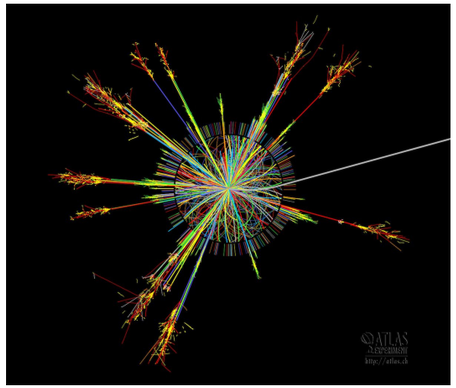
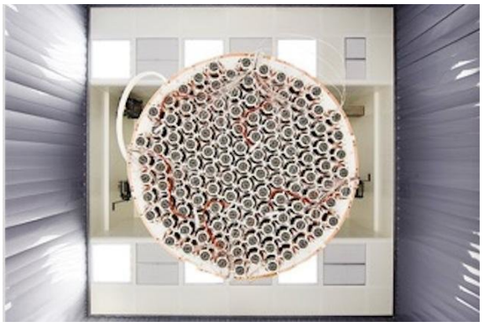
Dark Matter and Mediators Investigated with Jets at the LHC

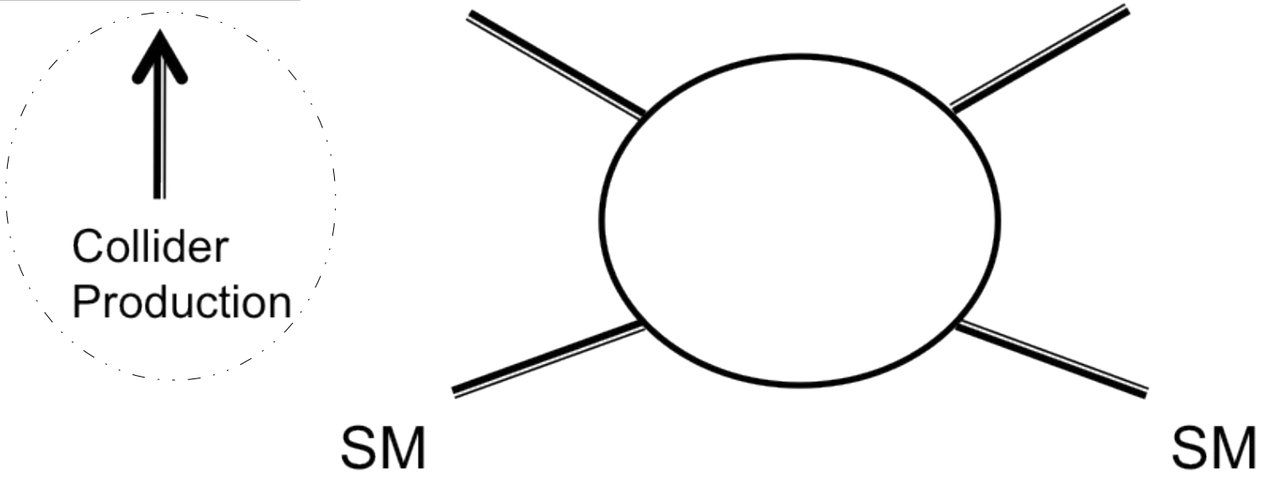
Alison Elliot
Queen Mary University of London

On behalf of the ATLAS, CMS, and LHCb Collaborations

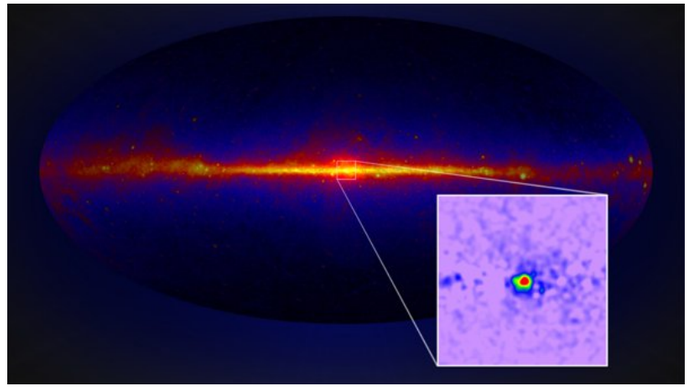
How do we find out what Dark Matter is?



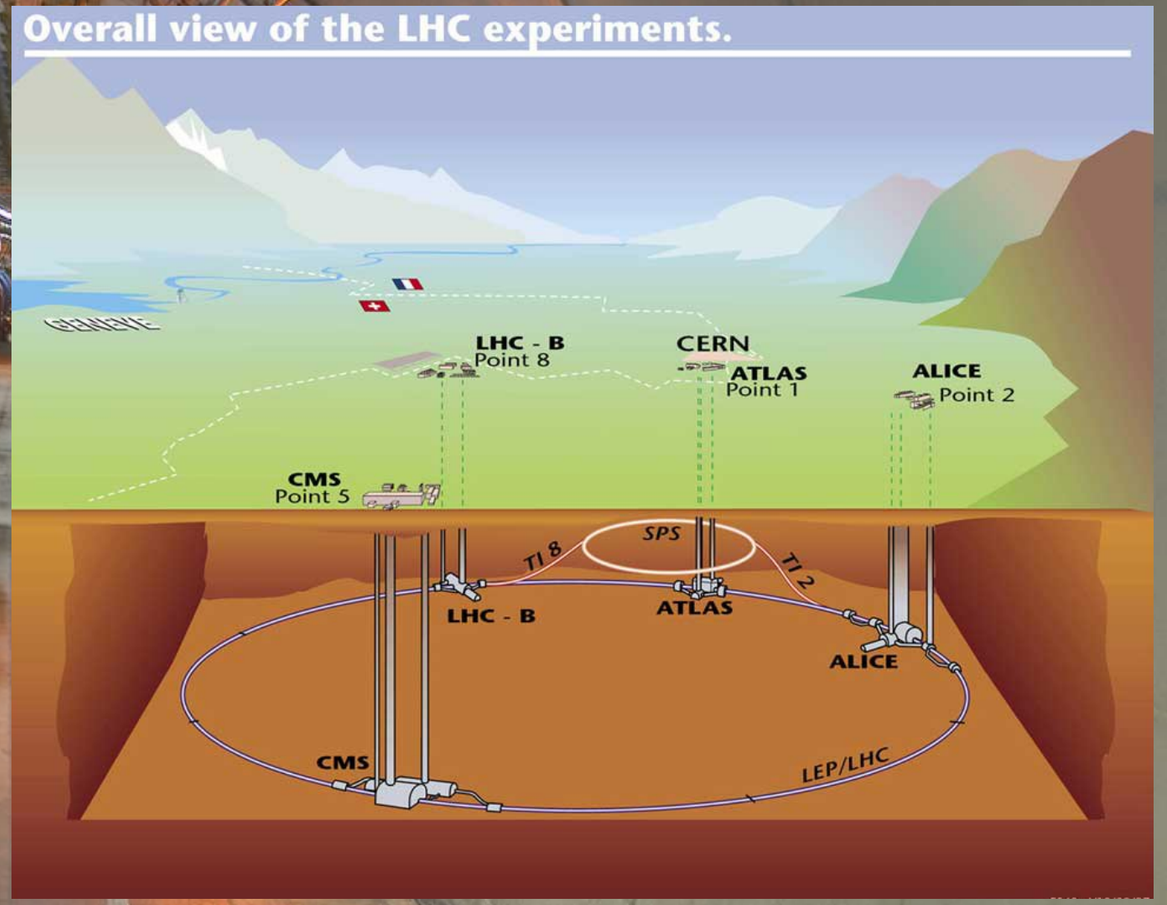




Dark Matter
Annihilation

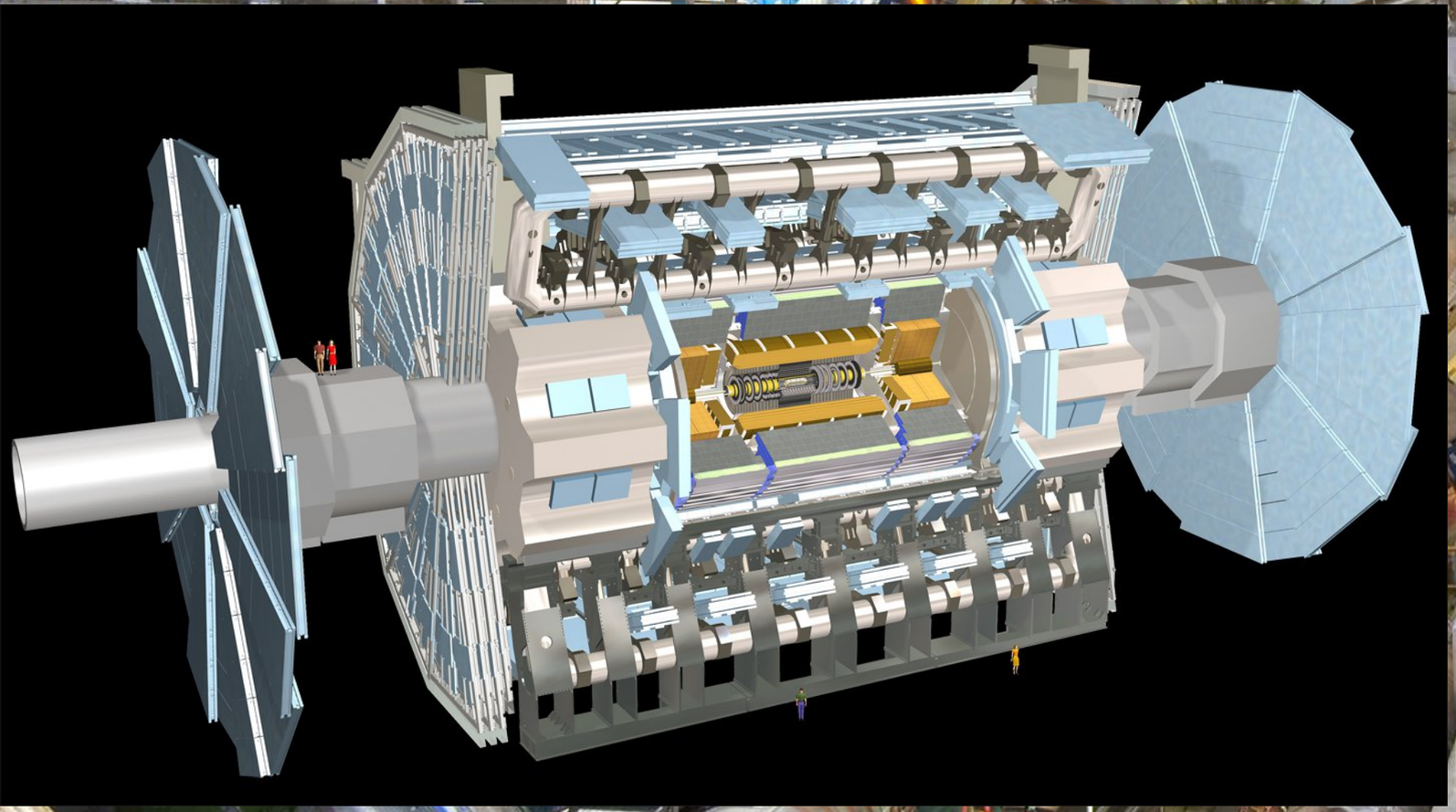


Experimental setup: the Large Hadron Collider

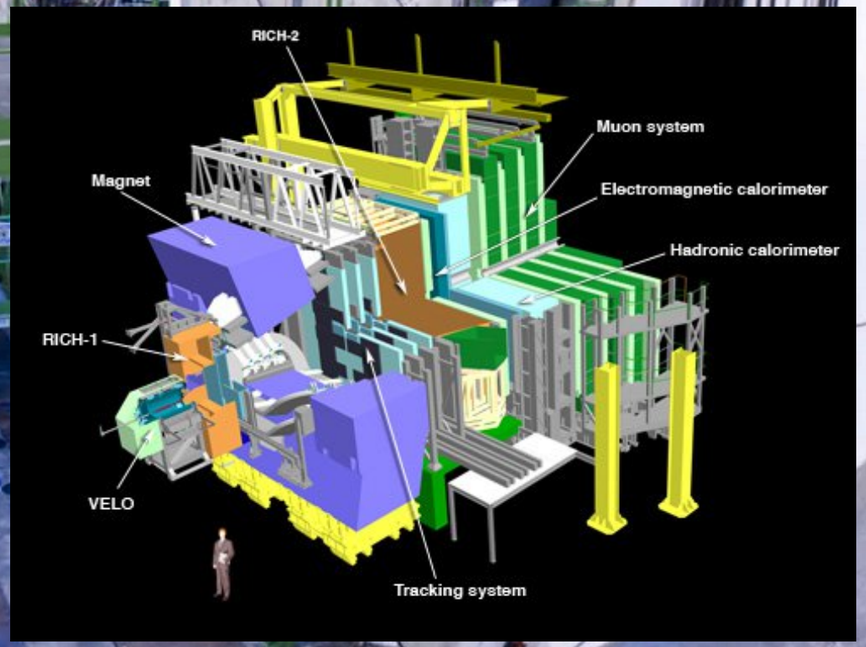


Detector: CMS

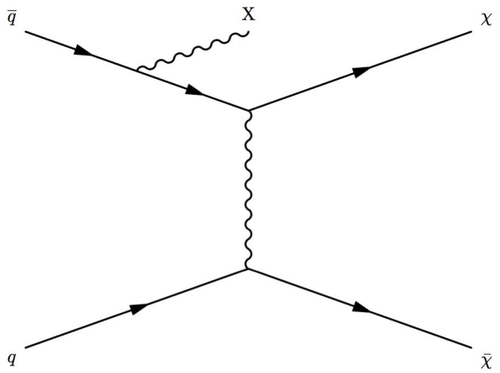
Detector: ATLAS

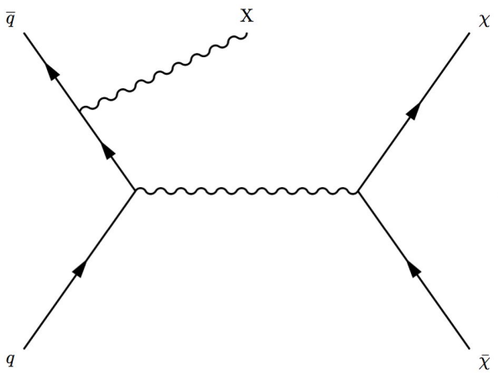


The detector: LHCb

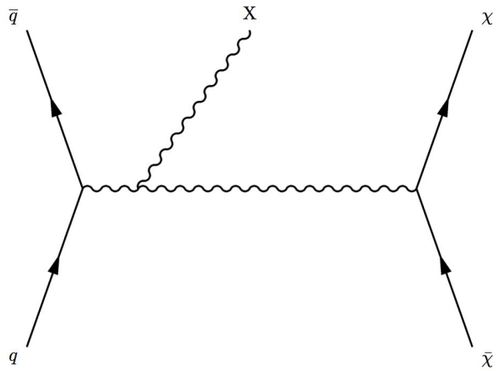


Simple models of Dark Matter at the LHC





"Simplified models" with a mediator



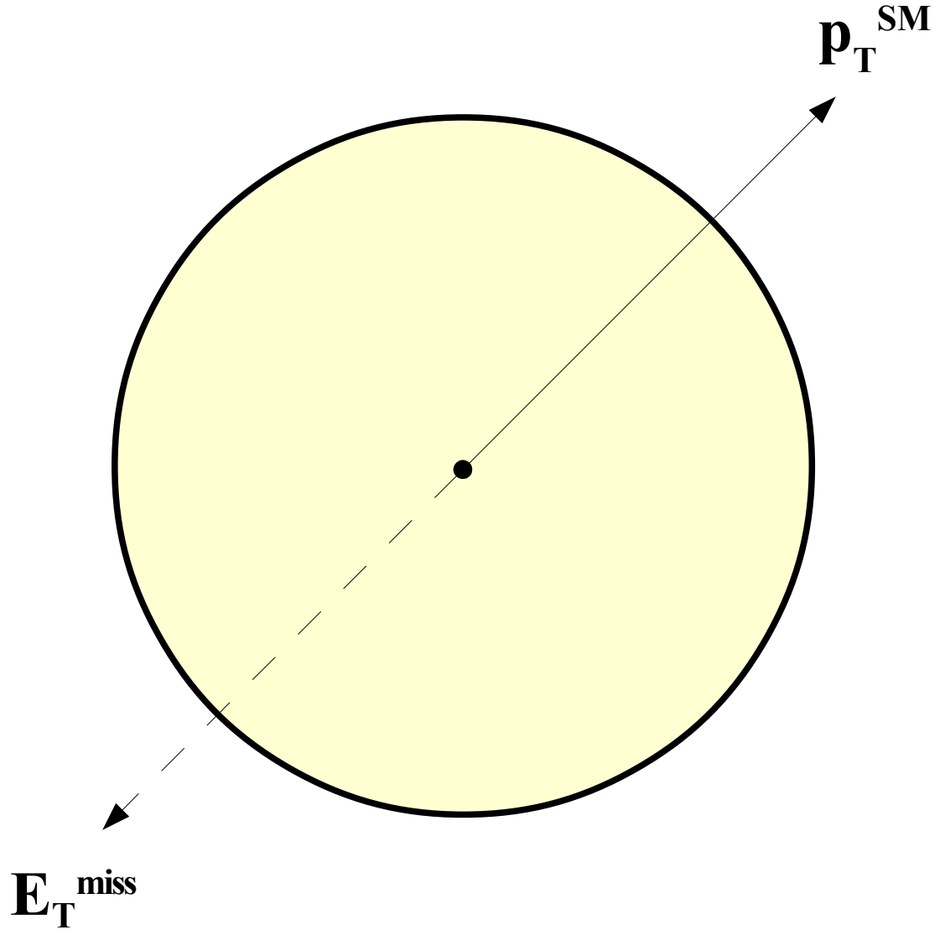
Initial state radiation

Other interactions

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

“Mono-X” searches

- Presence of dark matter inferred from momentum imbalance in the ATLAS or CMS detector
- Key variable is the magnitude of *missing momentum* $|\mathbf{E}_t^{miss}|$ transverse to beam direction, known as missing energy E_T^{miss}
- Large *separation* $\Delta\varphi$ required between $\mathbf{E}_T^{miss}$ and $\mathbf{p}_T^{SM}$ to guard against mismeasurement
- Suppression of *fake* E_T^{miss} through a cut on any coming from other sources: $E_T^{miss}/\sqrt{\Sigma E_T}$



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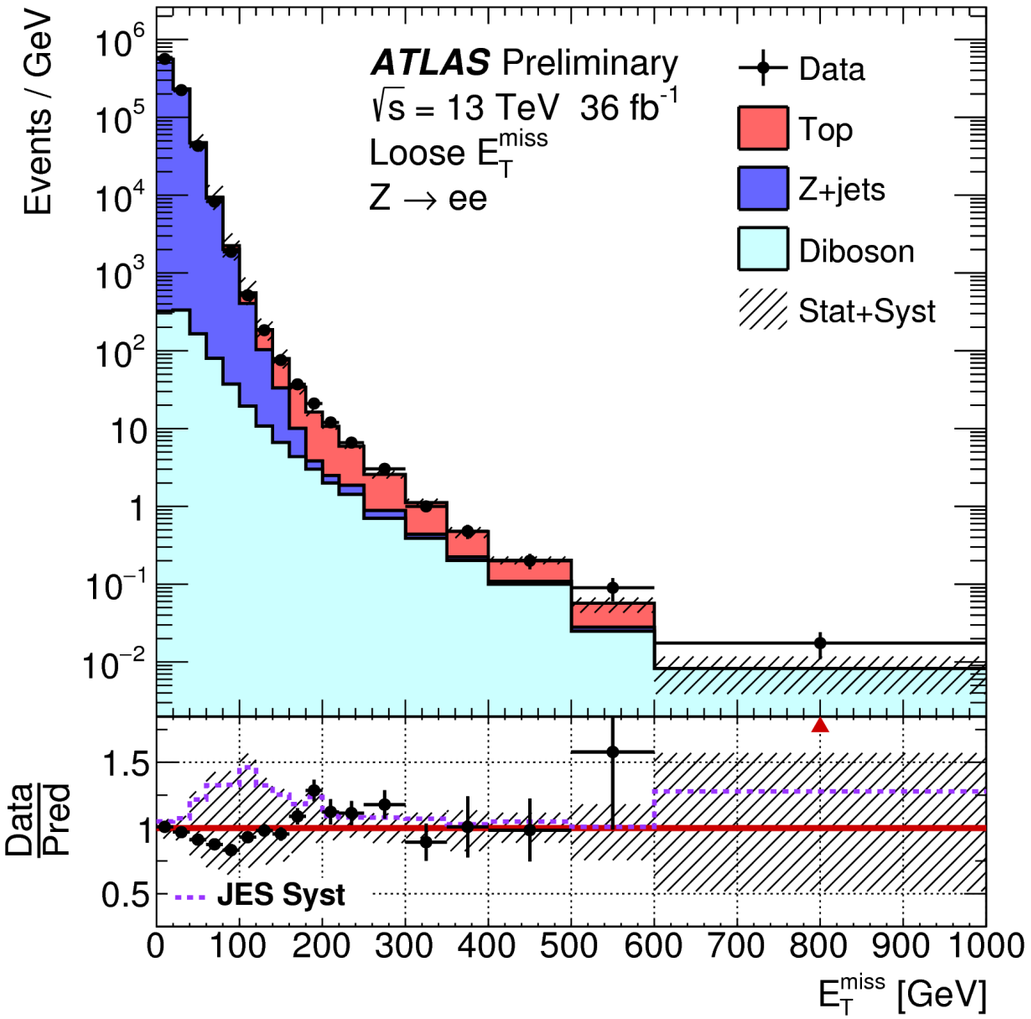


