Dark Matter Searches with Mono-X Signatures at the ATLAS Experiment

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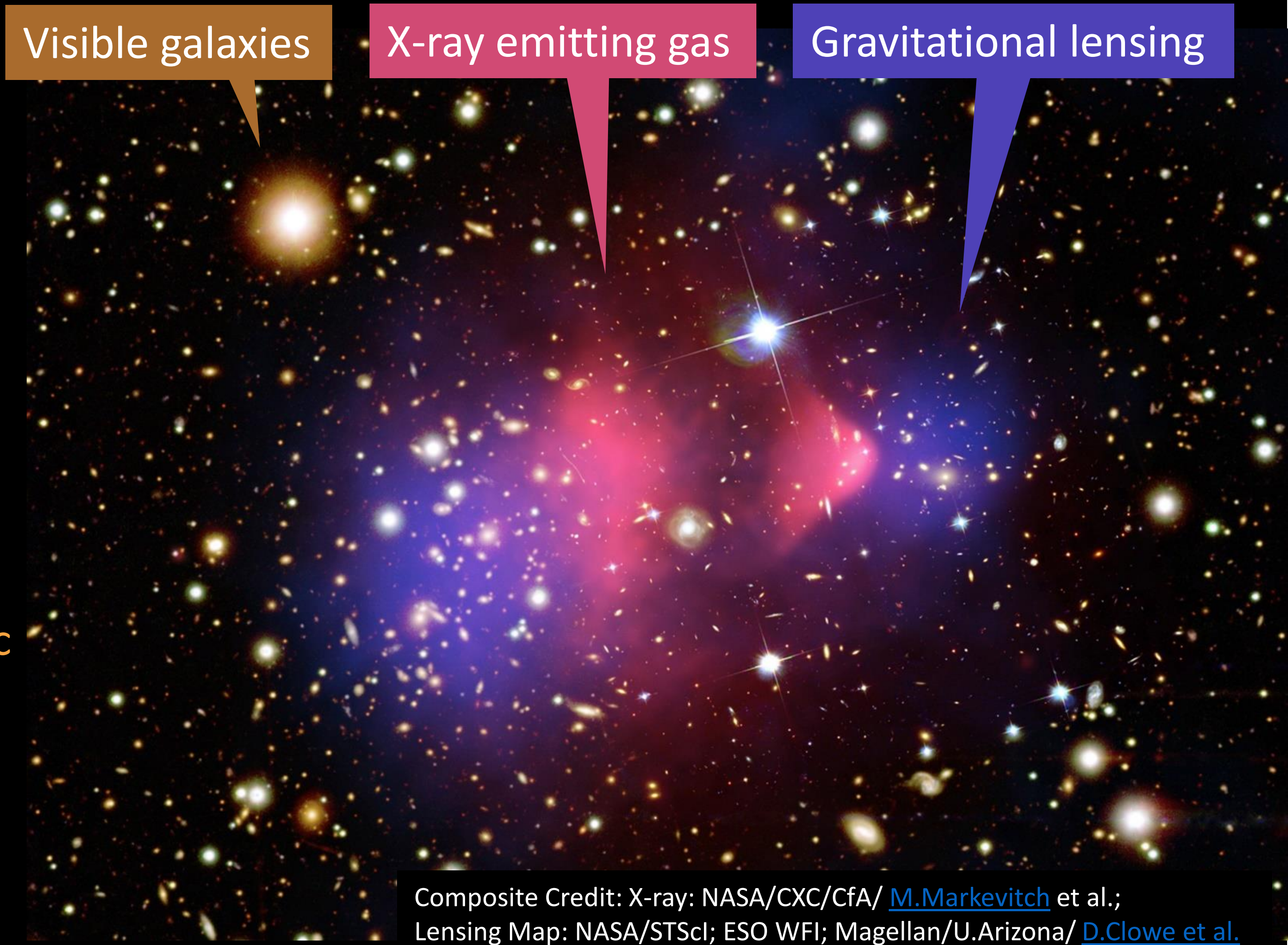
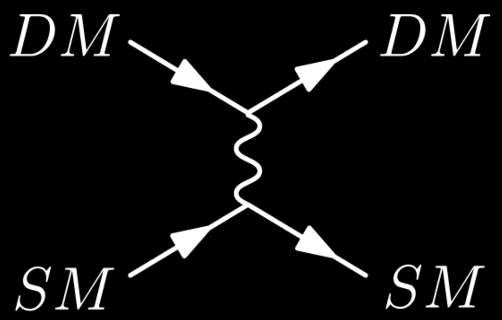
Evidence for Dark Matter

- Astrophysical and cosmological anomalies
  - Inconsistent with current understanding of gravitation & cosmology
  - Bullet cluster
- Dark matter (DM)
  - Nonluminous, noninteracting particle
  - Universe is 5% ordinary matter and 26% dark matter [arXiv:1502.01582]
- Many DM theories
  - Black holes, axions, unknown particles, etc
- Weakly Interacting Massive Particles
  - Assume that DM couples weakly to the Standard Model (SM)
  - Produced in early universe
  - Thermal relic density

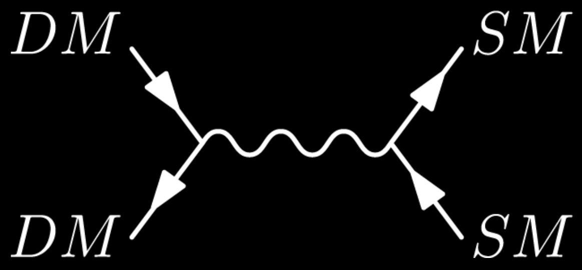


Composite Credit: X-ray: NASA/CXC/CfA/ M.Markevitch et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al. Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

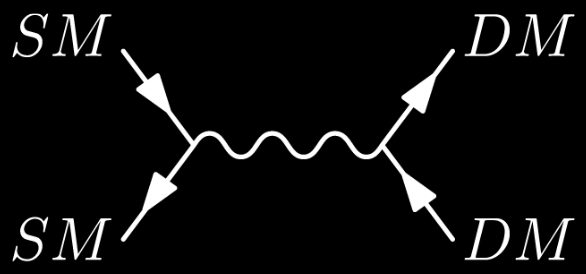
Detecting Dark Matter



Direct Detection
DM-nucleon scattering

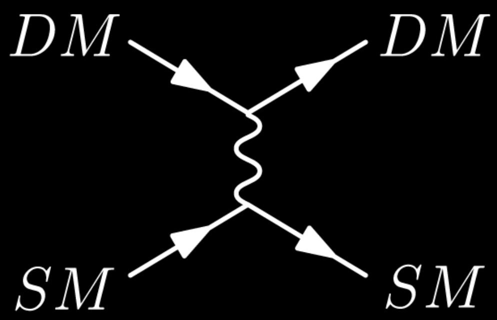


Indirect Detection
DM-DM annihilation



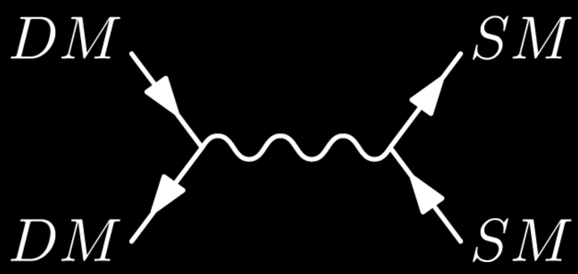
Production at Colliders

Detecting Dark Matter



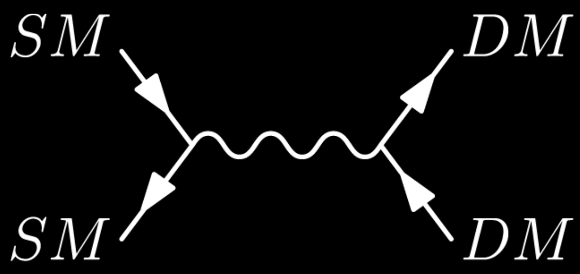
Direct Detection

DM-nucleon scattering



Indirect Detection

DM-DM annihilation

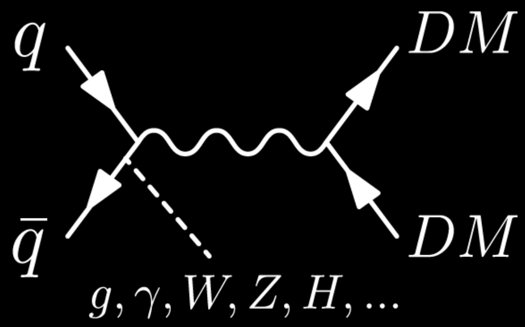


Production at Colliders

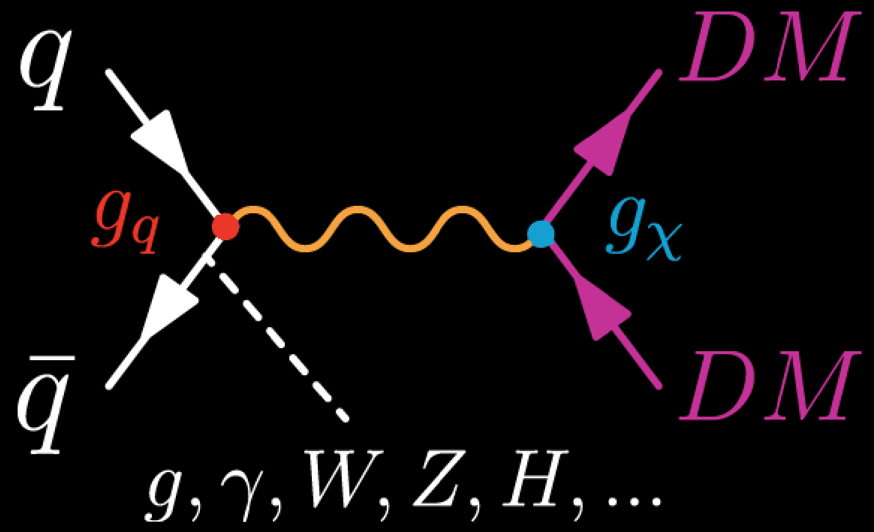
Mono-X Signature

DM pair production in association with **X** (jet, photon, etc)

➡ Need X for event to be visible in detector



Simplified Models

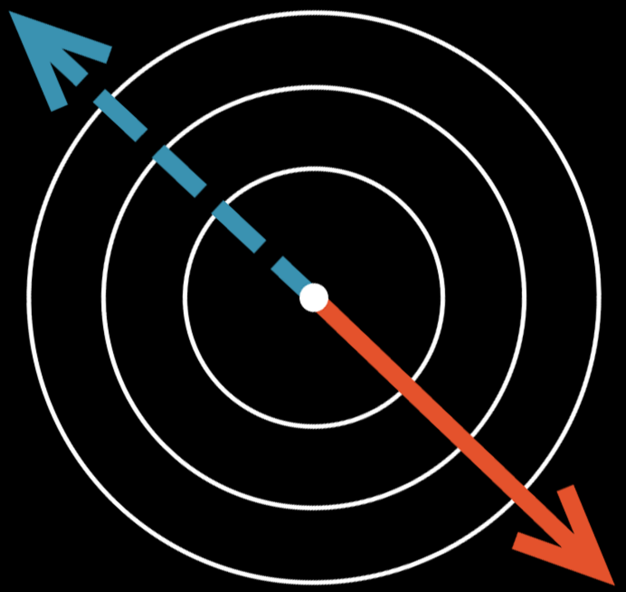


- Mono-X search results interpreted in simplified model framework
  - General framework valid at high Q^2 (unlike EFT)
- Mediator particle connects the SM quarks to DM particles
  - Axial Vector, Pseudoscalar, etc
- Model depends on four parameters:
  - DM mass
  - Mediator mass
  - SM-mediator coupling
  - DM-mediator coupling

