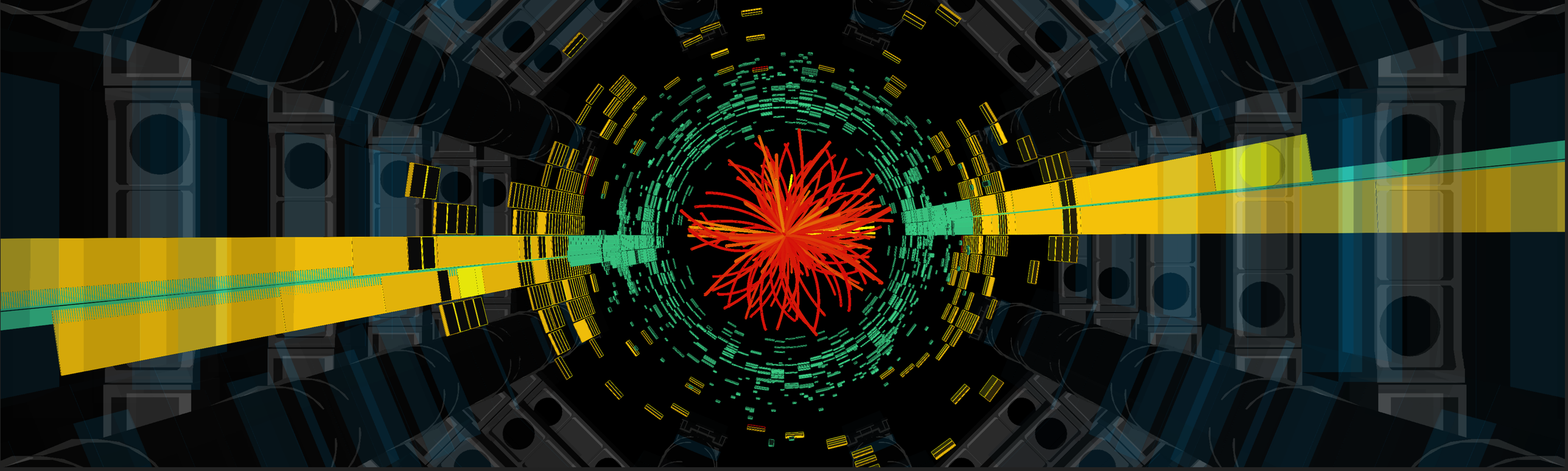


KATE WHALEN (U. OREGON)
ON BEHALF OF THE ATLAS COLLABORATION

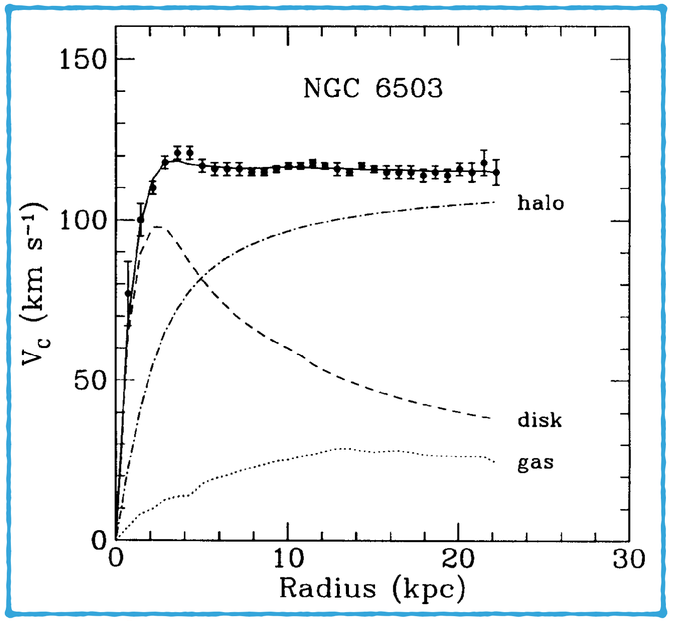
ICPPA 2017

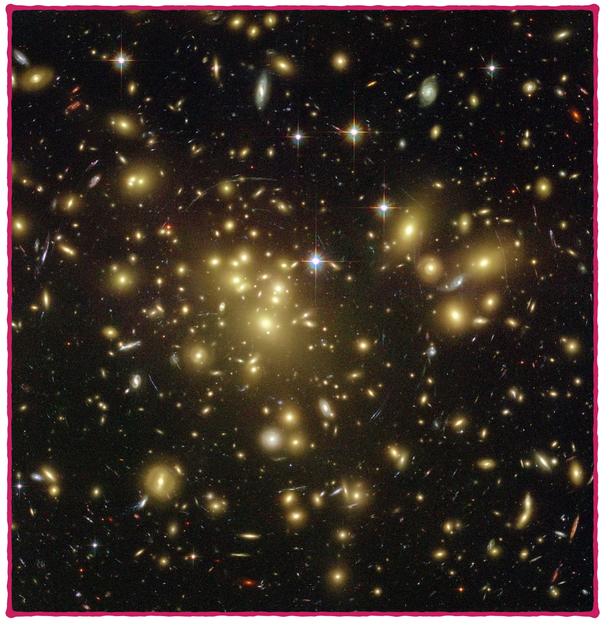
DARK MATTER SEARCHES WITH THE ATLAS DETECTOR

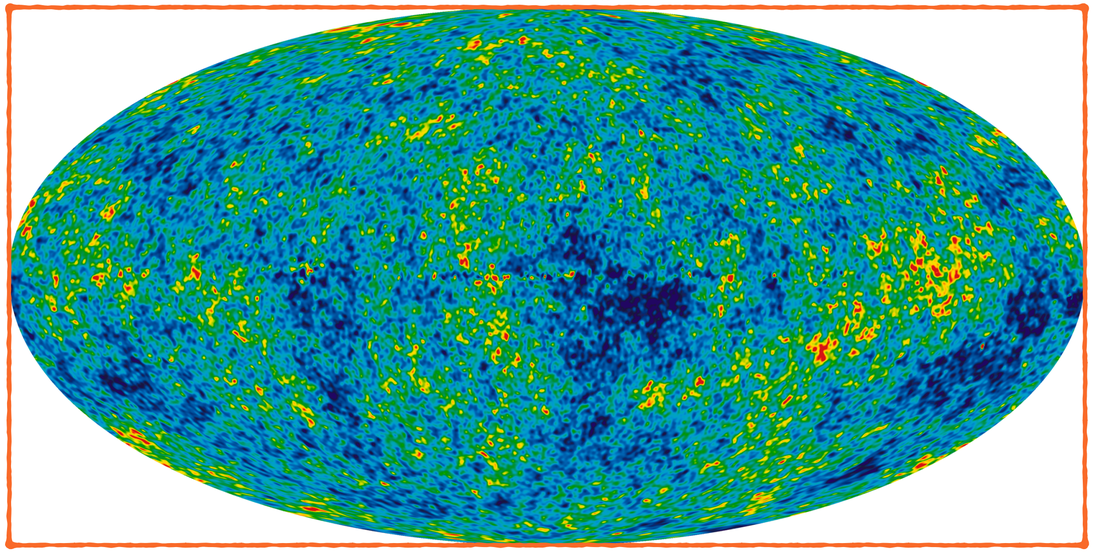
ATLAS EXPERIMENT

INTRODUCTION

- Plentiful evidence for dark matter
  - Galactic rotation curves
  - Gravitational lensing
  - Cosmic microwave background
- DM candidate should be
  - Electrically neutral
  - Weakly interacting
  - Massive







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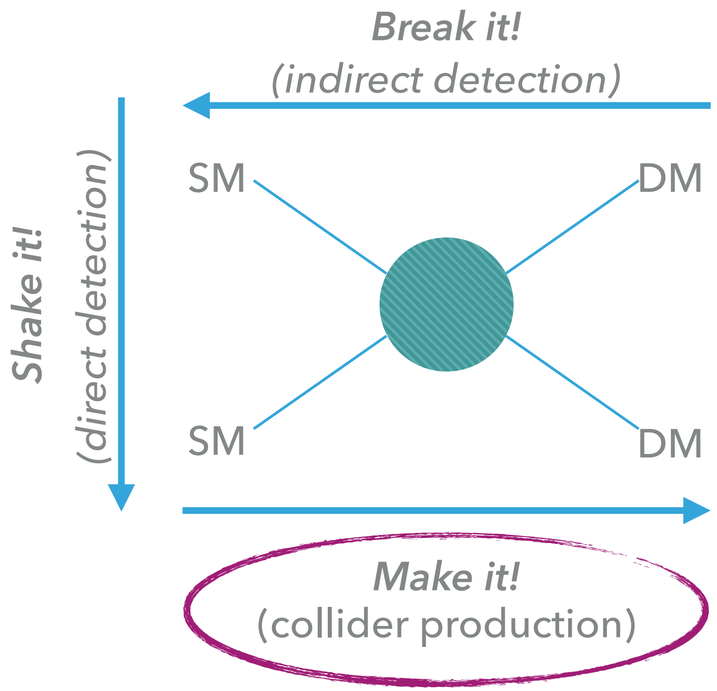
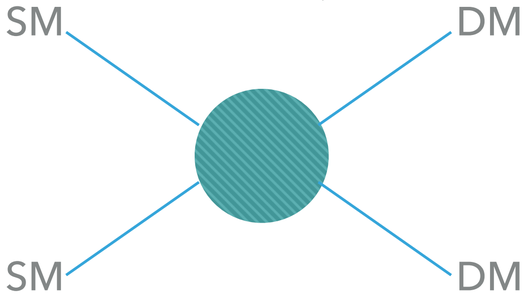
DARK MATTER SEARCHES

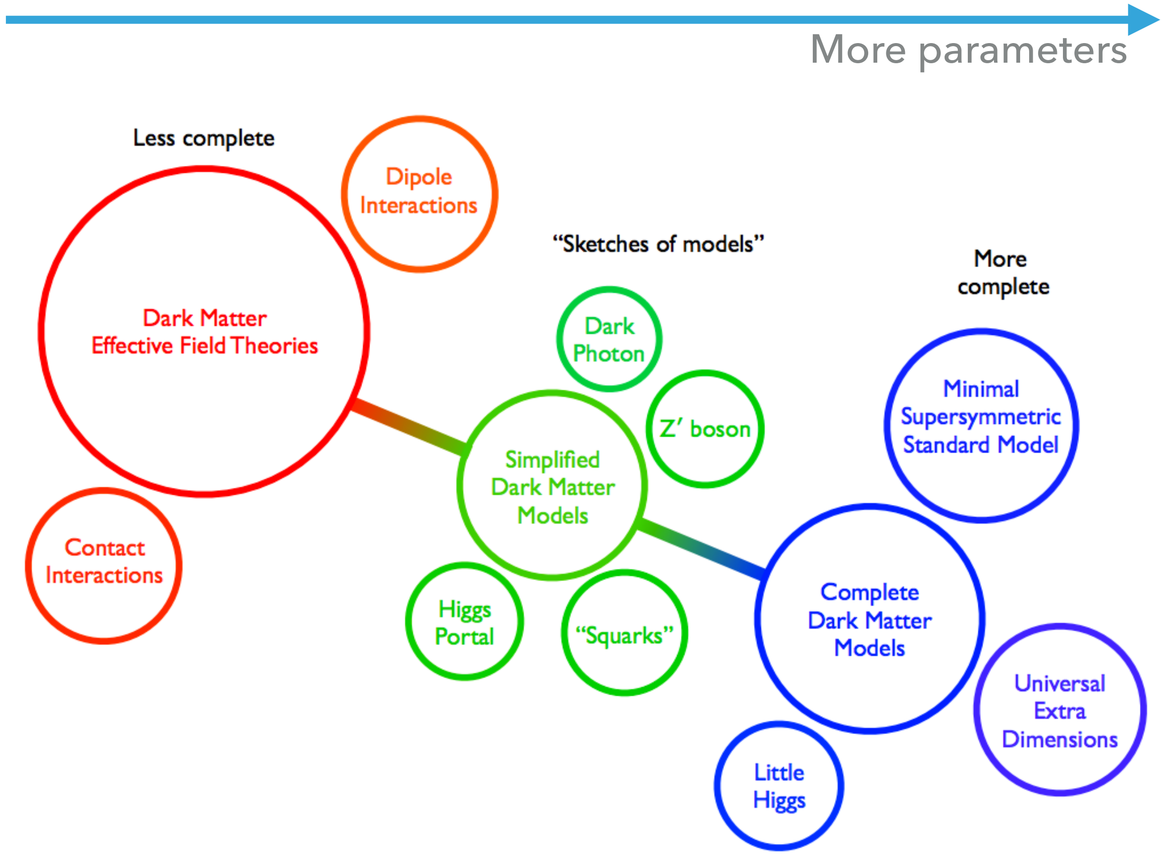
- Three complementary methods
  - Indirect detection: annihilation / decay products, e.g. gamma rays, cosmic rays, neutrinos
    - FERMI-LAT, AMS, ICECUBE…
  - Direct detection: WIMP-nucleon scattering
    - DEAP, PICASSO, CDMS, XENON, LUX…
  - Collider production
    - Will review a selection of searches (not all of them!) with the ATLAS detector for dark matter produced at the LHC



DARK MATTER MODELS AT THE LHC (RUN 1)

- Effective field theories (EFT)
  - Run 1 DM searches at the LHC
  - Contact interactions
  - Described in terms of effective energy scale and m_{DM}
  - Invalid at large momentum transfer: problematic in Run 2 (13 TeV LHC)



