Direct search for dark matter in the mono-X final state with 13 TeV data

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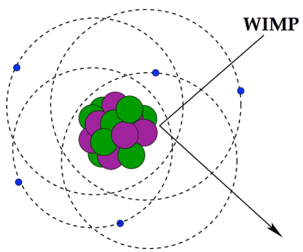
on behalf of the ATLAS and CMS collaborations

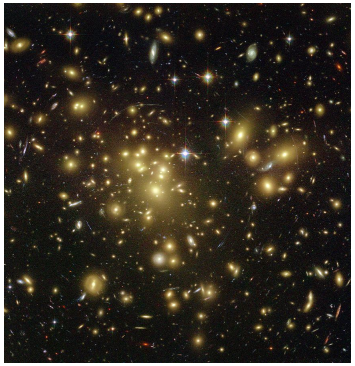
52nd Rencontres de Moriond
EW interactions and unified theories
March 18-25, 2017

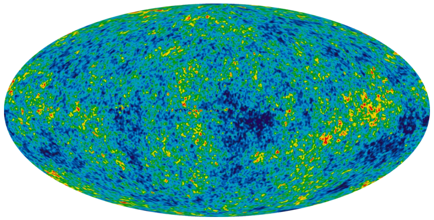
Dark matter (non-)observations

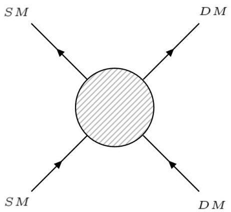
Sub-atomic scale | **Galaxies & clusters** | **Observable universe**



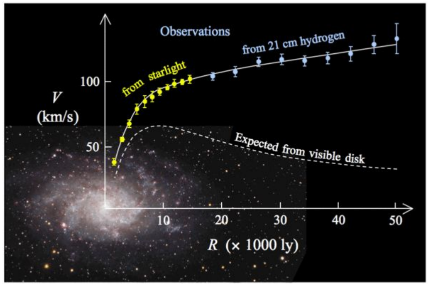
Rotational curves
Velocity dispersion
Gravitational lensing

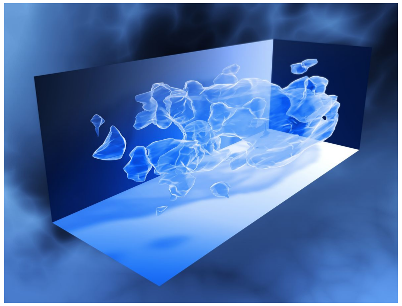






Production
Annihilation
Scattering





Large scale structures,
Cosmic Microwave Background

Weak interaction?

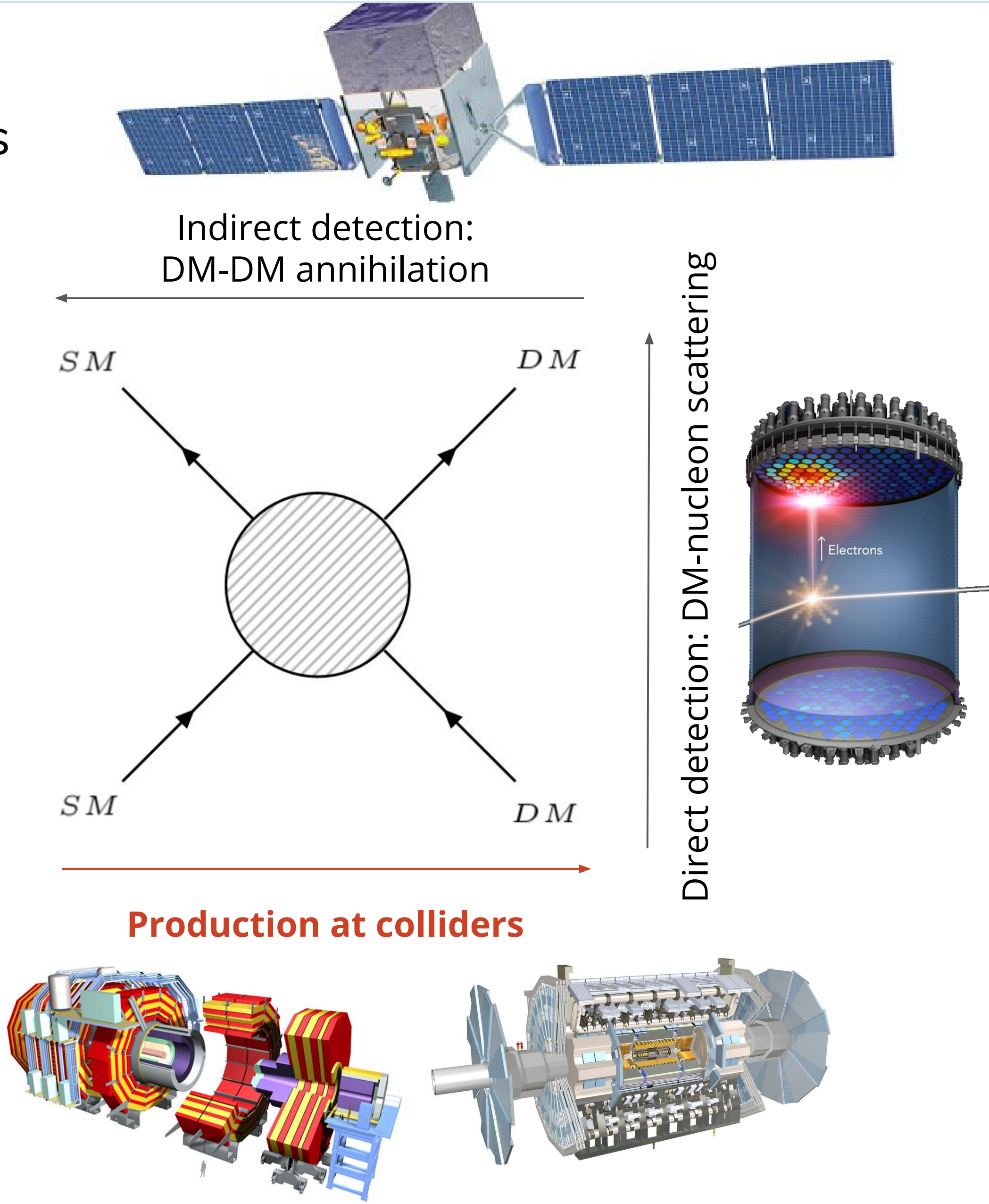
NOT OBSERVED

Gravitational interaction

OBSERVED

Dark Matter Searches at the LHC using Mono-X

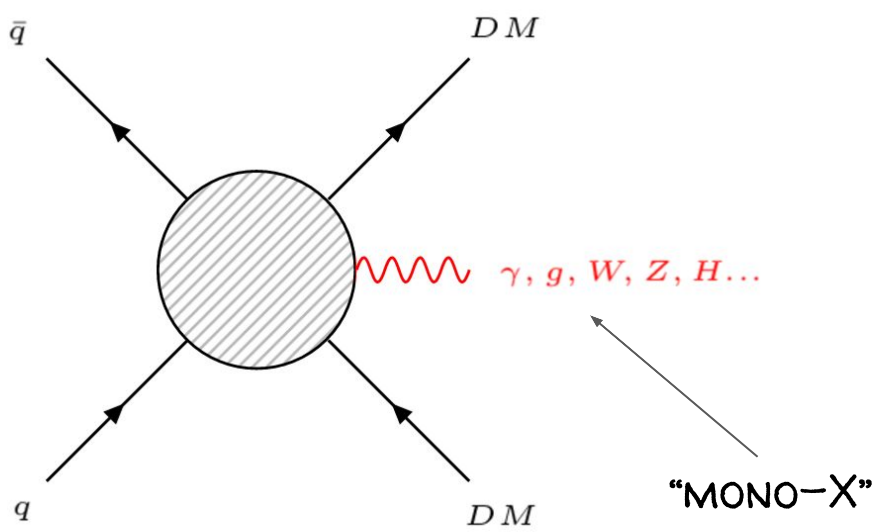
- Astrophysical evidence that **Dark Matter (DM) exists** and is >5x more abundant in the universe than ordinary matter. **Its nature is unknown**.
- A DM sector largely composed of Weakly Interacting Massive Particles (WIMPs) is well motivated and facilitates comparison of results between three areas of research.
- **The LHC may be able to produce DM particles.**

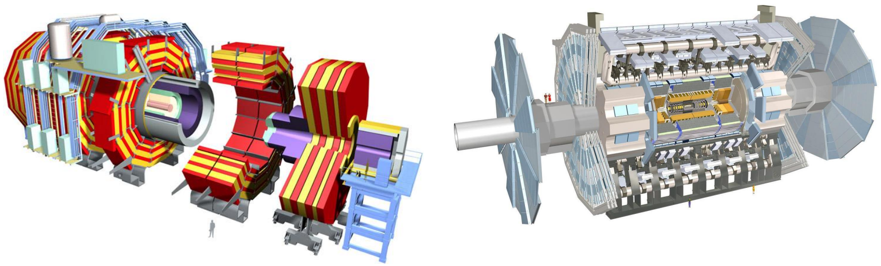


Dark Matter Searches at the LHC using Mono-X

- Astrophysical evidence that Dark Matter (DM) exists and is >5x more abundant in the universe than ordinary matter. Its nature is unknown.
- A DM sector largely composed of Weakly Interacting Massive Particles (WIMPs) is well motivated and facilitates comparison of results between three areas of research.
- **The LHC may be able to produce DM particles but ATLAS and CMS can not detect them.**

We need a SM particle recoiling against the invisible DM.