[ArXiv:1506.03116 - Simplified Models for DM Searches at the LHC]

Mono-X Searches

Non-interacting DM particles
➥Missing transverse energy (MET)



X (jet, photon, etc)

General Analysis Strategy

- Require MET
- Select for X
- Veto other objects
- Additional cuts to suppress backgrounds
- Data-driven techniques to estimate background
  ➥ Invert vetoes

Mono-X Searches

ATLAS 13 TeV Mono-X Searches

Mono-jet
- ➥Jet from initial state radiation (ISR)
- ➥Most sensitive mono-X channel

Mono-photon
- ➥ ISR photon
- ➥ Probe DM coupling to photons

[arXiv:1604.01306]

Mono-W/Z
- ➥ ISR Boson
- ➥ Probe DM coupling to Z

[ATLAS-CONF-2015-080]

Mono-Higgs
- ➥ DM coupling to Higgs

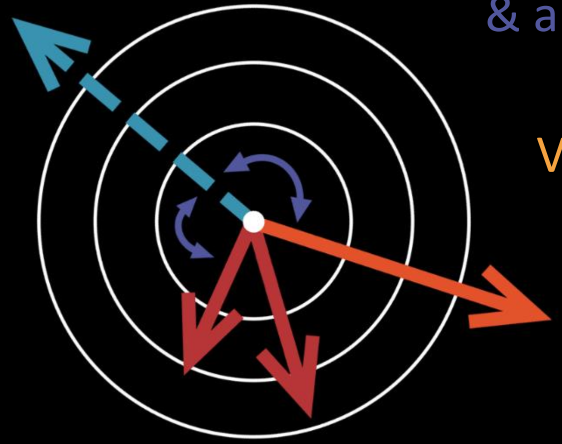
[H→γγ: ATLAS-CONF-2016-011]
[H→bb: ATLAS-CONF-2016-019]
[H→ZZ: ATLAS-CONF-2015-059]

Mono-Jet

Signal Region Definition

MET > 250 GeV

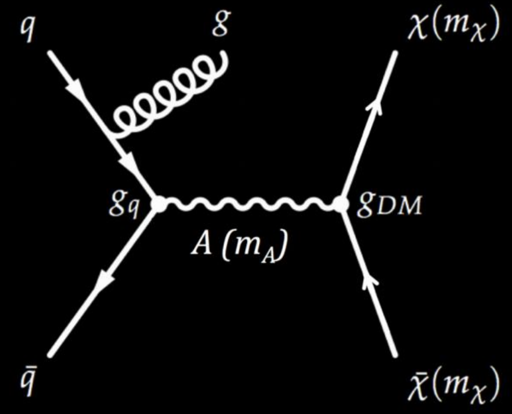
Δϕ between MET & any jet > 0.4



Veto e & μ

Jet pT > 250 GeV
|eta| < 2.4
Additional quality requirements

Up to 3 other jets
With p_T > 30 GeV



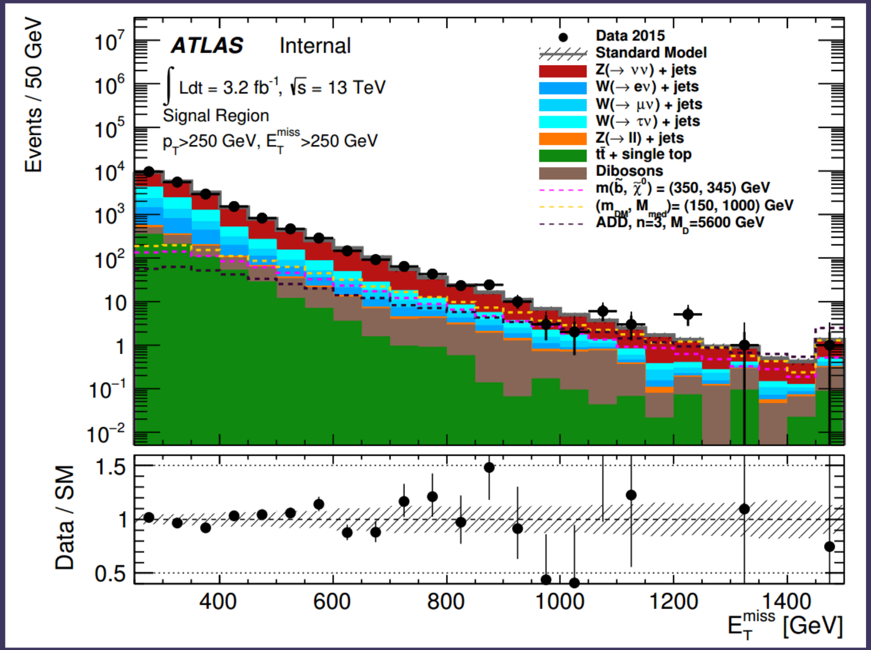
Most sensitive mono-X channel

➥ X (jet) has α_s coupling to initial state quarks

Mono-Jet

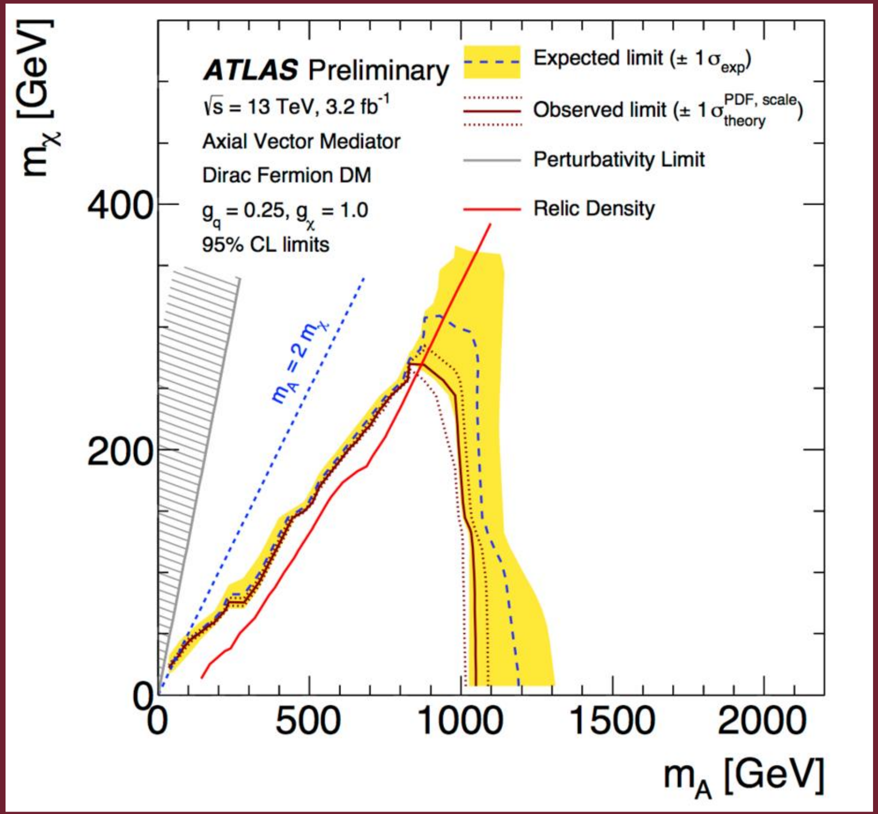
- W+jets & Z+jets background estimated with simultaneous fit in signal and control regions
  - Three control regions (with 1μ, 1e, or 2μ)
  - Muons treated as invisible in MET calculation
    - MET ~ Boson p_T in muon control regions
  - Fit for three *MET-dependent* normalization factors
    - MET-dependent: reduce sensitivity to boson p_T modeling
    - Use **W → μ ν** to model **Z → ν ν**
      - Systematic uncertainty for W/Z transfer
- Other backgrounds
  - Non-collision background (data)
  - Multijet background (data)
  - Z→ee, top, diboson (MC)
- Dominant uncertainties
  - statistical (3-10%), top (~3%), boson+jet modeling (2-4%)

