Dark Matter Searches with the ATLAS detector

Alison Elliot
University of Victoria

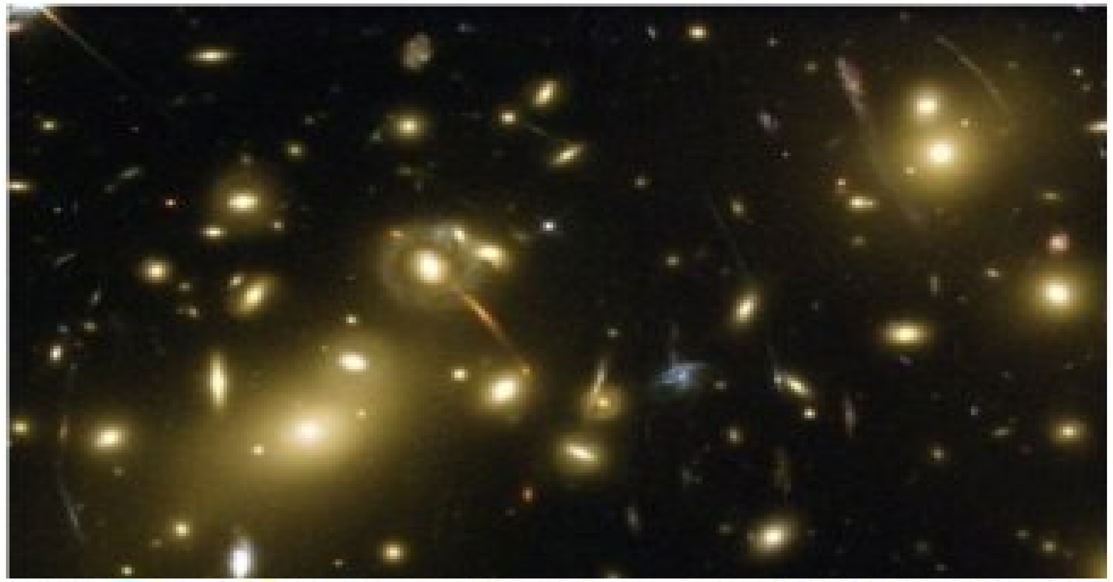
On behalf of the ATLAS Collaboration

The presence of a non-baryonic dark matter component in the Universe is inferred from the observation of its gravitational interaction. If dark matter interacts weakly with the Standard Model it would be produced at the LHC, escaping the detector and leaving a large missing transverse momentum as their signature. The ATLAS detector has developed a broad and systematic search program for dark matter production in LHC collisions. The results of these searches on the first 13 TeV data, their interpretation, and the design and possible evolution of the search program will be presented.

Big picture motivation

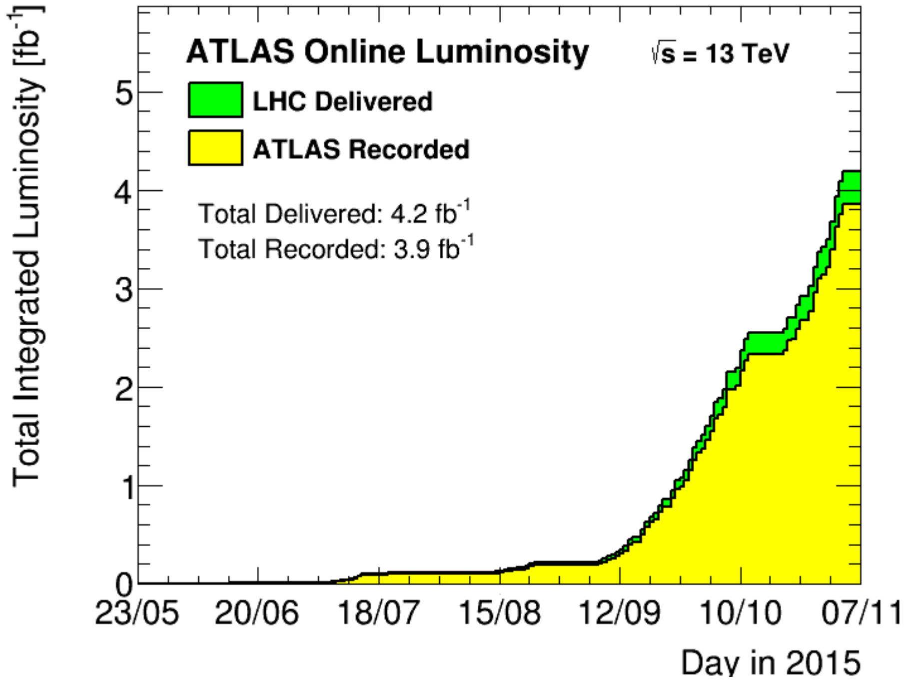
- Dark Matter: Unsolved problem
    - No Standard Model theory can explain it
    - Something beyond this theory clearly exists
- Astrophysical indicators
    - Cosmic Microwave Background
    - Gravitational lensing
    - Galaxy and galaxy cluster motion
- How do we detect it?

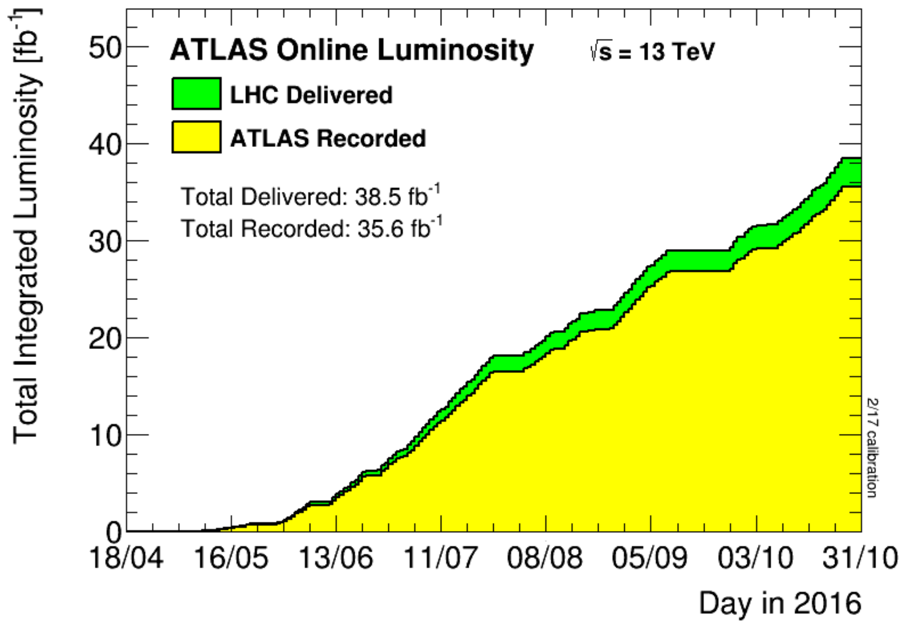
  Assume it interacts weakly with the SM
    - Emission from galactic sources
    - Direct nuclear recoil underground
    - **Particle production in colliders**



Datasets used in various analyses

- Total 2015 'good for physics' data: 3.2 fb^{-1}
- Total 2016 'good for physics' data: 32.9 fb^{-1}
- Three datasets used:
    - 2015 only (3.2 fb^{-1})
    - 2015 + partial 2016 (13.3 fb^{-1})
    - 2015 + full 2016 (36.1 fb^{-1})





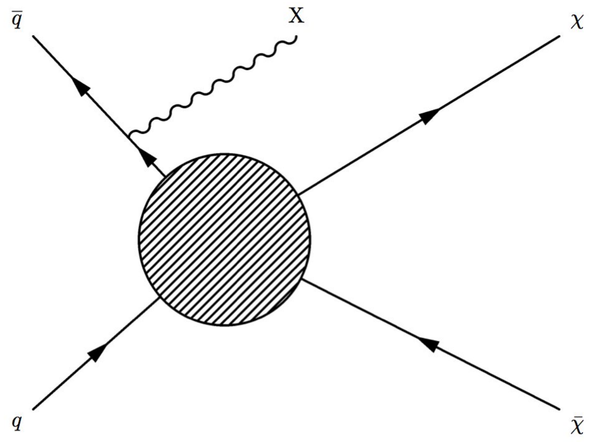
Dark Matter searches in ATLAS at 13 TeV

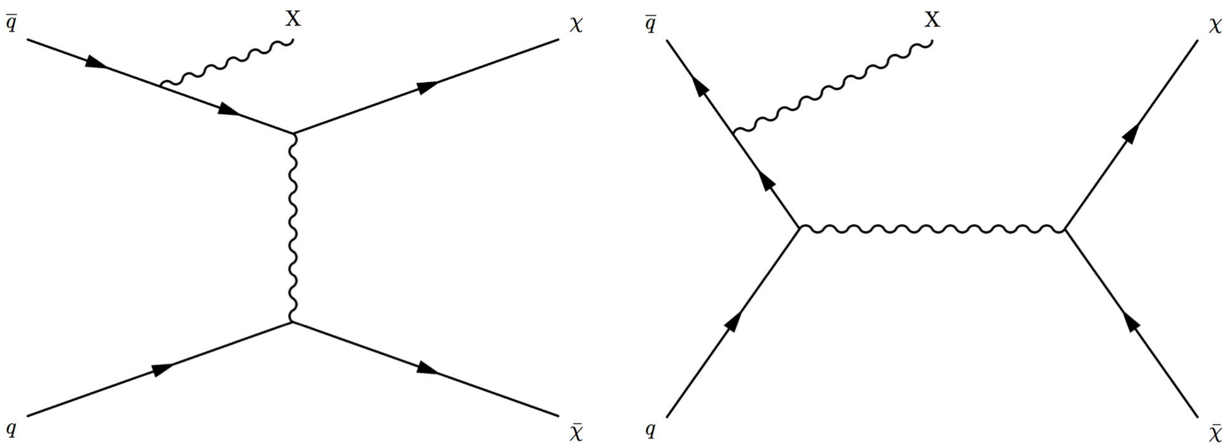
Guidelines and benchmark models detailed in arxiv:1507.00966 [hep-ex]

Effective field theory model

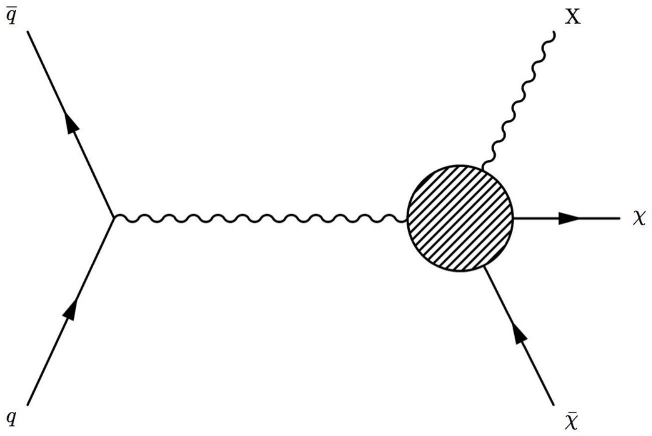
"Simplified model" with a mediator

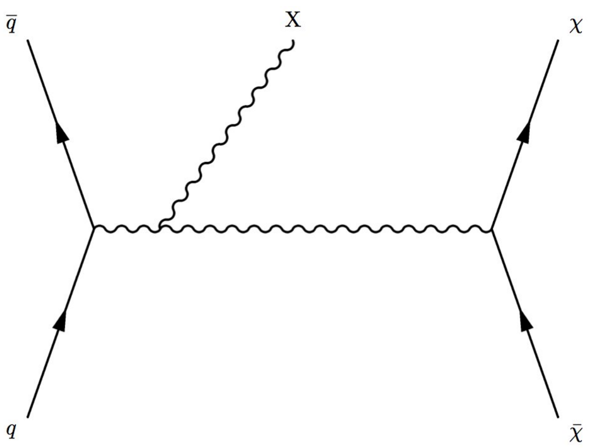
Initial state radiation





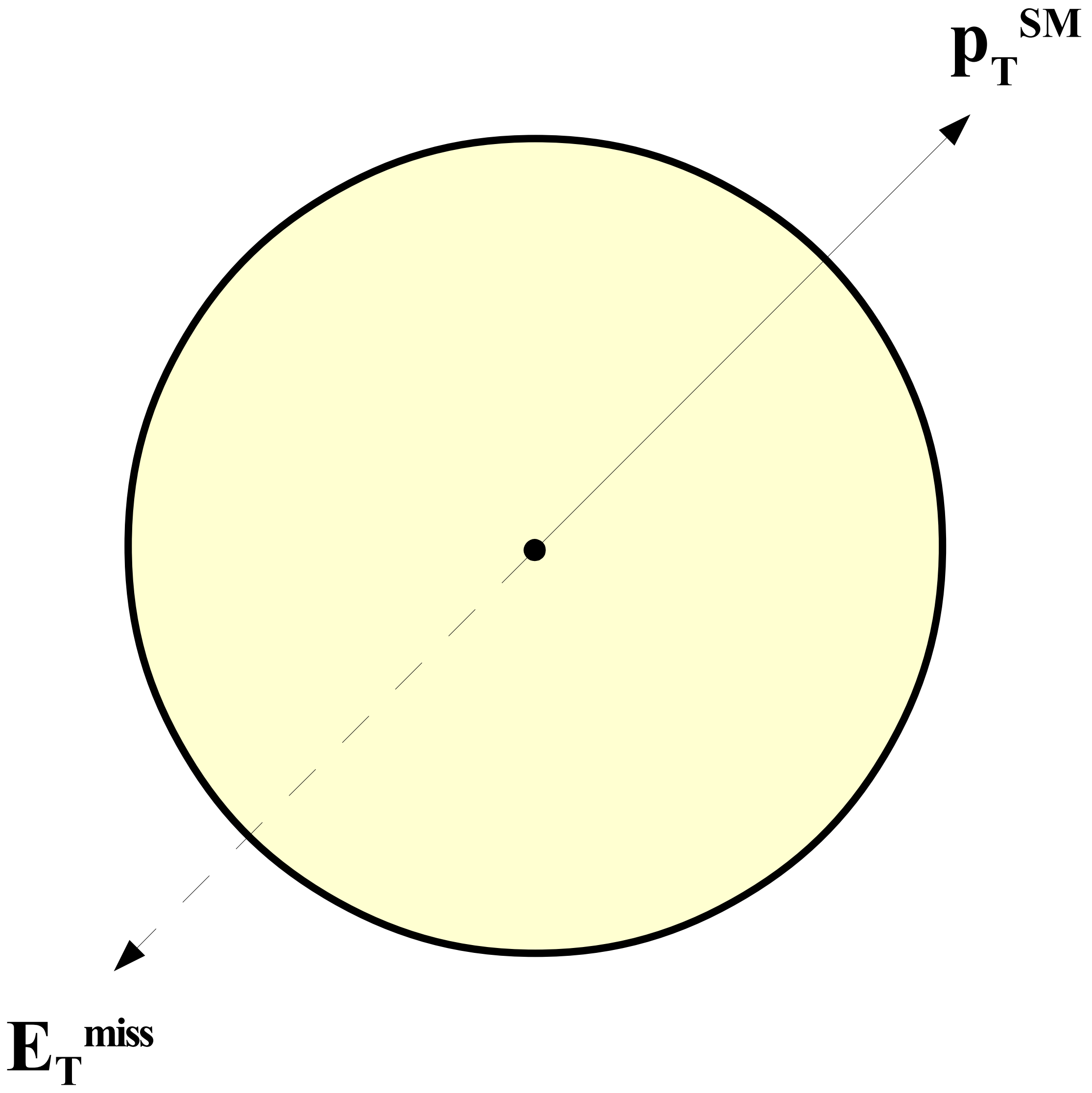
Contact interaction





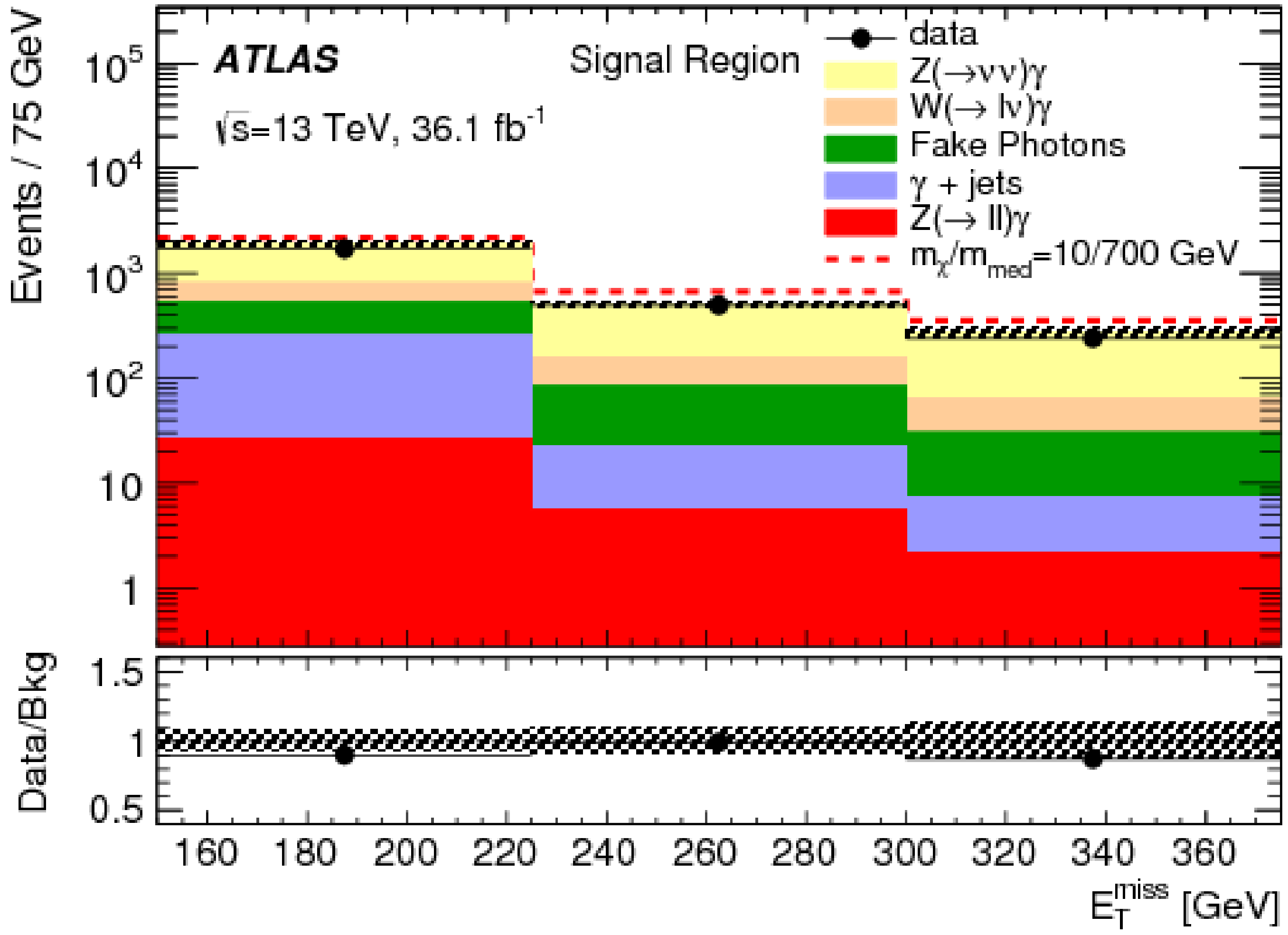
"Mono-X" searches

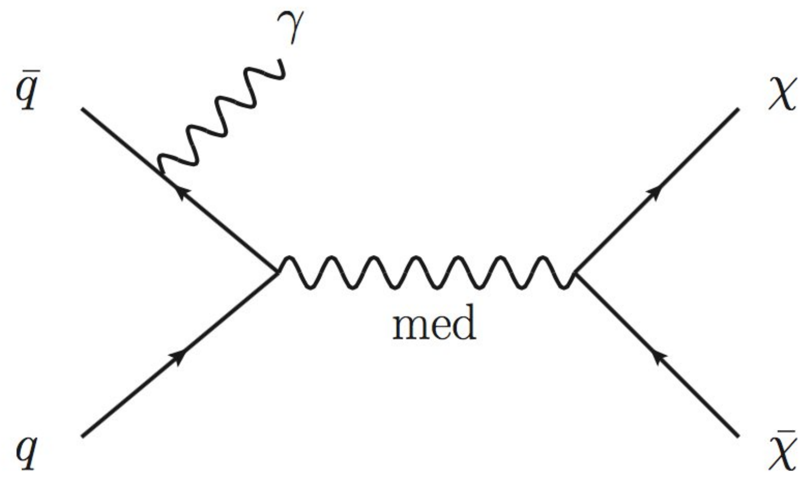
- Presence of dark matter inferred from momentum imbalance in the ATLAS detector
- Key variable is the magnitude of *missing momentum* $|\mathbf{E}_t^{miss}|$ transverse to beam direction, known as missing energy E_T^{miss}
- Suppression of *fake* E_T^{miss} through a proxy on its uncertainty: $E_T^{miss}/\sqrt{\Sigma E_T}$
- Large *separation* Δφ required between $\mathbf{E}_T^{miss}$ and $\mathbf{p}_T^{SM}$
- Further separation between $\mathbf{E}_T^{miss}$ and hadronic activity guards against mismeasurement