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2018-023/

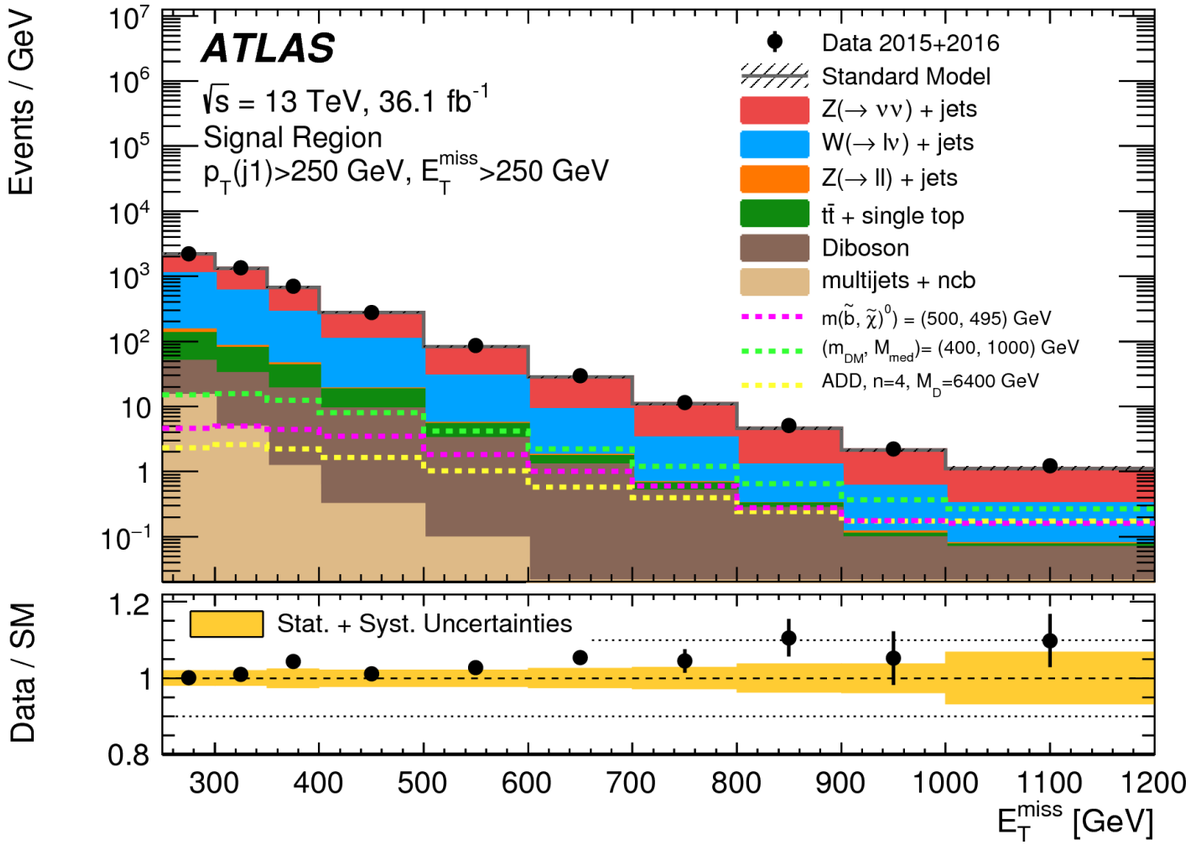
Mono-jet – ATLAS

Queen Mary University of London

JHEP 01 (2018) 126

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

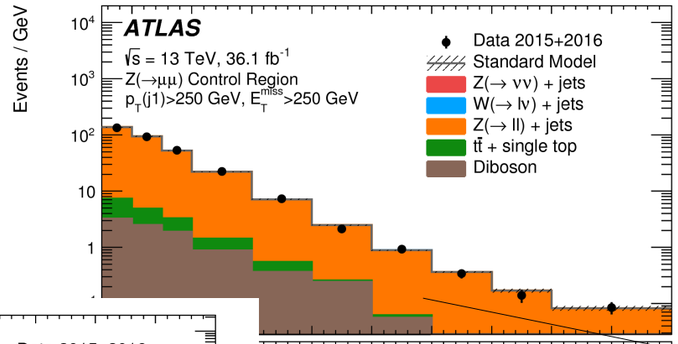
- Event selection highlights
  - Both E_T^{miss} and p_T (1st jet) > 250 GeV
  - At most 4 jets
  - Lepton veto (e or μ)
- Main backgrounds & estimation:
  - Z(→ νν)+jets: two lepton control region
  - W(→ lν)+jets: one lepton control region
  - Top-quark backgrounds: one lepton control region plus b-jets

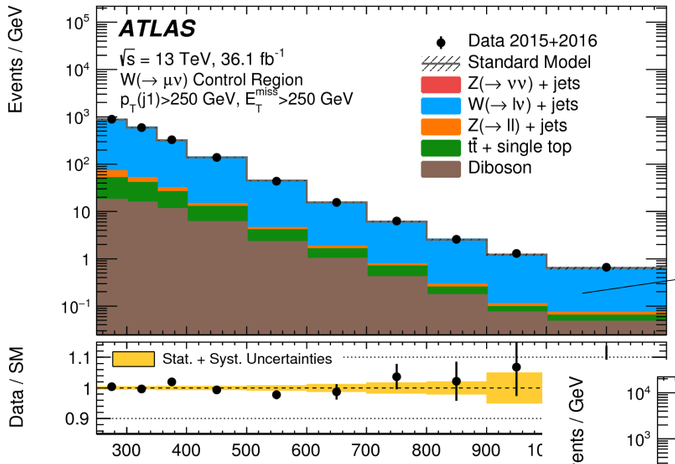


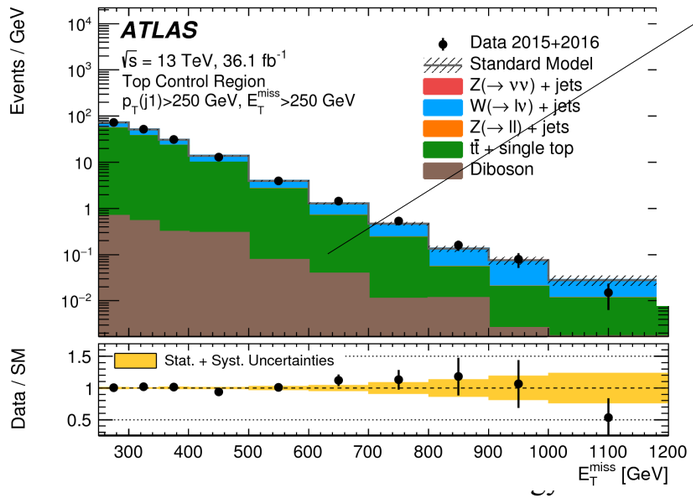
arXiv:1603.04156Â [hep-ex]Â

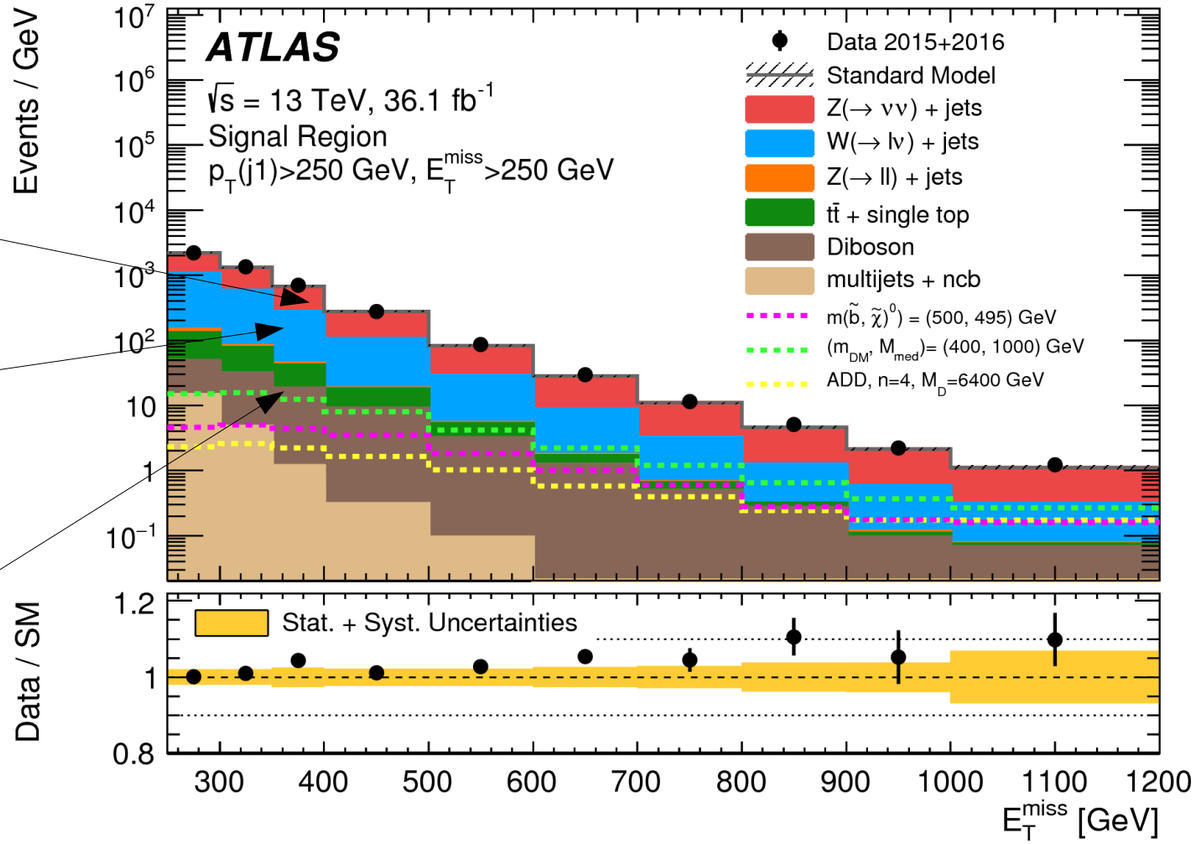
Mono-jet backgrounds – ATLAS

JHEP 01 (2018) 126

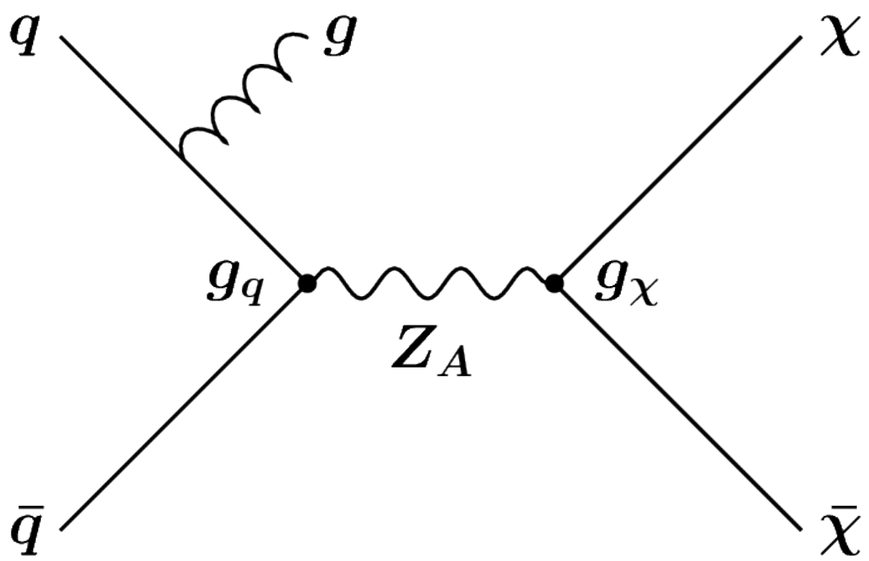




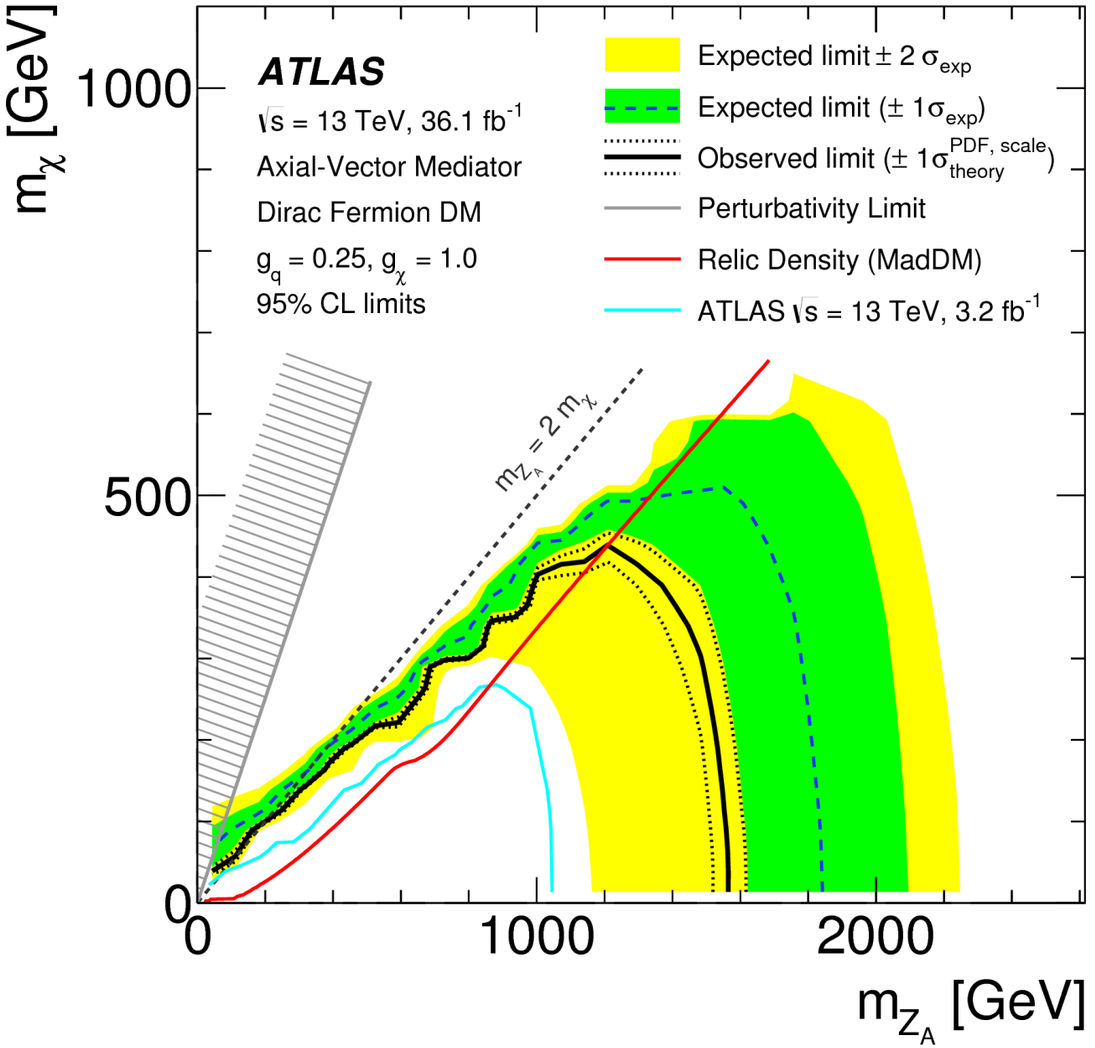




Mono-jet results – ATLAS

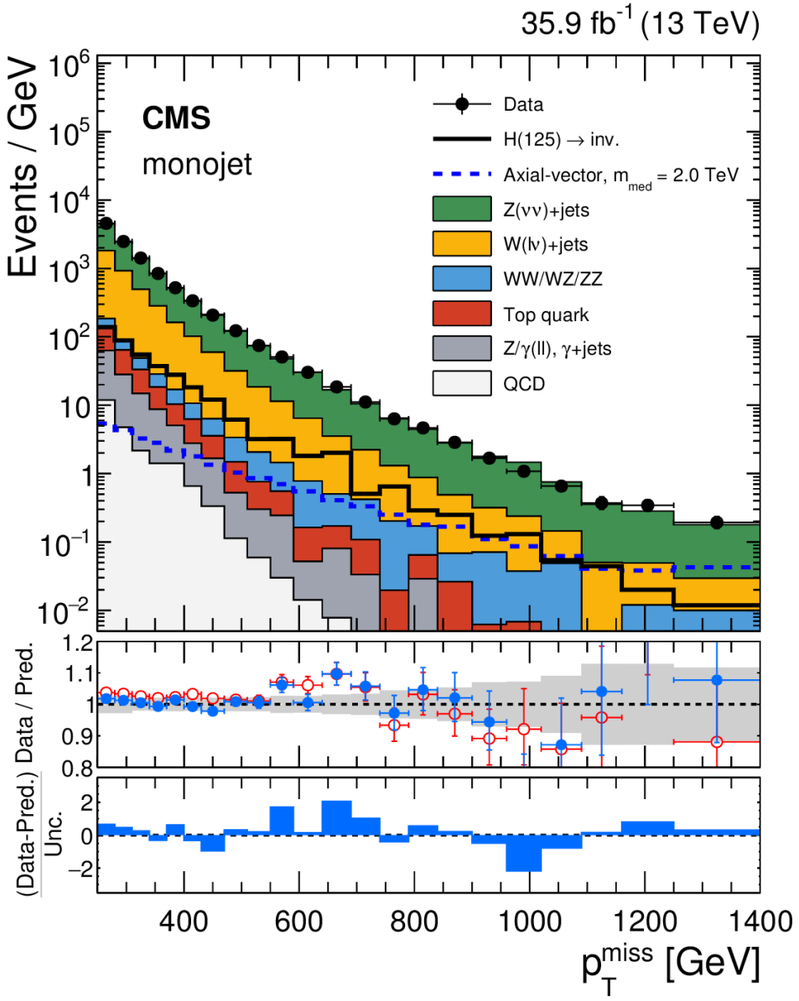


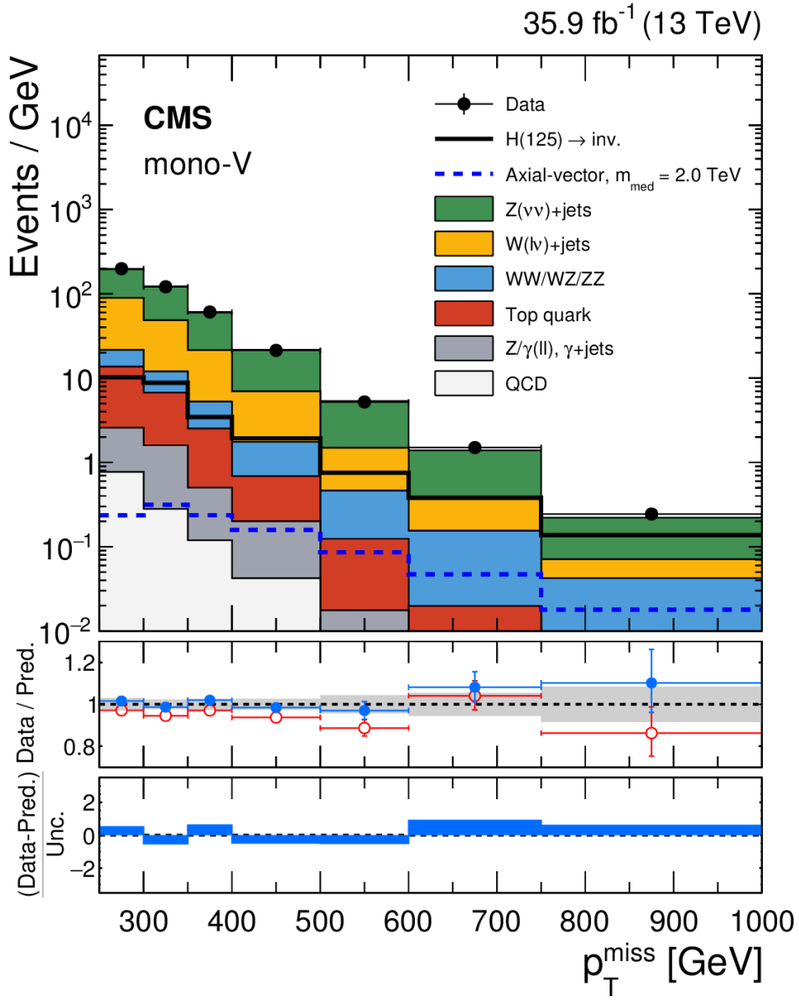
- Limits are set on mediators masses up to 1.5 TeV
- Strong limits can be set on low and mid-range dark matter masses



Mono-jet – CMS

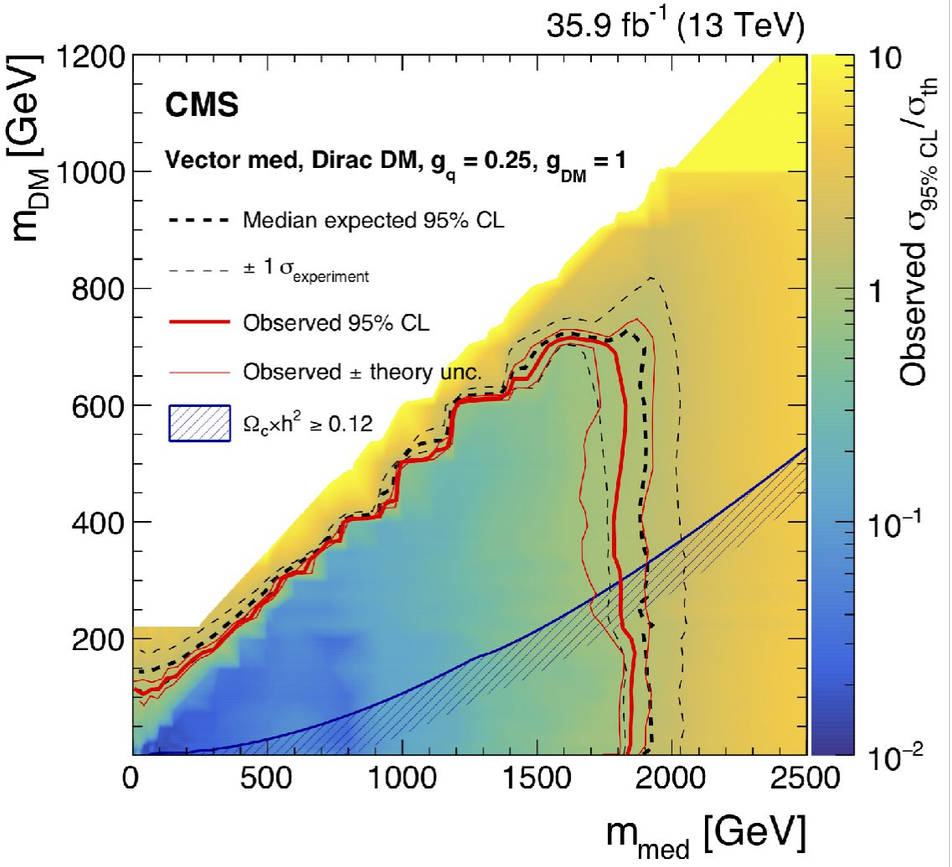
Phys. Rev. D 97 (2018) 092005

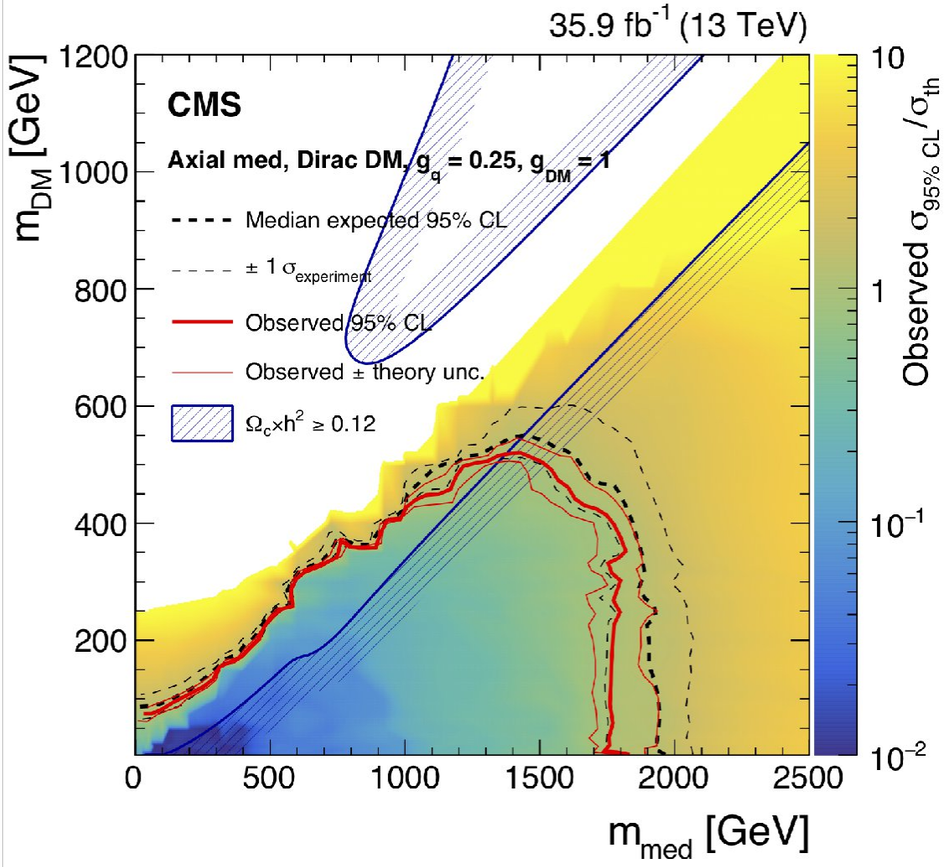




- Dataset: 35.9 fb^{-1} (2015+2016)
- Event selection highlights
  - $E_T^{miss} > 250$ GeV
  - Lepton veto (e or μ)
  - Single jet *or*
  - Single V-jet
- Main backgrounds & estimation:
  - Z(→ νν)+jets: 2 CR
  - W(→ lν)+jets: 1 CR