Signal Region MET



➥ No excess observed

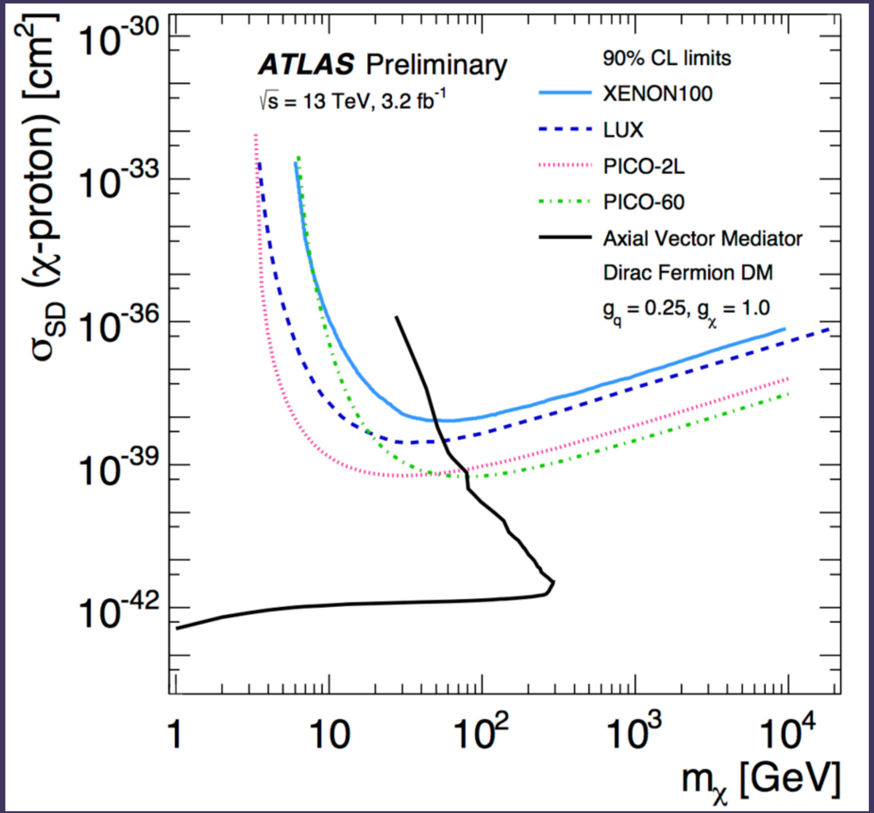
Mono-Jet



Limits as a function of DM & mediator mass

➥ Axial vector mediator, fixed values of g_{DM} & g_{SM}

DM excluded up to 250GeV for 1 TeV mediator

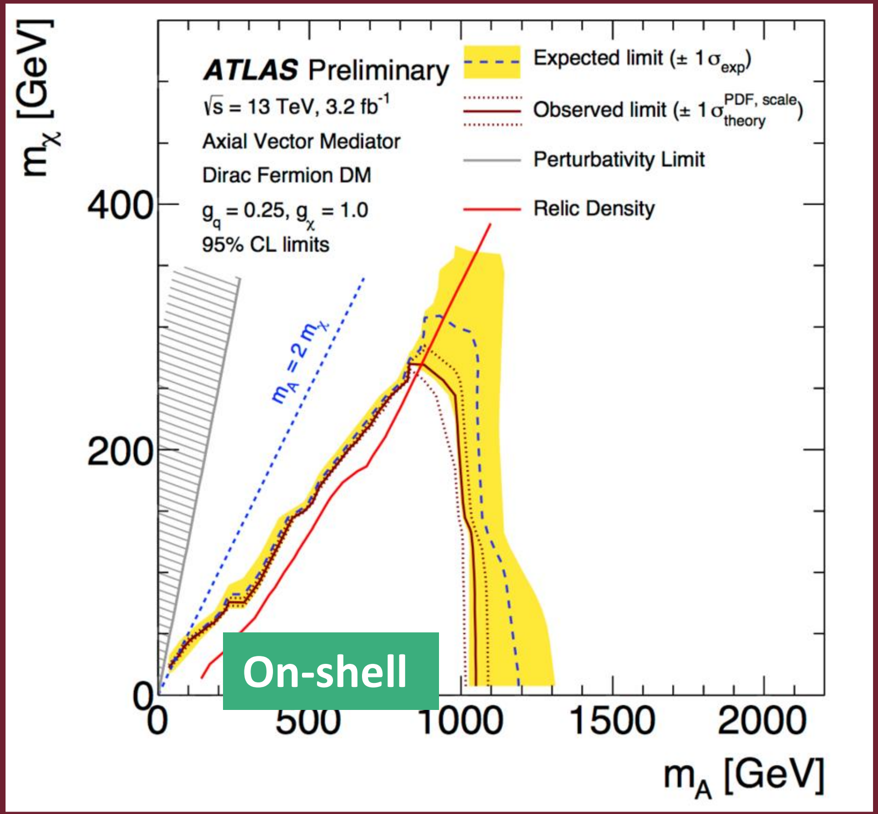


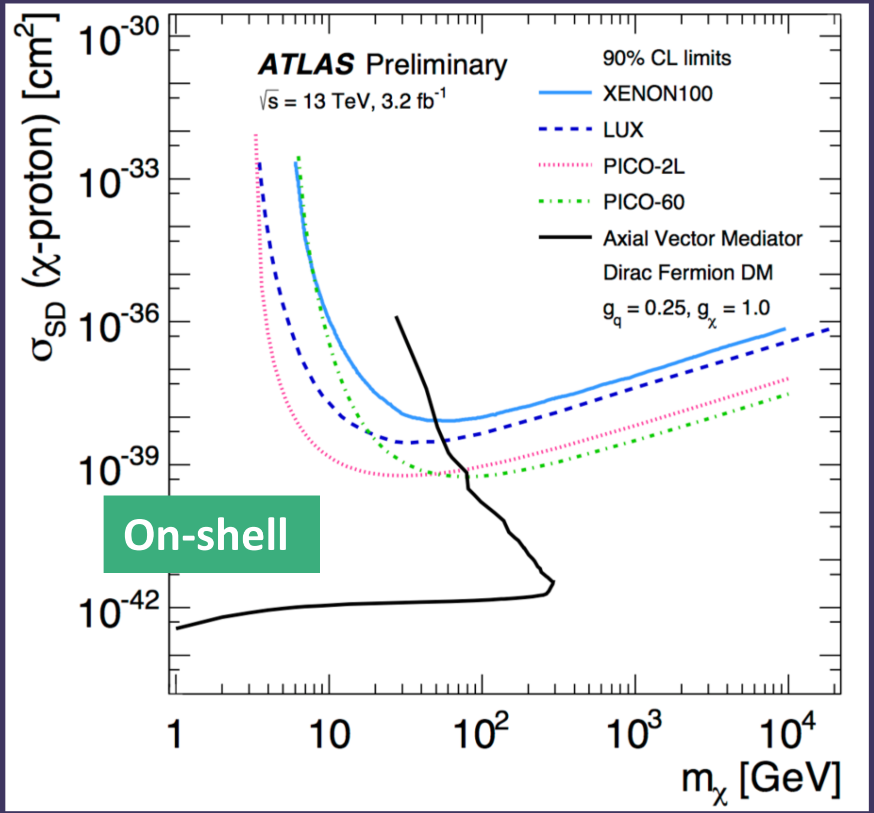
LHC limits reinterpreted as limit on DM-proton scattering cross-section

➥ LHC complementary at low m_{DM}

Parameter values & limit interpretation as recommended by the LHC Dark Matter Working Group [ArXiv:1603.04156]