Mono-photon

Eur. Phys. J. C 77 , 6 (2017) 393

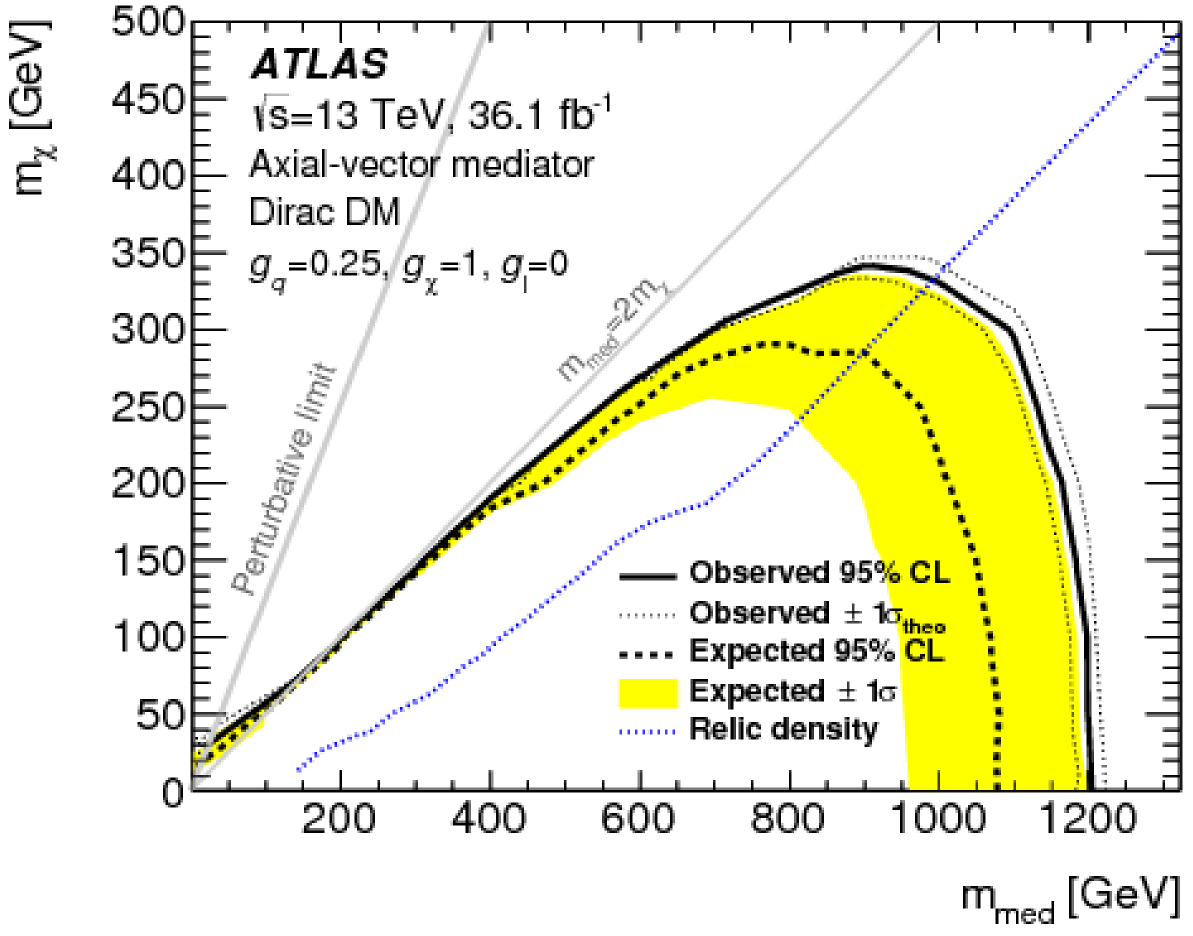


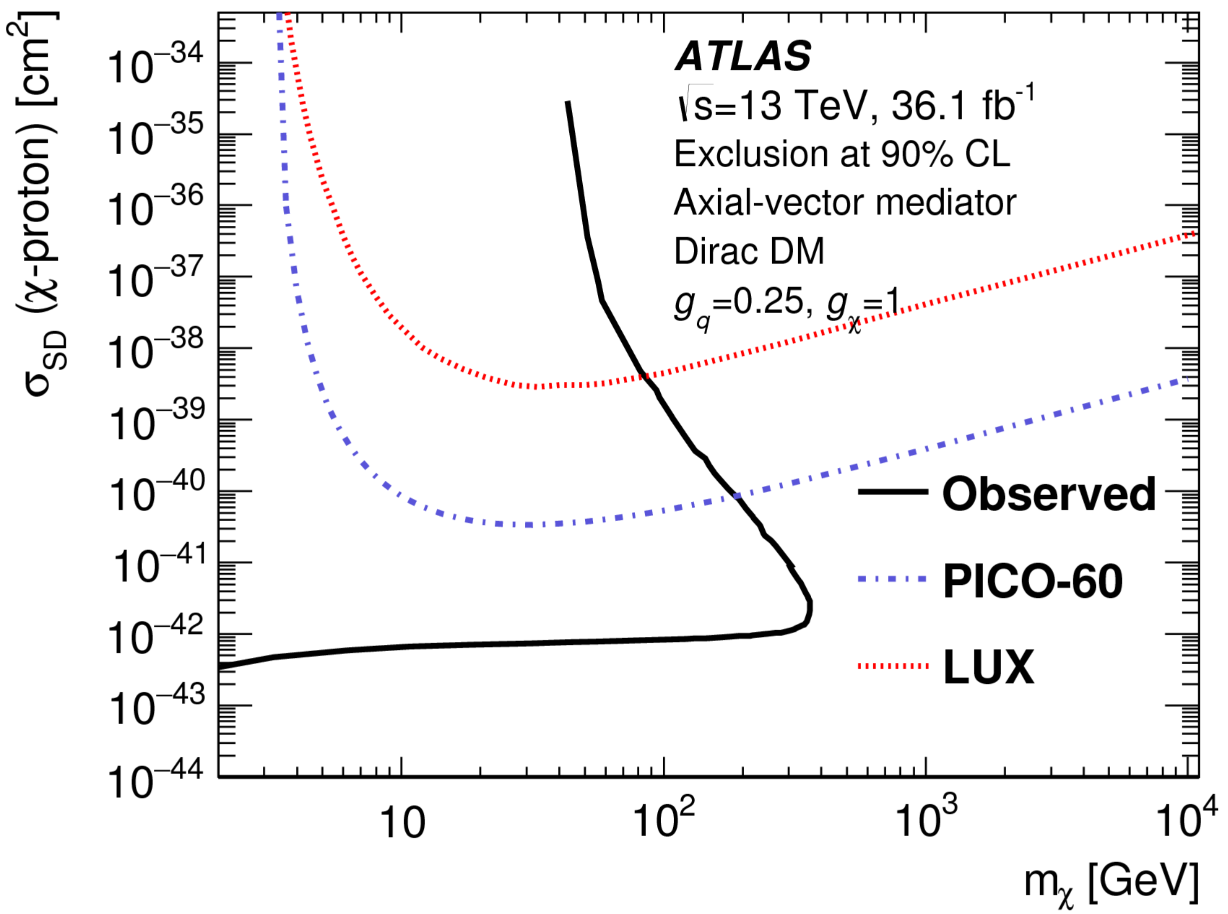


Dataset: 36.1 fb^{-1} (2015+2016)

- Event selection highlights
  - Photon p_T and E_T^{miss} > 150 GeV
  - 0 or 1 jets, lepton veto (e or μ)
- Main backgrounds & estimation:
  - Z(→ νν)/W(→ lν)+γ
  - Normalization factors from simultaneous background only fit
  - Fake photons – estimated through tag and probe
  - γ+jets – extrapolated from control region in data

Mono-photon results





Inclusive signal regions:

- $E_t^{miss} > 150$ GeV
- $E_T^{miss} > 225$ GeV
- $E_T^{miss} > 300$ GeV

Exclusive signal regions:

- $E_T^{miss} \in [150\text{-}225]$ GeV
- $E_T^{miss} \in [225\text{-}300]$ GeV

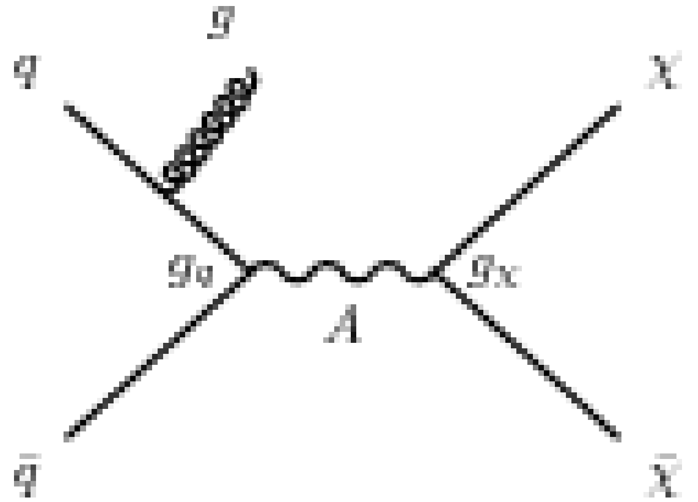
- Limits set on mediator masses up to 1.2 TeV
- Competitive limits at low and mid-range dark matter masses compared to direct detection experiments

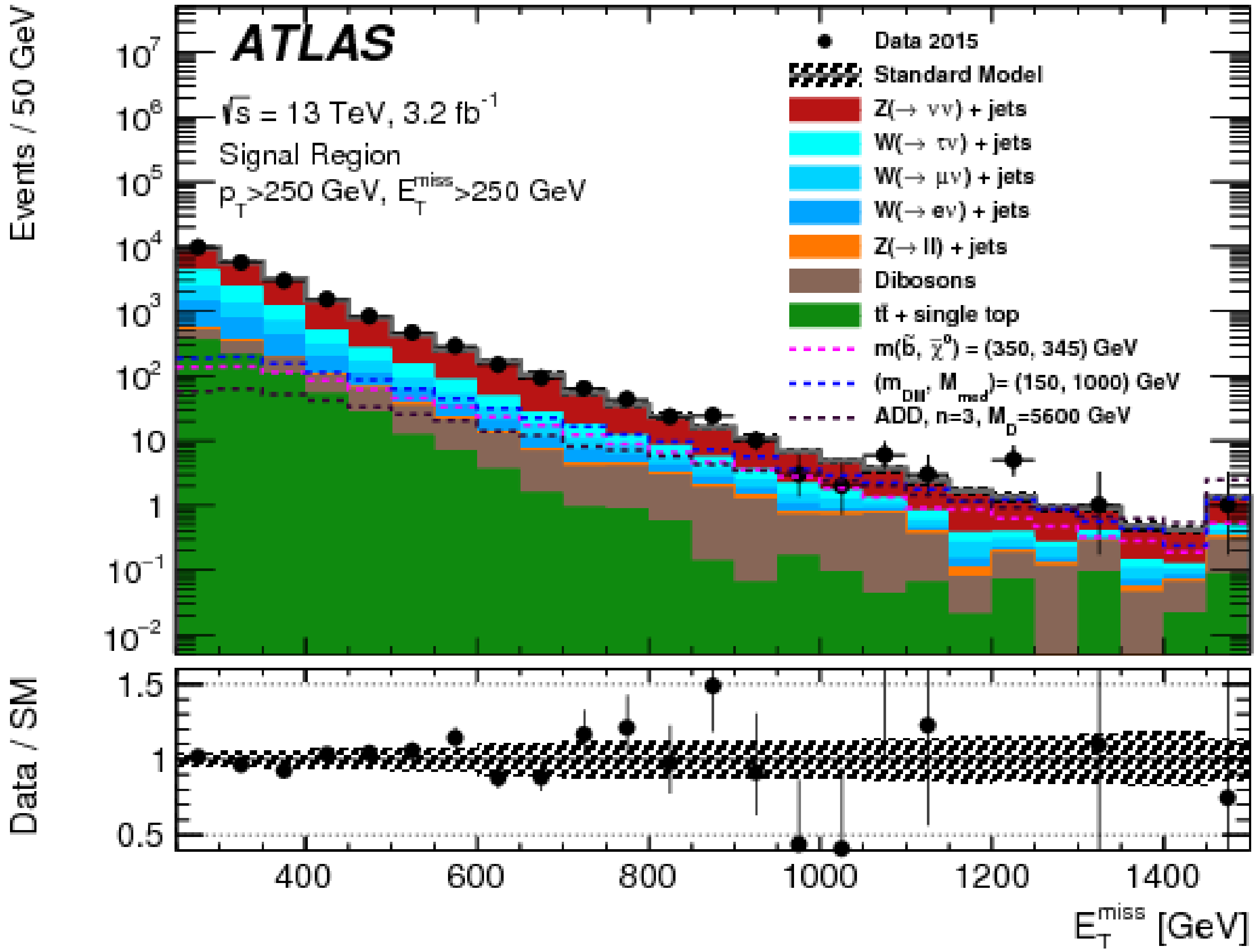
Mono-jet

Dataset: 3.2 fb^{-1} (2015)

Phys. Rev. D 94, 032005 (2016)

- Event selection highlights
  - Both E_T^{miss} and p_T (1^{st} jet) > 250 GeV
  - At most 4 jets
  - Lepton veto (e or μ)
- Main backgrounds & estimation:
  - Z(→ νν)+jets and W(→ lν)+jets
  - Z(→ ll)+jets
  - Top-quark backgrounds estimated by MC





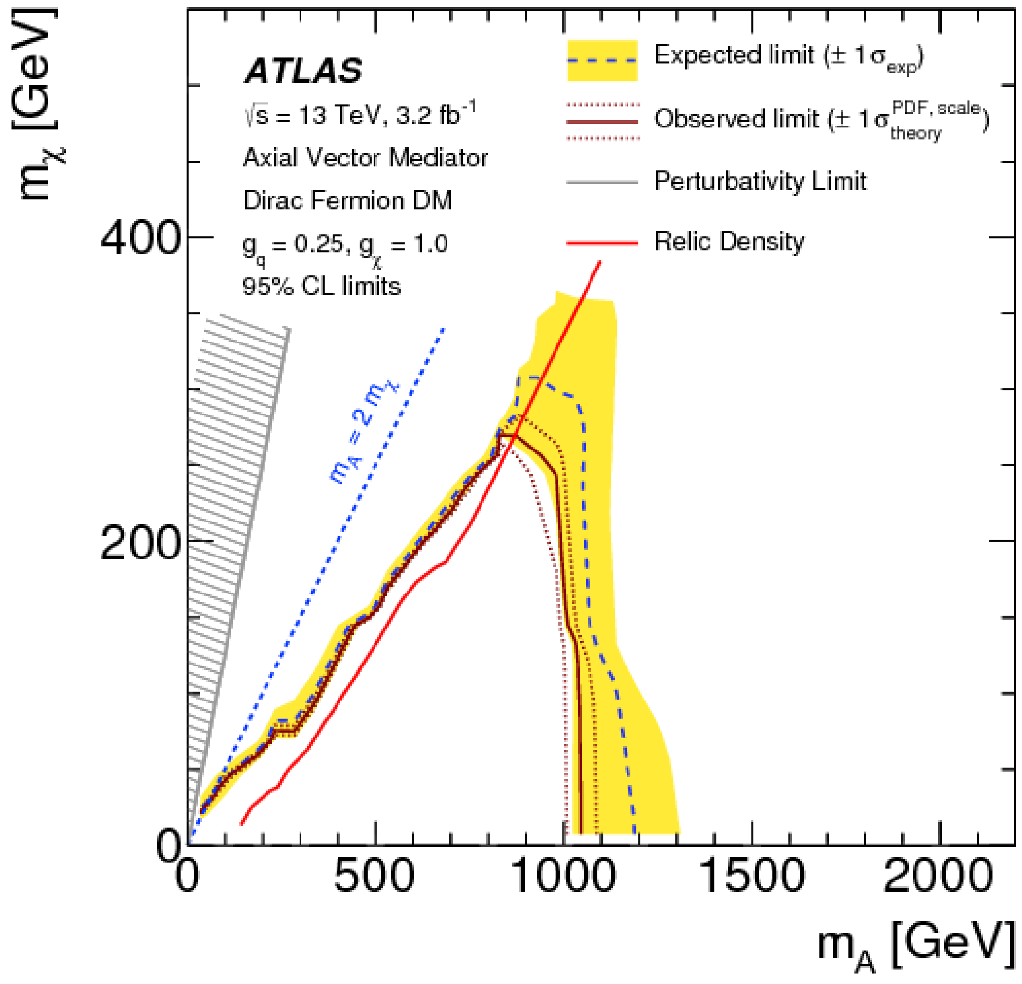
Mono-jet results

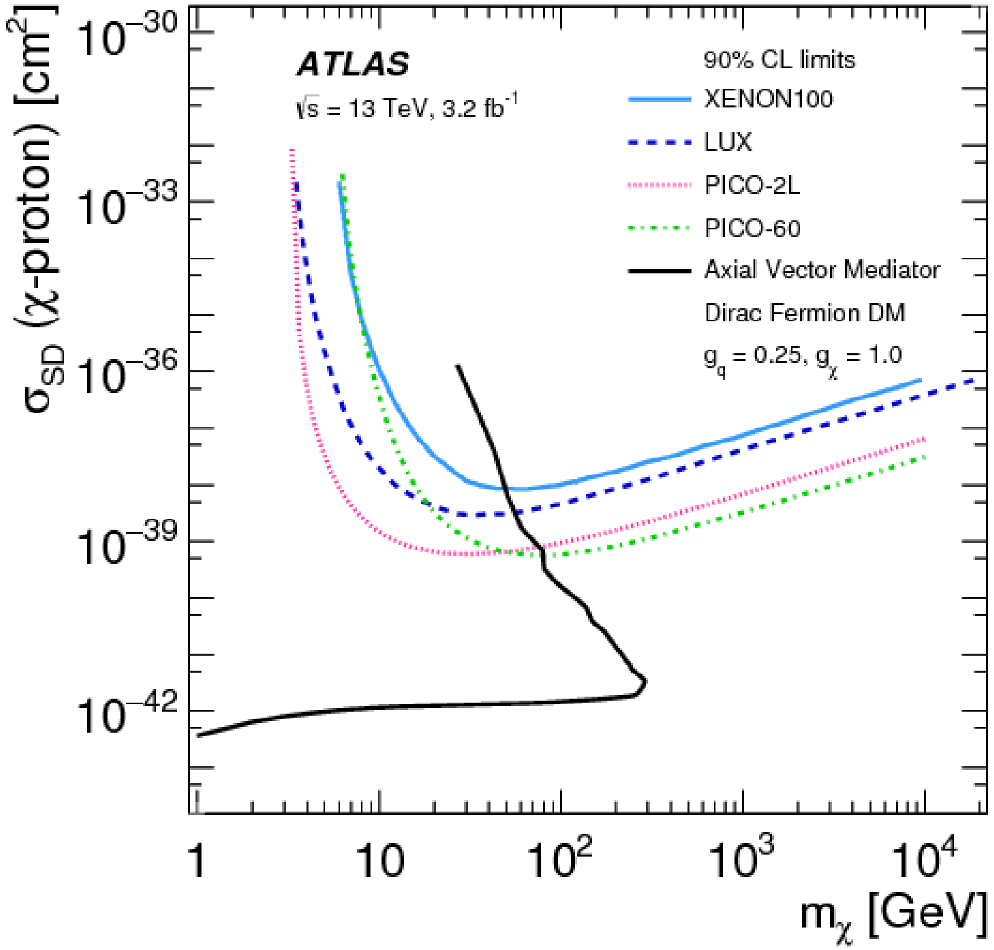
Inclusive signal regions:

- E_t^{miss} > **250**, > 300, > 350, > 400, > 500, > 600, > **700** GeV

Exclusive signal regions:

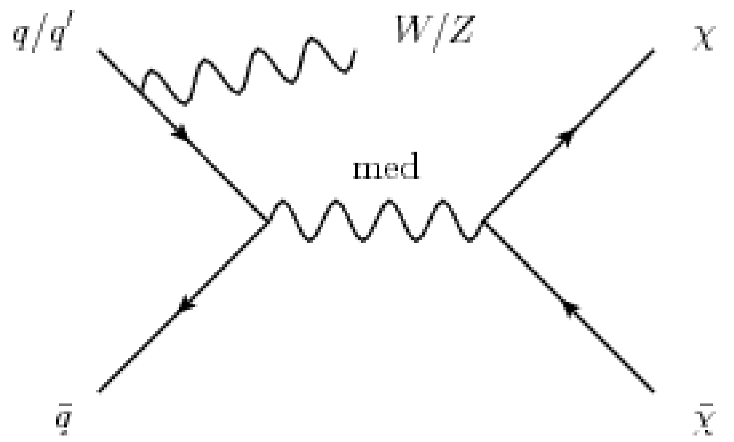
- E_T^{miss} in [250-300] ……............................... [600, 700] GeV



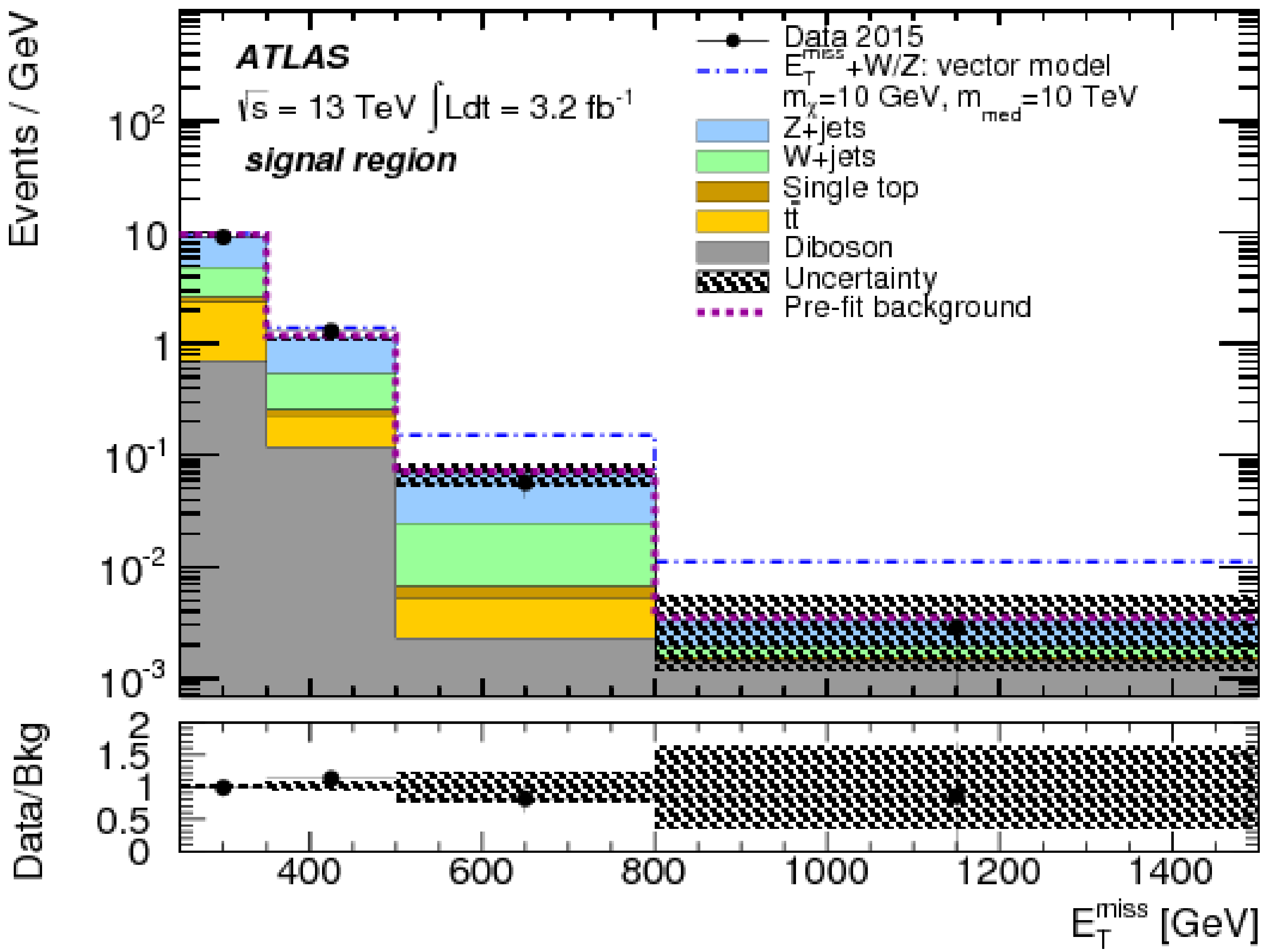


- Limits are set on mediators masses up to 1 TeV
- Very competitive limits for low and mid-range dark matter masses compared to direct detection

Mono-V(hadronic)