Mono-jet Results – CMS

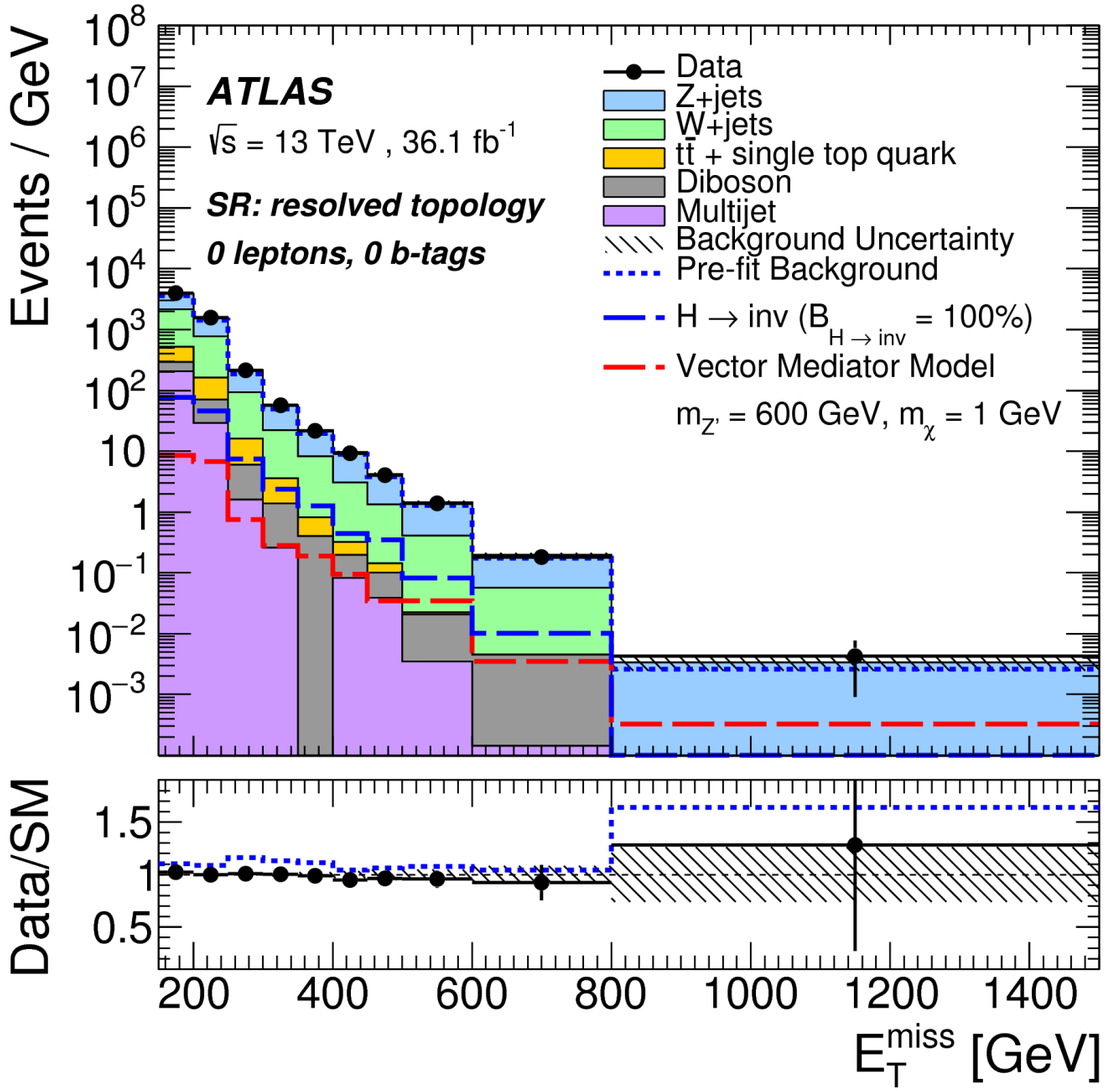




- Limits are set on masses up to 1.8 TeV for vector mediators, and 1.7 for axial-vector mediators
- Strong limits set on low and mid-range dark matter masses

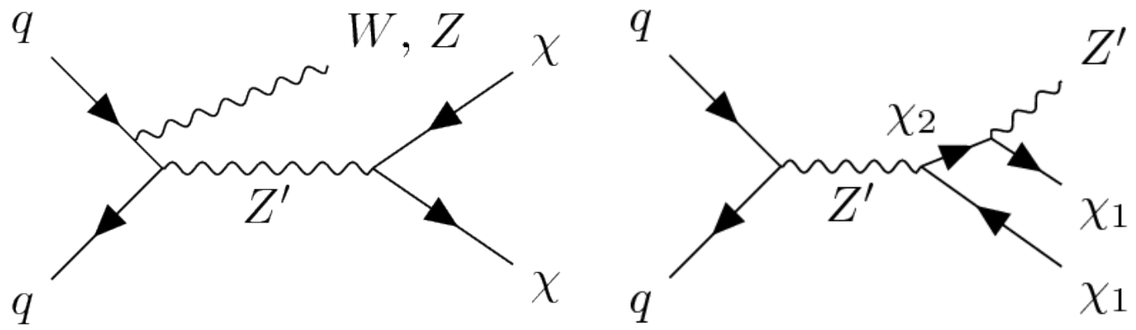
Mono-V(hadronic) – ATLAS

arXiv:1807.11471

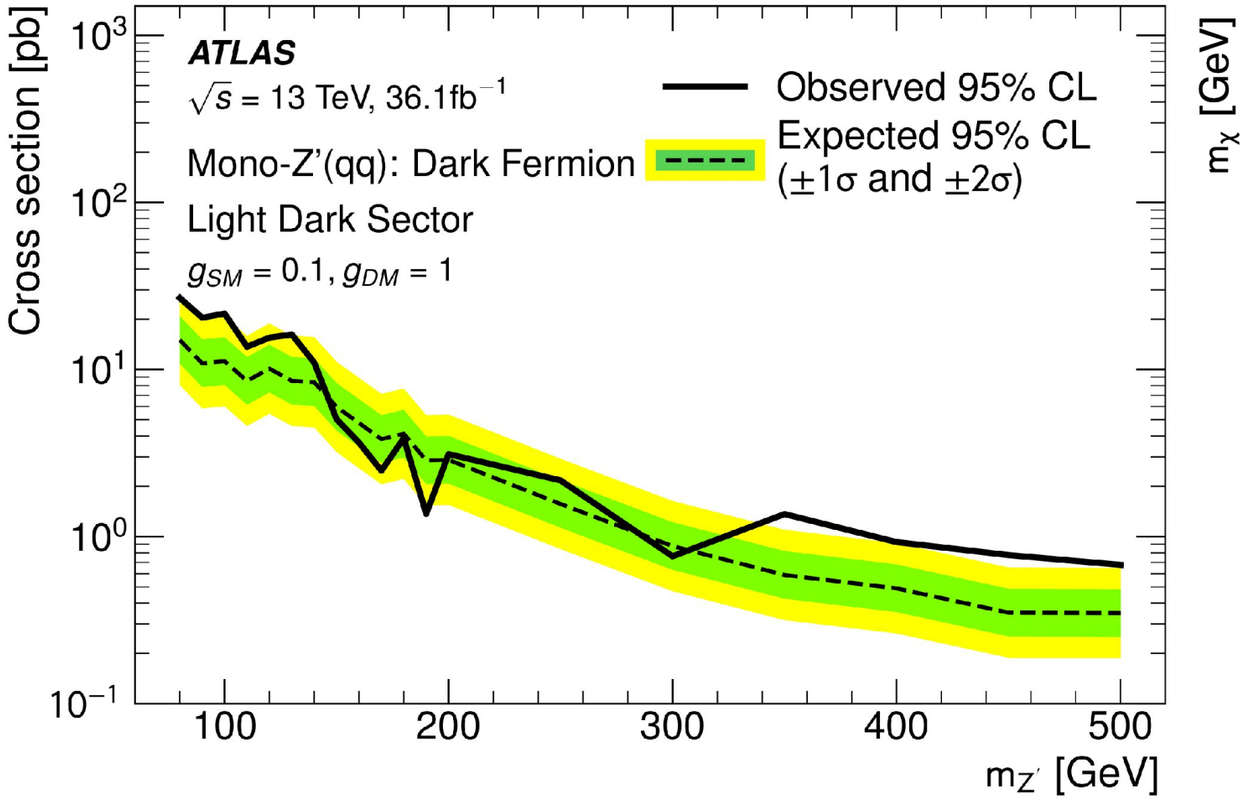


Dataset: 36.1 fb^{-1} (2015+2016)

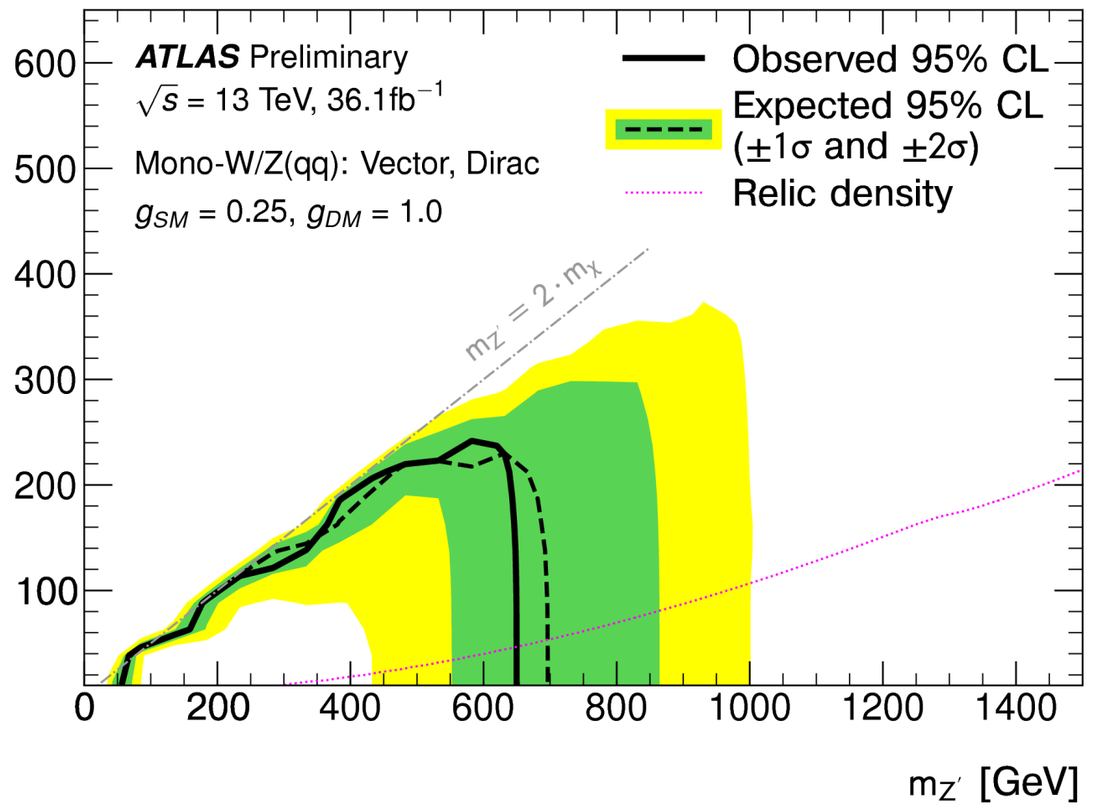
- Event Selection highlights
  - $E_T^{miss} > 250$ GeV
  - Boosted or resolved jet substructure consistent with a W or Z boson
- Backgrounds & estimation:
  - Z(→ νν)+jets , W/Z(→ lν/ll)+jets
  - ttbar – estimated through MC, normalization from data



Mono-V(hadronic) results – ATLAS



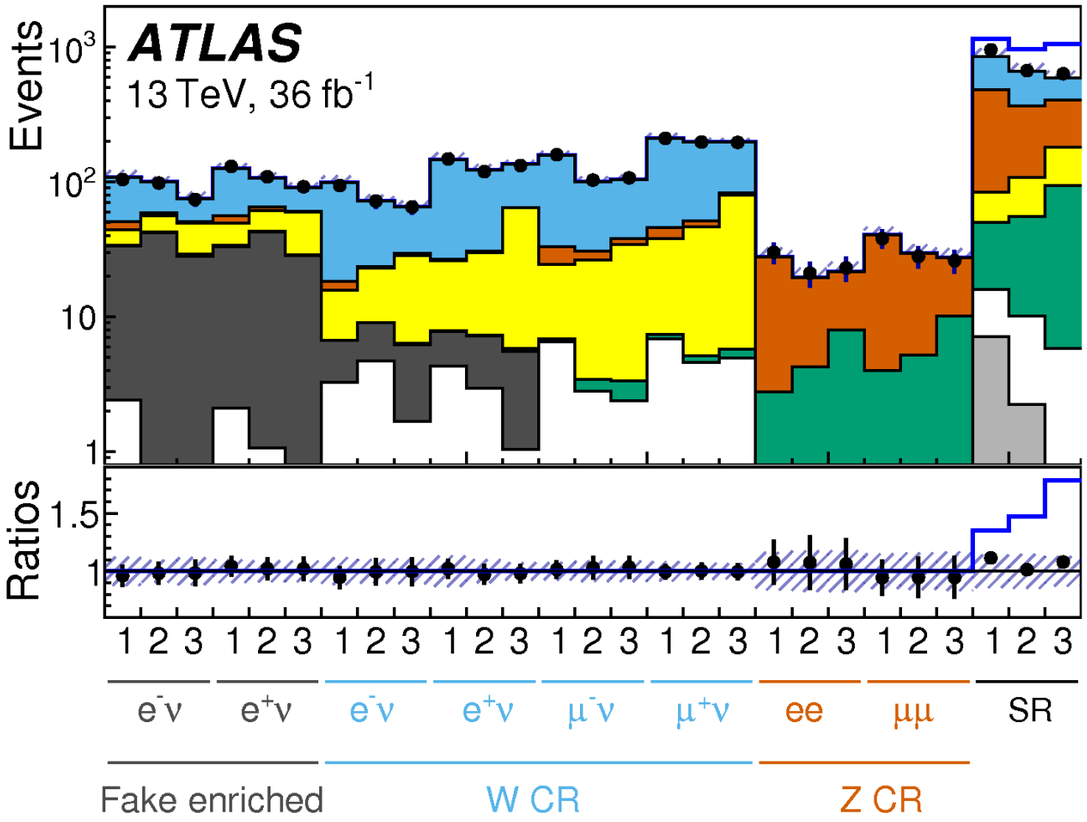
Limits are set on the cross section times branching fraction of models with a Z' in the final state

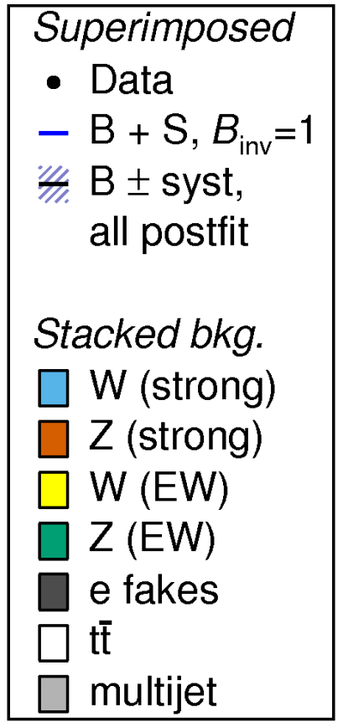


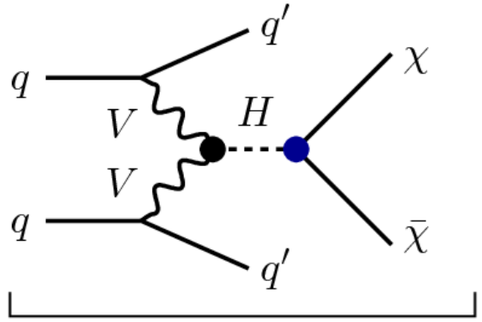
Exclusion contours are set on mediator masses up to 650 GeV

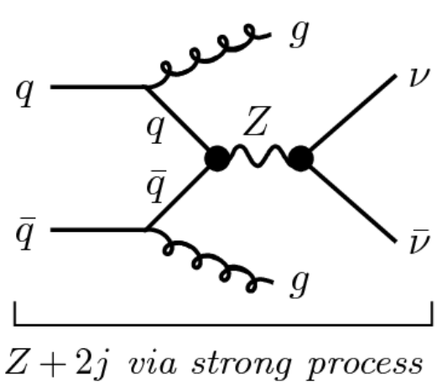
Search for invisible Higgs decays – ATLAS

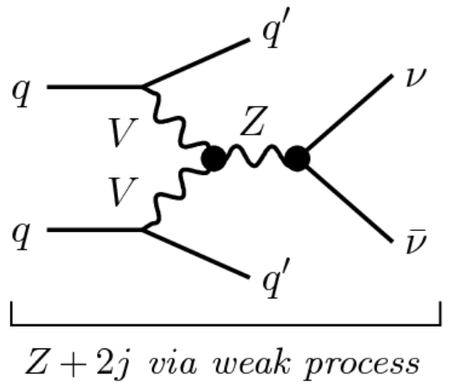
New result: arXiv:1809.06682











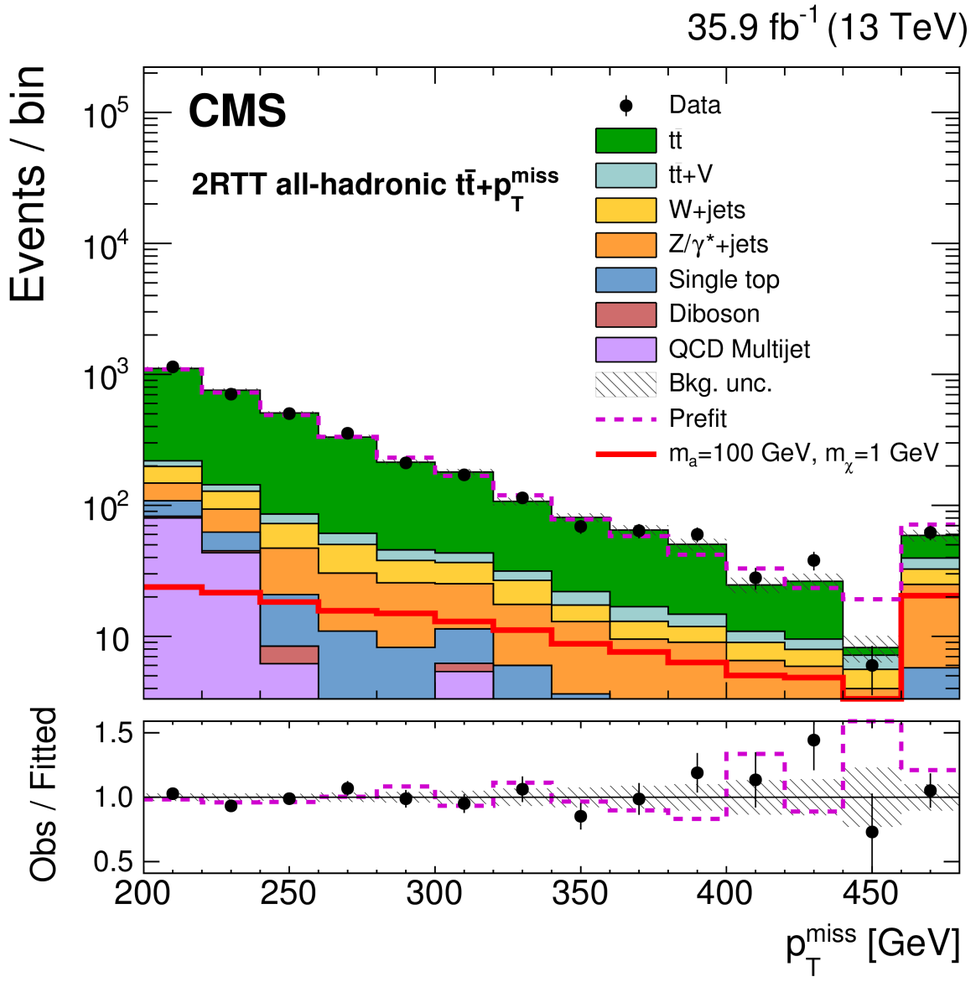
The 1, 2, and 3 bin label corresponds to the three m_{jj} bins with [1, 1.5, 2, -] TeV boundaries, respectively

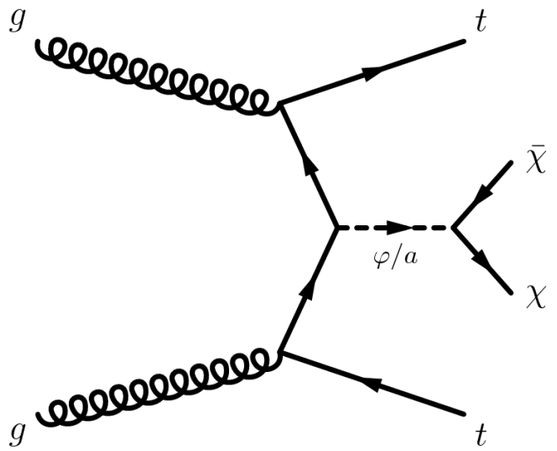
MET + Heavy Flavour Jets – CMS

CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-16-049/

ATLAS: JHEP 06 (2018) 108, Eur. Phys. J. C 78 (2018) 18

See talk by Alberto Zucchetta tomorrow!!





