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Dark Matter searches at the LHC

Henning Flächer
H.H. Wills Physics Laboratory
University of Bristol

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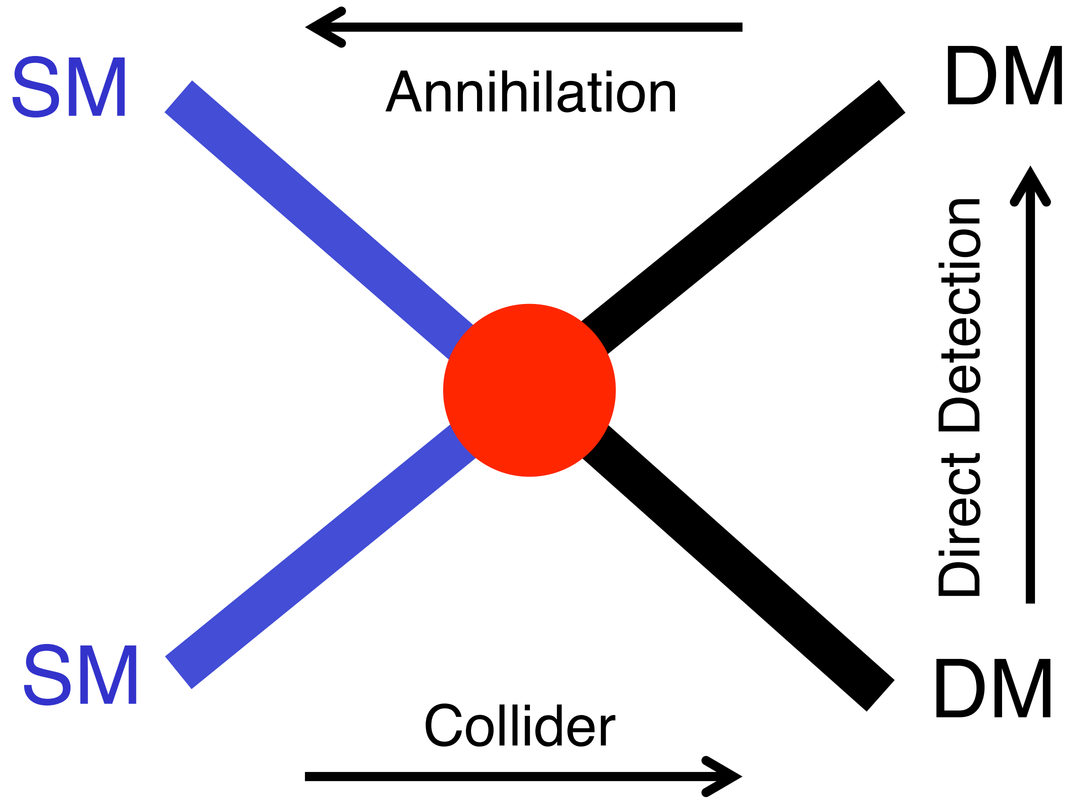
Dark Matter @ the LHC

- Overwhelming evidence for Dark Matter but corresponding particle missing from SM

- When searching for Dark Matter, the big question is:
  - How does it interact?

- All evidence for Dark Matter so far is gravitational
  - Why look for it a colliders?



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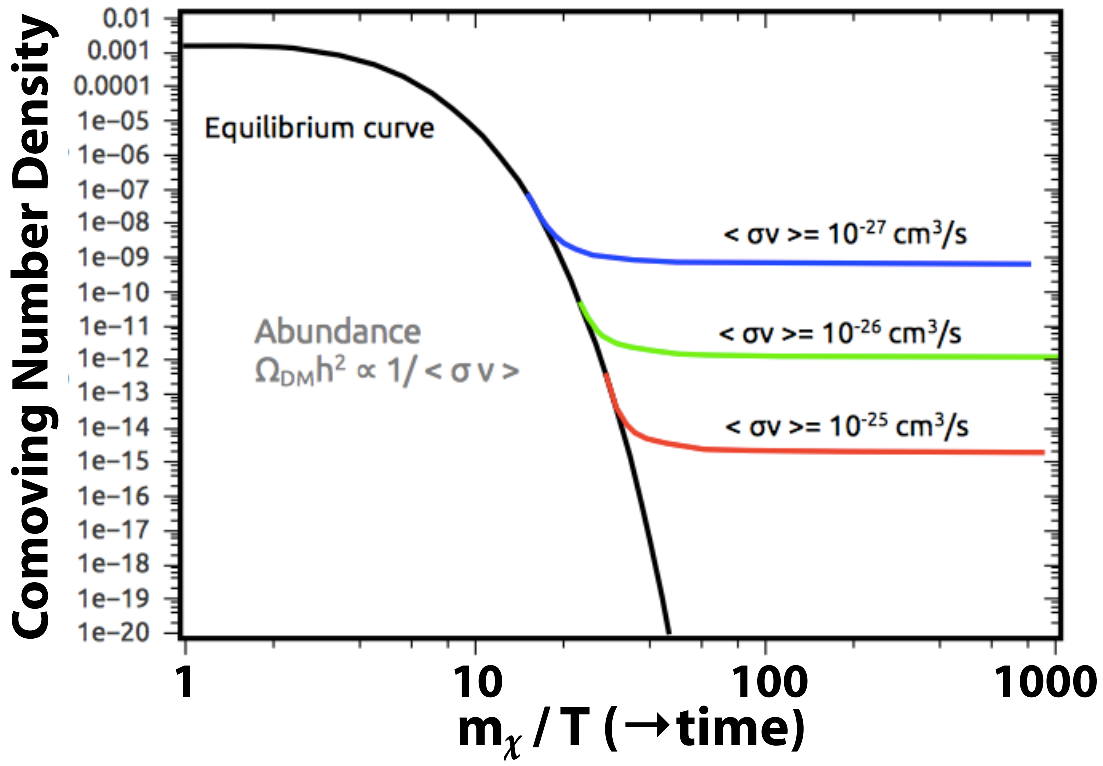
Introduction/Motivation

- Why look for DM at colliders?
- Assumption that in early universe DM was in thermal equilibrium with SM matter
  - some interaction with SM matter
- As universe expands and cools down, DM decouples
- DM abundance determined by annihilation cross section at freeze-out
- A particle with weak scale interactions and mass of O(100 GeV) gives relic density in agreement with our measurements
  - “WIMP miracle”

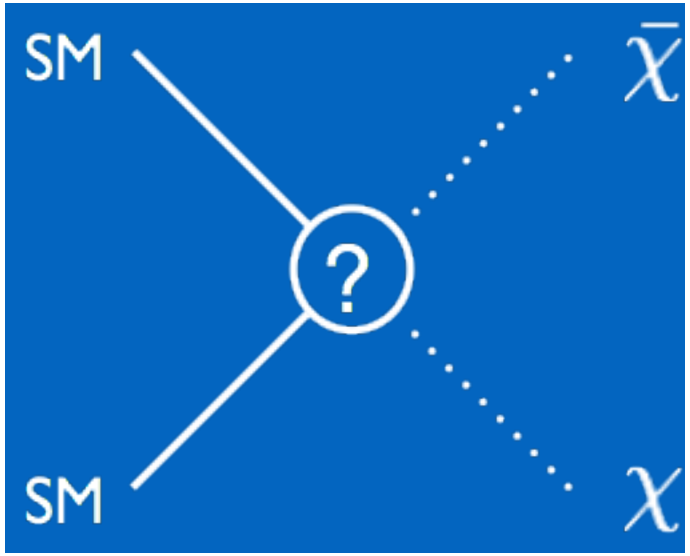


$$\Omega_\chi h^2 \simeq 0.1 \times \left(\frac{3 \times 10^{-26} cm^3 s^{-1}}{\langle \sigma v \rangle}\right)$$

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} cm^3 s^{-1}$$
$$\sim \pi\alpha^2/(100\ \mathrm{GeV})^2$$

What interactions to probe?

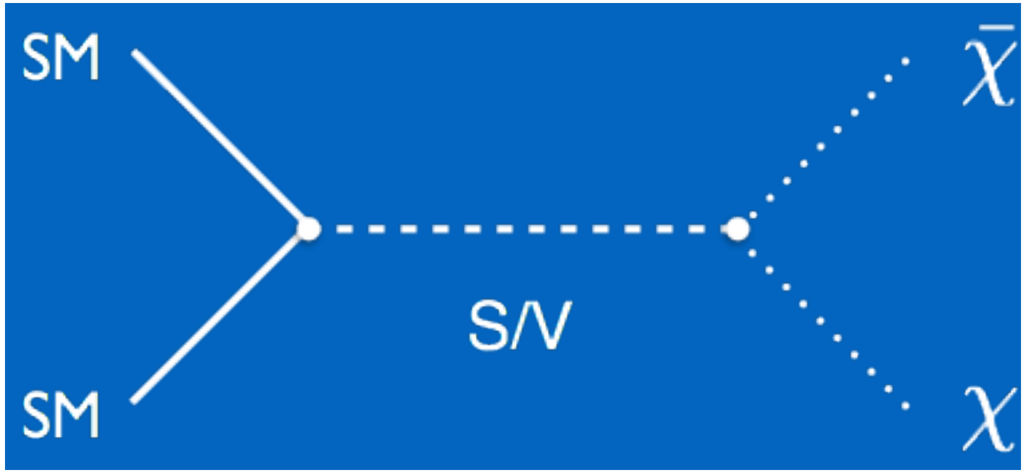
- Start with minimal assumptions
  - Effective Field Theories



- Described in terms of Lorentz structure, DM mass and cut-off scale

- Need to be careful at LHC @ 13 TeV
- EFT only valid if Q^2 << M

- Simplified models
  - Resolve the interaction

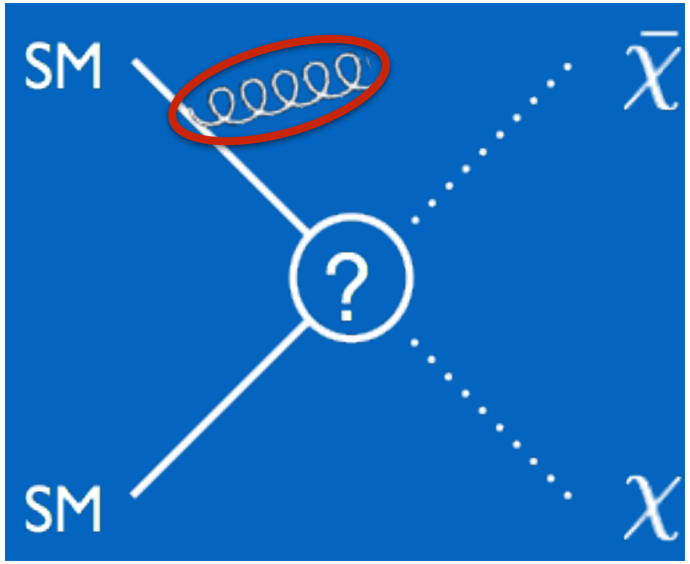


- Come with different assumptions for interactions/mediators

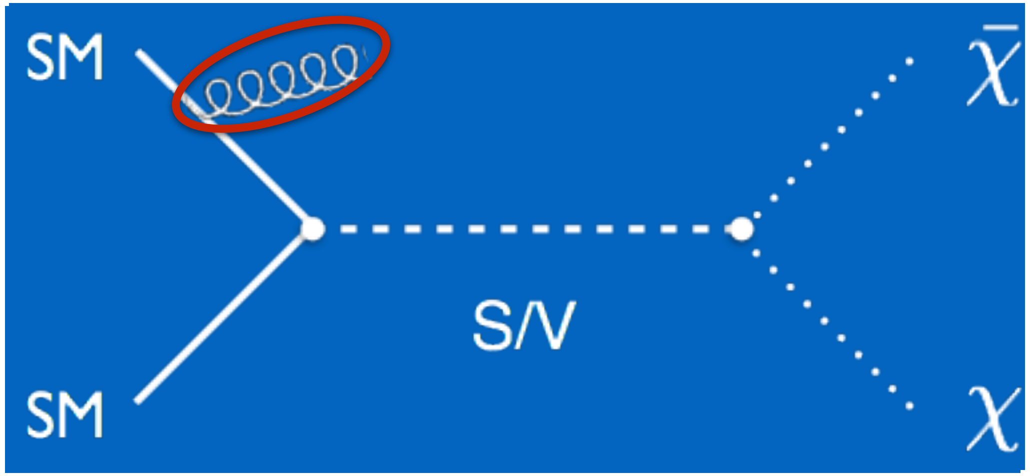
- scalar $(\psi\psi)$
- pseudo scalar $(\psi\gamma^5\psi)$
- vector $\psi\gamma^\mu\psi$,
- axial-vector $(\psi\gamma^\mu\gamma^5\psi)$

What interactions to probe?

- Start with minimal assumptions
  - Effective Field Theories



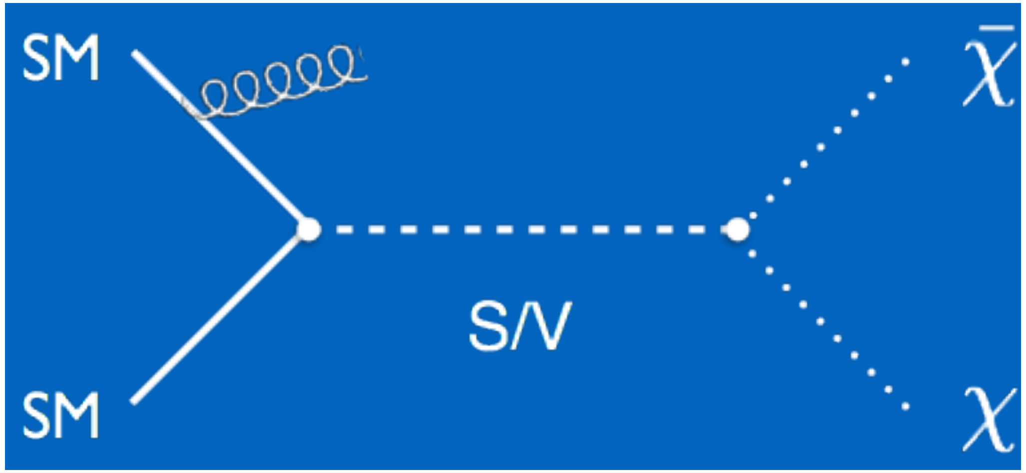
- Simplified models
  - Resolve the interaction



We also typically need additional radiation (ISR)
as WIMPs are invisible to the detectors

Simplified Dark Matter models

- Typically parameterized by 5 parameters:



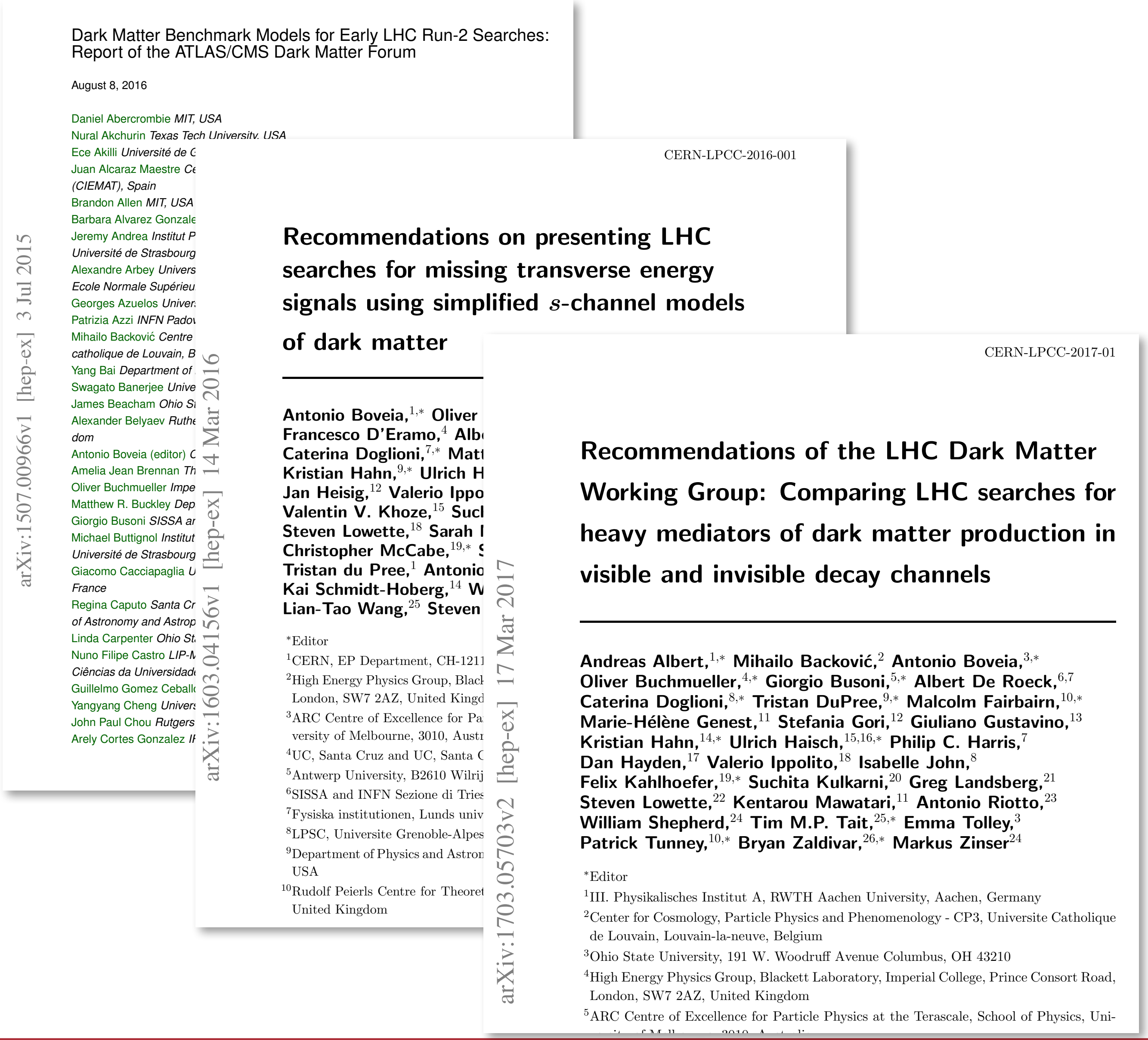
- mass of DM particle, m_{χ}
- mass and width of mediator particle, m_{med}, Γ_{med}
- coupling of mediator to SM sector, g_q
- coupling of mediator to DM sector, g_{χ}

- A/A-V: $g_q = 0.25$, $g_{\chi} = 1$
- S/P-S: $g_q = 1$, $g_{\chi} = 1$

- Searches focus on two main signatures:
- DM production via mediator
  - Missing energy searches as a result of escaping DM particles
  - Mono-X signatures
    - X = jet, photon, W, Z, H,…
  - Resonant production of mediator particle and decay back to SM particles
    - di-jet, di-lepton,di-top,… resonances

Dark Matter LHC Working Group

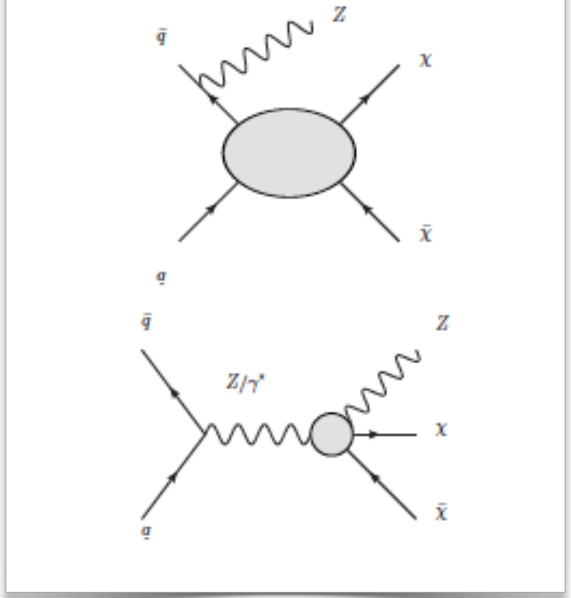
- Systematic approach pursued through Dark Matter LHC Working group
  - https://lpcc.web.cern.ch/content/lhc-dm-wg-wg-dark-matter-searches-lhc
  - with involvement of both experimentalists and theorists
- Recommendations for models and their implementation
- Guidelines on how to compare collider searches with direct detection limits
- Recommendations for comparison of searches for heavy mediators of DM production