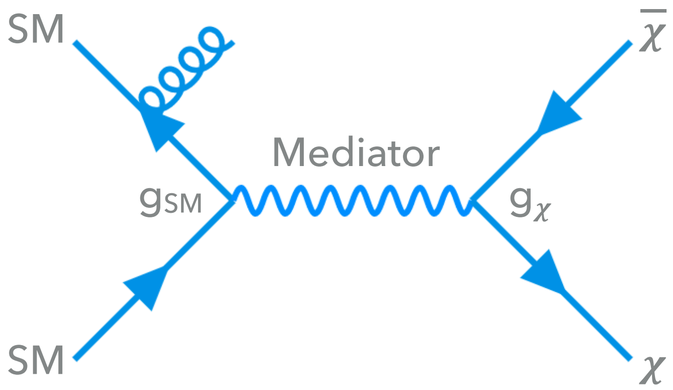


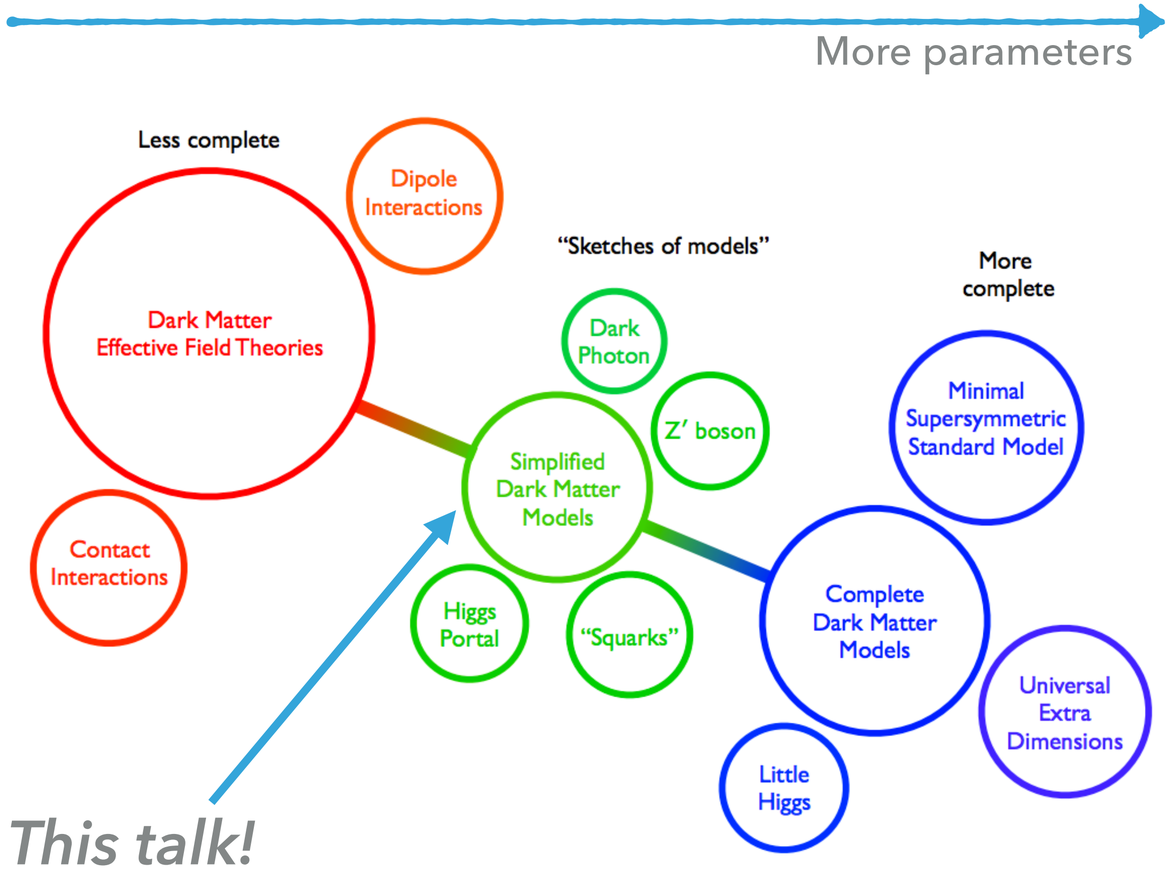
LHCDMWG (arXiv:1506.03116)

DARK MATTER MODELS AT THE LHC (RUN 2)

ATLAS / CMS DM forum
arXiv:1507.00966

- Simplified models
  - Contain a stable or very long-lived DM candidate "χ"
  - Introduce a mediator that couples to SM and DM to resolve the contact interaction into s- / t-channel interactions
  - Permit more complete descriptions of DM production kinematics at the LHC
  - Need more parameters (masses and couplings): m_{χ}, m_{med}, g_{SM}, g_{χ}





LHCDMWG (arXiv:1506.03116)

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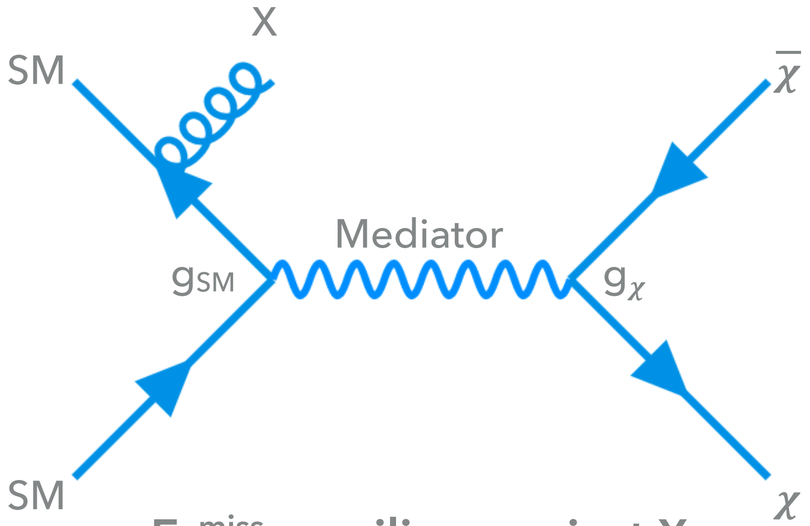
SIMPLIFIED MODELS AT THE LHC

- Typical signatures at the LHC:

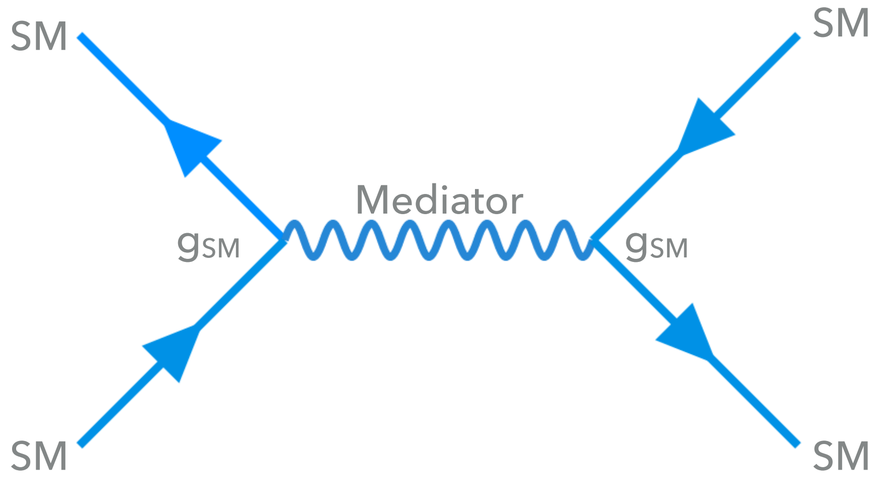
Note! Results presented depend on couplings to DM, SM

Mono-X



E_T^{miss} recoiling against X
(X=jet, H, W, Z, γ…)

Di-X resonance

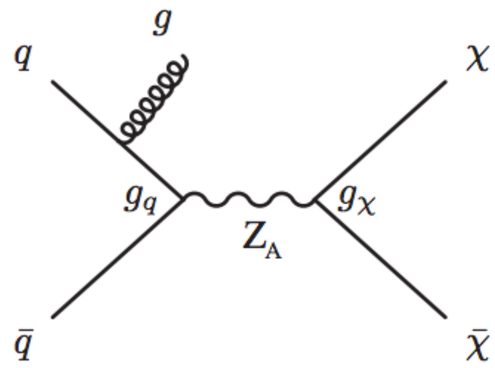


Dijet, dilepton…
(mediator search)

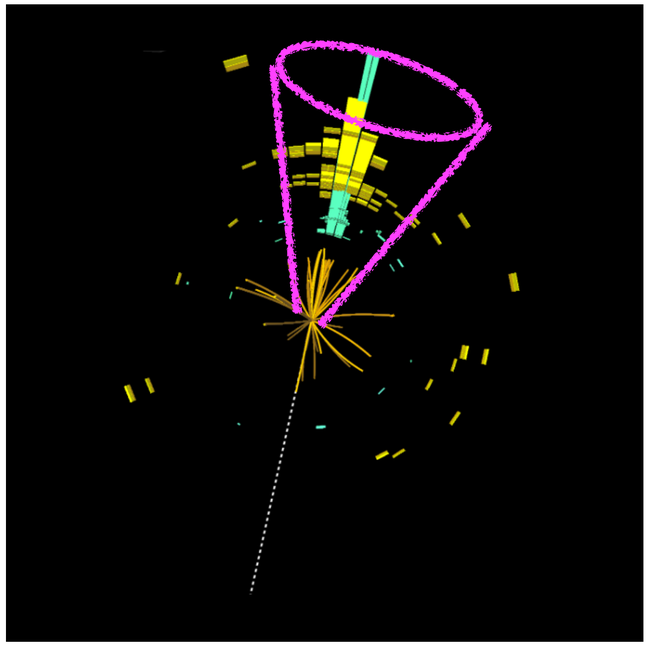
MONO-X SEARCHES

MONO-JET SEARCH

ATLAS-CONF-2017-060

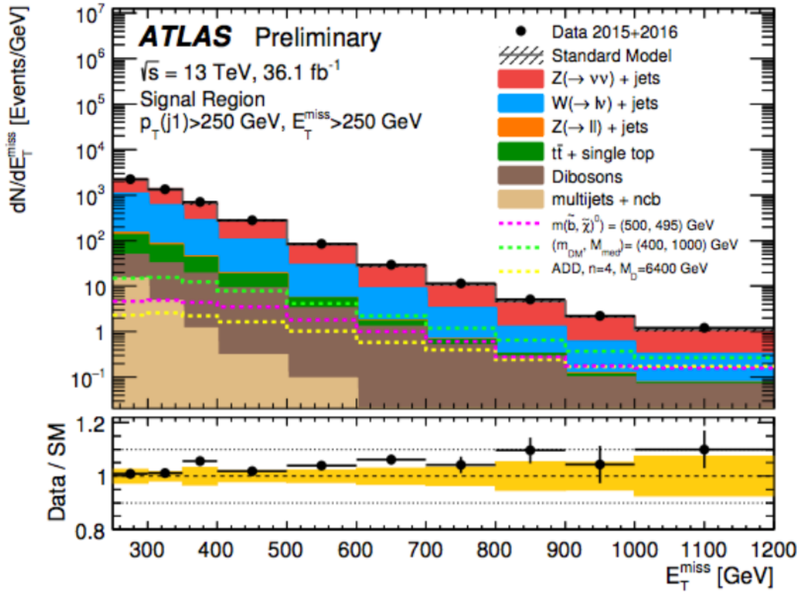


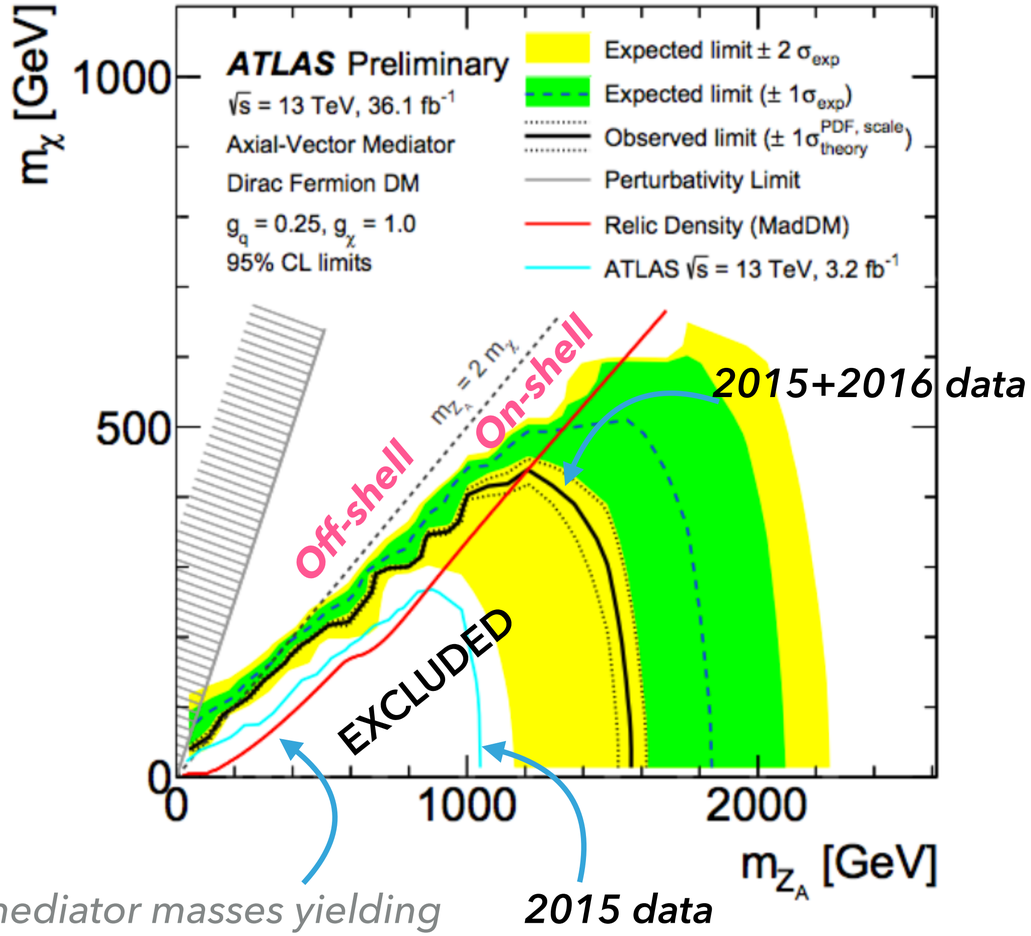
- Dirac fermion WIMPs produced via s-channel exchange of leptophobic spin-1 mediator with axial-vector couplings
- Search for large E_T^{miss} recoiling against a high-p_T jet
  - E_T^{miss}, p_T^{jet} > 250 GeV
  - N_{jets} (p_T>30 GeV) ≤ 4, $\Delta\phi$(jet, p_T^{miss}) > 0.4
  - Veto events containing electrons or muons
- Dominant Z(→νν)+jets background constrained using simultaneous fit to E_T^{miss} distribution in W(→ℓν)/Z(→ℓℓ) + jets control regions
  - W/Z+jets MC predictions (NLO SHERPA) reweighted to account for higher-order corrections (arXiv:1705.04664 [hep-ph])
  - 0.7-1% theoretical uncertainty on extrapolation from control regions
- Background uncertainty ~2-5% (dominated by jet/energy scale & resolution)



MONO-JET RESULTS

- 10 signal regions in bins of E_T^{miss}
- 95% CL exclusion limits on axial-vector mediator with $g_q = 0.25$, $g_\chi = 1$
  - Mediator masses below 1.55 TeV excluded for very light WIMPS
- Also considered pseudoscalar mediator with g_q, $g_\chi = 1$ (not yet sensitive; see backup)





