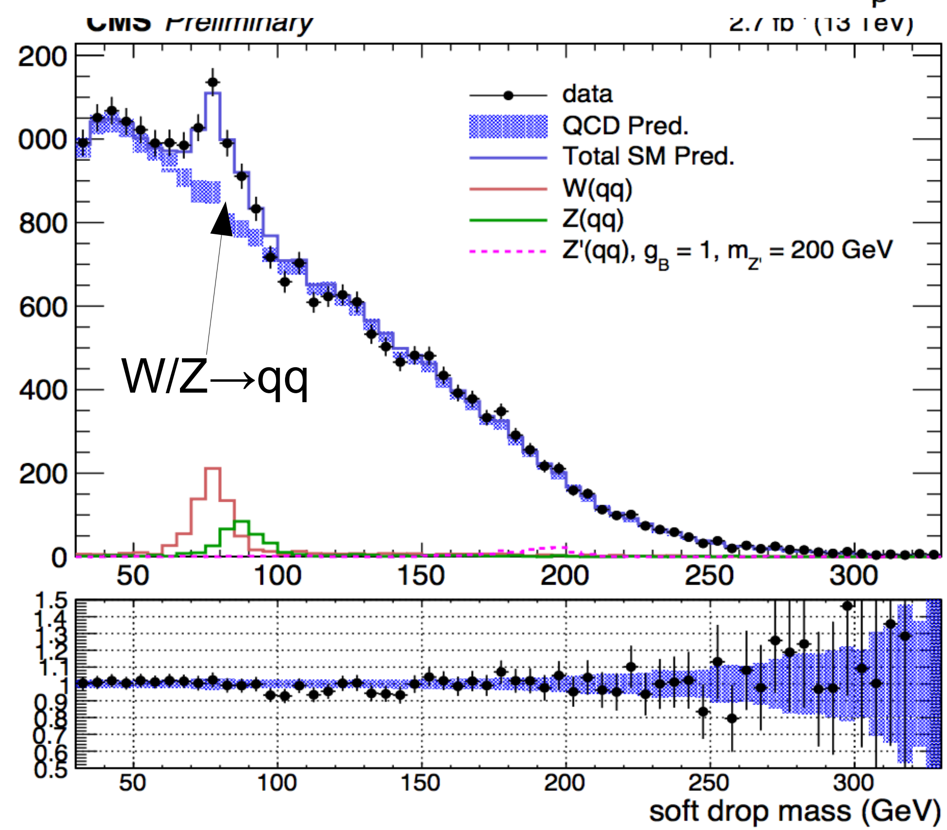
g_{SM}=0.1

g_{DM}=1.5

Design a transfom to decorrelate against mass and p_T



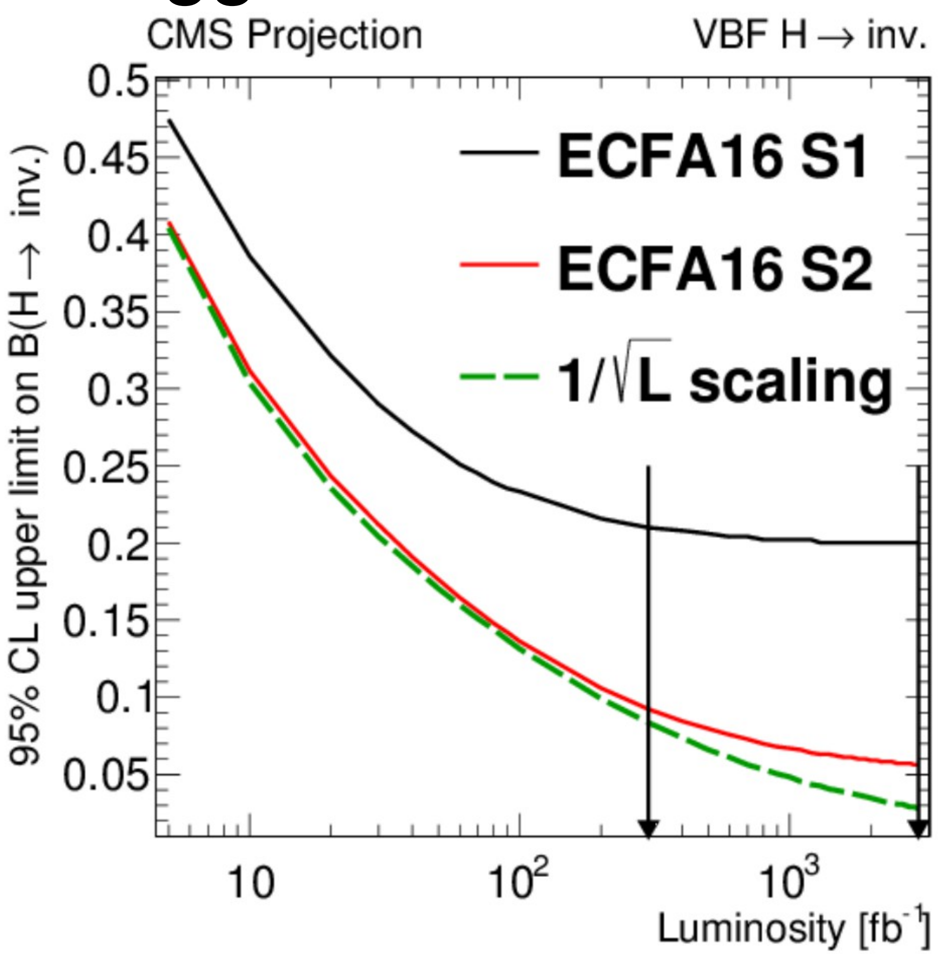




arXiv:1603.00027

How will things scale?

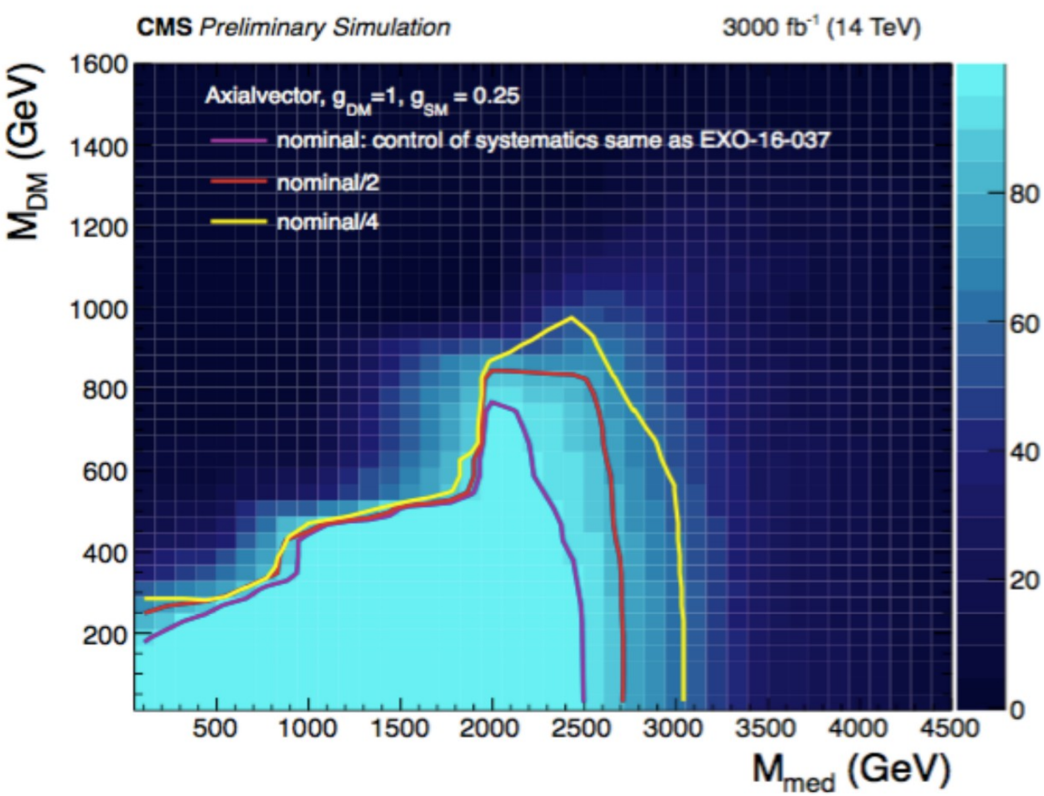
- Higgs to Invisible

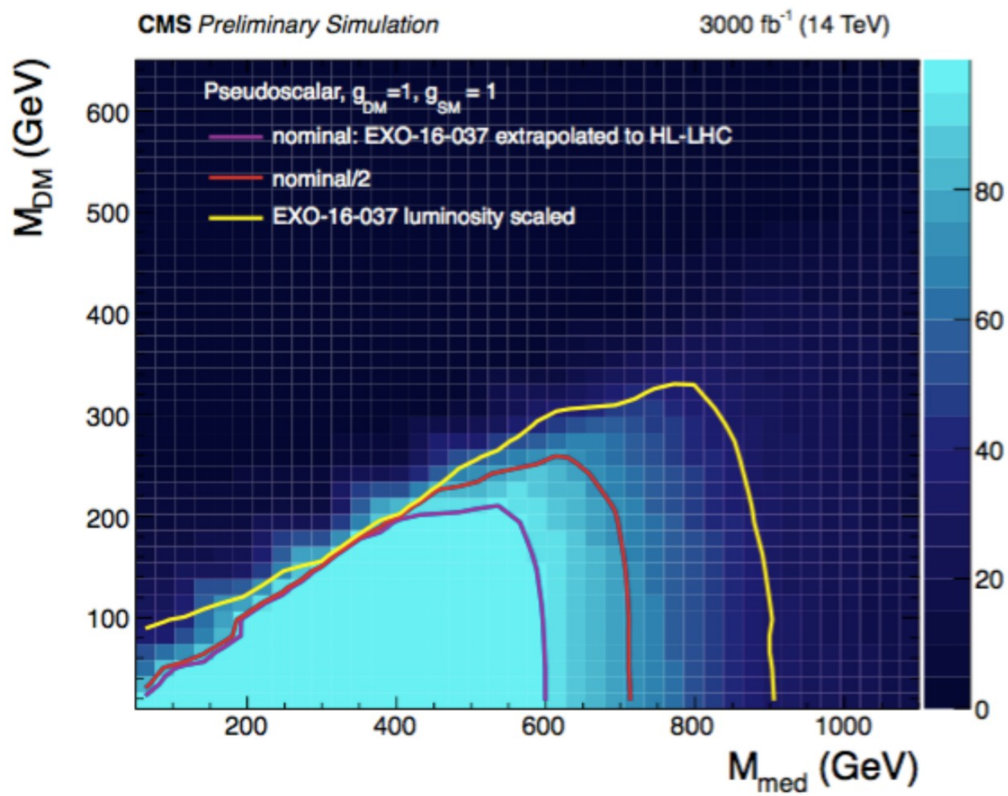


Can reach
BR(H→Inv) < 5.6% in VBF
All channels BR(H→Inv) < 3%

	ECFA16 S1	ECFA16 S2	$1/\sqrt{L}$ scaling
300 fb^{-1}	0.210	0.092	0.084
3000 fb^{-1}	0.200	0.056	0.028

Monojet Projections





For Vector/Axial-Vector reach is 3 TeV

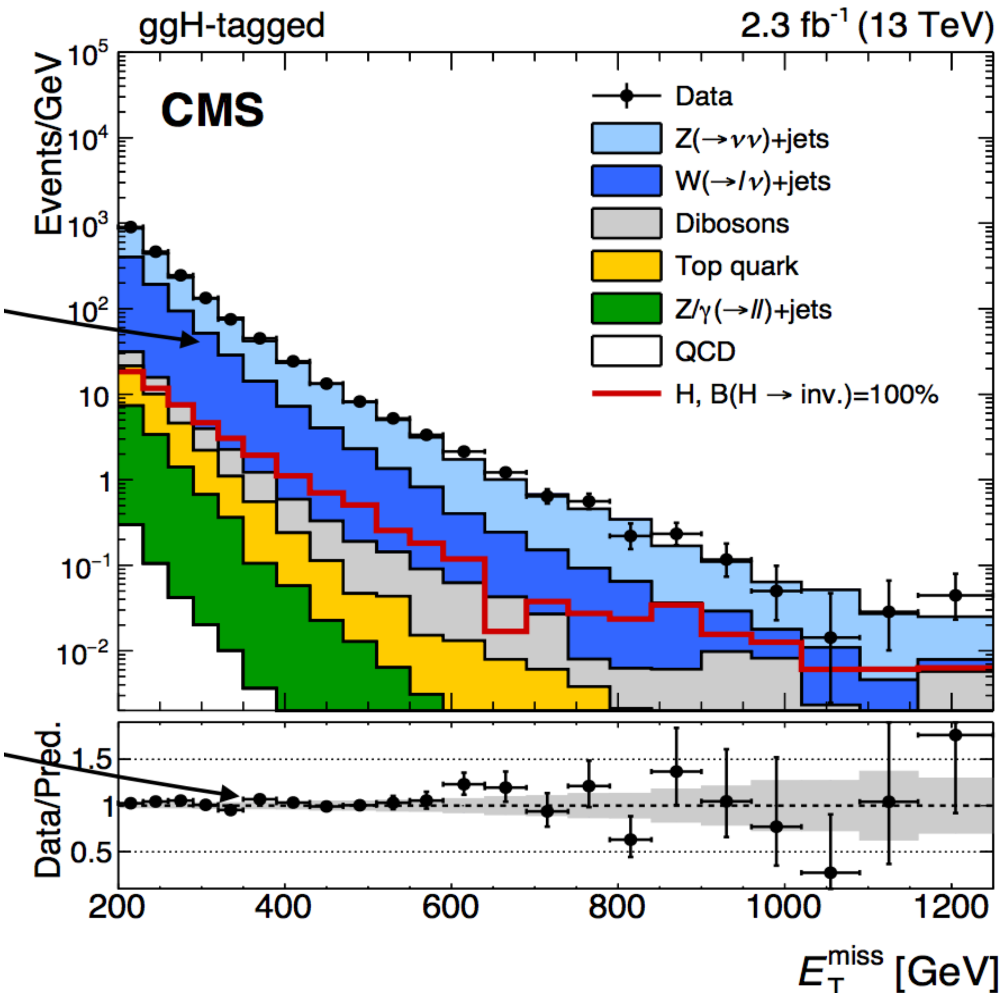
For Peudoscalar reach is 800-900 GeV
Scalar reach is 600-700 GeV

CERN-CMS-DP-2016-064

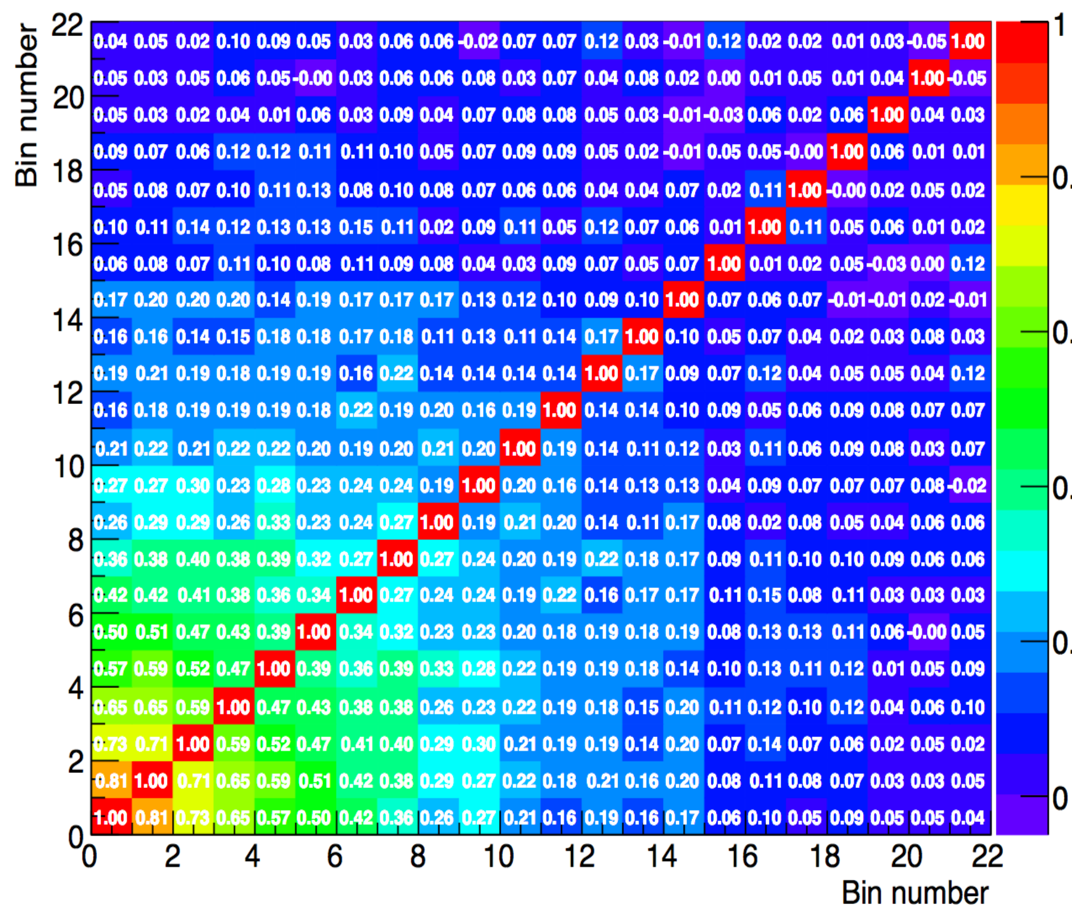
Re-interpreting the Analysis

- Future plans from LHC→simplified likelihoods
  - What is it? => Reduced control fit to 2 objects

MET distribution



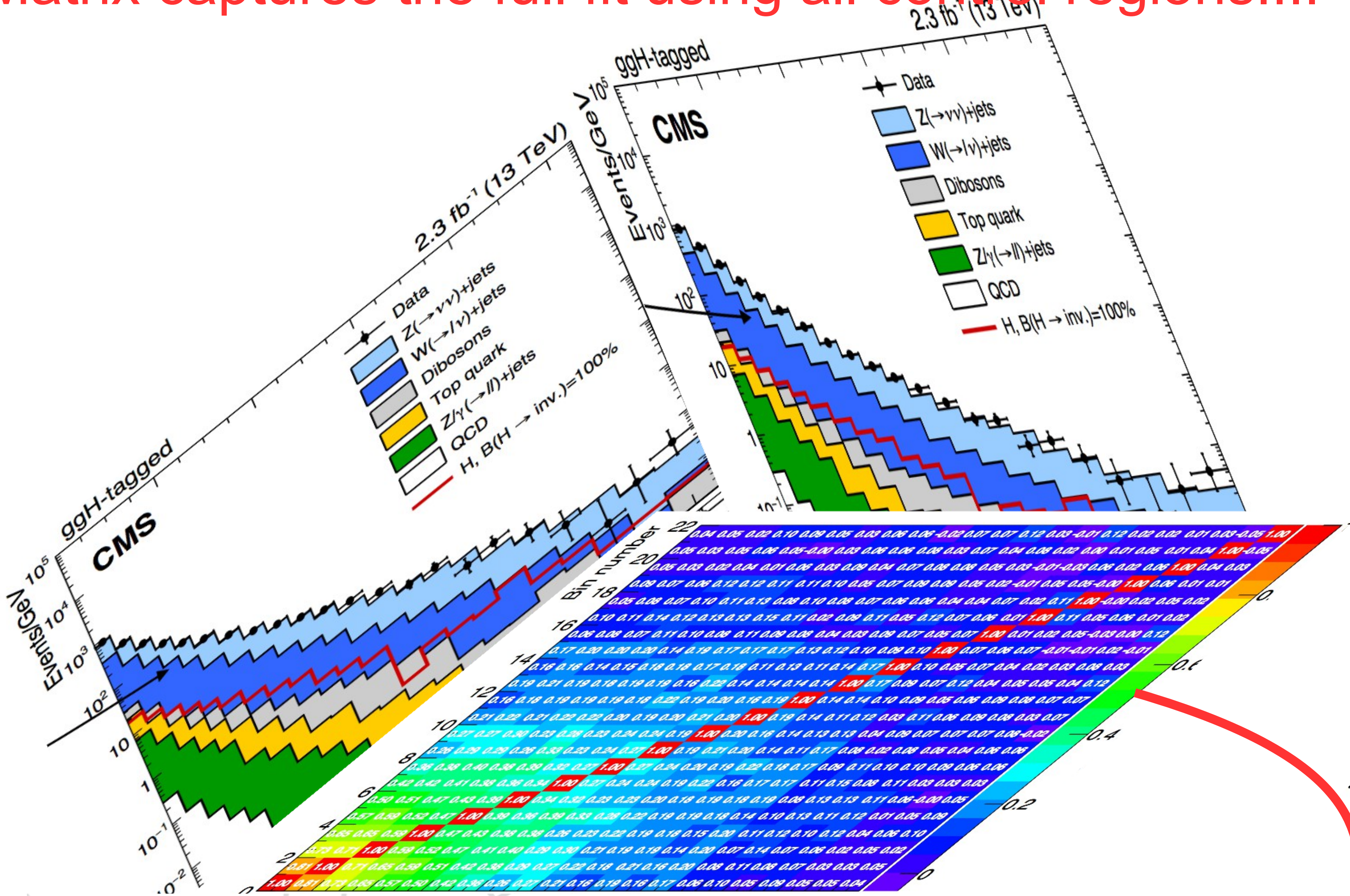
Toy Bin by bin covariance



From this: setup full CL_s get both expected and observed

Simplified likelihood

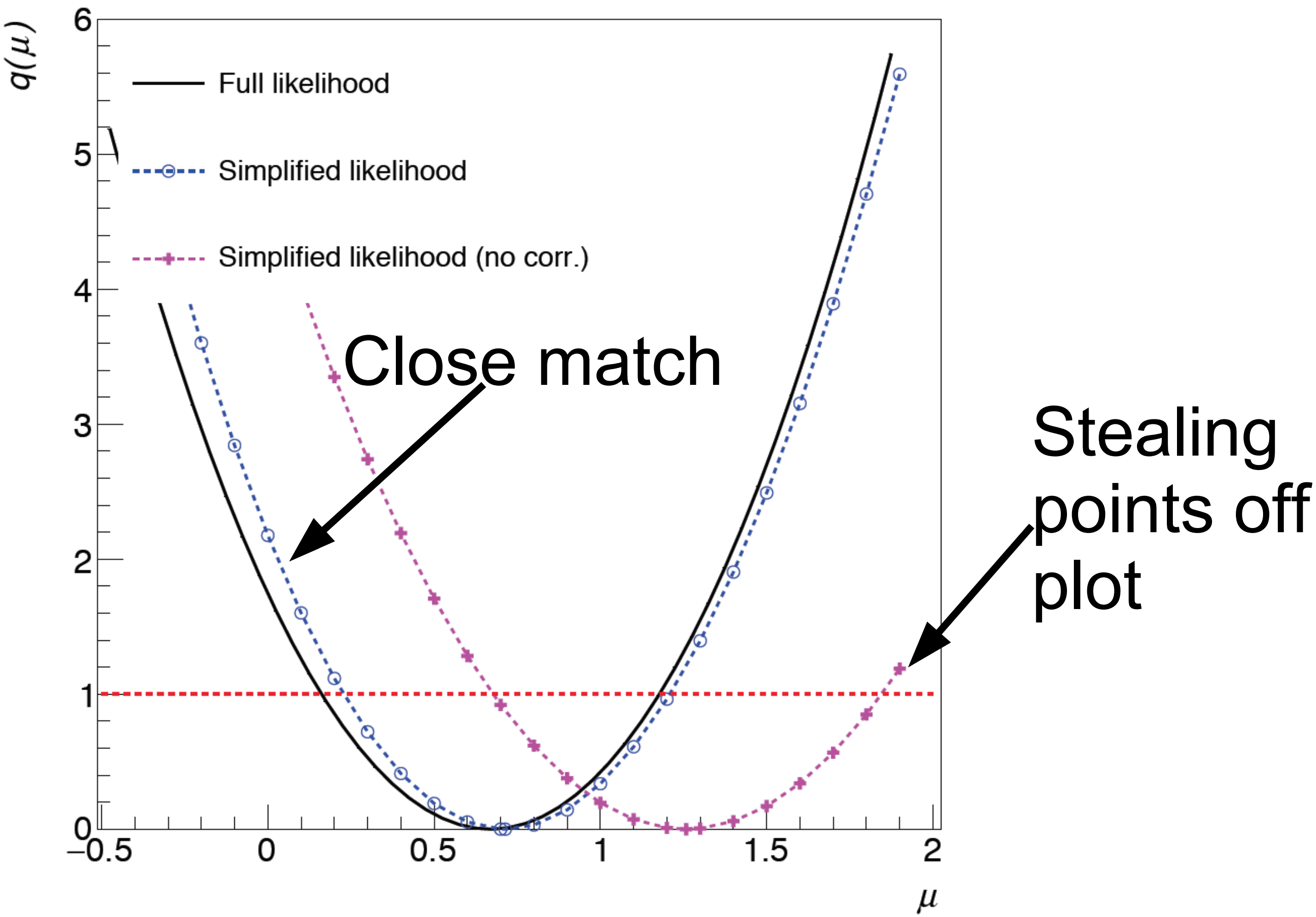
Matrix captures the full fit using all control regions....



$$\mathcal{L}_S(\mu,\boldsymbol{\theta}) = \prod_{i=1}^{N} \frac{(\mu \cdot s_i + b_i + \theta_i)^{n_i} e^{-(\mu \cdot s_i + b_i + \theta_i)}}{n_i!} \cdot \exp\left(-\frac{1}{2}\boldsymbol{\theta}^T \mathbf{V}^{-1} \boldsymbol{\theta}\right)$$

Signal background

Whats the accuracy?



CMS is aiming to release simplified likelihoods for all future SUSY and Dark matter searches

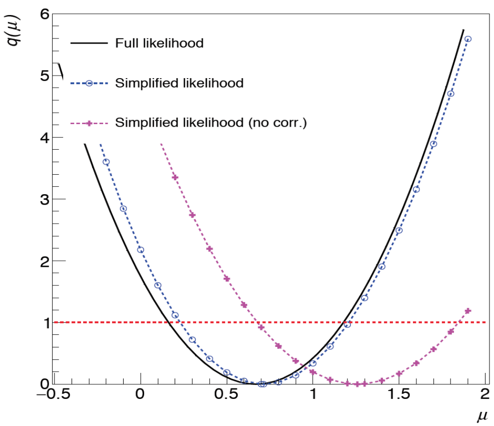
What does this mean?

Lets say you have a new model

Final States

Likelihood fit

"Almost" Actual LHC exclusion



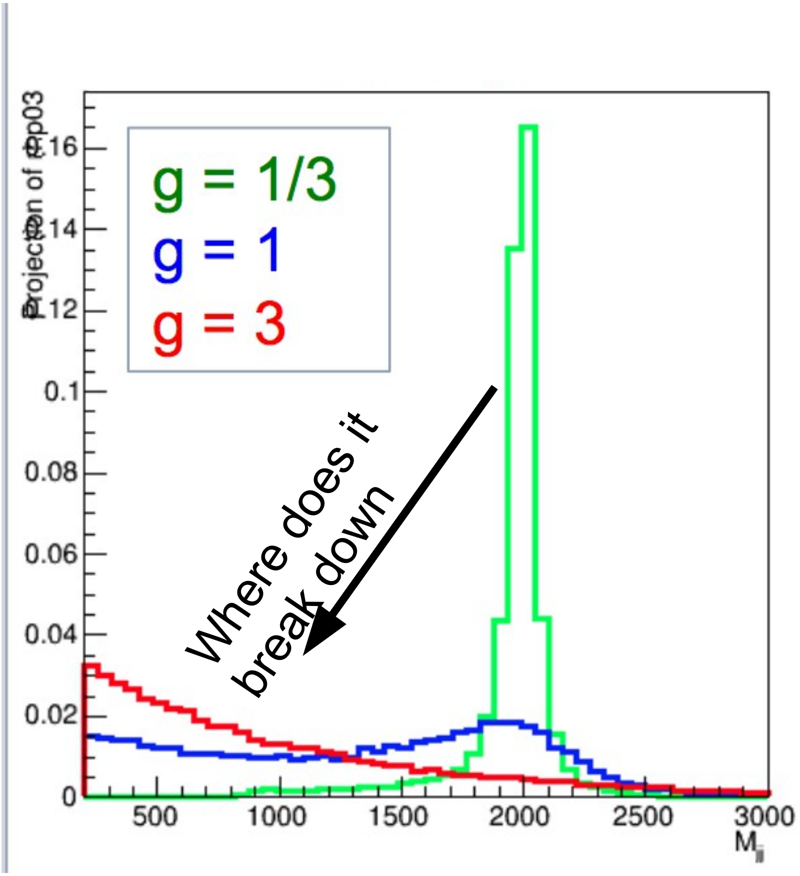
CMS data cast into simplified covariance matrix

Real reaon for this :

We are tired of running every theorists' model

Follow up

- The resonant searches break down
  - Larger the coupling the wider the resonance
  - Bump hunts only work with a relatively narrow bump
  - With large couplings cross section is larger



- To probe wide resonance
  - Alternative search strategy
  - Typically with angular analysis
  - Searches tend to be weaker
- Good to know if there is missing phase space

Adding EWSB in a better way

Khoze *et al.*, 1505.03019

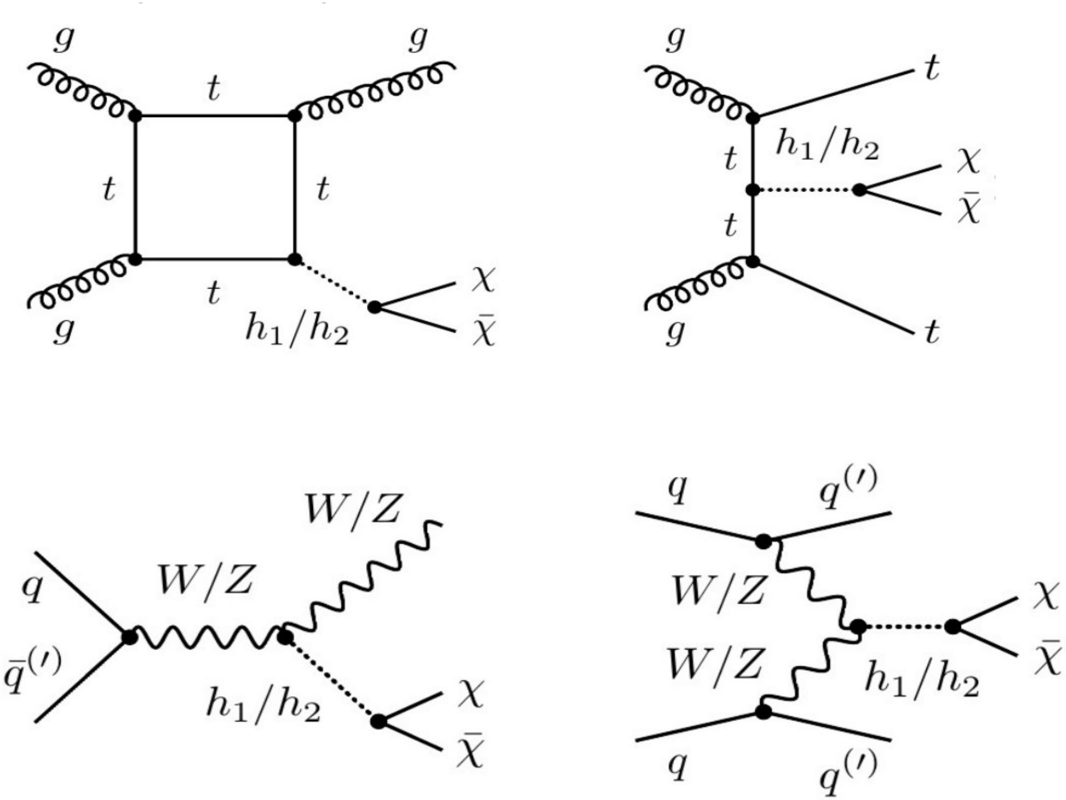
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

$$\mathcal{L} \supset -\, y_{\rm DM}\left(\sin\theta\, h_1 + \cos\theta\, h_2\right)\bar{\chi}\chi$$
$$+\left(\cos\theta\, h_1 - \sin\theta\, h_2\right)\left(\frac{2M_W^2}{v}W_\mu^+W^{-\mu} + \frac{M_Z^2}{v}Z_\mu Z^\mu - \sum_f \frac{m_f}{v}\bar{f}f\right)$$

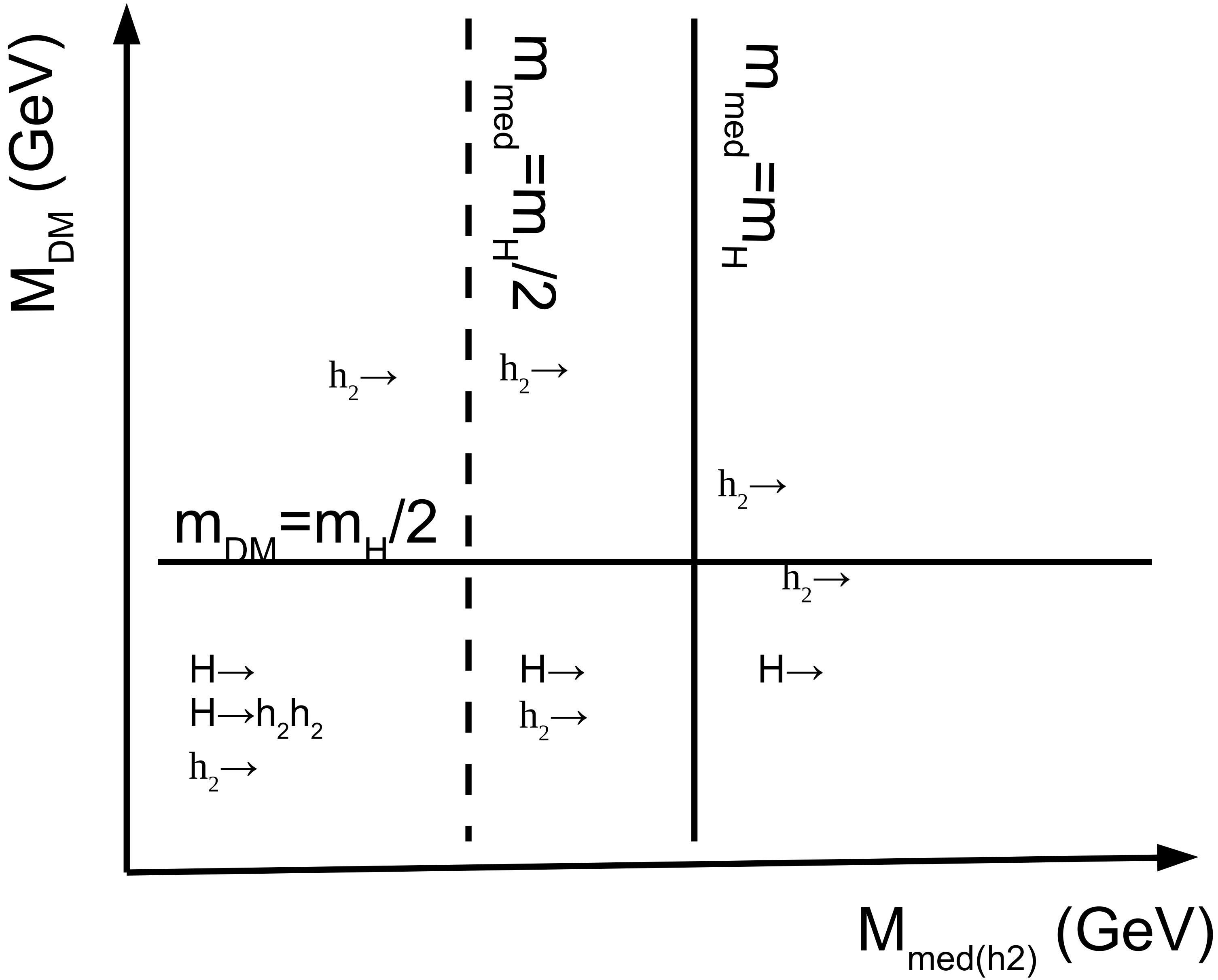
$$g_{\rm DM} \longrightarrow y_{\rm DM}\cos\theta$$

$$g_{\rm SM} \longrightarrow -\sin\theta$$

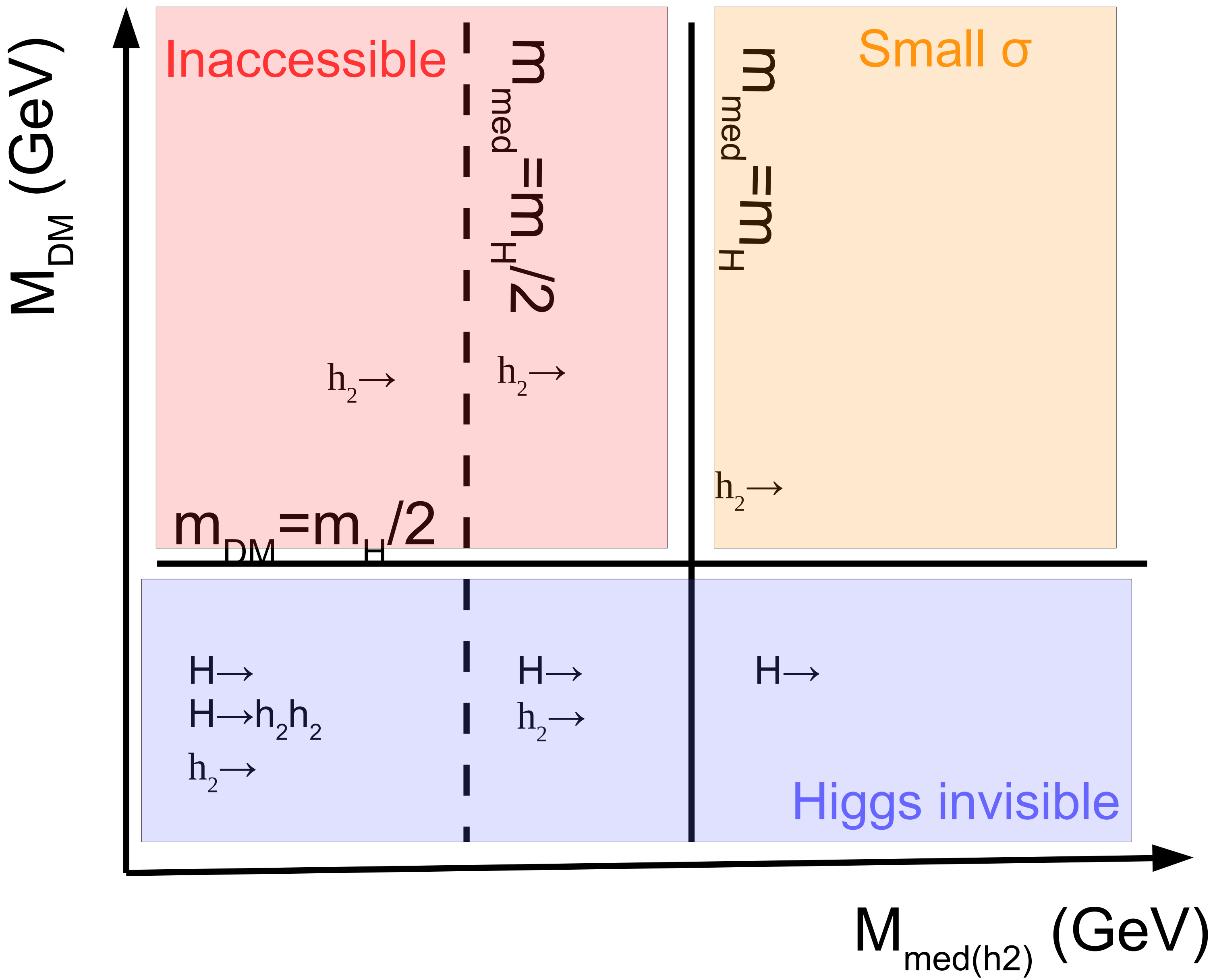
$$\boxed{\Gamma(h_1 \to \chi\bar{\chi}) = \frac{y_{\rm DM}^2 \sin^2\theta\, m_{h_1}}{8\pi}\left(1 - \frac{4m_\chi^2}{m_{h_1}^2}\right)^{3/2}}$$



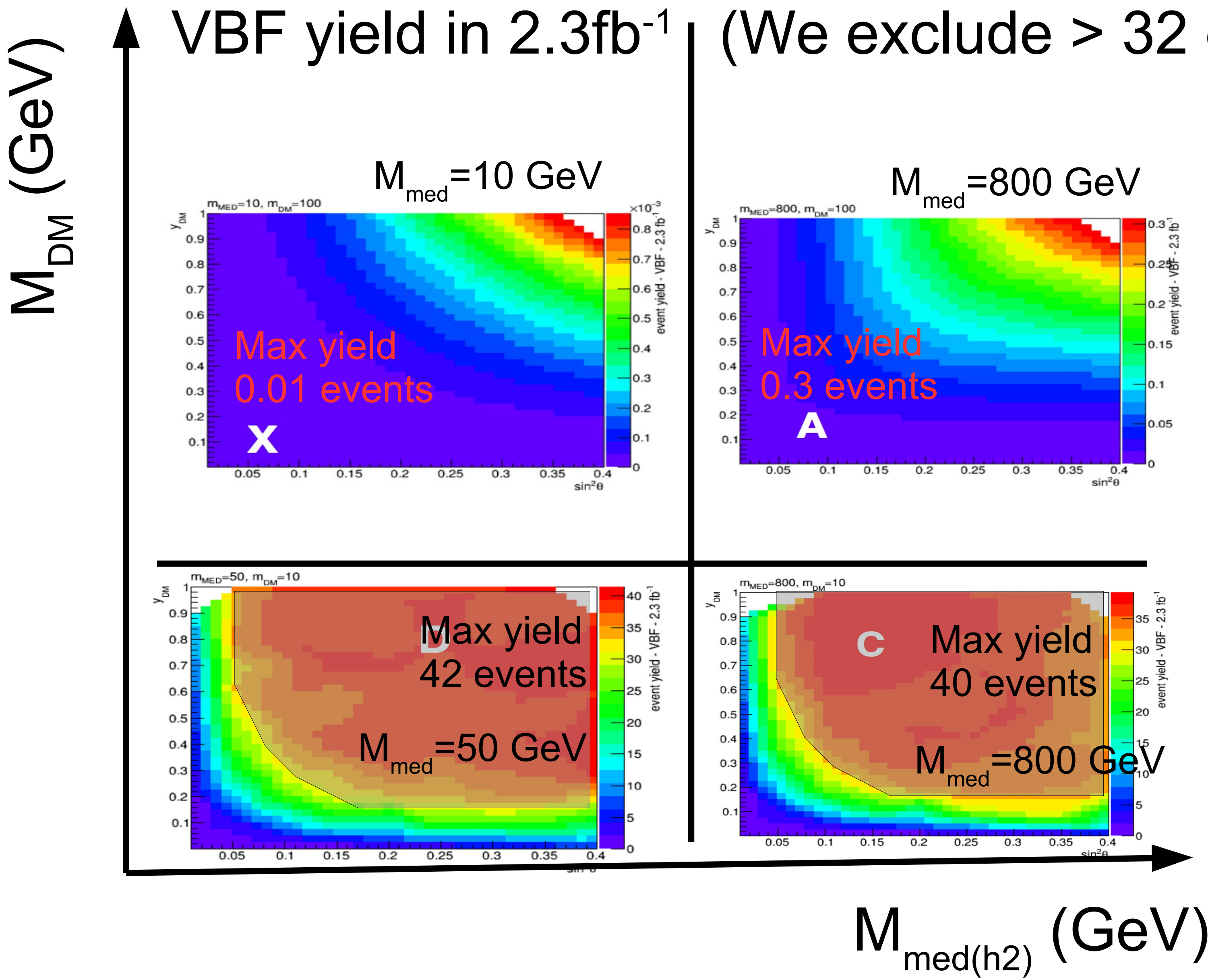
Whats the scope of phase space?



Whats the scope of phase space?



Whats the scope of phase space?



Adding EWSB in an even better way

Looking to embed dark matter in 2HDMs

There has been a lot of work already

Are the current simplified models sufficient?

Dark matter working group actively investigating

Previous slides are a simple example

Composite Models

Z'+jet

*** Discussion title: Review of EXO-16-030

Dear Authors

I noticed that in your PAS the introduction refers to UA1 and UA2 results at sqrt(s)=300 GeV. These results came out when I was on UA2 in fact, and the SppS ran at sqrt(s)=630 GeV.

Best regards Joe[Incandela]

Broke a record almost 30 years old

SEOUL 1988

Rio2016™

Incidentally this did not happen at the olympics

How does this translate to DM?

With the standard cross section formula

$$\sigma = \frac{g^4_{SM}}{\Gamma} \frac{C}{M^4_{med}}$$

Dijet cross section@LO

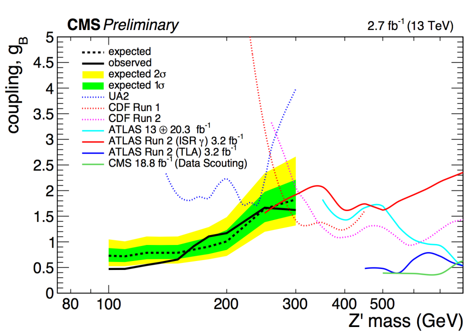
Solve for coupling bound with DM

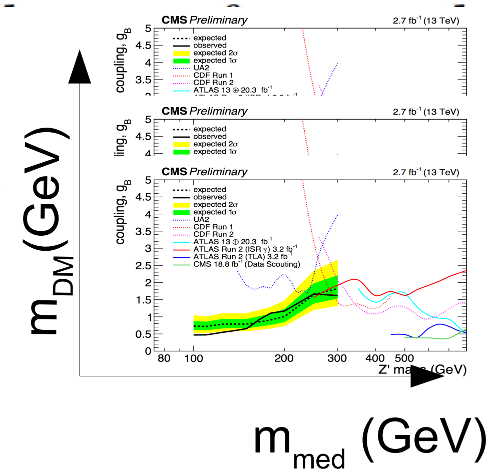
$$\sigma_0(g_B) = \sigma_{DM}(g'_B, g_{DM} = 1, m_{DM});$$

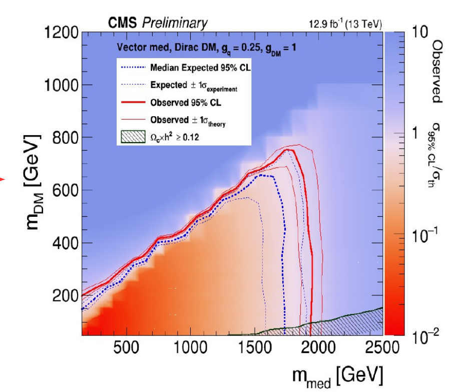
Add DM contribution

$$(g'_B)^2 = \frac{g_B^2}{2}\left(1 + \sqrt{1 + 4\frac{\Gamma_{DM}}{\Gamma(g_B)}}\right)$$

Coupling bound



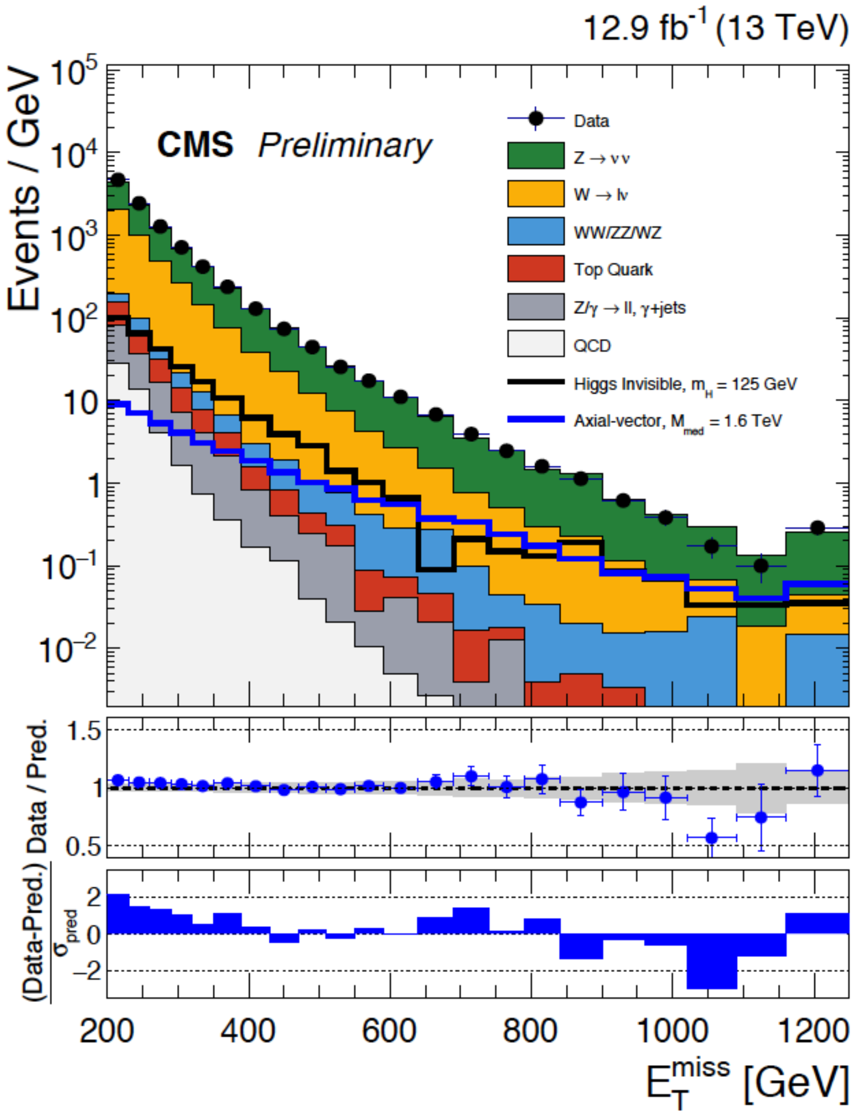




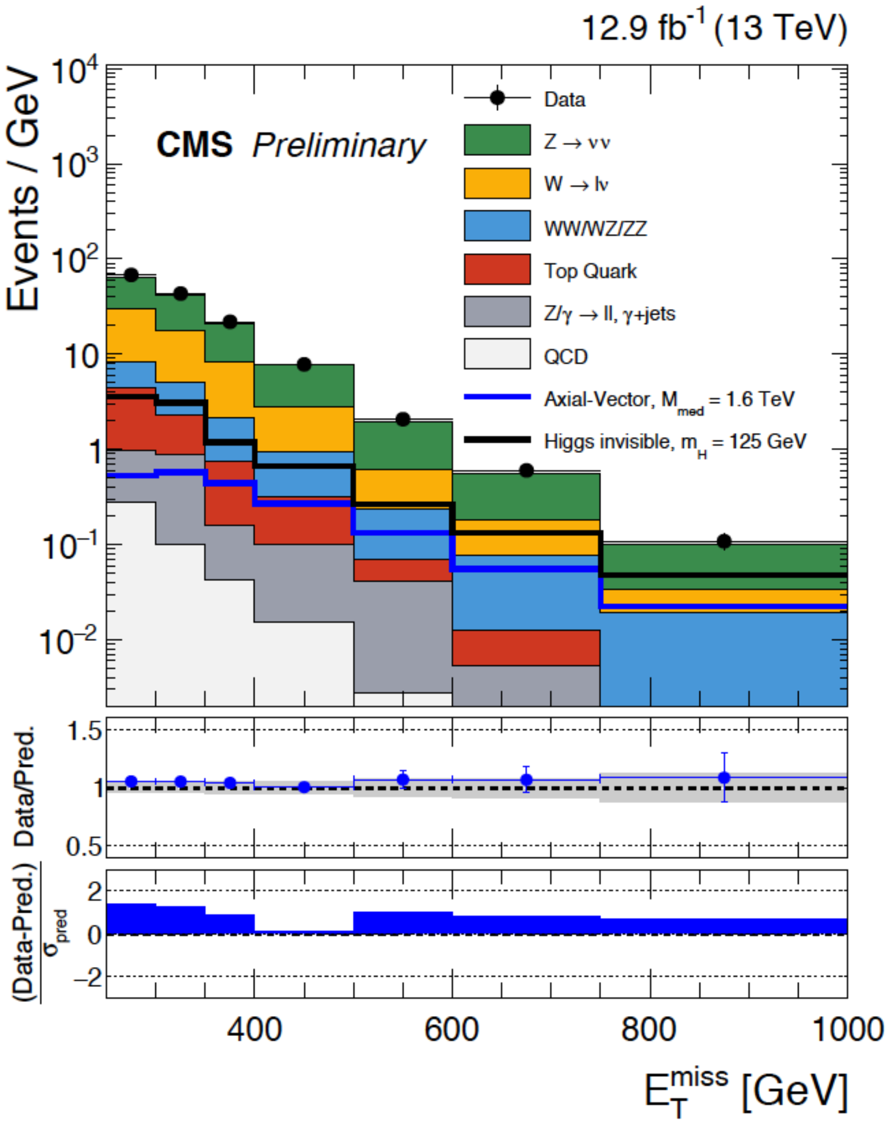
Total Luminosity : 12.9 fb^{-1} (2016)
Final State : J/V→qq+*MET*

Monojet/V

Monojet Category



V-tagged Category



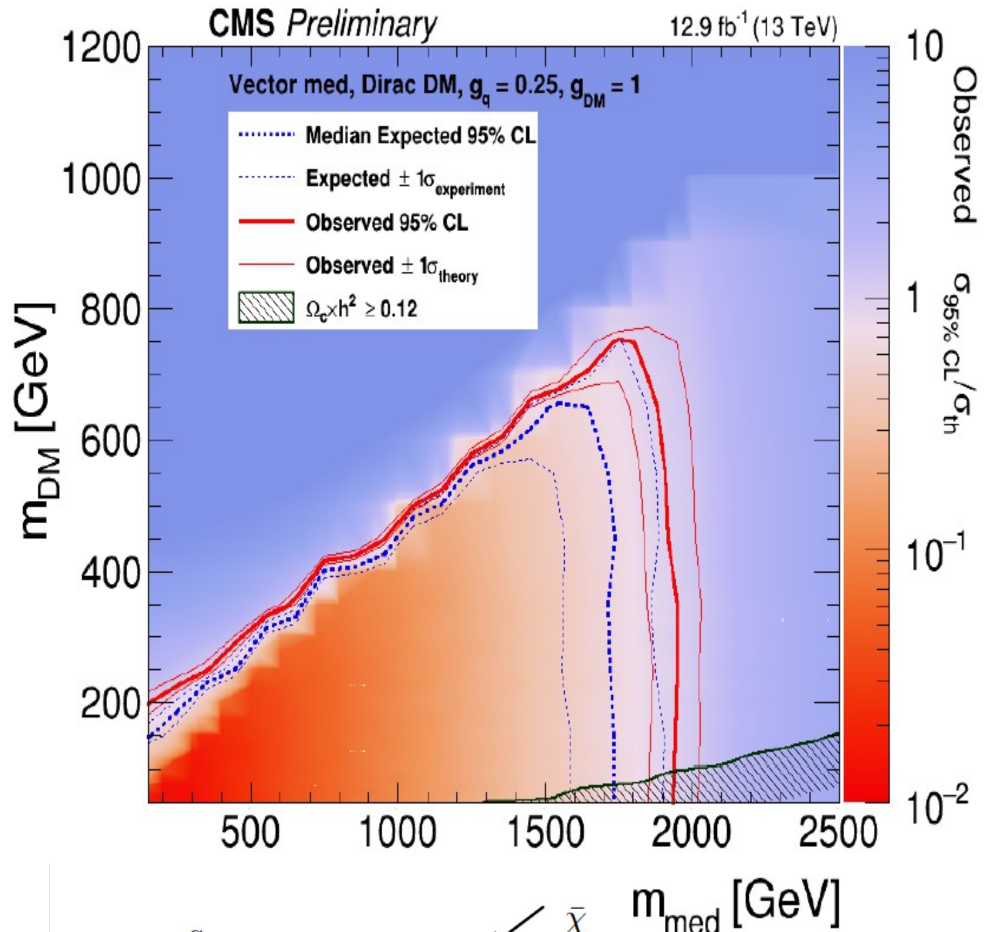
EXO-16-037

Total Luminosity : 12.9 fb^{-1} (2016)