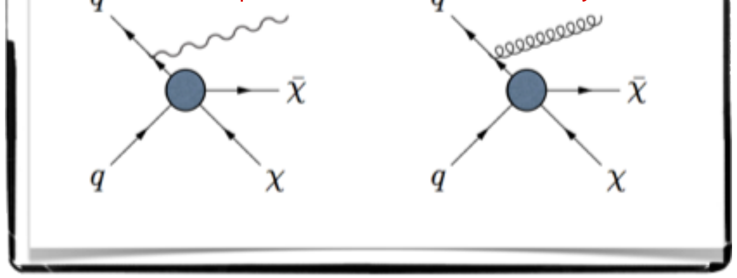
Simplified Dark Matter models

Mono-mania @ the LHC…

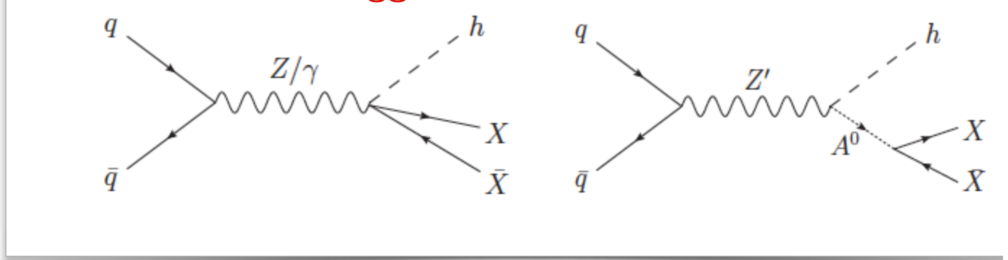
Mono-Z



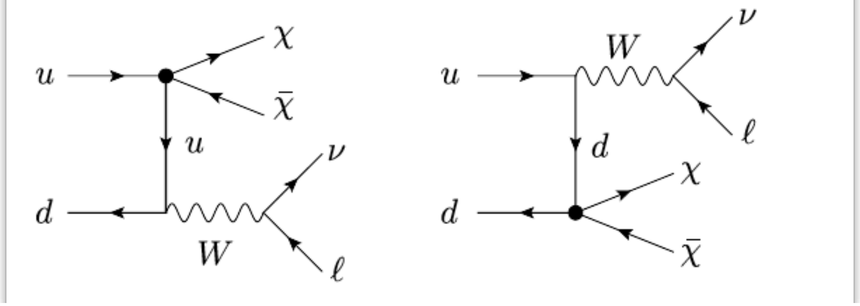
Mono-photon Mono-jet



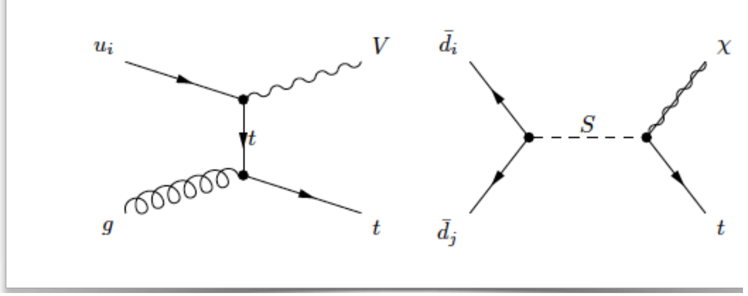
Mono-Higgs



Mono-W



Mono-top

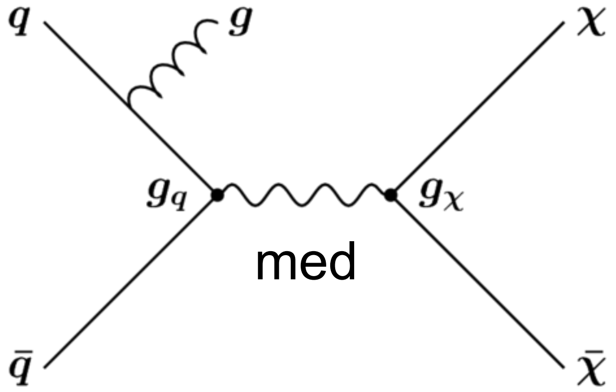


… complemented by searches for "full", UV-complete models, such as

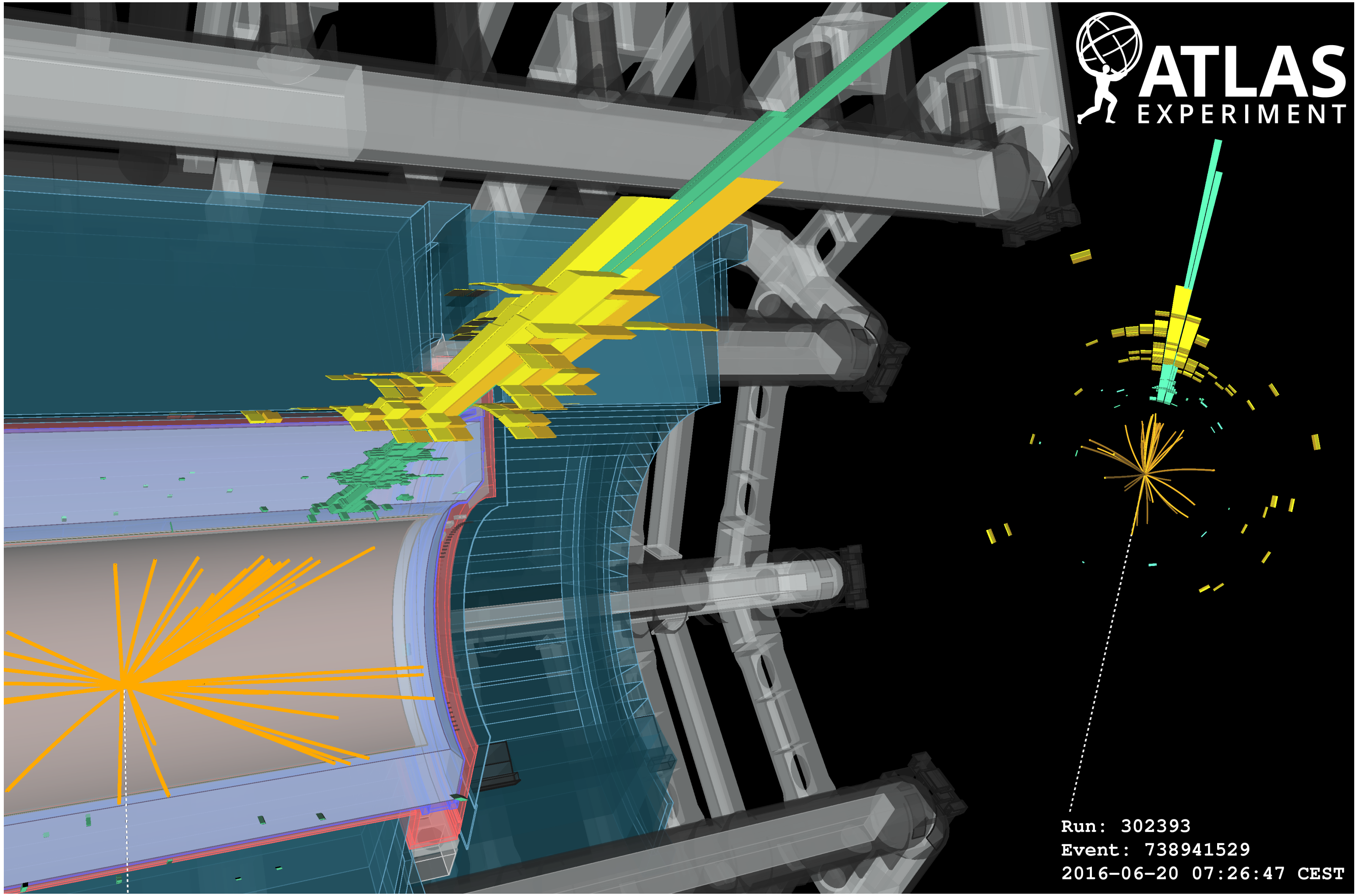
- Supersymmetry
- Kaluza-Klein extra dimensions
- Little Higgs models
- etc.

- …and of course there are also other DM candidates but this talk will mainly focus on WIMPs

Mono-mania



q
g
χ
g_q
g_χ
med
$\bar{q}$
$\bar{\chi}$



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EXPERIMENT
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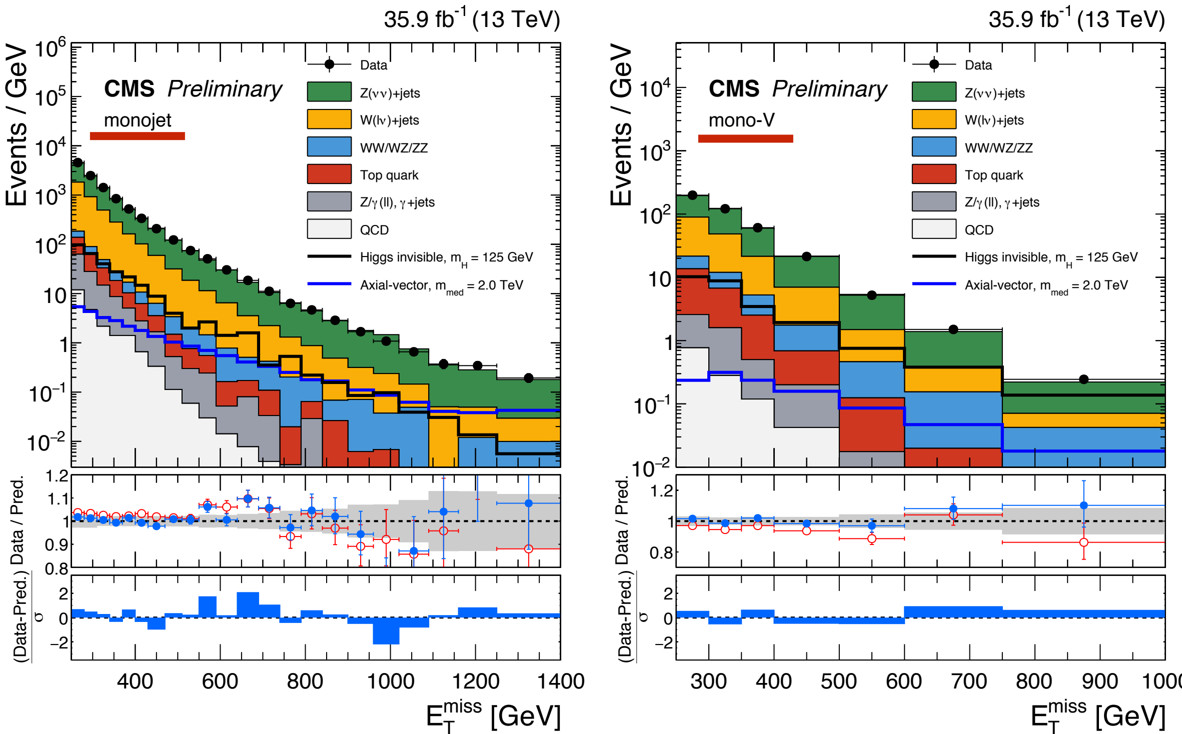
2016-06-20 07:26:47 CEST

Mono-jet & Mono-V Searches

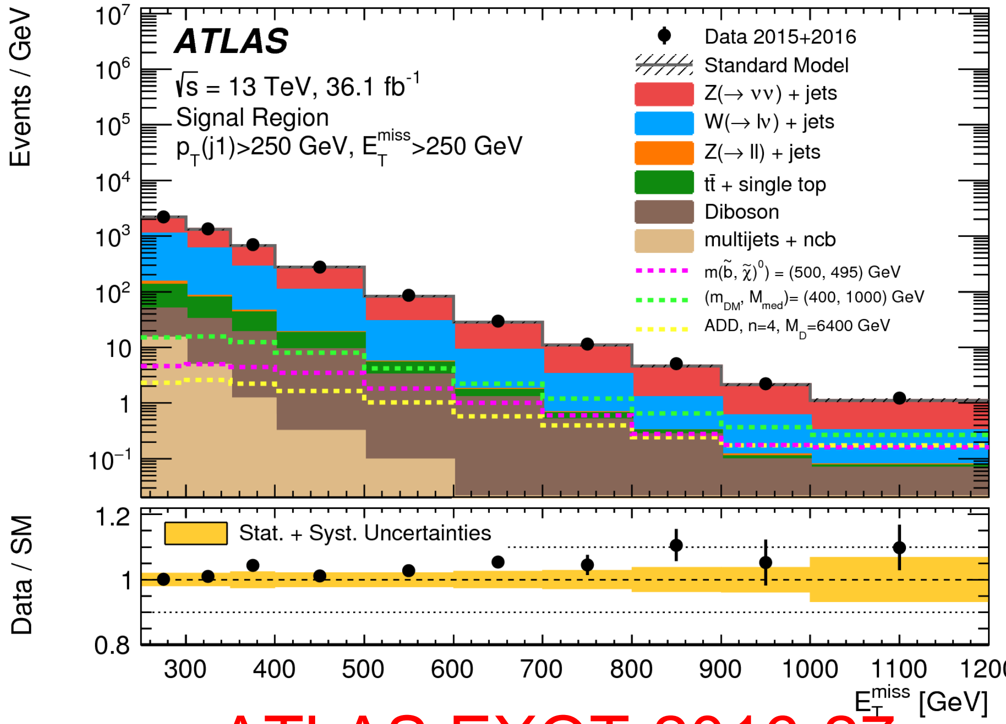
- Search for jets with missing energy
  - Jets or boosted vector bosons (W,Z)

- Comparison of data with background prediction

- Main background from Z → νν + jets and W+jets production



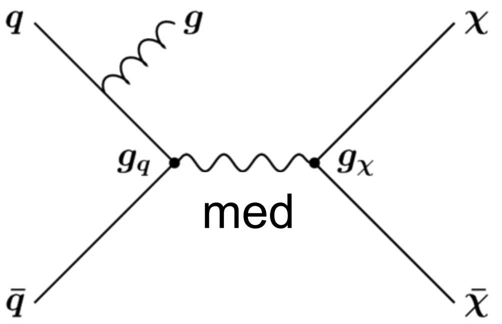
CMS EXO-16-048



ATLAS EXOT-2016-27

Mono-jet & Mono-V Searches

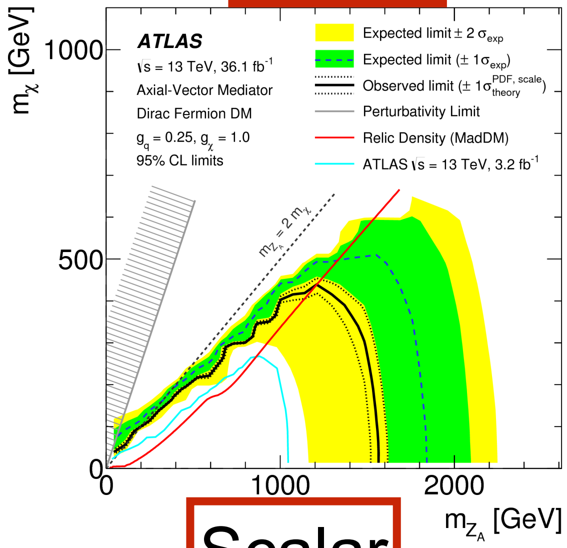
- Interpretation in simplified DM models
- s-channel with different mediators



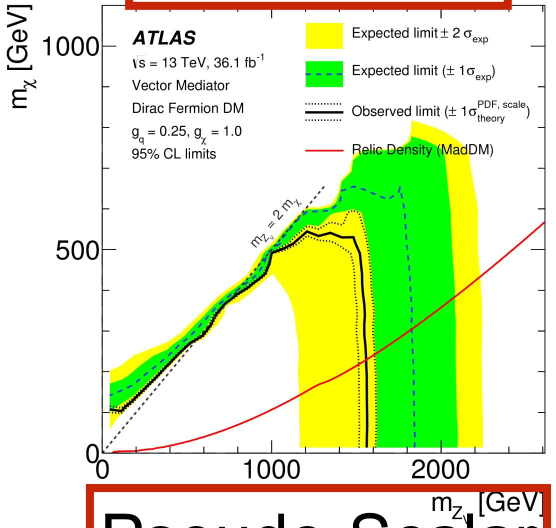
- Set limits on allowed masses and coupling strength (next slide)

- Further interpretations in
  - fermion portal models
  - coloured scalar mediator models
  - nonthermal dark matter model

