Searches for Dark Matter at ATLAS

Francesco Conventi on behalf of the ATLAS Collaboration

Università Parthenope and INFN, Napoli

ATLAS EXPERIMENT

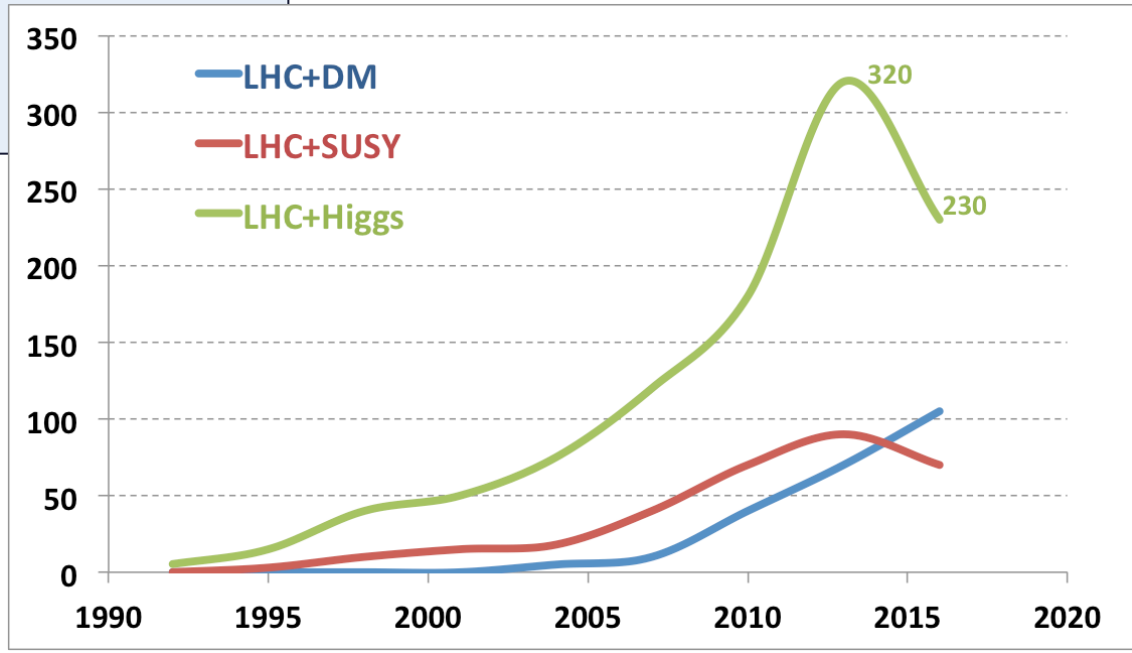
INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITA' DEGLI STUDI DI NAPOLI PARTHENOPE

Outline

- *DM@LHC*
- *LHC and ATLAS detector*
- *Mono-X searches*
- *Other searches: DM+HF, Dijets*
- *Tools: Trigger, Boosted jets*
- *Future for DM@ ATLAS*

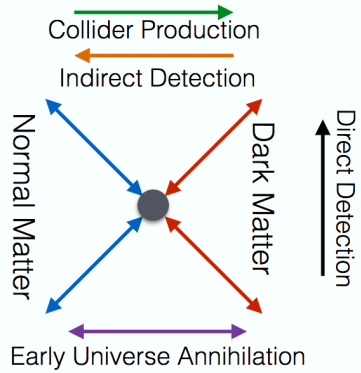
Number of arXiv entries vs year

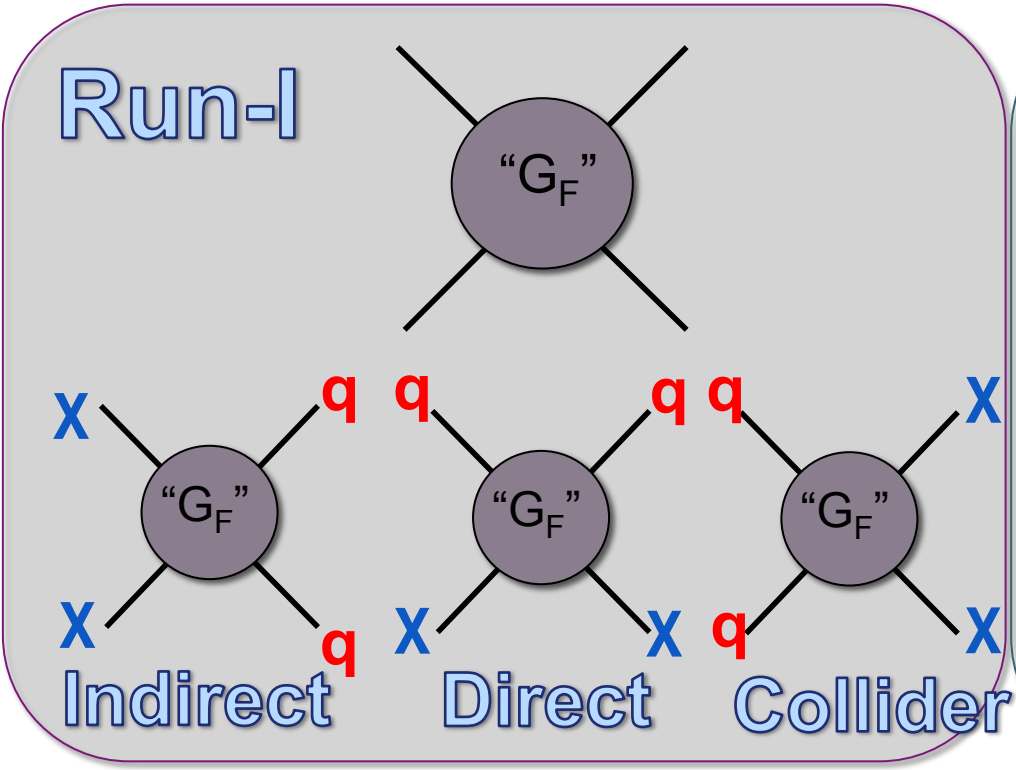


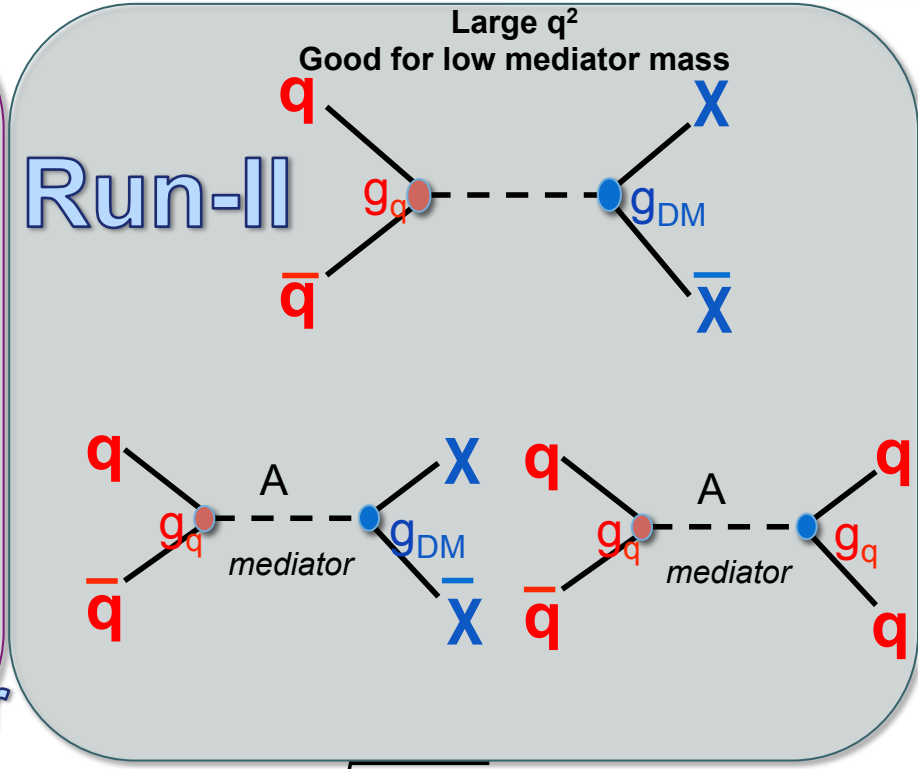
ATLAS EXPERIMENT

Motivation for Dark Matter @ LHC

- A thermal relic of the Early Universe → Detectors capable of measuring weak-scale interactions with SM
- Focus on WIMP model for dark matter: weakly interacting, massive (non relativistic), stable







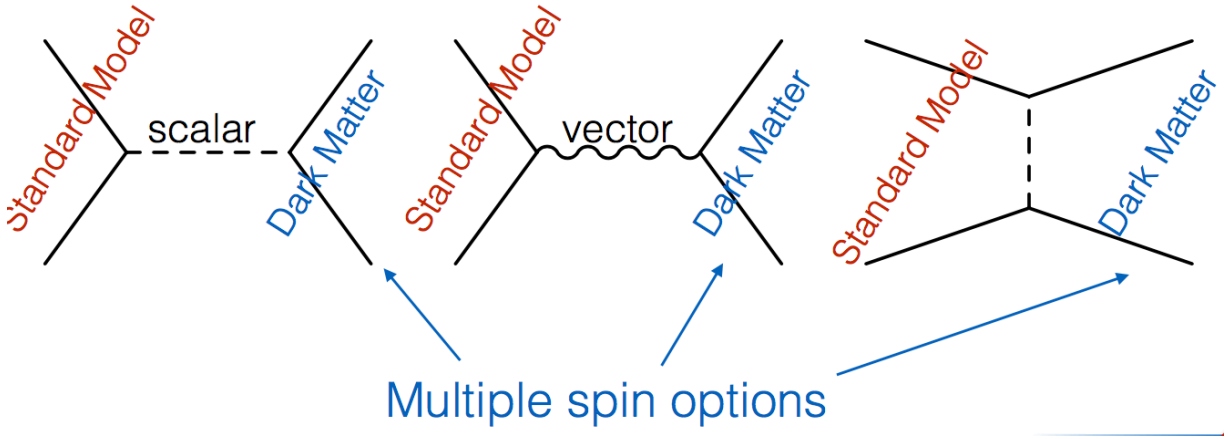
At the LHC

Effective theory is only valid if

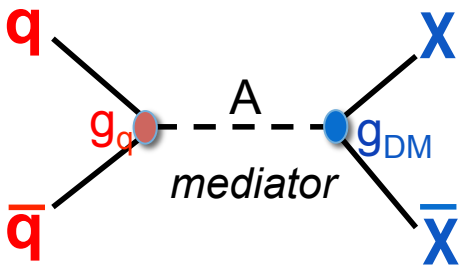
$$Q_{transfer} < M = \sqrt{g_\chi g_q \Lambda} < 4\pi\Lambda$$

$$Q_{transfer} \propto p_T(jet)$$

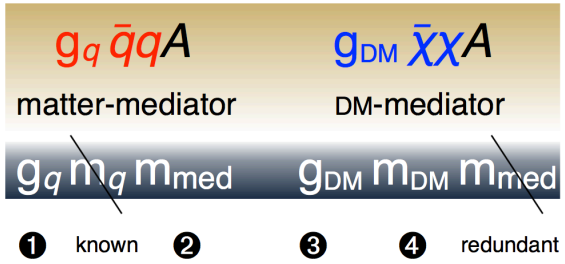
Simplified Models at LHC [1507.00966]



Lagrangian parameters



	spin 0	spin 1
charge Q	Q = 0 for s-channel	
mass	unknown	
Mediator A	H,Φ	γ,Z,Z'
Lorentz structure	scalar pseudoscalar	vector axial-vector
coupling	∝ mass	∝ charge
Example channel	DM+HF	Di-jet



Matrix element = 4 parameters
2d exclusion plot must assume 2 other params

CERN-LPCC-2016-001

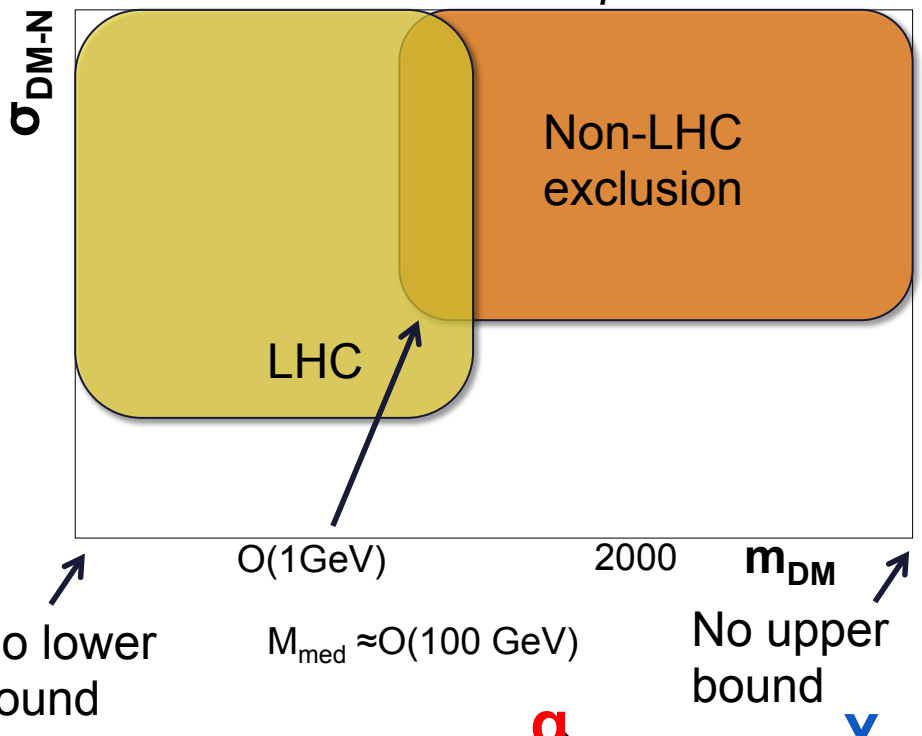
Complementarity

Generic features of results **non-LHC** vs **LHC**! [1703.05703]

