Dark Matter searches at LHC

Warsaw workshop on non-standard dark matter: multicomponent scenarios and beyond
Warsaw, Poland

2nd-5th June 2016

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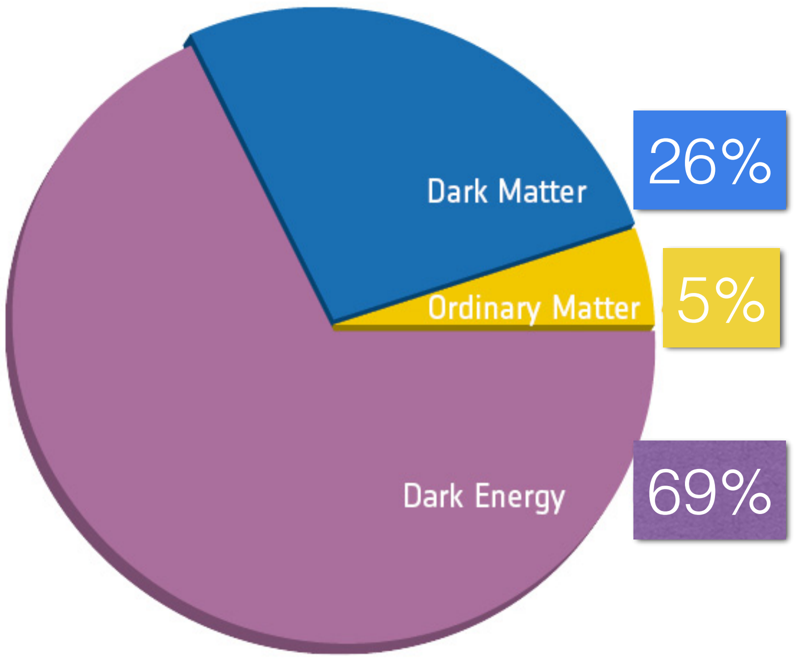
On behalf of CMS and ATLAS collaboration

Outline

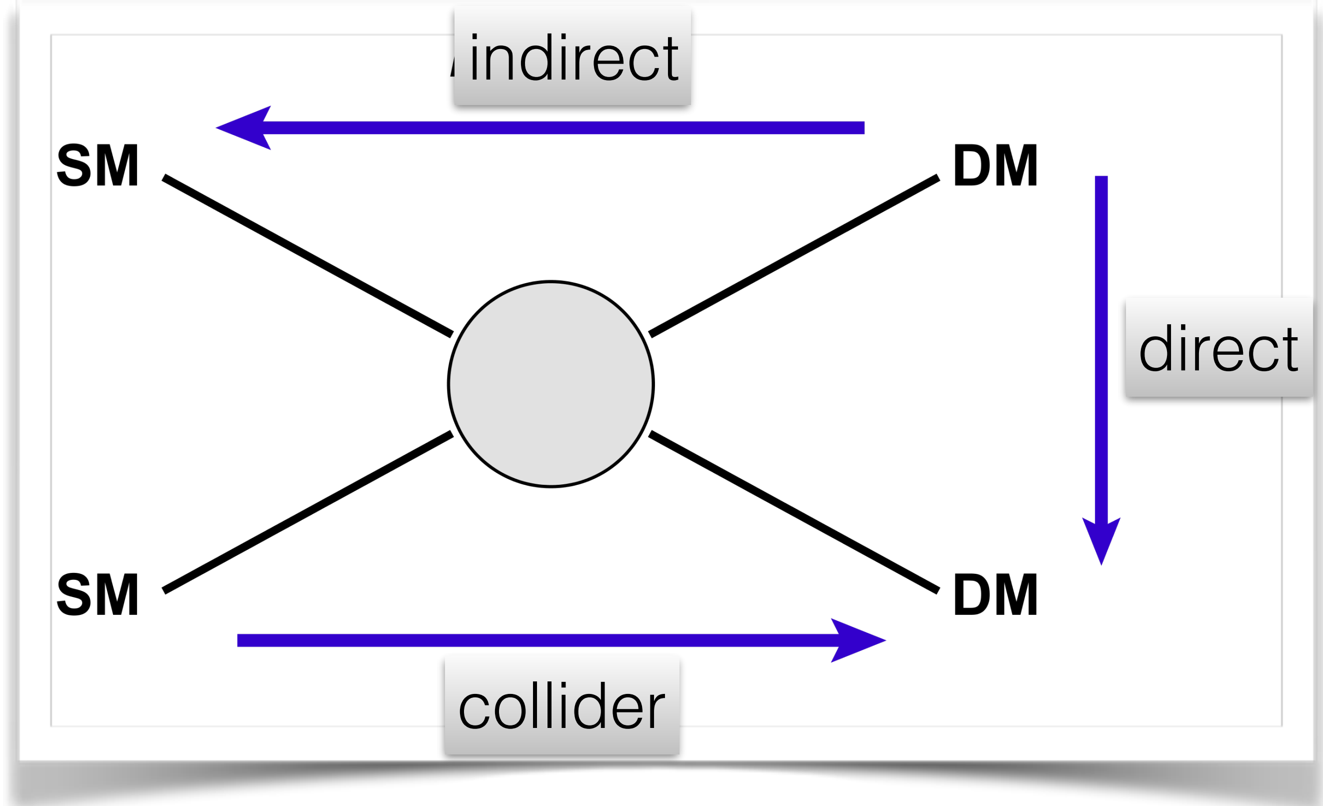
- ☐ Introduction
- ☐ Why searching Dark Matter at LHC?
- ☐ Where do we look for Dark Matter?
  - ☑ Pool of MET+X analysis
  - ☑ Simplified model summary
  - ☑ Many more but not covered in this presentation.
- ☐ Summary



- How do we find Dark Matter?

How do we find Dark Matter?

- Direct detection:
  - ☑ $\chi + SM \rightarrow \chi + SM$
- Indirect detection:
  - ☑ $\chi + \chi \rightarrow SM + SM$
- Collider experiment:
  - ☑ $SM + SM \rightarrow \chi + \chi$



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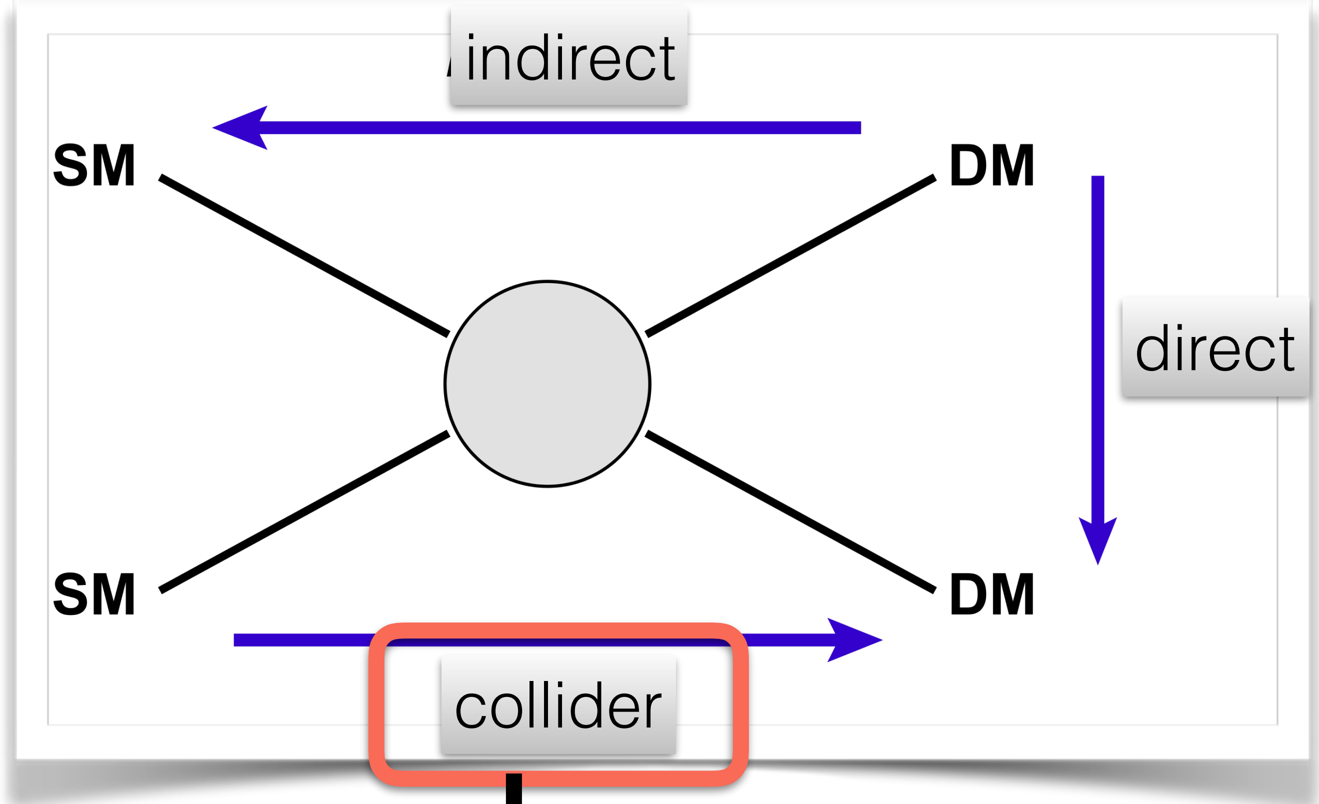


Covered in this presentation

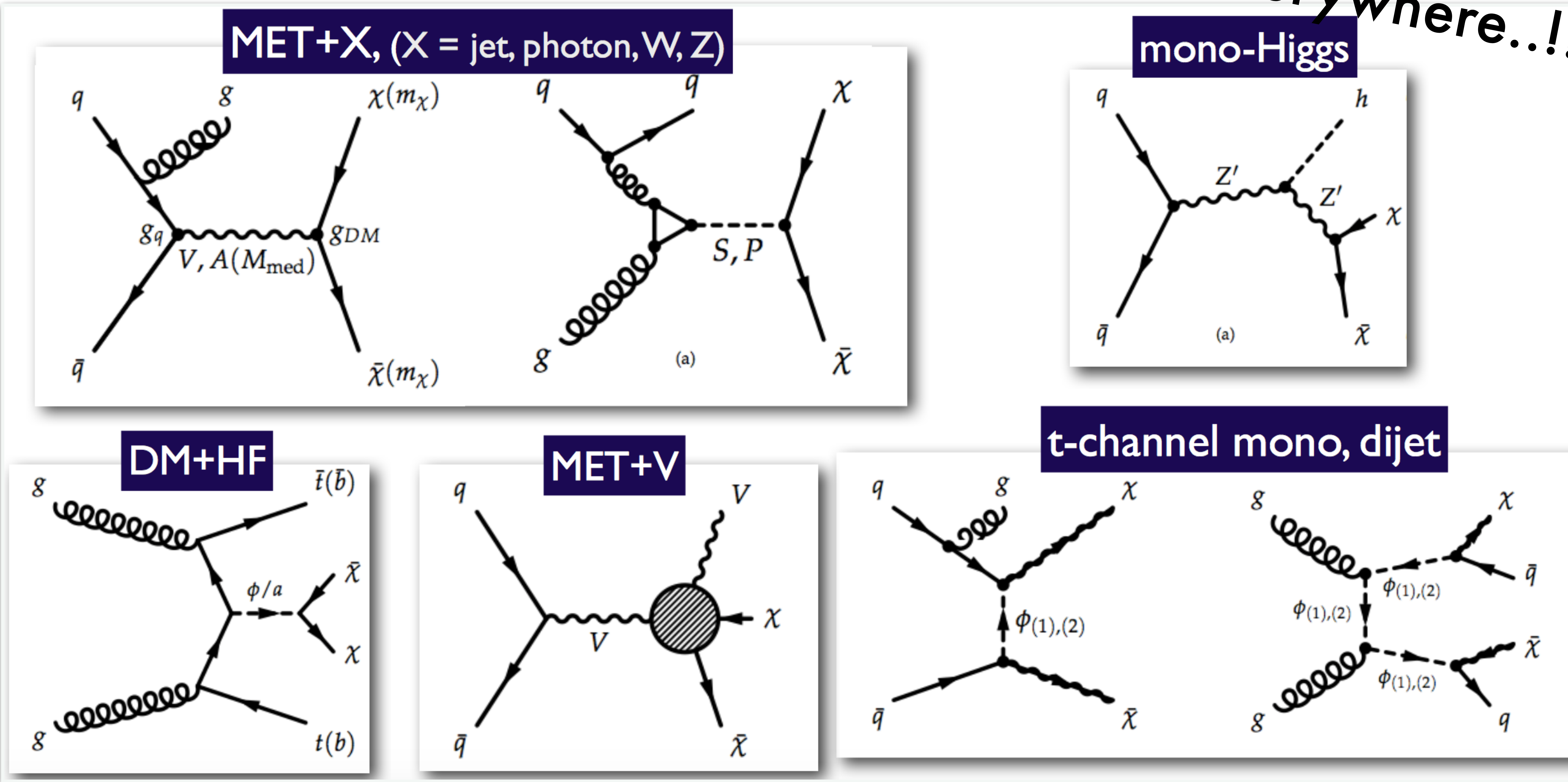
Dark Matter at LHC

- Pros
  - Independent of astrophysical uncertainties.
    - Local density/velocity
    - Galaxy density
  - Only possible way to create DM particles at laboratory.
  - Complementary to other DM experiments.
  - Rich physics results due to many signatures.
- Cons
  - Main property of Dark Matter
    - It is DARK
    - Invisible things are hard to see in the collider experiments detectors.
  - Many objects can fake invisible particles.
  - Requires interaction with some component of proton.

- In which final state(s) one should look for Dark Matter at LHC?

In which final state(s) one should look for Dark Matter?

Everywhere..!!

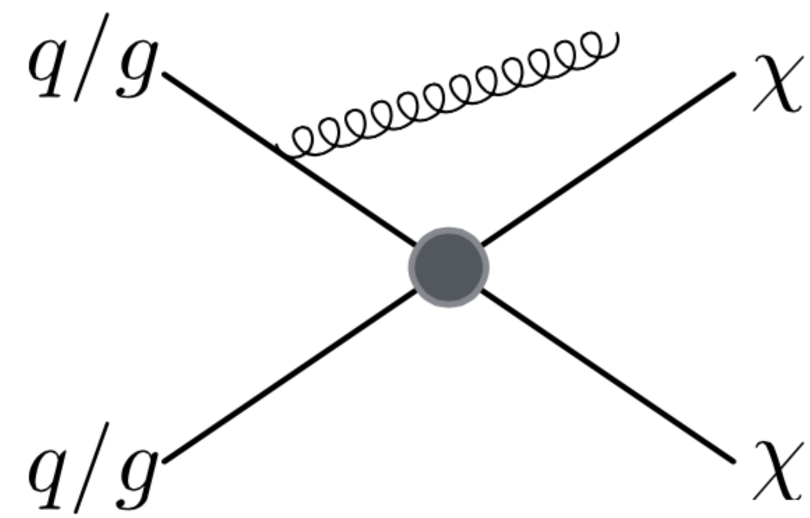


List of simplified models discussed in ATLAS-CMS DM Forum:
http://arxiv.org/pdf/1507.00966v1.pdf

Effective Field Theories

ATLAS: http://arxiv.org/abs/1502.01518

- [ ] Be as general as possible: everything but mediator is heavy

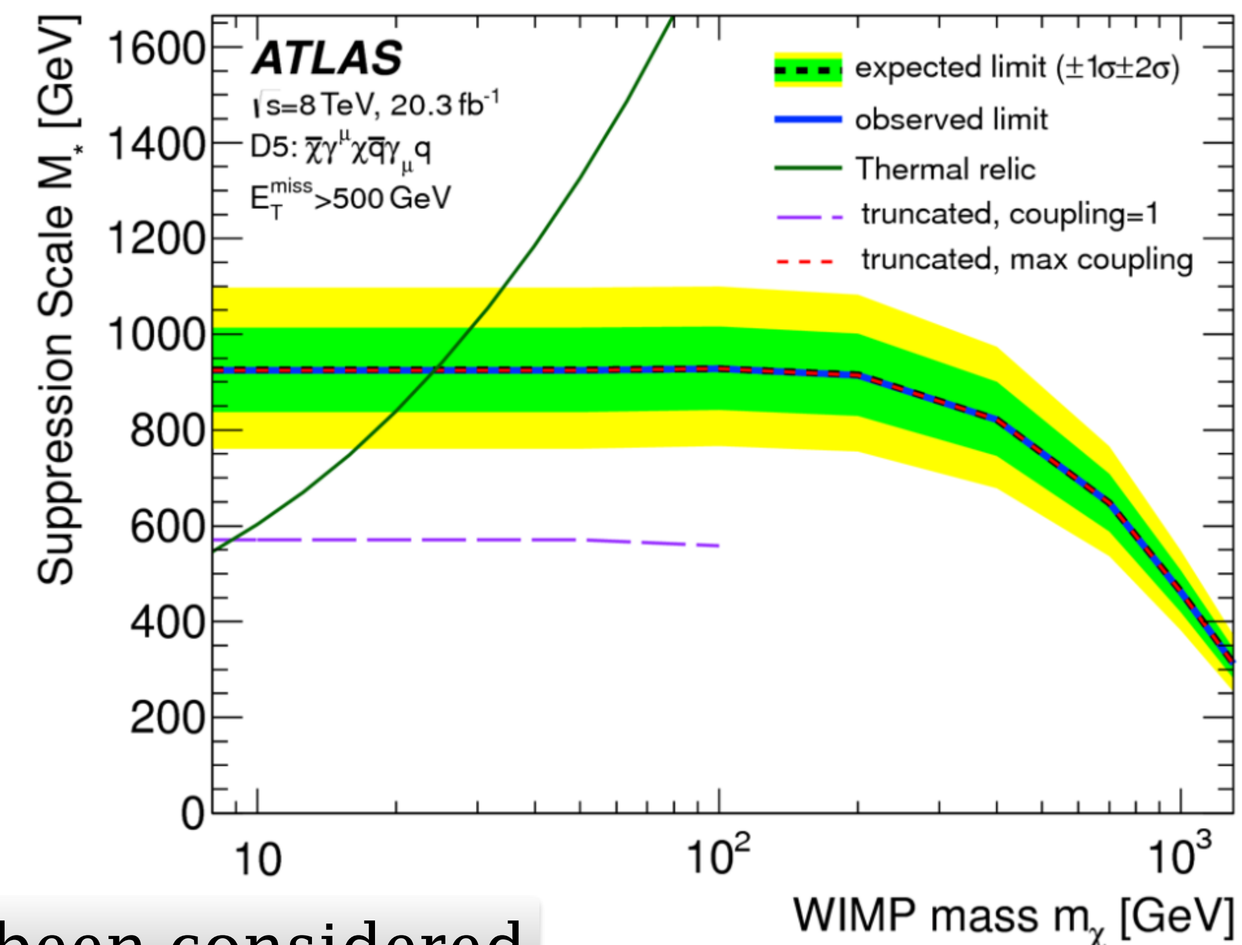


- [x] Vary Lorentz structure, spin assignment.

$$\mathcal{L}_{D5} = \frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$$

$$\mathcal{L}_d \propto \Lambda^{4-d} \Rightarrow \sigma \propto \Lambda^{2(4-d)}$$

$$\Lambda \sim M/\sqrt{g_{\chi}g_q}$$



Several EFT Models have been considered

Failure of EFTs

- Have to check that assumptions are valid. Can we really integrate out the mediators?