ATLAS & CMS Mono-X searches @ 13 TeV

SM particle	signature	CMS	ATLAS
Gluon	narrow jet	arXiv:1703.01651	PRD 94 (2016) 032005
W	wide jet		Phys. Lett. B 763 (2016)
Z			
	dilepton	CMS PAS EXO-16-038	ATLAS-CONF-2016-056
Photon	photon	CMS PAS EXO-16-039	JHEP 06 (2016) 059 Apr 2016 *)
Higgs	diphoton	CMS PAS EXO-16-011	ATLAS-CONF-2016-056
	bb (resolved)	CMS PAS EXO-16-012	Phys. Lett. B 765 (2017)
	bb (merged)		
	4 leptons		ATLAS-CONF-2015-059
b	1 b-jet	CMS PAS-B2G-15-007	
bb	2 b-jets		ATLAS-CONF-2016-086
t	wide jet	CMS PAS-EXO-16-040	
tt	all-hadronic	CMS PAS-EXO-16-005	ATLAS-CONF-2016-077
	semi-leptonic		ATLAS-CONF-2016-050
	dileptonic	CMS PAS-EXO-16-028	ATLAS-CONF-2016-076

2-3 fb^{-1}

13 fb^{-1}

*) Updated with 36 fb^{-1}

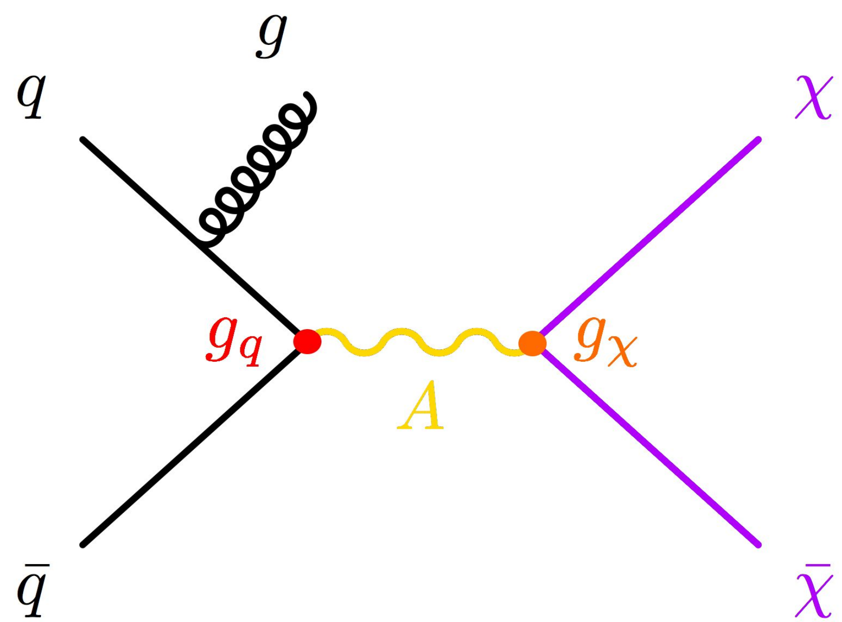
Interpretations of Mono-X results

Effective Field Theory (EFT)

- Commonly used for interpretations of Run 1 results.
- The SM-DM mediator is integrated out.
- Two parameters: DM mass and effective energy scale.
- Valid only when momentum transfer << mediator mass.
- Restricted range of validity at the LHC, more so in Run 2.

Simplified Models

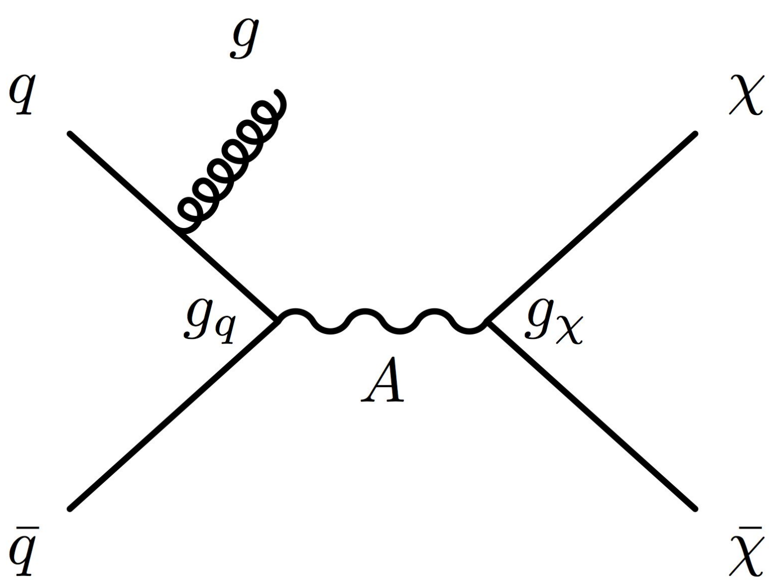
- Focus of Run 2 searches.
- One DM and one new mediator on top of the Standard Model.
- Multiple parameters:
  - DM mass
  - Mediator mass and width
  - Mediator SM coupling
  - Mediator DM coupling



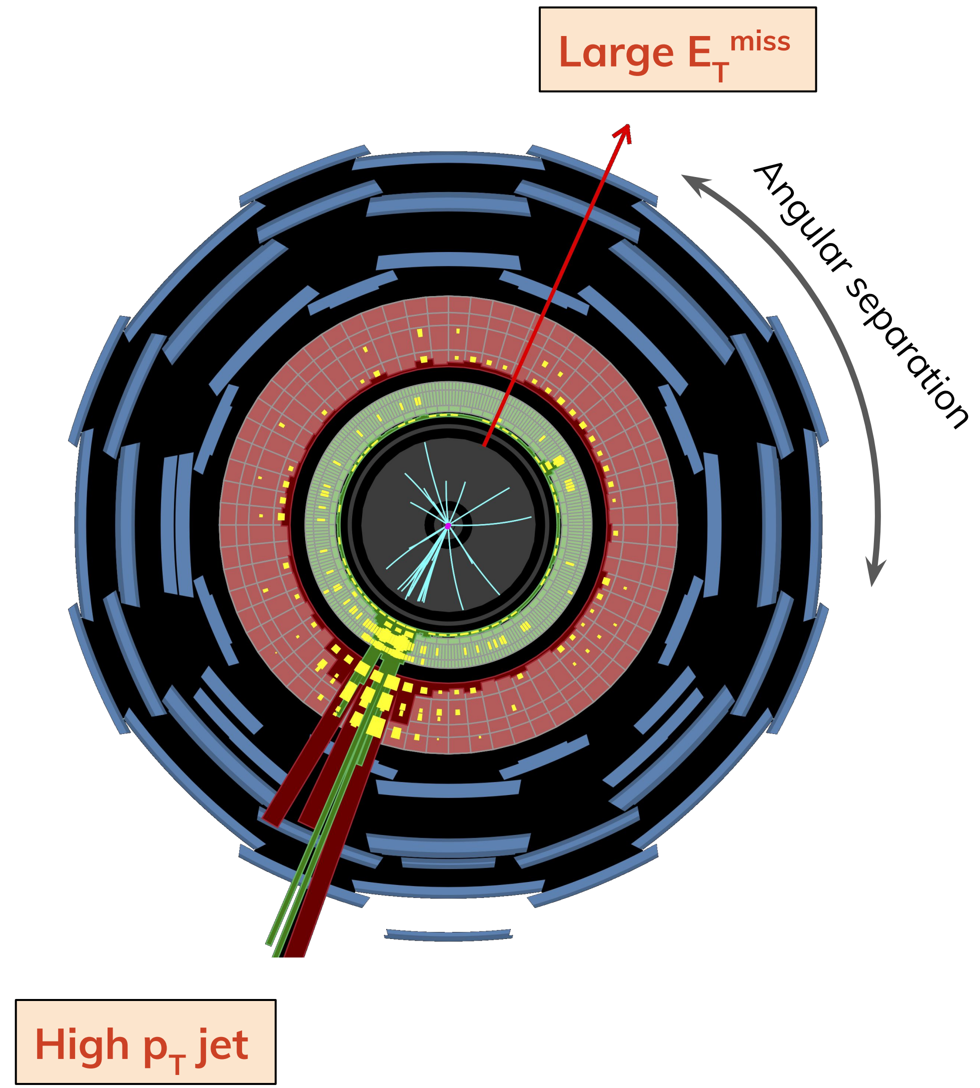
- Benchmark parameter choices recommended by LHC DM Forum and LHC DM Working Group (arXiv:1507.00966, arXiv:1603.04156).

