SUSY 2018
Barcelona, Spain
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Searches for Dark Matter mediators with the ATLAS detector

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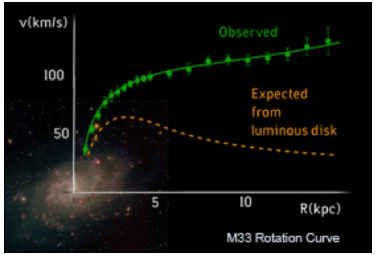
on behalf the ATLAS collaboration

Dark matter: observations

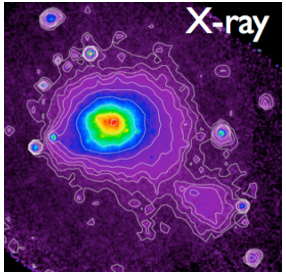
Evidence of dark matter

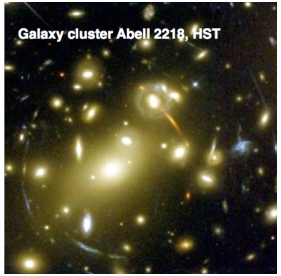
- From astrophysics and cosmology observations at **different scales, all consistent**

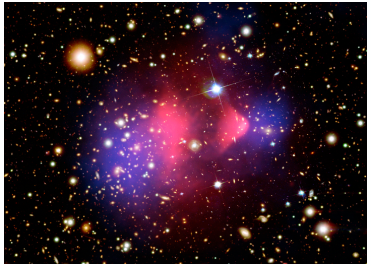
Galaxy rotation



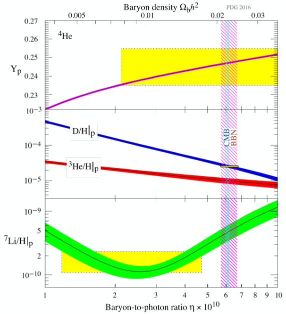
Galaxy clusters via Xrays and gravitational lensing, collisions





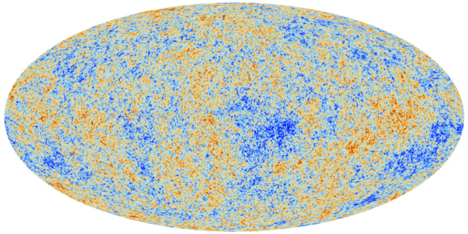


Nucleosynthesis



(Schramm & Turner 1998).

Cosmic microwave background



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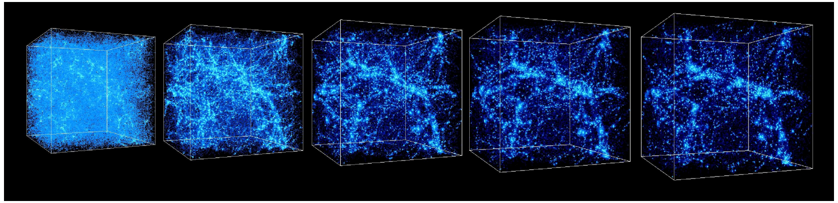
Large scale structure formation



© simulations were performed at the National Center for Supercomputer Applications by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University).
Visualizations by Andrey Kravtsov.

Dark matter: how to detect it ?

Indirect detection

- Search for charged cosmic rays, gamma rays or neutrinos

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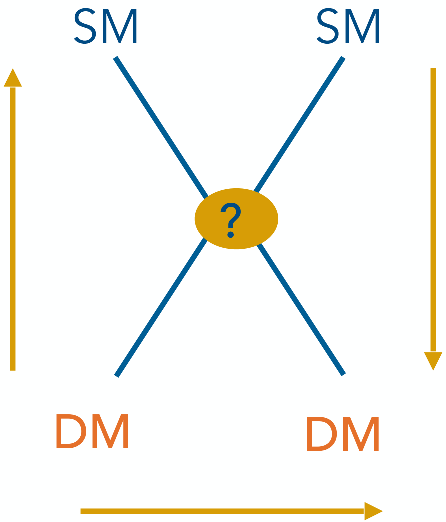
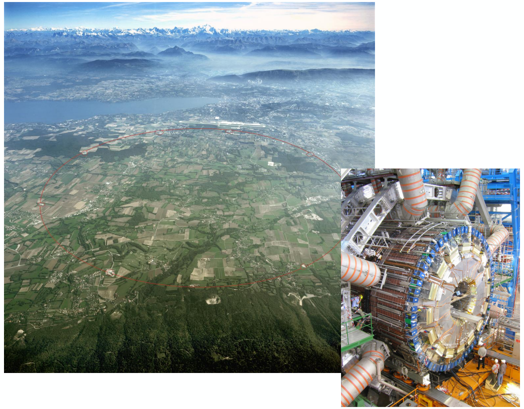


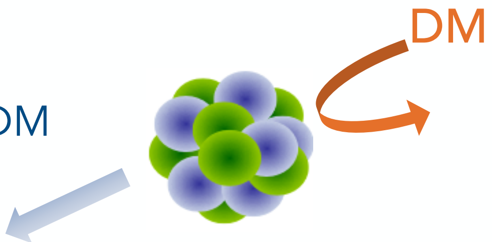
Collider search

- Produce DM particles from SM particles collisions



Direct detection

- Use scattering of DM on a nucleus



➜ hyp: the dark matter is made up Weakly Interacting Massive Particles (WIMPS)

Dark matter search at LHC

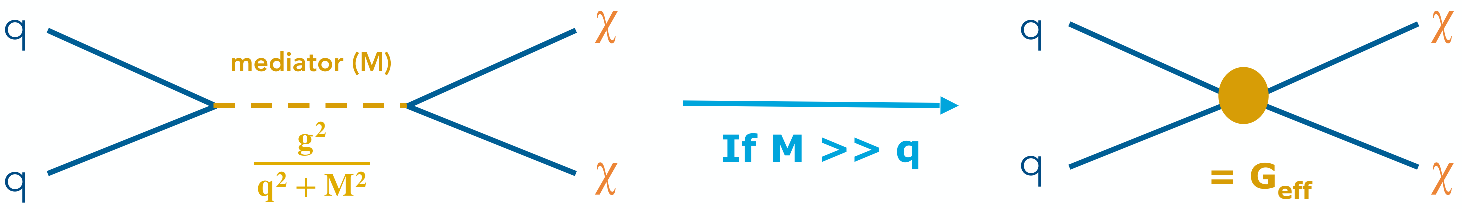
Search for particles from (UV) complete theories

➜ simulate particles decays, dark matter reconstructed as missing transverse energy

- Supersymmetry, Extra dimensions , Little Higgs, …

Use of effective field theory (EFT)

➜ many theories show common low energy behaviour, EFT allows more general searches



➜ describes new interactions with few operators

➜ focus of LHC run 1 analyses

➜ Advantages:

- model independent
- Allows to translate LHC results into direct search frames (with some care on the hypothesis)

➜ Limitations:

- EFT valid only if M >> q ➪ Run 1 limits M ~1 TeV => should not use E > 1 TeV
- Loose correlations that can be used in a complete theory

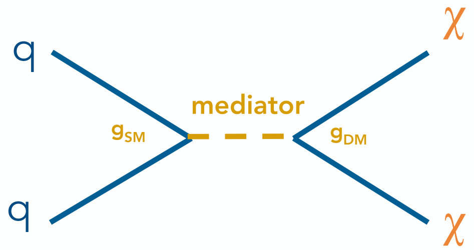
Dark matter search at LHC: simplified models