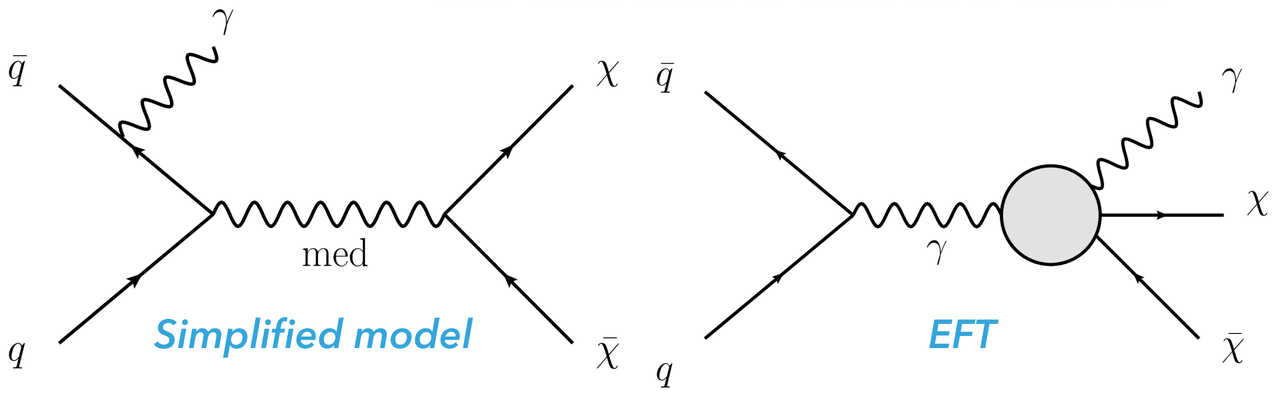
Relic density: DM and mediator masses yielding the correct abundance of DM in the universe

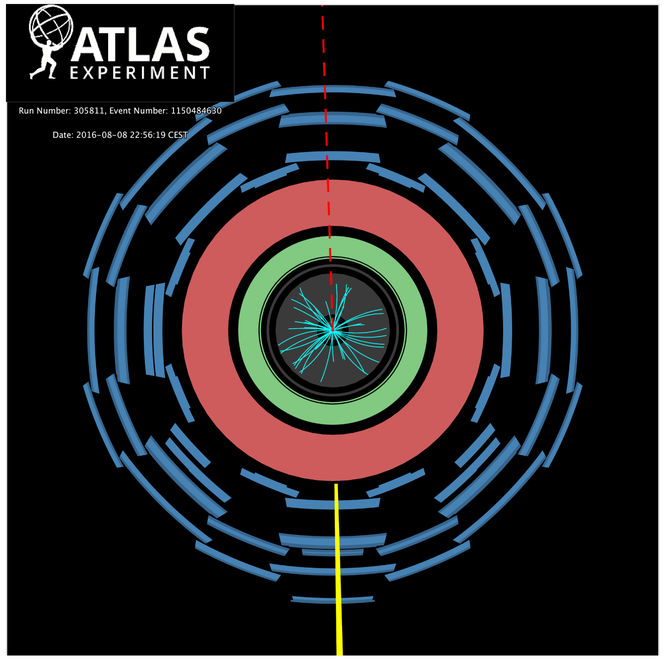
K. Whalen (ICPPA2017)

MONO-PHOTON SEARCH

[Eur. Phys. J. C 77 (2017) 393]

- Simplified model with vector or axial-vector couplings
- Also consider dimension-7 EFT operator
- Search for large E_T^{miss} recoiling against a high-E_T photon
  - E_T^{miss}, $E_T^{\gamma} > 150$ GeV
  - $\Delta\phi(\gamma, E_T^{miss}) > 0.4$
  - $N_{jets} \leq 1$
  - Veto events containing electrons or muons
- Dominant backgrounds ($Z\gamma$, $W\gamma$, γ+jets) normalized in control regions using a simultaneous likelihood fit

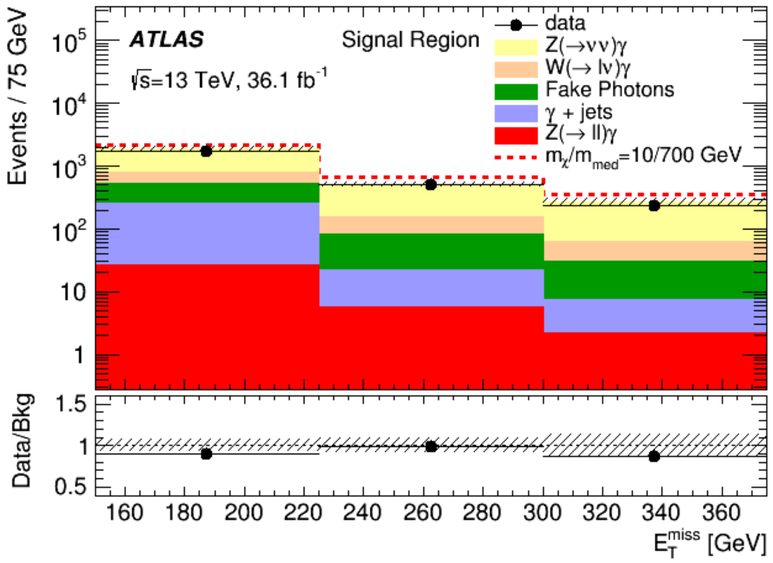


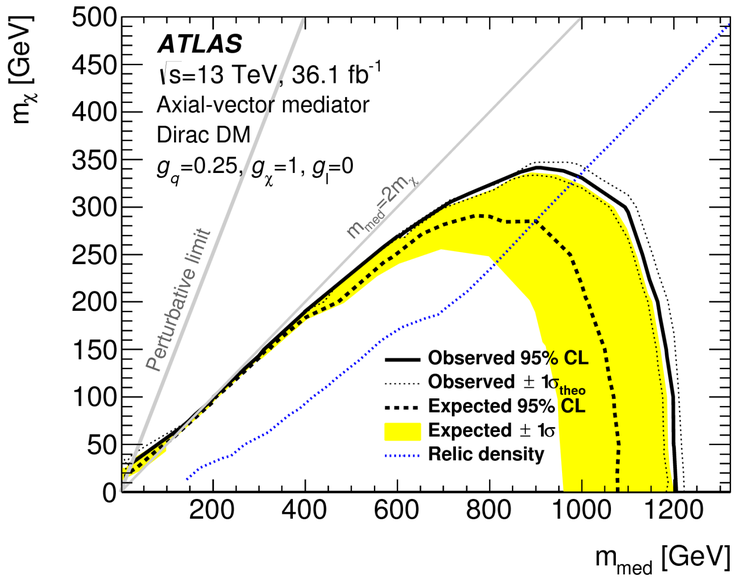


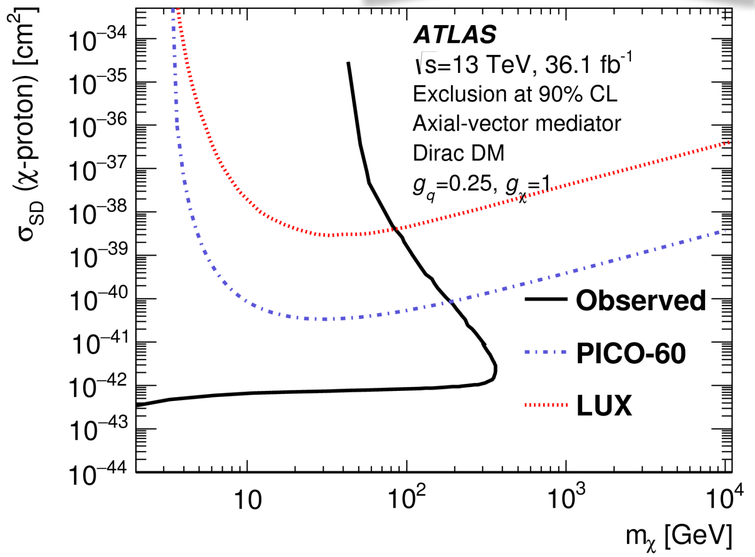
MONO-PHOTON RESULTS

- Three inclusive signal regions in E_T^{miss}
- Results presented for axial-vector mediator with couplings g_q=0.25, g_χ=1
  - Excluded axial-vector and vector mediators below 750–1200 GeV for χ masses below 230–480 GeV
  - Converted to limits on χ-nucleon scattering cross-section
  - See backup for vector mediator, other couplings, EFT interpretation

(2015+2016 data)





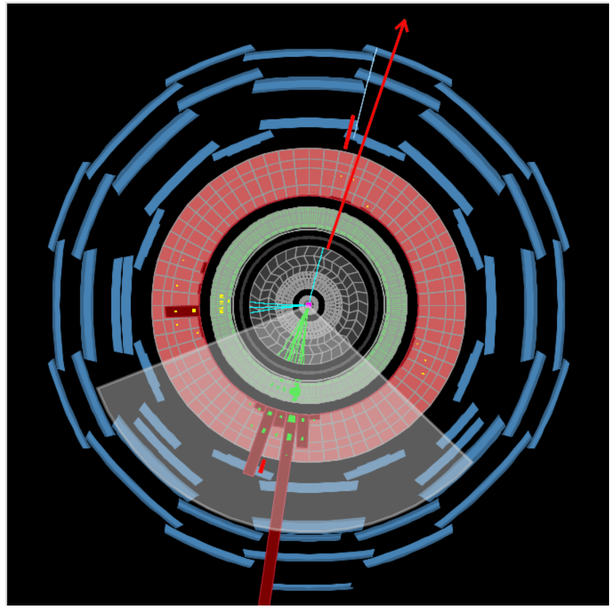


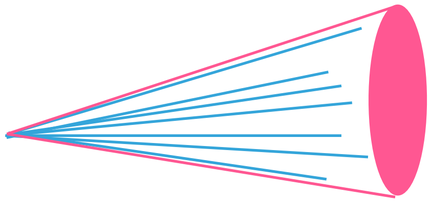
K. Whalen (ICPPA2017)

MONO-W/Z (HADRONIC) SEARCH

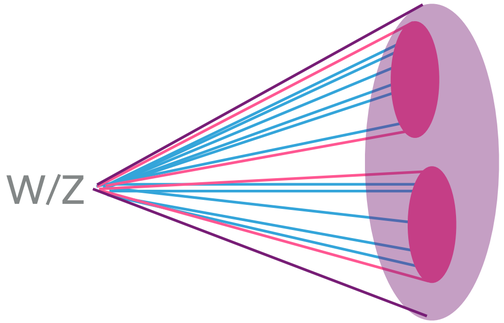
Phys. Lett. B 763 (2016) 251

- Highly boosted hadronically decaying W/Z recoiling against large E_T^{miss} (> 250 GeV)
- Jet substructure techniques used to tag large-R (anti-k_T R=1.0) jets from W/Z boson decays:
  - Require m_{jet} within 15 GeV of W/Z mass
  - D_2 variable (energy correlation ratio, see ATLAS-CONF-2017-064, e.g.) used to select jets with two-pronged substructure





QCD jet



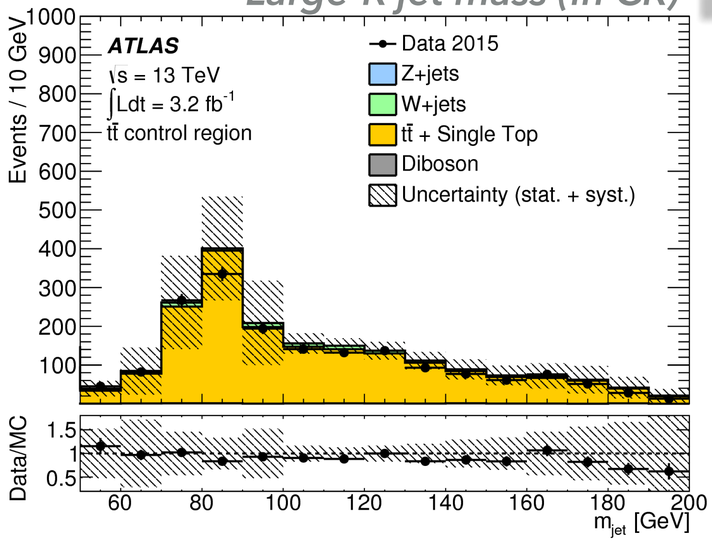
Large-R jet from W/Z decay

MONO-W/Z (HADRONIC) RESULTS

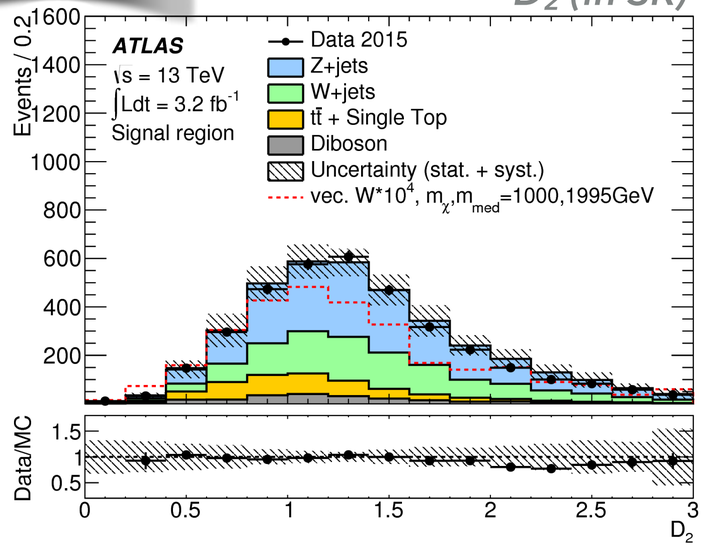
- Dominant backgrounds (Z+jets, W+jets, ttbar) normalized in control regions using a profile likelihood fit to the E_T^{miss} distribution
- Set limits on simplified model with vector mediator and couplings $g_q = 0.25$, $g_\chi = 1$

(2015 data)

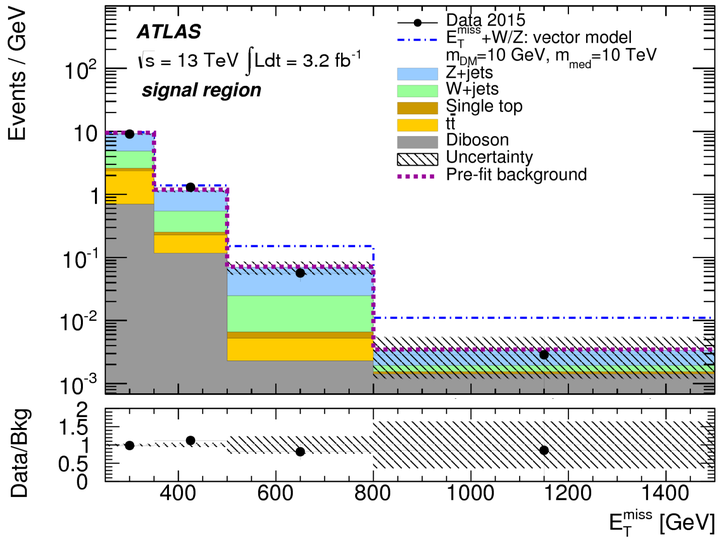
Large-R jet mass (in CR)