Vector

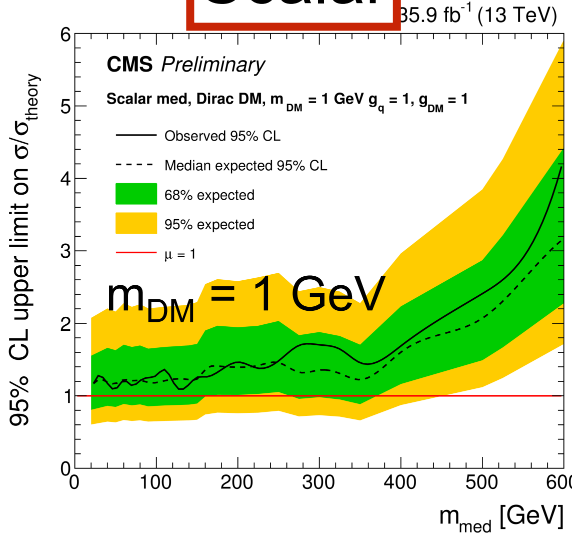


Axial-Vector

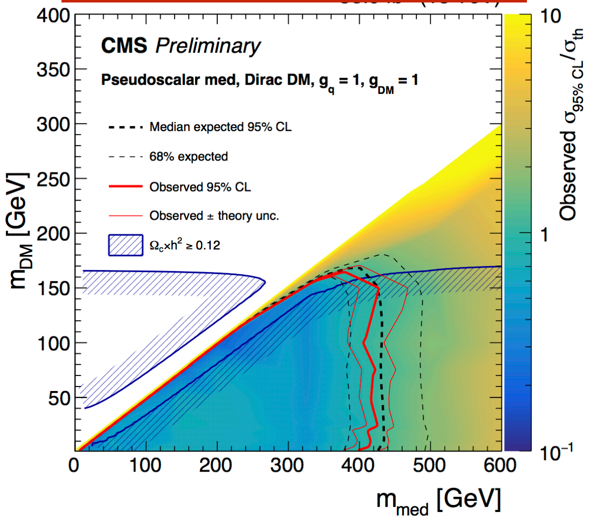


ATLAS EXOT-2016-27

Scalar



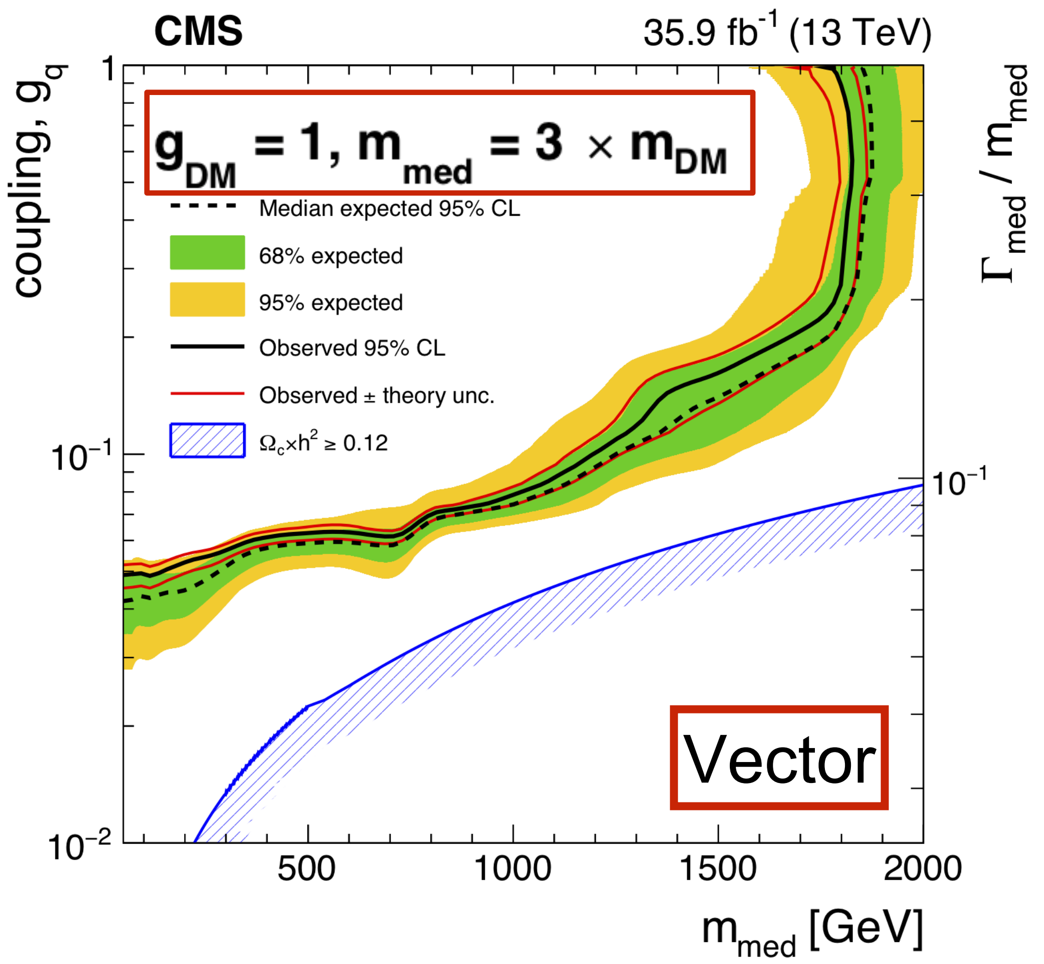
Pseudo-Scalar

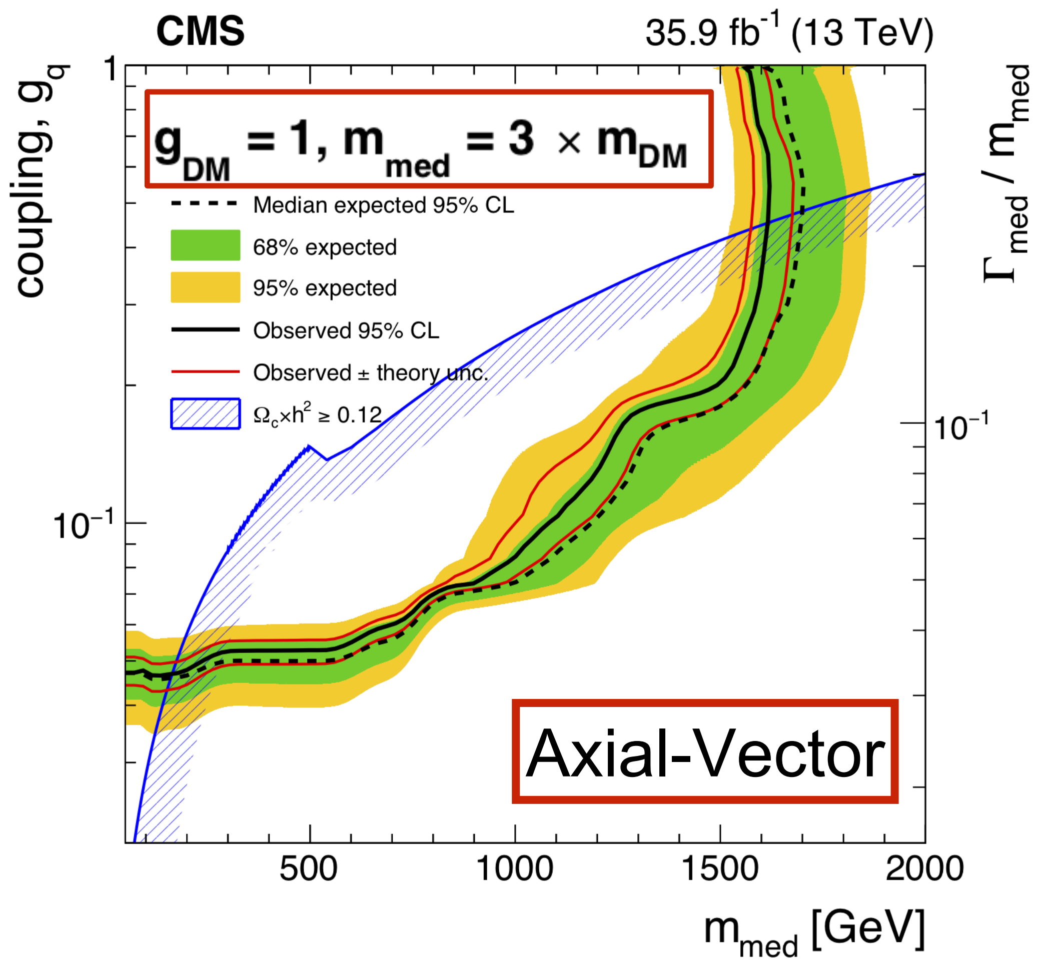


CMS EXO-16-048

Mono-jet & Mono-V Searches

- Interpretation in simplified DM models
- s-channel with different mediators

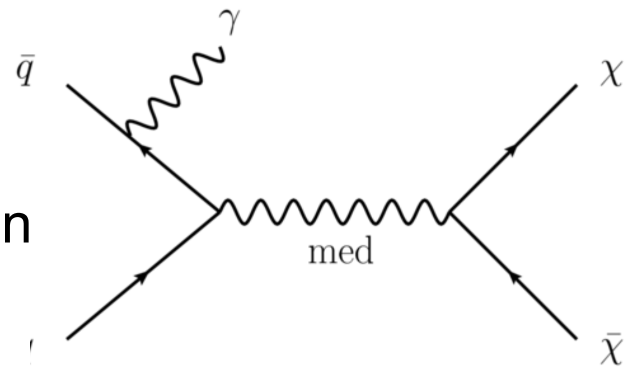


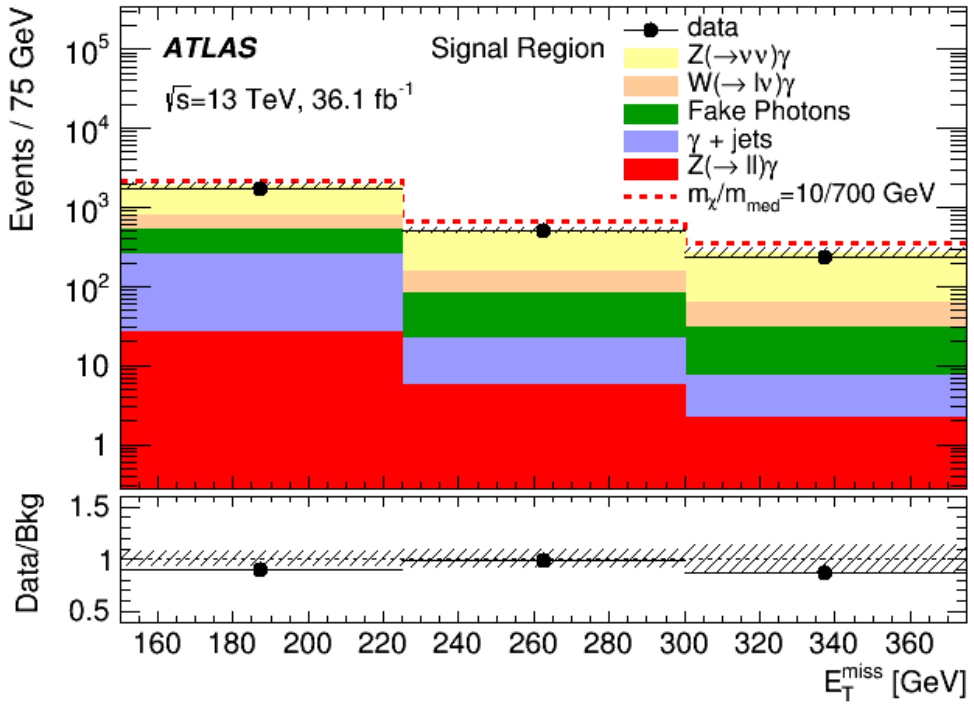


CMS EXO-16-048

Mono-photon

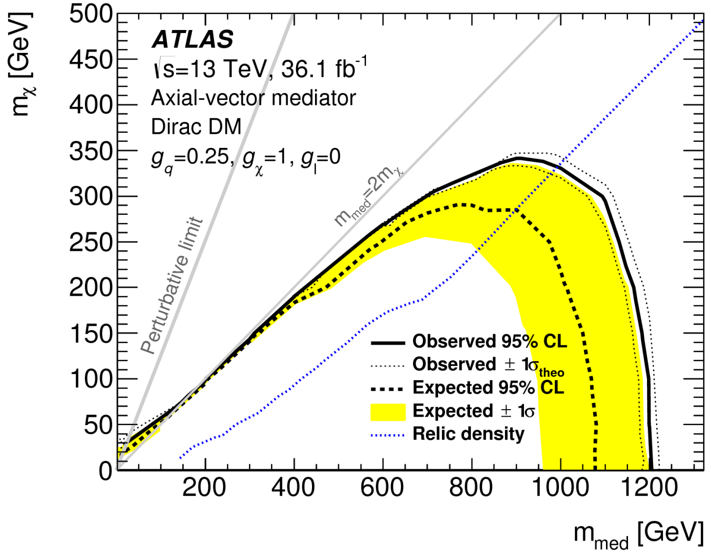
- Photon p_T > 150 GeV
- Veto events with more than 1 jet
- Require angular separation between photon and missing energy

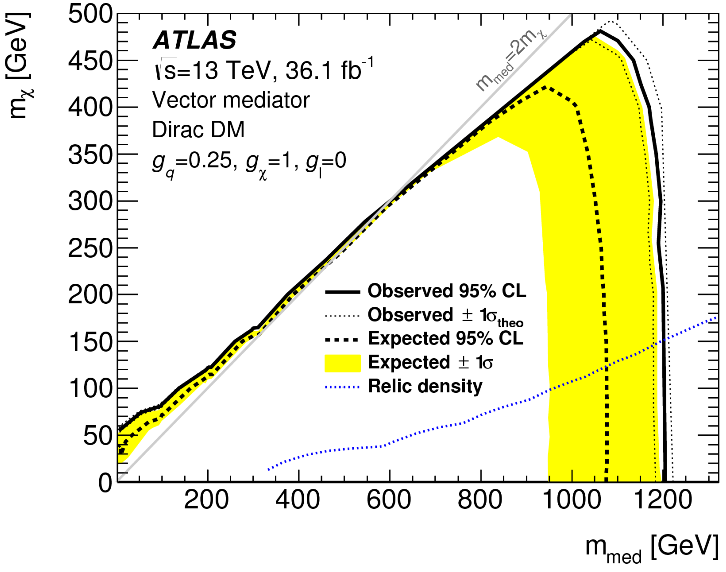




Weaker sensitivity compared to mono-jet ISR searches

But also EFTs with direct couplings to photons



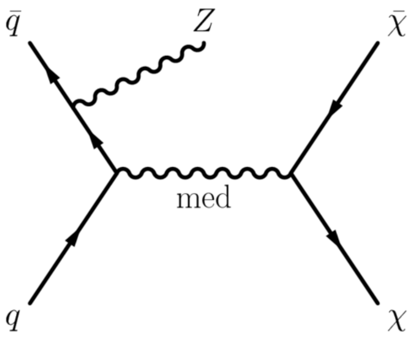


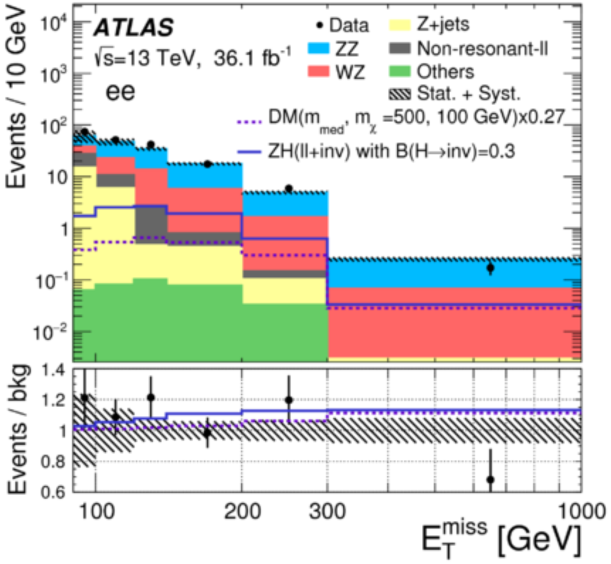
ATLAS: Eur. Phys. J. C 77 (2017) 393

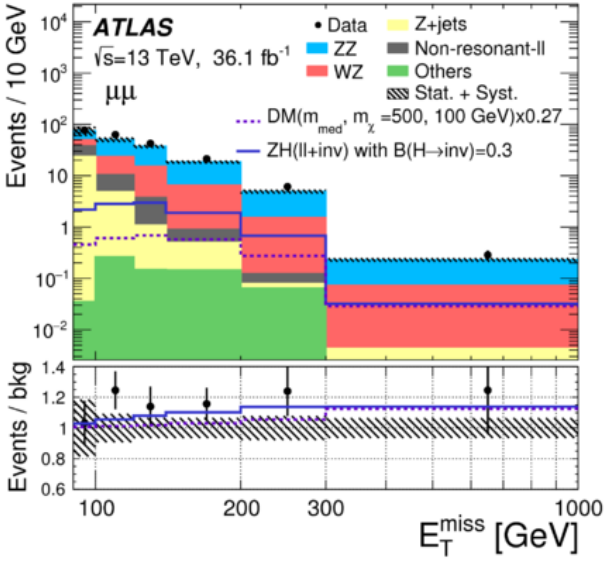
Comparable CMS analysis: JHEP 10 (2017) 073

Mono-Z

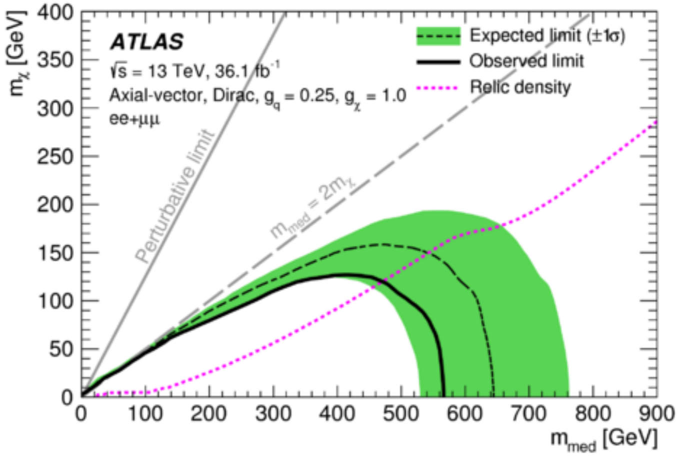
- Search for dark matter candidates produced in association with a Z boson
- *ATLAS: PLB 776 (2017) 318*, **arXiv:1708.09624**





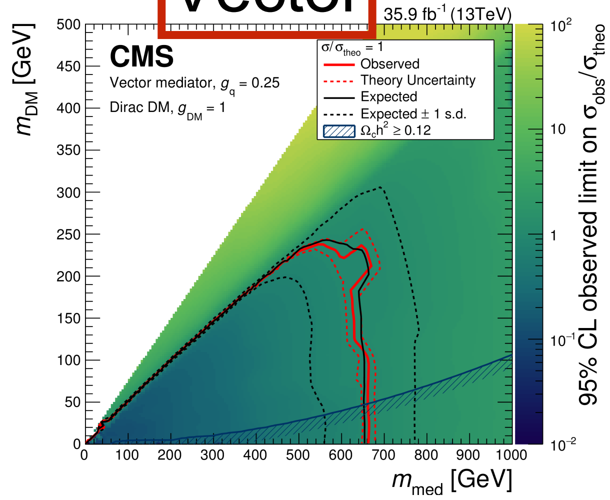


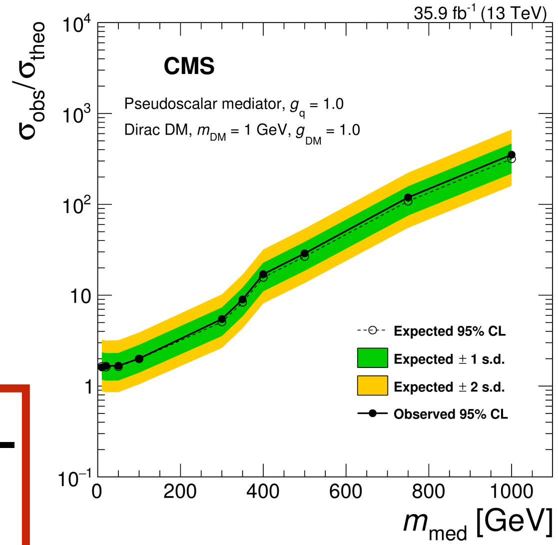
Axial-Vector



CMS-EXO-16-052

Vector



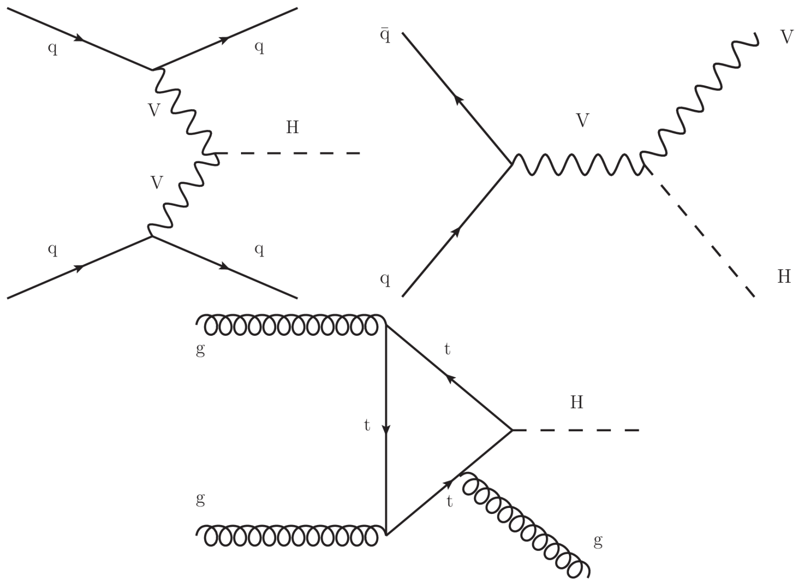


Pseudo-scalar

Scalar almost identical

Higgs as a portal to Dark Matter

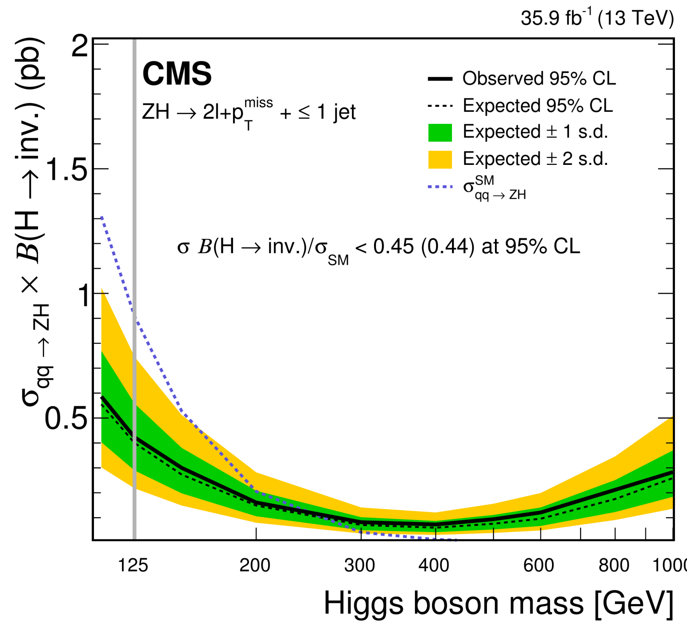
- Study of Higgs → invisible branching fraction in VBF, association with V and gluon fusion production modes.
- As Higgs couples proportionally to mass, making it a viable portal to DM
  - Only sensitive to DM masses < 0.5 m_H



- Additional searches for Higgs in conjunction with DM in bb and γγ final states (→ backup)

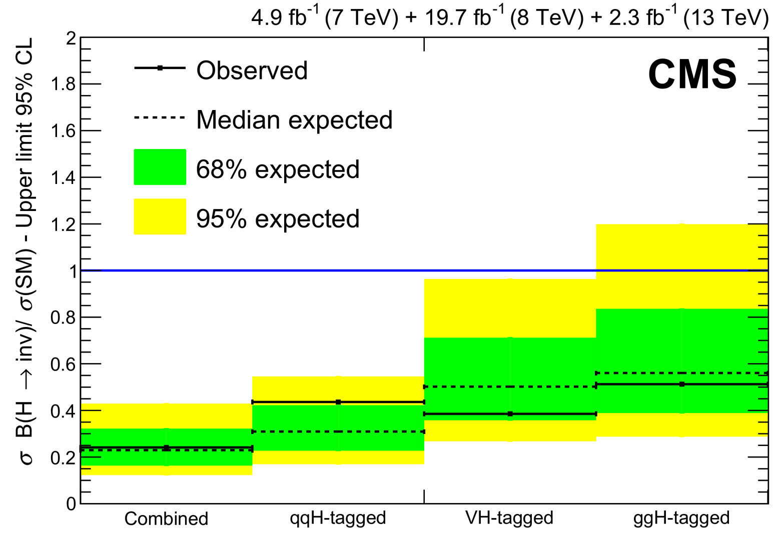
- Higgs production in association with Z → ll