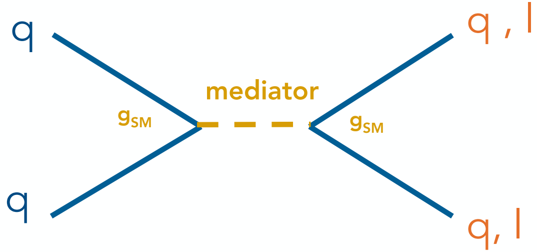
Simplified models

- In between EFT and complete theory: add a single DM candidate (Dirac fermion) and a mediator

➜ Allow to relax the q^2 limit but more model dependent

➜ Allow to use other signatures to probe mediator and thus constrain the model





Common model and scenarios

- ATLAS/CMS + theory Dark Matter forum defined the DMSimp model (arXiv:1507.00966)
- Recommendations for benchmark scenarios (arXiv:1703.05703)
- Madgraph implementation (LO/NLO)

Dark matter search at LHC: simplified models

Simplified models

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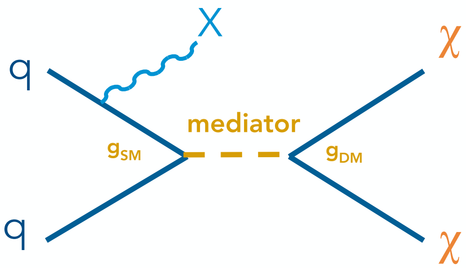
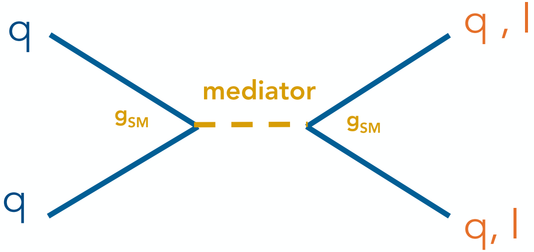




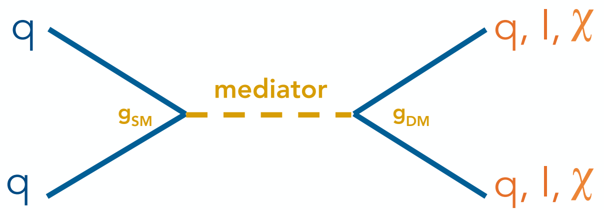
➜ MET + X signatures were the focus of Michaela Queitsch-Maitland's talk

➜ di-fermion signatures are the focus of this talk

- Mediator could have spin 0 or 1, charged or neutral
  - recent results about spin 1, neutral mediator will be shown here

Simplified model: neutral (axial-)vector mediator

Model:



$$\mathcal{L}_{\text{vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_{\mu}\bar{q}\gamma^{\mu}q + g_{\chi}Z'_{\mu}\bar{\chi}\gamma^{\mu}\chi$$

$$\mathcal{L}_{\text{axial-vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_{\mu}\bar{q}\gamma^{\mu}\gamma^{5}q + g_{\chi}Z'_{\mu}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi$$

- Free parameters: m(χ), m(med), g_{DM} and g_q, g_l
- Minimal width computed according to couplings and considered particles mass
  - mediator decays considered = ones strictly necessary to maintain model self-consistency

Scenarios	g_q	g_{DM}	g_l
V1: vector model with only couplings to quarks	0.25	1.0	0.
V2: vector model with small couplings to leptons	0.1	1.0	0.01
A1: axial-vector model with only couplings to quarks	0.25	1.0	0.
A2: axial-vector model with equal coupling to quarks & leptons	0.1	1.0	0.1

Scenarios:

- Chosen to show the complementarity of the DM production analyses (mono X) and the mediator-to-visible analyses (di X)

Di-jet: high mass

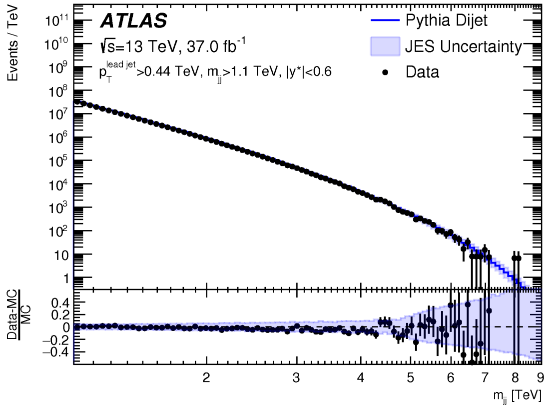
$\sqrt{s}$ = 13 TeV, L = 36.1 fb^{-1}
- EXOT-2016-21
- Phys. Rev. D 96 (2017) 052004

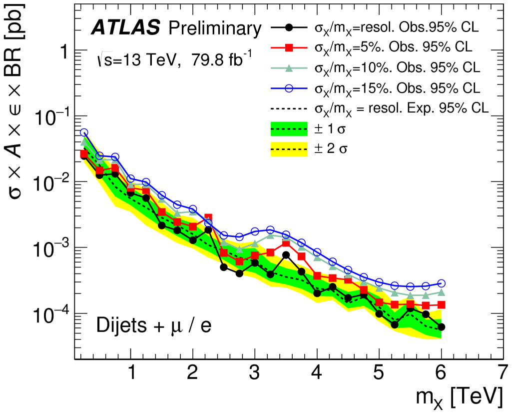
Analysis

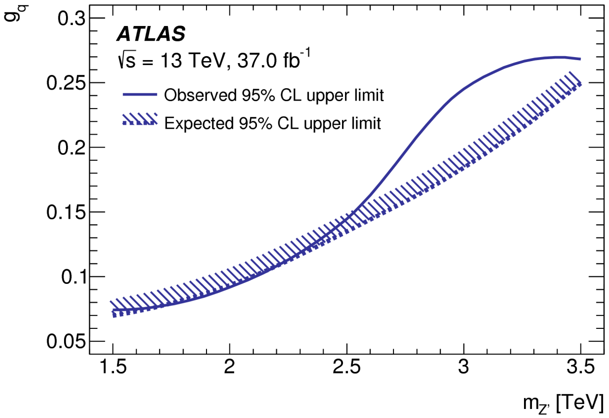
- 2 small R-jets j selected with p_T > 440 GeV and 60 GeV
  - |y*| < 0.6 to reduce background from QCD process ➜ m(jj) > 1.1 TeV
- Background obtained fitting the m(jj) distribution
- BumpHunter [Arxiv: 804.03496] algorithm used to quantify statistical significance of any local excess/deficit

➜ No deviation from SM observed, limit set on cross-section and coupling to quarks

y* is the jet rapidity difference:
$y = 1/2 \ln [(E + p_Z)/(E - p_Z)]$
$|y^*| = 0.5 \cdot |y_1 - y_2|$



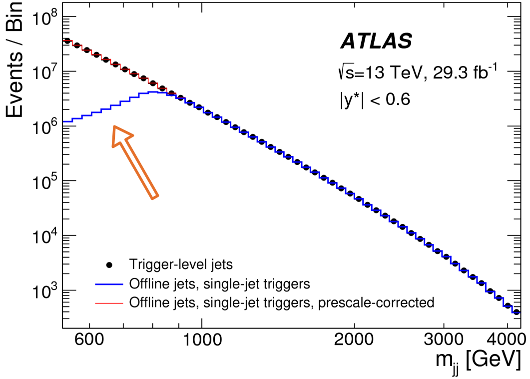




Di-jet: how to get sensitive to lower masses

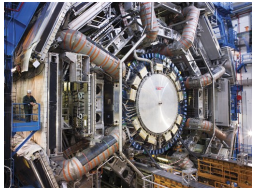
Di-jet analysis uses single jet trigger: lowest unprescaled ATLAS trigger has p_T threshold at 380 GeV

➜ restrain sensitivity of analysis on m_{jj} above 1.1 TeV



To recover sensitivity at lower mass, 2 strategies:

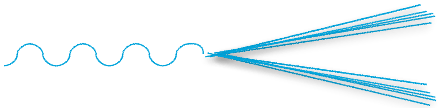
- Trigger level analysis (TLA)