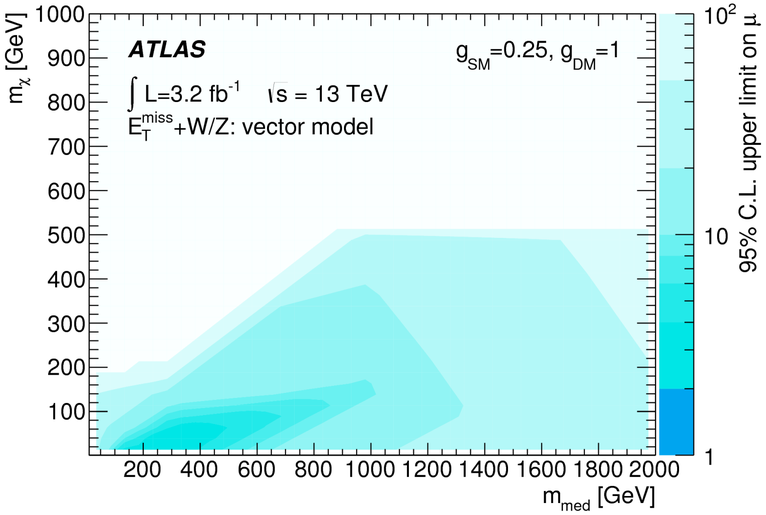


D_2 (in SR)



E_T^{miss} (in SR)





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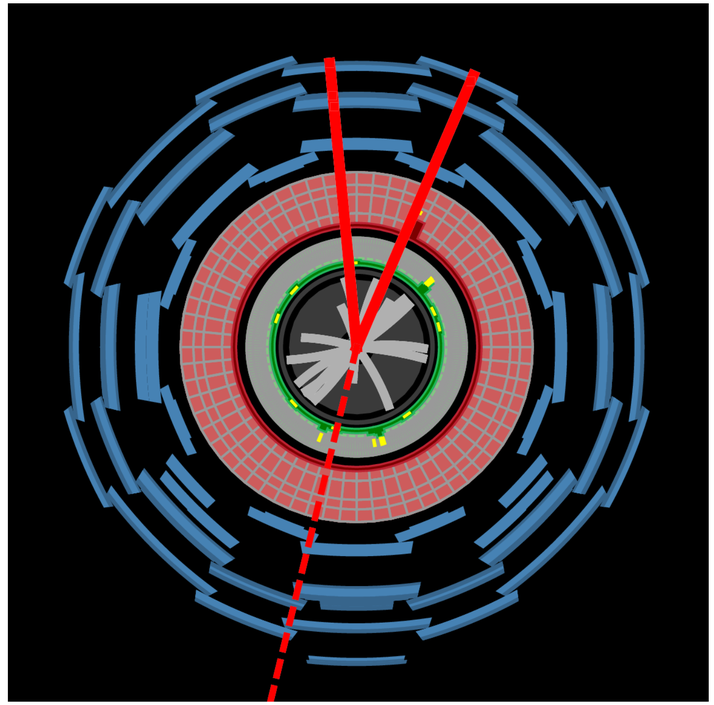
MONO-Z (LEPTONIC)

arXiv:1708.09624

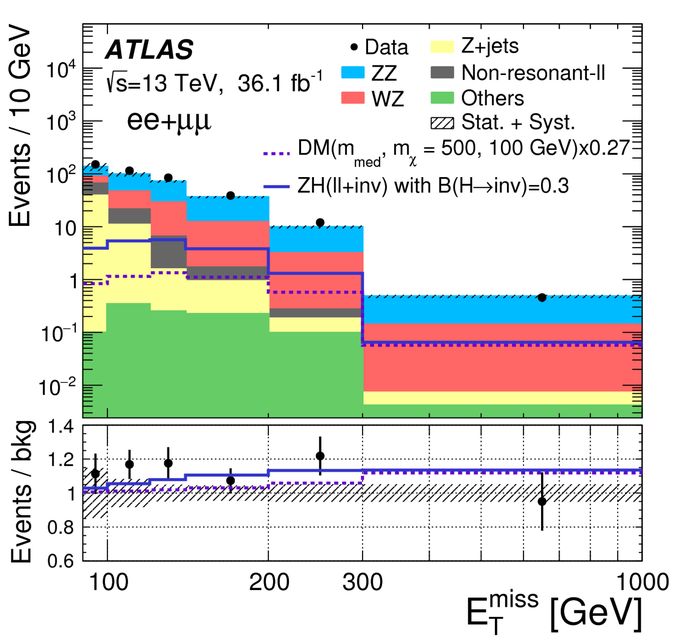
- Search for boosted $Z(\rightarrow \ell\ell)$ + E_T^{miss}
- Require two same-flavour, opposite-sign leptons (ee, μμ) with $|m_Z - m_{\ell\ell}| < 15$ GeV
- Boosted topology: $E_T^{miss} > 90$ GeV, small angular separation between leptons ($\Delta R_{\ell\ell} < 1.8$)
- Irreducible ZZ background estimate from MC; WZ, Z+jets from data-driven methods

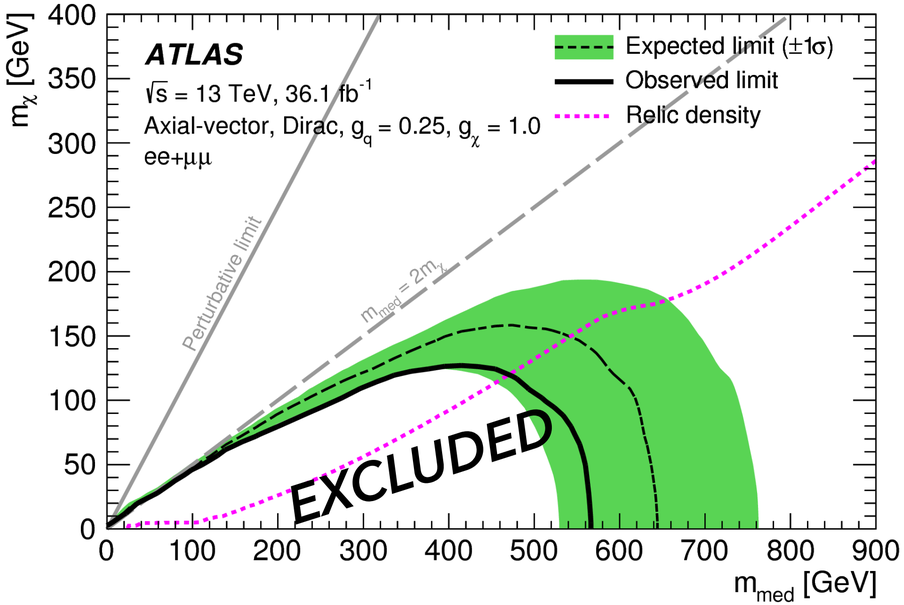


MONO-Z (LEPTONIC) RESULTS

(2015+2016 data)

- Low-mass (E_T^{miss} > 90 GeV) search sets limits on simplified WIMP DM model with axial-vector mediator, g_q=0.25, g_χ=1
  - Mediator up to 560 GeV excluded for light WIMPs
  - WIMPs up to 130 GeV excluded (for 400 GeV mediator)
- Other interpretations in high-mass signal region (E_T^{miss} > 120 GeV):
  - ZH production: (Z→ℓℓ, H→invisible)
  - Heavy resonances (e.g. 2HDM, RS graviton) decaying to ZZ→ℓℓνν





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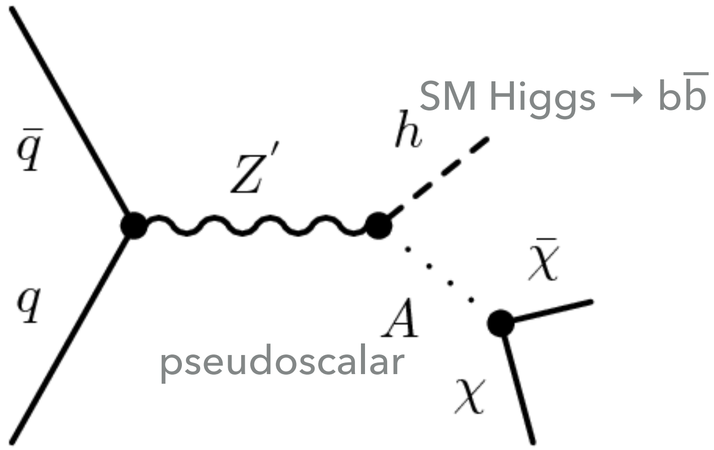
MONO-HIGGS

arXiv:1707.01302

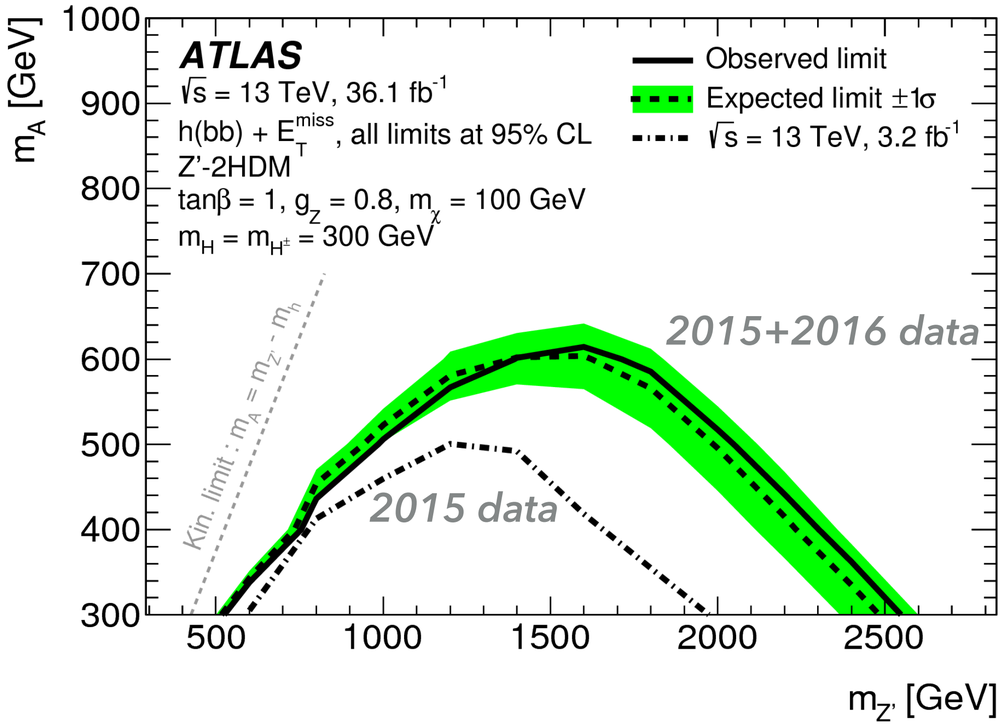
- Initial-state Higgs radiation highly suppressed: mono-Higgs production allows a direct probe of SM-DM interactions
- Target model: Z′–2HDM, with SM h→b$\bar{b}$
- Multivariate b-tagging (ATLAS-CONF-2016-039)
- Resolved topology (150 < E_T^{miss} < 500 GeV)
  - Two small-R jets; one or two b-tags
- Boosted topology (E_T^{miss} > 500 GeV)
  - Large-R jet with b-tagging applied to small-R track jets matched to large-R jet

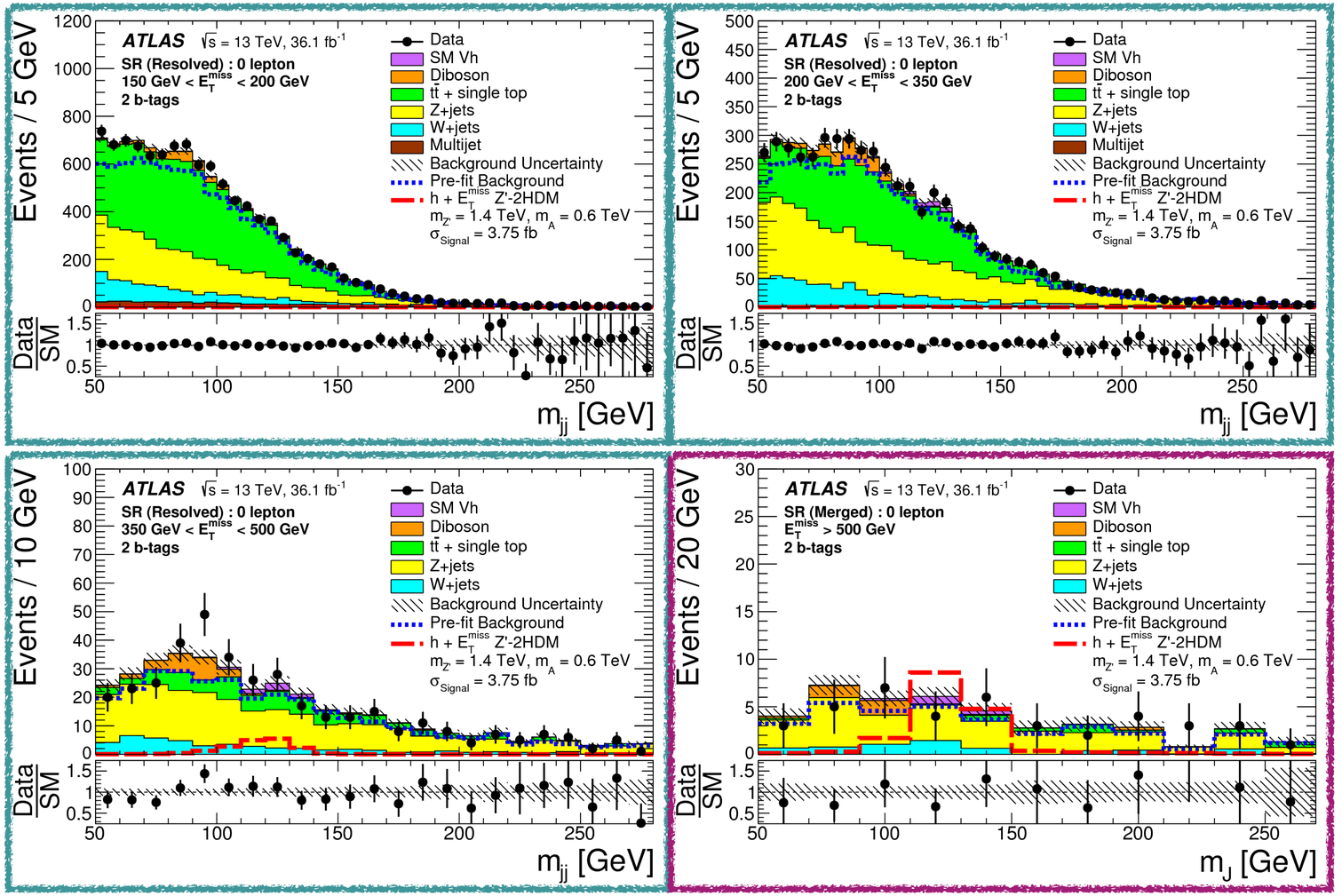


Other final states:
4ℓ (ATLAS-CONF-2017-042)
γ γ (arXiv:1706.03948)