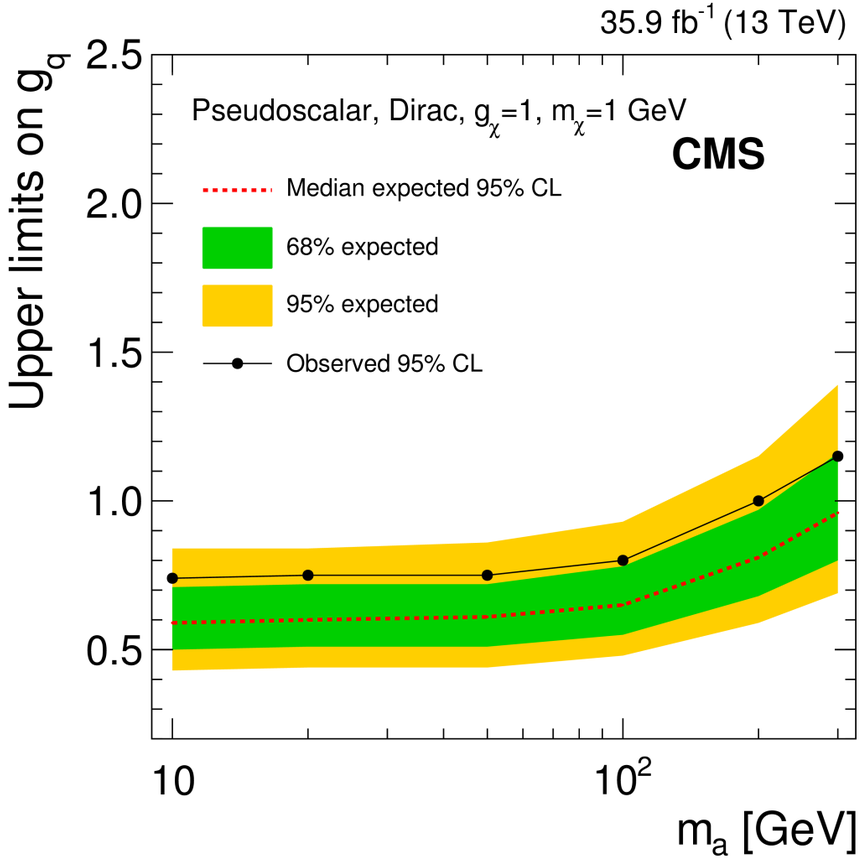
t-quarks primarily decay to *b*-quarks

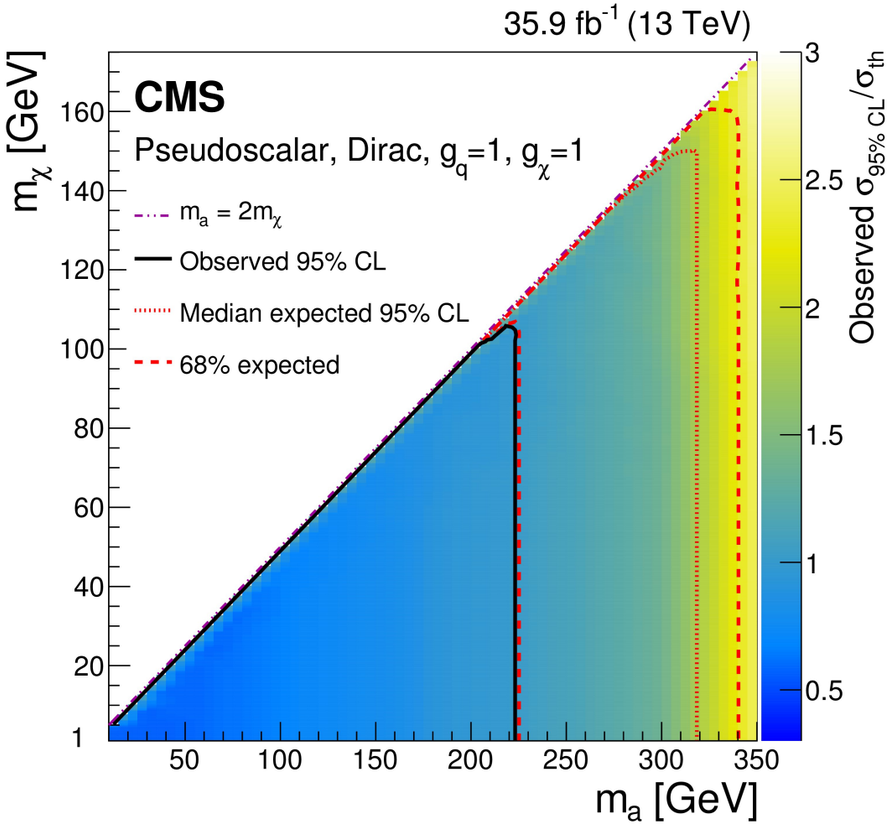
Dataset: 35.9 fb^{-1} (2015 + 2016)

- Event selection highlights
  - *b*-tagged jets
  - $E_T^{miss} > 200$ GeV
  - Lepton veto
- Backgrounds & estimation:
  - W+jets, Z(→ νν)+hf jets, SM ttbar
  - Backgrounds fit simultaneously in CRs

MET + tt results – CMS

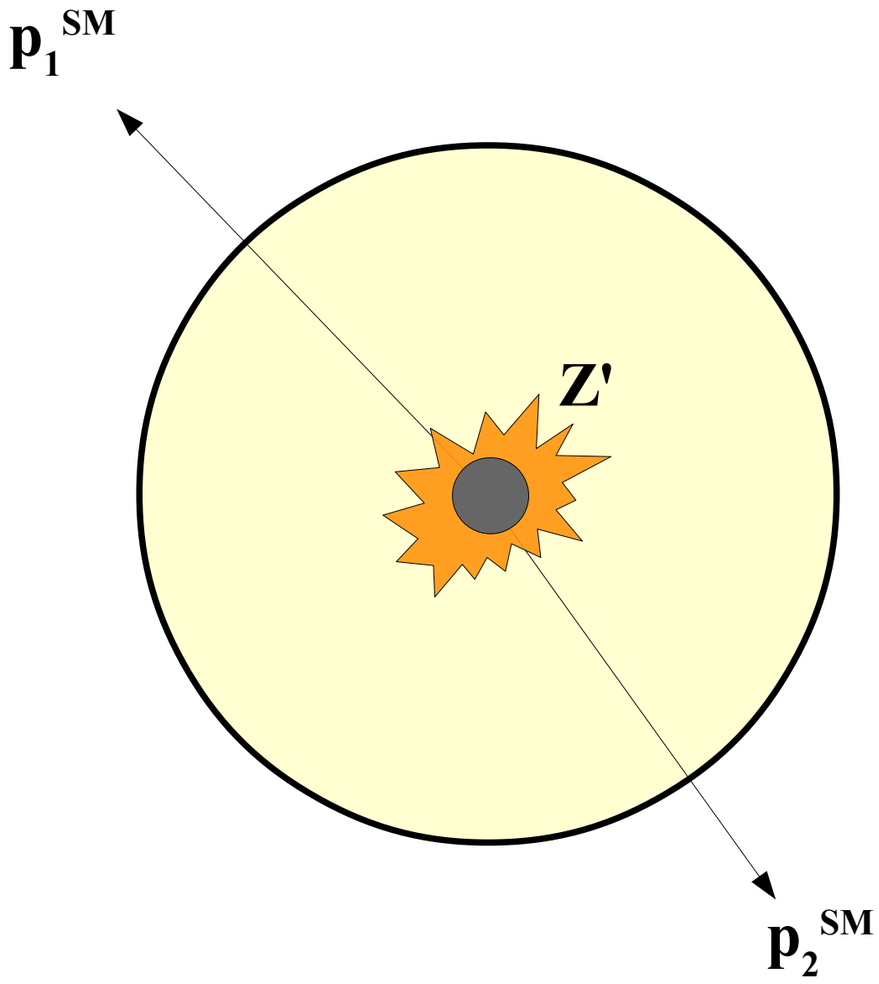
See talk by Alberto Zucchetta tomorrow!!





The best observed upper limit on the coupling strength for pseudoscalar mediator (left) and on signal strength (right)

Mediator searches

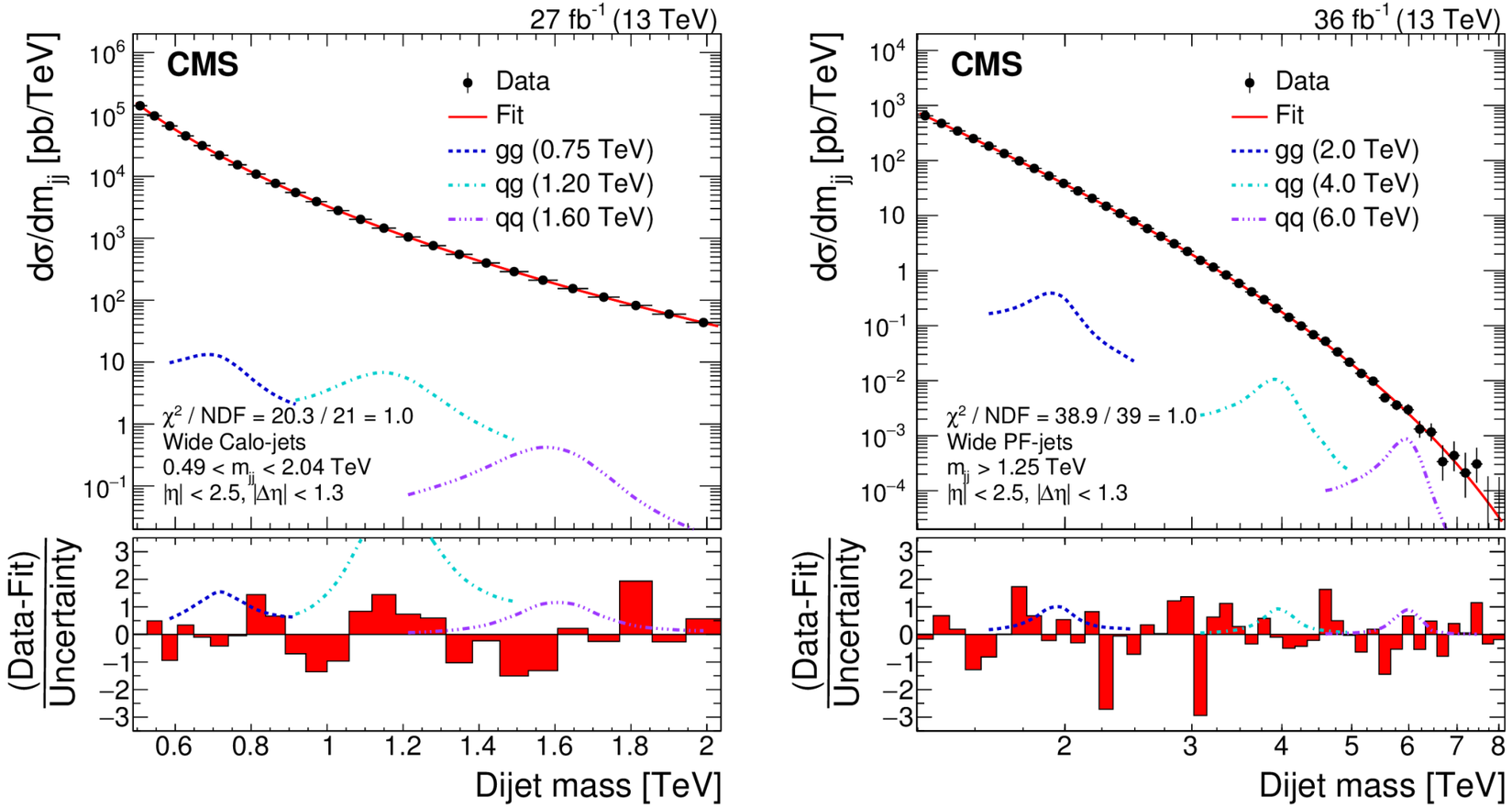


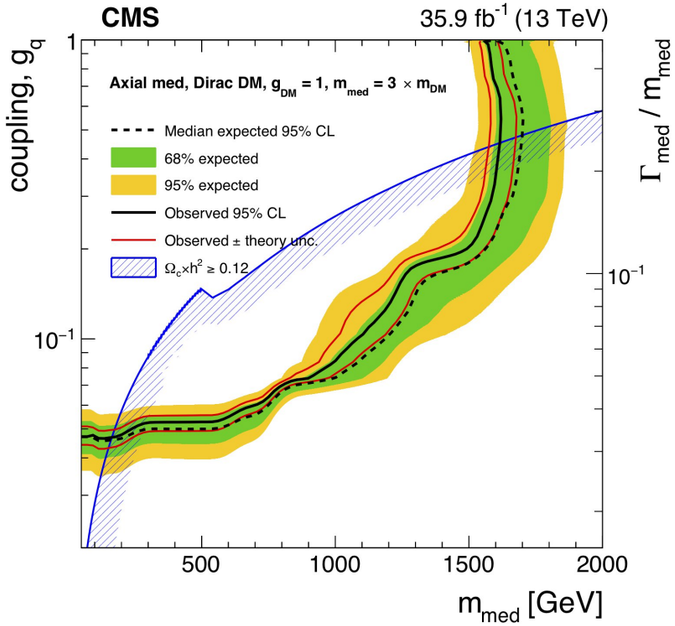
- If the dark matter's mediator can be produced at the LHC, then it could decay back to SM particles
- This can show up as a *resonance*, such as a Z' resonance, in the invariant mass of the decay products.
- This can also look like an *overall extra* number of events, if the new particles are not produced in a resonant way

Dijet – CMS

JHEP 08 (2018) 130

Dataset: 27 or 36 fb^{-1} (2015 + 2016)

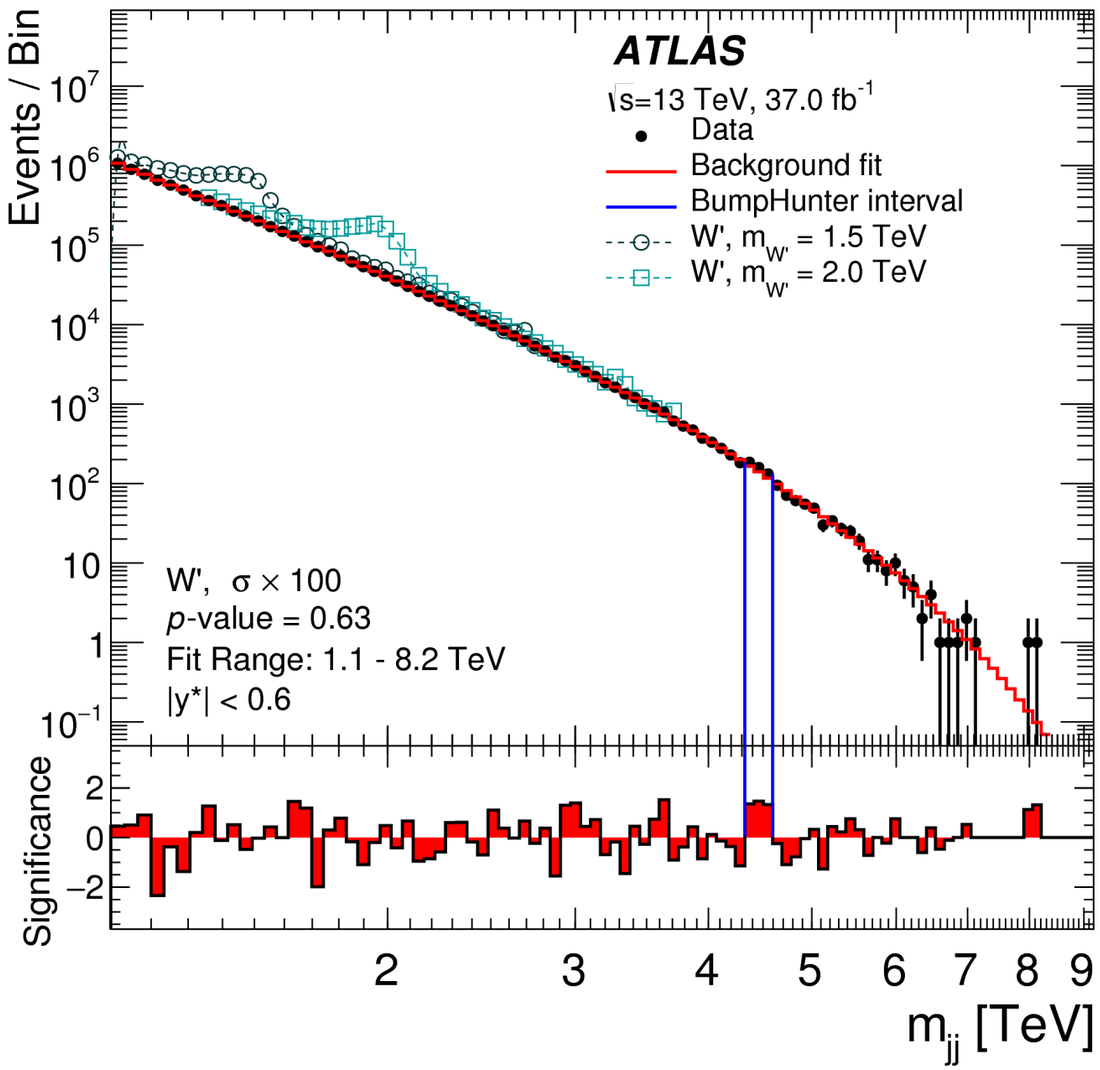


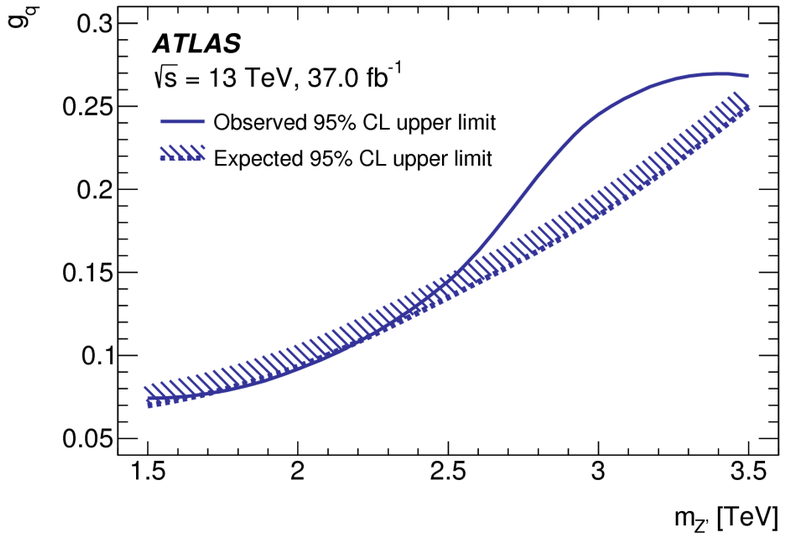


- Datascouting (trigger level) used for low mass search (< 2 TeV)
- QCD background parameterized and fit
- Z' (SM-like couplings) ruled out for < 2.6 TeV
- DM$_{med}$ excluded for energies < 2.7 TeV

arXiv:1703.09127 [hep-ex]

Dijet – ATLAS





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)

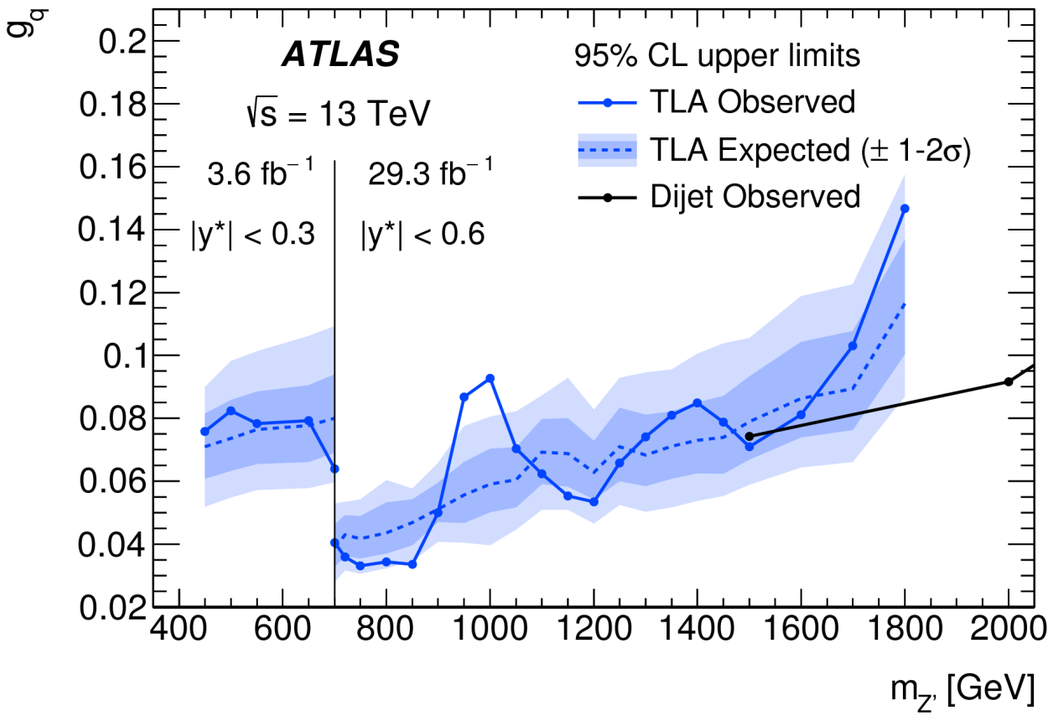
Dijet Trigger-object Level Analysis

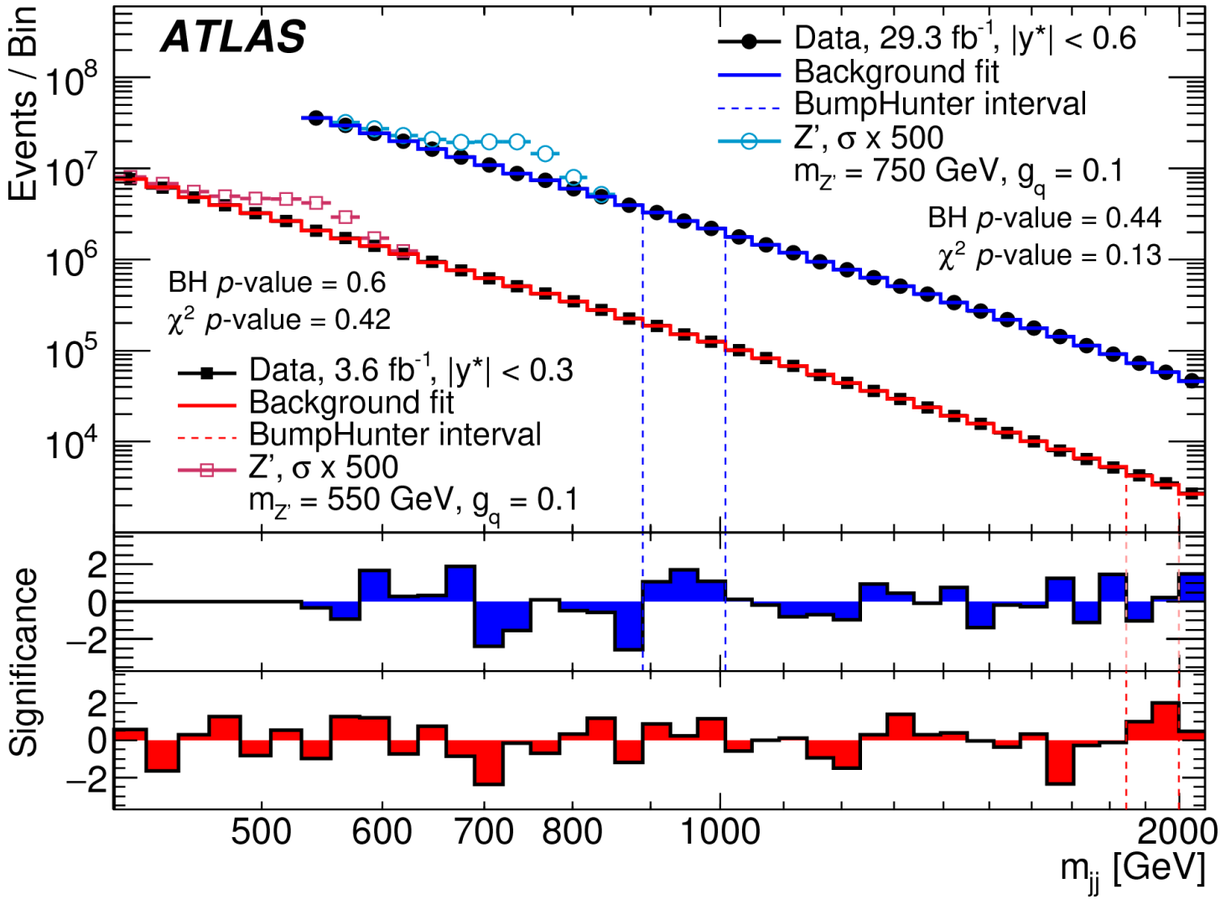
Queen Mary University of London

arXiv:1804.03496 [hep-ex]