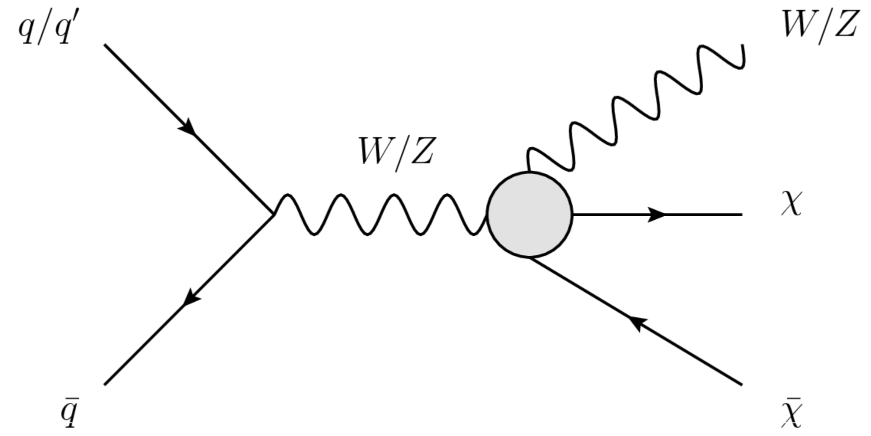


Phys. Lett. B 763 (2016) 251

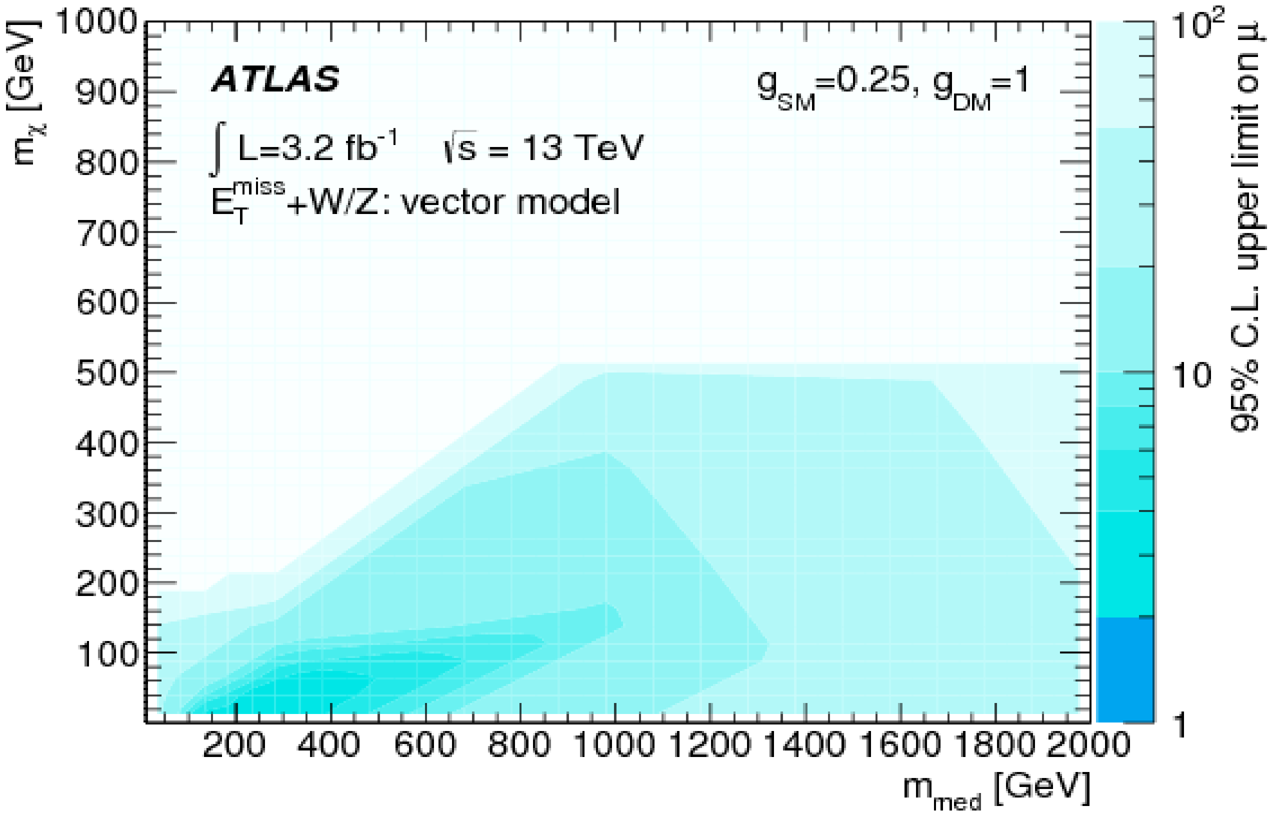


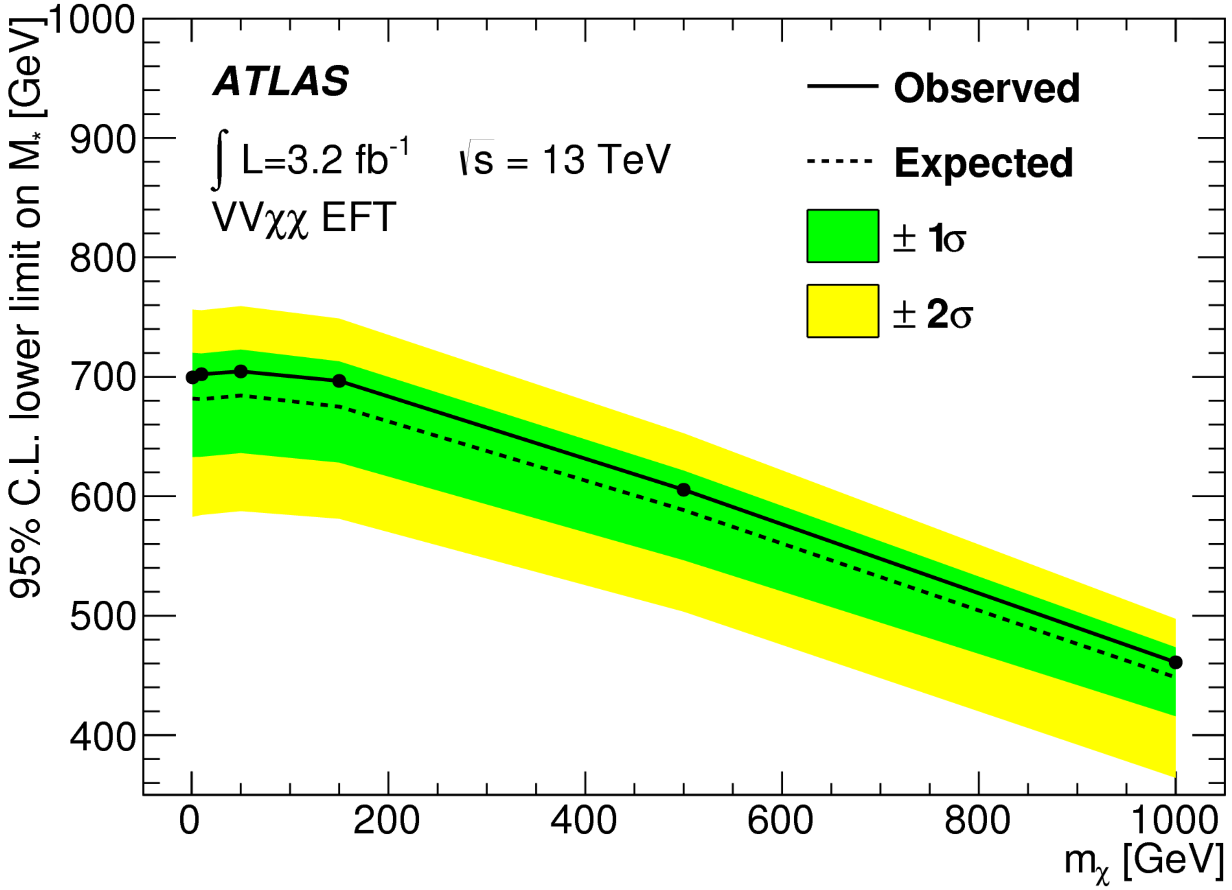
Dataset: 3.2 fb^{-1} (2015)

- Event Selection highlights
  - $E_T^{miss} > 250$ GeV
  - A Jet > 200 GeV with boosted substructure consistent with a W or Z boson
- Backgrounds & estimation:
  - Z(→ νν)+jets , W/Z(→ lν/ll)+jets
  - ttbar – estimated through MC, normalization from data



Mono-V(hadronic) results

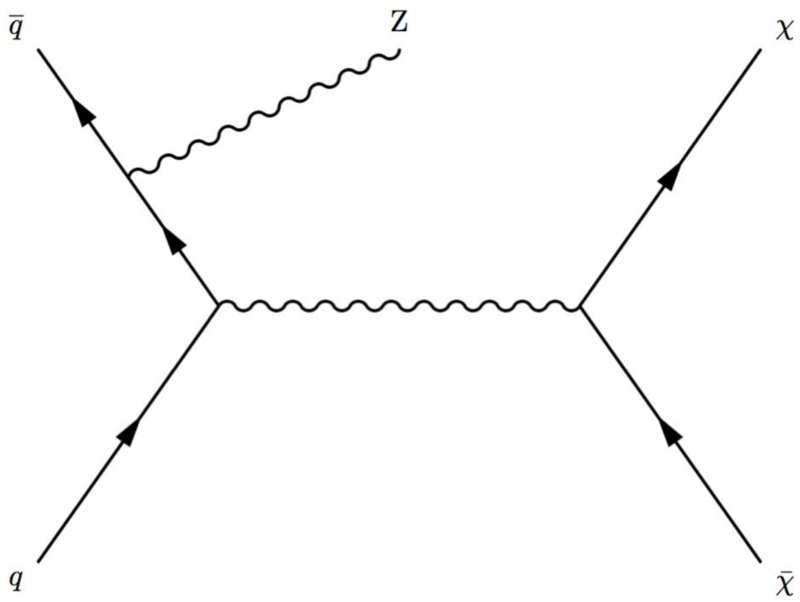




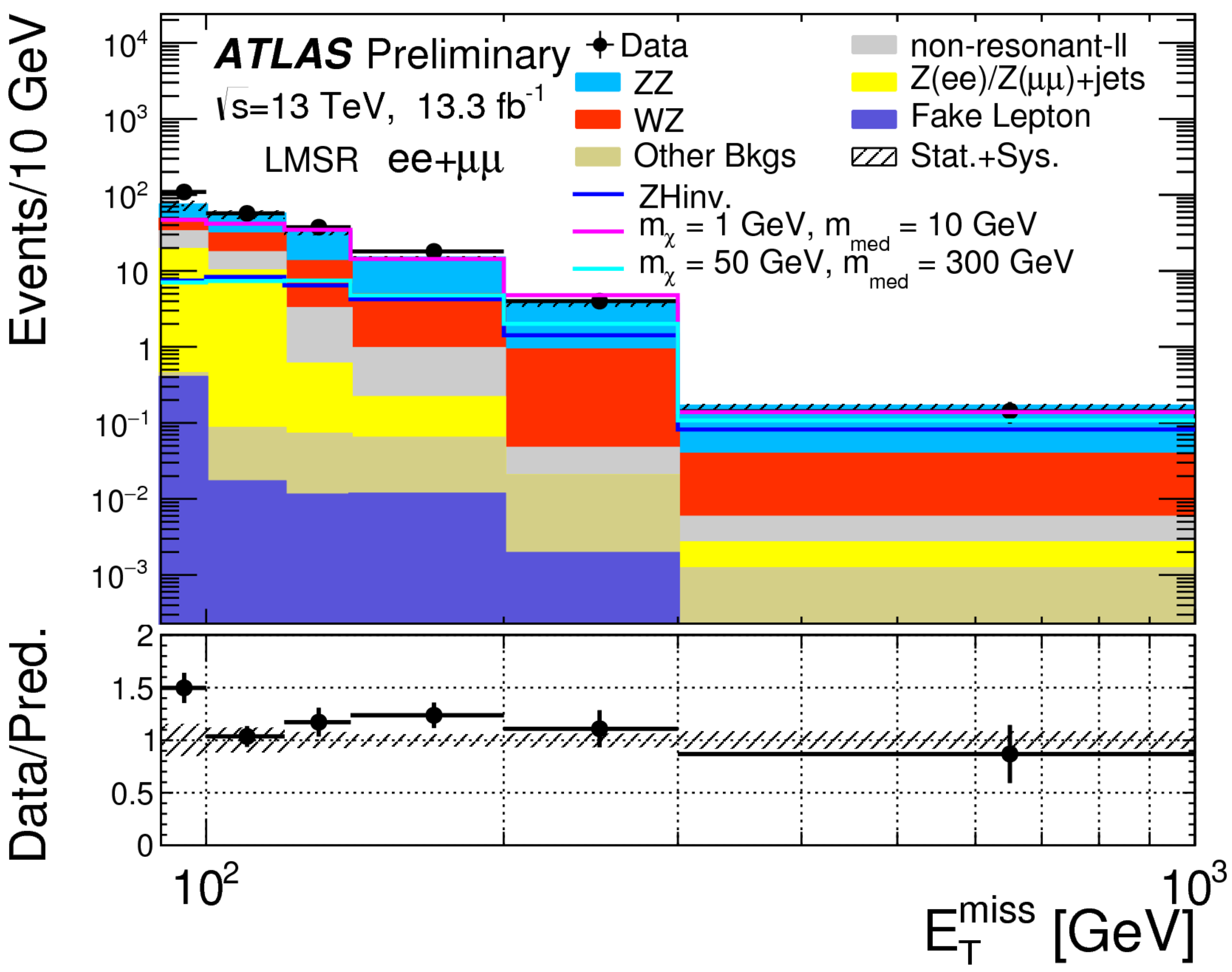
Fit to binned E_T^{miss} in signal region to determine the signal strength, μ

- Limits are set on the signal strength of the mediator model
- Limits are set on mass scales up to 700 GeV at low dark matter mass

Mono-Z(ll)



ATLAS-CONF-2016-056

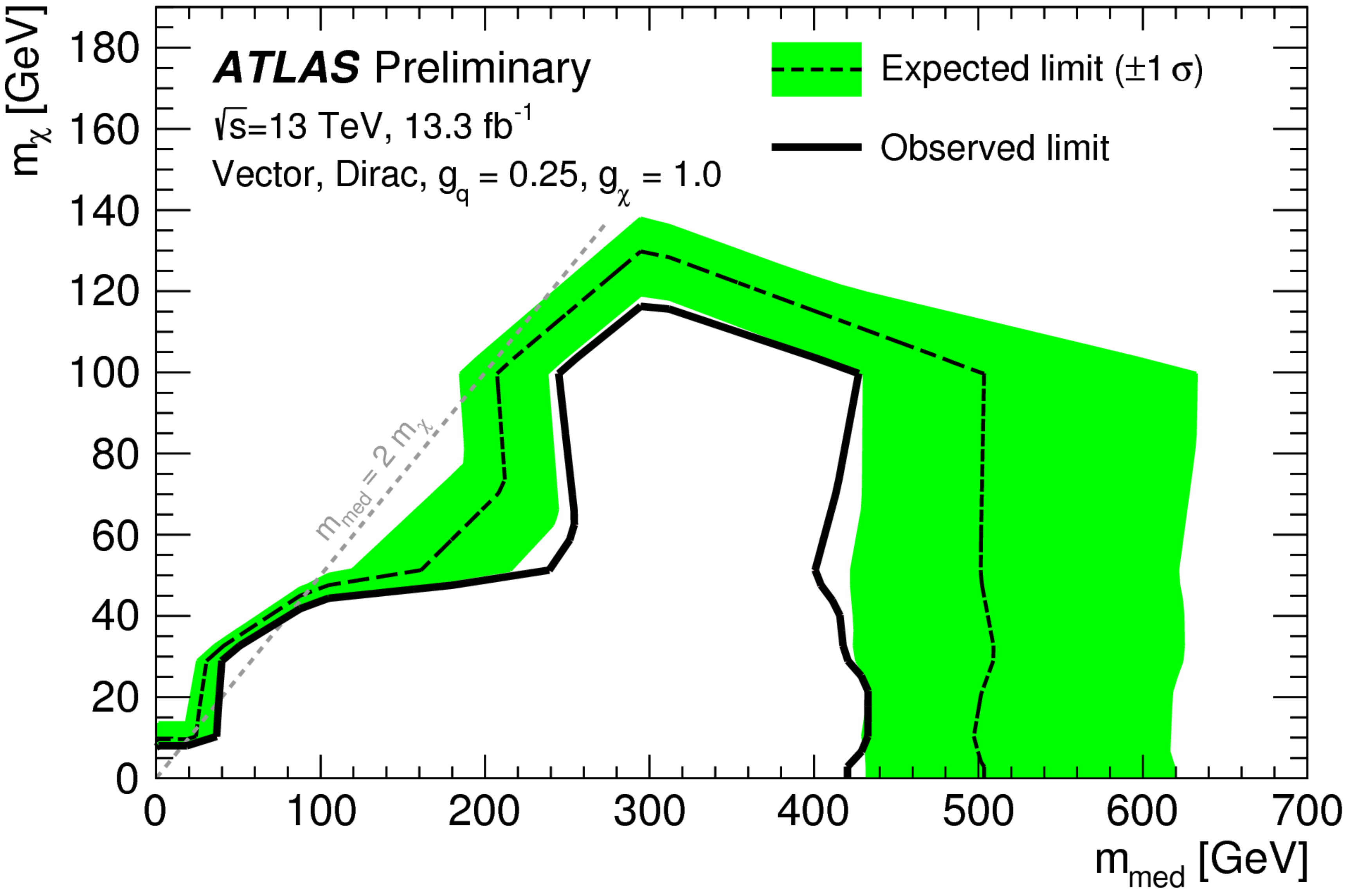


Dataset: 13.3 fb^{-1} (2015+ partial 2016)

- Event selection highlights
  - $E_T^{miss} > 90$ GeV
  - B-jet veto, third lepton veto
- Main backgrounds & estimation:
  - ZZ(→ llvv)
  - WZ(→ llvl), Z(→ ll,) ll non-resonant

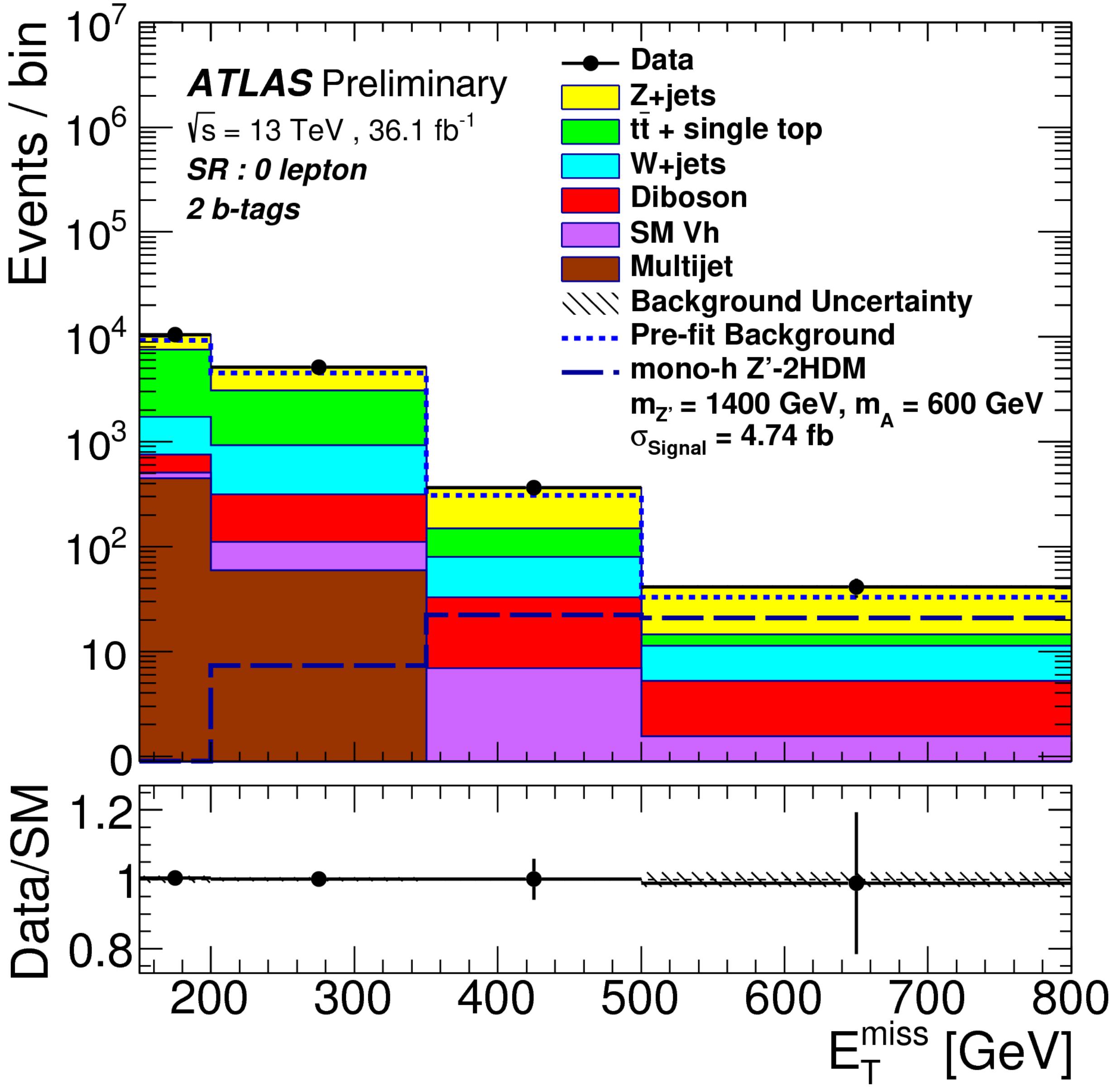
Mono-Z(ll) results

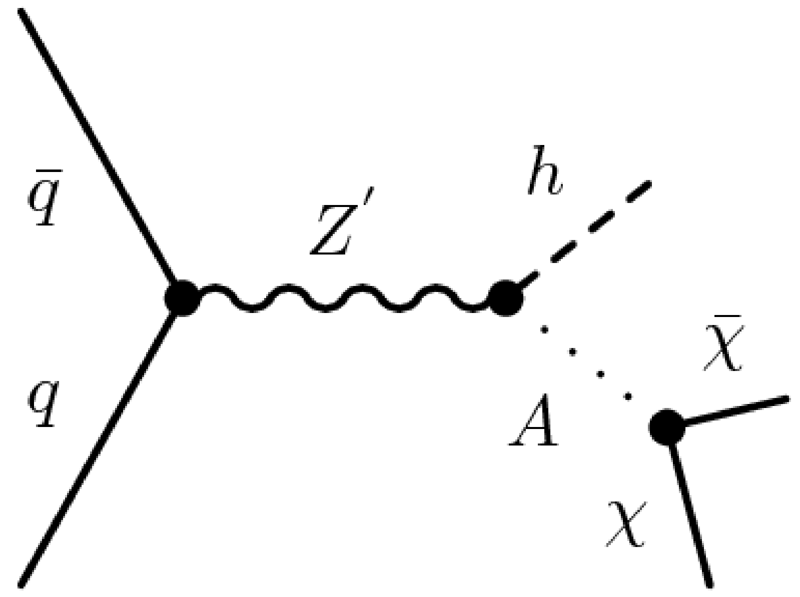
- Two signal regions:
  - final states with ee
  - final states with μμ
- Limits are set on the mediator mass to about 400 GeV



Mono-H(bb)