CMS-EXO-16-052



- Combination of H → invisible production modes
- B(H → inv) < 0.24 @95%CL

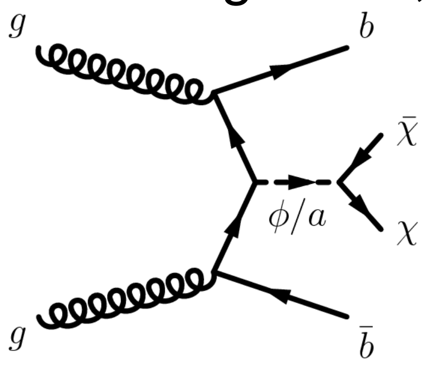
CMS-HIG-16-016



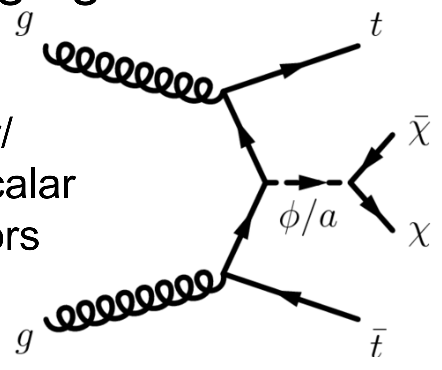
DM in association with heavy flavours

- DM in association with bottom or top quarks
- VBF like signature, b-jet tagging

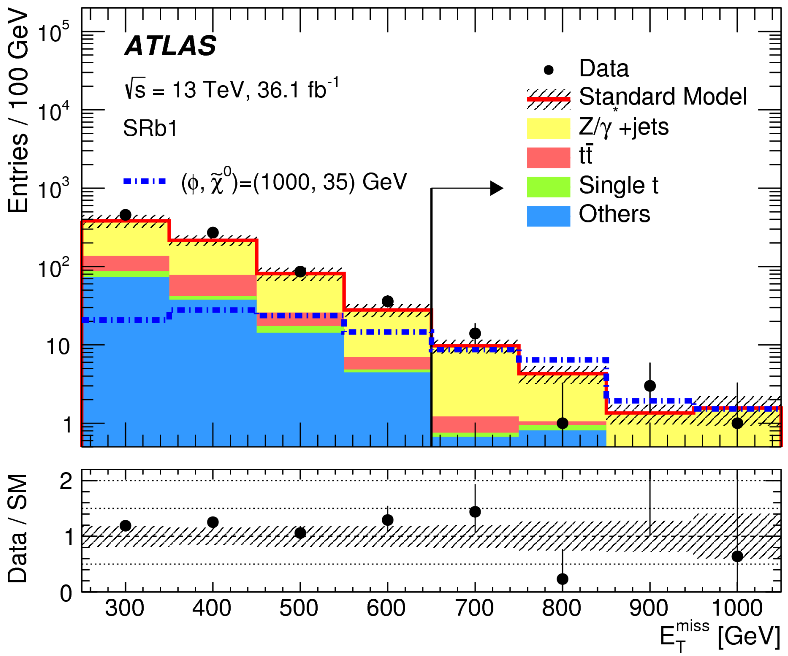
arXiv:1710.11412



Scalar/
Pseudoscalar
mediators



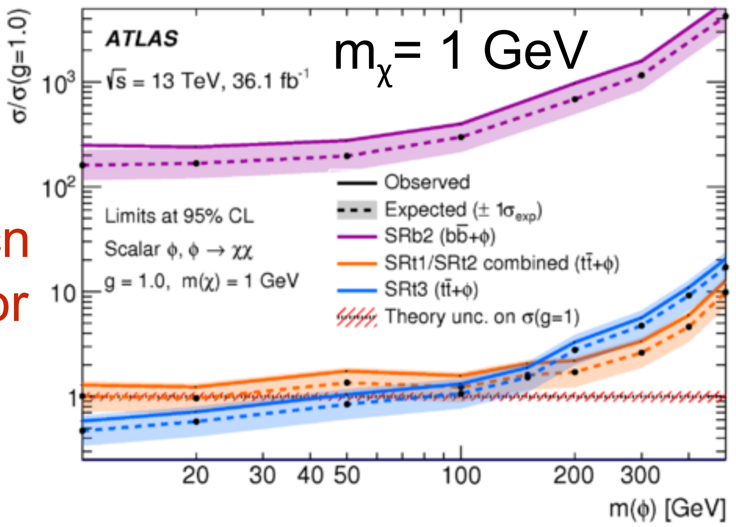
- Interpretation in colour-neutral $t\bar{t}/b\bar{b}+\varphi$ scalar and $t\bar{t}/b\bar{b}+a$ pseudoscalar models
- Not yet sensitive to bb + φ/a production
- Also searches with single top
  - CMS EXO-16-051



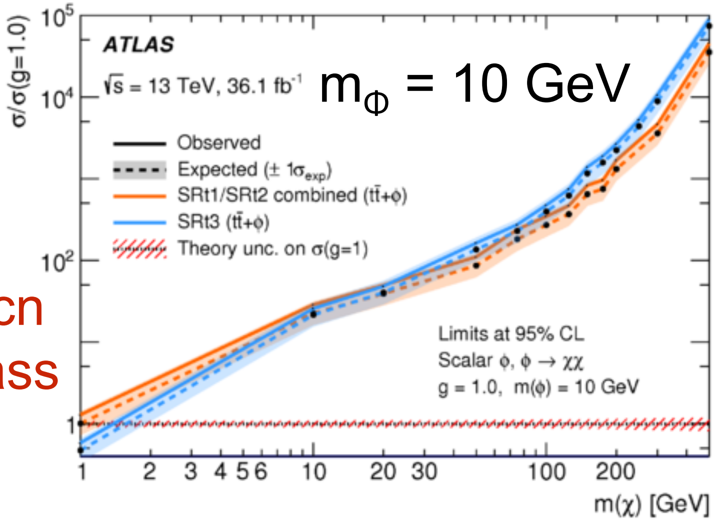
- Fixed DM mass
- Limit as fcn of mediator mass

Scalar

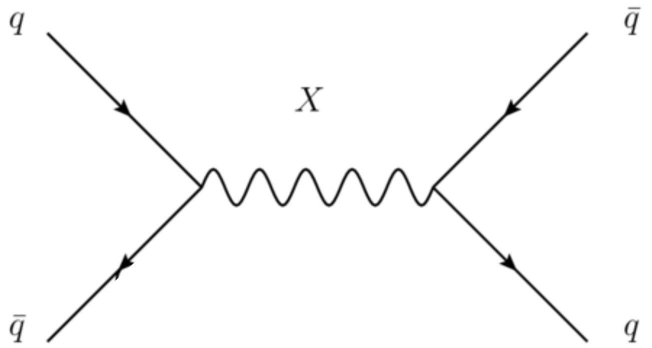
Similar sensitivity to pseudoscalar

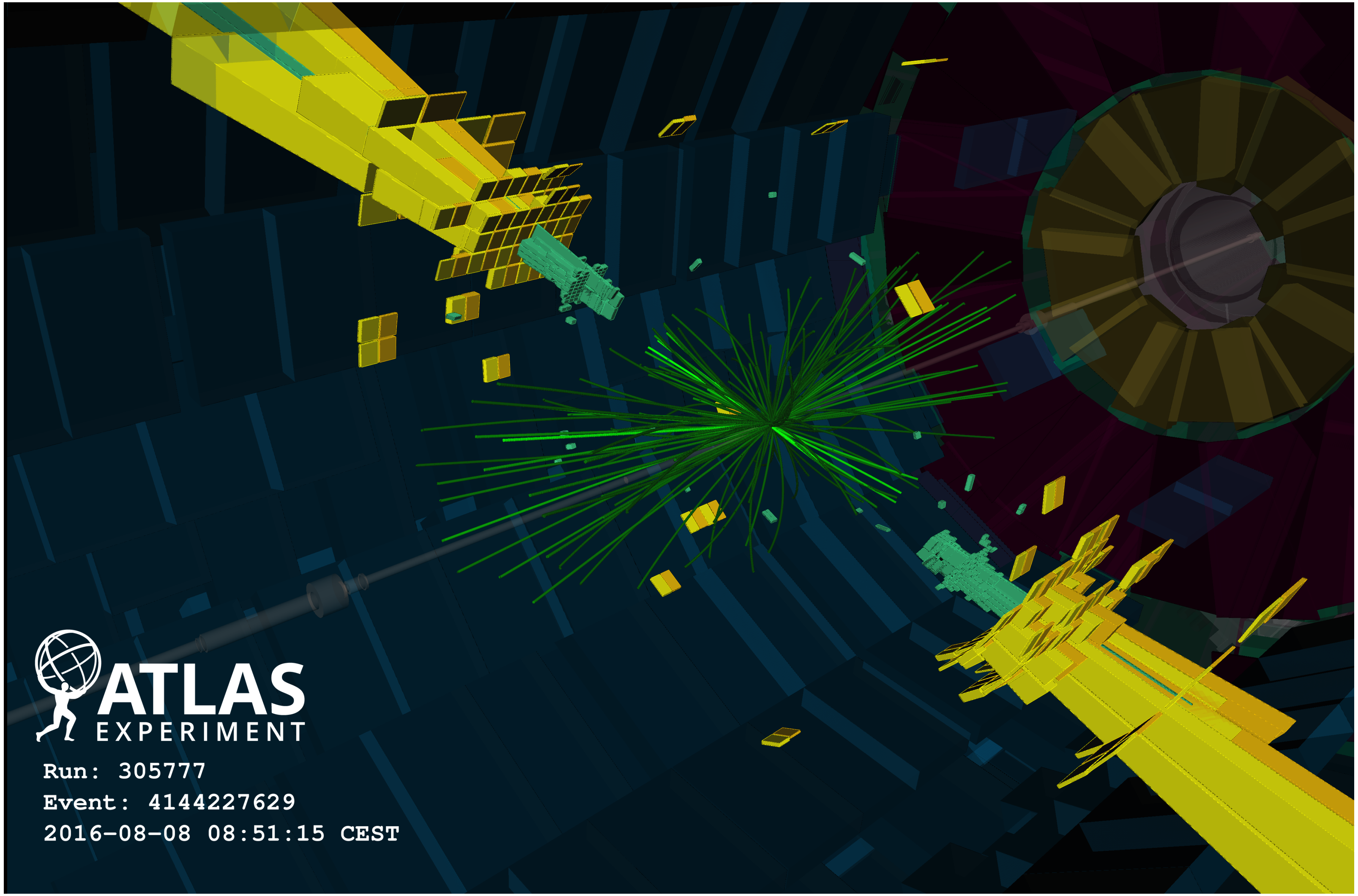


- Fixed mediator mass
- Limit as fcn of DM mass



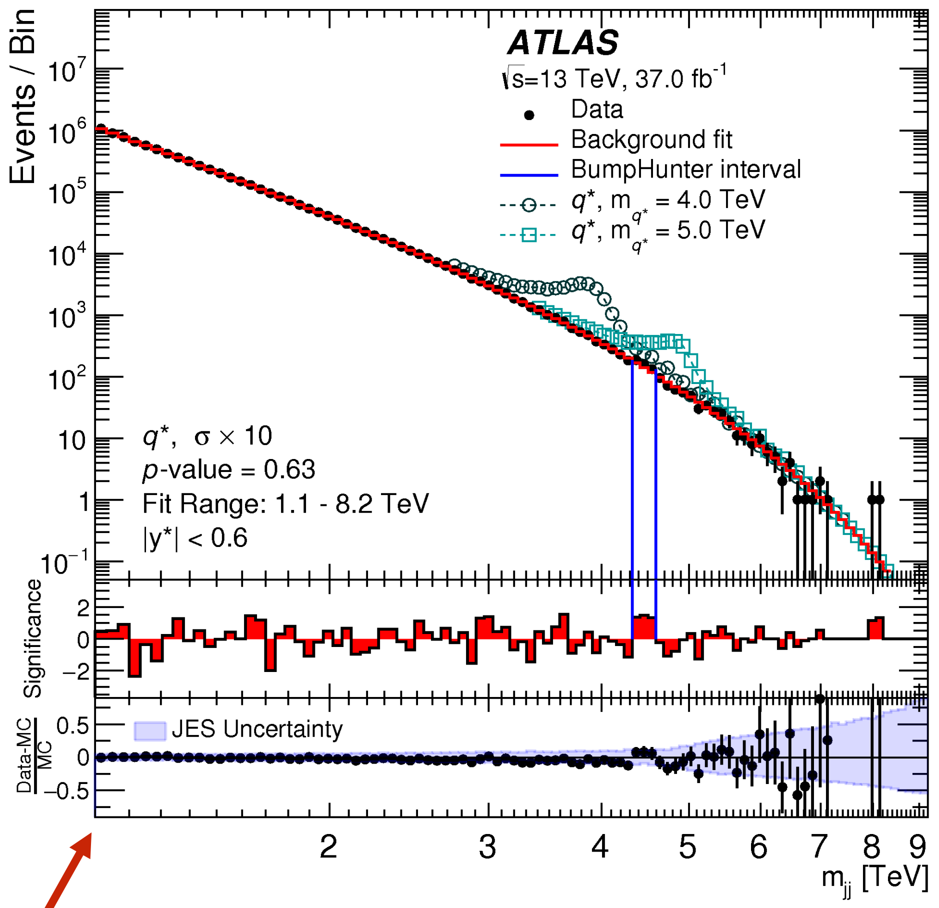
Mediator Searches



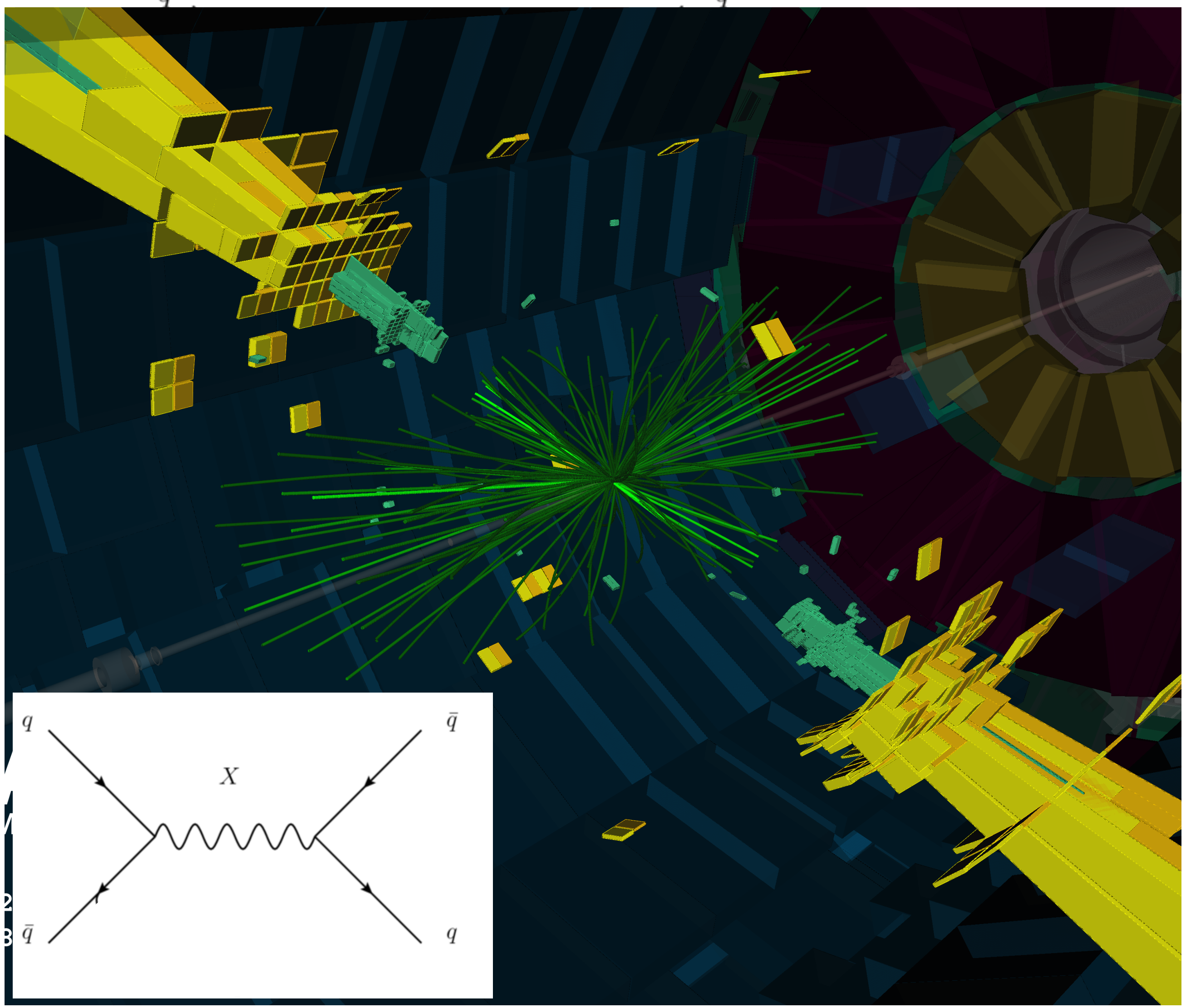


High-mass dijet resonances

- Search for resonance in dijet invariant mass spectrum



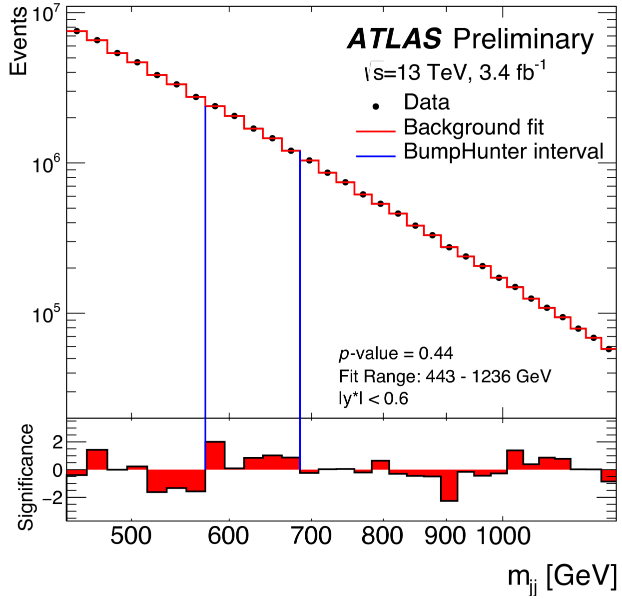
1 TeV



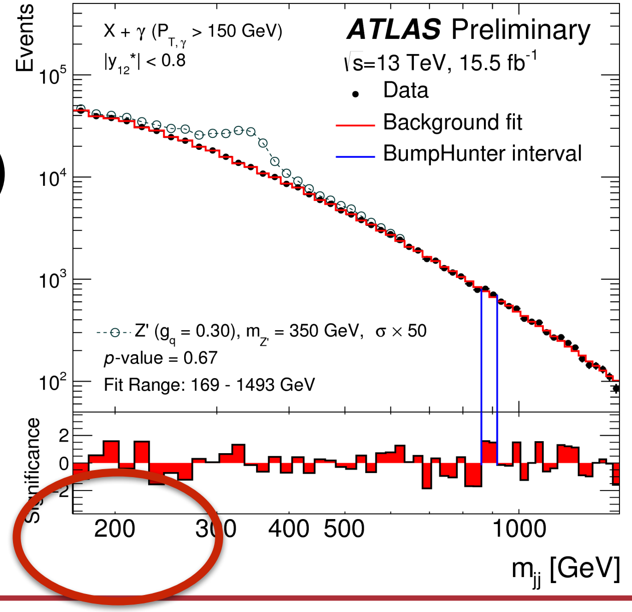
Low-mass dijet resonances

- Low mass mediators are difficult to constrain because of huge QCD dijet background
  - difficult/impossible to cope with total event rate
- Possible ways out:
  - "Data scouting": perform analysis on dataset that contains reduced event information (trigger level), allowing to store data at very high rate
  - Trigger on high-pT ISR jet or photon and search for low mass resonance in recoil system
  - Trigger on high-pT ISR jet and search for merged, boosted resonance in recoil, using jet subtructure