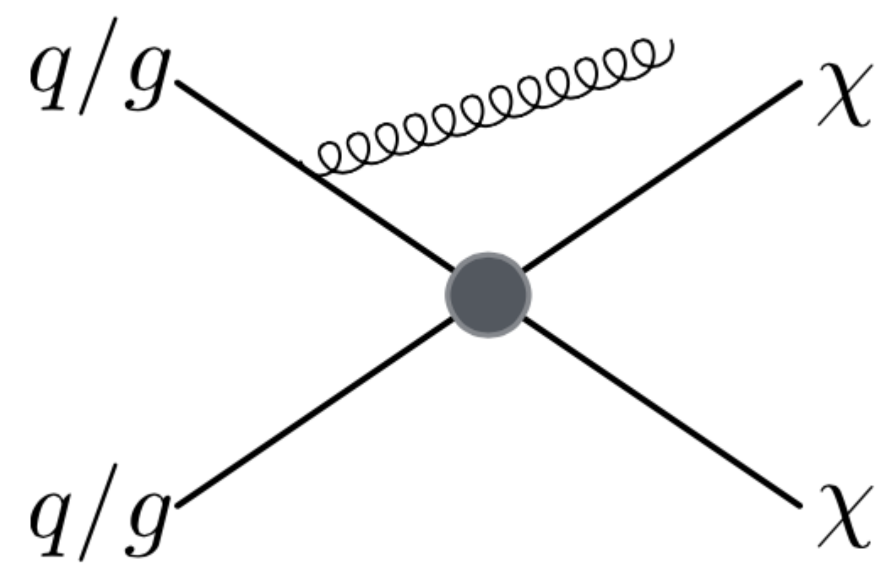
$$(g_\chi g_q) \times \frac{i}{q^2 - M^2} \to -\frac{g_\chi g_q}{M^2}\left(1 + \mathcal{O}(q^2/M^2)\cdots\right)$$

$$\Lambda^2 \equiv \frac{M^2}{g_\chi g_q}$$

- Effective theory is only valid if

$$Q_{\mathrm{transfer}} < M = \sqrt{g_\chi g_q}\Lambda < 4\pi\Lambda$$

- At the LHC $Q_{\mathrm{transfer}} \propto p_{T,\mathrm{jet}}$



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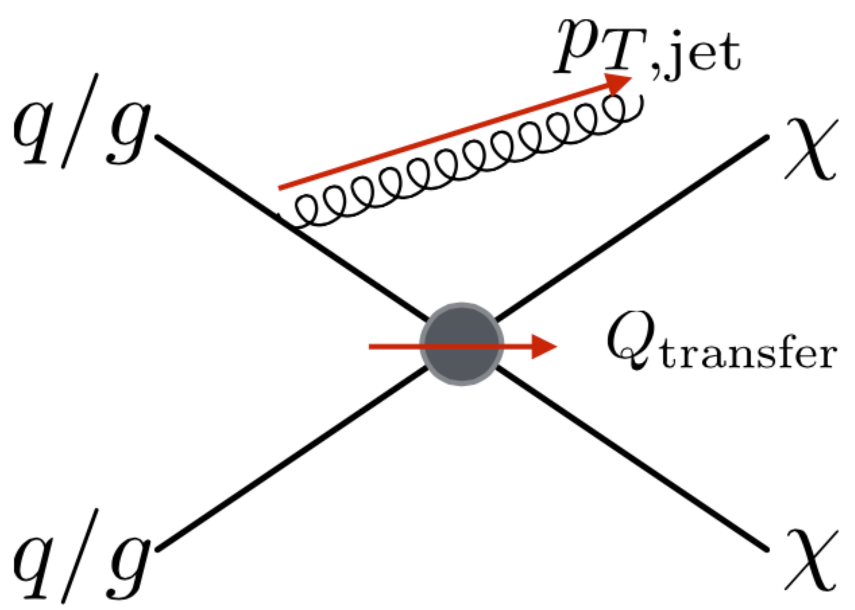
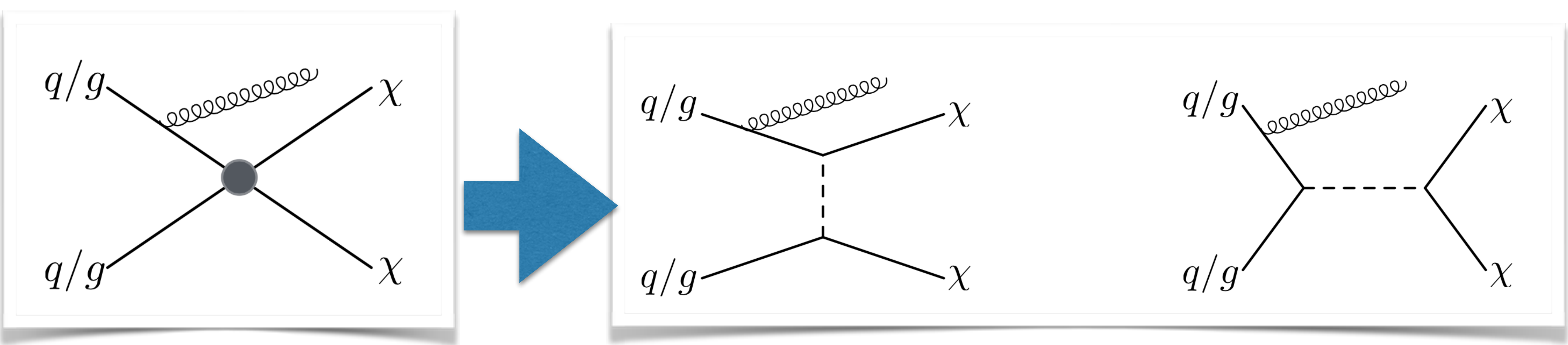


Simplified Models

- Now we have turned a 1-D problem into a multi-dimensional one.
  - m_χ, $m_{mediator}$, g_χ, g_q, $\Gamma_{mediator}$ …



Analysis strategy for Mono-X

- Discussing one example of Mono-Jet in details

- Rest of the analysis can be seen in details from quoted references.

- Jet + E_T^{miss}
- W/Z (→lep/jet) + E_T^{miss}
- t/b + E_T^{miss}
- γ + E_t^{miss}
- H + E_T^{miss}

Classifying the models

Vector

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

EWK style coupling
(equal to all leptons)

Axial

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

EWK style coupling
(equal to all leptons)

Scalar

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

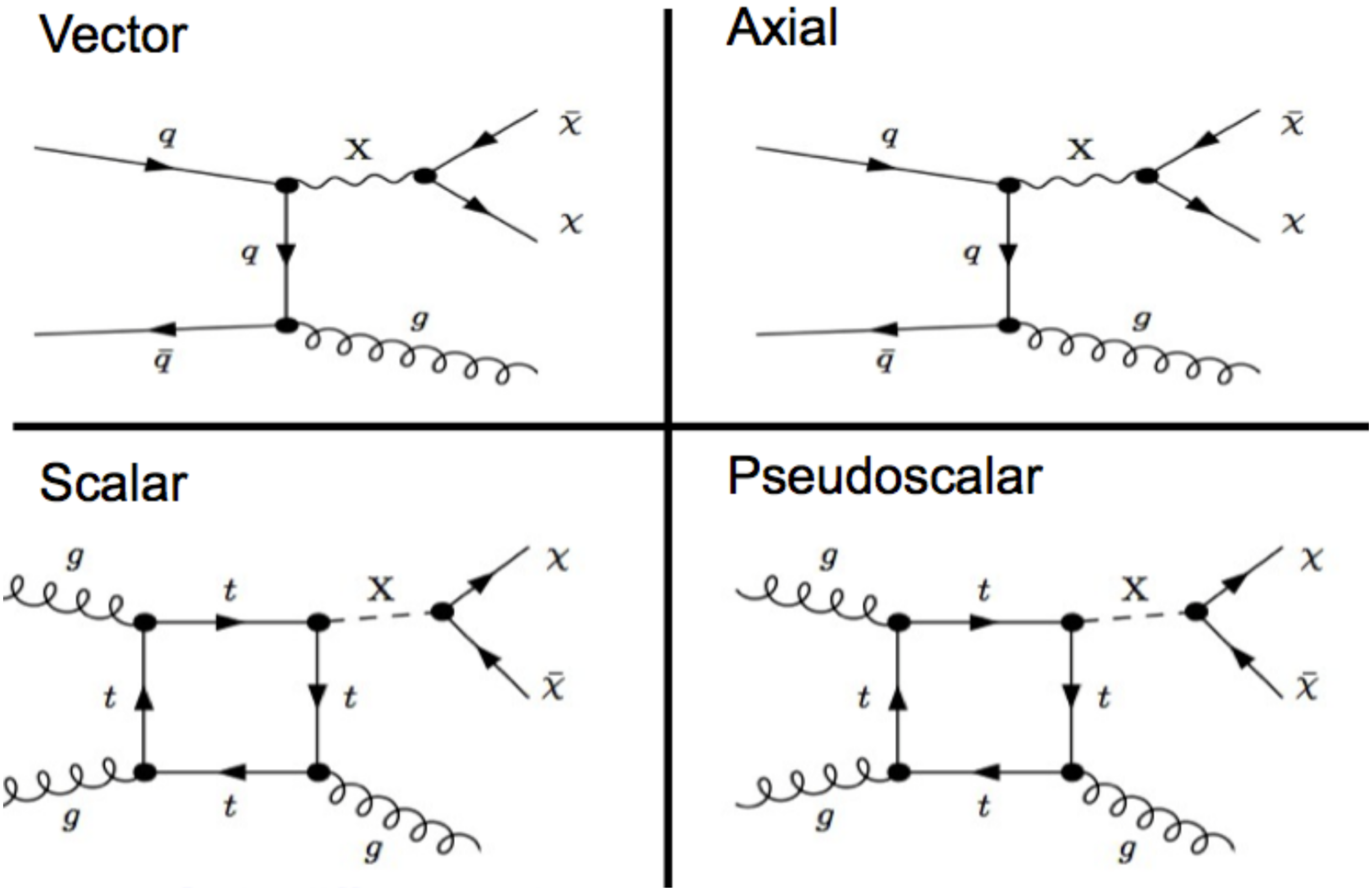
Yukawa style coupling
(Mass based coupling)

Pseudoscalar

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

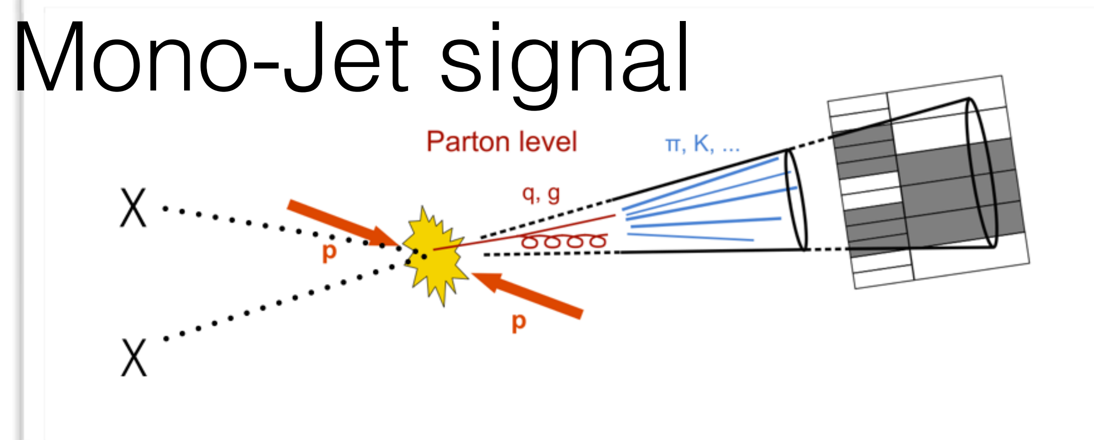
Yukawa style coupling
(Mass based coupling)

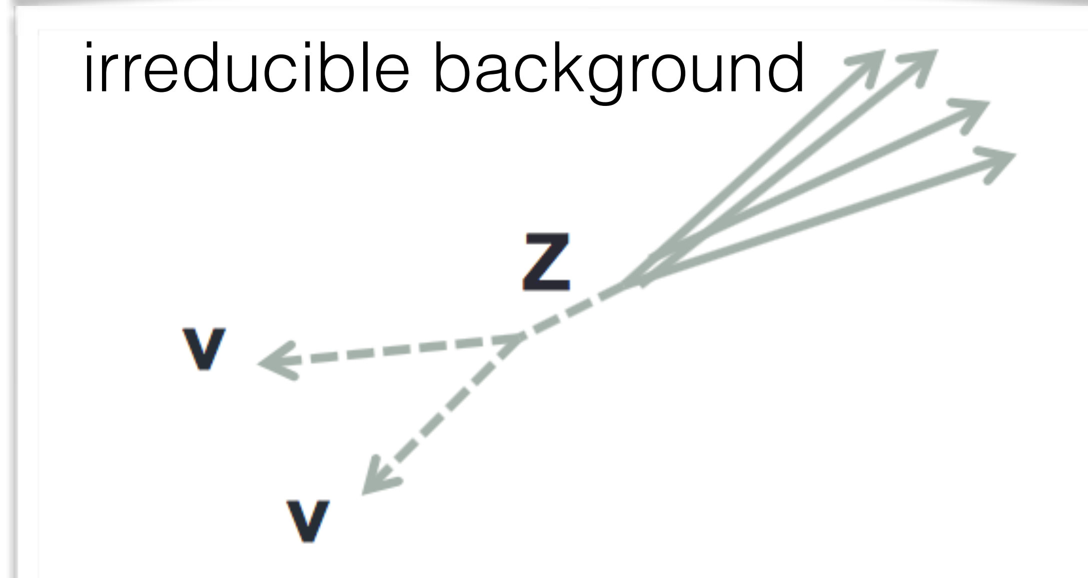
Classifying the models

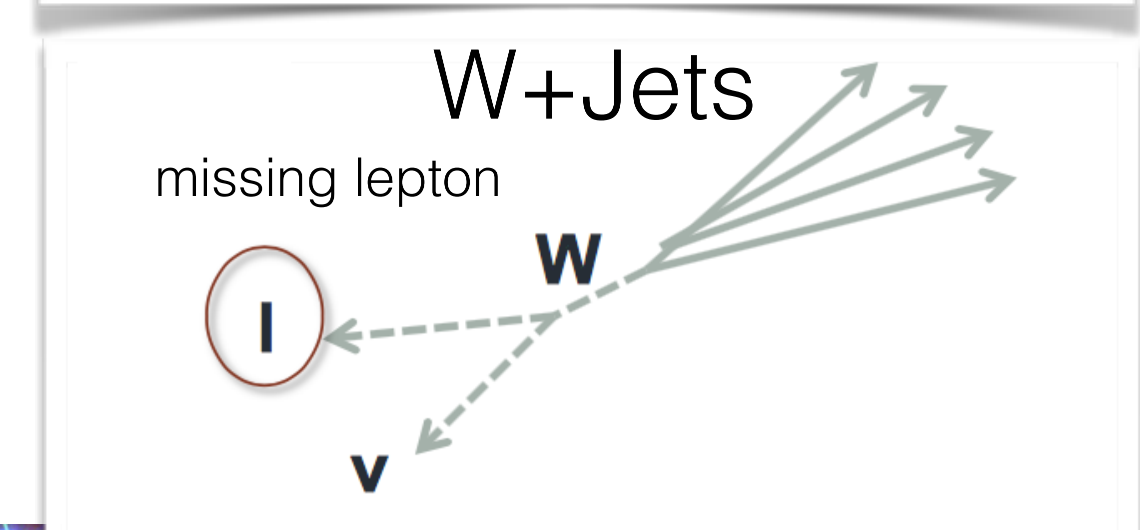


Background composition

- Main backgrounds:
  - $Z \rightarrow \nu\nu$ is the main background [irreducible]
  - $W \rightarrow l\nu$ when one lepton is out of acceptance or not identified.
- Minor backgrounds:
  - Top: Semi-leptonic tt
  - Di-boson: WW and WZ production mainly
  - γ+Jets
  - QCD multijet







Mono-Jet/Hadronic V selection

CMS Analysis

CMS-PAS-EXO-16-013

- Look for events with high p_T jet and high MET.
  - ☑ event categorisation:
    - ✦ Mono V
      - ❖ AK08 jet with $p_T > 250$ GeV
      - ❖ mass compatible with W/Z mass window (65-105 GeV)
      - ❖ MET > 250 GeV
    - ✦ Mono-jet
      - ❖ No AK08 jets
      - ❖ Two AK04 jets with leading jet $p_T > 100$ GeV.
      - ❖ MET > 200 GeV
- Dedicated MET triggers.
- No additional lepton (e,μ,τ) in the event to reduce ZJets and WJets
- No additional photons to reduce γ+Jets.
- No additional b-jets to reduce the Top backgrounds.

Background extraction

γ+Jets

$W \rightarrow \mu\nu$+Jets

$W \rightarrow e\nu$+Jets

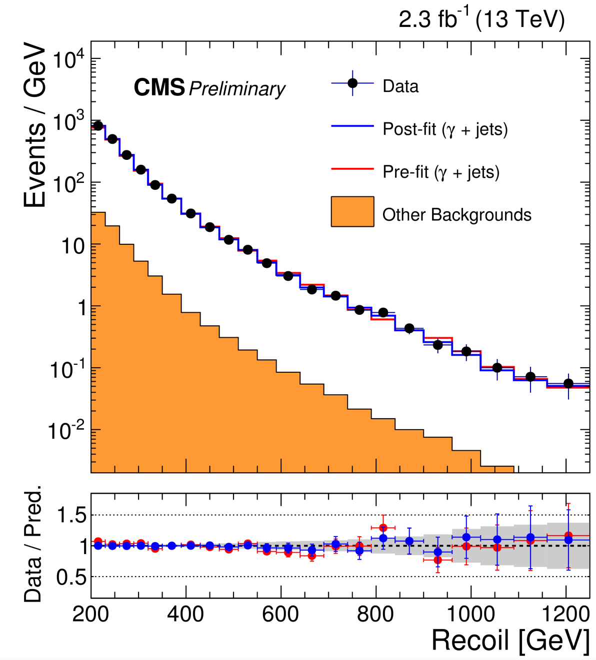
Main backgrounds Z/W +Jets are estimated from data considering 5 control regions.

