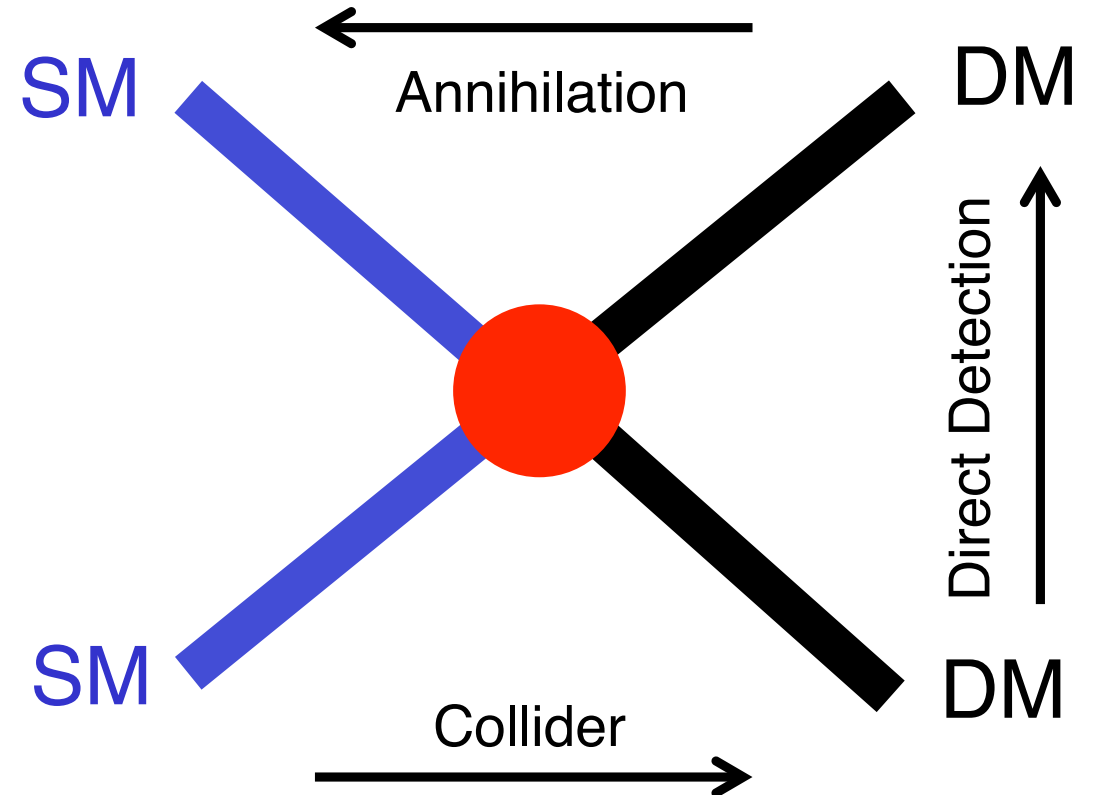


Dark Matter searches at the LHC

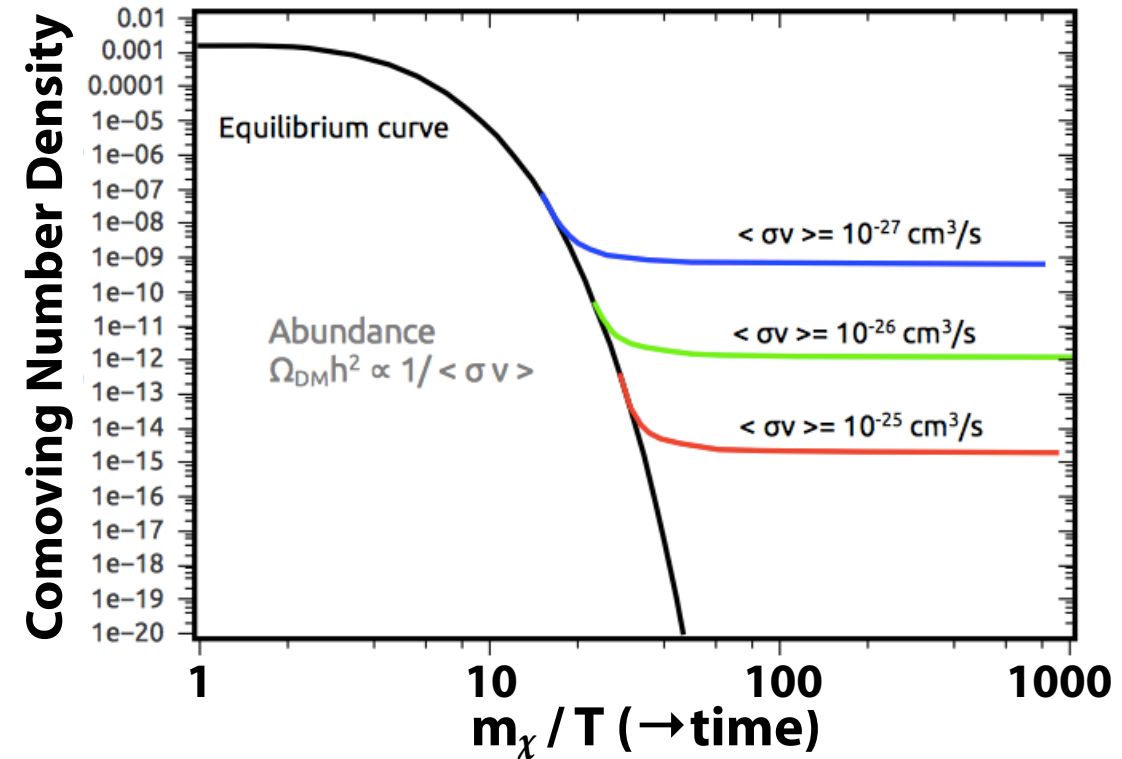
Henning Flücher
H.H. Wills Physics Laboratory
University of Bristol

DM UK Meeting, Bristol – 17 Jan 2018

- 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?



- 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”

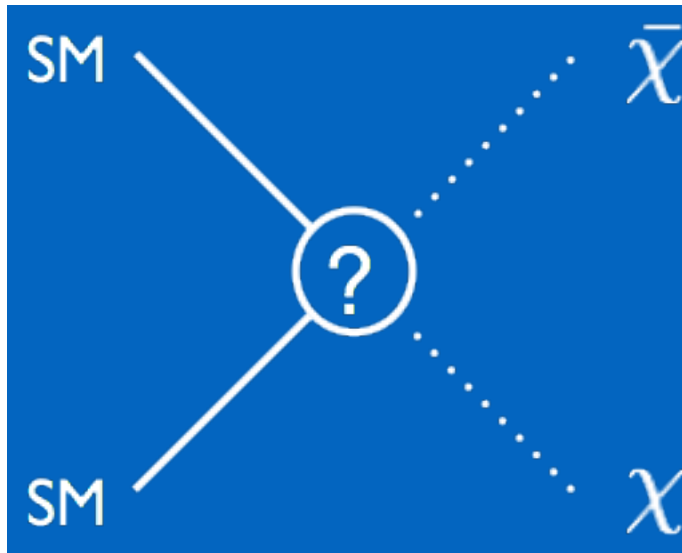


$$\Omega_{\chi} h^2 \simeq 0.1 \times \left(\frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle} \right)$$

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

What interactions to probe?

- Start with minimal assumptions
 - Effective Field Theories



- Simplified models
 - Resolve the interaction



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

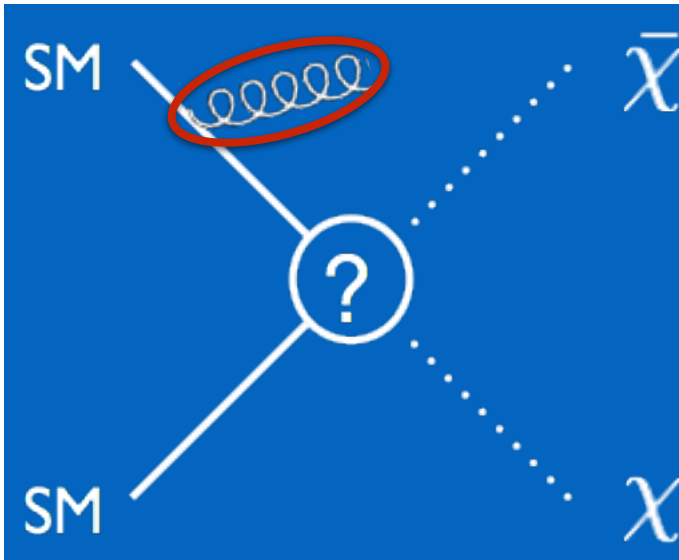
- Need to be careful at LHC @ 13 TeV
- EFT only valid if $Q^2 \ll M$

- Come with different assumptions for interactions/mediators

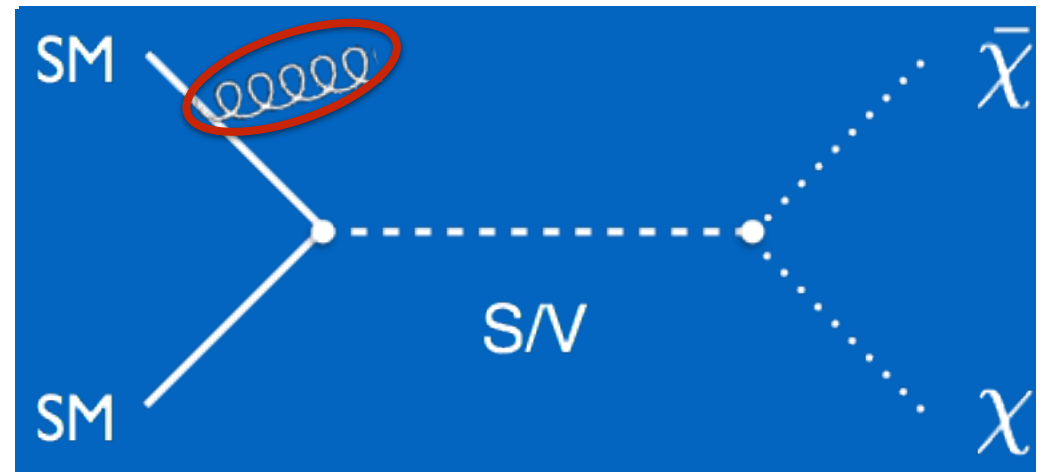
- scalar ($\psi\psi$)
- pseudo scalar ($\psi\gamma^5\psi$)
- vector $\psi\gamma^\mu\psi$,
- axial-vector ($\psi\gamma^\mu\gamma^5\psi$)

What interactions to probe?

- Start with minimal assumptions
 - Effective Field Theories



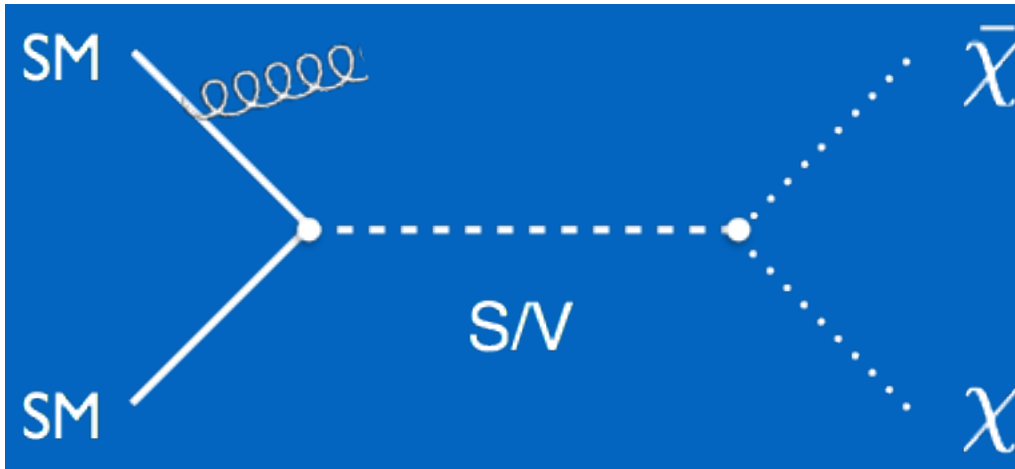
- Simplified models
 - Resolve the interaction



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, $m_{\text{med}}, \Gamma_{\text{med}}$
- 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
 - $X = \text{jet, photon, W, Z, H, ...}$
- Resonant production of mediator particle and decay back to SM particles
 - di-jet, di-lepton, di-top, ... resonances

- 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

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

August 8, 2016

Daniel Abercrombie *MIT, USA*
 Nural Akchurin *Texas Tech University, USA*
 Ece Akilli *Université de C*
 Juan Alcaraz Maestre *Ce*
(CIEMAT), Spain
 Brandon Allen *MIT, USA*
 Barbara Alvarez Gonzalez
 Jeremy Andrea *Institut P*
Université de Strasbourg
 Alexandre Arbey *Univers*
Ecole Normale Supérieure
 Georges Azuelos *Univer*
 Patrizia Azzi *INFN Padova*
 Mihailo Backović *Centre*
catholique de Louvain, B
 Yang Bai *Department of*
 Swagato Banerjee *Unive*
 James Beacham *Ohio St*
 Alexander Belyaev *Ruthe*
dom
 Antonio Boveia (editor) *C*
 Amelia Jean Brennan *Th*
 Oliver Buchmueller *Impe*
 Matthew R. Buckley *Dep*
 Giorgio Busoni *SISSA ar*
 Michael Buttignol *Institut*
Université de Strasbourg
 Giacomo Cacciapaglia *U*
France
 Regina Caputo *Santa Cr*
of Astronomy and Astrop
 Linda Carpenter *Ohio St*
 Nuno Filipe Castro *LIP-IN*
Ciências da Universidadi
 Guillermo Gomez Ceballos
 Yangyang Cheng *Univer*
 John Paul Chou *Rutgers*
 Arelly Cortes Gonzalez *IF*

arXiv:1507.00966v1 [hep-ex] 3 Jul 2015

arXiv:1603.04156v1 [hep-ex] 14 Mar 2016

CERN-LPCC-2016-001

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s -channel models of dark matter

Antonio Boveia,^{1,*} Oliver Francesco D'Eramo,⁴ Alberto Caterina Doglioni,^{7,*} Matt Kristian Hahn,^{9,*} Ulrich H. Jan Heisig,¹² Valerio Ippo Valentin V. Khoze,¹⁵ Sudhakar Steven Lowette,¹⁸ Sarah I Christopher McCabe,^{19,*} Tristan du Pree,¹ Antonio Kai Schmidt-Hoberg,¹⁴ W Lian-Tao Wang,²⁵ Steven

*Editor
¹CERN, EP Department, CH-1211
²High Energy Physics Group, Black London, SW7 2AZ, United Kingd
³ARC Centre of Excellence for Pa
 versity of Melbourne, 3010, Austr
⁴UC, Santa Cruz and UC, Santa C
⁵Antwerp University, B2610 Wilrij
⁶SISSA and INFN Sezione di Tries
⁷Fysiska institutionen, Lunds univ
⁸LPSC, Université Grenoble-Alpes
⁹Department of Physics and Astron
 USA
¹⁰Rudolf Peierls Centre for Theoret
 United Kingdom

arXiv:1703.05703v2 [hep-ex] 17 Mar 2017

CERN-LPCC-2017-01

Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels

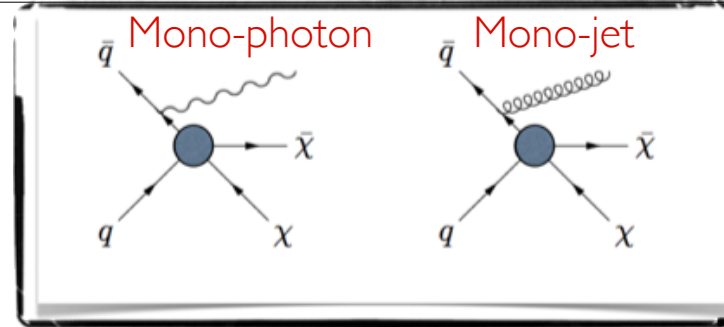
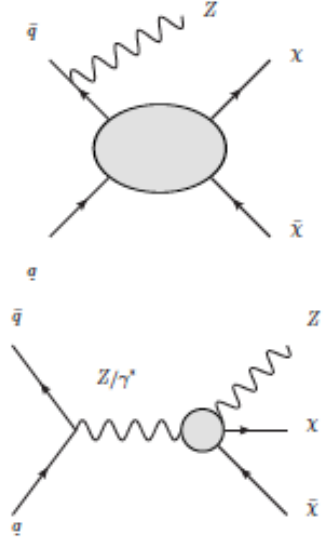
Andreas Albert,^{1,*} Mihailo Backović,² Antonio Boveia,^{3,*} Oliver Buchmueller,^{4,*} Giorgio Busoni,^{5,*} Albert De Roeck,^{6,7} Caterina Doglioni,^{8,*} Tristan DuPree,^{9,*} Malcolm Fairbairn,^{10,*} Marie-Hélène Genest,¹¹ Stefania Gori,¹² Giuliano Gustavo, ¹³ Kristian Hahn,^{14,*} Ulrich Haisch,^{15,16,*} Philip C. Harris,⁷ Dan Hayden,¹⁷ Valerio Ippolito,¹⁸ Isabelle John,⁸ Felix Kahlhoefer,^{19,*} Suchita Kulkarni,²⁰ Greg Landsberg,²¹ Steven Lowette,²² Kentarou Mawatari,¹¹ Antonio Riotto,²³ William Shepherd,²⁴ Tim M.P. Tait,^{25,*} Emma Tolley,³ Patrick Tunney,^{10,*} Bryan Zaldivar,^{26,*} Markus Zinser²⁴

*Editor
¹III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
²Center for Cosmology, Particle Physics and Phenomenology - CP3, Université Catholique de Louvain, Louvain-la-neuve, Belgium
³Ohio State University, 191 W. Woodruff Avenue Columbus, OH 43210
⁴High Energy Physics Group, Blackett Laboratory, Imperial College, Prince Consort Road, London, SW7 2AZ, United Kingdom
⁵ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, Uni-

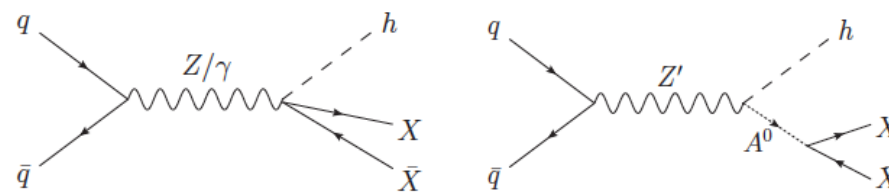
Simplified Dark Matter models

Mono-mania @ the LHC...