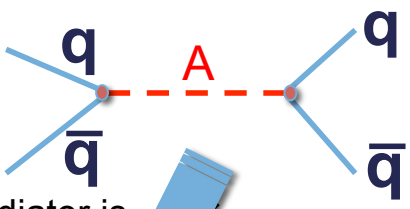
$$\sigma^{SD}_{DM-p} \approx (g_q \cdot g_{DM} \cdot \frac{m_{DM}}{m^2_{med}})^2$$

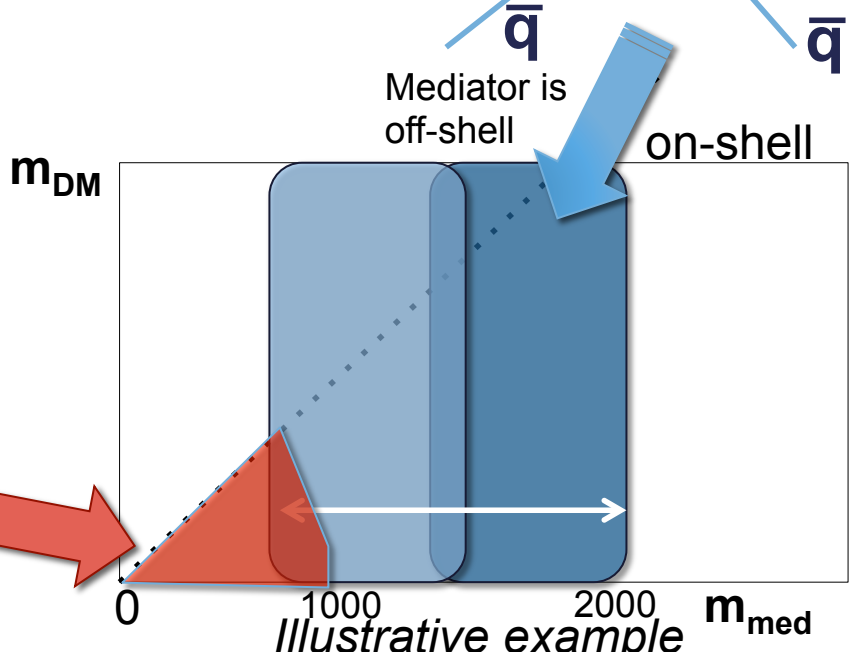
complementarity depends on the model assumptions!!

Illustrative example

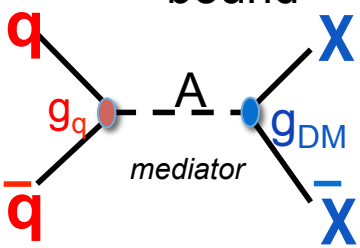


Also have complementarity among various LHC results!!





Illustrative example

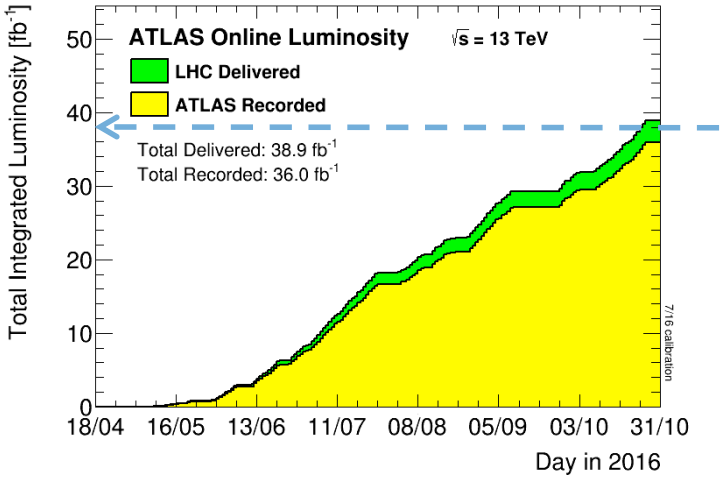


ATLAS EXPERIMENT

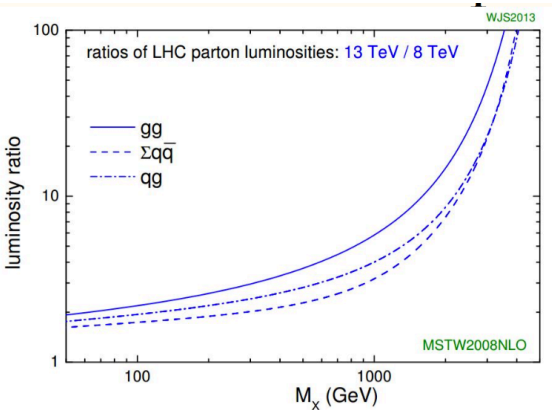
Atlas detector and Run-II @ LHC

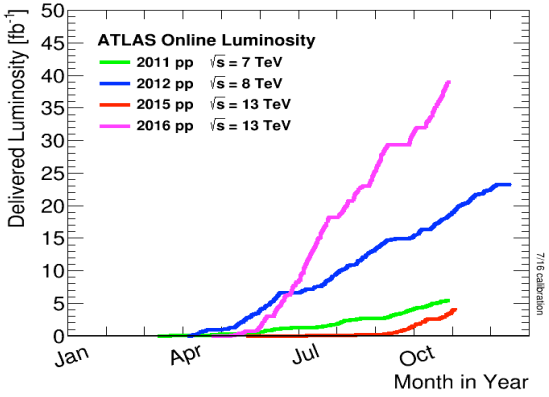
- LHC started run-2 in 2015
  proton vs proton @ √s=13 TeV

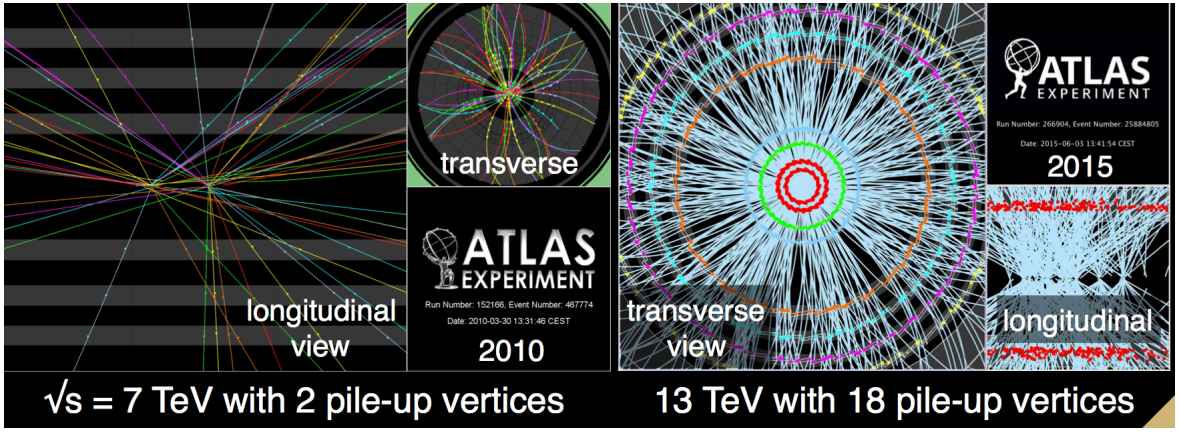
- Parton luminosity for producing massive states is greatly enhanced -> great opportunity for searches!

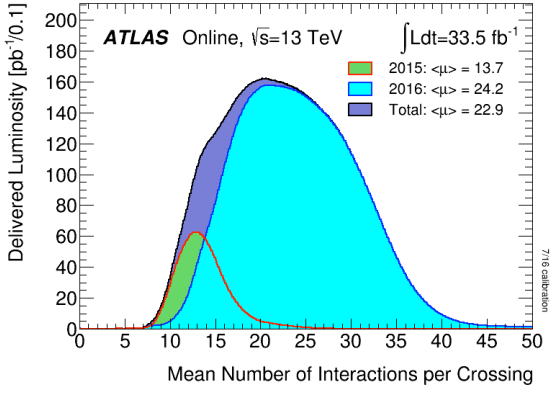


Almost 40fb^{-1} of data collected by the ATLAS experiment with excellent performance





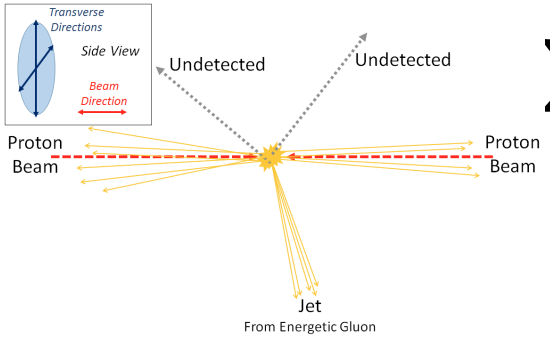




How to look for dark matter?

Mono-X

- WIMPs can only be recognised as missing energy at the LHC
- Need for a recoiling object: jets, W/Z, γ, Higgs boson
- Focus on simplified models and searches in event signatures denoted as **Mono-X** for:



inferred

$$\sum \vec{P}_{visible} + E_T^{miss} = 0$$

measured

Dark Matter

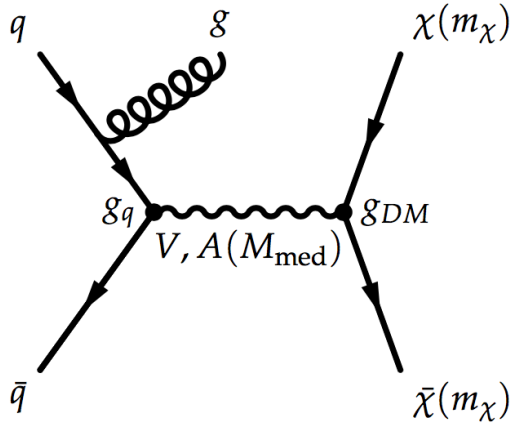
- Mono-**X** **X** = γ, Z, W, H, b , t

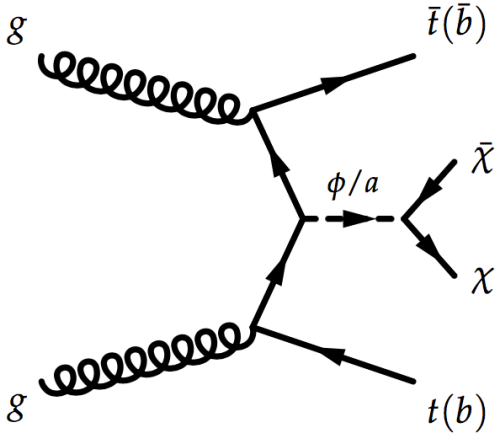
Mediators

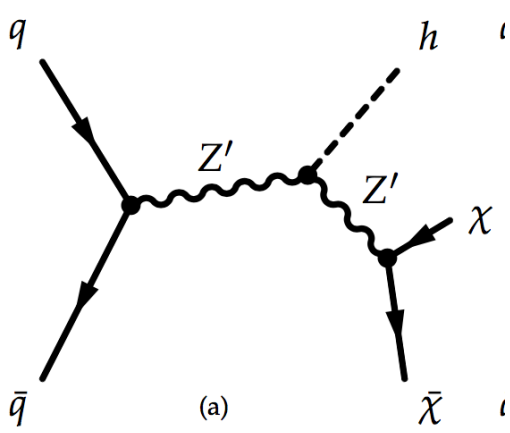
- Di-jets

(mediator can also decay to quarks)

- Higgs: $H + E_T^{miss}, H \rightarrow \chi\chi$



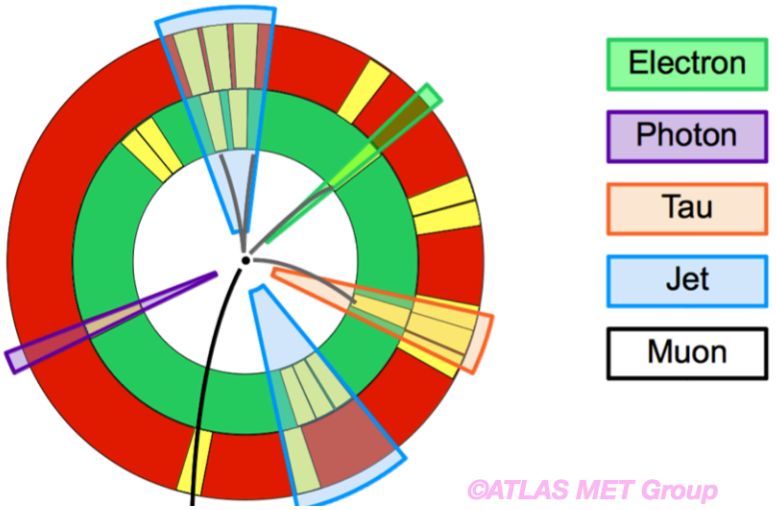




Tools for Mono-X searches

It is indirect measurement of WIMP or ν → very relevant for DM searches

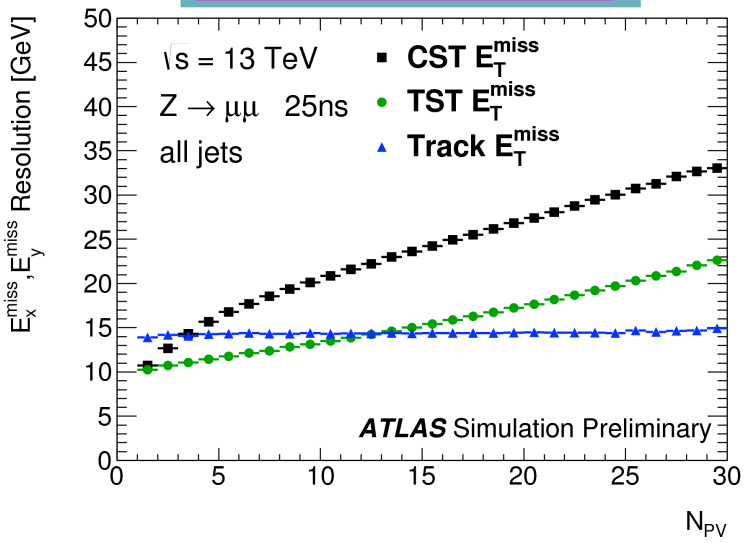
*In these searches **missing transverse momentum** $\not{E}_T$ → $p_T(XX)$, reconstruction of jets, identifications of bosons are the key ingredients*