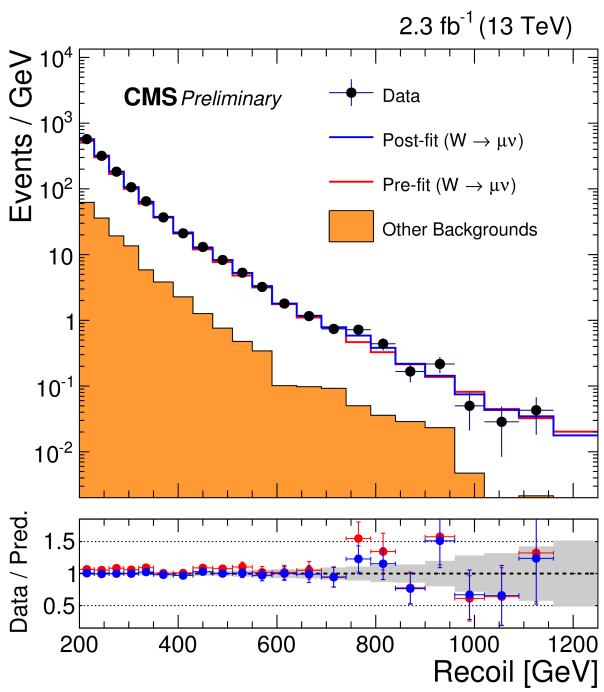
$Z \rightarrow \mu\mu$+Jets

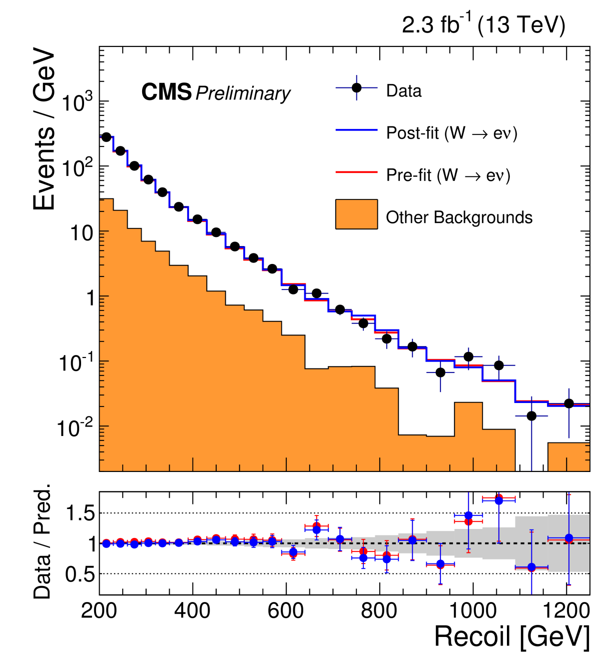
$Z \rightarrow ee$+Jets

Background extraction

CMS-PAS-EXO-16-013







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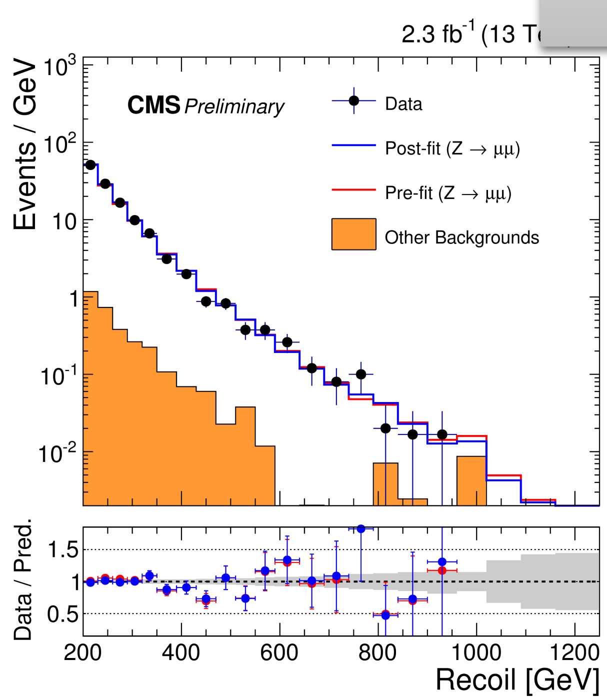
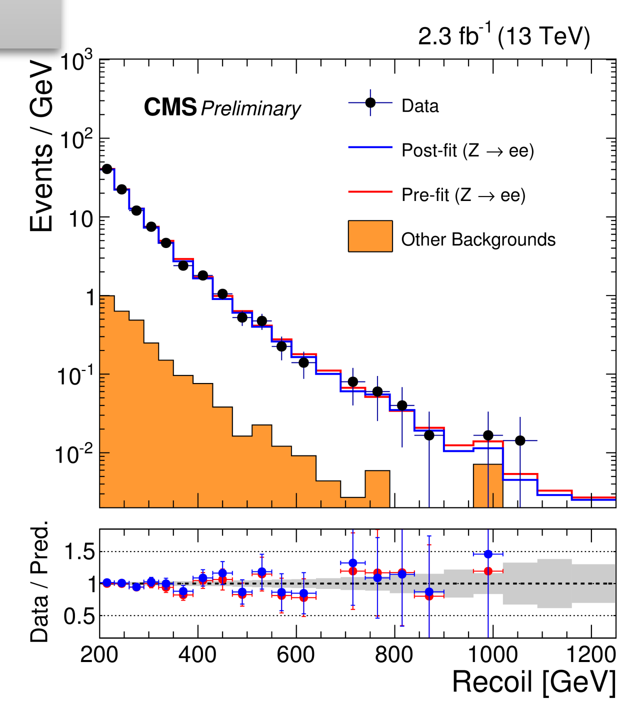
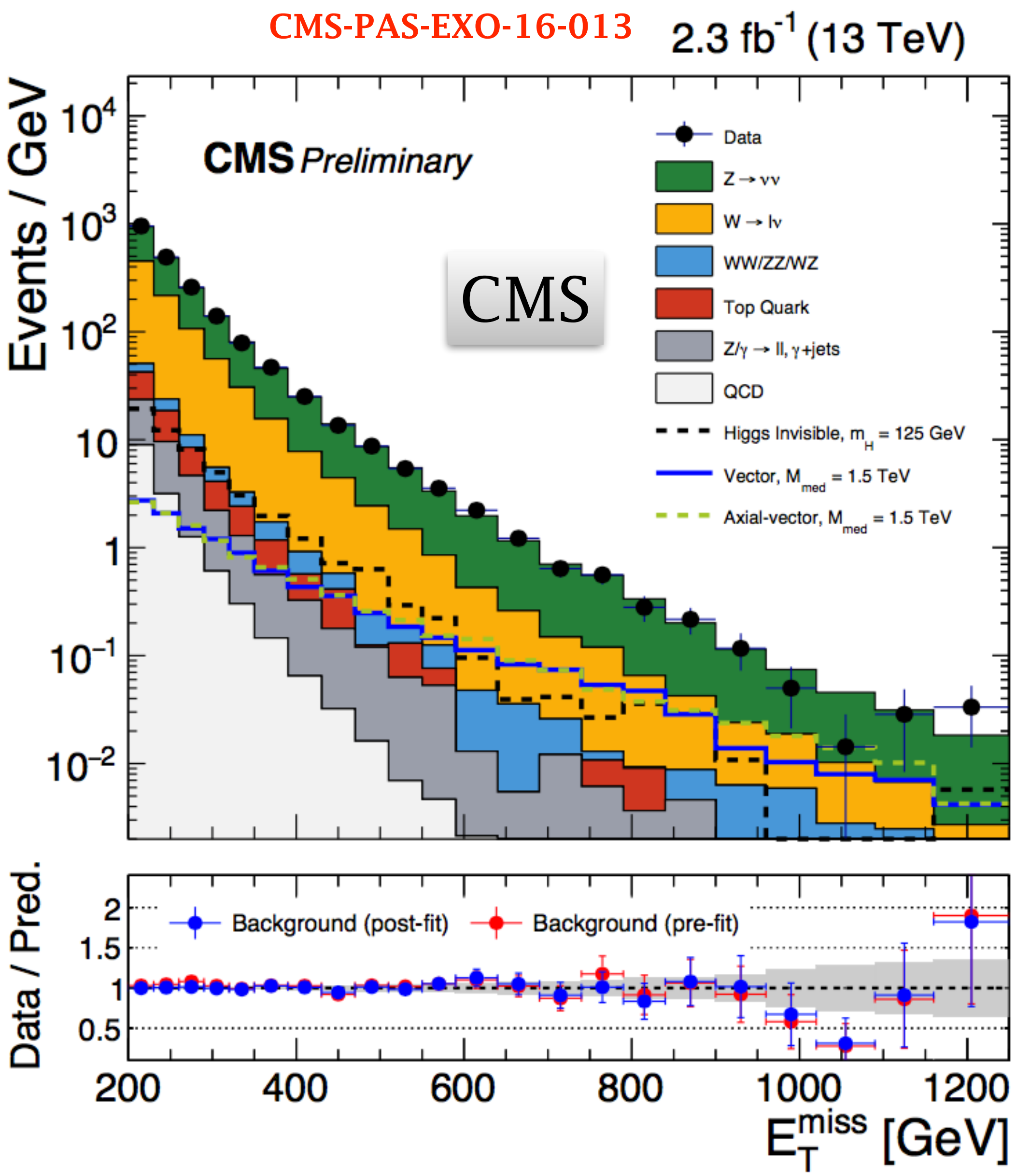