Mono-jet

Mono-Jet

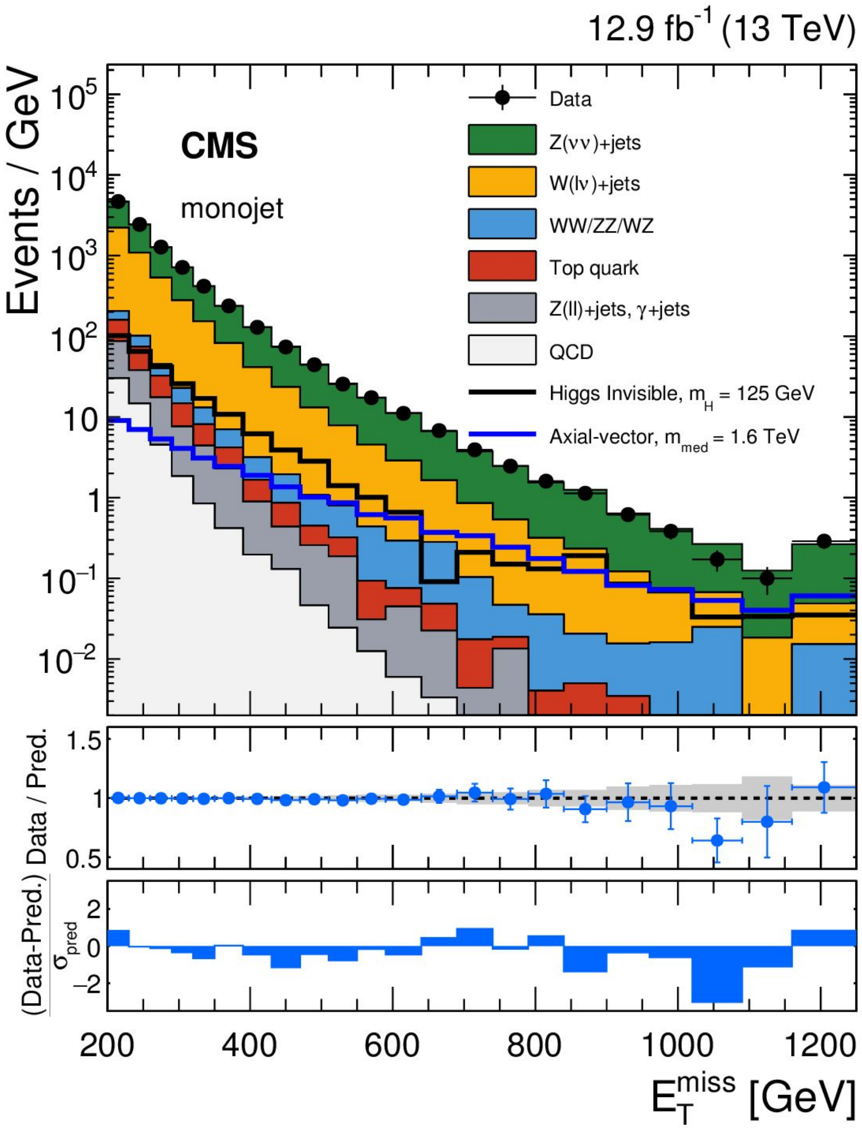


g
q
χ
g_q
g_χ
A
$\bar{q}$
$\bar{\chi}$



Large E_T^{miss}
Angular separation
High p_T jet

Mono-Jet

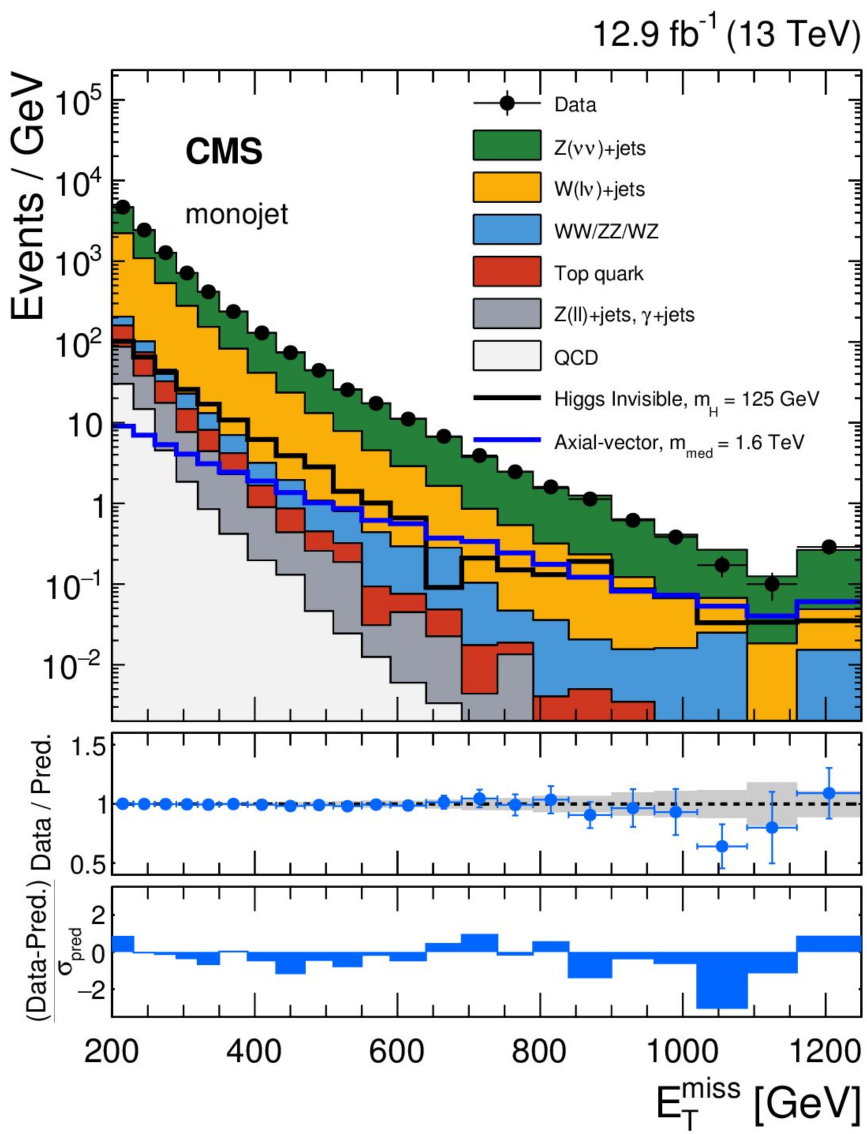


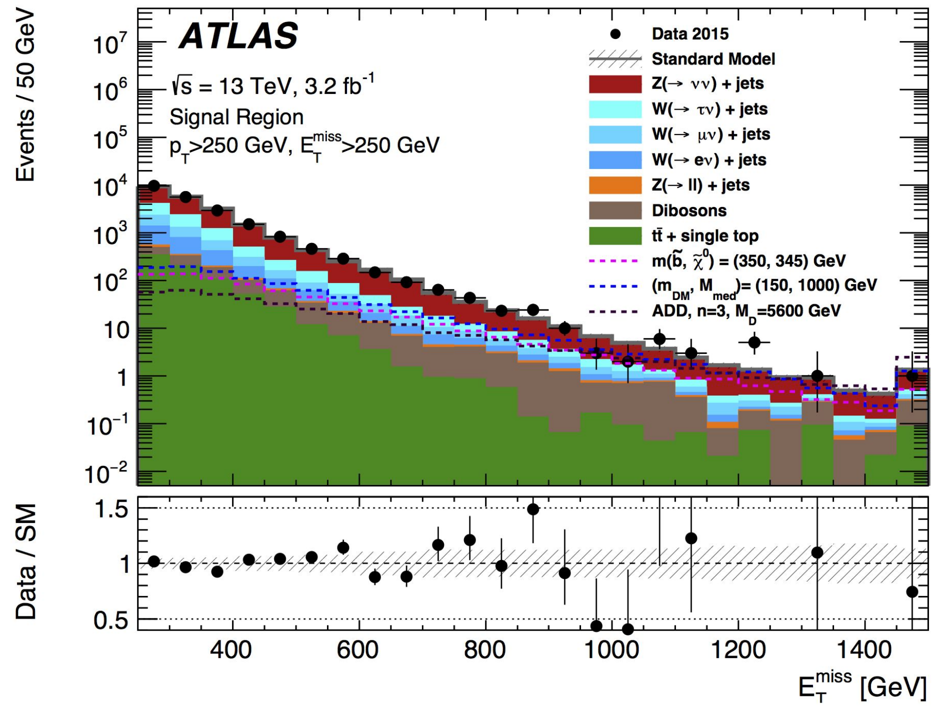
Precise background modelling needed - achieved through normalization of simulated samples in control regions.

Crucially, **γ+jets** (CMS) and **W+jets** (ATLAS & CMS) events are used to constrain the **dominant and irreducible Z⇨νν+jets background**.

Compared to Z⇨ll control regions alone, this strategy benefits from **higher statistics**, which **is paid for with modeling uncertainties** from PDF, scale choices, EW corrections…

Mono-Jet

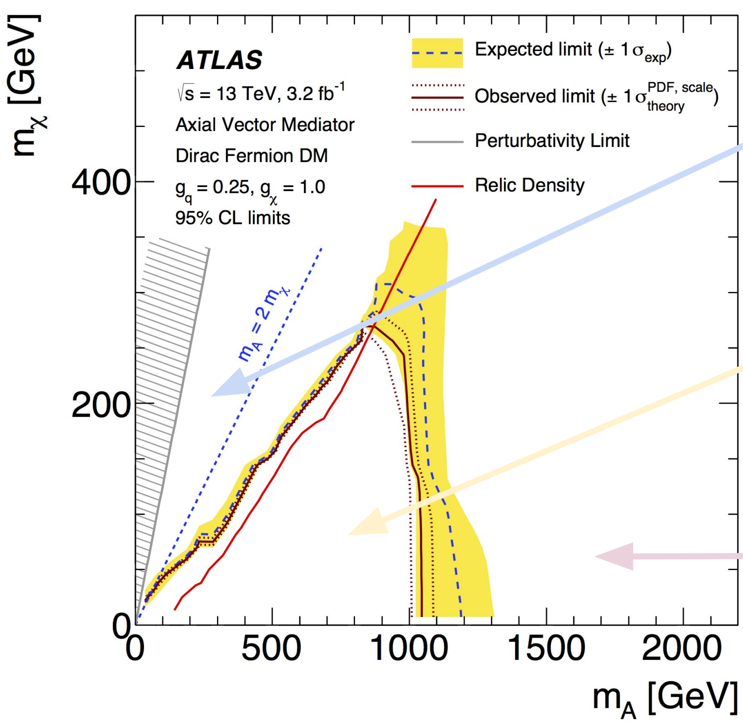




No excess observed ⇨ signal exclusion limits obtained from simultaneous fit to signal and control regions in bins of E_T^{miss} with independent background normalizations.

Mono-Jet

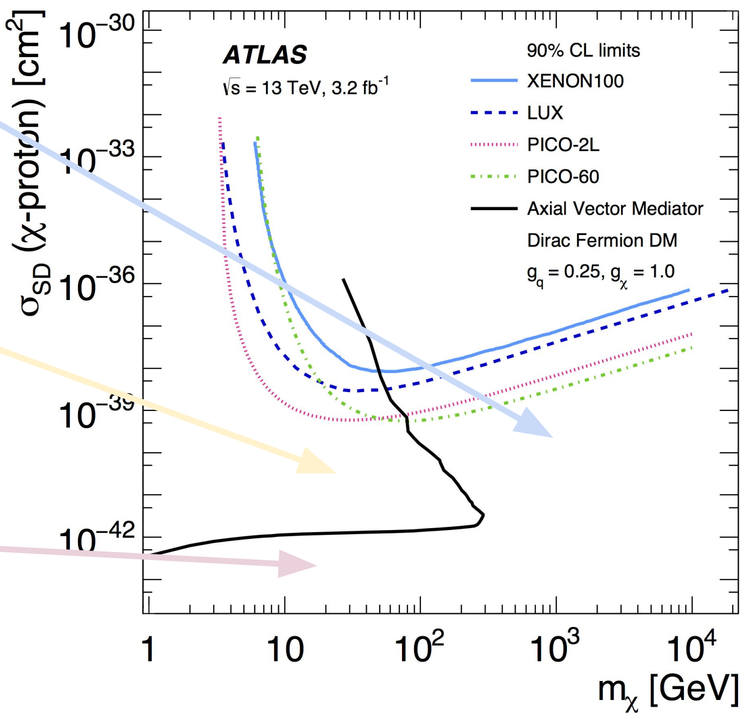
ATLAS limits on axial vector mediator with g_q=0.25, g_χ=1.0



Mediator decay to DM suppressed, relic DM underproduced

LHC exclusion

Mediator production suppressed, relic DM overproduced



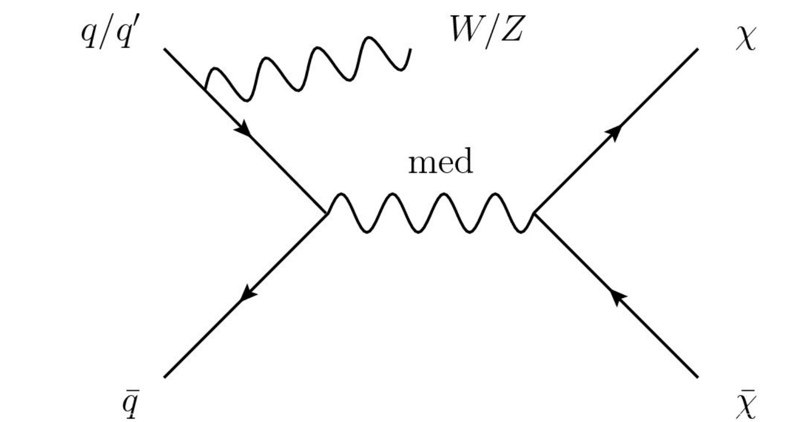
DM excluded up to 250 GeV for mediator mass of 1 TeV.