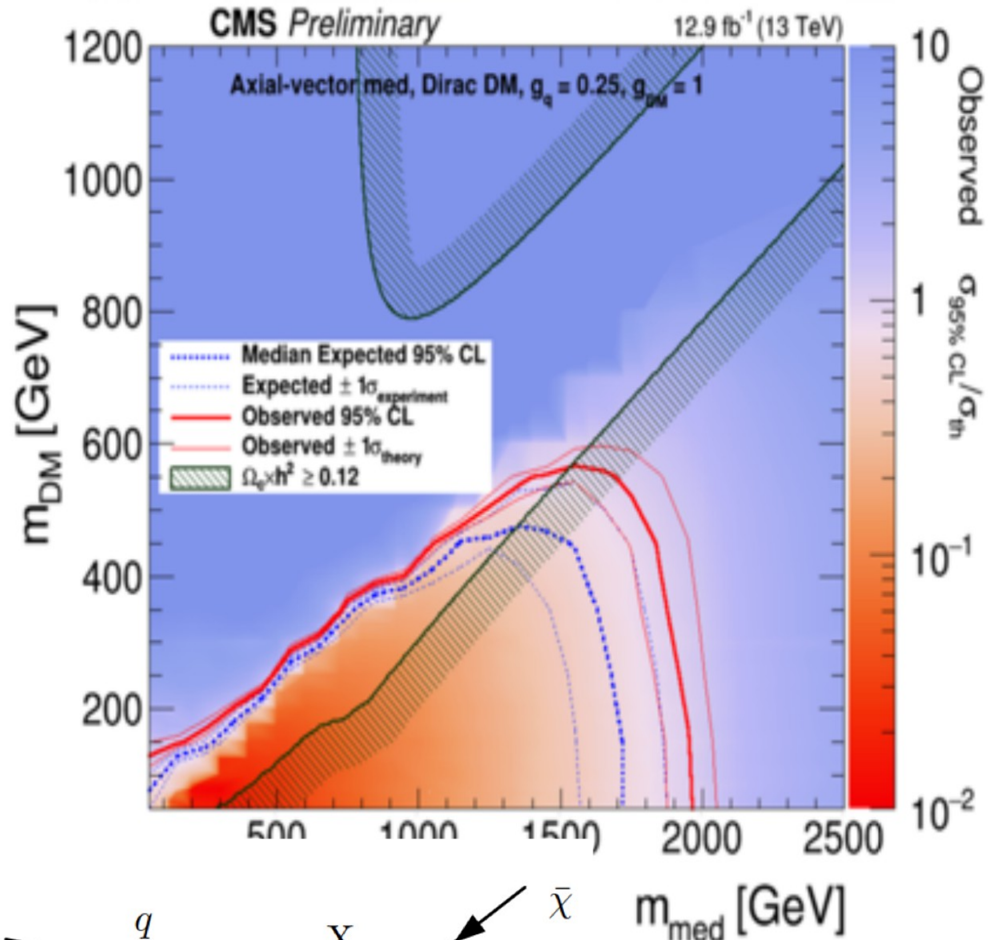
Final State : J/V→qq+*MET*

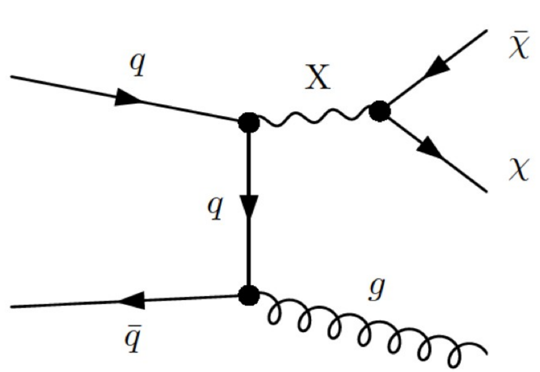
Monojet/V

$u\gamma^{\mu}u$

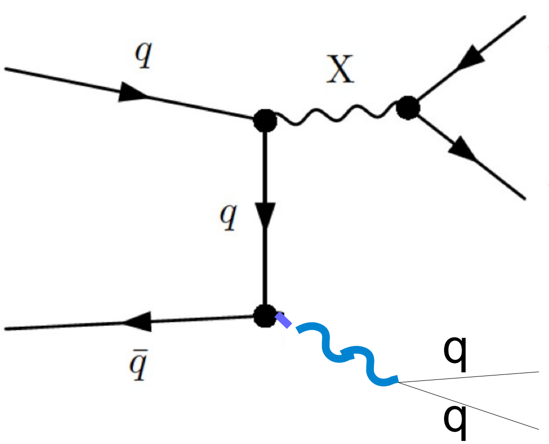


$u\gamma^{5}u$





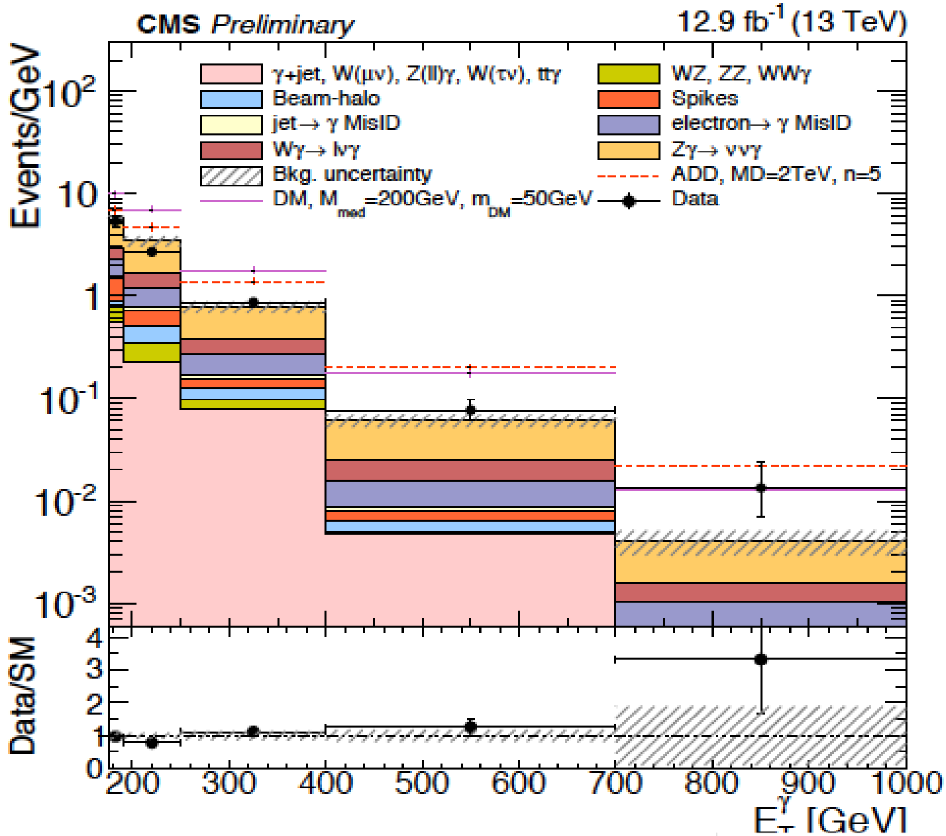
+

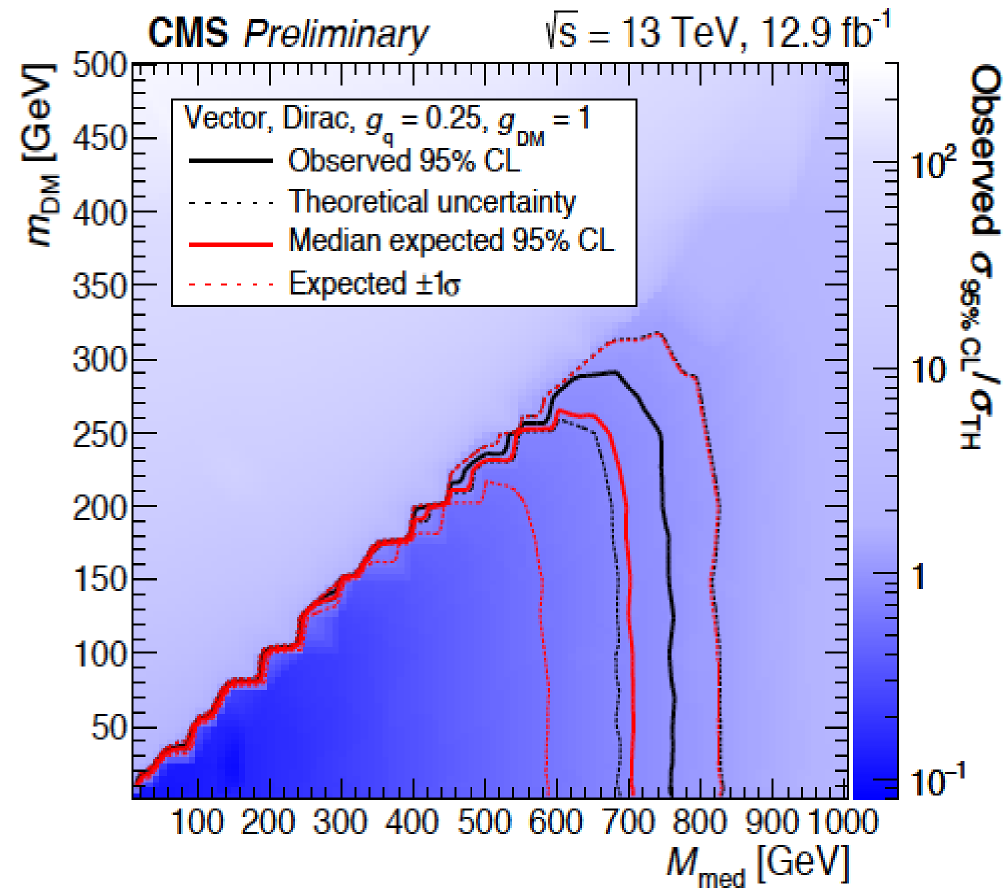


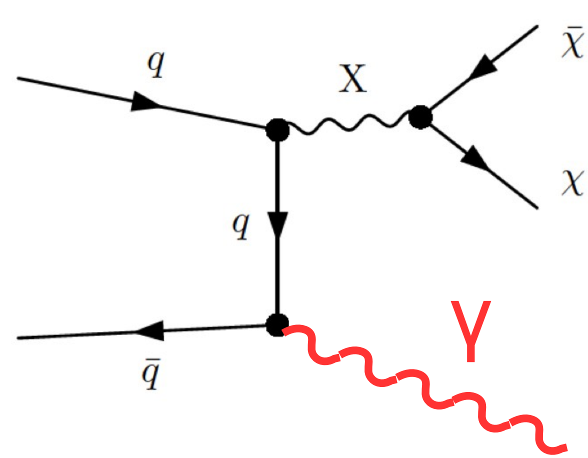
EXO-16-037

Total Luminosity : 12.9 fb^{-1} (2016)
Final State : γ+*MET*

Mono-γ



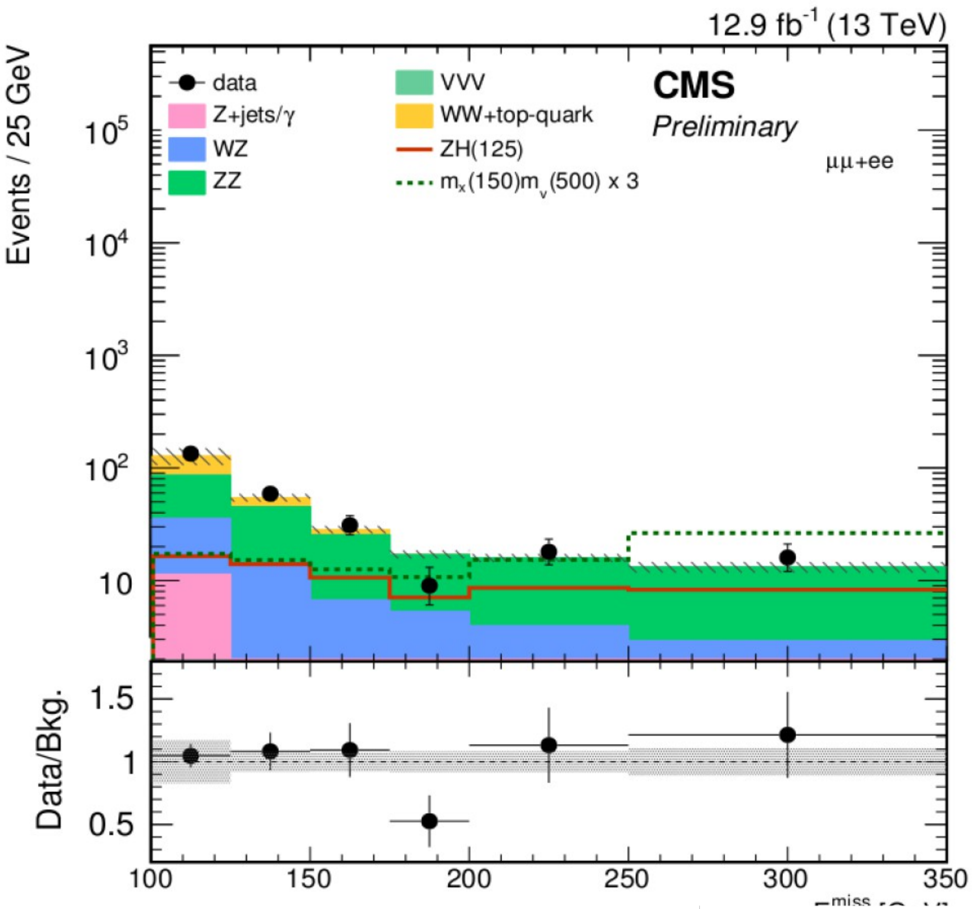


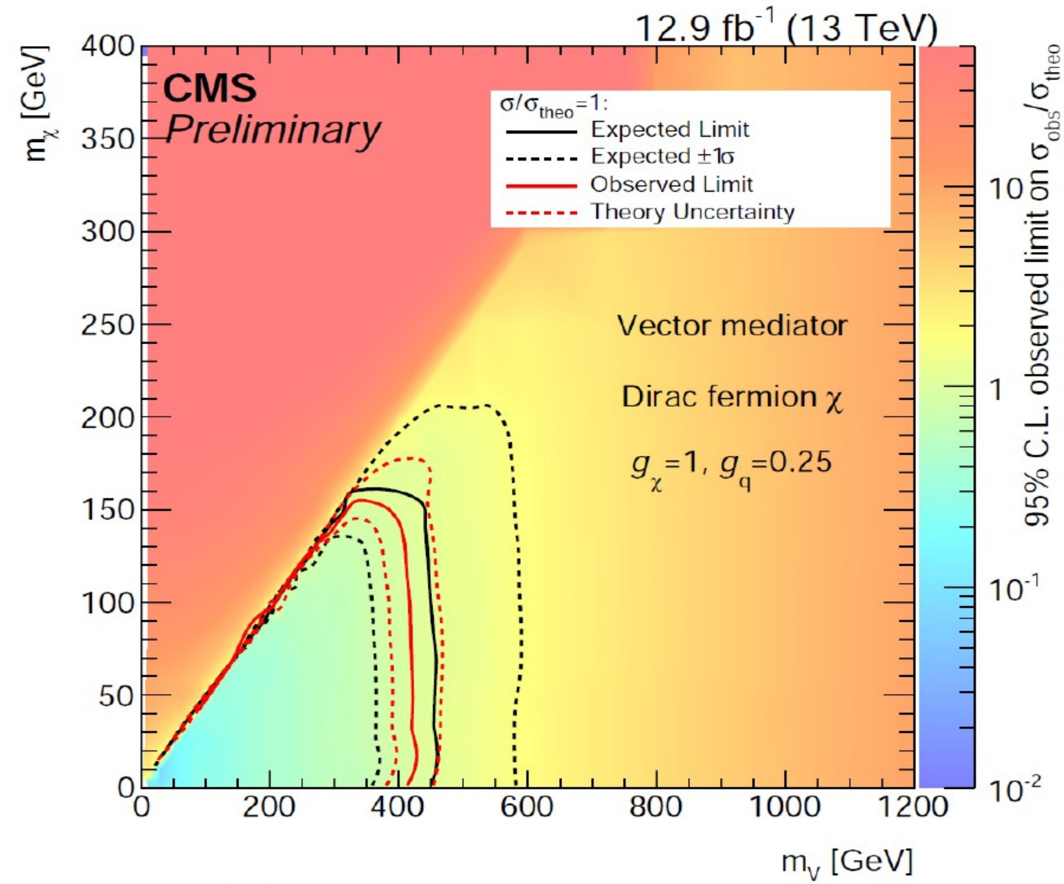


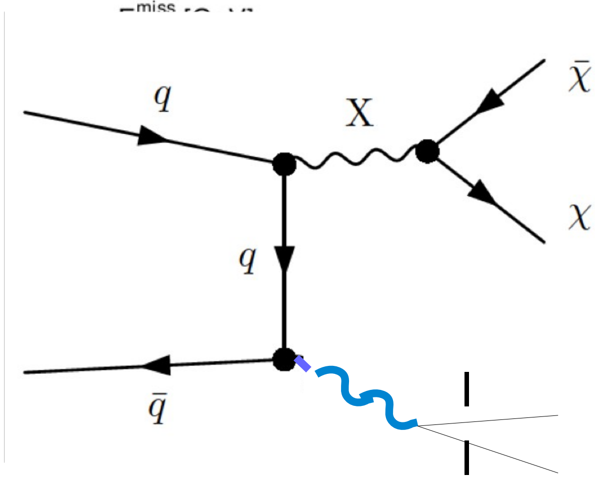
EXO-16-039

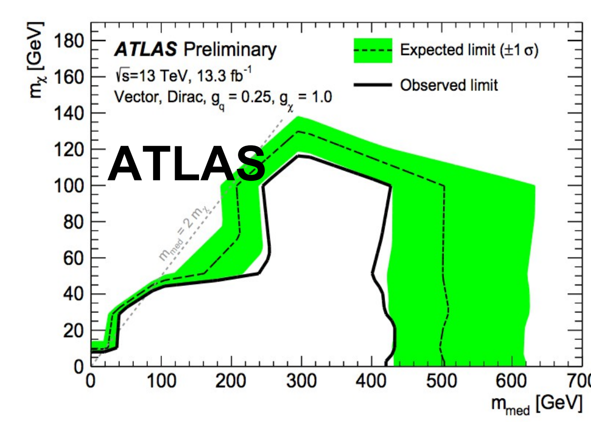
Total Luminosity : 12.9 fb^{-1} (2016)
Final State : $Z \rightarrow ll + MET$

Mono-Z





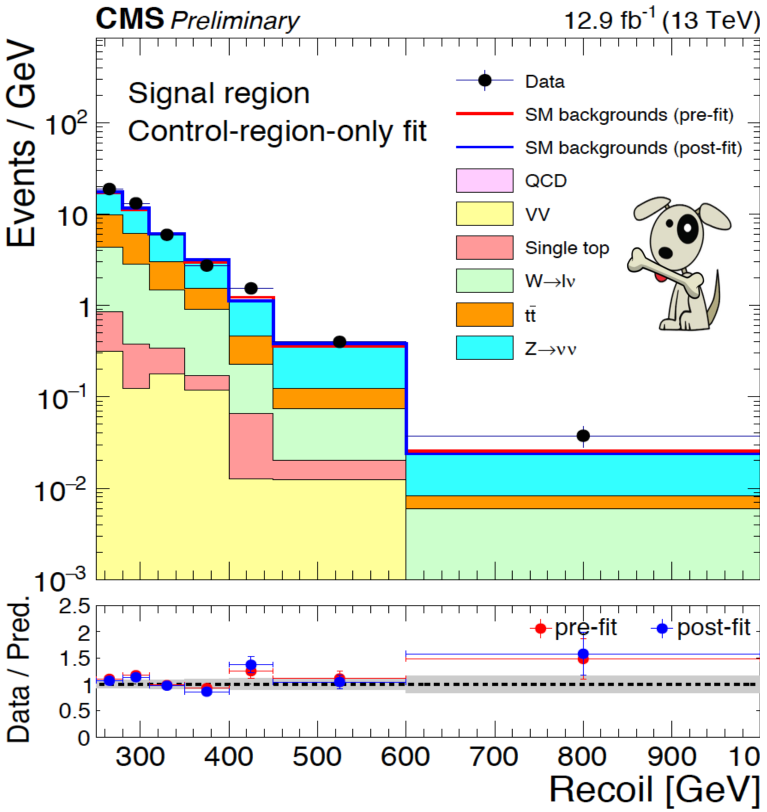


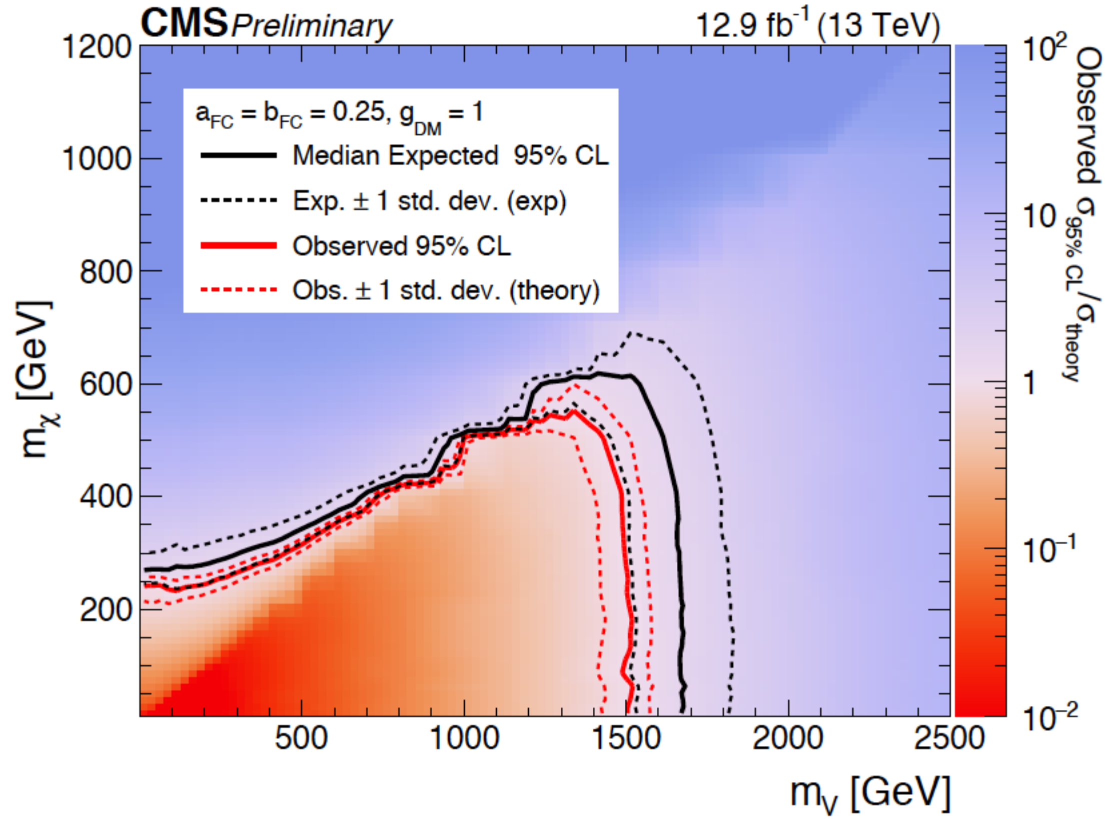


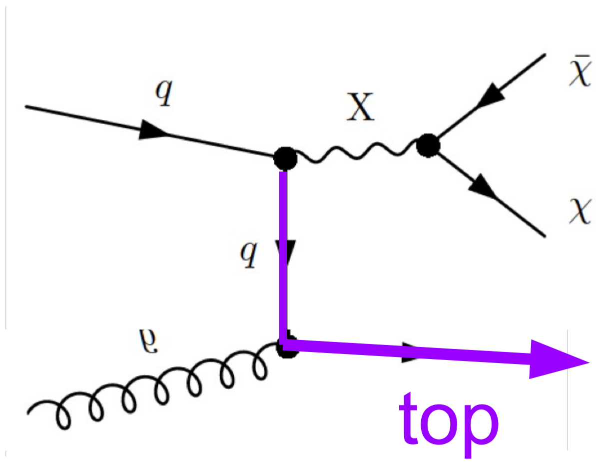
EXO-16-038

Total Luminosity : 12.9 fb^{-1} (2016)
Final State : top+*MET*

Mono-Top



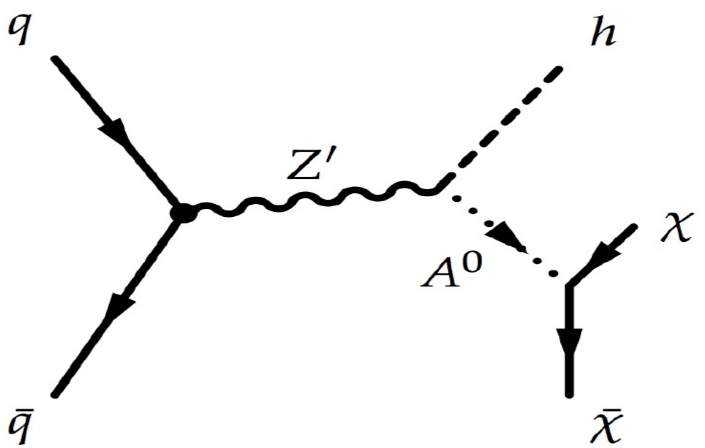




EXO-16-040

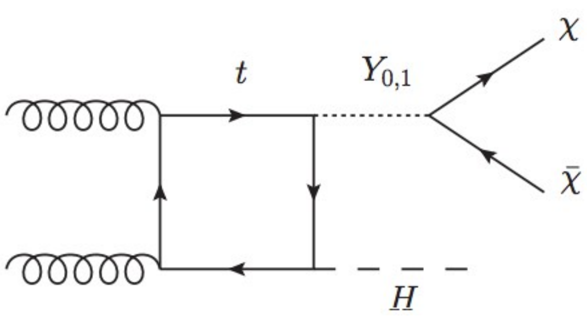
Going beyond one mediator

- Currently only being used for mono-Higgs



Searching for Z' and and Pseudoscalar

- Signature highlights the use of mono-H analysis
  - Mono-H can be added to the simplified models
    - However cross section is small



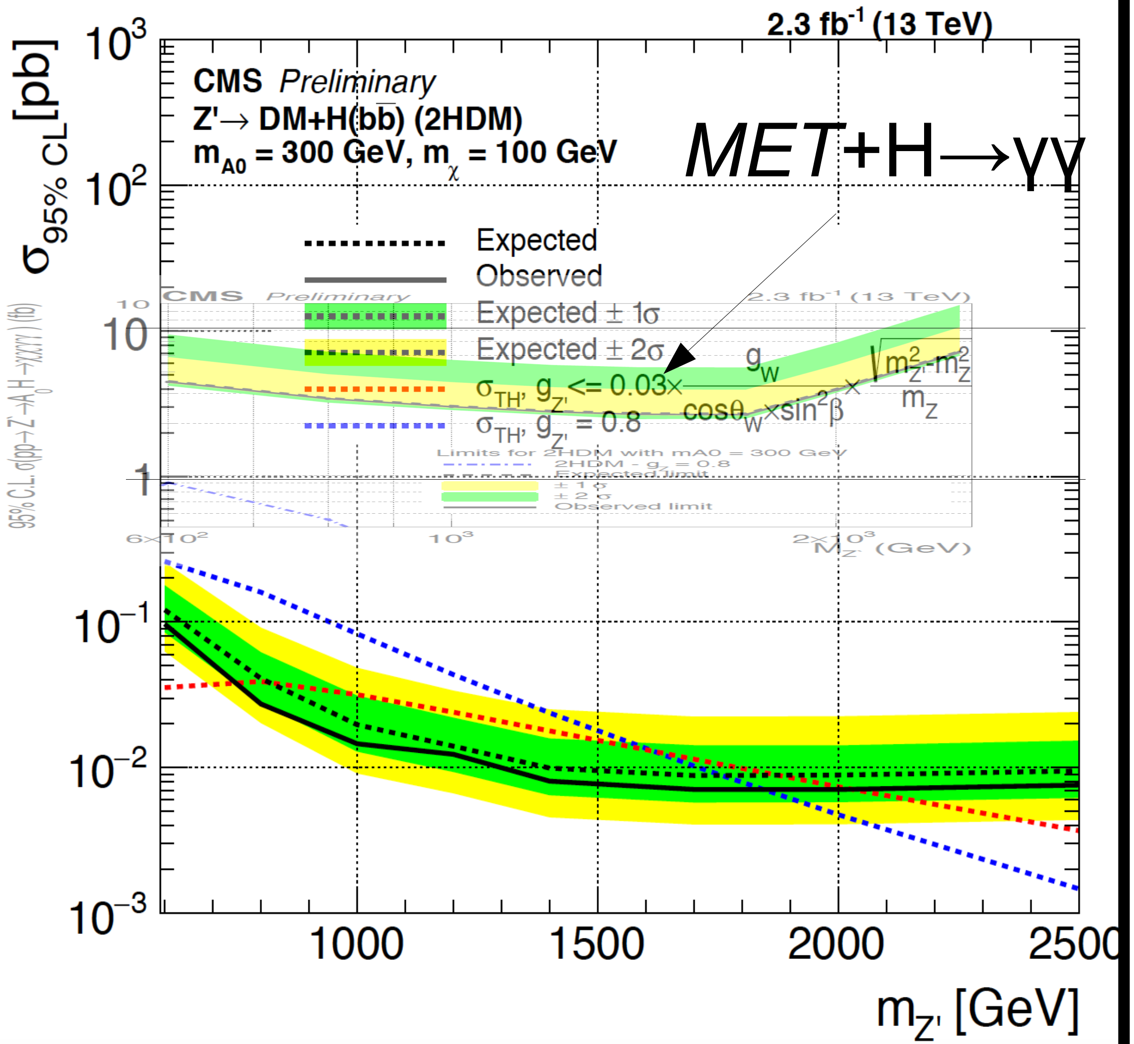
Total Luminosity : 2.3 fb^{-1} (2015)

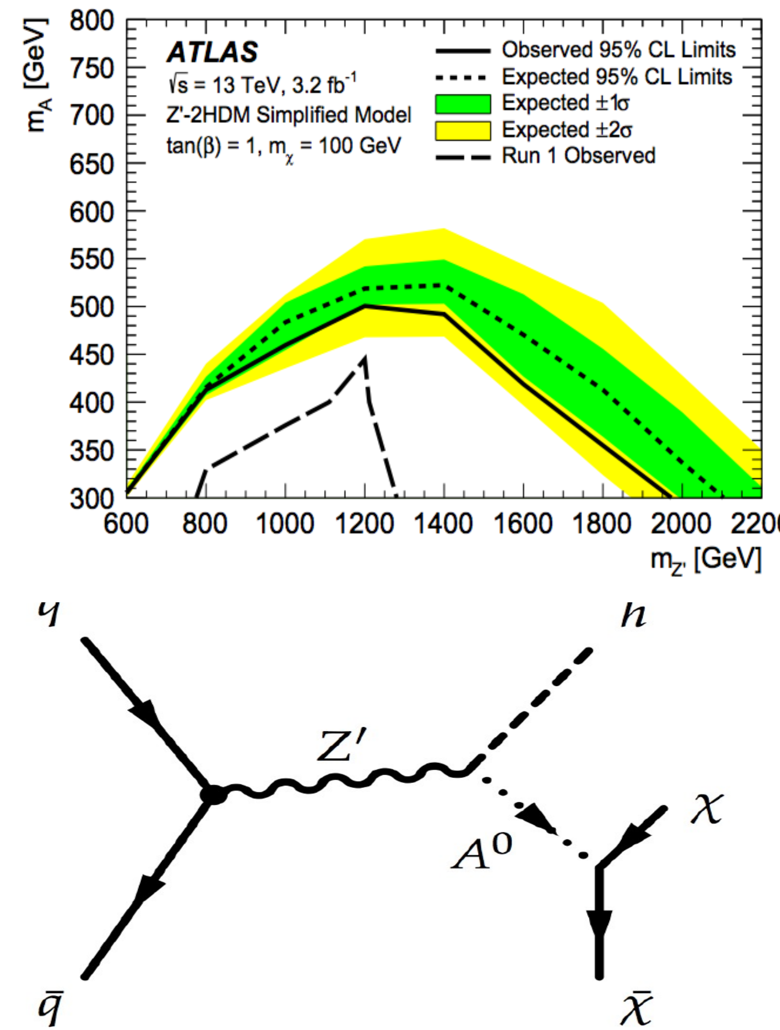
Final State : Higgs(bb/γγ)+*MET*

Mono-Higgs

MET+H→bb

ATLAS results a little better

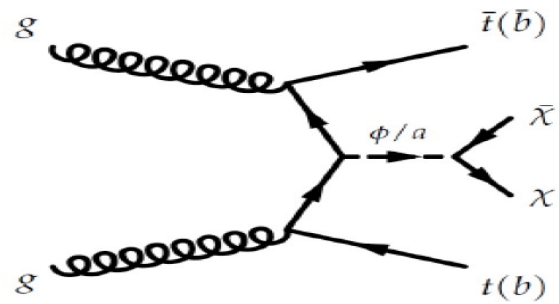


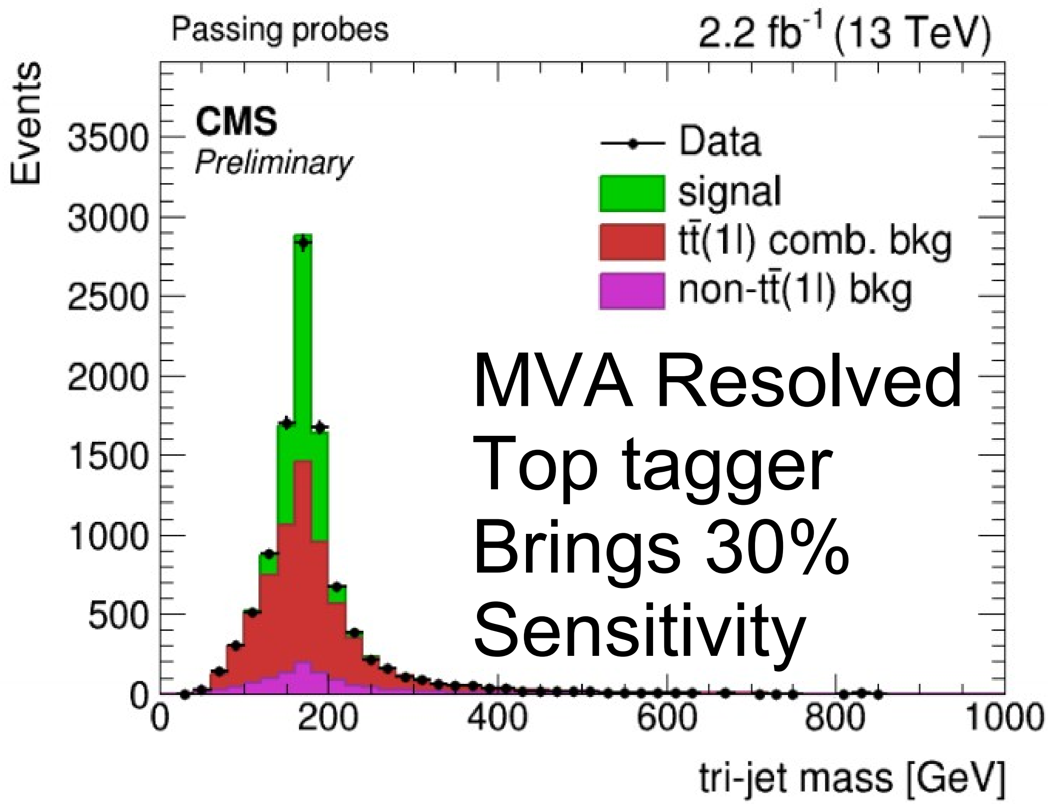


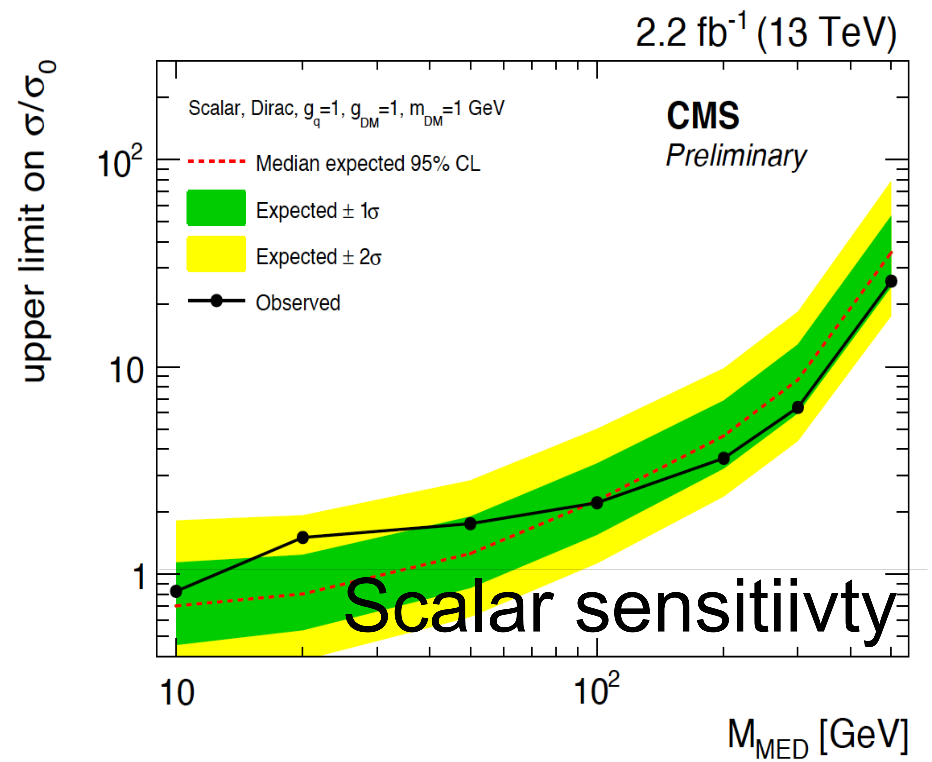
EXO-16-011/EXO-16-012

Total Luminosity : 2.3 fb^{-1} (2015)
Final State : tt+*MET*

tt+DM





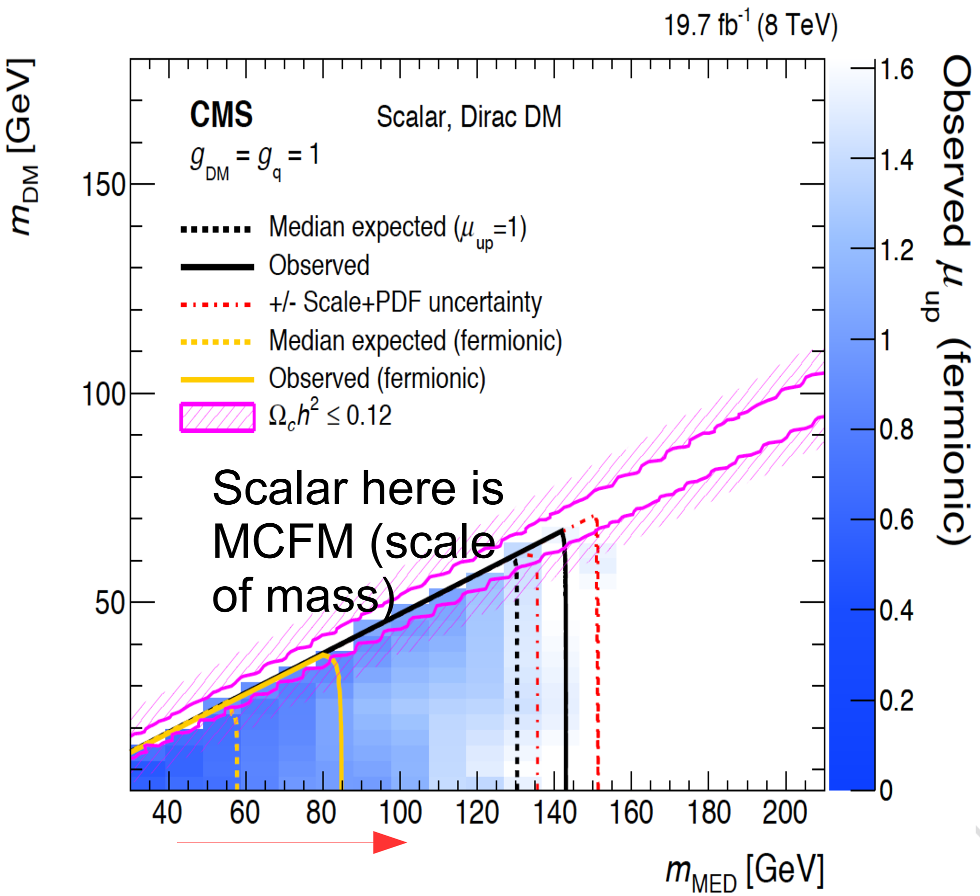


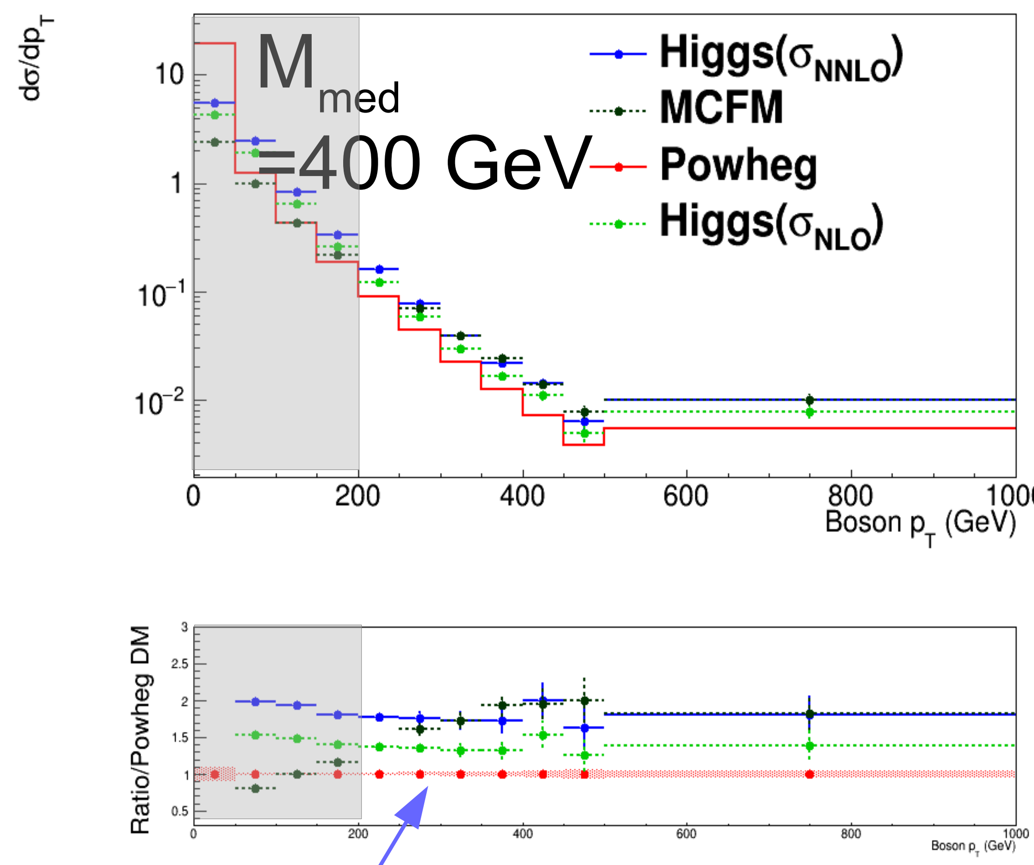
Sensitivity pushed to exclude Scalar mediator models

EXO-16-005

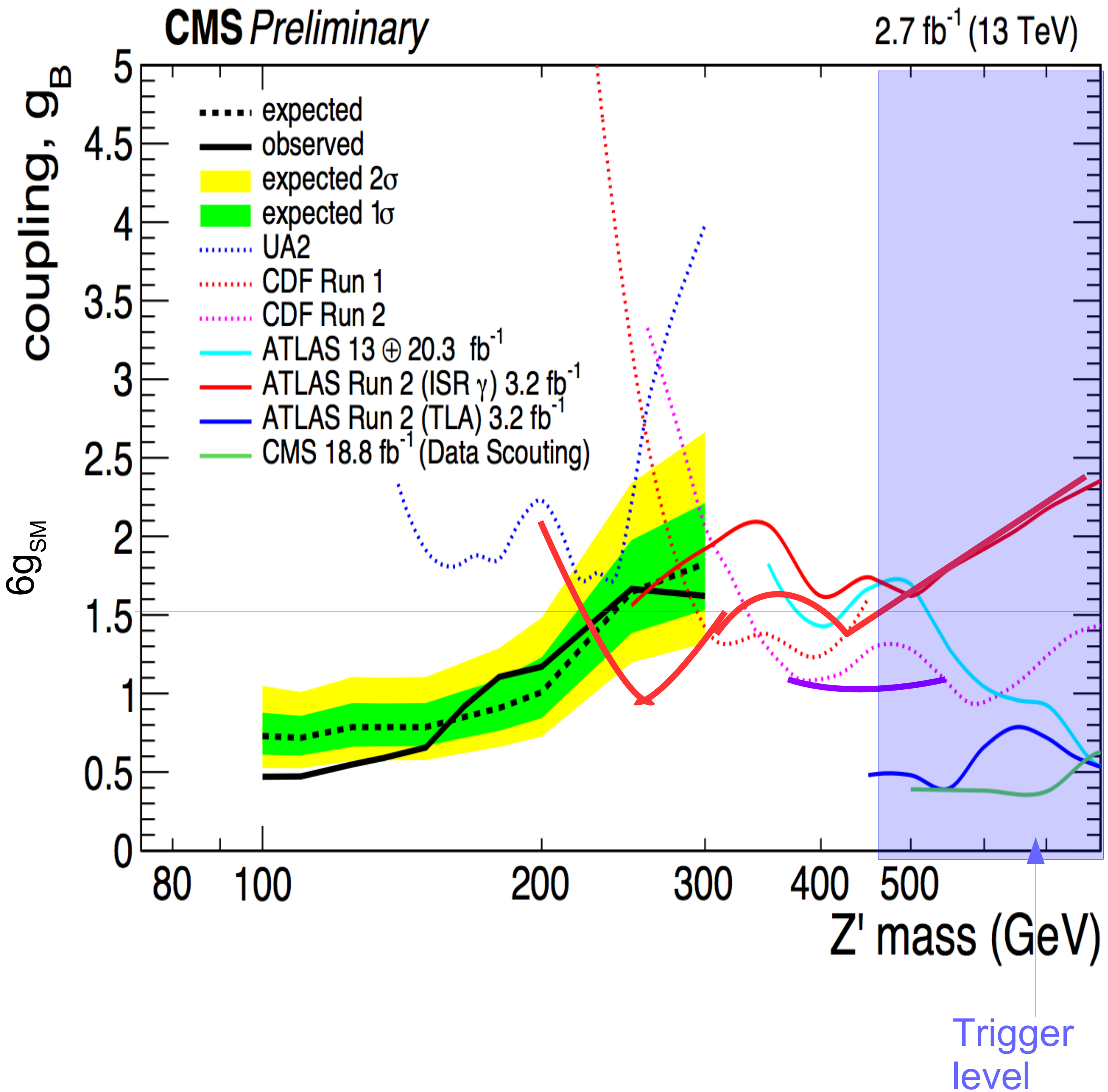
Scalar : Comparing with Old results

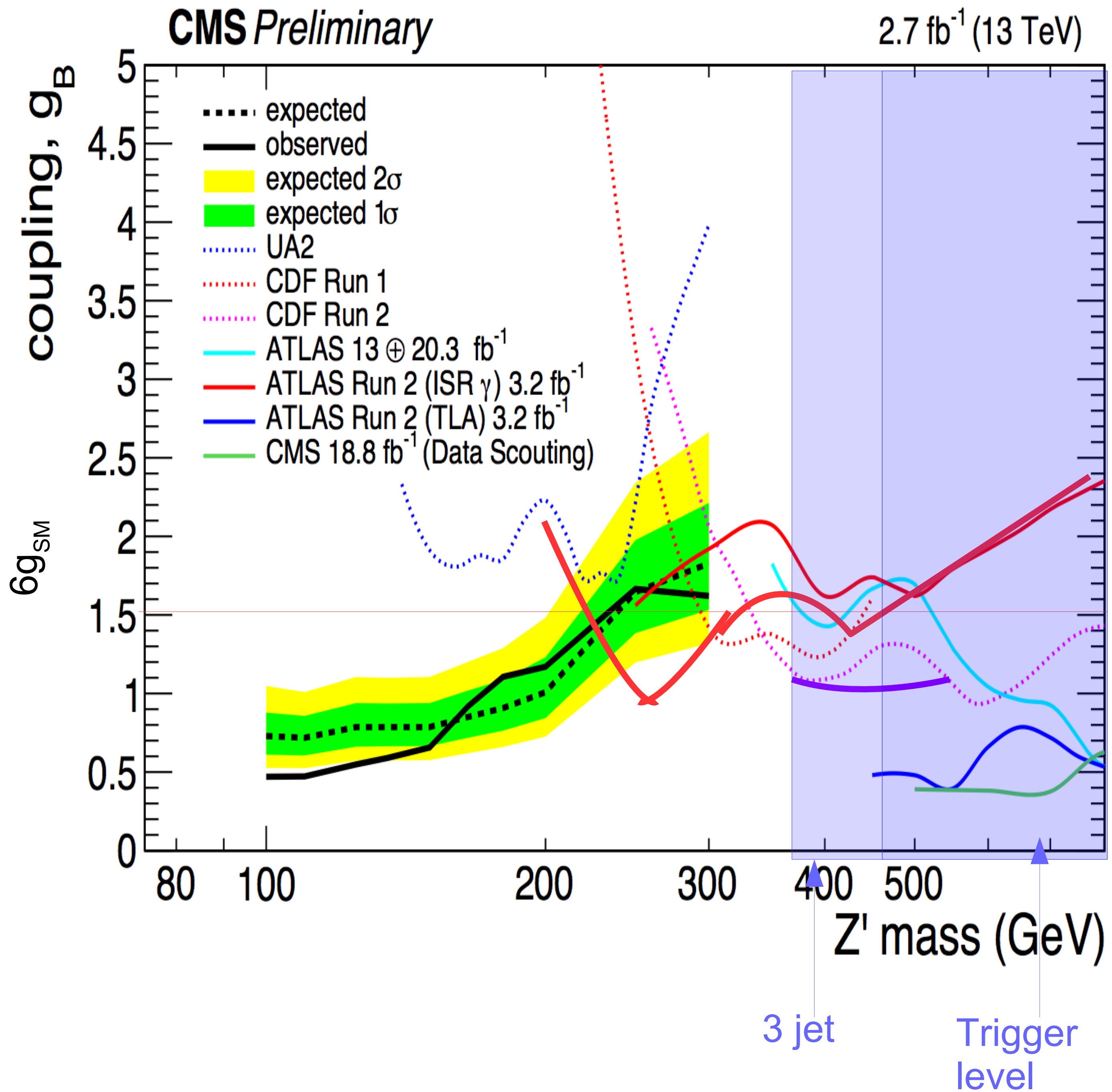
- Exclusion up to 80 GeV but not 13 TeV
  - Two reasons : 13 TeV is systematics limited (for now)



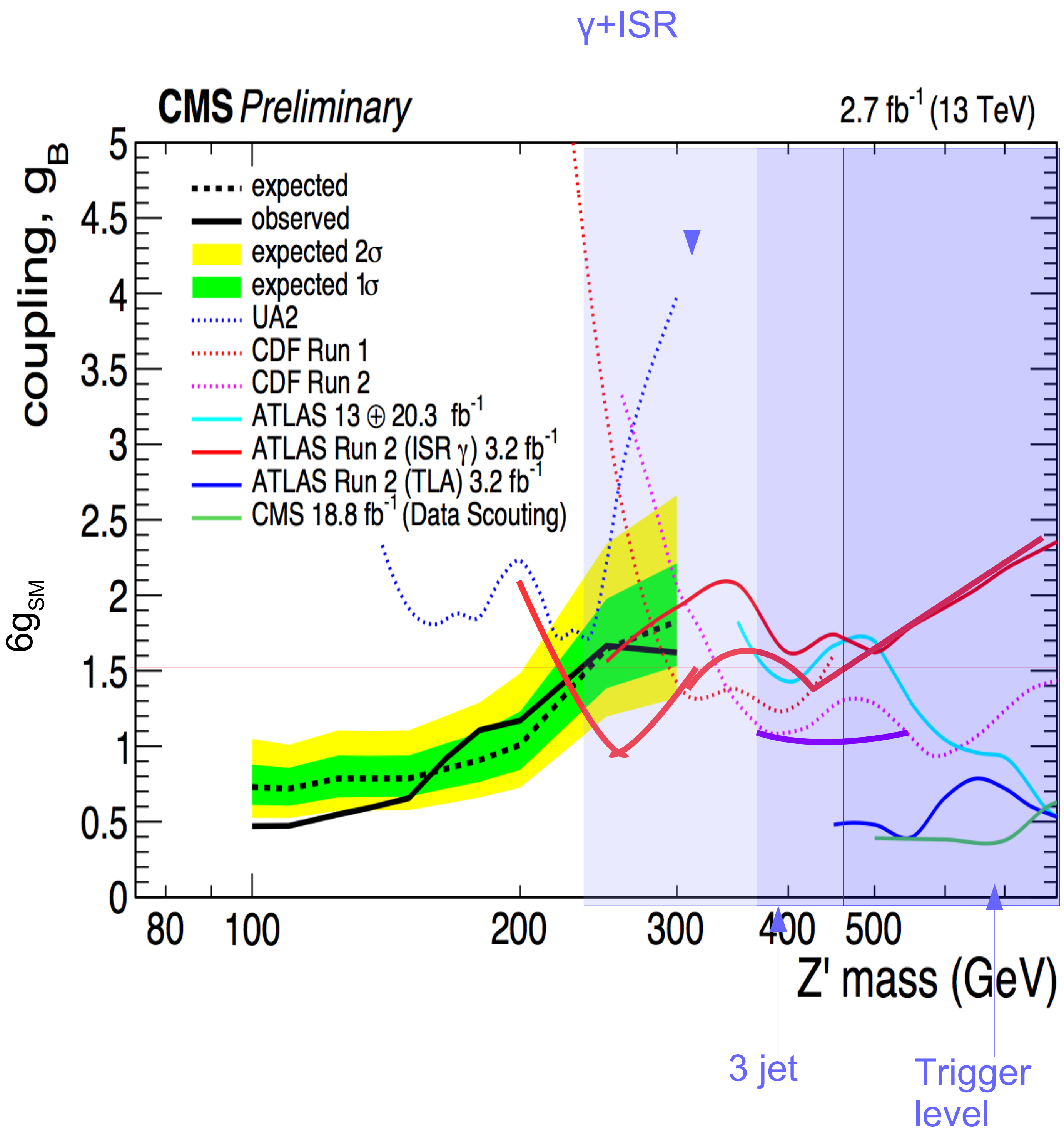


8 TeV is using MCFM (larger scale matches Higgs)


CMS Preliminary
2.7 fb-1 (13 TeV)
coupling, gB
6gSM
expected
observed
expected 2σ
expected 1σ
UA2
CDF Run 1
CDF Run 2
ATLAS 13 ⊕ 20.3 fb-1
ATLAS Run 2 (ISR γ) 3.2 fb-1
ATLAS Run 2 (TLA) 3.2 fb-1
CMS 18.8 fb-1 (Data Scouting)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
80
100
200
300
400
500
Z' mass (GeV)
Trigger
level



CMS Preliminary
2.7 fb-1 (13 TeV)
coupling, gB
6gSM
expected
observed
expected 2σ
expected 1σ
UA2
CDF Run 1
CDF Run 2
ATLAS 13 ⊕ 20.3 fb-1
ATLAS Run 2 (ISR γ) 3.2 fb-1
ATLAS Run 2 (TLA) 3.2 fb-1
CMS 18.8 fb-1 (Data Scouting)
Z' mass (GeV)
3 jet
Trigger level


γ+ISR
CMS Preliminary
2.7 fb-1 (13 TeV)
coupling, gB
6gSM
expected
observed
expected 2σ
expected 1σ
UA2
CDF Run 1
CDF Run 2
ATLAS 13 ⊕ 20.3 fb-1
ATLAS Run 2 (ISR γ) 3.2 fb-1
ATLAS Run 2 (TLA) 3.2 fb-1
CMS 18.8 fb-1 (Data Scouting)
0
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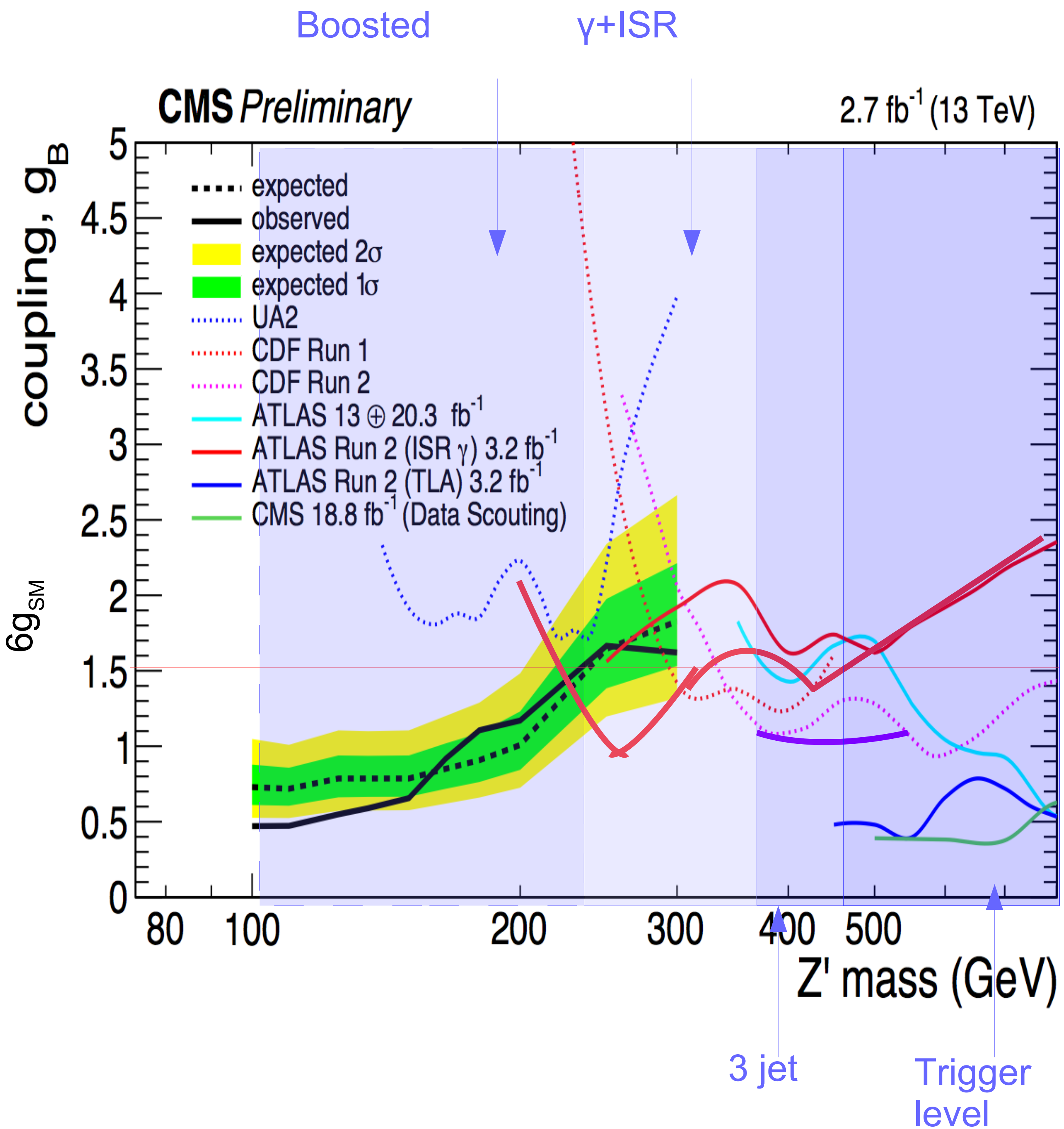
80
100
200
300
400
500
Z' mass (GeV)
3 jet
Trigger level



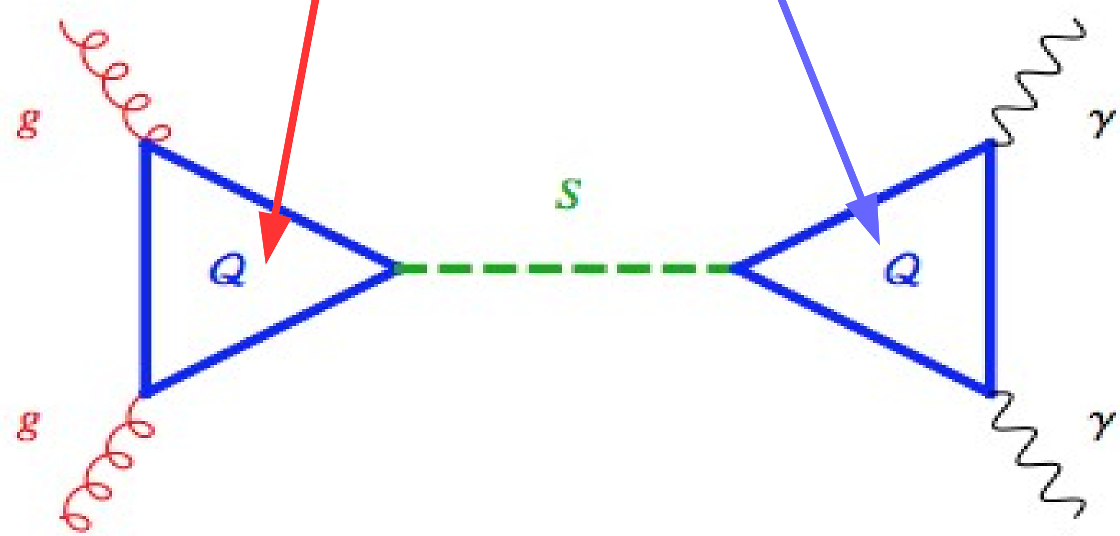
Boosted
γ+ISR
CMS Preliminary
2.7 fb^{-1} (13 TeV)
coupling, g_B
$6g_{SM}$
expected
observed
expected 2σ
expected 1σ
UA2
CDF Run 1
CDF Run 2
ATLAS 13 ⊕ 20.3 fb^{-1}
ATLAS Run 2 (ISR γ) 3.2 fb^{-1}
ATLAS Run 2 (TLA) 3.2 fb^{-1}
CMS 18.8 fb^{-1} (Data Scouting)
Z' mass (GeV)
3 jet
Trigger level

The simplest DM model

- Lets try to make something super basic
  - Basic model

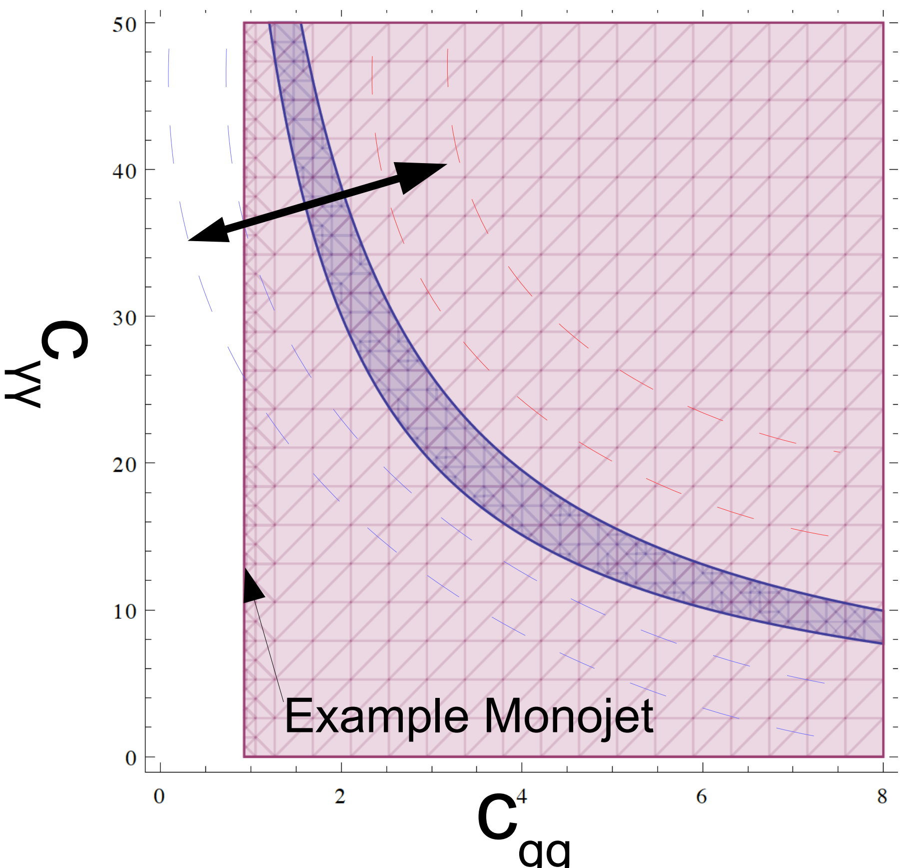
$$\mathcal{L}_S = g_\chi S \bar{\chi}\chi + \frac{\alpha_s}{4\pi}\frac{c_g}{\Lambda} S G^a_{\mu\nu} G^{a\,\mu\nu} + \frac{\alpha}{4\pi}\frac{c_\gamma}{\Lambda} S F_{\mu\nu} F^{\mu\nu}$$

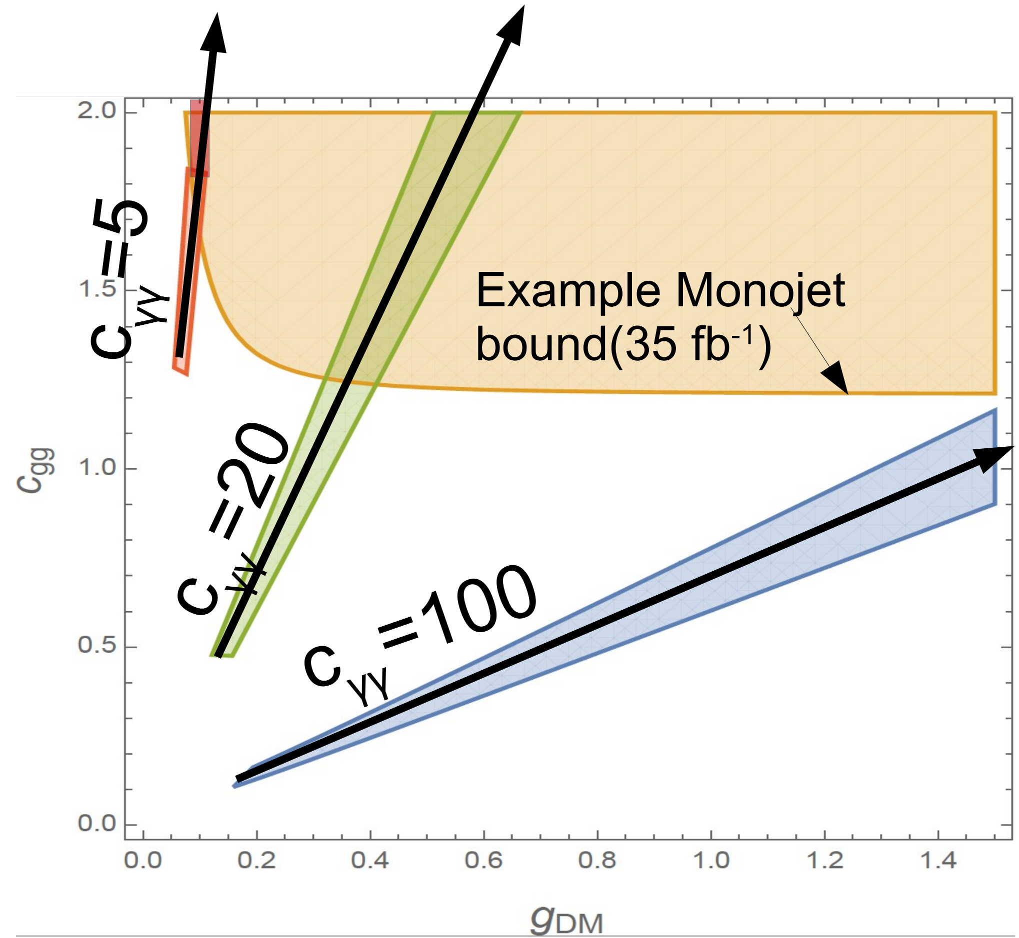
??