ATLAS-CONF-2017-028

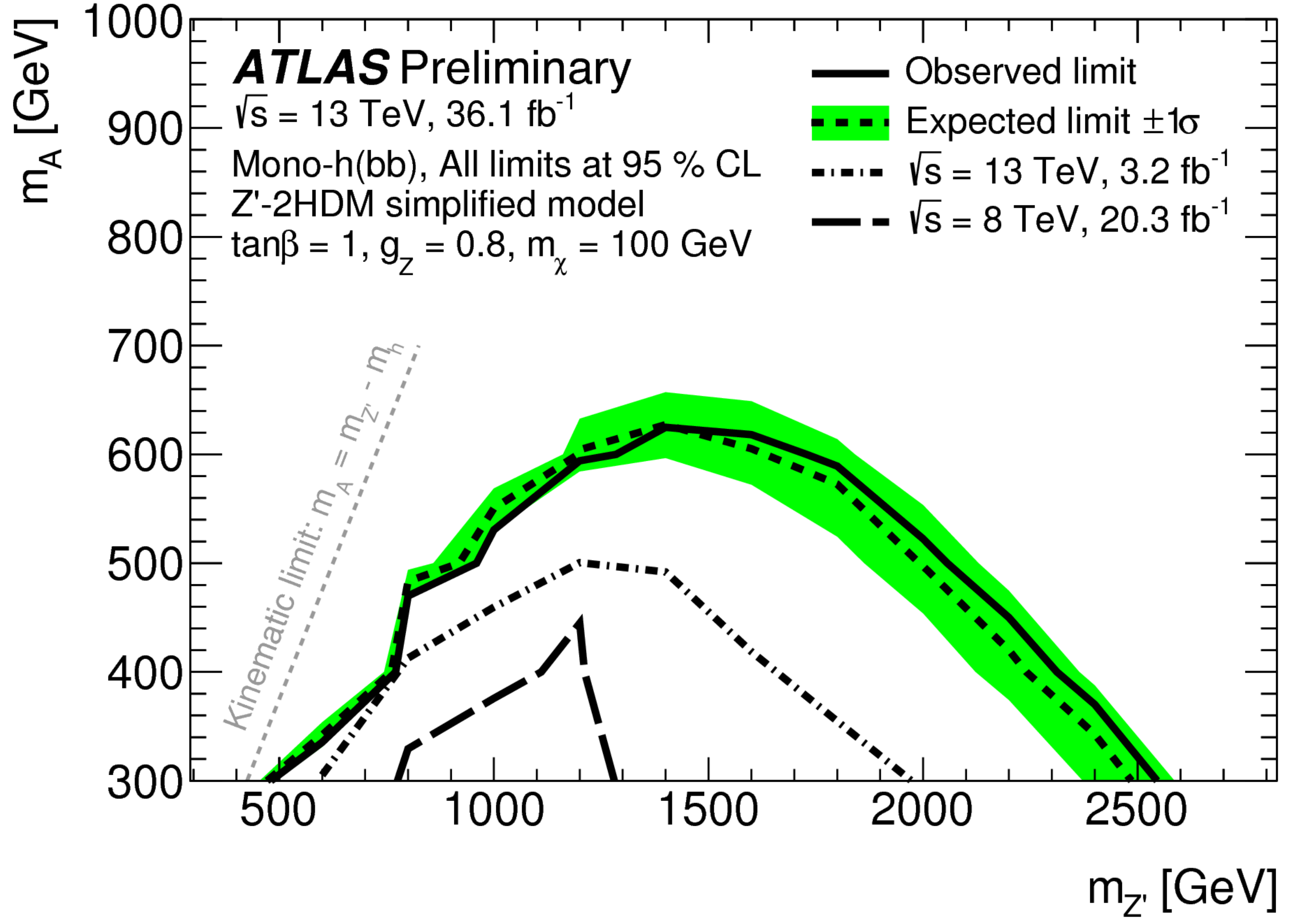




Dataset: 36.1 fb^{-1} (2015+2016)

- Event selection highlights
  - E_T^{miss} > 150 GeV
  - 1 or 2 b-jets tagged and lepton veto on e or μ
- Main backgrounds
  - Z(→ νν)+jets, ttbar background, W+jets

Mono-H(bb) results

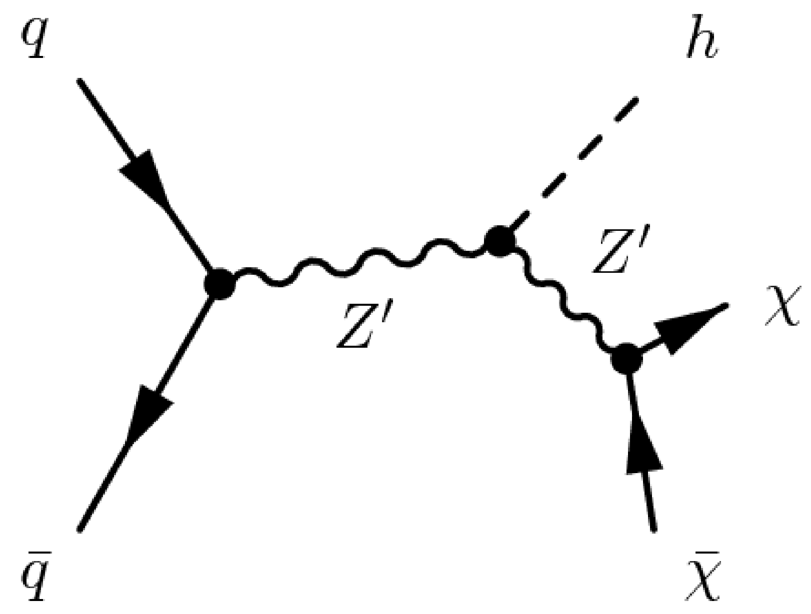


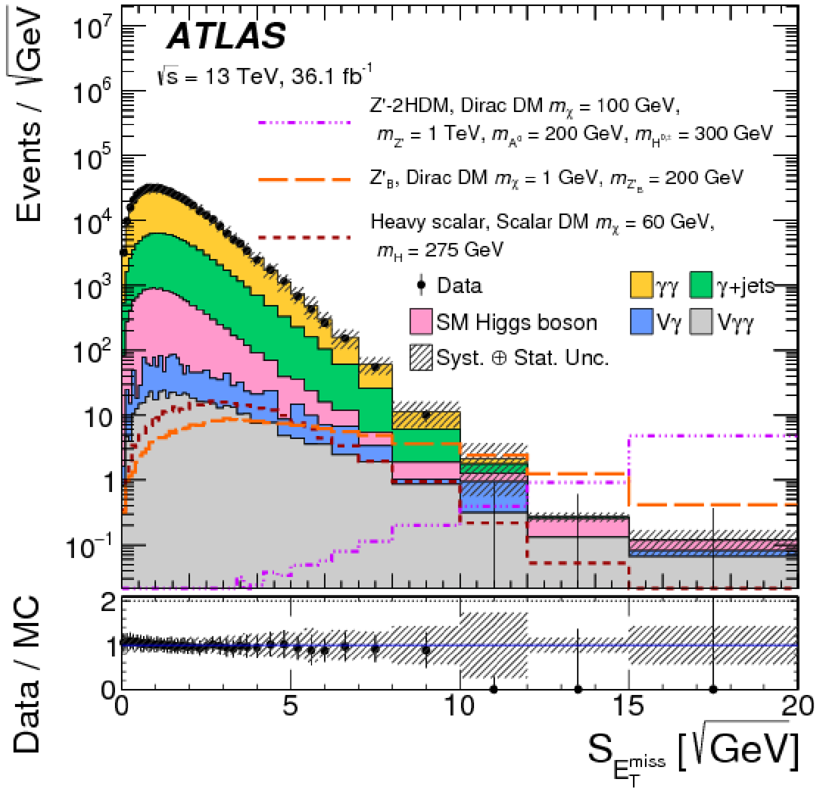
- Limits set on a two higgs doublet model (with specific parameters) on a massive Z' excluded up to 2.5 TeV

- Signal regions: resolved:
  - $E_T^{miss} \in [150, 500]$ GeV
- Signal region: merged:
  - $E_T^{miss} > 500$ GeV

Mono-H(γγ)

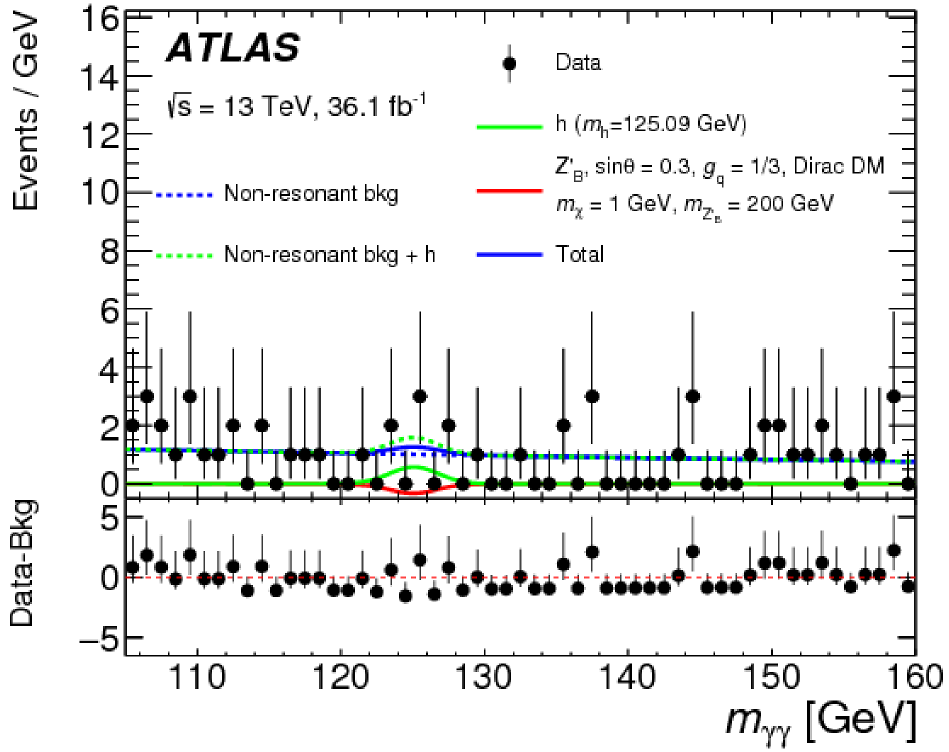
arXiv:1706.03948 [hep-ex]



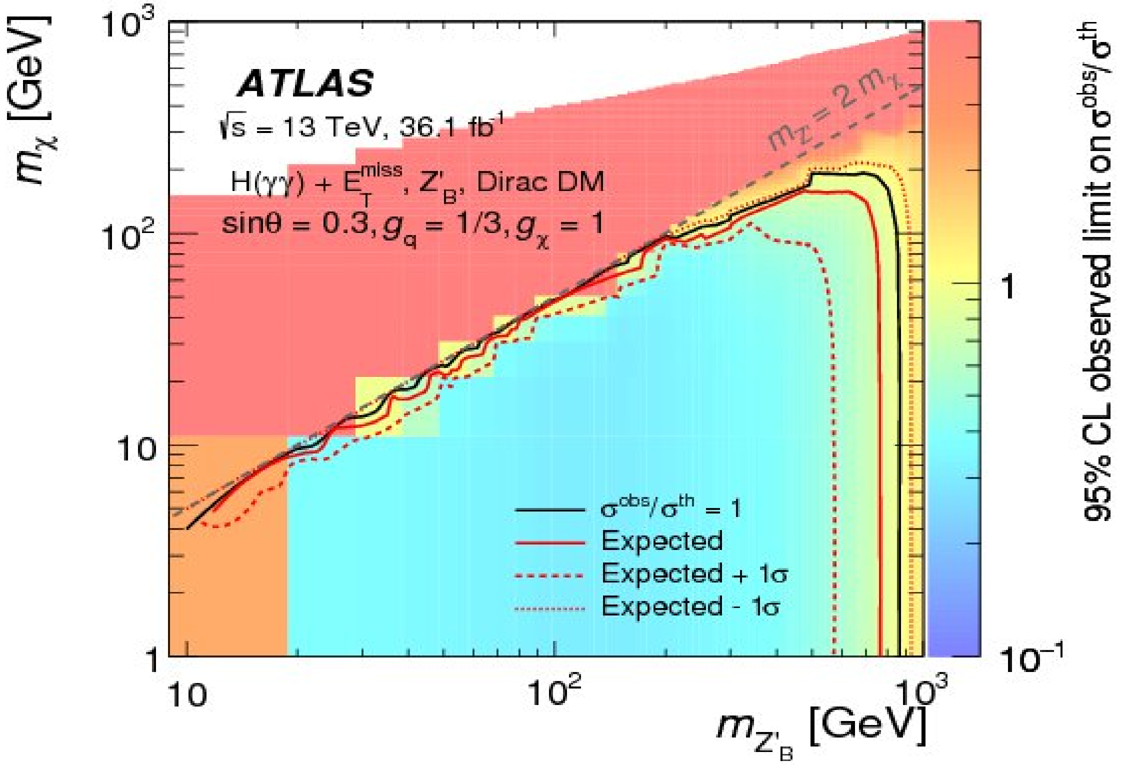


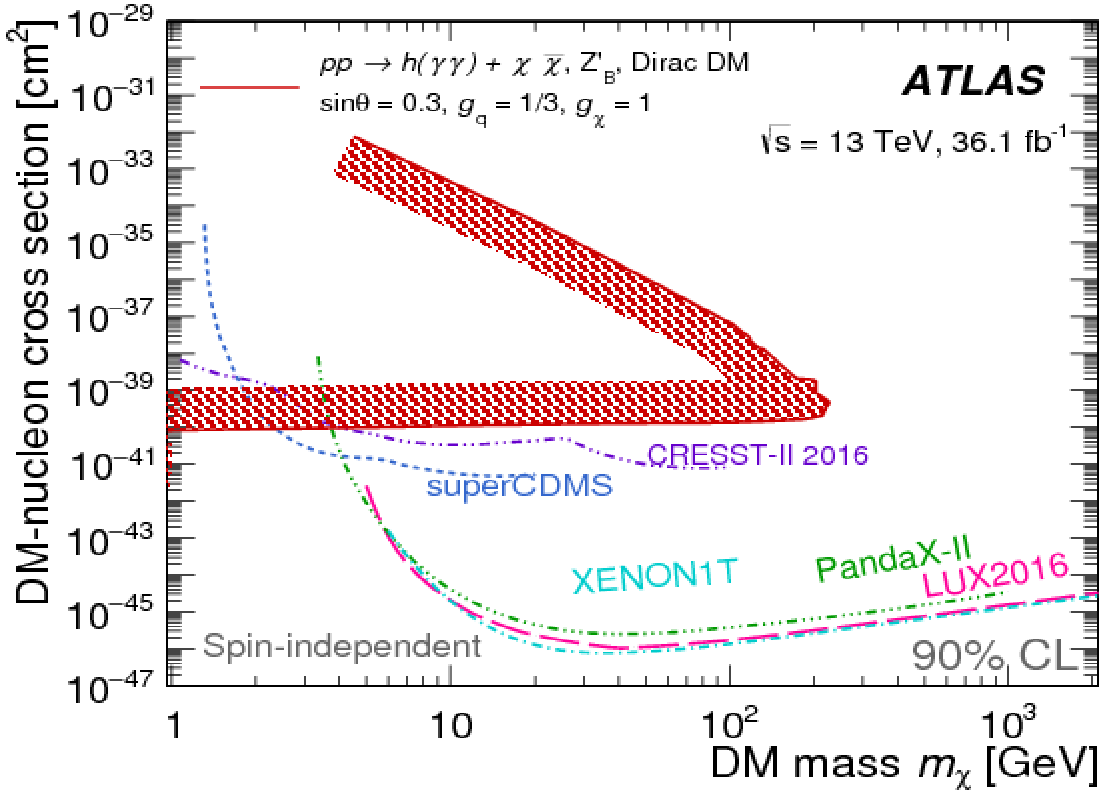
Dataset: 36.1 fb^{-1} (2015+2016)

- Event selection highlights
  - $E_t^{miss} / \sqrt{\Sigma E_T} > 7\ GeV^{1/2}$
  - $p_T^{\gamma\gamma} > 90$ GeV and lepton veto
- Backgrounds & estimation:
  - γγ nonresonant, H → γγ, γ+jets
  - Backgrounds parameterized with fit functions



Mono-H(γγ) results



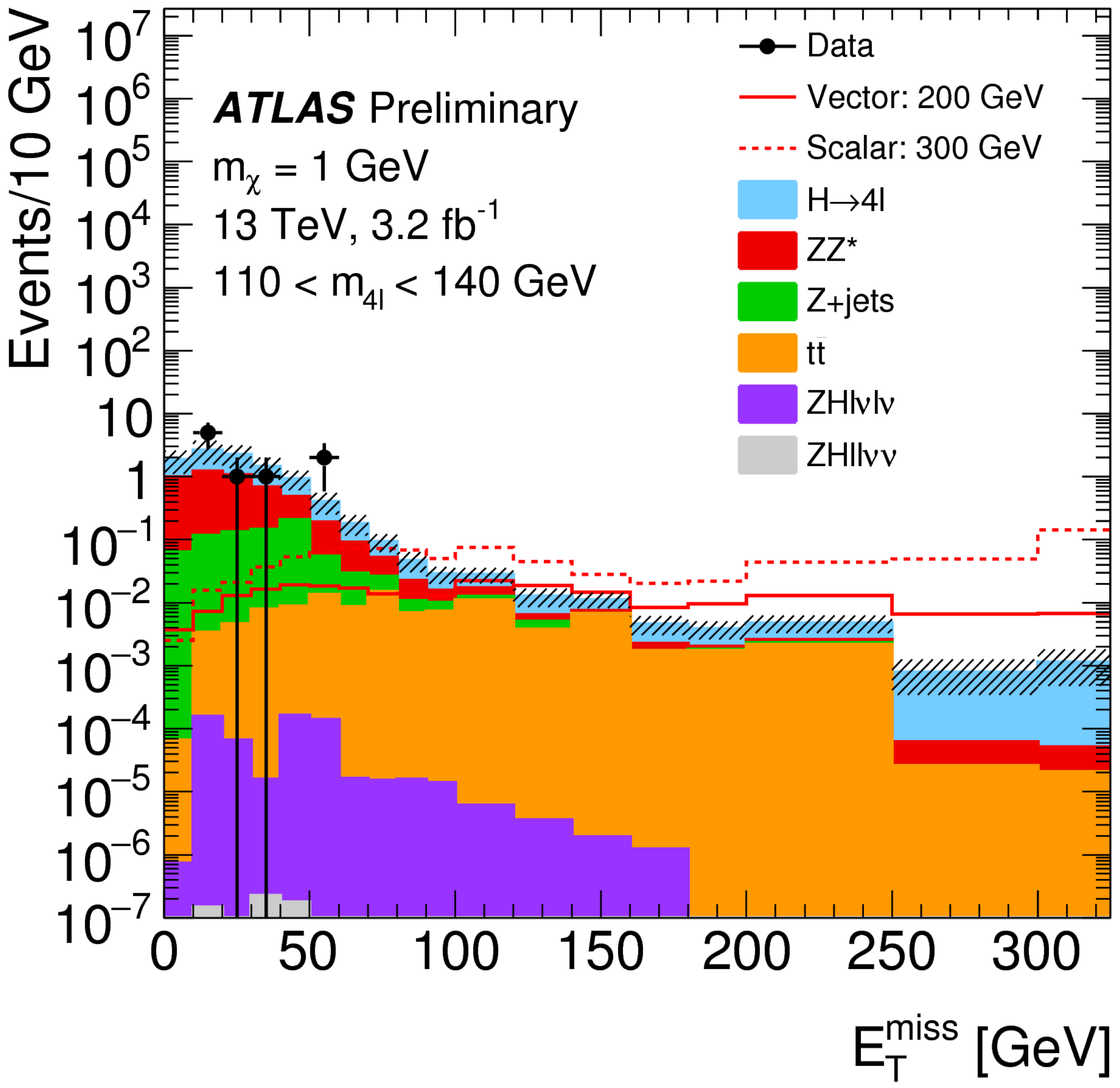


- Signal regions:
  - Most sensitive: $E_T^{miss} / \sqrt{\Sigma E_T} > 7\ \sqrt{\text{GeV}}$
- Exclusive signal regions used for other analyses:
  - High E_T^{miss}: $E_T^{miss} / \sqrt{\Sigma E_T} > 5.5\ \sqrt{\text{GeV}}$
  - Intermediate E_T^{miss}: $E_T^{miss} / \sqrt{\Sigma E_T} > 4\ \sqrt{\text{GeV}}$

- Results exclude dark matter from a Z_B' > 850 GeV
- The results are competitive with direct detection limits at the lowest dark matter masses

Mono-H(4l)

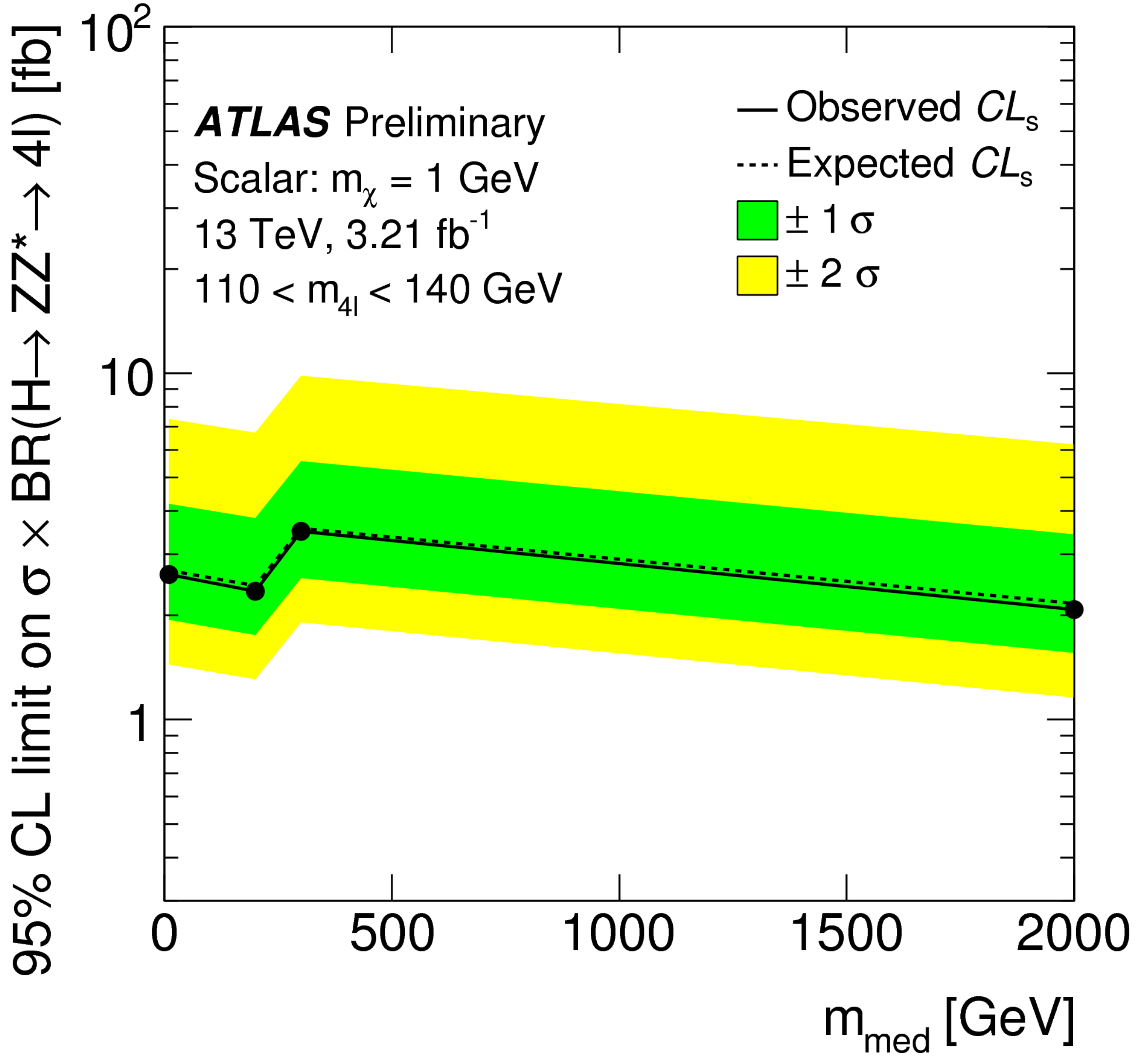
ATLAS-CONF-2015-059

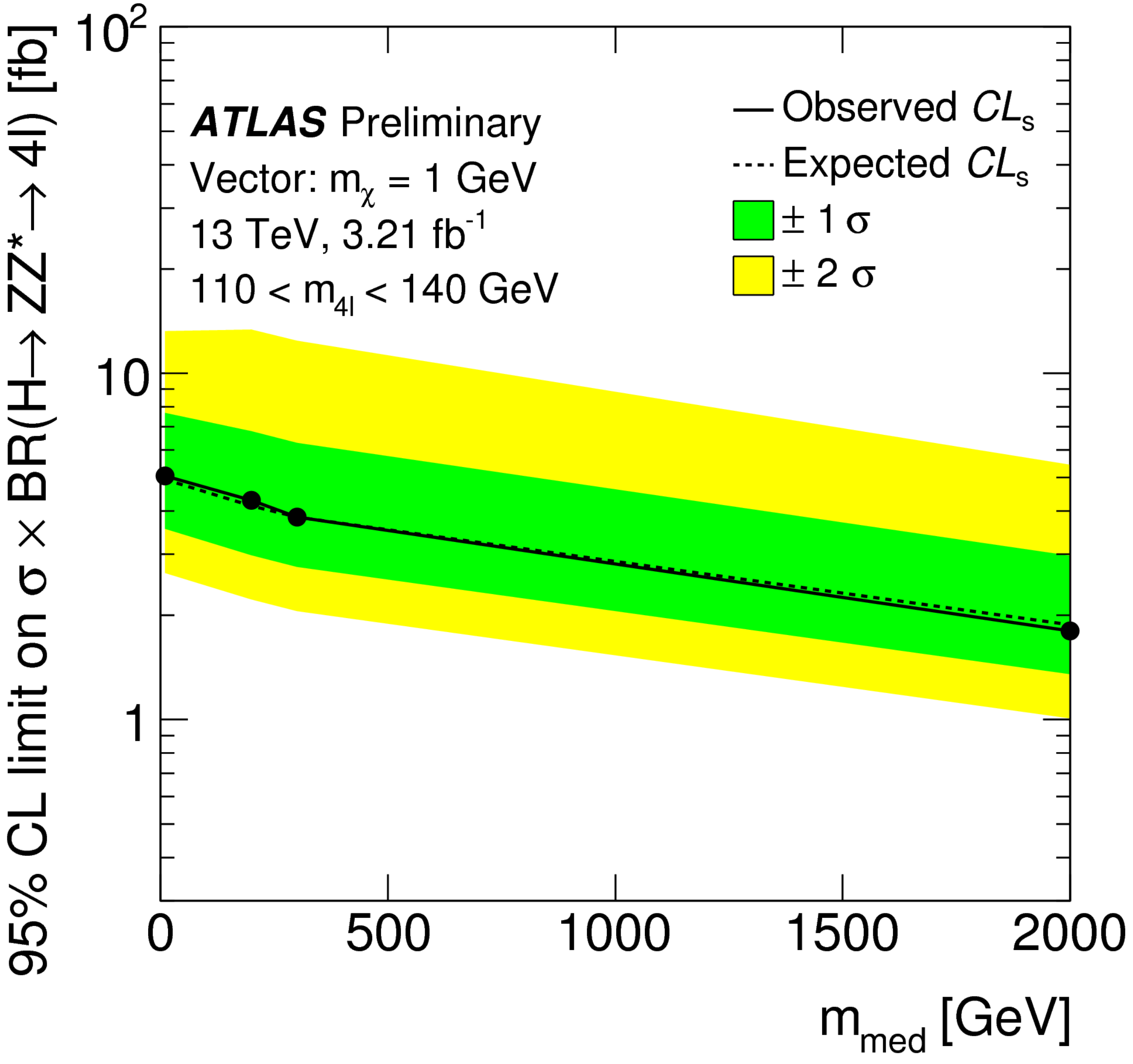


Dataset: 3.2 fb^{-1} (2015)