ATLAS
Trigger Level Analysis
ATLAS-CONF-2016-030

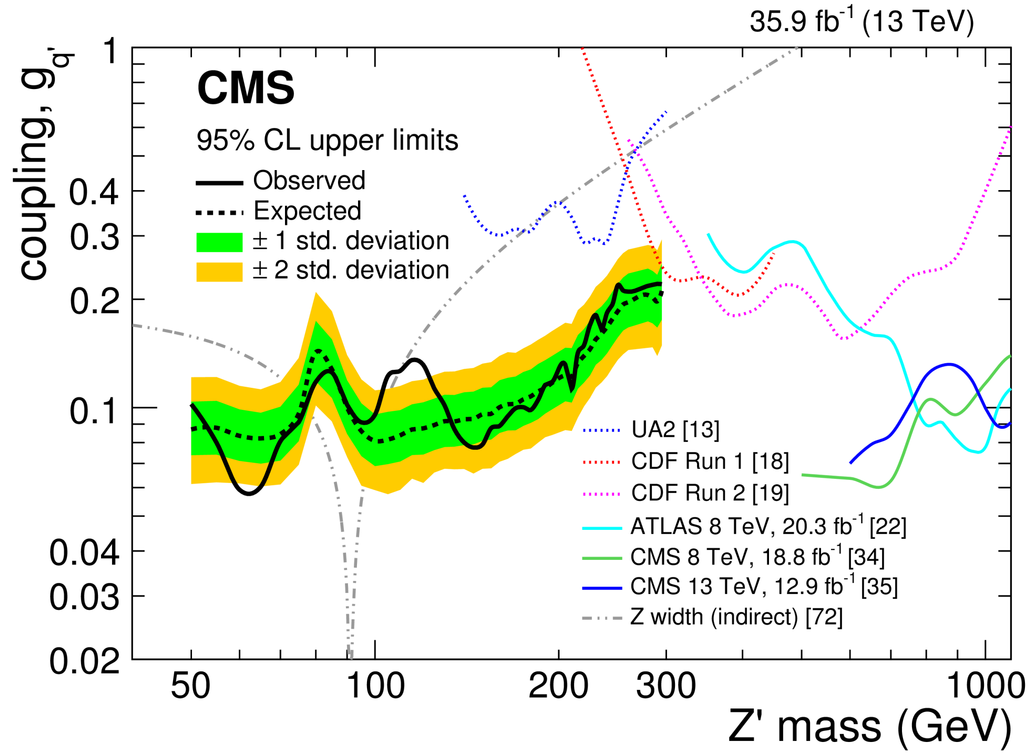


ATLAS
ISR search (photon)
ATLAS-CONF-2016-070



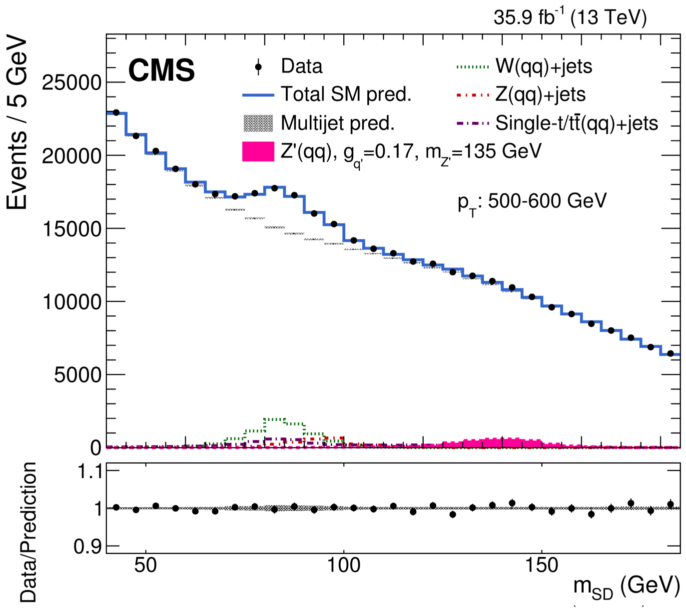
Low-mass dijets– boosted topology

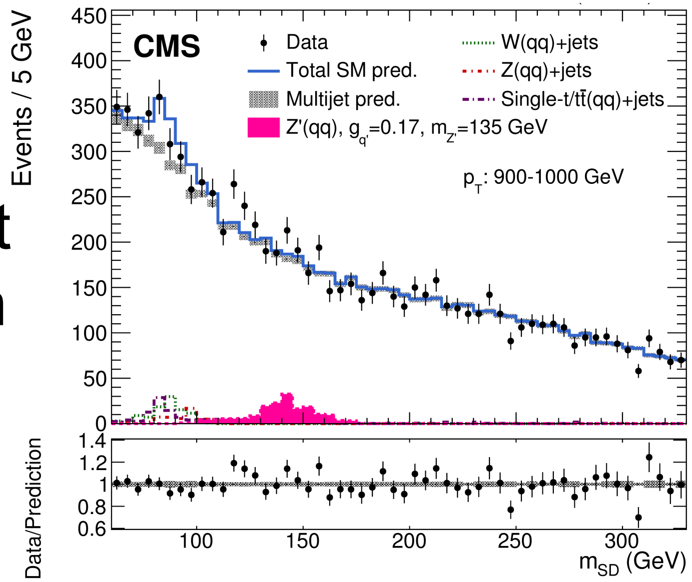
- Resonance is produced with sufficiently high transverse momentum that its decay products are merged into a single jet with two-prong substructure.



CMS-EXO-17-001

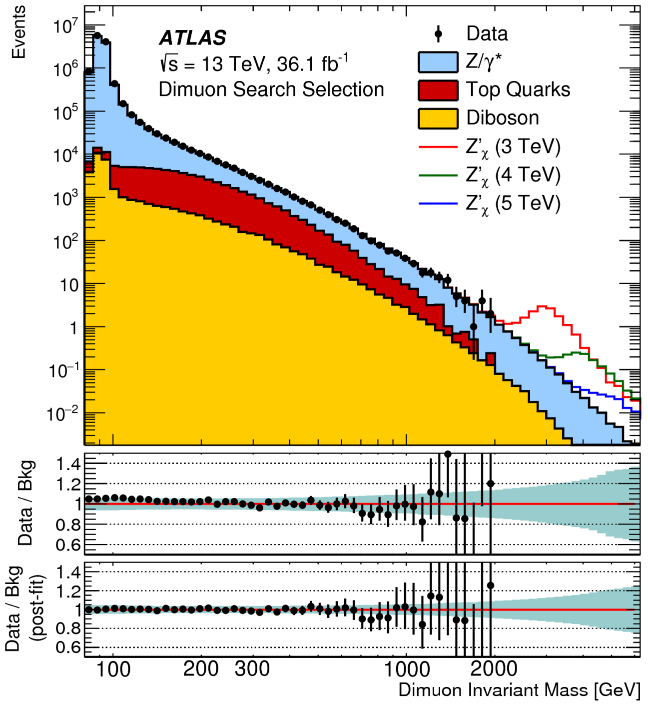
- Soft drop mass for jets in different p_T ranges
- Peak from Ws and Zs clearly visible
- Sensitive to dijet resonances with masses as low as 50 GeV

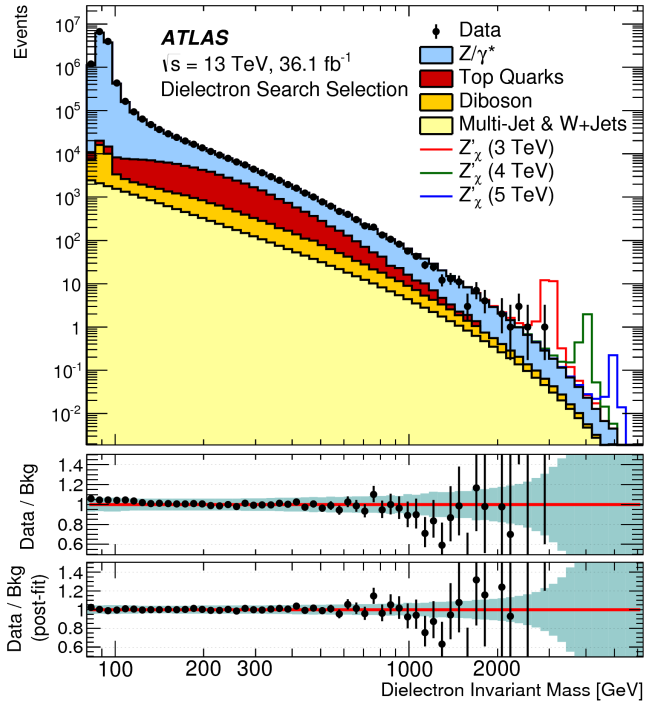


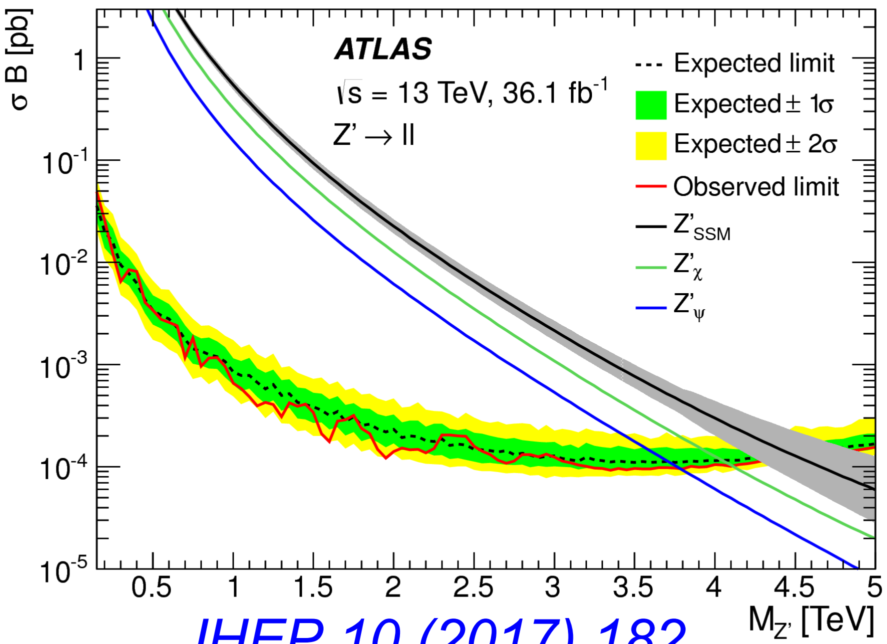


Dilepton resonances (Z’)

- Z’ → e^+e^- and Z’ → $\mu^+\mu^-$ searches
  - Require high-p_T same flavour, opposite charge dilepton pair
  - Limits on Z’ mass of around 4 - 4.5 TeV





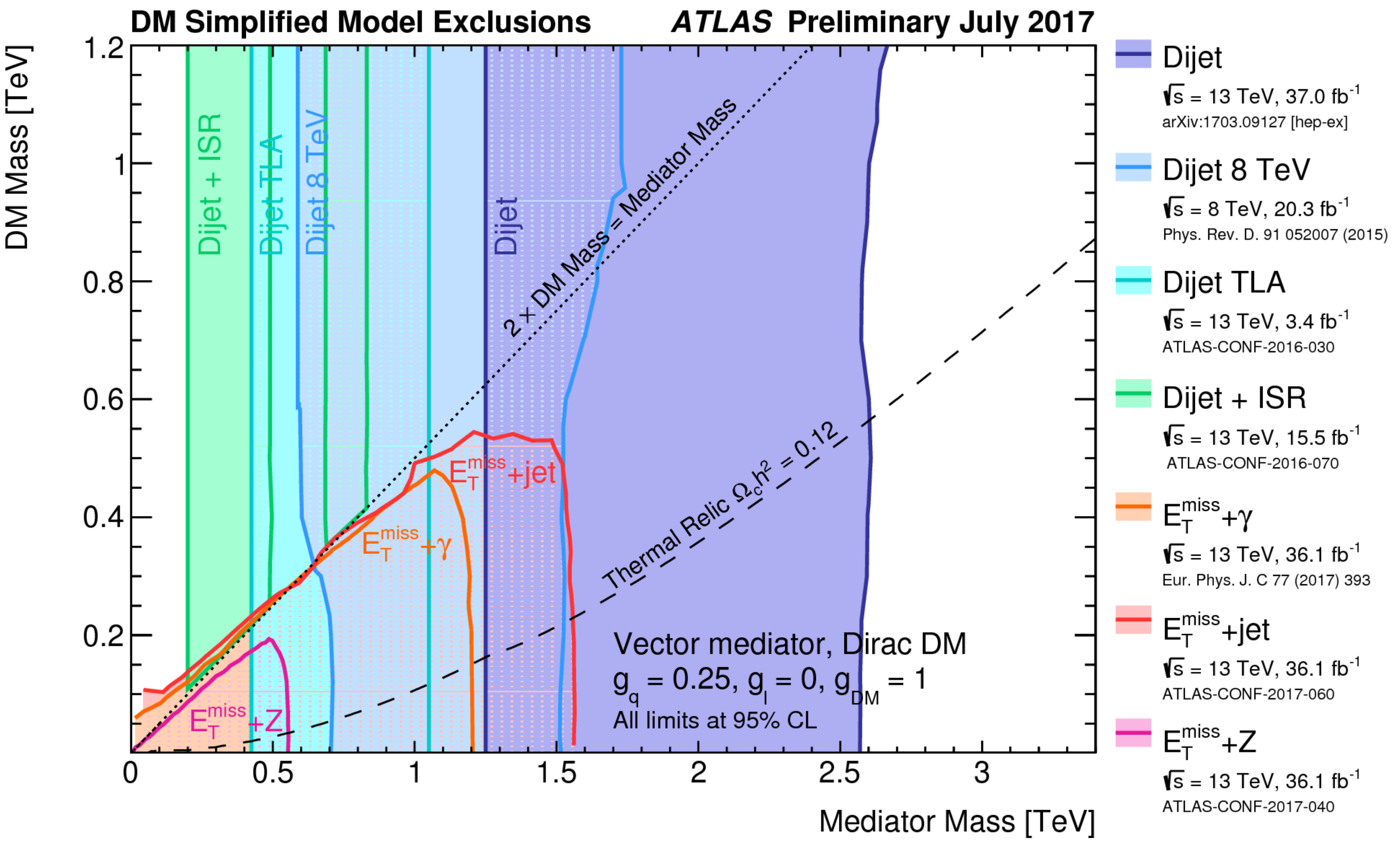


JHEP 10 (2017) 182

Model	Width [%]	θ_{E_6} [rad]	Lower limits on $M_{Z'}$ [TeV]					
			ee		$\mu\mu$		$\ell\ell$	
			Obs	Exp	Obs	Exp	Obs	Exp
Z'_{SSM}	3.0	-	4.3	4.3	4.0	3.9	4.5	4.5
Z'_{χ}	1.2	0.50 π	3.9	3.9	3.6	3.6	4.1	4.0
Z'_{S}	1.2	0.63 π	3.9	3.8	3.6	3.5	4.0	4.0
Z'_{I}	1.1	0.71 π	3.8	3.8	3.5	3.4	4.0	3.9
Z'_{η}	0.6	0.21 π	3.7	3.7	3.4	3.3	3.9	3.8
Z'_{N}	0.6	−0.08 π	3.6	3.6	3.4	3.3	3.8	3.8
Z'_{ψ}	0.5	0 π	3.6	3.6	3.3	3.2	3.8	3.7

The grand picture

- Can combine searches for DM signal (missing energy) and those for mediators to constrain allowed model parameter space



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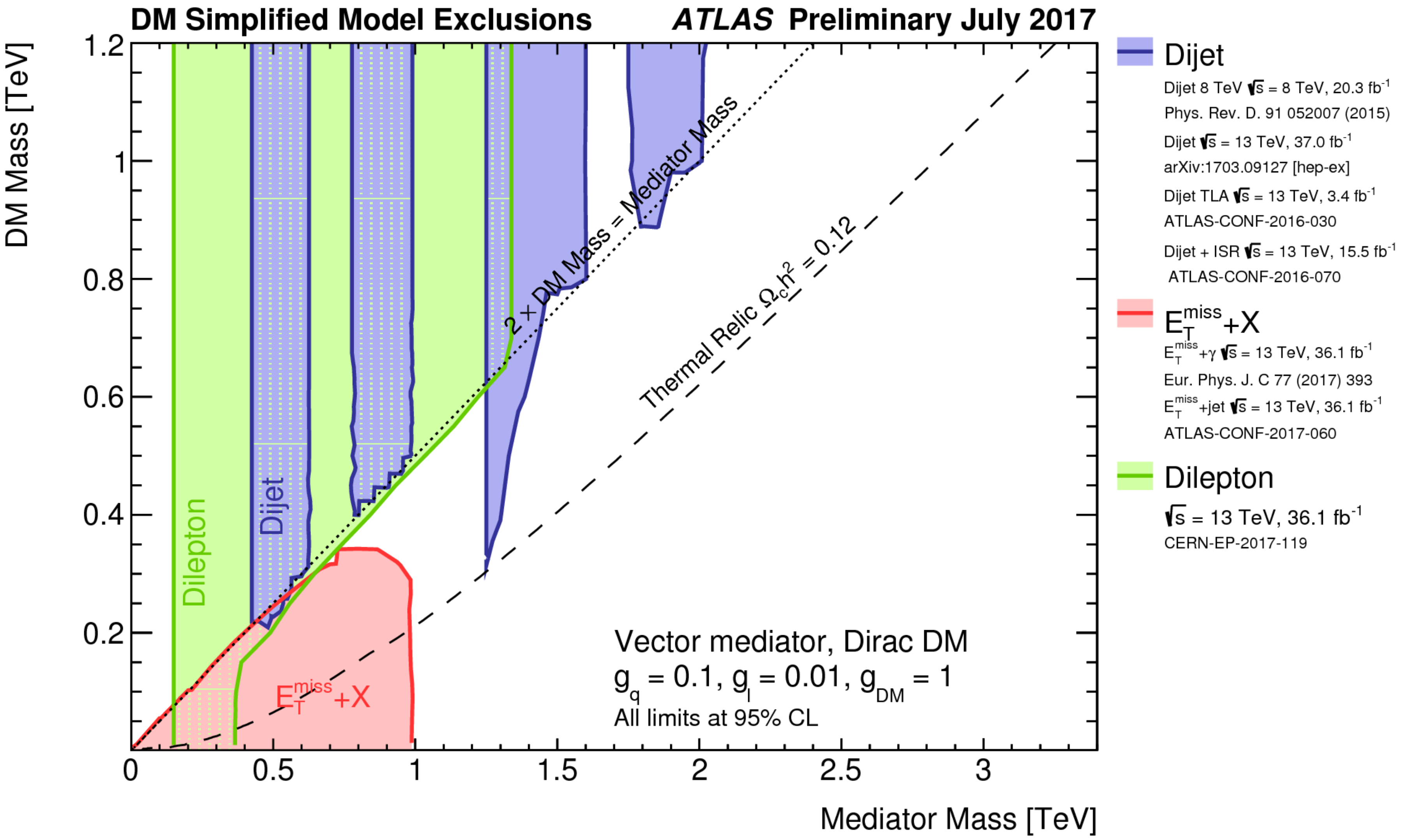
The grand picture

- Can combine searches for DM signal (missing energy) and those for mediators to constrain allowed model parameter space
- Exclusion strongly depends on choices for additional parameters, e.g., coupling to quarks but also leptons!