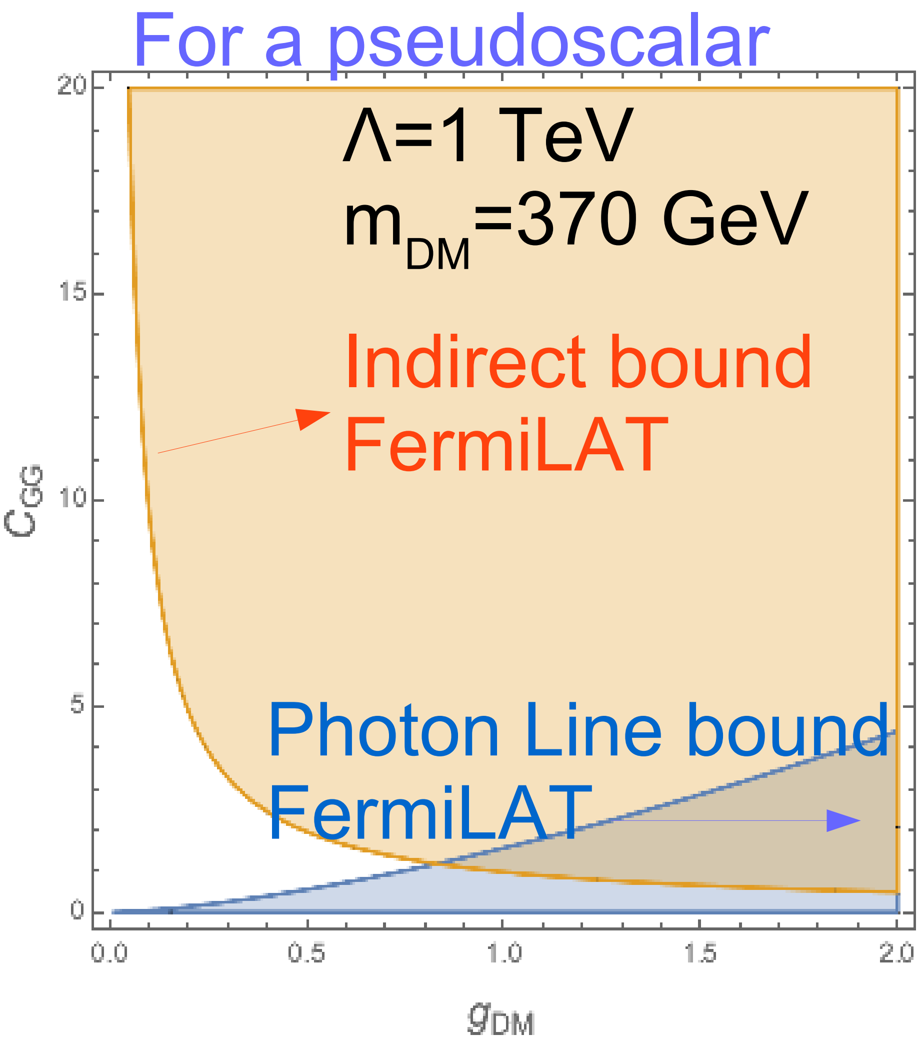
Using the best fit cross section

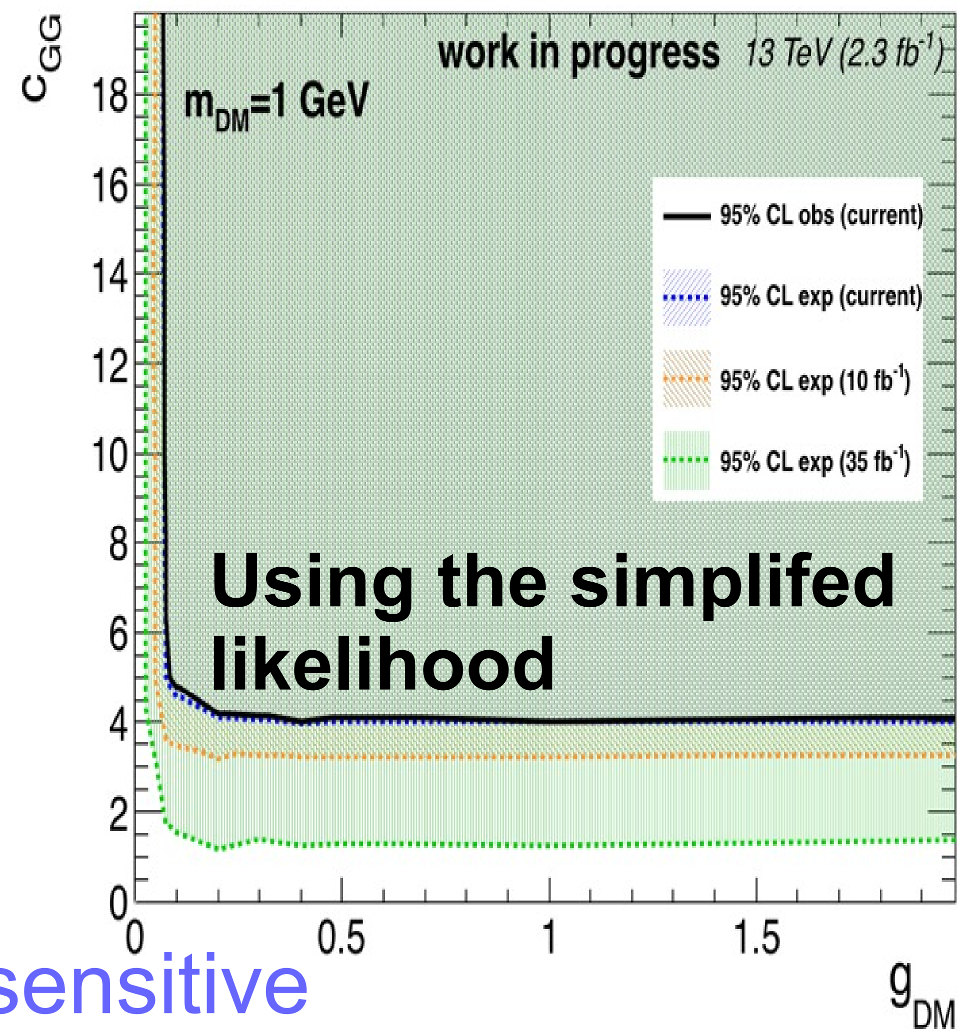
- We have 3 free couplings :
  - $g_{DM}, c_{GG}, c_{\gamma\gamma}$
- Taking the photon best fit can constrain one





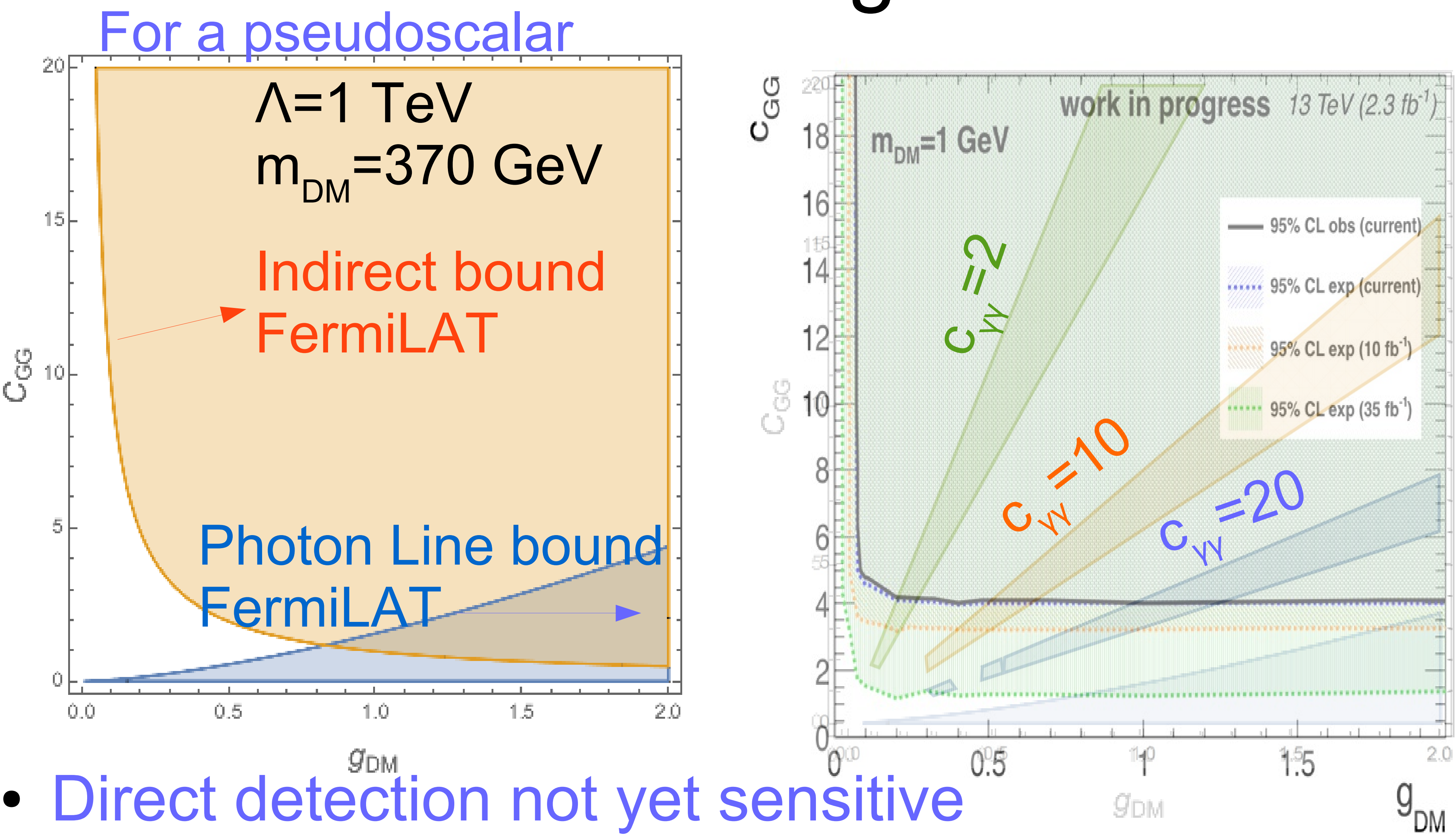
Considering All Constraints





- Direct detection not yet sensitive
- Indirect detection limits on-shell production
- Photon Line bounds limit photon coupling < 100

Considering All Constraints



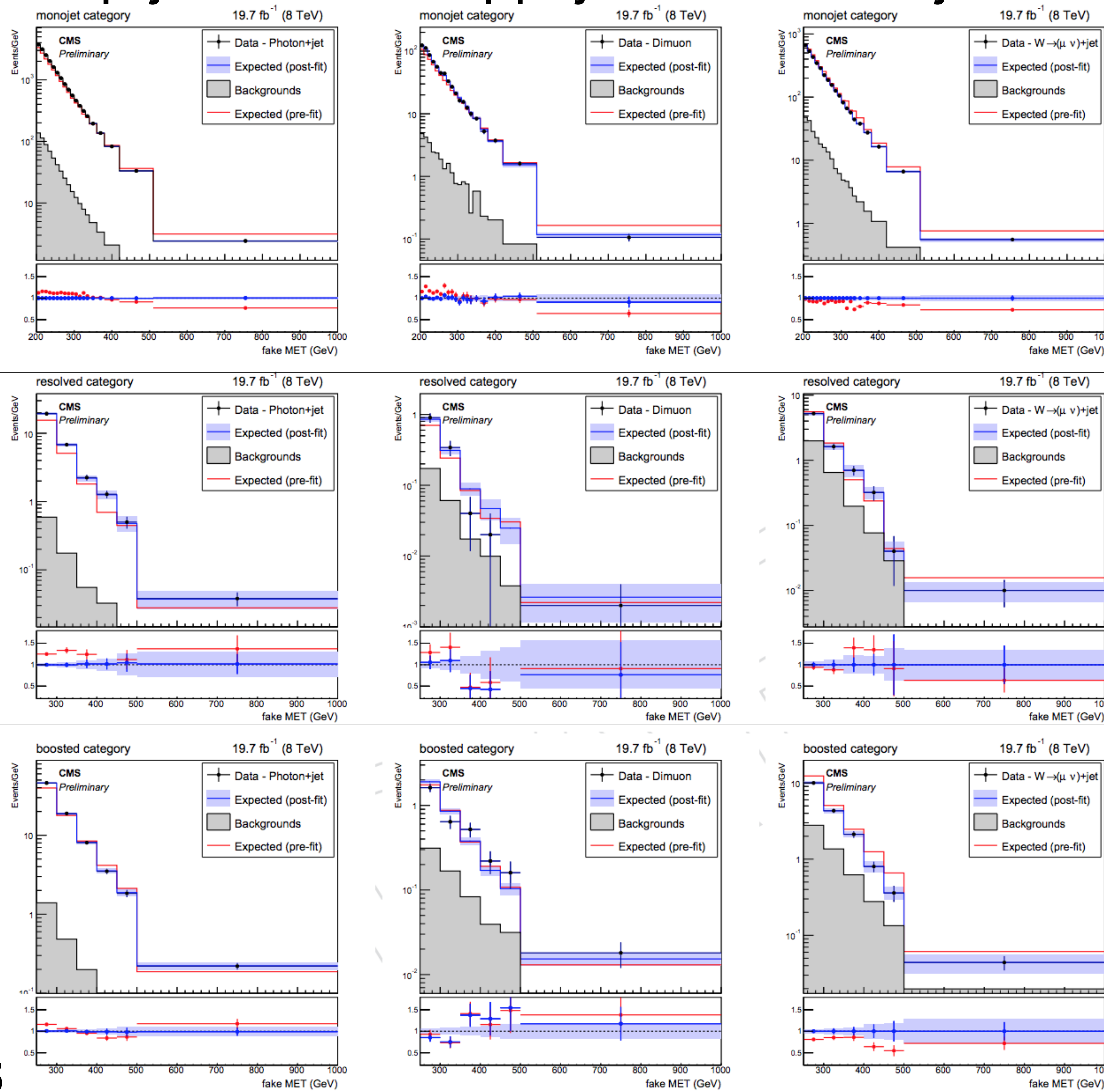
- Direct detection not yet sensitive
- Indirect detection limits on-shell production
- Photon Line bounds limit photon coupling < 100

γ+jets | Zμμ+jets | Wlν+jets

Monojet category

Di-jet category

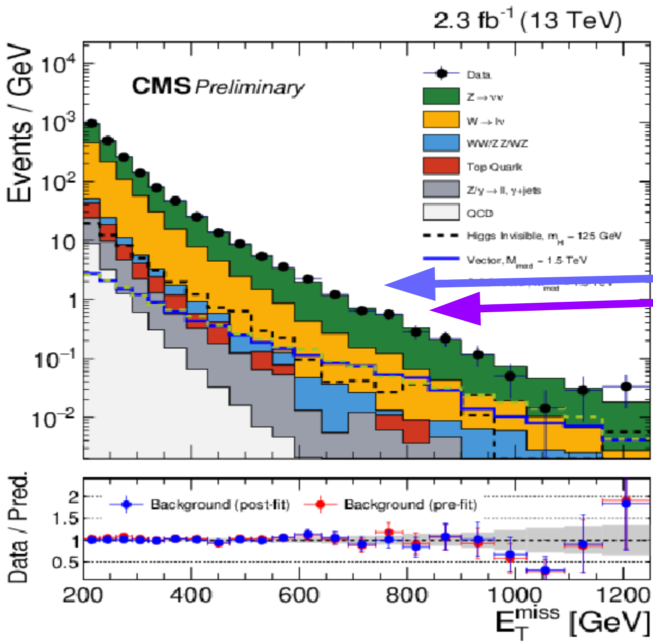
Single jet category

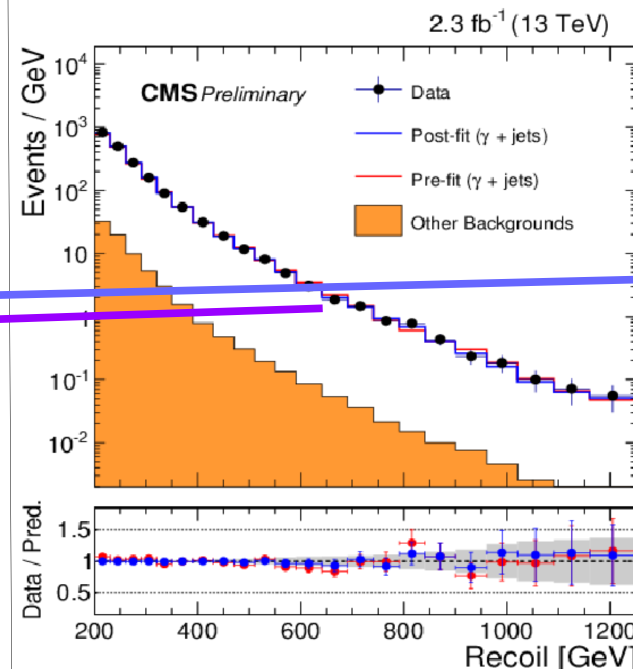


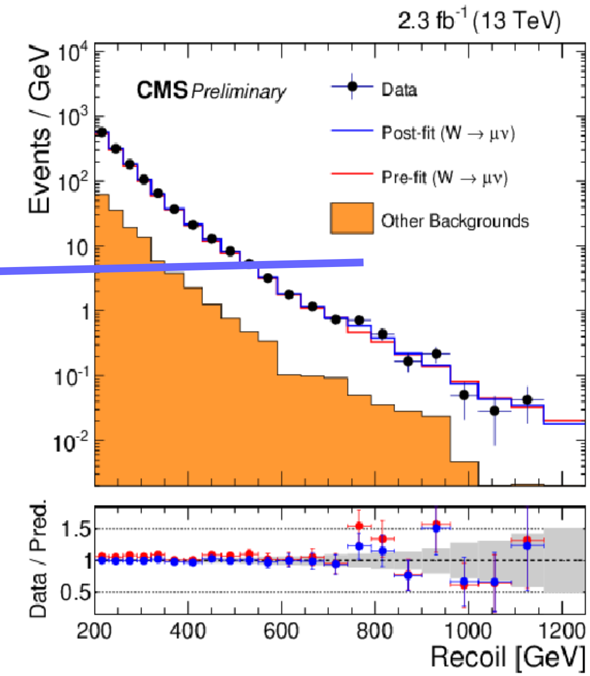
CMS-EXO-12-055

Signal | CRs: γ+jets | + W + ...

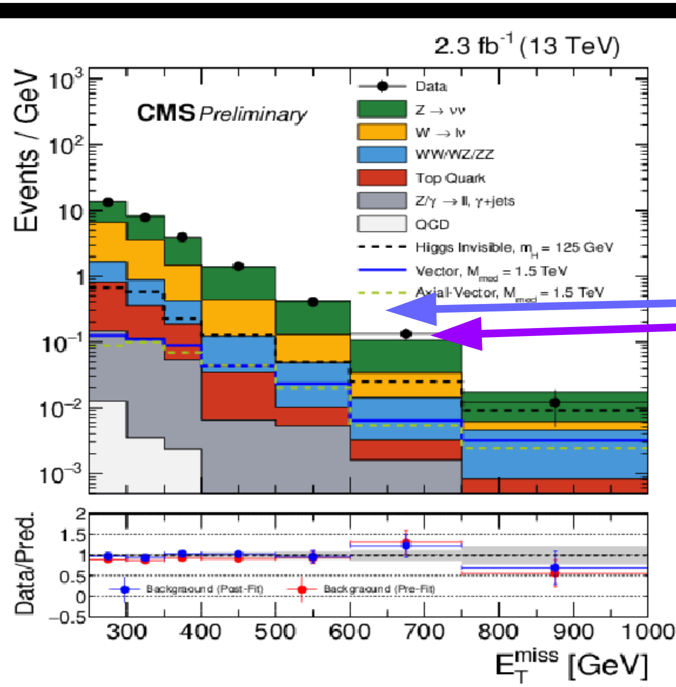
Monojet

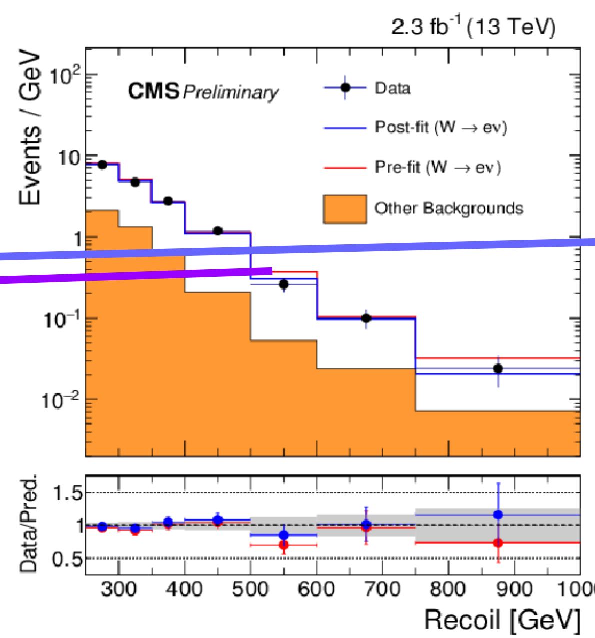


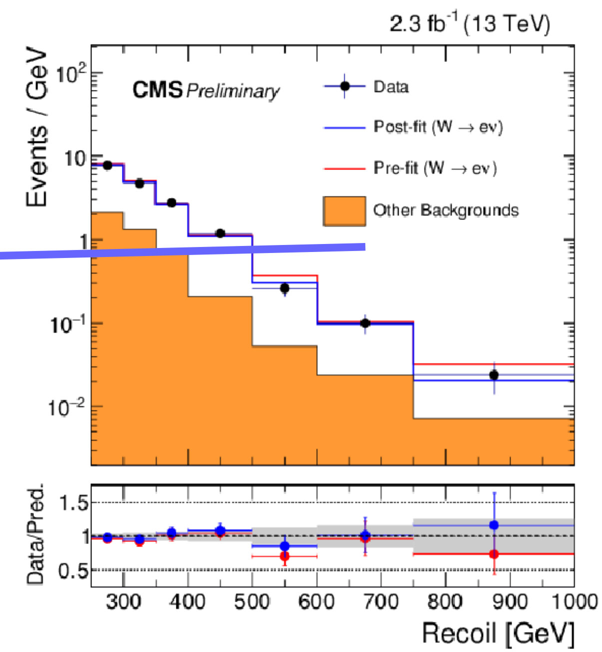




Mono-V

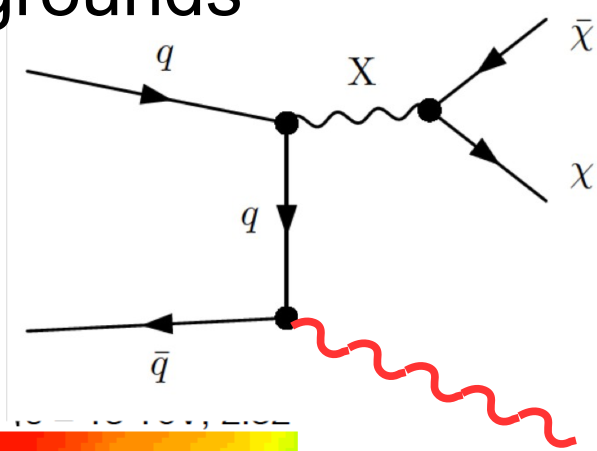


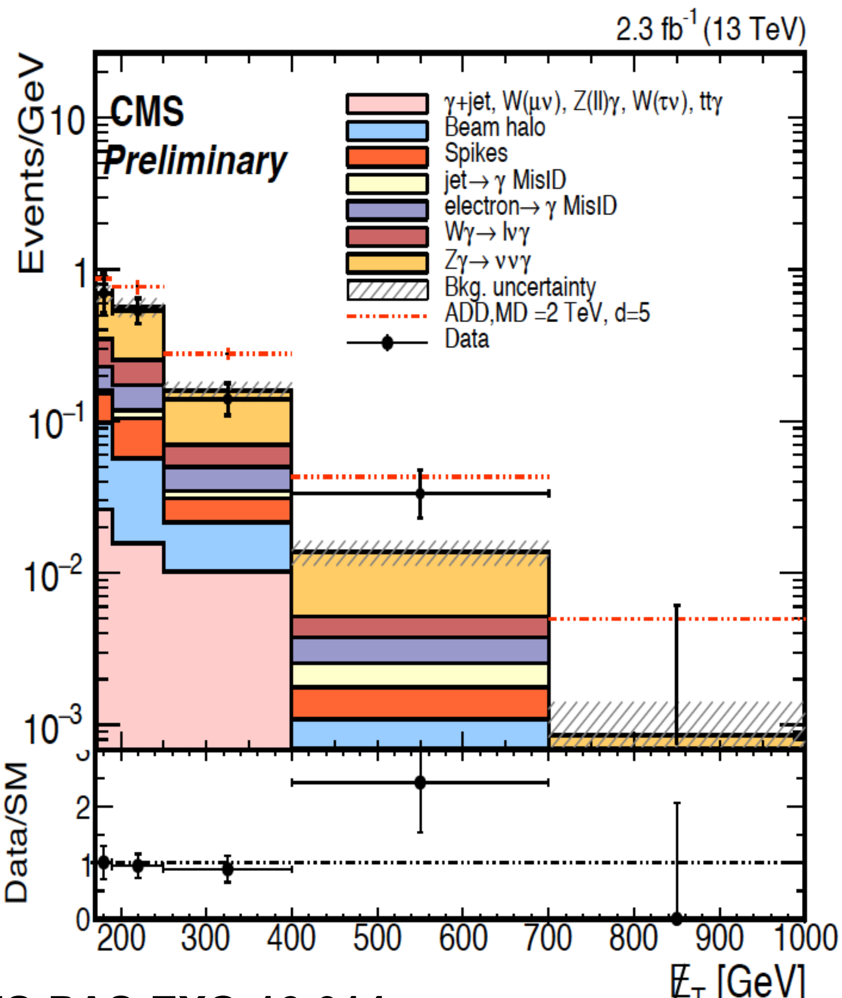


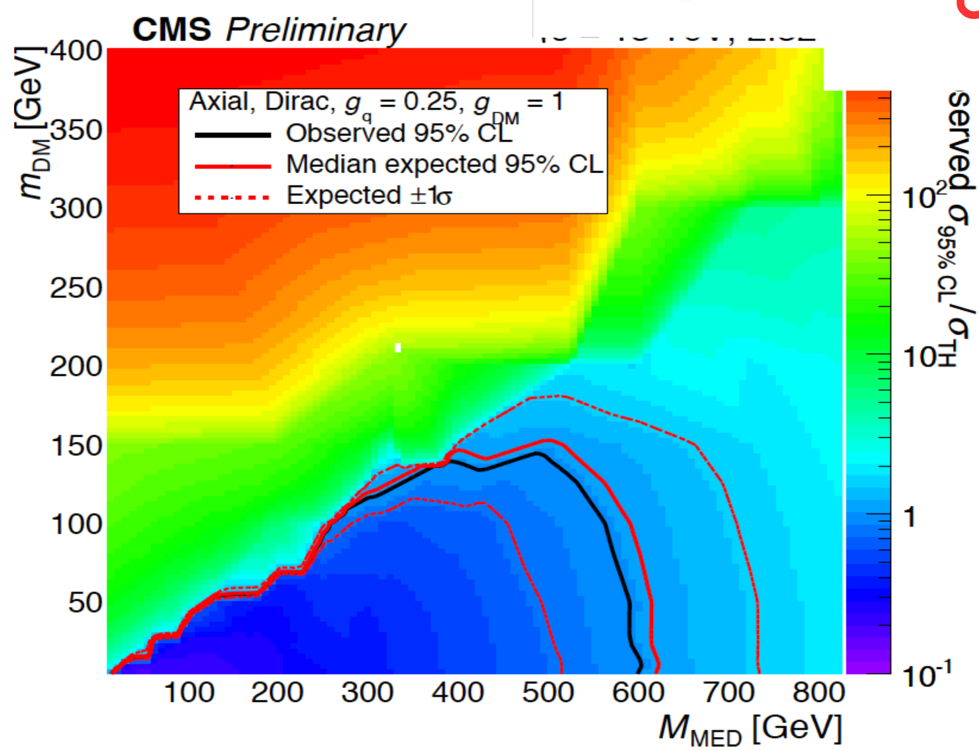


Monophoton

- Tag a photon and look for *MET*
  - Many challenging experimental backgrounds







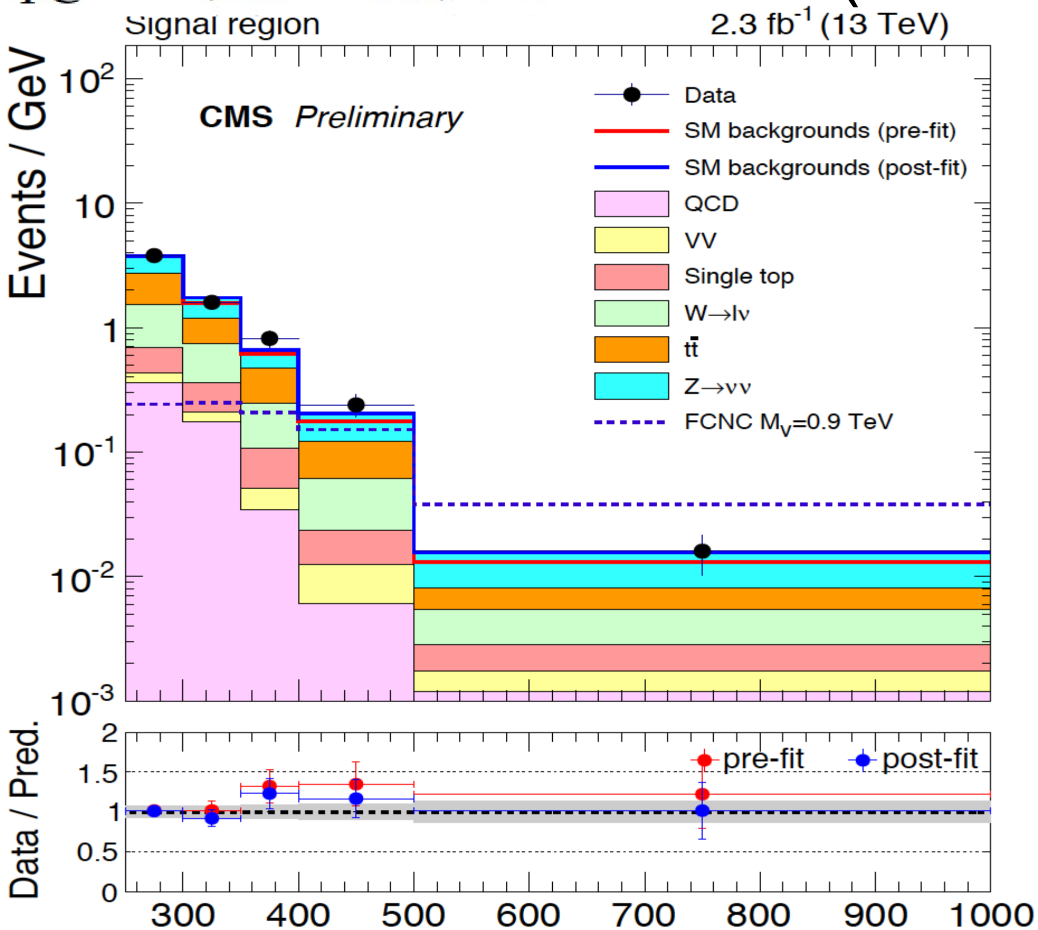
CMS-PAS-EXO-16-014

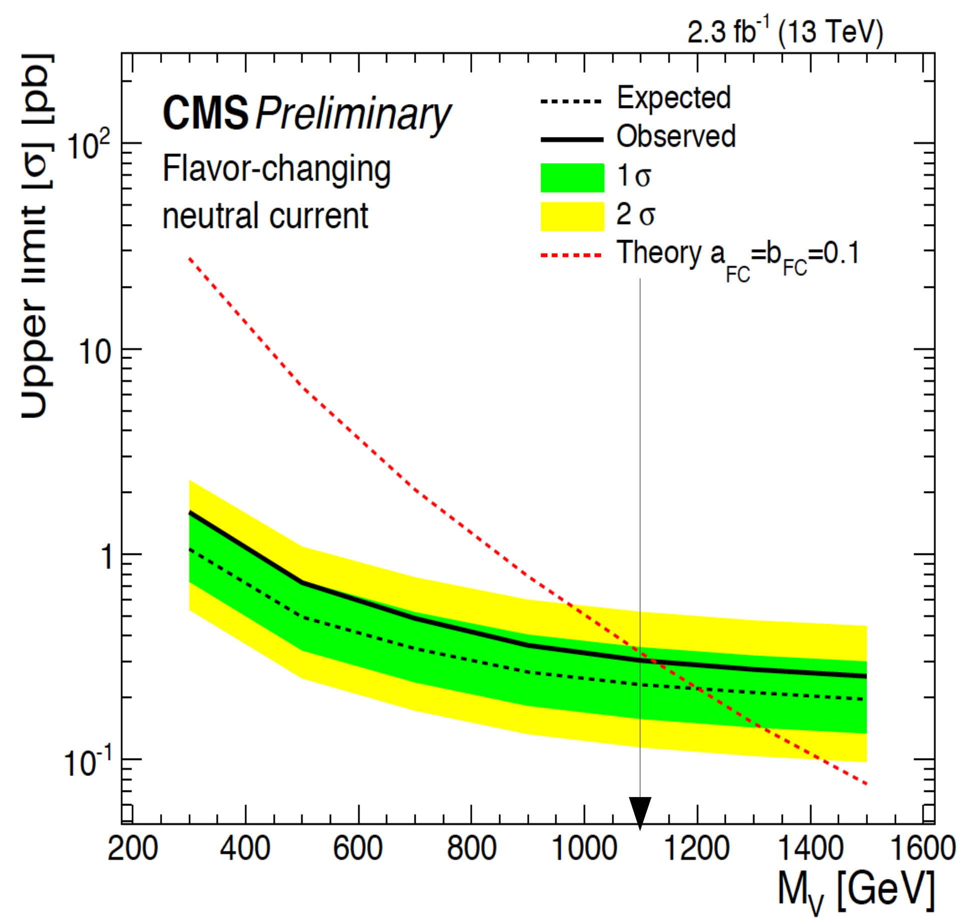
Monotop

$$V_\mu \overline{u}_i[(a^1_{FC})^{ij}\gamma^\mu + (b^1_{FC})^{ij}\gamma^\mu\gamma^5]u_j$$

$$a^1_{FC} = (a_R + a_L)/2$$
$$b^1_{FC} = (a_R - a_L)/2$$

Taking a_i=0.1
(DM forum choice 0.25→x10)

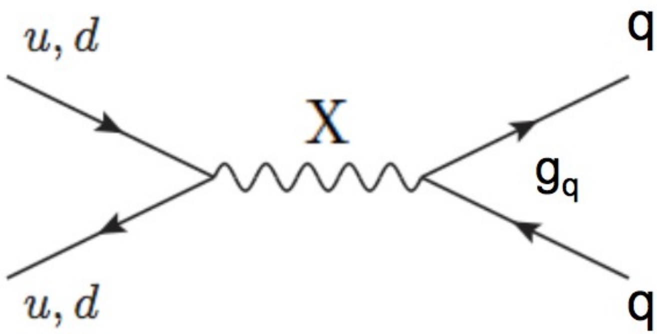


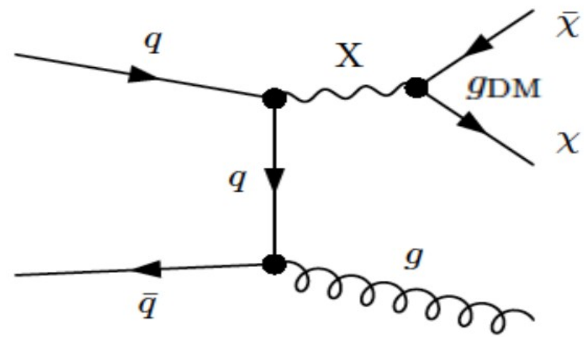


CMS-PAS-EXO-16-017

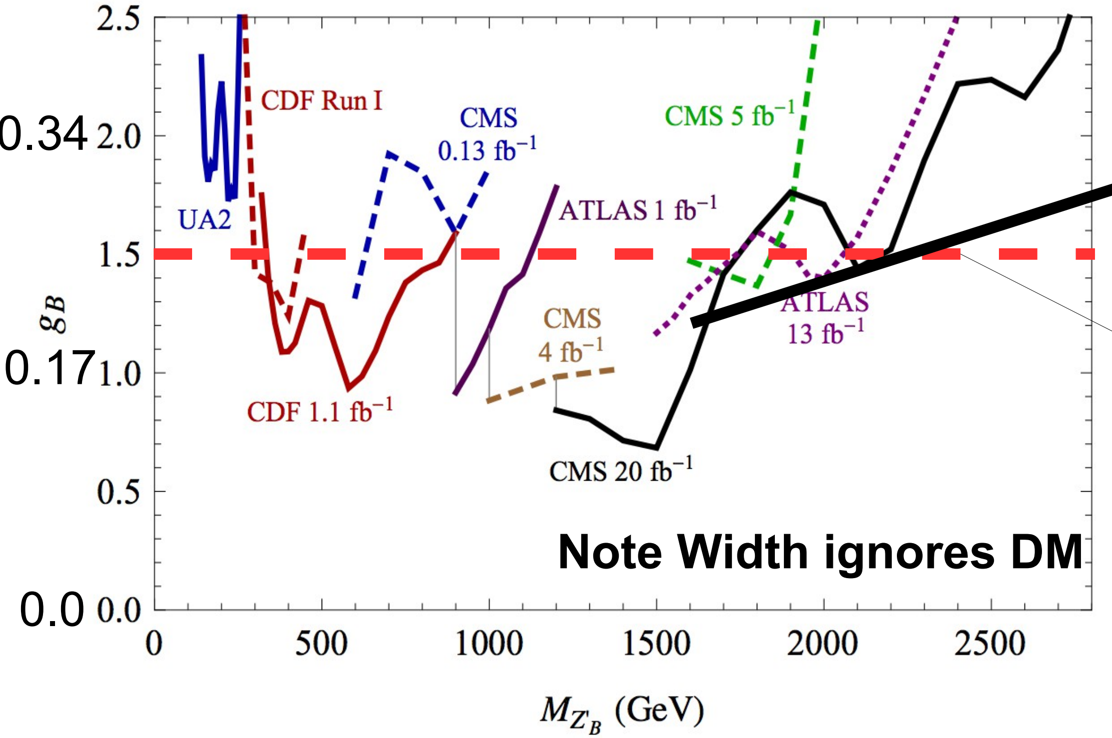
Mediator Search

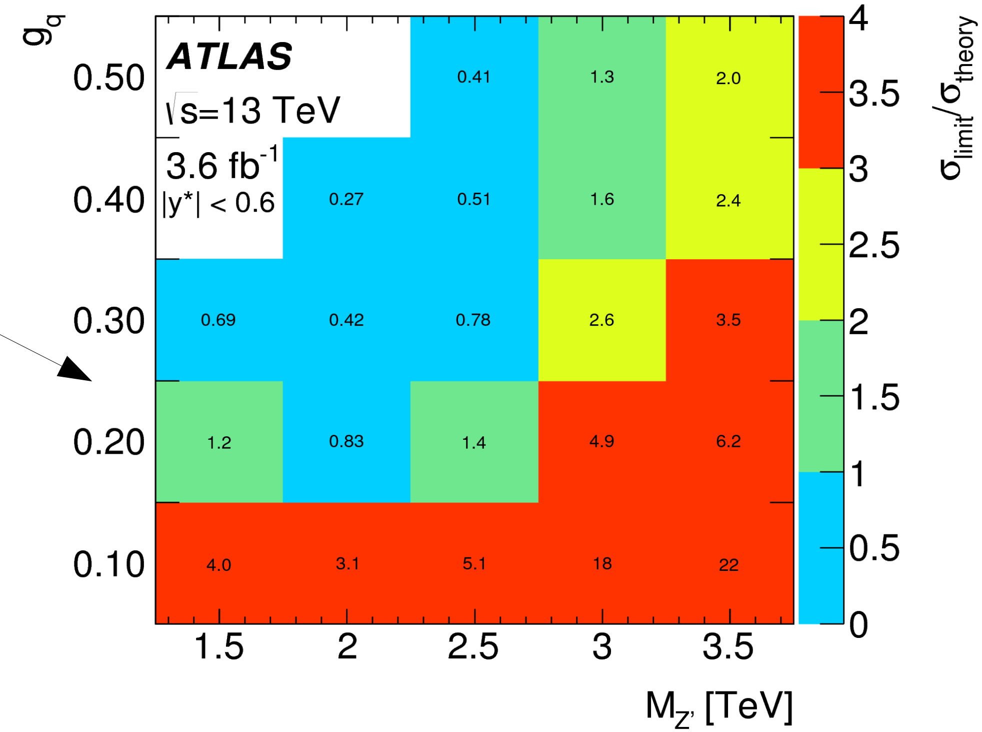
- In addition we can just look for the mediator



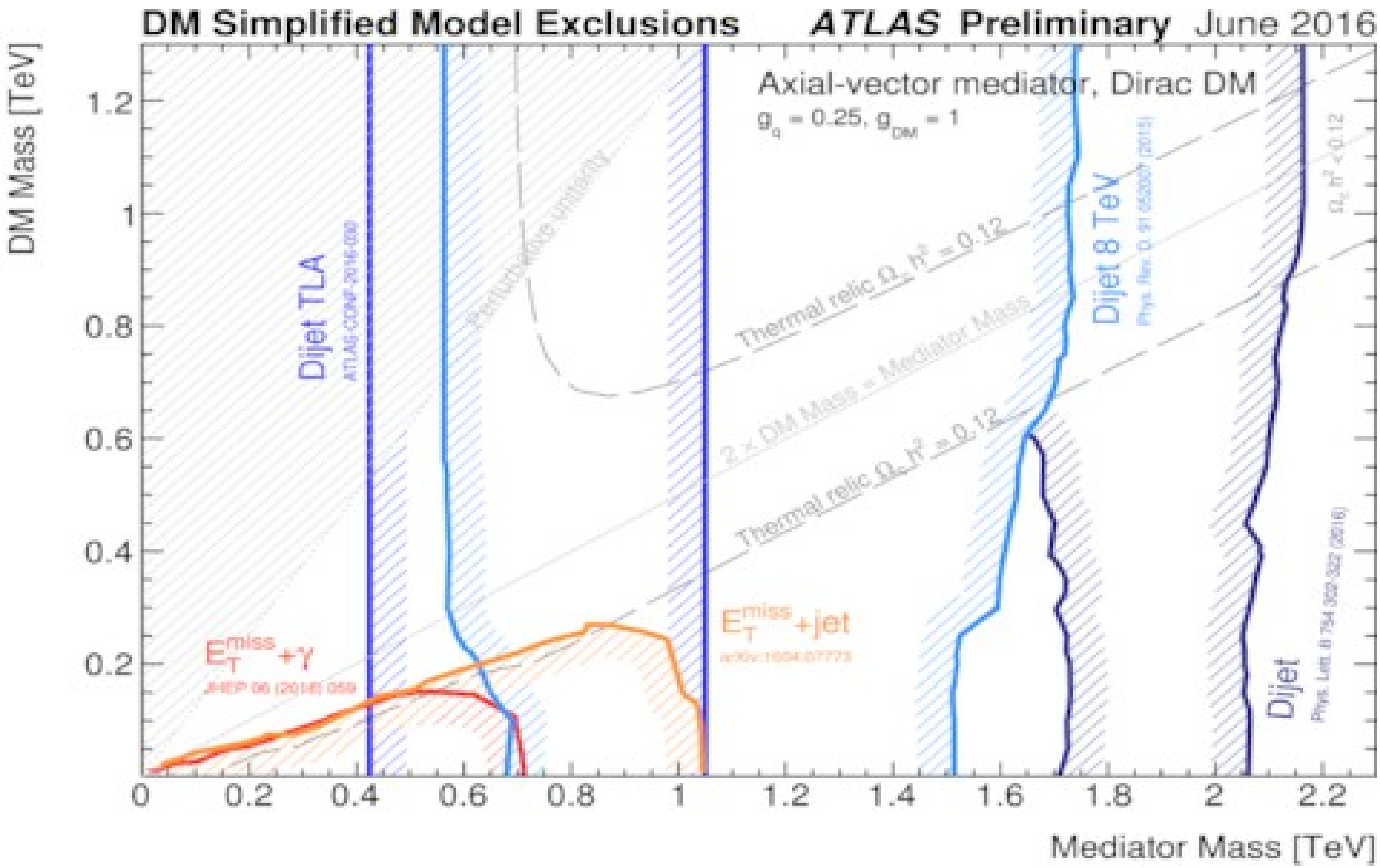


See Krisztian Peters' talk for more

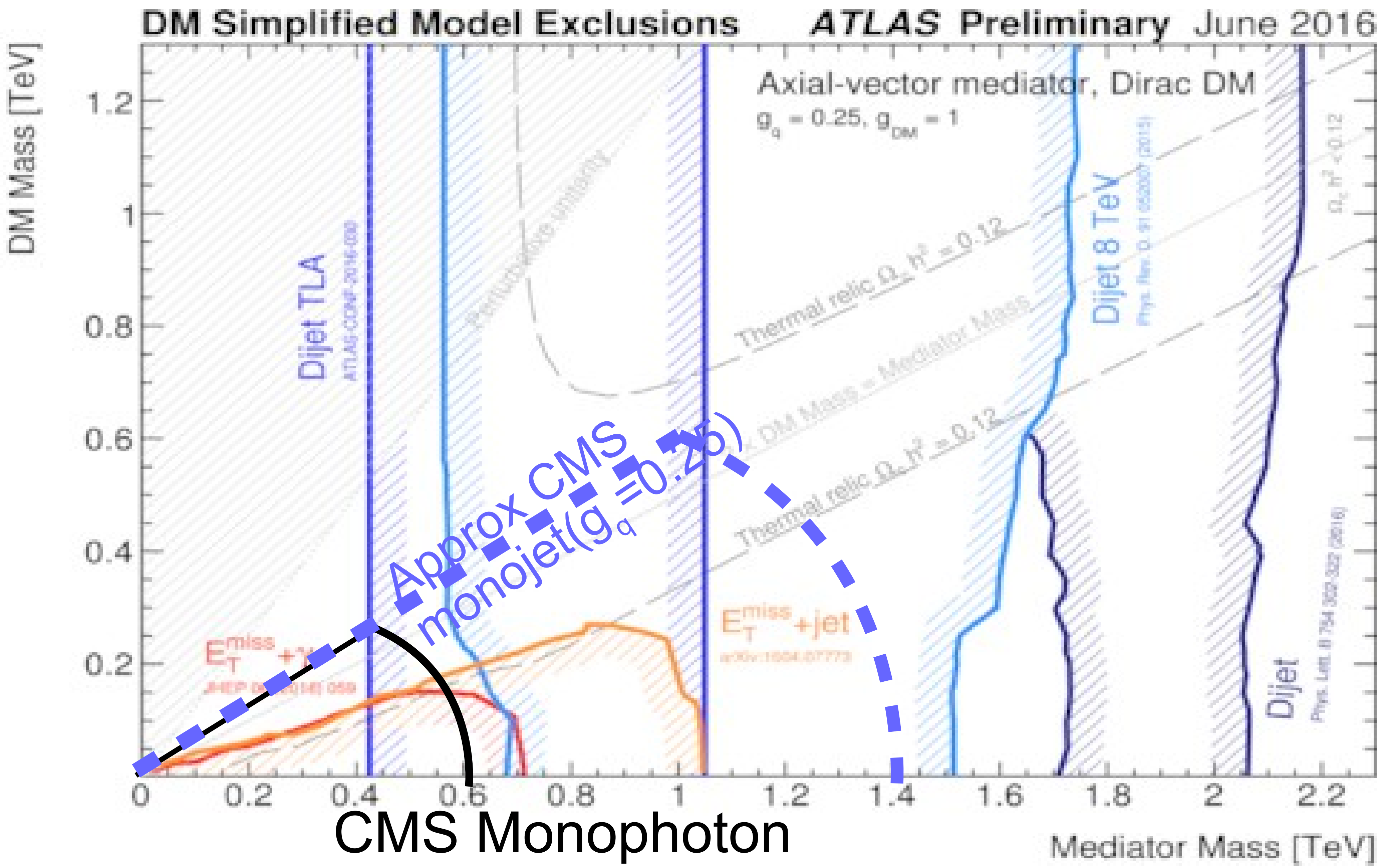




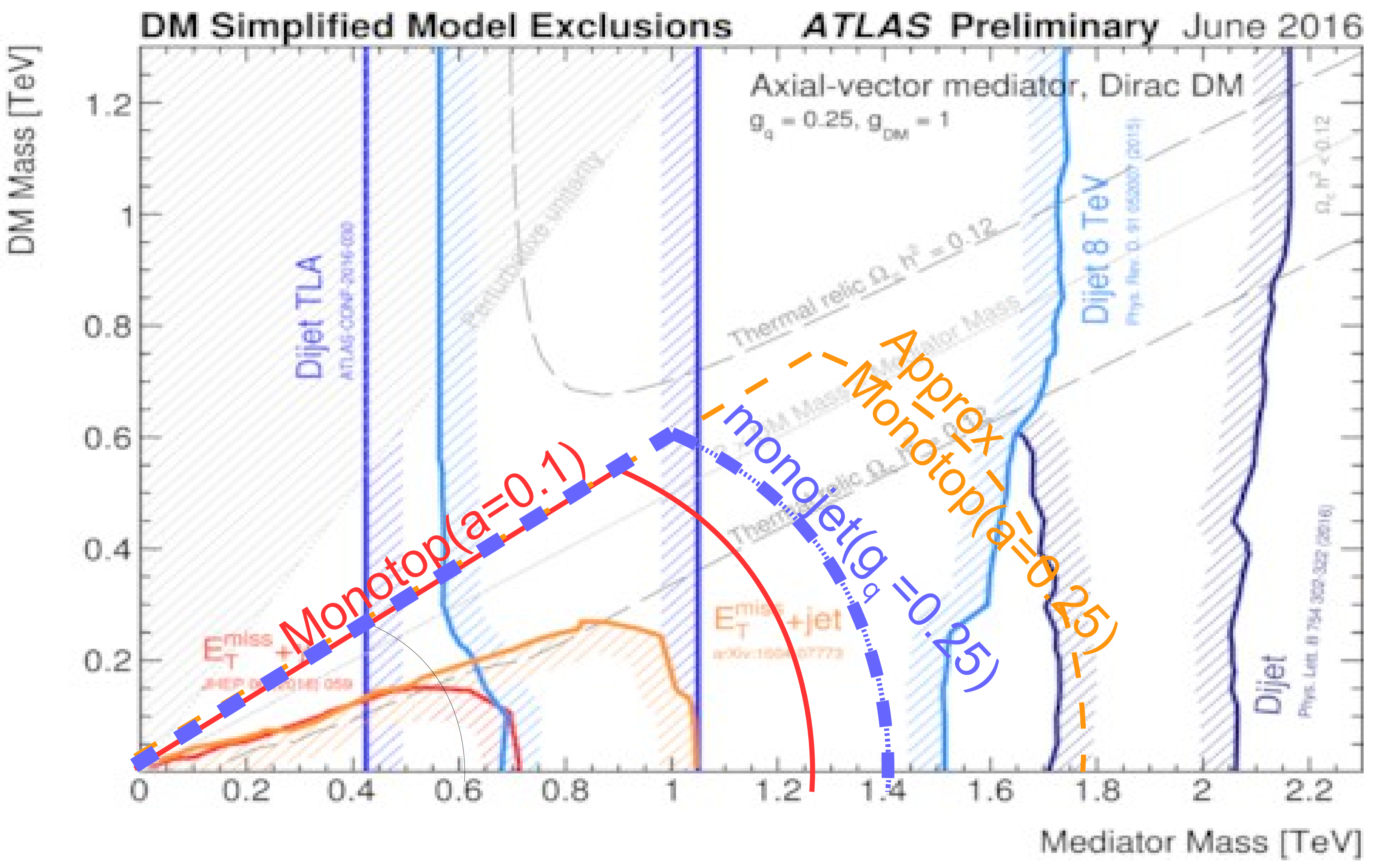
Putting it all together



Putting it all together



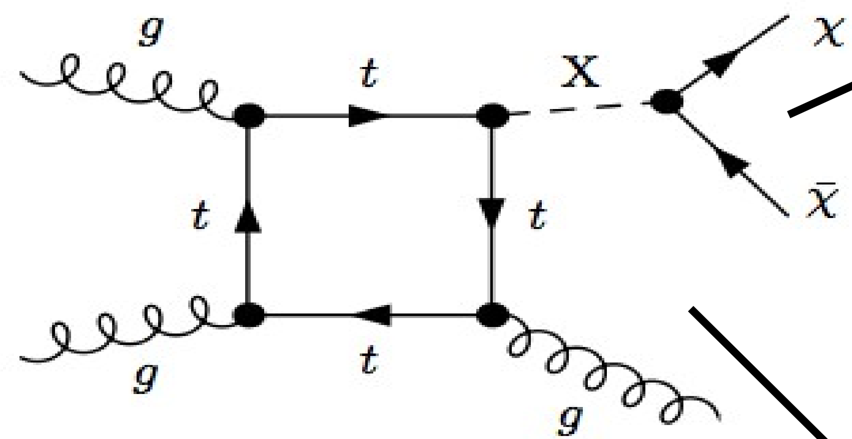
Putting it all together

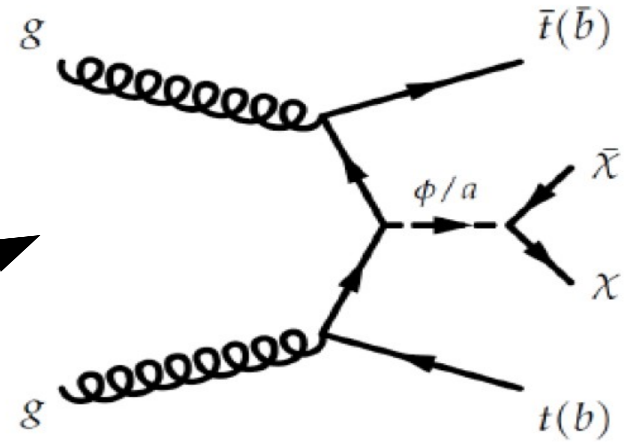


Spin 0

What can you do with Spin 0?

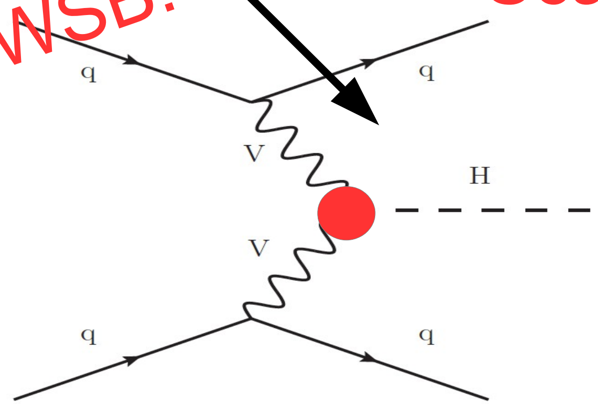
Big Assumption :
No mixing w/Higgs

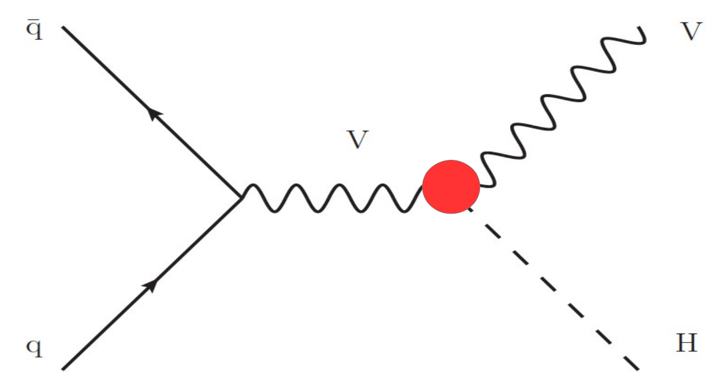




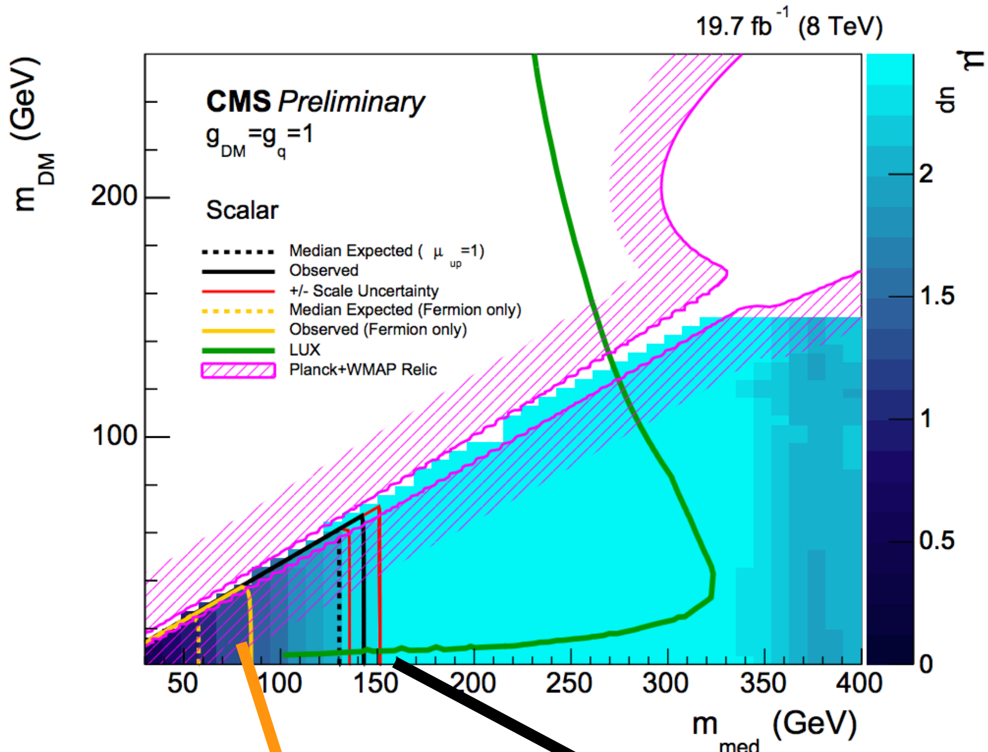
Applying EWSB!

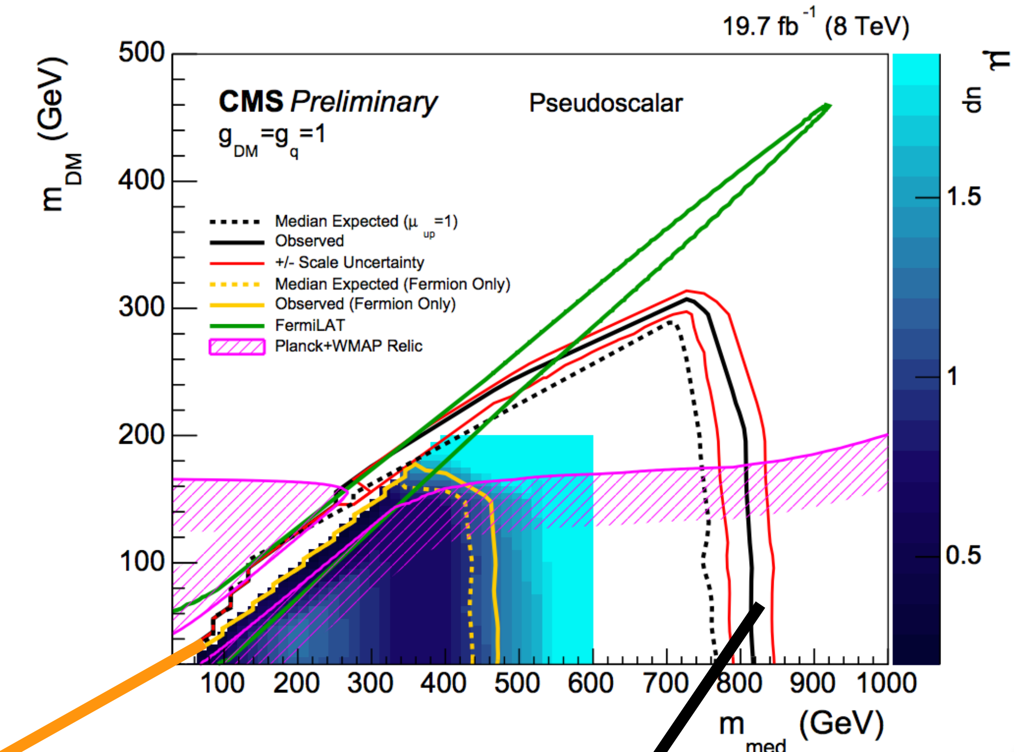
Higgs invisible or
Scalar w/EWSB





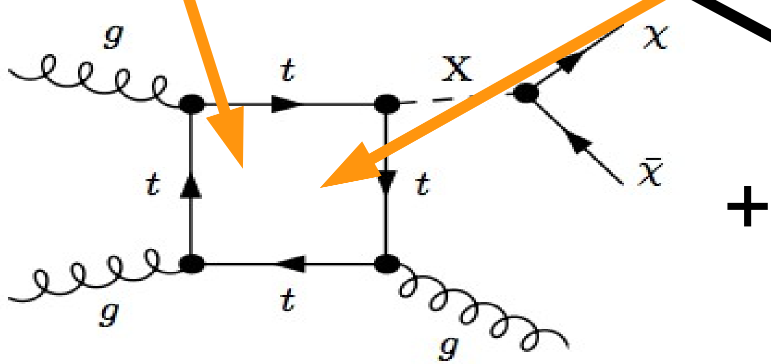
Our Current Scalar & Psuedo results



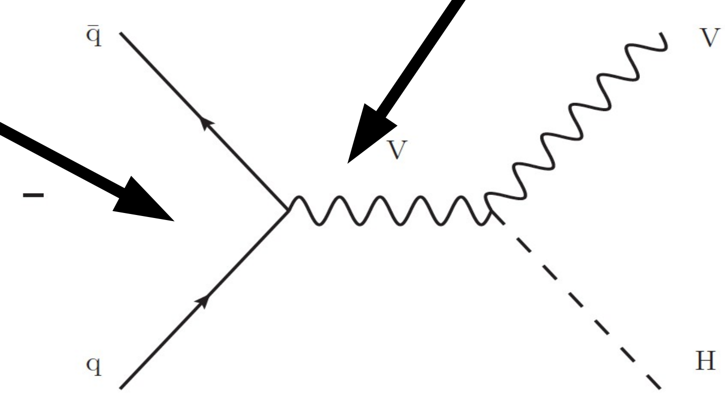


- Currently driven by 8TeV exclusion

Clear that there are issues

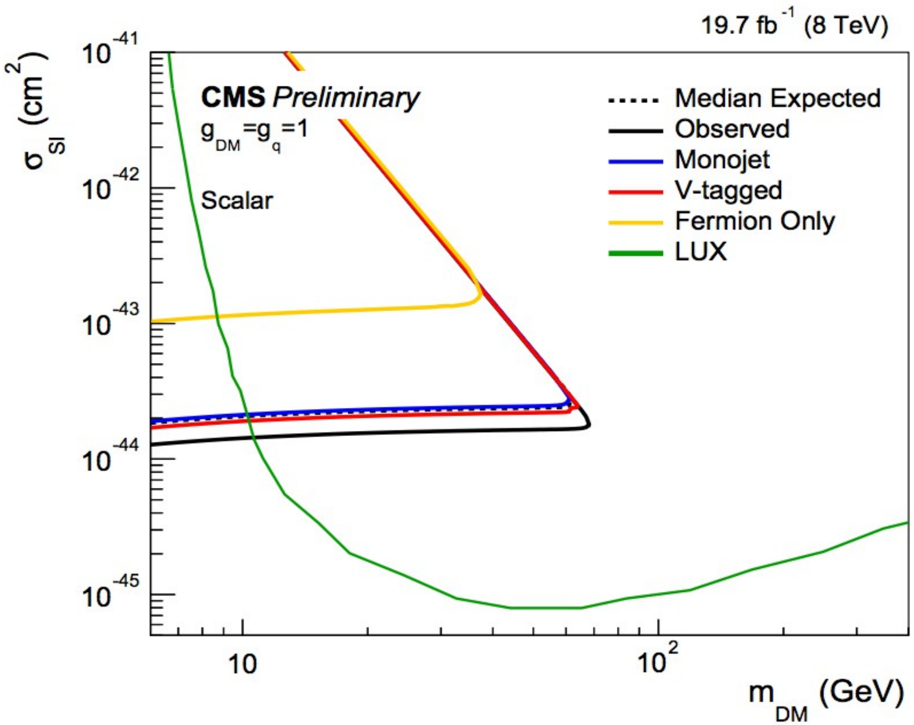


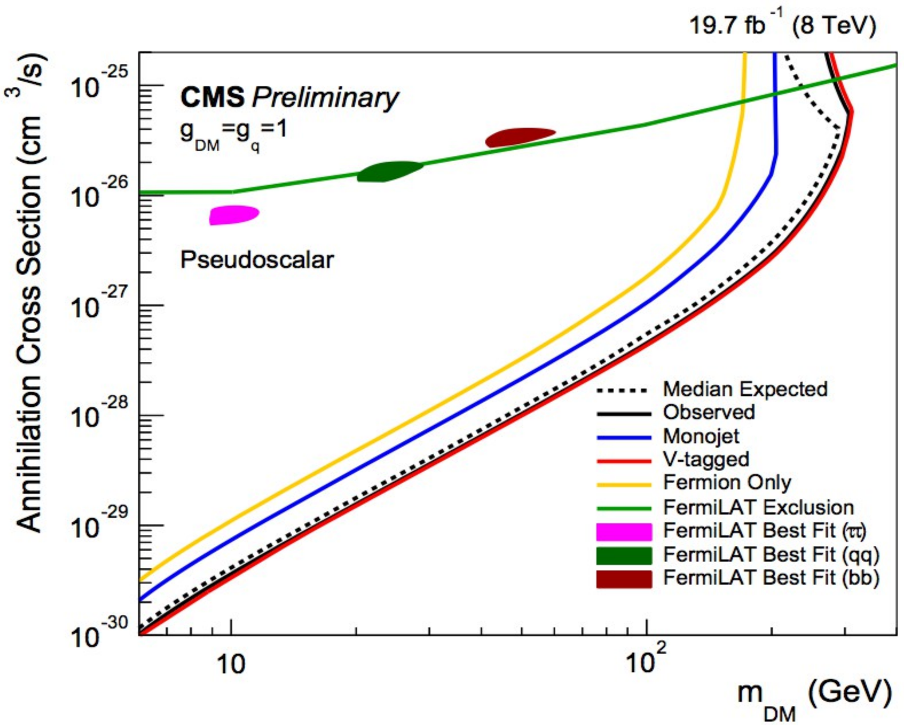
+



CMS-PAS-EXO-12-055

Our Current Scalar & Psuedo results



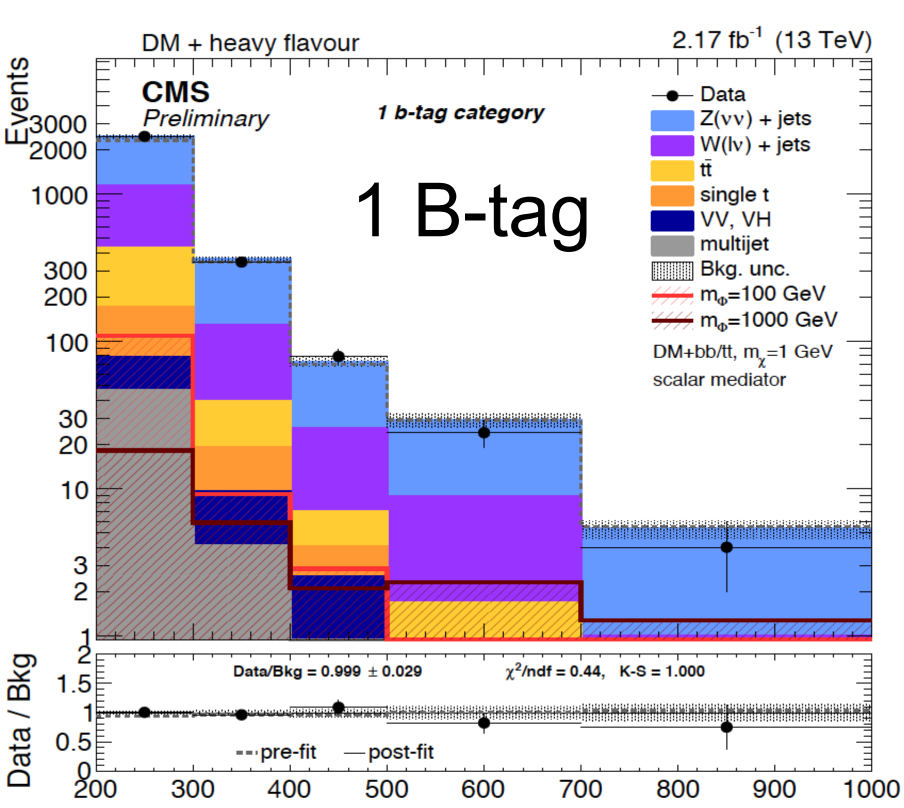


- When the dark matter is not onshell
  - Strong exclusion of pseudoscalar interpreation of LAT
  - Scalar and Direct detection are in close comopetition
    - Expect LHC to pass LUX this summer