Mono-Jet

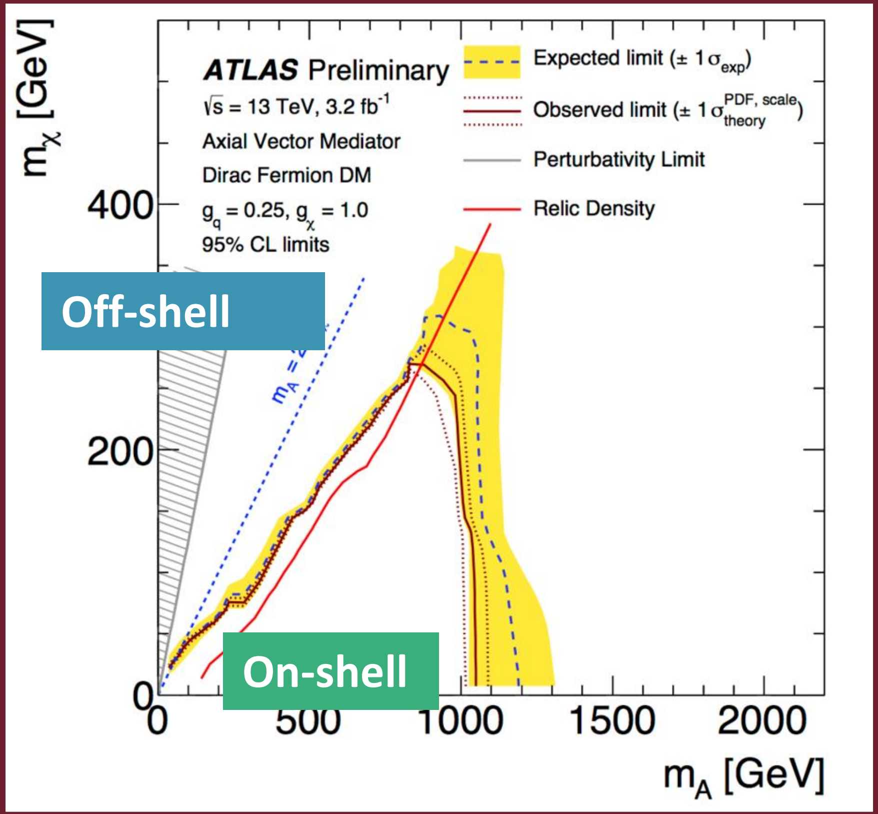


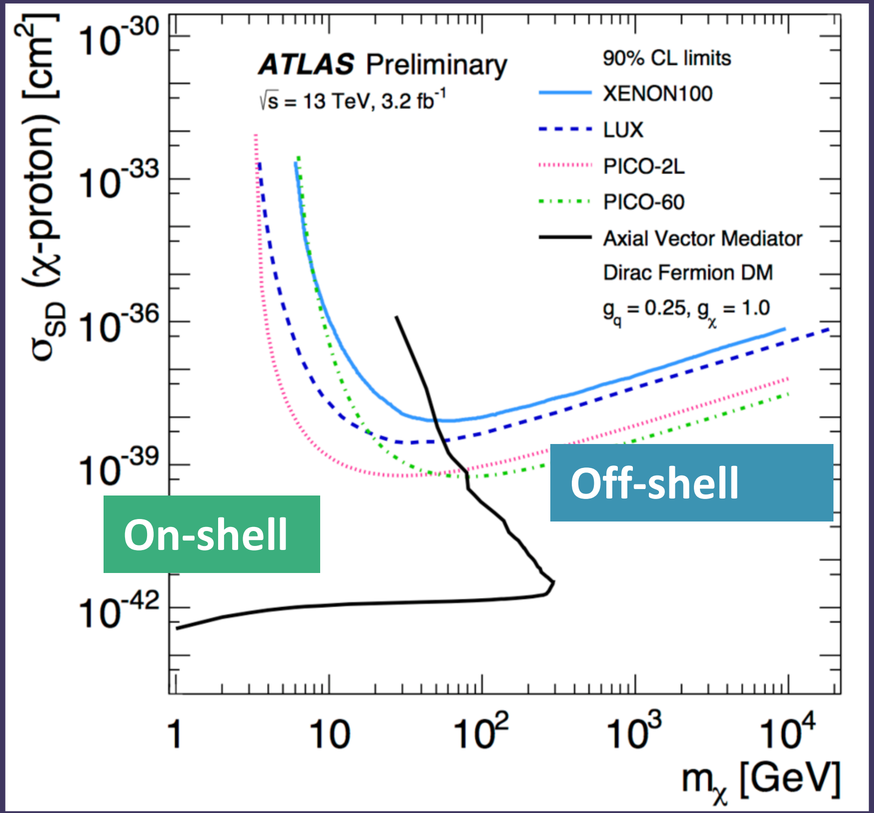


On-shell

➥ LHC exclusion

Mono-Jet





On-shell

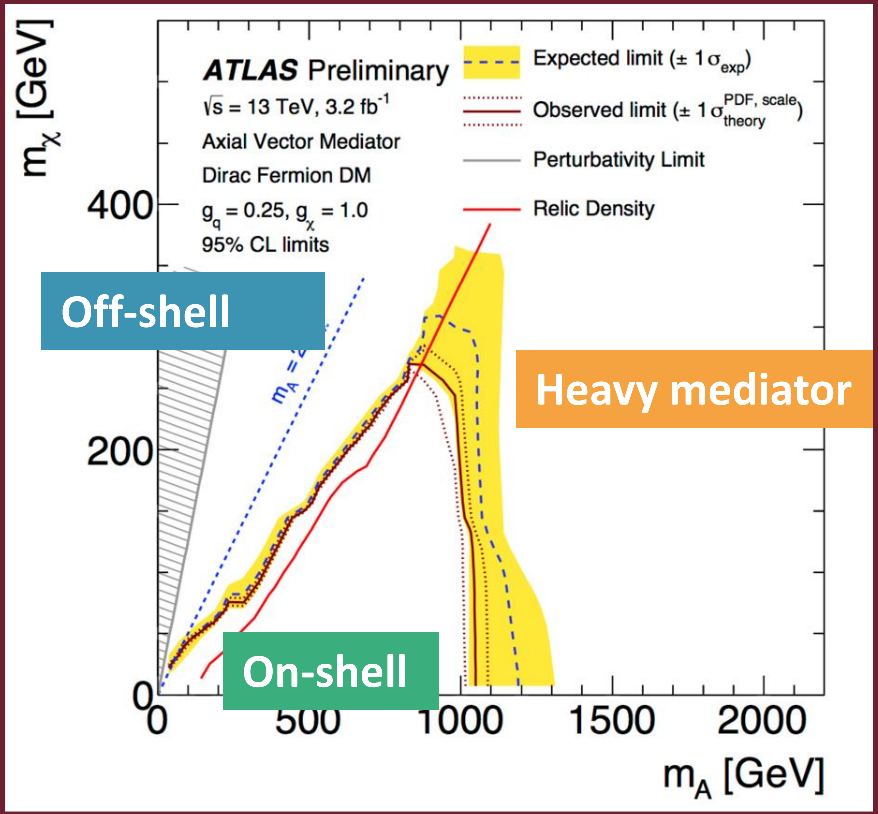
➥ LHC exclusion

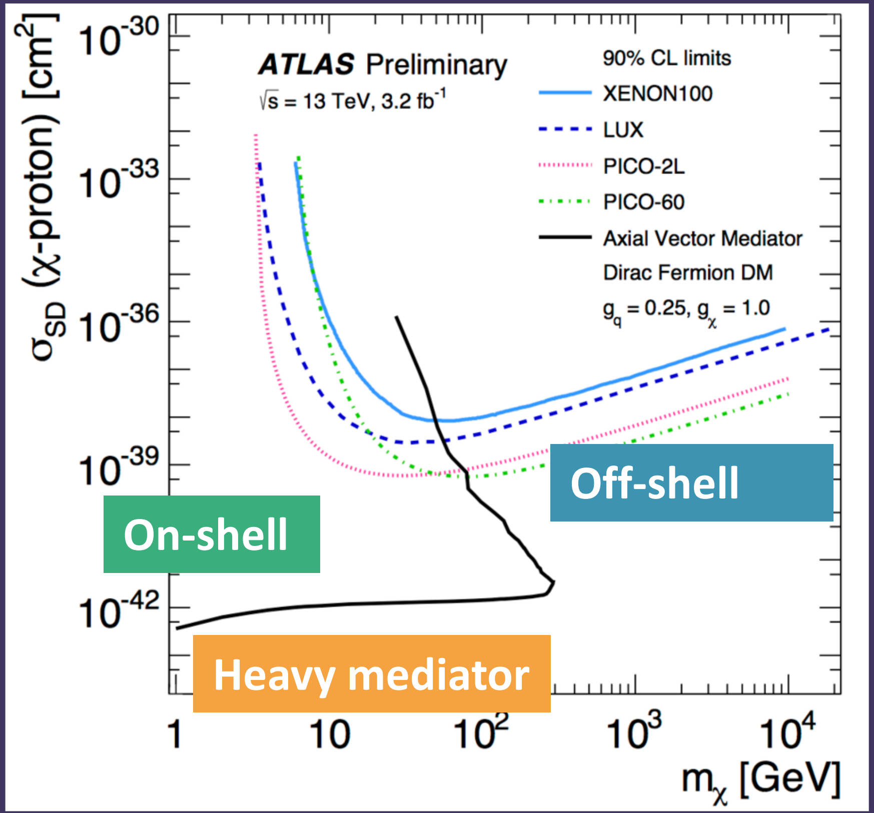
Off-shell

➥ Mediator decay to DM suppressed

➥ Relic DM underproduced

Mono-Jet





On-shell

➥ LHC exclusion

Off-shell

➥ Mediator decay to DM suppressed

➥ Relic DM underproduced

Heavy mediator

➥ Mediator production suppressed

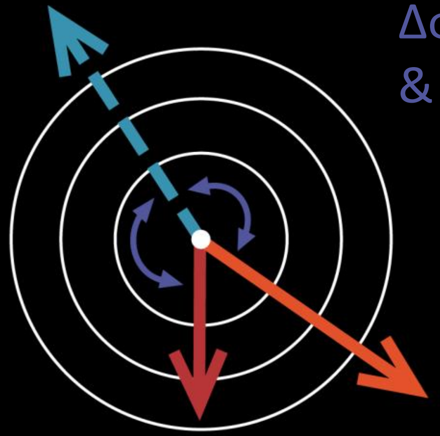
➥ Relic DM overproduced

Mono-Photon

Signal Region Definition

MET > 150 GeV

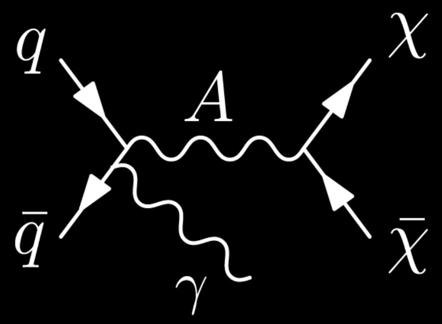
Δϕ between MET
& photon or any jet > 0.4



Veto e & μ

Photon pT > 150 GeV
|eta| < 2.37
Quality (tight) & isolation requirements

Up to 1 jet with pT > 30 GeV

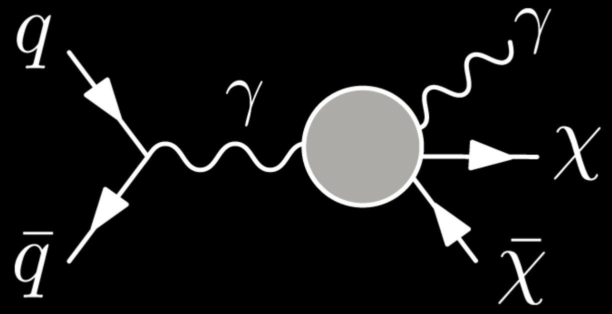


Lower statistics with respect to mono-jet

➡ X (photon) has α_{EM} coupling to initial state quarks

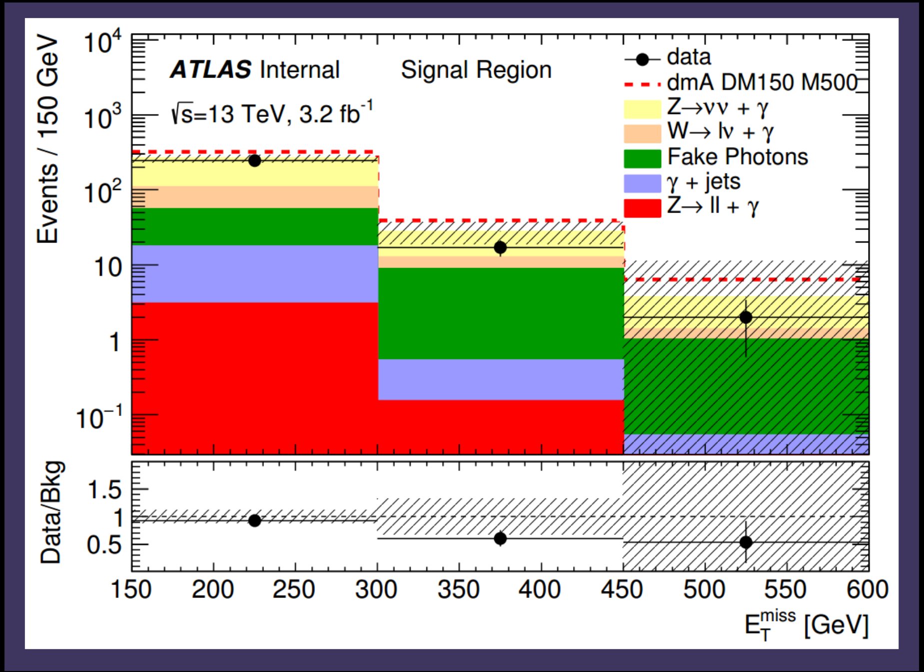
Sensitive to (γγ χ χ) effective vertex

➡ Galactic center excess



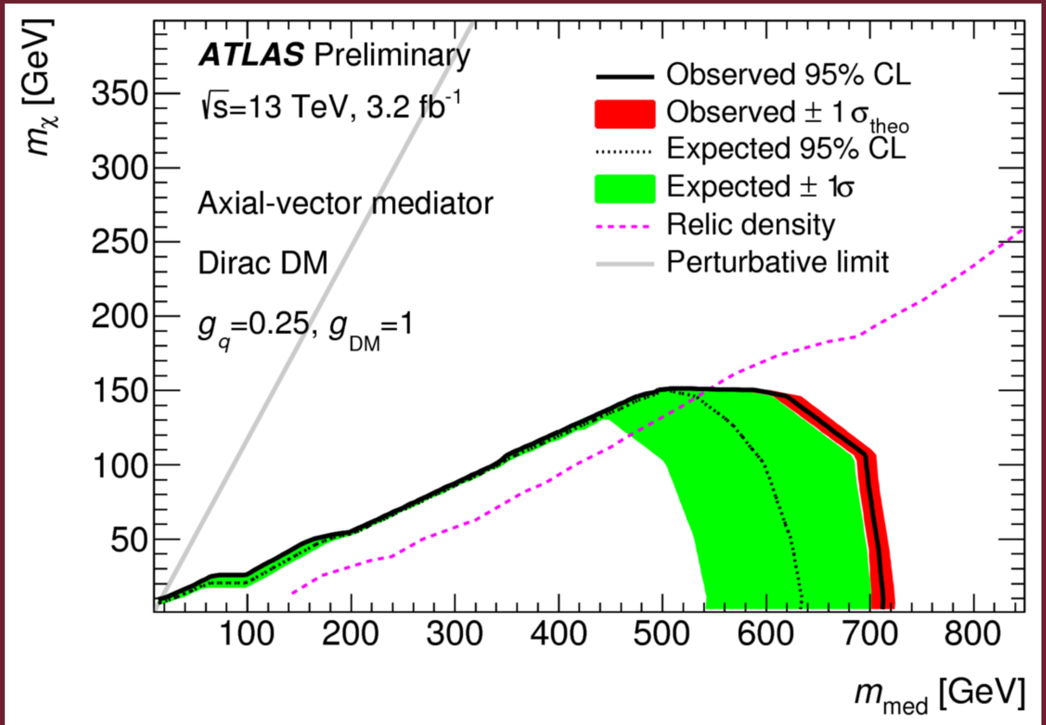
Mono-Photon

- Background estimated with simultaneous fit to four CRs
  - Z+γ ➞ 2e and 2μ CRs
  - W+γ ➞ 1μ CR
  - γ+jets ➞ γ+jet CR (85 < MET < 110 GeV, Δϕ(MET,γ)<3.0)
- Fake γ estimation
  - Electrons: derive e->γ misID factor in ee vs eγ events
  - Jets: ABCD method using photon quality & isolation
- Dominant Uncertainties
  - statistics (9%), e->γ fake factor (6%)