MONO-HIGGS RESULTS

- 2 b-tag category gives highest signal sensitivity for resolved (binned in E_T^{miss}) and boosted regimes



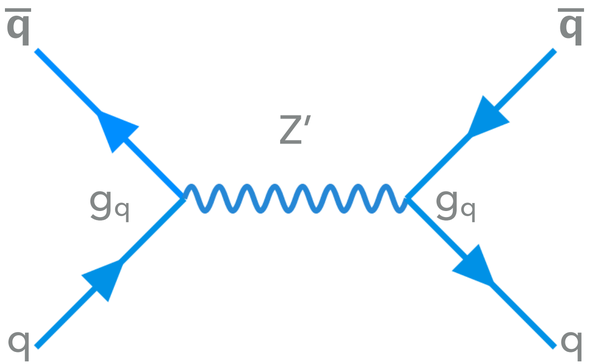


K. Whalen (ICPPA2017)

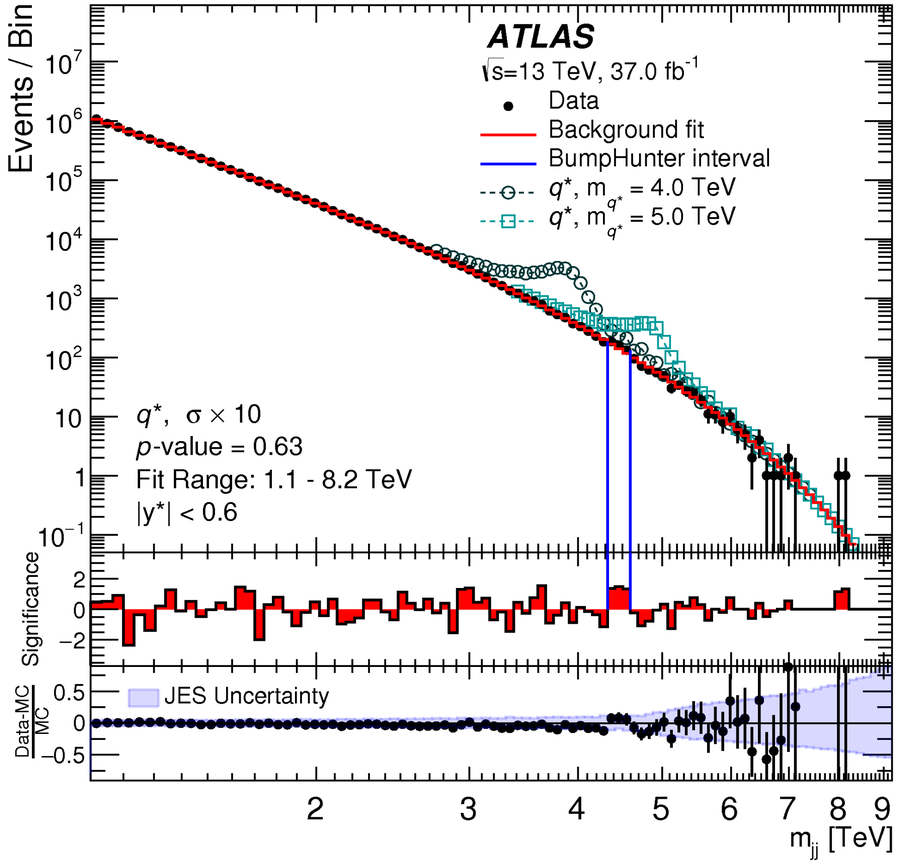
DI-X RESONANCE (MEDIATOR) SEARCHES

DIJET RESONANCES

- High-mass dijet search probes a wide range of signatures in mass range above ~1 TeV
  - Z′ (dark matter mediator), W′, W*, quantum black holes, excited quarks
- Lowest unprescaled single-jet trigger: $p_T^{jet} > 380$ GeV
- Multijet background prediction: sliding-window fit



arXiv:1703.09127

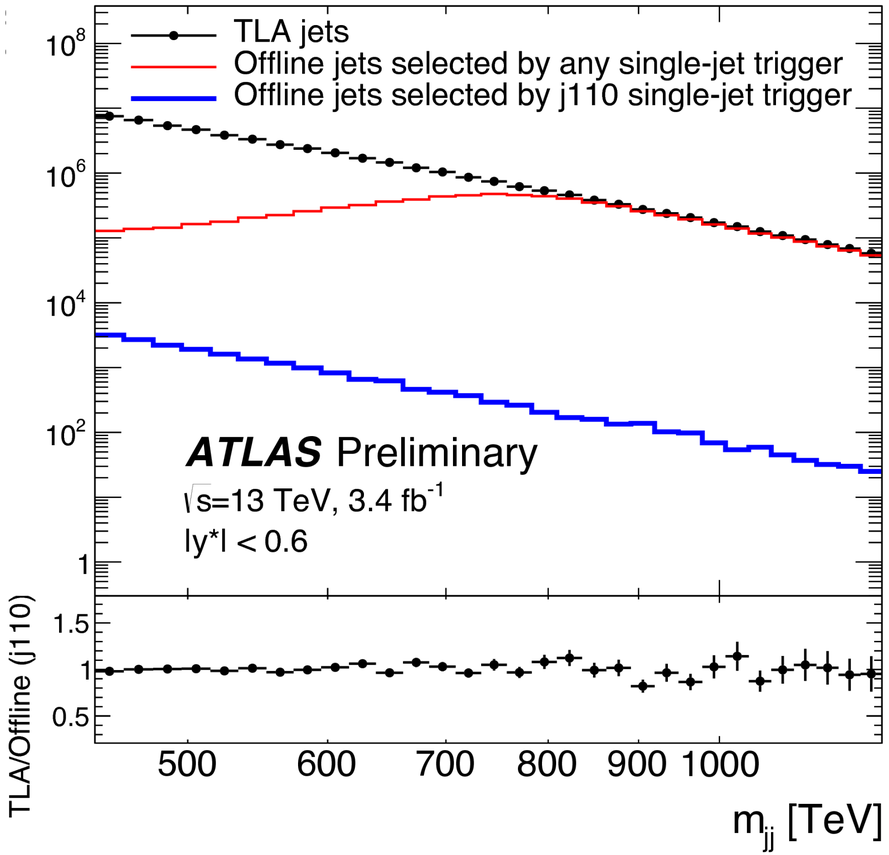


Di-b result: Phys. Lett. B 759 (2016) 229-246

NEW TECHNIQUES: TRIGGER-LEVEL DIJET ANALYSIS

ATLAS-CONF-2016-030

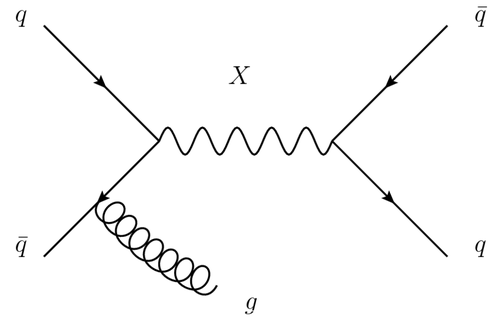
- Bandwidth & detector readout limitations force prescaling of single-jet triggers at p_T < ~400 GeV
  - Lose dijet events below m_{jj} ~ 1 TeV
- Avoid by recording trigger-level objects containing limited information
  - Jet four-momentum, identification variables
  - No tracking, muon, calorimeter cell info
  - Event size < 5% of typical fully-built event
- Special data-scouting stream records all events containing jet regions of interest with E_T > 75 GeV (level-1)
- Search targets resonance masses between 450-950 GeV

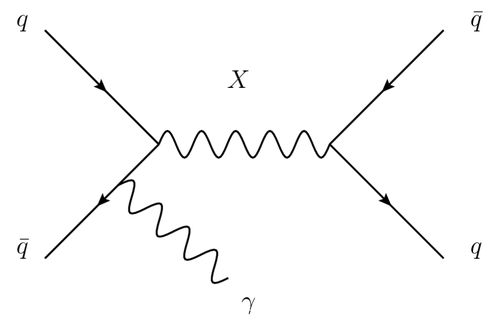


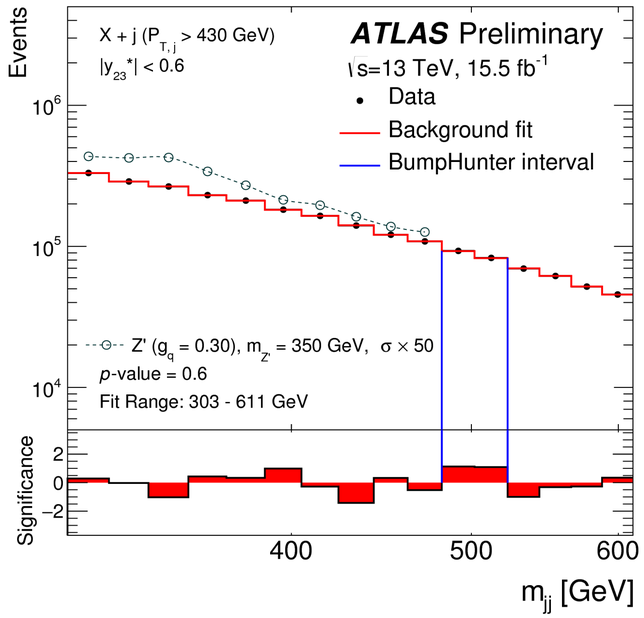
NEW APPROACHES: DIJET+ISR

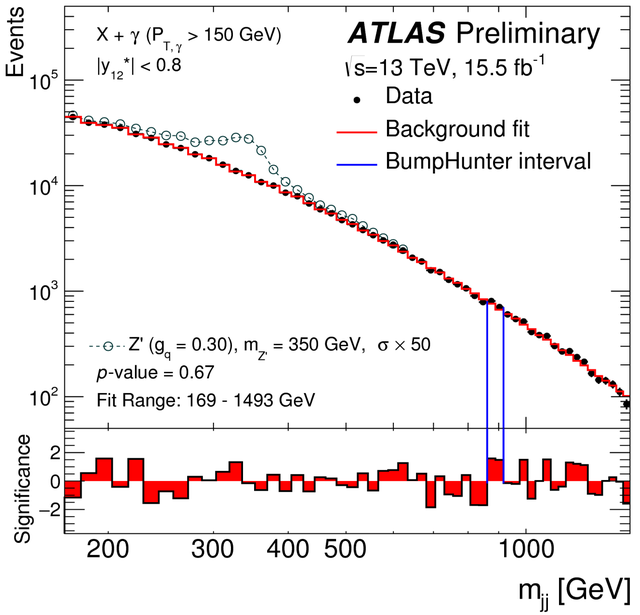
ATLAS-CONF-2016-070

- Extend dijet resonance search to even lower masses and smaller couplings
  - Sensitivity of traditional searches limited by trigger thresholds to $m_{jj} \sim 2p_T^{min}$
- Trigger on initial-state radiation (jet or photon) and search for recoiling dijets
  - ISR jet threshold: $E_T > 380$ GeV
  - ISR photon threshold: $E_T > 140$ GeV









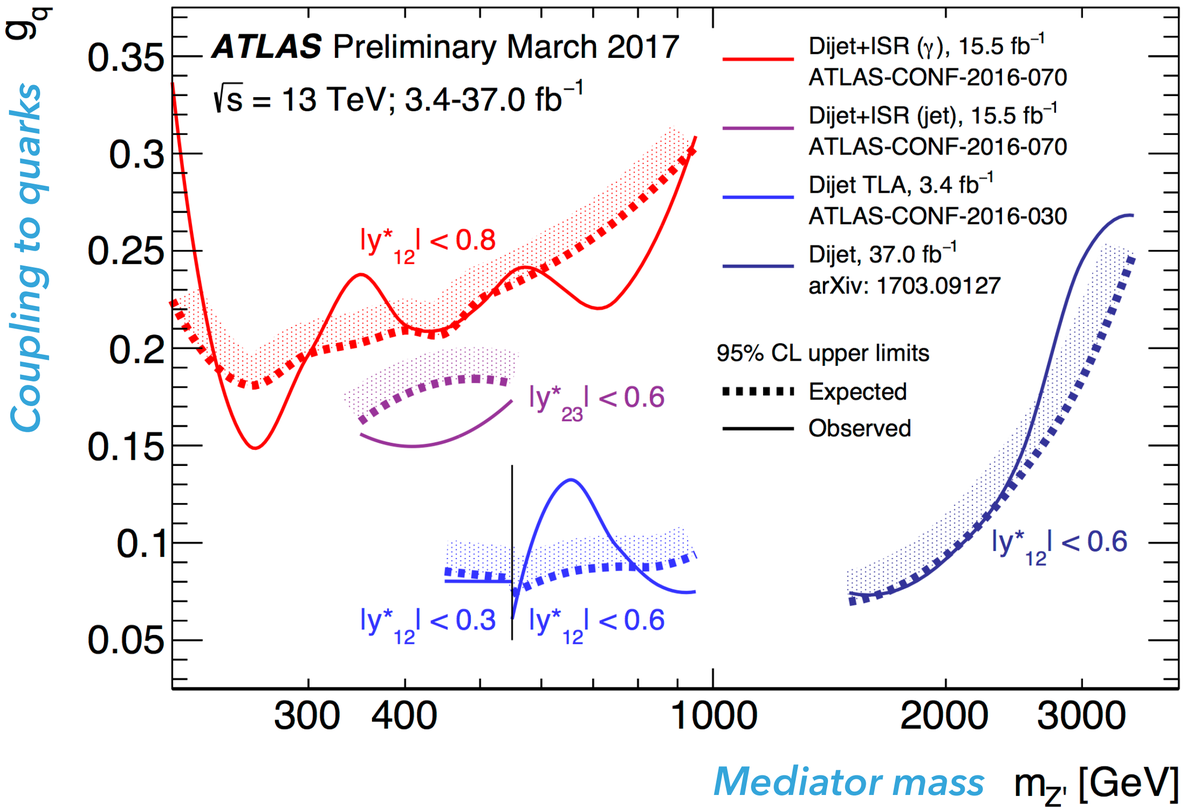
DIJET RESONANCE SEARCH RESULTS

- Searches set limits on leptophobic axial-vector Z′ mediators across a broad mass range
- Signal regions restrict y* to reduce multijet backgrounds

$$y_{12}^* = (y_{j1} - y_{j2})/2$$

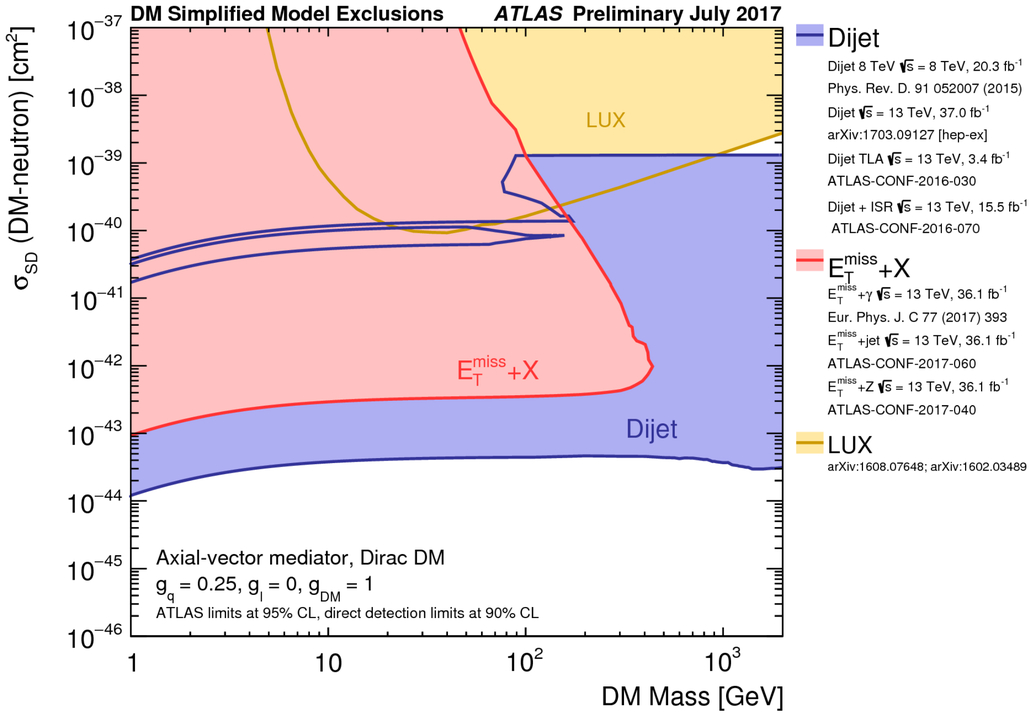
- Trigger-level analysis and dijet+ISR search extend limits at lower masses and smaller couplings