40 MHz → Level 1 trigger → 100 kHz → High Level trigger HLT → Main stream = 1 kHz, ~1Mb/evt

HLT → Trigger Level ana = 2-3 kHz, < 5 kb/evt

- Trigger on an other object: use di-jet + ISR topology
  - ISR = jet or photon, boost the di-jet resonance

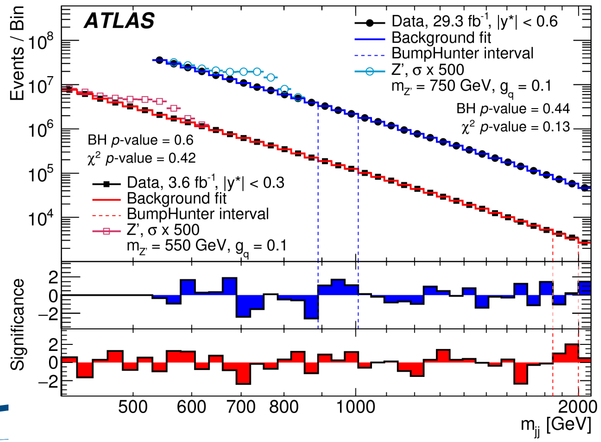


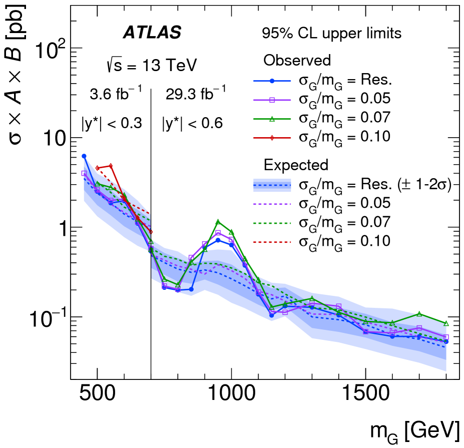
➜ gives access to lower mass range at the price of lower cross-section

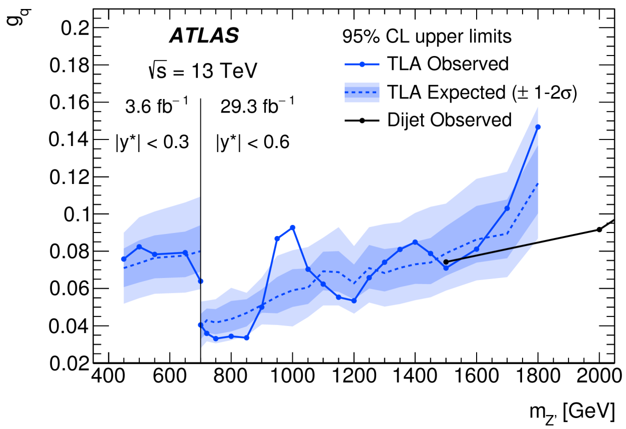
Di-jet: trigger level analysis

√s = 13 TeV, L = 29.3 fb^{-1}
- EXOT-2016-20
- arXiv:1804.03496

➜ Analysis done at HLT trigger level
- 2 (calibrated) jets selected with p_T > 185 GeV and 85 GeV (minimal info stored: 0.5% of an event)
- 2 rapidity regions defined:
  - |y*| < 0.6 for 700 GeV < m_{jj} < 1800 GeV for L1 trigger with E_T > 100 GeV threshold
  - |y*| < 0.3 for m_{jj} > 450 GeV for L1 trigger with E_T > 75 GeV threshold
- sliding window fit, no deviation wrt SM observed, limits set

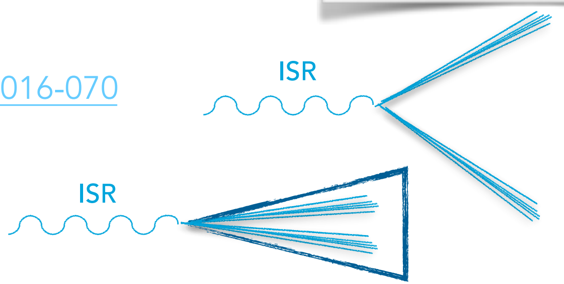






Di-jet (large R-jet) + ISR

$\sqrt{s}$ = 13 TeV, L = 29.3 fb^{-1}
- EXOT-2017-01
- arXiv:1801.08769



Di-jet + ISR

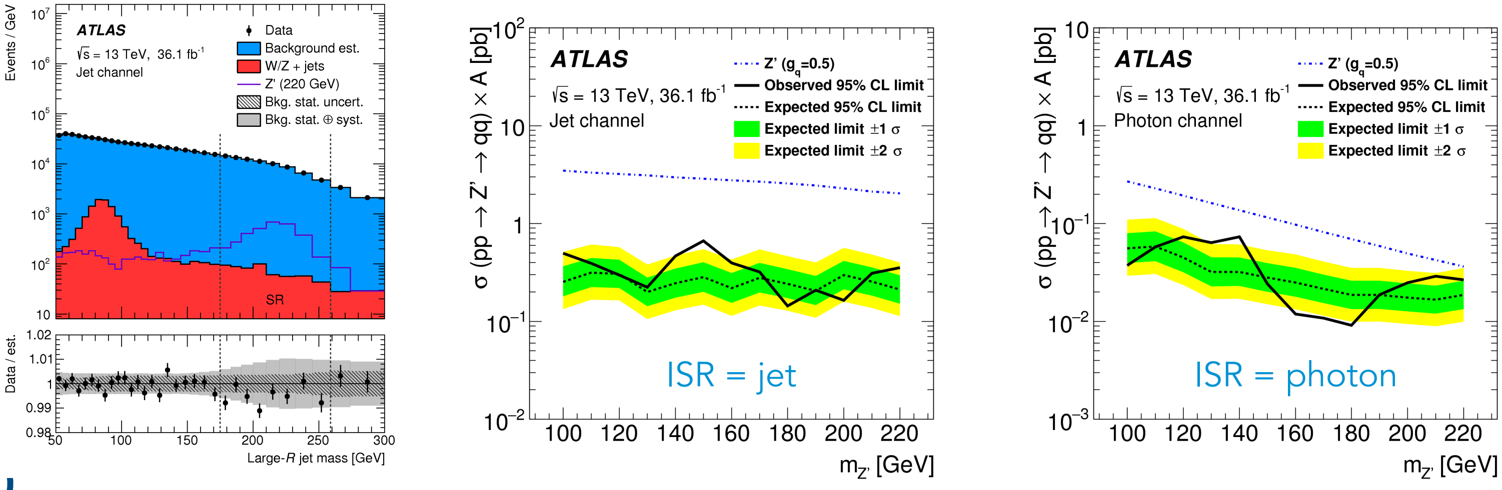
- Previous analysis done at $\sqrt{s}$ = 13 TeV with L = 15.5 fb^{-1} ATLAS-CONF-2016-070

Boosted di-jet +ISR

➜ use high p_T ISR to lower trigger threshold for the event, ISR = jet or photon
  - at the price however of smaller cross-section

➜ use boosted topology: select a single large-radius jet (consistent with di-jet substructure) recoiling against a hard jet or photon from ISR