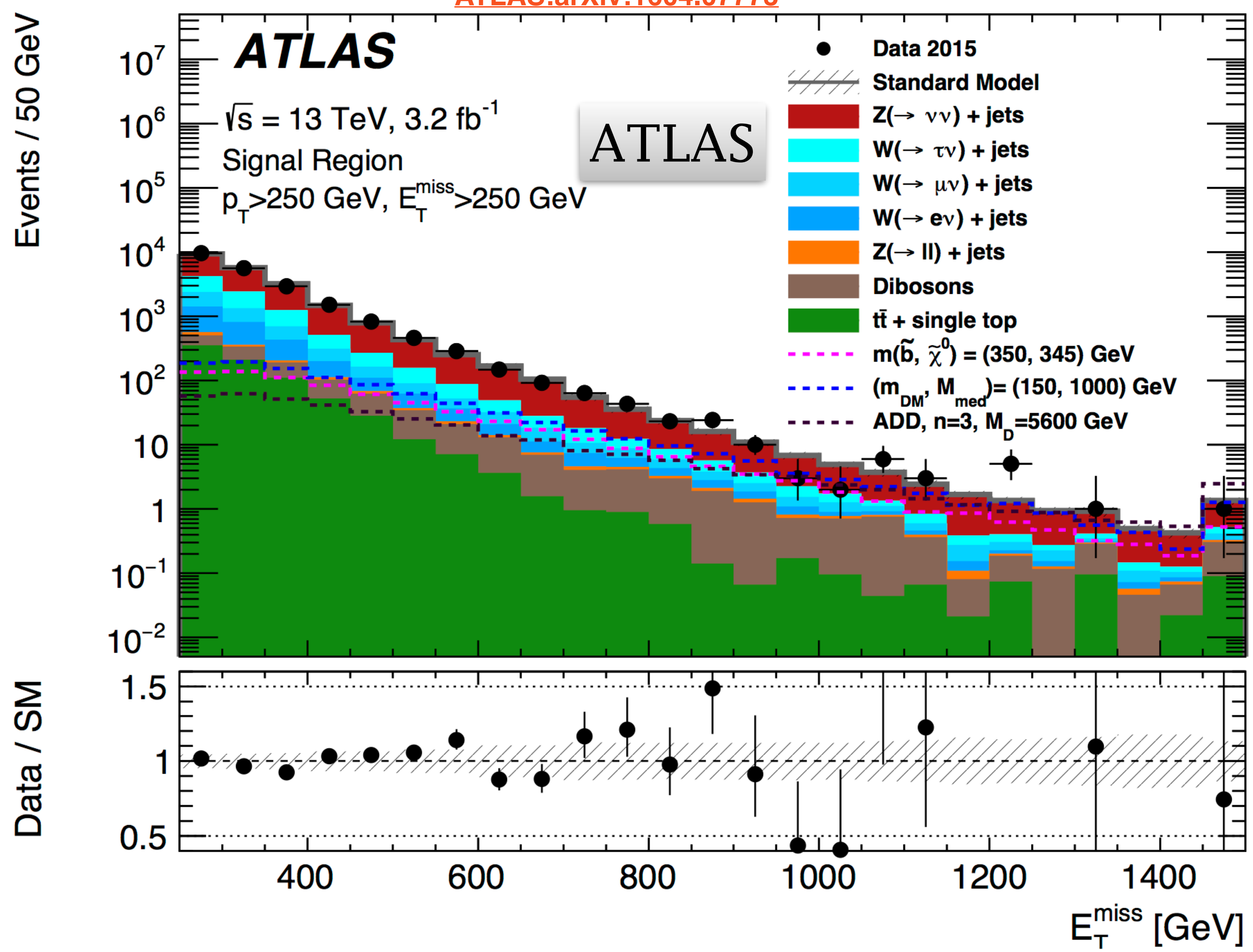


Mono-Jet

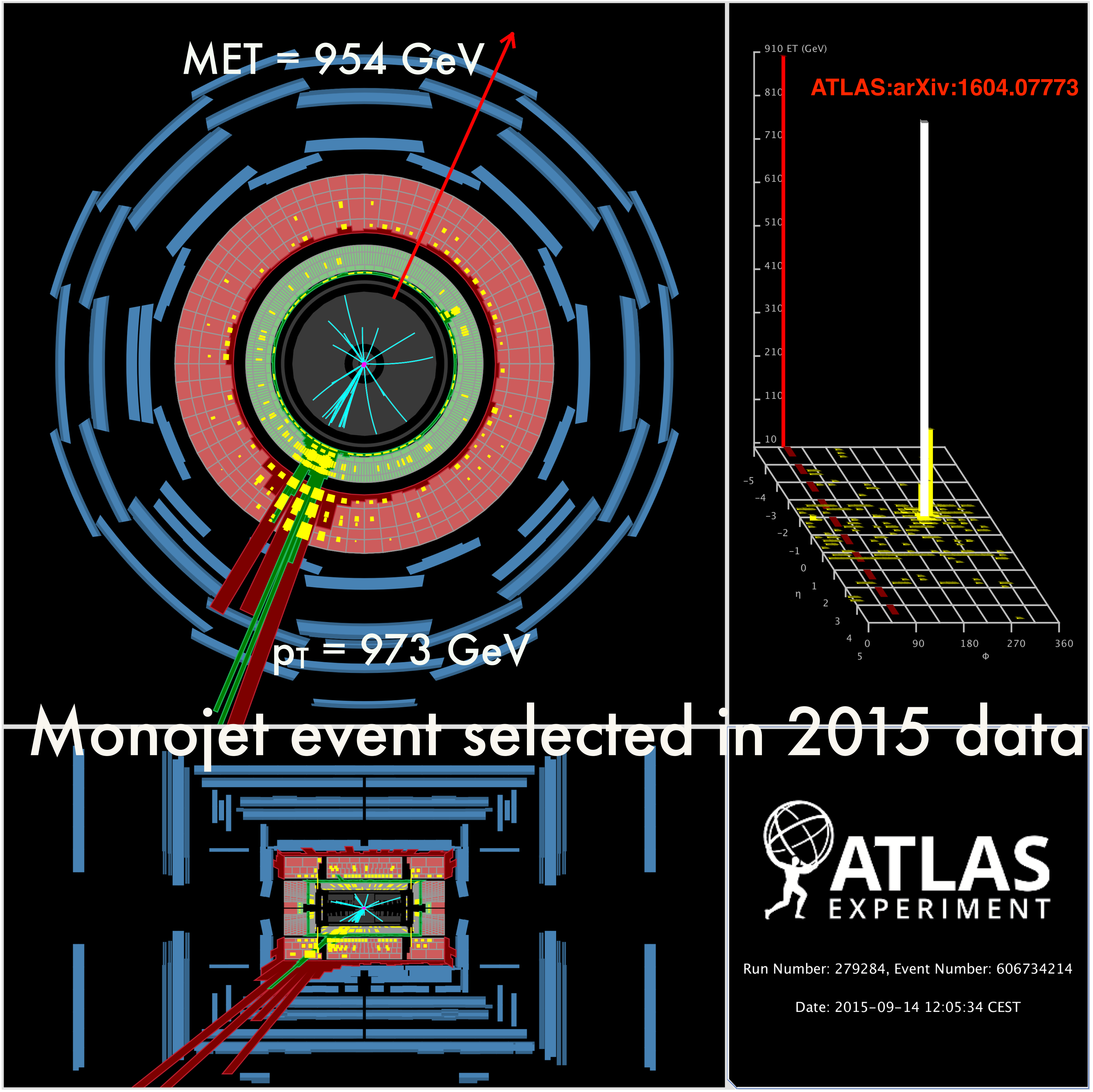
CMS-PAS-EXO-16-013



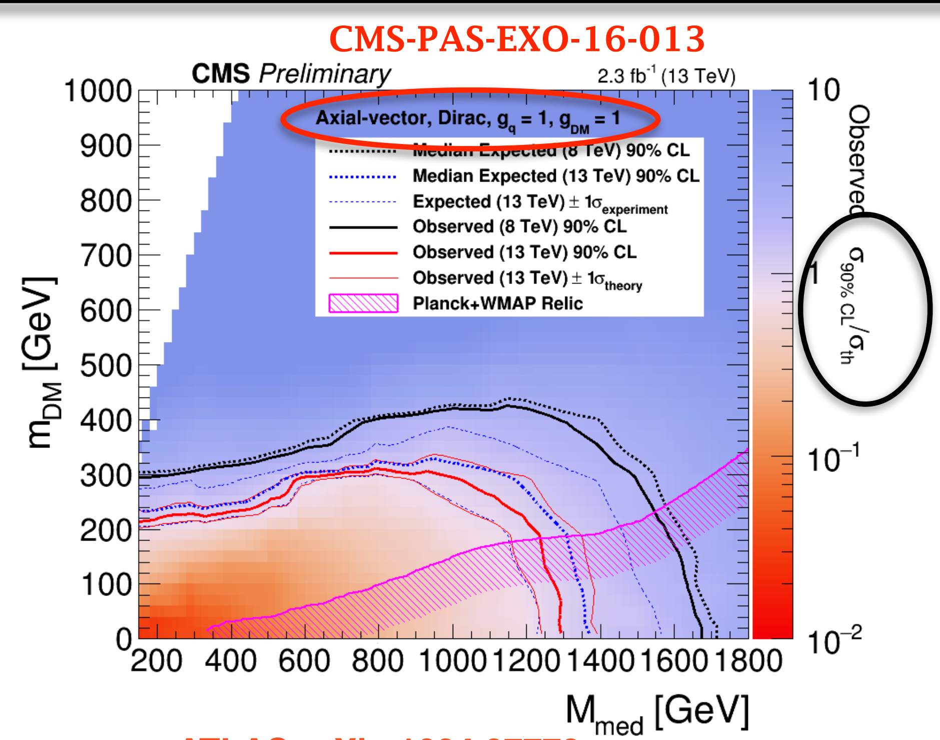
ATLAS:arXiv:1604.07773

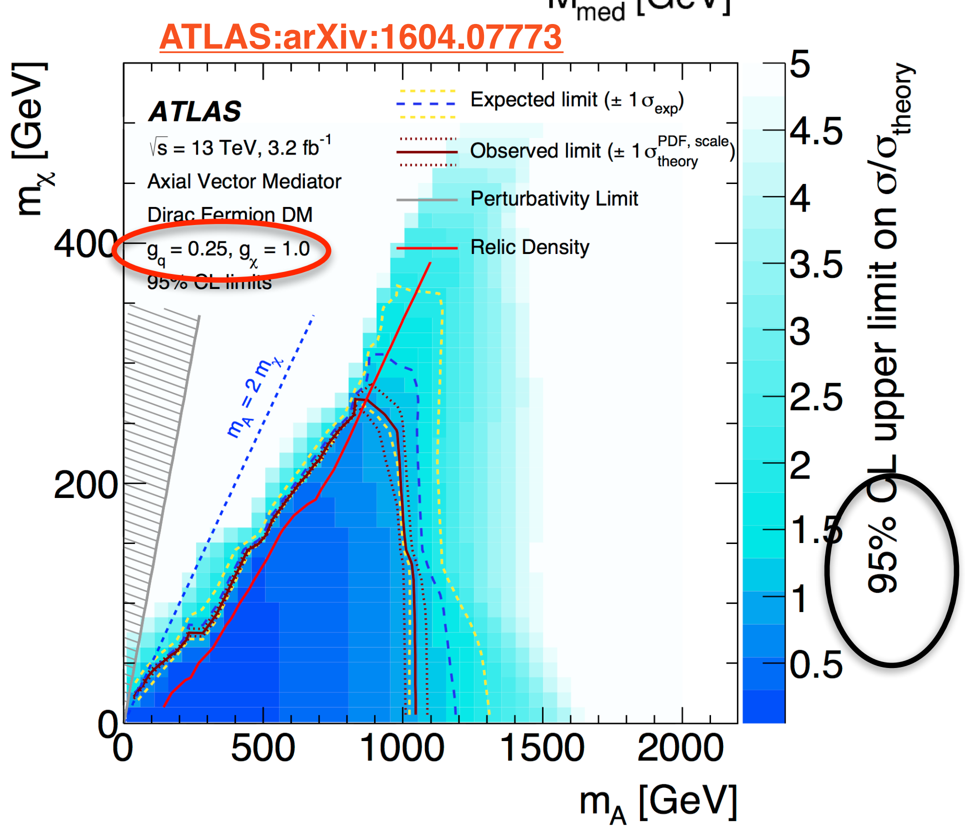


MonoJet Event in ATLAS

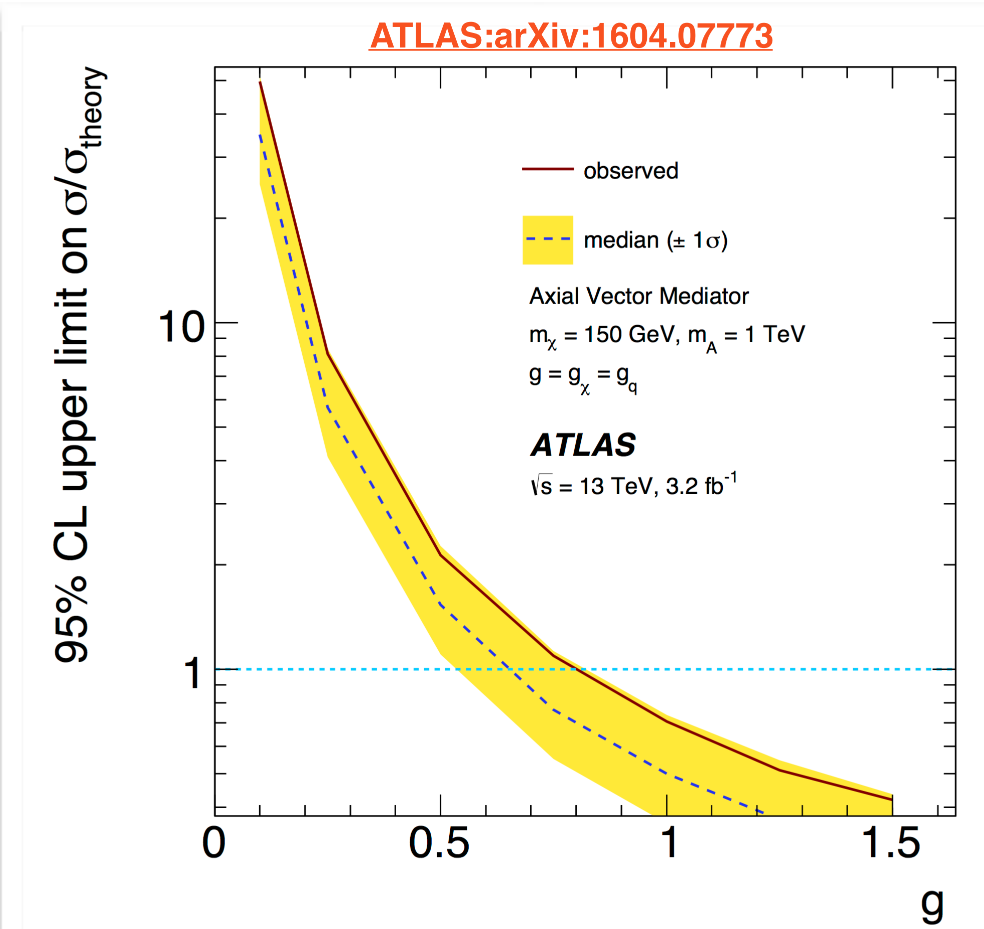


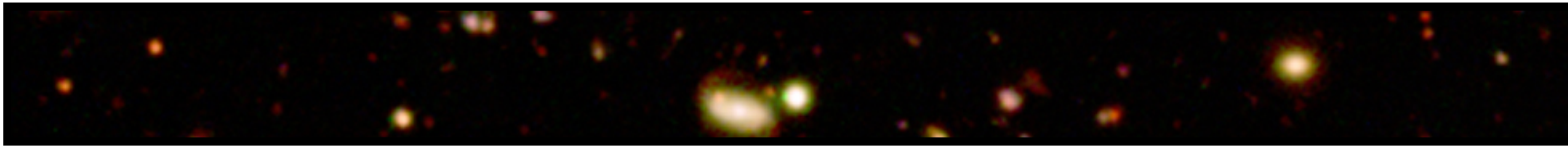
Mono-Jet





- Not directly comparable.
- Different couplings.
- Different confidence level.





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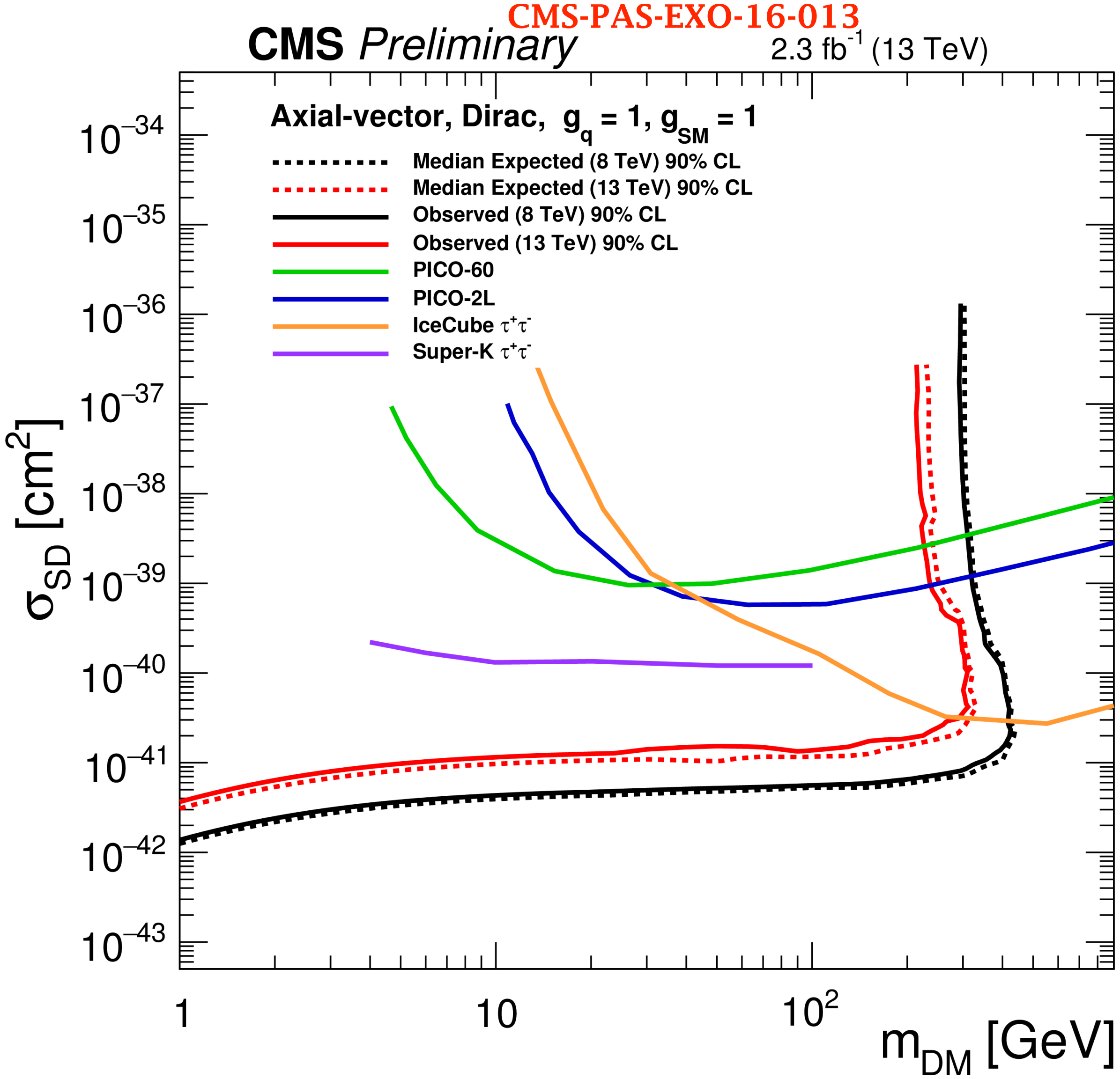

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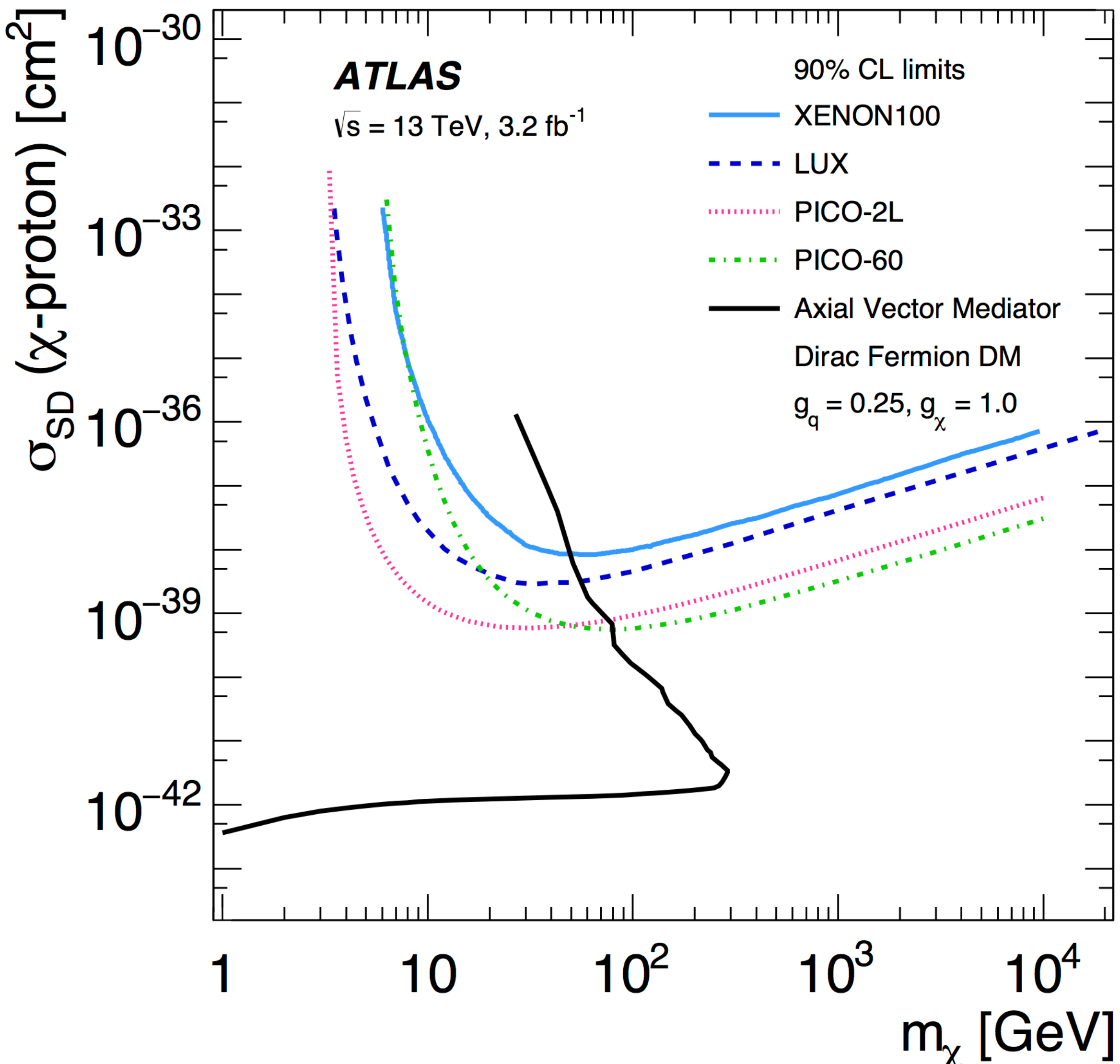
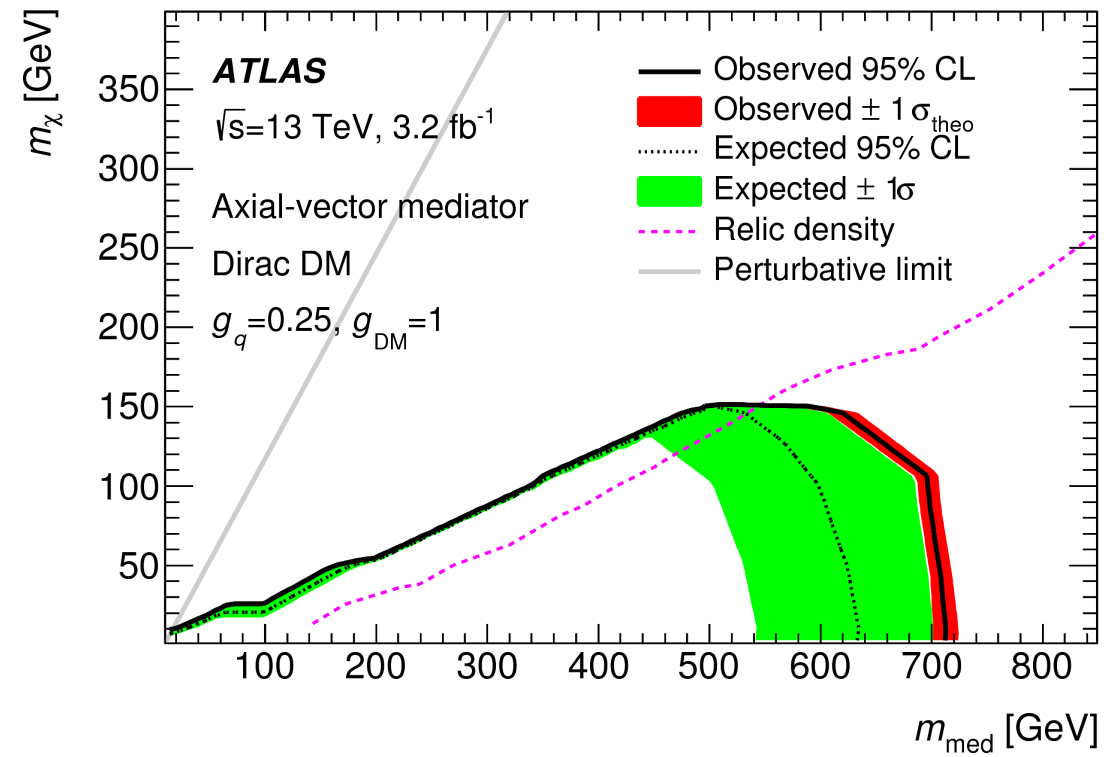


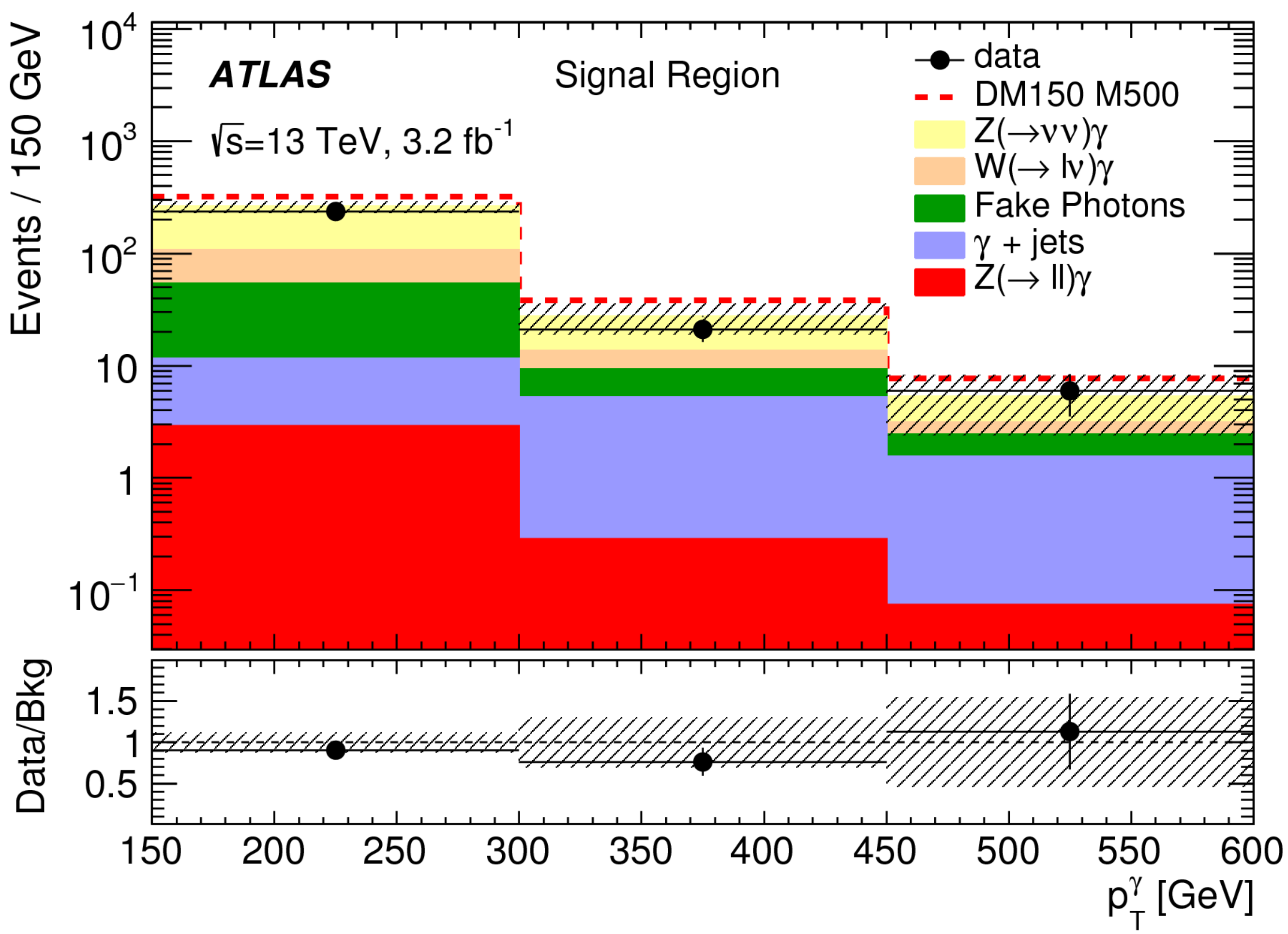
- ☐ Different coupling
- ☐ Different X and Y scale

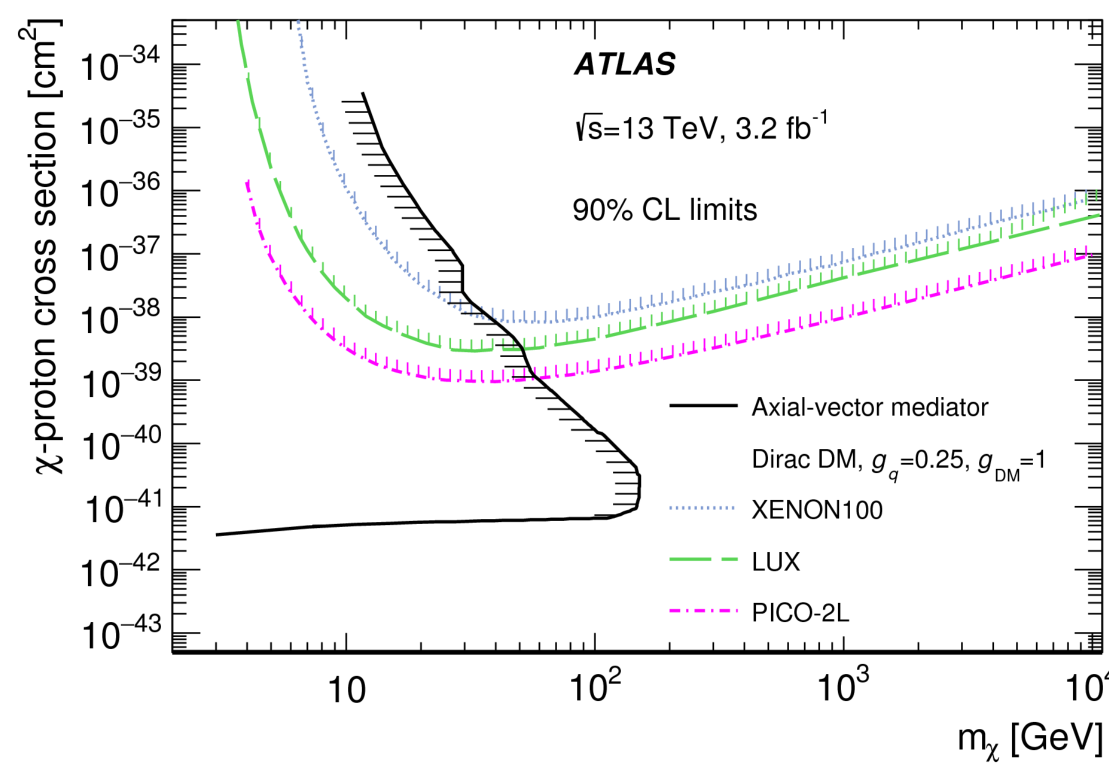
Mono-γ

ATLAS: arXiv:1604.01306

- ☐ Main challenges:
  - ☑ Mis-identification rate
  - ☑ Non-collision backgrounds