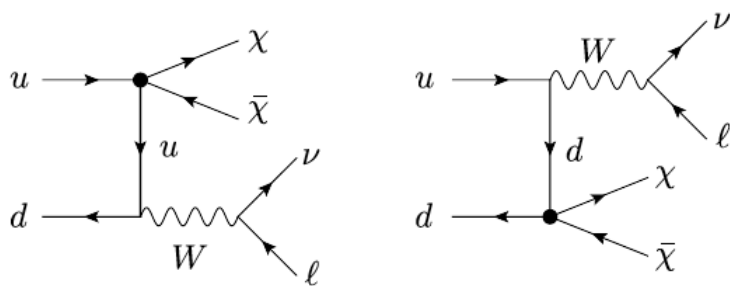
Mono-Z



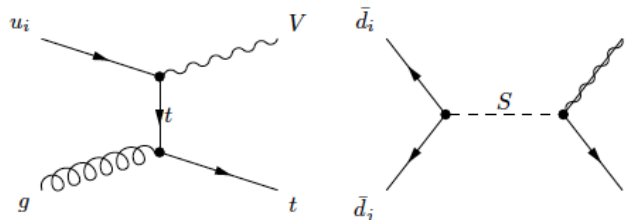
Mono-Higgs



Mono-W



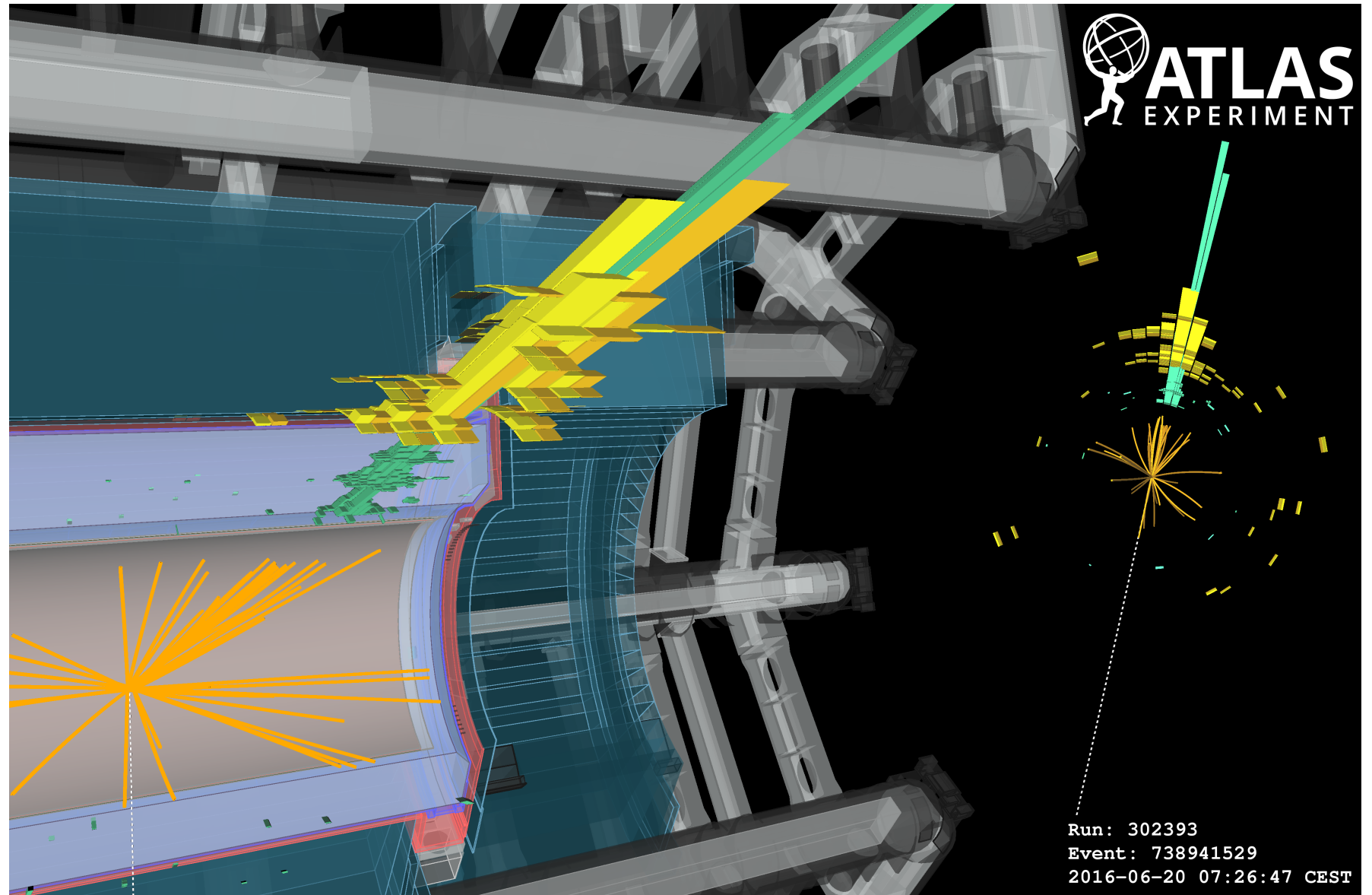
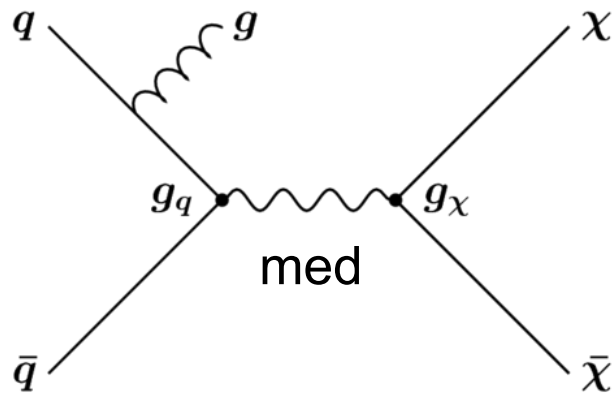
Mono-top



... complemented by searches for “full”, UV-complete models, such as

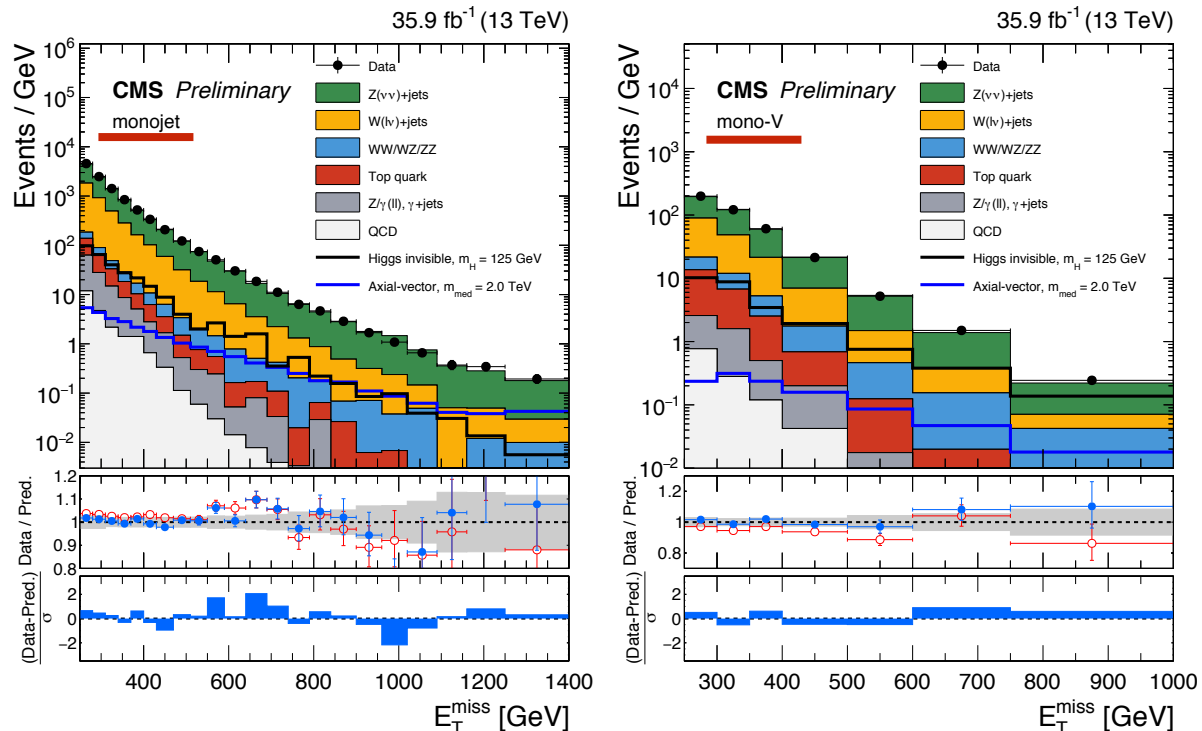
- Supersymmetry
 - Kaluza-Klein extra dimensions
 - Little Higgs models
 - etc.
- ...and of course there are also other DM candidates but this talk will mainly focus on WIMPs

Mono-mania



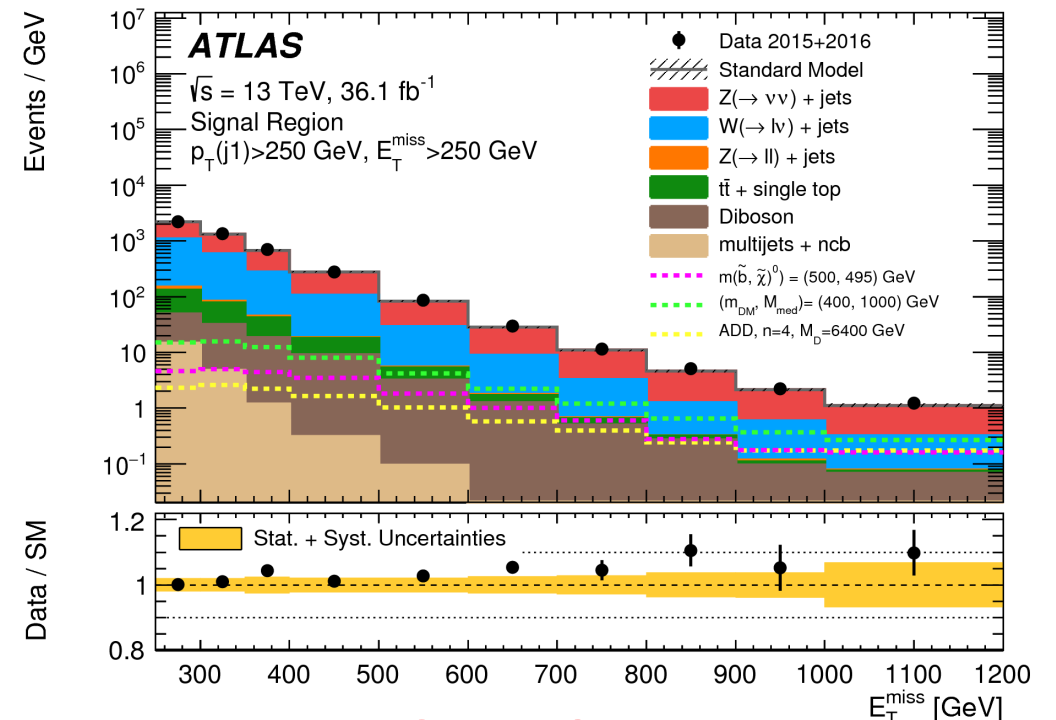
Mono-jet & Mono-V Searches

- Search for jets with missing energy
 - Jets or boosted vector bosons (W,Z)
- Comparison of data with background prediction



CMS EXO-16-048

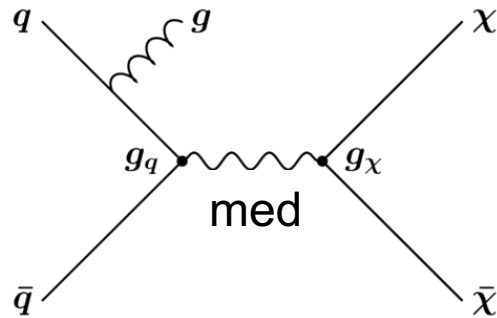
- Main background from $Z \rightarrow \nu\nu + \text{jets}$ and $W + \text{jets}$ production



ATLAS EXOT-2016-27

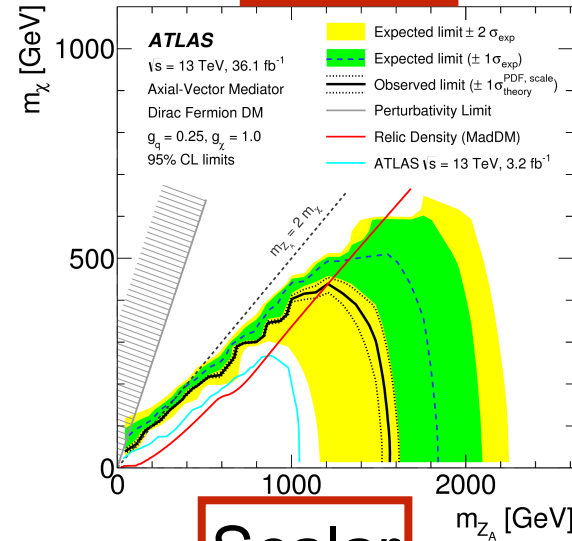
Mono-jet & Mono-V Searches

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

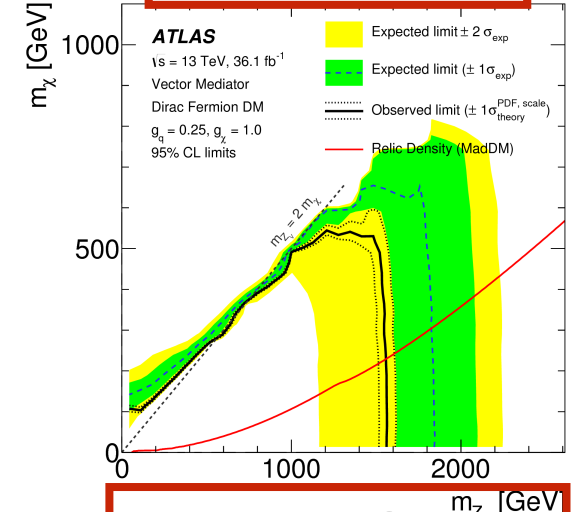


- Set limits on allowed masses and coupling strength (next slide)
- Further interpretations in
 - fermion portal models
 - coloured scalar mediator models
 - nonthermal dark matter model

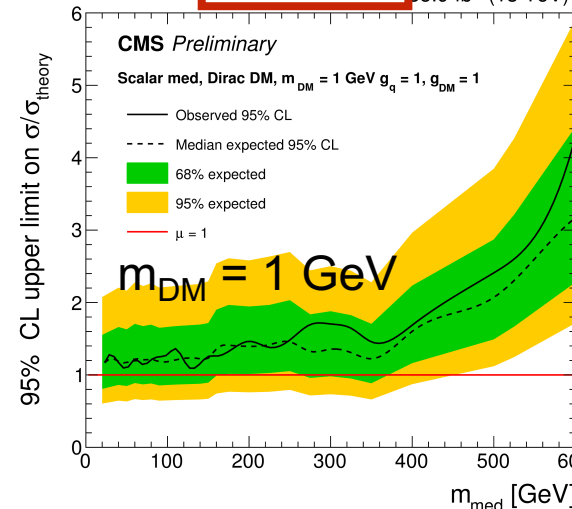
Vector



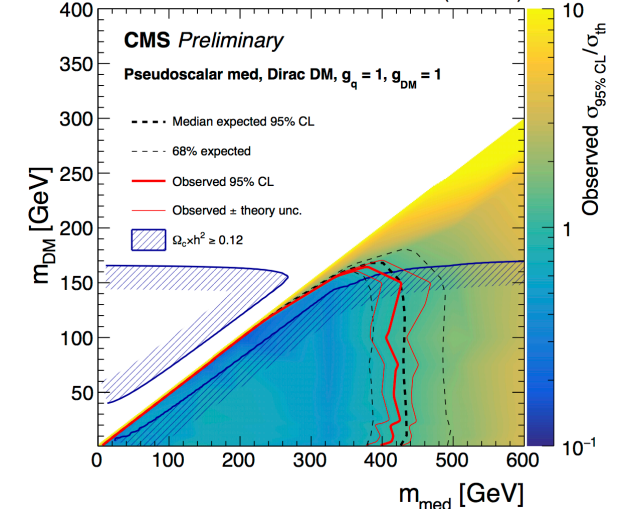
Axial-Vector



Scalar

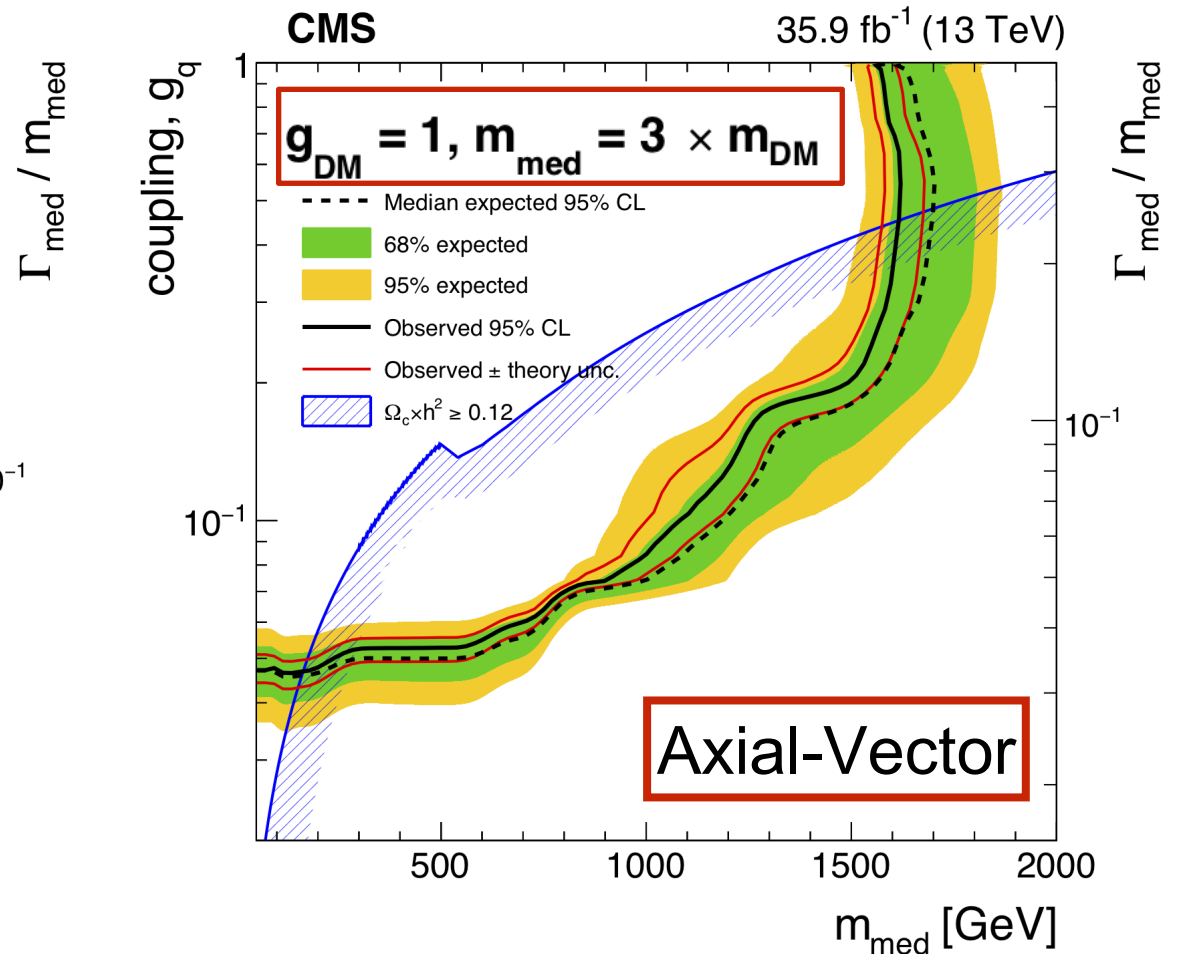
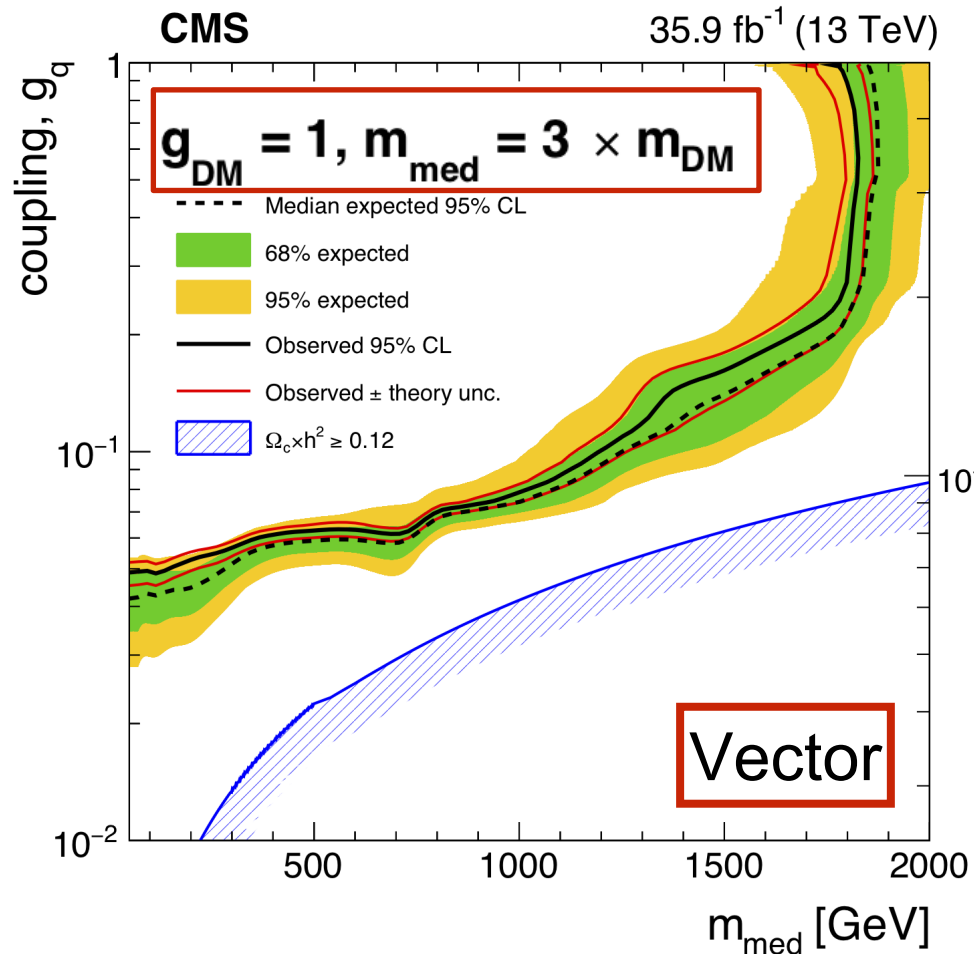