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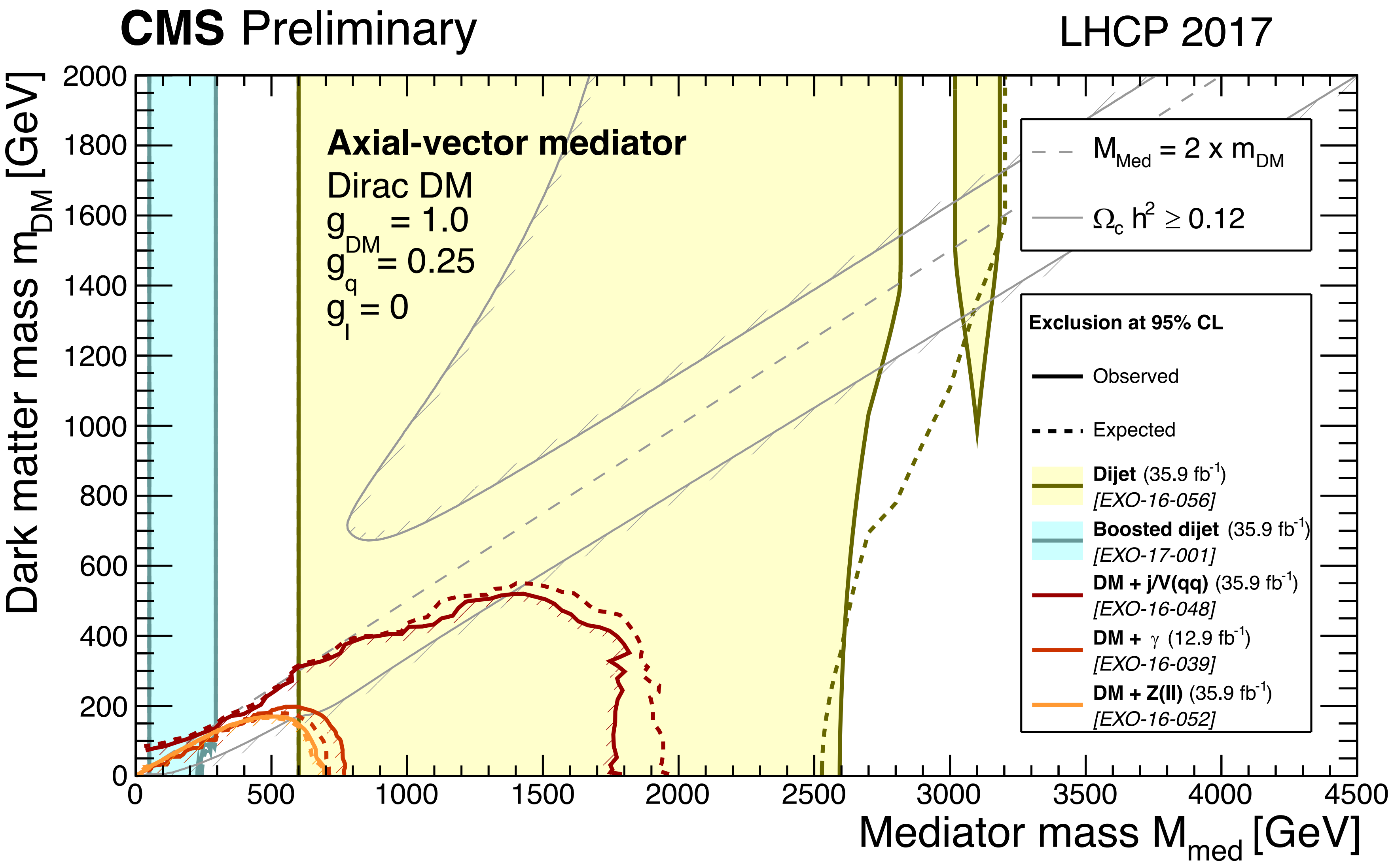

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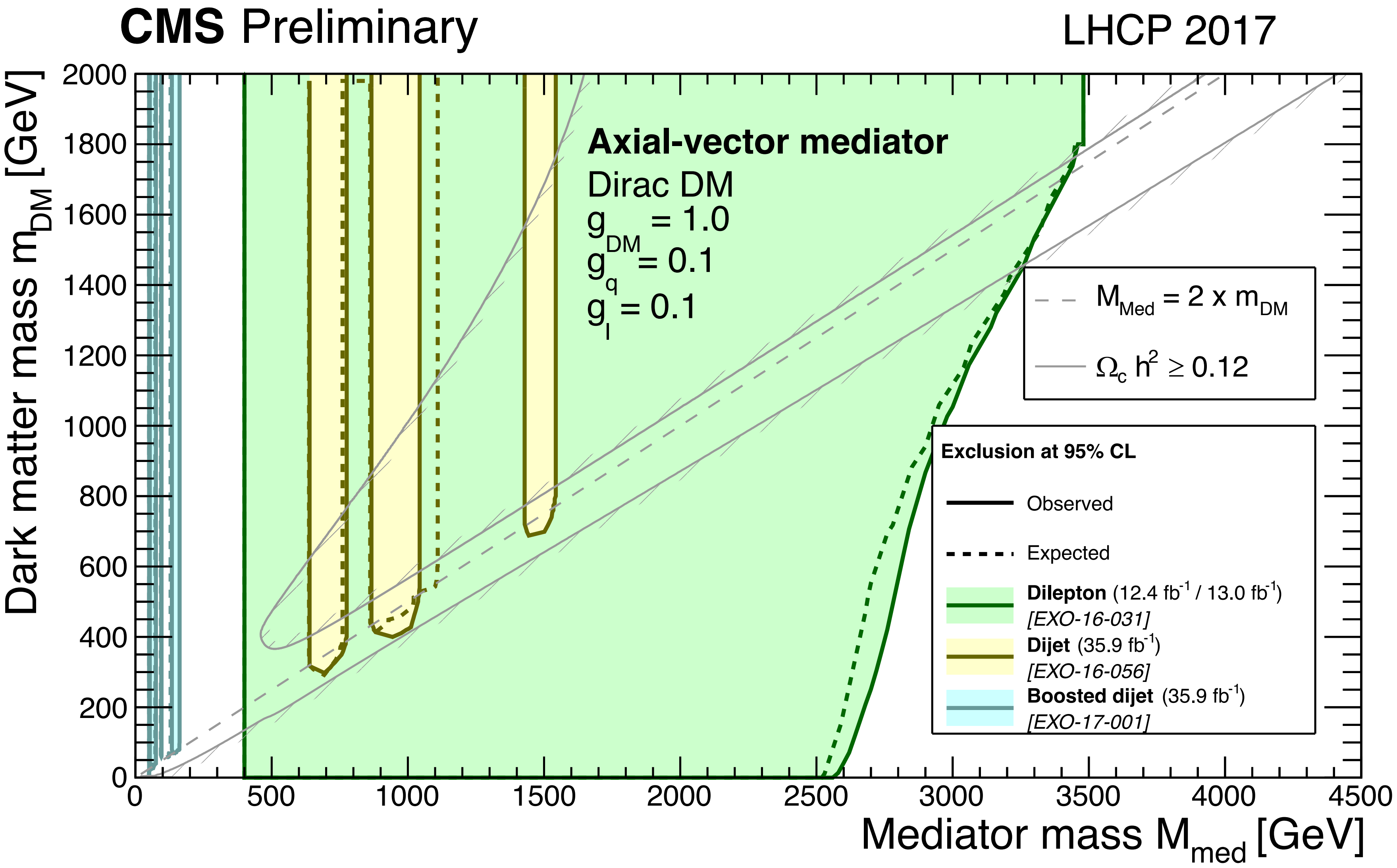
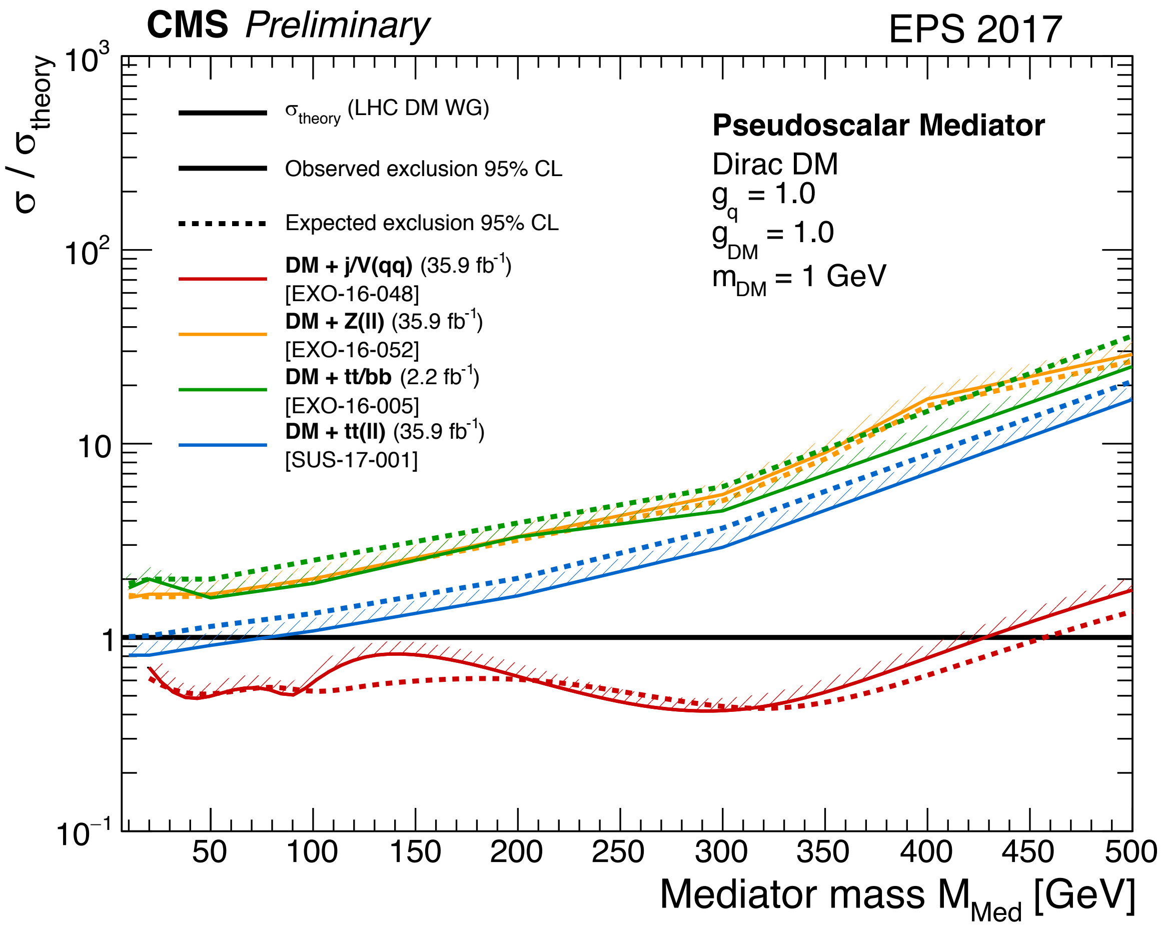
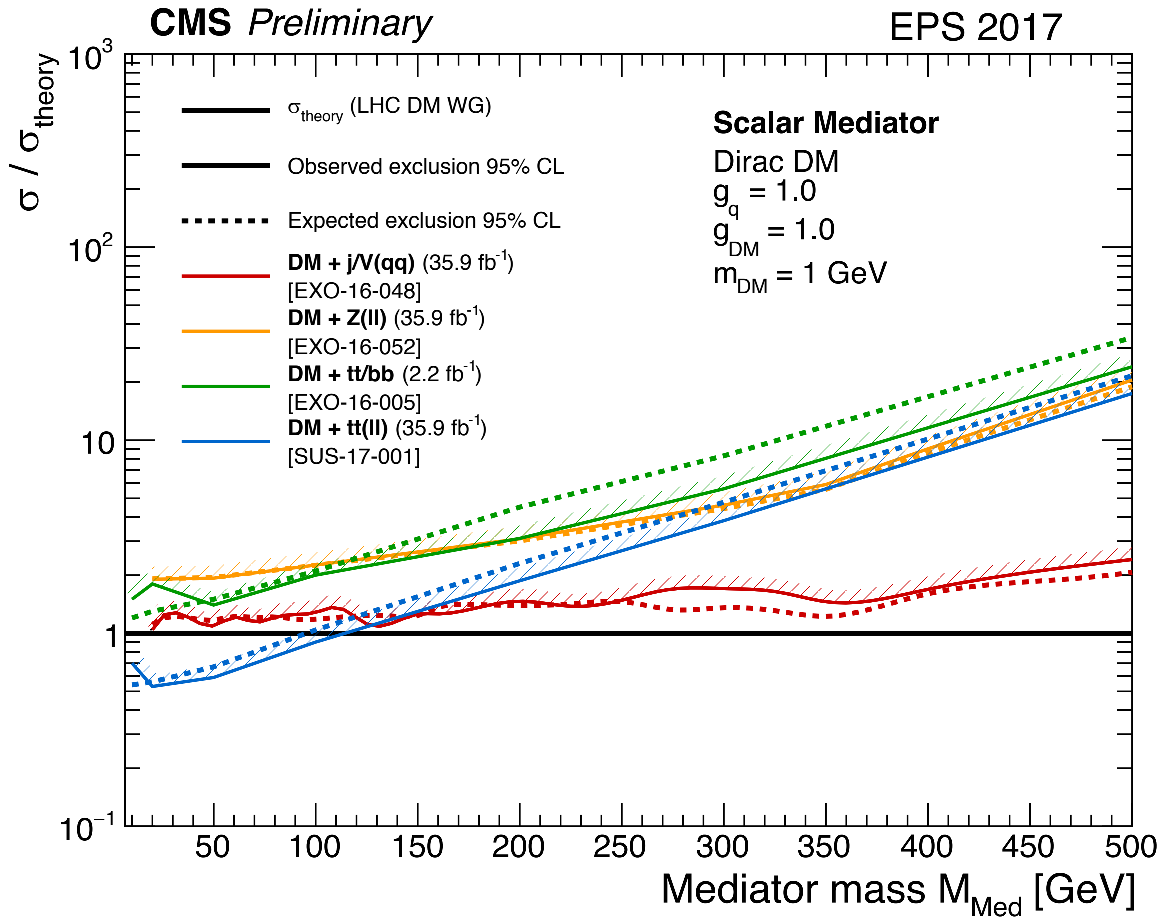


The grand picture

- Much weaker constraints on Scalar and Pseudo-Scalar mediators
- Exclusion only for very light DM and couplings $g_q = g_{DM} = 1$.

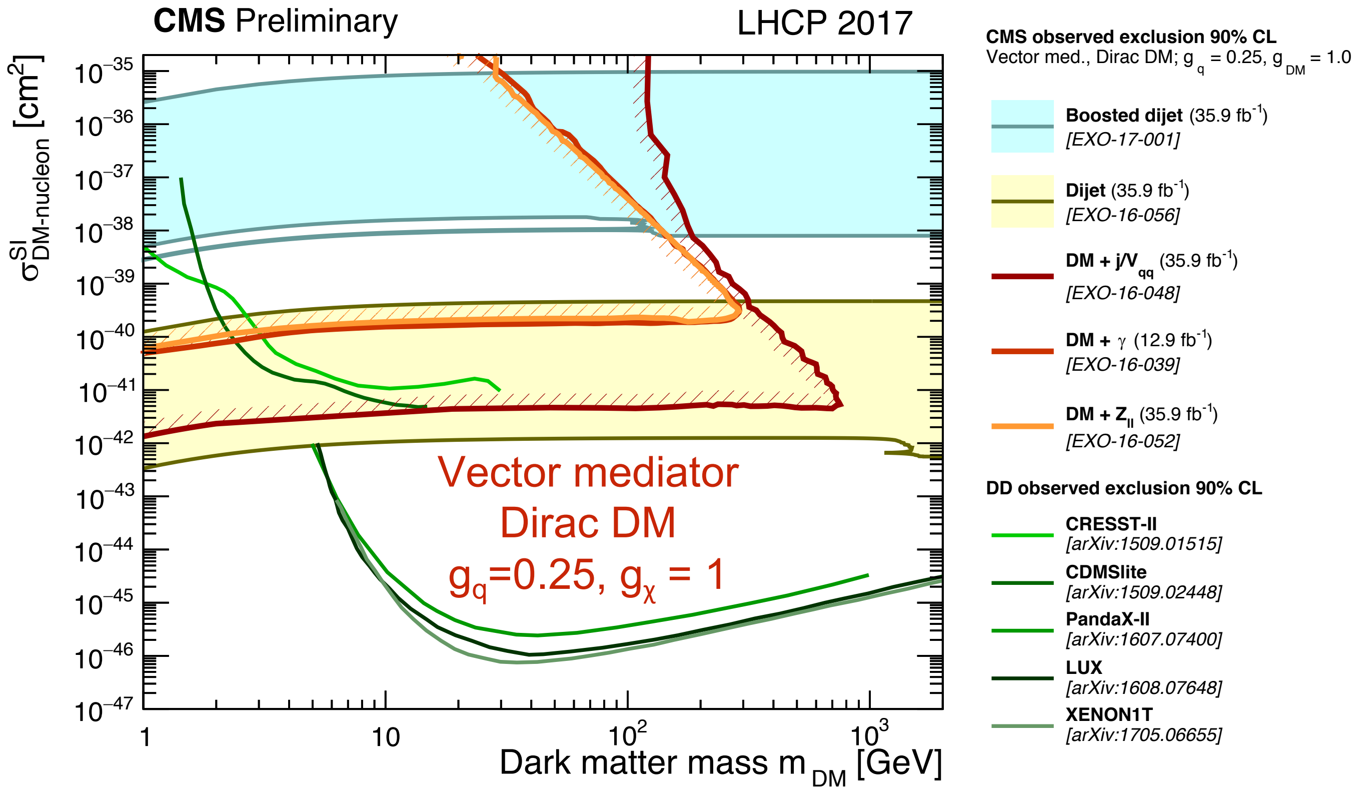




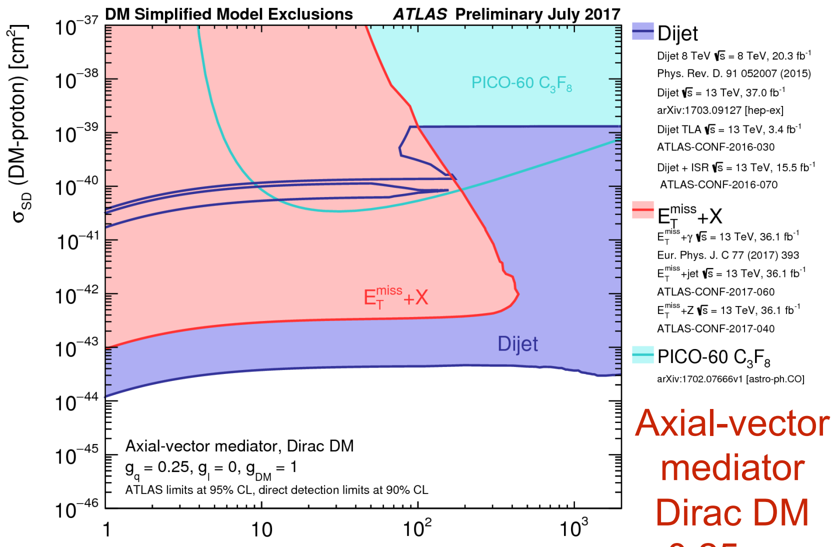
Comparison with Direct Detection

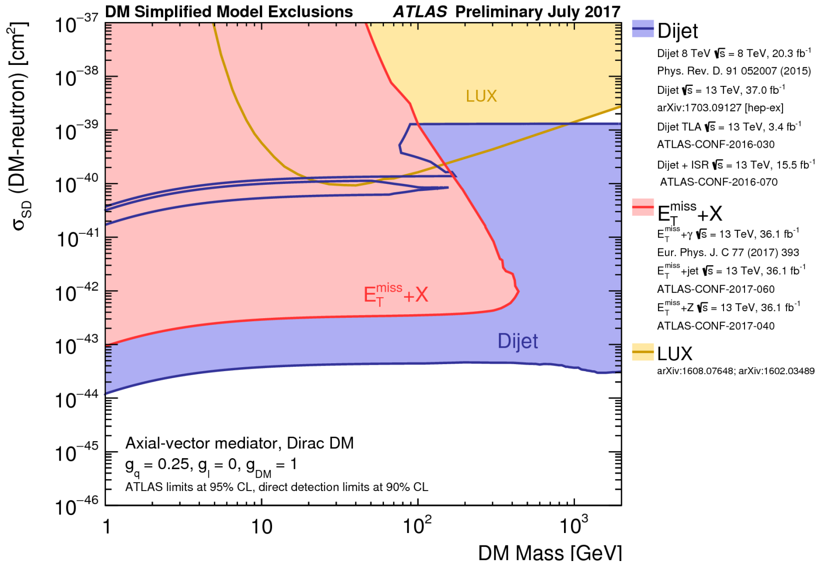
- Complementarity with Direct Detection clearly visible
- Sensitivity strongly depends on type of DM interaction
  - Can be used to learn about underlying physics in case one or the other sees a signal
- Collider searches more powerful for small DM masses