Missing transverse momentum ($\not{E}_T$) is the p_T imbalance of the reconstructed physics objetcts:

$$E^{miss}_{x(y)} = -p^{e}_{x(y)} - p^{\gamma}_{x(y)} - p^{\tau_{had}}_{x(y)} - p^{jets}_{x(y)} - p^{\mu}_{x(y)} - p^{soft}_{x(y)}$$

ATL-PHYS-PUB-2015-023

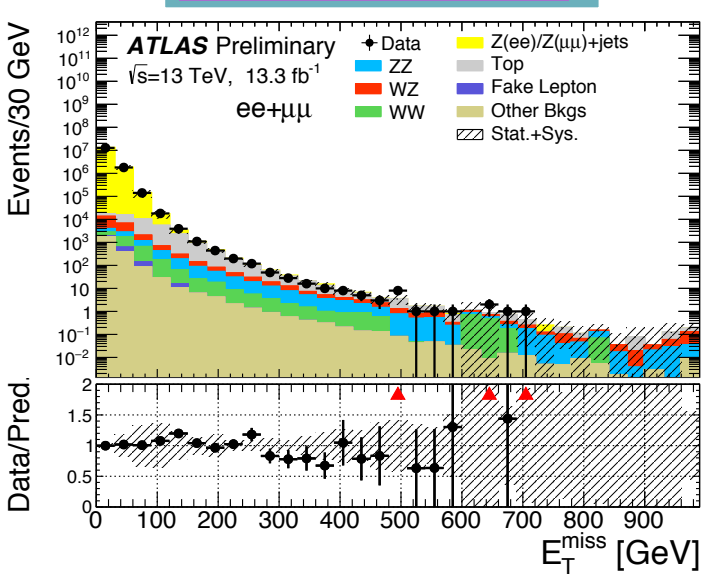


CST E_T^{miss}: Algorithm using Calorimeter Soft Term

TST E_T^{miss}: Algorithm using Track Soft Term

Track E_T^{miss}: Purely reconstructed from tracks

ATLAS-CONF-2016-056

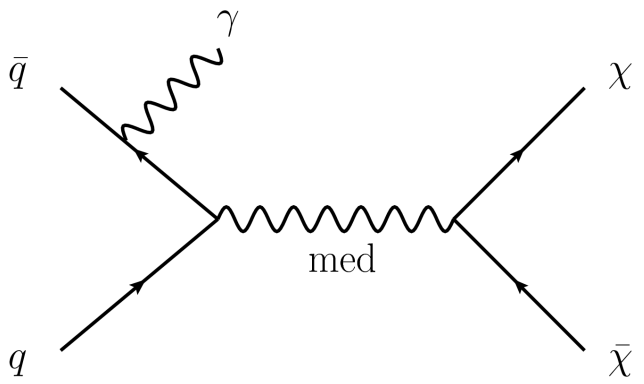


Monophoton search

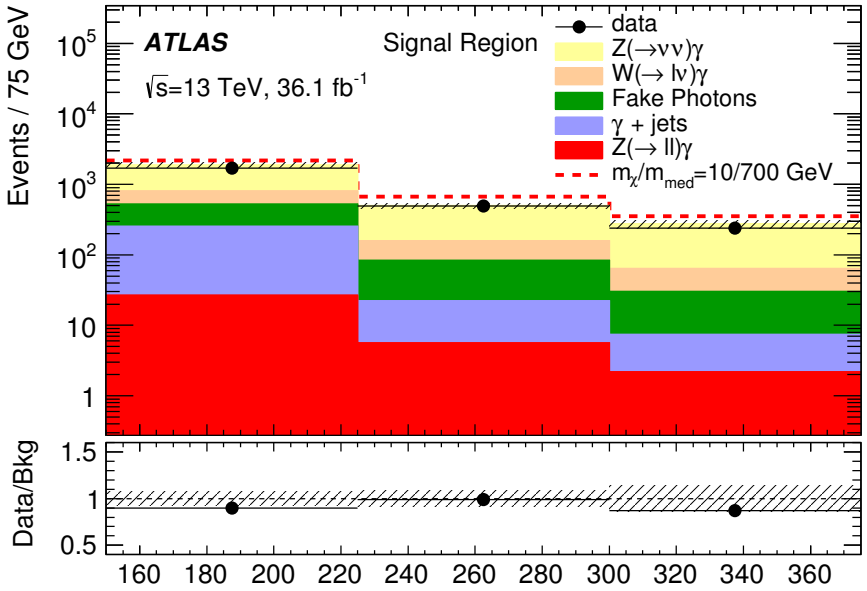
Search **for** $pp \rightarrow \chi\bar{\chi}+\gamma$ *for this channel* $X=\gamma$

New results with 36.1 fb^{-1} (submitted to EPJC, [1704.03848])

Axial-vector mediator



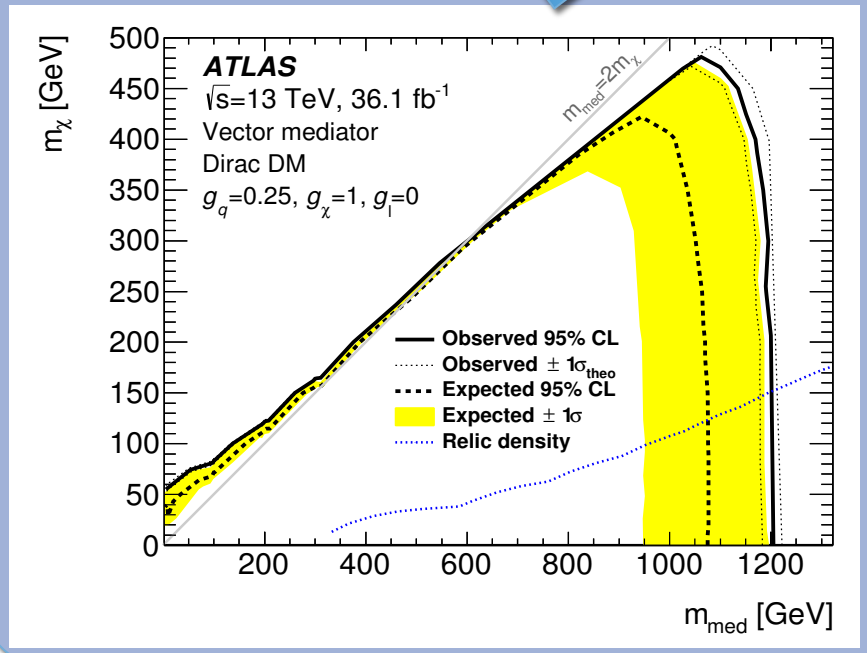
- 1 isolated photon (pT > 150 GeV) and no leptons
- E_T^{miss}>150GeV, at most one jet with pT >30GeV
- Combination of purely data-driven methods for fake backgrounds and MC normalized to data in specific CRs: Dominant irriducible background Z(νν)γ normalised by Z(ll)γ scale factors
- fit to E_T^{miss}: W/Zγ backgrounds scale factors

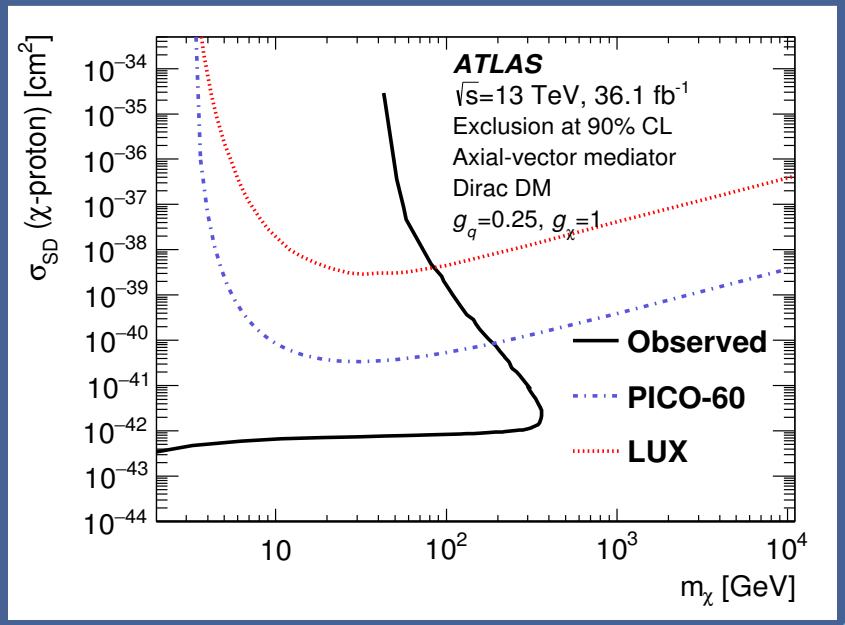


Monophoton search

Exclusion plot in ($\mathbf{m_{DM}}$, $\mathbf{m_{med}}$) and ($\boldsymbol{\sigma}_{\mathbf{DM\text{-}proton}}$, $\mathbf{m_{DM}}$) 2d plane

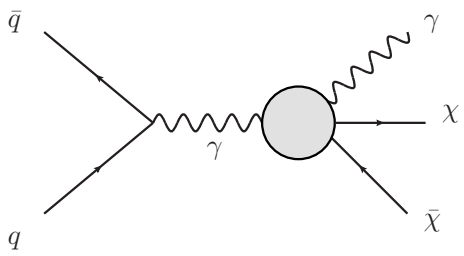
$$\sigma^{SD}_{DM-p} \approx (g_q \cdot g_{DM} \cdot \frac{m_{DM}}{m^2_{med}})^2$$

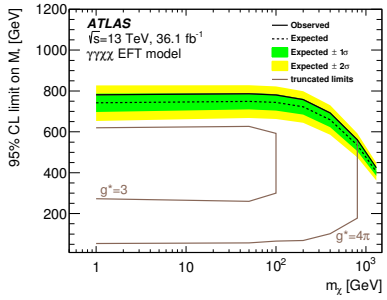




- σ depends on m_{DM} and m_{med}

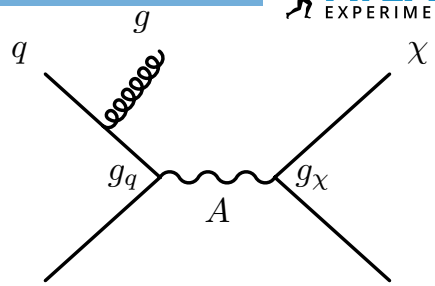
EFT results: 95% CL limits on M* for a dimension-7 operator in [1704.03848]





Monojet

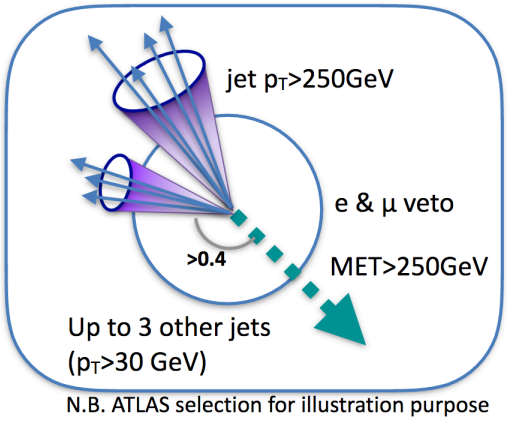
Search **for** $pp \rightarrow \chi\bar{\chi}$**+jet**

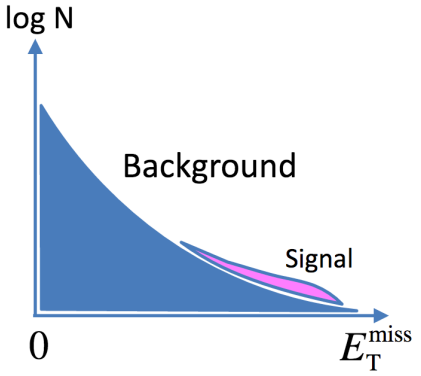


Results with 3.2 fb^{-1} (Phys Rev D 94, 032005)

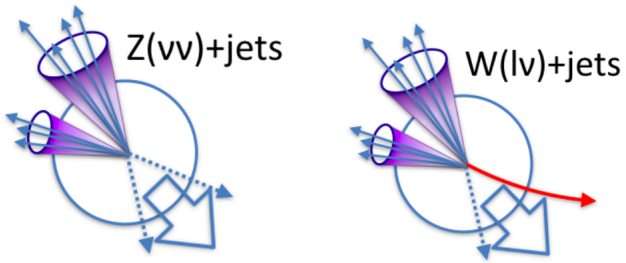
Search for an abundance of events with high $\not{E}_T$ + high p_T jet + 0 leptons