ATLAS dark matter summary plots

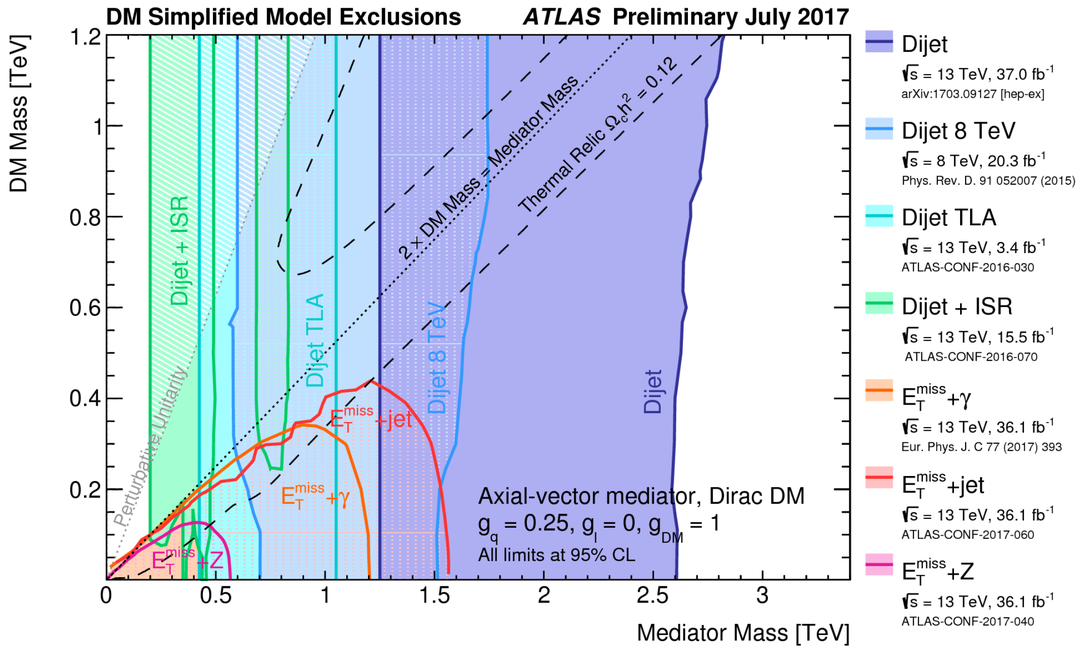


SUMMARY

- The ATLAS Run 2 physics programme includes many searches for a wide variety of dark matter signatures
  - E_T^{miss} + X and resonance (mediator) searches



ATLAS Exotics summary plots



- Excluded a broad range of DM and mediator masses, and continue to set stronger limits on couplings using new techniques
- Nice complementarity with direct / indirect detection experiments

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CONCLUSION

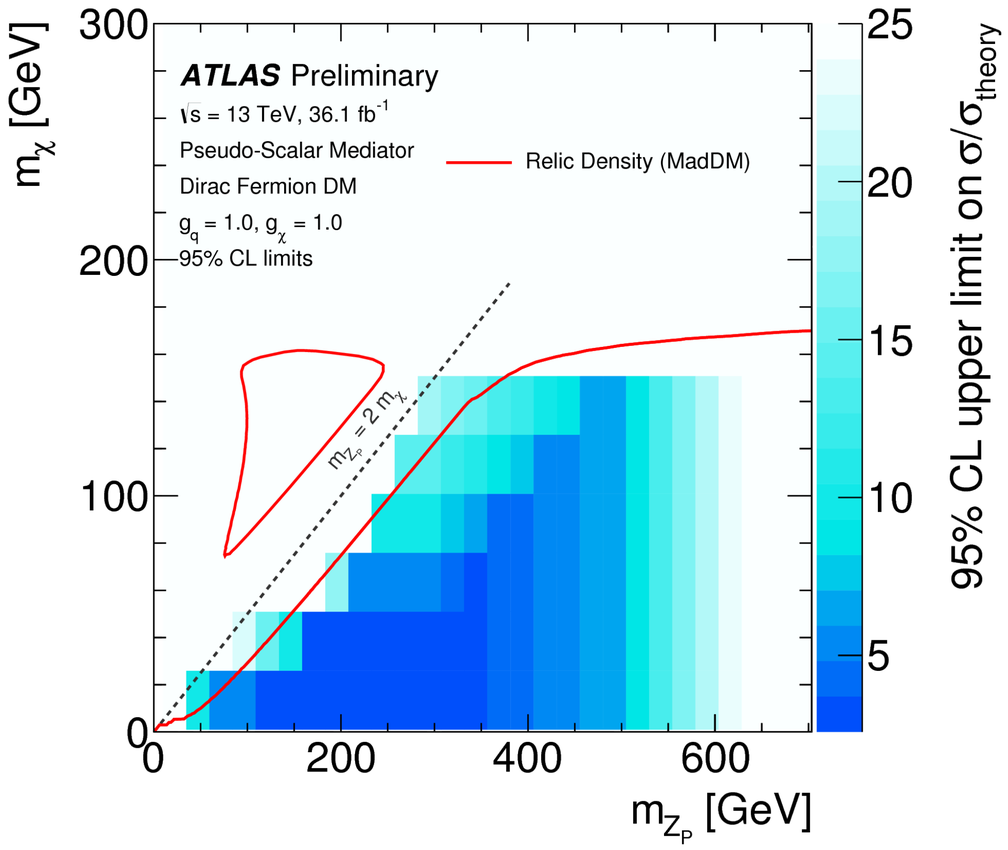
- For more information and recommendations… *LHC Dark Matter Working Group*
- …and the results I didn't have time to cover! *ATLAS Exotics public results*

Thank you! Спасибо!

BACKUP

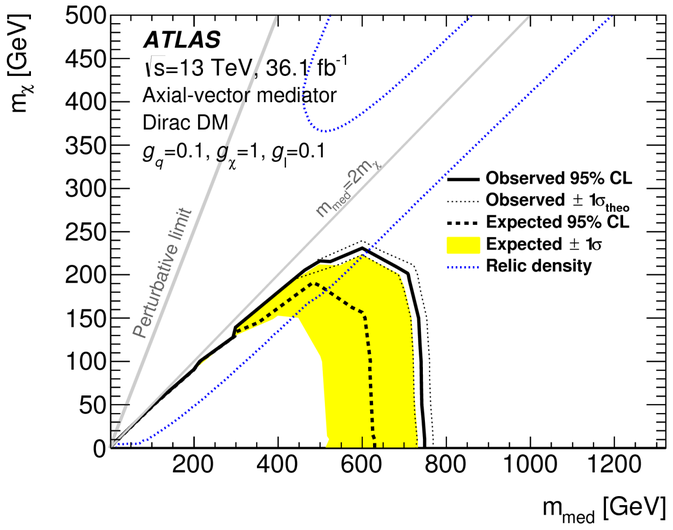
MONOJET RESULTS (PSEUDOSCALAR MEDIATOR)

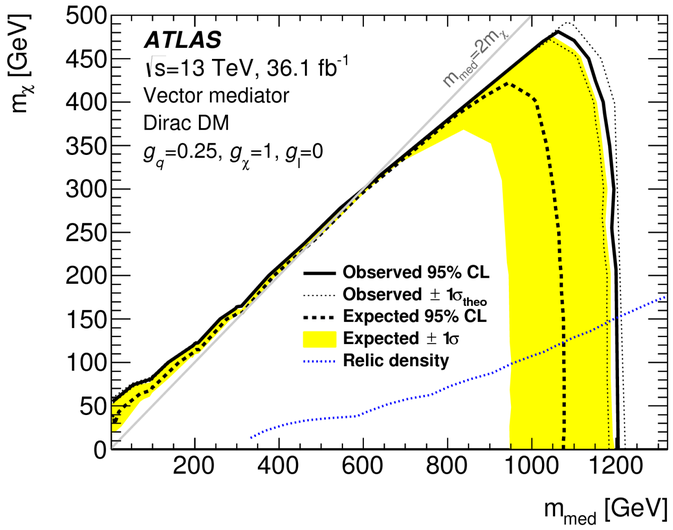
ATLAS-CONF-2017-060

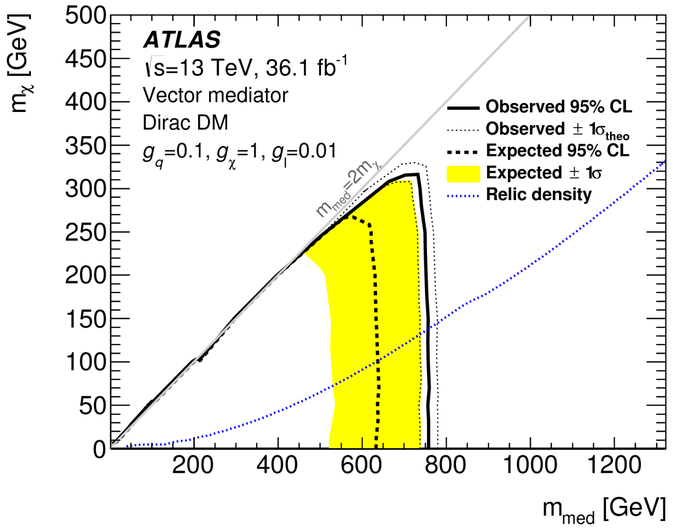


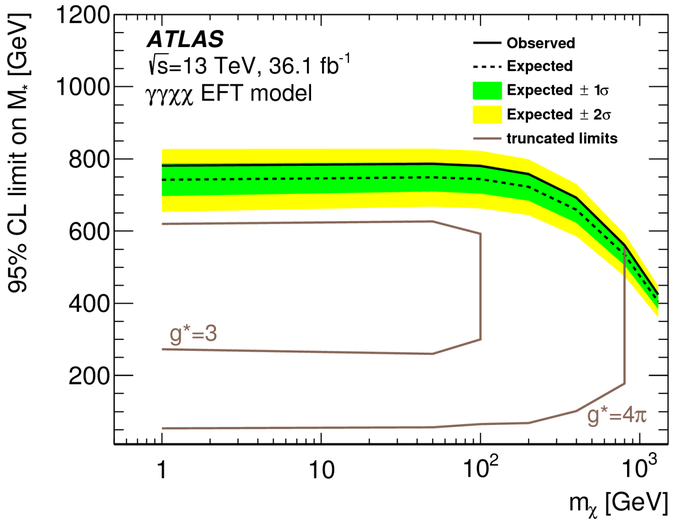
MONO-PHOTON RESULTS

[Eur. Phys. J. C 77 (2017) 393]