Spin-independent



Spin-dependent



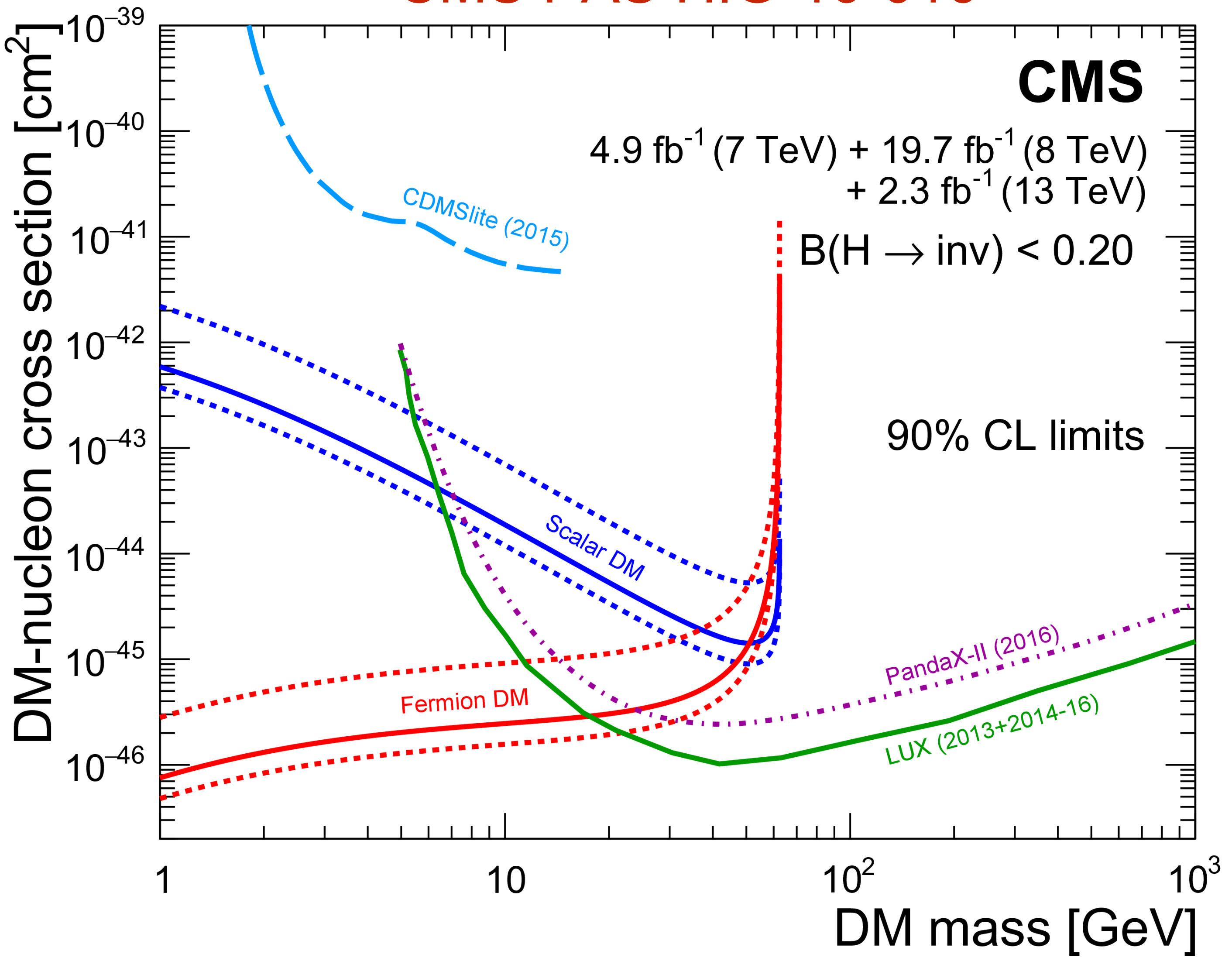


Axial-vector mediator
Dirac DM
$g_q=0.25$, $g_\chi = 1$

Comparison with Direct Detection

- Constraints on $B(H \rightarrow inv)$ can be translated to limits in scattering cross section vs DM mass plane to compare with direct detection experiments.
- Sensitive to masses < 0.5 m_H
- very sensitive at low DM masses

CMS PAS HIG-16-016



Pros and Cons: Collider vs Direct Detection

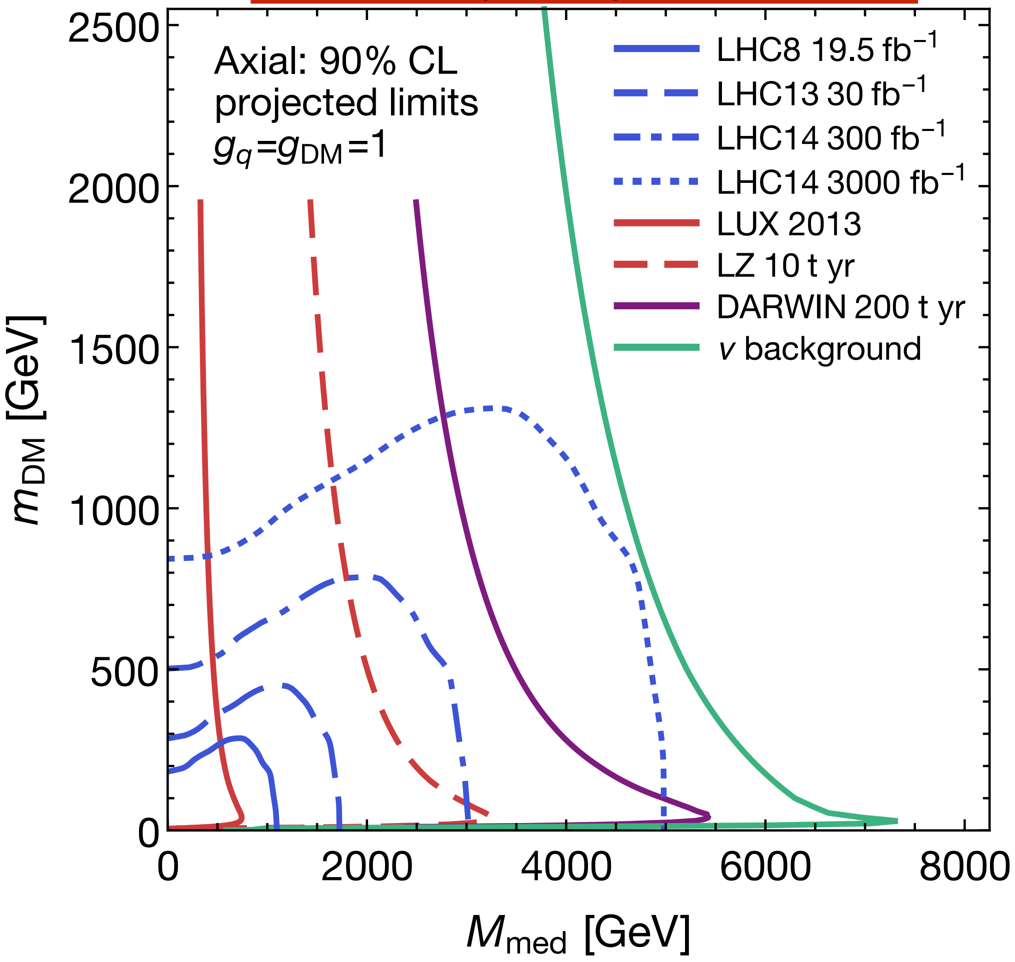
Wimp – Nucleon Interaction	
Spin-Independent (SI)	**Spin-Dependent (SD)**
Basic Mediators	
Vector *Besides low DM masses DD provides best sensitivity.* *Complementarity at low DM masses (<5 GeV)!*	**Axial-vector** *DD and collider are equal in overall sensitivity but probe different regions of parameter space!* *Complementarity in full parameter space!*
Scalar *Besides low DM masses DD provides best sensitivity.* *Complementarity at low DM masses (<5 GeV)!*	**Pseudoscalar** *Effectively no limits from DD above a few GeV in M_{med}, Collider and ID probe region at larger M_{med}.* *Complementarity in M_{med}!*

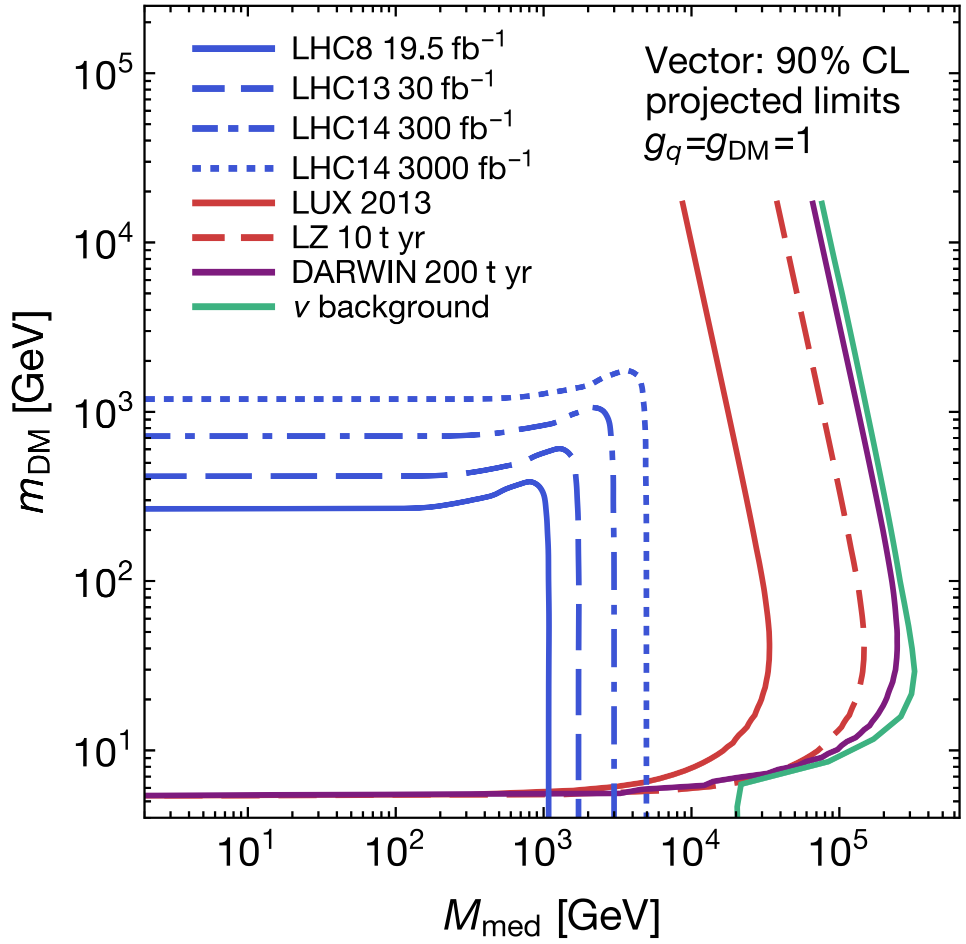
from
O. Buchmueller

Outlook – Where next?

Axial-Vector mediator
$g_q = g_\gamma = 1$

Vector mediator
$g_q = g_\gamma = 1$





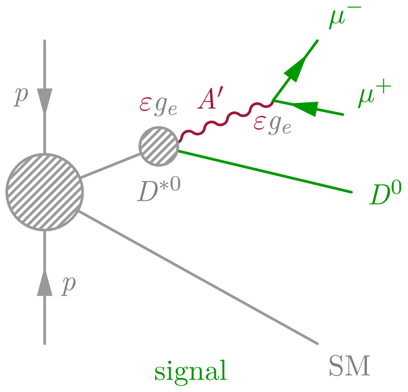
from arXiv:1409.4075, Phys.Dark Univ. 9-10 (2015) 51-58

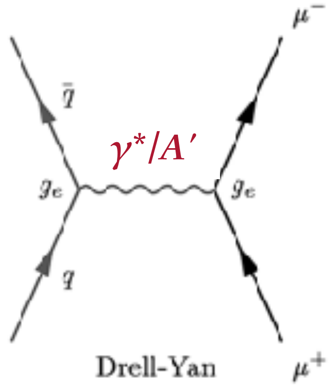
Dark Photon search @ LHCb

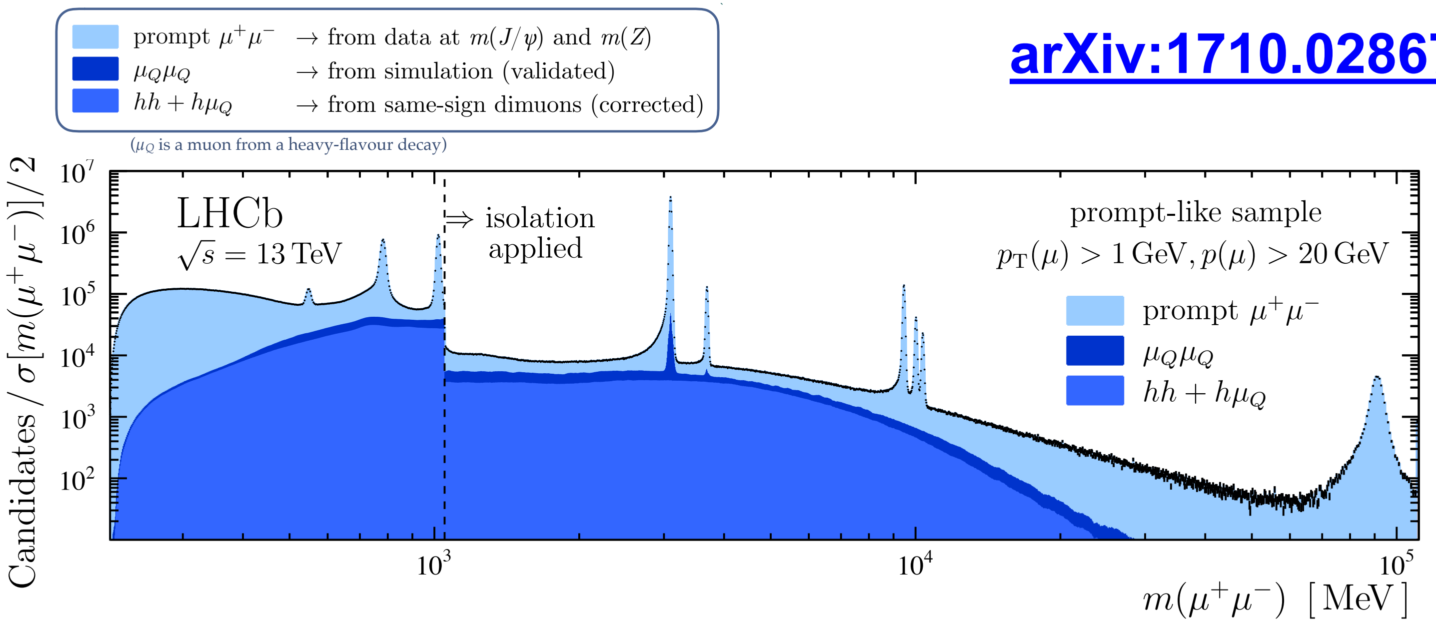
University of Bristol

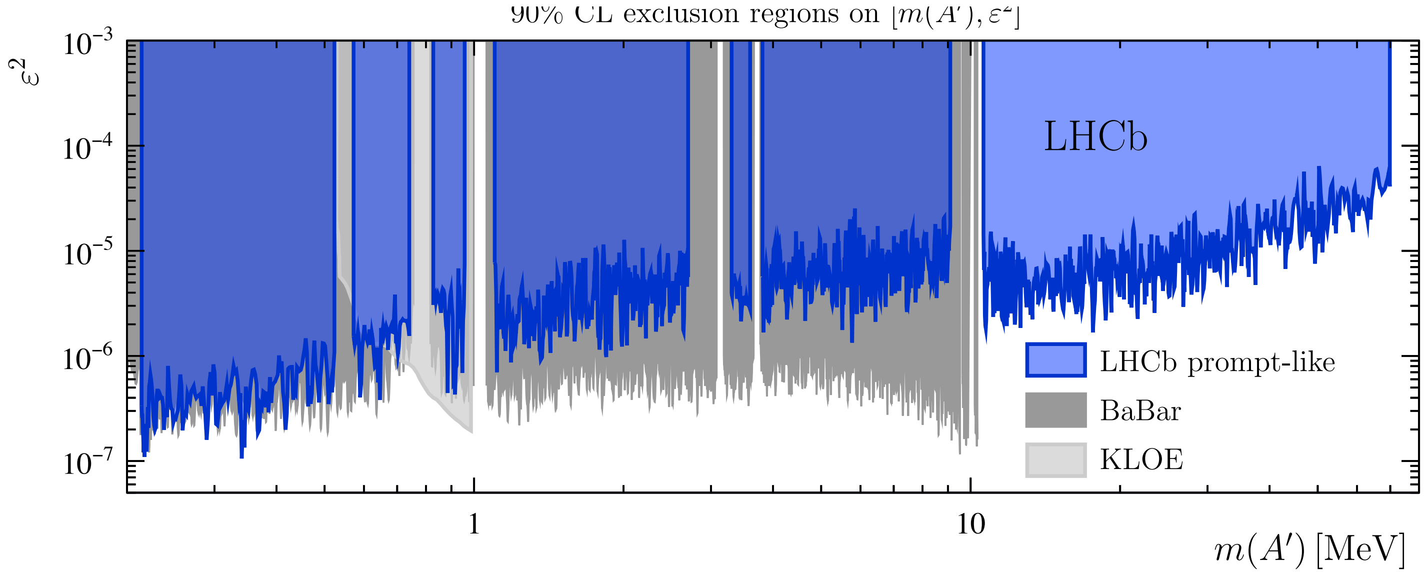
[arXiv:1710.02867](https://arxiv.org/abs/1710.02867)

- Assume a dark sector, a collection of particles that are not charged directly under the SM strong, weak, or electromagnetic forces.
- Dark photon, A′, whose coupling to the electromagnetic current is suppressed relative to that of the ordinary photon, γ, by a factor of ε
- Dark Photon would also couple to DM
- Search for Dark Photon decay to di-muon pair in meson decays









Summary

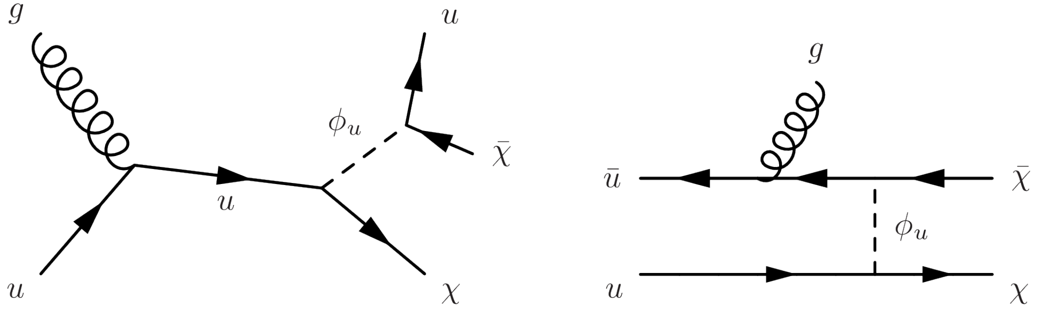
- Comprehensive search programme for dark matter is underway at LHC
- So far focused on WIMP signatures
  - Guidance from simplified Dark Matter models
  - Search strategy includes searching for DM production but also for mediators that couple to both SM and DM
- Long-lived signatures to be added to search portfolio
- Extend searches beyond WIMP signatures

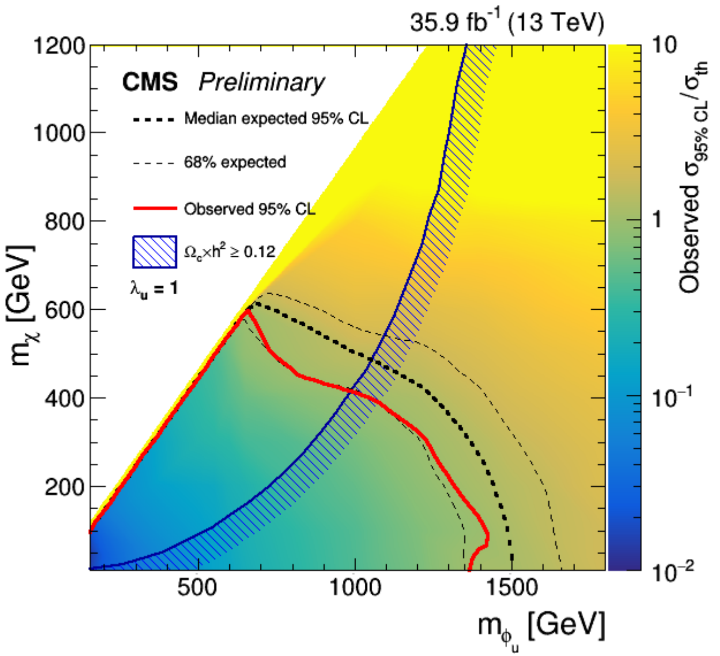
- DM searches @ LHC a powerful tool
  - In particular sensitivity to small DM masses
  - Sensitivity strongly depends on assumptions made for DM interaction, spin structure of mediator and coupling strength
  - In many ways complementary to direct detection searches
  - This could be crucial for understanding the underlying physics in case of a signal from either approach