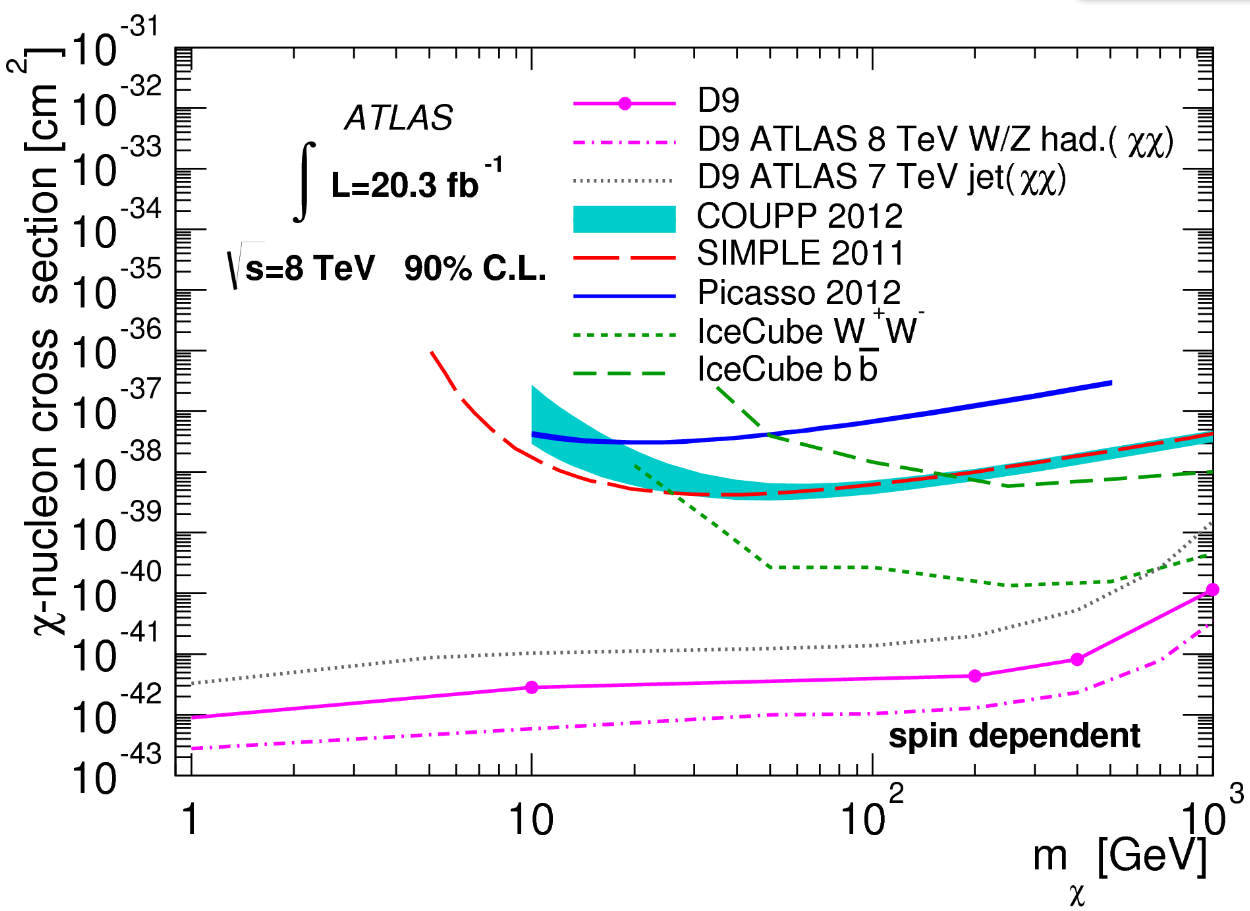


Mono-Z(→ll)

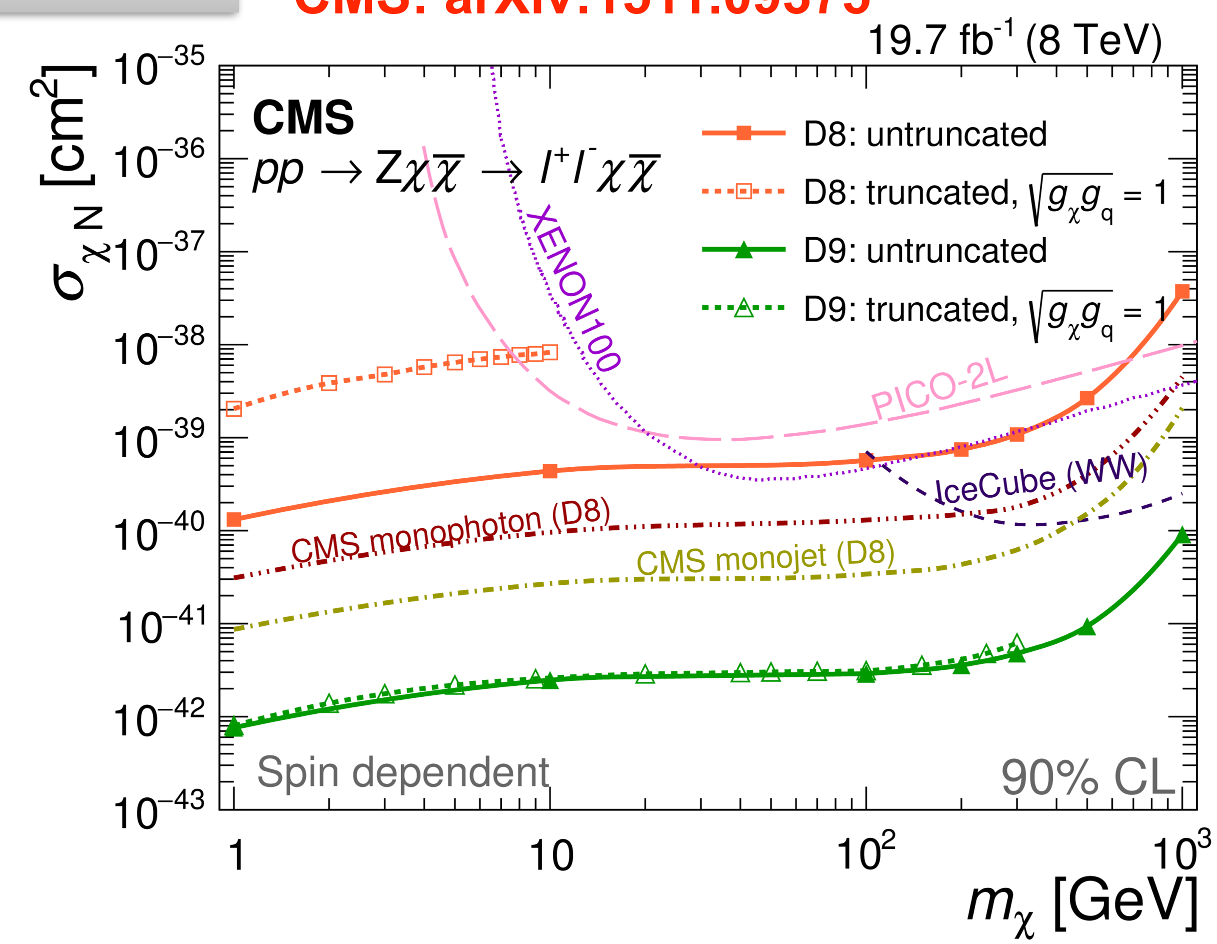
- Main background: ZZ production.
- Very critical to understand the ZZ p_T spectrum.

Spin dependent

ATLAS: arXiv:1404.0051



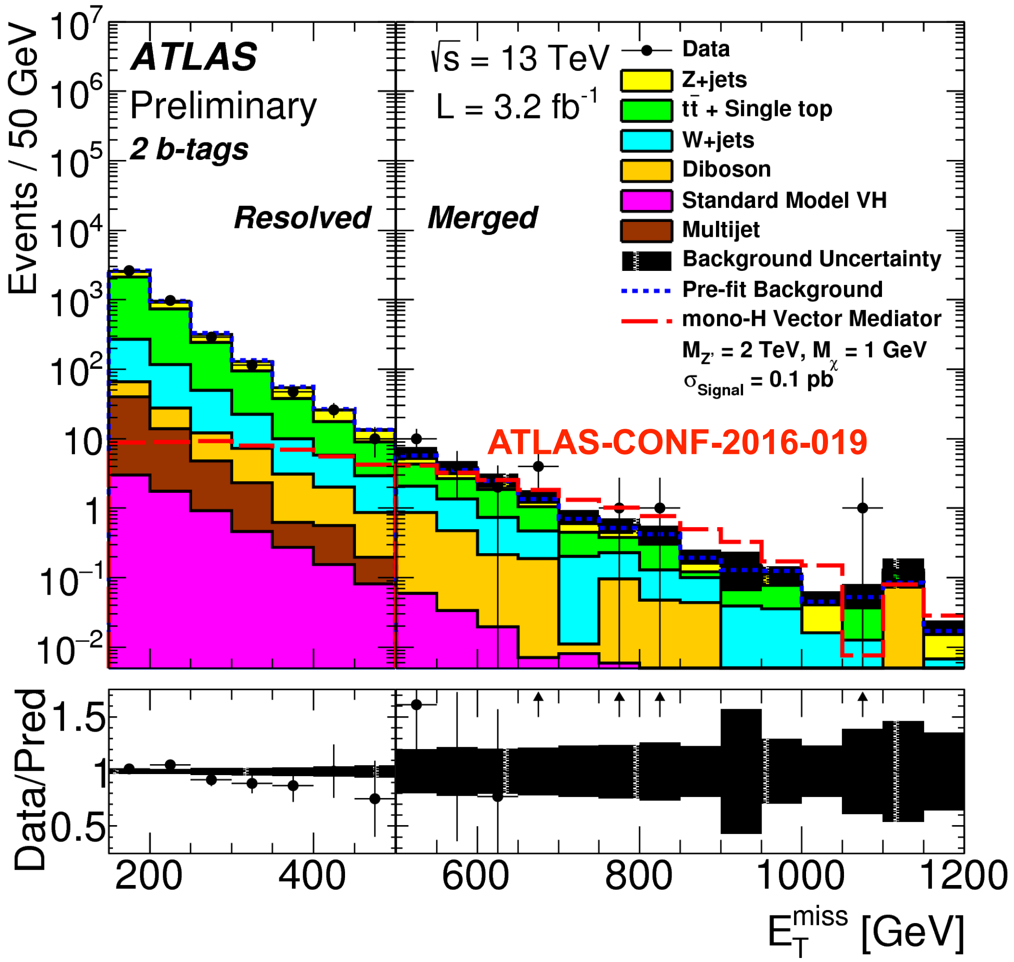
CMS: arXiv:1511.09375



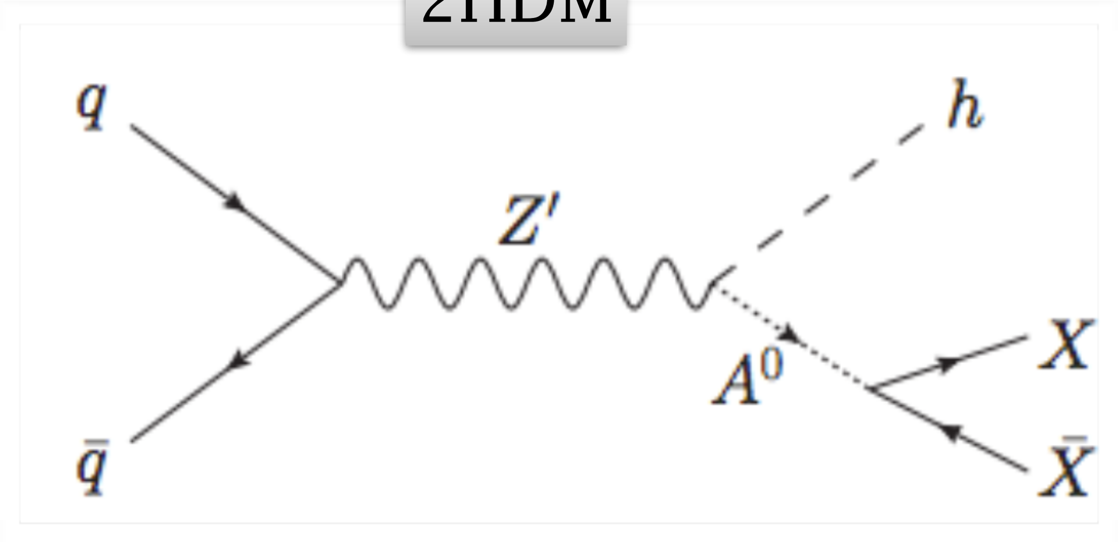
Mono-H

MonoH→γγ ATLAS-CONF-2016-011
MonoH→ZZ ATLAS-CONF-2015-059

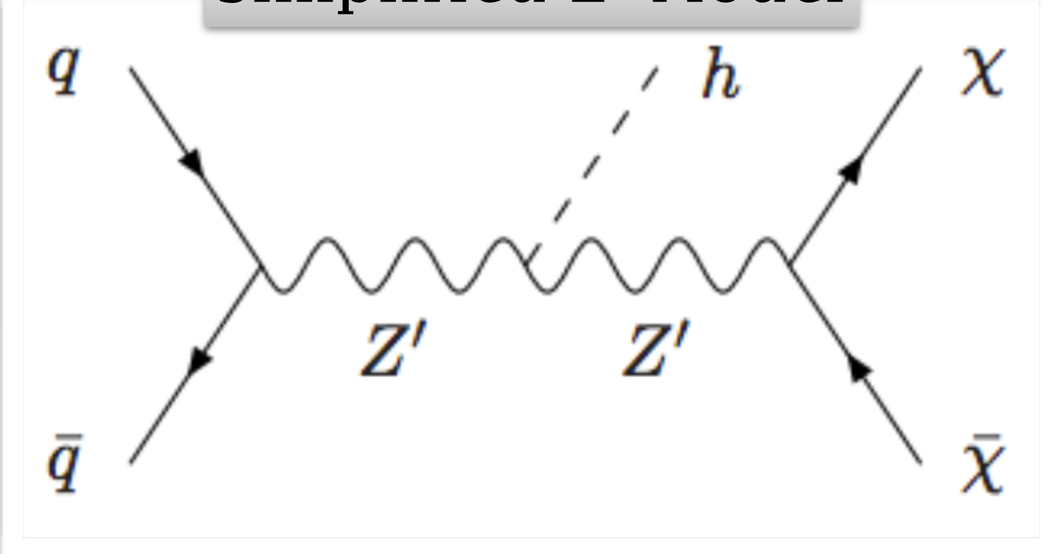
- New area to search for DM opens with the discovery of SM Higgs boson.
- Interpretation in terms of simplified models.
- Two decay channel considered:
  - ☑ bb
    - ✦ Main challenge: boosted vs resolved categorisation.
  - ☑ γγ
    - ✦ Main challenge: low cross-section/statistics