Inclusive regions => no shape analysis

Mono-Photon

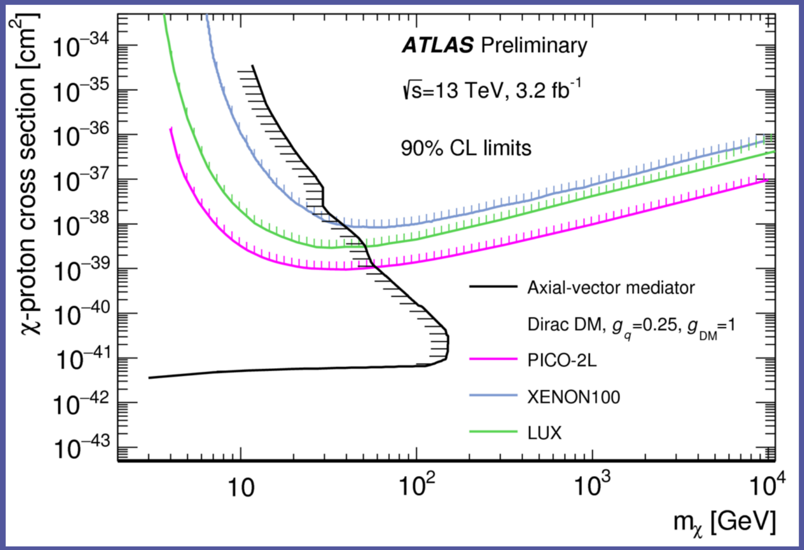


Limits as a function of DM & mediator mass

➡ Axial vector mediator, fixed coupling values

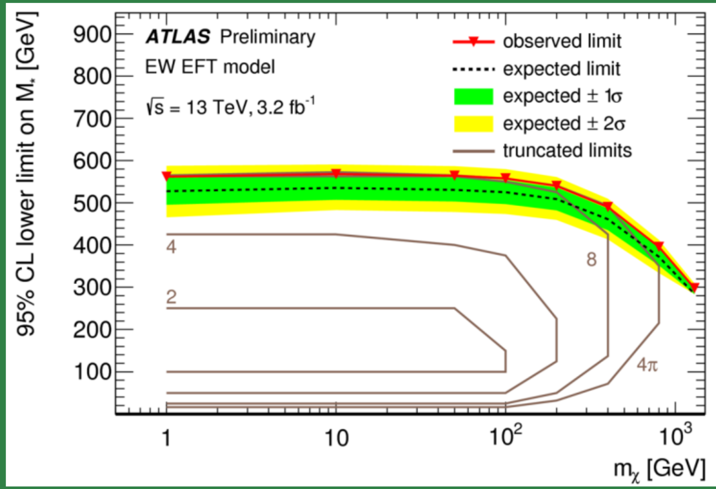
Excludes subset of mono-jet space

➡ DM excluded up to 150 GeV for 500 GeV Med.



Limit on scale of new physics M* as a function of DM mass

➡ DM mass excluded up to ~200 GeV for M* below 550 GeV



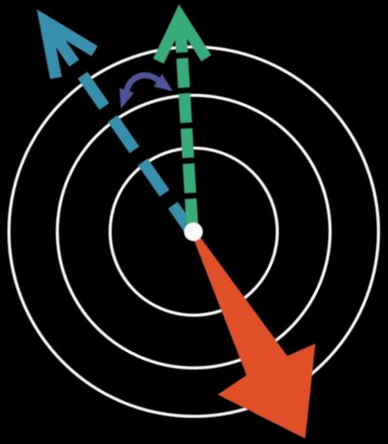
Mono-W/Z (hadronic)

Signal Region Definition

Track MET > 30 GeV

MET > 250 GeV

Δφ between MET
& track MET < pi/2



Veto e & μ

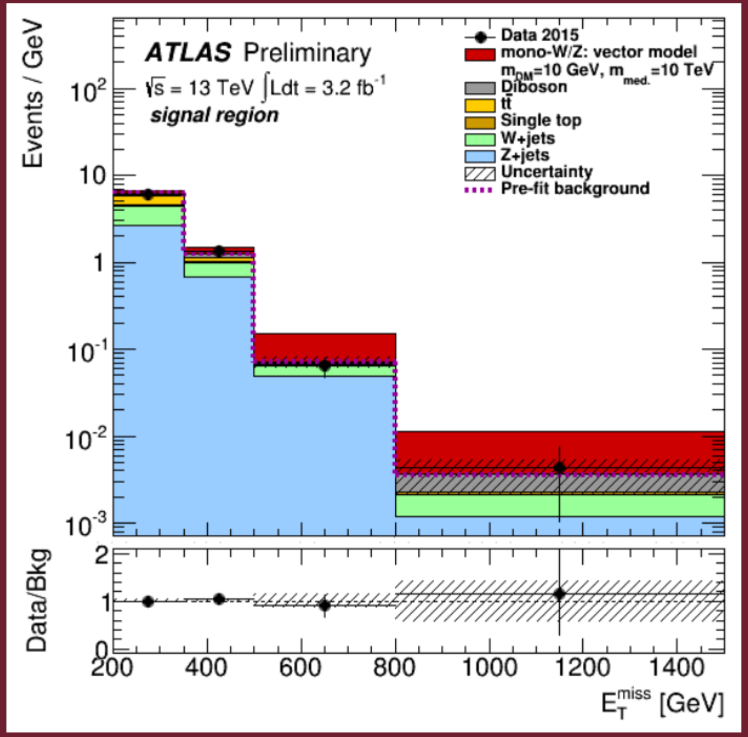
Large-radius jet
➥ Identify hadronic W/Z decay using jet mass & substructure (bifurcation variable D2)

Backgrounds constrained in dedicated CRs
➥ Z+jets (2muon)
➥ W+jets (1 muon & no b-jet)
➥ ttbar (1 muon & 1 b-jet)

Simultaneous fit with three normalization factors (Z, W, ttbar)

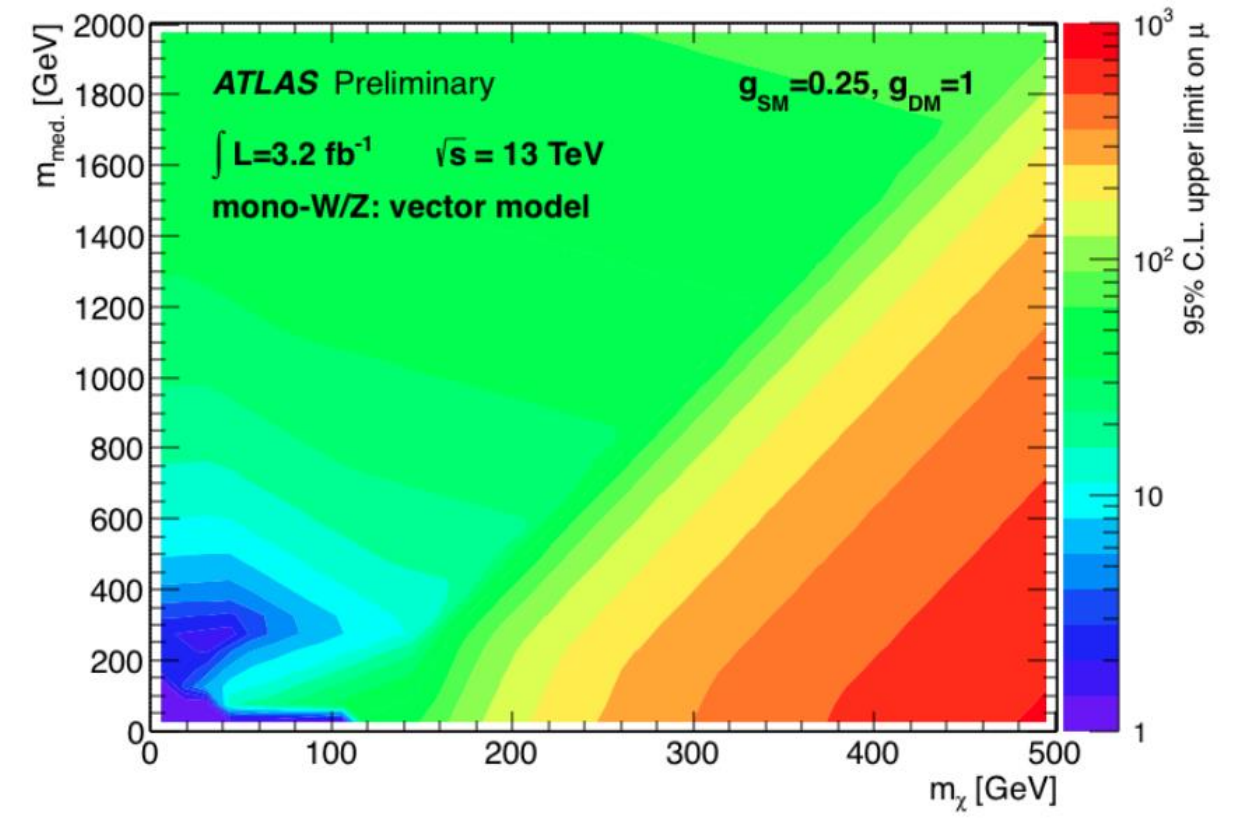
Largest uncertainty from modeling of large-radius jet parameters
➥ Uncertainties on D2 ~ 10%

Signal Region MET



➥ No excess observed

Mono-W/Z (hadronic)

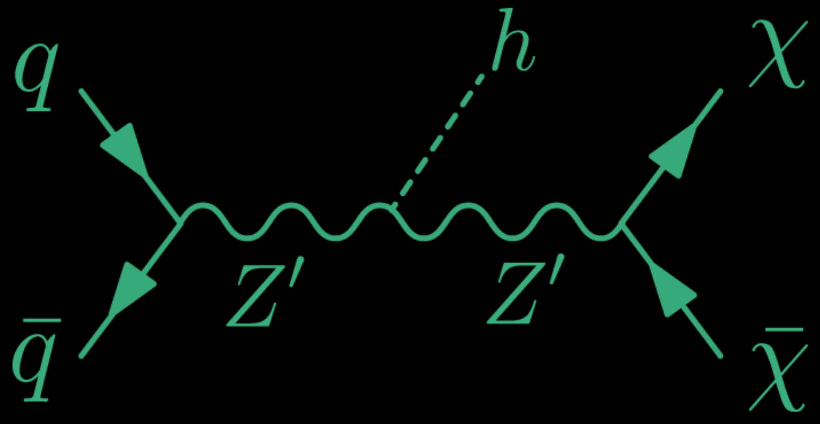


Signal strength limits as a function of DM & mediator mass

➥ Vector mediator, fixed values of g_{DM} & g_{SM}

Mono-H

Consider models in which Higgs couples to dark sector particles

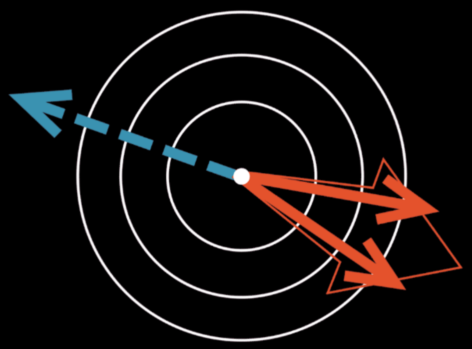


Higgs coupling to mediator

Multiple Mono-H final states

H→γγ H→bb H→ZZ→4ℓ

Mono-H(→γγ)