- $\not{E}_T$ >250GeV
- At most four jets (pT > 30 GeV)
- Leading jet pT > 250 GeV

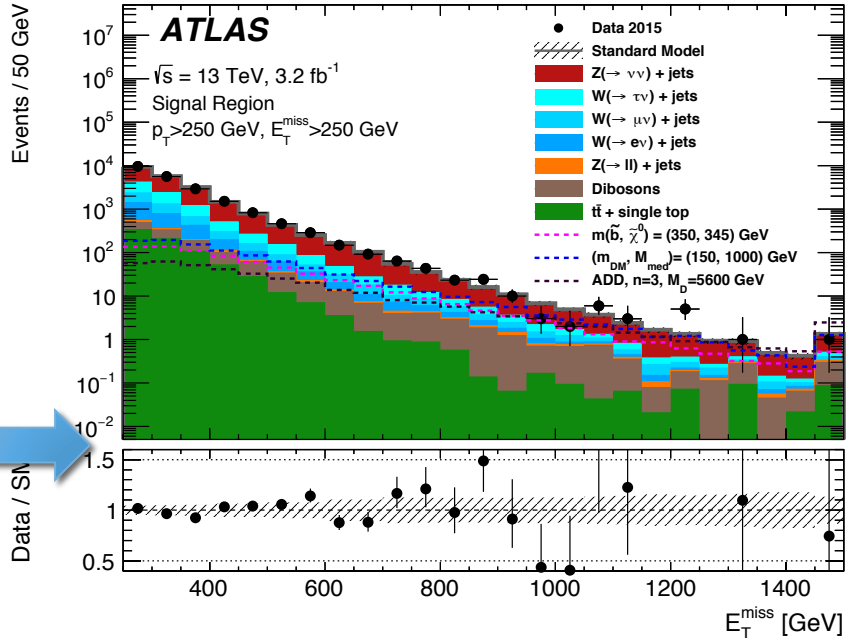




Dominant background: **Z(vv)+jets**: normalised via W(μν)+jets scale factor, theory transfer uncertainty applied in signal region

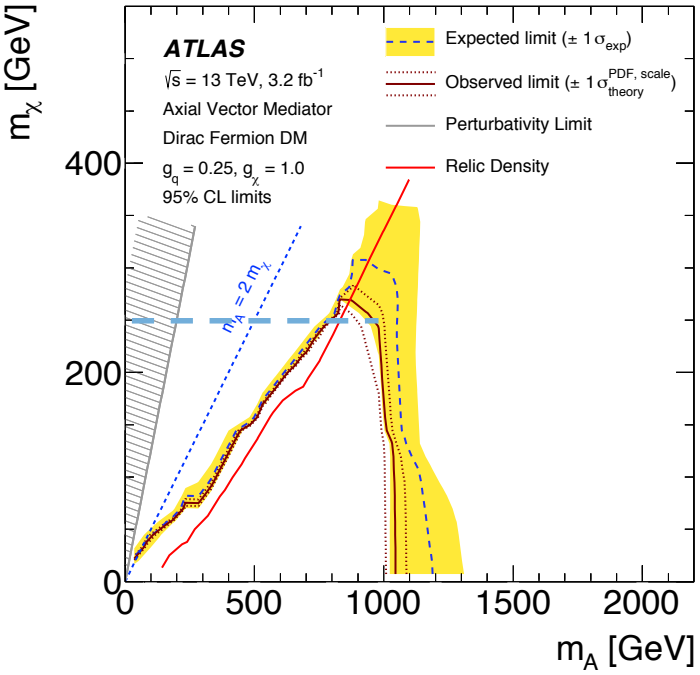


Simultaneous fit to $\not{E}_T$: → $\not{E}_T$ dependent scale factors for background normalisation

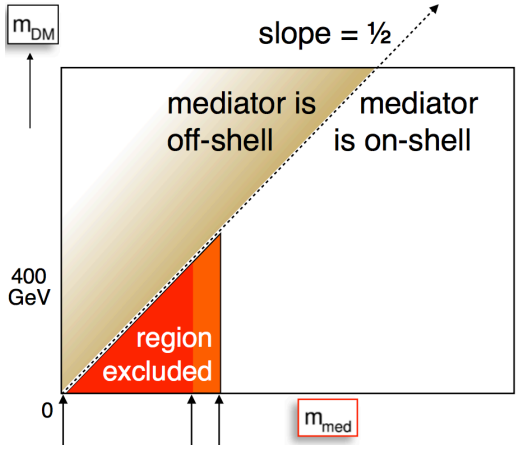


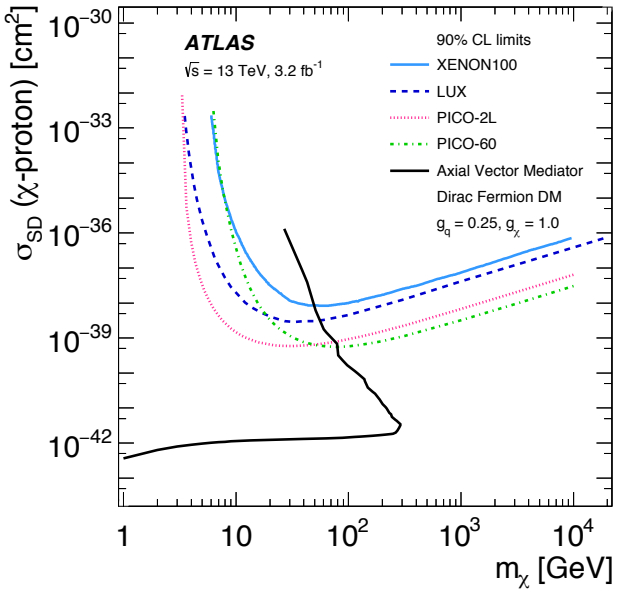
Monojet

Exclusion plot in ($\mathbf{m_{DM}}$, $\mathbf{m_{med}}$) and ($\boldsymbol{\sigma_{DM\text{-}proton}}$, $\mathbf{m_{DM}}$) 2d plane (g_q= 0.25 g_{DM}= 1)



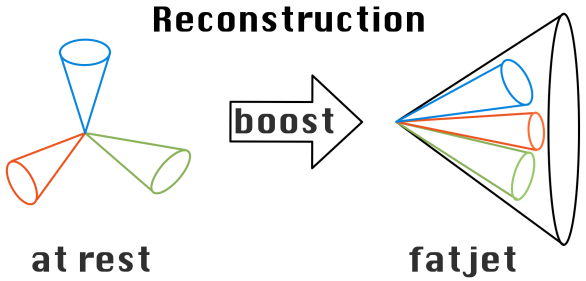
Monojet (3.2 fb^{-1})
Monophoton (36.1 fb^{-1})





In ATLAS (L=3.2 fb-1), observed (expected) limit on Mediator mass at 1.0 TeV (1.2 TeV) for m_{DM} <250 GeV (300 GeV) at 95% CL

Tools for Mono-X searches



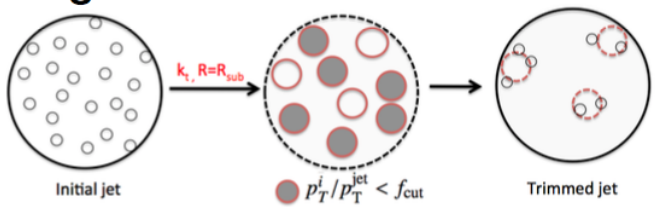
Run-I analysis used anti-k_T jets with **R=0.4**

Boosted topologies: two-jets overlap and form a fat-jet (R=1.0)

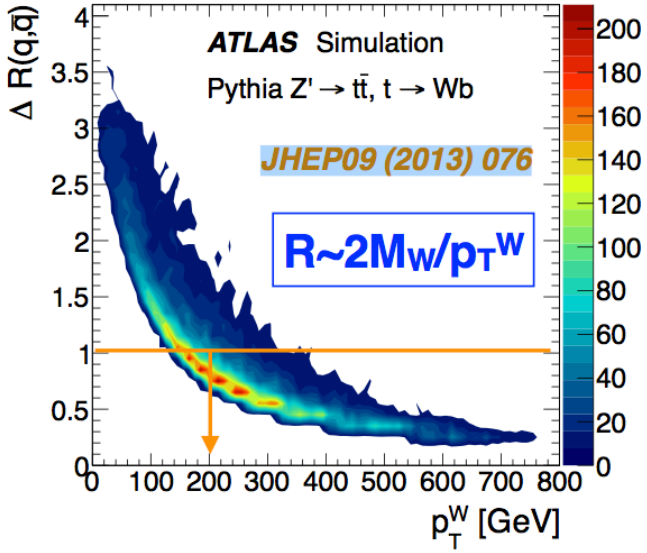
Jet grooming to reduce the impact of pile-up in ATLAS→ jet **trimming**:

- k_T algorithm to create sub-jets with R=0.2
- sub-jets with $p_T^i/p_T^{jet} < 5\%$ are removed

Trimming



Cut on substructure variables e.g. D2 (energy correlation ratio; offers separation for 1- & 2-prong decays) is applied to reduce the multijet bkg



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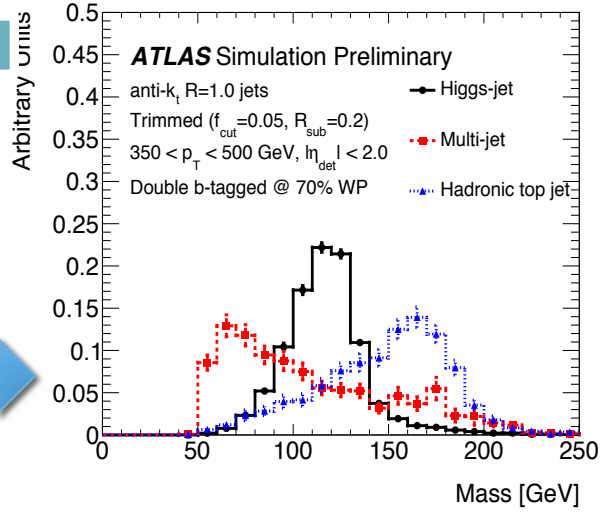
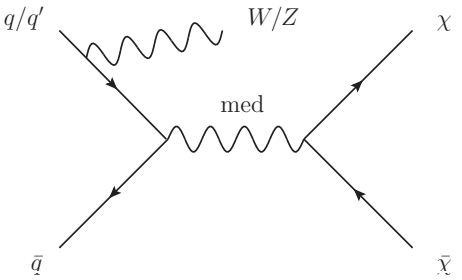
jets with mass consistent with m_V or m_H are selected



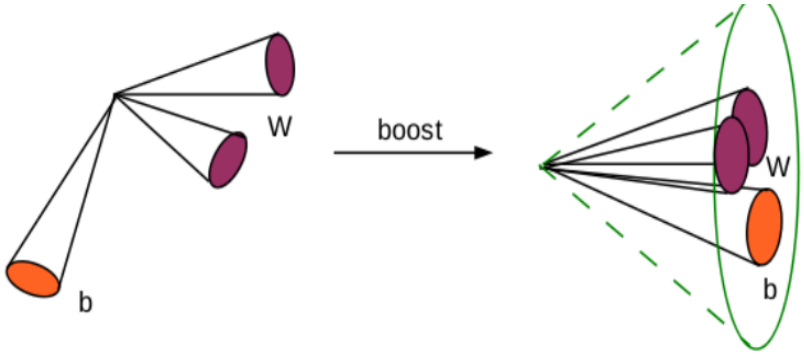
Mono-V(*V→ hadrons*)

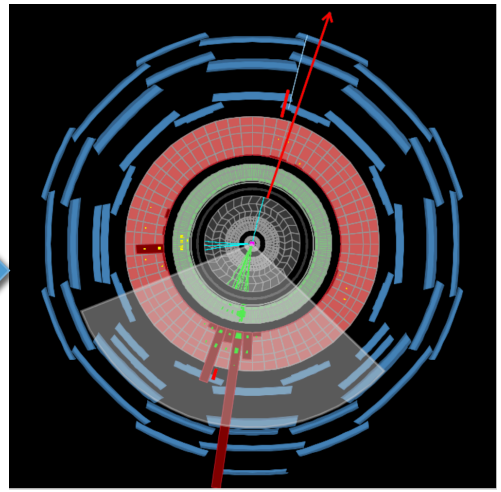


Search **for** $pp \rightarrow \chi\bar{\chi}+\gamma$ *for this channel* ***X*** *=W,Z*

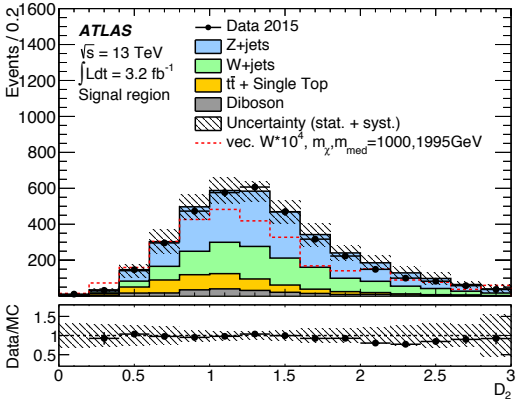
Results with 3.2 fb^{-1} (Phys. Lett. B 763 (2016) 251)