Pseudo-Scalar



Mono-jet & Mono-V Searches

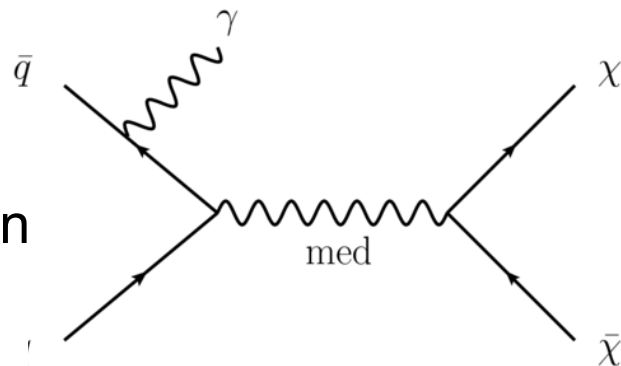
- Interpretation in simplified DM models
- s-channel with different mediators



CMS EXO-16-048

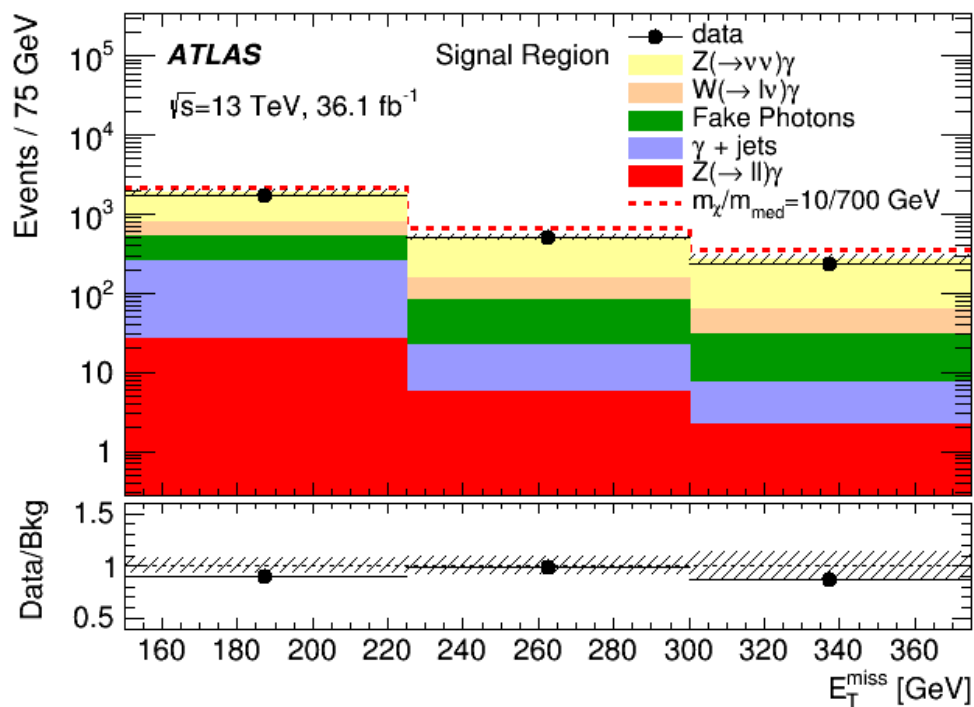
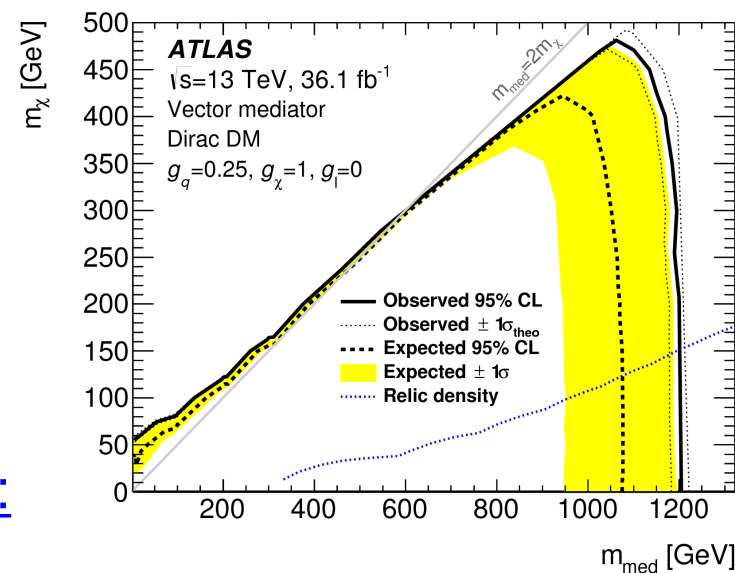
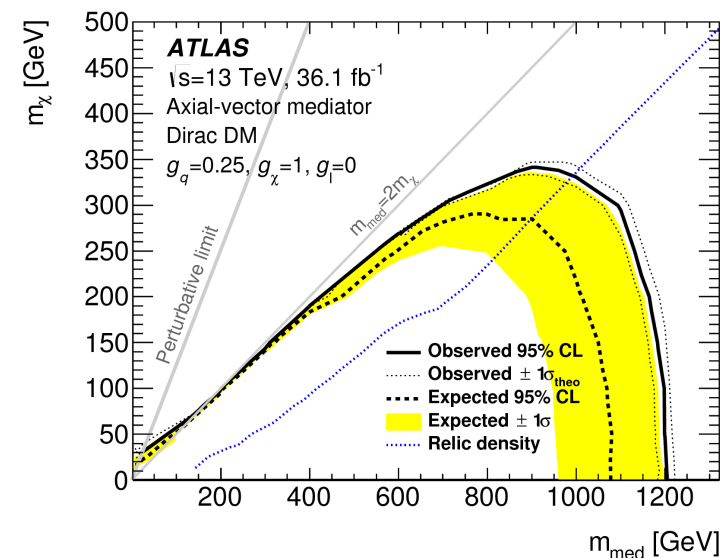
Mono-photon

- 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:](#)

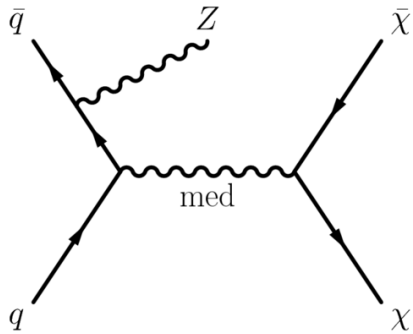
[Eur. Phys. J. C 77 \(2017\) 393](#)

[Comparable CMS analysis:](#)

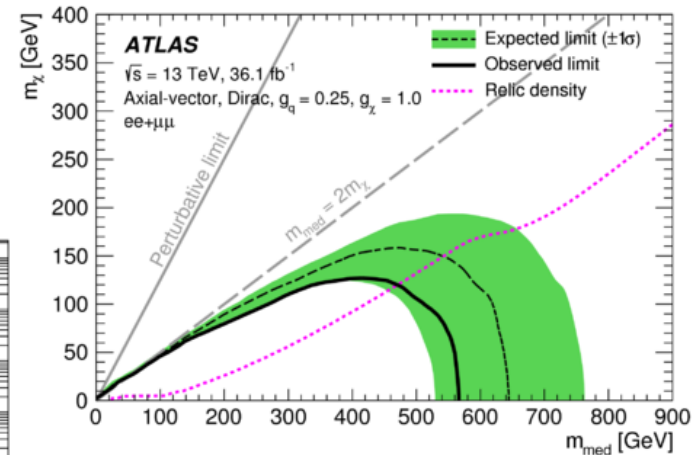
[JHEP 10 \(2017\) 073](#)

Mono-Z

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



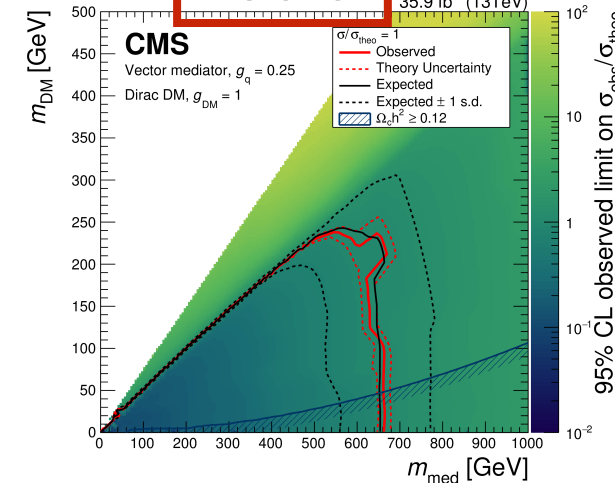
Axial-Vector



Pseudo-scalar

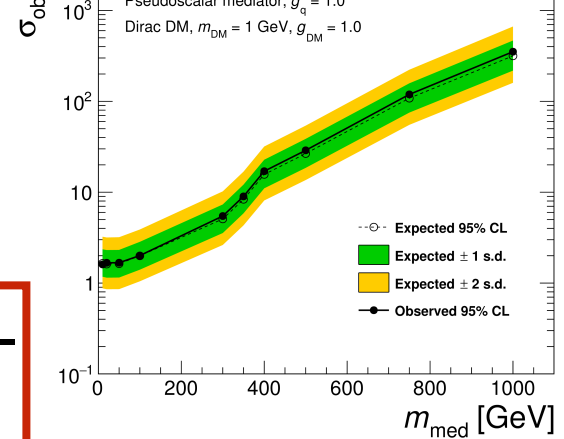
CMS-EXO-16-052

Vector

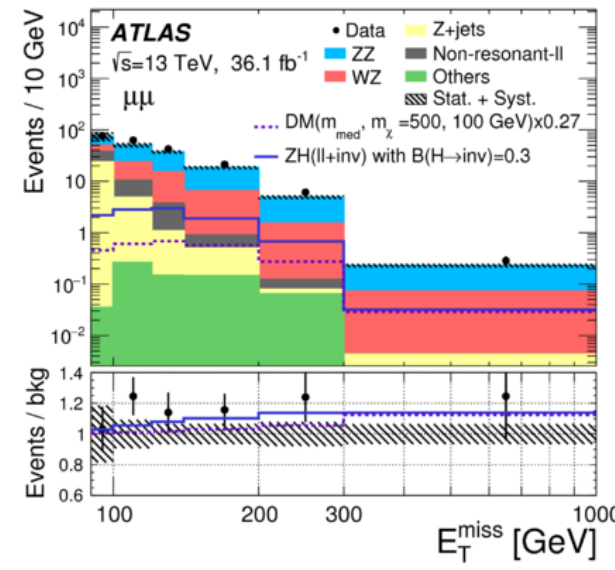
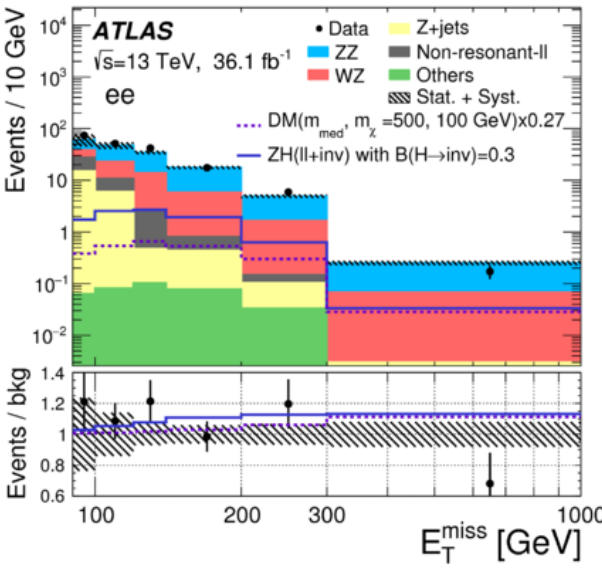


35.9 fb⁻¹ (13 TeV)

CMS
Pseudoscalar mediator, $g_q = 1.0$
Dirac DM, $m_{DM} = 1 \text{ GeV}$, $g_{DM} = 1.0$

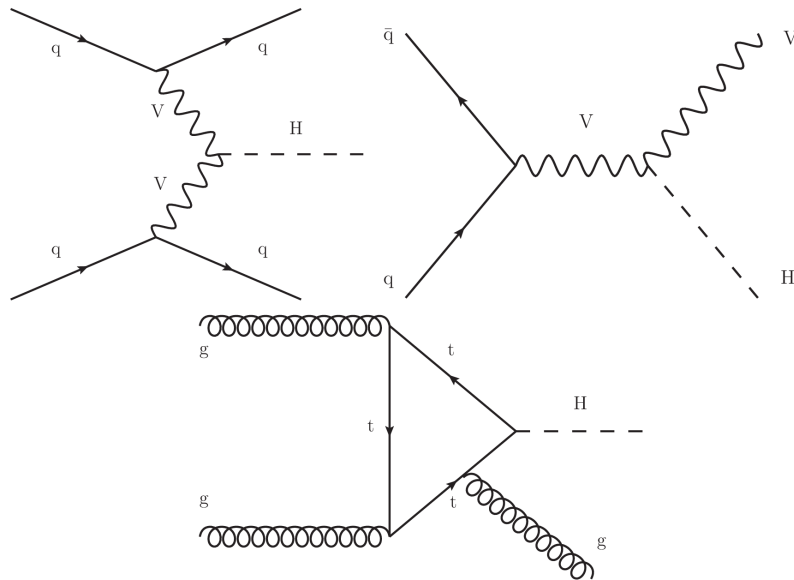


Scalar almost identical



Higgs as a portal to Dark Matter

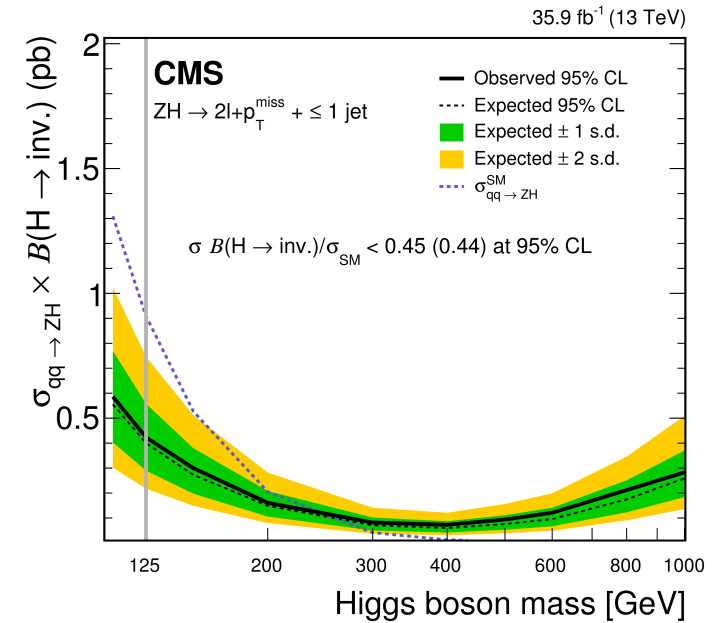
- Study of Higgs \rightarrow invisible branching fraction in **VBF, association with V and gluon fusion** production modes.
- As Higgs couples proportionally to mass, making it a viable portal to DM
- Only sensitive to DM masses $< 0.5 m_H$



- **Additional searches for Higgs in conjunction with DM in bb and $\gamma\gamma$ final states (\rightarrow backup)**

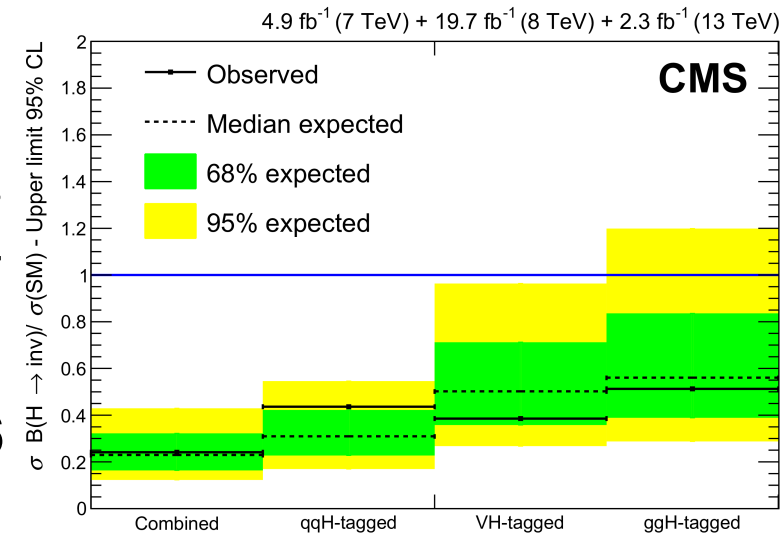
Higgs production in association with $Z \rightarrow \ell\ell$

CMS-EXO-16-052



- Combination of H \rightarrow invisible production modes
- $B(H \rightarrow \text{inv}) < 0.24$ @95%CL