At least 2 γ
105 GeV < $m_{\gamma\gamma}$ < 160 GeV
Tight, isolated, &
other quality requirements

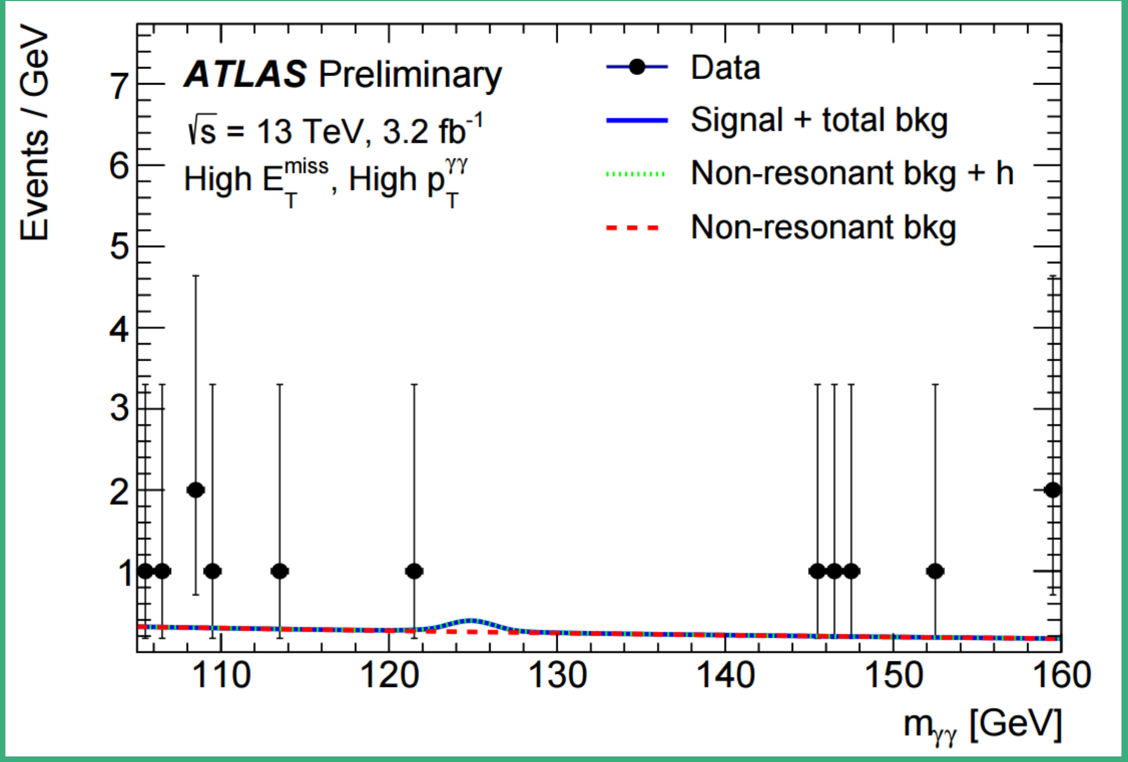
Four Signal Regions

1 - MET > 100 GeV & $p_T^{\gamma\gamma}$ > 100 GeV

2 - MET > 100 GeV & $p_T^{\gamma\gamma}$ < 100 GeV

3 - 50 < MET < 100 GeV & $p_T^{\text{all jets}+\gamma}$ > 40 GeV

4 - $p_T^{\gamma\gamma}$> 15 GeV

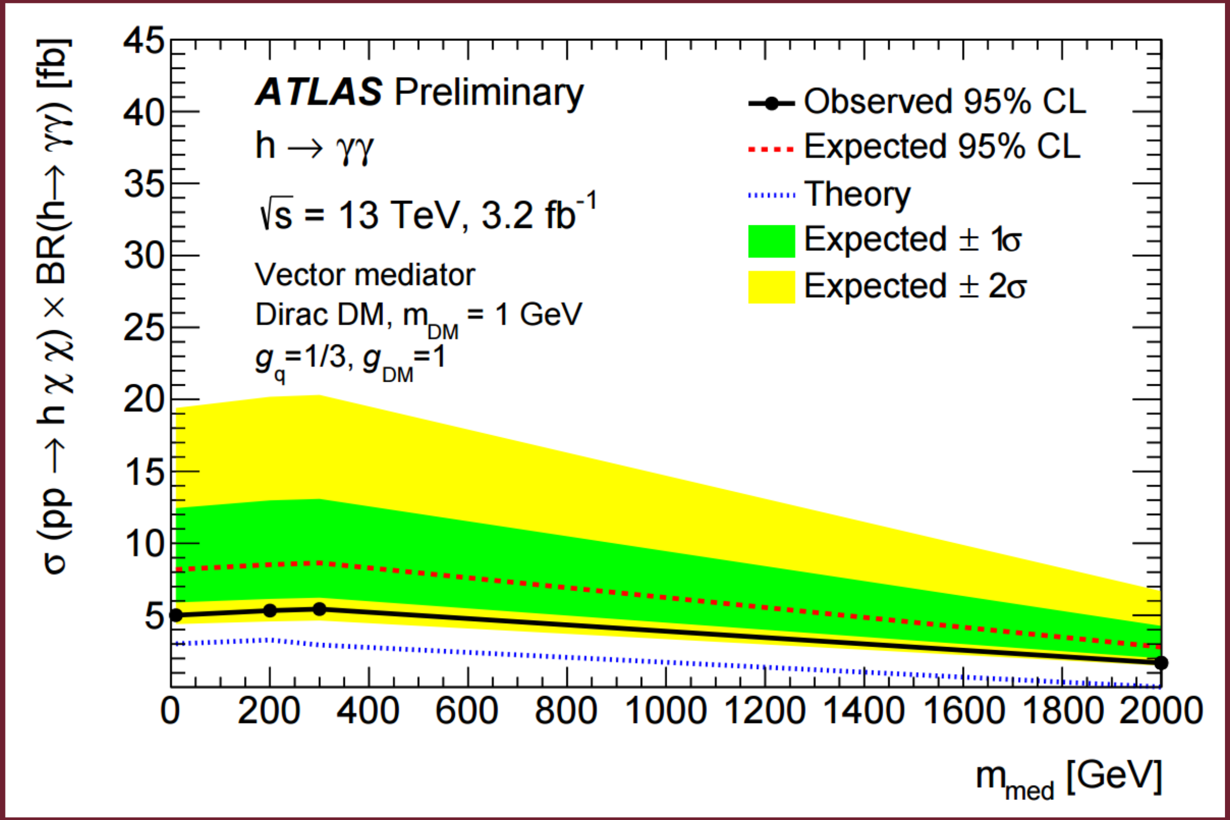


Background estimated with function fit to $m_{\gamma\gamma}$ distribution

➡ Main uncertainties from gg->H (50%)

➡ No excess observed

Mono-H(→γγ)

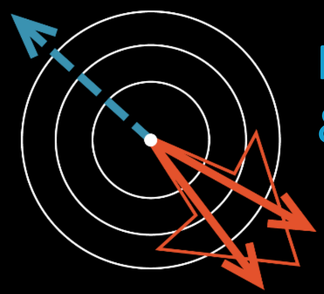


Cross section limits as a function mediator mass for m_{DM} = 1 GeV

➥ Vector mediator, fixed values of g_{DM} & g_{SM}

Mono-H(→bb)

Resolved Signal Region



MET > 150 GeV
& MET < 500 GeV

At least 2 jets

Merged Signal Region

MET > 500 GeV

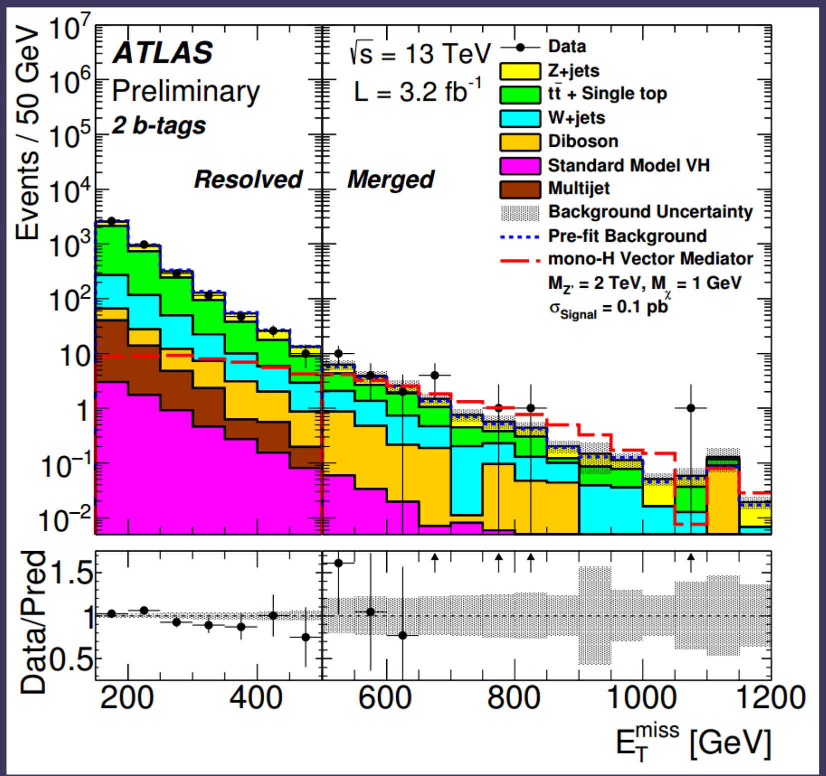
One large-radius jet associated with two track jets

Background estimated with simultaneous shape fit to jet mass distribution

- 1 muon (invisible in MET) control region constrains W+jets & ttbar
- 2 lepton control region constrains Z+jets
- Signal & control regions further divided into 0-, 1-, and 2-b-tag regions