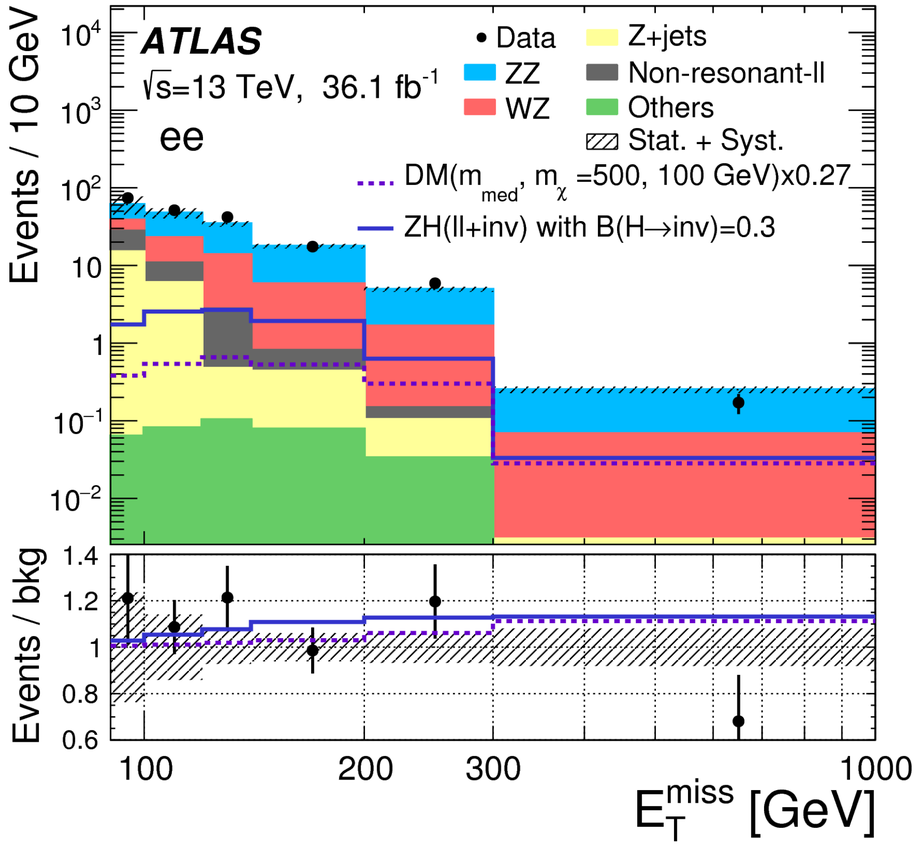


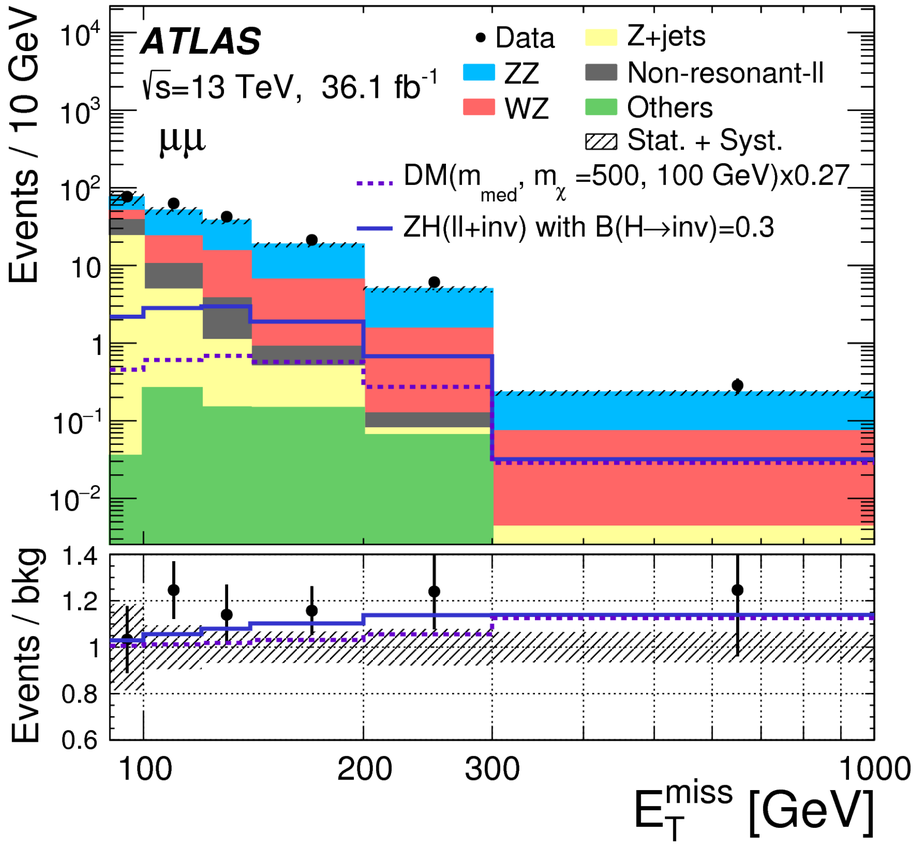




MONO-Z (LEPTONIC)

arXiv:1708.09624 [hep-ex]



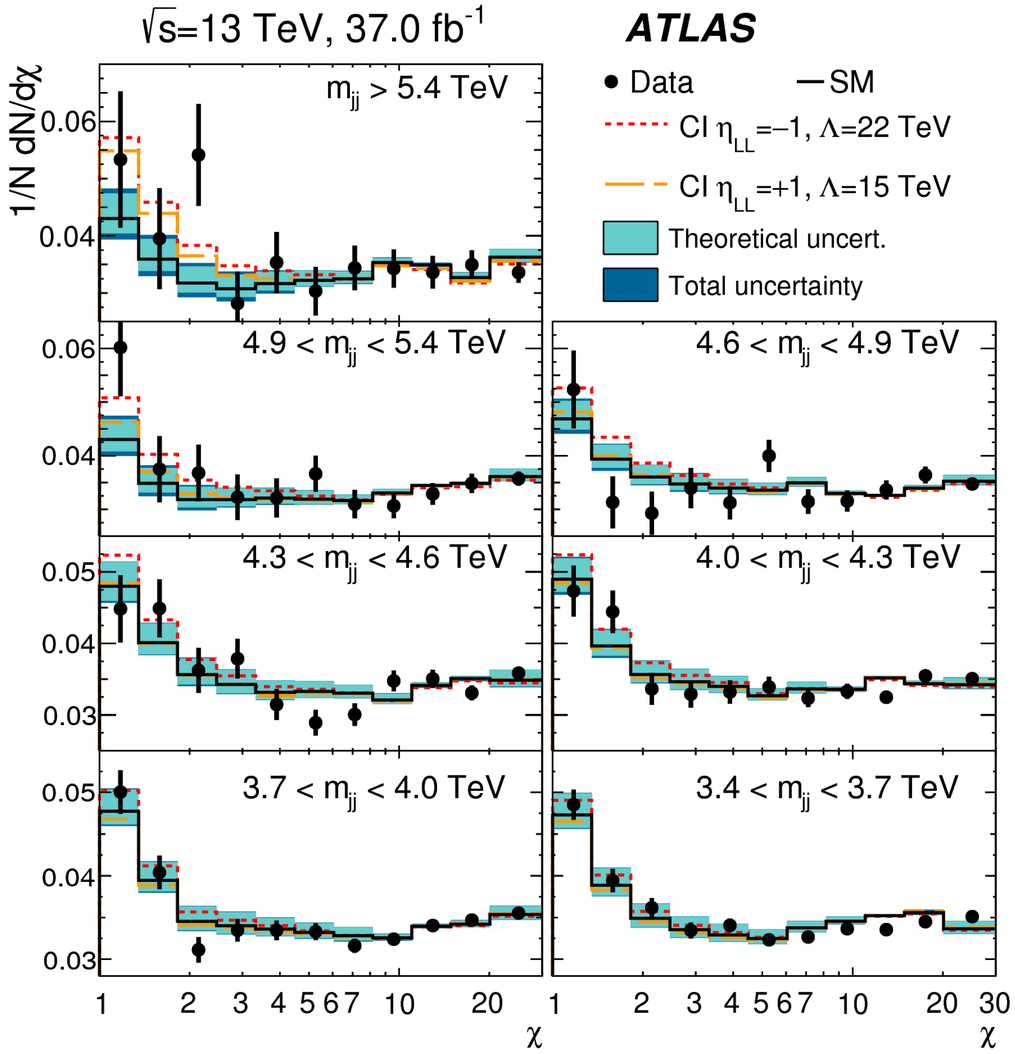


DIJET ANGULAR ANALYSIS

arXiv:1703.09127

- Search for BSM contributions to angular distribution sets limits on contact interaction scale

$$\chi = e^{2|y^*|} \sim \frac{1 + \cos\theta^*}{1 - \cos\theta^*}$$



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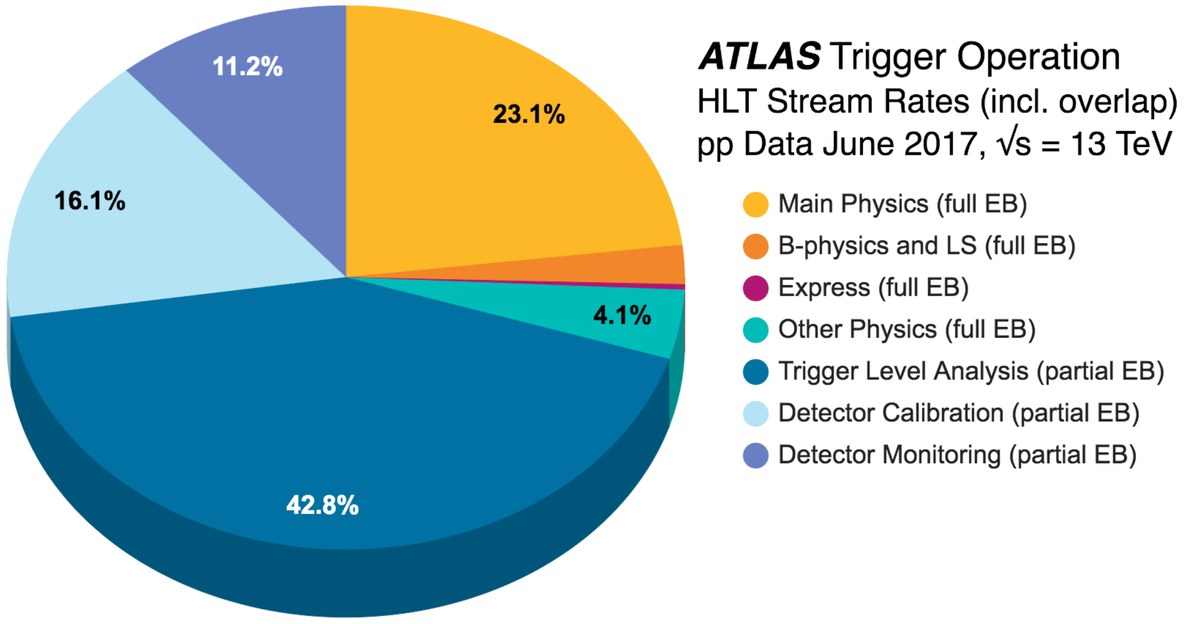
DIJET INTERPRETATIONS

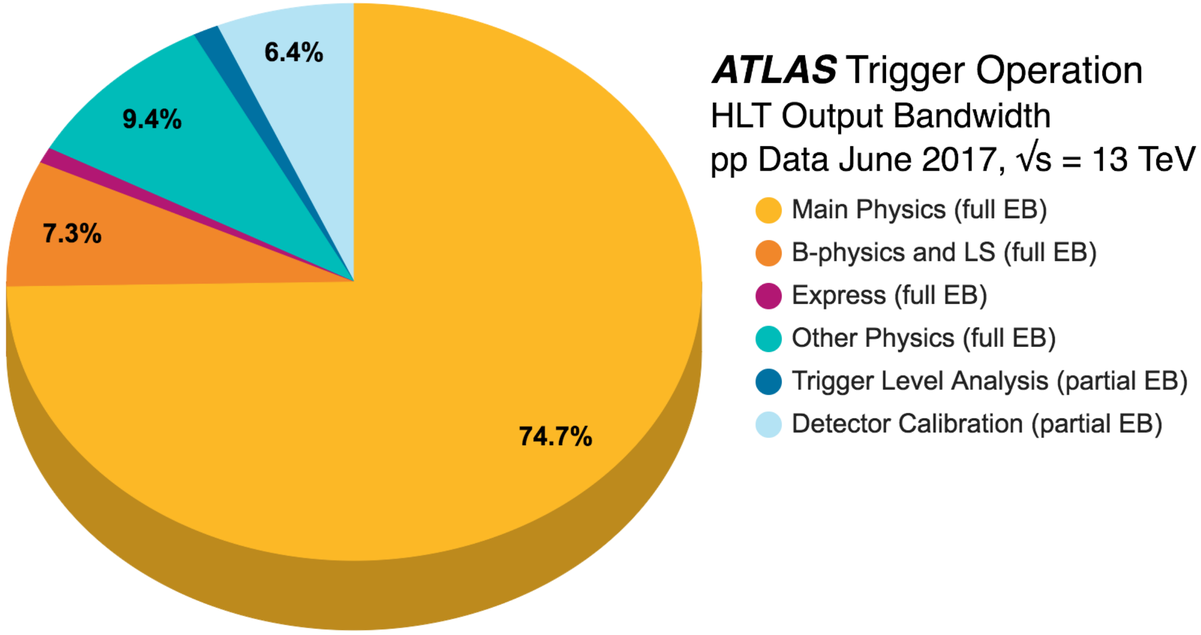
arXiv:1703.09127

Model	95% CL exclusion limit	
	Observed	Expected
Quantum black hole	8.9 TeV	8.9 TeV
W'	3.6 TeV	3.7 TeV
W^*	3.4 TeV 3.77 TeV – 3.85 TeV	3.6 TeV
Excited quark	6.0 TeV	5.8 TeV
Z' $(g_q = 0.1)$	2.1 TeV	2.1 TeV
Z' $(g_q = 0.2)$	2.9 TeV	3.3 TeV
Contact interaction $(\eta_{\mathrm{LL}} = -1)$	21.8 TeV	28.3 TeV
Contact interaction $(\eta_{\mathrm{LL}} = +1)$	13.1 TeV 17.4 TeV – 29.5 TeV	15.0 TeV

DIJET TRIGGER-LEVEL ANALYSIS: RATE & BANDWIDTH

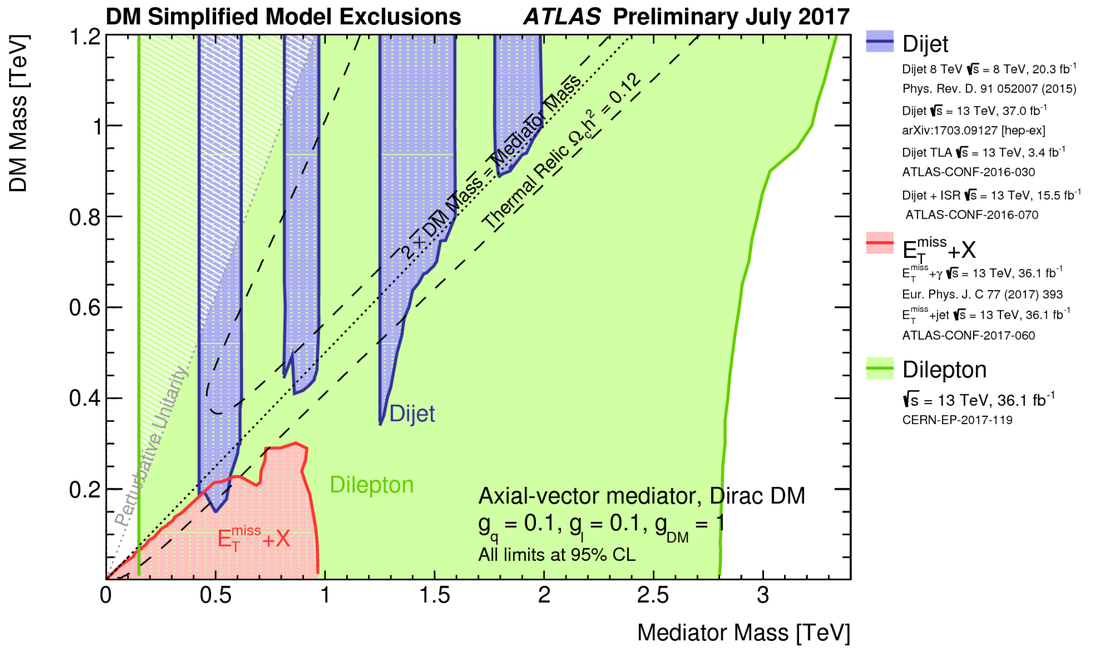
ATLAS trigger operation public results





DARK MATTER SUMMARY PLOT (AXIAL-VECTOR MEDIATOR)