- ISR jet (photon): large R-jet p_T > 450 (200) GeV, ISR p_T > 450 (155) GeV

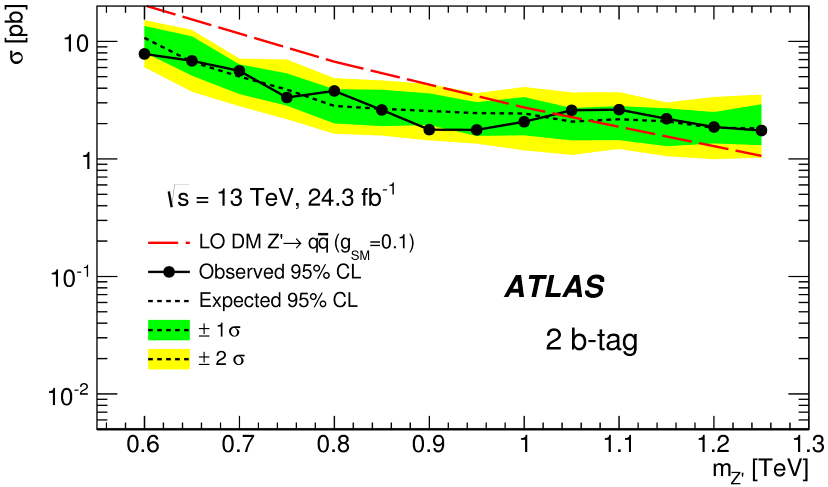


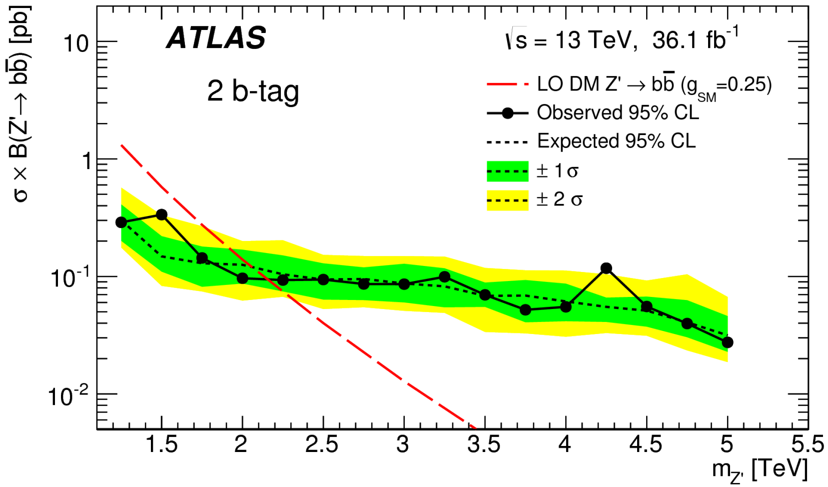
Di-bjet

√s = 13 TeV, L = 36.1-24.3 fb⁻¹
- EXOT-2016-33
- arXiv:1805.09299

Analysis

- Low and high mass regions probed
  - ➜ high mass: m(jj) > 1.2 TeV, p_T(j) > 430 GeV, 80 GeV, using usual jet trigger
  - ➜ low mass: 570 GeV < m(jj) < 1.5 TeV, using di-jet trigger (p_T threshold 150 and 50 GeV) with online b-tagging; p_T(j)> 200 GeV
- To reduce background and enhance s-channel process, cut on rapidity difference $y^* = (y_1 - y_2)/2$ between jets: $|y^*| < 0.8$ (0.6) for high (low) mass