Dataset: 29.3 fb^{-1} (2015+2016)

- Trigger stream of jets reconstructed by the High-Level Trigger (no tracking or muon information)
- Backgrounds & estimation: same strategy as the full dijet analysis, dedicated calibrations needed on TLA jets
- Signal regions – lower kinematic reach than the dijet analysis, searching for lighter resonances



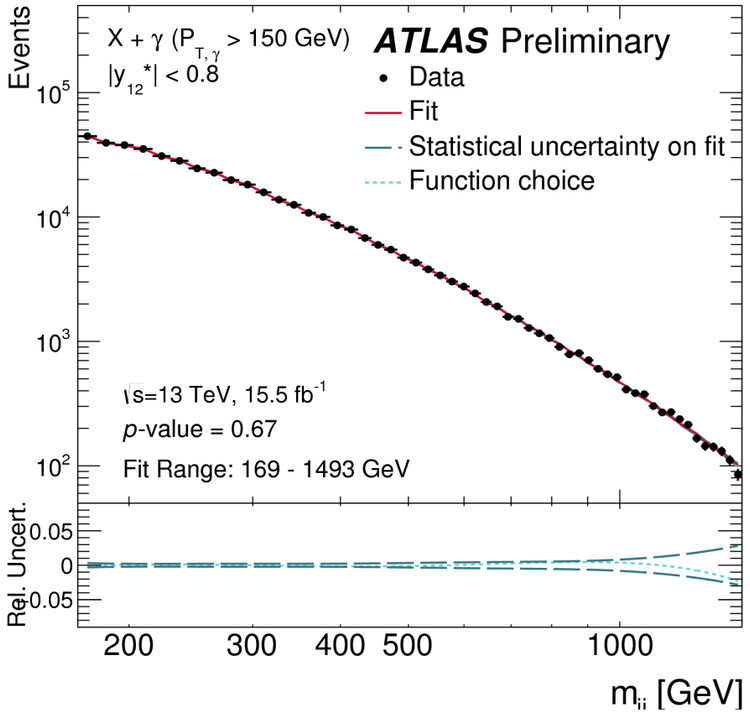


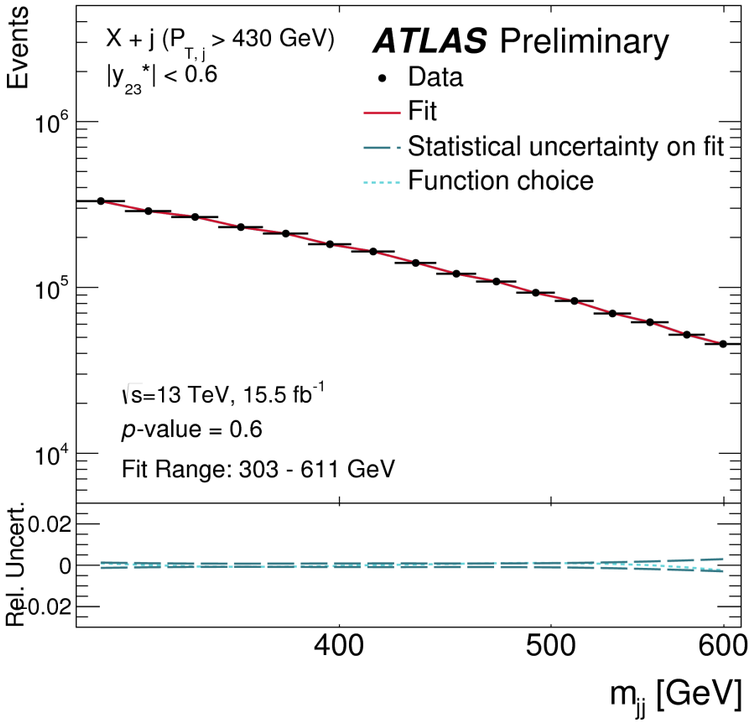
← Couplings excluded above line

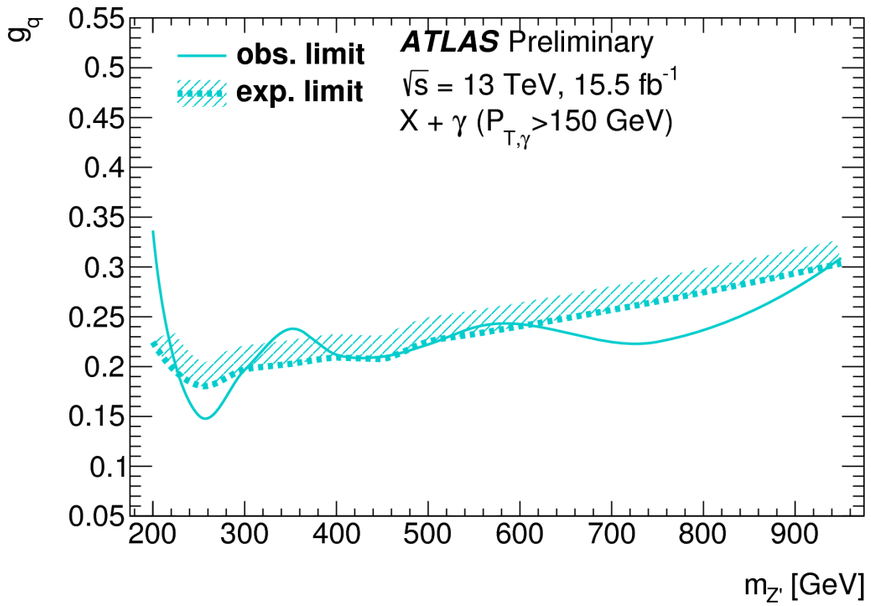
Dijet + ISR (jet or γ)

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

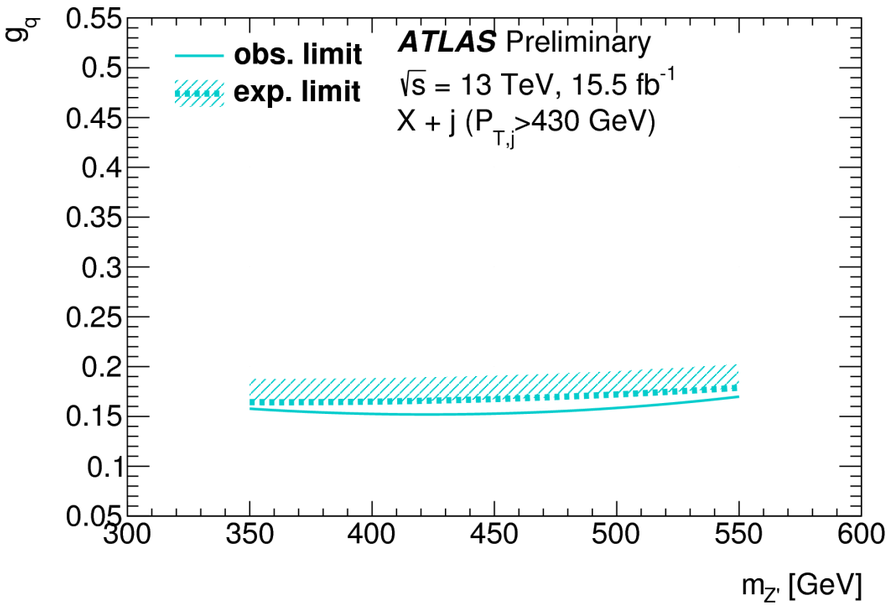




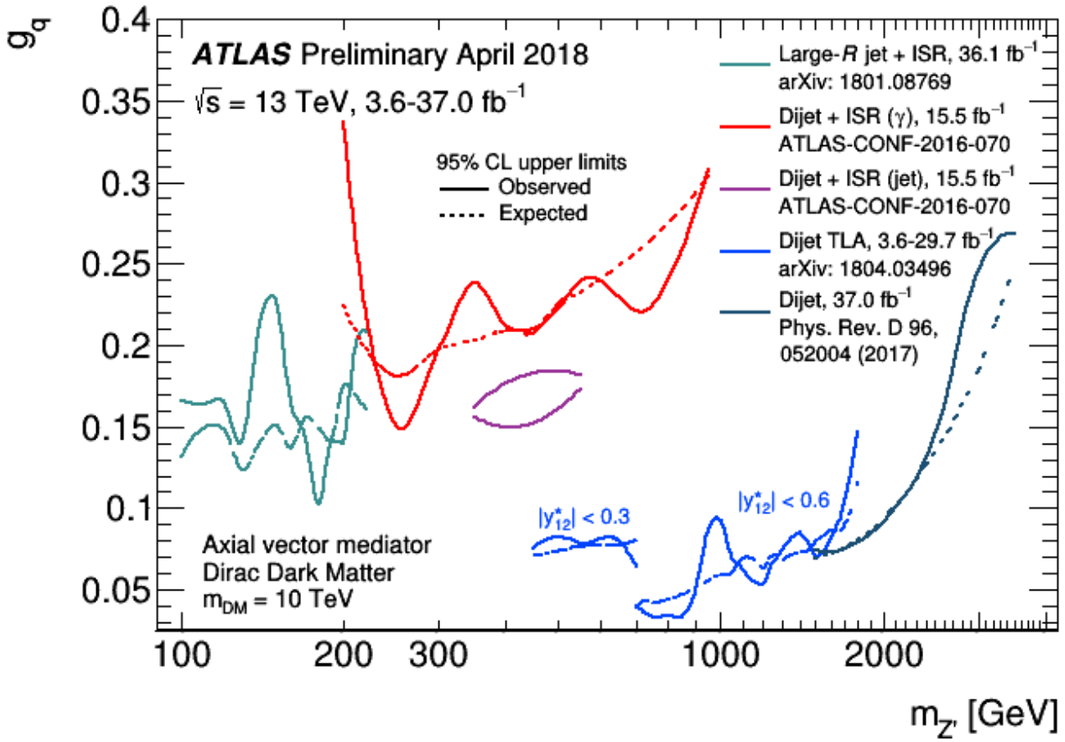


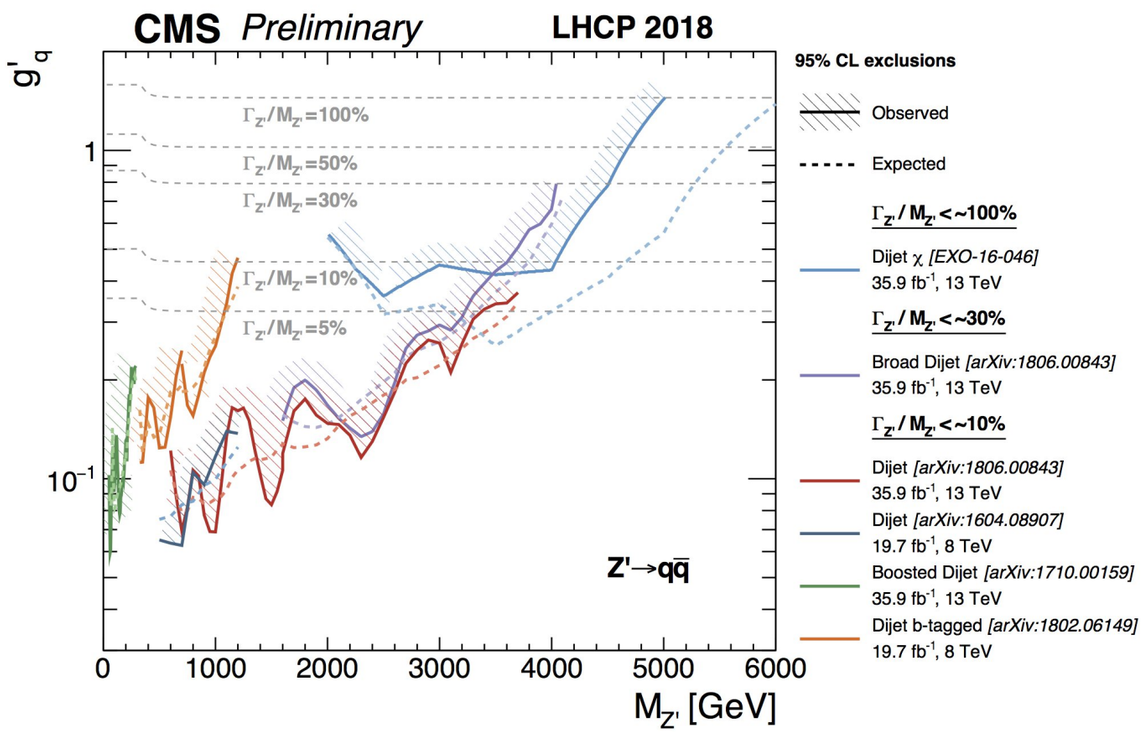
ATLAS-CONF-2016-070

Updated results found:
arXiv:1801.08769 [hep-ex]



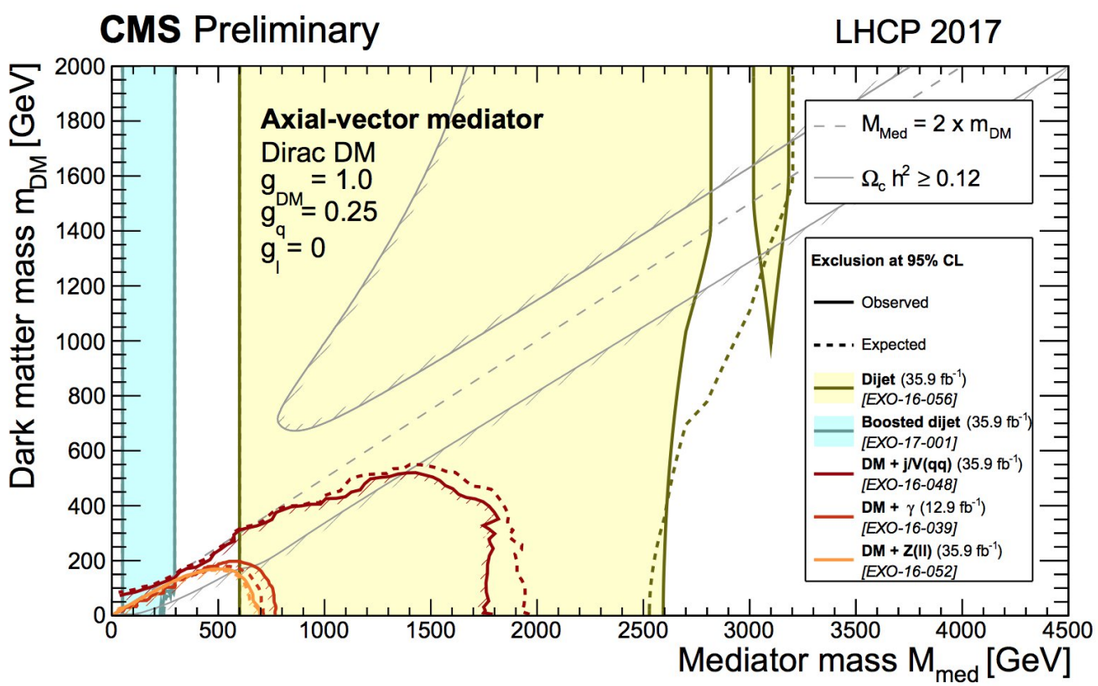
Dijet Combinations

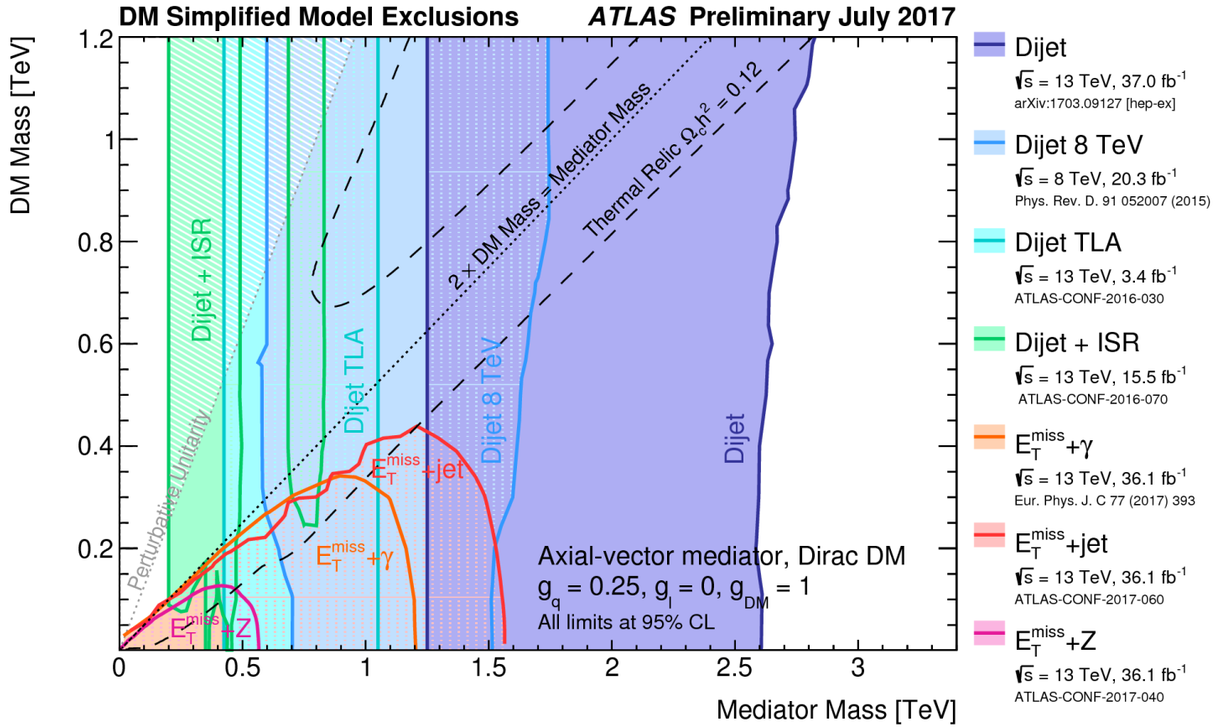




Combinations of mediator searches

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/
https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsEXO/DM-summary-plots-Jul17.pdf

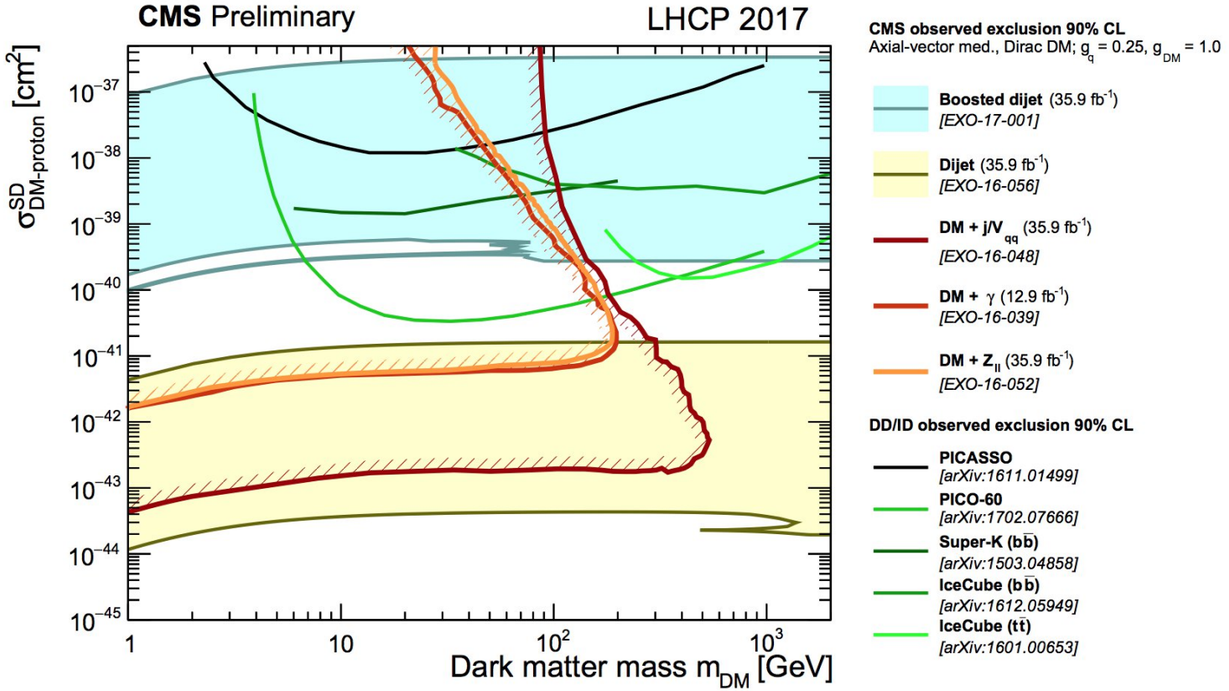


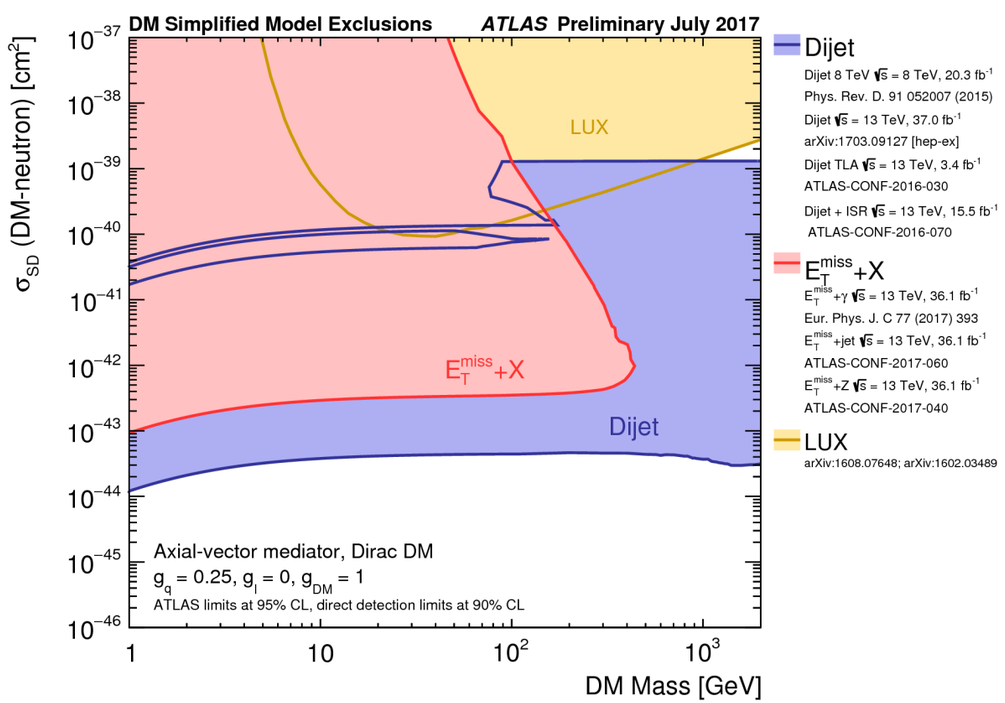


- Axial vector mediators with **no leptonic couplings**, only mediators coupling to quarks and dark matter.