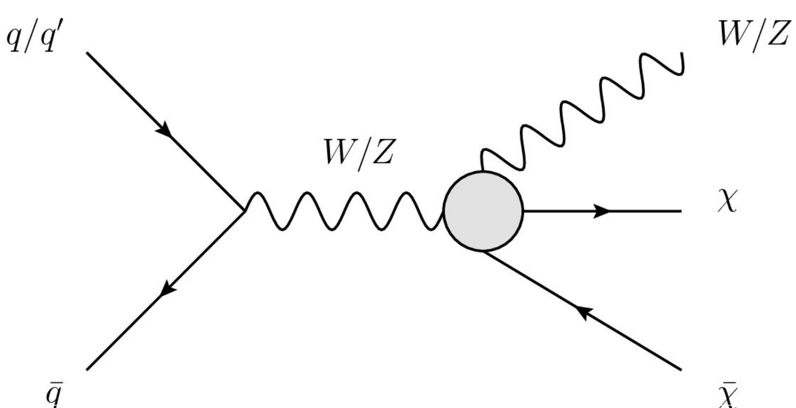
Interpretation as limit on DM-proton scattering cross section

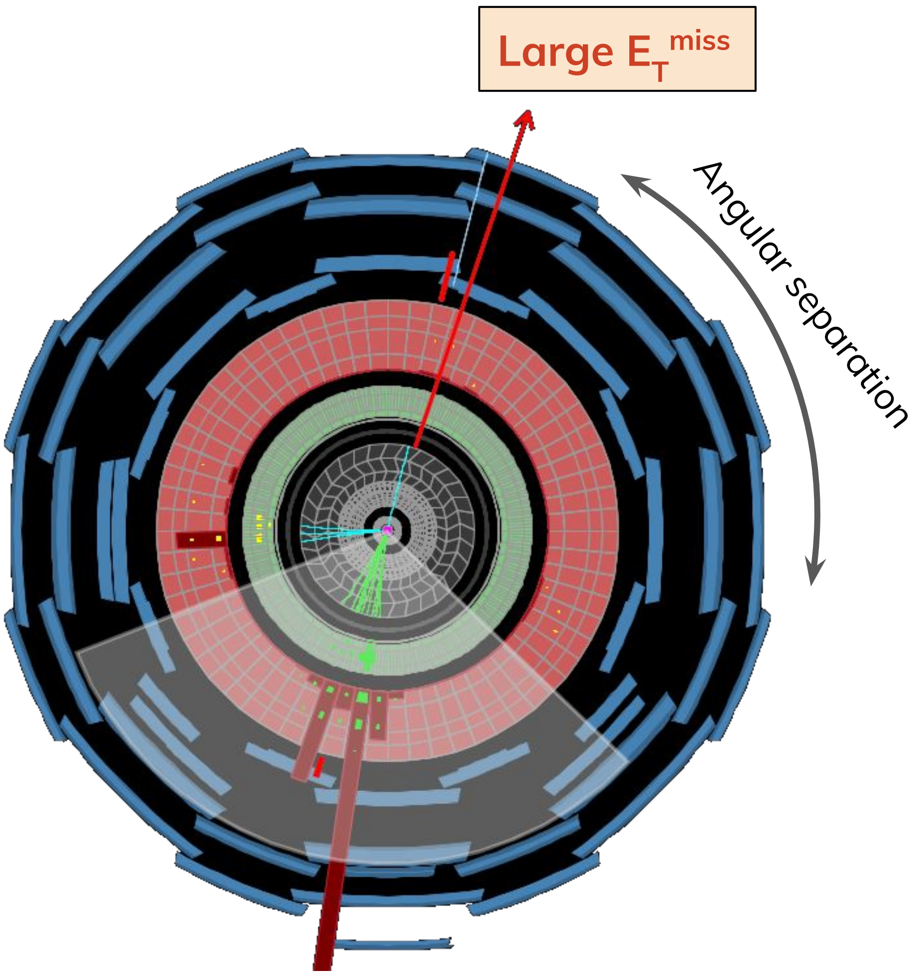
- LHC adds sensitivity at low m_χ
- Comparison is model dependent.

Mono-W/Z

Mono-W/Z (hadronic)





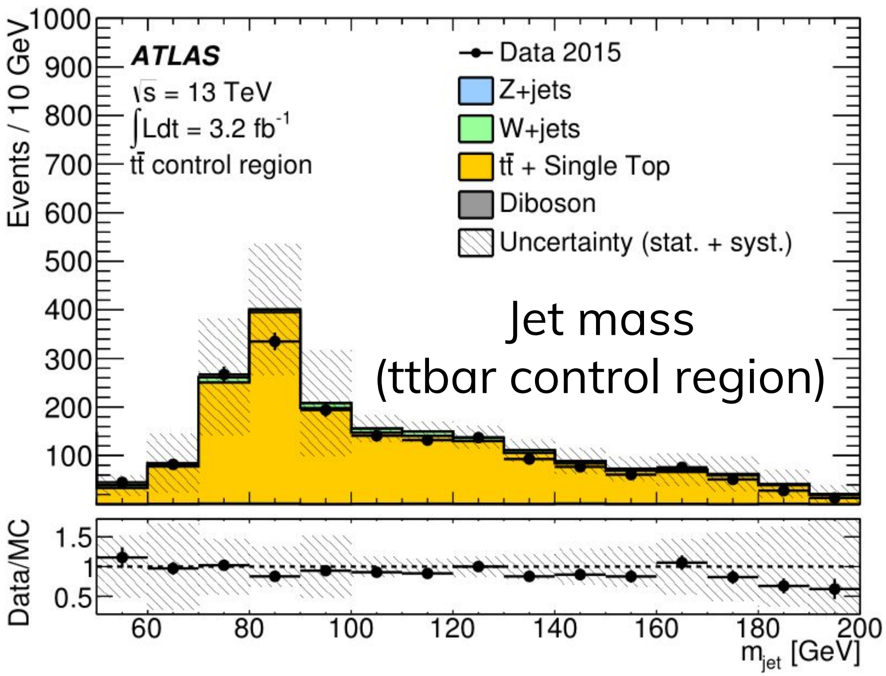


Hadronically decaying, highly boosted W or Z boson, reconstructed as a single wide-R jet.

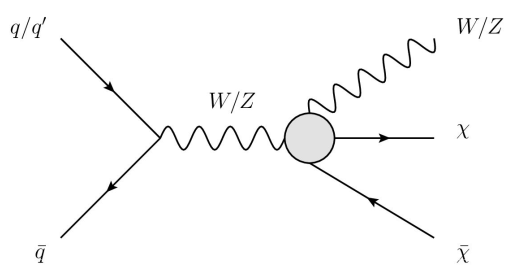
(Mono-Z in the dilepton final state is also searched for, but not shown here.)

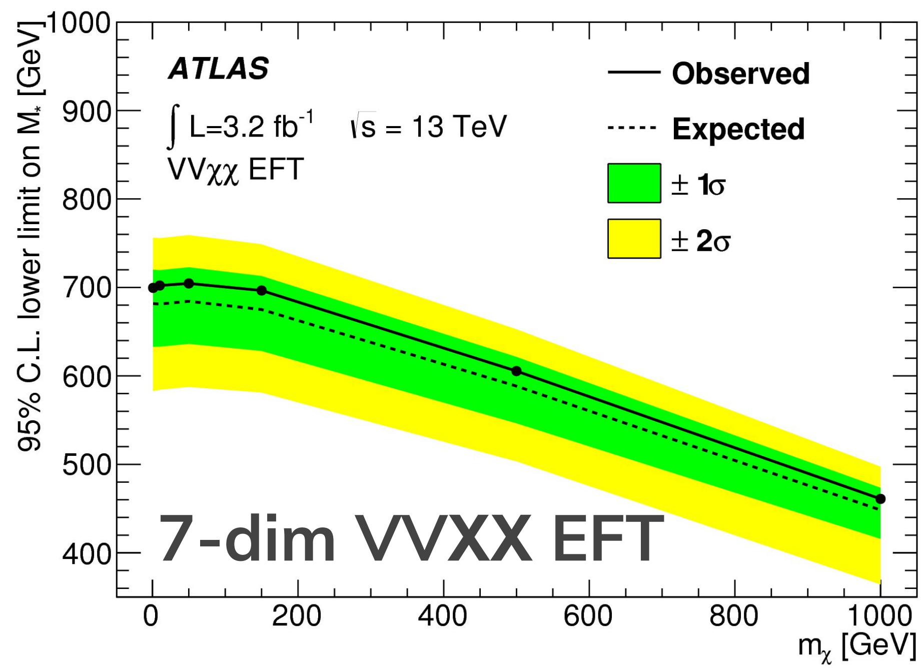
Mono-W/Z (hadronic)

Vector boson tagging using jet mass and substructure information is a key tool here.



The **tagging efficiency is a major source of uncertainty** with 5-15% effect on signal yield.