CMS-HIG-16-016

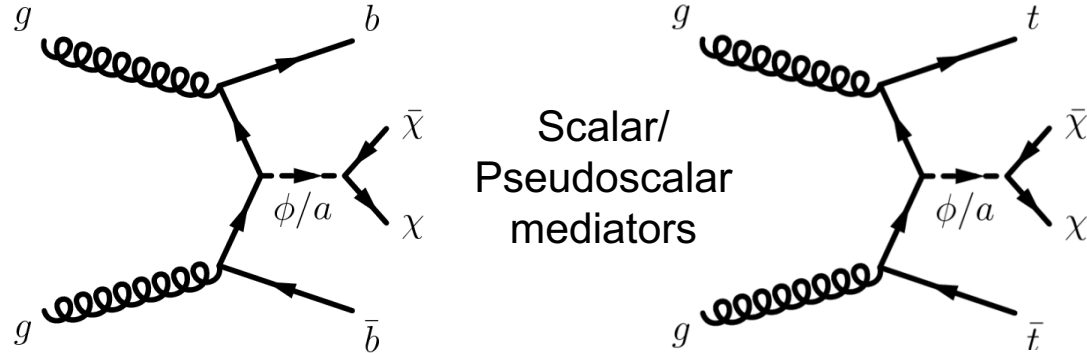


DM in association with heavy flavours

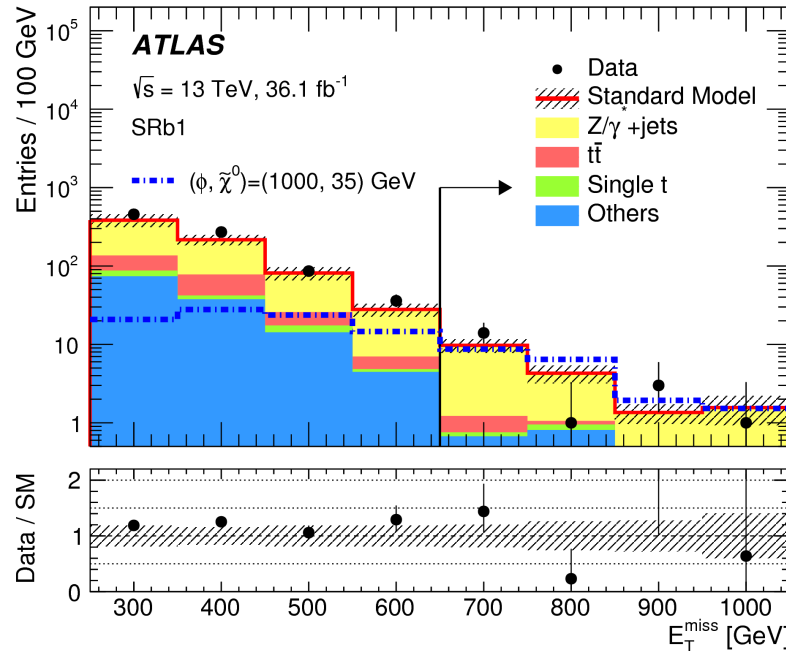
- DM in association with bottom or top quarks
- VBF like signature, b-jet tagging

arXiv:1710.11412

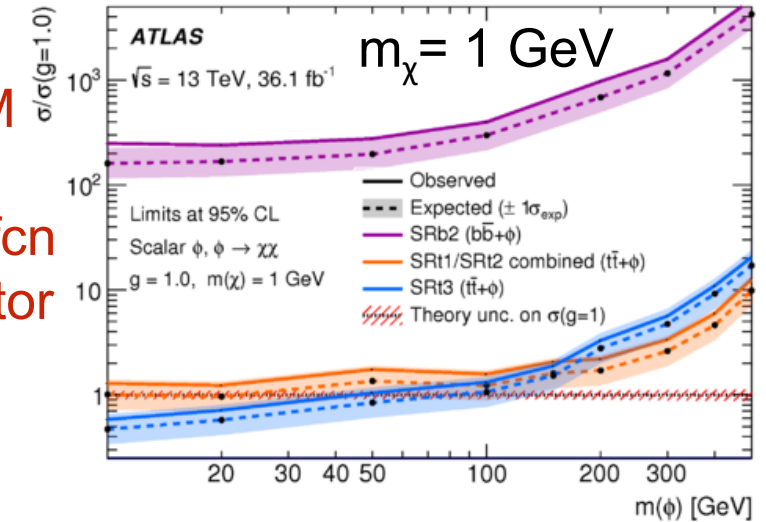
Scalar Similar sensitivity to **pseudoscalar**



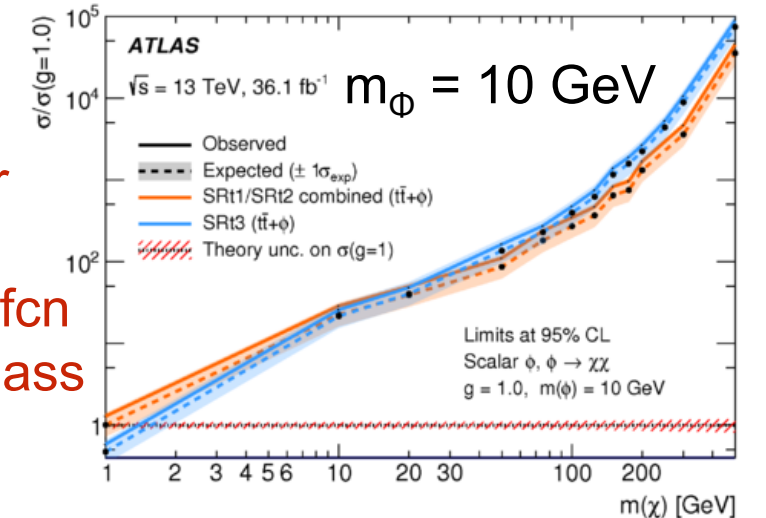
- Interpretation in colour-neutral $t\bar{t}/b\bar{b} + \phi$ scalar and $t\bar{t}/b\bar{b} + a$ pseudoscalar models
- Not yet sensitive to $bb + \phi/a$ production
- Also searches with **single top**
 - **CMS EXO-16-051**



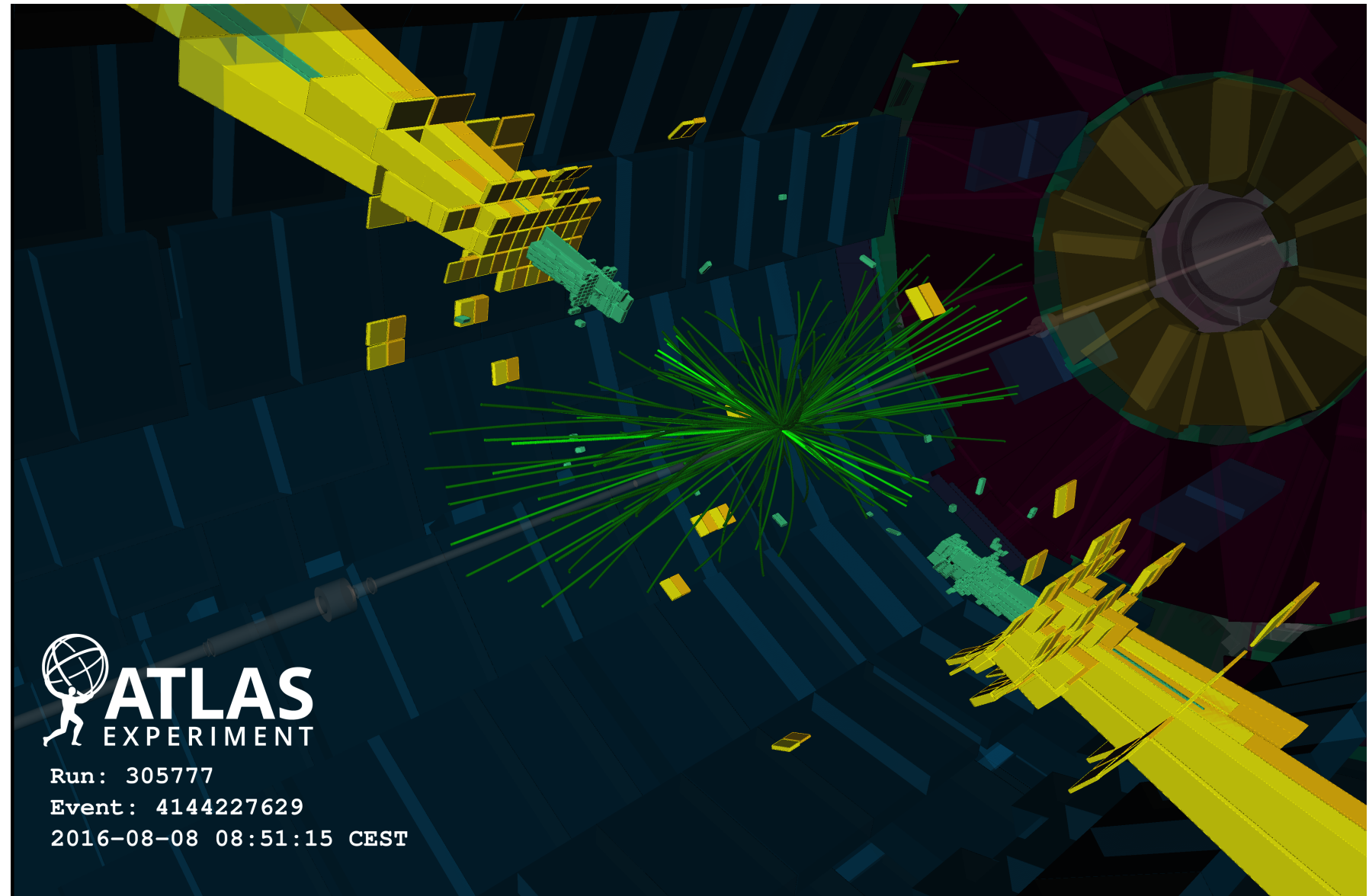
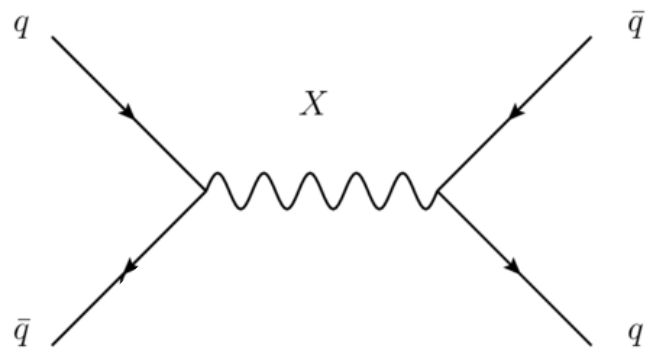
- **Fixed DM mass**
- **Limit as fcn of mediator mass**



- **Fixed mediator mass**
- **Limit as fcn of DM mass**

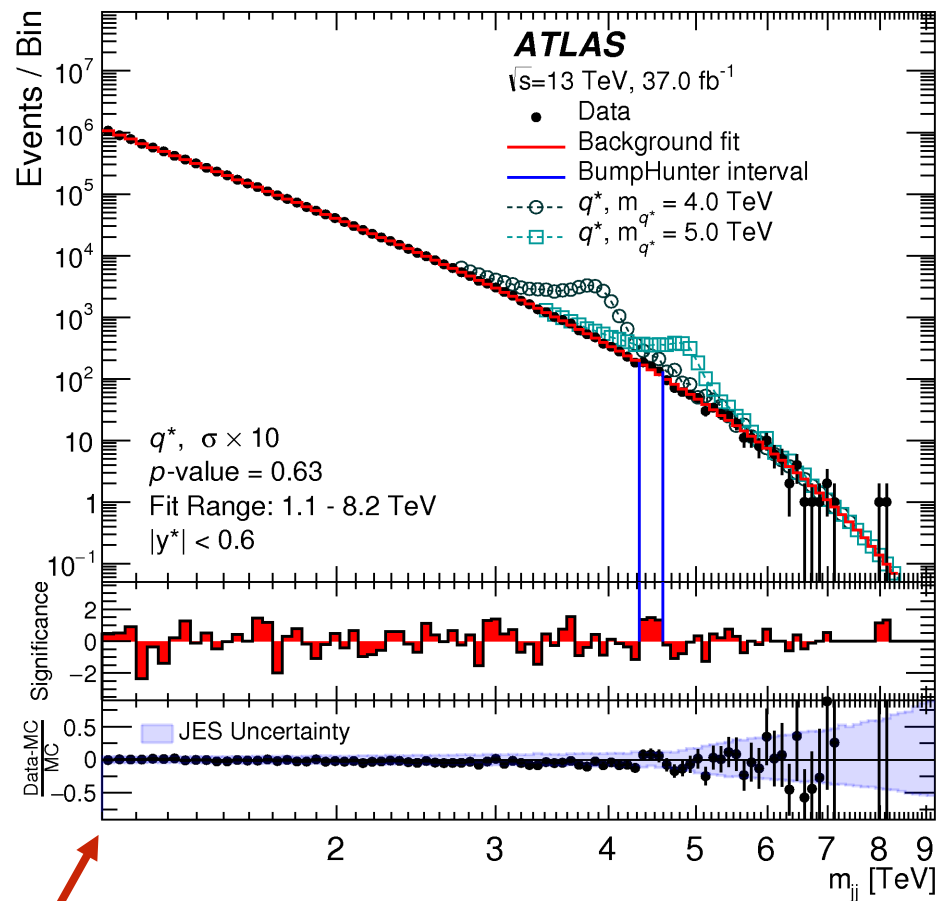


Mediator Searches

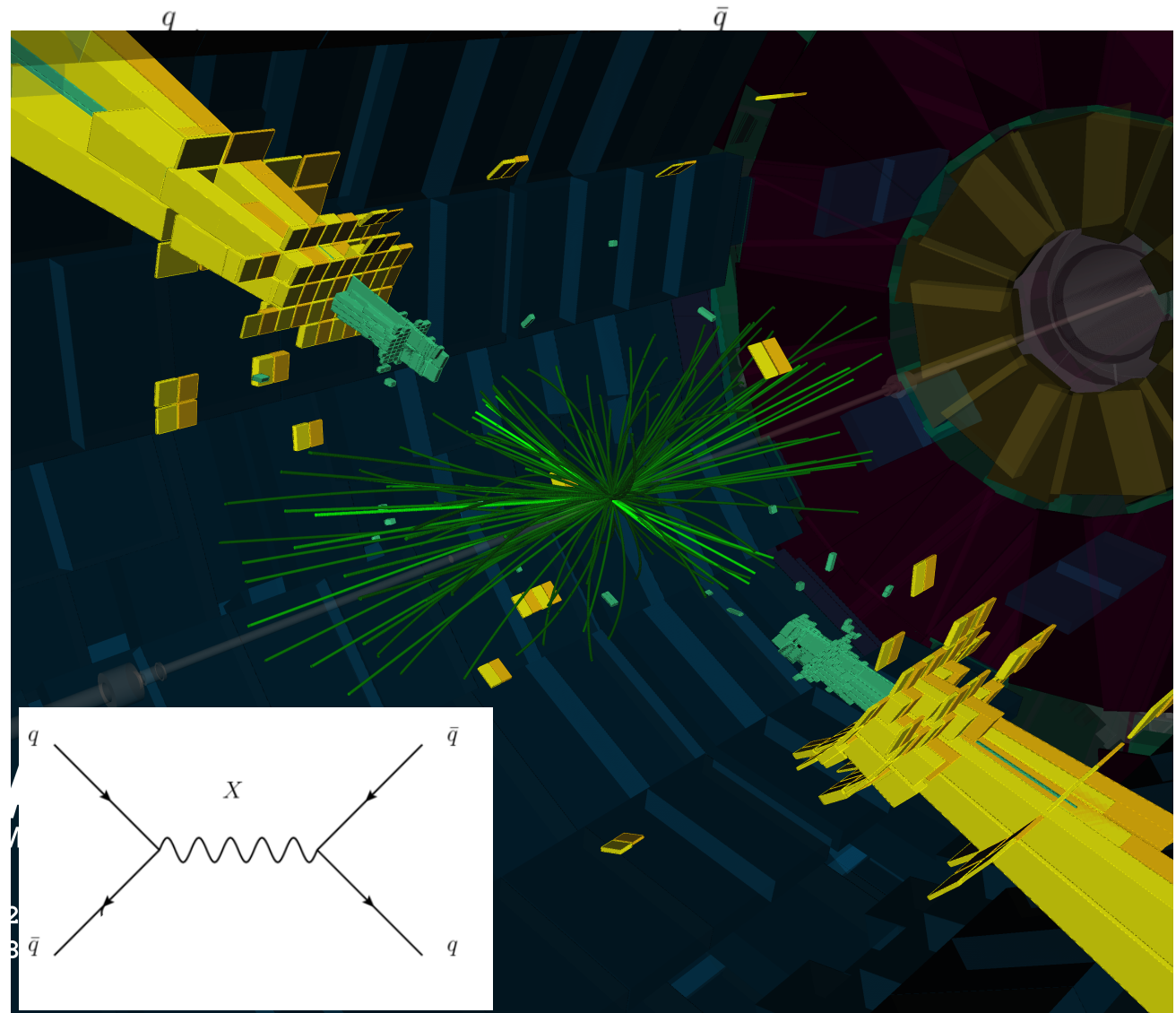


High-mass dijet resonances

- Search for resonance in dijet invariant mass spectrum



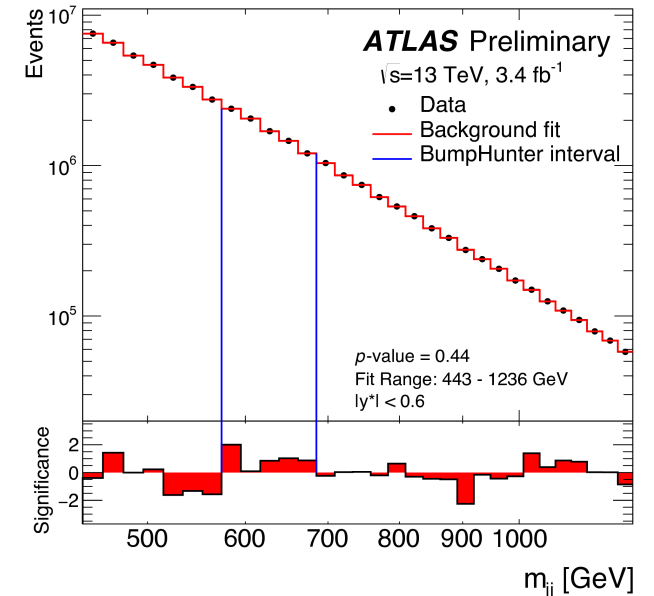
1 TeV



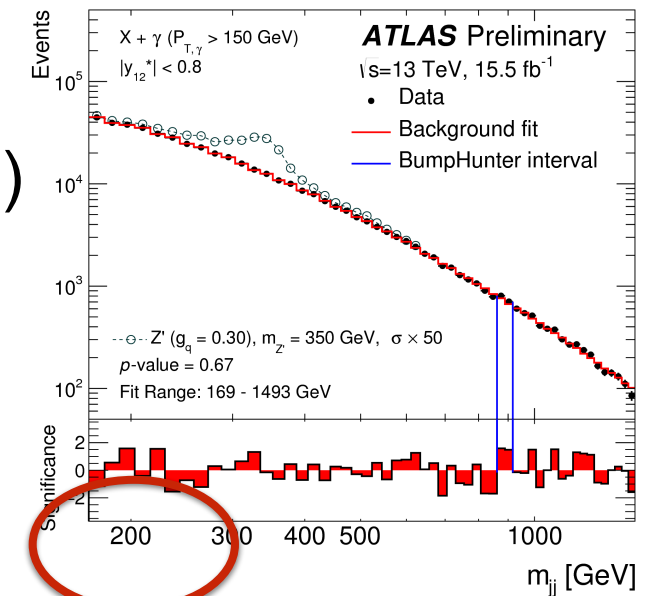
Low-mass dijet resonances

- 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- p_T ISR jet or photon** and search for low mass resonance in recoil system
 - Trigger on high- p_T ISR jet and search for merged, boosted resonance in recoil, using **jet substructure**