- Event Selection highlights
  - Four isolated leptons
  - Same flavour lepton pairs near m_Z
- Backgrounds & estimation:
  - ZZ (nonresonant)
  - Z(→ ll)+jets & ttbar – data fit extrapolation

Mono-H(4l) results

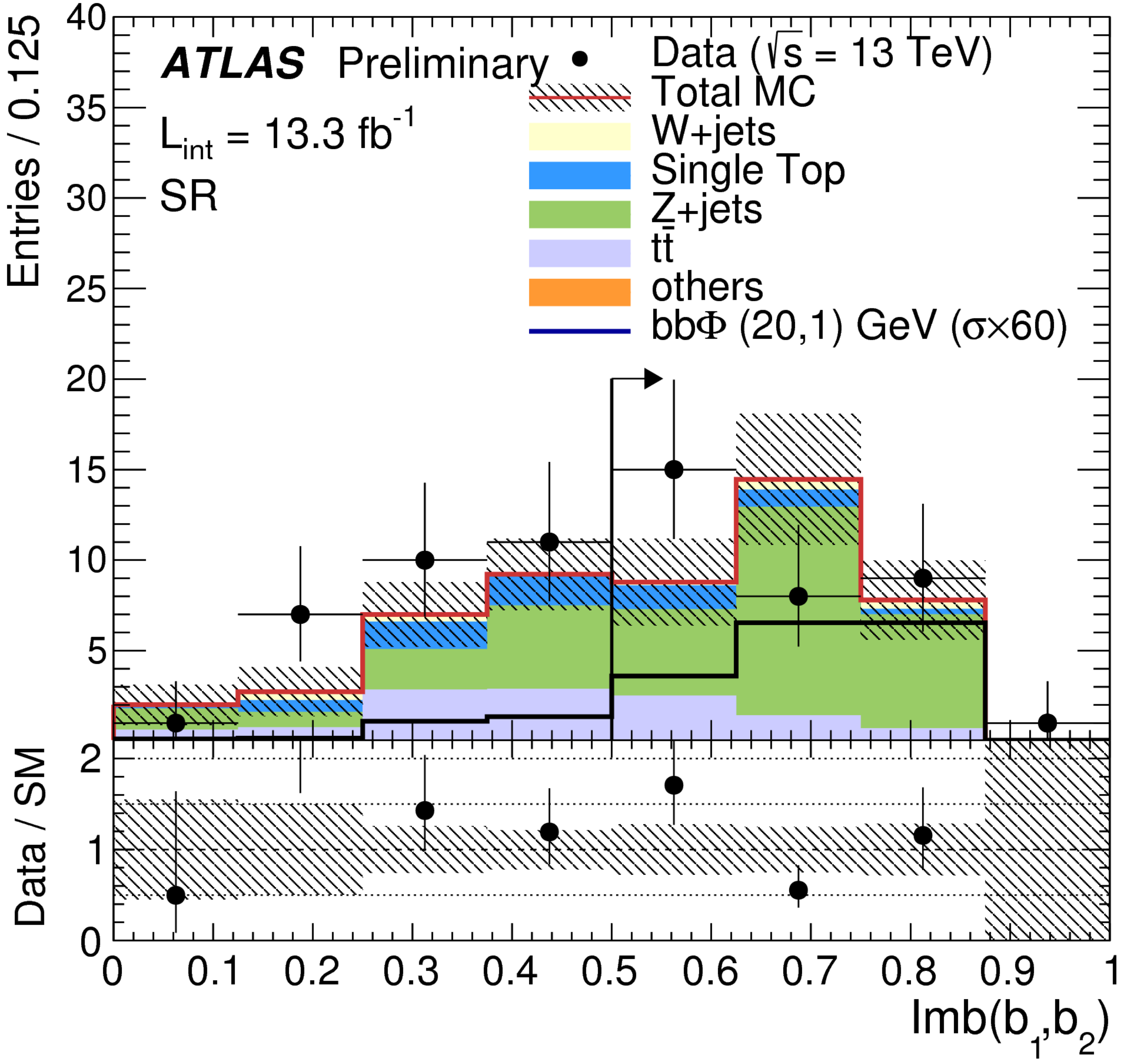


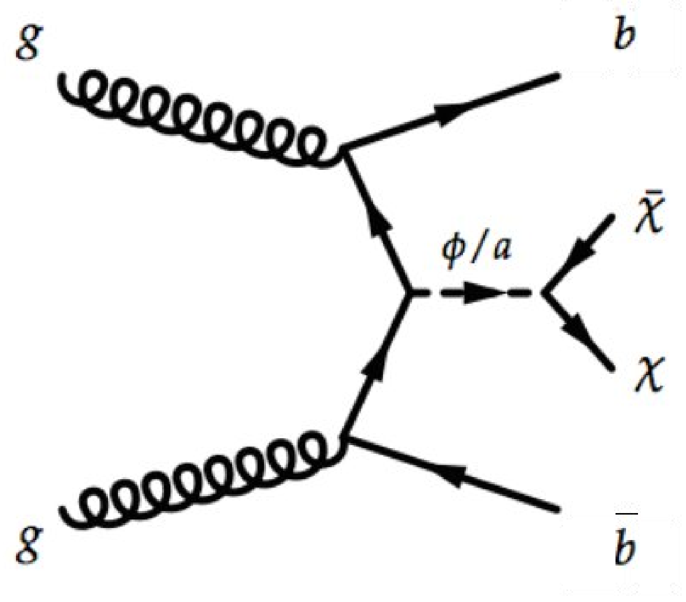


- Signal regions: 4e, 2e2μ, 2μ2e, 4μ
- Upper limits set on σ×Br for 1 GeV dark matter

MET + bb

ATLAS-CONF-2016-086

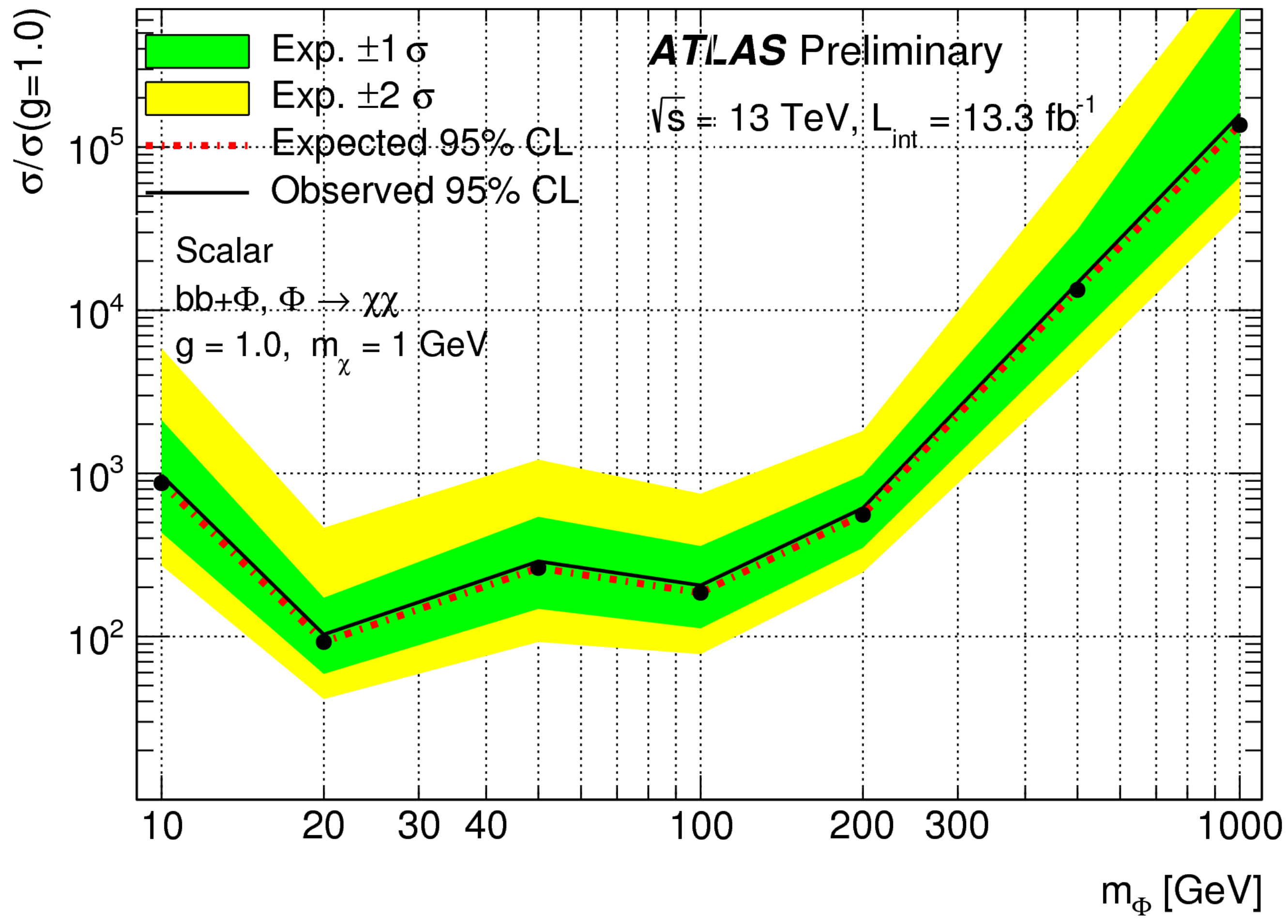


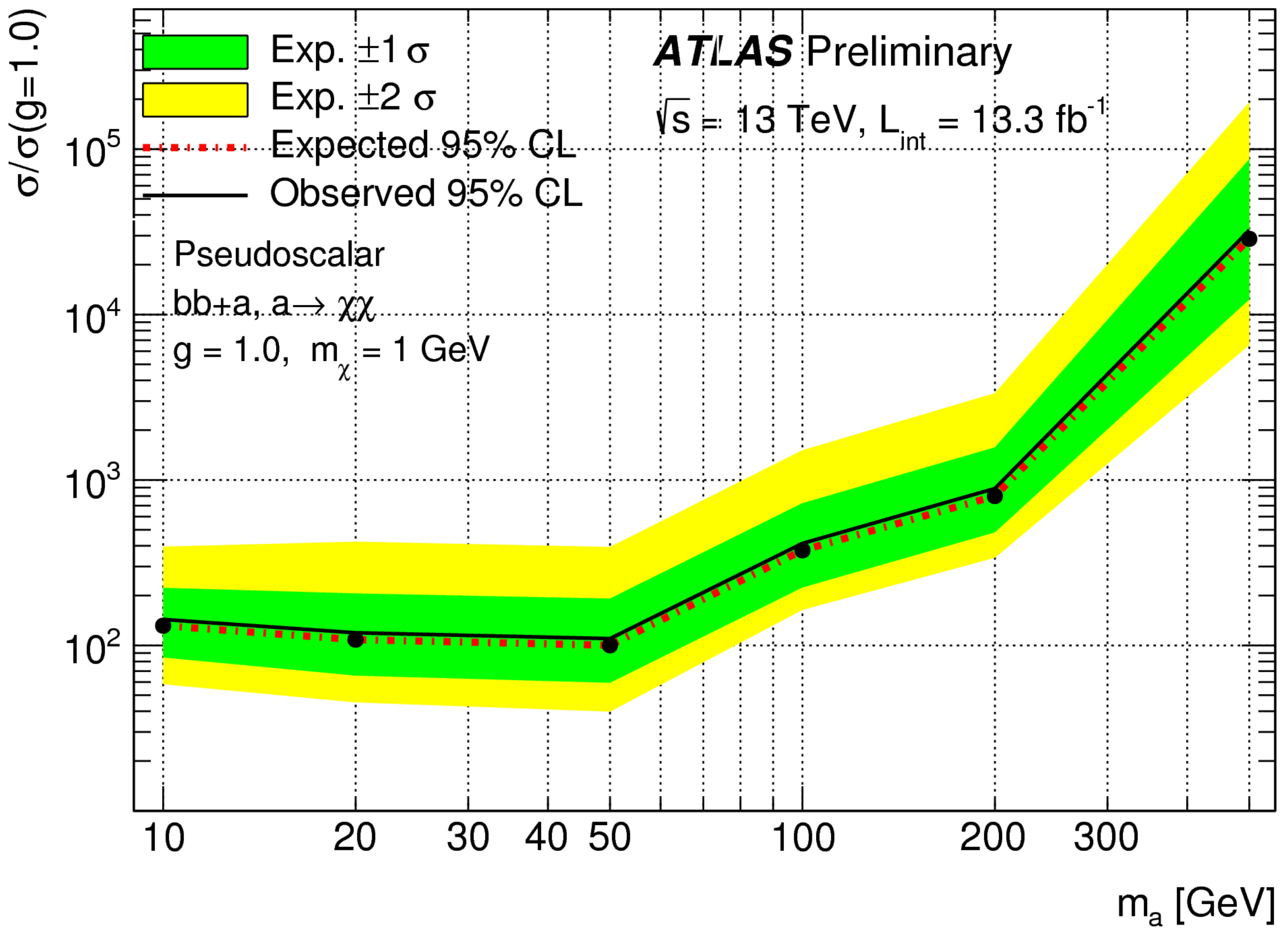


Dataset: 13.3 fb^{-1} (2015 + partial 2016)

- Event selection highlights
  - Two b-tagged jets, imbalanced in p_T
  - E_T^{miss} > 150 GeV
  - Lepton & 3rd jet veto
- Backgrounds & estimation:
  - W+jets, Z(→ νν)+hf jets, Top
  - Backgrounds fit simultaneously in CRs

MET + bb results



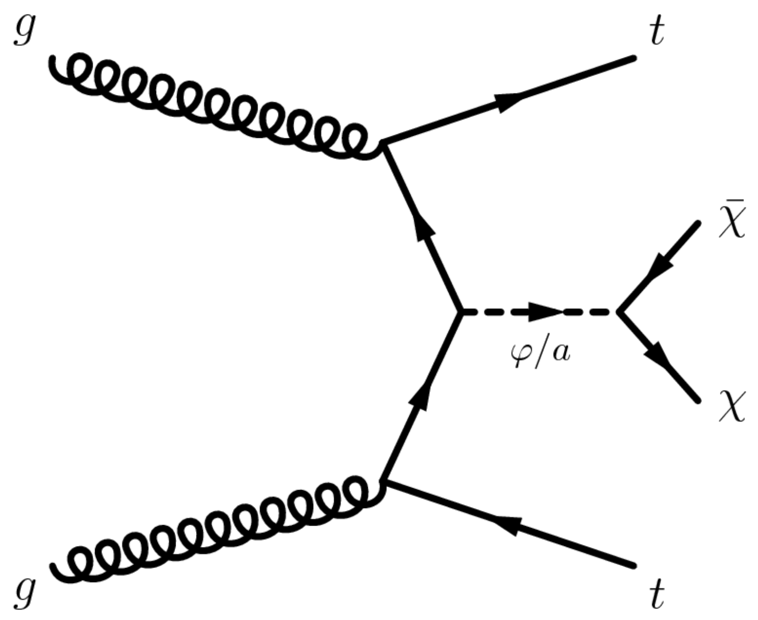


The best observed upper limit on the signal strength for scalar or pseudoscalar mediator with a dark matter mass of 1 GeV is for a mediator with mass of 20 GeV

MET + tt

Dataset: 13.3 fb^{-1} (2015 + partial 2016)
(1 lepton analysis updated with full 2015+16, but results shown with partial dataset)

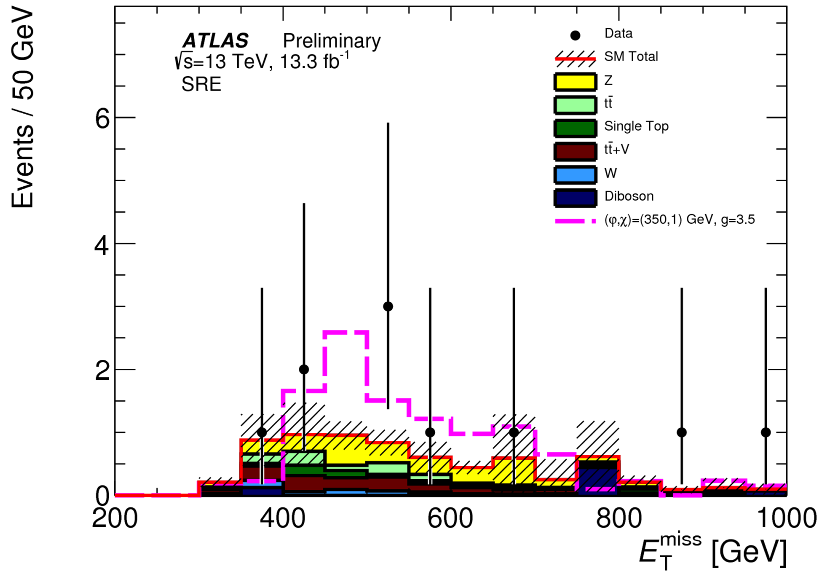
- Event selection
  - 0, 1, or 2 leptons
  - E_T^{miss} > 350, 300, 180 GeV for 0, 1, 2 leptons
  - 2 b-jets (for 0 and 1 lep) or 1 b-jet (for 2 lep)
  - $E_T^{miss}/\sqrt{\Sigma E_T}$ > 14 $GeV^{1/2}$ (0, 1 lep)
  - m_{ll} > 120 GeV (2 lep)
- Backgrounds & estimation:
  - Z+jets – estimated from control regions in data
  - SM top backgrounds - estimated from CR in data
- Signal regions
  - Defined from E_T^{miss} selections



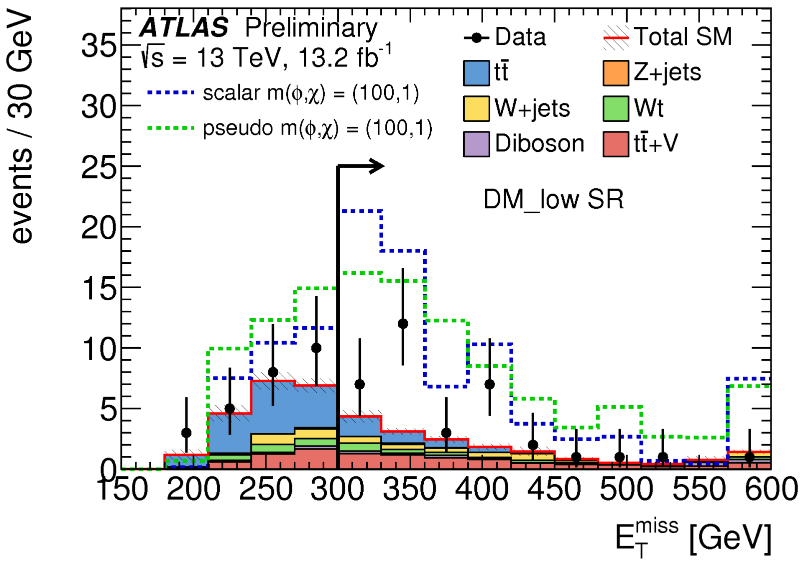
0 lepton	ATLAS-CONF-2016-077
1 lepton	ATLAS-CONF-2016-050, ATLAS-CONF-2017-037
2 lepton	ATLAS-CONF-2016-076