ATLAS Exotics summary plots



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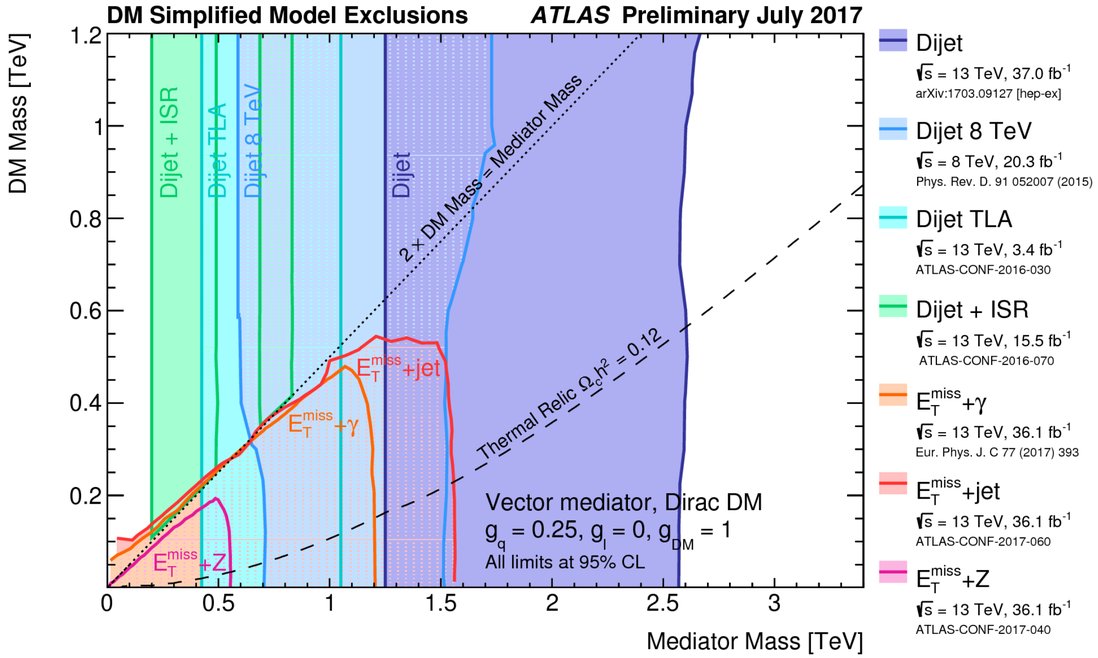
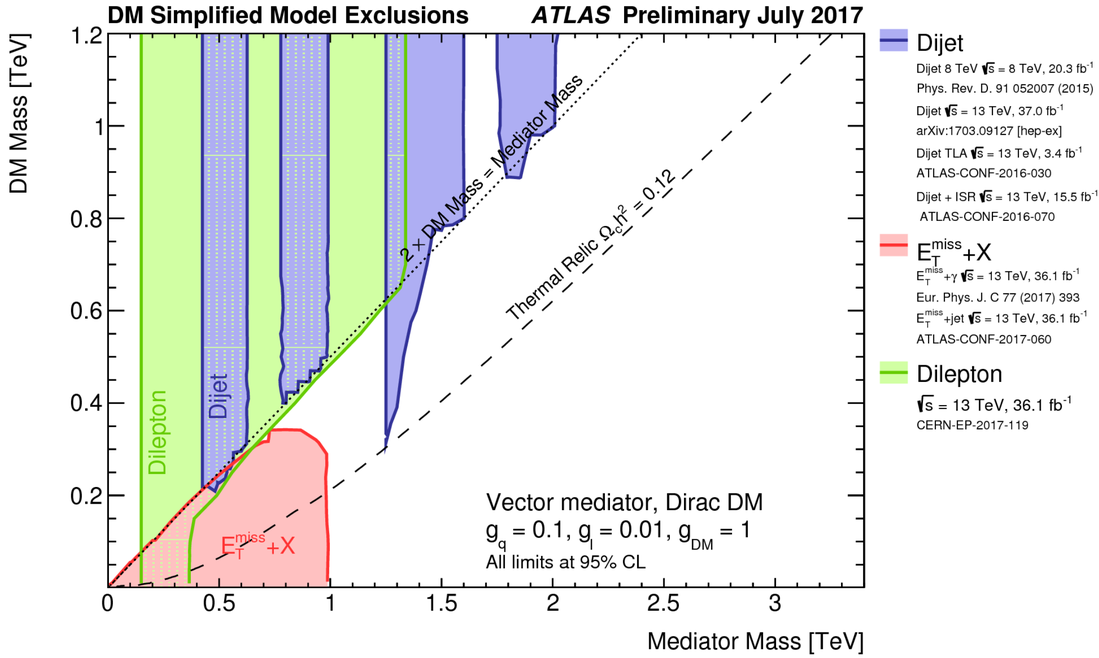
DARK MATTER SUMMARY PLOTS (VECTOR MEDIATOR)

ATLAS Exotics summary plots





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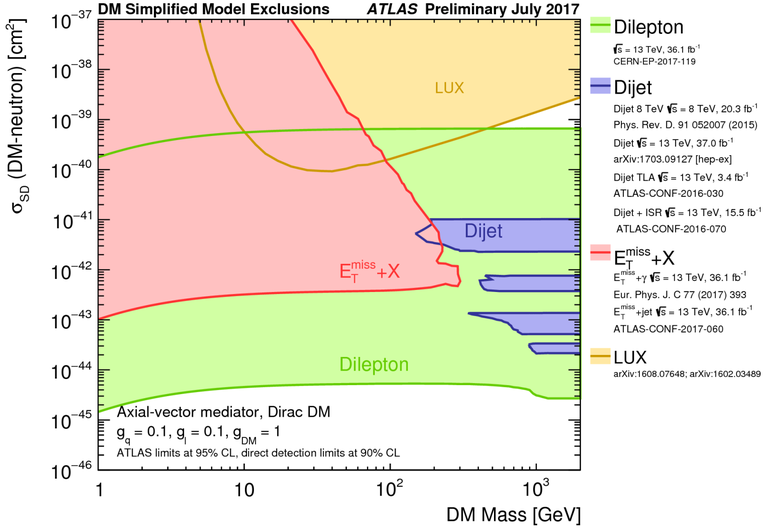
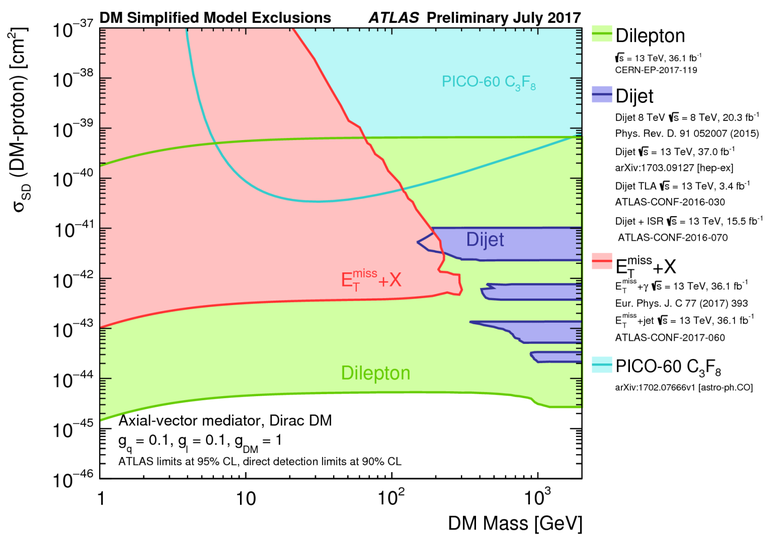
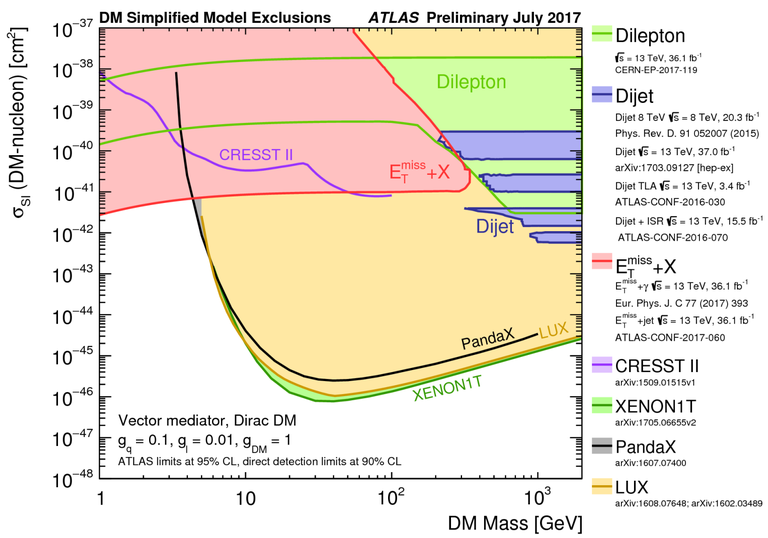
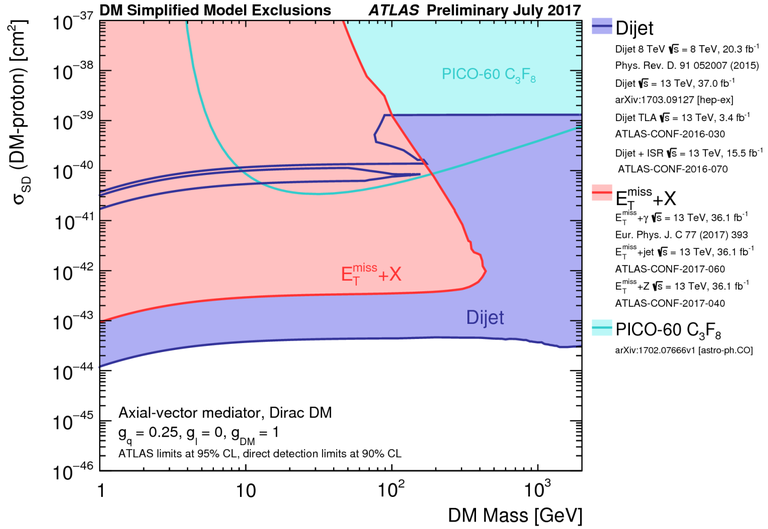
COMPARISON WITH DIRECT DETECTION EXPERIMENTS

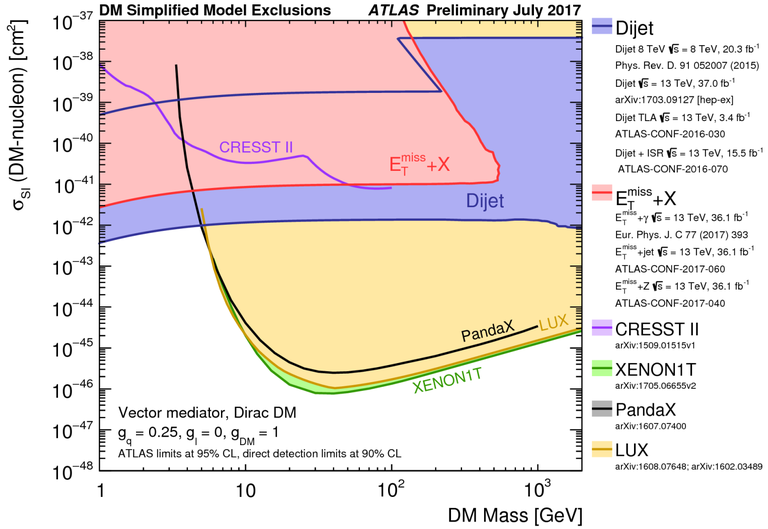
ATLAS Exotics summary plots











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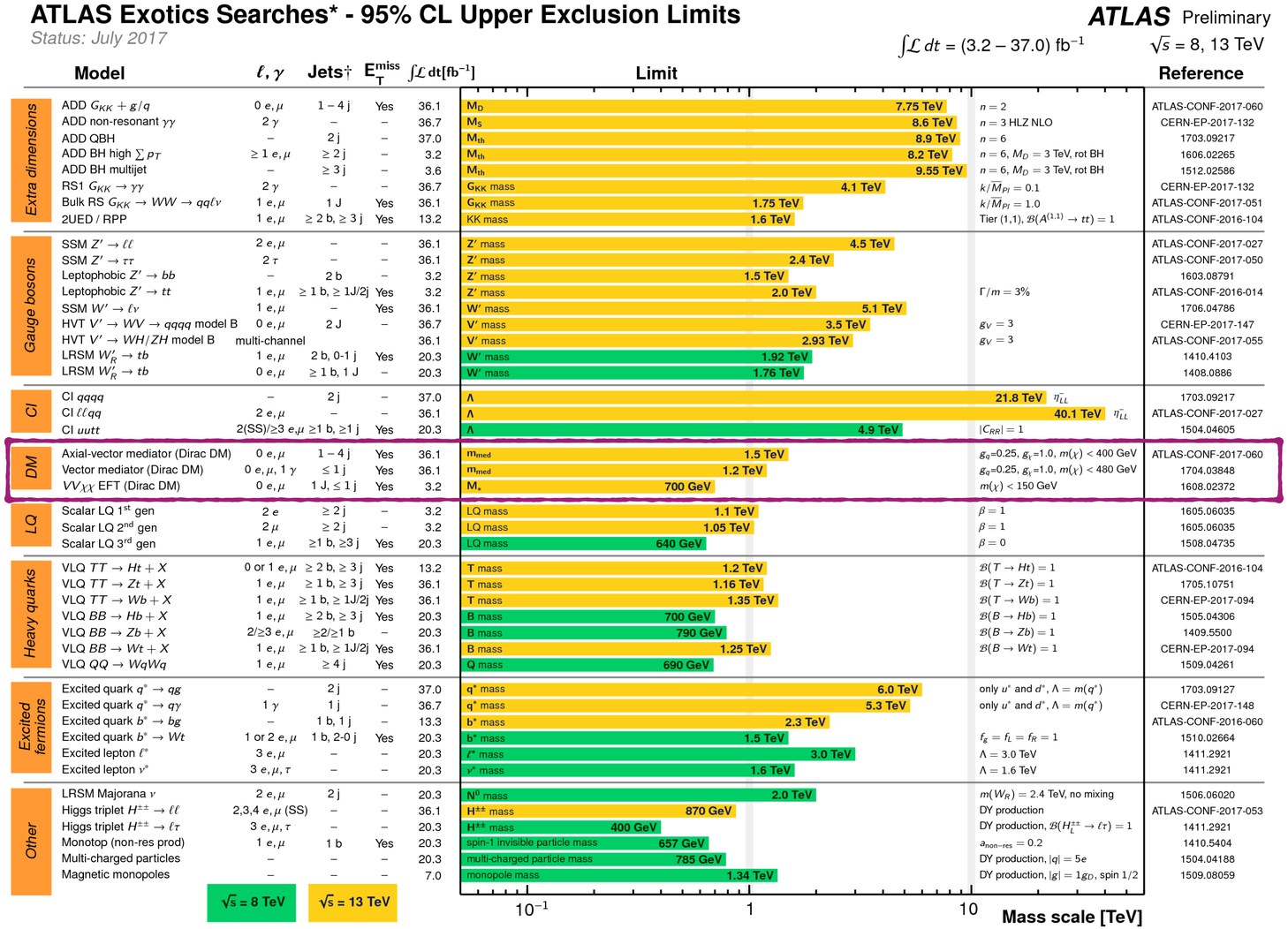
ATLAS EXCLUSION LIMITS

ATLAS Exotics summary plots



*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

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