ATLAS Trigger Level Analysis ATLAS-CONF-2016-030



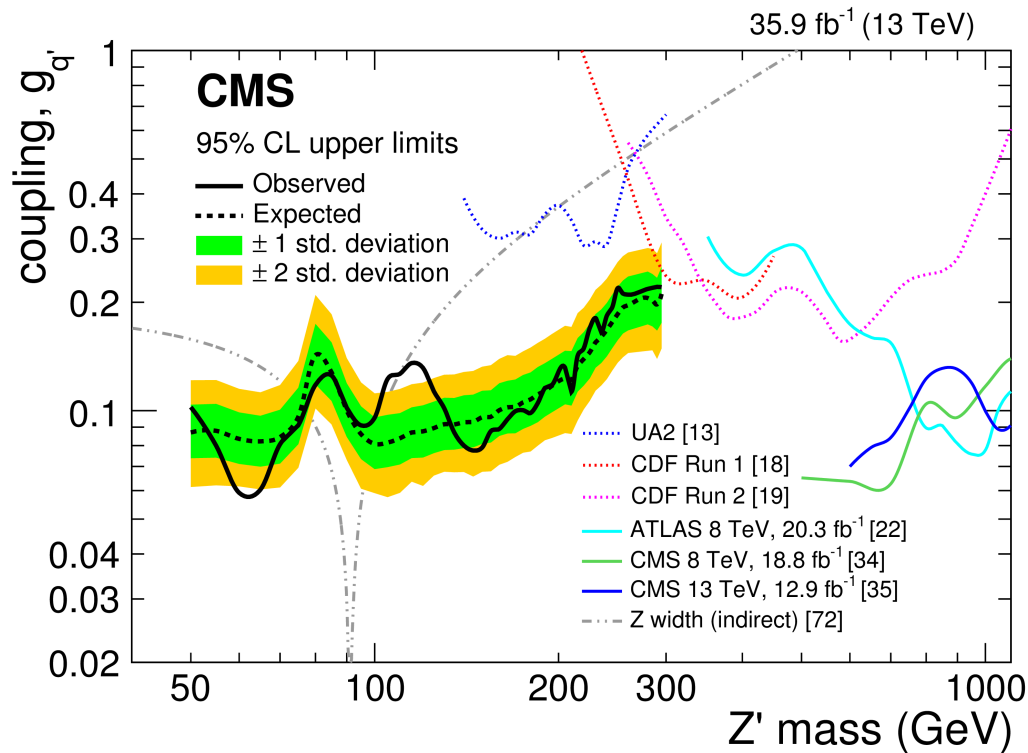
ATLAS ISR search (photon) ATLAS-CONF-2016-070



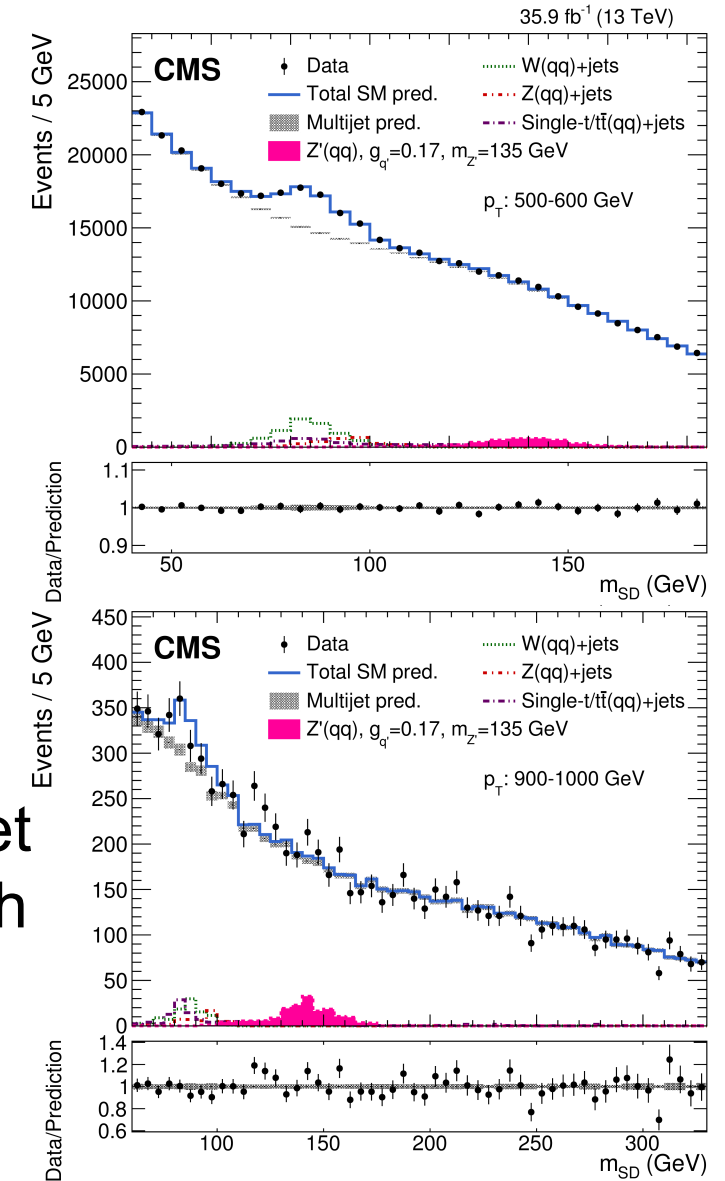
Low-mass dijets– boosted topology

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

- 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

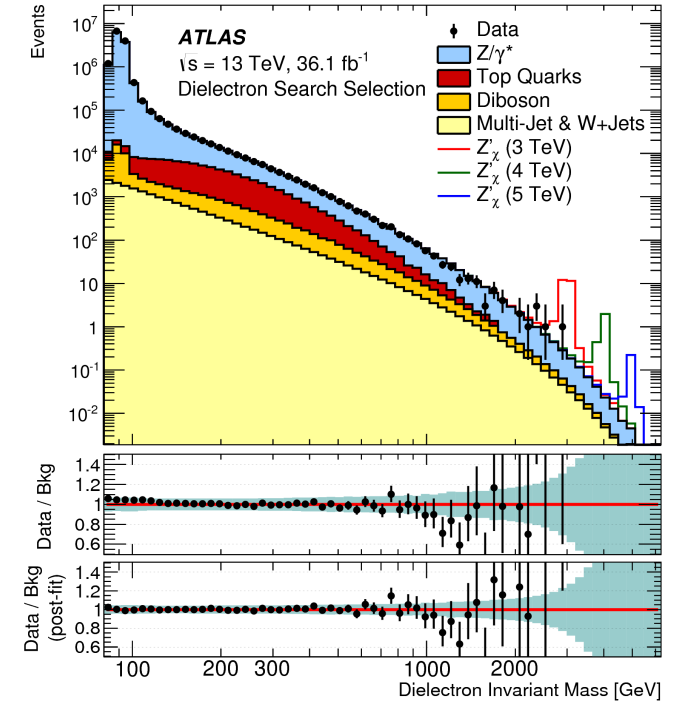
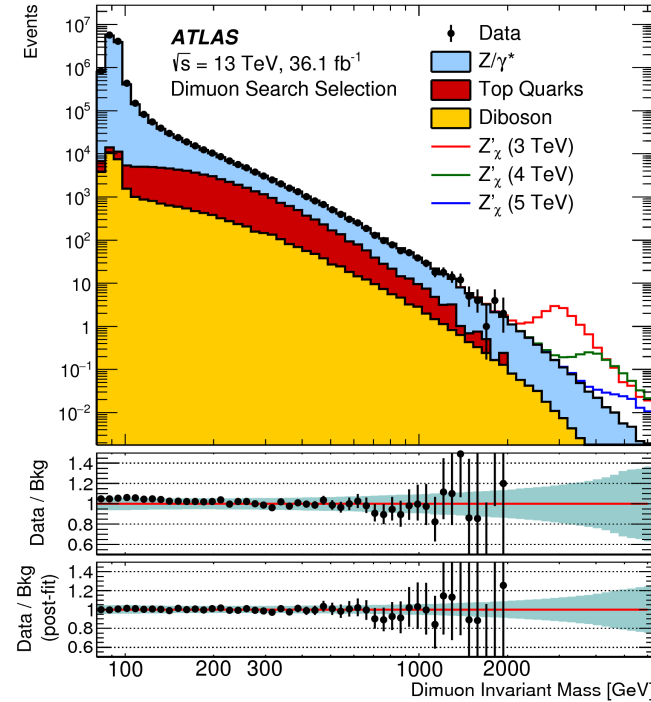
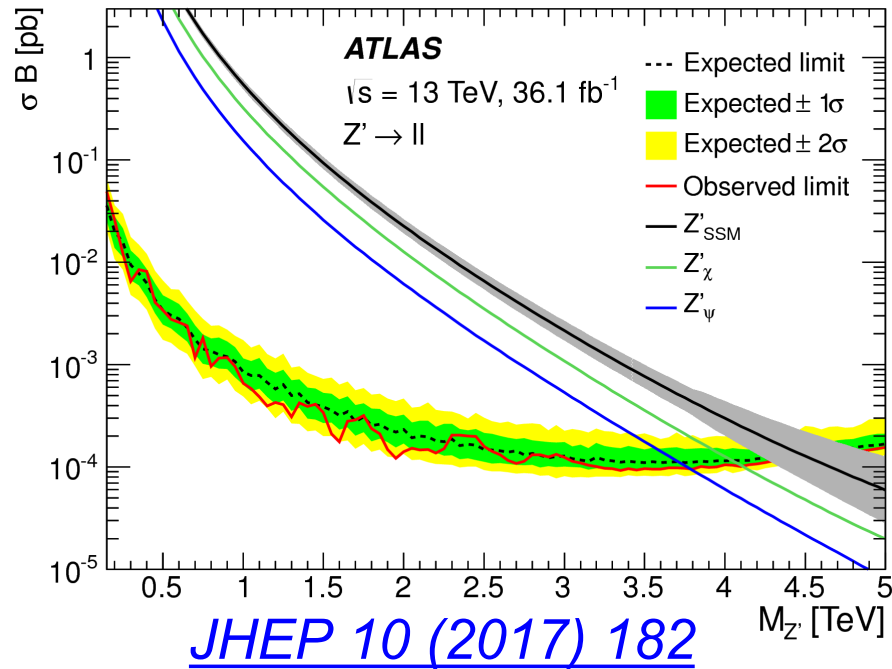


CMS-EXO-17-001



Dilepton resonances (Z')

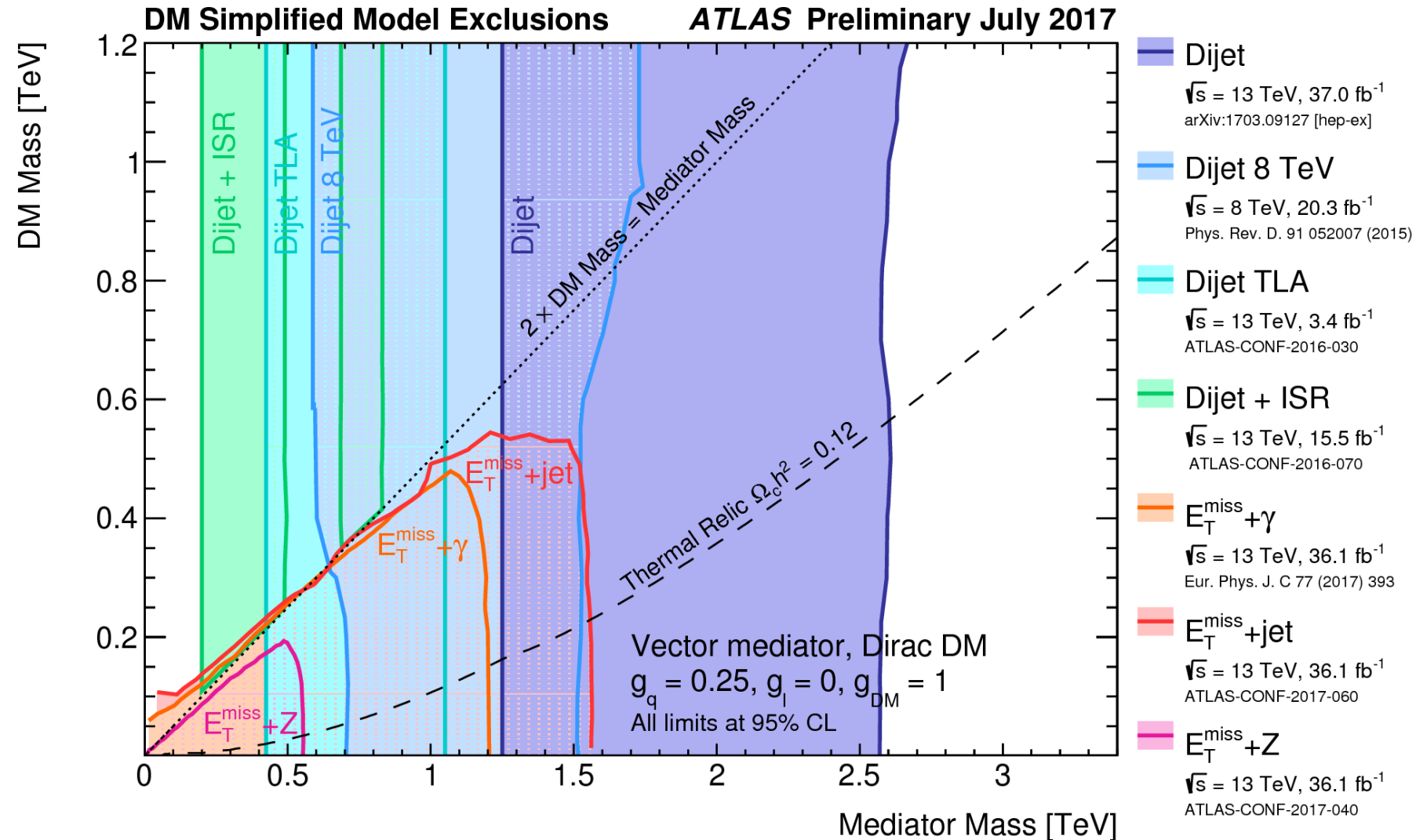
- $Z' \rightarrow e^+e^-$ and $Z' \rightarrow \mu^+\mu^-$ searches
- Require high- p_T same flavour, opposite charge dilepton pair
- Limits on Z' mass of around 4 - 4.5 TeV



Model	Width [%]	θ_{E_6} [rad]	Lower limits on $M_{Z'}$ [TeV]					
			ee		$\mu\mu$		ll	
			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	0.50π	3.9	3.9	3.6	3.6	4.1	4.0
Z'_S	1.2	0.63π	3.9	3.8	3.6	3.5	4.0	4.0
Z'_I	1.1	0.71π	3.8	3.8	3.5	3.4	4.0	3.9
Z'_η	0.6	0.21π	3.7	3.7	3.4	3.3	3.9	3.8
Z'_N	0.6	-0.08π	3.6	3.6	3.4	3.3	3.8	3.8
Z'_ν	0.5	0π	3.6	3.6	3.3	3.2	3.8	3.7

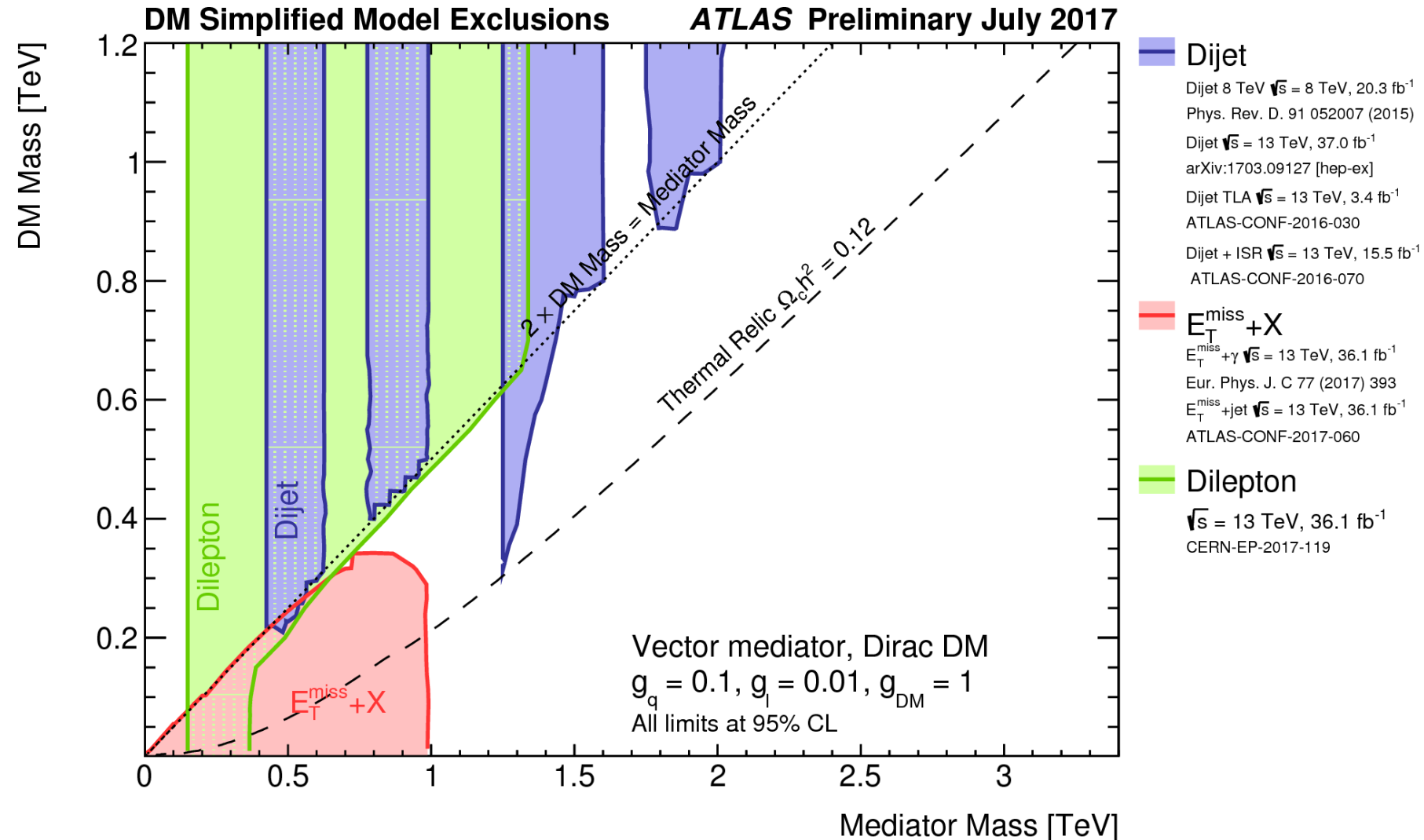
The grand picture

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



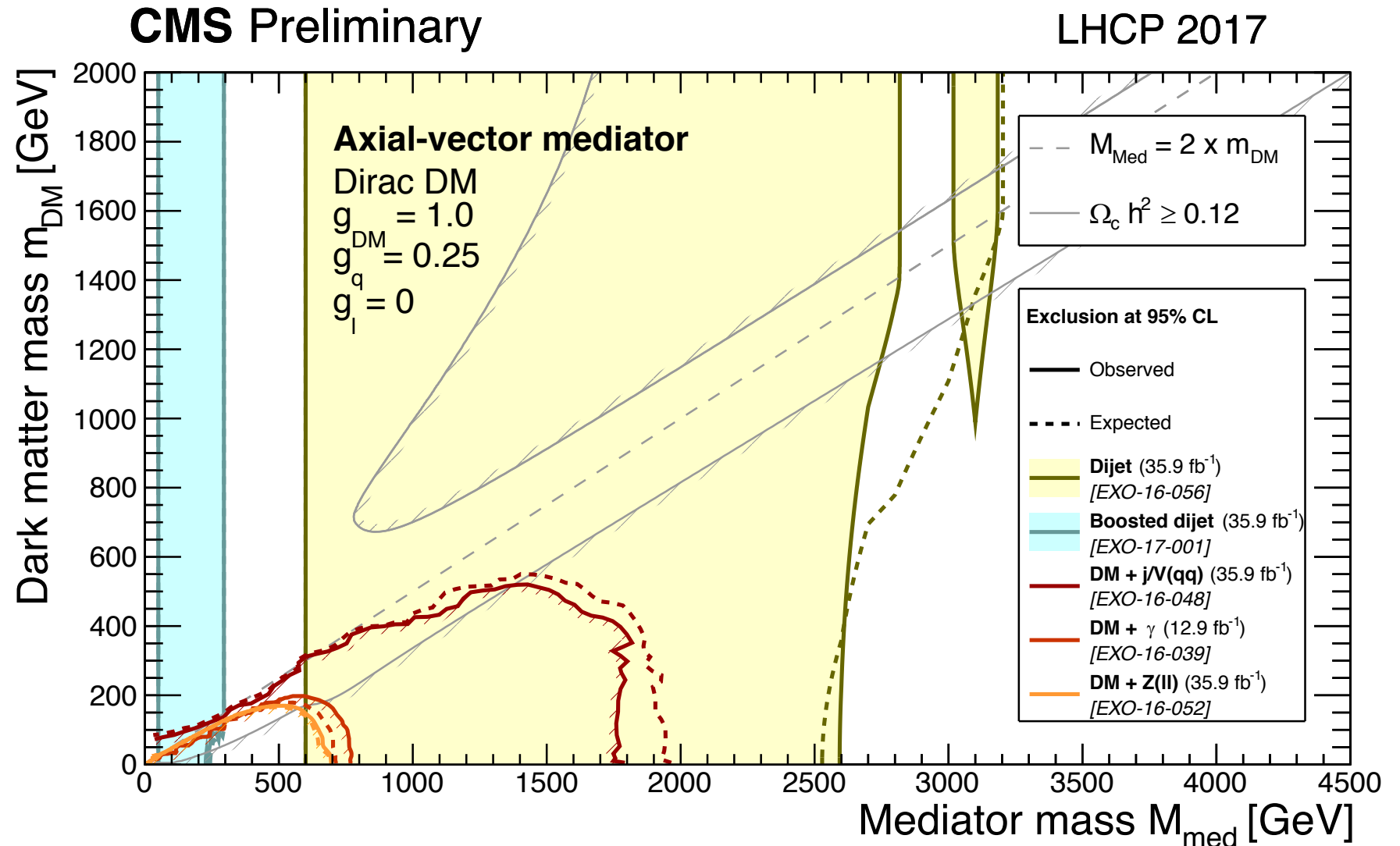
The grand picture

- 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!