MET + tt results

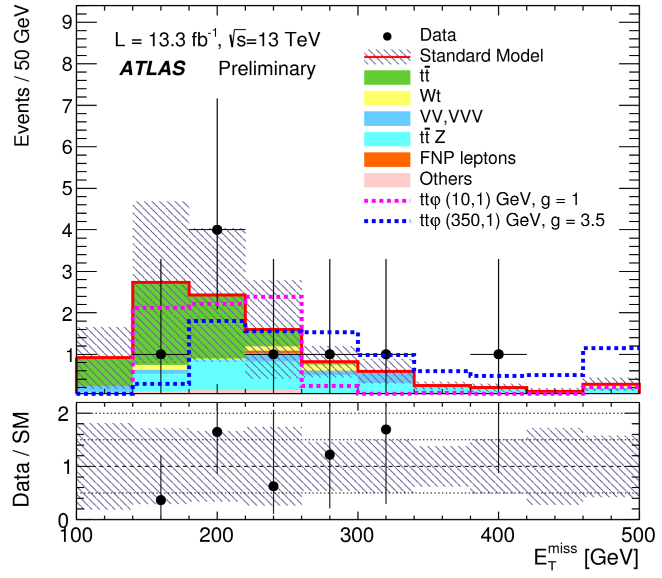
0 lepton

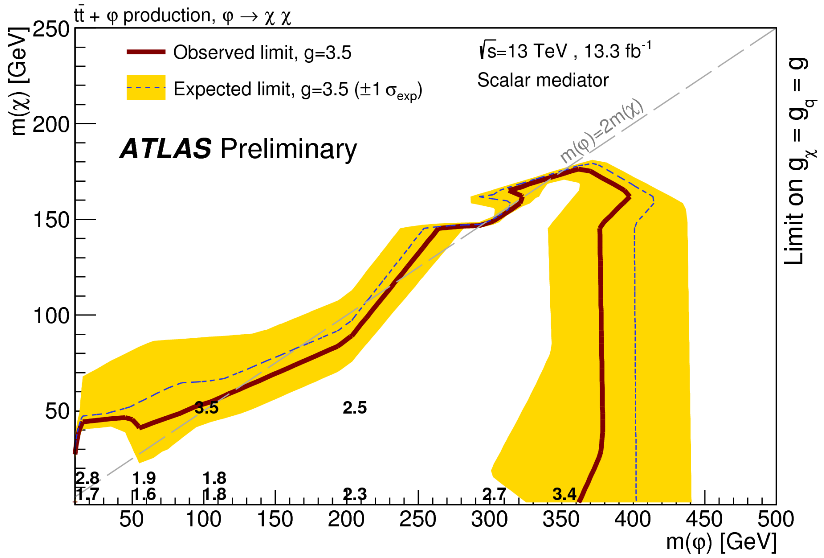


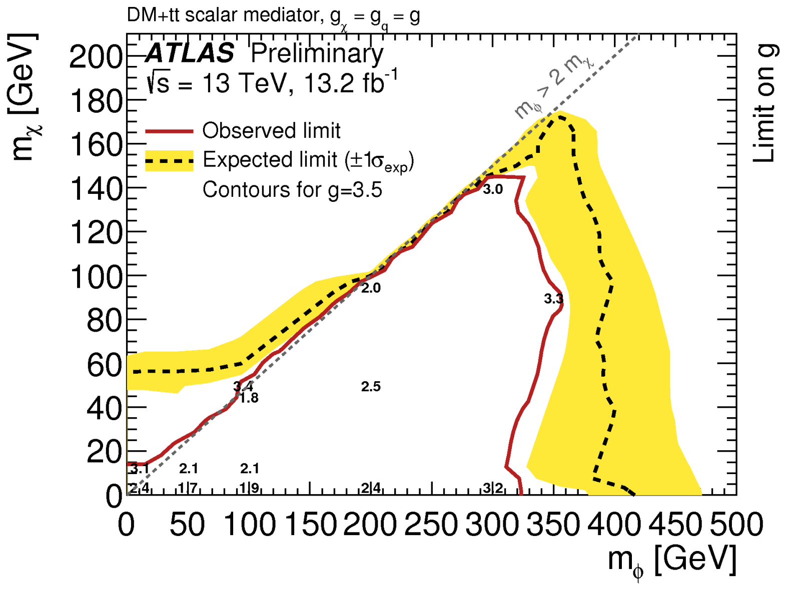
1 lepton

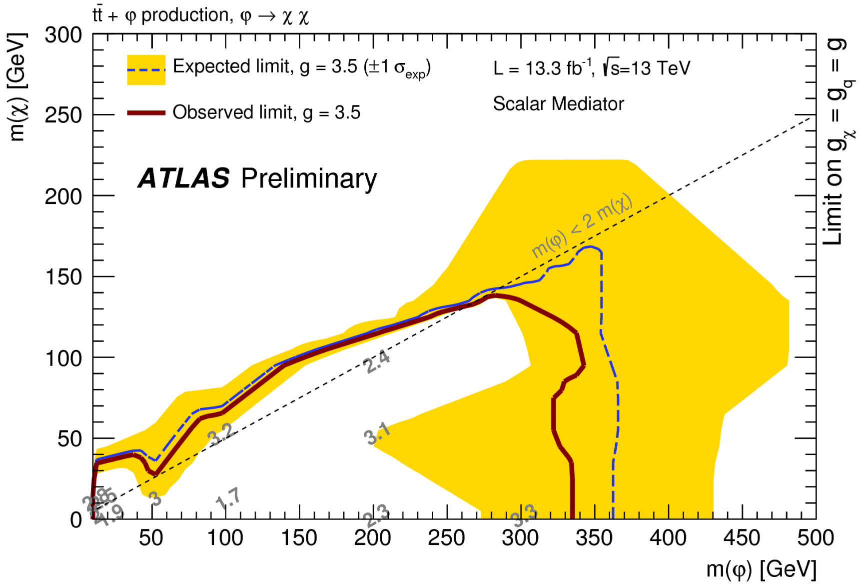


2 lepton

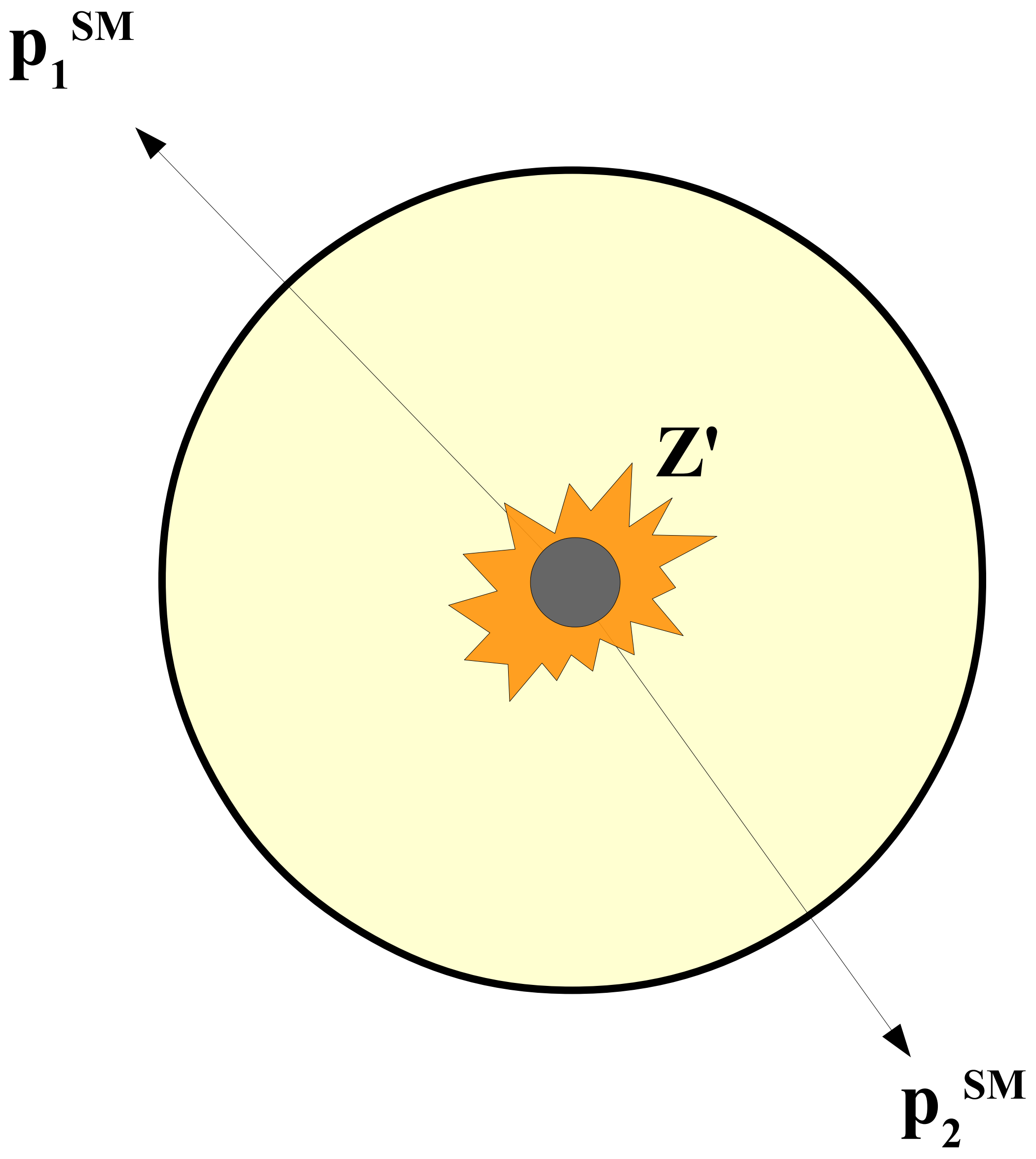








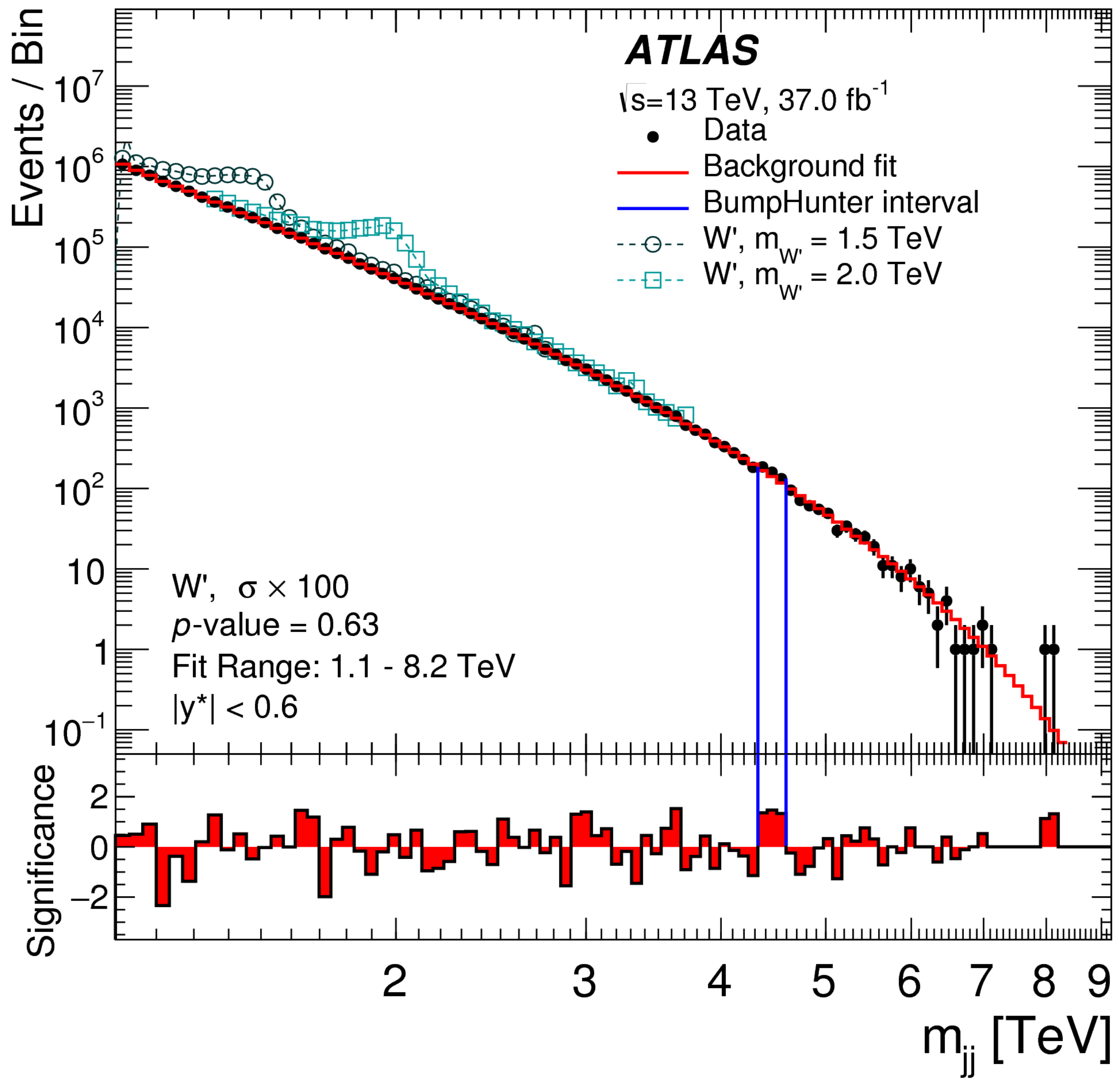
Mediator searches

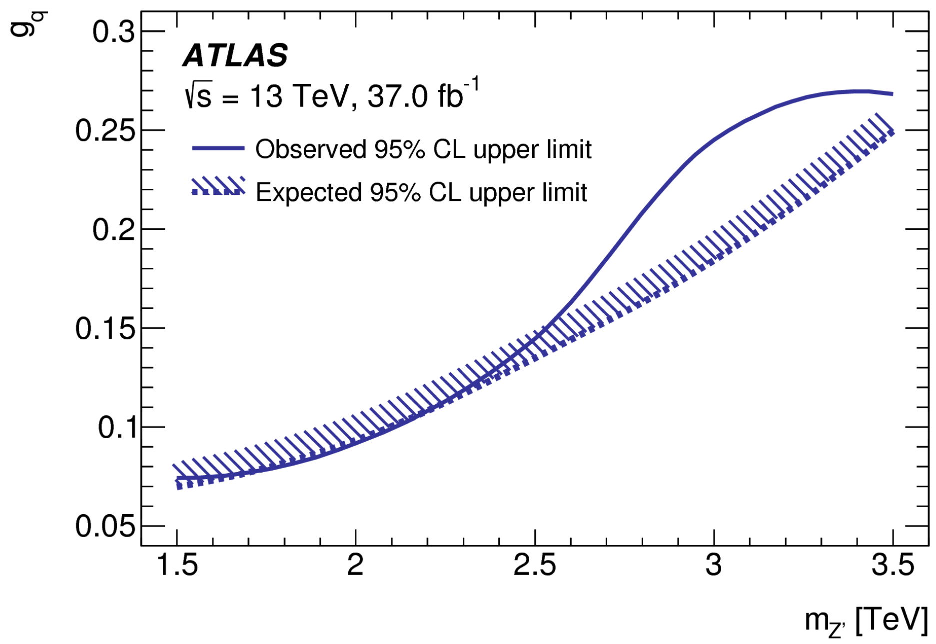


- If the dark matter mediator is produced at the LHC, then it must decay back to SM particles
- This will show up as a *resonance*, such as a Z' resonance, in the invariant mass of the decay products.
- This *invariant mass* is the parameter of interest for these searches

arXiv:1703.09127 [hep-ex]

Dijet





Dataset: 37 fb^{-1} (2015 + 2016)

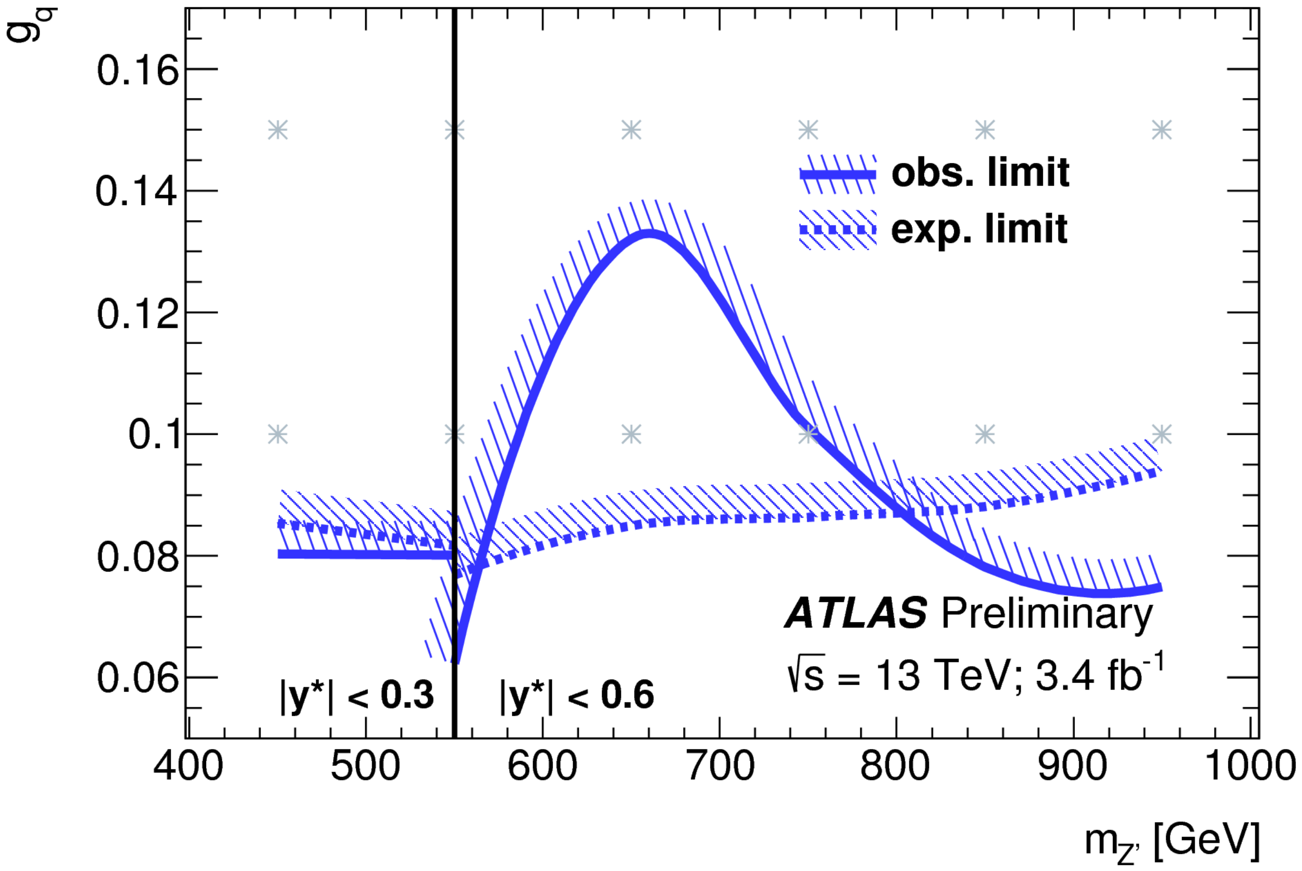
- At least two jets, leading p_T > 440 GeV
- Background is modeled using a fit function to the smoothly falling m_{jj} QCD spectrum
- Signal regions defined by rapidity variable (for balance): $|y^*| \equiv (y_1 - y_2) / 2$
- Z' (g_q = 0.1) ruled out for < 2.1 TeV obs (2.1 TeV exp)
- Z' (g_q = 0.2) ruled out for < 2.9 TeV obs (3.3 TeV exp)

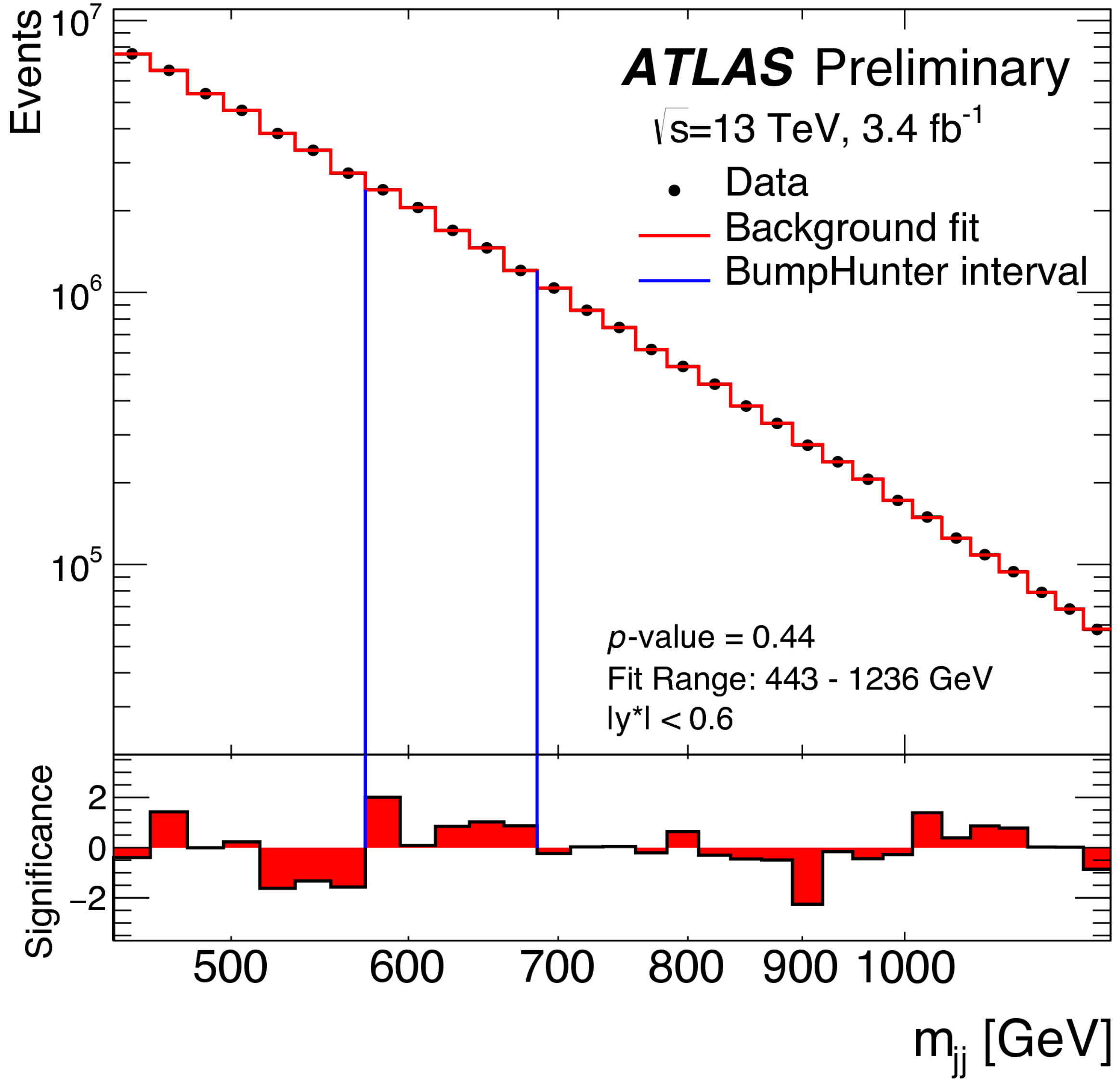
Dijet Trigger-object Level Analysis

Dataset: 3.4 fb^{-1} (2015)

ATLAS-CONF-2016-030

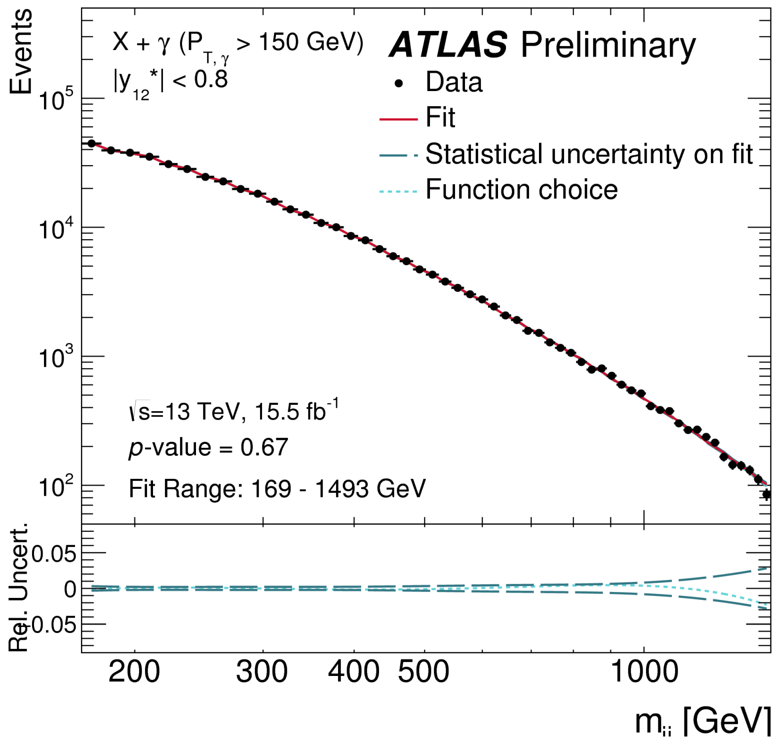
- Trigger stream of partially rebuilt objects in the detector (no tracking or muon information)
- Backgrounds & estimation: same strategy as the full dijet analysis, more calibrations needed on TLA jets
- Signal regions – lower kinematic reach than the dijet analysis, searching for lighter resonances