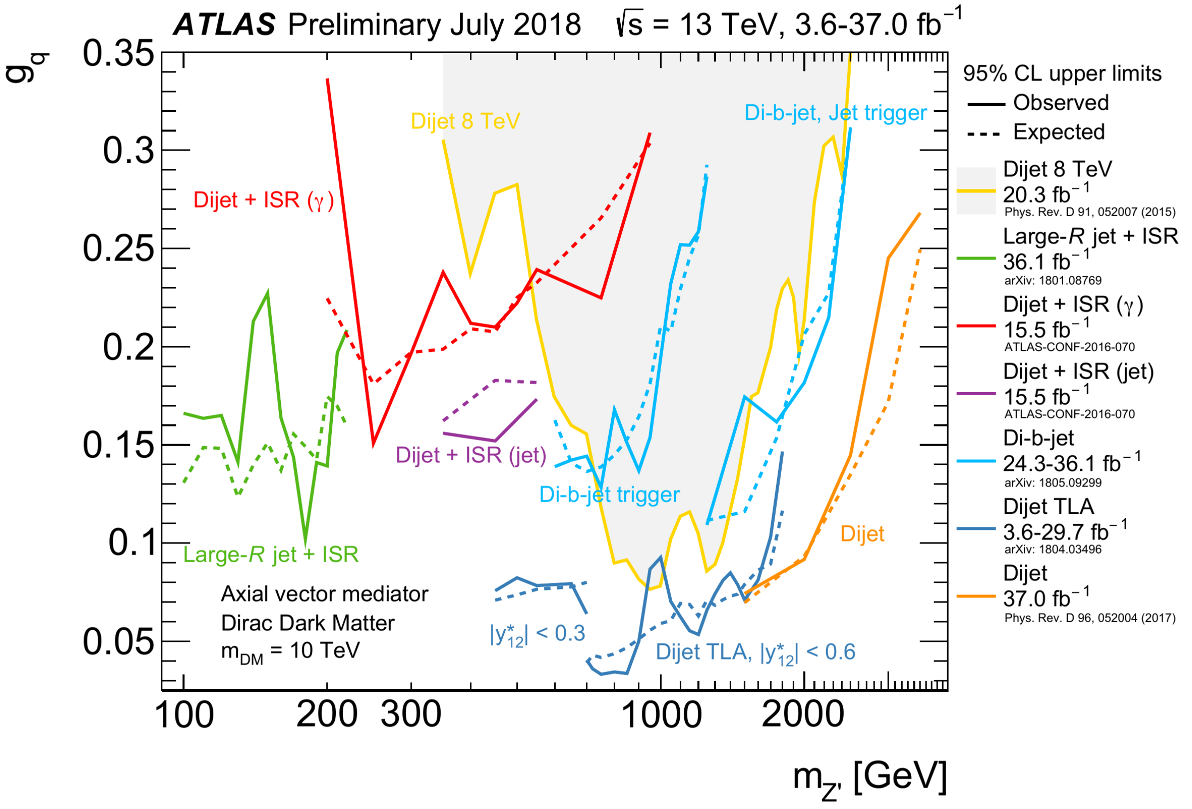




Di-jet analysis complementarity

√s = 8-13 TeV, L = 3.6-37 fb⁻¹
✦ ATLAS EXOTIC SUMMARY PLOTS

➜ Limits on the DM mediator coupling to quarks

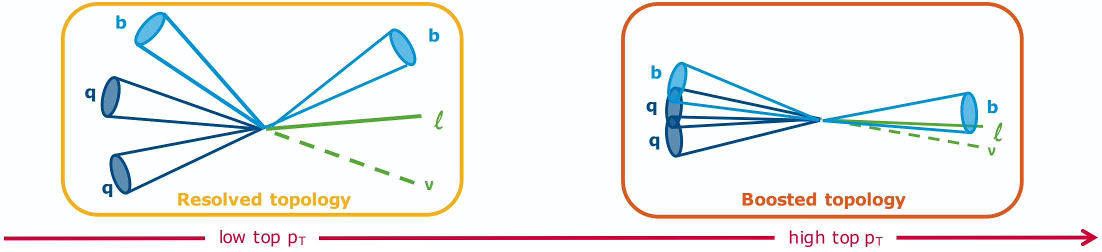


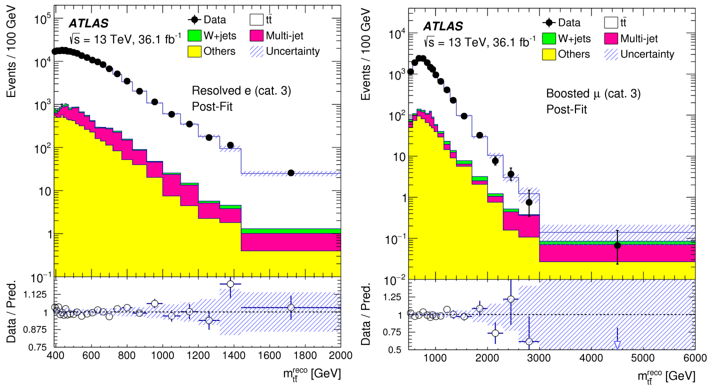
Top quark pair

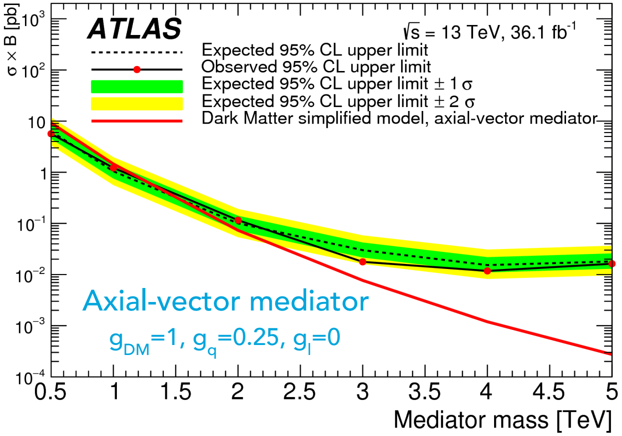
Analysis

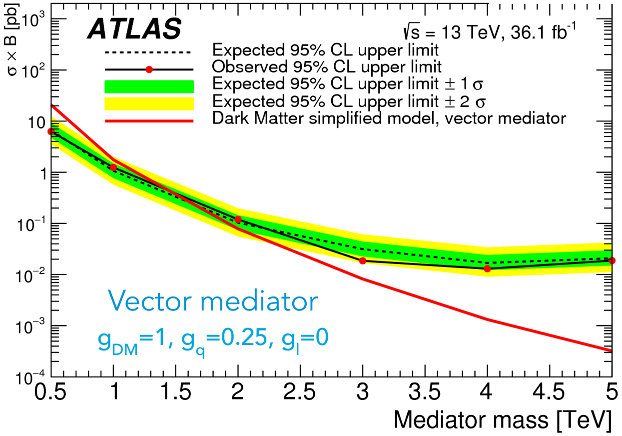
√s = 13 TeV, L = 36 fb⁻¹
- EXOT-2015-04
- Eur. Phys. J. C 78 (2018) 565

- lepton+jets final state, resolved and boosted regimes









➜ will be interesting to look at (pseudo-)scalar mediators
- Interference !
- done at 8 TeV:
  - EXOT-2016-04/
  - Phys. Rev. Lett. 119 (2017) 191803

Di-lepton analysis

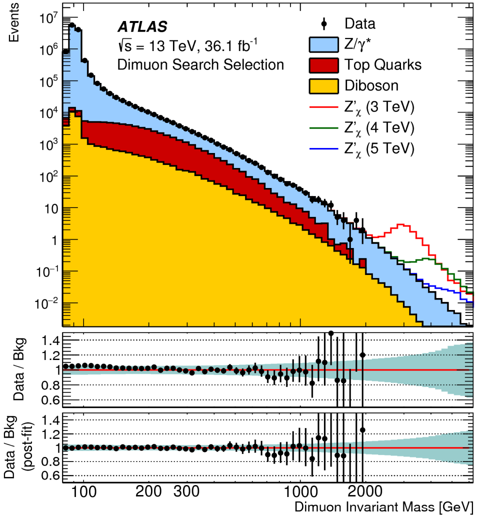
$\sqrt{s}$ = 13 TeV, L = 36 fb^{-1}

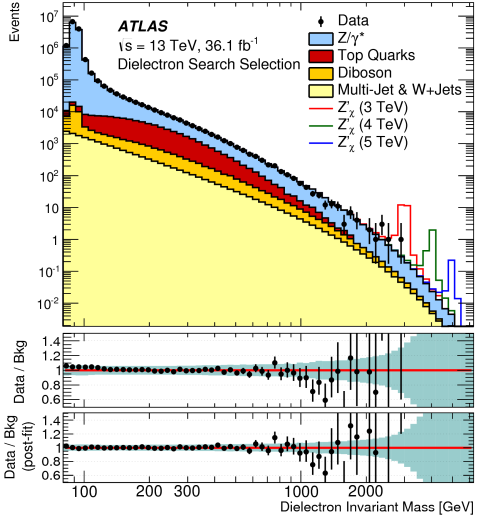
- EXOT-2016-05
- JHEP 10 (2017) 182

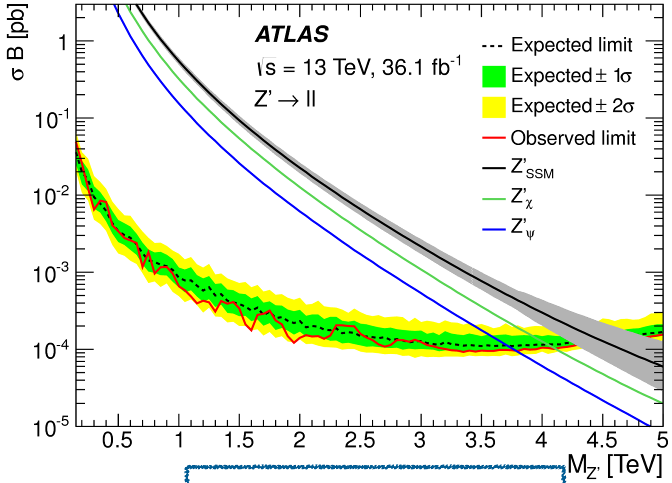
Analysis

- Select 2 same flavour leptons (opposite sign for muon channel)
  - $E_T(e) > 30$ GeV, $p_T(\mu) > 30$ GeV

➜ Clean final state and much lower trigger threshold than for di-jet analyses







Combined ee and $\mu\mu$ limit

Complementarity with mono X + MET analyses

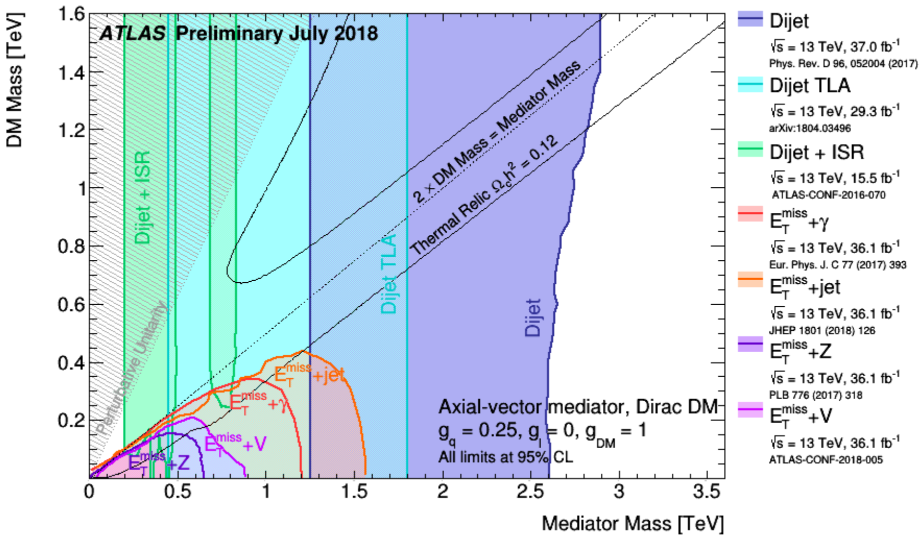
$\sqrt{s}$ = 8-13 TeV, L = 3.6-37 fb^{-1}