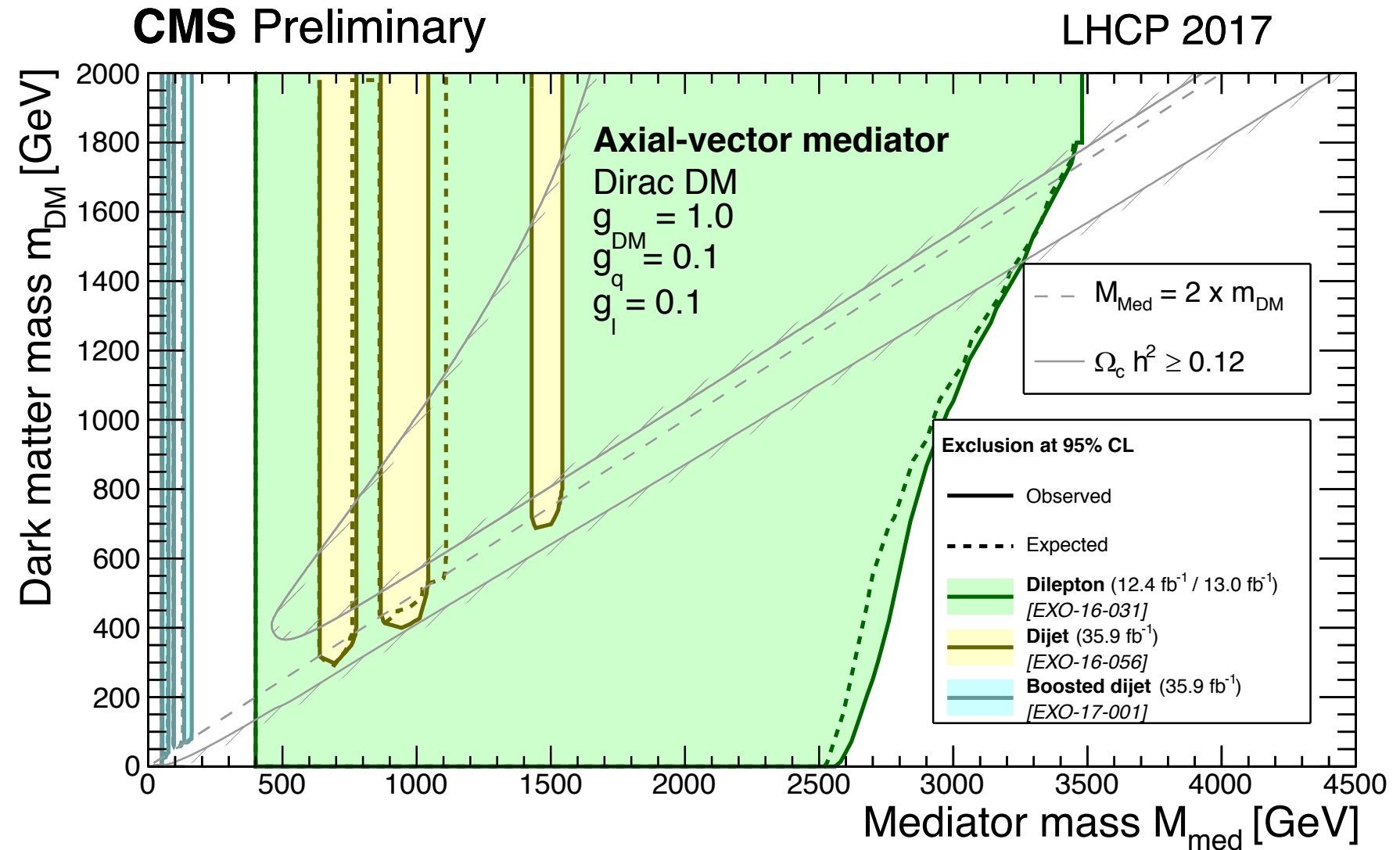
The grand picture

- 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!



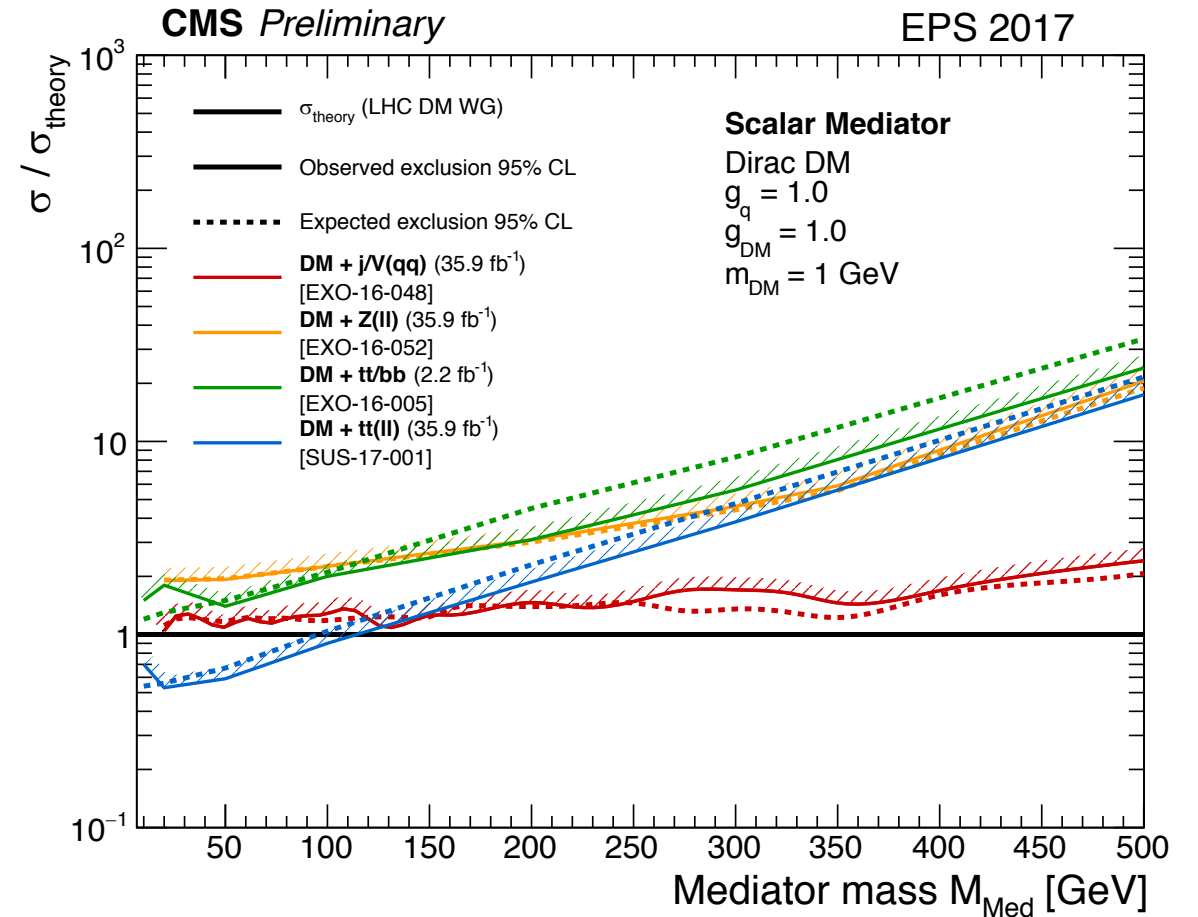
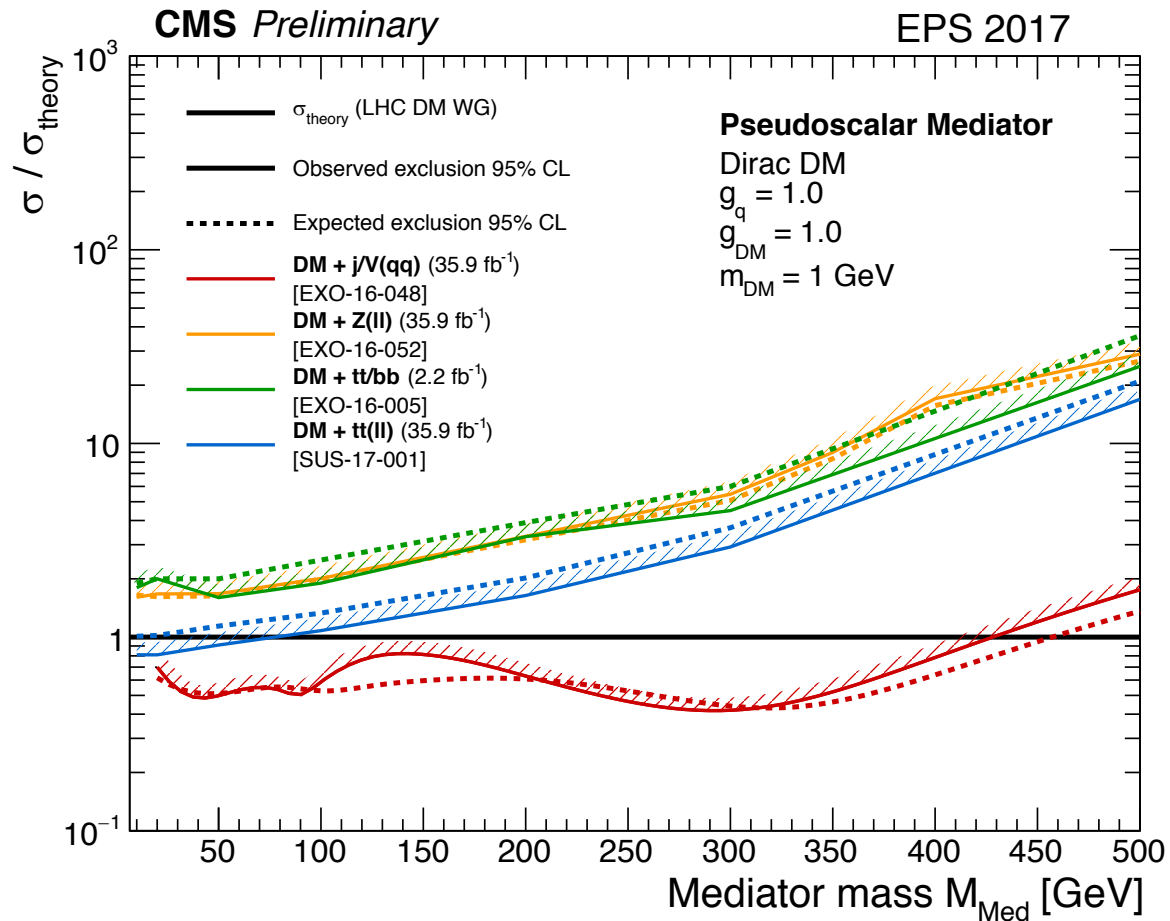
The grand picture

- 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!



The grand picture

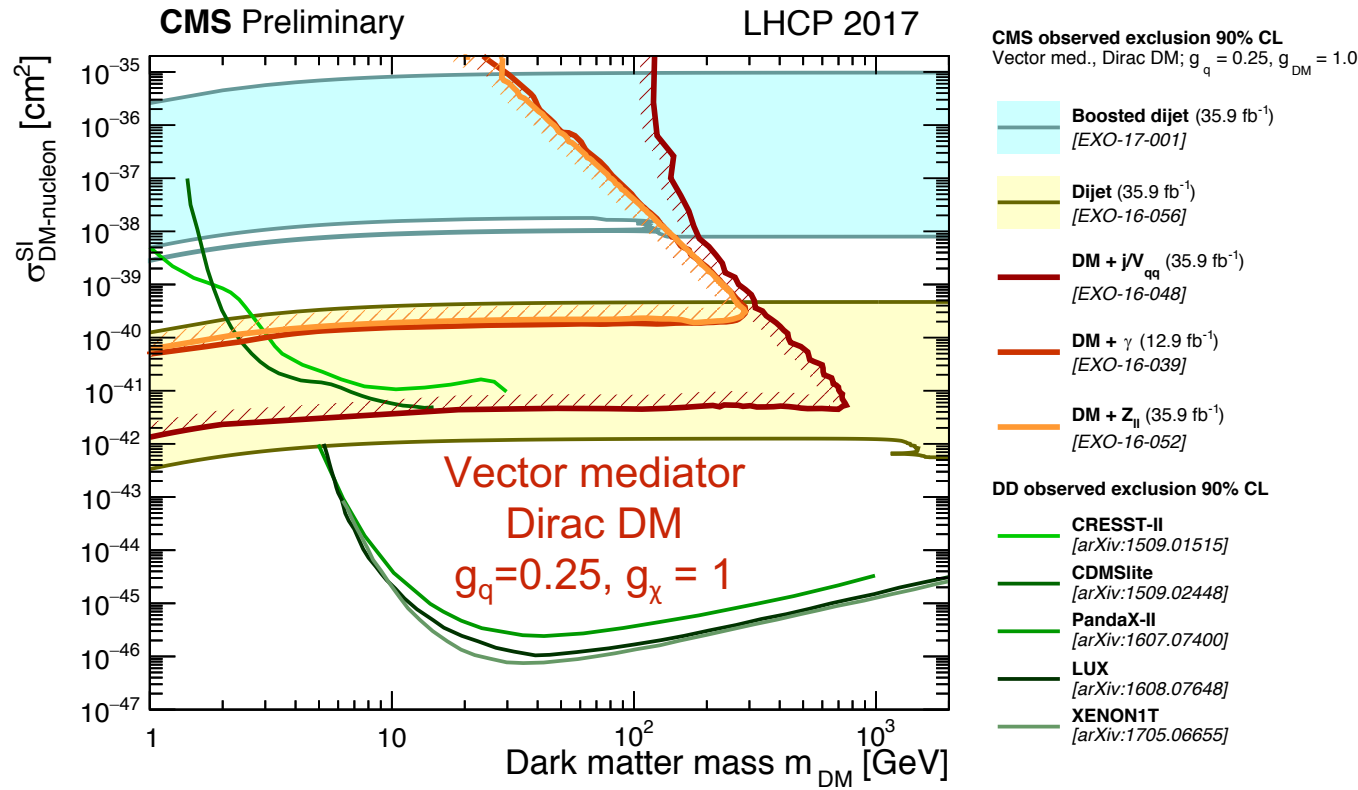
- Much weaker constraints on Scalar and Pseudo-Scalar mediators
- Exclusion only for very light DM and couplings $g_q = g_{DM} = 1$.