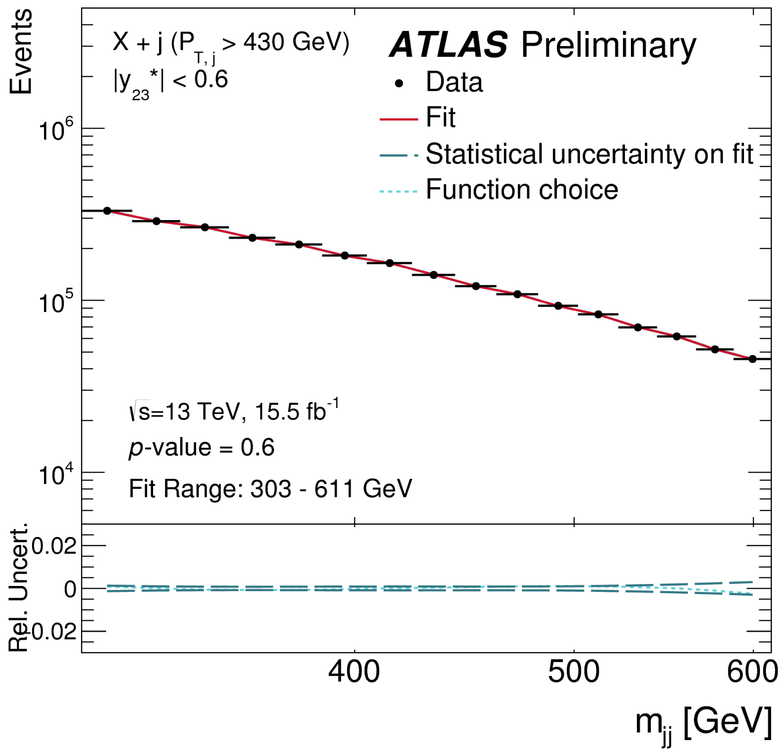
← Couplings excluded above solid line

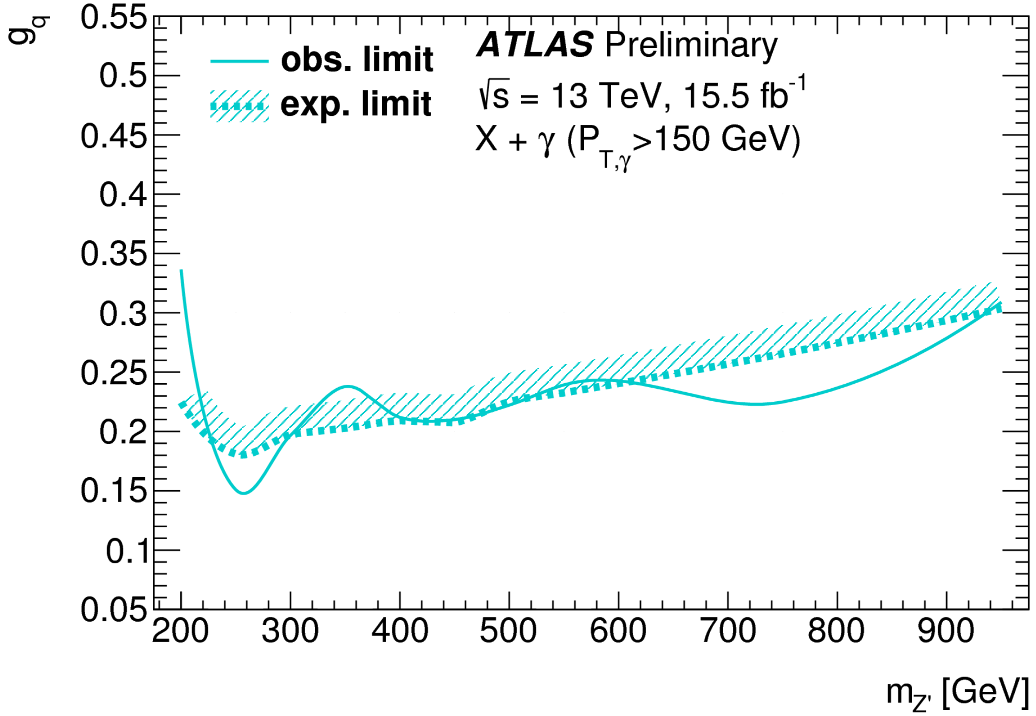
Dijet + ISR (jet or γ)



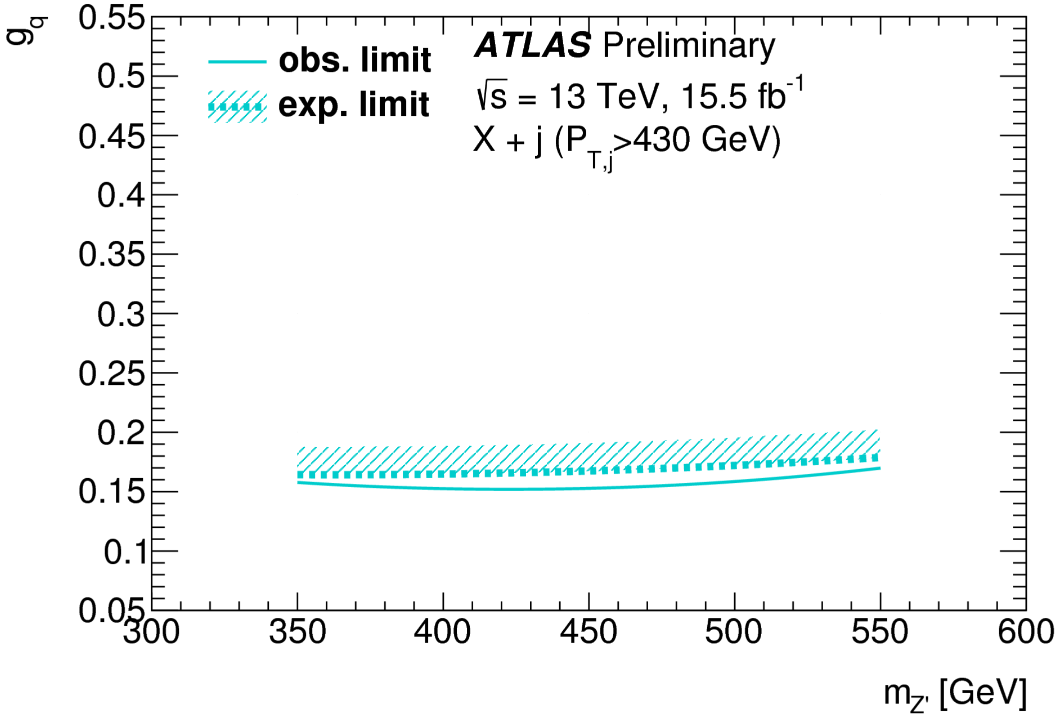
Dataset: 15.5 fb^{-1} (2015 + partial 2016)

- Triggering on an event with an energetic photon or jet to look for lower mass dijets
- Backgrounds and estimation similar to the other dijet analyses
- Signal regions separate for ISR jets and γ's, and for the $|y^*|$ parameter
  - Limits placed on low mass mediators with a range of coupling to a Z' model

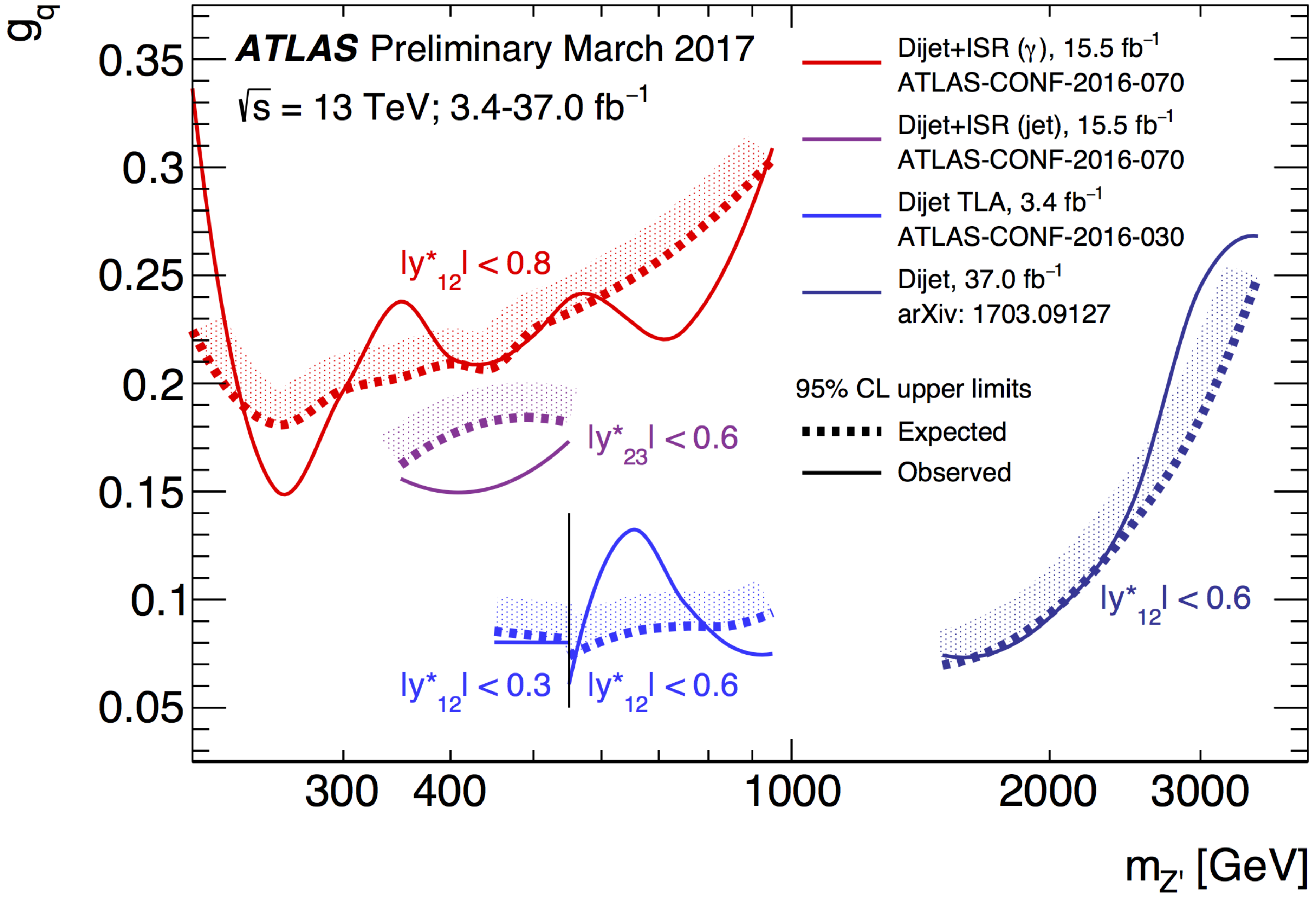




ATLAS-CONF-2016-070

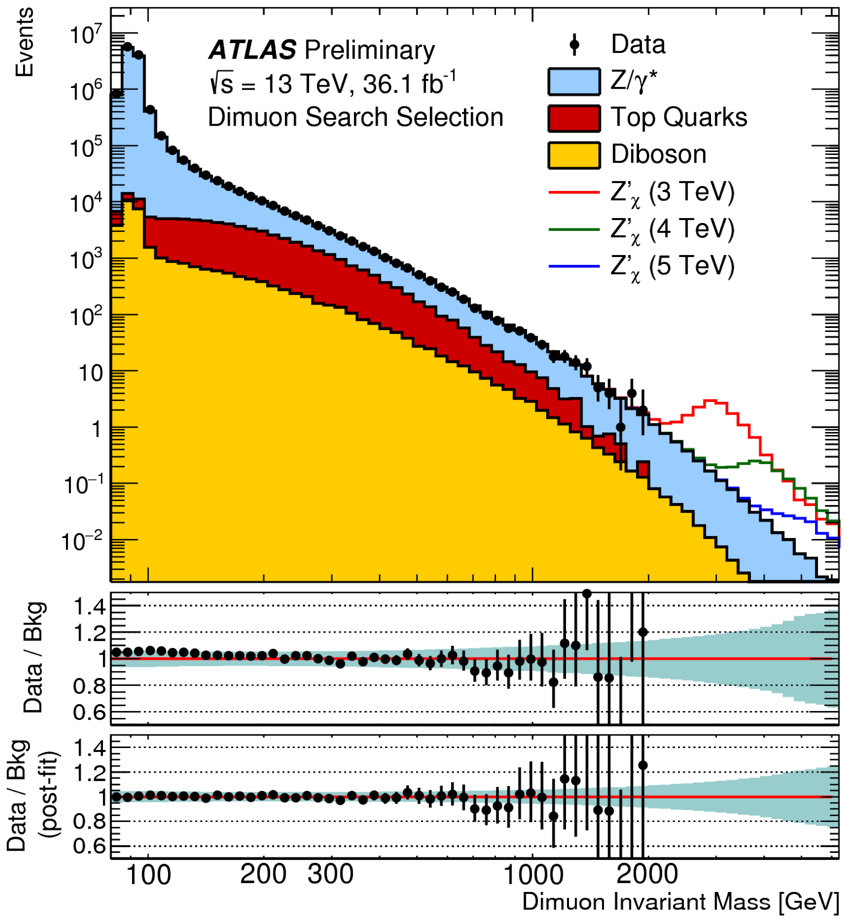


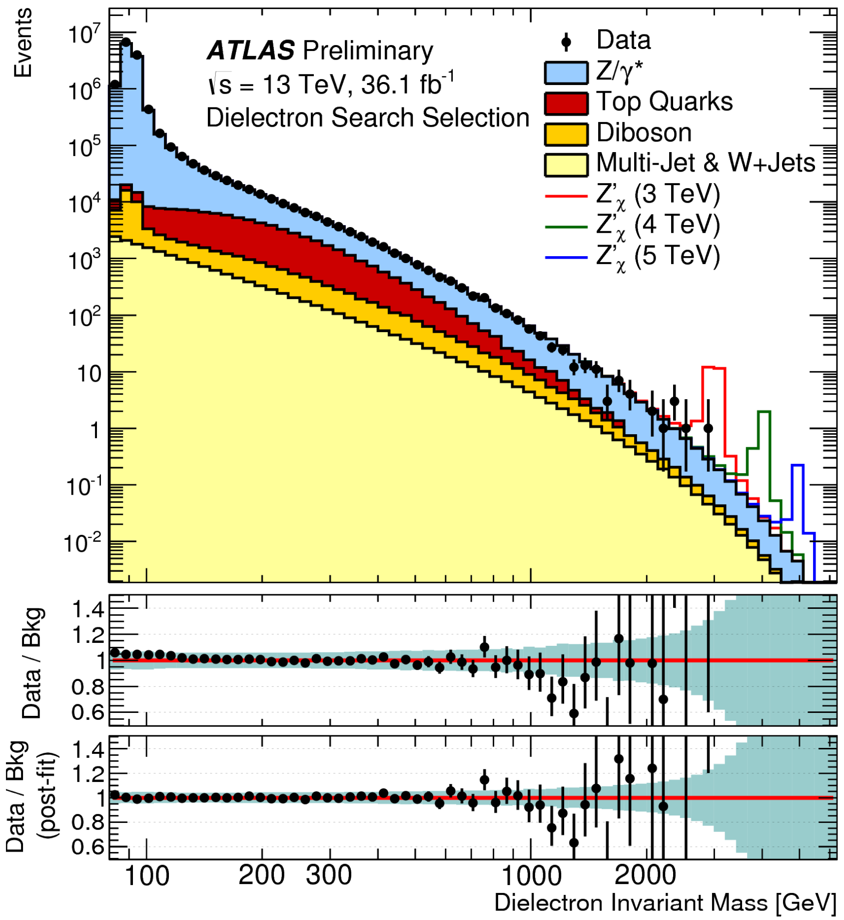
Dijet Combination

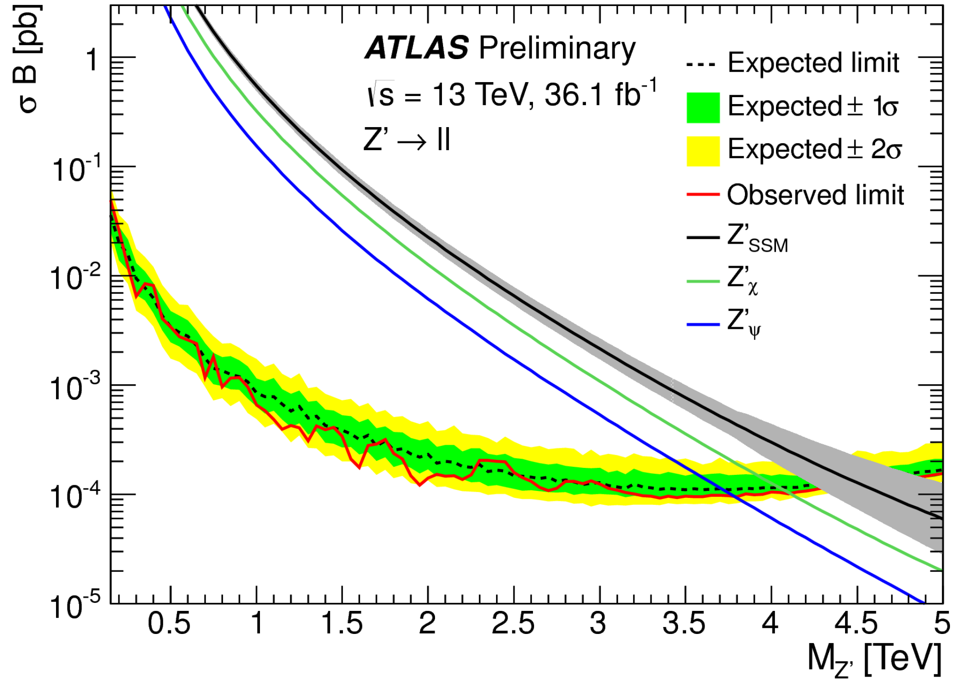


Dilepton

ATLAS-CONF-2017-027







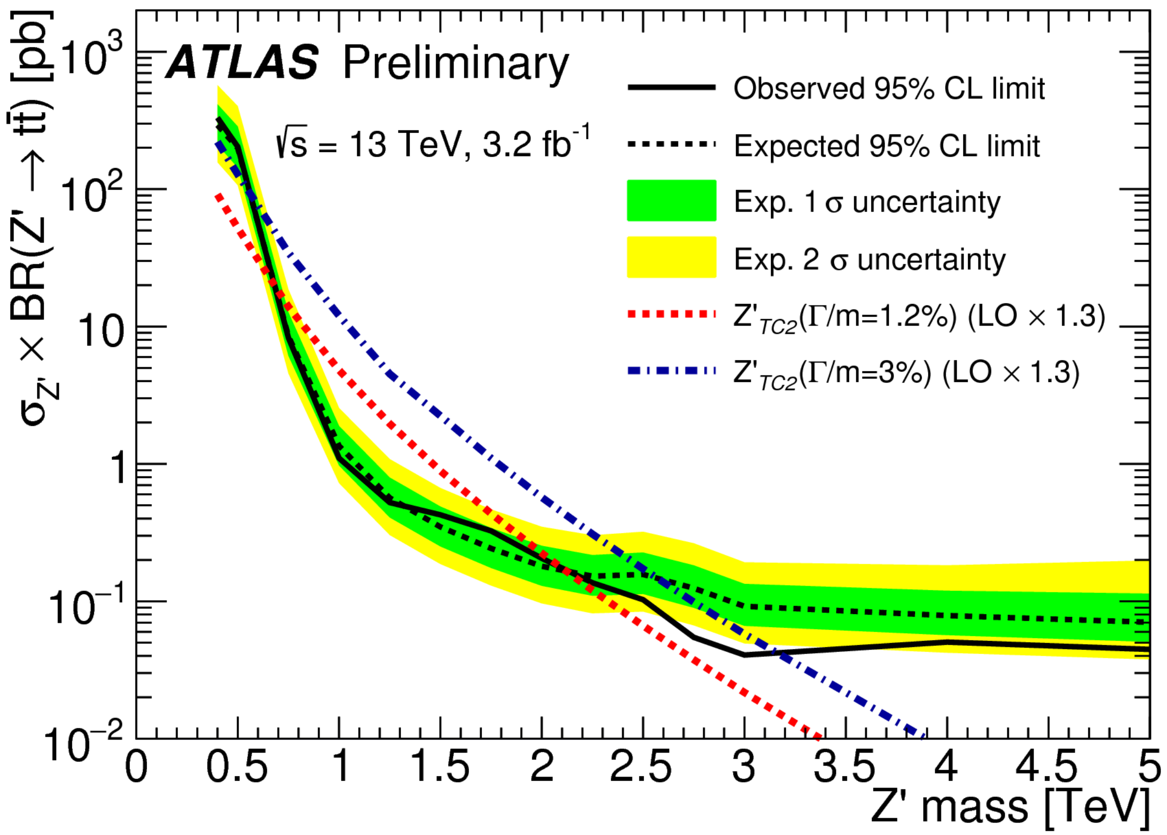
Dataset: 36.1 fb^{-1} (2015 + 2016)

- Events are selected by finding two same flavour, isolated leptons
- Backgrounds: Drell-Yan, top, and dibosons are all modeled through MC
- Signal regions are defined in ee, μμ, and combined, and no excesses at:
  4.1 TeV (4.0 TeV) obs (exp)

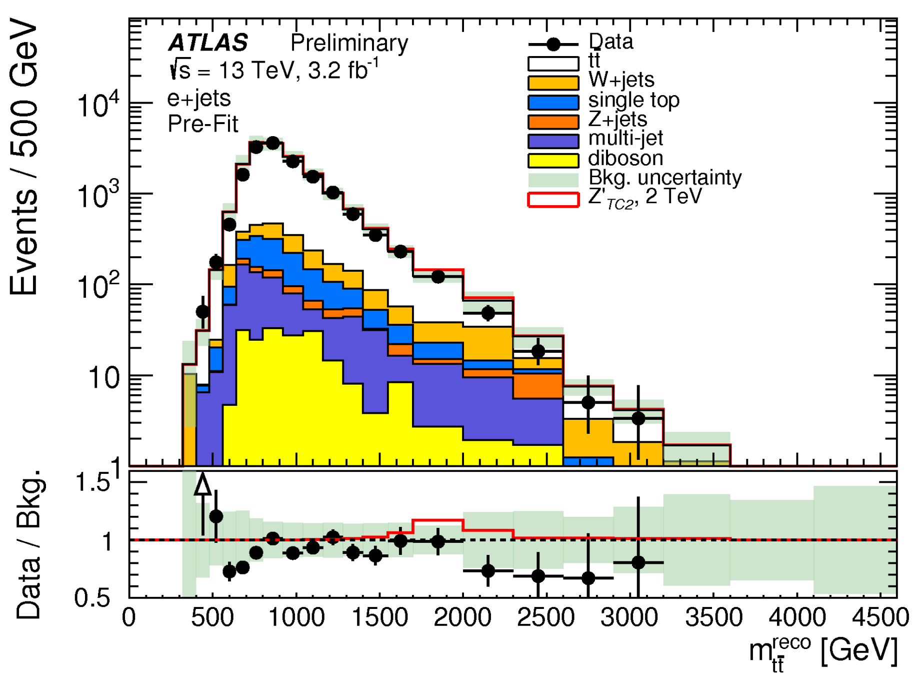
tt resonances

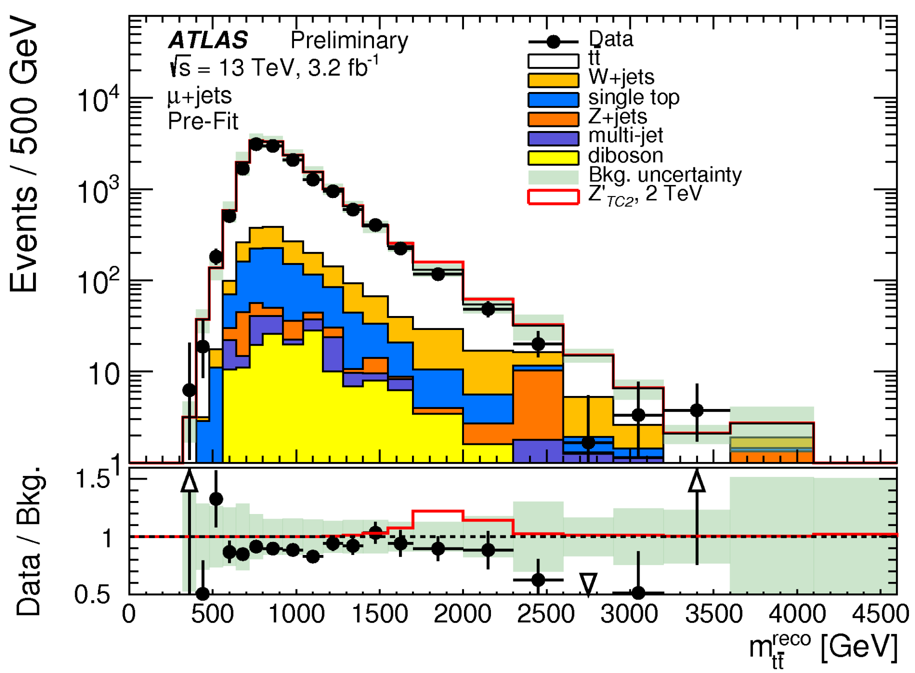
Dataset: 3.2 fb^{-1} (2015)