- ATLAS EXOTIC SUMMARY PLOTS

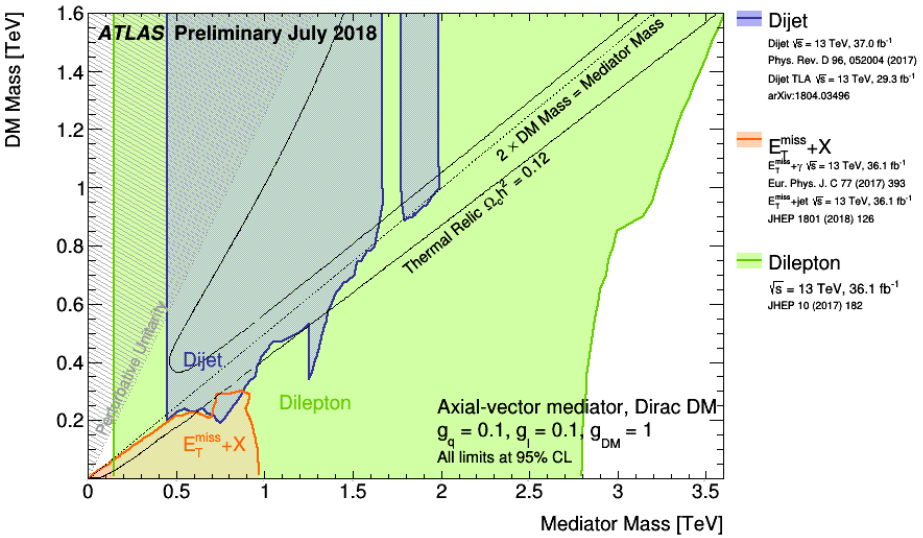
➜ Exclusions from mono-jet, mono-photon and di-jets for axial-vector coupling

- Note: coupling dependence is important !
- Resonance search independent of mediator mass for $m_{med} < 2 \cdot m_{DM}$

A1: g_{DM}=1, g_q=0.25, g_l=0



A2: g_{DM}=1, g_q=0.1, g_l=0.1

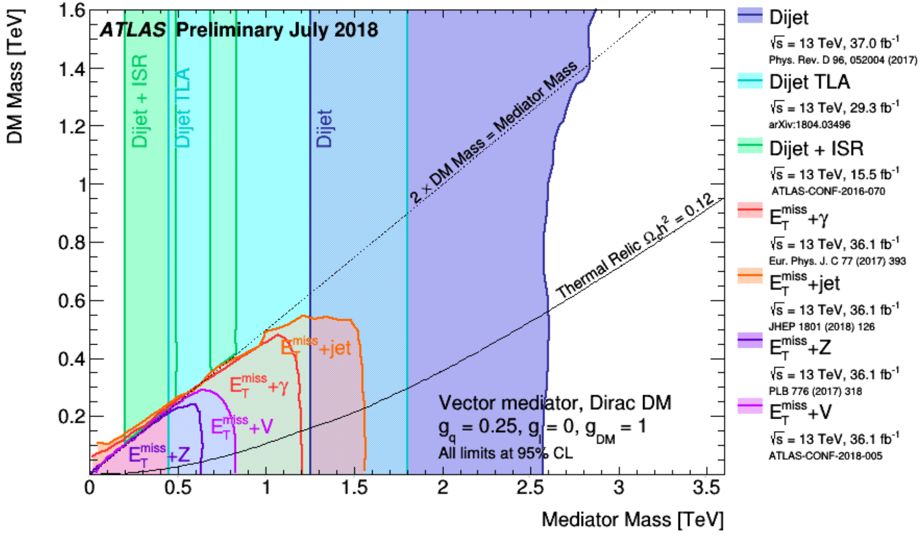


Complementarity with mono X +MET analyses

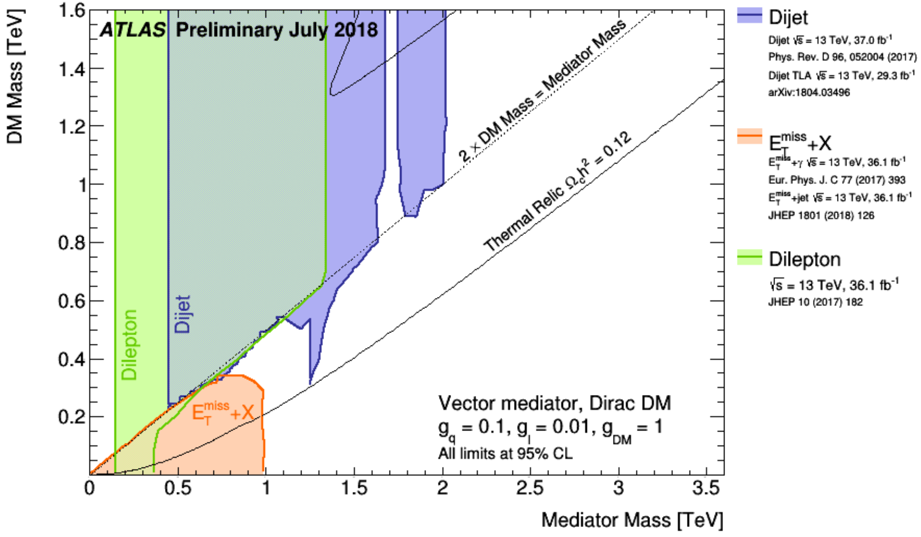
$\sqrt{s}$ = 8-13 TeV, L = 3.6-37 fb^{-1}
- ATLAS EXOTIC SUMMARY PLOTS

➜ Exclusions from mono-jet, mono-photon and di-jets for vector coupling
- Note: couplings dependence is important !

V1: g_{DM}=1, g_q=0.25, g_l=0



V2: g_{DM}=1, g_q=0.1, g_l=0.01



Complementarity with direct detection

$\sqrt{s}$ = 8-13 TeV, L = 3.6-37 fb^{-1}

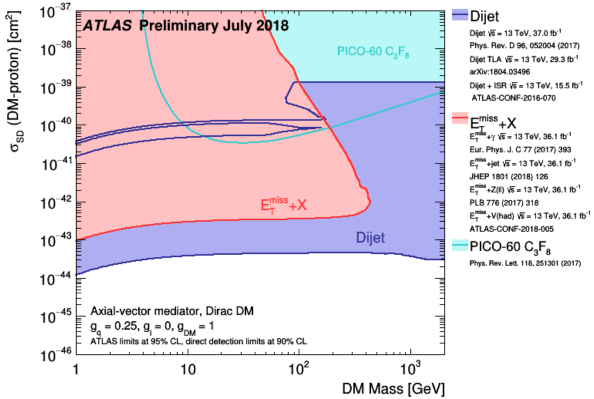
- ATLAS EXOTIC SUMMARY PLOTS

Beware ! validity only for this choice of model…

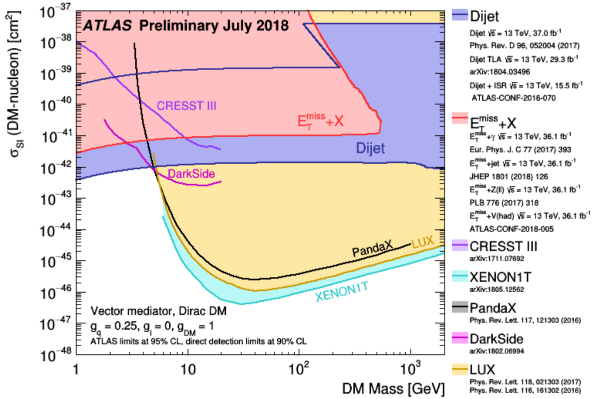
Note: limits at 95% CL for ATLAS, 90% CL for direct detection…