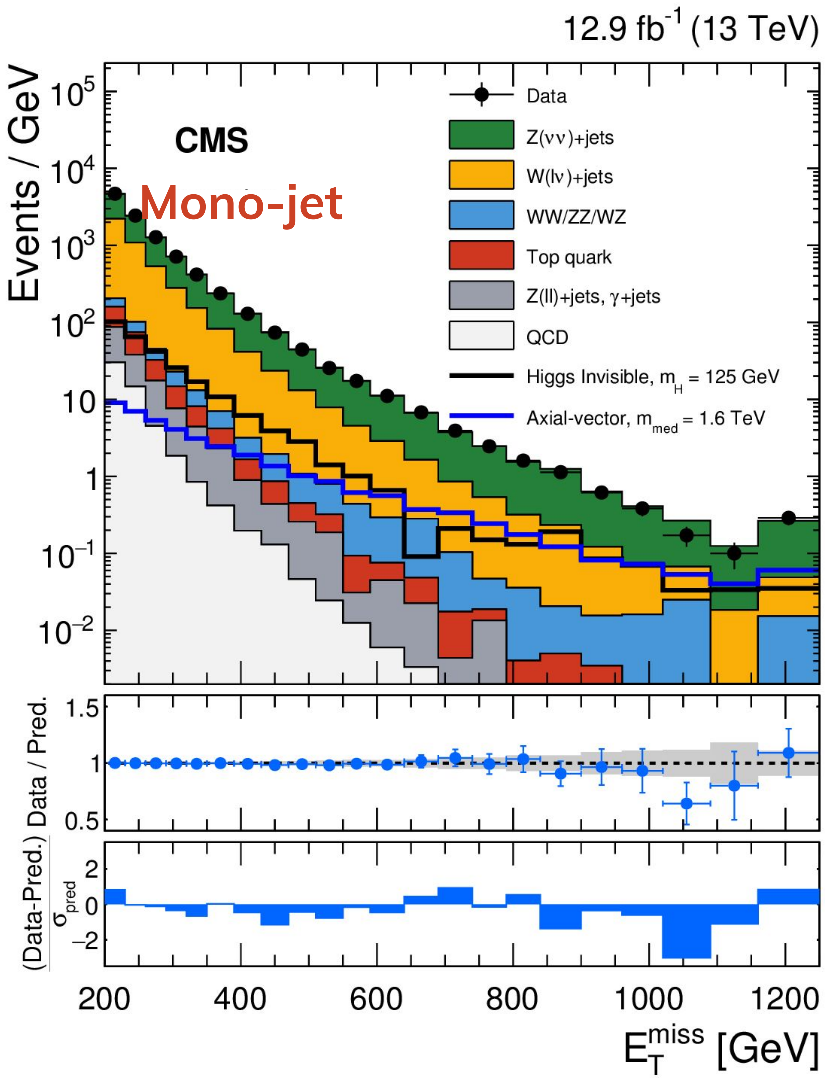


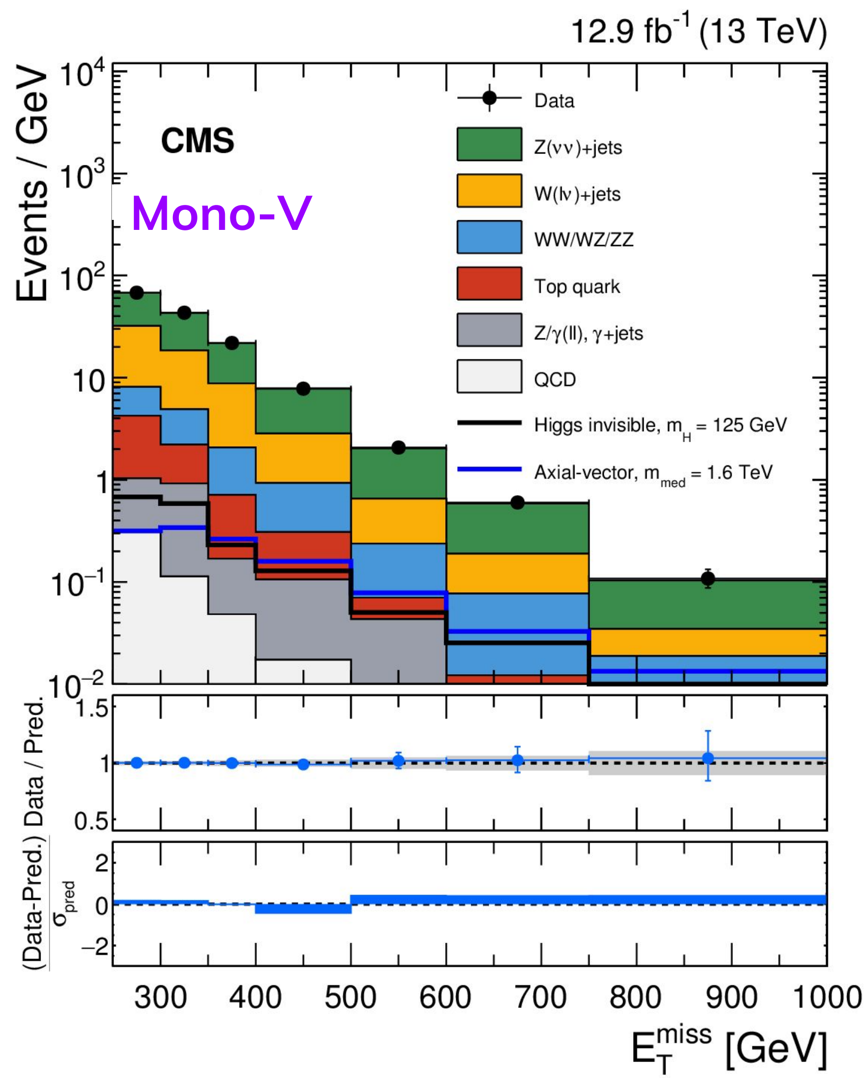


Uniquely, this channel allows us to probe for a **VVXX contact interaction**.

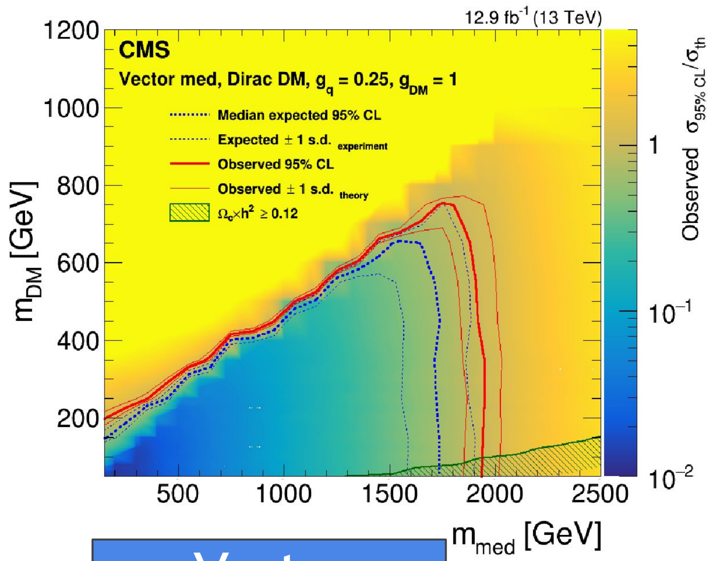
Mono-Jet and -W/Z (hadronic) in CMS

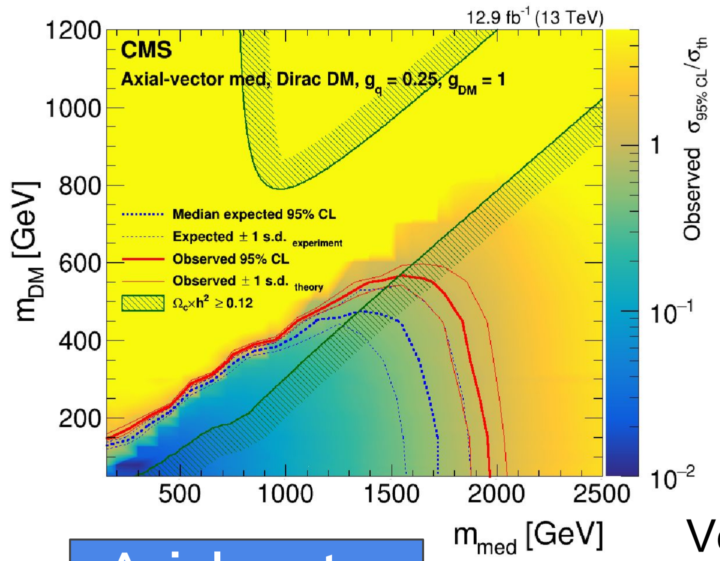
The two channels are very similar - CMS treats them both in a single analysis



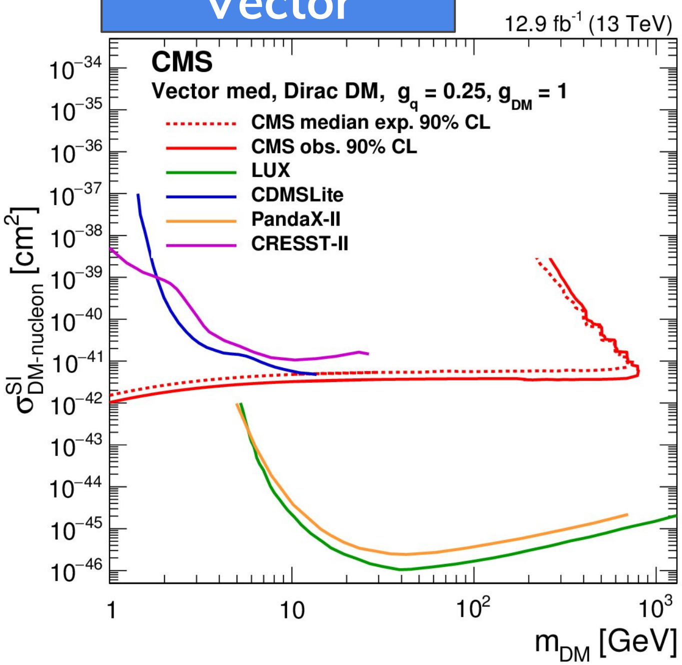


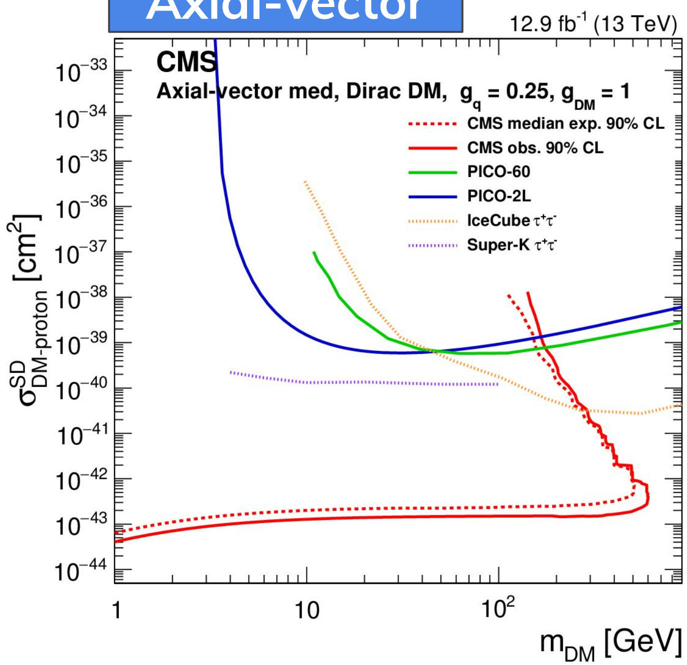
Mono-Jet and -W/Z (hadronic) in CMS





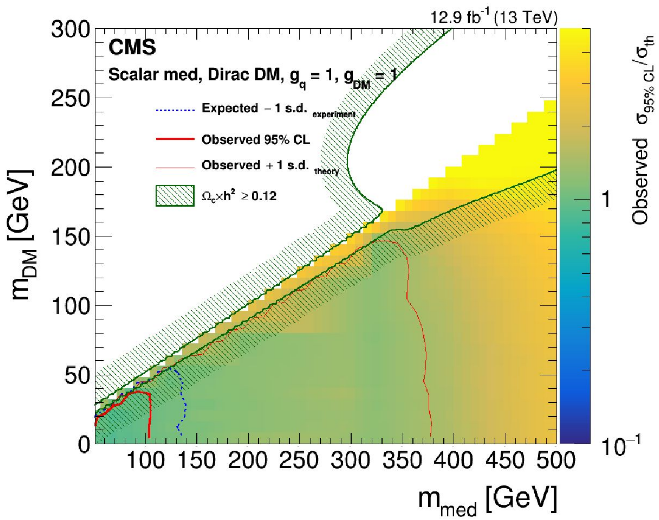
Vector | **Axial-vector**



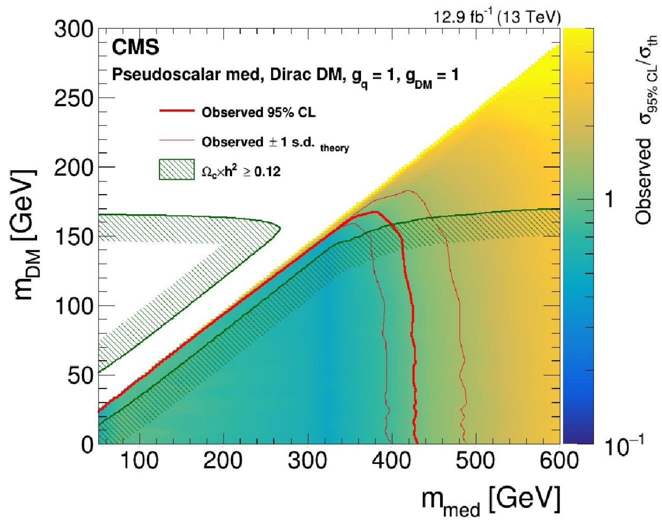


Vector and axial-vector mediators excluded up to 1.95 TeV.