2HDM



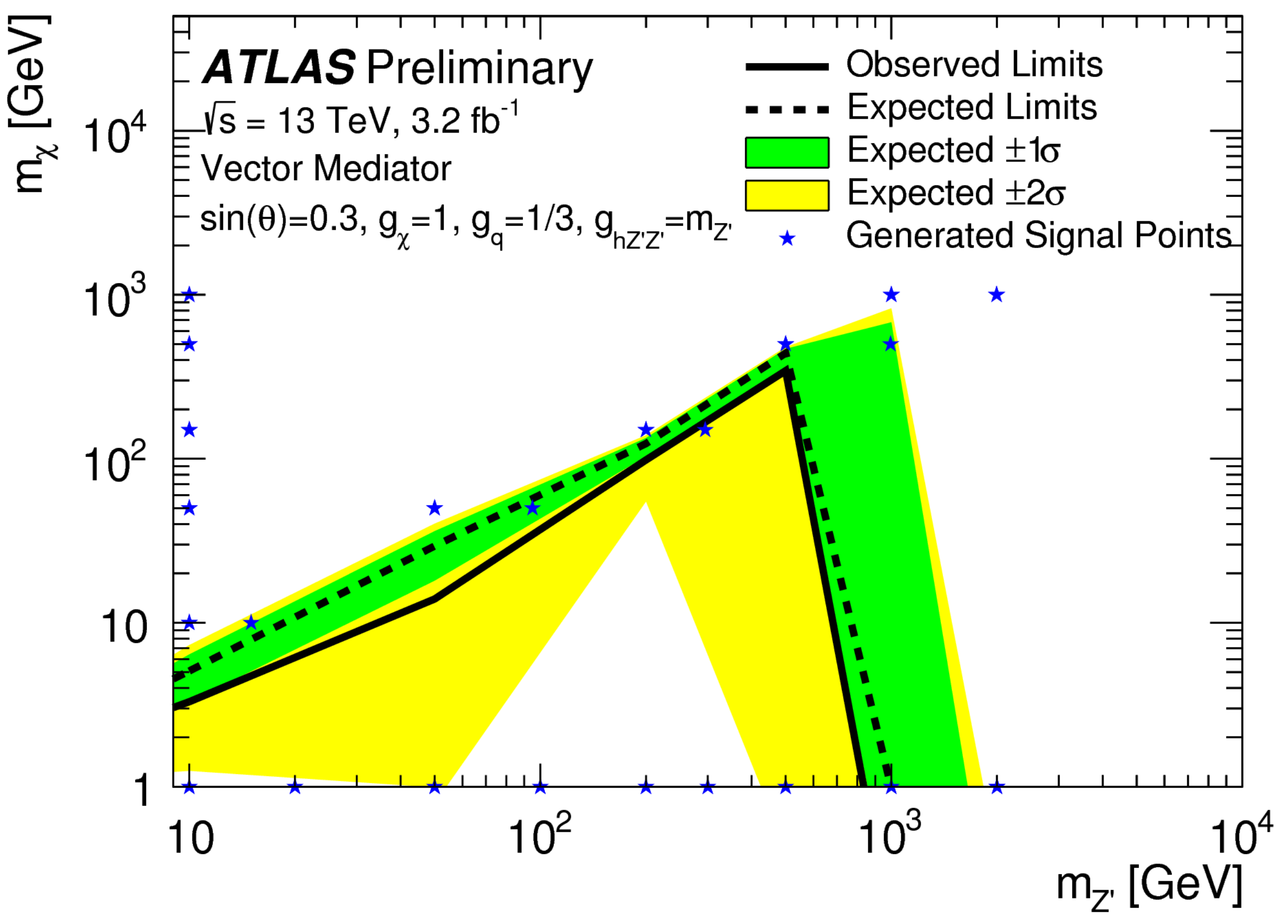
Simplified Z' Model



Mono-H

ATLAS-CONF-2016-019

ATLAS-CONF-2016-019



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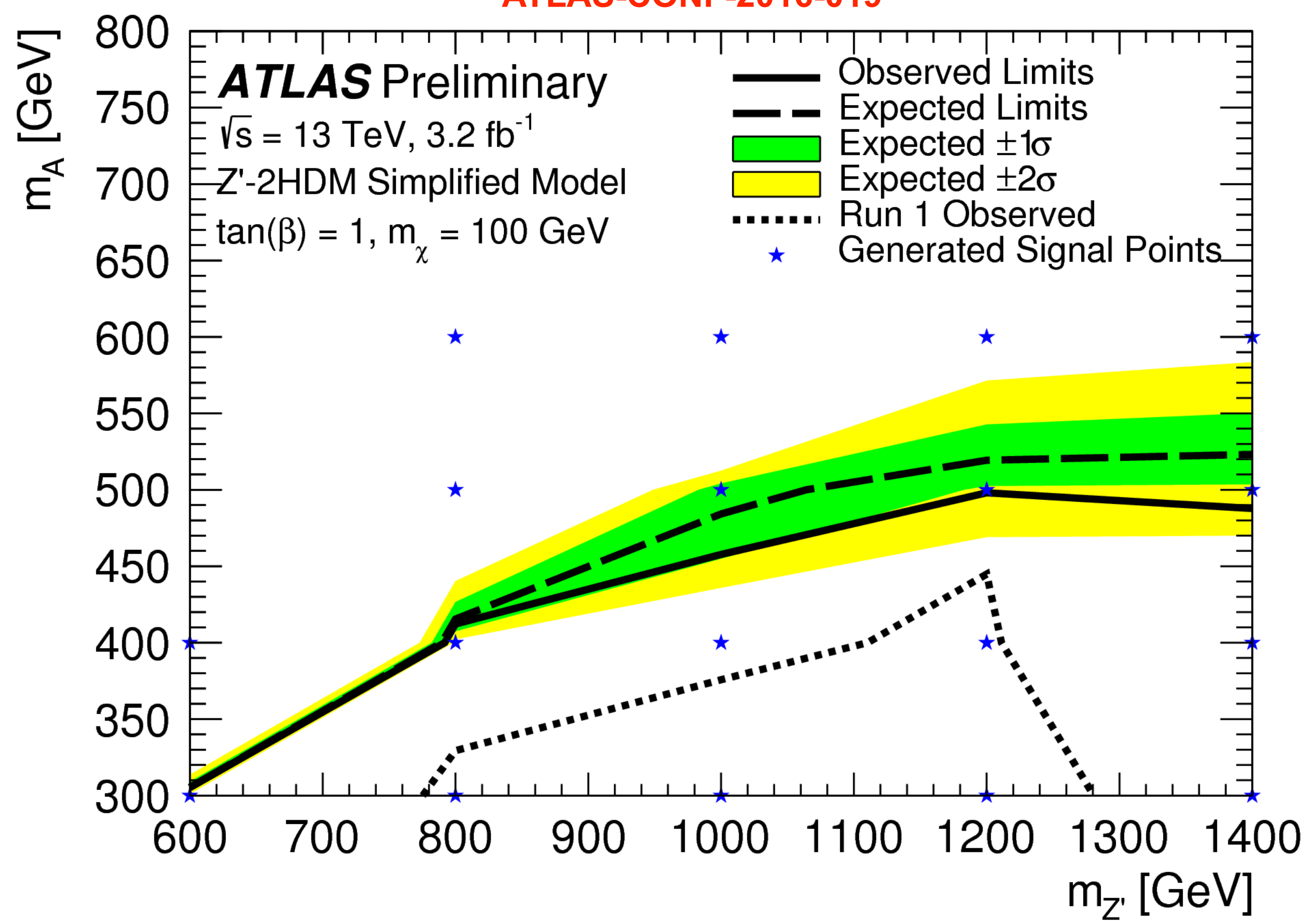
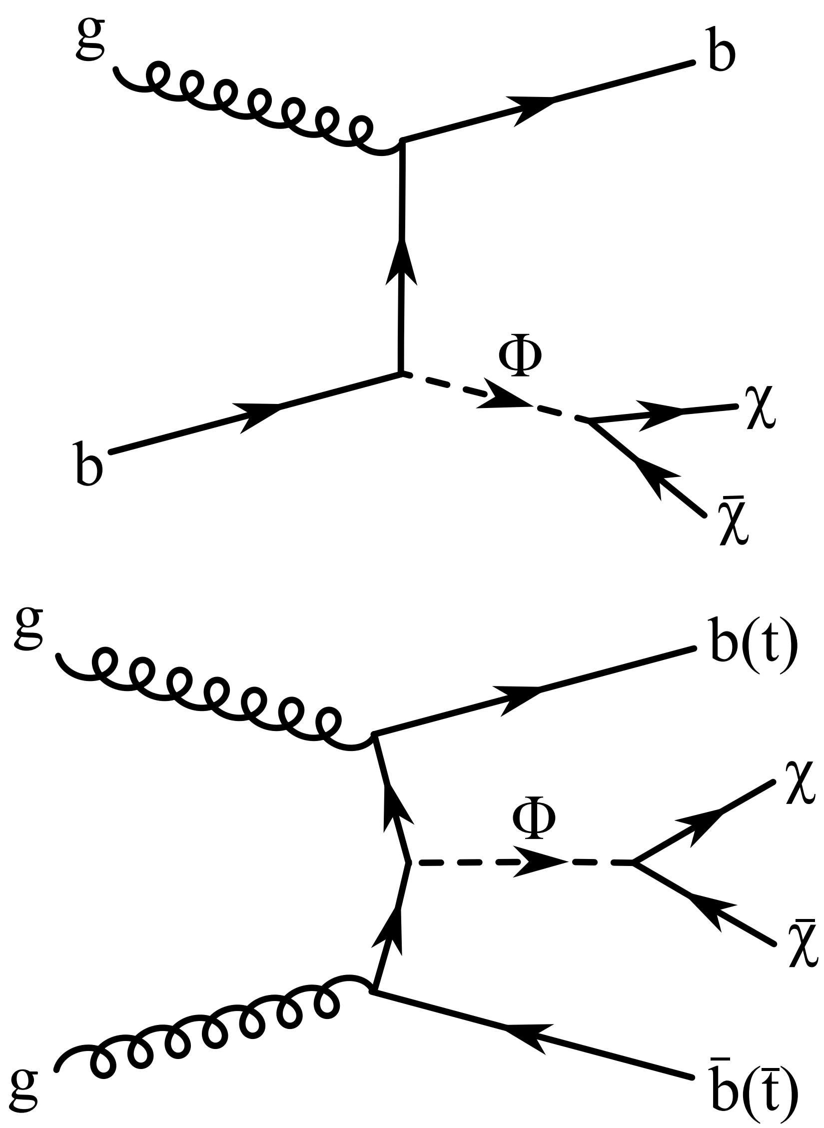
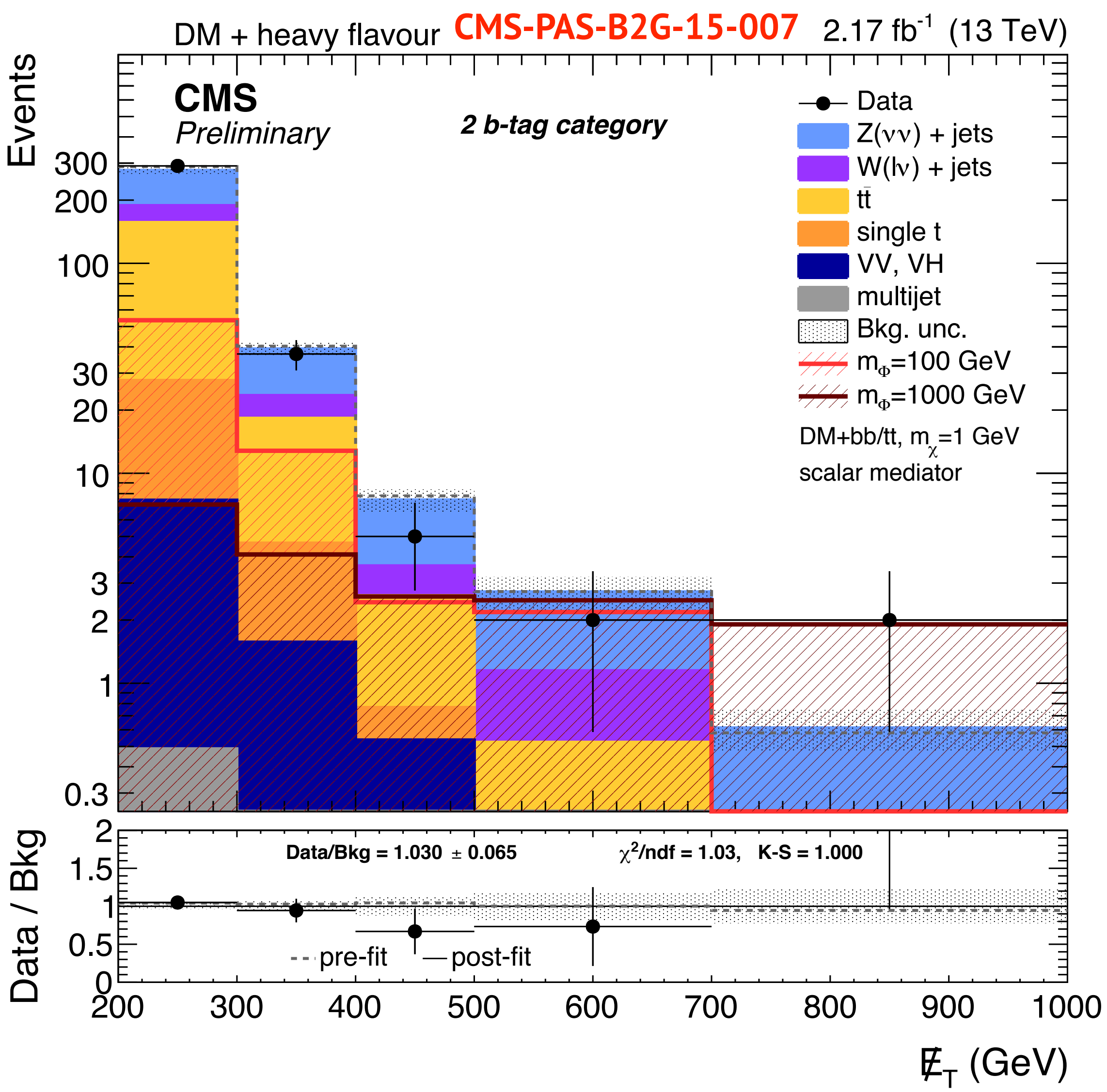


Heavy Flavour

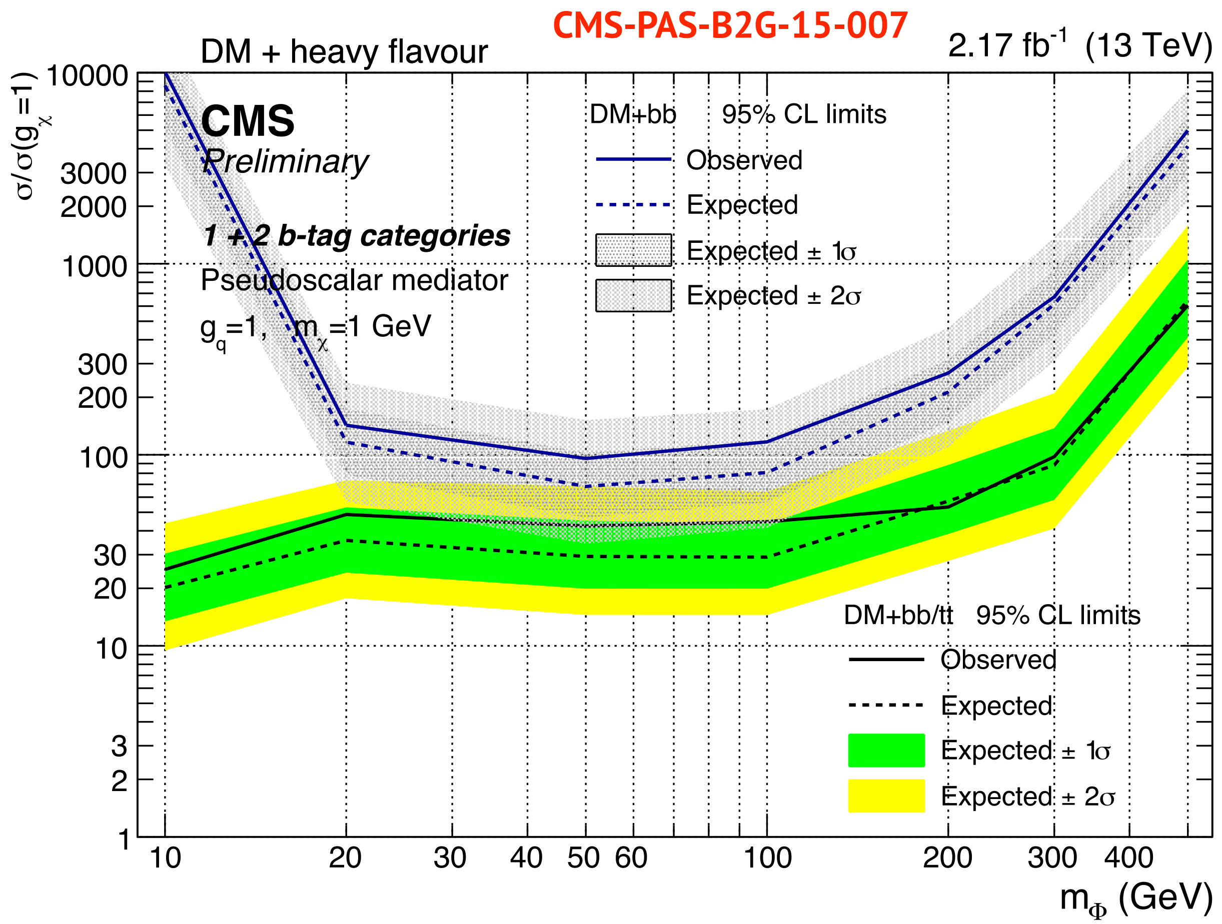
- Sensitive to scalar and pseudo-scalar mediators.
- Categorisation based on # of jets and # of b-tagged jets.

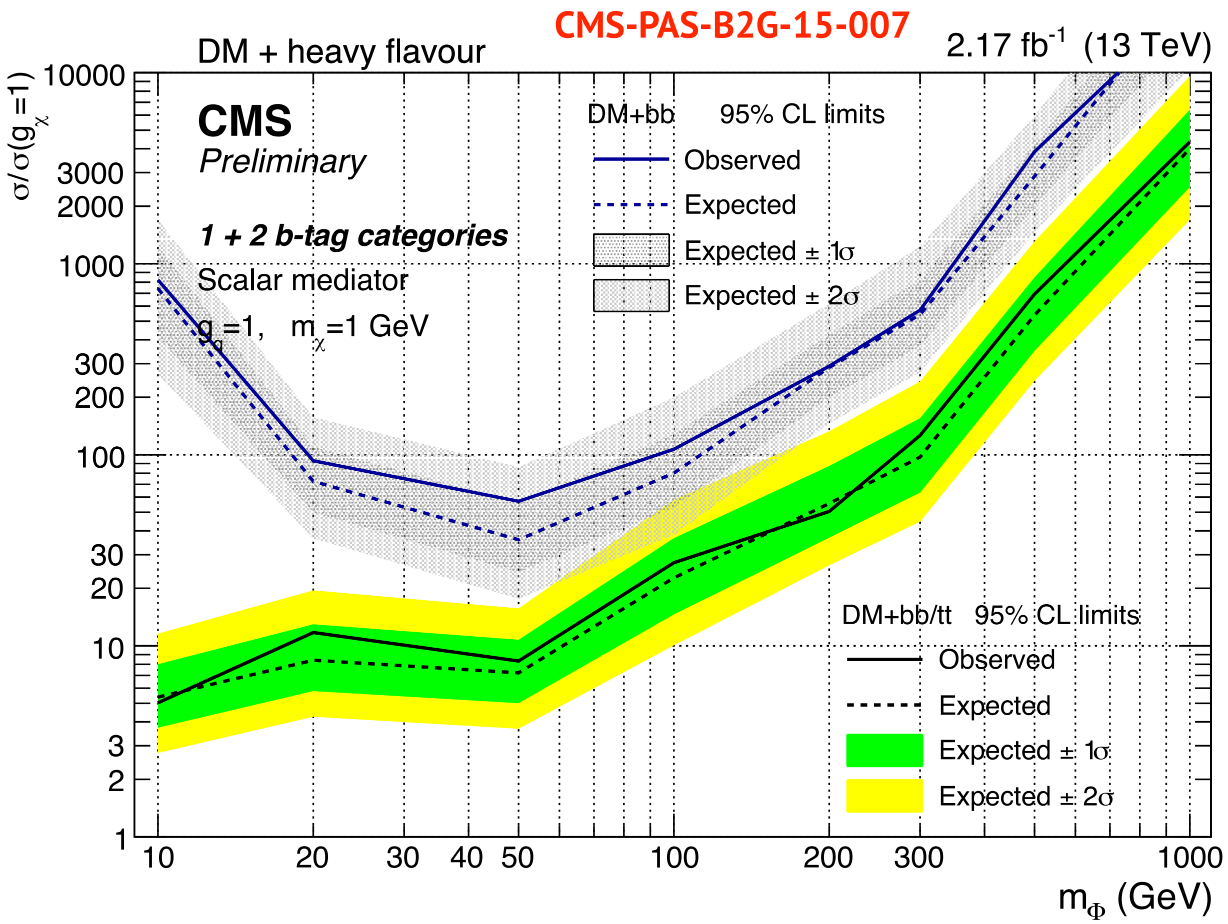




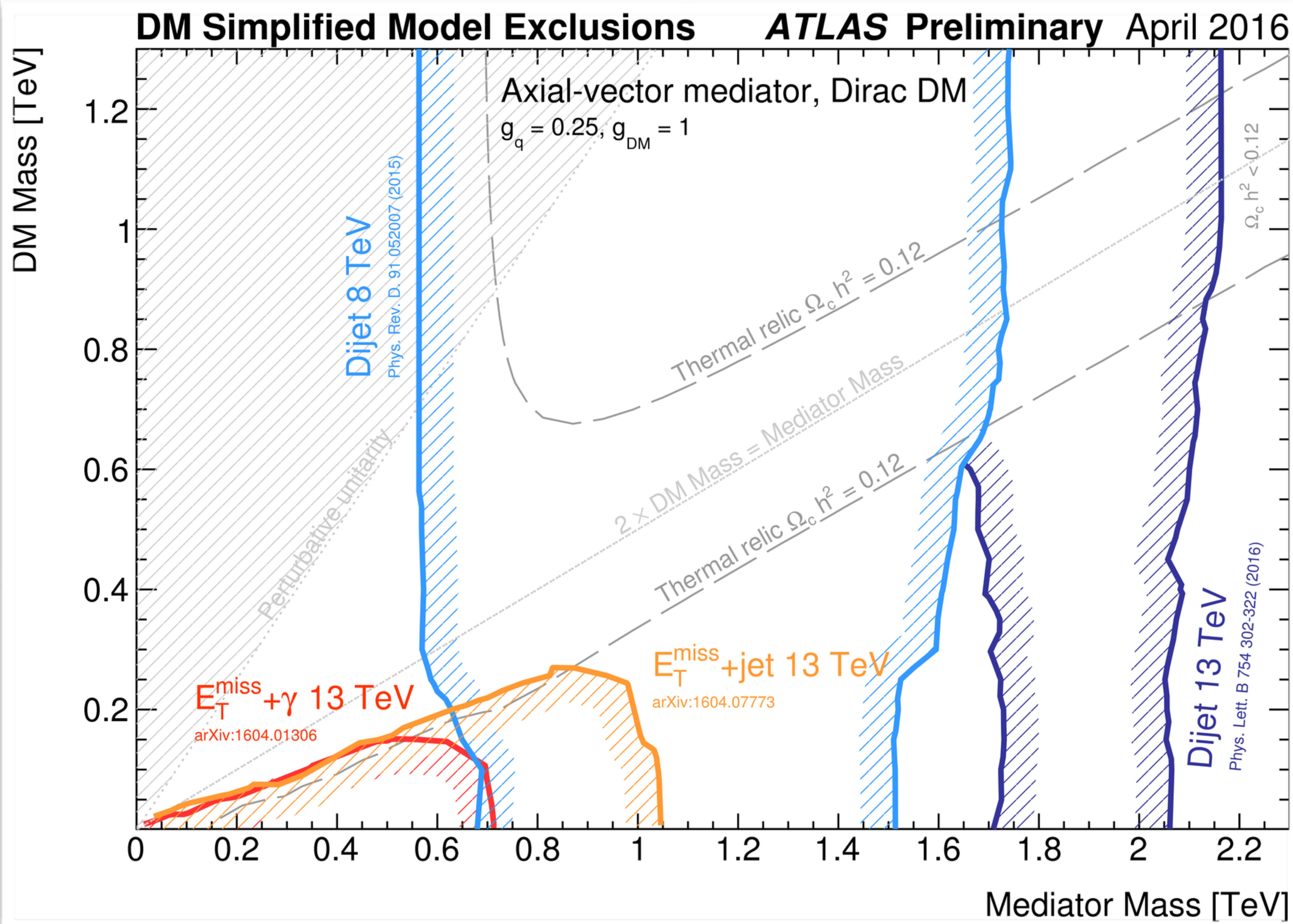
Heavy Flavour

- Sensitive to relatively light (pseudo-)scalar





Simplified model summary



Summary and Conclusions

- A summary of dark matter search analyses at LHC experiments (CMS and ATLAS) are presented.
- Results include usage of latest data collected in 2015 and from Run1.
- Proven to deal with main challenges from Run1 and early Run2.
- Restricting the phase space for simplified models using existing data.
- Consistent signal models within ATLAS and CMS.
- We are completing the picture:
  - Prepared to do various interpretations.
- Looking forward to dark matter signal at LHC.
- This is just scratching the surface of the possibilities, and the program will become much richer (more searches, more signals) as Run 2 continues.