Axial-Vector mediator / Spin dependent

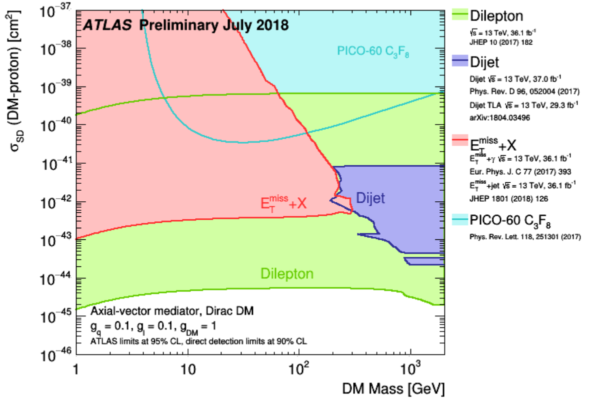
g_{DM}=1, g_q=0.25, g_l=0



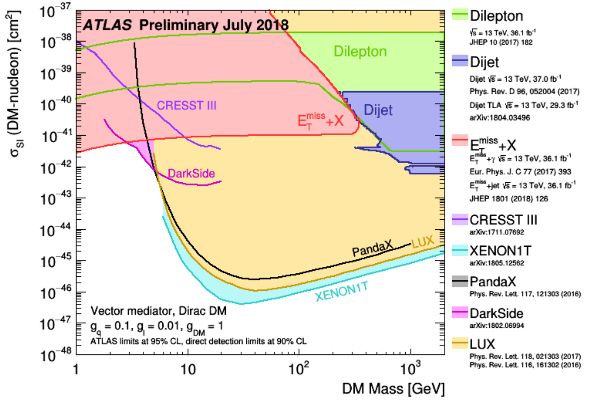
Vector mediator / Spin independent



g_{DM}=1, g_q=0.1, g_l=0.1



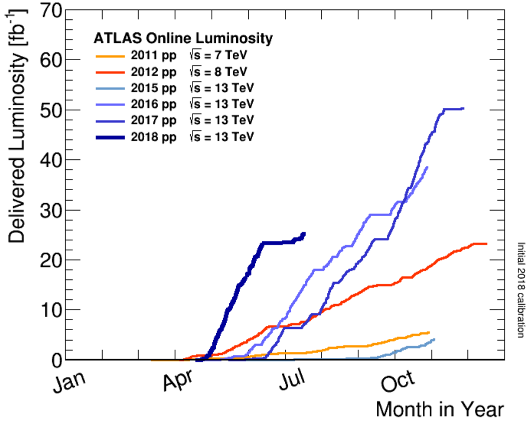
g_{DM}=1, g_q=0.1, g_l=0.01



Summary and perspectives

Extensive program of dark matter search with the ATLAS experiment

- In the context of simplified model, analyses looking for DM mediator decaying into SM particles are powerful and show nice complementarity with DM MET signatures
- No sign of dark matter though, in the 36 fb^{-1} run 2 data scrutinised
  … but much more to come (x4 data on tape)!
- These results are also complementary to dark matter direct searches



Much more to explore…

- Spin 1 charged mediator, FCNC, spin 0 mediator in simplified model with 1 mediator and 1 DM particle
- Extension of 2 HDM with a pseudo-scalar: very rich phenomenology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POUR AUJOUR
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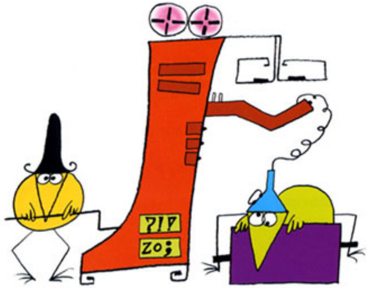
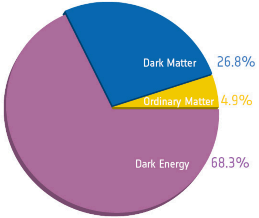


TO GO FURTHER…

Dark matter: what do we know about ?

Properties



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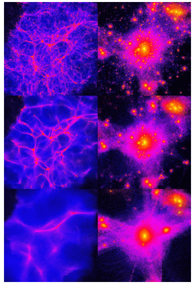
- It makes up 85% of the matter in the Universe
  - It is massive
- It interacts weakly with ordinary matter (at least through gravitation)
  - It is neutral

- It interacts weakly with itself
- It is stable (a minima very long-lived, order of the age of the universe)
  - ⇨ Ruled out SM Z and Higgs
  - Need a symmetry to prevent it to decay ex T-parity
- It is "cold" ie non relativistic
  - ⇨ ruled out SM neutrinos (also not enough massive)



© Cold, Warm, and Hot dark matter simulations, credit ITP, University of Zurich.

Dark matter: which candidates ? Associated theories ?

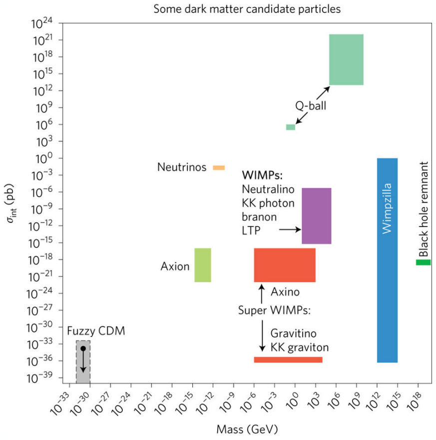
Candidates

- WIMPs = Weakly Interacting Massive Particles

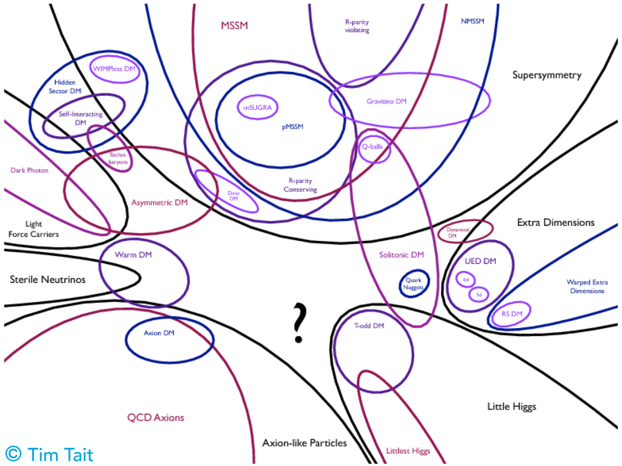
  ➜ WIMP "miracle" : weak cross-section + particle mass ~1 TeV ~ relic density
  - Susy neutralinos
  - Kaluza-Klein photon

- Very Weak Interacting Massive Particles
  - gravitinos
  - Axions: to solve the strong CP problem, unstable but long lived
  - Sterile neutrinos: to explain neutrino masses
  - Kaluza Klein gravitons
  - …

- Could be also a more complex sector with several particles and interactions



https://science.energy.gov/~/media/hep/pdf/files/pdfs/dmsagreportjuly18_2007.pdf



© Tim Tait

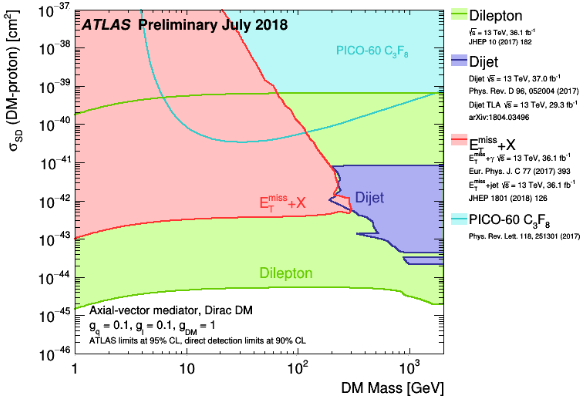
Theories

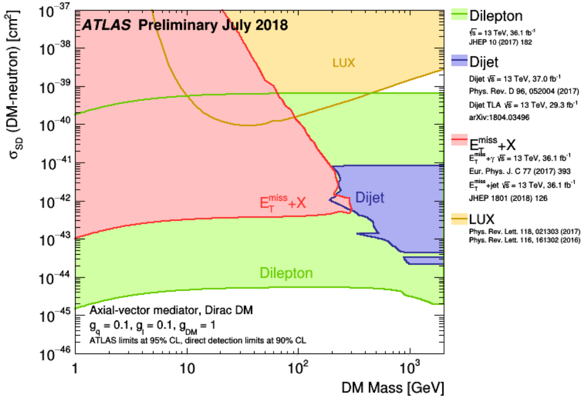
- Supersymmetry
  - Symmetry: R-parity
- Extra dimensions
  - Symmetry : KK parity
- Little Higgs
  - Symmetry: T-parity
- QCD axions
- …