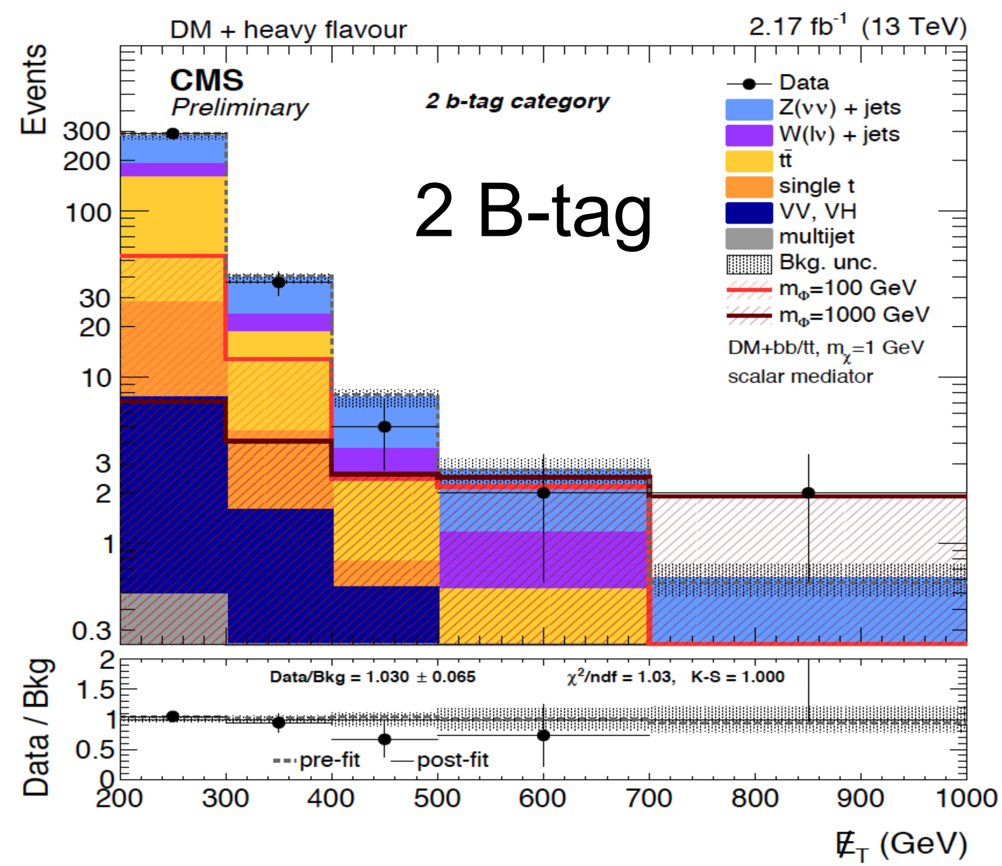
CMS-PAS-EXO-12-055

Heavy Flavor

- Mono-B or B(s)
  - Require less than 4 jets
  - Basically the monojet analysis with either 1 or 2 bs
  - Inject both tt+DM and bb+DM into the analysis

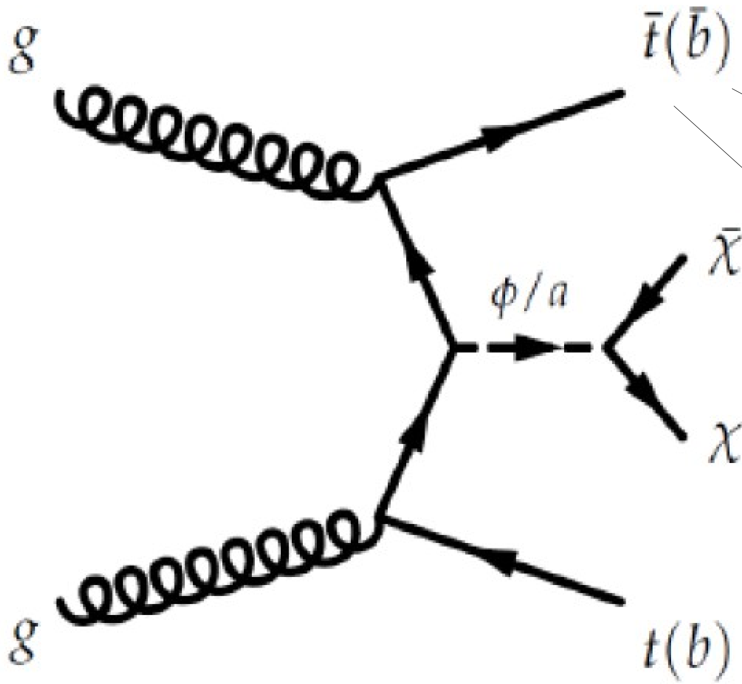


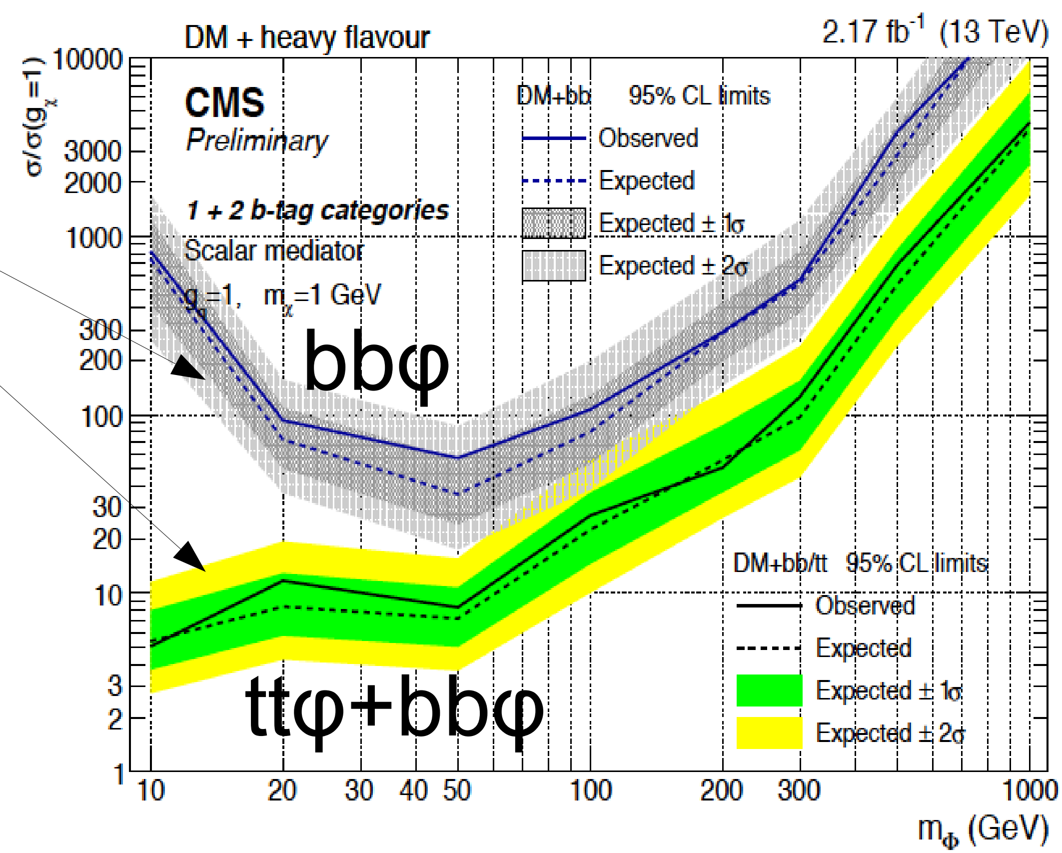
CMS-PAS-B2G-15-007



Heavy Flavor Results

- Mono-B or B(s)
  - Note that this is only < 4 jets
  - Inject both tt+DM and bb+DM into the analysis

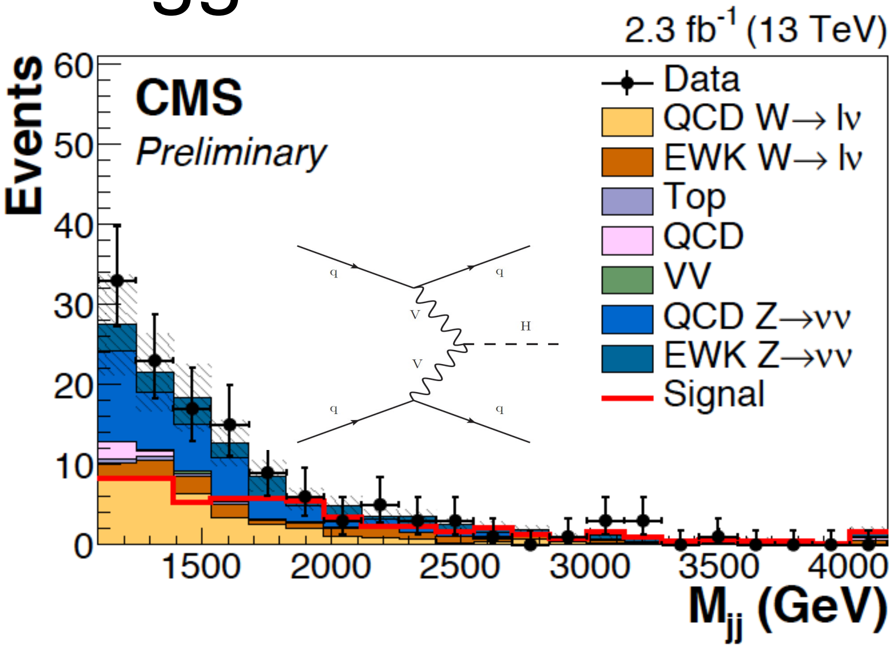


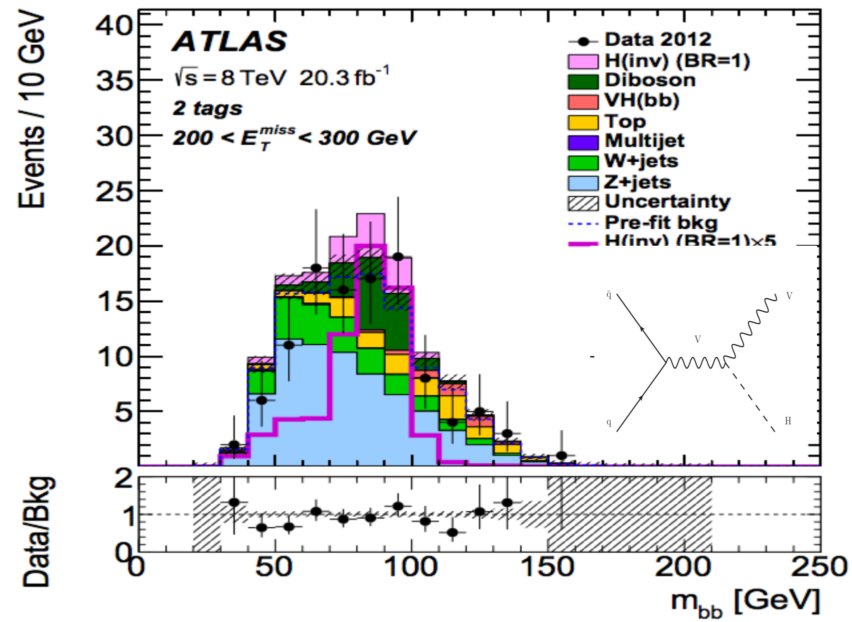


CMS-PAS-B2G-15-007

Higgs Invisible Interpretation

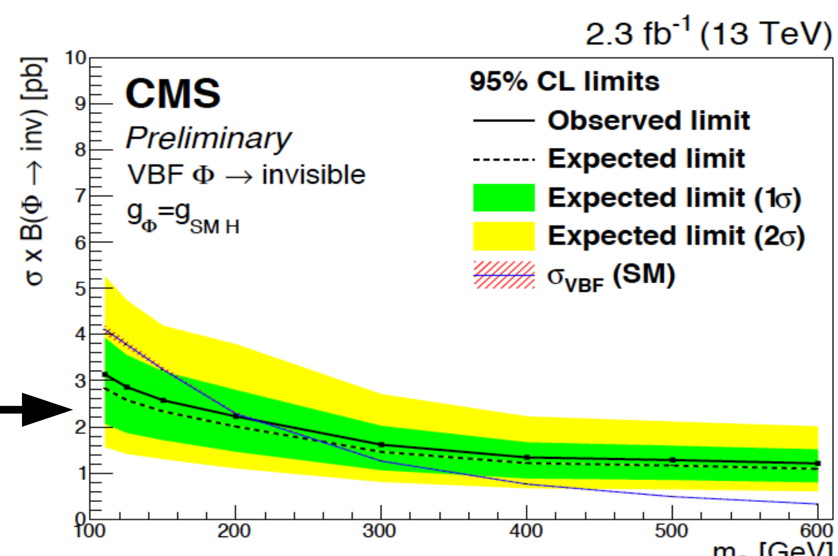
- Higgs Invisible is scalar model with EWSB





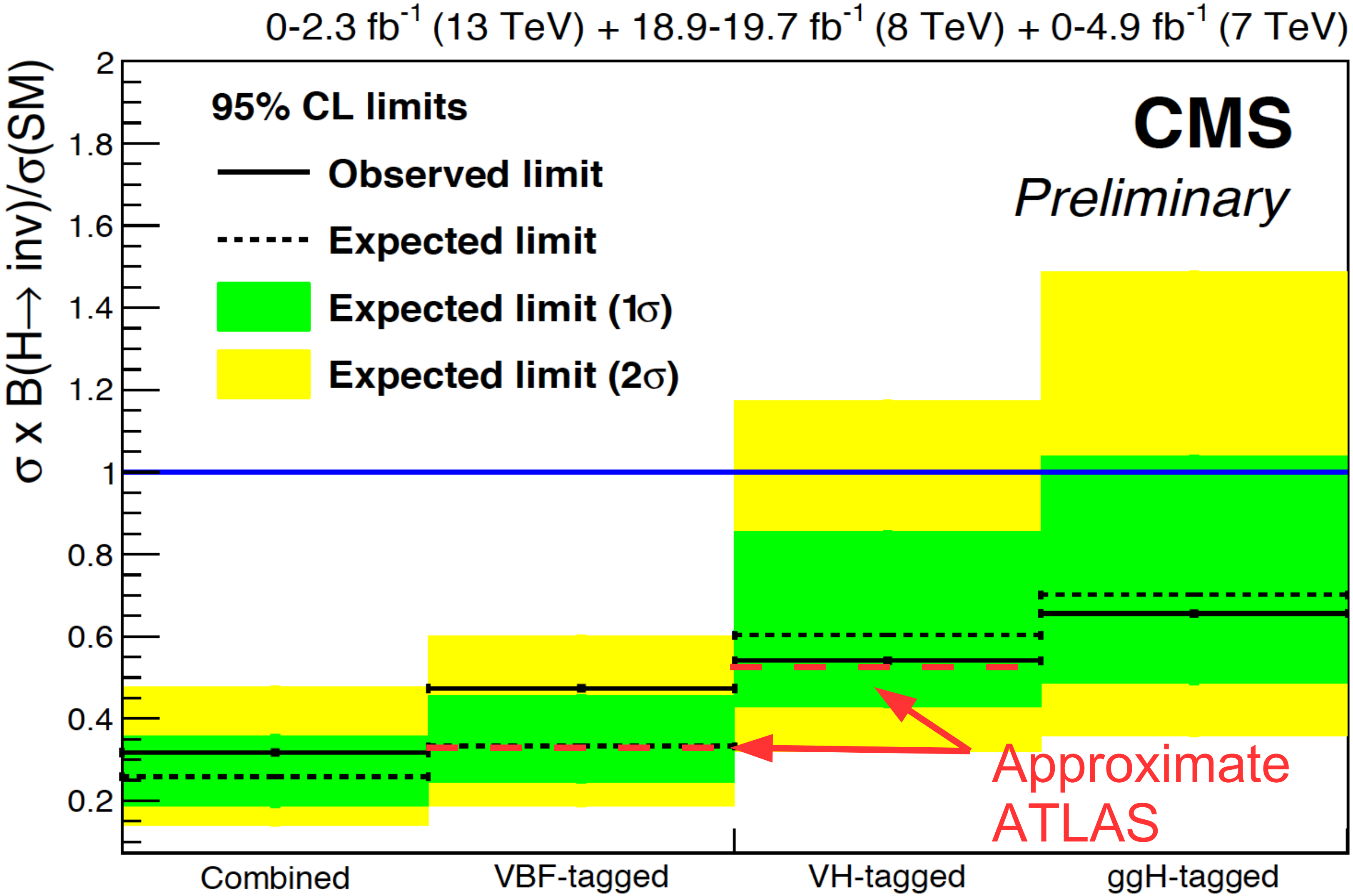
30% improvement in VBF from tying the W→Z constraints together in control regions

Starting to scan mass



CMS-PAS-HIG-16-009/ATLAS-HIGG-2015-03

Results



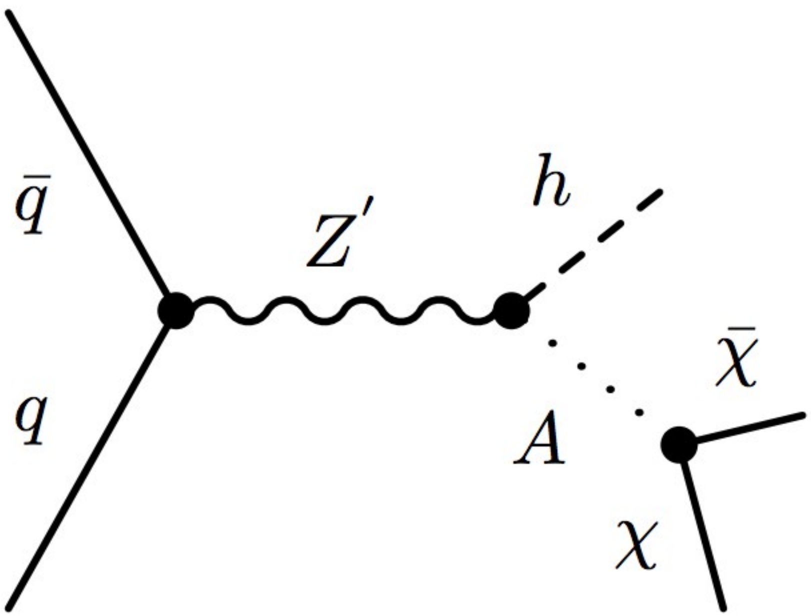
CMS : BR(H→Inv) < 0.32 (0.26 expected)

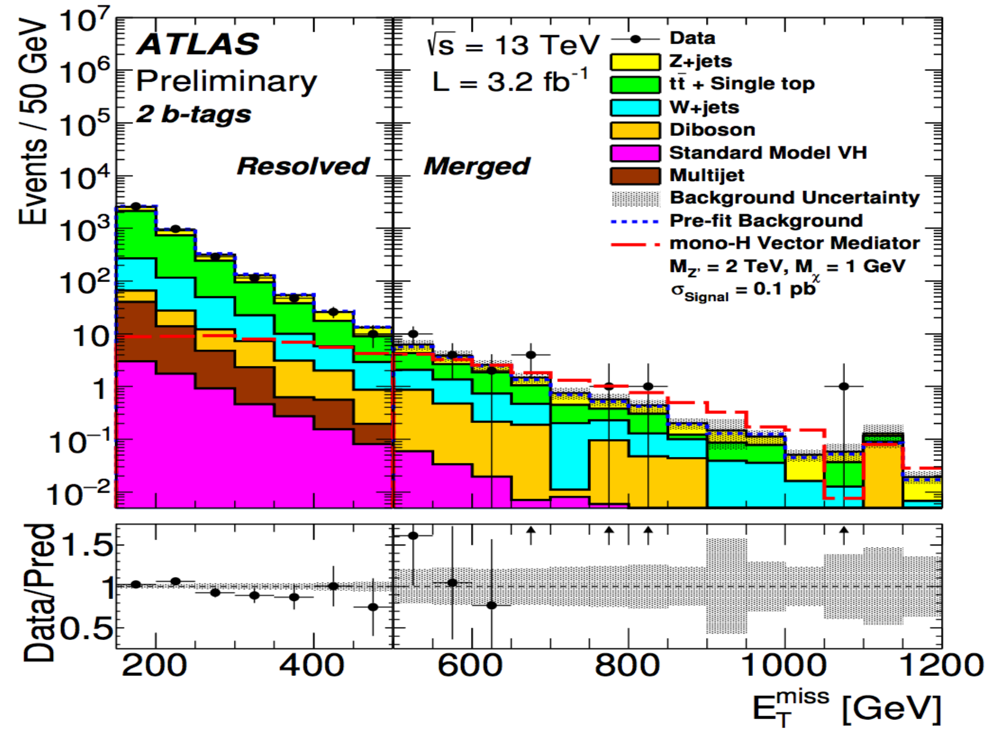
ATLAS : BR(H→Inv) < 0.25 (0.27 expected)

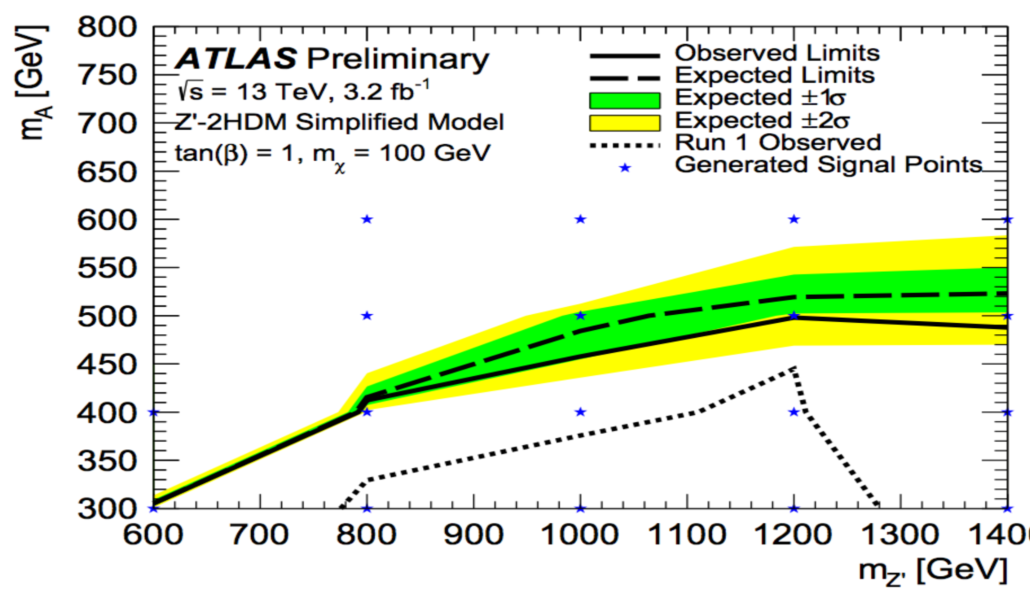
CMS-PAS-HIG-16-009/ATLAS-HIGG-2015-03

Mono-Higgs

Adding Spin 1 and Spin 0 mediators





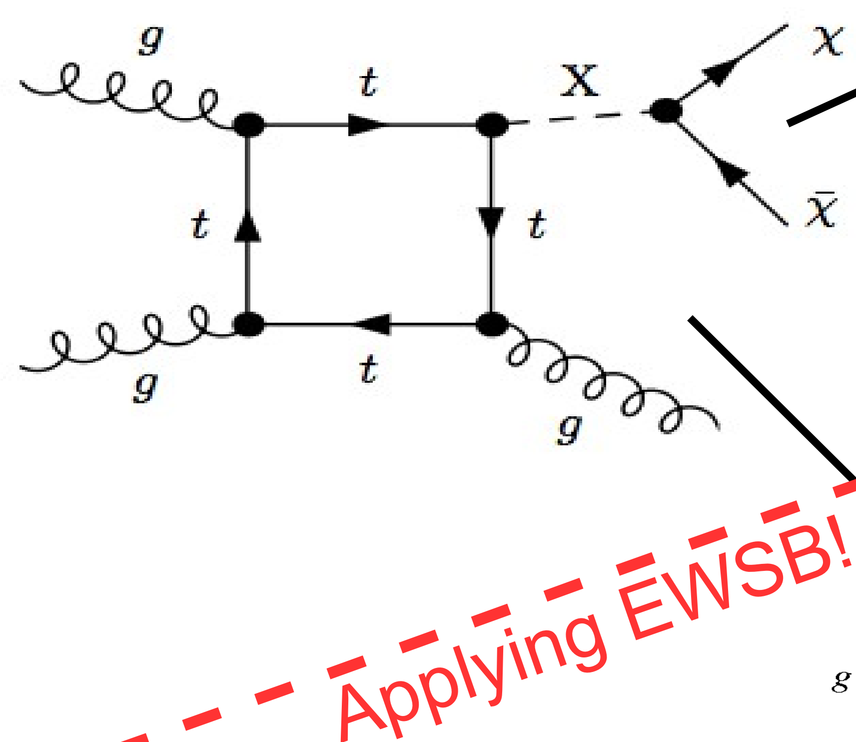


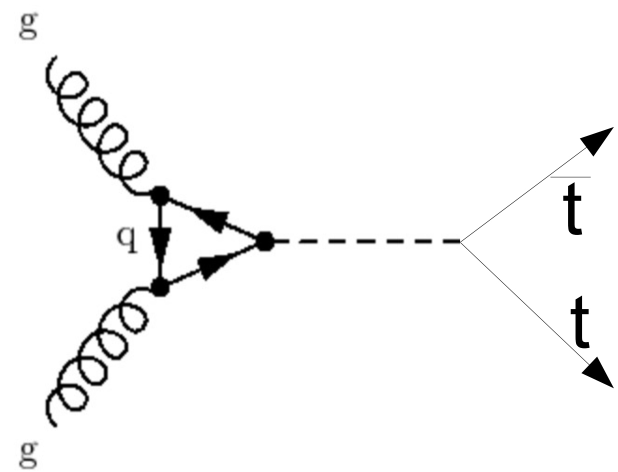
h→bb bounds drive mono-Higgs

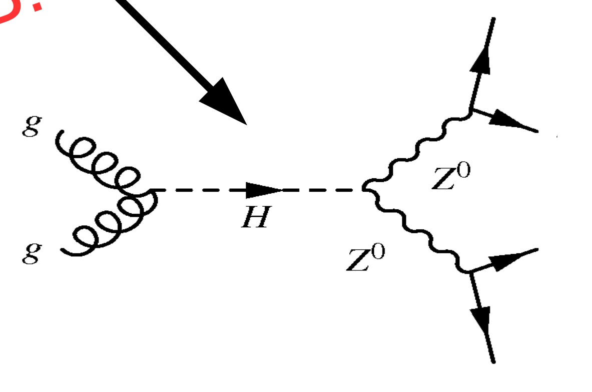
B-tagging forces ttbar background to drive analysis

ATLAS-CONF-2016-019

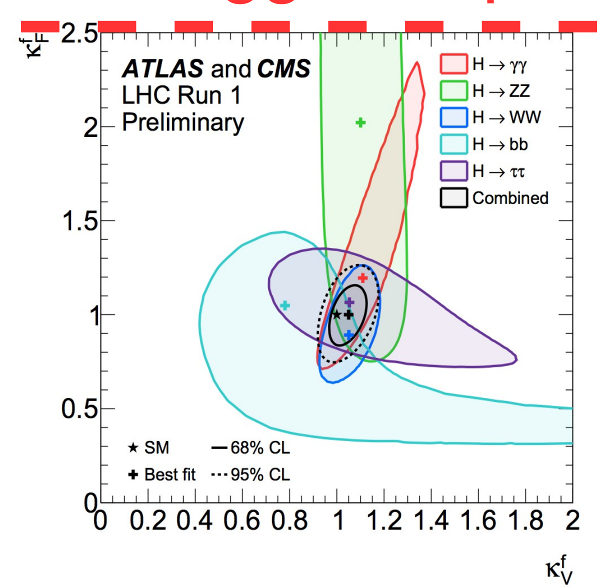
What about the visible?



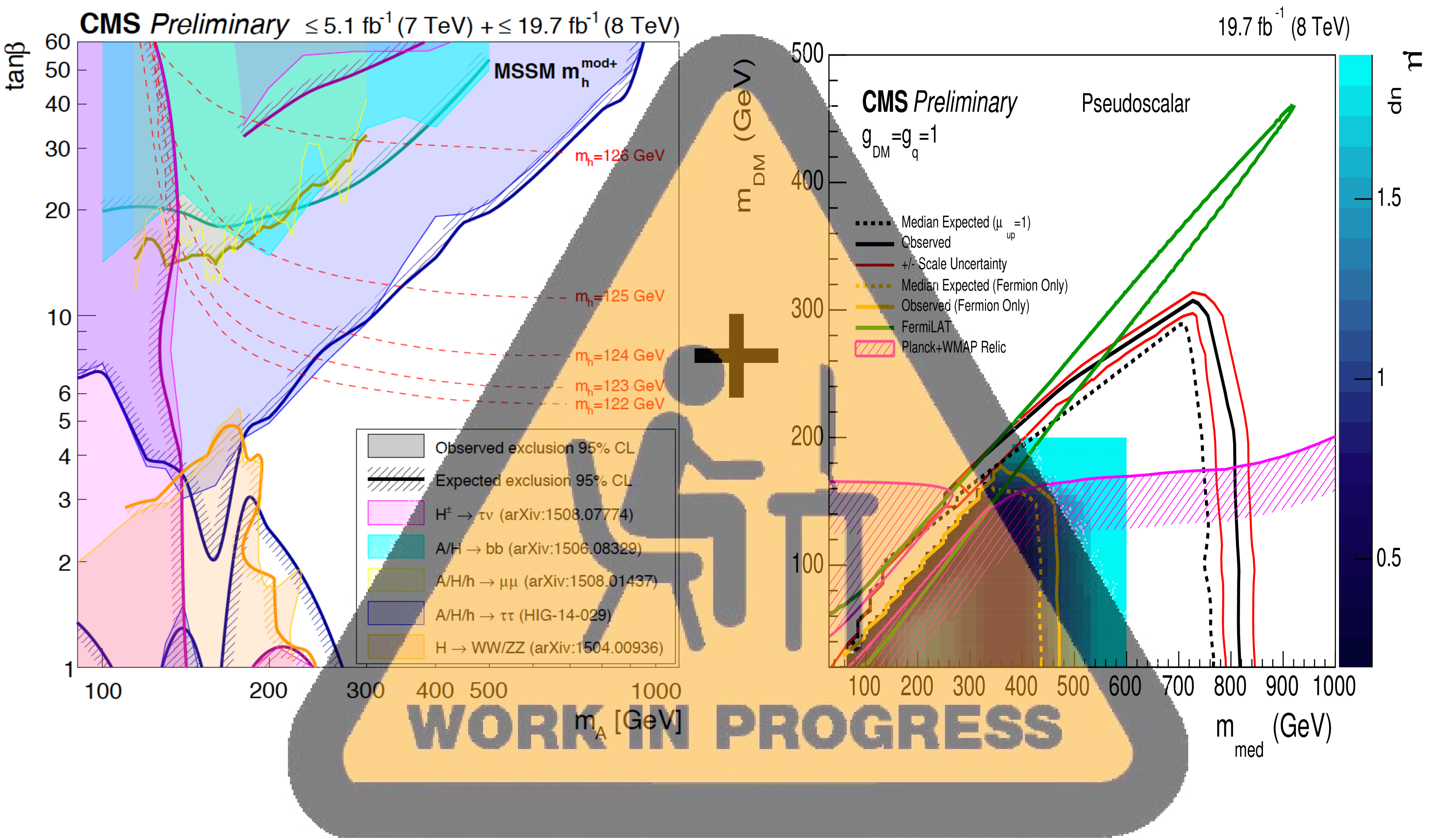




Higgs couplings



Not yet available



Spin 0
Di-photon
(미안 해요)

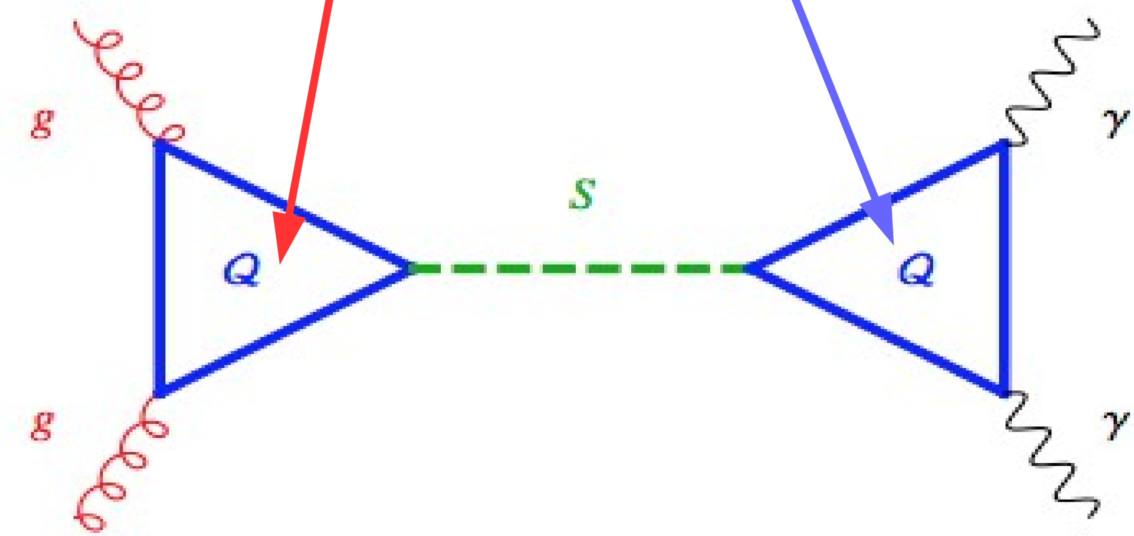
Preliminary
Work with U. Haish,O. Buchmuller,K. Hahn,N. Wardle, T. Du Pree

The simplest DM model

- Lets try to make something super basic
  - Basic model

$$\mathcal{L}_S = g_\chi S \bar{\chi}\chi + \frac{\alpha_s}{4\pi}\frac{c_g}{\Lambda} S G^a_{\mu\nu} G^{a\,\mu\nu} + \frac{\alpha}{4\pi}\frac{c_\gamma}{\Lambda} S F_{\mu\nu} F^{\mu\nu}$$

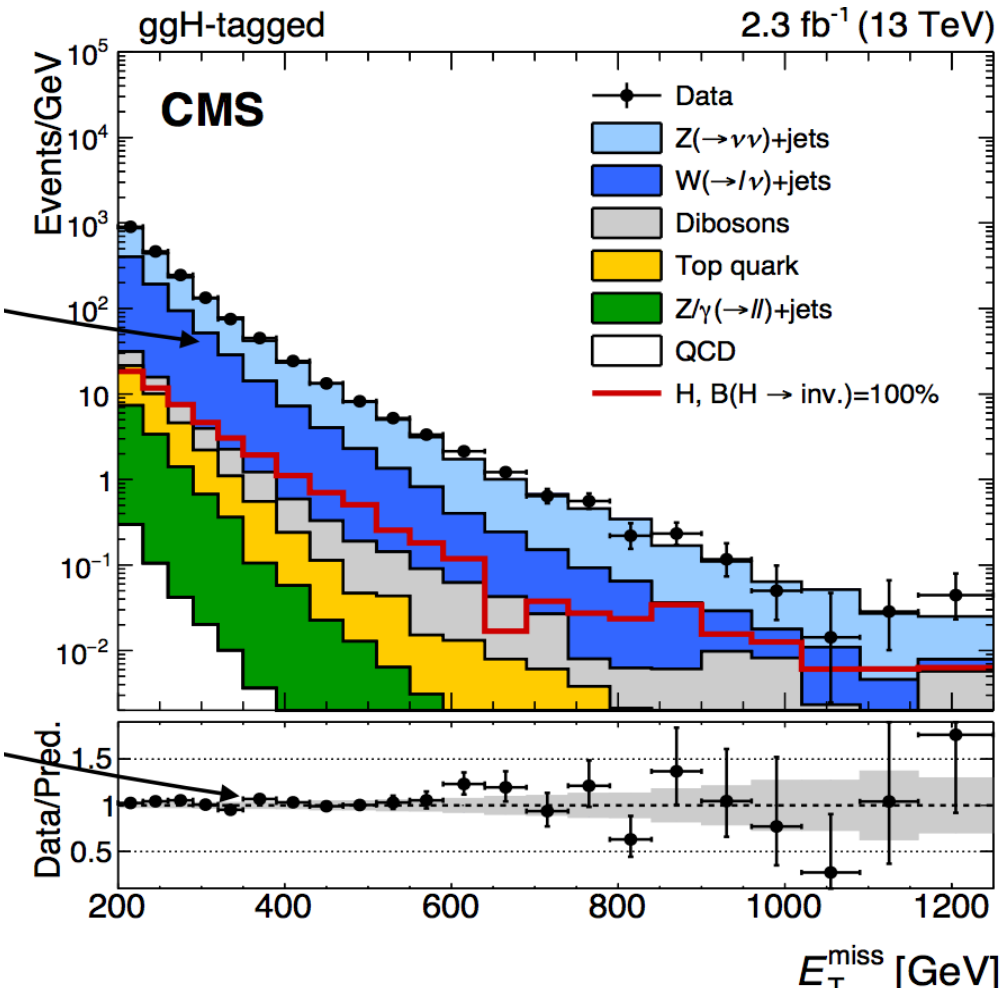
??



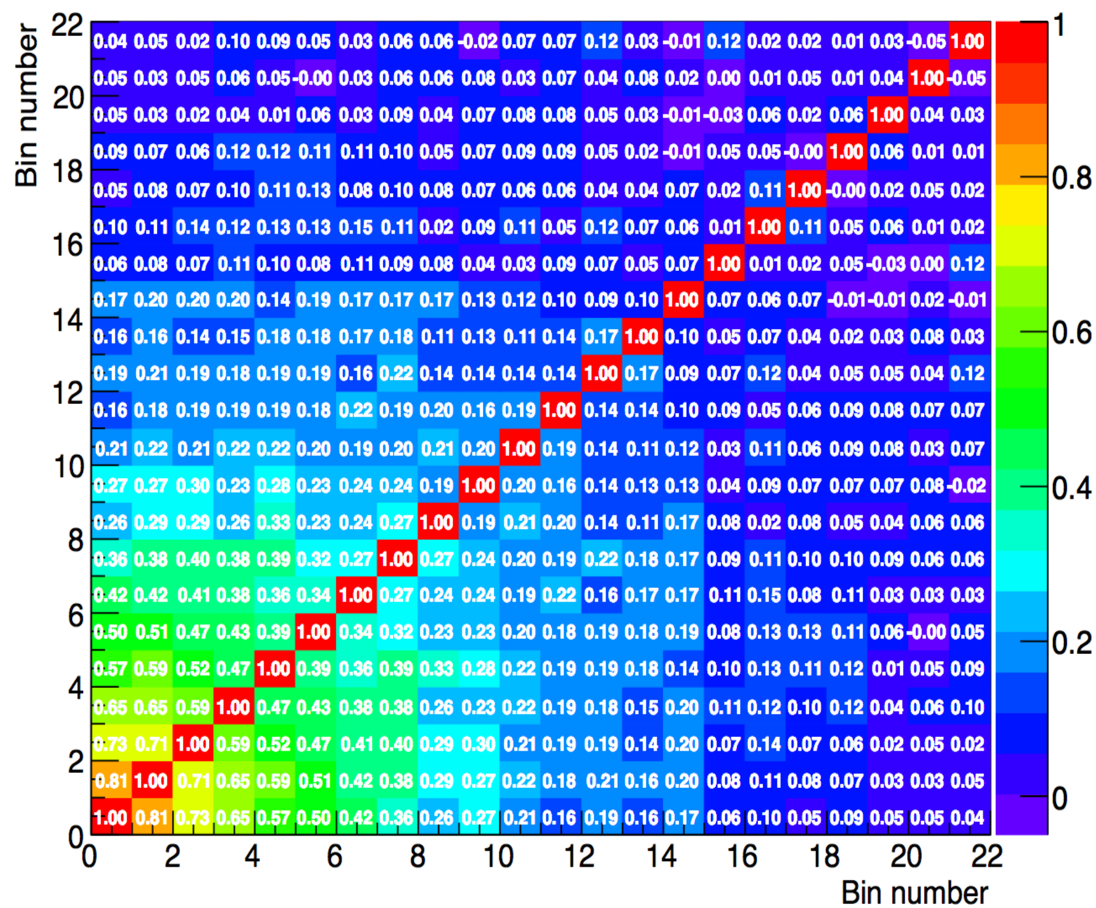
Re-interpreting the Analysis

- Future plans from LHC→simplified likelihoods
  - What is it? => Reduced control fit to 2 objects

MET distribution



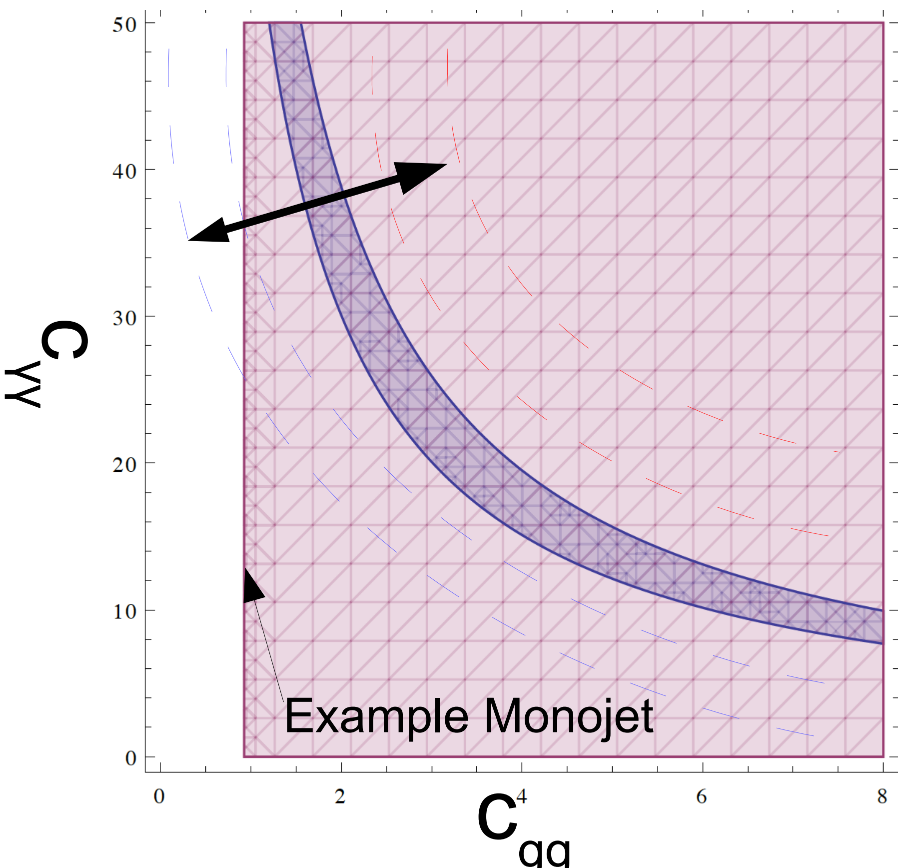
Toy Bin by bin covariance

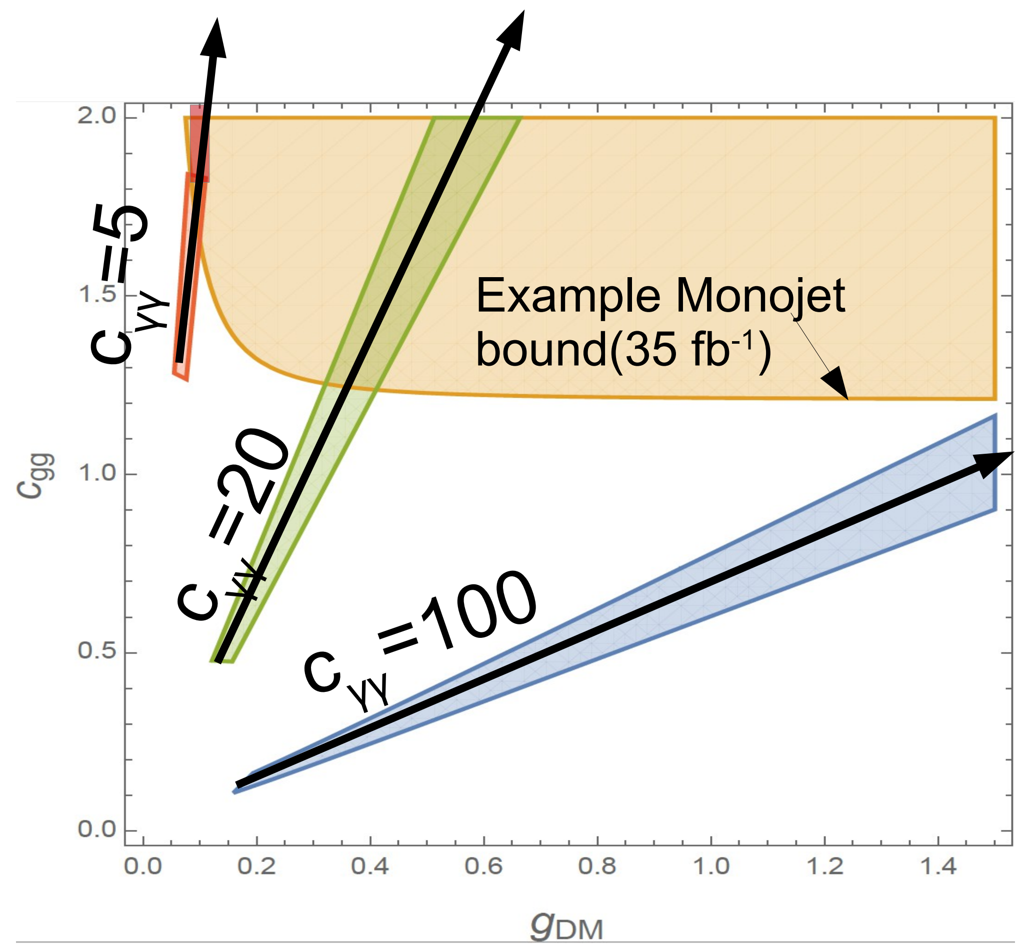


From this: setup full CL_s get both expected and observed

Using the best fit cross section

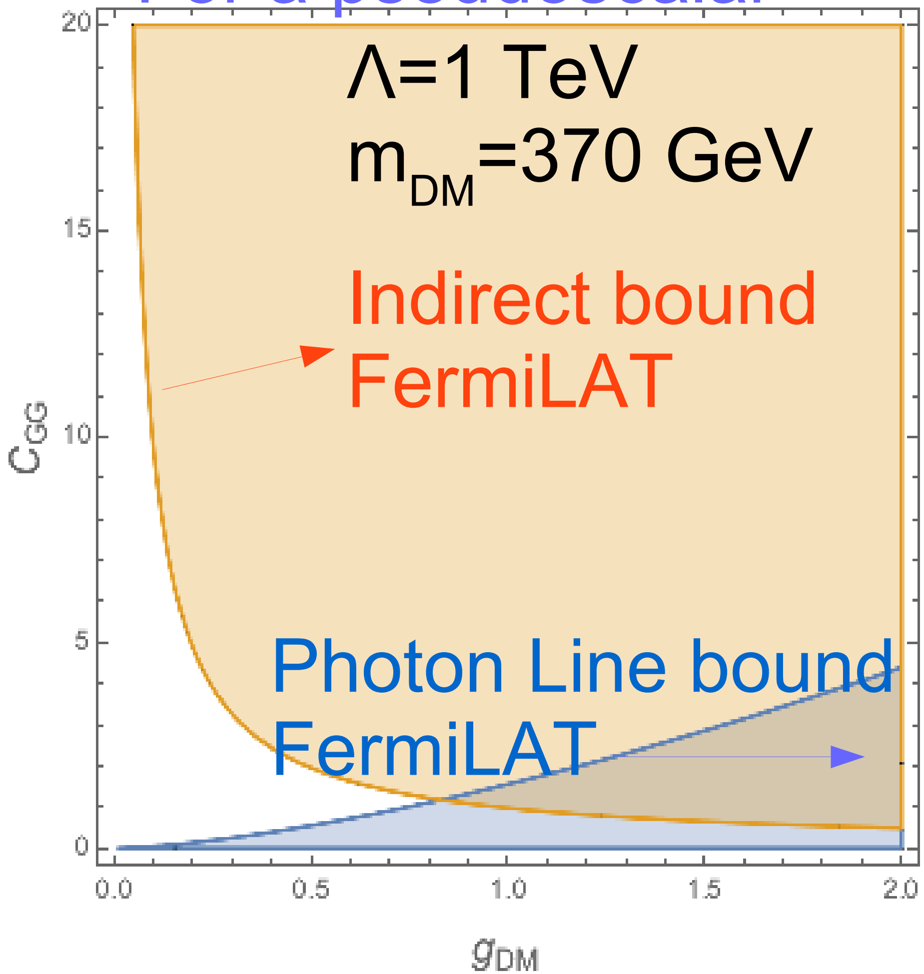
- We have 3 free couplings :
  - $g_{DM}, c_{GG}, c_{\gamma\gamma}$
- Taking the photon best fit can constrain one

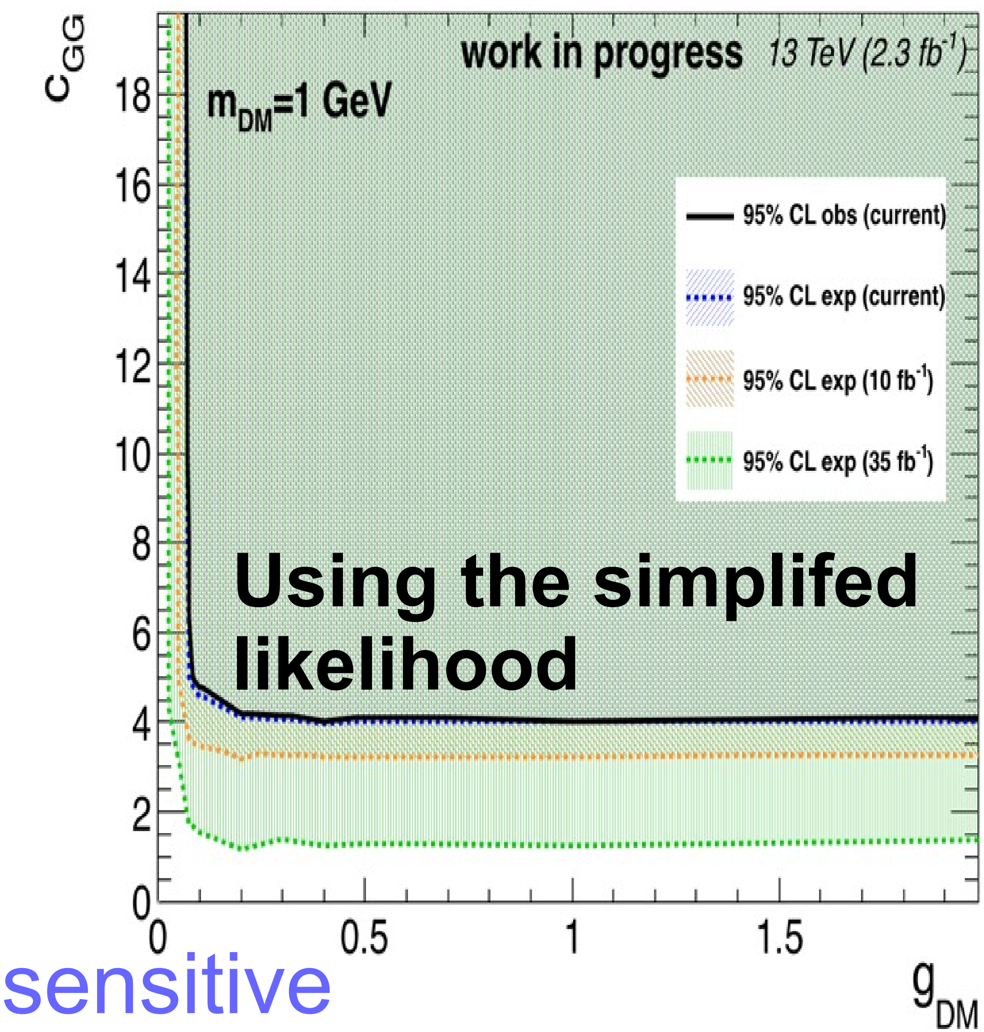




Considering All Constraints

For a pseudoscalar

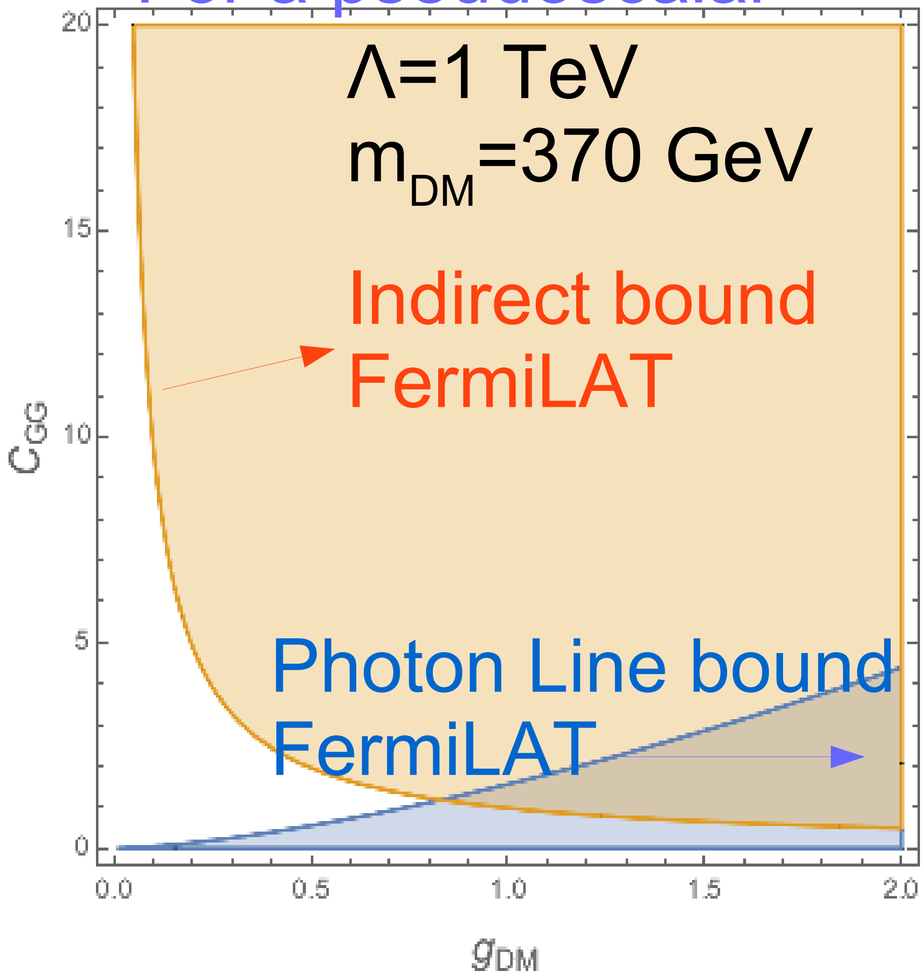


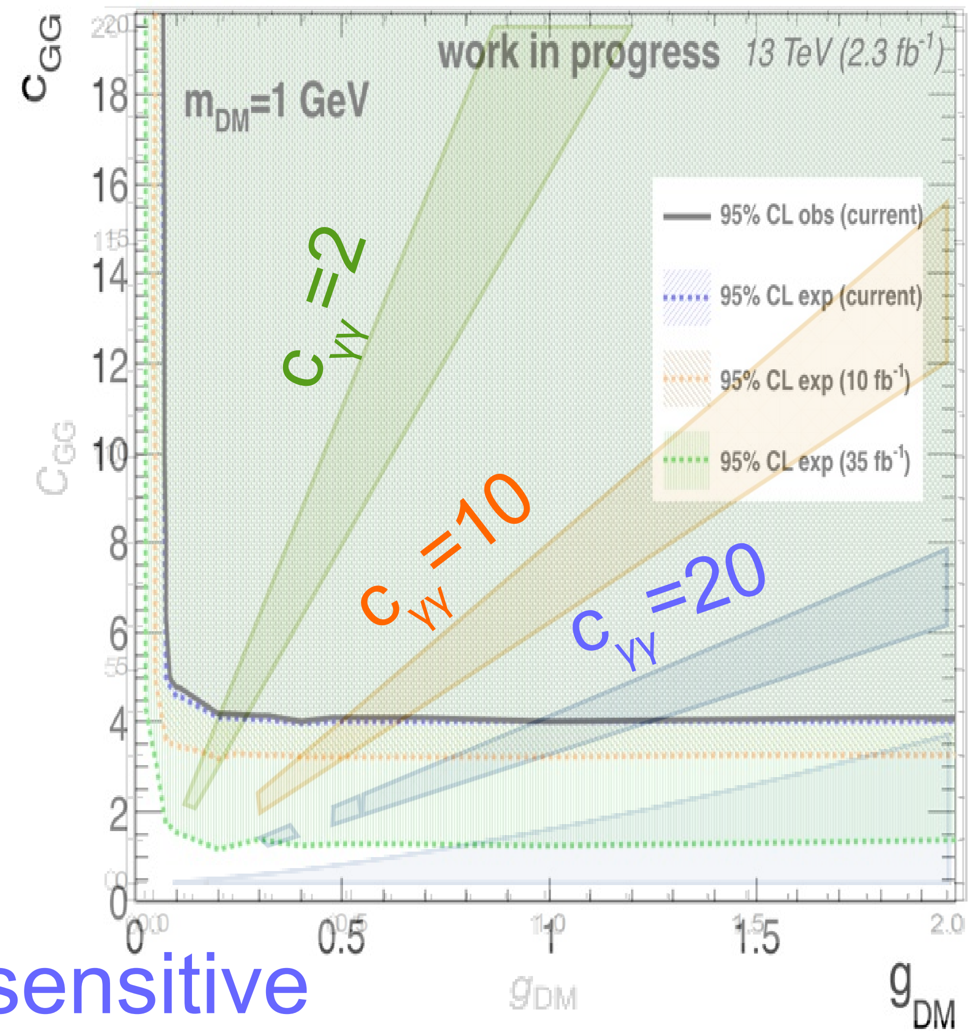


- Direct detection not yet sensitive
- Indirect detection limits on-shell production
- Photon Line bounds limit photon coupling < 100

Considering All Constraints

For a pseudoscalar





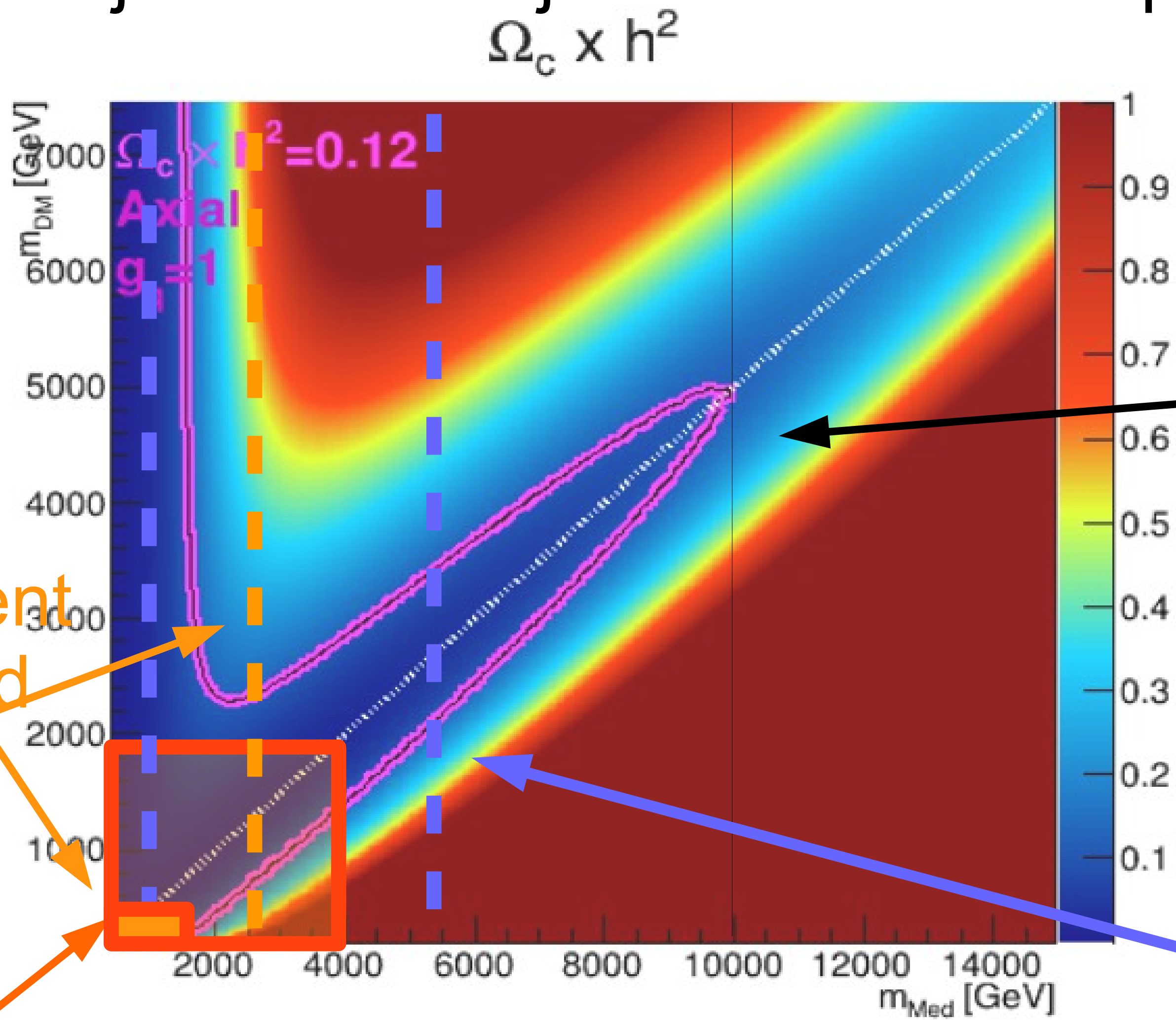
- Direct detection not yet sensitive
- Indirect detection limits on-shell production
- Photon Line bounds limit photon coupling < 100