Comparisons to direct detection

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/
https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsEXO/DM-summary-plots-Jul17.pdf

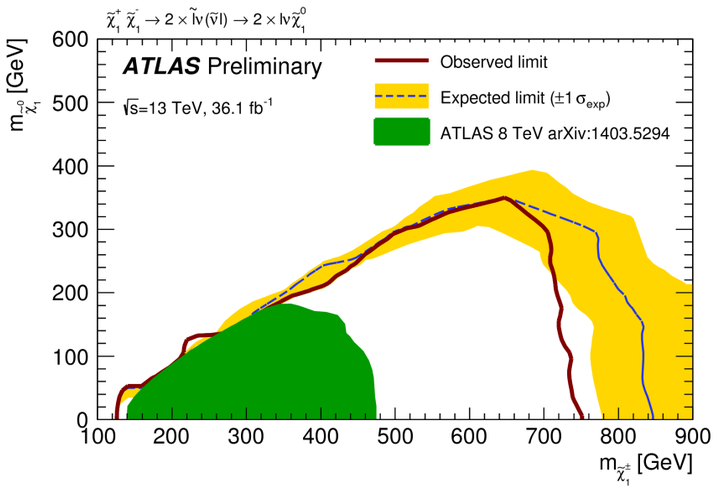




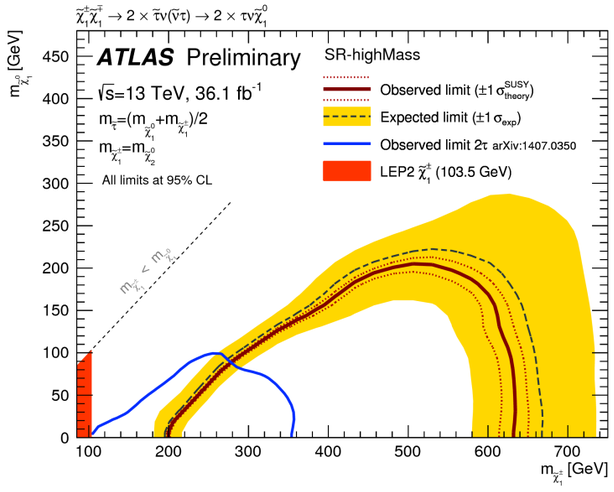
- *Dijet* analyses place the most stringent limits in the high mediator mass range for collider searches
- Complementarity between collider searches and direct detection searches!

Bonus: SUSY dark matter searches

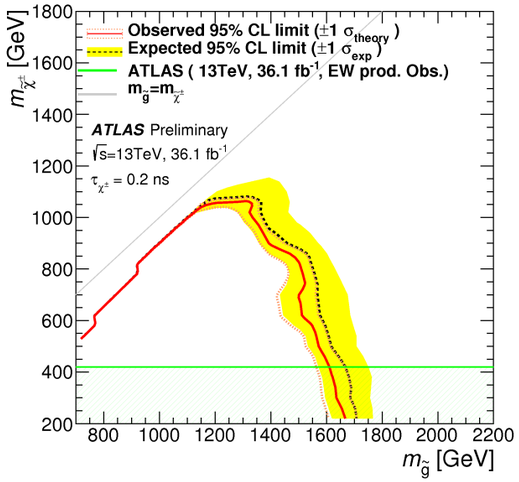
ATLAS-CONF-2017-039



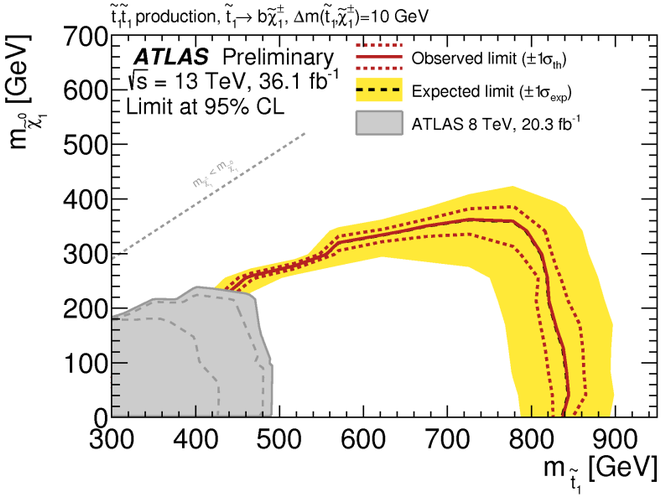
ATLAS-CONF-2017-035



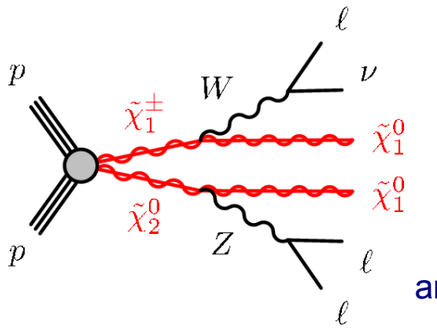
ATLAS-CONF-2017-017



ATLAS-CONF-2017-037

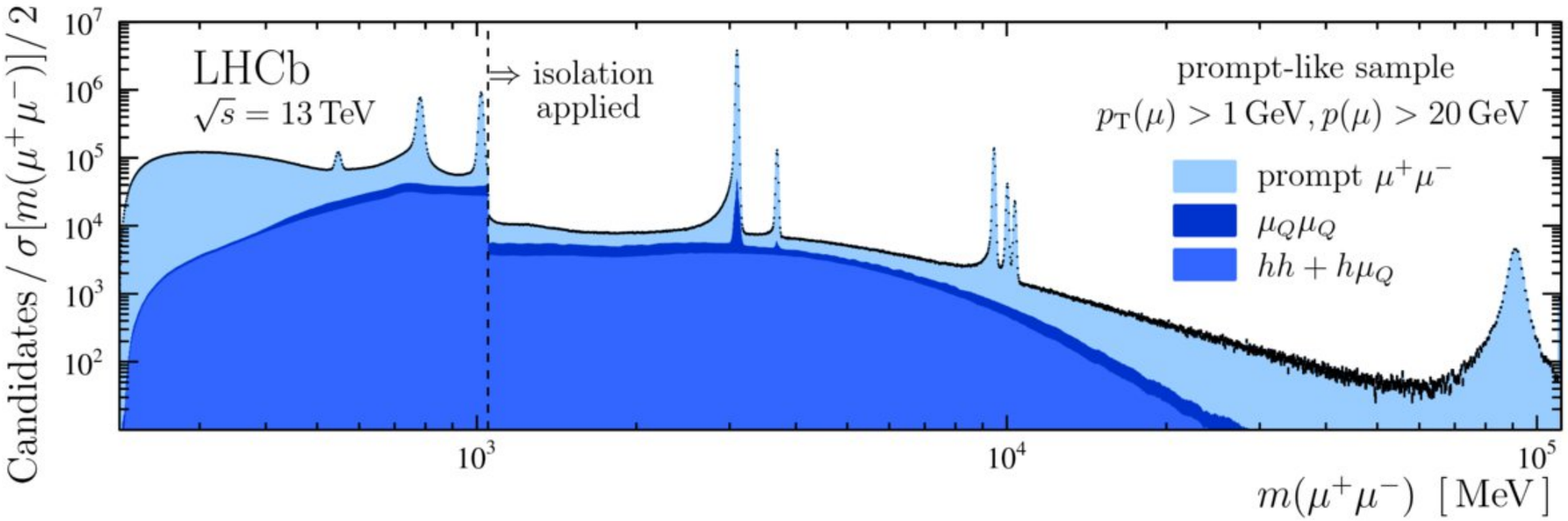


- There are a large variety of searches at the LHC to find dark matter. The ones presented previously are not the only ones that are competitive!
- SUSY searches for the lightest supersymmetric particles and mediators have excellent discrimination power
- Following methods similar to those in JHEP09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



arXiv:1806.02293

LHCb dark sector searches



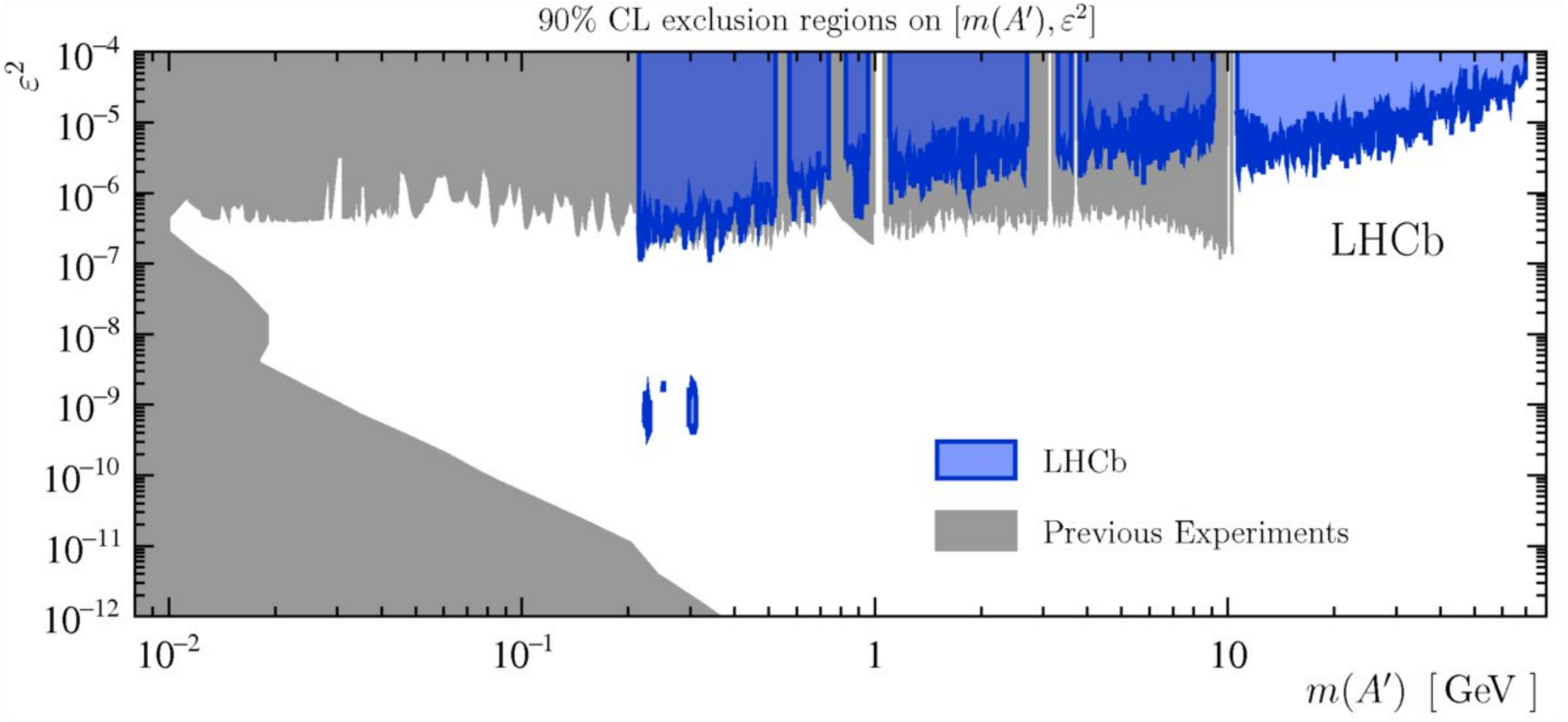
PRL (2018) 120 061801

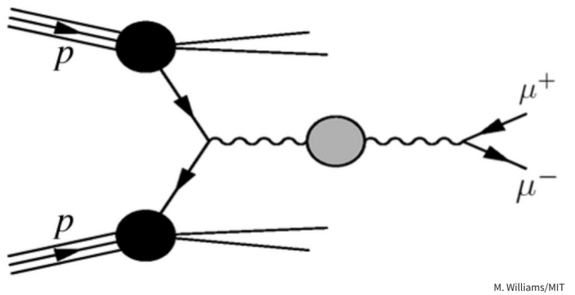
LHCb has excellent sensitivity to very light masses or *the hidden sector*

- Very soft triggers → low masses
- Forward acceptance → boosted particles
- Excellent resolution → narrow peaks

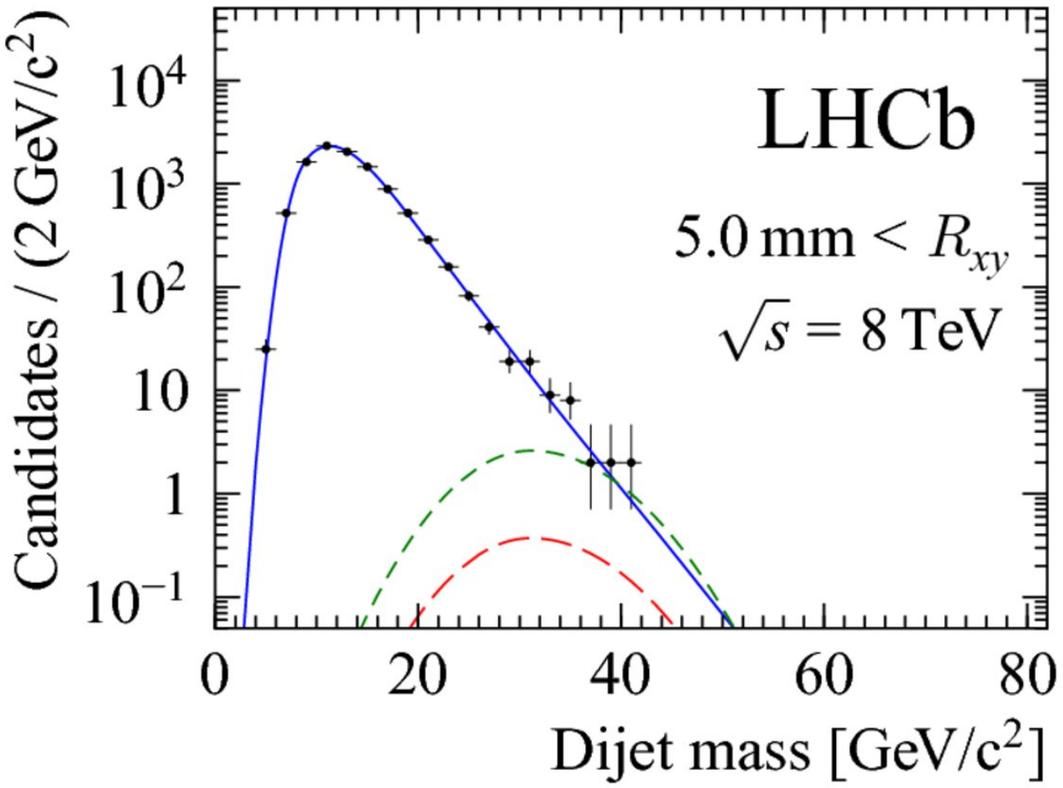
- Dark photons
- Dark Higgs
- Dark bosons
- Dark pions

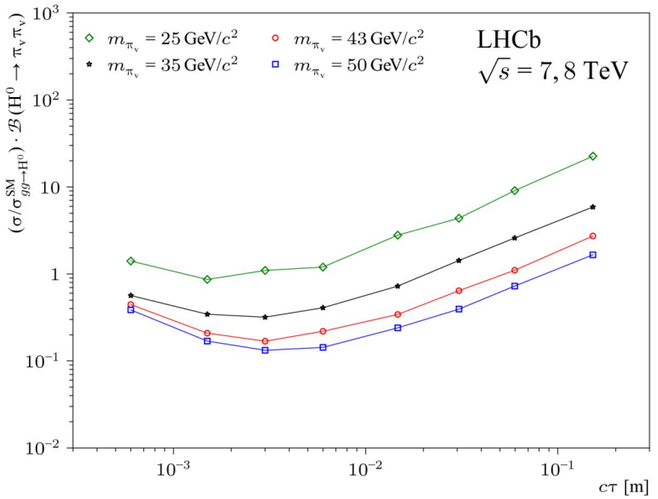
LHCb models: dark photons





LHCb: long lived particles with jets





- Long-lived particles with mass: 25 - 50 GeV
- Lifetime between 2 and 500 ps
- Integrated luminosity: 2.0 ifb at 7 and 8 TeV
- Pair-produced from SM, 125 GeV Higgs decay
- Single long-lived particle, identified by a displaced vertex with two associated jets.
- Limits set on the cross-section as a function of the mass and lifetime

Summary

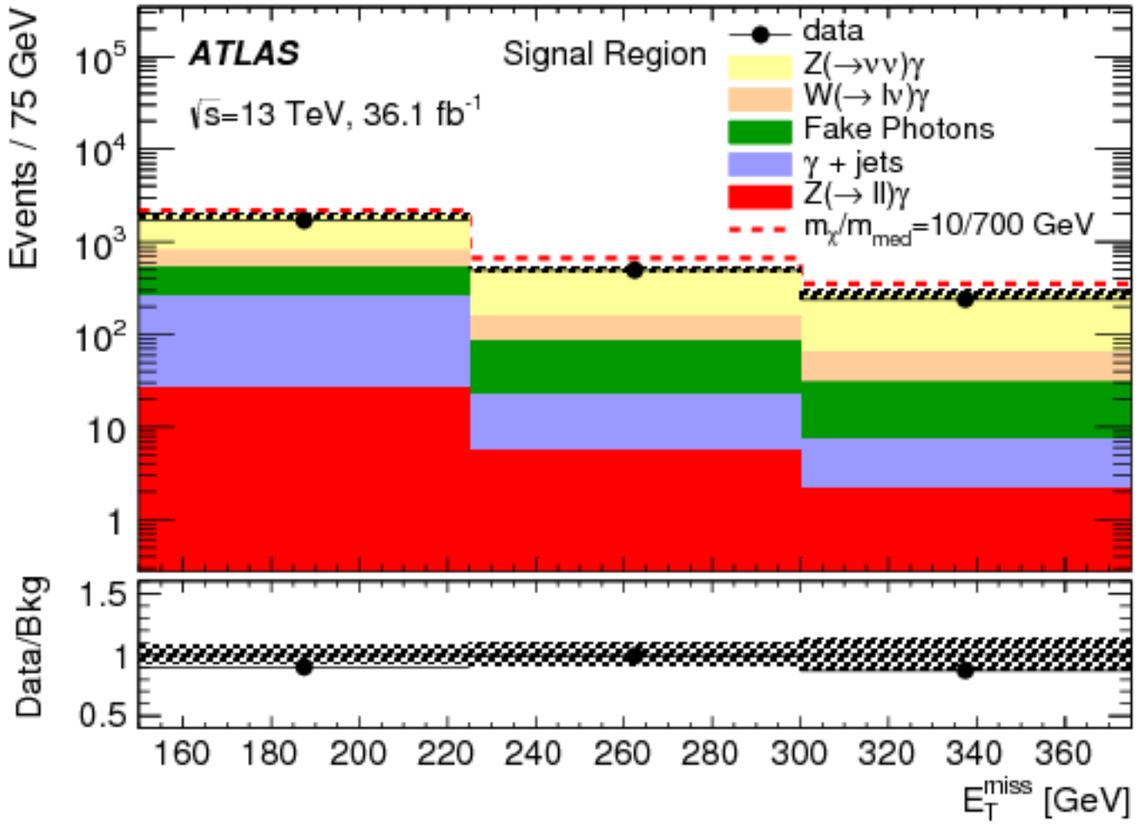
- There is a wide spectrum of searches at ATLAS, CMS, and LHCb
- There are many levels of complementary dark matter searches ongoing
    - Within the detector communities
    - Within the broader LHC search community
    - In the dark matter community at large
- Once someone finds something, we can all cross-check!
- Lots of data to analyse!

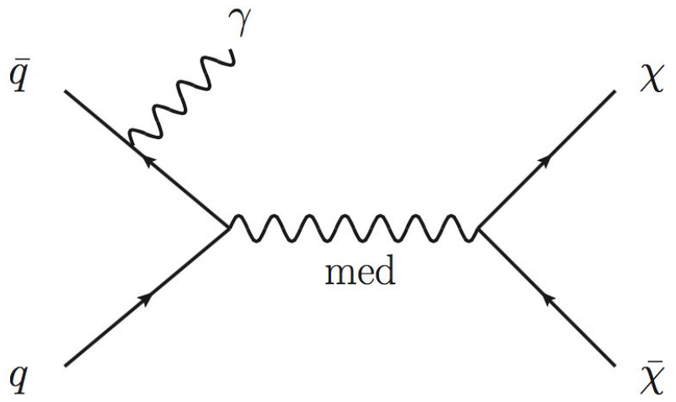
Questions?

backup

Mono-photon

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

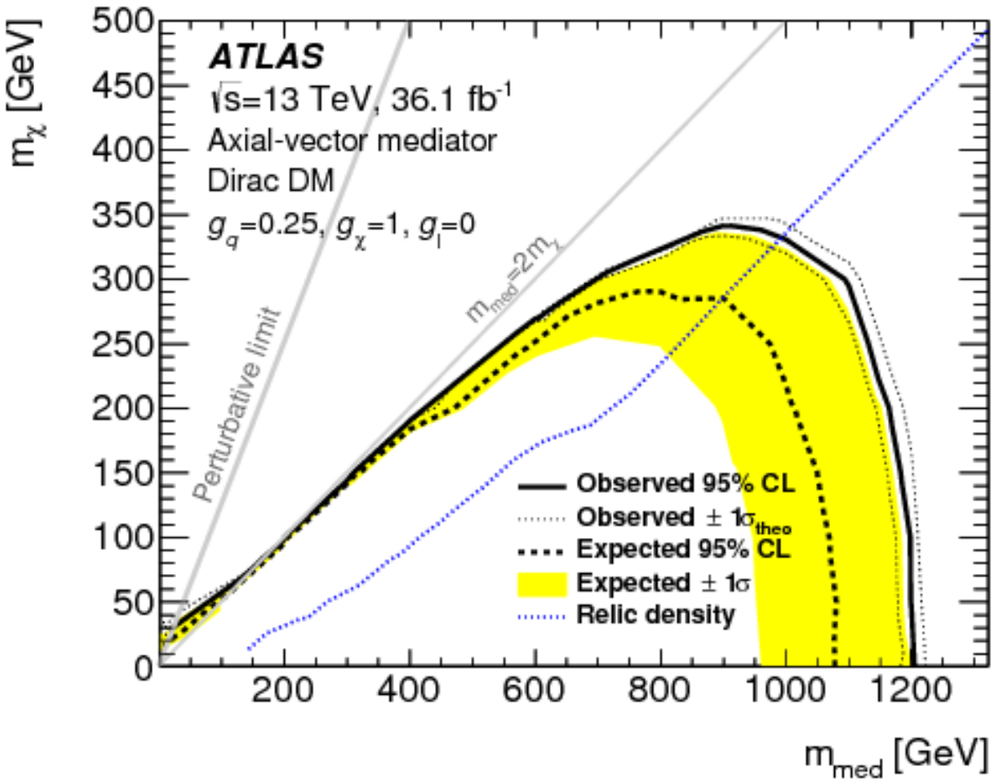


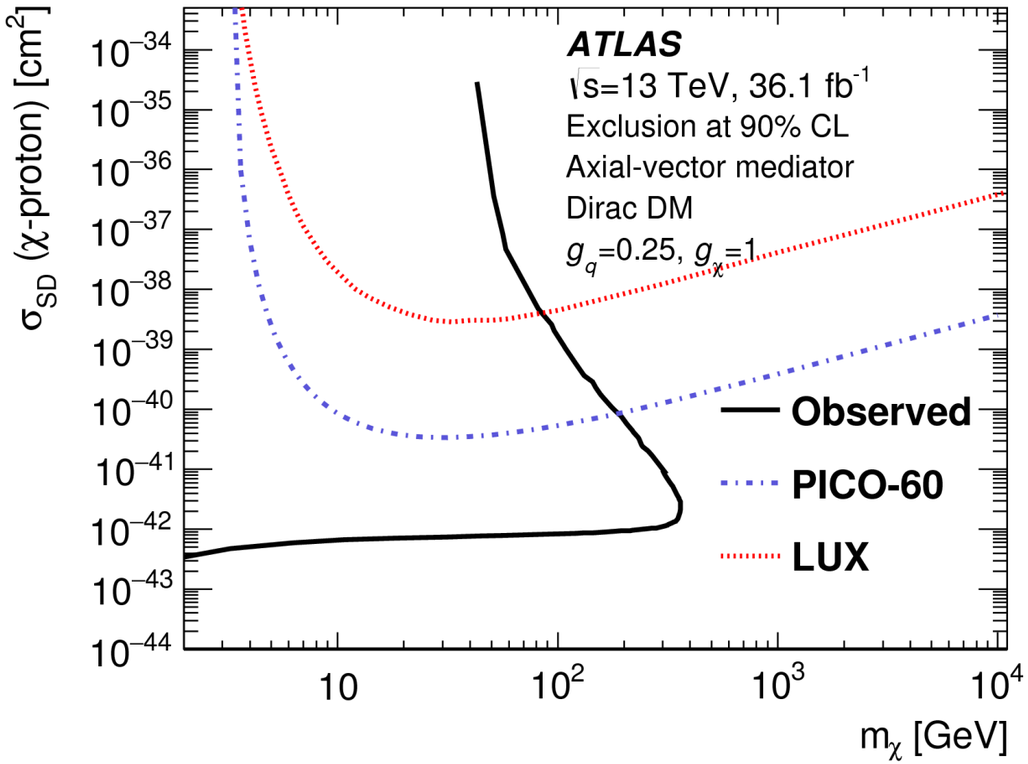


Dataset: 36.1 fb^{-1} (2015+2016)