Analysis similar to monojet search but with focus on **large-R jets**





- Background: Z(νν) + jets, W(lν) + jets, W(lν) from top
- Select events with MET>250 GeV and boosted W/Z (pT>200 GeV)
- Require **large-R jets**: both decay products of W/Z contained inside large jet (R = 1.0, anti-k_t)
- large-R jet substructure described by jet mass and D2 variable (two distinct energy concentrations)



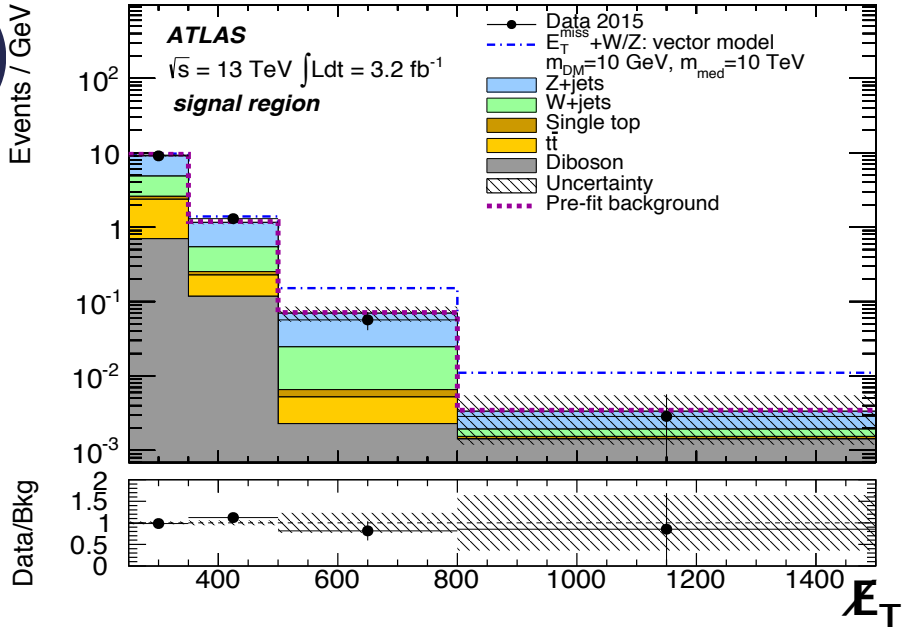
Mono-V(*W,Z→ hadrons*)

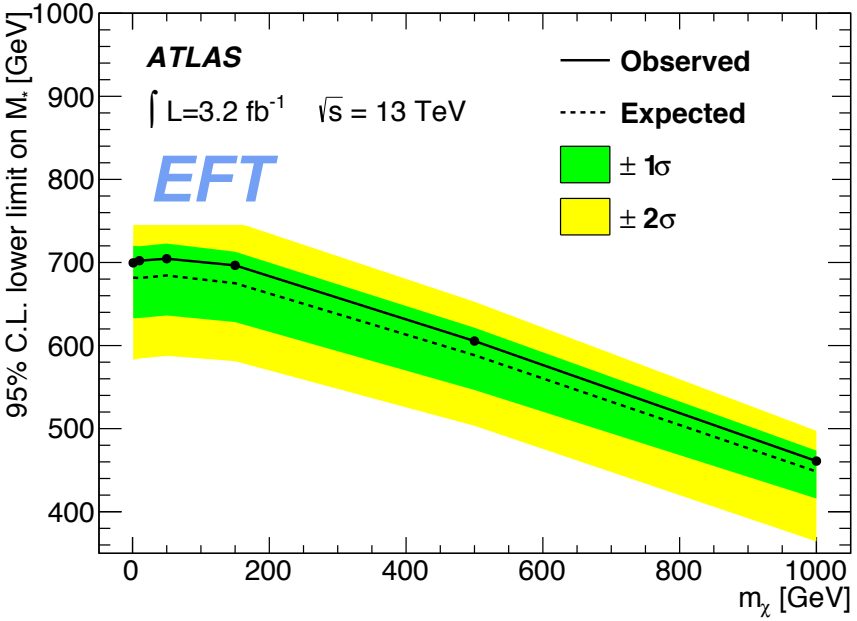
No excess over SM prediction observed

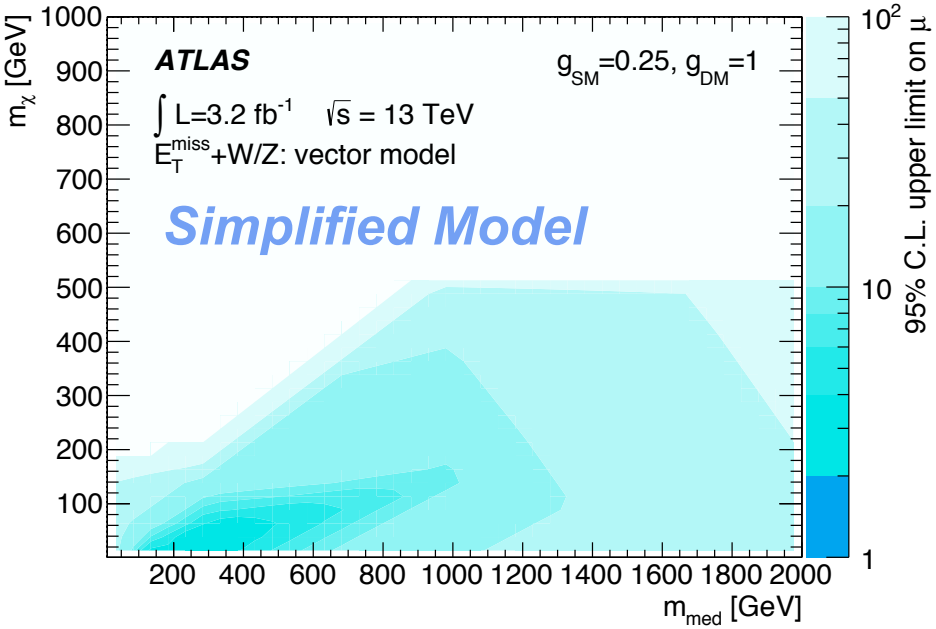
Results interpreted in:

- **EFT model**
  (mass scale of the model vs DM mass)
- **Simplified model**

(observed limit on the signal strength in 2D plane of m_{med} and m_{DM})







Mono-Z($Z \rightarrow ll$)

Search **for** $pp \rightarrow \chi\bar{\chi}+l^+l^-$ *for this channel* $X = Z$

Results with 13.3 fb^{-1} (ATLAS_CONF_2016_056)

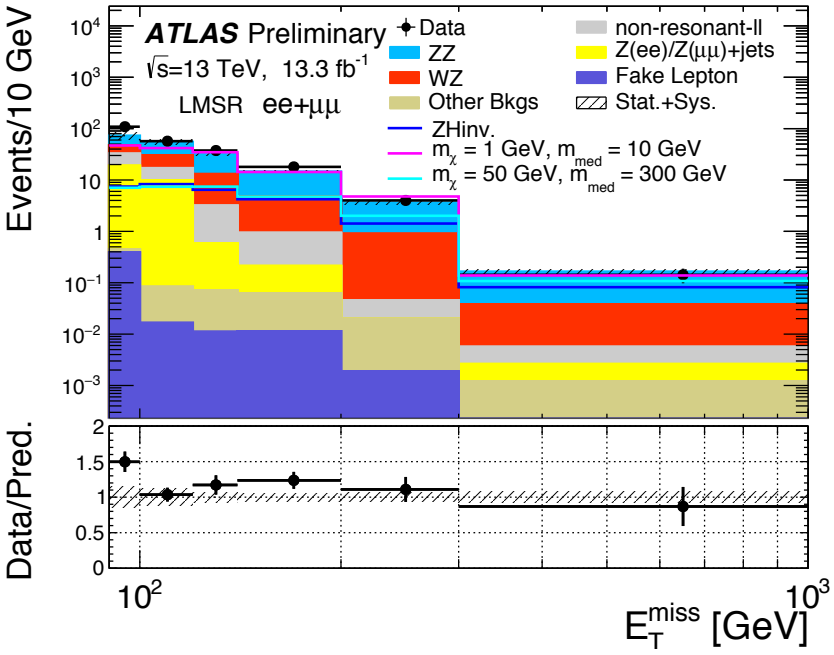
Signature: opposite sign leptons and $\not{E}_T$

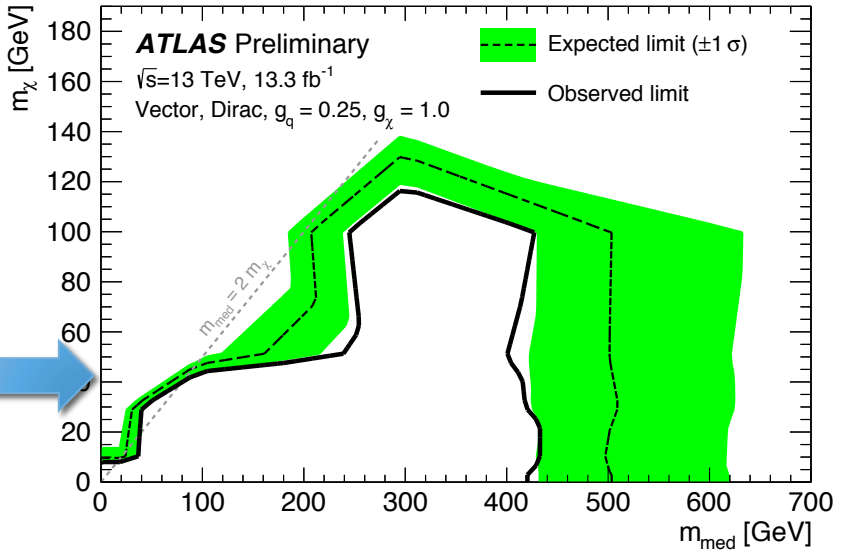
- $\not{E}_T > 90$ GeV
- boosted Z-boson with $\Delta R(ll) < 1.8$, b-veto

Dominant background ZZ → llvv from MC corrected to NNLO QCD and NLO EW calculation.

- WZ and Z+jets (small) normalised via CRs using scale factor.
- Bkg **uncertainty dominated by Z+jets**

Limit on DM production in simplified model for vector mediator

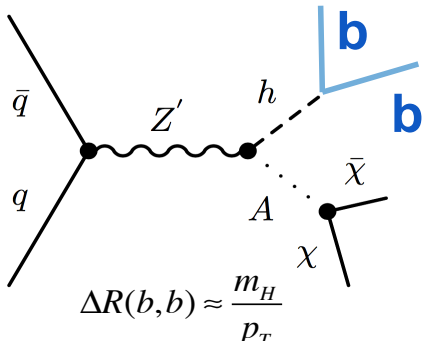




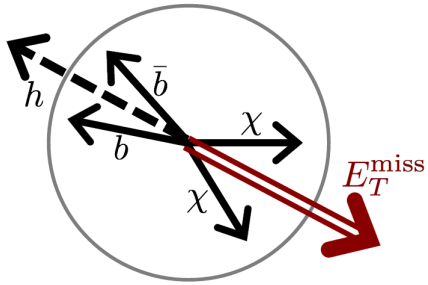
MonoHiggs ($H \to bb$)

Search **for** $pp \to \chi\bar{\chi}$ **+bb** *for this channel* $X = H$

New Results with 36.1 fb^{-1} (ATLAS_CONF_2017_028)

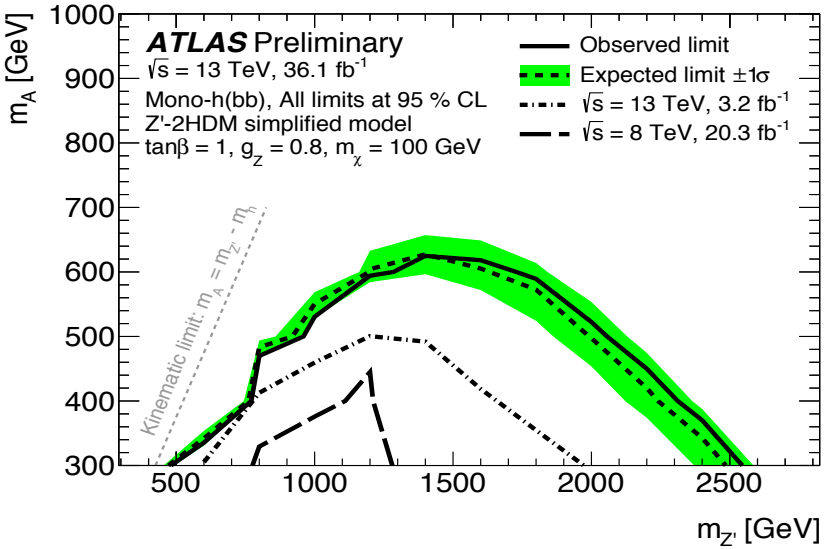


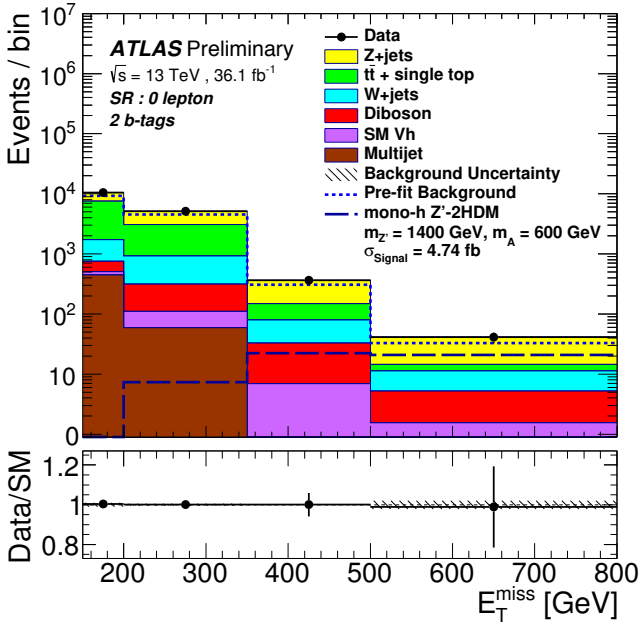
Higgs involved in WIMP production in different models:
- coupling to heavy mediator Z′
- coupling to Z′ and pseudo-scalar A (2HDM)
- Heavy scalar model