Mono-Jet and -W/Z (hadronic) in CMS

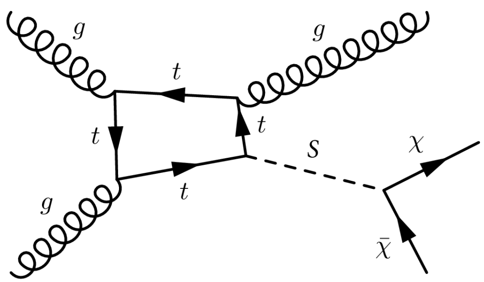


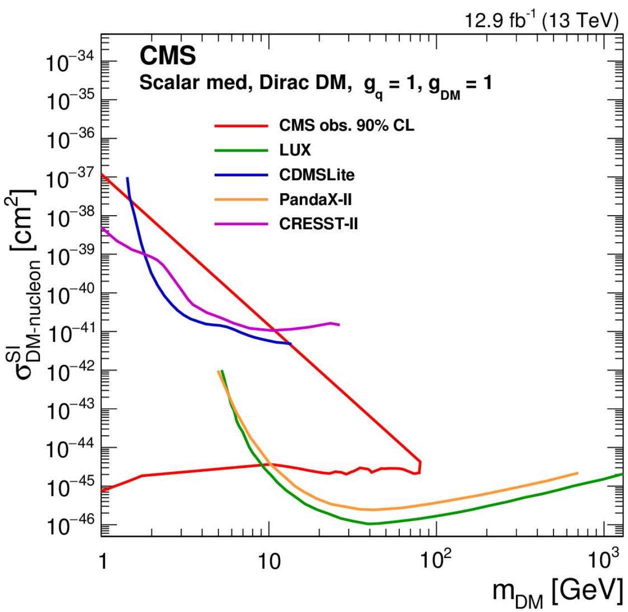
Scalar

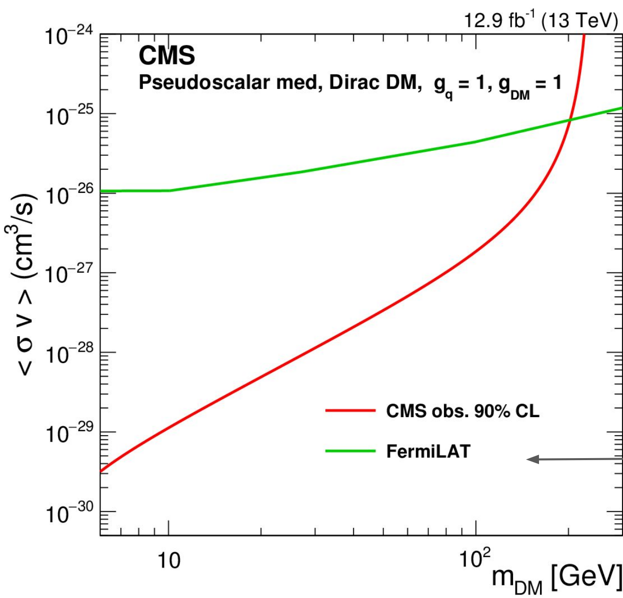


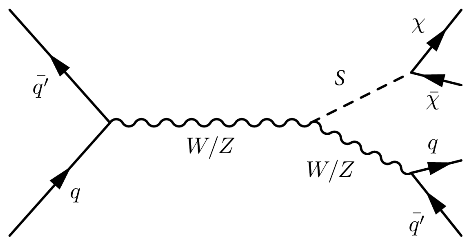
Pseudoscalar

Limits on spin-0 mediators are also provided by CMS.







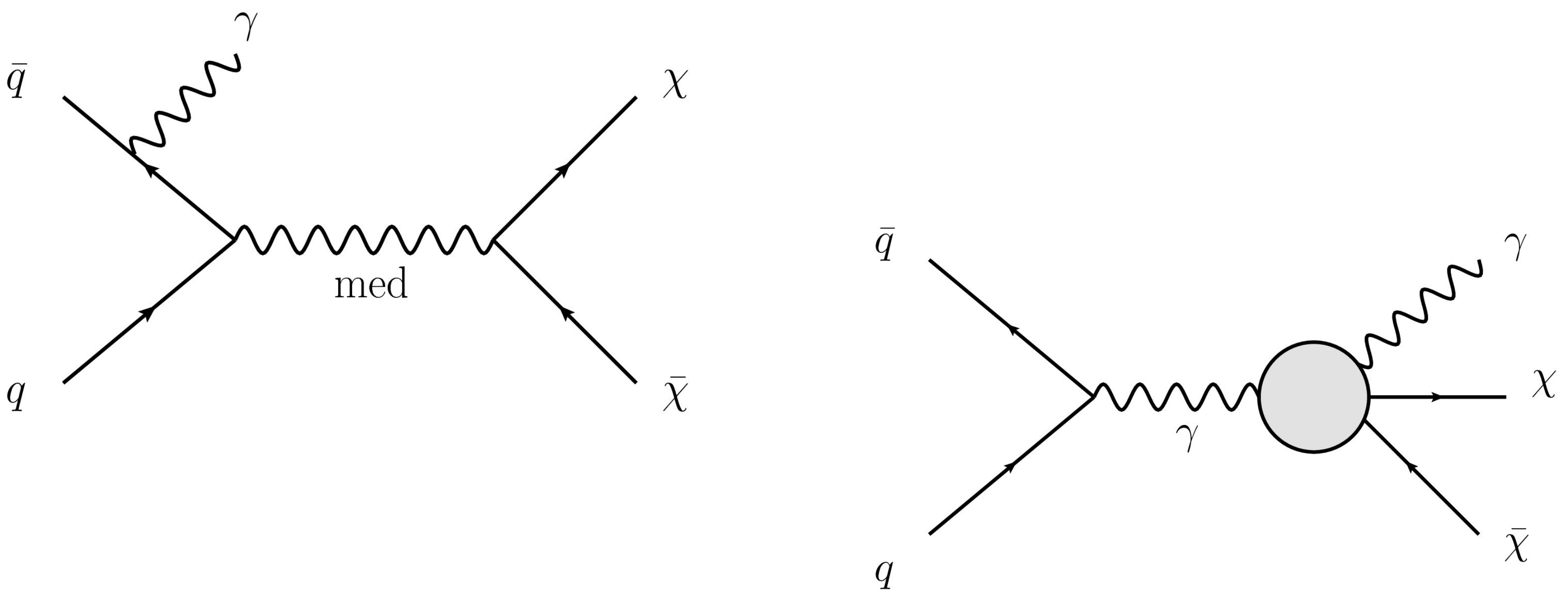


Only other limits on pseudoscalar mediator are from Fermi-LAT

Mono-photon

Mono-Photon

Mono-photon offers **clean events with low background**.
Similar to mono-Z/W, we can probe for a **γγXX contact interaction** in addition to the simplified models.



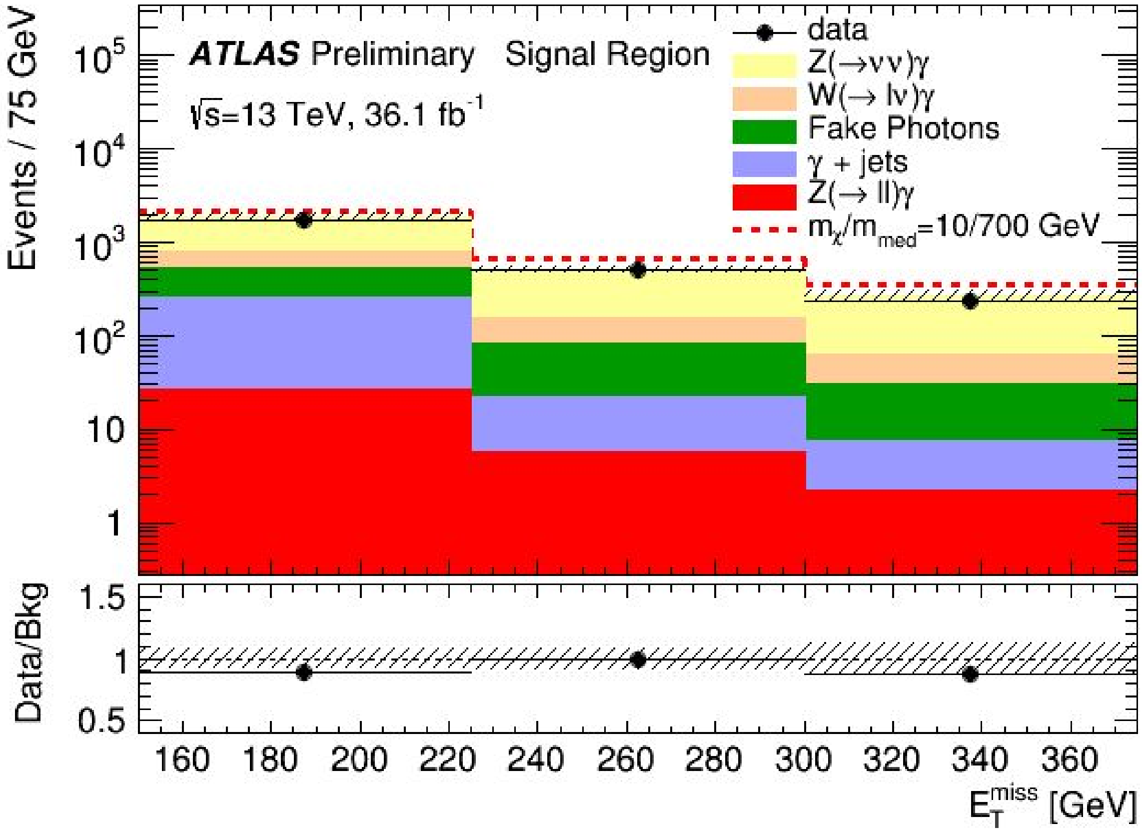
Fake photon backgrounds are estimated using data driven methods.
Z/W/jet+photon backgrounds are taken from simulations, normalized in control regions (2e and 2μ, 1μ, inverted γ/jet separation) by ATLAS.

Mono-Photon

NEW! 36 fb^{-1}

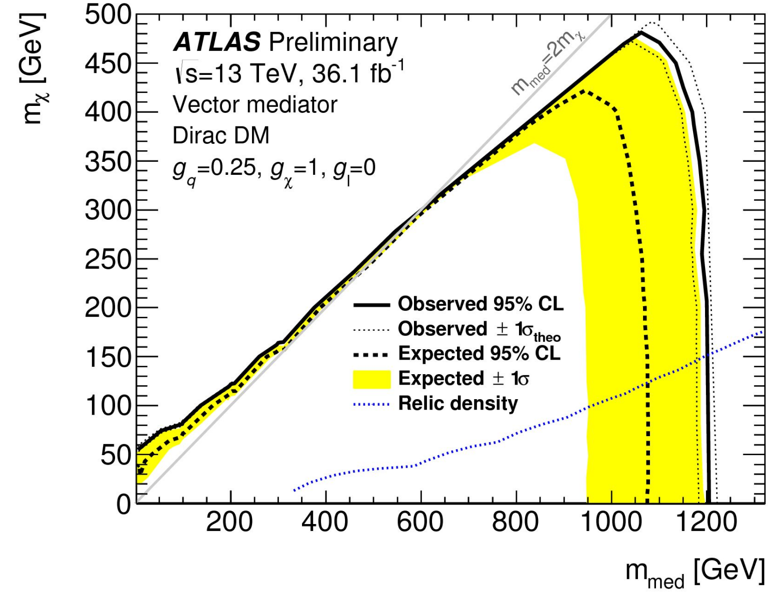
The **ATLAS** mono-photon analysis has been updated to the full 2015+2016 dataset (to appear on arXiv soon).