- 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:

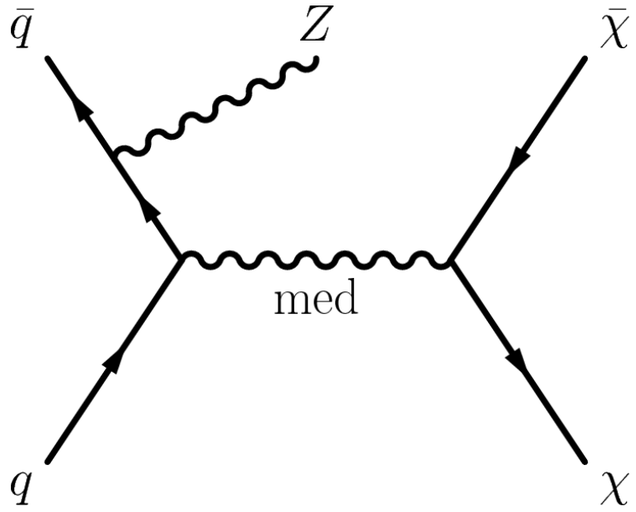
- $E_t^{miss} > 150$ GeV
- $E_T^{miss} > 225$ GeV
- $E_T^{miss} > 300$ GeV

Exclusive signal regions:

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

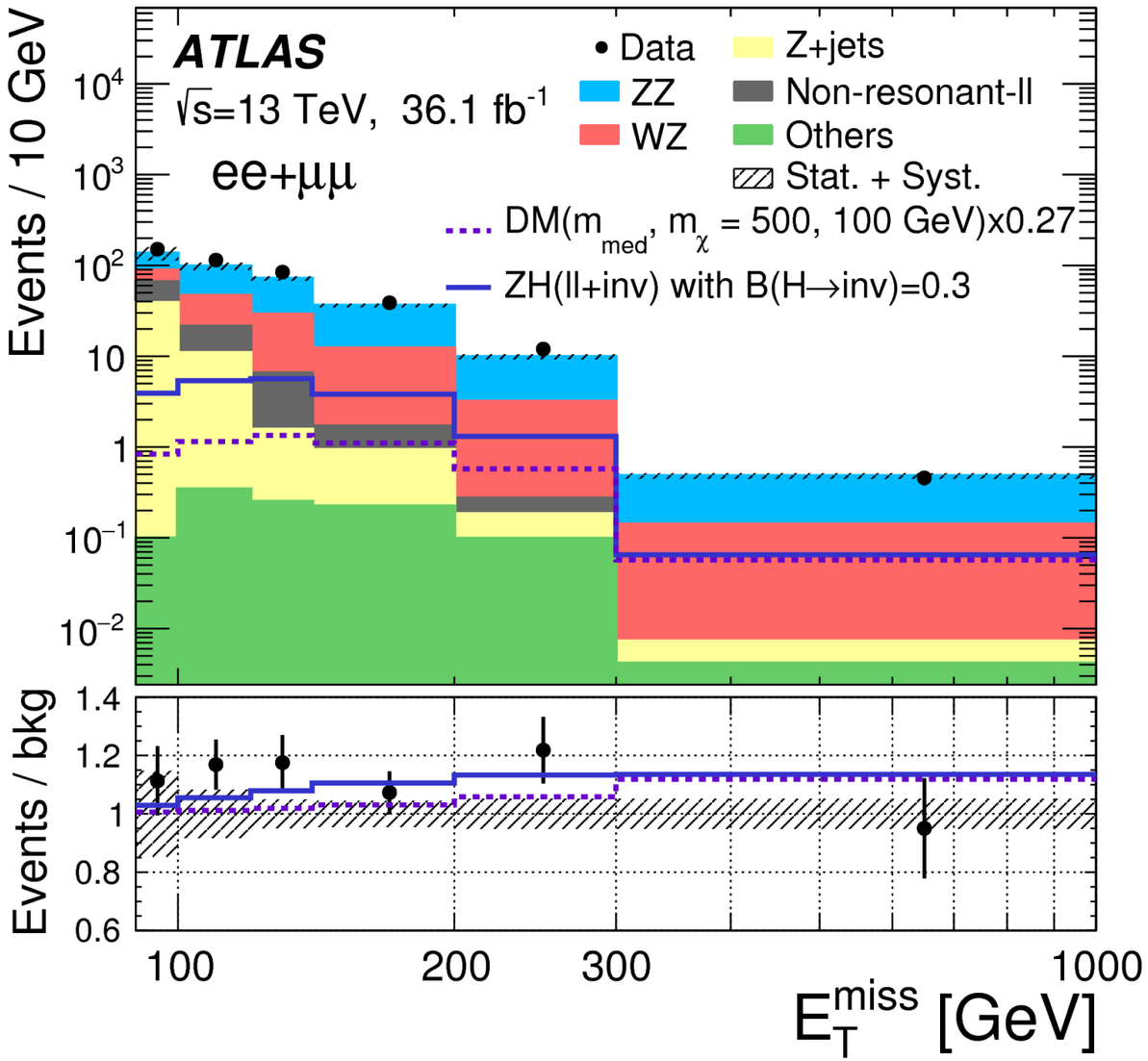
- Limits set on mediator masses up to 1.2 TeV
- Competitive limits at low and mid-range dark matter masses compared to direct detection experiments

Mono-Z(ll)



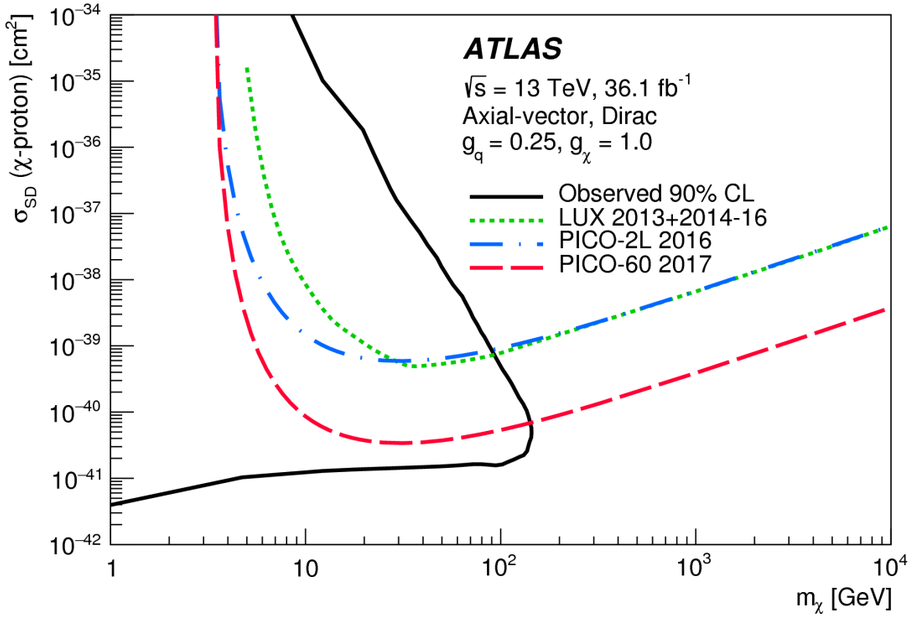
Dataset: 36.1 fb^{-1} (2015+2016)

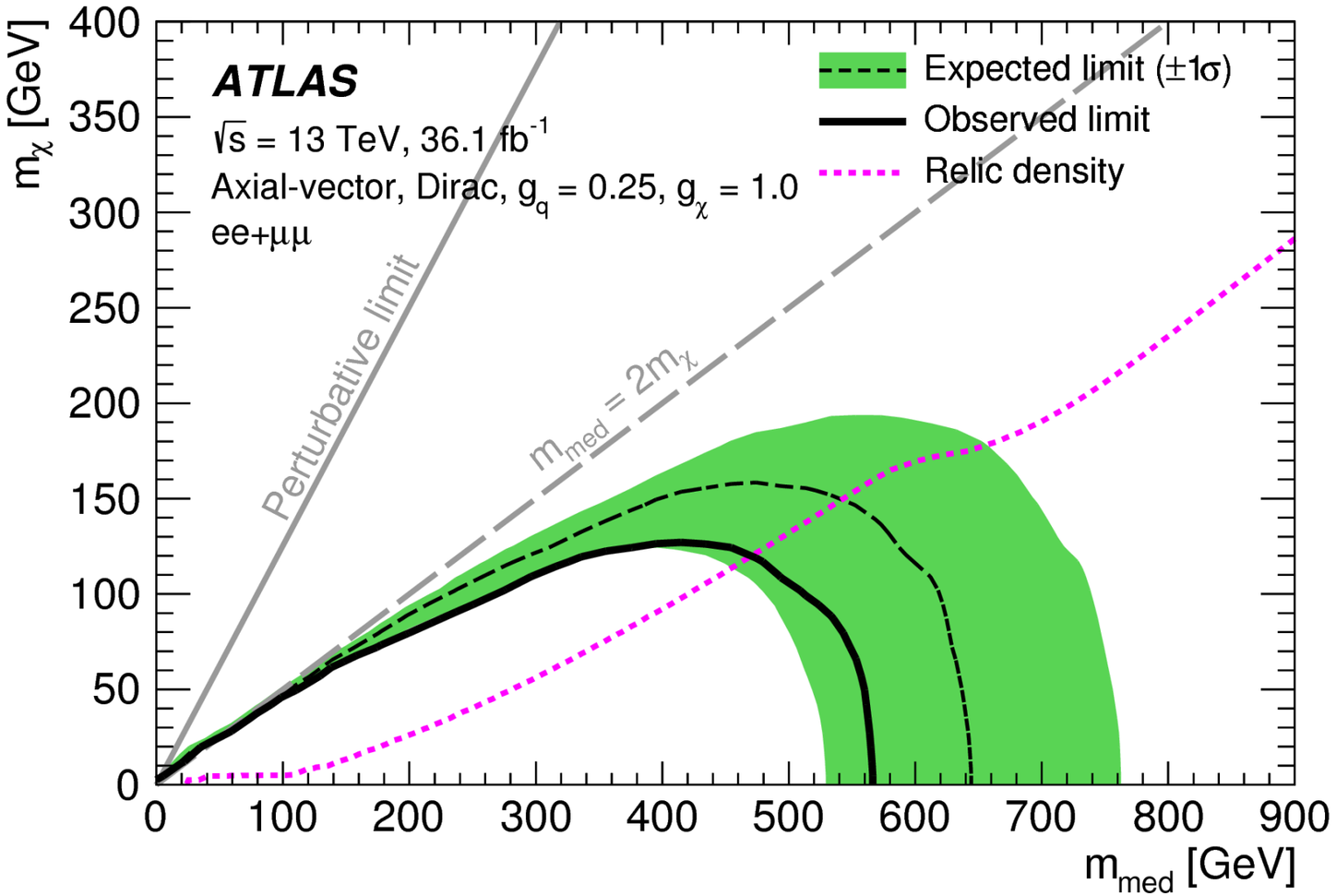
- Event selection highlights
  - $E_T^{miss} > 90$ GeV
  - B-jet veto, third lepton veto
- Main backgrounds & estimation:
  - ZZ(→ llvv)
  - WZ(→ llvl), Z(→ ll,) ll non-resonant



Mono-Z(ll) results

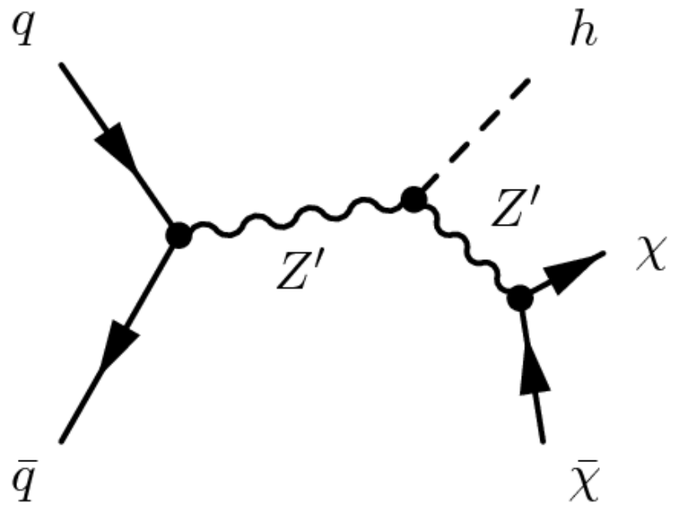
- Two signal regions:
  - final states with ee
  - final states with μμ
- Limits are set on the mediator mass to about 550 GeV





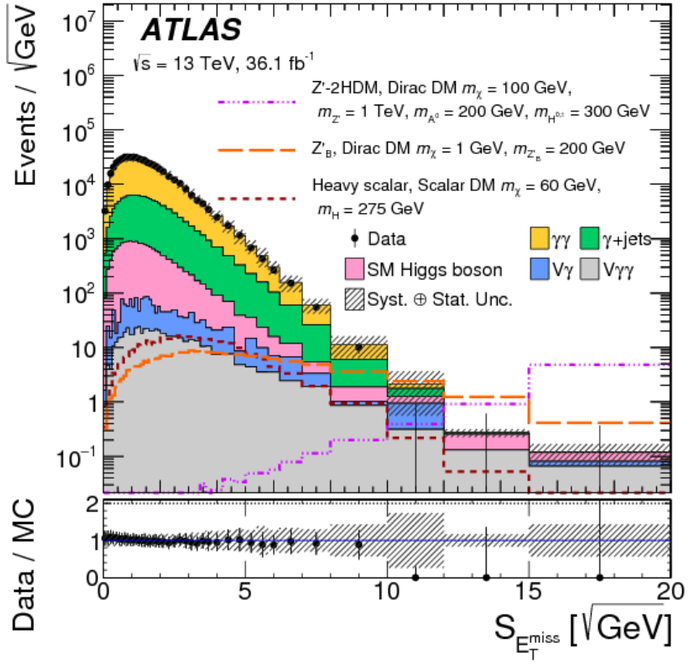
Mono-H(γγ)

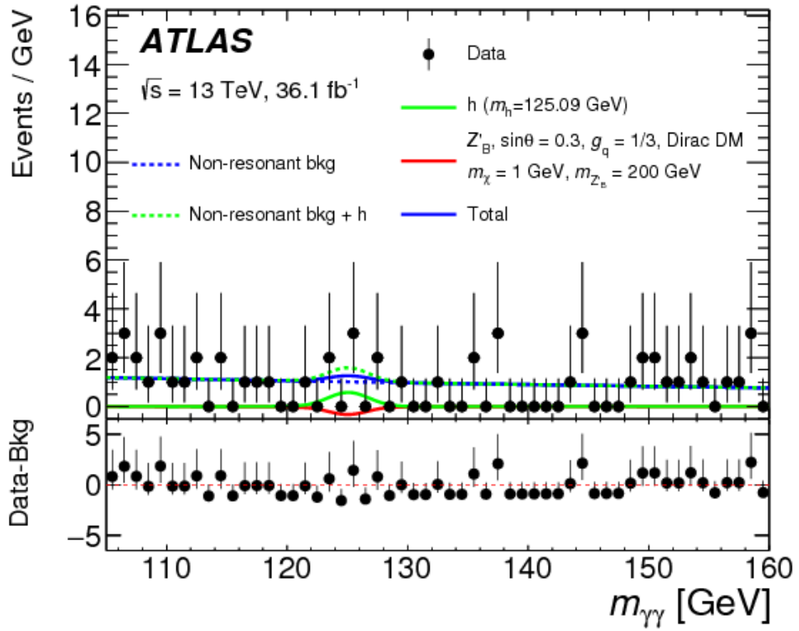
arXiv:1706.03948 [hep-ex]



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

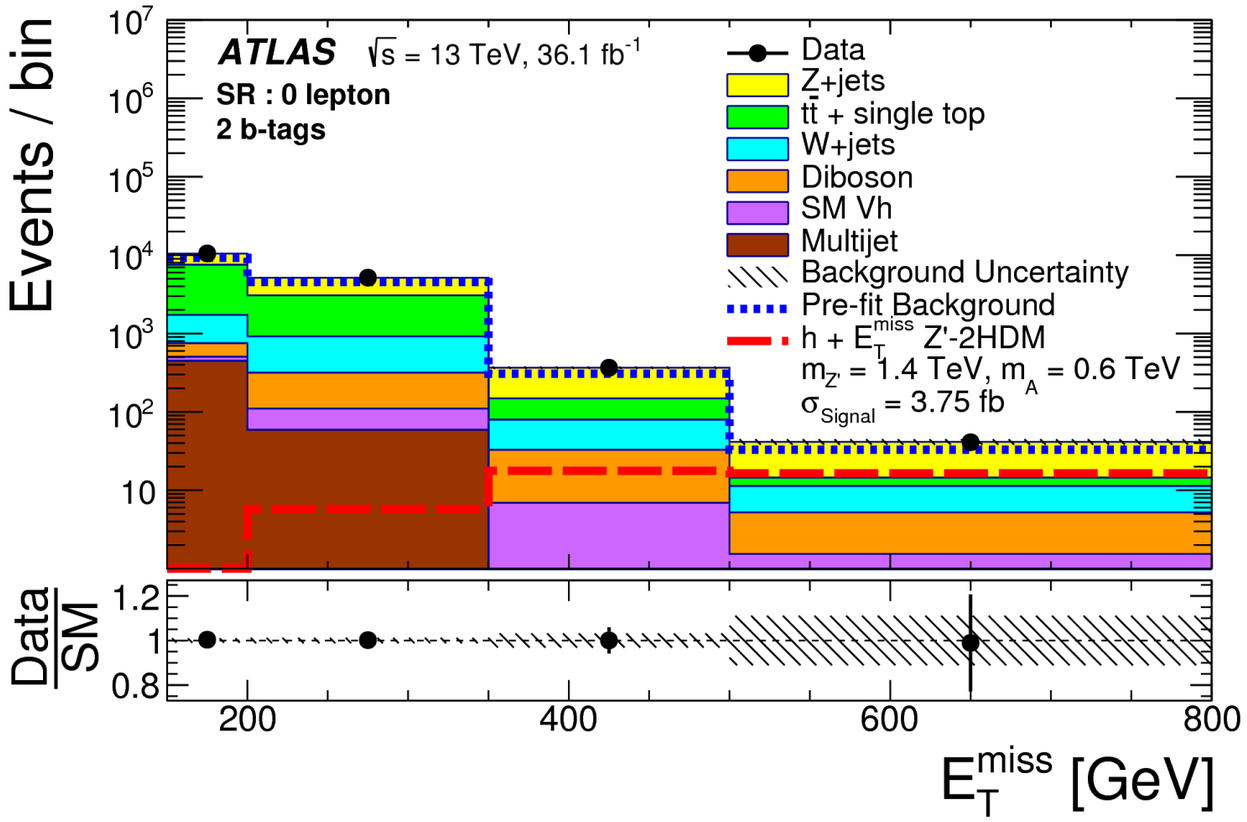
- Event selection highlights
  - $E_t^{miss} / \sqrt{\Sigma E_T} > 7$ GeV$^{1/2}$
  - $p_T^{\gamma\gamma} > 90$ GeV and lepton veto
- Backgrounds & estimation:
  - γγ nonresonant, H → γγ, γ+jets
  - Backgrounds parameterized with fit functions

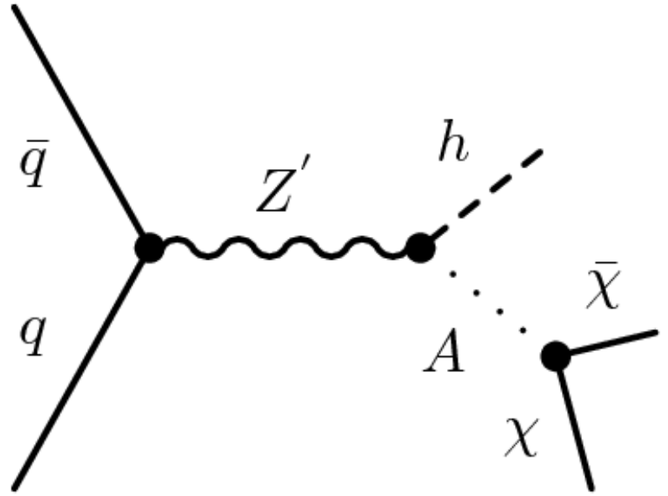




Mono-H(bb)