- $\not{E}_T$ < 500 GeV: Resolved region →two distinct b-jets
- $\not{E}_T$ > 500 GeV: boosted Higgs → large-R jet with substructure (as in mono-V)
- Main backgrounds: W/Z+jets, tt
- Shape-fit to mjj or mJ (boosted region) in different $\not{E}_T$ bins and #b-jets

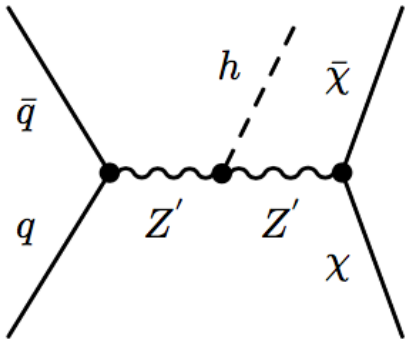
Gap in (m_A,$m_{Z'}$) is due to MET trigger threshold





MonoHiggs ($H\to\gamma\gamma$)

Higgs ISR suppressed due to Yukawa coupling

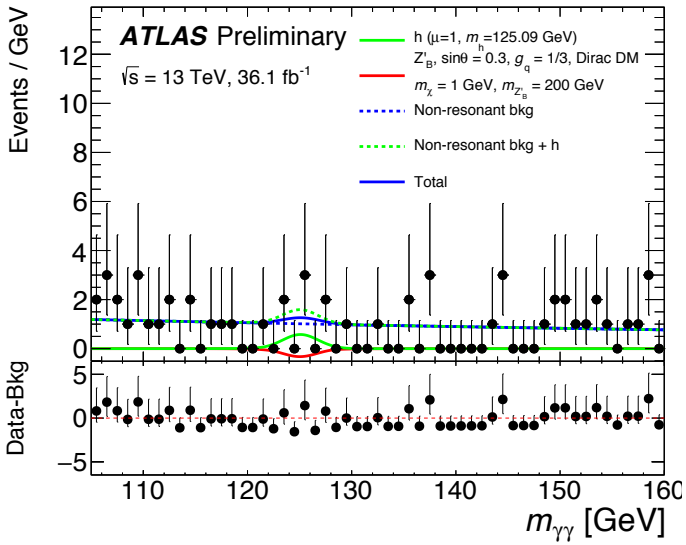


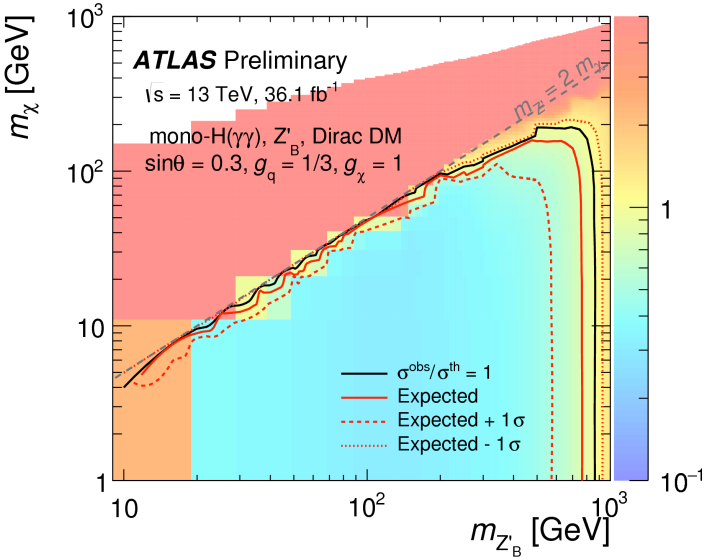
Search **for** $pp \to \chi\bar{\chi}+bb$ *for this channel* $X = H$

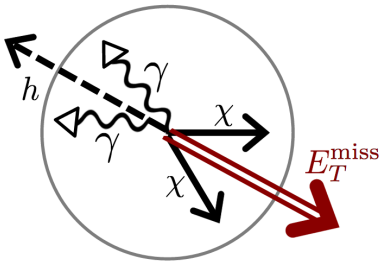
New Results with 36.1 fb^{-1} (ATLAS_CONF_2017_024)

Signature: Two photons with $m_{\gamma\gamma}$ in [105,160] GeV and $\not{E}_T$

- **5 categories** formed based on $\not{E}_T$ significance ($\not{E}_T/\sqrt{\Sigma E_T}$) and $p_T(\gamma\gamma)$, p_T^{hard}, # of leptons and $|z_{PV}^{hard} - z_{PV}^{\gamma\gamma}|$ with different sensitivity:
  - → First category for vector Z' and 2HDM models
  - → All categories for heavy resonce H
- Background in $m_{\gamma\gamma}$ fitted with exponential function+double sided crystal ball→*for SM Higgs resonance*







95% CL observed limit on σ^{obs}/σ^{th}

$$S_{E_T^{miss}} = E_T^{miss}/\sqrt{\sum E_T}$$

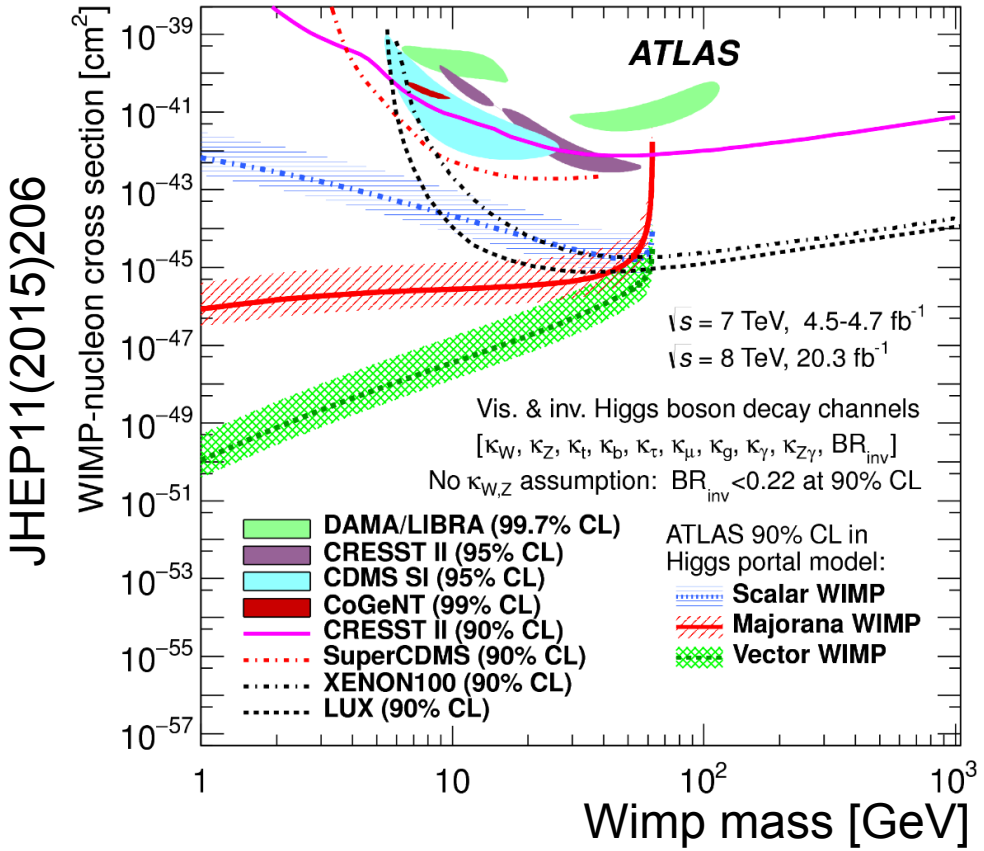
$$p_T^{hard} = \left| \sum \vec{p}_T^{\,\gamma} + \sum \vec{p}_T^{\,jet} \right|$$

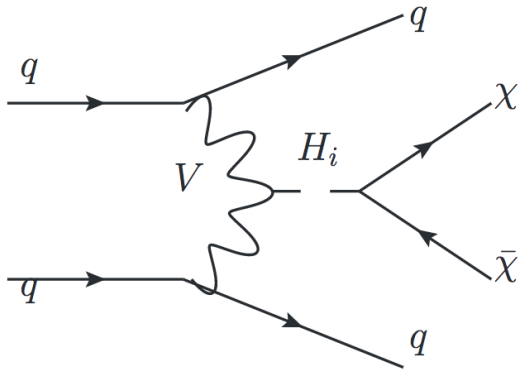
ATLAS EXPERIMENT

Higgs → invisible

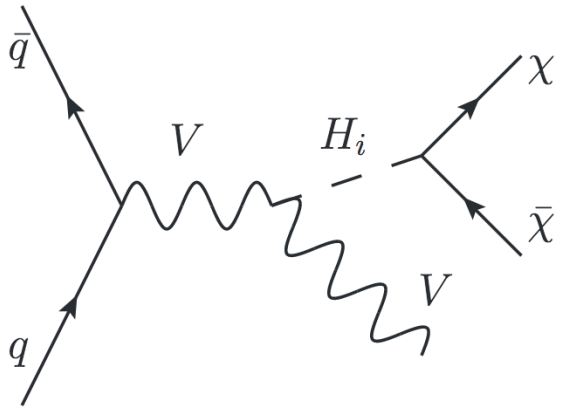
- Direct searches for H→invisible
  (Vector-boson fusion,associated VH production)
- Higgs production and decay rates:
  bb,γγ,ZZ,WW,μμ,ττ

Combined upper limit on BR(Higgs→invisible)<22%



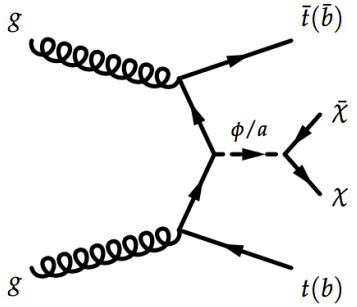


Vector boson fusion (VBF)
20.3 fb^{-1}@ 8 TeV
(JHEP01(2016)172



Higgs Strahlung (VH)
13.3 fb^{-1}@ 13 TeV
(ATLAS-CONF-2016-056)

DM + Heavy Flavour Searches

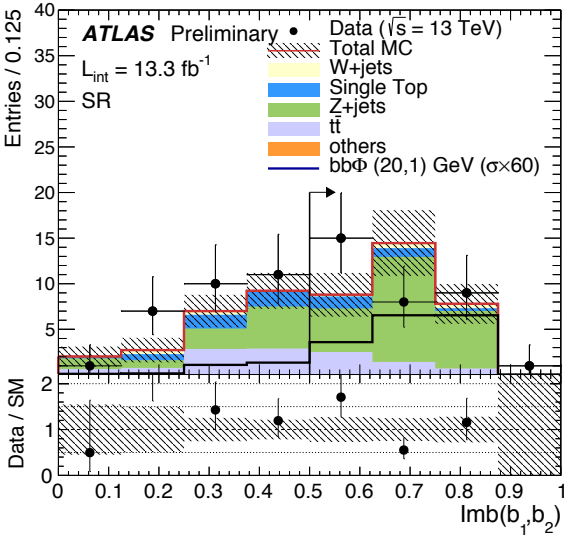


Searches for bb +$\not{E}_T$ and t$\bar{t}$+ $\not{E}_T$ production:
→ sensitive to (pseudo-)scalar mediator

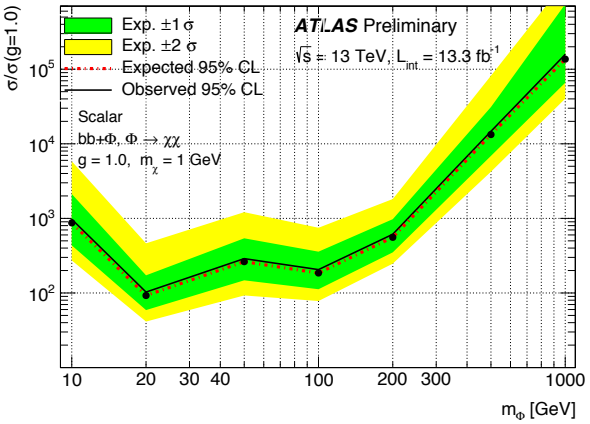
DM+bb: (ATLAS_CONF_2016_086) *Results with 13.3 fb^{-1}*

Signature:
Exactly two b-jets, 3rd jet veto,no leptons and $\not{E}_T$

- Dominant background Z(vv) + b-jets reduced by cut requiring well separated b-jets $\Delta R(b_1,b_2)$ and momentum imbalance between b-jets (Imb(b1,b2)

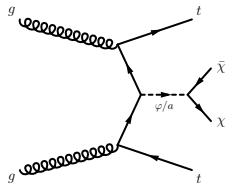


- Background normalization using 3 CRs:
  Z(vv) + bjets constrained from Z(ll) + b