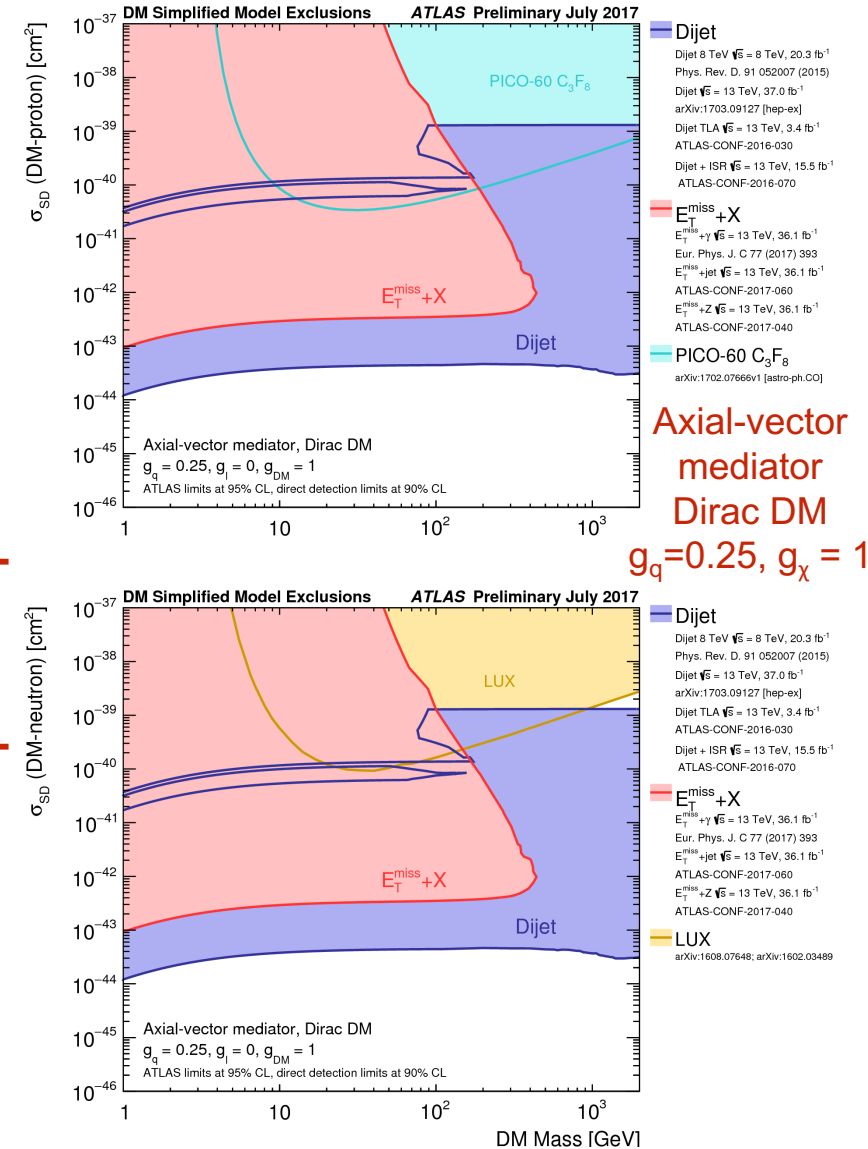
Comparison with Direct Detection

- 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

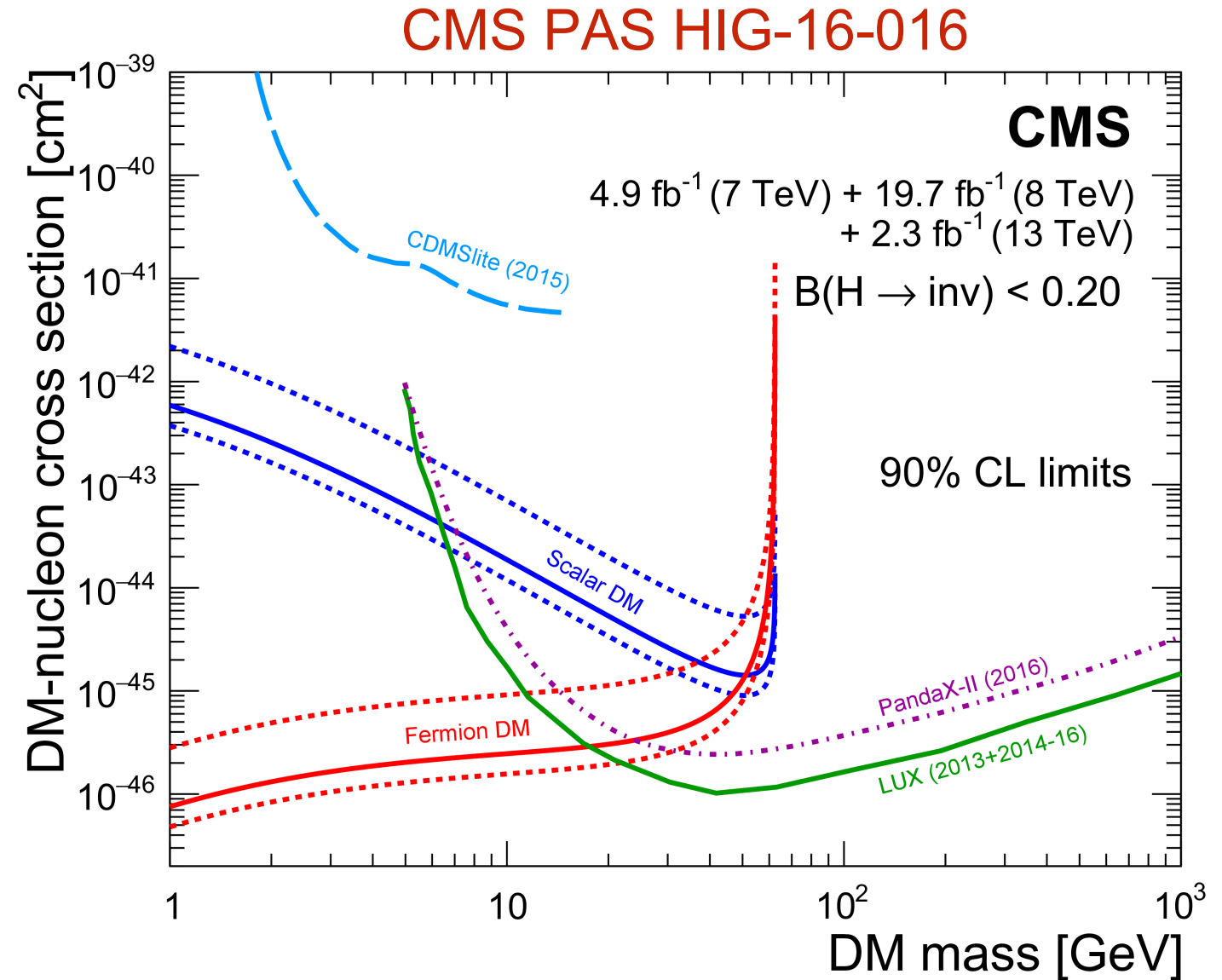


Spin-dependent



Comparison with Direct Detection

- Constraints on $B(H \rightarrow \text{inv})$ 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



Pros and Cons: Collider vs Direct Detection

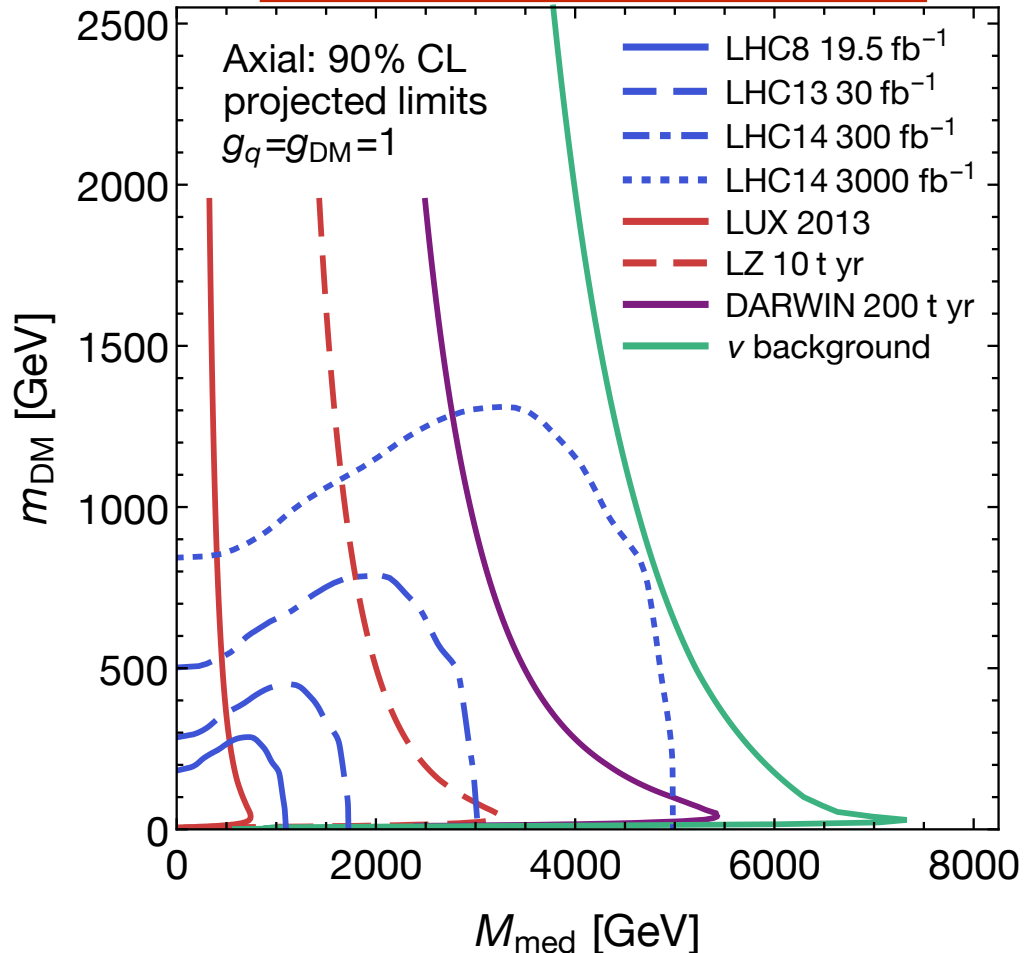
Wimp – Nucleon Interaction	
<u>Spin-Independent (SI)</u>	<u>Spin-Dependent (SD)</u>
Basic Mediators	
<p><u>Vector</u></p> <p><i>Besides low DM masses DD provides best sensitivity. Complementarity at low DM masses (<5 GeV)!</i></p>	<p><u>Axial-vector</u></p> <p><i>DD and collider are equal in overall sensitivity but probe different regions of parameter space! Complementarity in full parameter space!</i></p>
<p><u>Scalar</u></p> <p><i>Besides low DM masses DD provides best sensitivity. Complementarity at low DM masses (<5 GeV)!</i></p>	<p><u>Pseudoscalar</u></p> <p><i>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}!</i></p>

from
O. Buchmueller

Outlook – Where next?

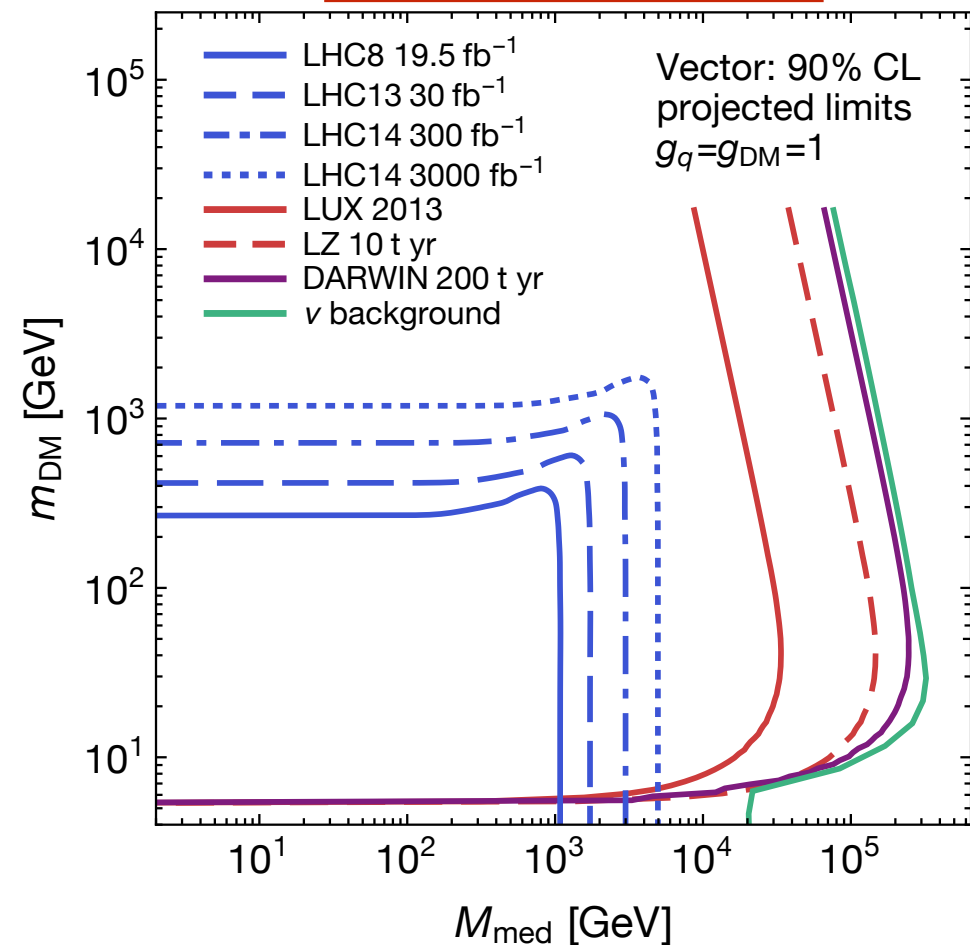
Axial-Vector mediator

$$g_q = g_Y = 1$$



Vector mediator

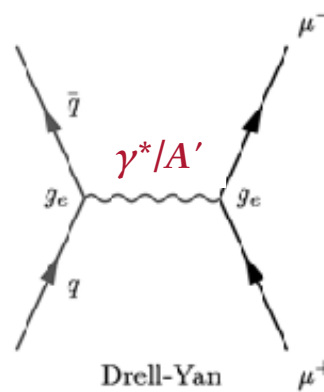
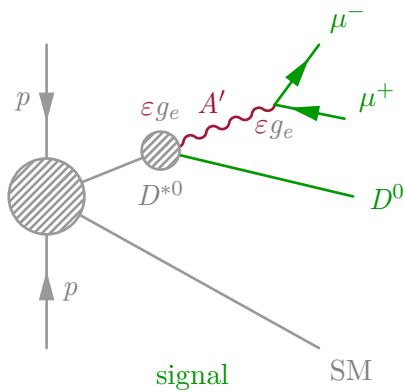
$$g_q = g_Y = 1$$



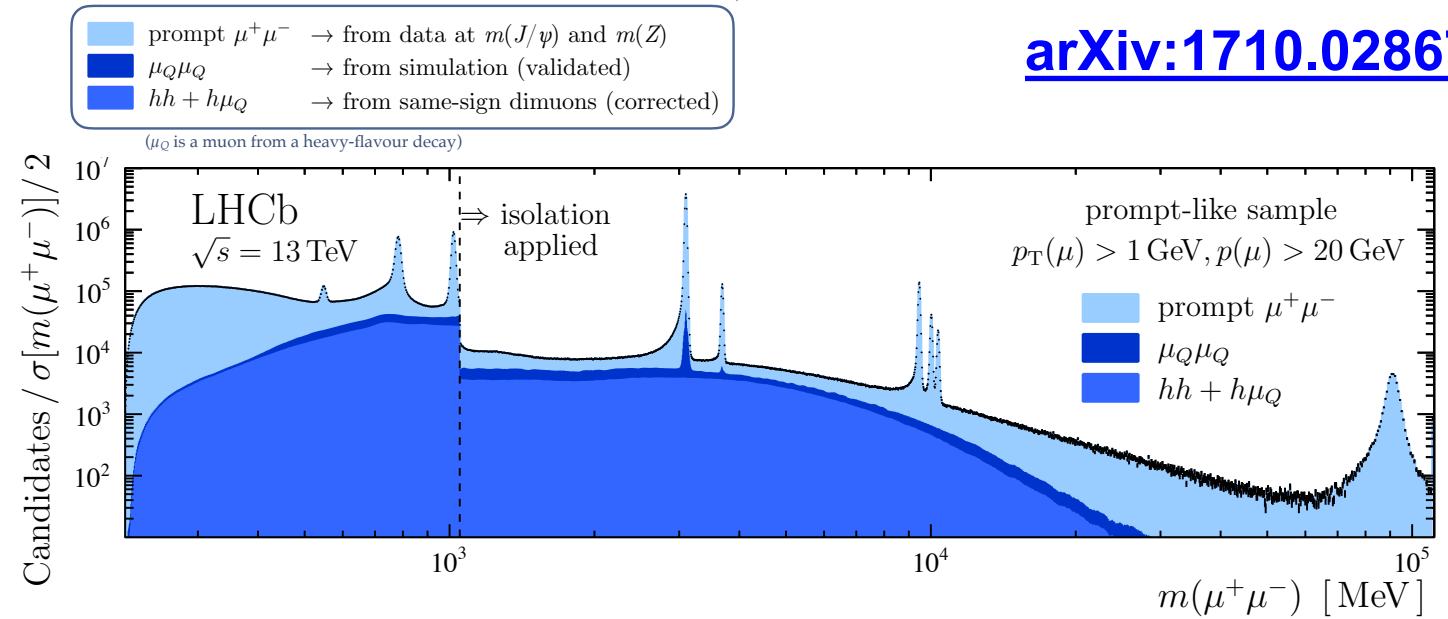
from arXiv:1409.4075, Phys.Dark Univ. 9-10 (2015) 51-58

Dark Photon search @ LHCb

- 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**



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



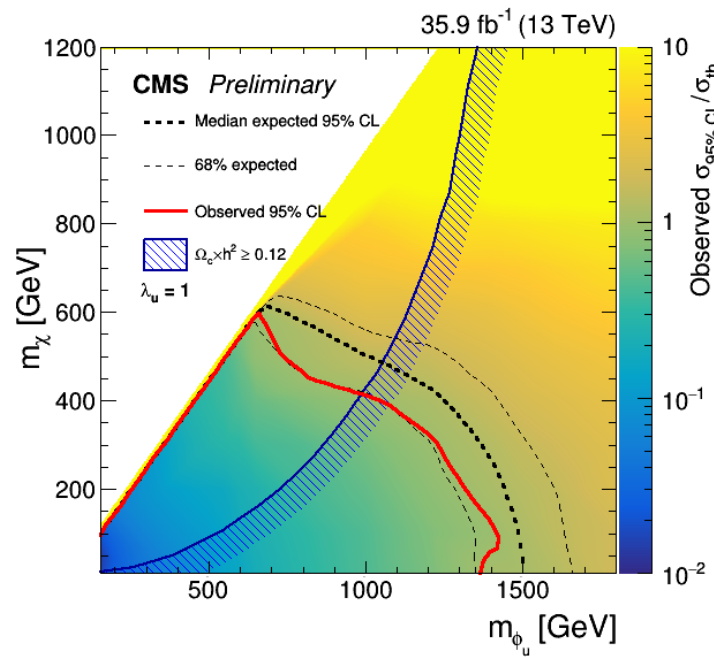
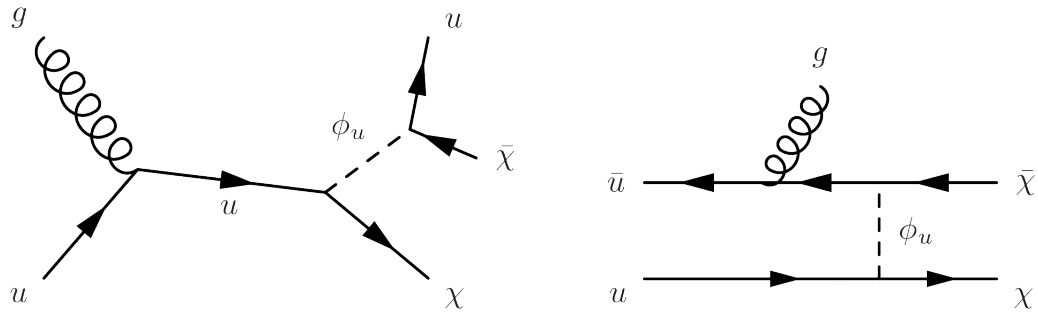
Summary

- 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

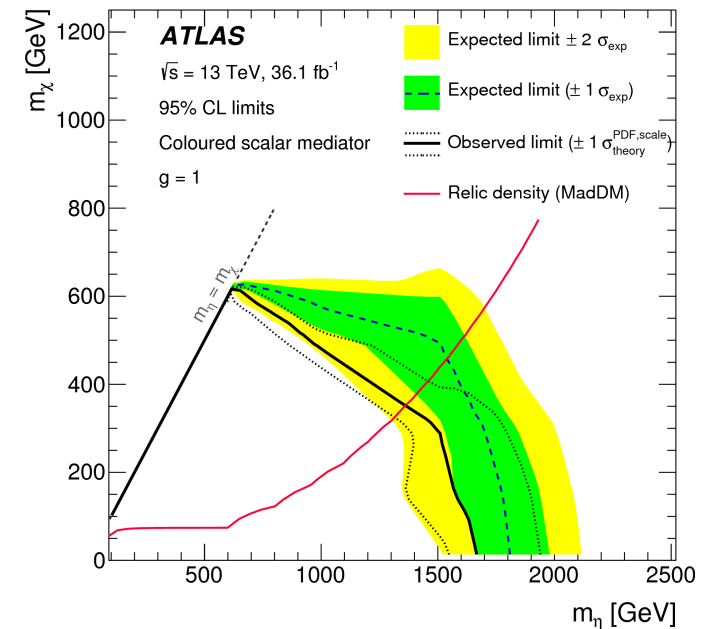
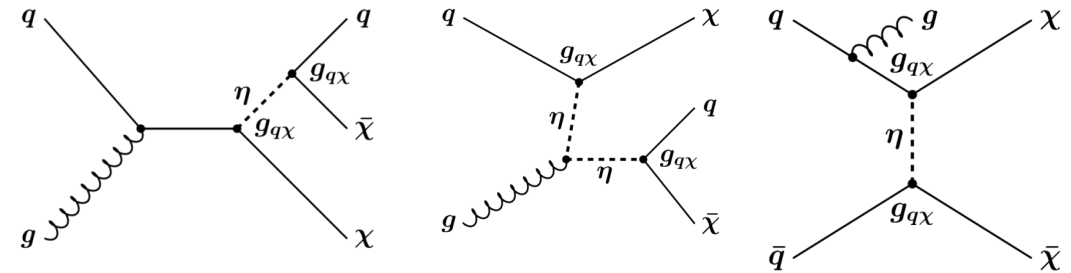
- Backup