Phys. Rev. Lett. 119 (2017) 181804

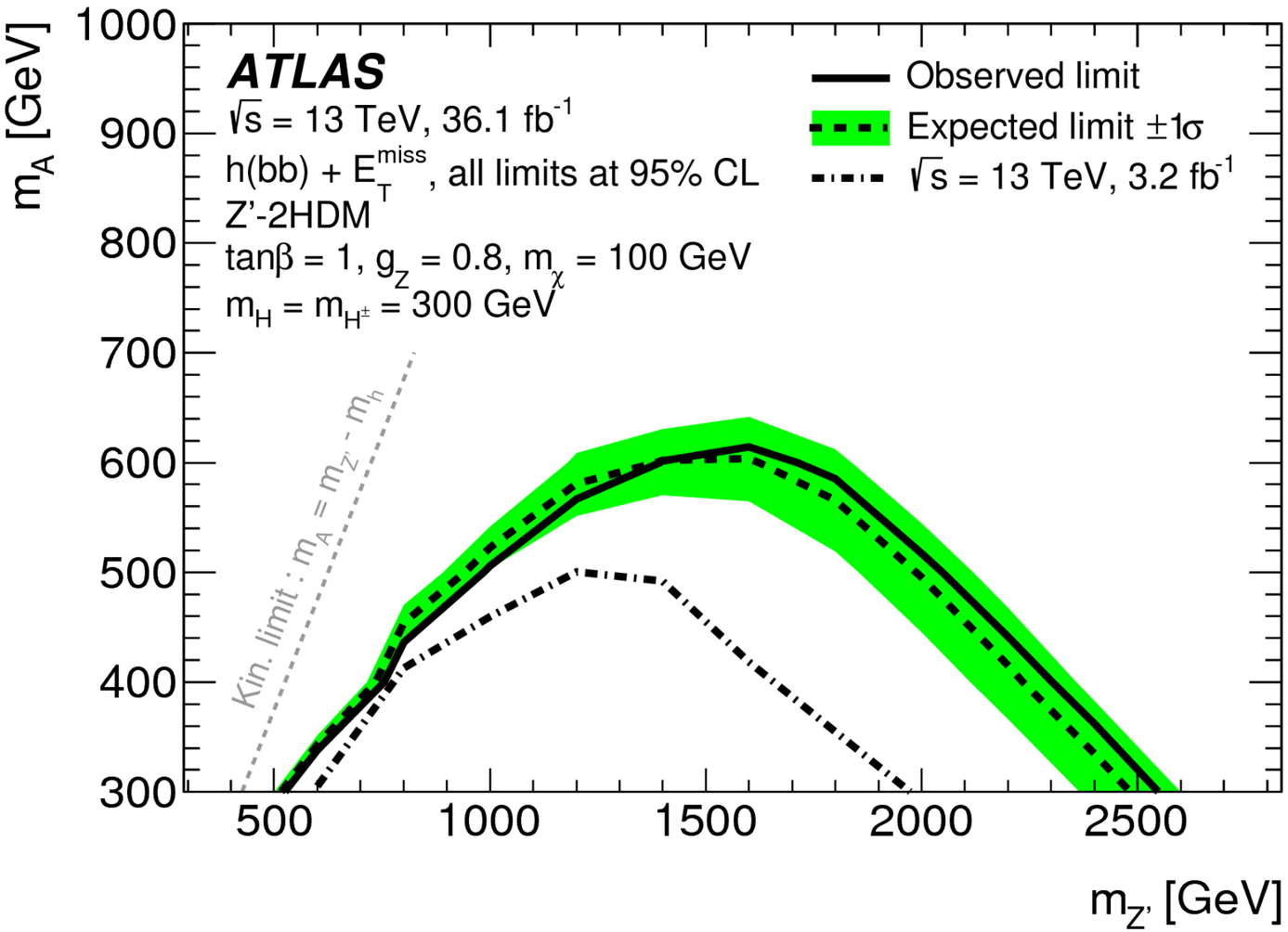




Dataset: 36.1 fb^{-1} (2015+2016)

- 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

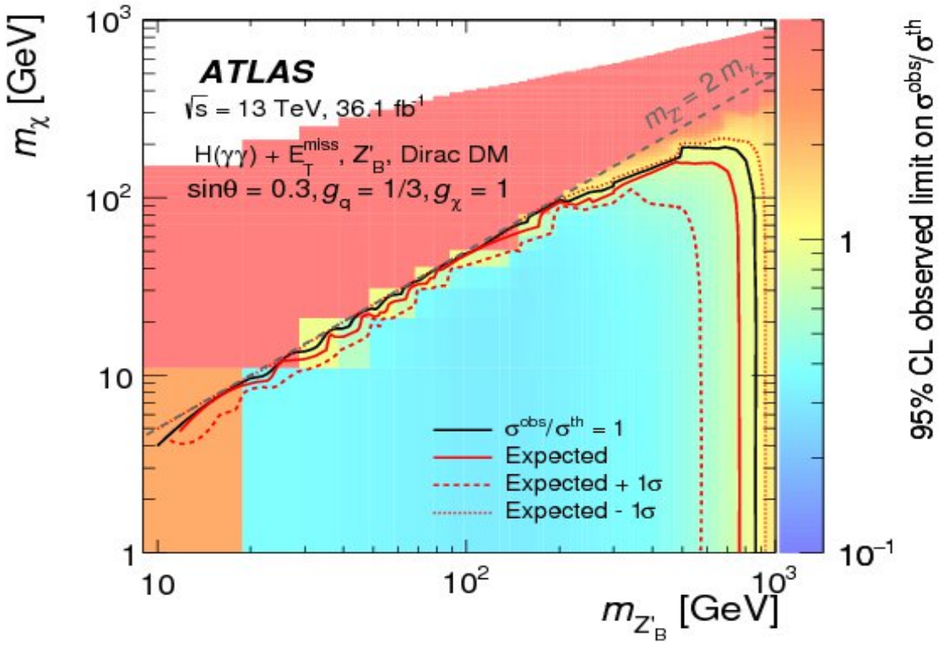
Mono-H(bb) results

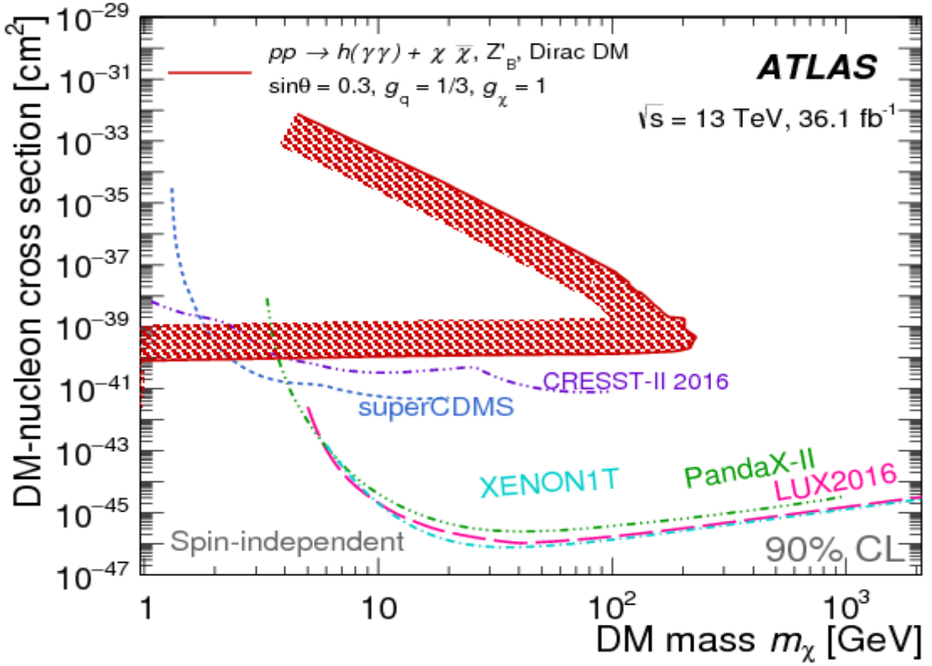


- Limits set with a two higgs doublet model (with specific parameters) on a massive Z' excluded up to 2.5 TeV

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

Mono-H(γγ) results



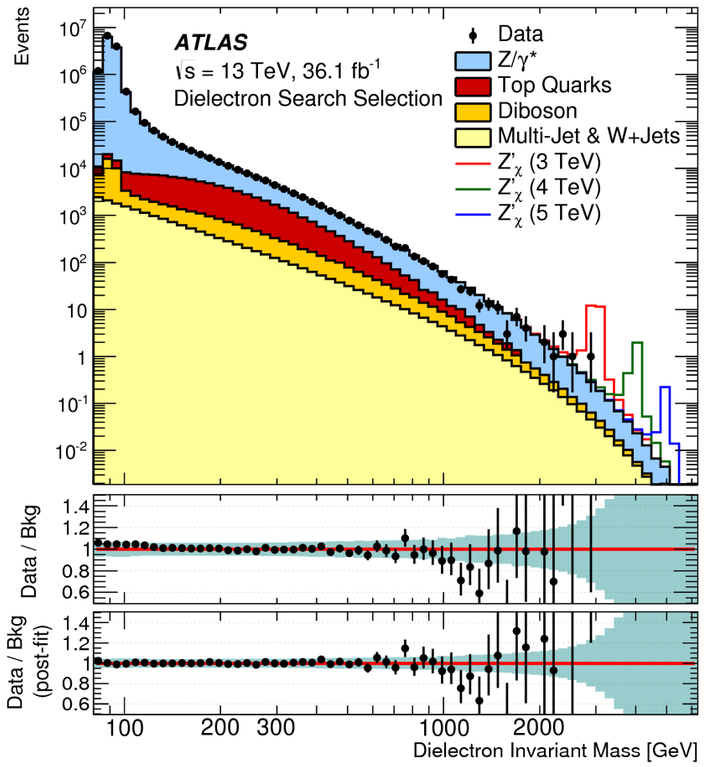


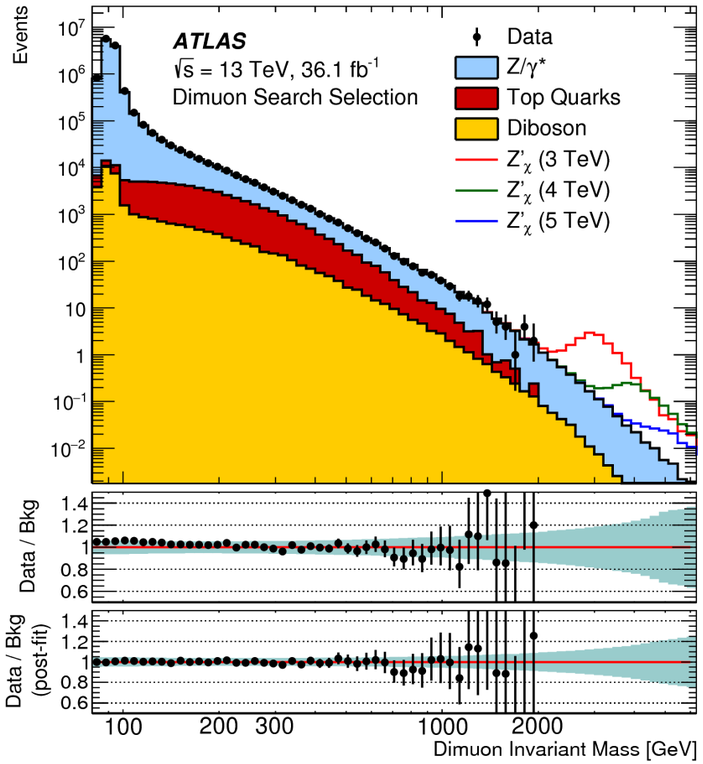
- Signal regions:
  - Most sensitive: $E_T^{miss} / \sqrt{\Sigma E_T} > 7 \sqrt{GeV}$
- Exclusive signal regions used for other analyses:
  - High E_T^{miss}: $E_T^{miss} / \sqrt{\Sigma E_T} > 5.5 \sqrt{GeV}$
  - Intermediate E_T^{miss}: $E_T^{miss} / \sqrt{\Sigma E_T} > 4 \sqrt{GeV}$

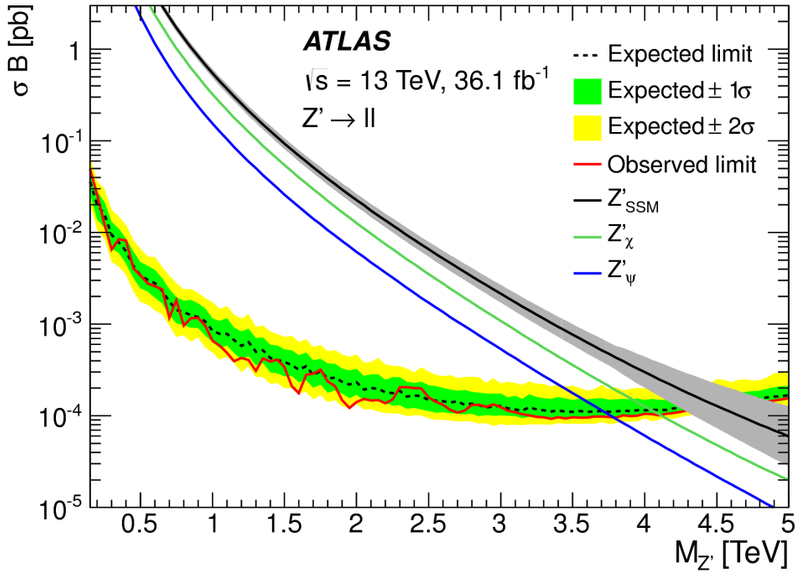
- Results exclude dark matter from a Z_B' > 850 GeV
- The results are competitive with direct detection limits at the lowest dark matter masses

Dilepton resonance search

JHEP 10 (2017) 182







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:

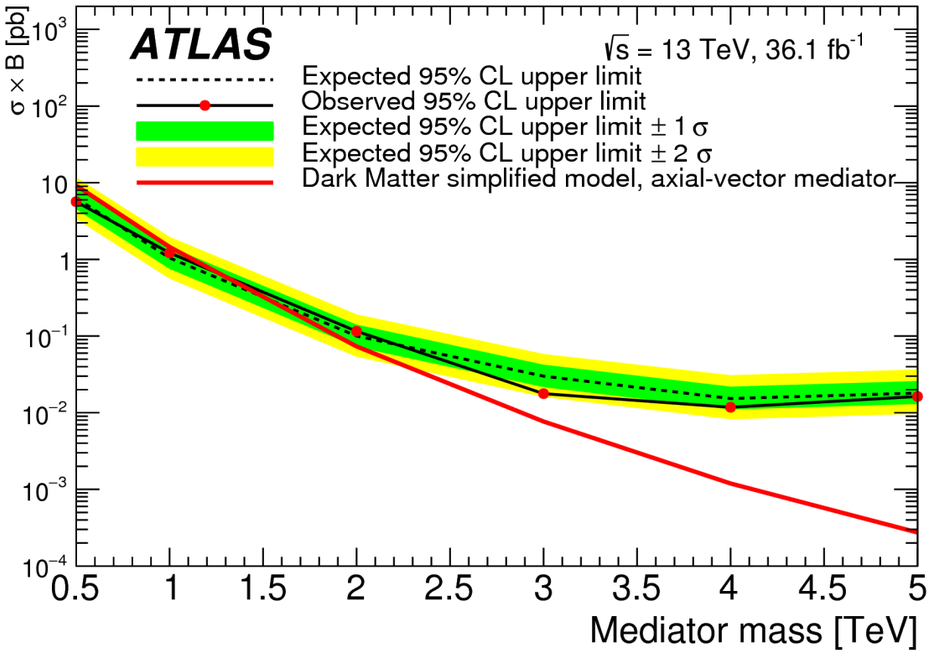
  4.1 TeV (4.0 TeV) obs (exp)

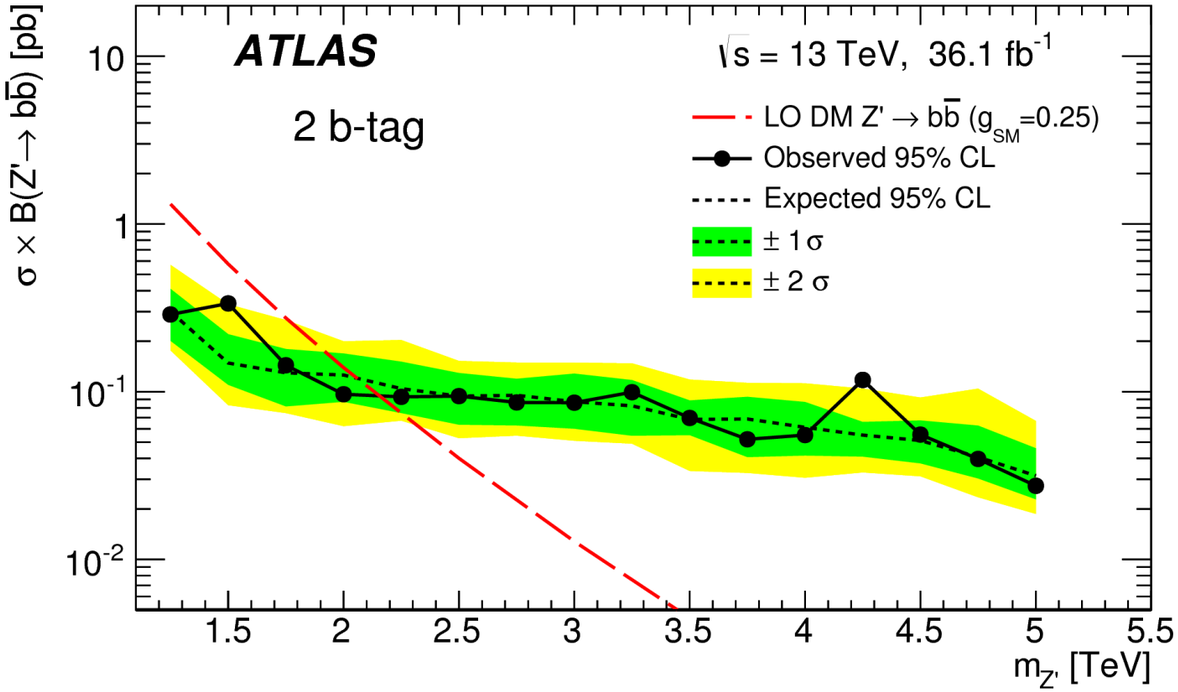
tt/bb resonances

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

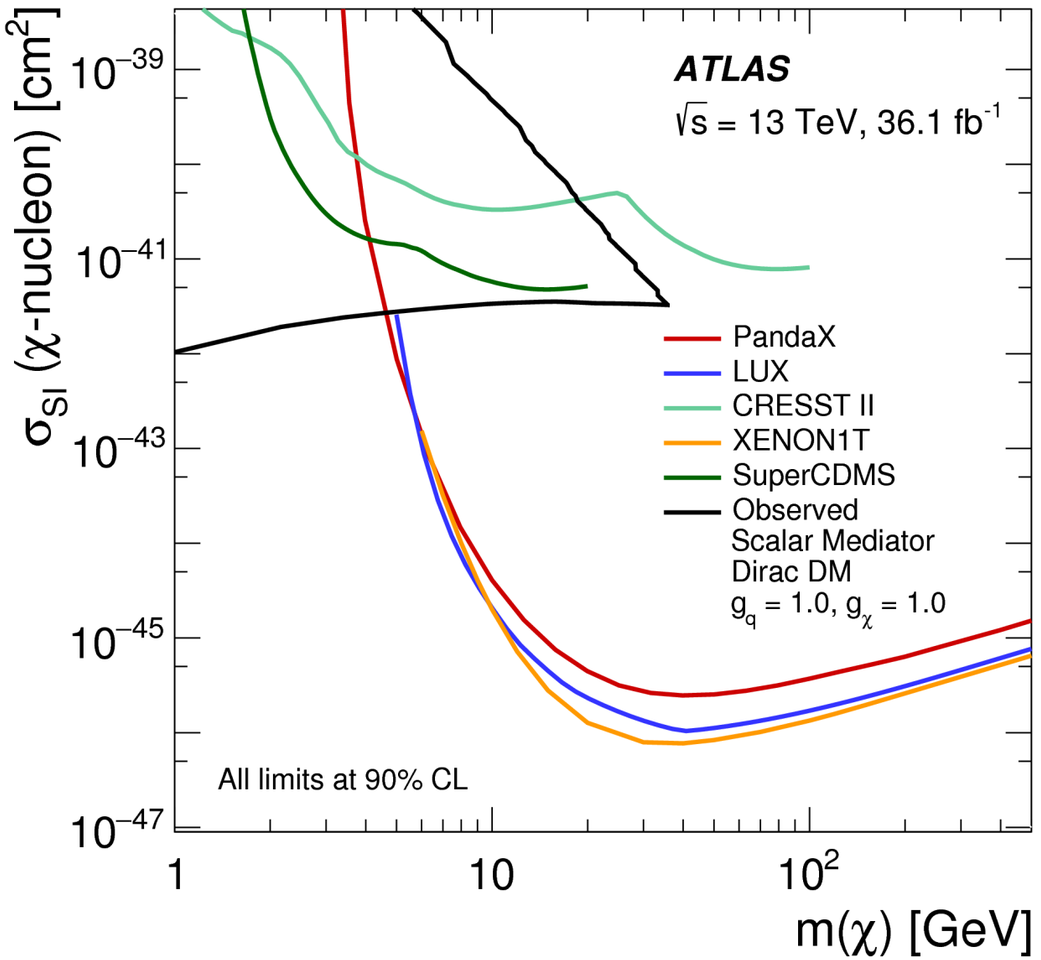
- Events are selected with one lepton, MET, and a jet, or b-tagged jets
- Backgrounds include tt, W/Z+jets, and diboson which are estimated in MC, and multi-jets, which are estimated in data
- The mass spectrum of the bb or tt system is searched for resonances, in the absence of those, a Z' is excluded at 95% CL at 1 and 2.0 TeV respectively

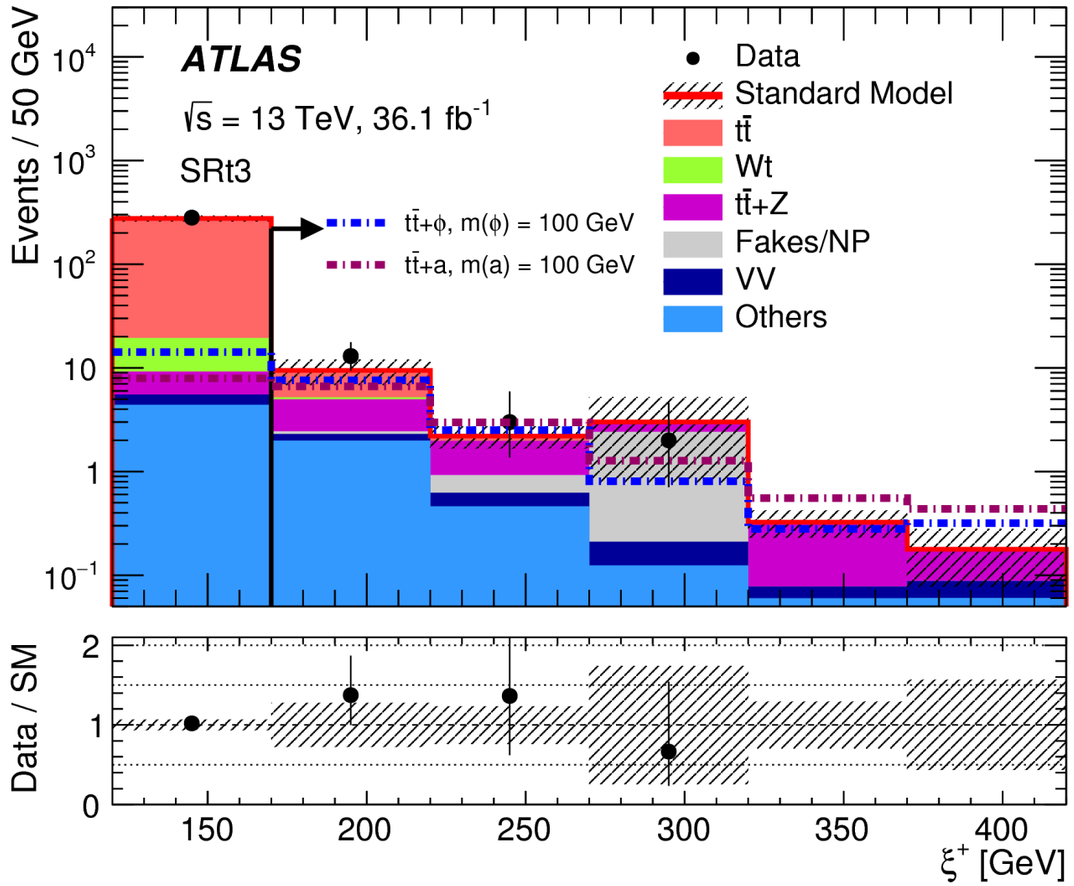
tt: arXiv:1804.10823 [hep-ex]
bb: arXiv:1805.09299 [hep-ex]





Combined HF results – ATLAS





Dark photons