- ☑ Thank you
- ☑ Stay tuned with new results from 2016 data.
- ☑ We may have new surprises this year.

Backup slides

Mono-Mania

- Pool of MET+X analysis
- MET+J
- MET+V_{had}
- MET+γ
- MET+HF
- MET+H ($\rightarrow\gamma\gamma$ and bb)
- MET+top

Mono-Jet CR selection

Single Muon ($W\mu\nu$)

- E_T^{miss} trigger
- Invert muon veto
- One tight muon $p_T > 20$ GeV

Single Electron ($We\nu$)

- Single Electron trigger
- Invert electron veto
- One tight electron $p_T > 40$ GeV
- $E_T^{miss} > 50$ GeV

Double Muon ($Z\mu\mu$)

- E_T^{miss} trigger
- Two loose muons
- At least one tight, $p_T > 20$ GeV
- $M_{\mu\mu}$ [60,120] GeV

Double Electron (Zee)

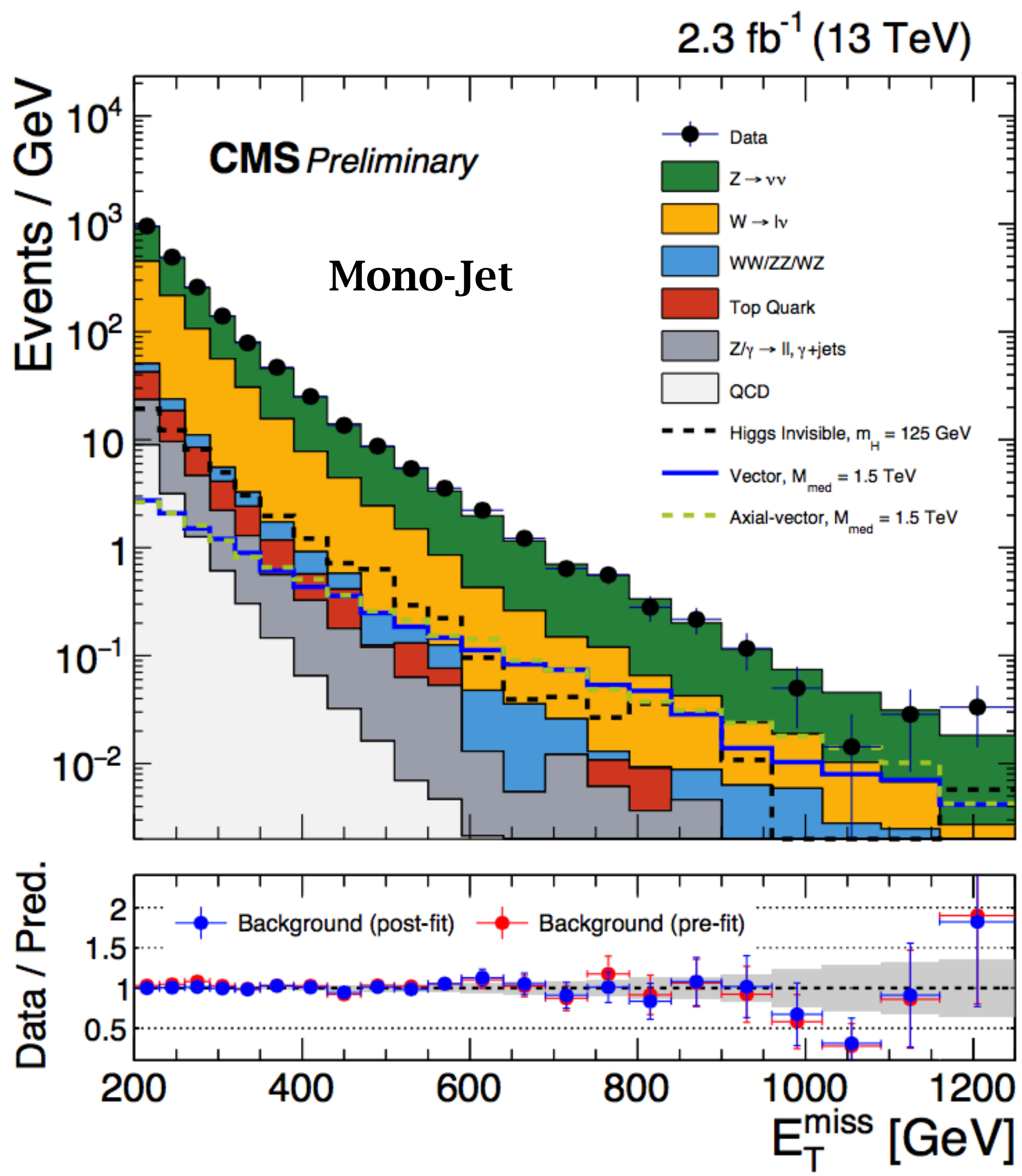
- Single Electron trigger
- Two loose electrons
- At least one tight, $p_T > 40$ GeV
- M_{ee} [60,120] GeV

Single Photon (γ+jet)

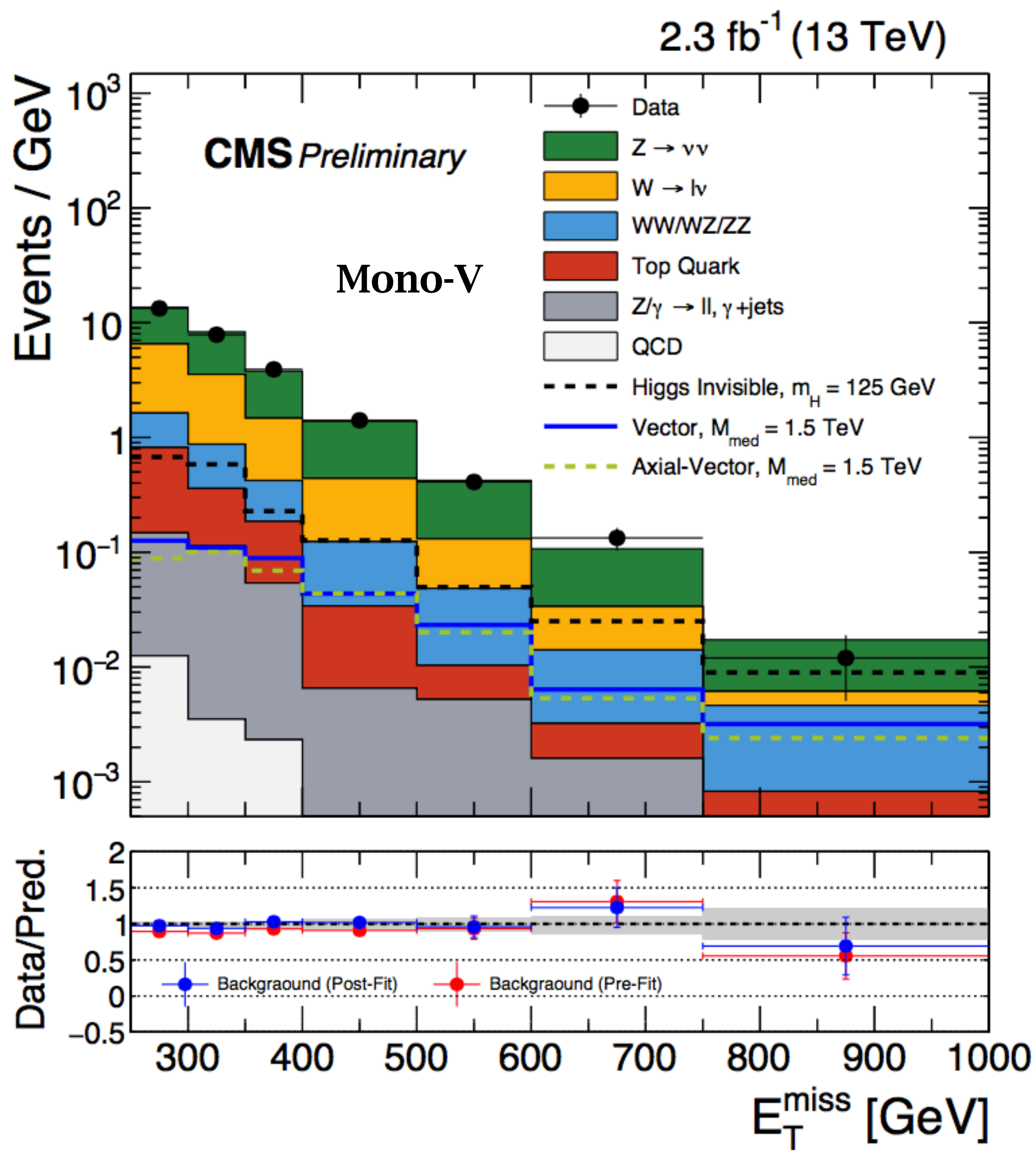
- Single Photon trigger
- One medium photon
- Photon $p_T > 175$ GeV, $|\eta| < 1.44$

- **Hadronic Recoil:**
  - Control regions contain identified objects: leptons (μ,e) and photons
  - Identified leptons and photons are added back to the missing energy
  - Used in the control regions as a proxy of the "real" E_T^{miss} in the signal one
  - This means consider the boson p_T as invisible (W, Z or γ)

Mono-Jet



2.3 fb^{-1} (13 TeV)
CMS Preliminary
Mono-Jet
Events / GeV
Data
Z → νν
W → lν
WW/ZZ/WZ
Top Quark
Z/γ → ll, γ+jets
QCD
Higgs Invisible, m_H = 125 GeV
Vector, M_{med} = 1.5 TeV
Axial-vector, M_{med} = 1.5 TeV
Data / Pred.
Background (post-fit)
Background (pre-fit)
E_T^{miss} [GeV]



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CMS Preliminary
Mono-V
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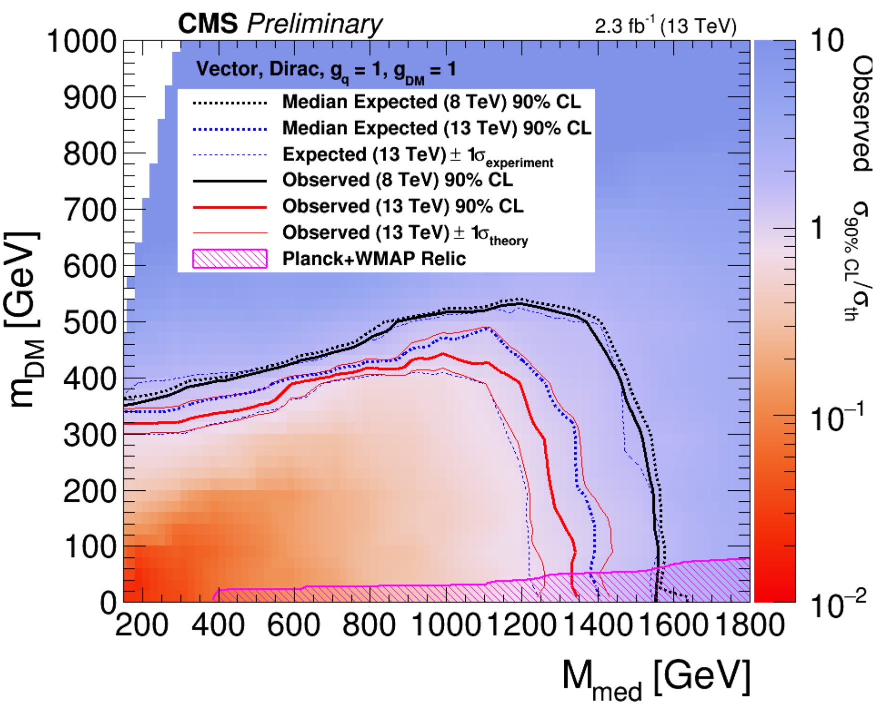
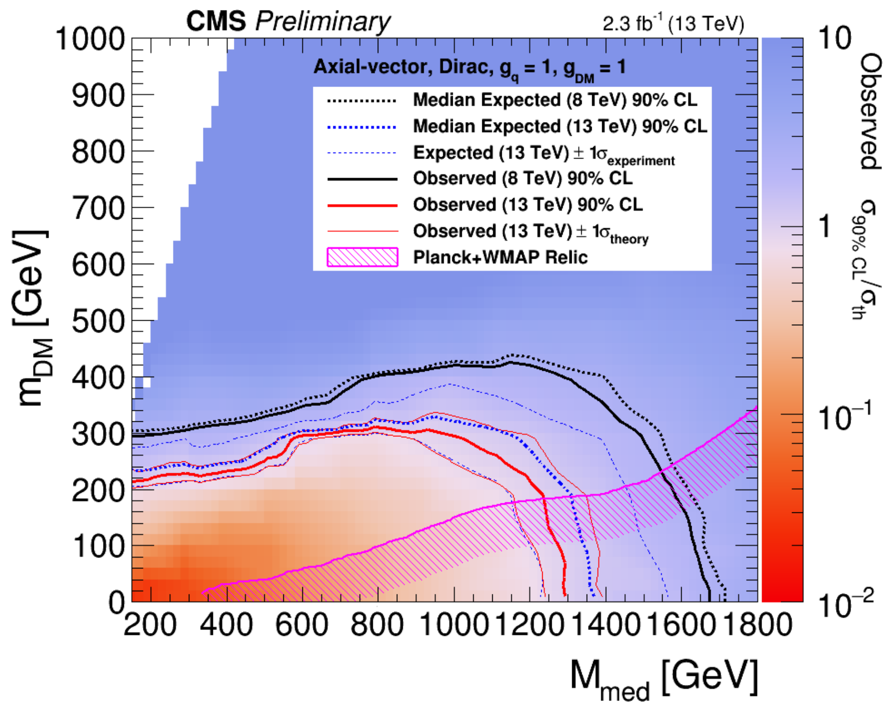
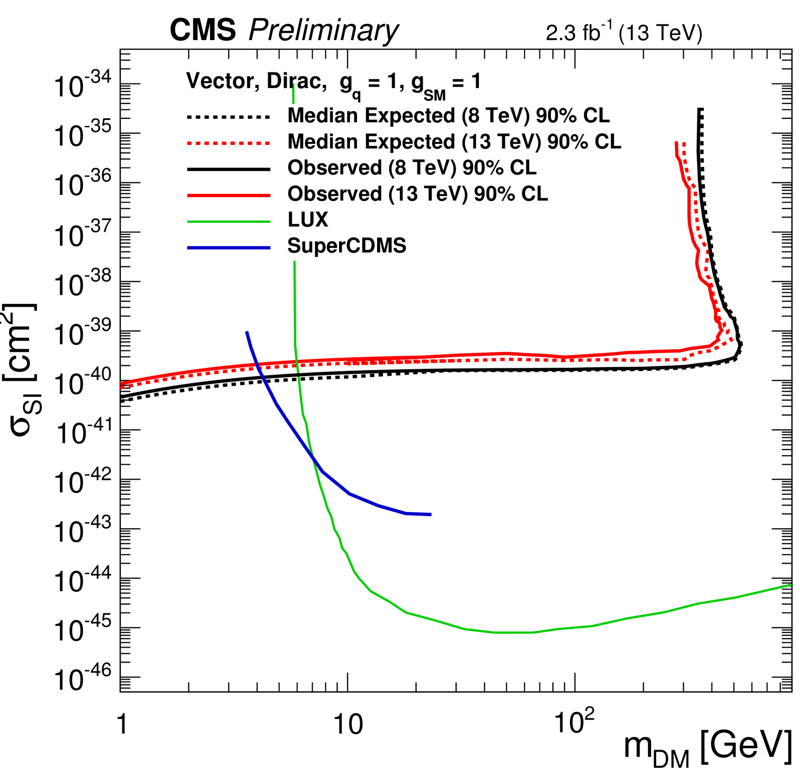
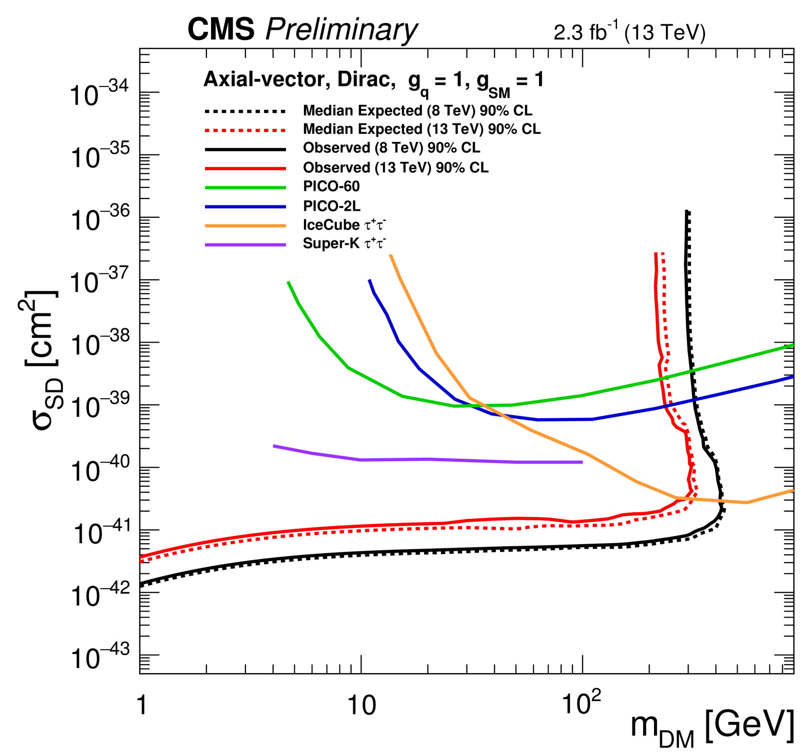
Backgraound (Post-Fit)
Backgraound (Pre-Fit)
E_T^{miss} [GeV]