Outlook

Hep-ph/1603.08525
Hep-ph/1509.02904
ATL-PHYS-PUB-2015-004

Outlook

- Spin 1 :
  - Dijet and monojet will continue to push out the bounds



Mediator mass Maxes out around 8-9 TeV

Smaller for coupling g_q<1

Current bound

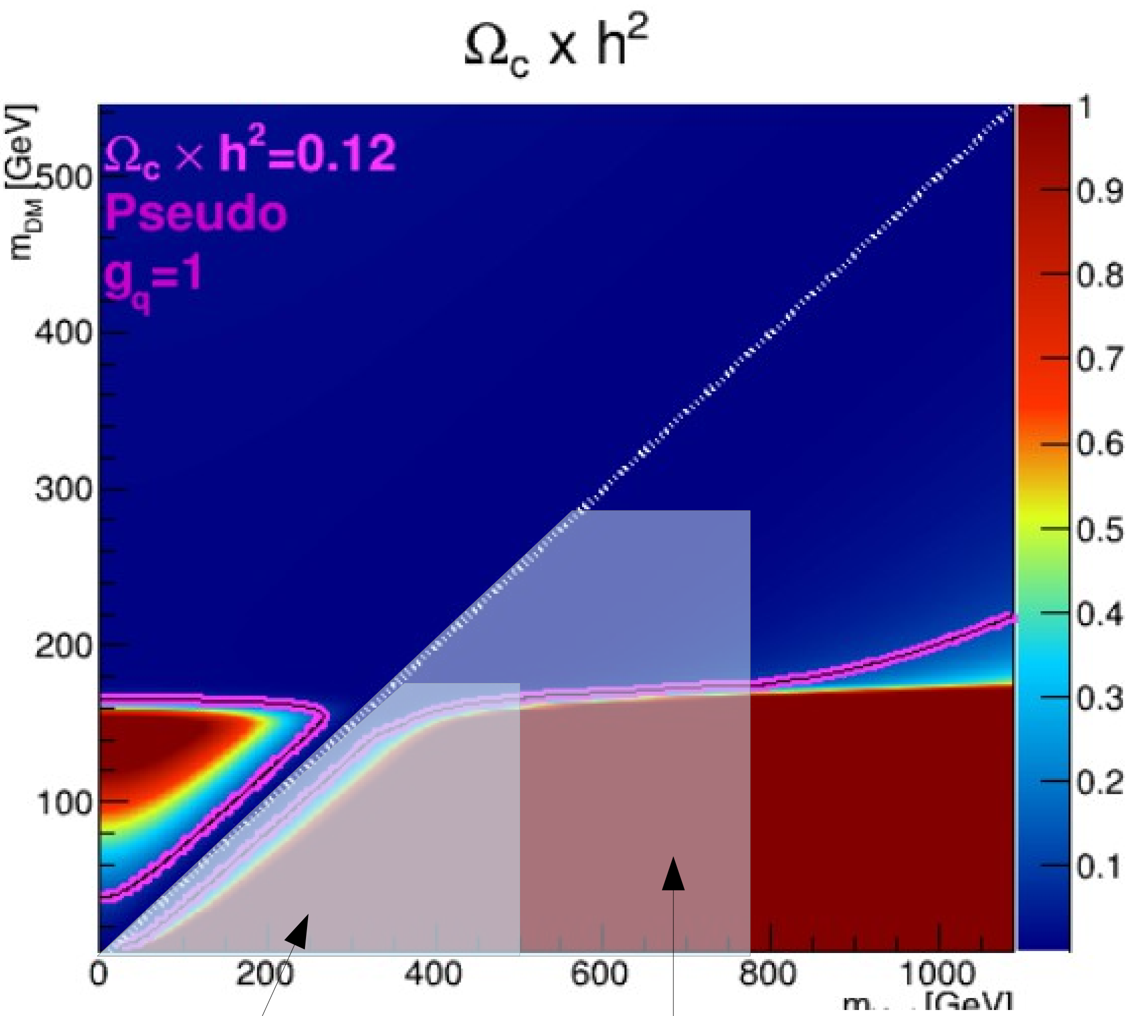
Approximate region monojet can probe

Approximate dijet reach

Hep-ph/1603.08525
Hep-ph/1509.02904
EXO-12-055
HIG-16-012

Outlook

- Spin 0 :
  - Yet to truly coalesce in 13 TeV



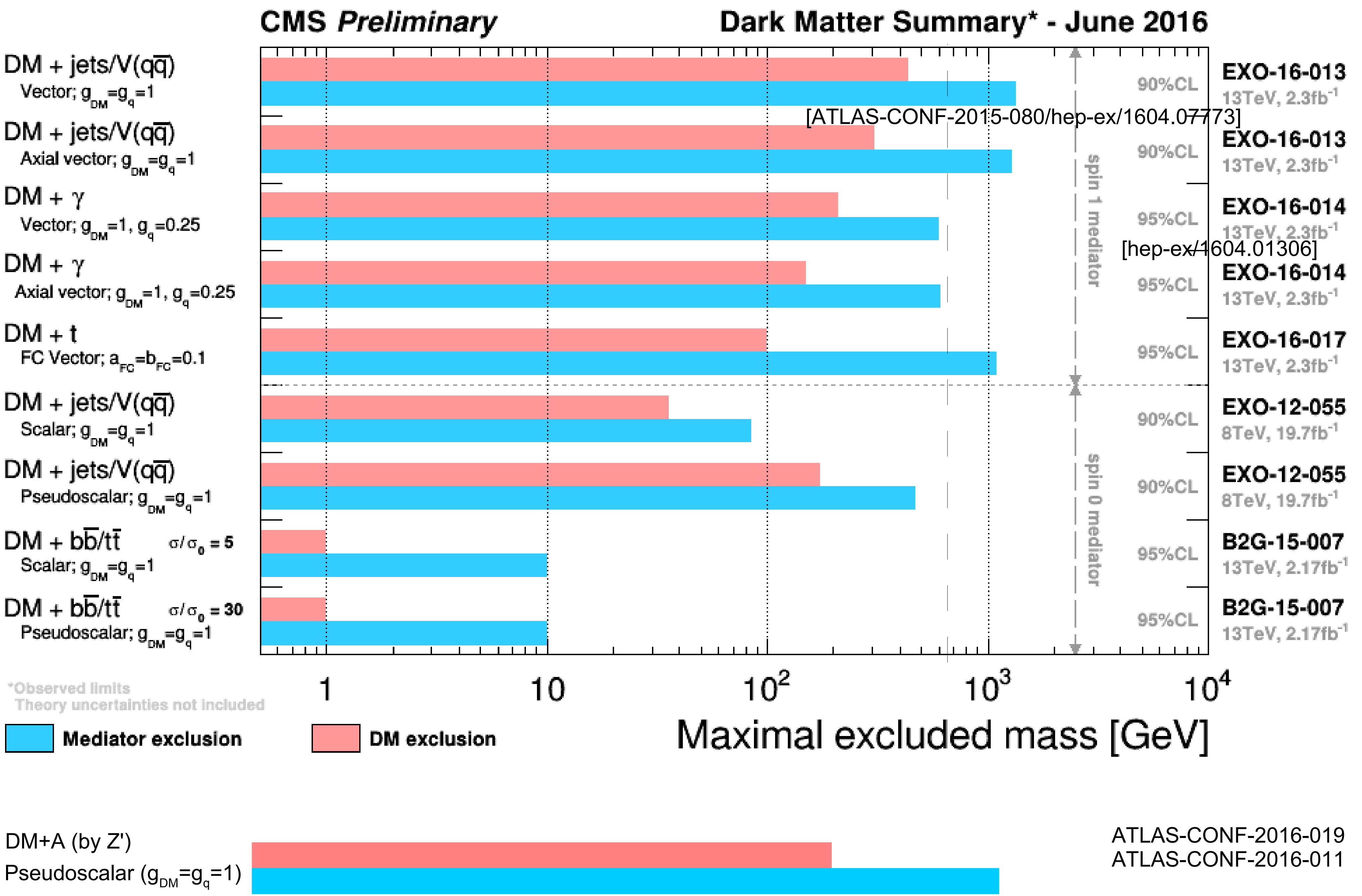
Current monojet   Approx future

Current reach for
Higgs-like Scalar
w/EWSB + no mixing

Mono-Z : 130 GeV
VBF : 250 GeV
Mono-V/j : 150 GeV

Heavy Flavor :
1st bb/tt+φ result
No exlcusion yet

Summary



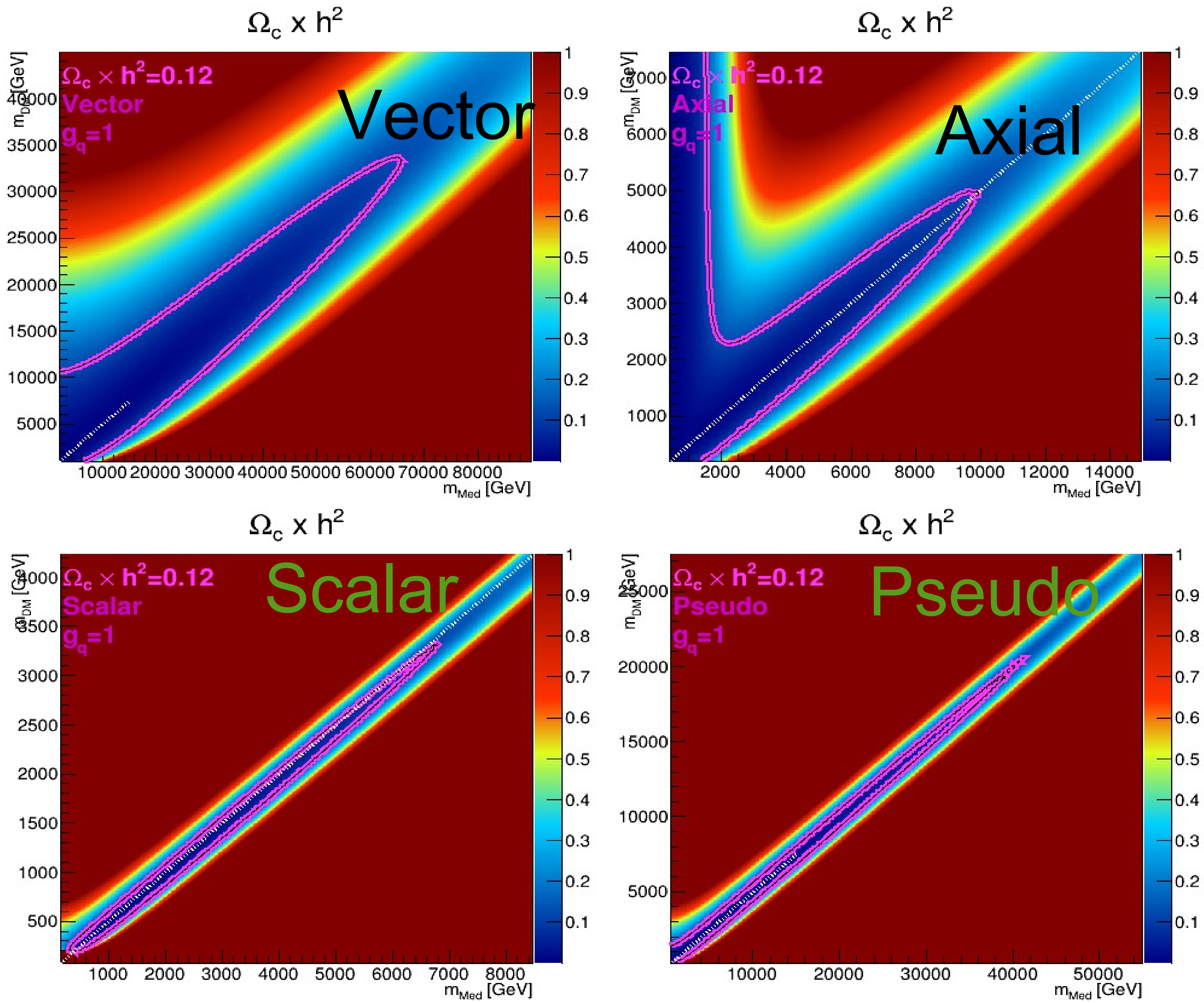
CMS Preliminary
Dark Matter Summary* - June 2016
DM + jets/V(qq̄)
Vector; g_DM=g_q=1
EXO-16-013
13TeV, 2.3fb-1
90%CL
[ATLAS-CONF-2015-080/hep-ex/1604.07773]
DM + jets/V(qq̄)
Axial vector; g_DM=g_q=1
EXO-16-013
DM + γ
Vector; g_DM=1, g_q=0.25
EXO-16-014
95%CL
[hep-ex/1604.01306]
DM + γ
Axial vector; g_DM=1, g_q=0.25
EXO-16-014
DM + t
FC Vector; a_FC=b_FC=0.1
EXO-16-017
DM + jets/V(qq̄)
Scalar; g_DM=g_q=1
EXO-12-055
8TeV, 19.7fb-1
DM + jets/V(qq̄)
Pseudoscalar; g_DM=g_q=1
EXO-12-055
DM + bb̄/tt̄ σ/σ_0 = 5
Scalar; g_DM=g_q=1
B2G-15-007
13TeV, 2.17fb-1
DM + bb̄/tt̄ σ/σ_0 = 30
Pseudoscalar; g_DM=g_q=1
B2G-15-007
spin 1 mediator
spin 0 mediator
1
10
10^2
10^3
10^4
Maximal excluded mass [GeV]
*Observed limits
Theory uncertainties not included
Mediator exclusion
DM exclusion
DM+A (by Z')
Pseudoscalar (g_DM=g_q=1)
ATLAS-CONF-2016-019
ATLAS-CONF-2016-011

Thanks

감사합니다

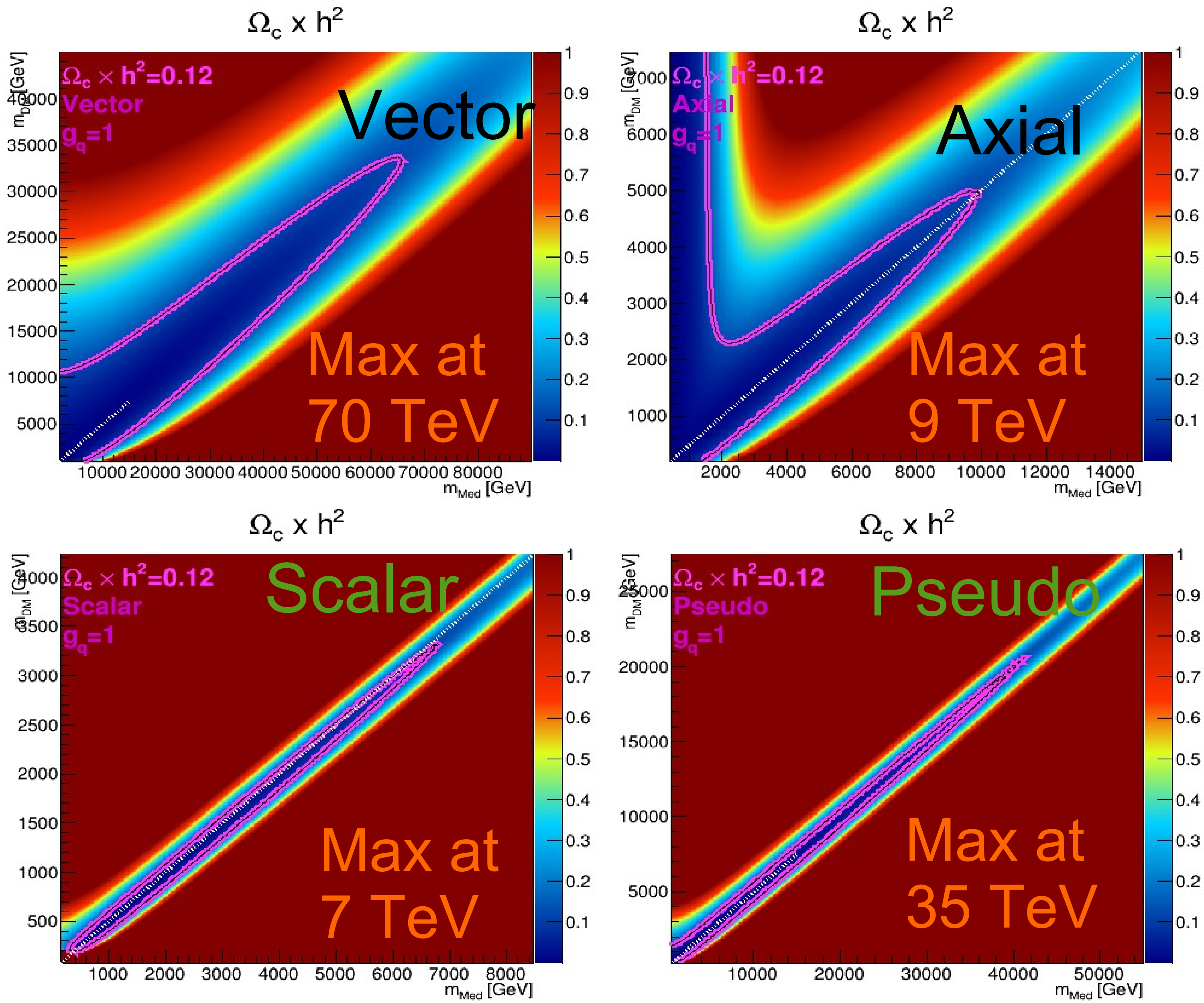
How does it look for our 4 friends?

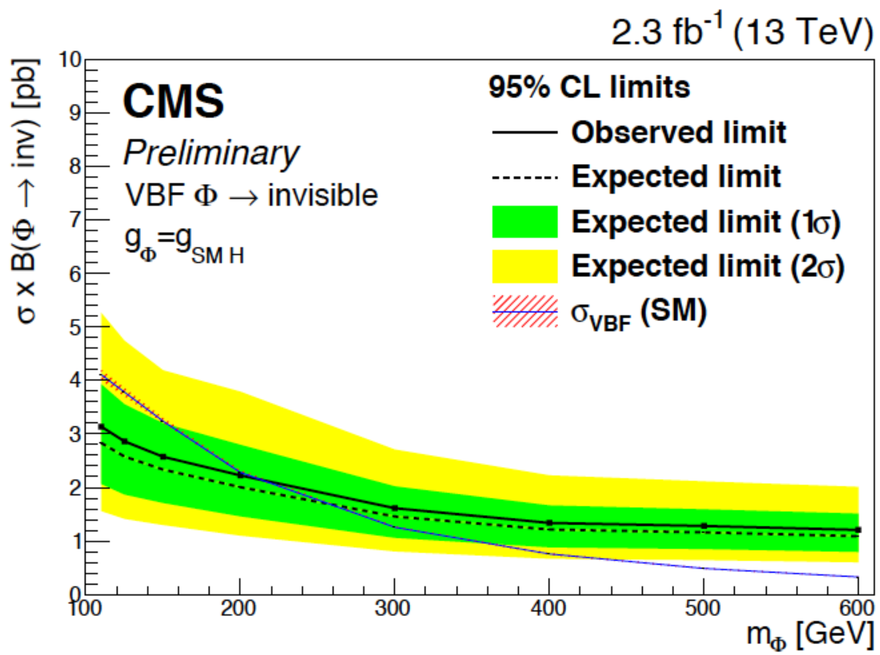
Coupling is set to 1 for all plots



How does it look for our 4 friends?

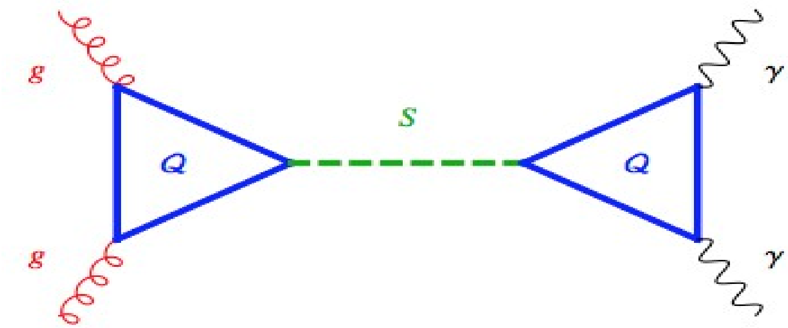
Coupling is set to 1 for all plots



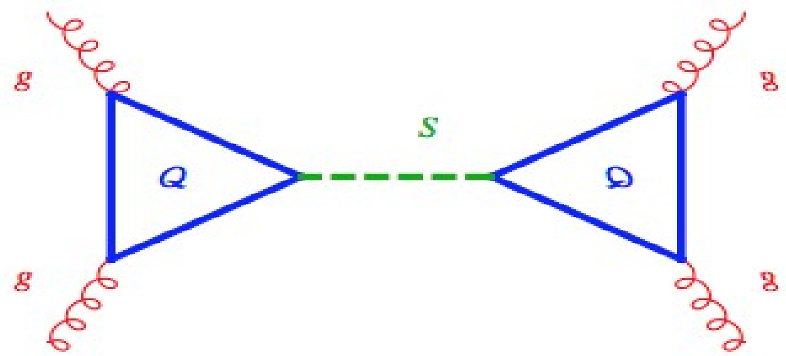

2.3 fb^{-1} (13 TeV)
CMS
Preliminary
VBF $\Phi \rightarrow$ invisible
$g_{\Phi}=g_{SM\ H}$
95% CL limits
Observed limit
Expected limit
Expected limit (1σ)
Expected limit (2σ)
σ_{VBF} (SM)
σ x B($\Phi \rightarrow$ inv) [pb]
m_{Φ} [GeV]
0
1
2
3
4
5
6
7
8
9
10
100
200
300
400
500
600

What are the decays

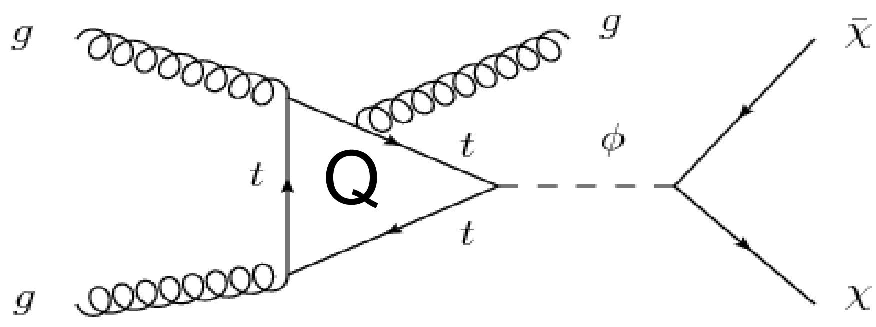
- We only really have a few decays:



Diphoton decays



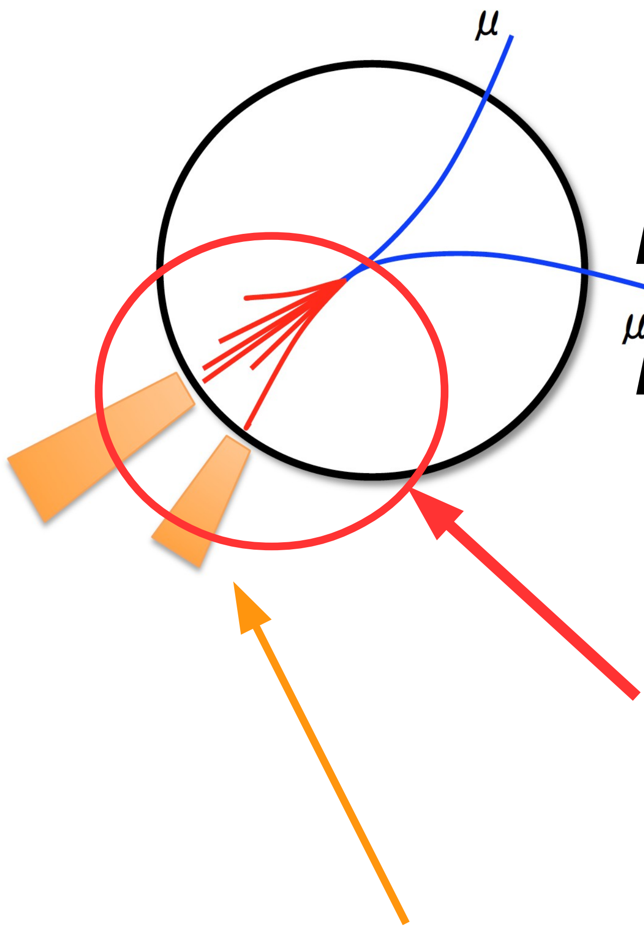
Dijet decays



Monojet decays

What goes into this?

- To find a signal we look for high *MET* :



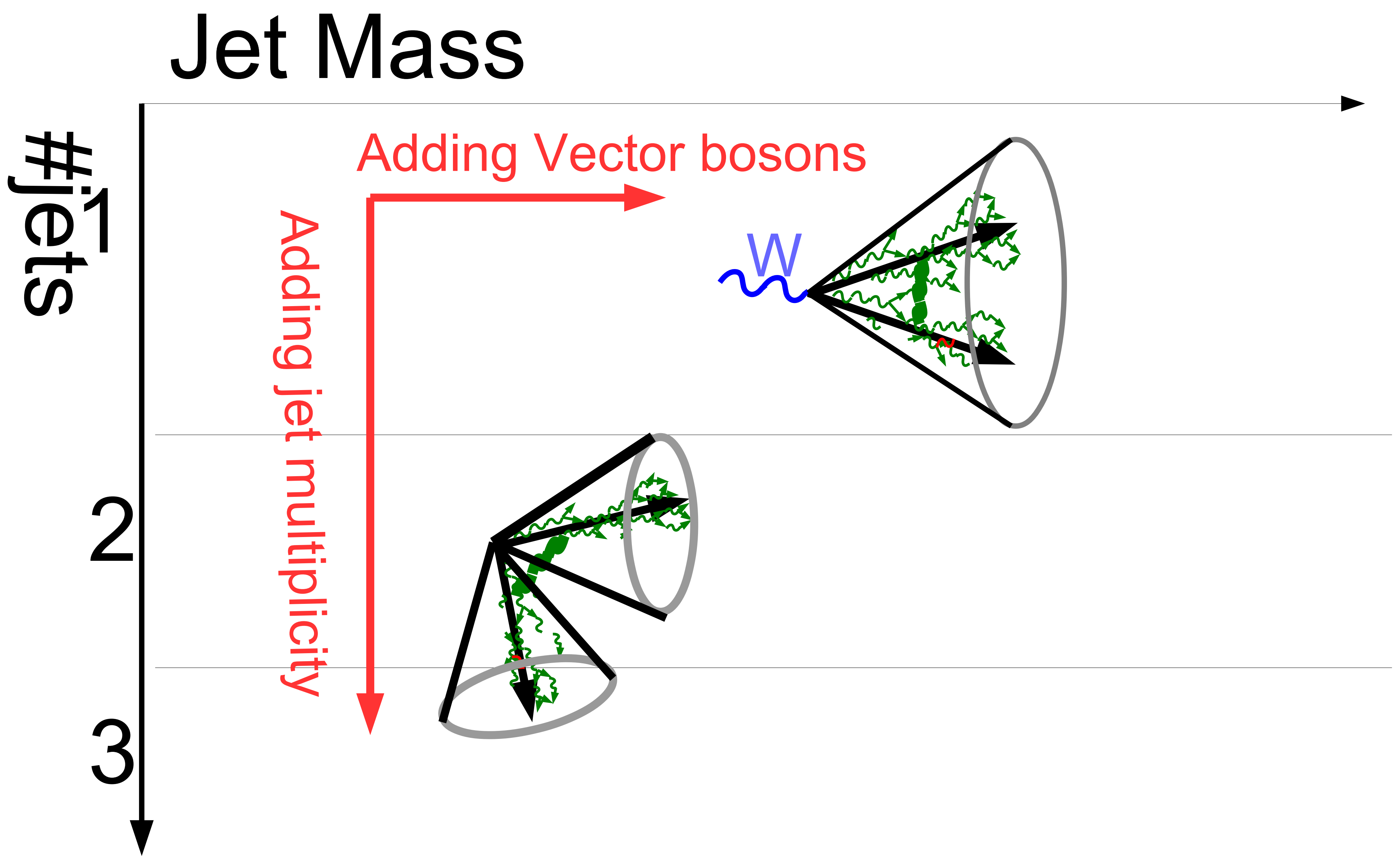
$$MET = -\Sigma_{All\ particles}\ p_T$$

$$MET(Z\rightarrow \nu\nu) = -\ Z\ recoil + p_T(\nu\nu)$$

Modeling of production mode is needed (HO corrections)

Modelling of the calorimeter response and resoltuion

Monojet Extenstion Plane



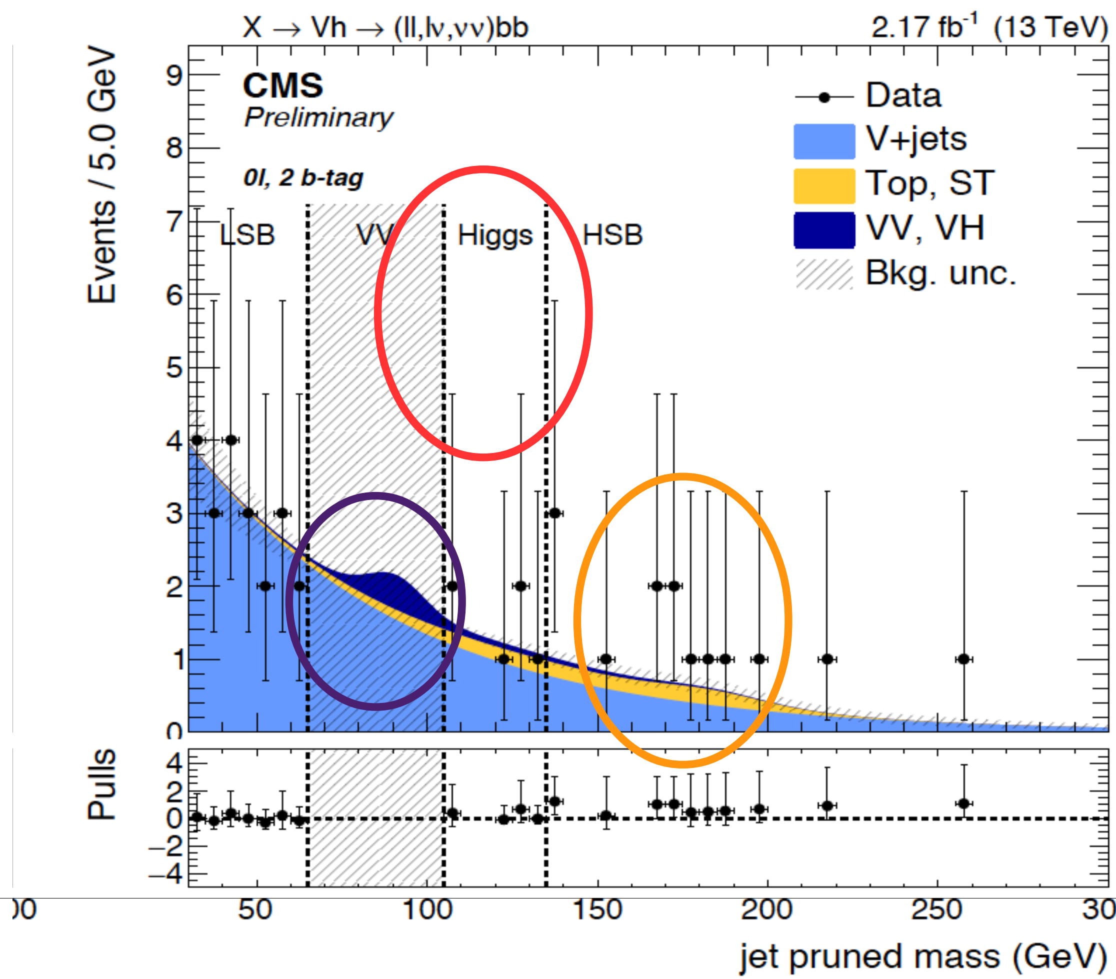
Monojet Extenstion #1 (V→qq)

Jet Mass

#jets

1

2



MET+V(qq),*MET*+H(bb),*MET*+t(qqb)

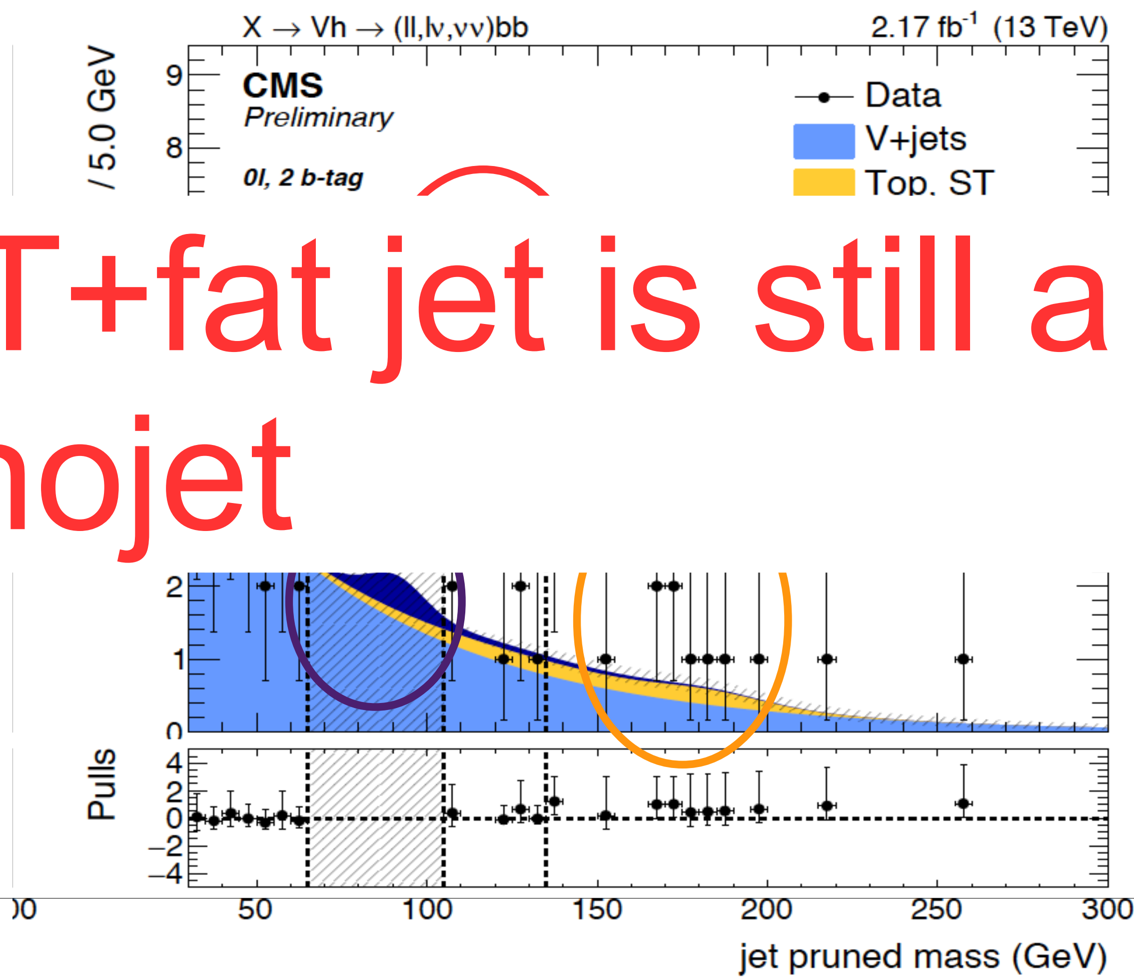
Beyond Monojet

Jet Mass

#jets

1

MET+fat jet is still a monojet

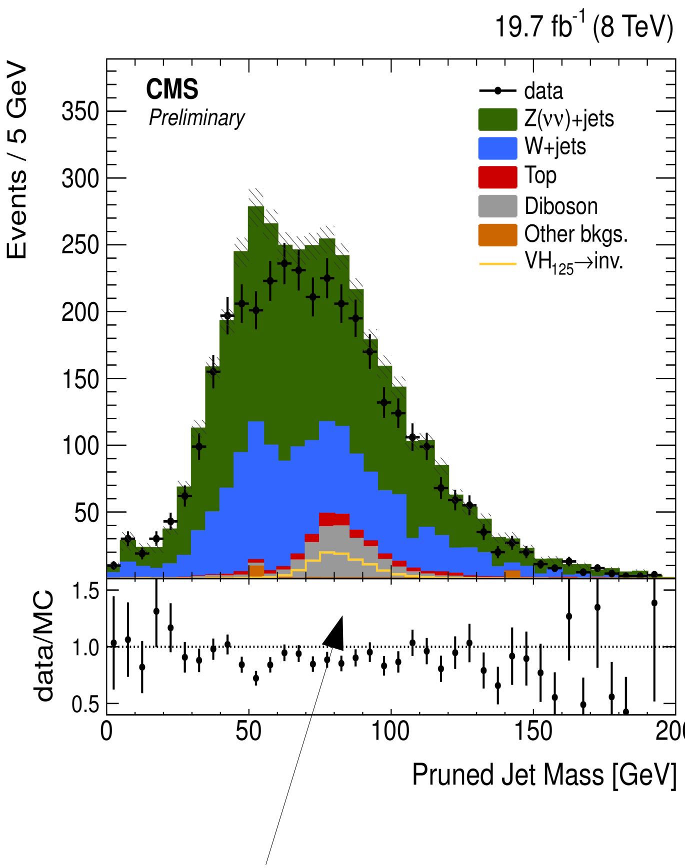


2

MET+V(qq),*MET*+H(bb),*MET*+t(qqb)

MET + fat jet

- There is no clean way to separate fat jets form jets



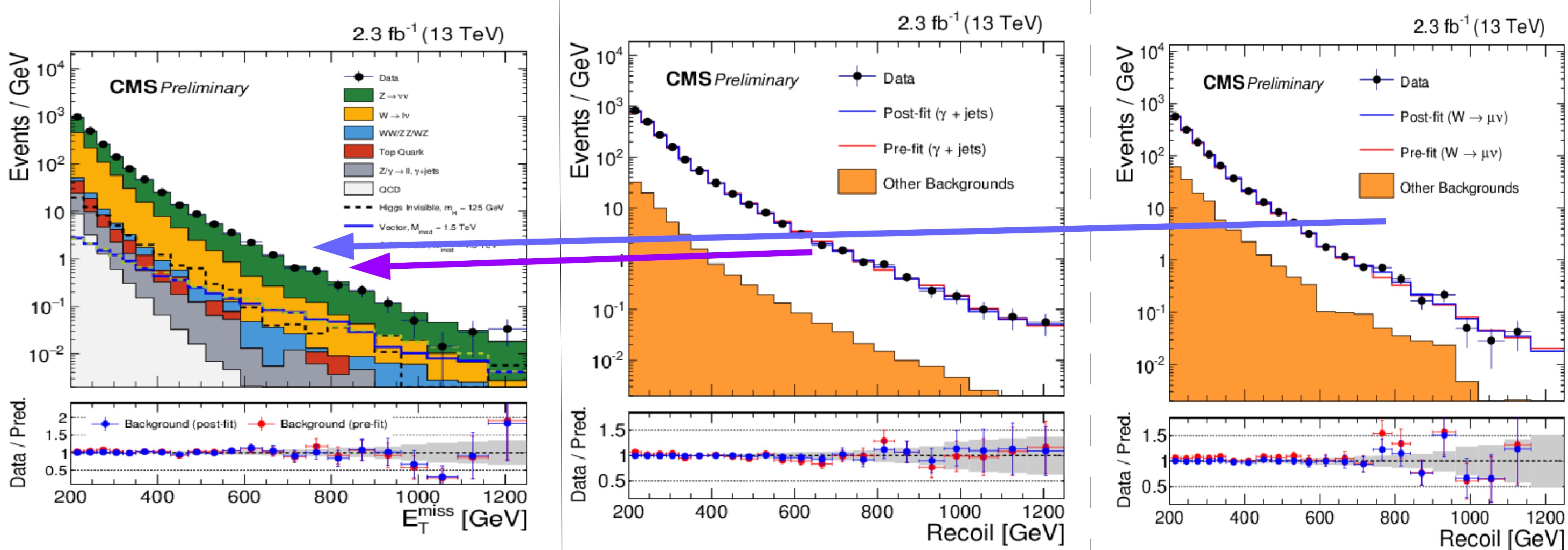
Is there room for improvement?

Yes

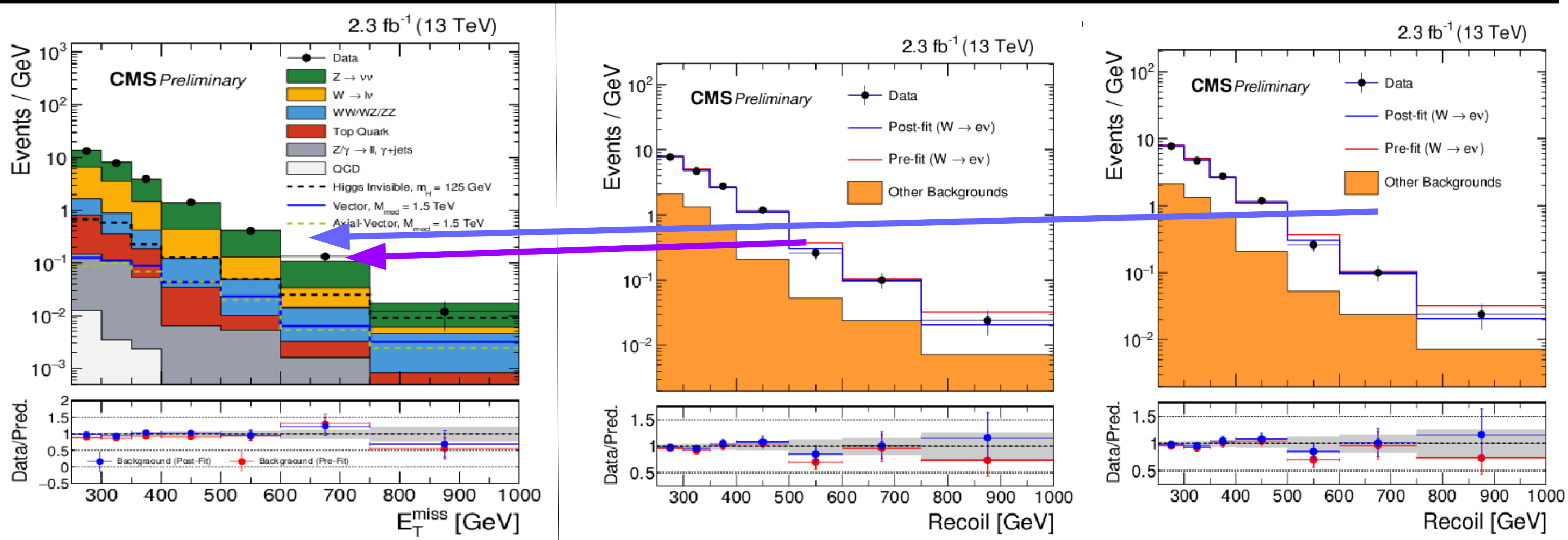
Currently require a simple :
jet mass cut + τ2/τ1

Signal | CRs: γ+jets | + W + ...

Monojet



Mono-V

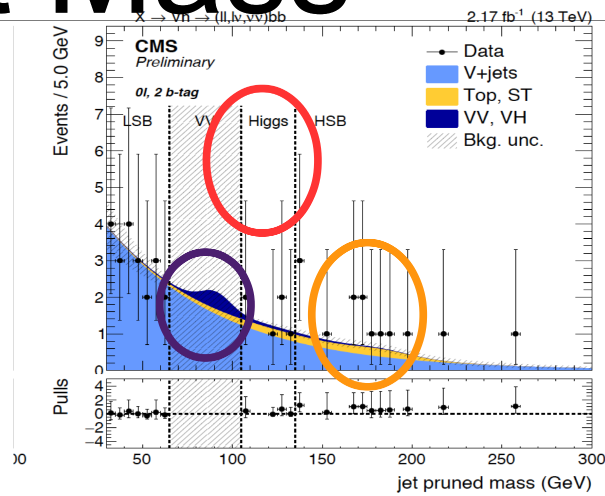


Beyond Monojet

Jet Mass

#jets

1

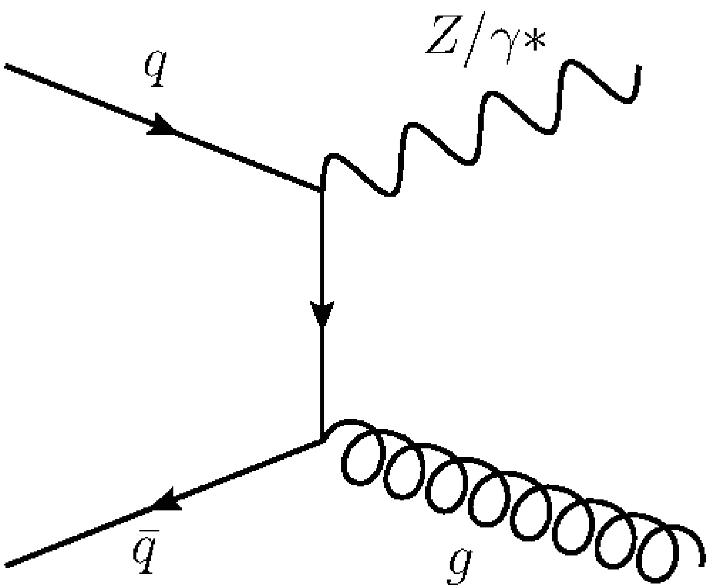


2

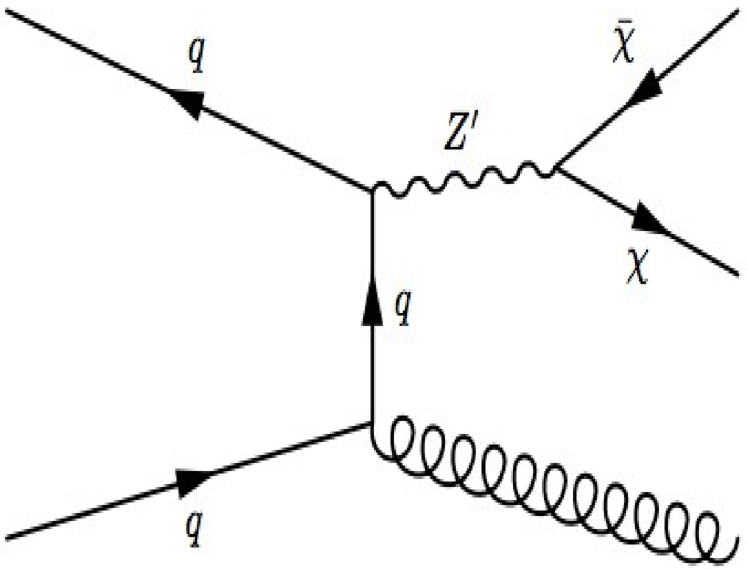
Using the 2nd jet or more can add to discrimination

3

Where do we gain from 2nd Jet?



VS



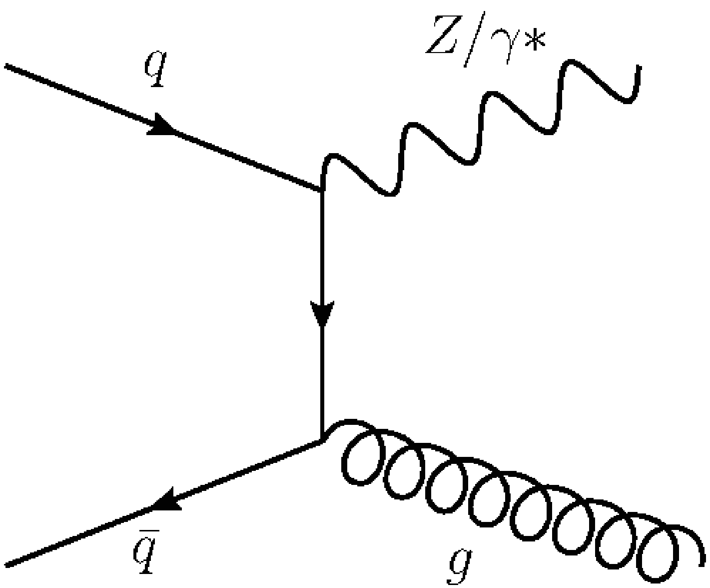
Background

Signal

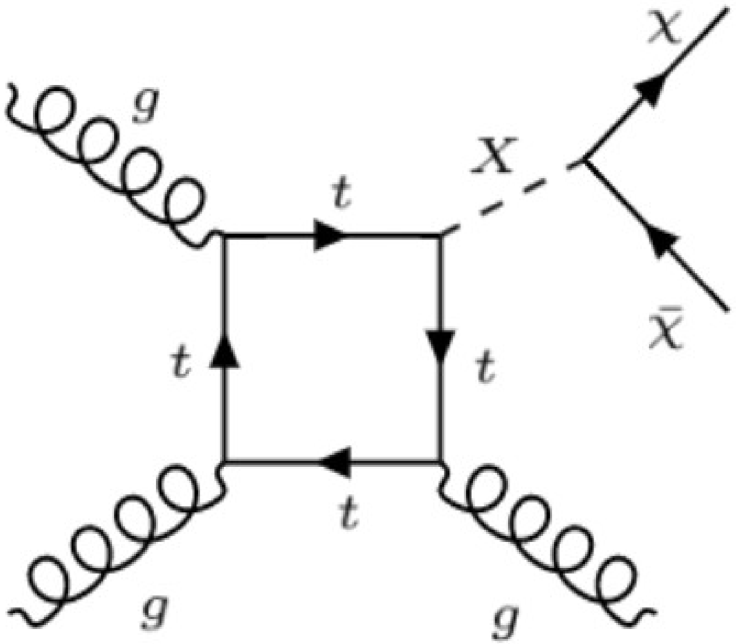
For Vector and Axial mediators not much

Only real difference is mediator mass

Where do we gain from 2nd Jet?



VS



Background

Signal

For Scalar and Pseudoscalar mediators more

Now the production modes are different

In addition to 2nd jet can consider a quarkgluon discriminator

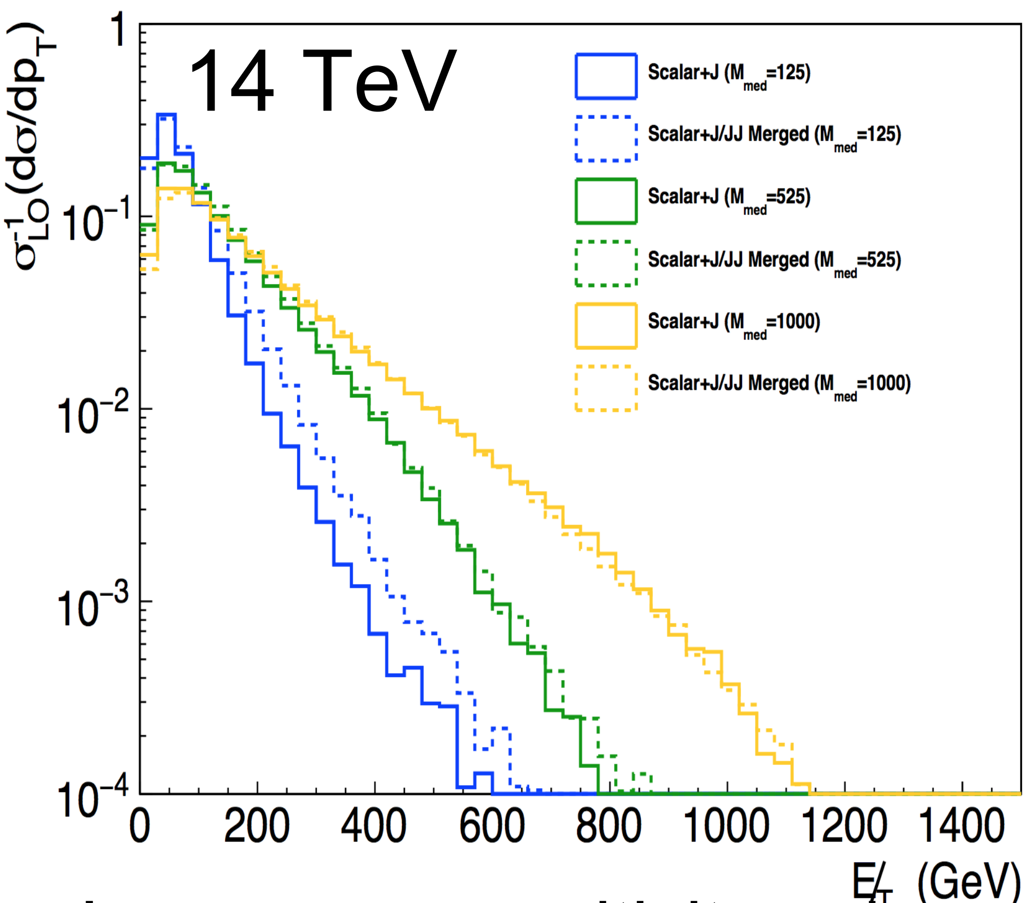
Spectrum of Signal MCs

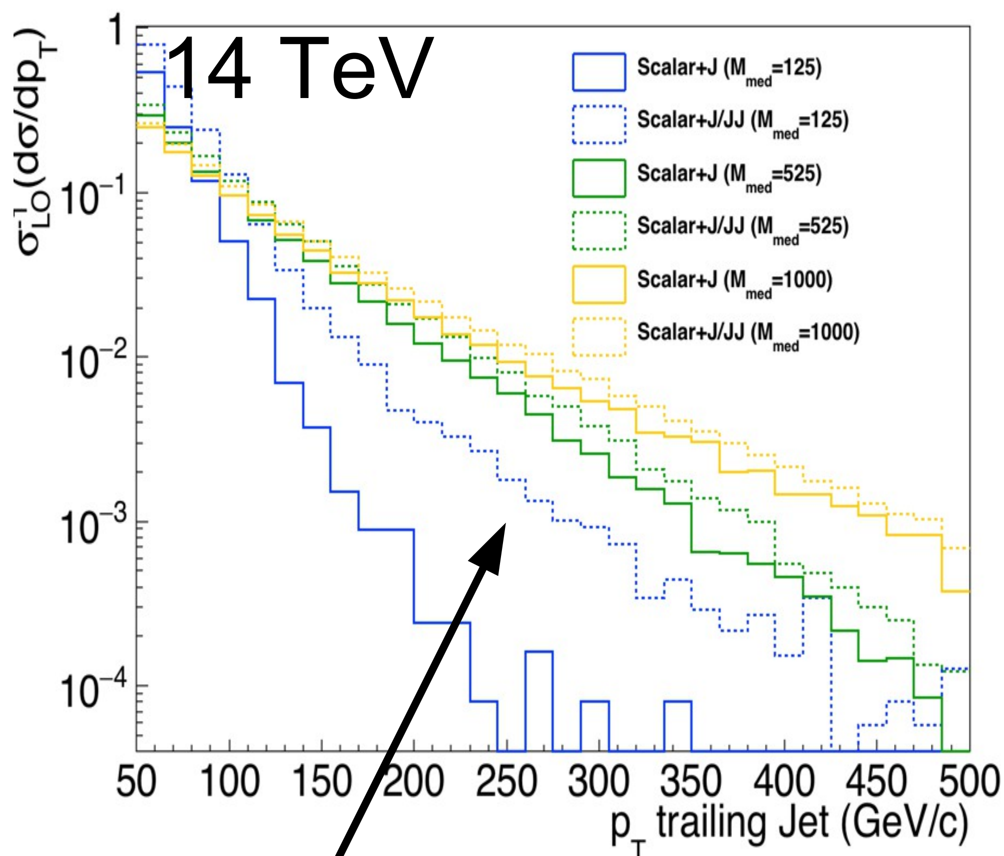
Sample	LO/ Leading Loop	LO in 2j	NLO,1,2j
Vector/ Axial	Madgraph MCFM	Powheg	aMC@NLO
Scalar/ Pseudoscalar	Powheg MCFM aMC@NLO	VBF@NLO aMC@NLO	

aMC@NLO+MG get highest order 1/2 jets merged

Advantage of merged MC

- Taking advantage of the new technology
  - Can consider exploring new regions of phase space

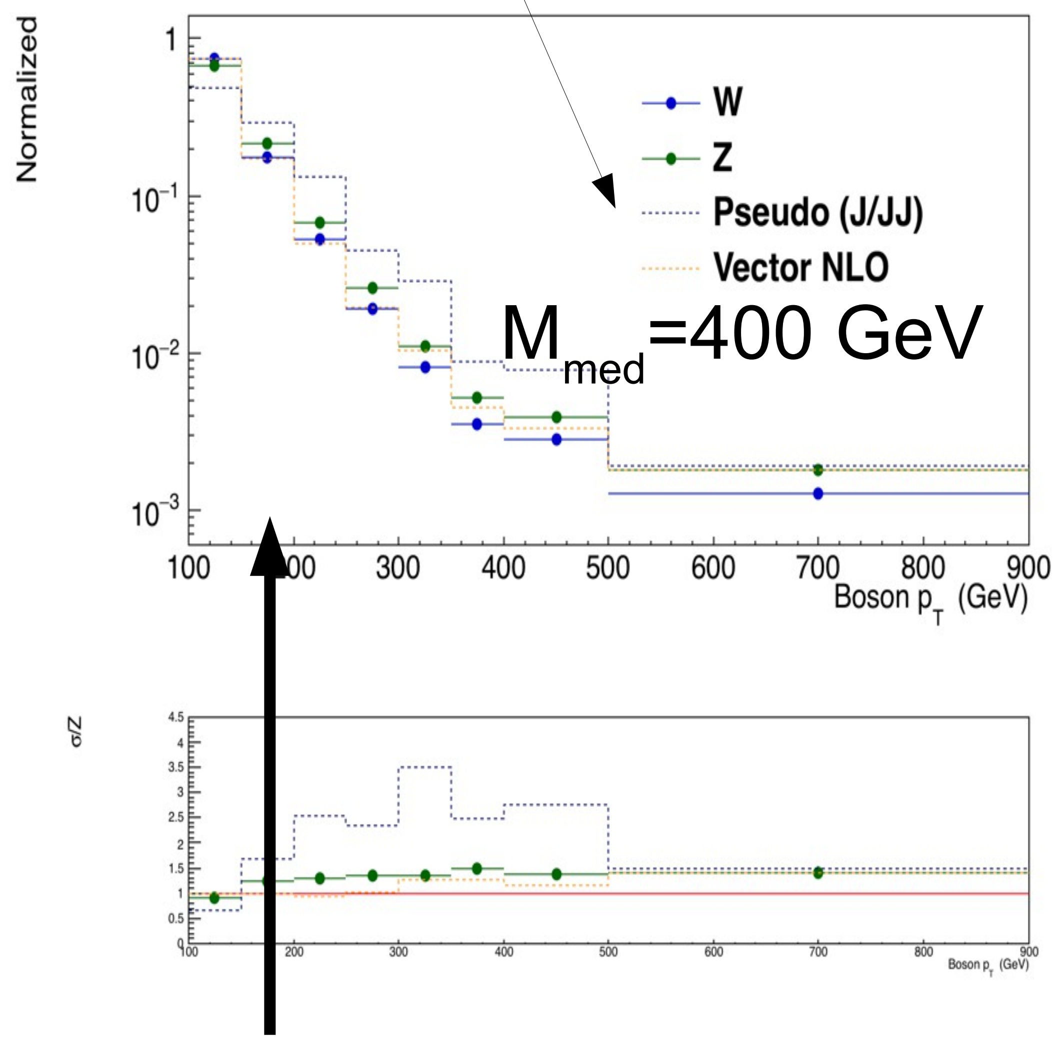


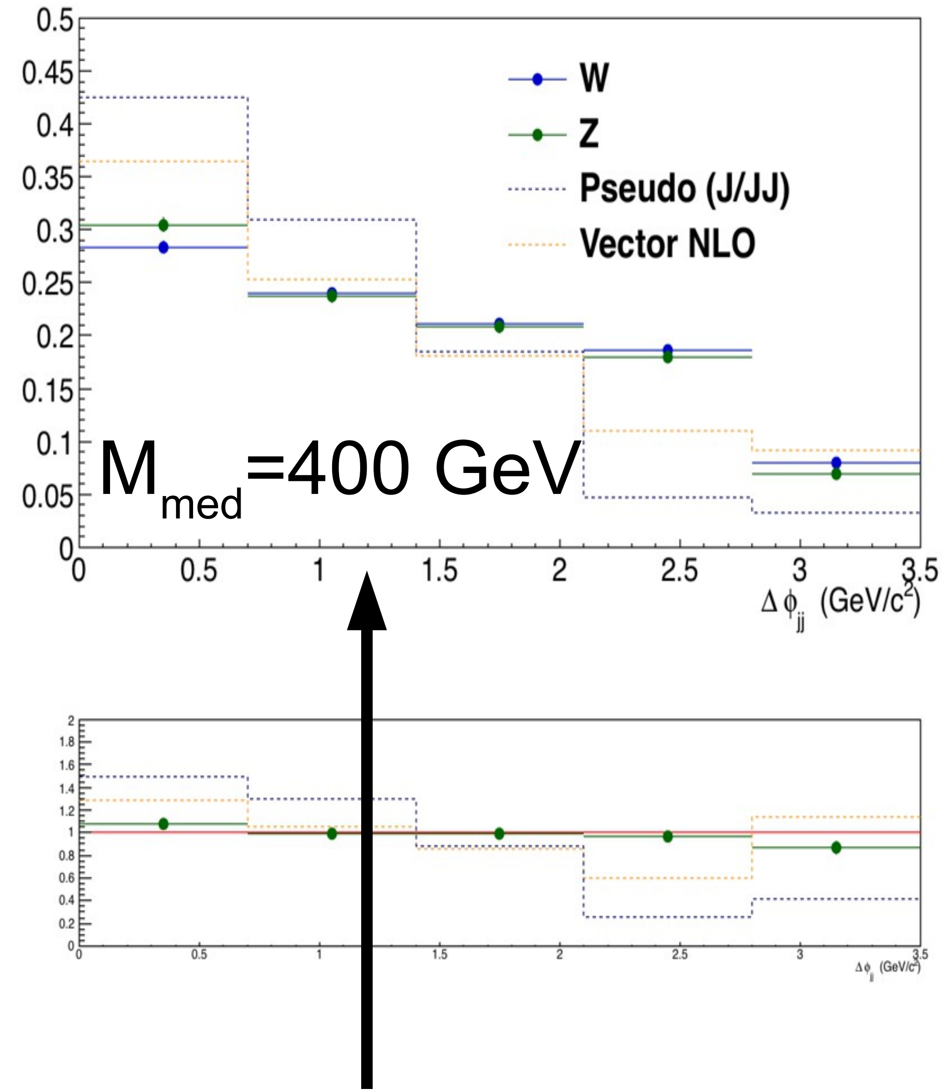


Low mass sensitivity enhanced in the multi jet final state

FYI aMC@NLO
merged 0,1,2jet
pseudoscalar

Basic Concept of Gains



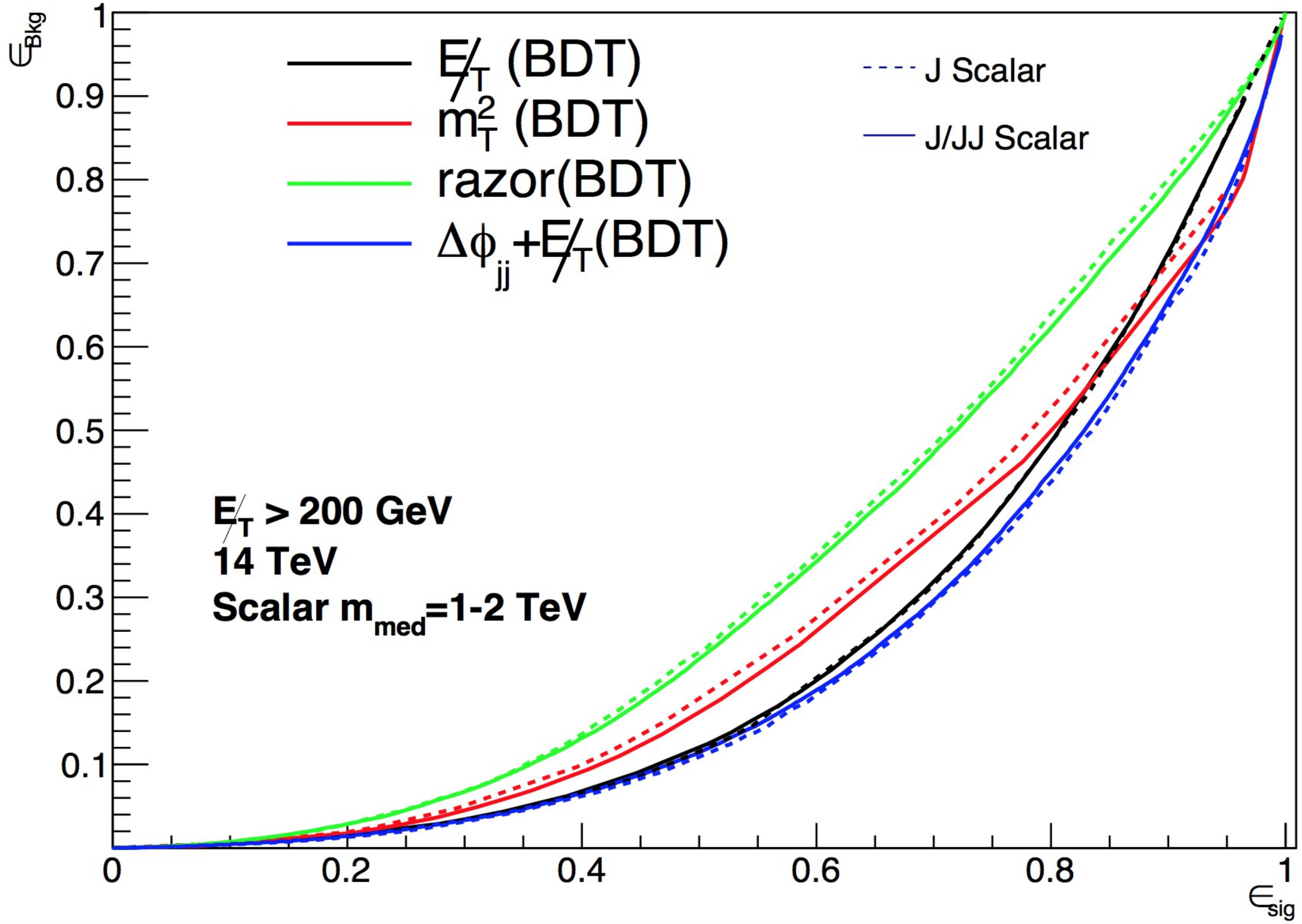


Gluon fusion induces
Higher pT spectrum

Heavier mediator forces
jets to be closer

How do the single variables perform?