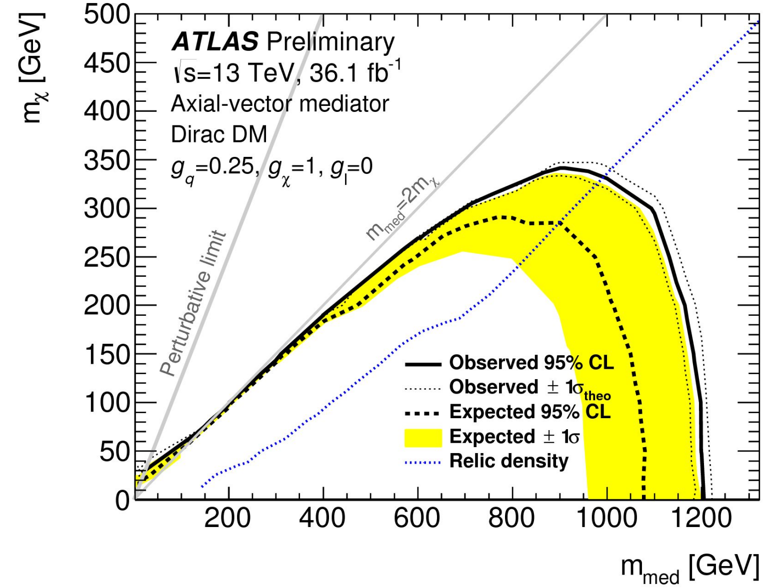
New in this version is **bins of E_T^{miss} with independent background normalizations** and an updated event selection making **use of a minimum cut on $E_T^{miss}/\sqrt{(\sum E_T)}$** due to high pileup in 2016 degrading the E_T^{miss} performance.

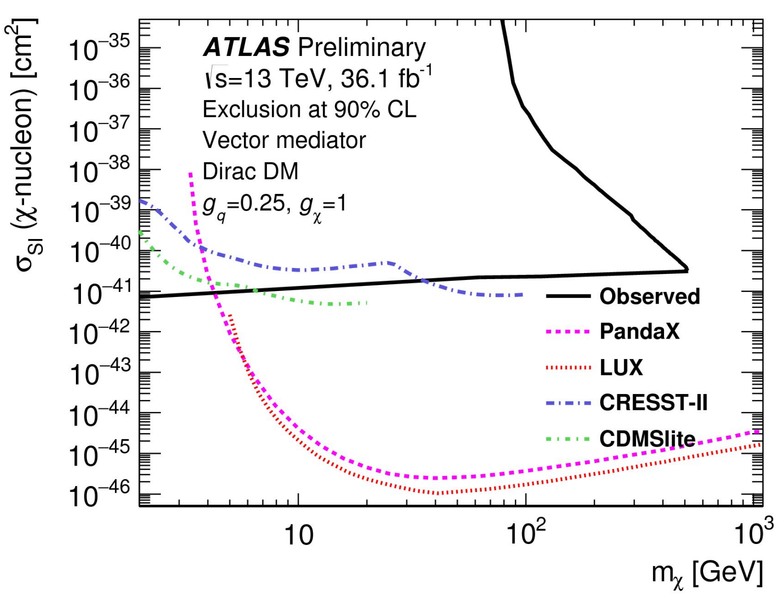


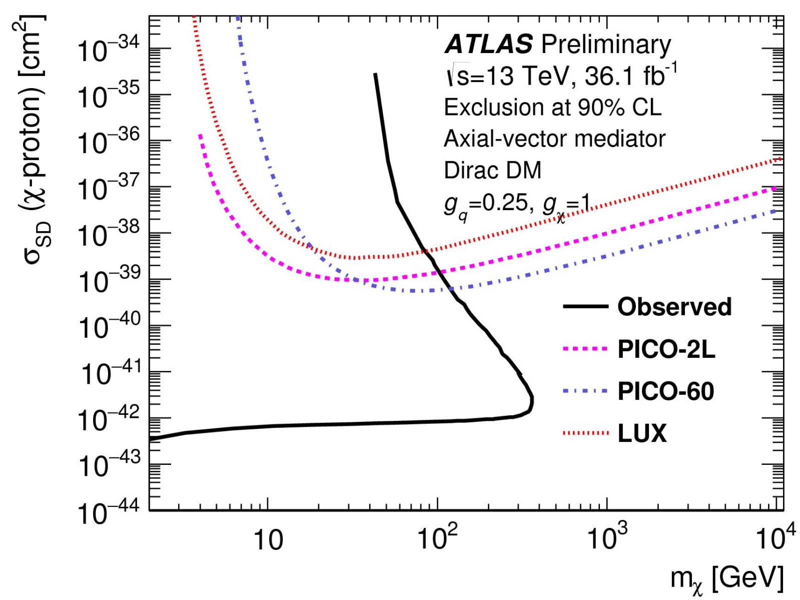
With 36 fb^{-1}, the sensitivity is still limited by statistics, but systematic uncertainties are also important. In particular on hadronic **jets faking photons**, contributing 1.3-5.3% uncertainty on the total background yield.

Mono-Photon


ATLAS Preliminary
√s=13 TeV, 36.1 fb-1
Vector mediator
Dirac DM
gq=0.25, gχ=1, gl=0
mmed=2mχ
Observed 95% CL
Observed ± 1σtheo
Expected 95% CL
Expected ± 1σ
Relic density
mχ [GeV]
mmed [GeV]


ATLAS Preliminary
√s=13 TeV, 36.1 fb-1
Axial-vector mediator
Dirac DM
gq=0.25, gχ=1, gl=0
Perturbative limit
mmed=2mχ
Observed 95% CL
Observed ± 1σtheo
Expected 95% CL
Expected ± 1σ
Relic density
mχ [GeV]
mmed [GeV]

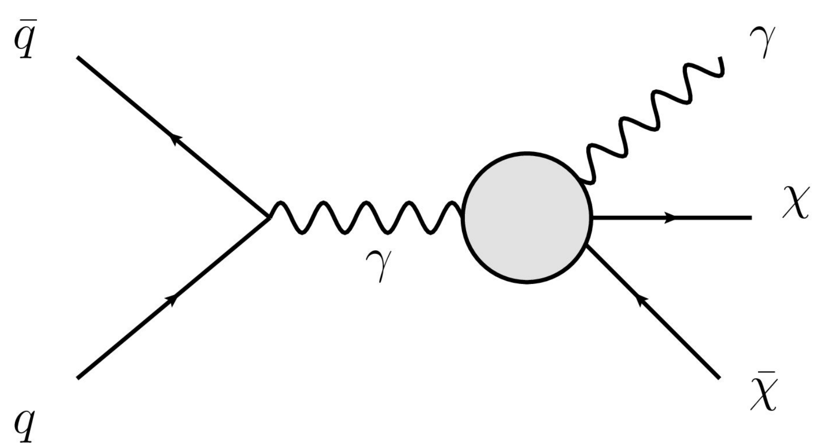

ATLAS Preliminary
√s=13 TeV, 36.1 fb-1
Exclusion at 90% CL
Vector mediator
Dirac DM
gq=0.25, gχ=1
Observed
PandaX
LUX
CRESST-II
CDMSlite
σSI (χ-nucleon) [cm2]
mχ [GeV]

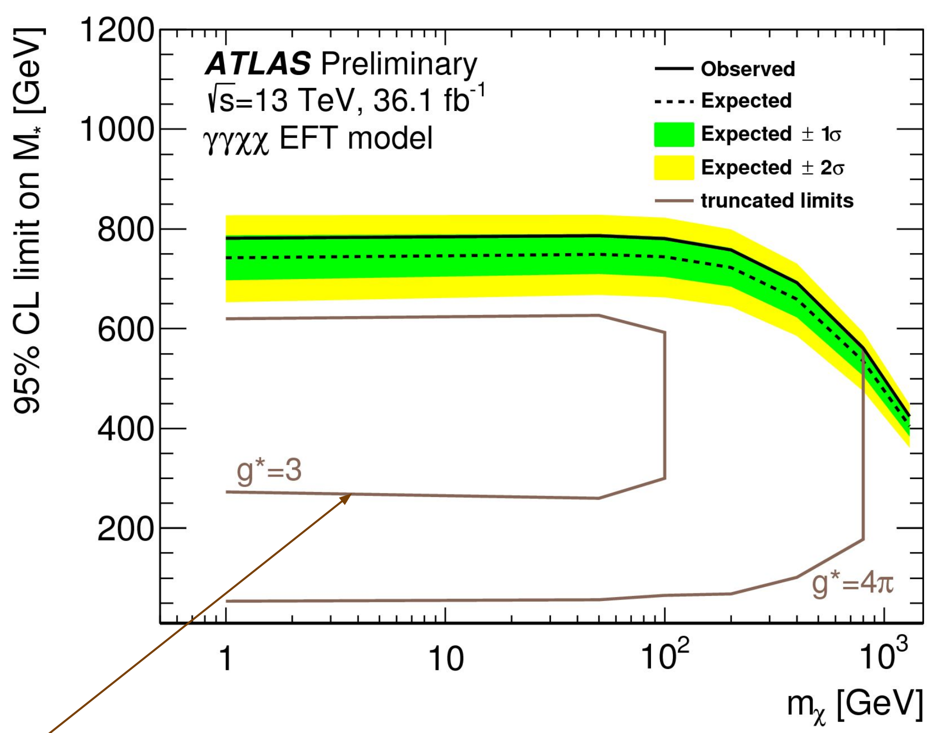

ATLAS Preliminary
√s=13 TeV, 36.1 fb-1
Exclusion at 90% CL
Axial-vector mediator
Dirac DM
gq=0.25, gχ=1
Observed
PICO-2L
PICO-60
LUX
σSD (χ-proton) [cm2]
mχ [GeV]

Mono-Photon

<u>γγXX Contact Interaction</u>

unique measurement in this channel





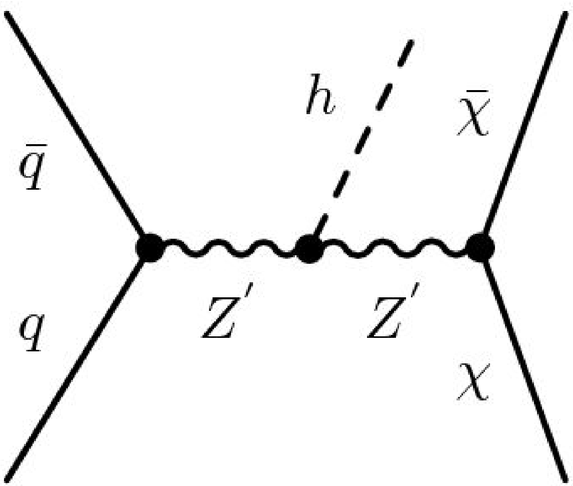
The EFT is not always valid!
"Truncation" results show the effect of recomputing the limit after removing events with too large center-of-mass energy at different ETF coupling strengths.