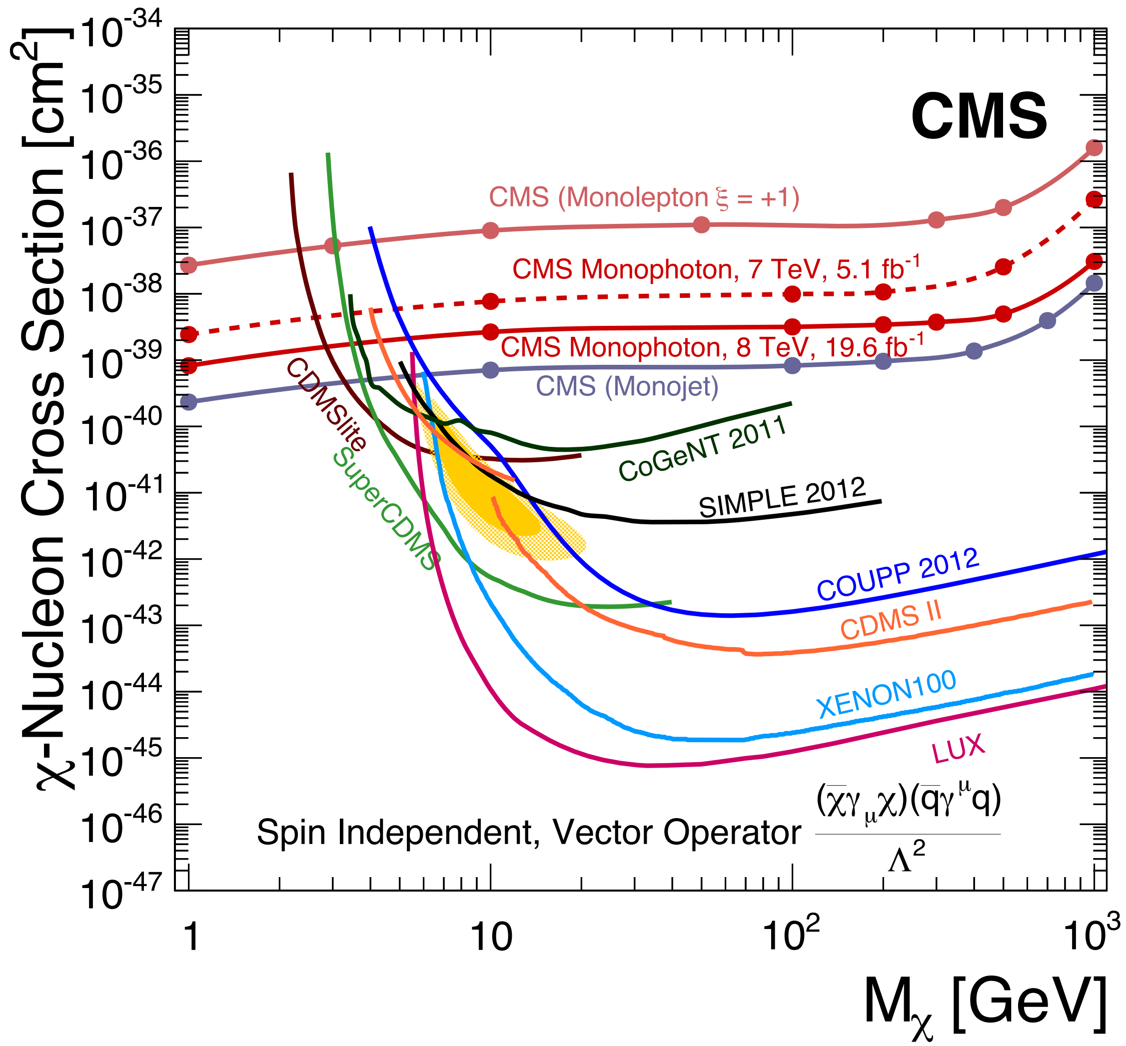


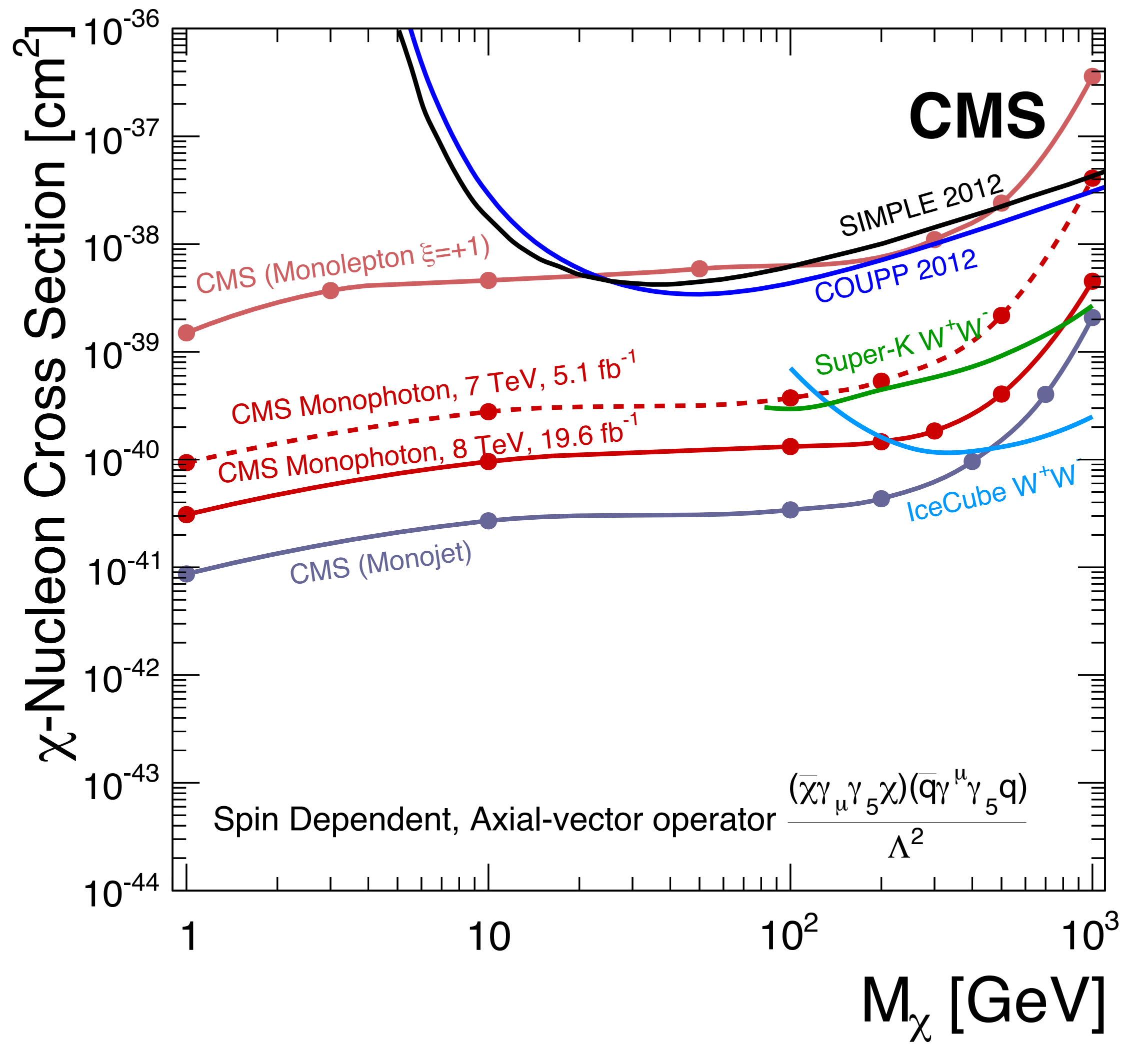
- Preliminary results from Mono-Jet at 13 TeV.

Mono-γ

CMS-PAS-B2G-15-007

CMS 8 TeV





Dark Matter @ LHC: Assumption

- [ ] DM can be discovered at LHC assuming that:
  - [x] the dark matter exist.
    - [ ] very likely exist.
  - [x] the dark matter is made from particles.
    - [ ] not established yet.
  - [x] the dark matter particles can be commonly produced at LHC in p-p collisions.
    - [ ] need not be the case.

Dirac DM Operators

Label	Operator	Usual coefficient	Dimension
$\mathcal{O}_{\mathrm{D1}}$	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3	6
$\mathcal{O}_{\mathrm{D2}}$	$\bar{\chi}i\gamma_5\chi\bar{q}q$	m_q/M_*^3	6
$\mathcal{O}_{\mathrm{D3}}$	$\bar{\chi}\chi\bar{q}i\gamma_5 q$	m_q/M_*^3	6
$\mathcal{O}_{\mathrm{D4}}$	$\bar{\chi}i\gamma_5\chi\bar{q}i\gamma_5 q$	m_q/M_*^3	6
$\mathcal{O}_{\mathrm{D5}}$	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$	6
$\mathcal{O}_{\mathrm{D6}}$	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$	6
$\mathcal{O}_{\mathrm{D7}}$	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma_5 q$	$1/M_*^2$	6
$\mathcal{O}_{\mathrm{D8}}$	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q$	$1/M_*^2$	6
$\mathcal{O}_{\mathrm{D9}}$	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$	6
$\mathcal{O}_{\mathrm{D10}}$	$\bar{\chi}i\sigma^{\mu\nu}\gamma_5\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$	6
$\mathcal{O}_{\mathrm{D11}}$	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_S/4M_*^3$	7
$\mathcal{O}_{\mathrm{D12}}$	$\bar{\chi}\gamma_5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_S/4M_*^3$	7
$\mathcal{O}_{\mathrm{D13}}$	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_S/4M_*^3$	7
$\mathcal{O}_{\mathrm{D14}}$	$\bar{\chi}\gamma_5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_S/4M_*^3$	7

With Collider

Vector(SI)

Large cross section

Axial (SD)

Same as vector

Scalar(SI)

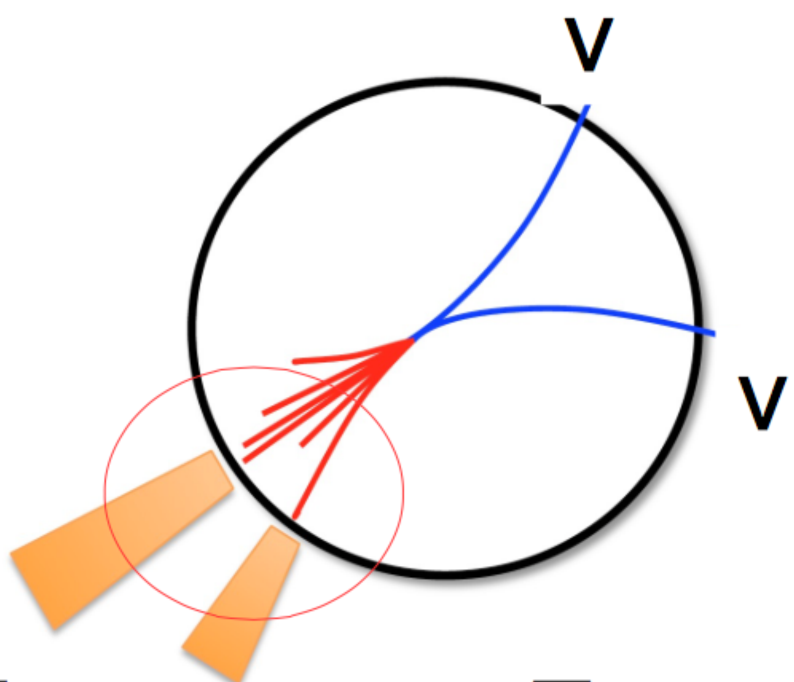
Low-ish cross section

Pseudoscalar

Better than scalar
Small cross section

What are we discriminating against

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



Analysis is a study of the hadronic recoil

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

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

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

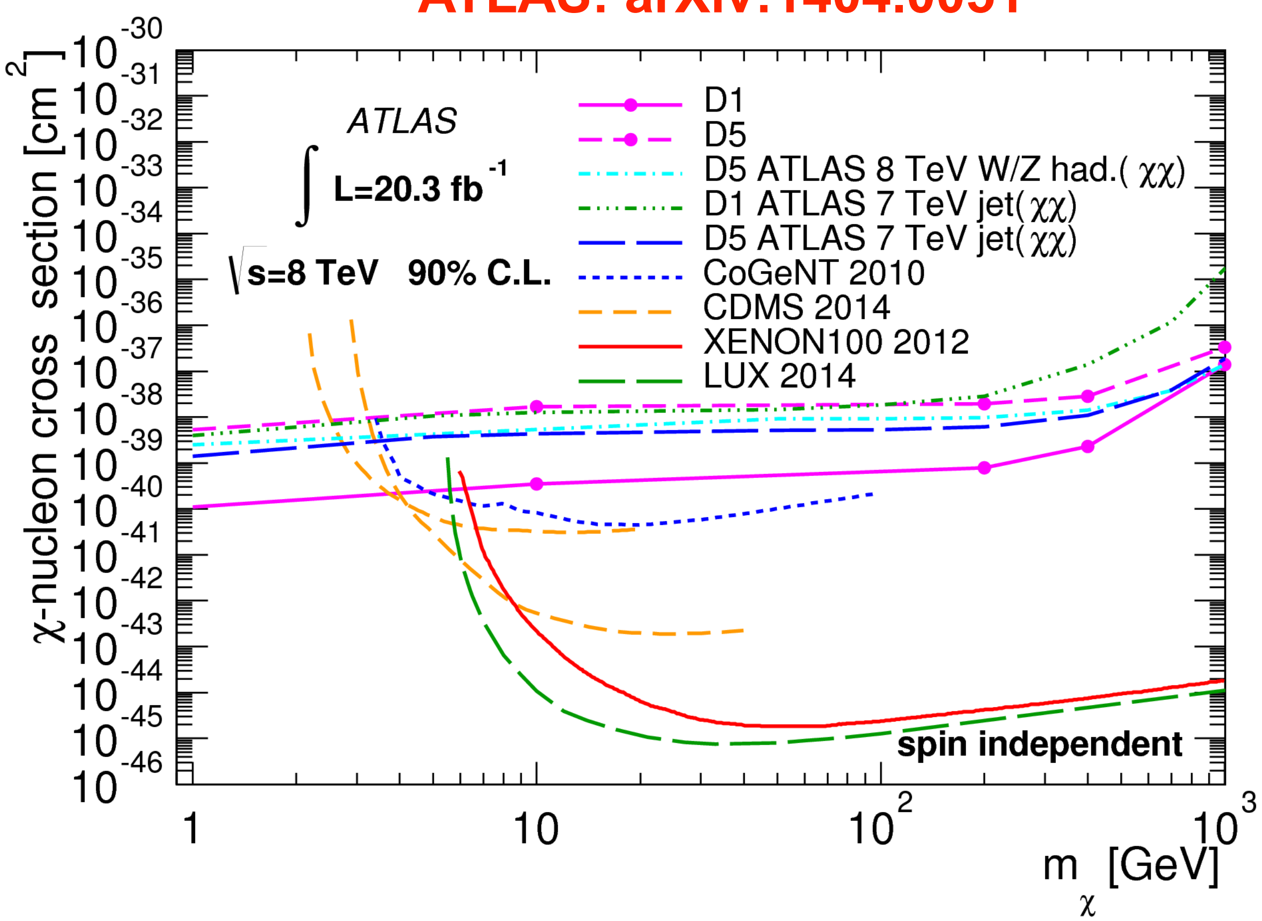
"To find nothing you have to reconstruct everything"[1]

Mono-Z(→ll)

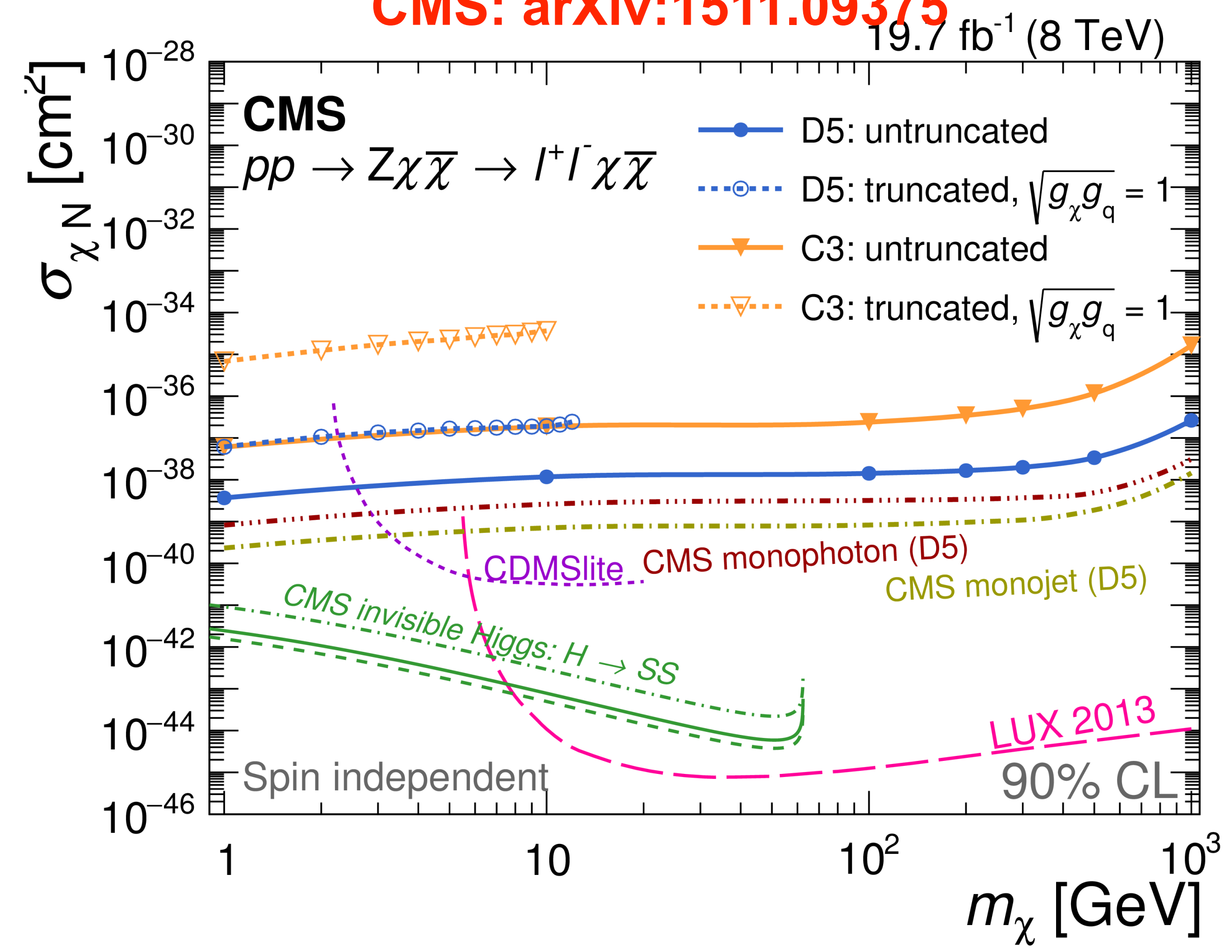
- Main background: ZZ production.
- Very critical to understand the ZZ p_T spectrum.

Spin independent

ATLAS: arXiv:1404.0051



CMS: arXiv:1511.09375



EFT Validation

http://arxiv.org/pdf/1603.08002v1.pdf

$$\frac{g_q g_\chi}{M_{\mathrm{med}}^2 - Q_{\mathrm{tr}}^2} = \frac{g_q g_\chi}{M_{\mathrm{med}}^2}\left(1 + \frac{Q_{\mathrm{tr}}^2}{M_{\mathrm{med}}^2} + \mathscr{O}\left(\frac{Q_{\mathrm{tr}}^4}{M_{\mathrm{med}}^4}\right)\right), \qquad (3)$$

1. When $Q_{\mathrm{tr}}^2 < M_{\mathrm{med}}^2 \equiv g_q g_\chi M_*^2$, the approximation in Eq. (3) holds. This is clearly the only region where the EFT approximation remains valid.
2. In the region where $Q_{\mathrm{tr}}^2 \sim M_{\mathrm{med}}^2$ the production cross-section undergoes a resonant enhancement. The EFT approximation misses this enhancement, and is therefore conservative relative to the full theory.
3. When $Q_{\mathrm{tr}}^2 \gg M_{\mathrm{med}}^2$, the expansion in Eq. (3) fails and the signal cross section falls like Q_{tr}^{-1} rather than M_{med}^{-1}. In this region the EFT constraints will be stronger than the actual ones.