Comparison with direct detection

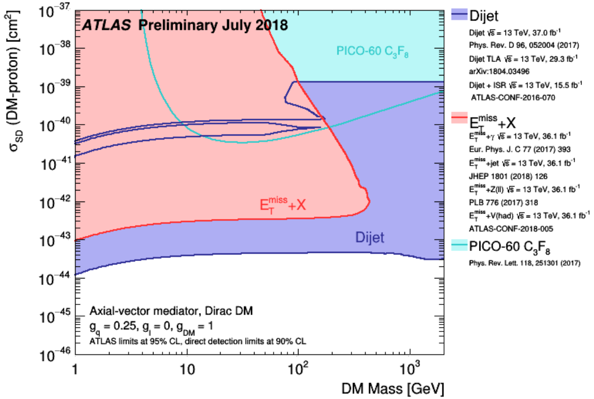
DM-proton | **DM-neutron**

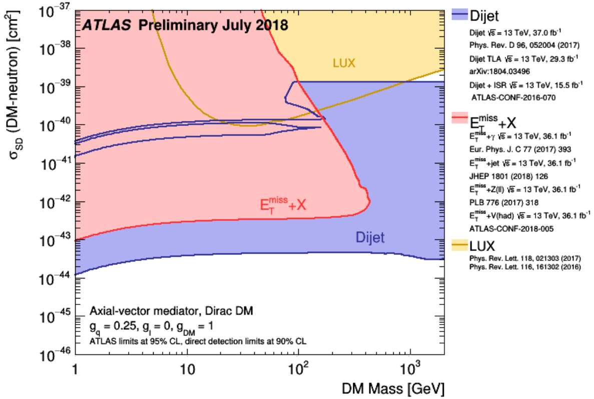
Axial-Vector mediator
g_q=0.1, g_l=0.1, g_{DM}=1





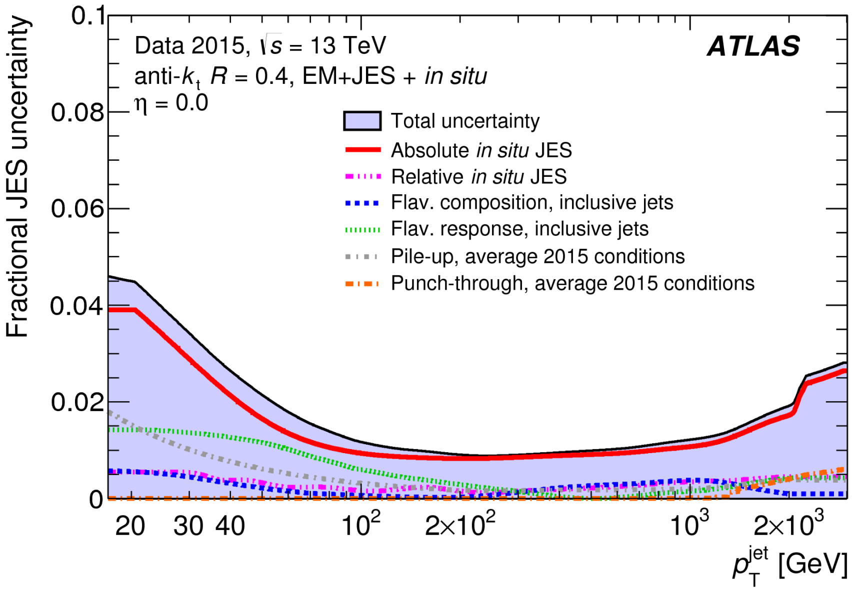
Axial-Vector mediator
g_q=0.25, g_l=0, g_{DM}=1

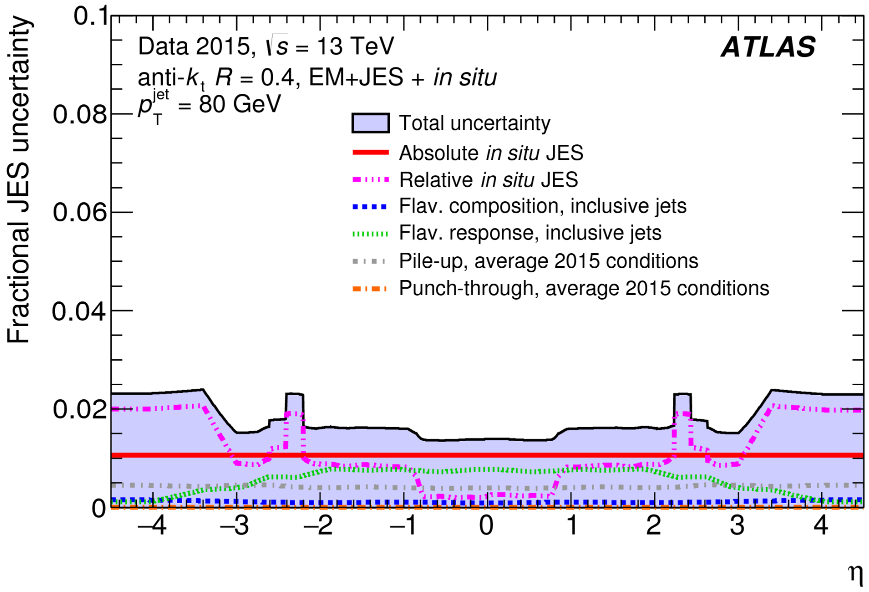




Jet Energy Scale

√s = 13 TeV, L = 36 fb⁻¹
- PERF-2016-04
- Phys. Rev. D 96 (2017) 072002





- Jet energy scale uncertainty is 1% for central jets with pT of 500 GeV and grows to 3% for jets with pT of 2 TeV
- Di-jet mass resolution is 2.4% and 2.0% for dijet masses of 2 TeV and 5 TeV, respectively

Dijet analyses

Di-jet invariant mass fit

- Used for previous analyses:

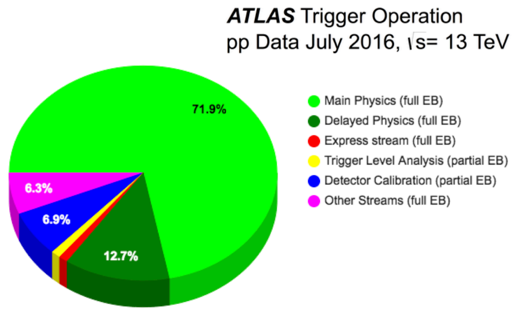
  $f(z) = p_1(1-z)^{p_2} z^{p_3} z^{p_4 \log z}$

  - where $z = m_{jj}/\sqrt{s}$ and the p_i are parameters

- New: sliding-window fitting technique fitting only restricted regions of the spectrum
  - windows ~ 1/2 total number of bins ➪ whole signal contained

  ➪ more flexibility, 3 parameters sufficient

  ➪ new method validated



TLA di-jet analysis

- Sliding window fit
- $f(x) = p_1 (1-x)^{p2} x^{p3+p4 \ln x+p5 \ln x2}$ or $f(x) = p_1 x^{-p2} e^{-p3x-p4x2}$