- Events are selected with one lepton, MET, and a jet
- Backgrounds include tt, W/Z+jets, and diboson which are estimated in MC, and multi-jets, which are estimated in data
- The mass spectrum of the tt system is searched for resonances, in the absence of those, a Z' is excluded at 95% CL between 0.7 and 2.0 TeV



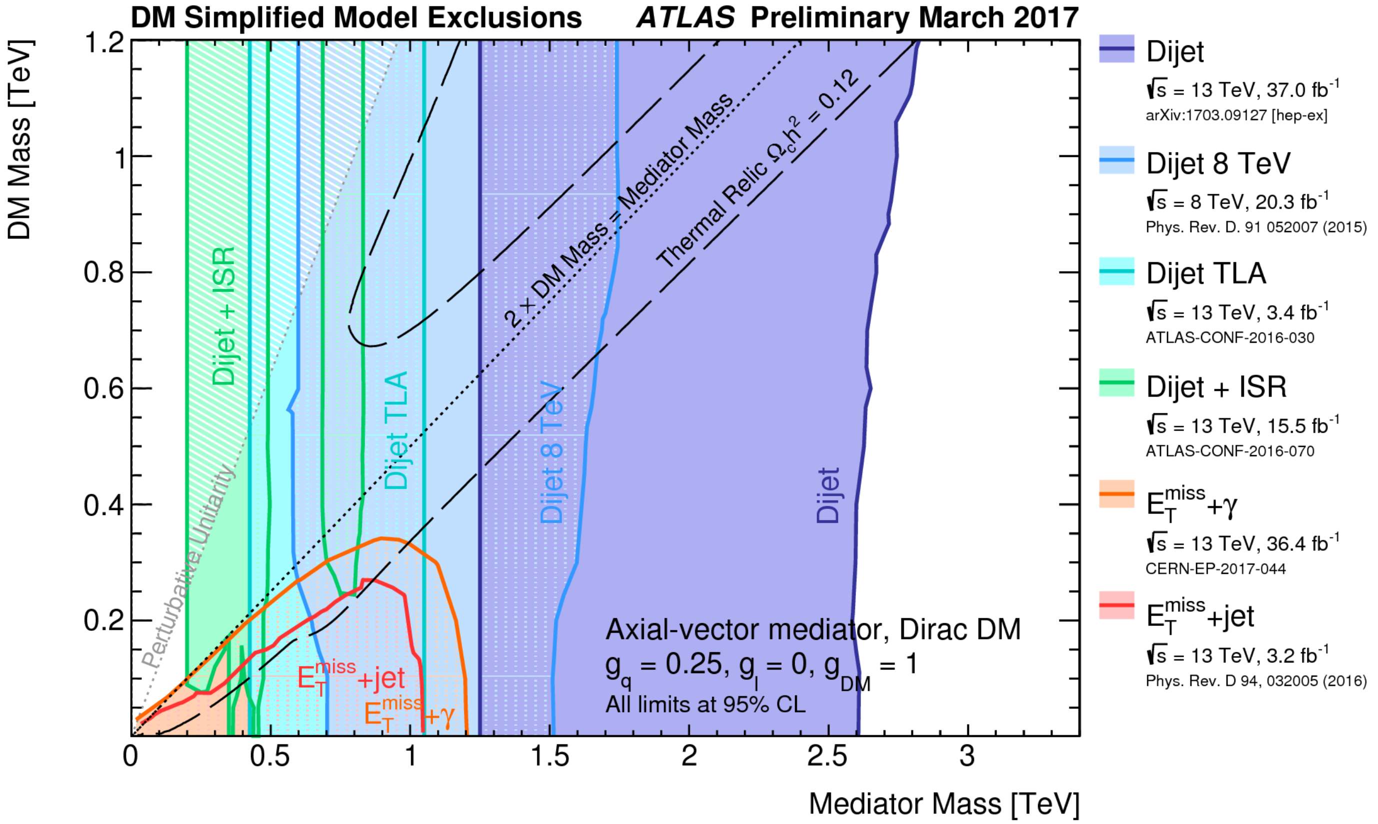
ATLAS-CONF-2016-014

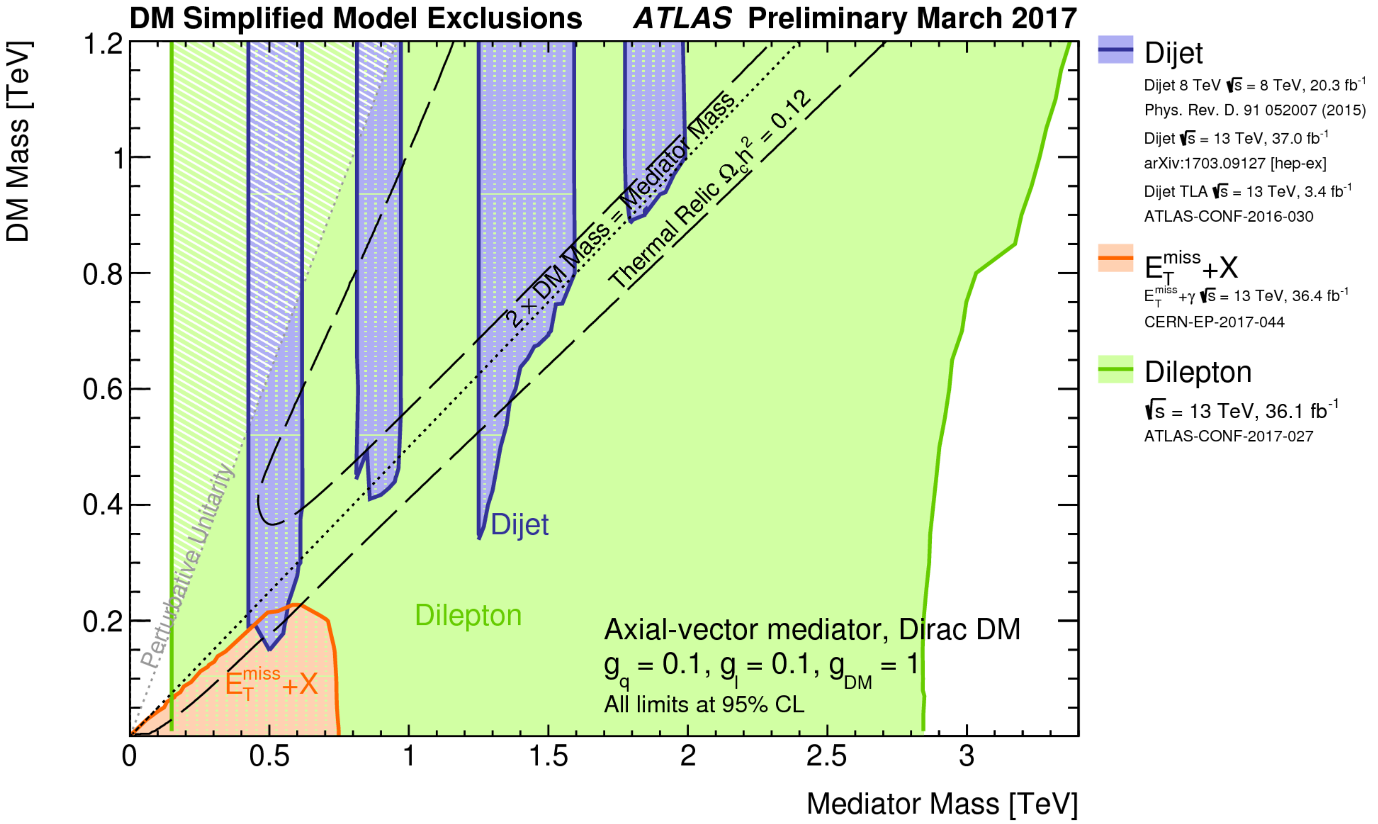




Combinations in mediator-DM mass plane

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



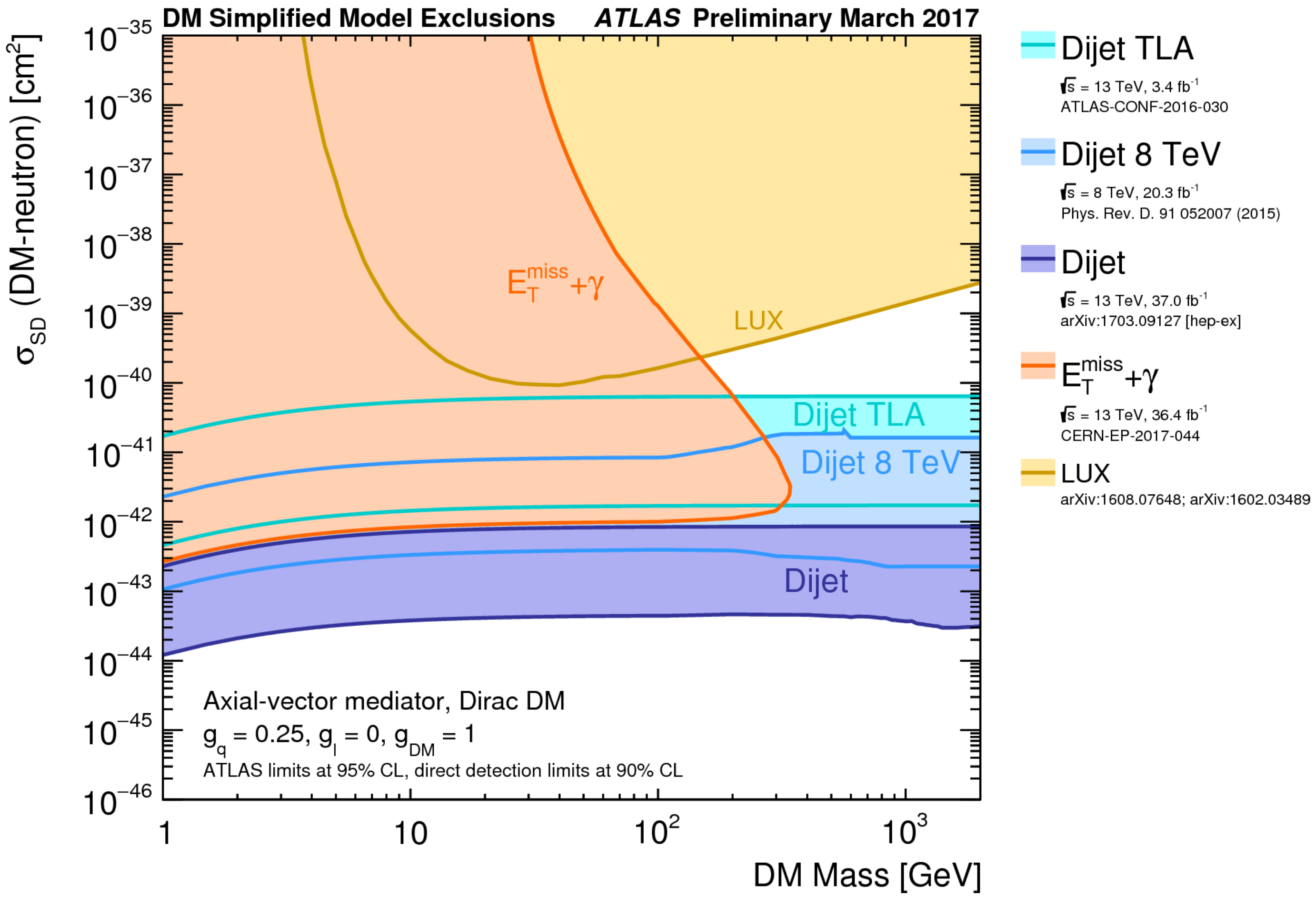


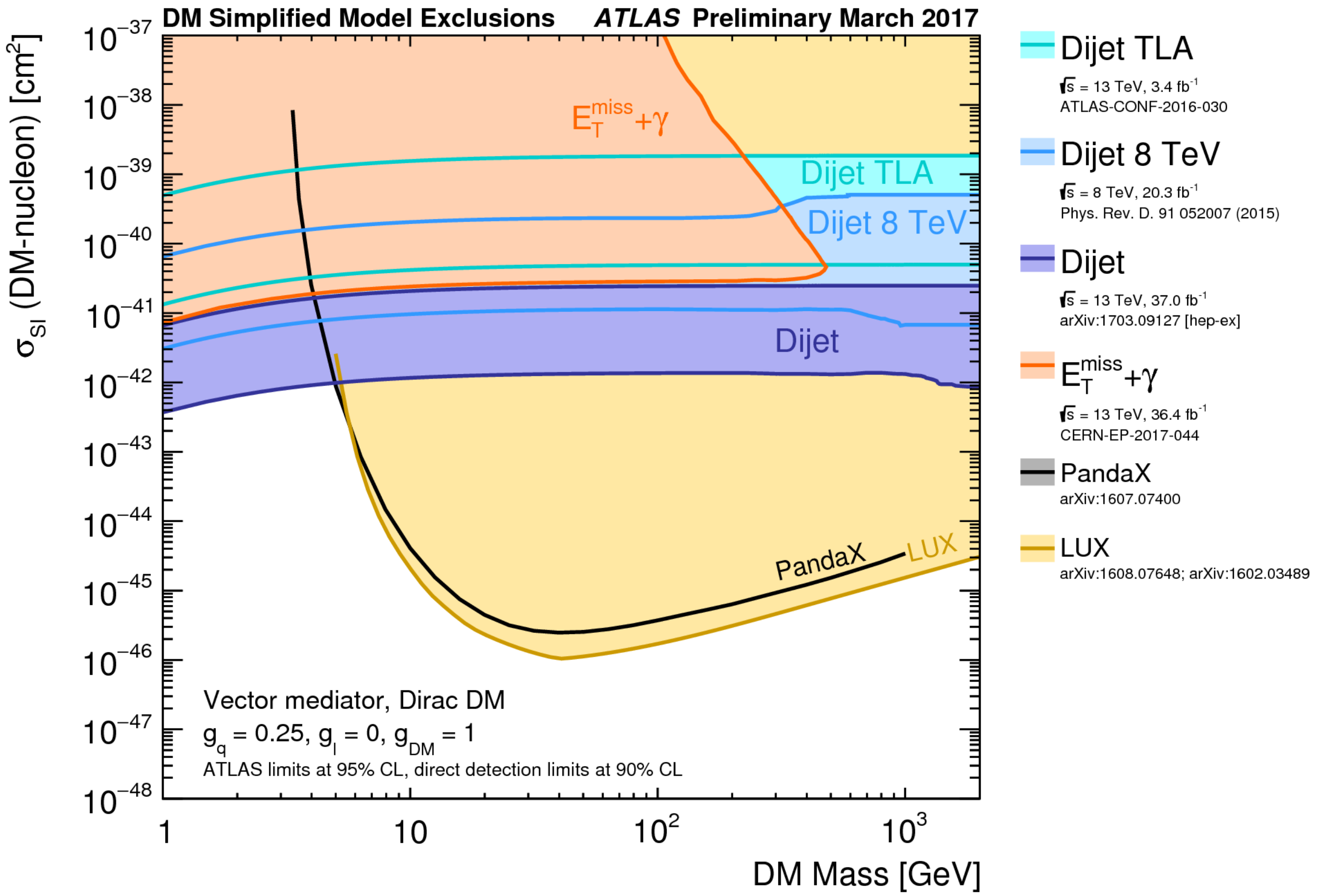
- Axial vector mediators with **no leptonic coupling**s, only mediators coupling to quarks and dark matter.
- *Dijet* analyses place the most stringent limits in the high mediator mass range

- Axial vector mediators with **small leptonic couplings** and mediators coupling to quarks and dark matter.
- *Dilepton* analyses place the most stringent limits in the high mediator mass range

Combination comparison to direct detection

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

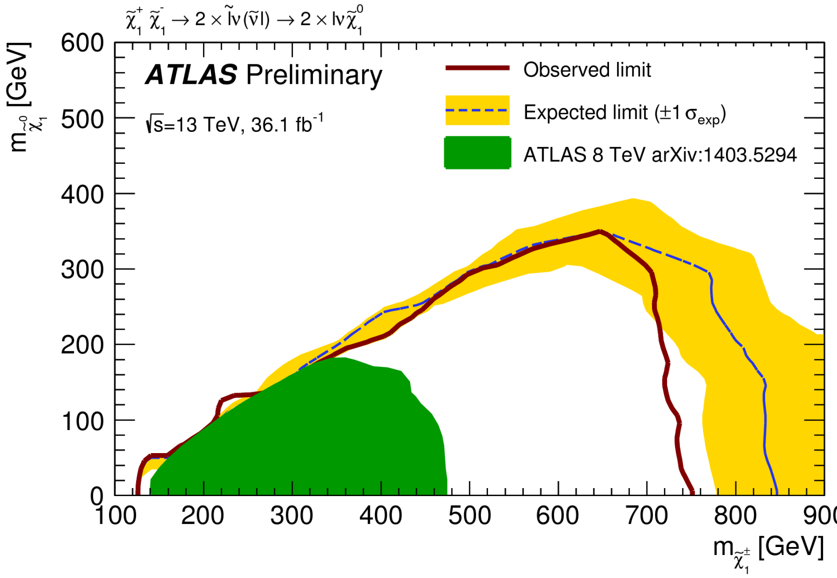




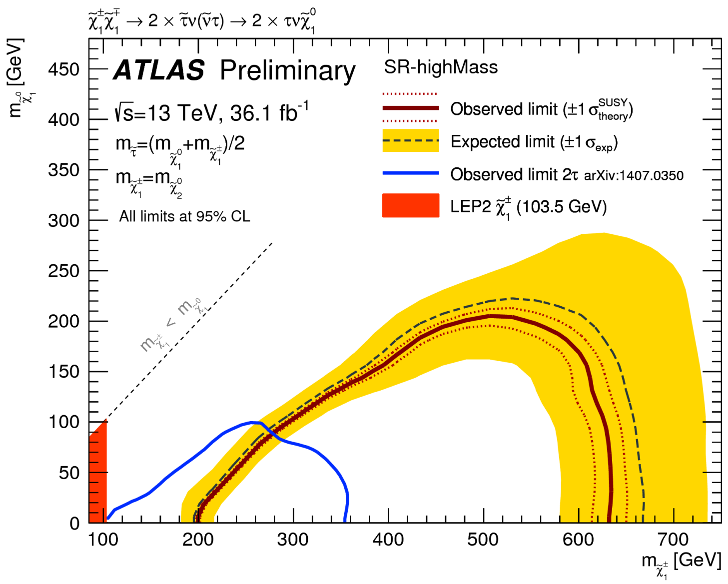
Axial-vector results are particularly important as they put the most stringent limits on the spin-dependent dark matter searches!

Bonus: SUSY dark matter searches

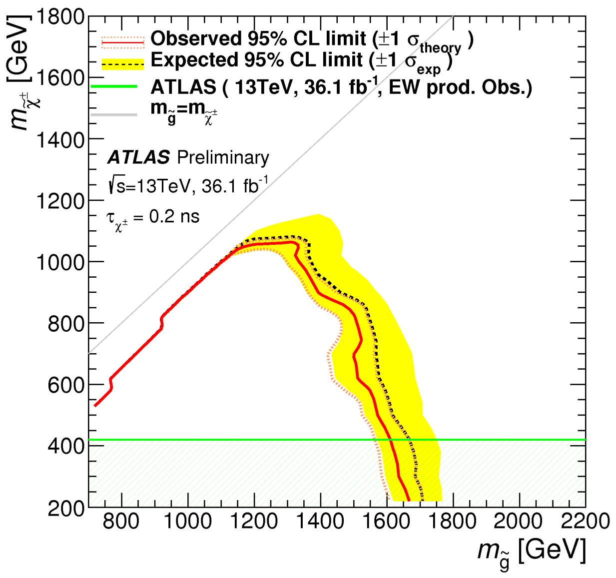
ATLAS-CONF-2017-039



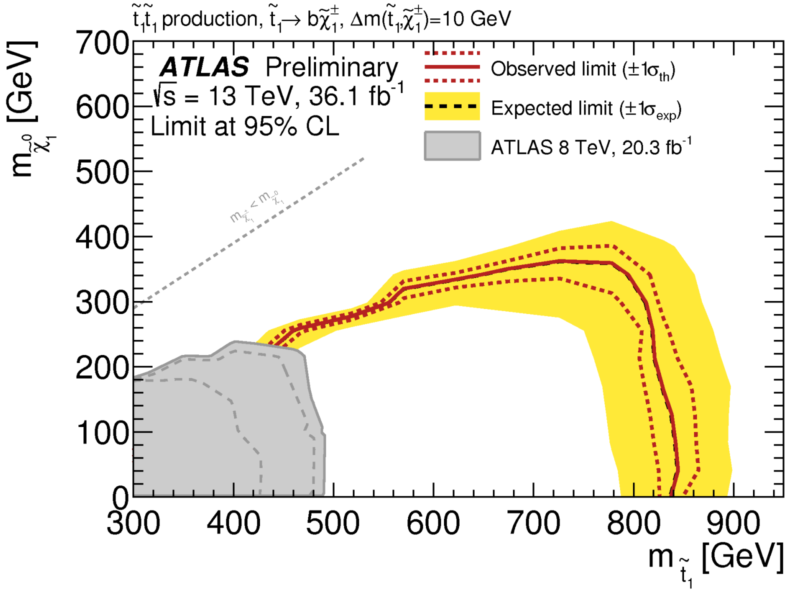
ATLAS-CONF-2017-035



ATLAS-CONF-2017-017



ATLAS-CONF-2017-037



- There are a large variety of searches at ATLAS to find dark matter. The ones presented previously are not the only ones that are competitive!
- SUSY searches for the lightest supersymmetric partner and their mediators have excellent discrimination power
- Following methods similar to those in JHEP09 (2016) 175, limits can be put on charginos $\tilde{\chi}_1^{\pm}$ and neutrilinos $\tilde{\chi}_1^{0}$

Summary

- Searches in ATLAS that are complimentary to each other and to direct detection searches
- Searches have moved from EFTs to mediator models, enabling searches for mediators themselves
- Many interesting 13 TeV results in both 2015 and 2016 data

….many more results to come!

backup