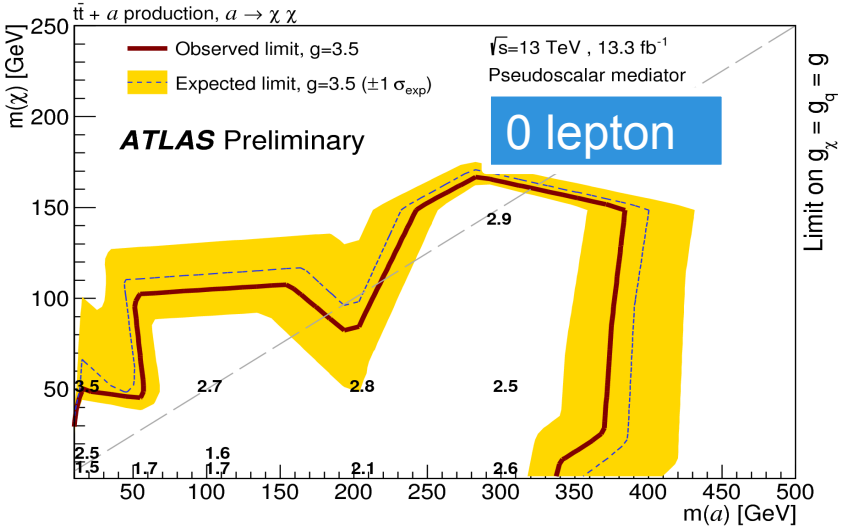
Limits on DM+ bb with pseudoscalar mediator (similar results for scalar mediator)

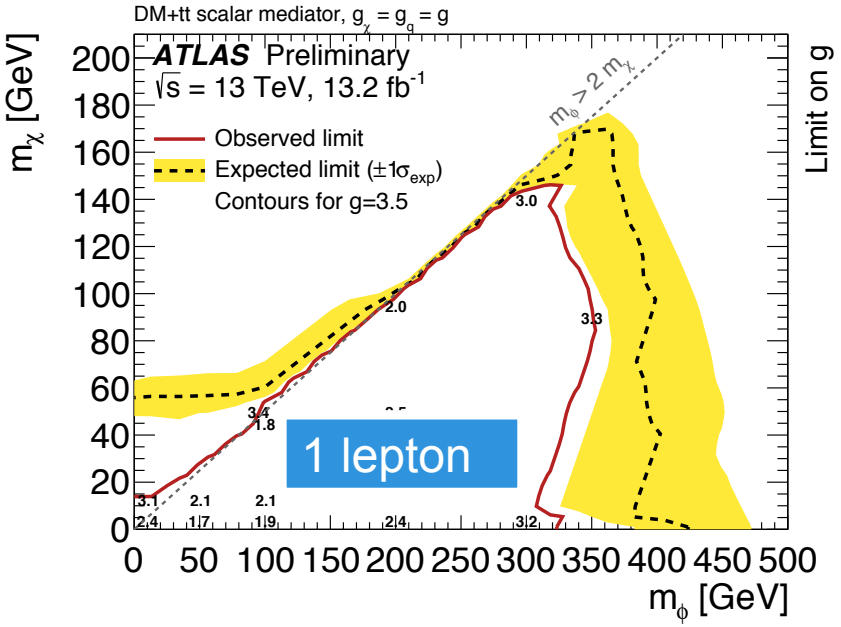
DM + Heavy Flavour Searches

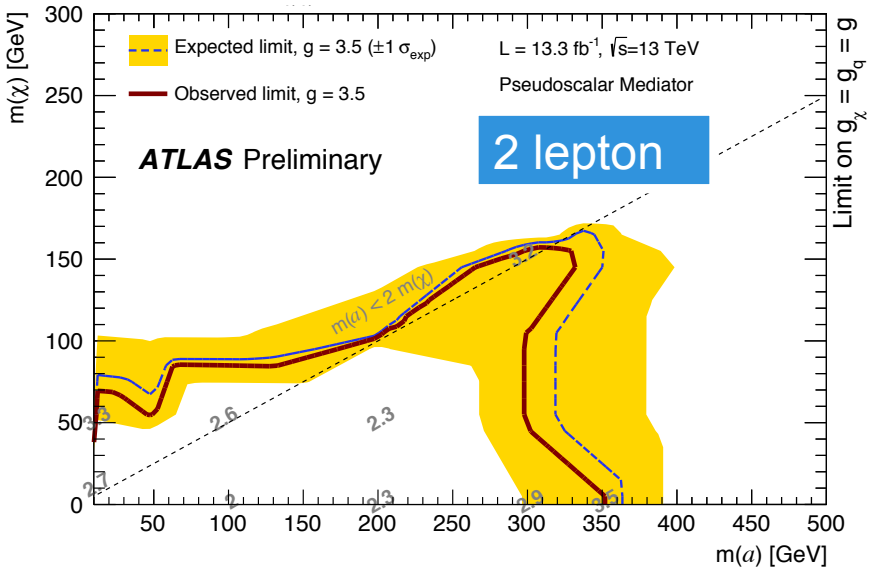


DM+tt : Results for 13.2 fb^{-1}
(*ATLAS_CONF_2016_077*, *2016_050*, *2016_076*)

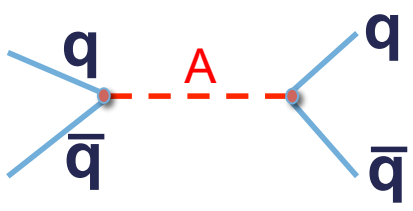
- In SUSY searches for stops with 0, 1 or 2 charged leptons produced limits also on DM for scalar/pseudoscalar mediator
- **Many SRs**, based on kinematics/topological **discriminating variables**, have **regions dedicated to DM searches**
- Similar sensitivities for 0,1,2 leptons channel

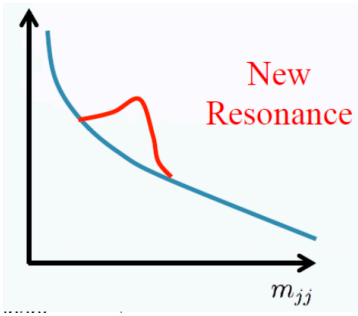






Di-jet resonance search

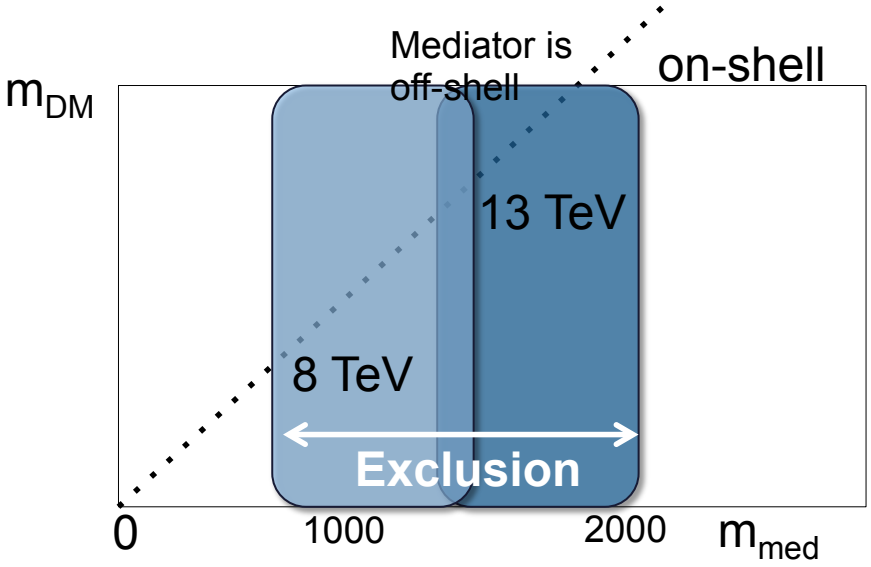


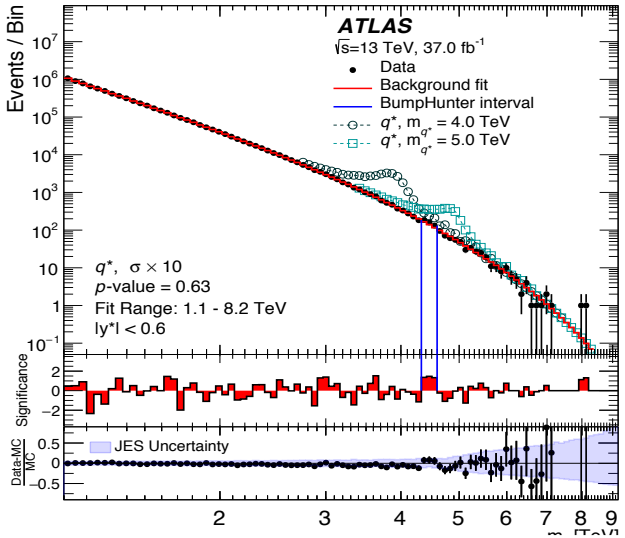


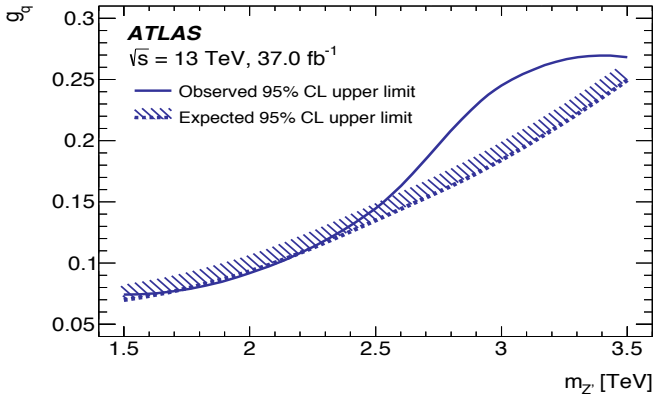
NEW Results with 37 fb^{-1} ([1703.09127])

Search for **resonances** on **m_{jj} spectrum**

- Limits are set on excited quarks q*, quantum black holes, W′,Z′,W*, generic Gauss-shaped resonances
- For simplified models: limit on coupling g_q to standard model particles as a function of the mediator mass mZ′



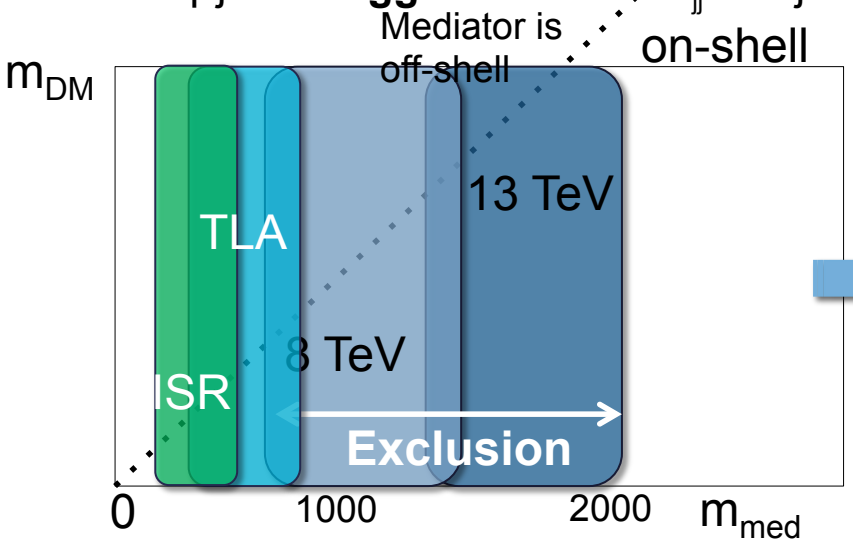




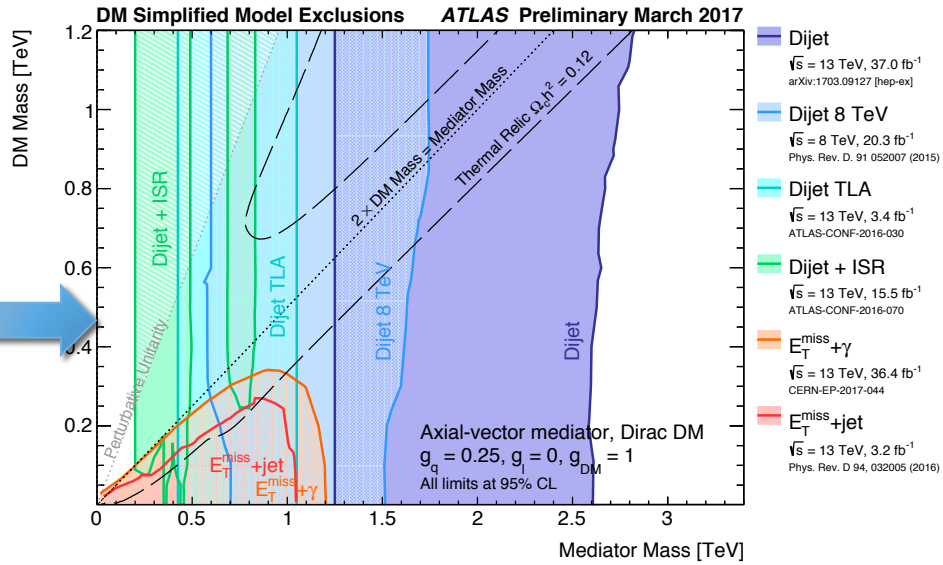
Di-jet resonance search

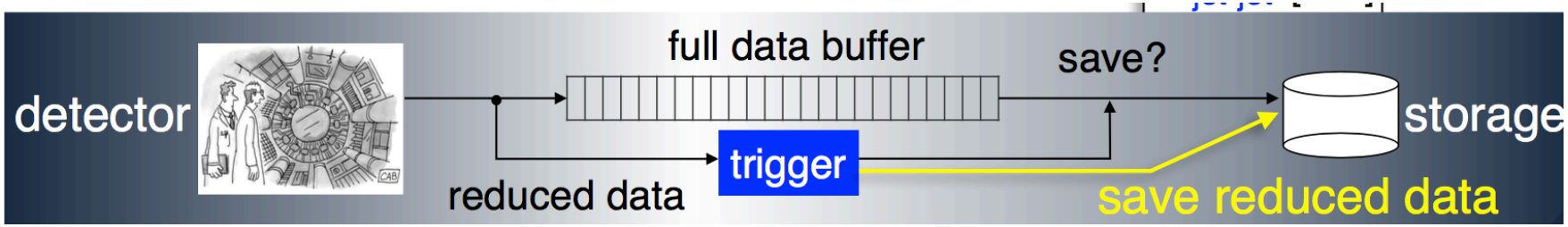
Use new approaches to cover the low mass region!!