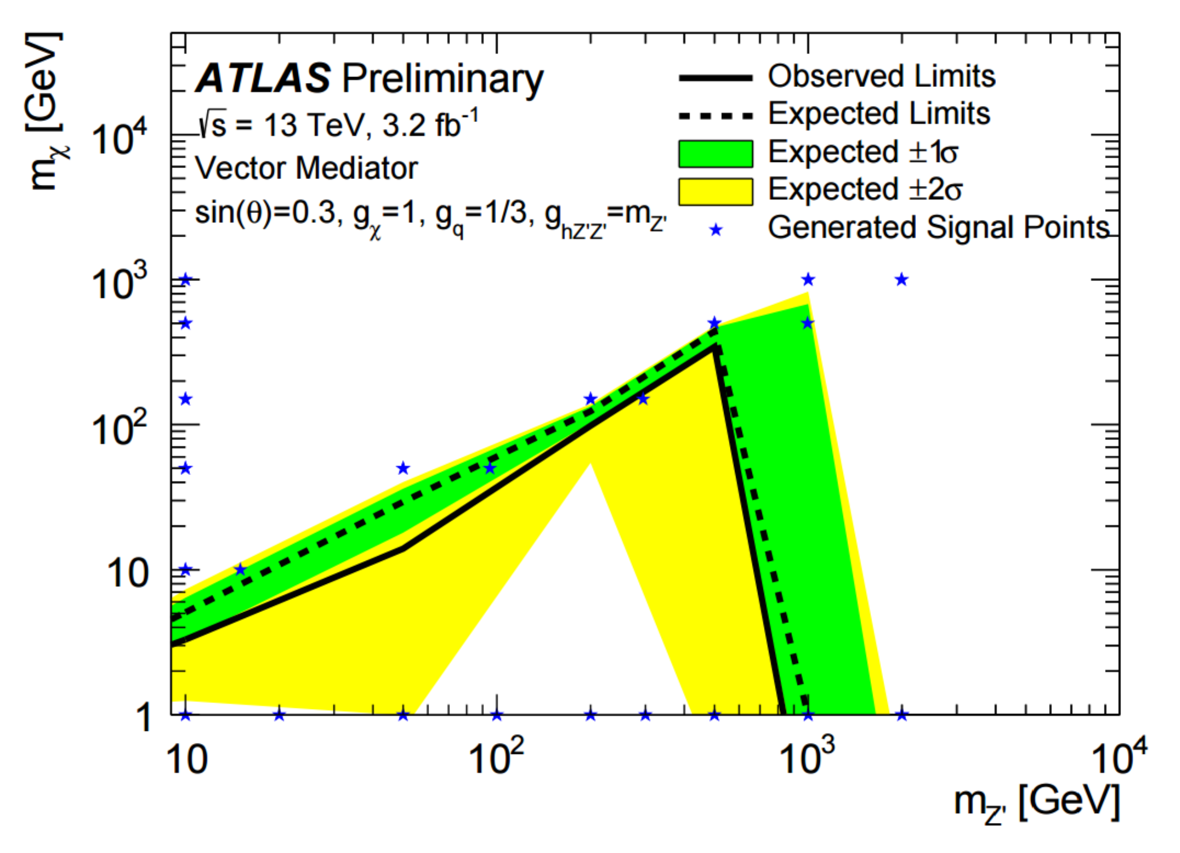
Tagging b-jets: 70% identification efficiency

Signal Region MET (2 b-tags)



Main systematic uncertainties from b-tagging efficiency (~5%) & jet mass/energy calibration (~5%)

Mono-H(→bb)

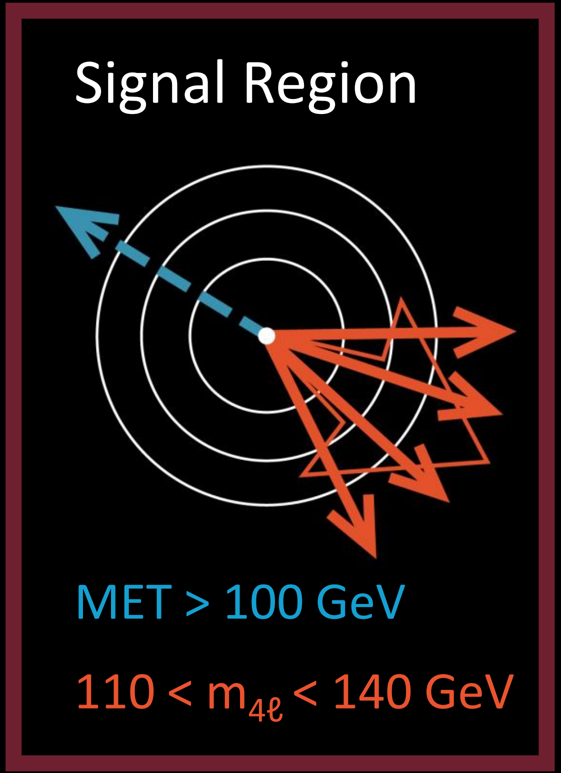


Limits as a function of DM & mediator mass

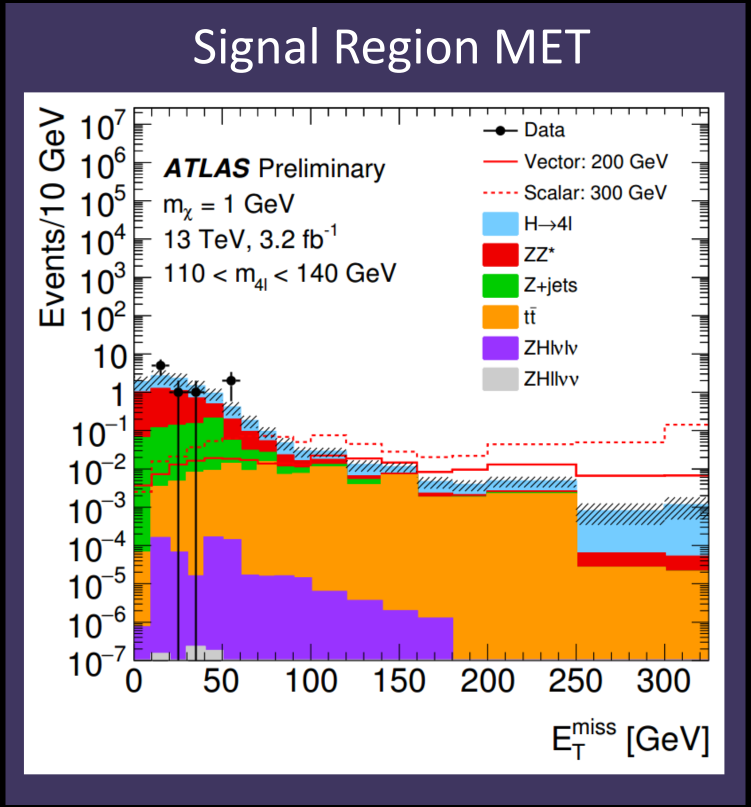
➥ Vector mediator, fixed values of g_{DM} & g_{SM}

DM excluded up to 200 GeV for 500 GeV mediator

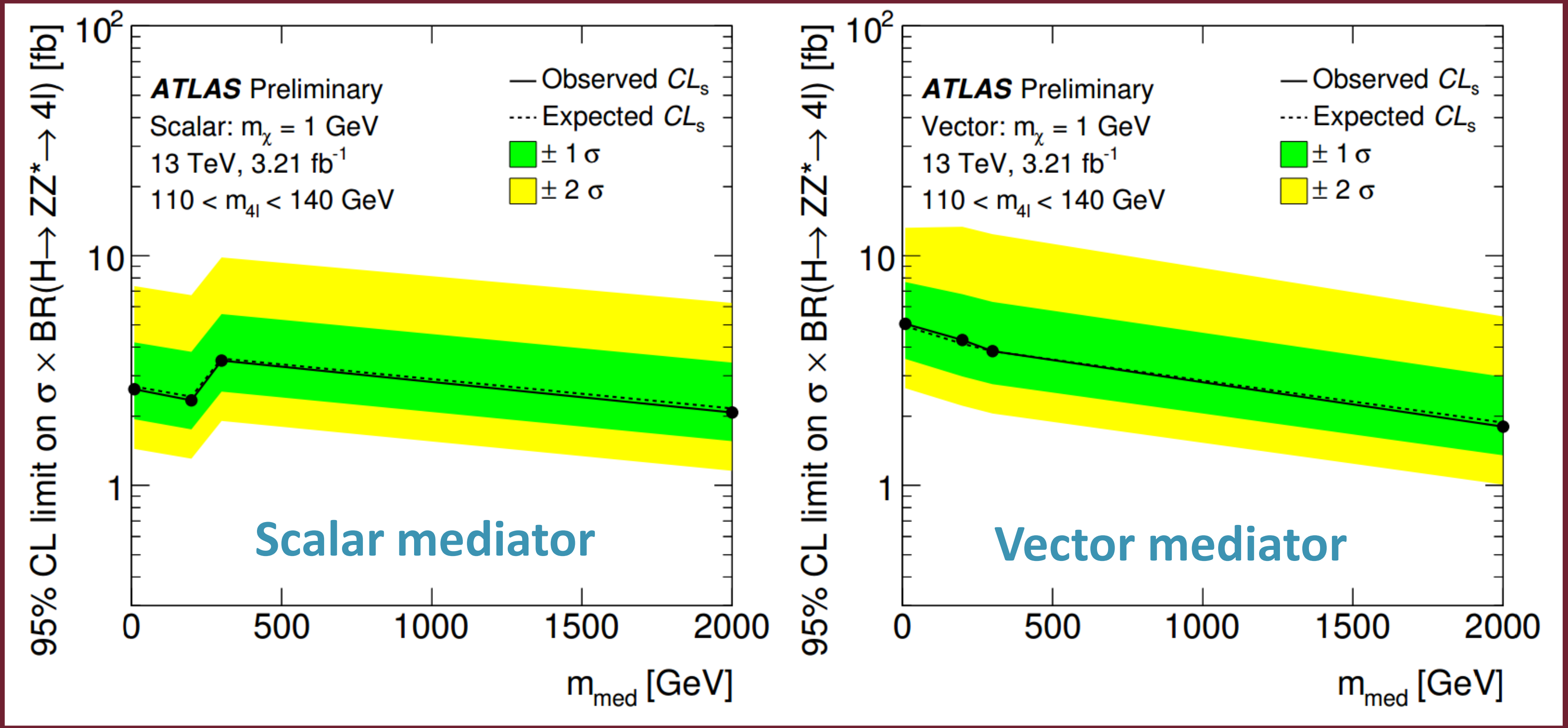
Mono-H(→ZZ)



- Higgs and ZZ* background from simulation
- Z+jets and ttbar estimated with simultaneous fit in dedicated control regions
    - ℓℓ + μμ CRs: invert lepton impact parameters, flavor pairs, isolation to enrich in backgrounds
- Main uncertainty from jet energy scale (~ 50%)