- Backup

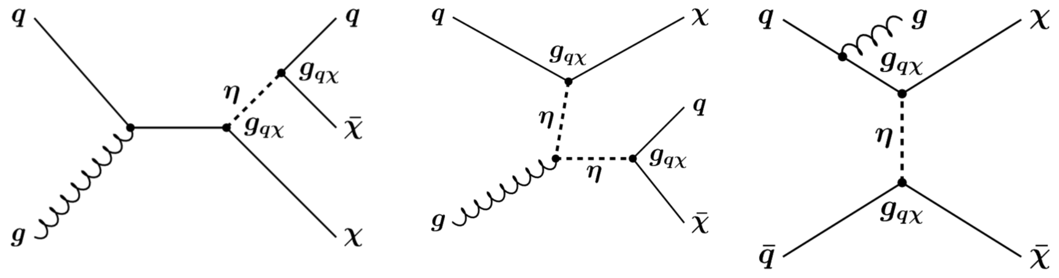
Mono-jet & Mono-V Searches

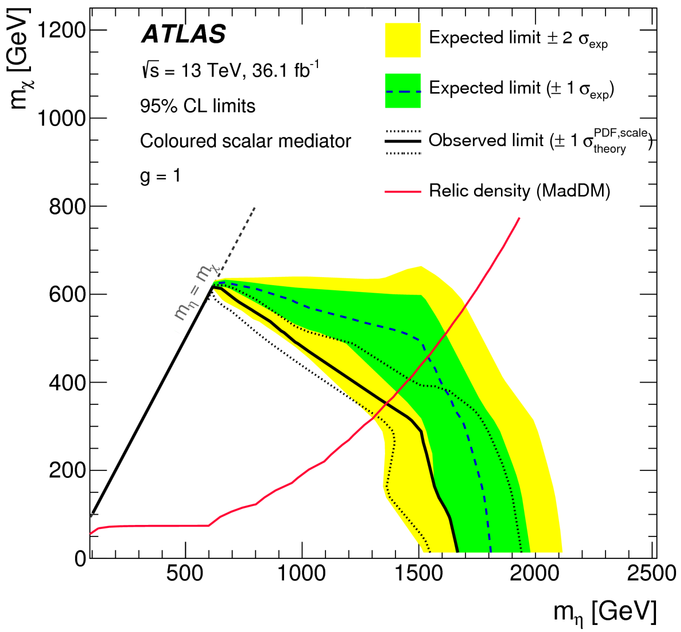
- Interpretation in simplified DM models
- Fermion portal models





- Interpretation in simplified DM models
- Coloured scalar mediator models



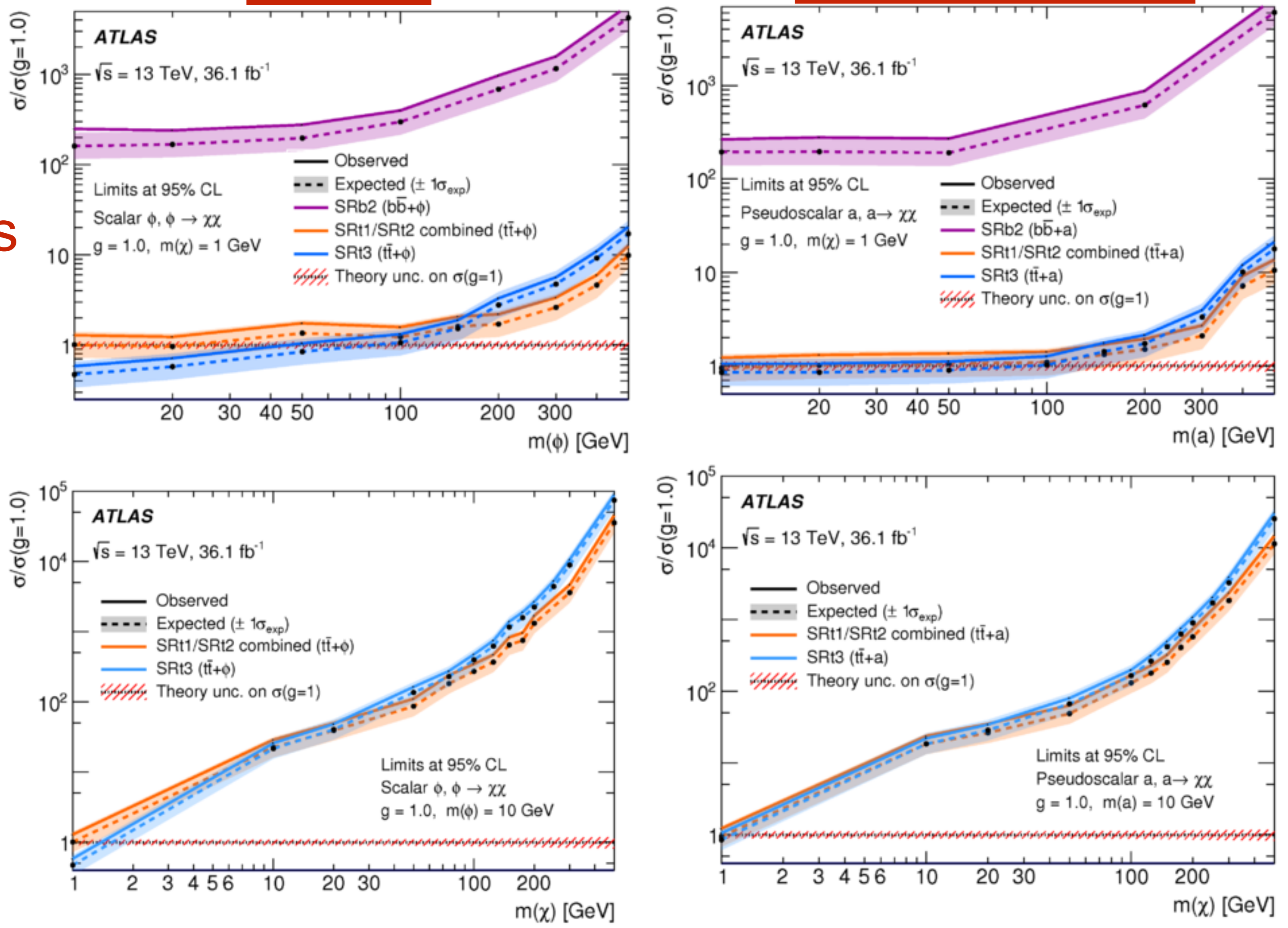


DM in association with heavy flavours

- Interpretation in colour-neutral $t\bar{t}/b\bar{b}+\varphi$ scalar and $t\bar{t}/b\bar{b}+a$ pseudoscalar models
  - Fixed DM mass
  - Limit as fcn of mediator mass
  - Fixed mediator mass
  - Limit as fcn of DM mass
- Not yet sensitive to bb + φ/a production

Scalar

Pseudo-Scalar



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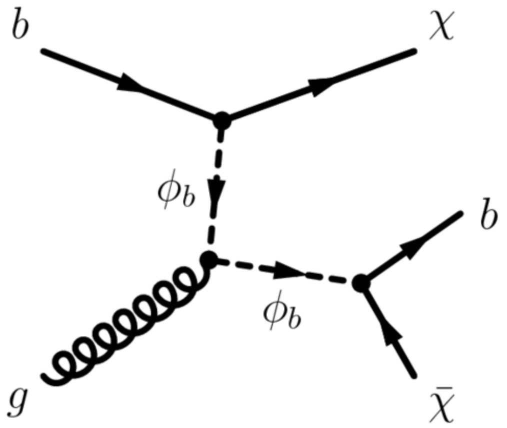
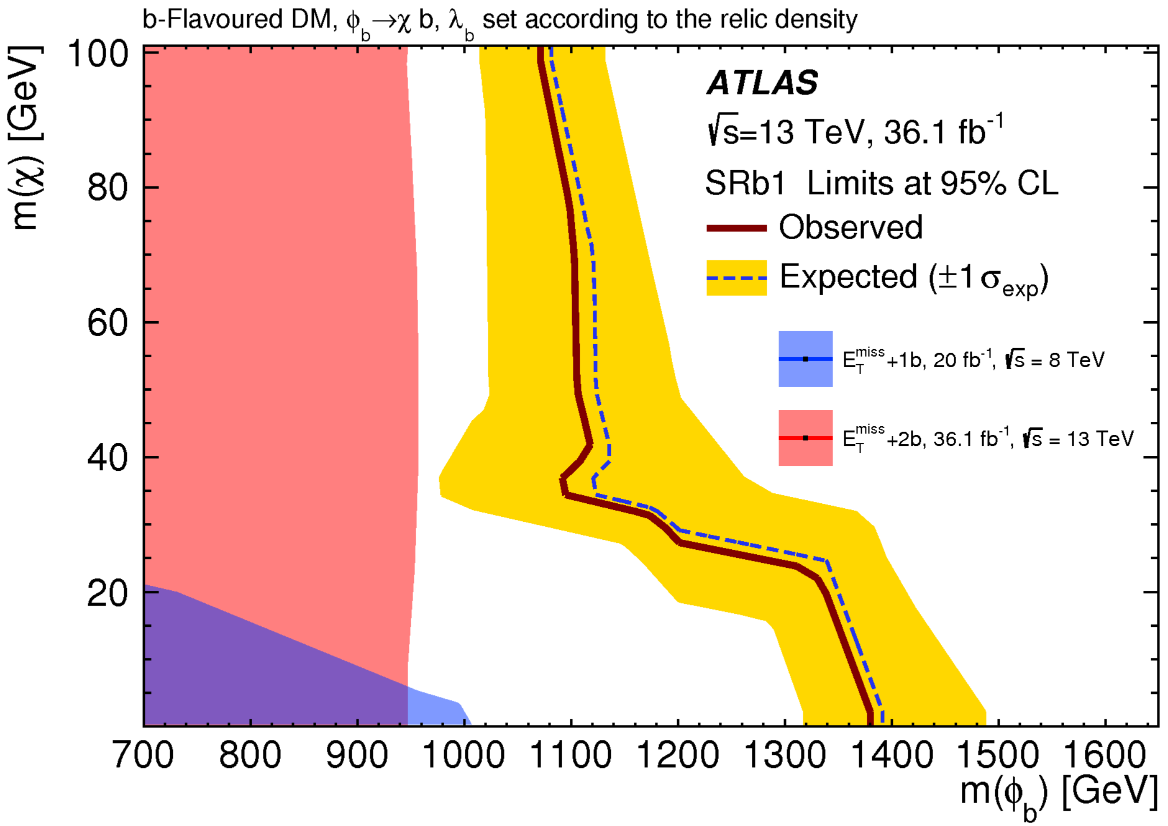
DM in association with heavy flavours

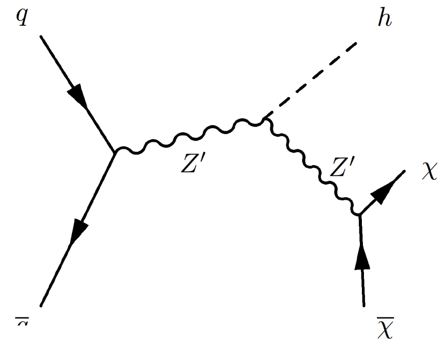
- colour-charged scalar mediators (b-FDM)

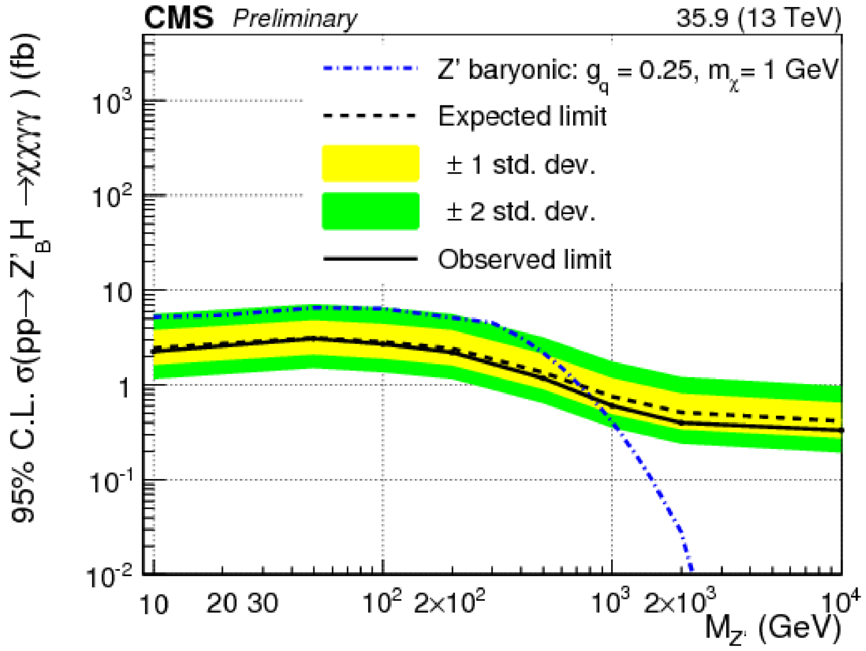




Mono-Higgs

- Higgs production in conjunction with DM
  - Higgs decay to γγ





CMS-PAS-EXO-16-054

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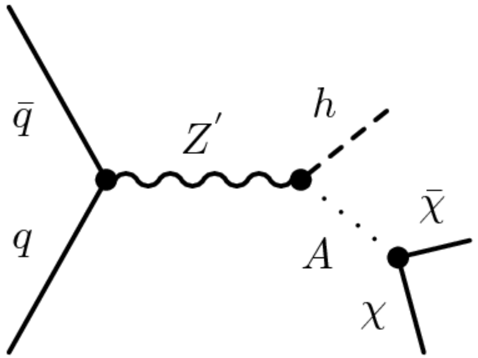
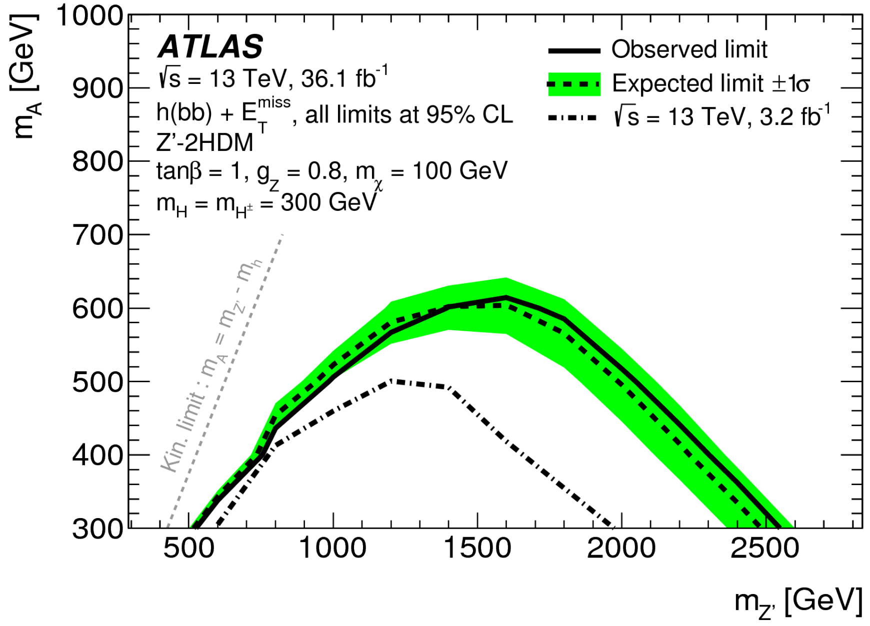
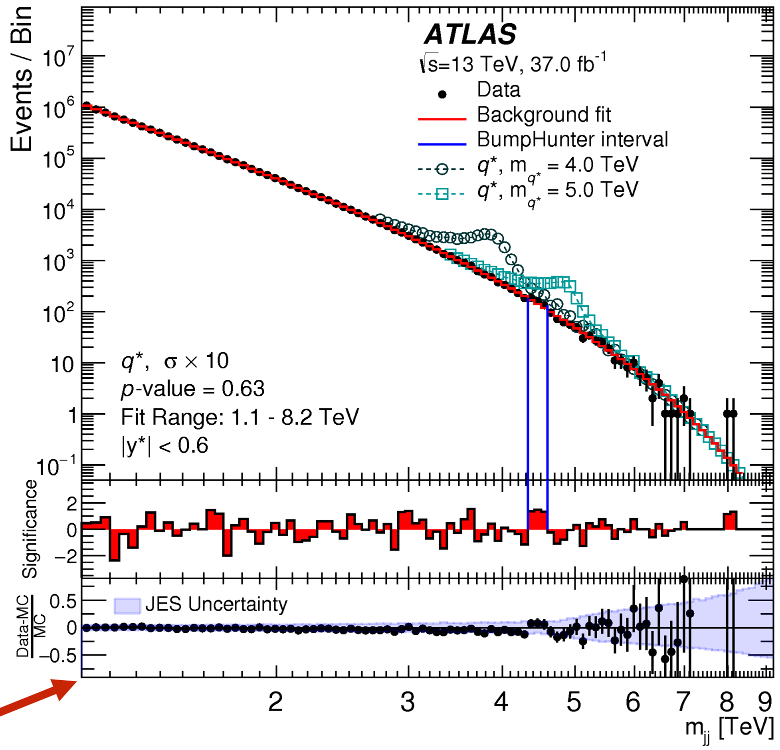




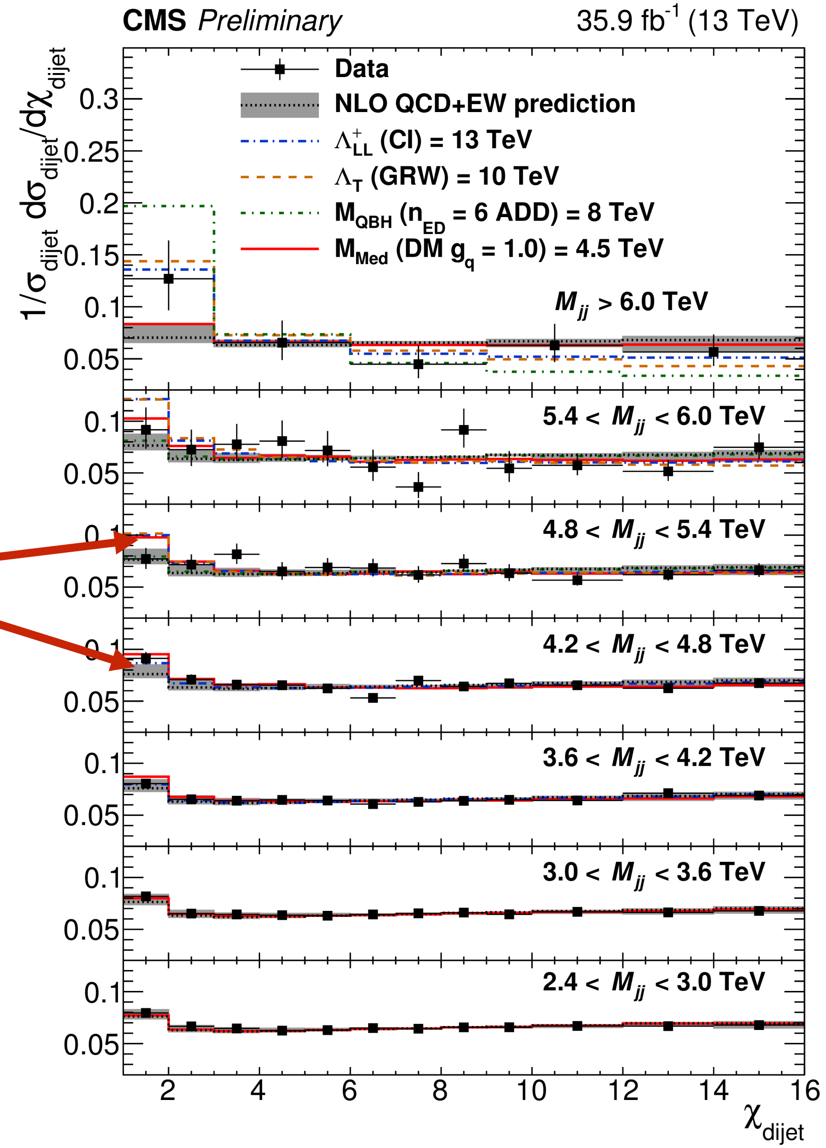
Phys. Rev. Lett. 119 (2017) 181804

High-mass dijet resonances

- Search for resonance in dijet invariant mass spectrum



1 TeV



DM mediator would show up here

- ”bump hunt” not effective for very wide resonances
- Investigate di-jet scattering angle in this case

Comparison with Direct Detection

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- Sensitivity strongly depends on type of DM interaction
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- Collider searches more powerful for small DM masses