- Trigger Level Analysis (TLA)
  partial info stored
- Di-jet + ISR
  ISR γ/jet -> **trigger** search in m_{jj} of dijet



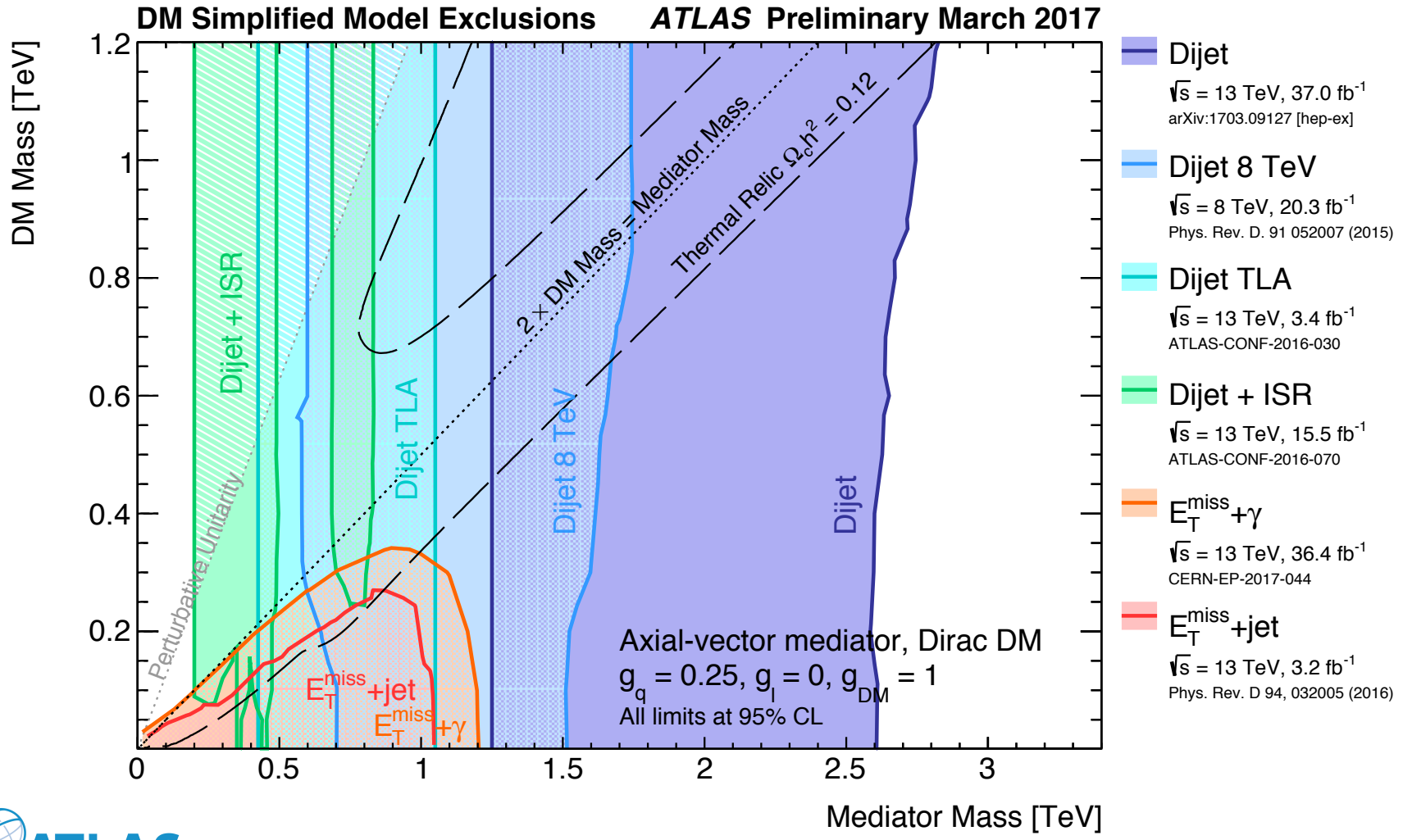
Full Event O(1-2MB) → trigger rate too high for dijet event
ATLAS **TLA**: store only jet related info (1-10 kB)





Simplified Models: Combination of Exclusion

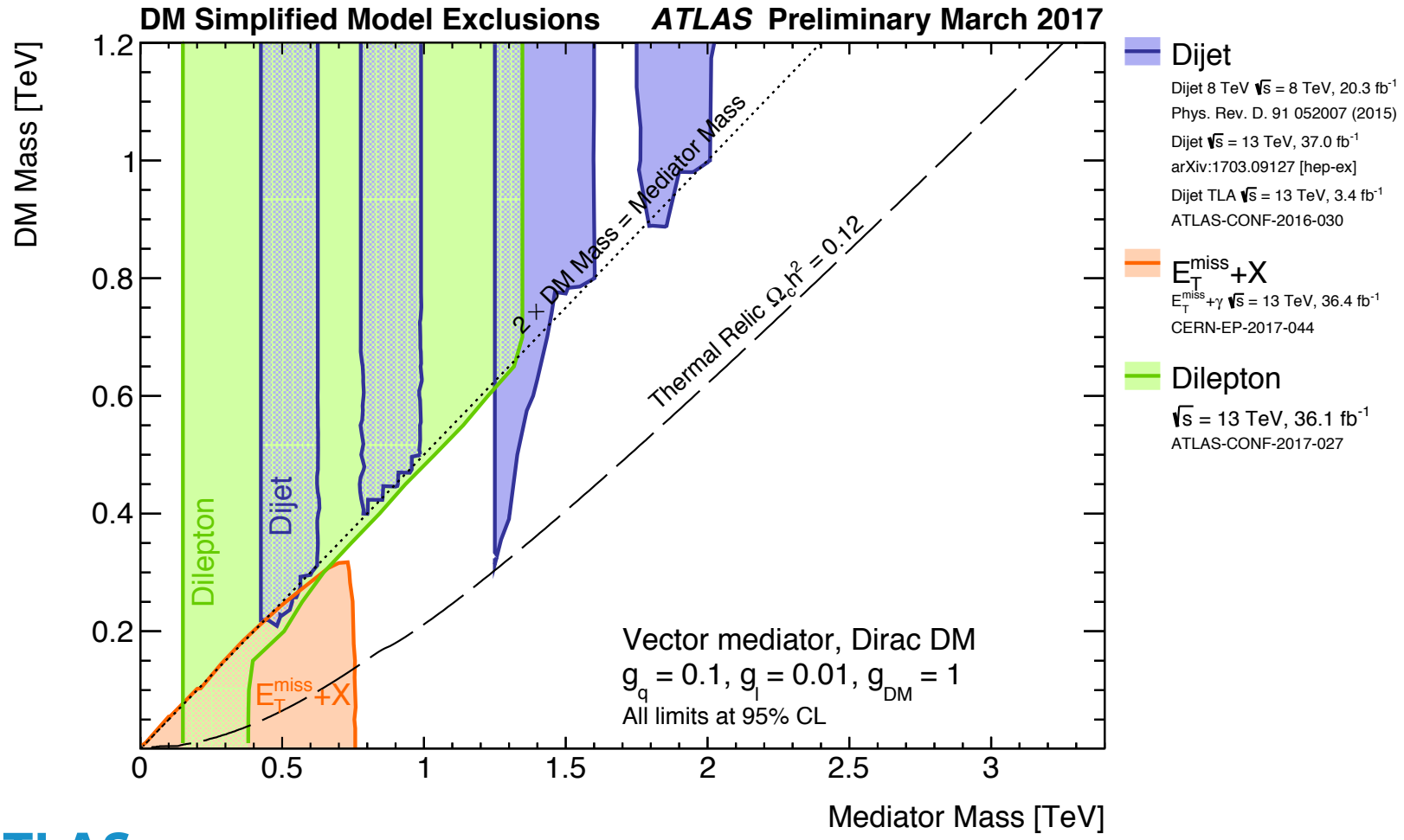
Combining dark matter searches in terms of simplified models with an axial-vector mediator model:



ATLAS EXPERIMENT

Simplified Models: Combination of Exclusion

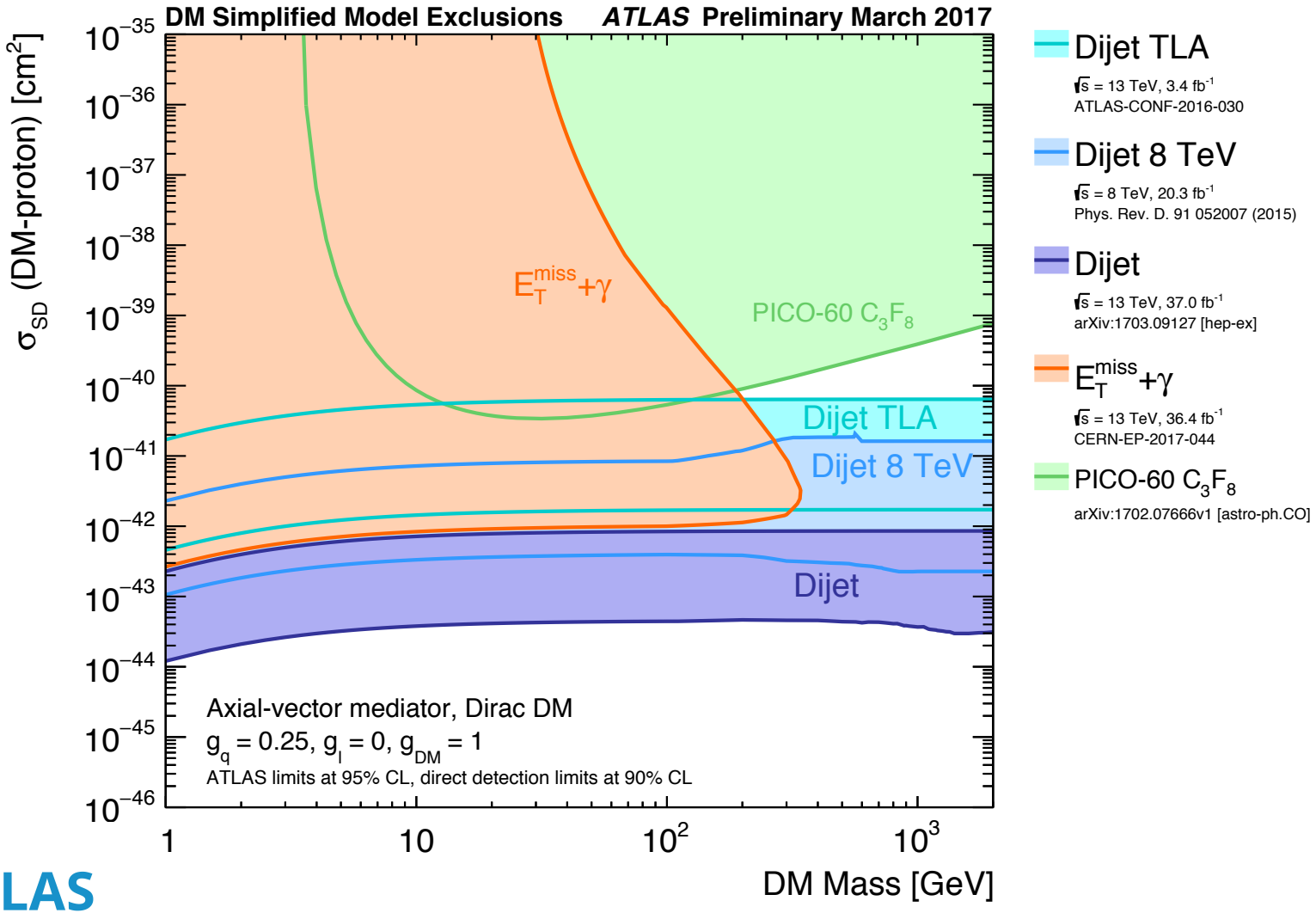
With non-zero coupling to leptons g_l=0.01 and less 'optimistic' coupling to standard model quarks: g_q = 0.1:



ATLAS EXPERIMENT

Simplified Models: Combination of Exclusion

Limit on spin-dependent WIMP-proton scattering cross section:



ATLAS EXPERIMENT

Summary and Outlook

- A variety of dark matter searches carried out throughout 2015 and 2016 Run-II data taking
  - *New results with full* **2015+2016 dataset > Run 1**
  - *Many others to come soon with full 2015+2016 data set*

- Interpretations focused on **Simplified models**:
  - DM production via heavy mediator (*mono-X*)
  - Model dependent approach
  - Complementary sensitivity compared to direct dark matter searches
  - Constraints from di-jet resonance searches

- Many ways to improve:
  - **Experimental techniques**: fitting strategies, jet substructure, flavour tagging, ...
  - **Interaction with theorists**: higher-order prediction for bkg, better control of theoretical uncertainties (relevant for many measurement), ...