Mono-jet & Mono-V Searches

- Interpretation in simplified DM models
- Fermion portal models



- Interpretation in simplified DM models
- Coloured scalar mediator models



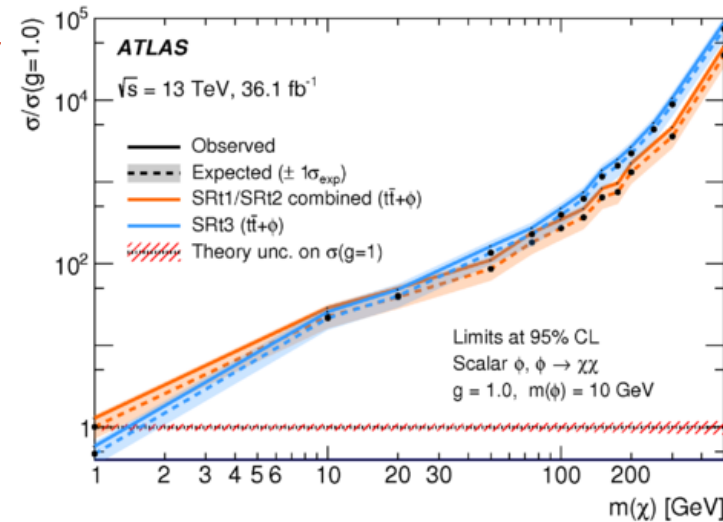
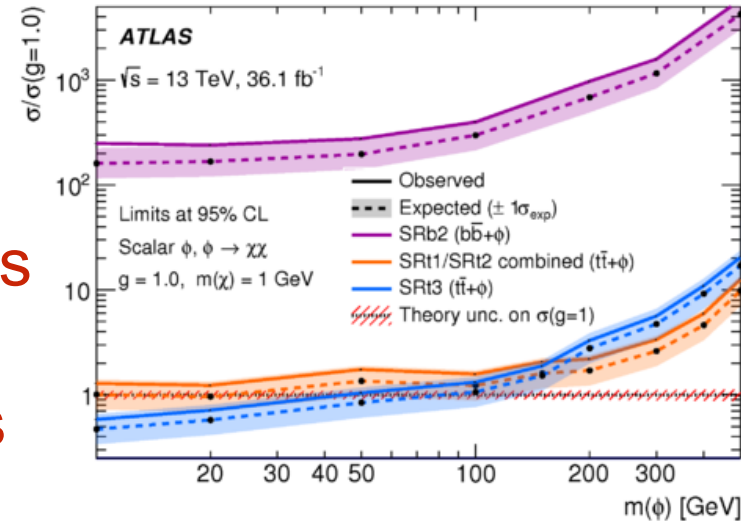
DM in association with heavy flavours

- Interpretation in colour-neutral $t\bar{t}/b\bar{b}+\phi$ scalar and $t\bar{t}/b\bar{b}+a$ pseudoscalar models

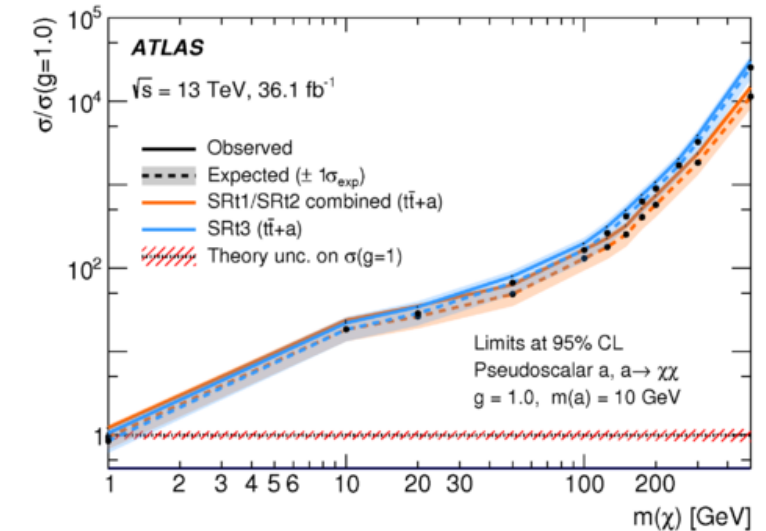
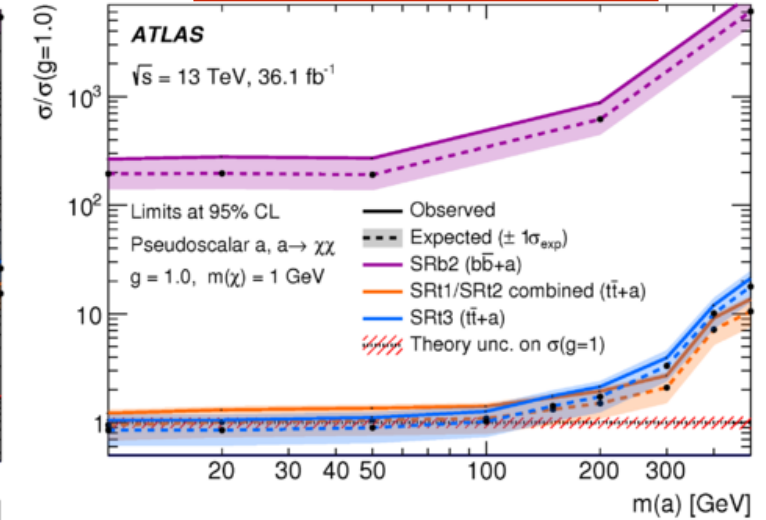
- Fixed DM mass
- Limit as fcn of mediator mass
- Fixed mediator mass
- Limit as fcn of DM mass

- Not yet sensitive to $b\bar{b} + \phi/a$ production

Scalar

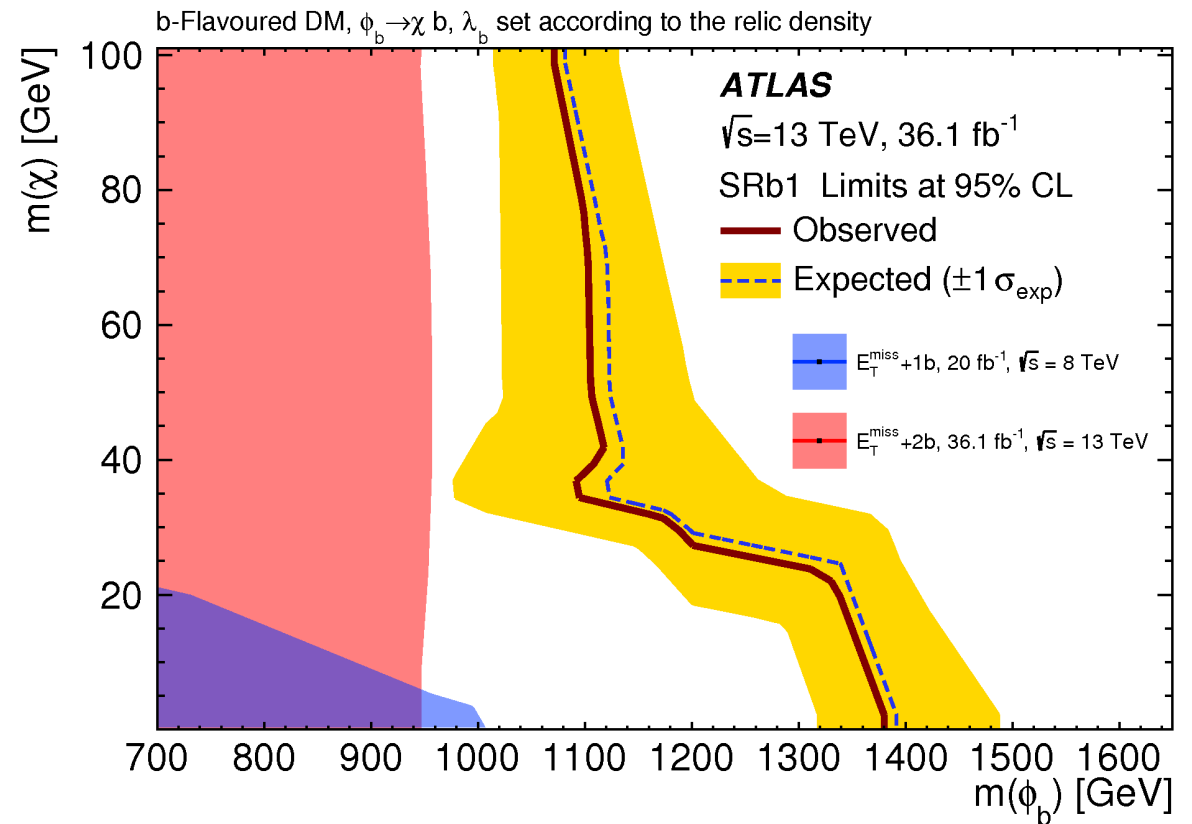
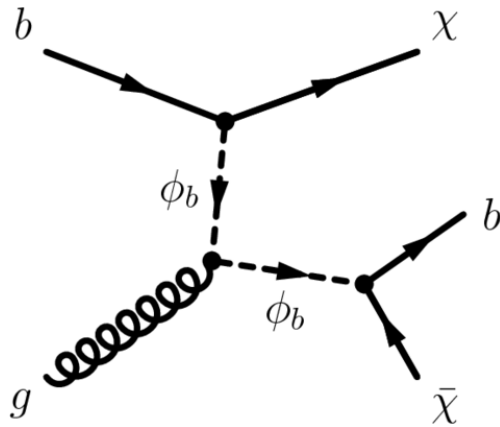


Pseudo-Scalar



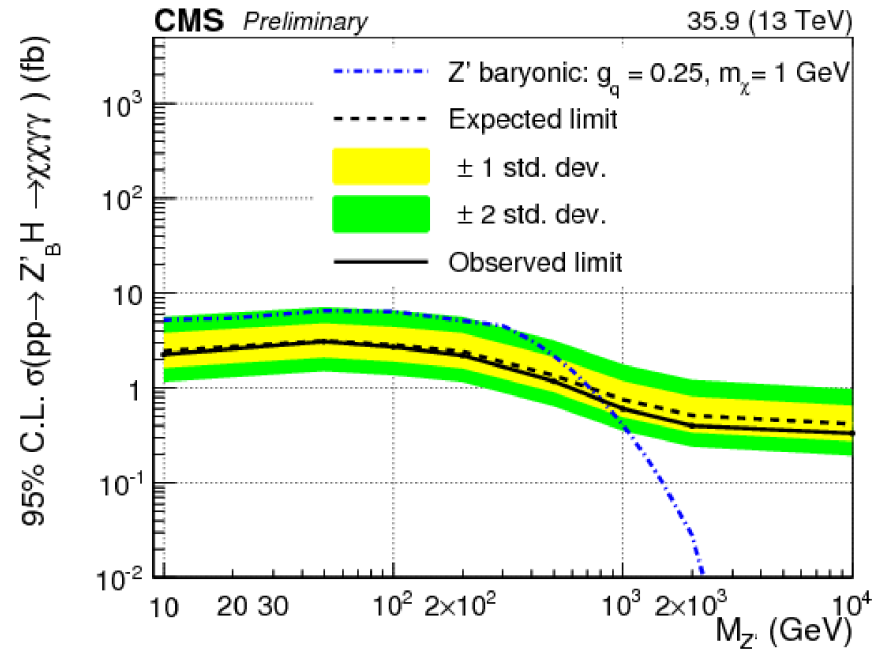
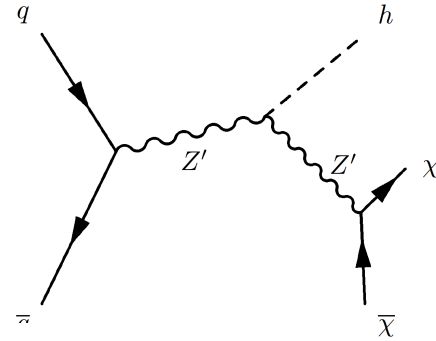
DM in association with heavy flavours

- colour-charged scalar mediators (b-FDM)



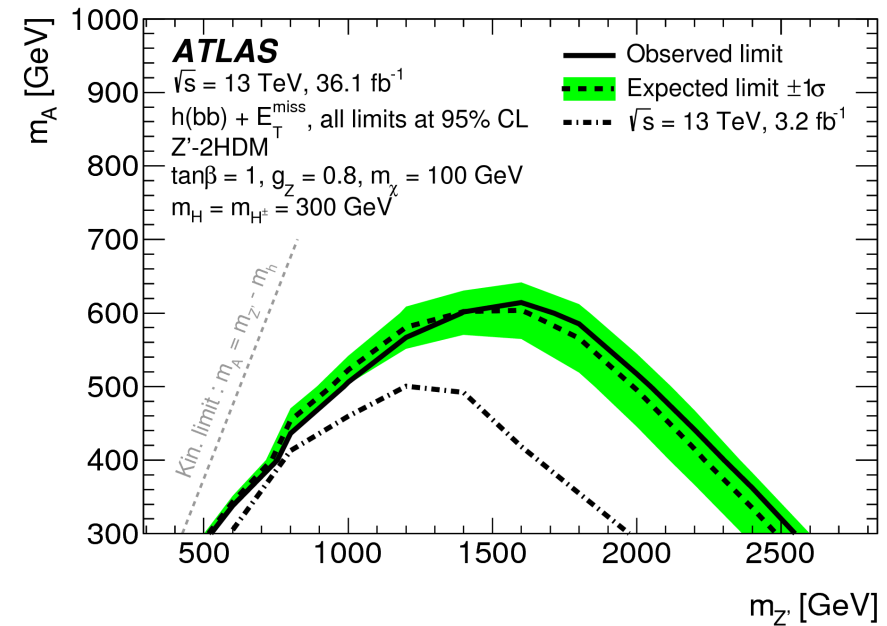
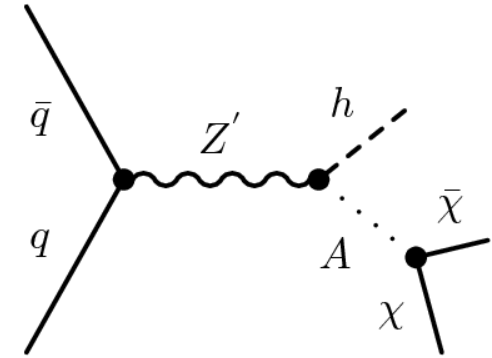
Mono-Higgs

- Higgs production in conjunction with DM
 - Higgs decay to $\gamma\gamma$



CMS-PAS-EXO-16-054

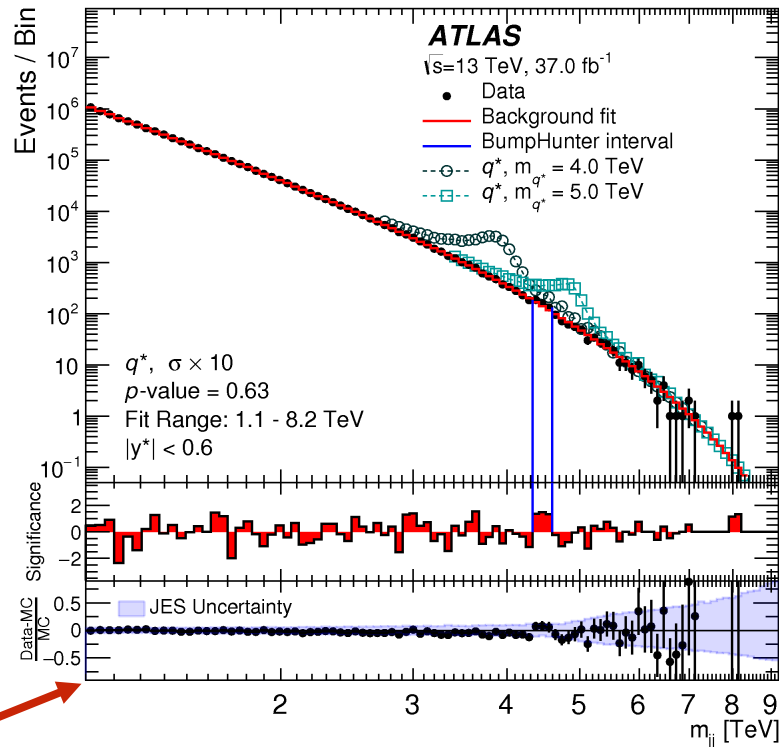
- Higgs production in conjunction with DM
 - Higgs decay to $b\bar{b}$



[Phys. Rev. Lett. 119 \(2017\) 181804](#)

High-mass dijet resonances

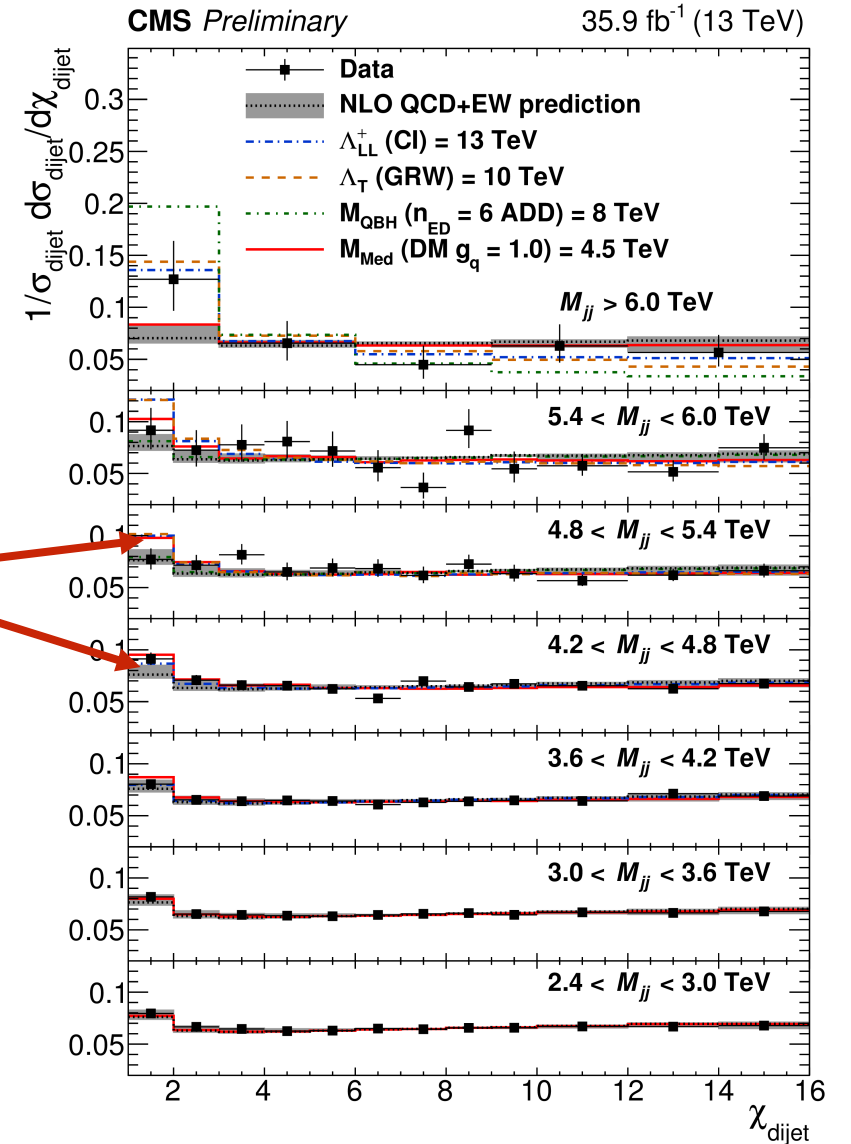
- Search for resonance in dijet invariant mass spectrum



1 TeV

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

DM mediator would show up here



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