- Comparison of single variables

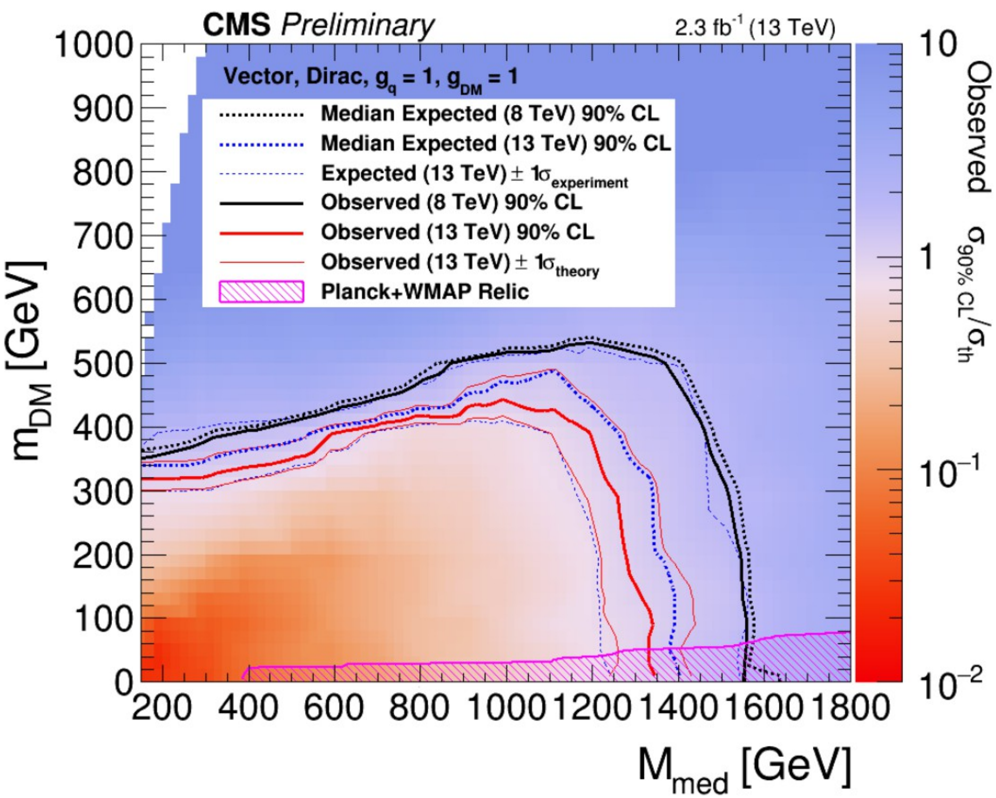


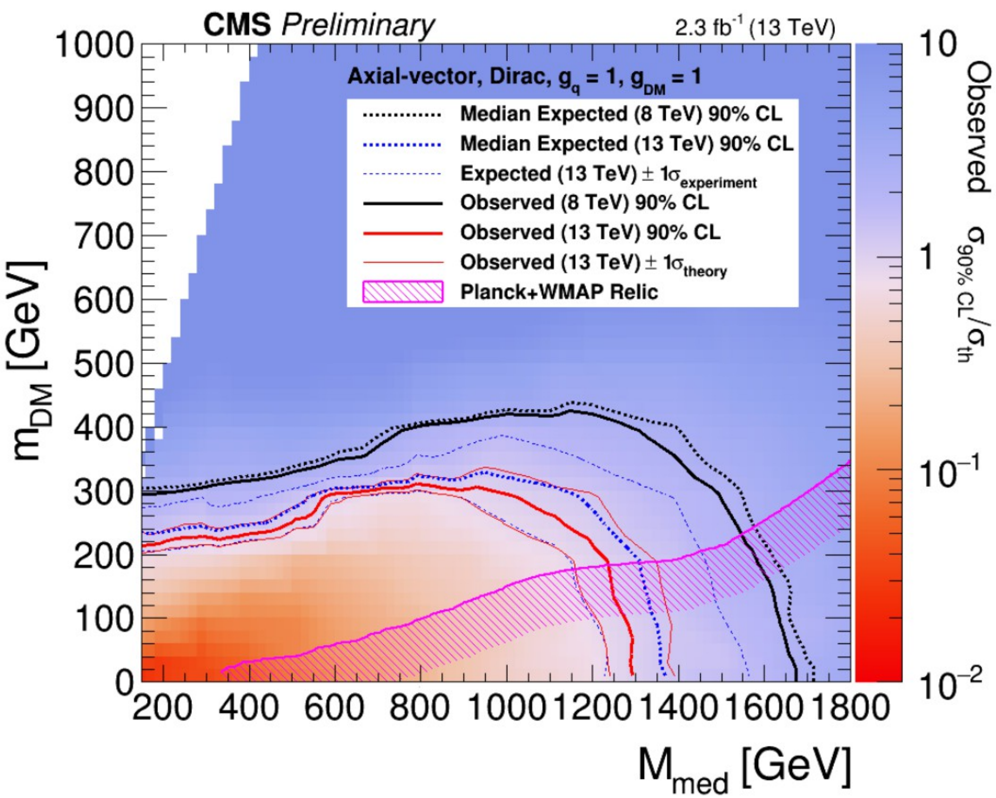
Gain comes from fact that light mass objects have collinear jets

Using $\Delta\varphi_{jj}$ can bring as much as 20% gain

Results

Our Current Public Results

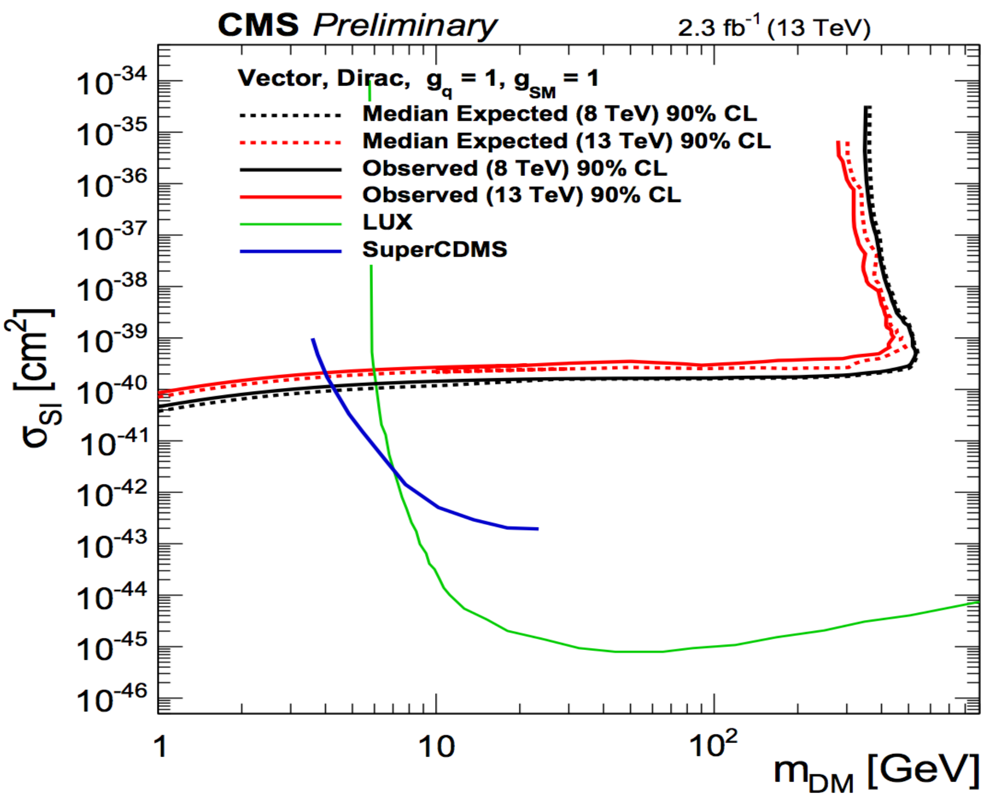


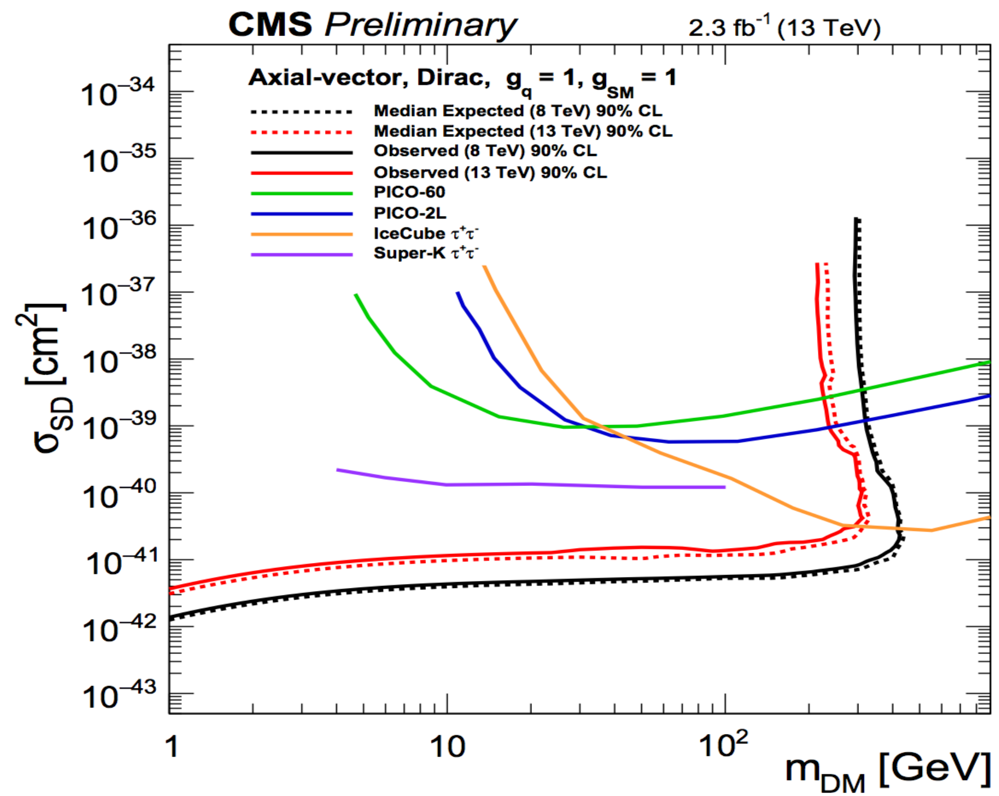


Both 13 TeV and 8 TeV analysis treat:
mono-V and monojet on equal footing

An 1-2σ excess is present in both data sets in tail

Our Current Public Results

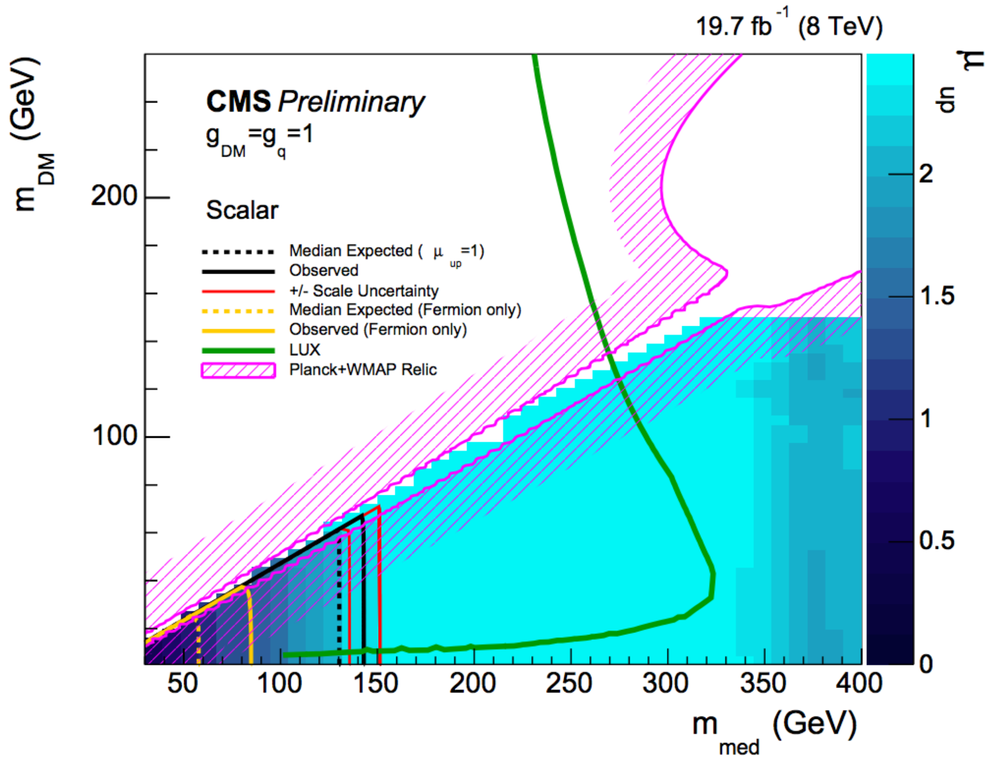


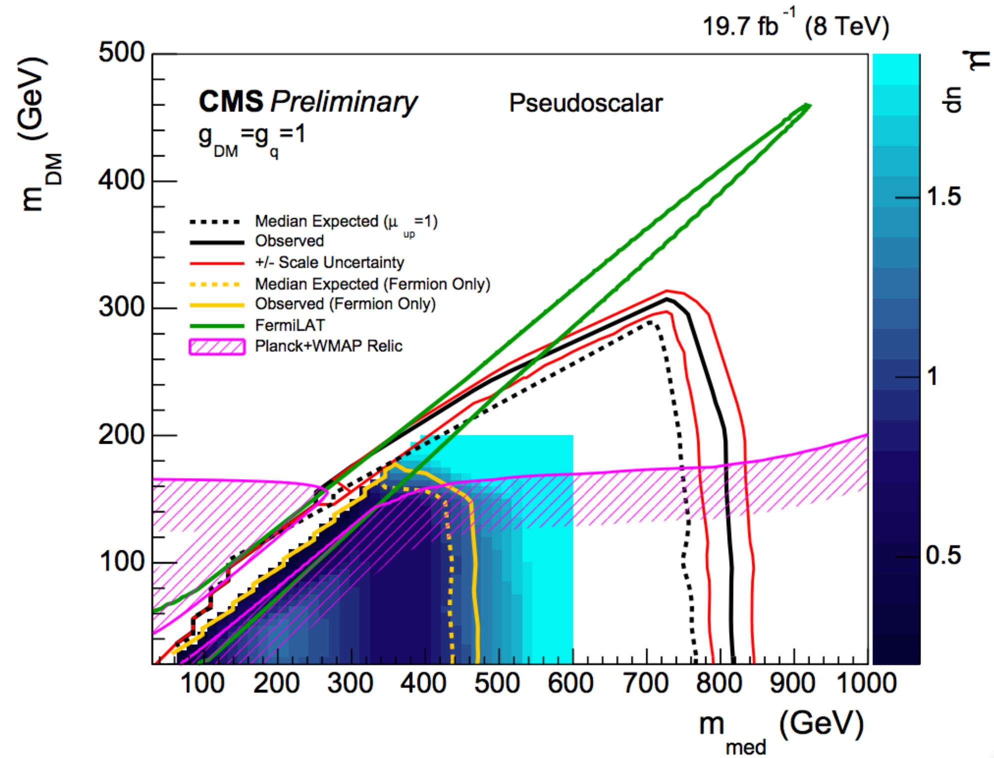


Translation to direct detection now standardized

An 1-2σ excess is present in both data sets in tail

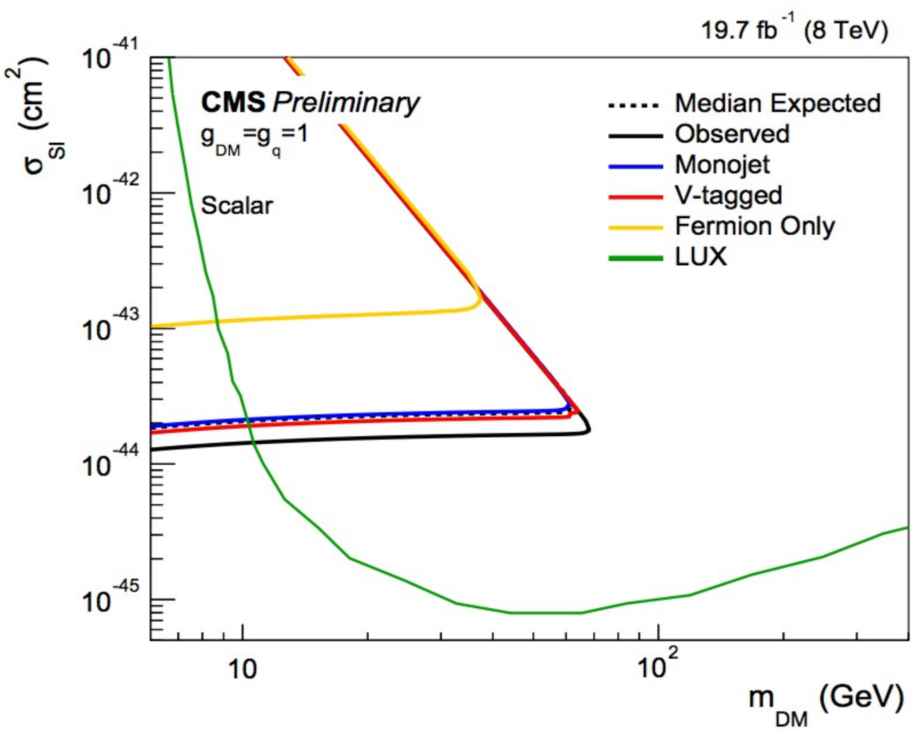
Our Current Scalar & Psuedo results

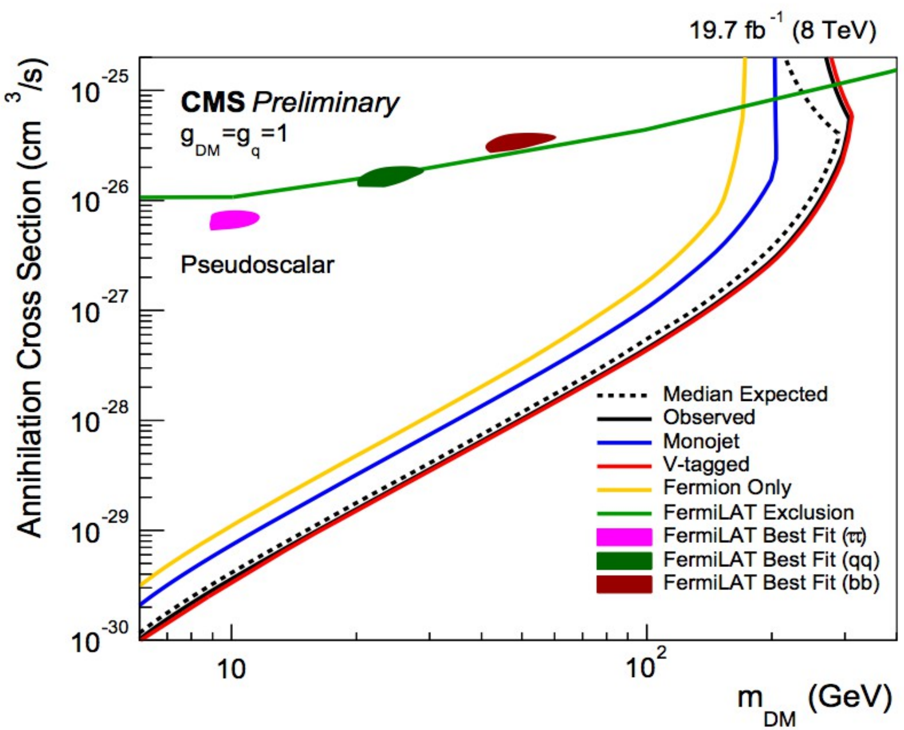




- Currently only have 8TeV exclusion
  - Yellow line : Official simplified models
  - Black/Red (controversial) : Simplified + EWSB
    - Allows us to add Higgsstrahlung

Our Current Scalar & Psuedo results

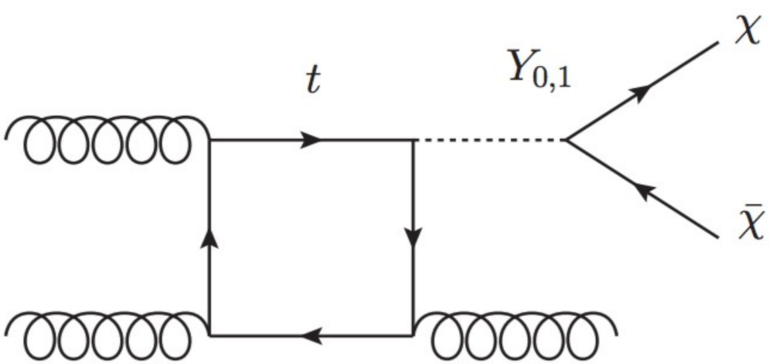


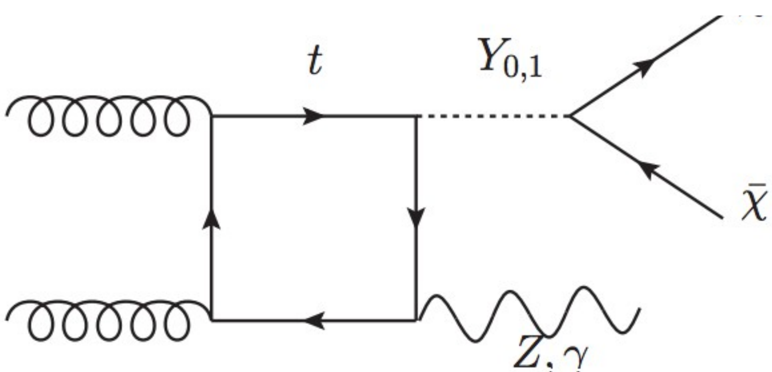


- When the dark matter is not onshell
  - Strong exclusion of pseudoscalar interpreation of LAT
  - Scalar and Direct detection are in close comopetition
    - Expect LHC to pass LUX this ~~summer~~ winter!

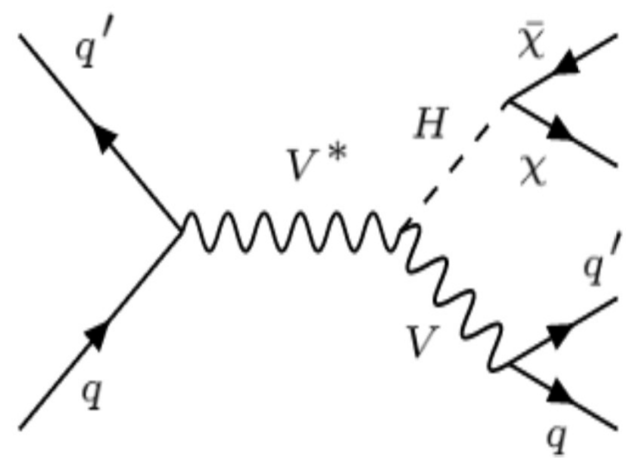
To break or not to break?

- EWK symmetry breaking adds lots of mono-V
  - Contribution can be very significant if pseudoscalar
- There are models that do that (e.g. 2HDM...)
  - Need physics at a higher scale (dim-7 operator)



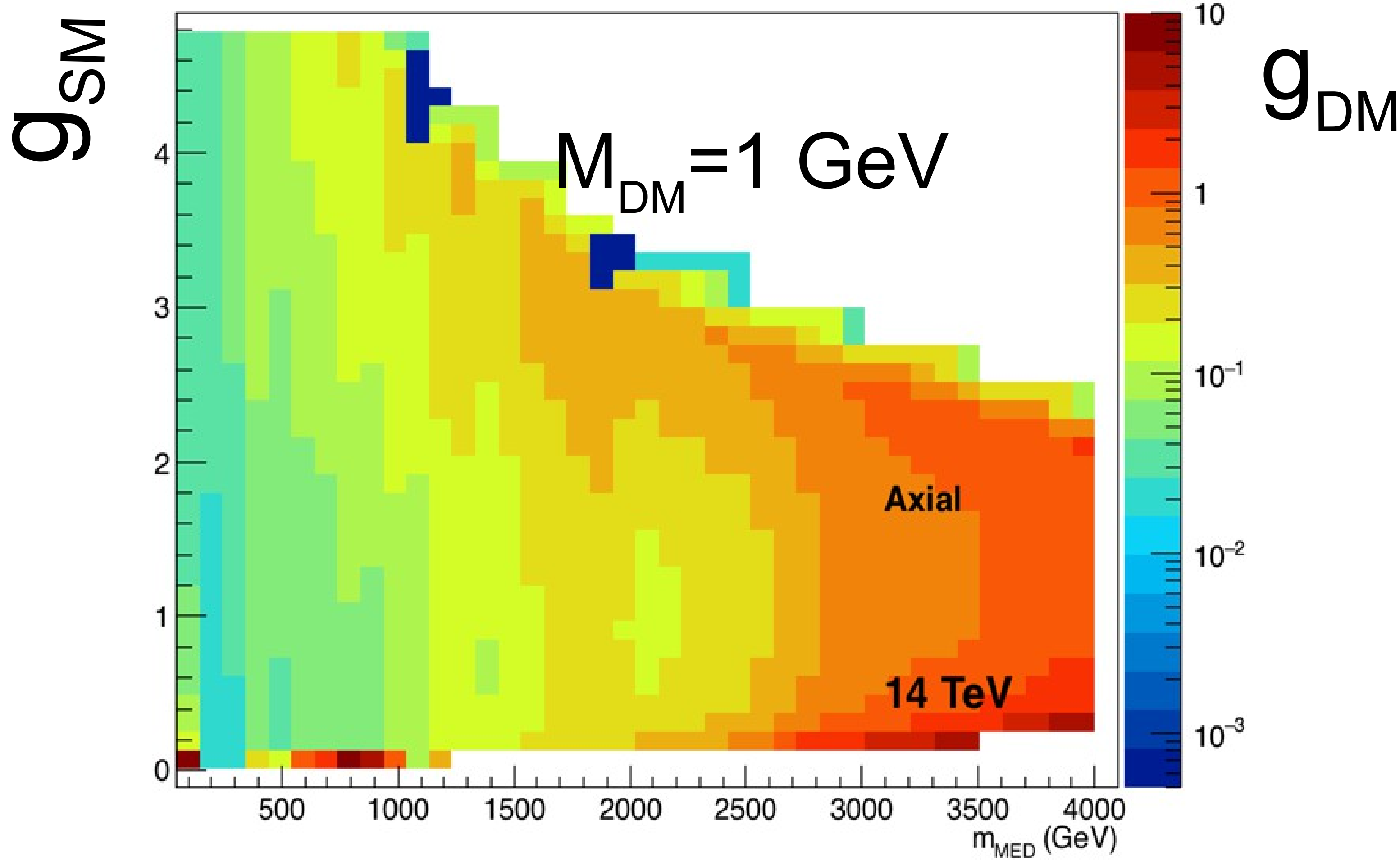


+?



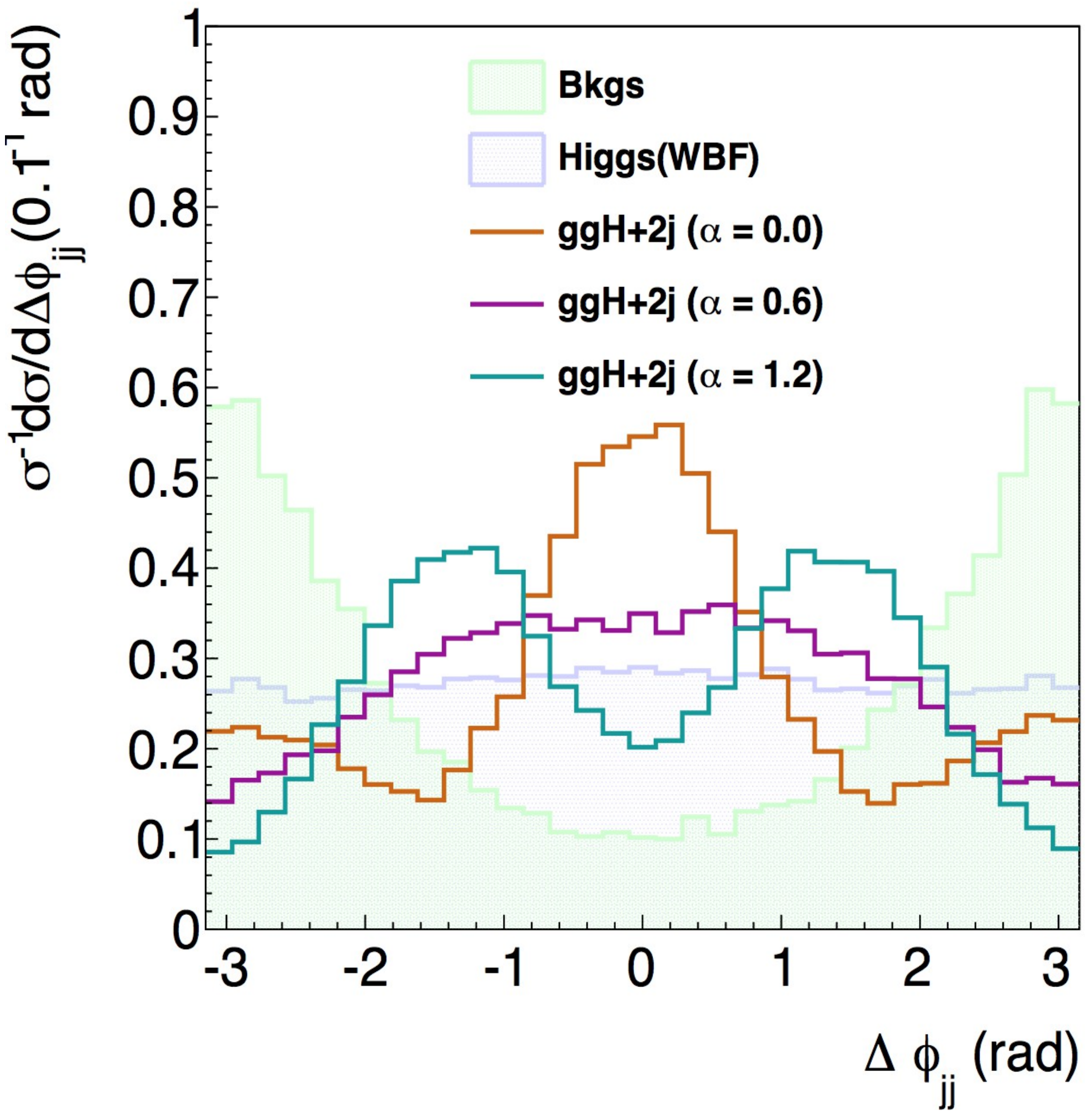
MIXING!?

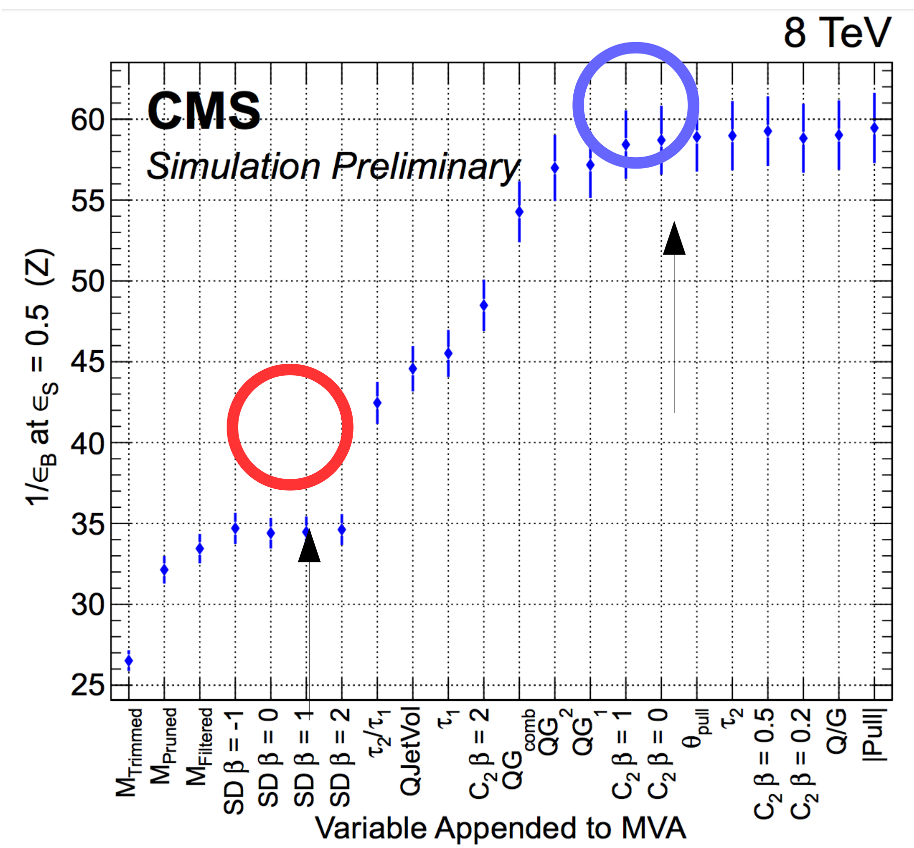
Extending Our results



Is it time to consider varying the couplings?

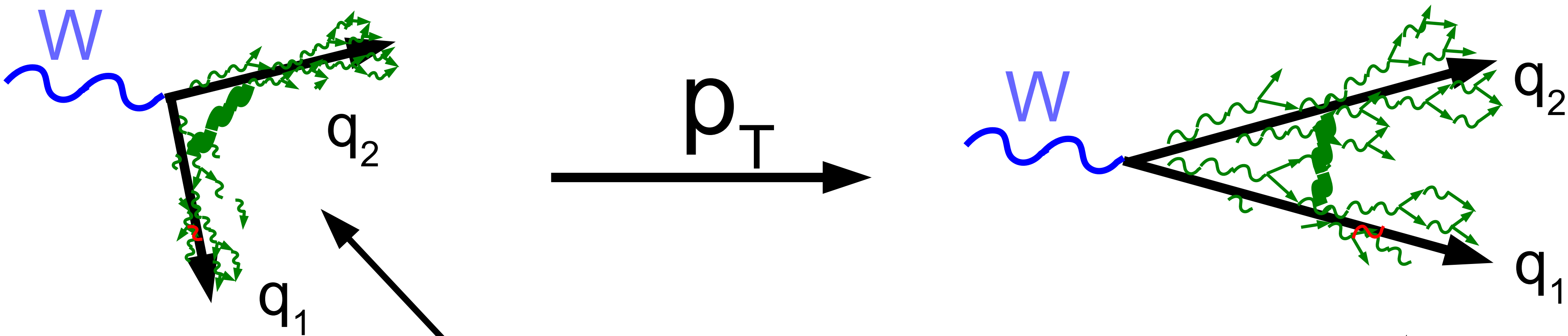
$$\mathcal{L}_{\text{axial}} \supset \frac{1}{2} m_{\text{MED}}^2 Z''_\mu Z''^\mu - g_{\text{DM}} Z''_\mu \bar{\chi}\gamma^\mu\gamma^5\chi - \sum_q g_{SM}^q Z''_\mu \bar{q}\gamma^\mu\gamma^5 q \,.$$


Bkgs
Higgs(WBF)
ggH+2j (α = 0.0)
ggH+2j (α = 0.6)
ggH+2j (α = 1.2)
$\sigma^{-1}d\sigma/d\Delta\phi_{jj}$ (0.1^{-1} rad)
$\Delta\,\phi_{jj}$ (rad)


8 TeV
CMS
Simulation Preliminary
$1/\epsilon_B$ at ϵ_S = 0.5 (Z)
Variable Appended to MVA
$M_{Trimmed}$
M_{Pruned}
$M_{Filtered}$
SD β = -1
SD β = 0
SD β = 1
SD β = 2
τ_2/τ_1
QJetVol
τ_1
C_2 β = 2
QG_{comb}
QG_2
QG_1
C_2 β = 1
C_2 β = 0
θ_{pull}
τ_2
C_2 β = 0.5
C_2 β = 0.2
Q/G
|Pull|

Building a V-tagger

- Evolution of effects



At low p_T "resolve" two jets : resolved tag

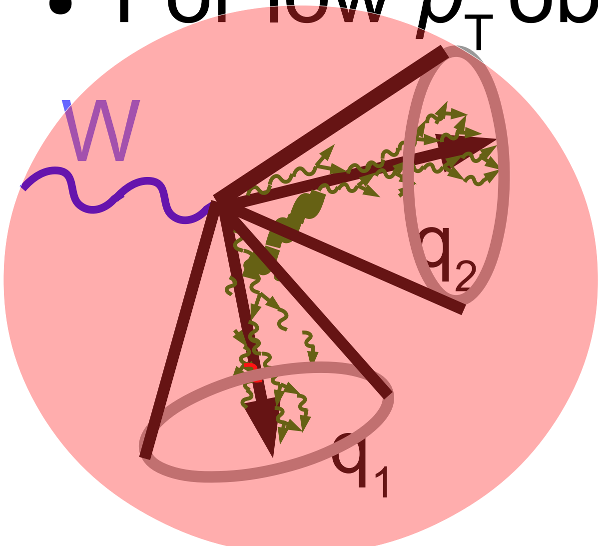
Focus on identifying <u>two</u> jets like a W

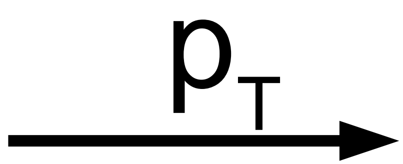
At high p_T we obtain one big jet

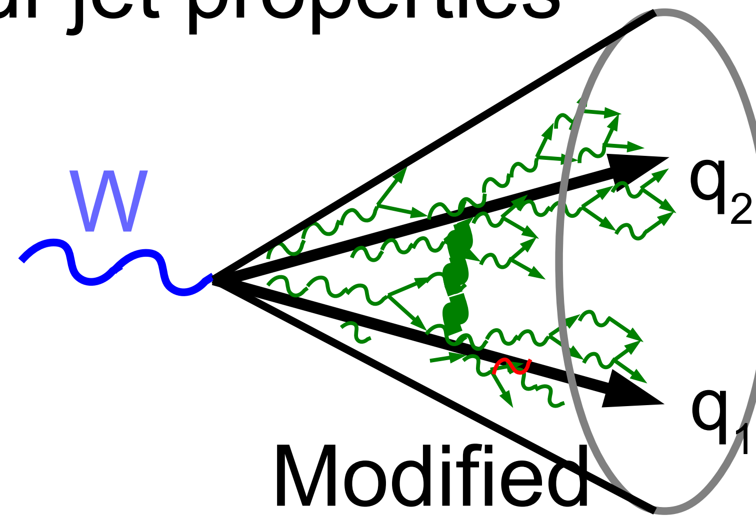
Focus on identifying <u>one</u> jet like a W

Resolved Tagger

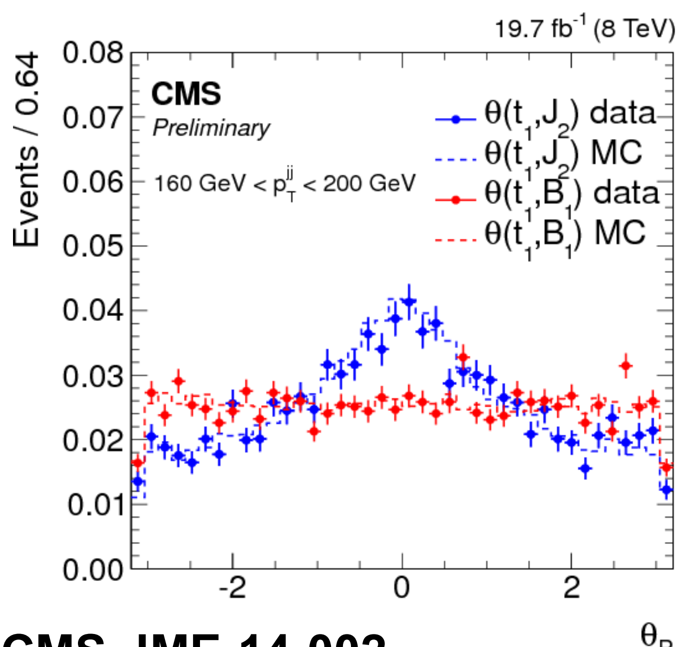
- For low p_T objects focus on di-jet properties

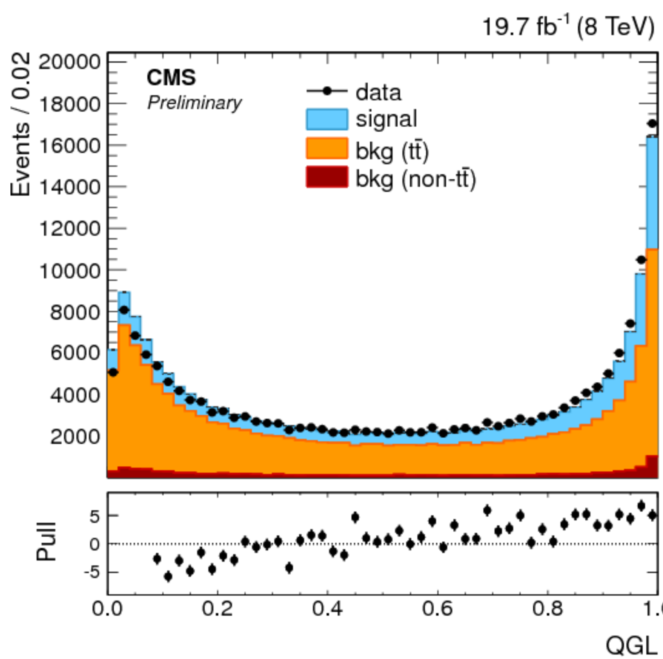






Color Flow + Jet Quark Gluon likelihood + Modified Mass drop





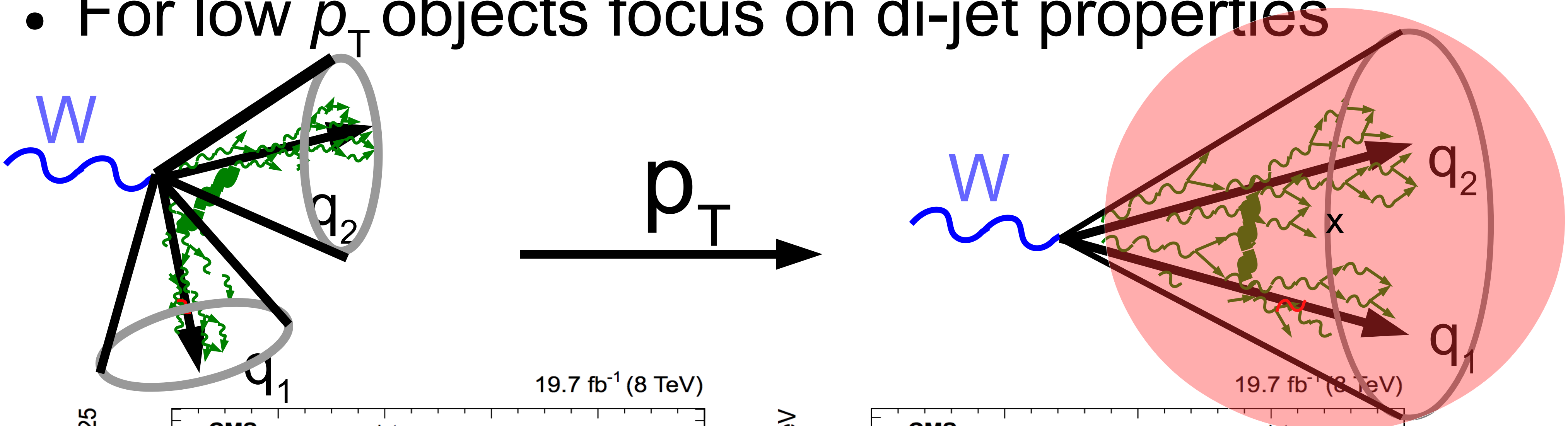
$$\zeta = \Delta R_{12} \cdot \max(m_{j1}, m_{j2})/m_{jj}$$

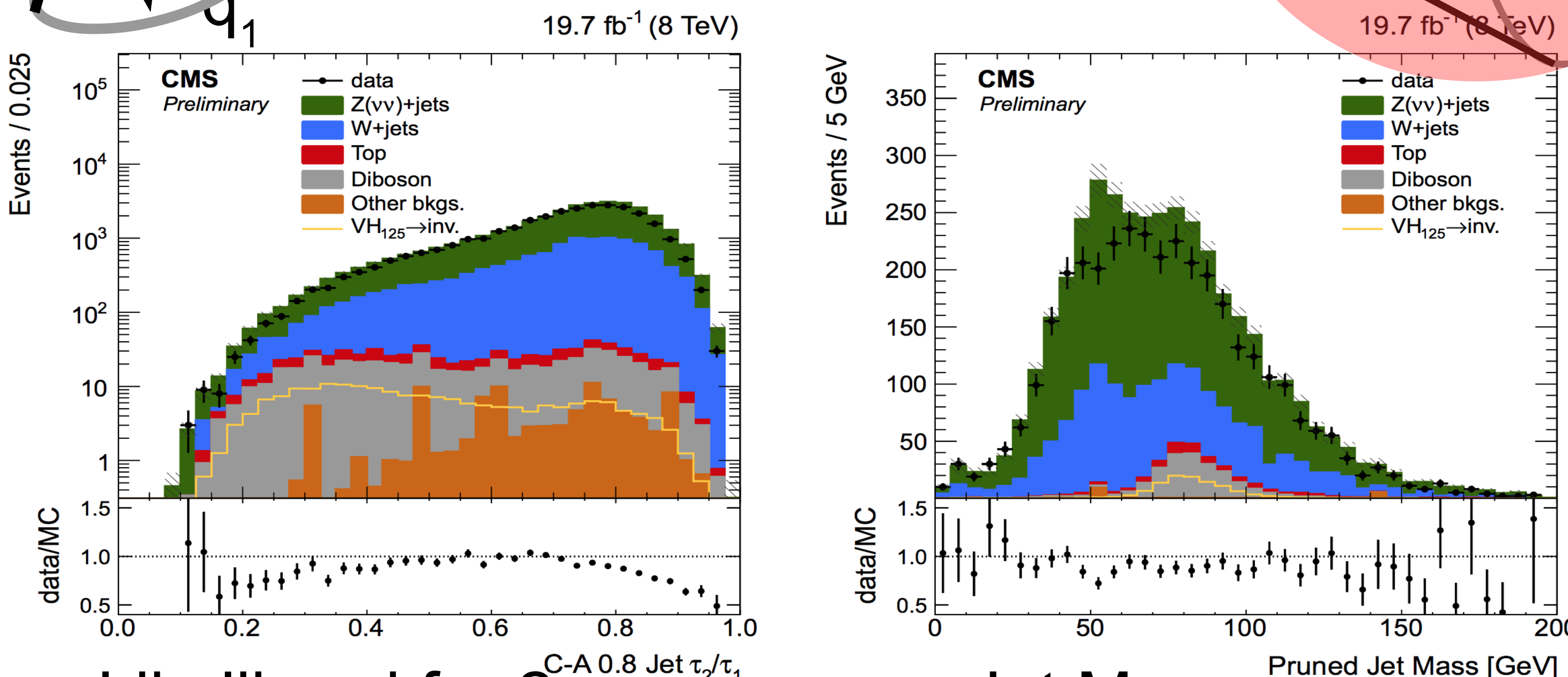
CMS-JME-14-002

arXiv:1407.7037

Boosted Tagger

- For low p_T objects focus on di-jet properties





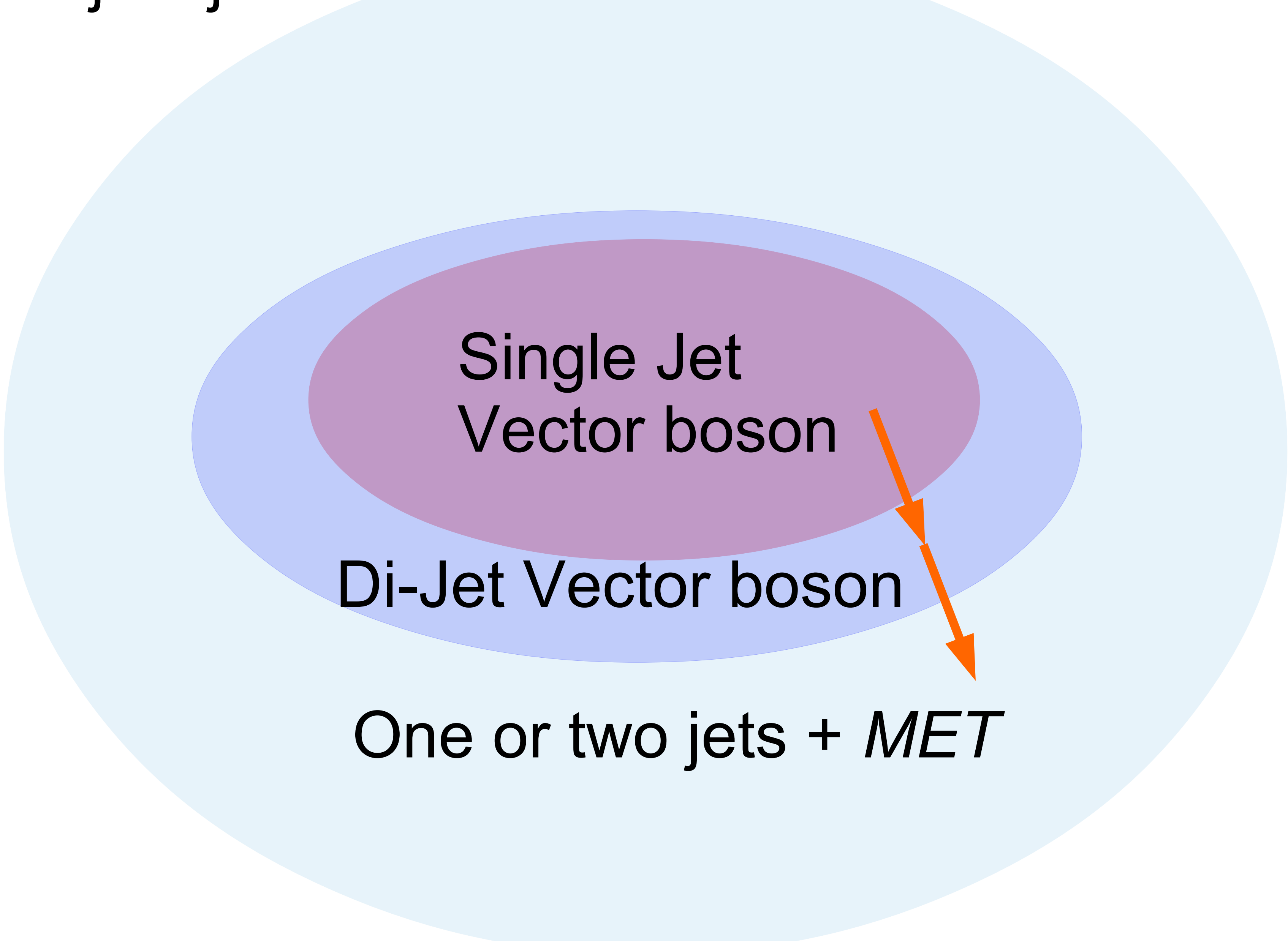
Likelihood for 2 prongs + Jet Mass

CMS-JME-13-006

arXiv:1407.7037

One Big Analysis

"Its all just jets and *MET*"

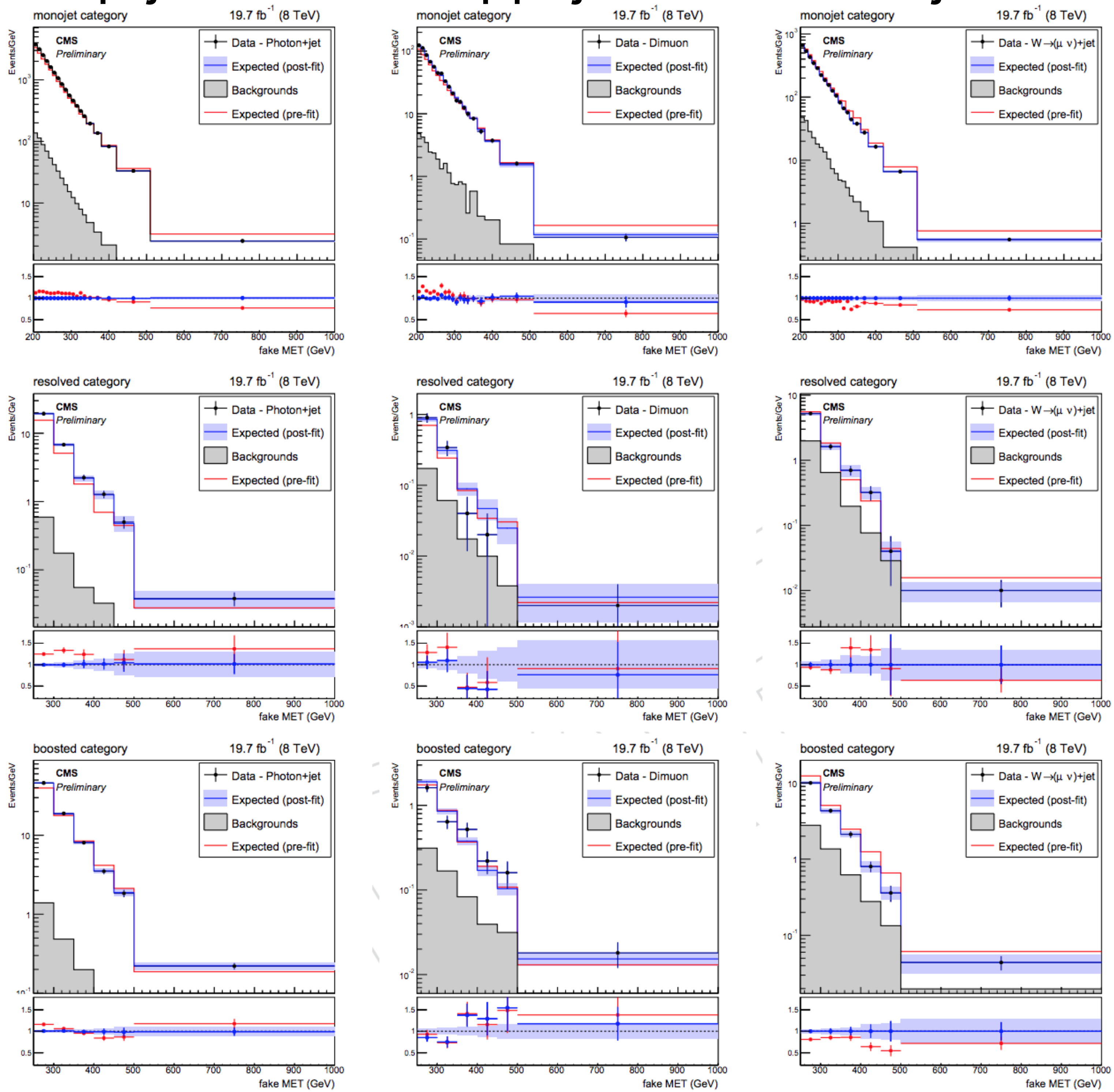


γ+jets Zμμ+jets Wlν+jets

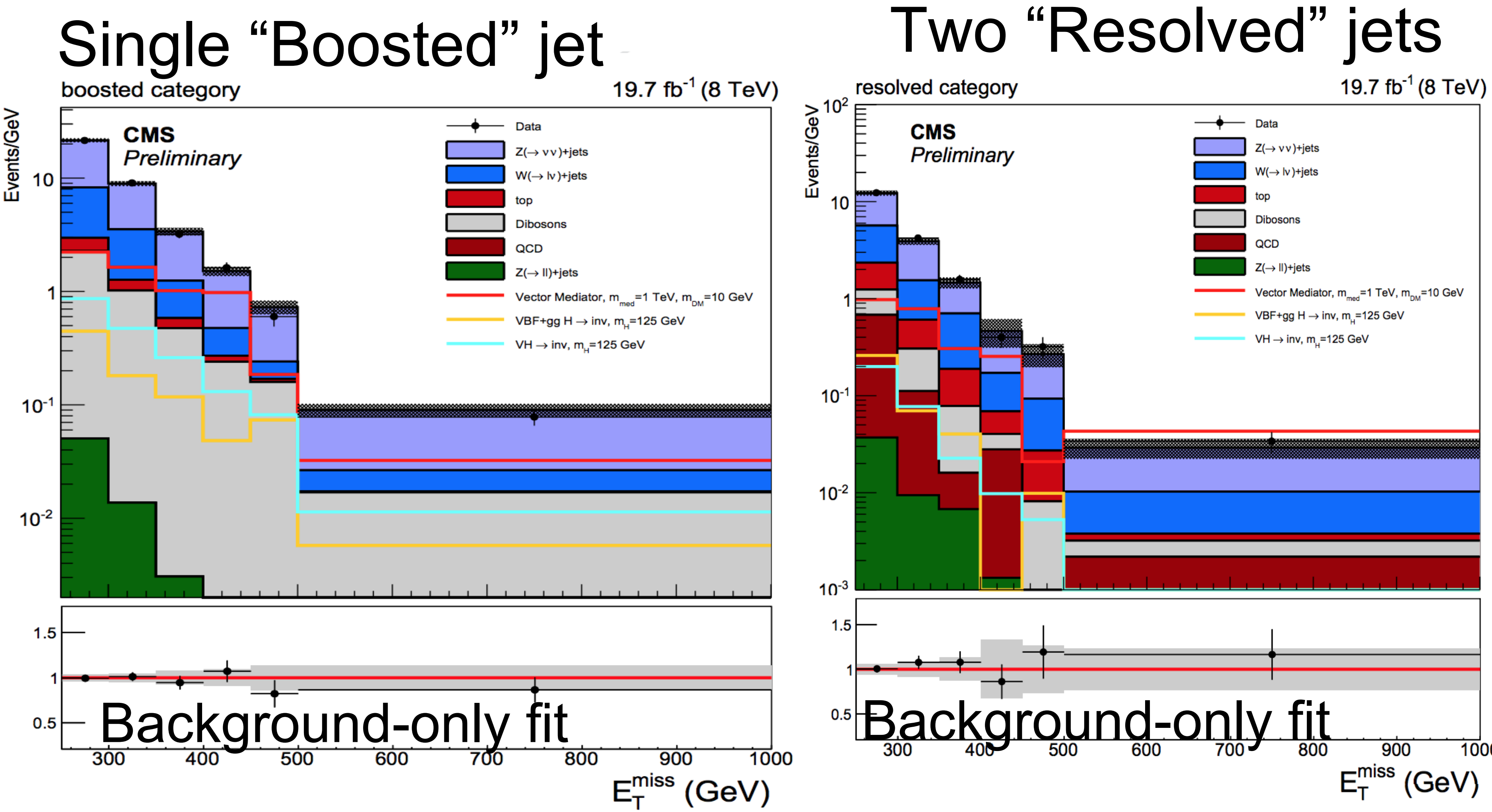
Monojet category

Di-jet category

Single jet category



CMS-EXO-12-055



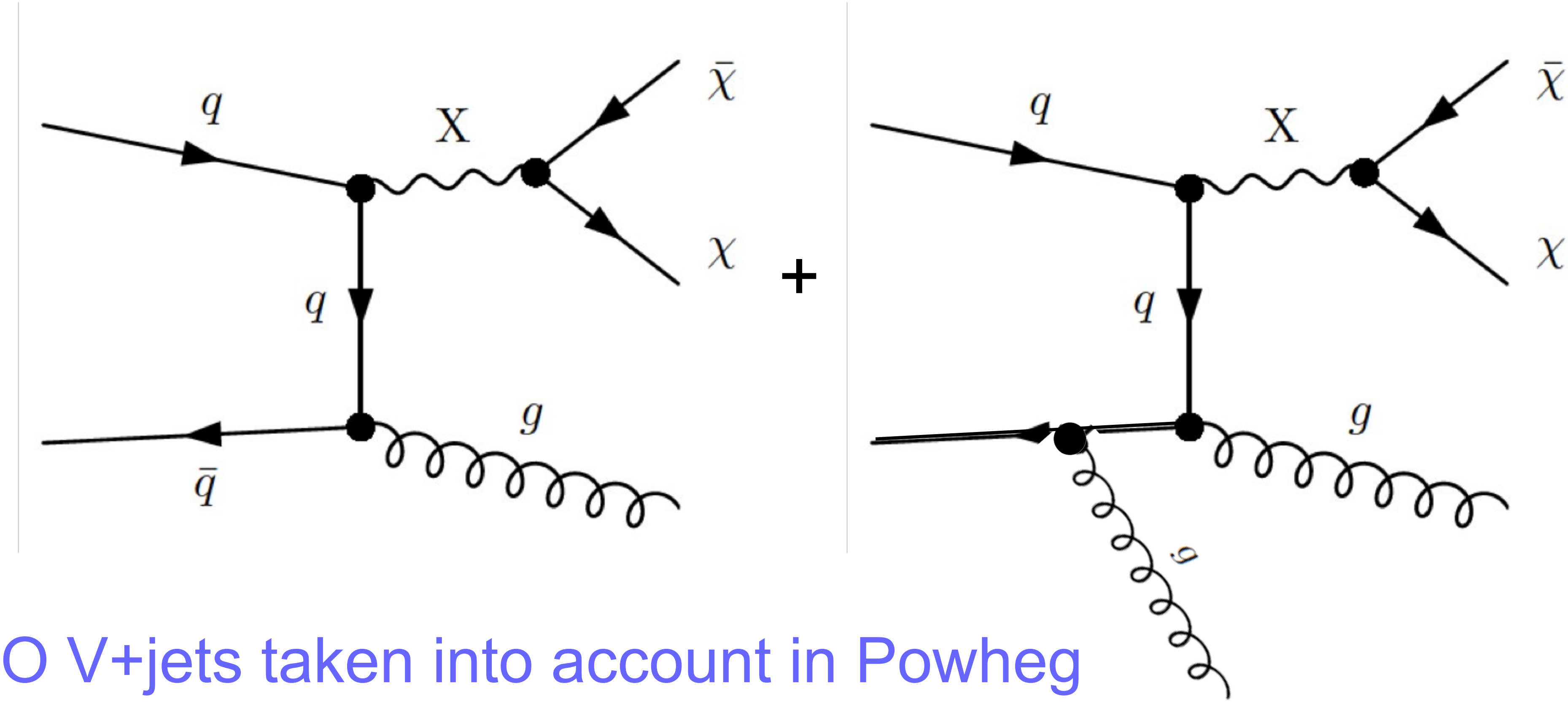
Observe a small excess in resolved *MET* tail (1σ)

Observe a small deficit in the mono-V *MET* tail (1.5σ)

CMS-EXO-12-055

2 Jets @ Vector/Axial Simplified Model

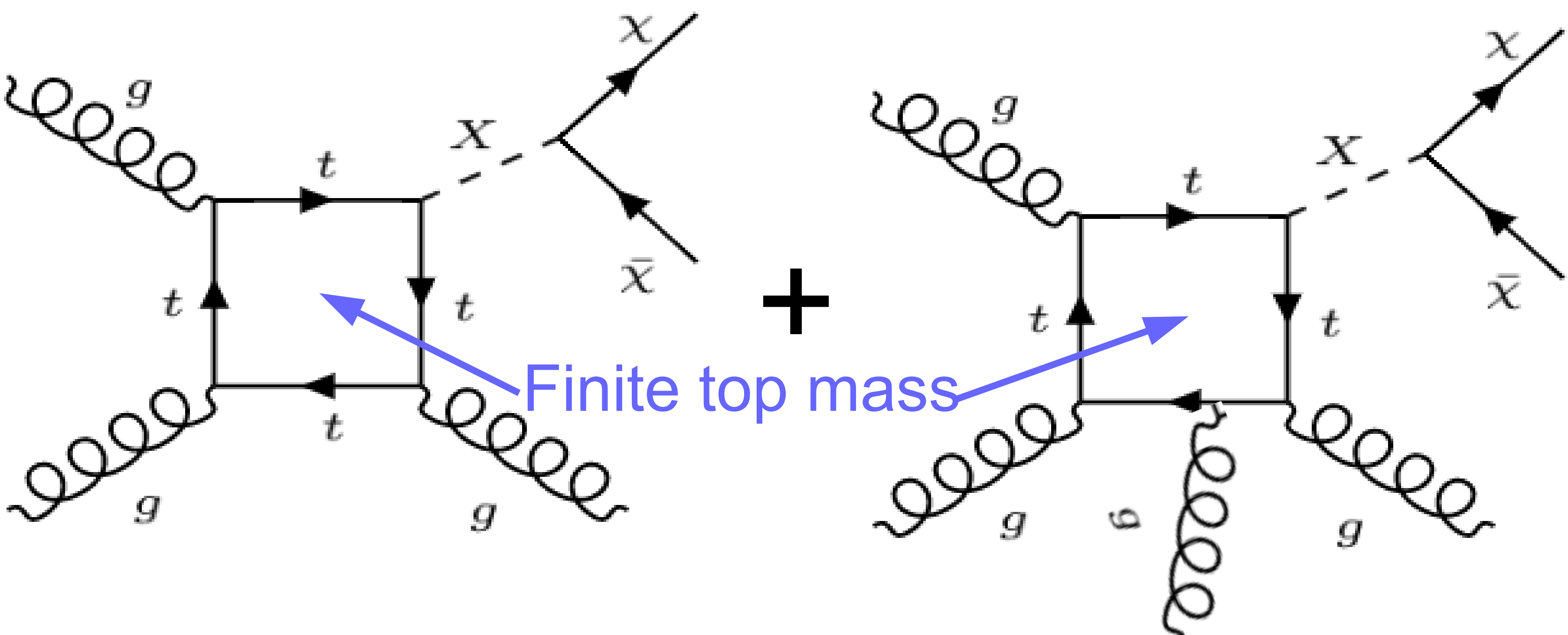
- At higher √s multi-jet final states predominant
- In light of building on new ideas