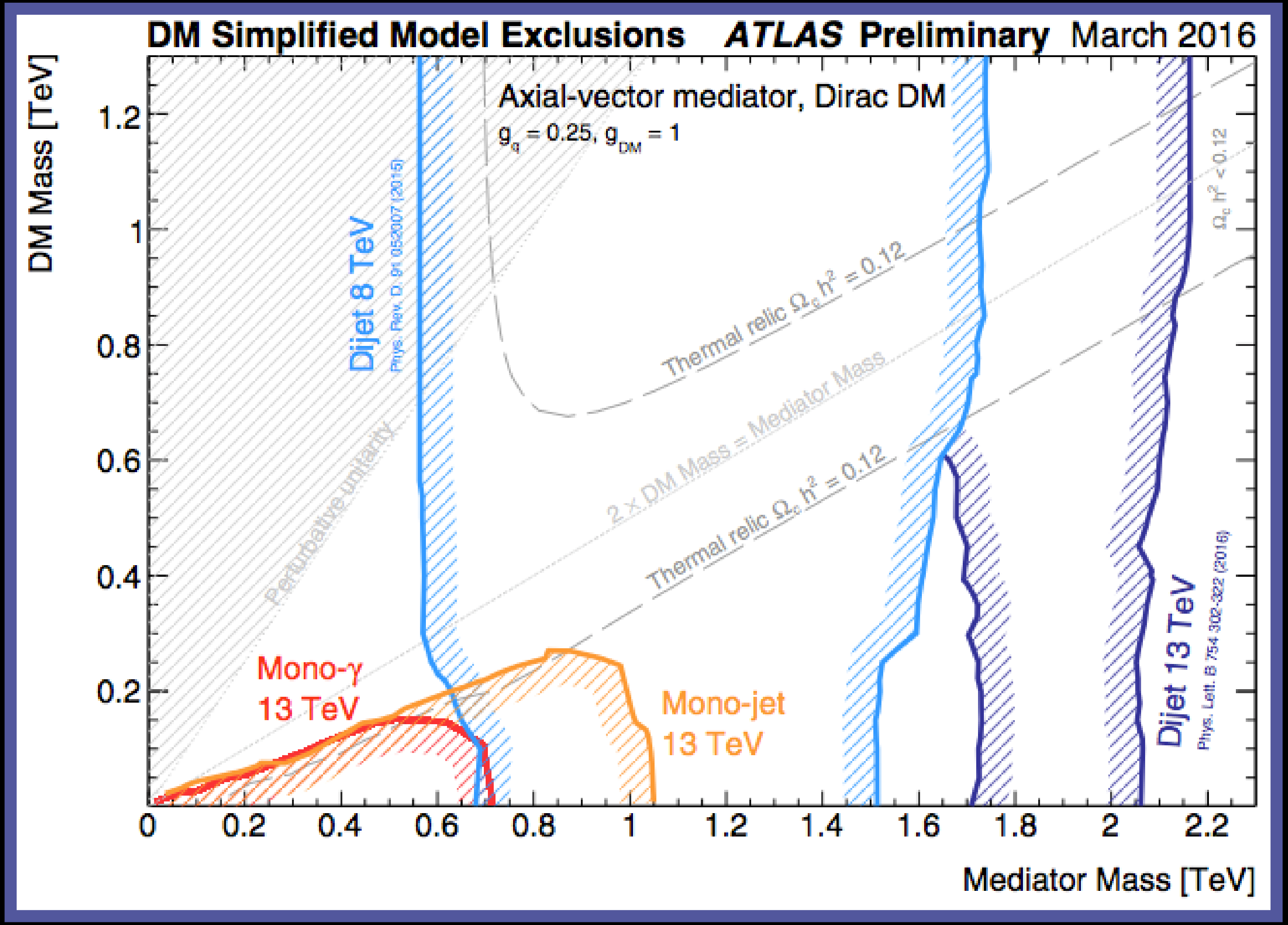


Mono-H(→ZZ)



Cross section limits as a function mediator mass for m_{DM} = 1 GeV

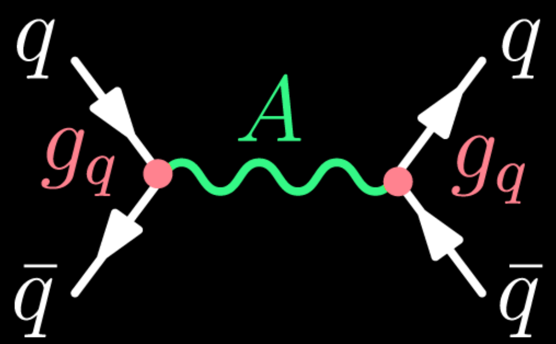
Mono-X & Dijet



[reference to be added]

Dijet limits can also constrain DM simplified models

➥putting limits on mediator mass



Exclusion power depends on the model couplings:

➥Monojet xsec ~ $g_q^2 g_x^2$

➥Dijet xsec ~ g_q^4

Conclusions

- DM searches at 13TeV are just starting!
  - ➥ First mono-X search results
- Simplified models provide common interpretation framework that allows ATLAS results to be compared with:
  - ➥ Dijet resonance searches
  - ➥ Direct & indirect detection experiments
  - ➥ Relic density
- Expecting 10-30 fb^{-1} of data in 2016
  - ➥ Increase discovery potential and exclusion power of DM searches

Backup

EFT vs Simplified Models

Effective field theories used at 8TeV

- ➥ Most general model possible
- ➥ Only parameters are m_{DM} and Λ

However, EFT is only valid if $Q^2 < 4\pi\Lambda$

- ➥ At the LHC Q^2 ~ jet p_T ~ 200 GeV
- ➥ Can truncate when $Q^2 > \Lambda$ but requires knowing masses, couplings, etc

Simplified models

- ➥ More parameters
- ➥ Valid in all regions of phase space

Narrow Width Mediator

Mediator in simplified model assumed to have minimal width

➥ only couples to quarks & DM (except in mono-H models)

As such, width depends on mediator mass, DM mass, and coupling values

Mono-Jet Bkg Estimation

Total bkg = $\left(Z \rightarrow \nu\nu \;\; W \rightarrow \mu\nu \right) \times k_{1\mu} + \left(W \rightarrow e\nu \;\; W \rightarrow \tau\nu \;\; Z \rightarrow \tau\tau \right) \times k_{1e} + \left(Z \rightarrow \mu\mu \right) \times k_{2\mu}$ + other backgrounds

- Non-collision background (data)
- Multijet background (data)
- Zee, top, VV (MC)

MC yields

Normalization factors from fit

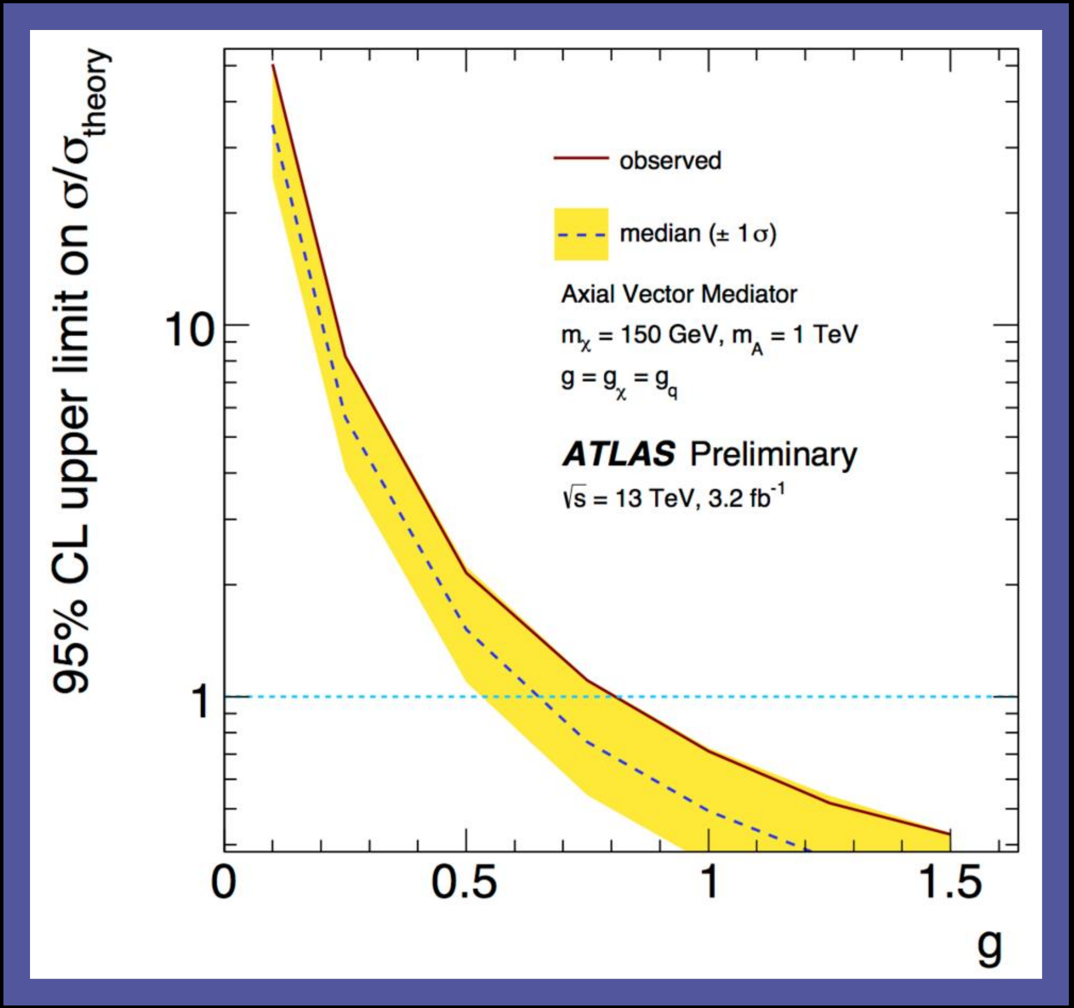
Mono-Photon Bkg Estimation

$$\text{Total bkg} = \frac{Z \rightarrow \nu\nu}{Z \rightarrow \ell\ell} \times k_{Z\gamma} + W \rightarrow \ell\nu \times k_{W\gamma} + \gamma + \text{jets} \times k_{\gamma+j} + \text{Fake } \gamma$$

➥ estimated from data

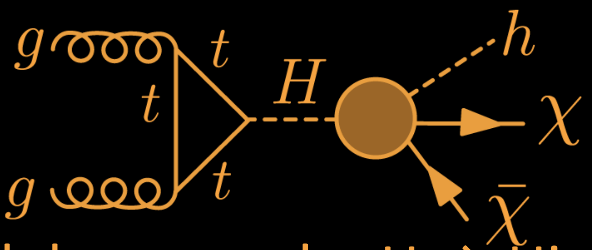
Mono-Jet Limits

Mono-jet limits with fixed mediator & DM mass and variable coupling

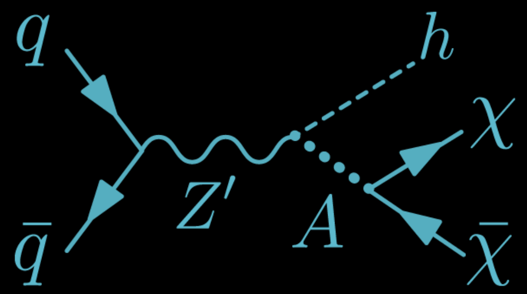


Mono-H Models

Other models:



EFT with heavy scalar H → Higgs + DM



DM & additional Higgs doublet