NLO V+jets taken into account in Powheg
Now available in Madgraph as well

(Pseudo)Scalar Simplified Model

- Requires finite top mass at 2 jets order
  - Available now in now with Madgraph
  - Also can do some hacky procedure



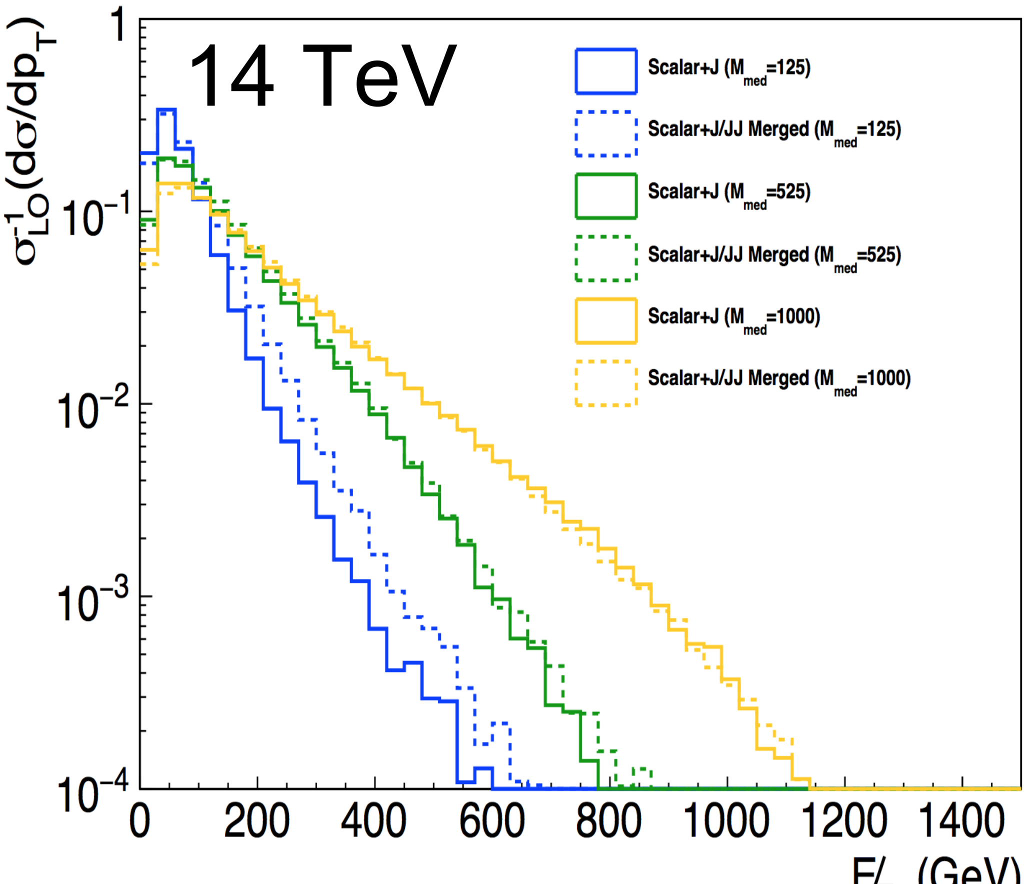
MCFM gluon fusion + 1 jet

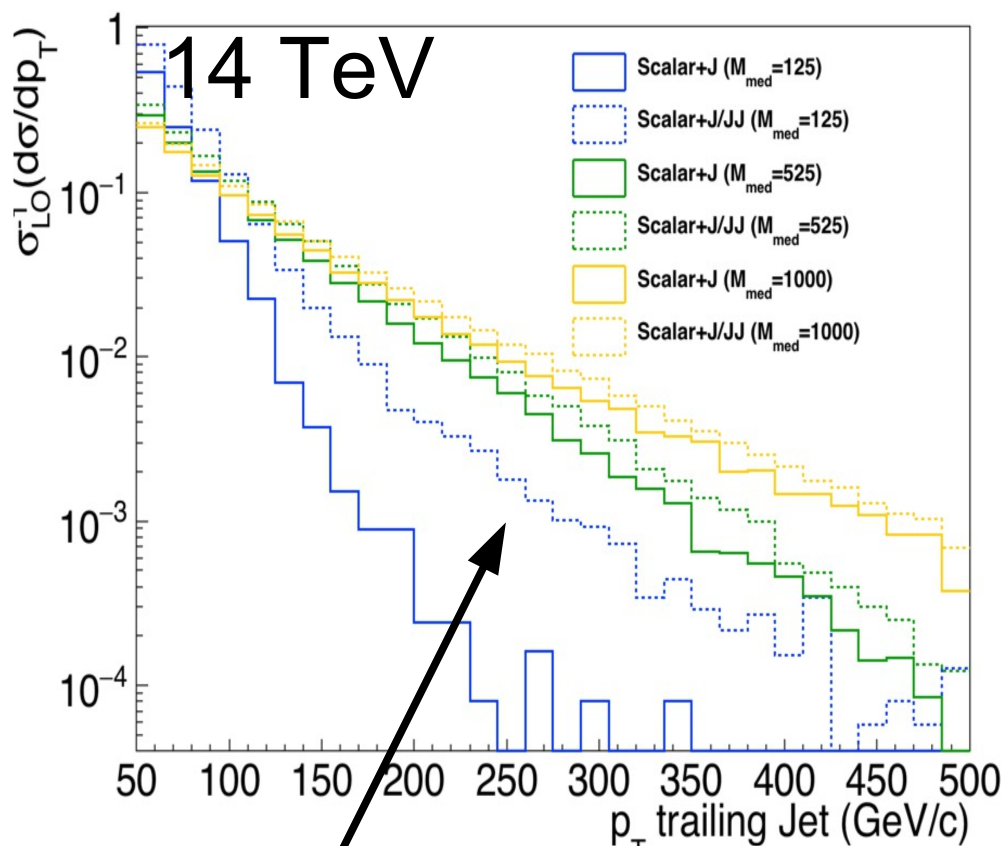
VBF@NLO gluon fusion + 2 jet

One caveat : On-shell production is only available for 2 jet final state

Advantage of merged MC

- Taking advantage of the new technology
  - Can consider exploring new regions of phase space





Low mass sensitivity enhanced in the multi jet final state

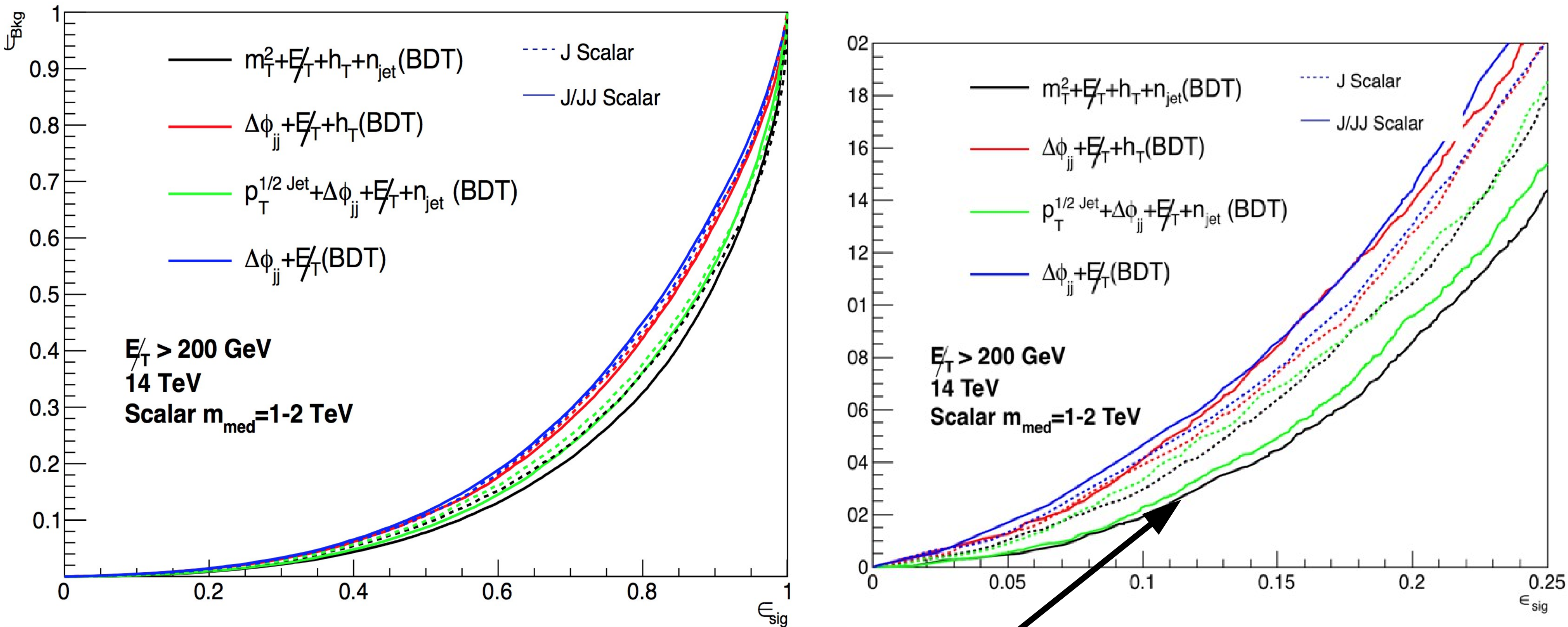
Question #2 : Advantage of MC

- With 2 jet MC : can now probe multijet final states
- Two questions can be answered :
  - Which variables are most sensitive with 2 jet MC?
  - Which variables are sensitive at 100 TeV?

- Considered a number of multi-jet variables :
  - M_T^2 : SUSY like variable obtained for pairwise sparticles
  - Razor variables : M_R , R : Related SUSY variables
  - *MET* : standard
  - $\Delta\varphi_{jj}$: angle between the two jets

Whats the maximum gain?

- Making an MVA combining all information



Background drops by a factor of 2

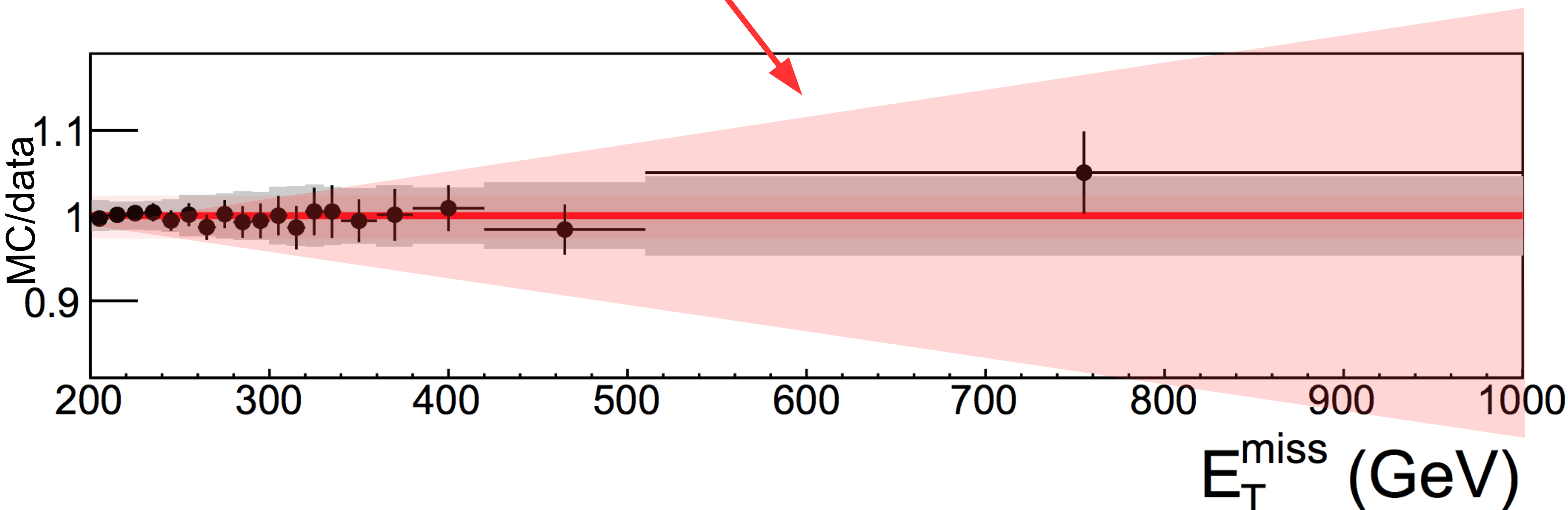
Can maximize sensitivity by an additional sqrt(2)

The only other way to gain is to reduce the systematics

Strategy to fix agreement

10x less Z→μμ than Z→νν

Z→μμ+Jets prediction uncertainty

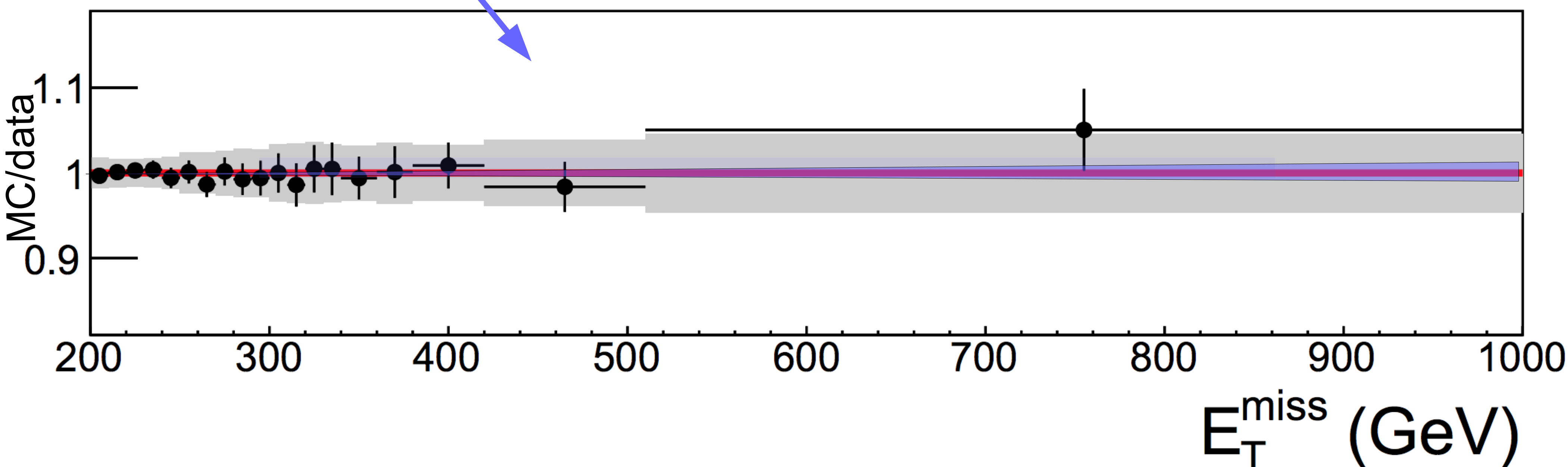


Statistical uncertainty too large

CMS-EXO-12-055

Strategy to fix agreement

5x More γ+Jets than Z→νν

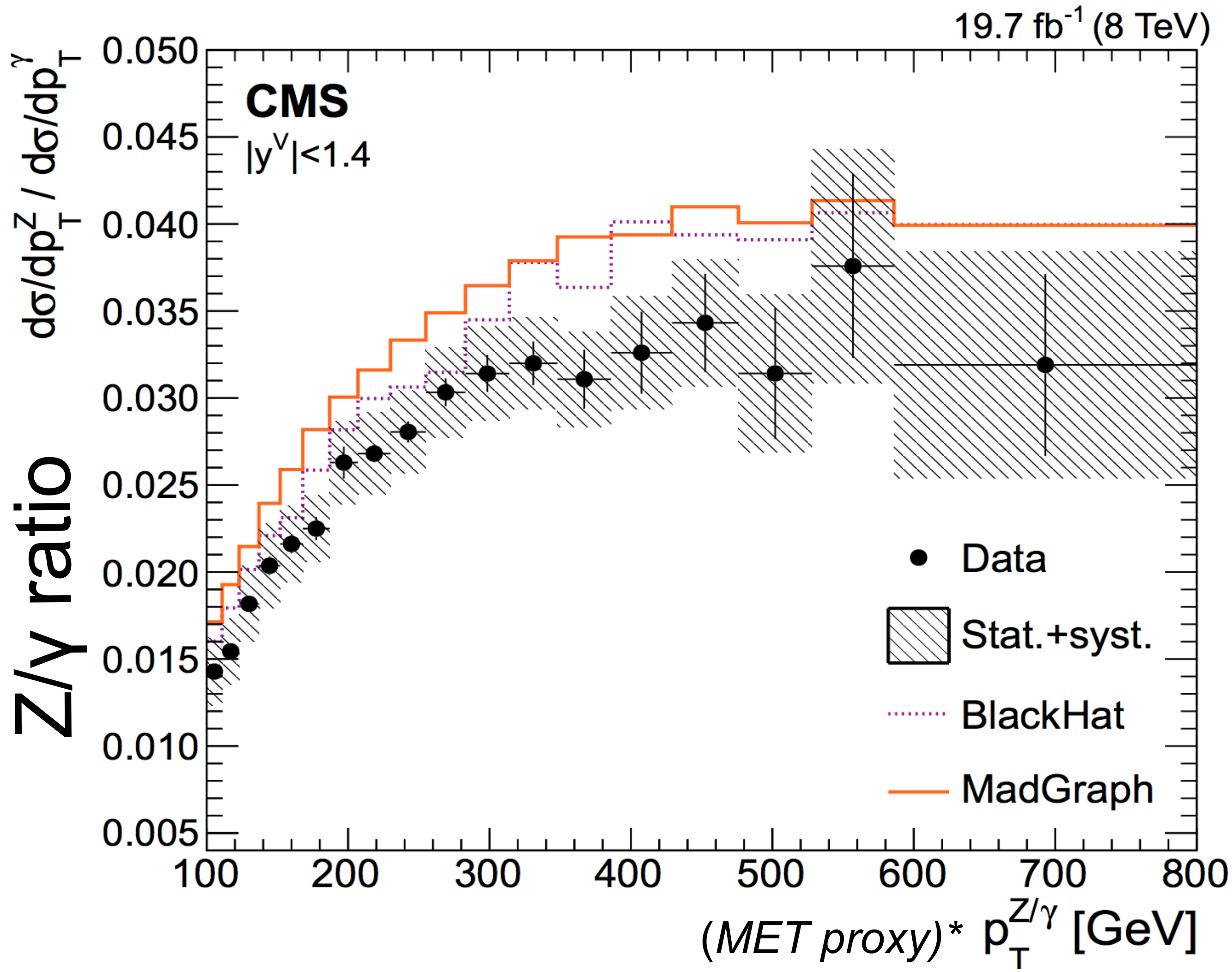


Statistical uncertainty small
….However

CMS-EXO-12-055

A mystery? Understanding Z/γ p_T

Can we really use Photons to model Zs ?

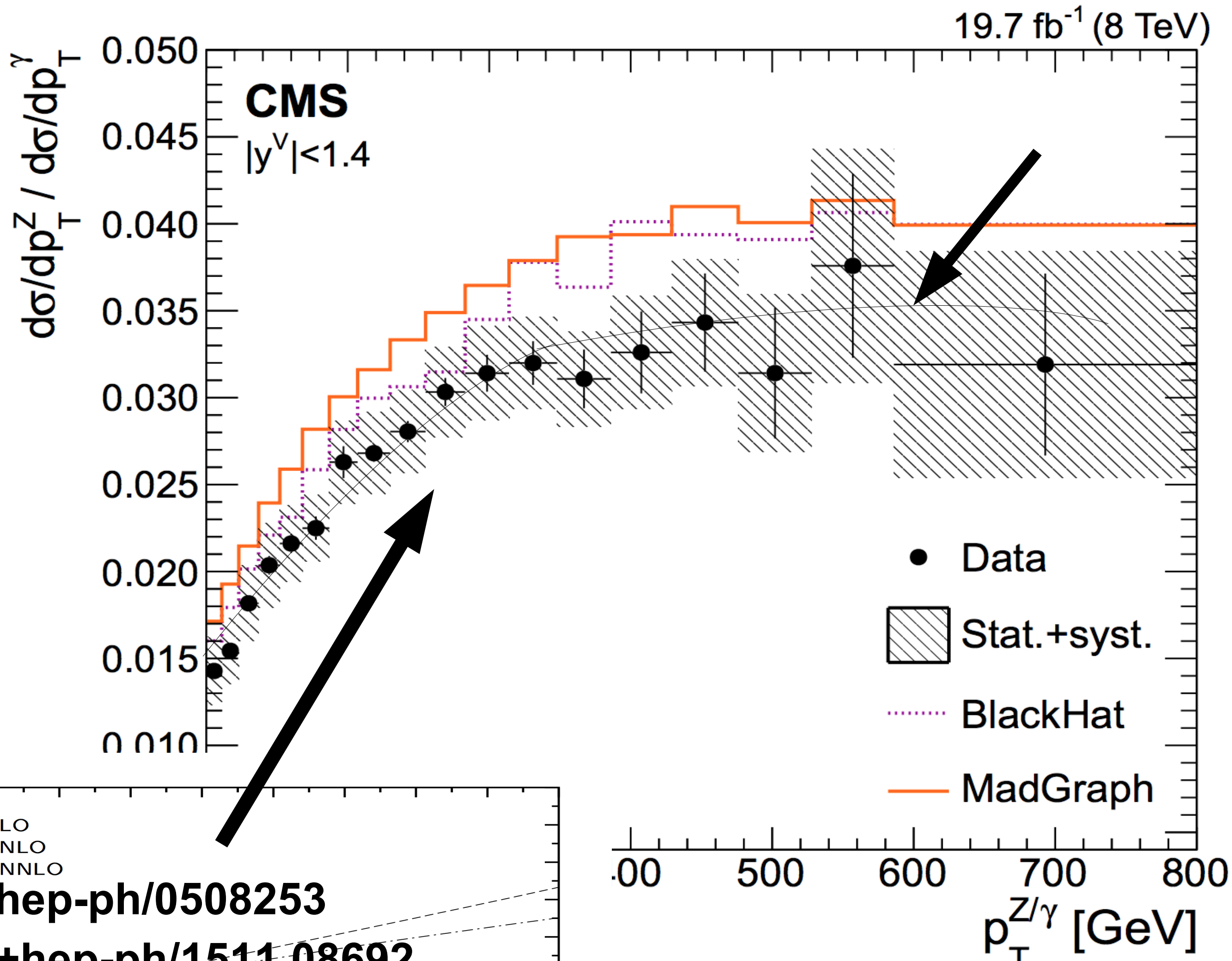


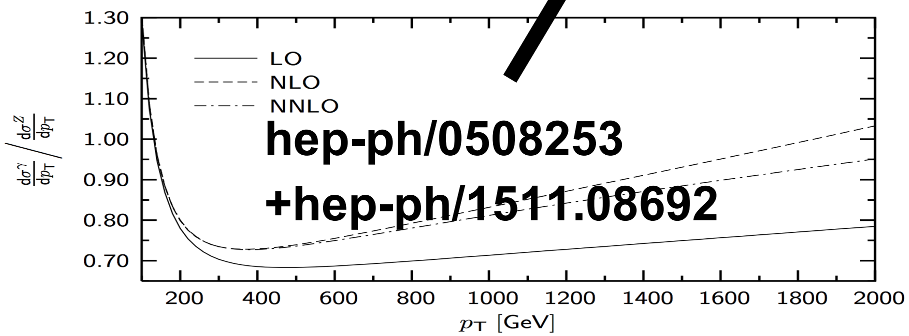
*See backup

CMS-SMP-14-005

A mystery? The Z p_T spectrum

- These results are missing NLO EWK corrections!





CMS-SMP-14-055

How do we fix this?

$$\frac{d\sigma^{\gamma}}{dp_T} \quad \text{and} \quad \frac{d\sigma^{Z}}{dp_T}$$

Before : $\sigma_{tot} = \sigma_{NLO}(0,1\text{jet})$

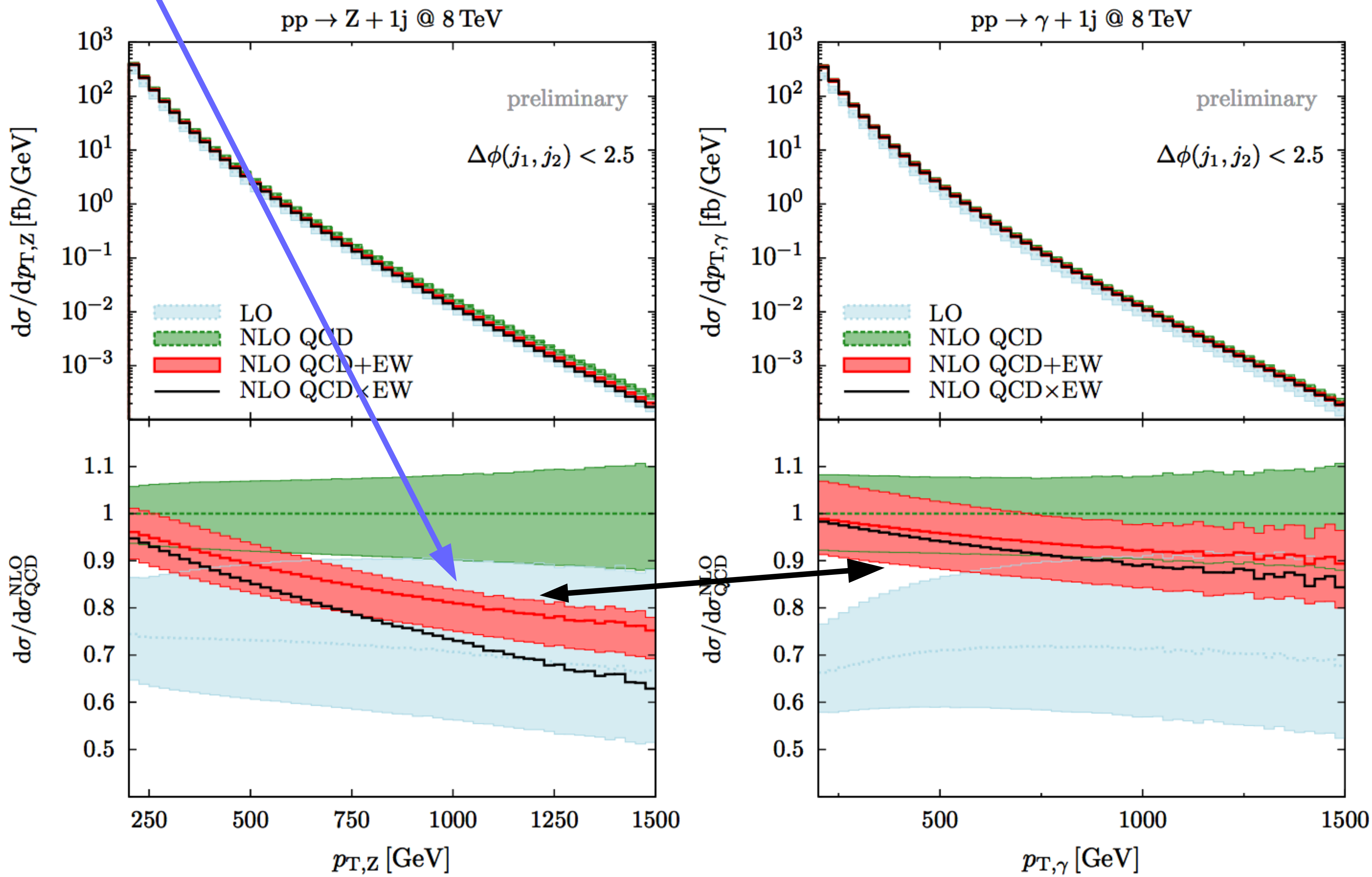
After : $\sigma_{tot} = \sigma_{NLO}(0,1,2\text{j})(1+\sigma_{EWK})$ (added)

Energy leakage outside of photon which biases *MET*

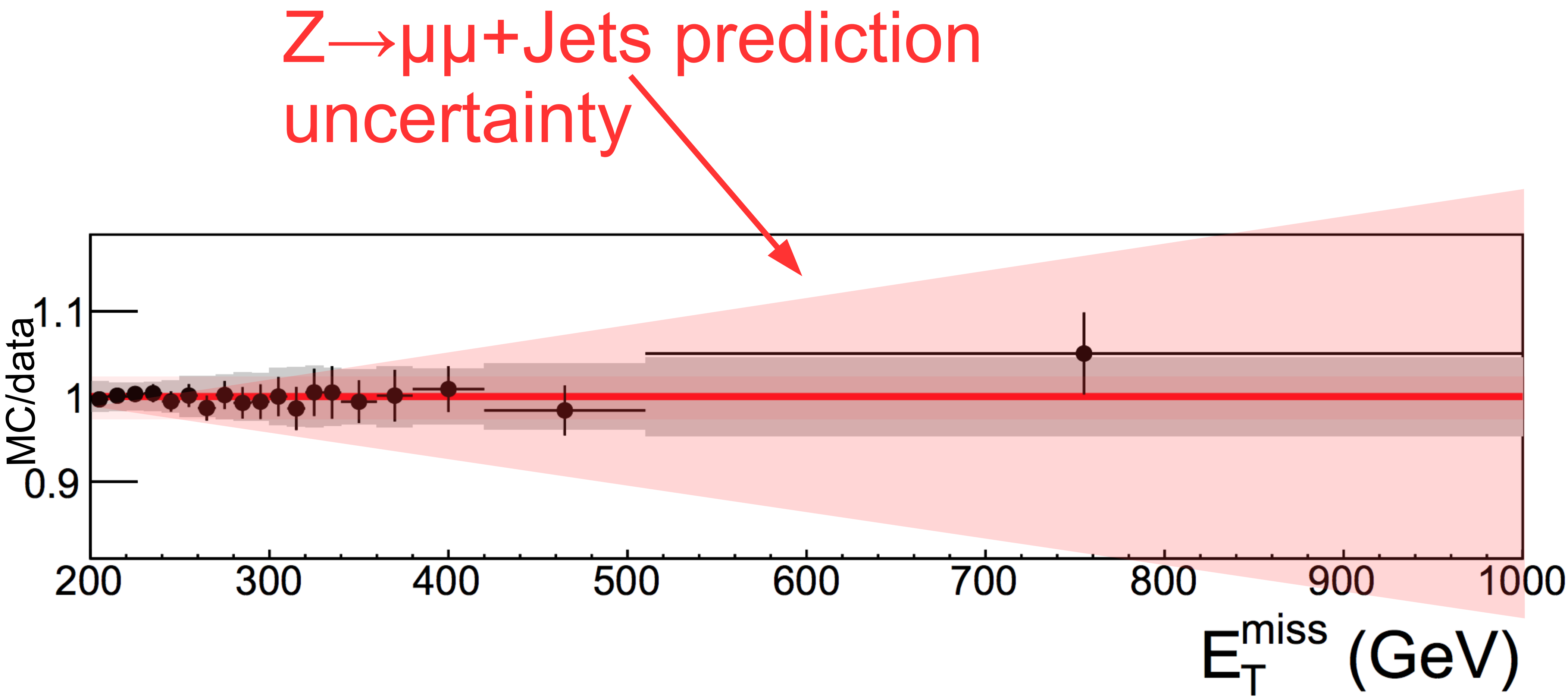
This was the harder one

How do we fix this?

Impact of the electroweak corrections

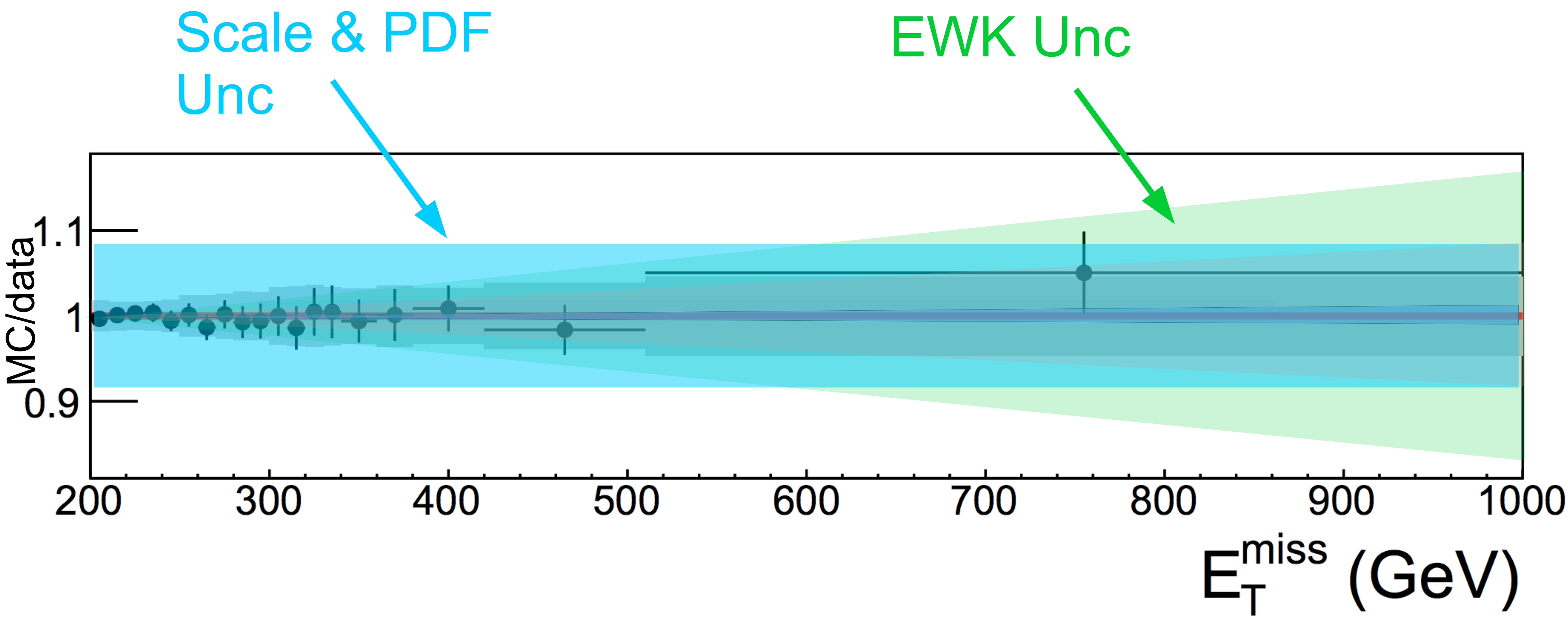


Strategy to fix agreement



CMS-EXO-12-055

Strategy to fix agreement



Updated unc still too large

CMS-EXO-12-055

What is the previous unc?

Scale & PDF
Unc

Unc. $\longrightarrow$ $$\frac{d\sigma^{\gamma}}{dp_T} \bigg/ \frac{d\sigma^{Z}}{dp_T} = d\sigma^{\gamma}/d\sigma^{Z}(\mu)$$

On the ratio

$$\begin{pmatrix} d\sigma^{\gamma}(+\sigma) \\ d\sigma^{Z}(+\sigma) \end{pmatrix} = \begin{pmatrix} 1 & C \\ C & 1 \end{pmatrix} \begin{pmatrix} d\sigma^{\gamma}(\mu^{up})/d\sigma^{i}(\mu_0) \\ d\sigma^{Z}(\mu^{up})/d\sigma^{i}(\mu_0) \end{pmatrix}$$

Adjust C until uncertainty is

$$\mathbf{d\sigma^{\gamma}/d\sigma^{Z}(+\sigma) < \max_i \left(d\sigma^{i}(\mu^{up})/d\sigma^{i}(\mu_0)\right)}$$

What is the previous unc?

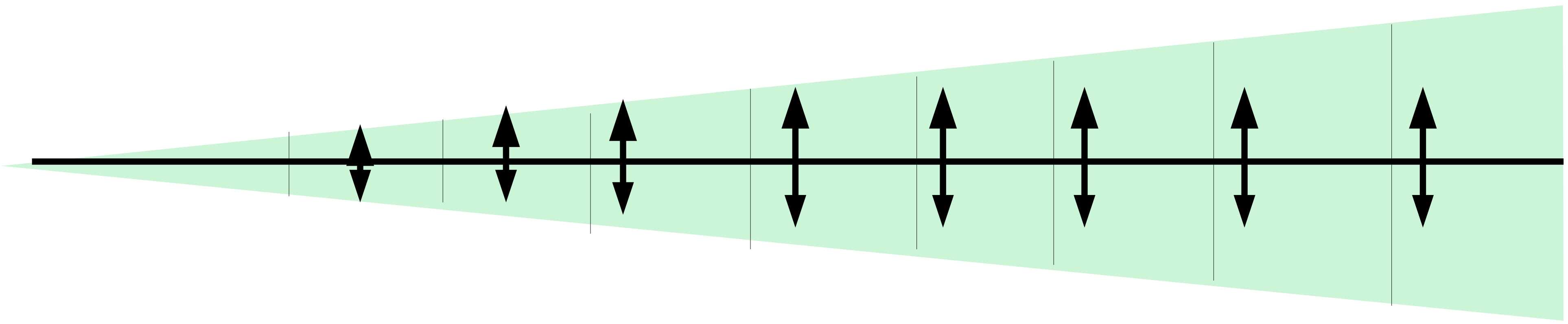
Scale & PDF
Unc

Unc. $\longrightarrow$ $\dfrac{d\sigma^{\gamma}}{dp_T} \Big/ \dfrac{d\sigma^{Z}}{dp_T} = d\sigma^{\gamma}/d\sigma^{Z}(\mu)$ $\uparrow$ On the ratio

$$\begin{pmatrix} d\sigma^{\gamma}(+\sigma) \\ d\sigma^{Z}(+\sigma) \end{pmatrix} = \begin{pmatrix} 1 & C \\ C & 1 \end{pmatrix} \begin{pmatrix} d\sigma^{\gamma}(\mu^{up})/d\sigma^{i}(\mu_0) \\ d\sigma^{Z}(\mu^{up})/d\sigma^{i}(\mu_0) \end{pmatrix}$$

Makes No
Sense

What about the EWK uncertainty?



In light of being conservative :

Treated full correction as an uncertainty

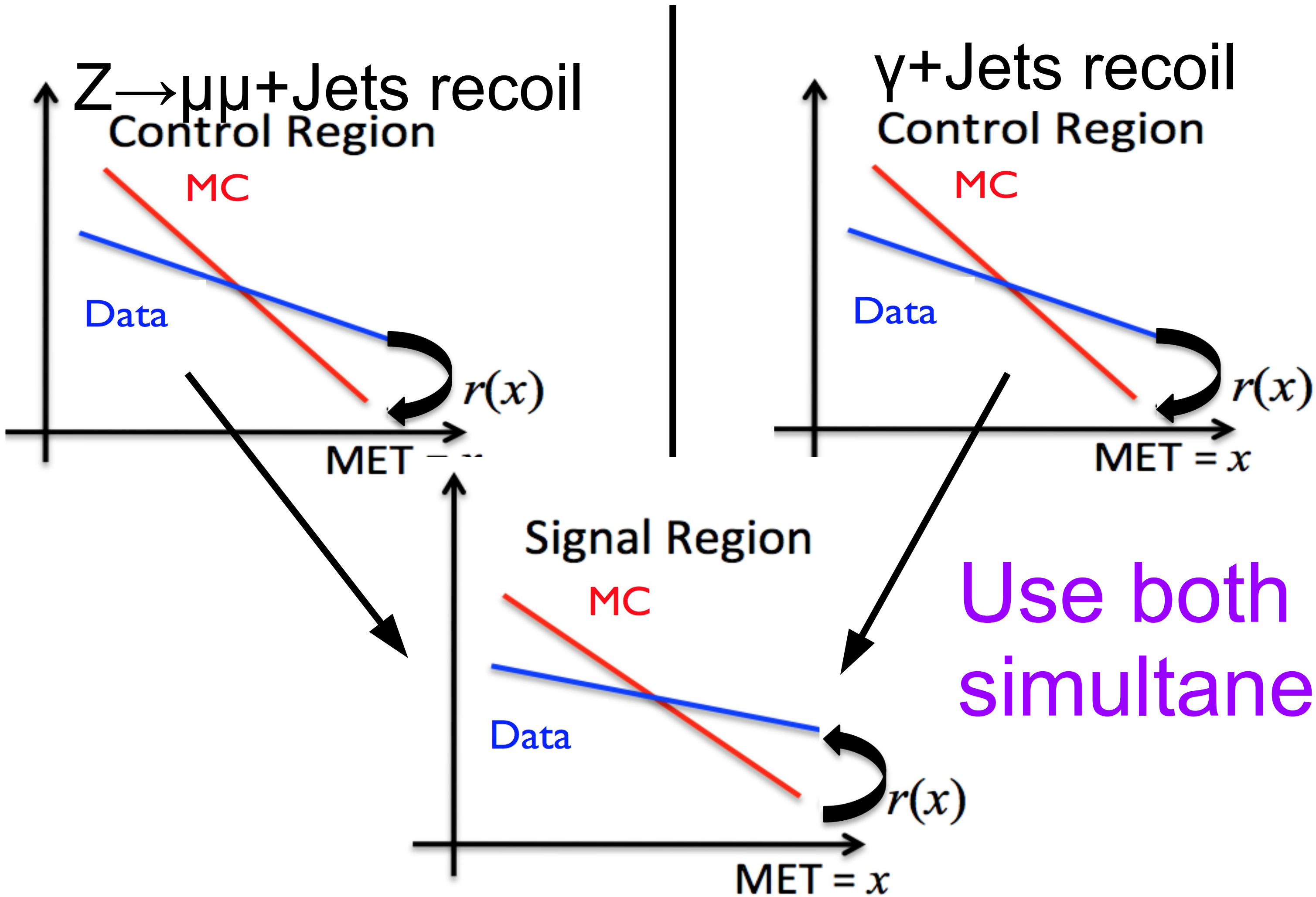
Additionally de-correlated this per bin

Avoids low *MET* to high *MET* constraints

Not very logical

Other (better) schemes exist

Strategy to fix agreement



Use both regions simultaneously

Strategy to fix agreement

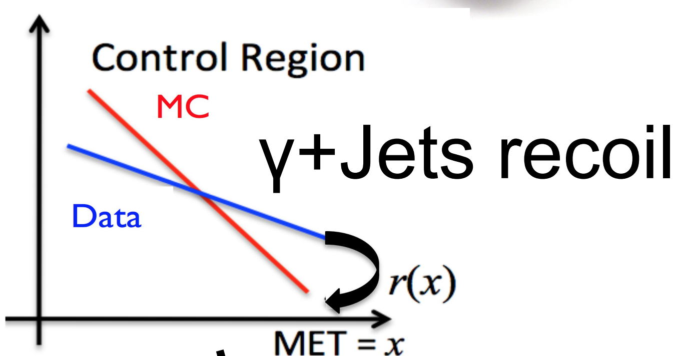
Coffee ?  or Tea? 

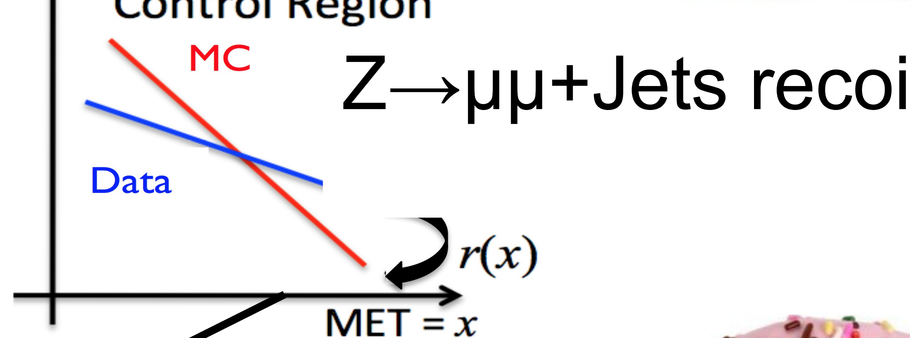
Answer : Yes Please

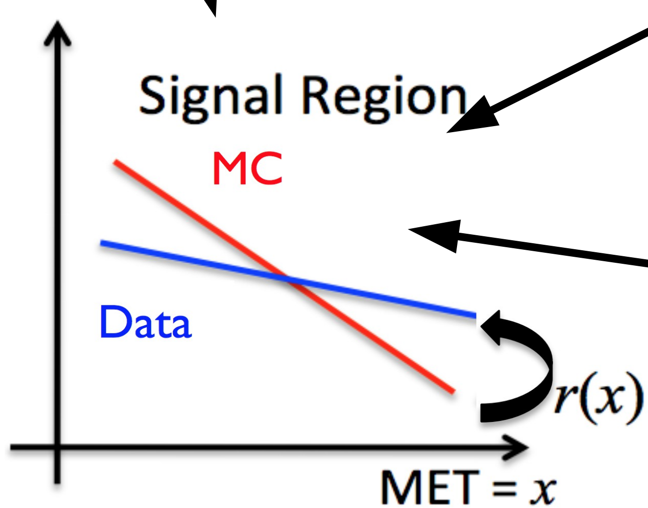
CMS-EXO-12-055

Strategy to fix agreement

Coffee ?  or Tea? 

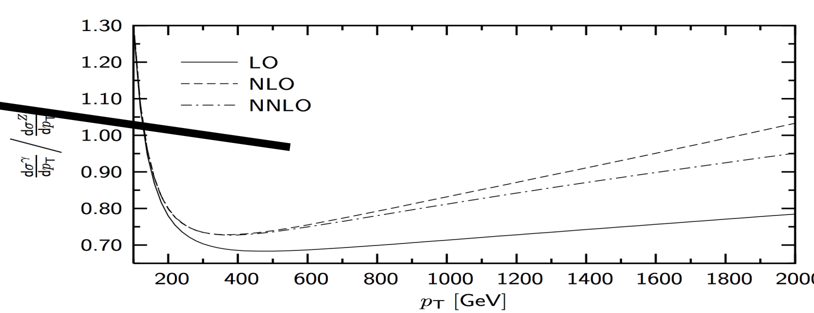






and Donuts

Not enough LO

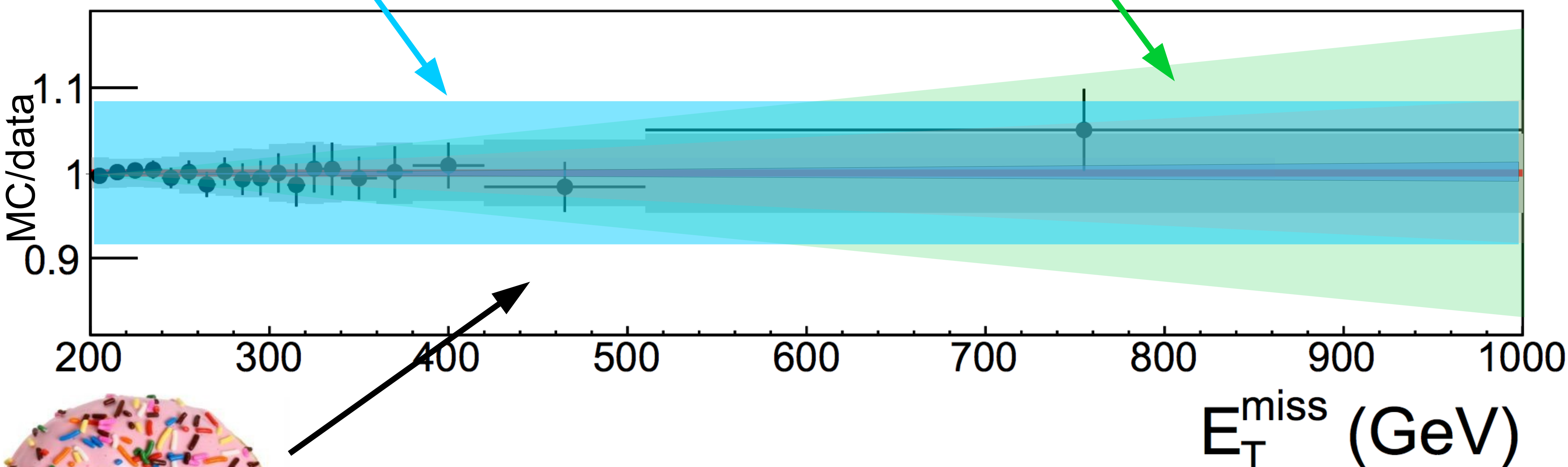


Strategy to fix agreement

Coffee ?  or Tea? 

Scale & PDF Unc

EWK Unc



Donuts? Constraint

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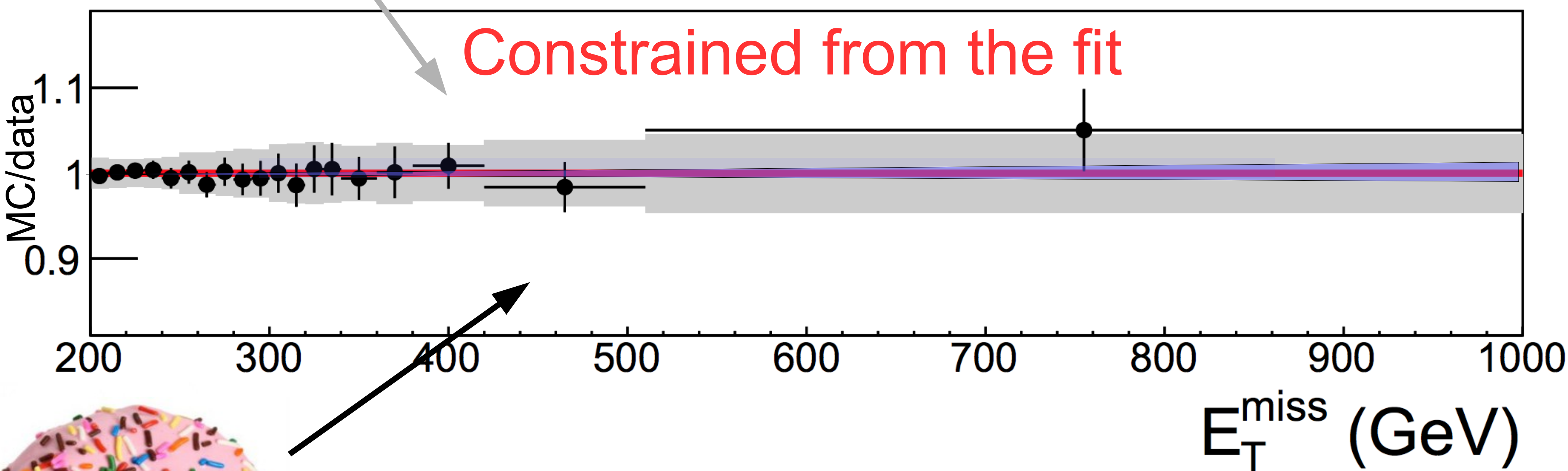
Strategy to fix agreement

Coffee ?  or Tea? 

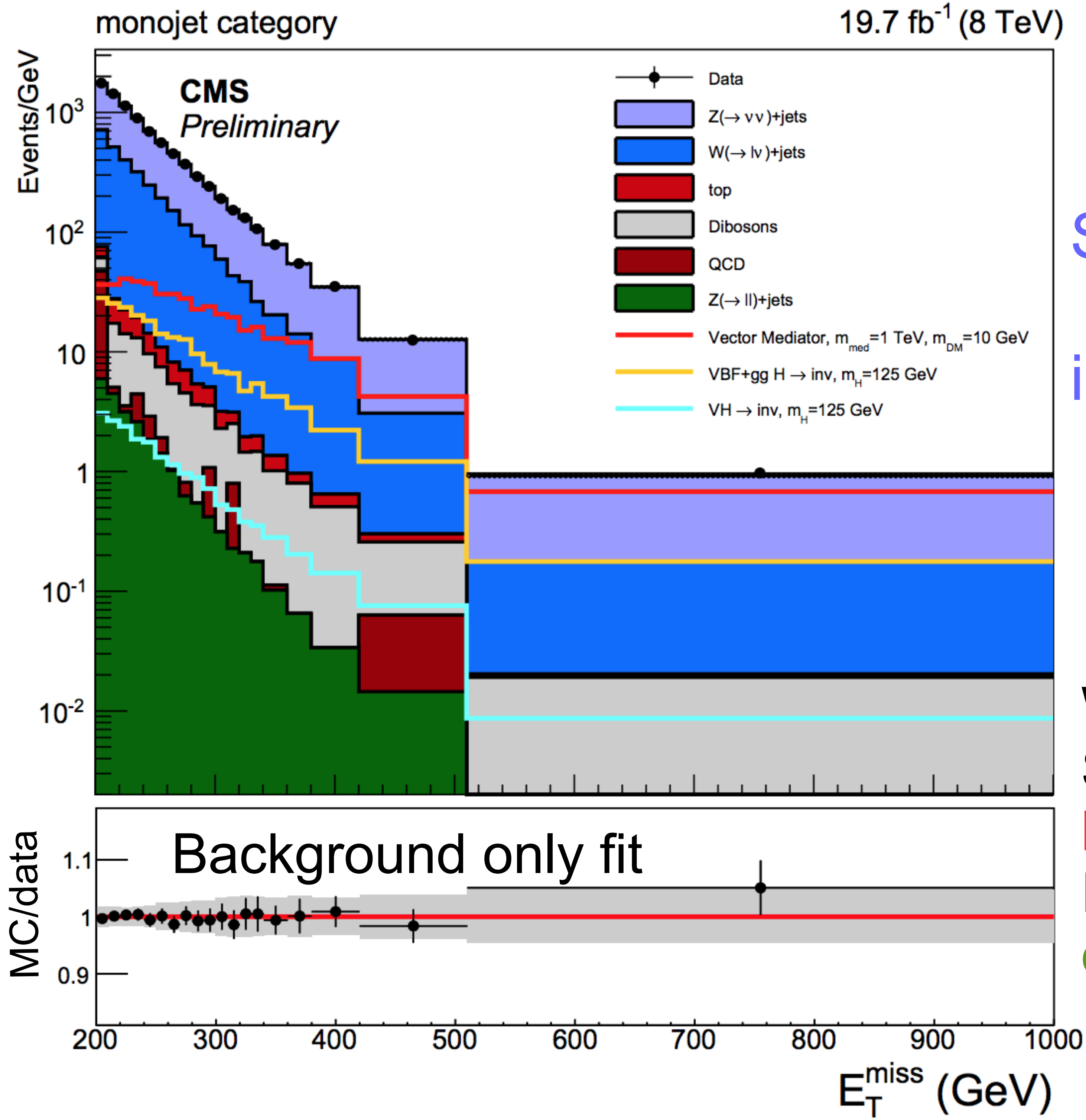
Actual Uncertainty we use



Donuts

CMS-EXO-12-055

The Result



Small excess (1-2σ) in *MET* tail

With new method Still systematics limited

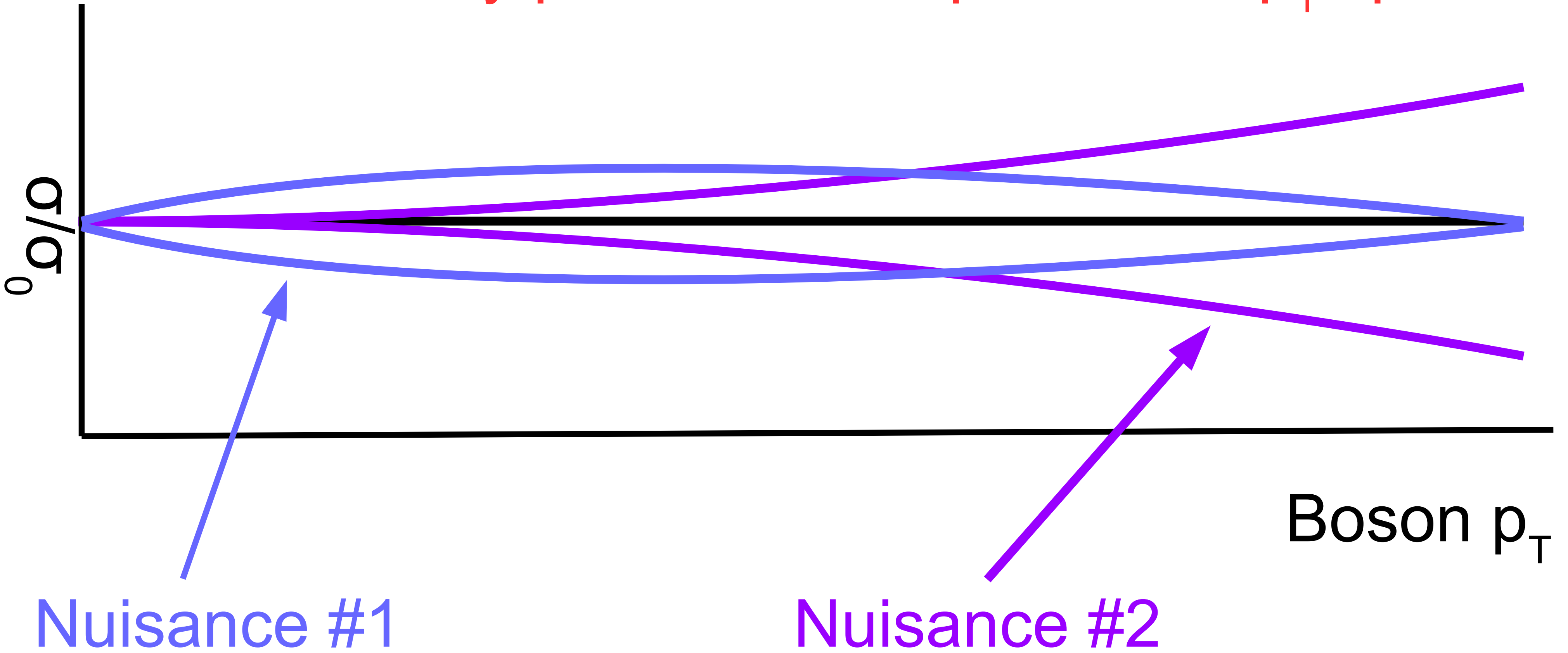
EWK uncertainty dominates

CMS-EXO-12-055

How do we do the fit?

The updated version of this search fits the W,Z,γ p_T simultaneously

Simultaneously profile the shapes of the p_T spectra



Can we bound our uncertainties into a class of shapes?

We are Stuck!

We are relying on

$$d\sigma^{\gamma}/d\sigma^{Z}\,(+\sigma) \;<\; \max_i \left(d\sigma^i(\mu^{up})/d\sigma^i(\mu_0)\right)$$

For the uncertainty on

$$\frac{d\sigma^{\gamma}}{dp_T} \Big/ \frac{d\sigma^{Z}}{dp_T}$$

We need a better a approach

Ideally one that we can embed to the likelihood(L)

$$\mathrm{Log}(L)=\mathrm{Log}(L_0)+(d\sigma^{\gamma}/d\sigma^{Z}(\theta)-d\sigma^{\gamma}/d\sigma^{Z}(\mu_0))/\sigma^2$$

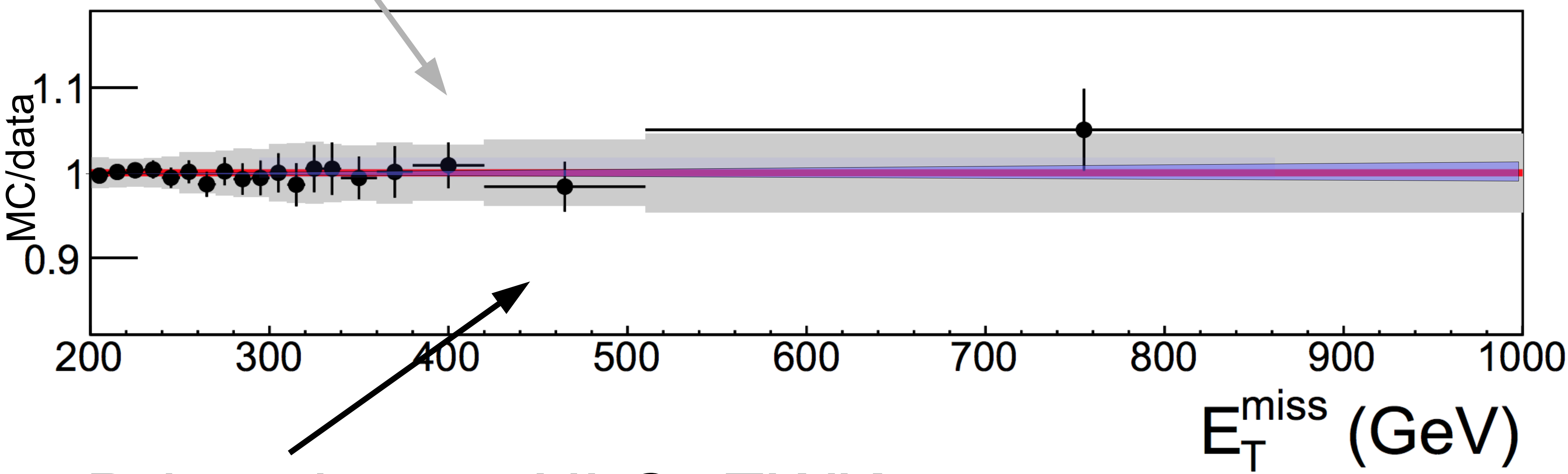
Profiled nuisance

Improved knowledge of high p_T spectrum drives search

Can we improve?

Monojet search will not improve quickly in the future

Systematics limited



Driven by our NLO+EWK uncertainties

CMS-EXO-12-055

Towards a complete statement on Dark Matter

Analyses presented

- Mono Jet:

Scalar Axial Higgs modified vector modified scalar mixture

Jets	Inclusive	V tag	Top	b tag	Higgs
1					
2					
3					
n					
leptons					
γ					
X→YY					

- Mono Everything: Extending to improve scalar at 100 TeV

Scalar Axial Higgs modified vector modified scalar mixture

Jets	Inclusive	V tag	Top	b tag	Higgs
1					
2					
3					
n					
leptons					
γ					
X→YY					

- Mono Everything:

Extending models to cover modified simplified models

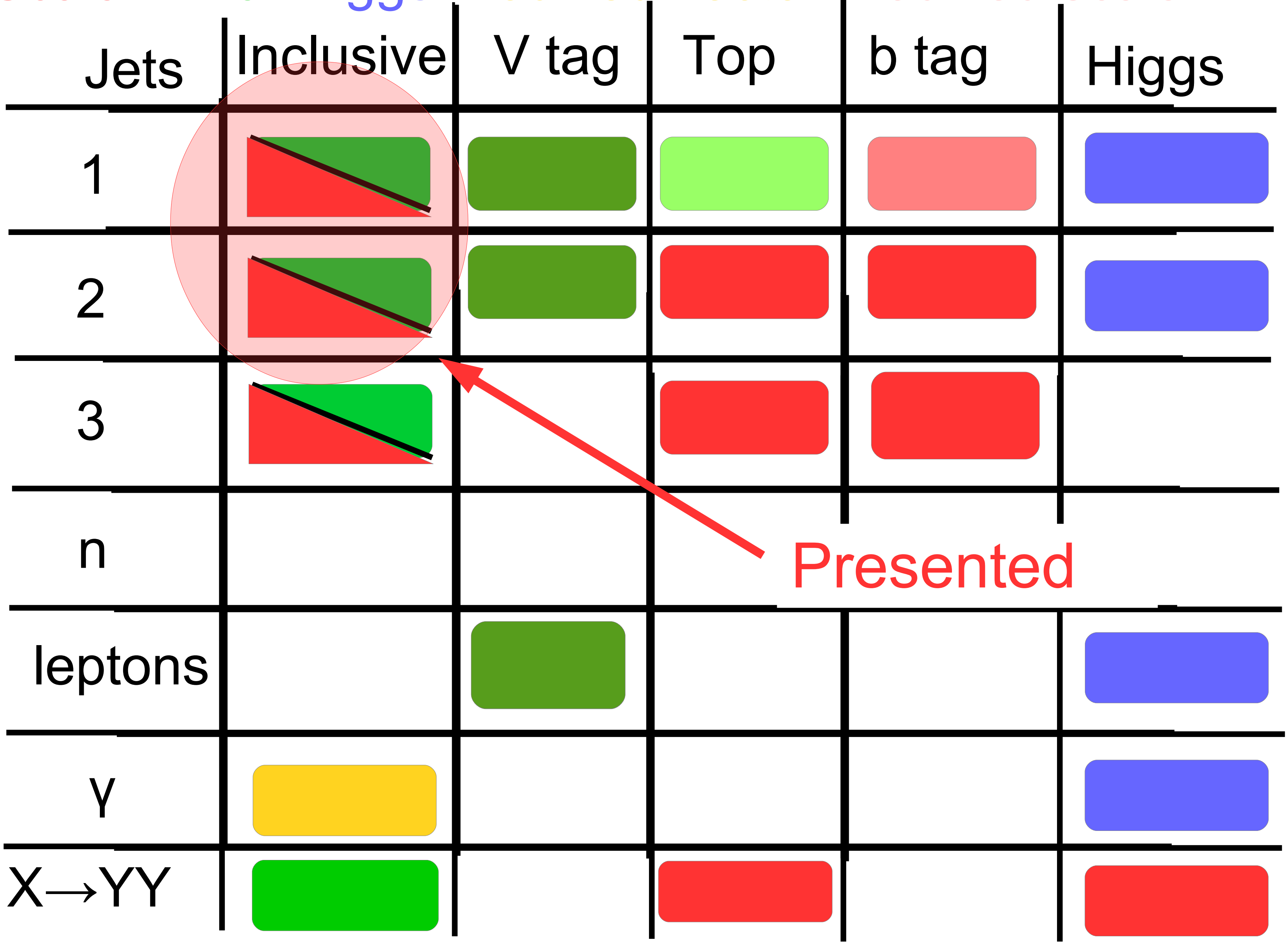
Scalar Axial Higgs modified vector modified scalar mixture

Jets	Inclusive	V tag	Top	b tag	Higgs
1					
2					
3					
n					
leptons					
γ					
X→YY					

- Mono Everything:

Extending models to cover modified simplified models

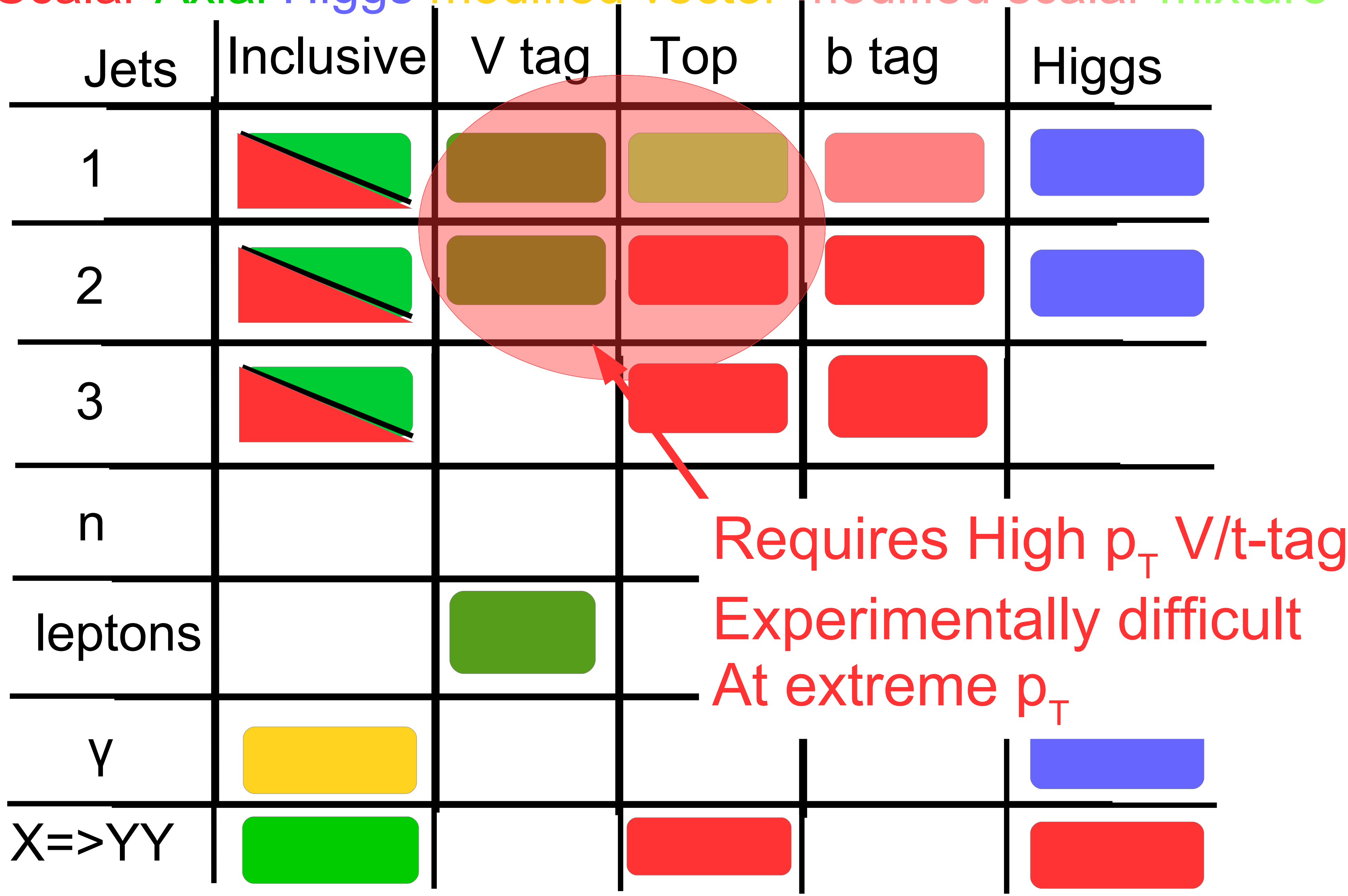
Scalar Axial Higgs modified vector modified scalar mixture



- Mono Everything:

Extending models to cover modified simplified models

Scalar Axial Higgs modified vector modified scalar mixture



- Mono Everything:

Extending models to cover modified simplified models

Scalar Axial Higgs modified vector modified scalar mixture

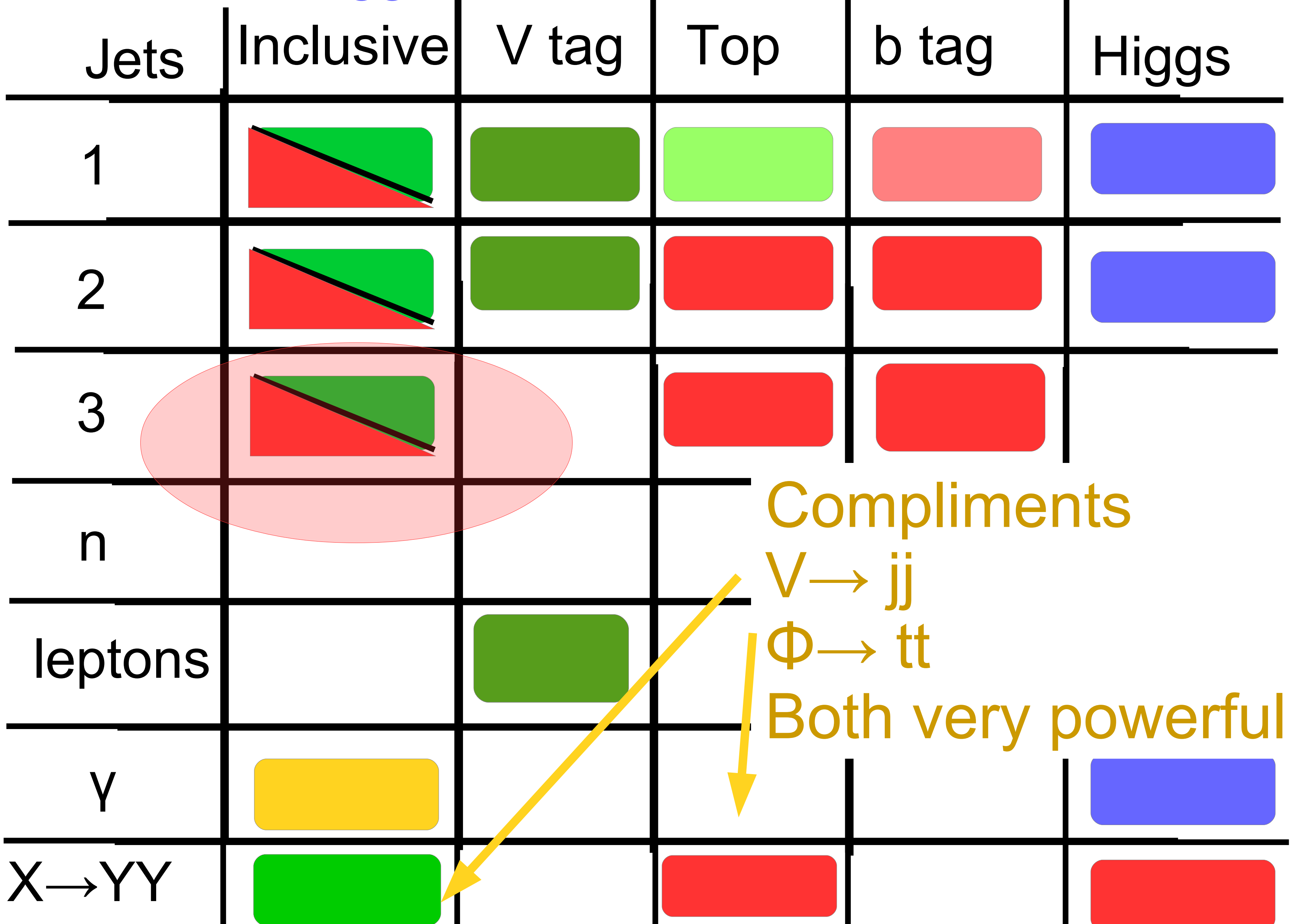
Jets	Inclusive	V tag	Top	b tag	Higgs
1					
2					
3					
n					
leptons					
γ					
X→YY					

VBF final state
Very useful in higgs portal models
Very challenging experimentally

- Mono Everything:

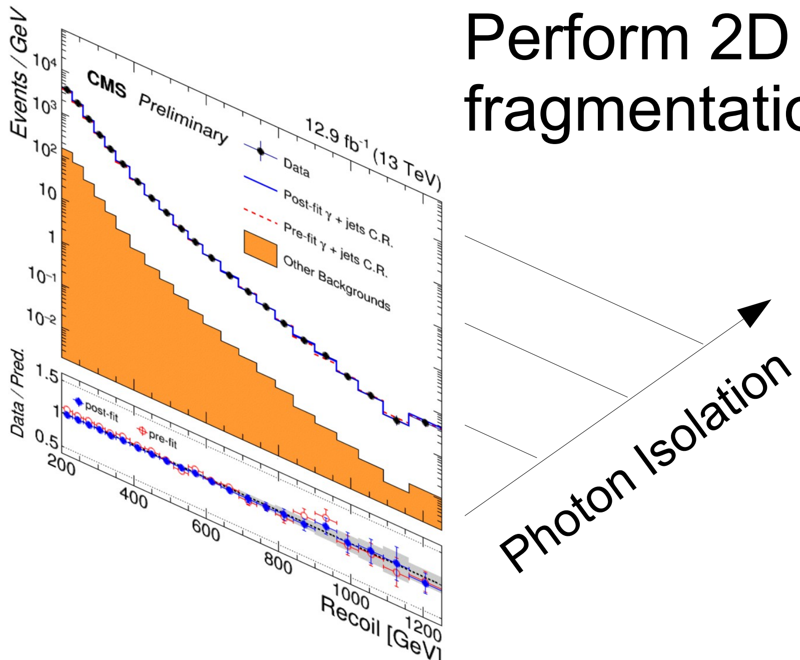
Extending models to cover modified simplified models

Scalar Axial Higgs modified vector modified scalar mixture



Common misnomers

- γ+jets control suffers from γ fragmentation model

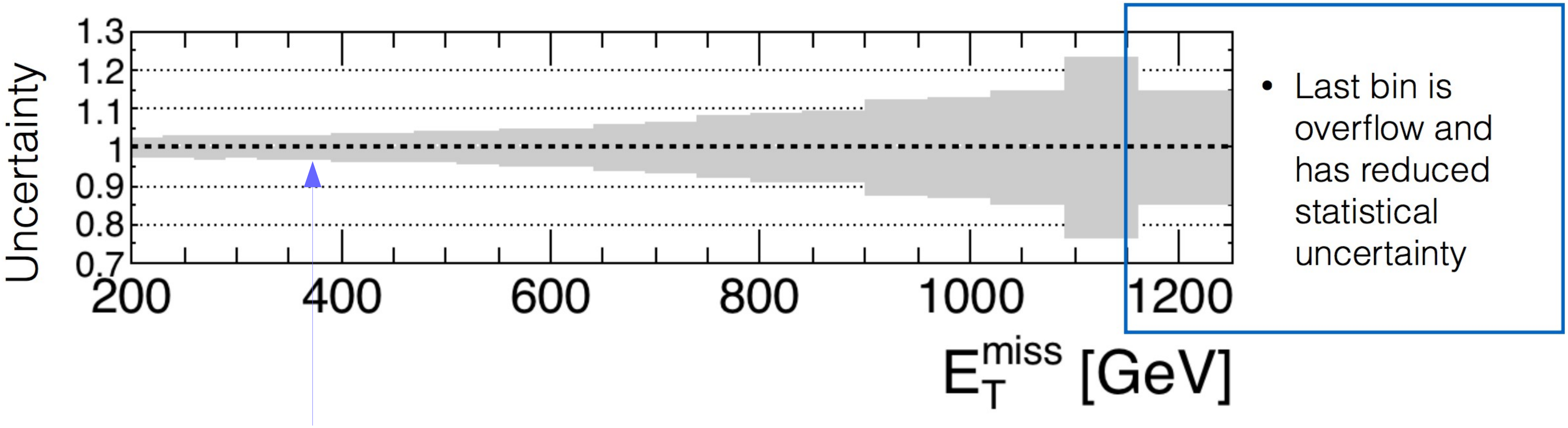


Perform 2D fit in isolation to compute fragmentation component

fit resolves issues of photon frag. component

- γ+jets EWK uncertainty too large to constrain
  - W+jets EWK corrections are much smaller
  - Point is we use both in simulatneous fit
  - Droping one or other is a >10% reduction in sensitivity

Projecting beyond this



Current low *MET* region unc. comes from Z→ll control region

Dominant uncertainty is the lepton efficiency measurement

Will improve considerably with updated analyses

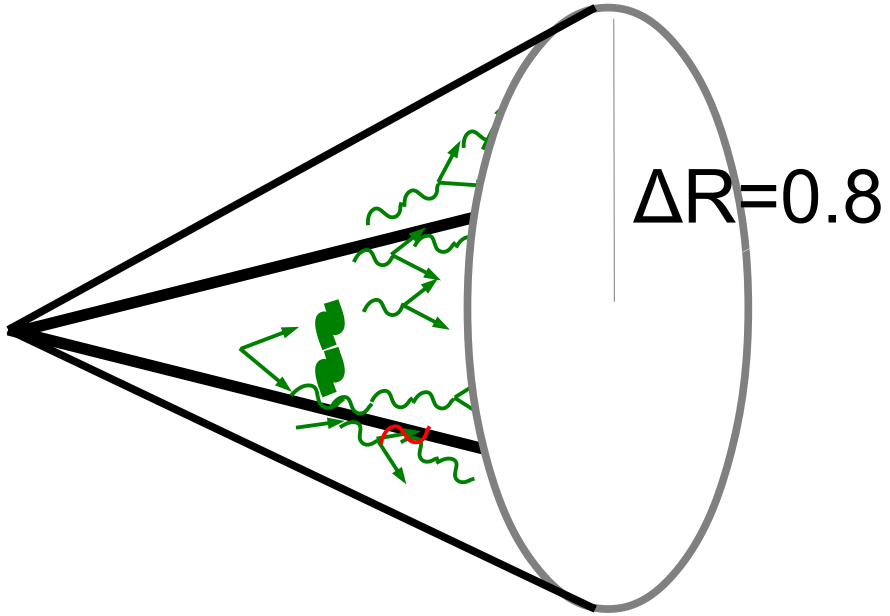
Current high *MET* region unc. from the γ & W control region

Will improve with new scale/EWK unc. Recommendatons

As lumi LHC increases correlated data approaches are critical

What differentiates them?

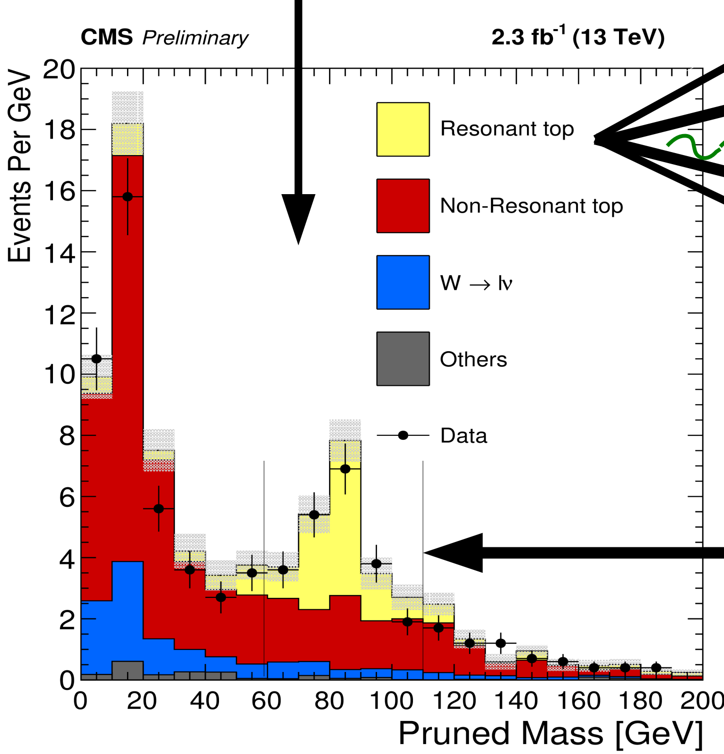
- For both the mono-top and mono-V we tag

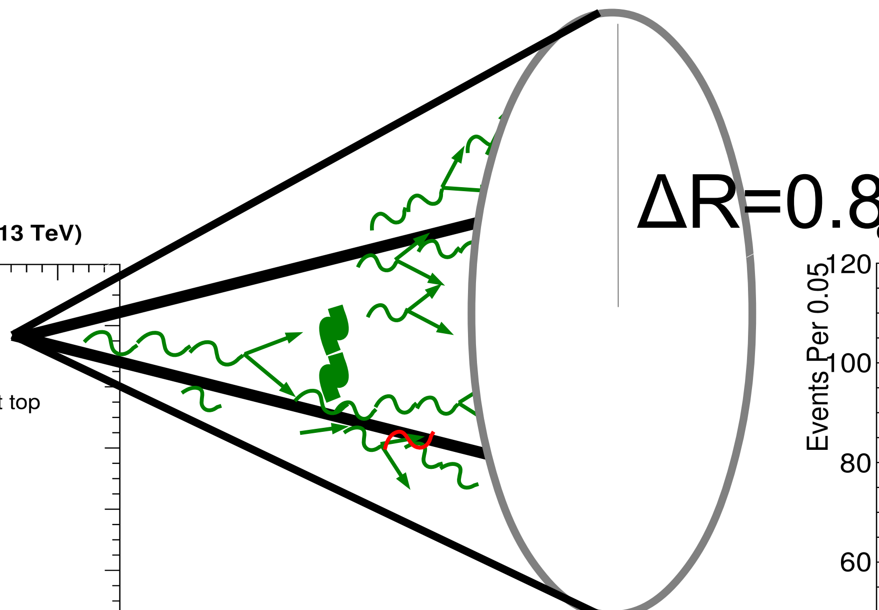


What differentiates them?

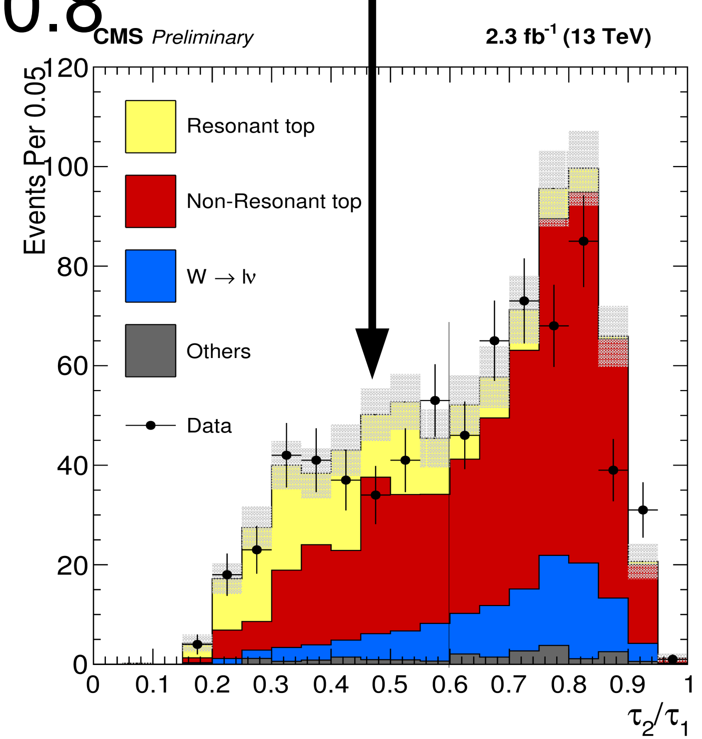
- For both the mono-top and mono-V we tag

Cut on mass





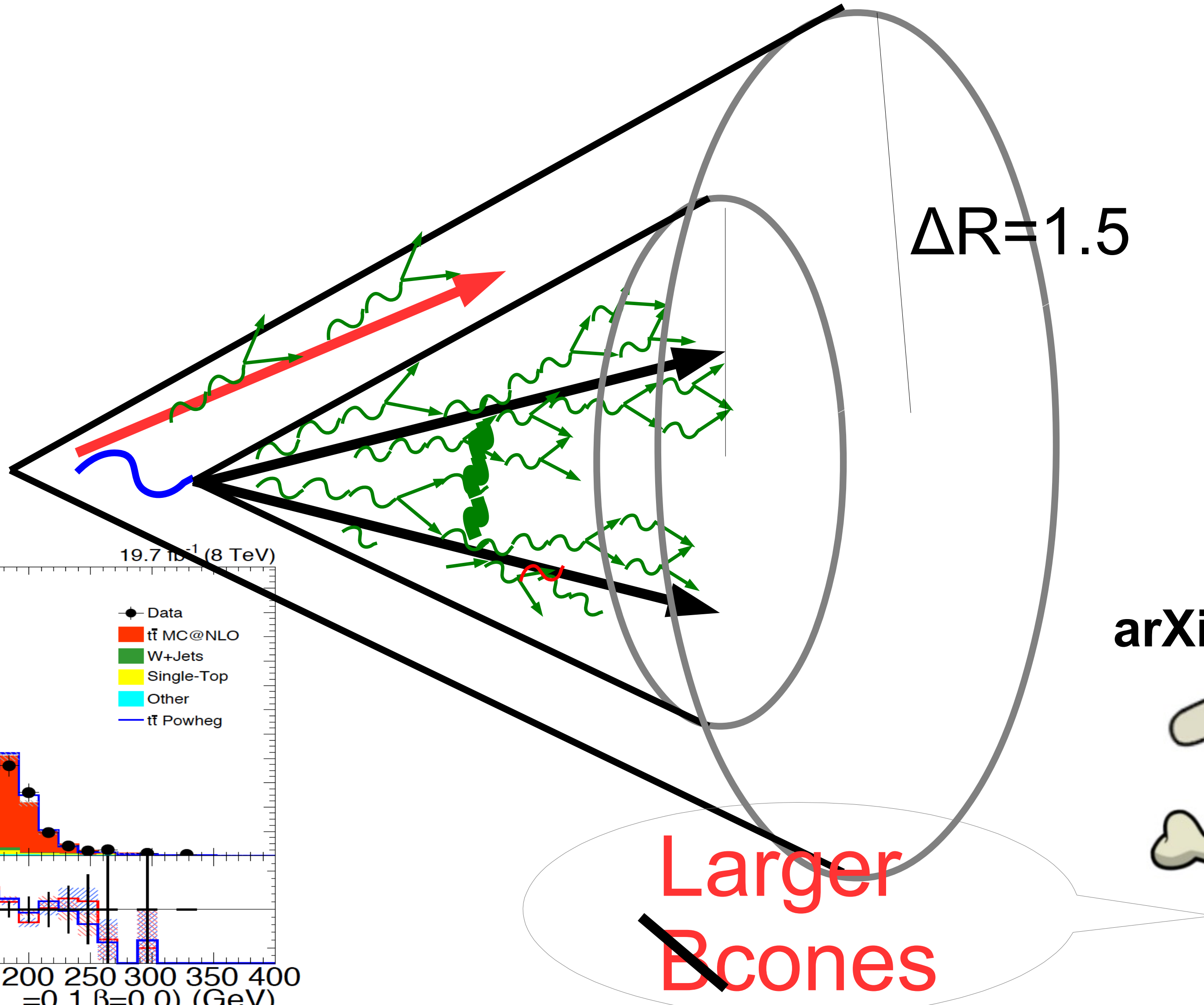
Cut on Likelihood of 2 prongs (τ_2/τ_1)

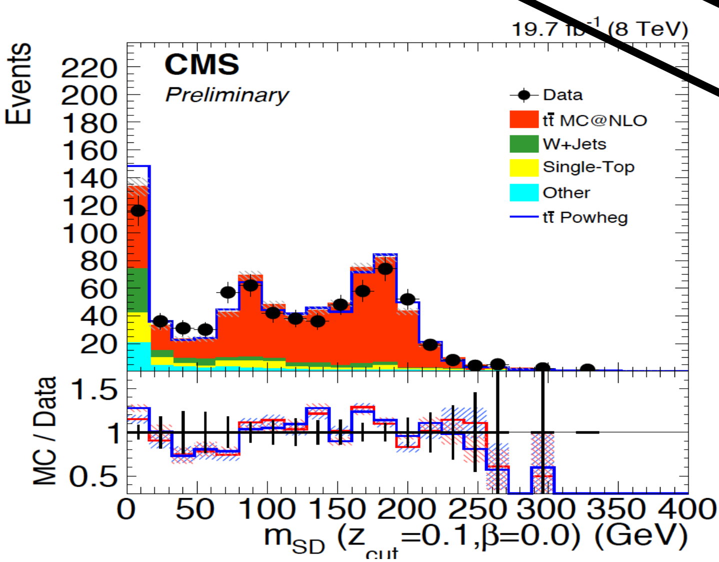


Tag & Probe on this peak
To get efficiency

What differentiates them?

- For both the mono-top and mono-V we tag

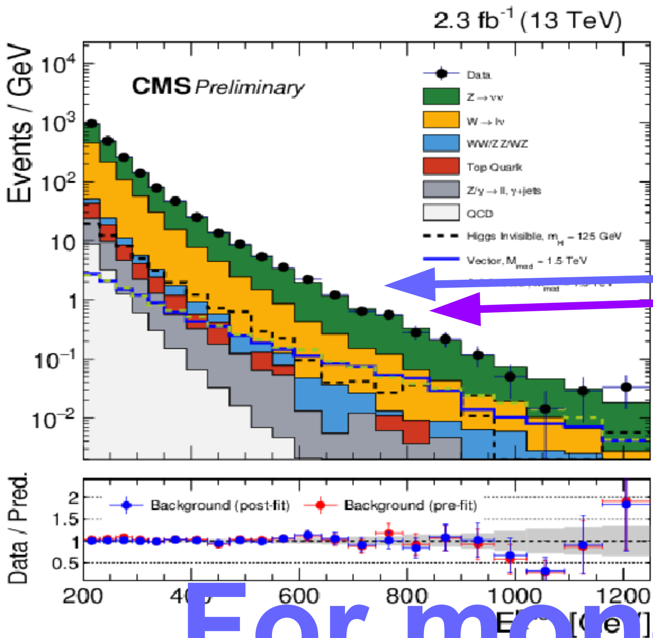


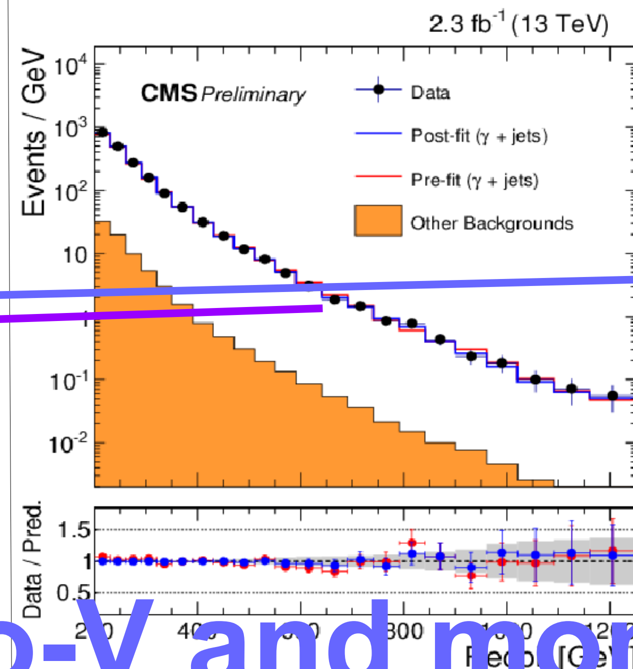


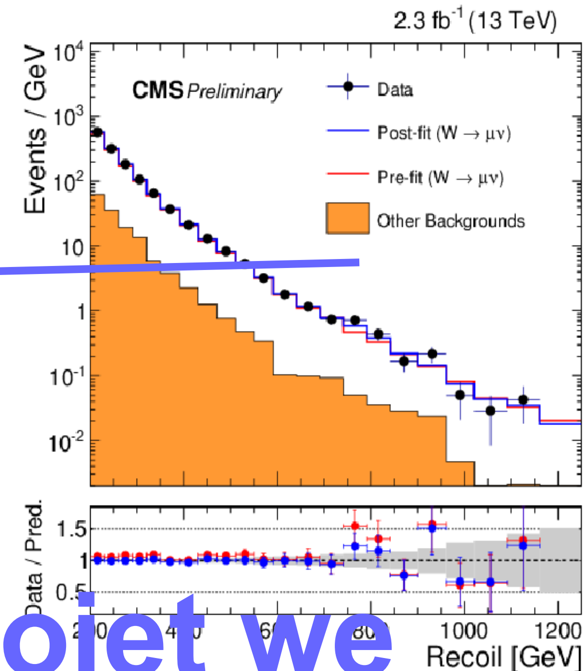
arXiv:1407.6013

Signal | CRs: γ+jets | + W + ...

Monojet

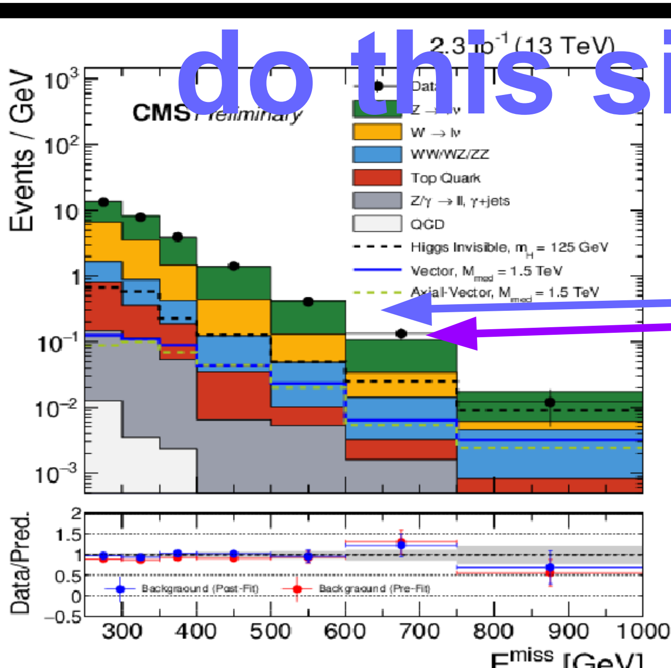


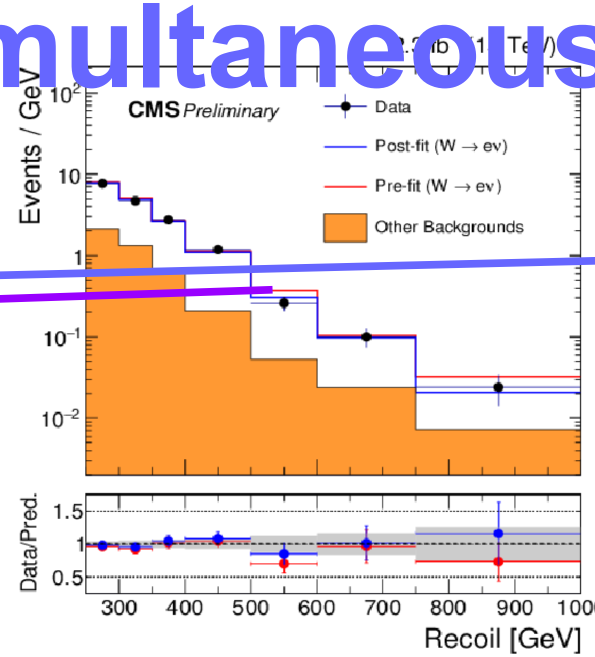


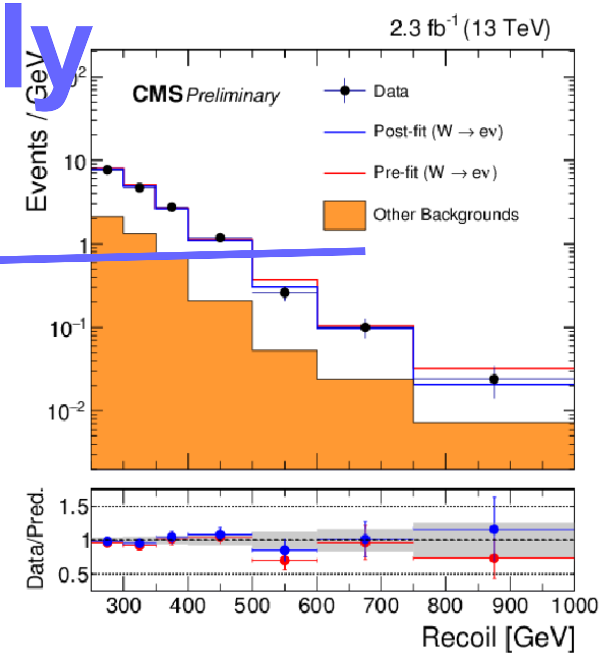


For mono-V and monojet we do this simultaneously

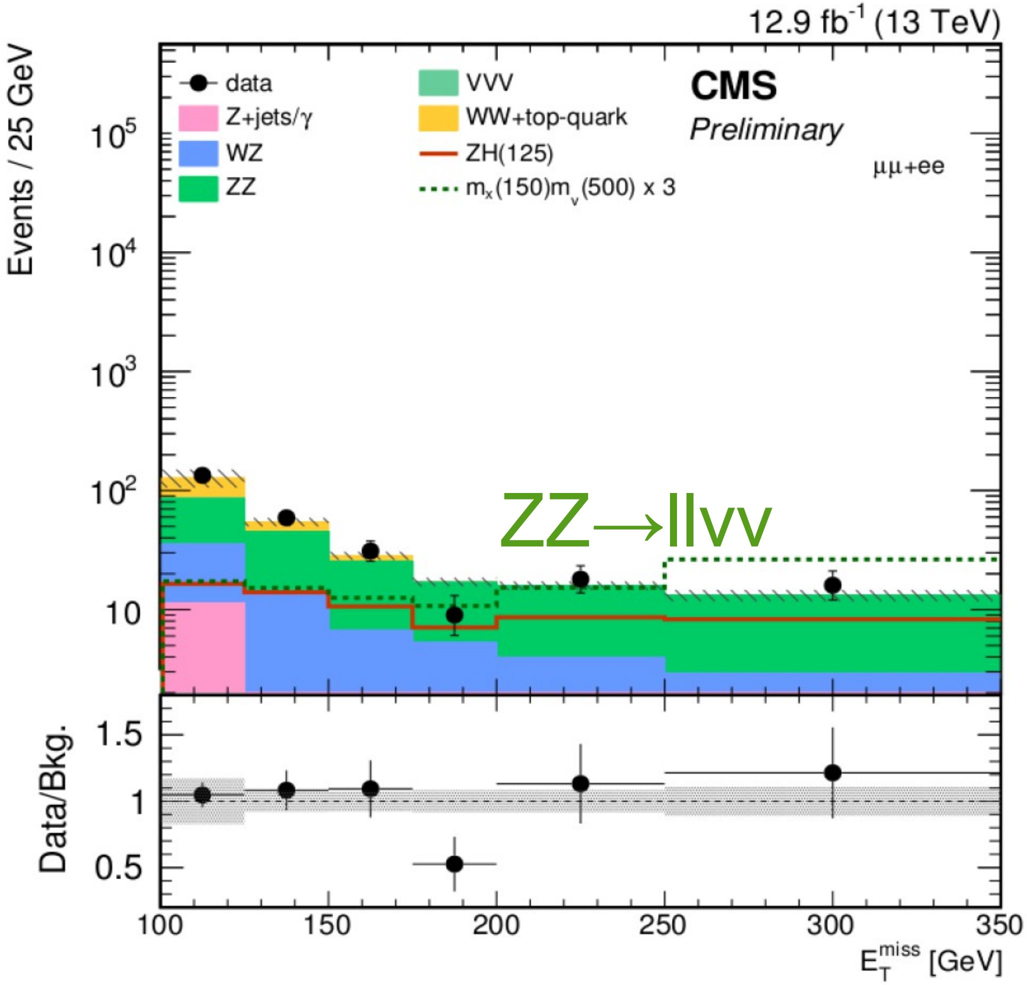
Mono-V





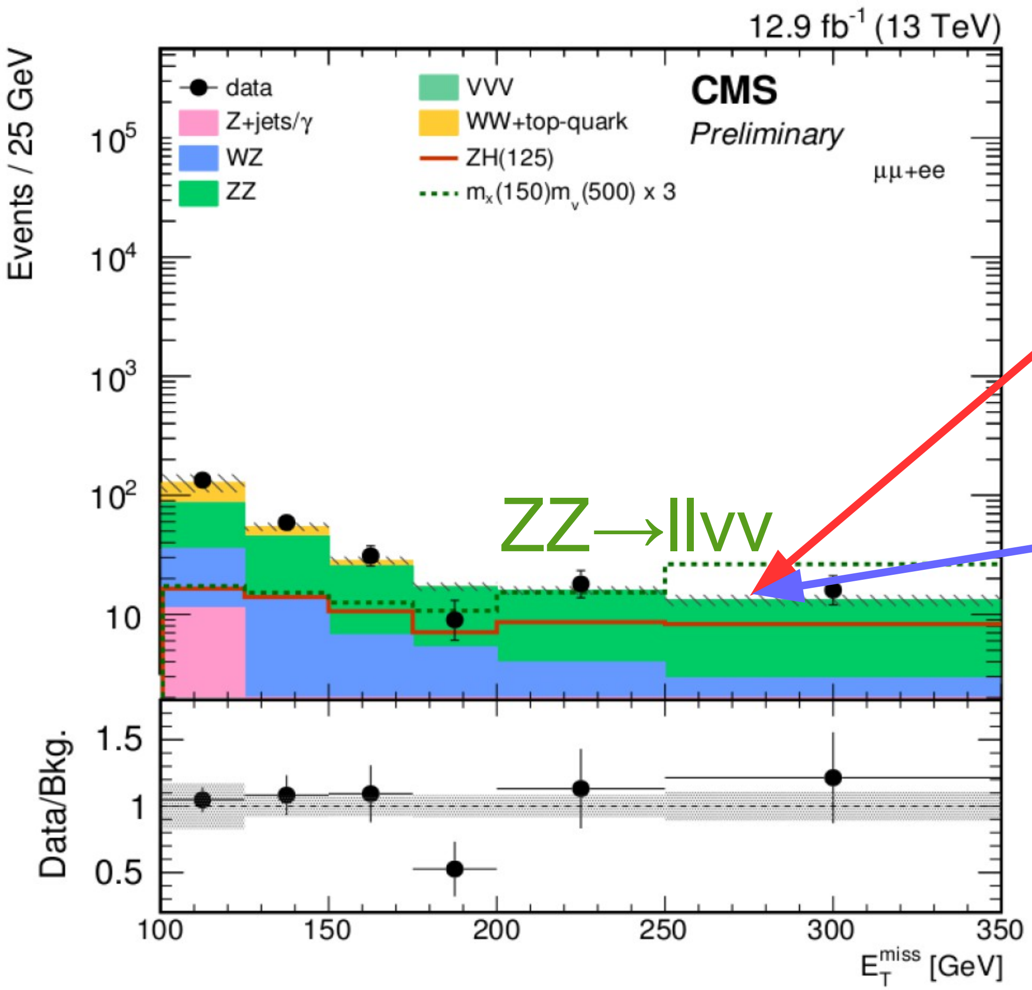


What would it be for Mono-Z?



Can modeled by

What would it be for Mono-Z?



Can modeled by

WZ→lllv

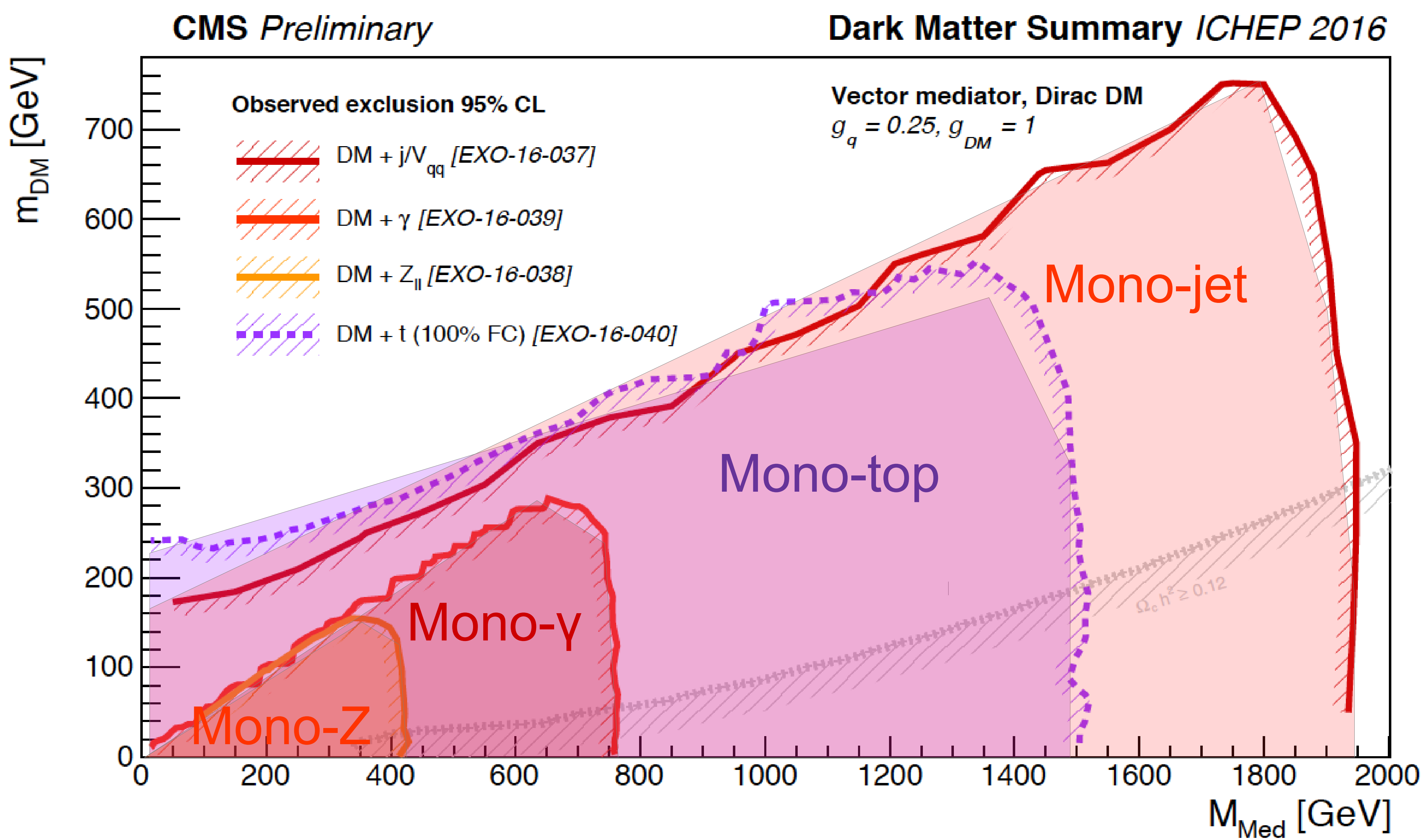
ZZ →llll

Simultaneously

While not done yet

Expect to see this result coming out soon

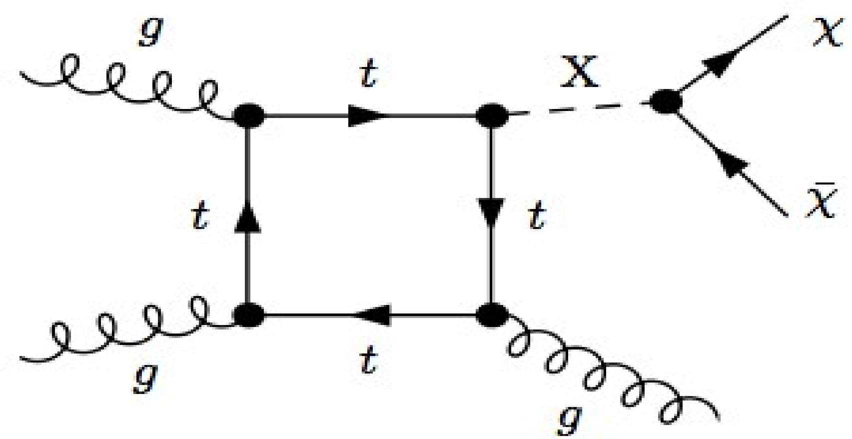
How do the channels compare?



Spin 0

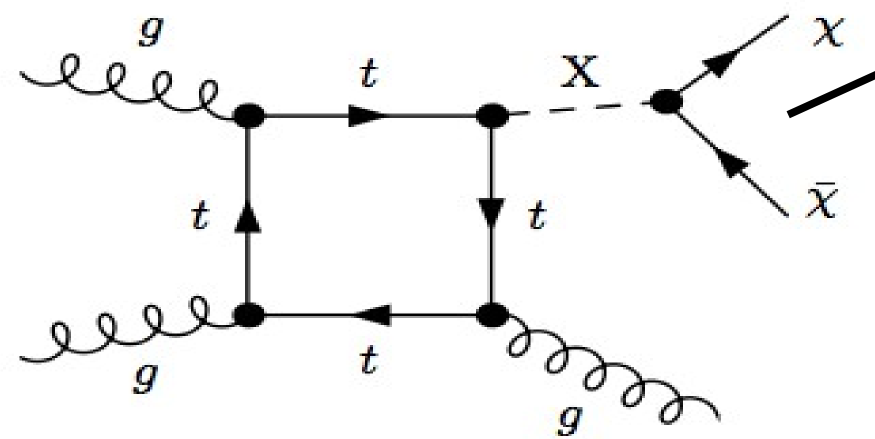
What can you do with Spin 0?

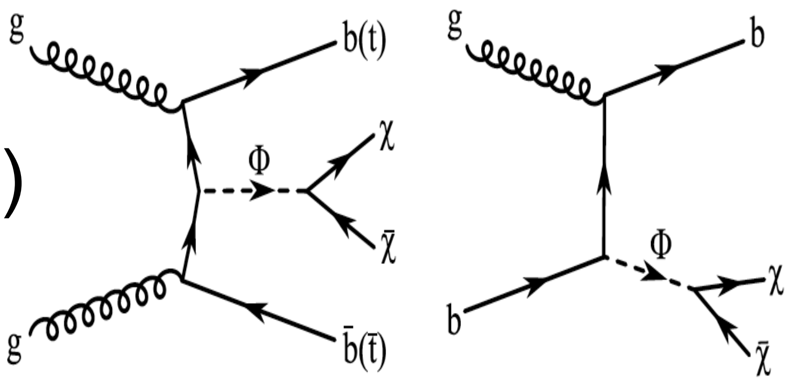
Basic production is gluon fusion
Amplitude is double for pseudoscalar mediator



What can you do with Spin 0?

Heavy flavor channels
Can be added with (same couplings)

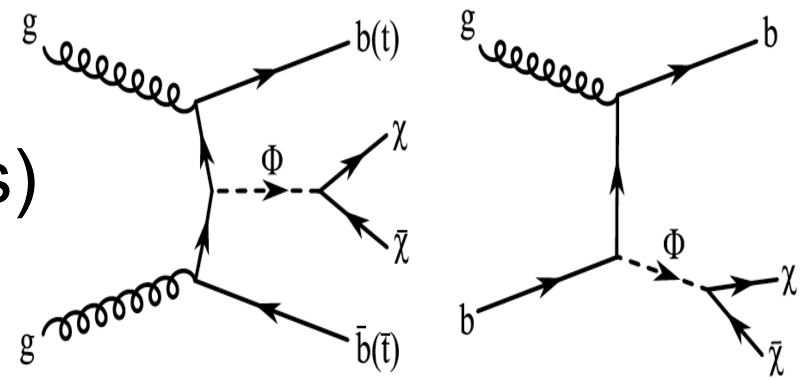


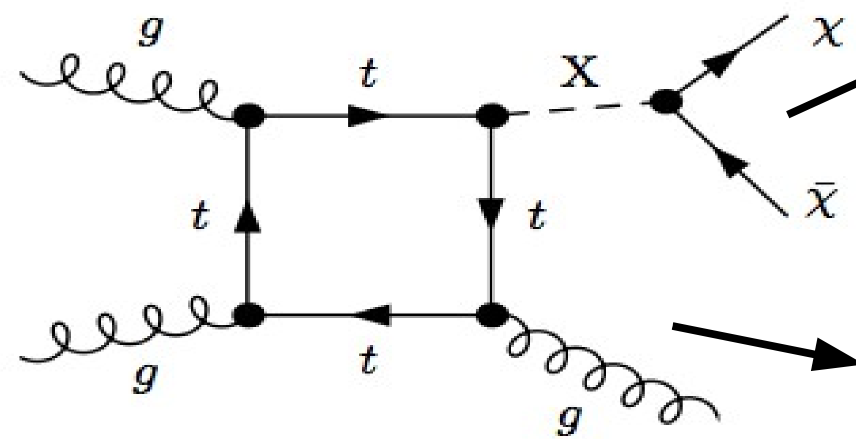


Heavy Flavor
final states

What can you do with Spin 0?

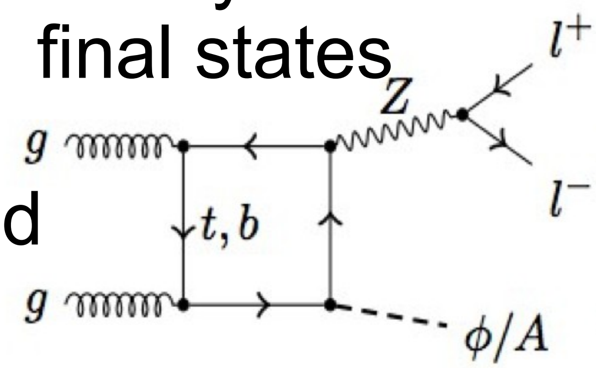
Heavy flavor channels
Can be added with (same couplings)





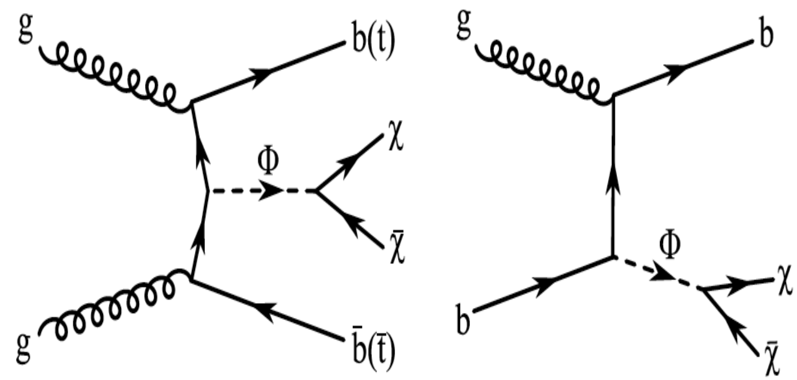
Heavy Flavor
final states

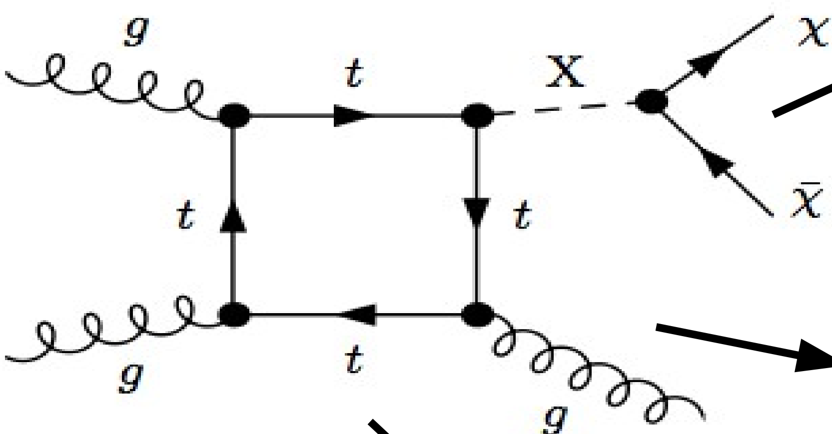
Loop induced
Z boson



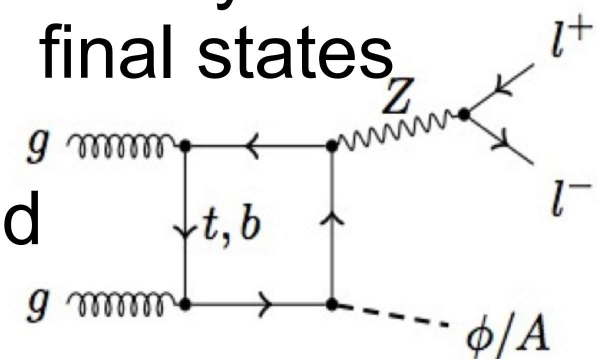
What can you do with Spin 0?

Big Assumption :
No mixing w/Higgs





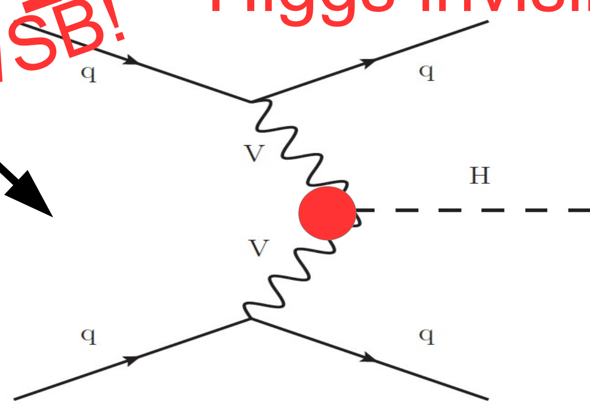
Heavy Flavor final states

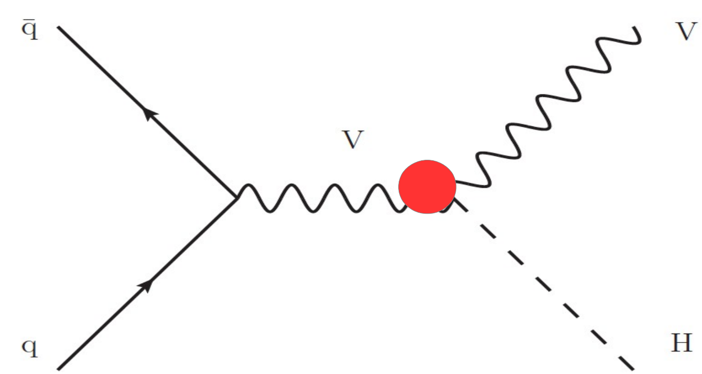


Loop induced Z boson

Higgs invisible or Scalar w/EWSB

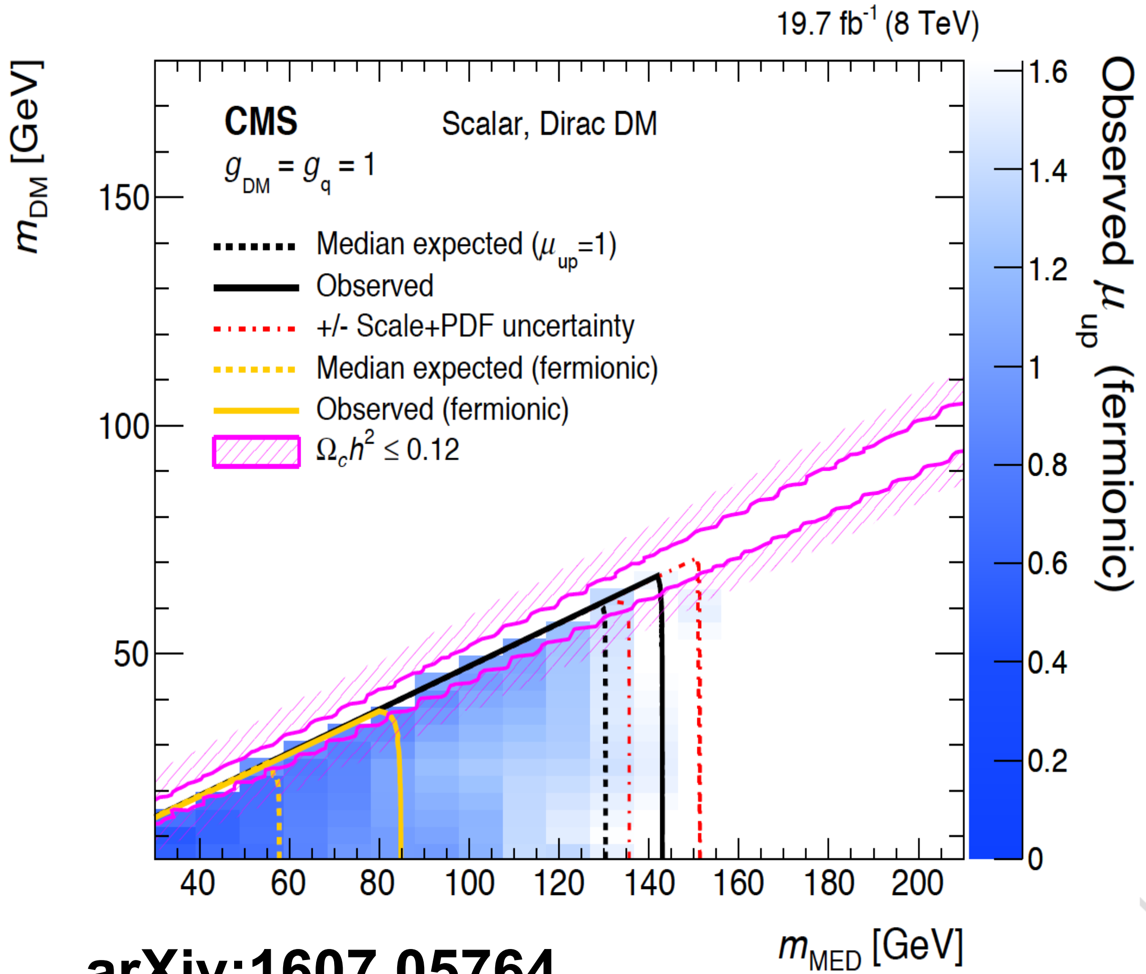
Applying EWSB!

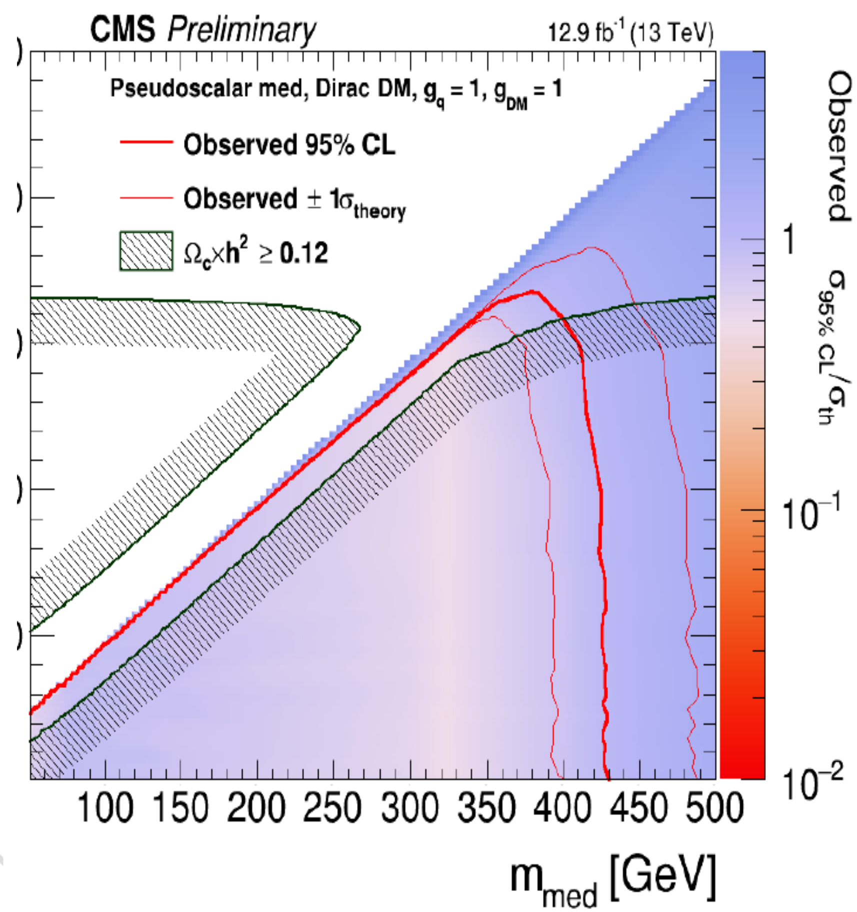




Spin 0
No EWSB

Spin 0 Bounds: No EWSB





arXiv:1607.05764

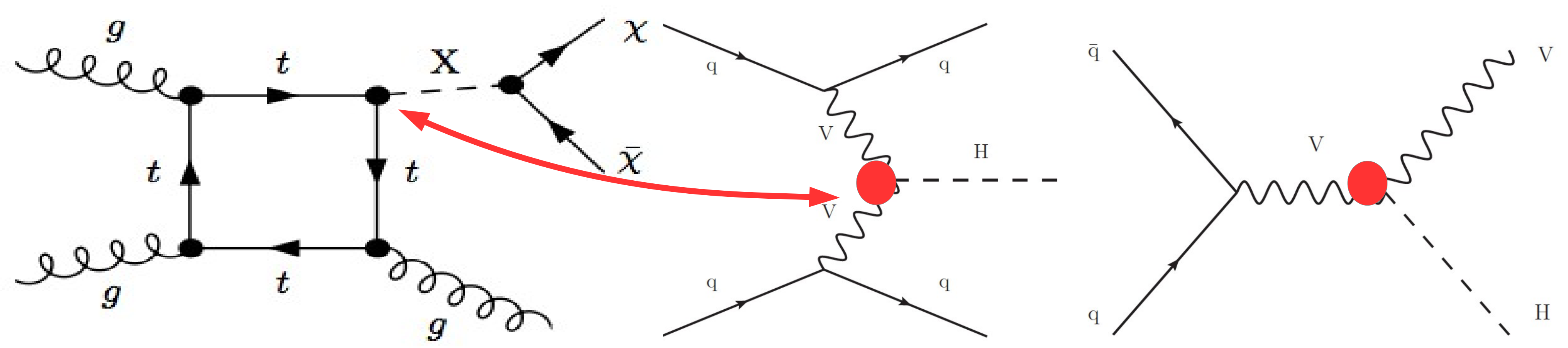
For scalar the 8TeV result slightly more sensitive

Expect next set of results to exclude much more

Spin 0
With EWSB

Issue with adding EWSB

- Whats the right ratio of vector boson couplings
  - Do we have to deal with mixing with the Higgs?



Simplest model (not necessarily realistic) :
Higgs, however other models exist