Mono-Higgs

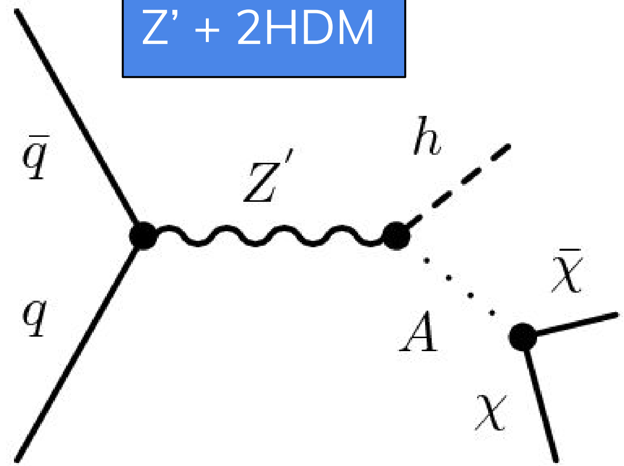
Mono-H (bb)

Higgs ISR is Yukawa suppressed, instead H can be emitted by the mediator itself - direct test of the SM-DM coupling structure.

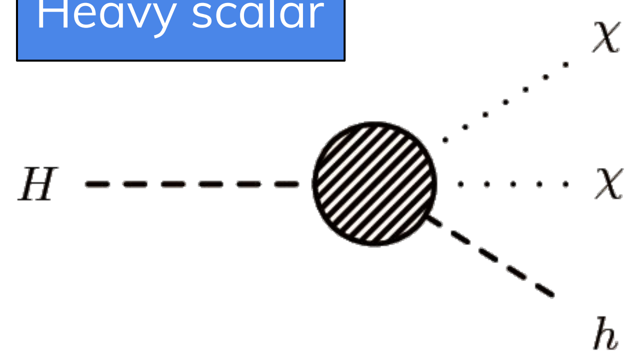
Z’ with Higgs boson coupling



Z’ + 2HDM



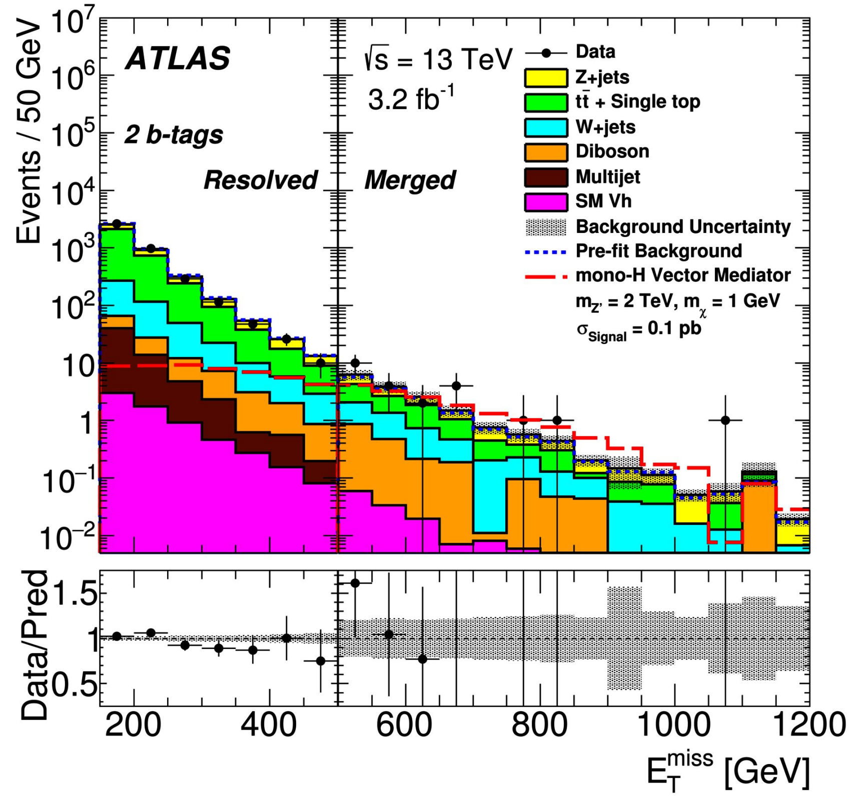
Heavy scalar

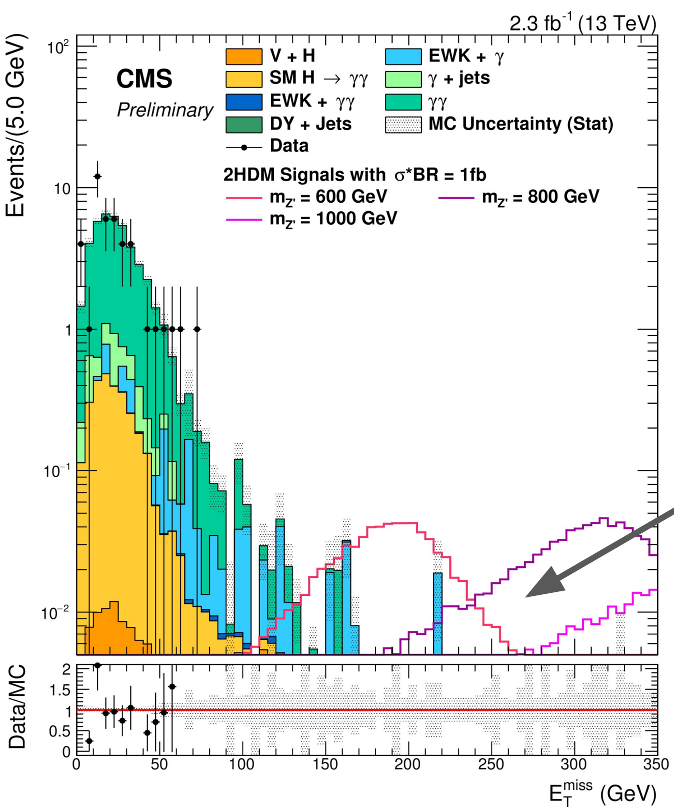


Mono-H (bb)

The bb decay channel is the most sensitive due to the large branching fraction.

Event categories with **two resolved jets or a single merged jet** (depending on the Higgs boost) are both considered.





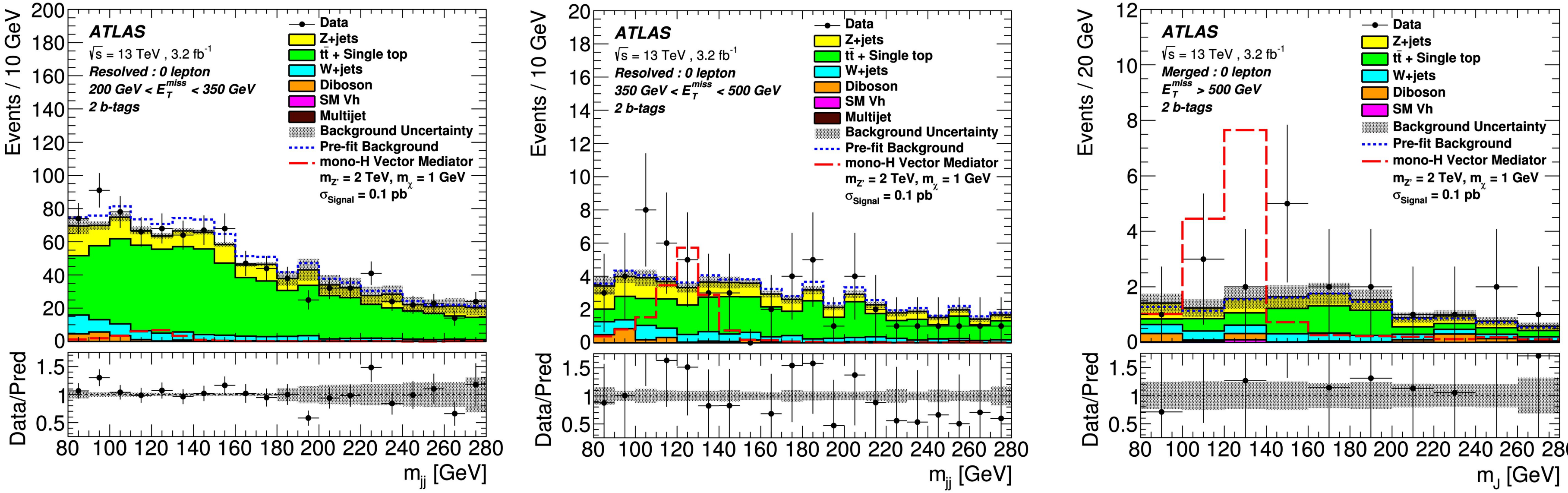
Diphoton channel offers clean event selection with very few background events at high E_T^{miss} after mass requirements.

ATLAS has also analyzed the DM + 4 lepton final state as part of the SM cross section measurement, but it suffers from low statistics.

Mono-H (bb)

Signal extraction is performed in bins of E_T^{miss}.

ATLAS fits the invariant mass distribution in each E_T^{miss} bin.

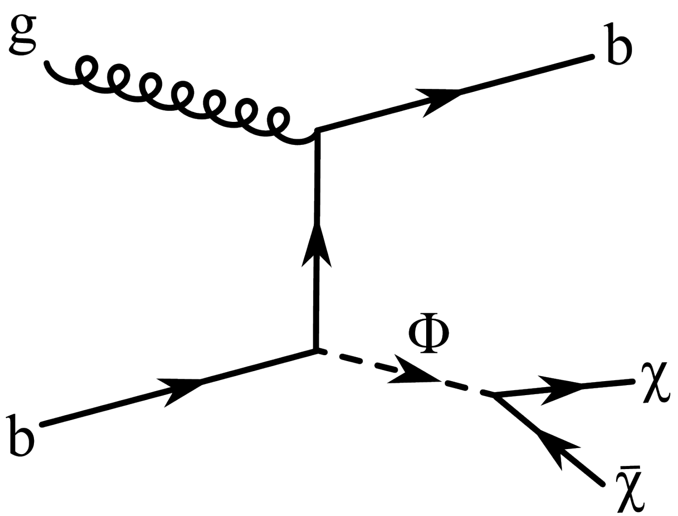


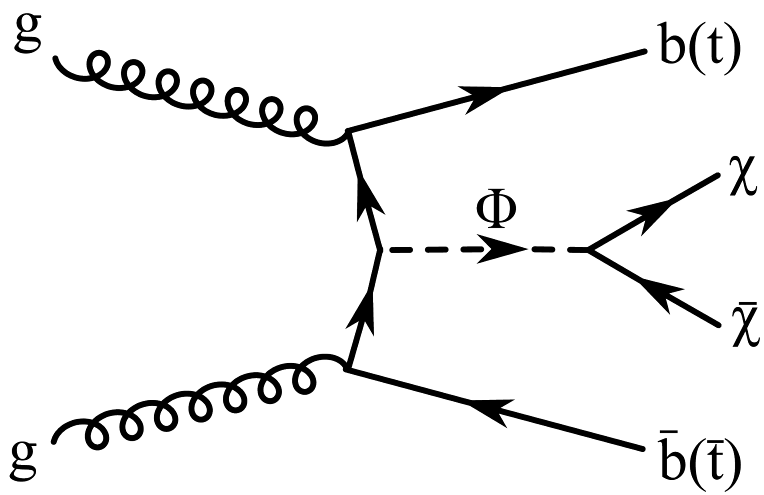
Main systematic is b-tagging efficiency, but with with 3 fb^{-1} the analysis is **limited by statistics**.

DM+HF

DM + Heavy Flavor

Yukawa couplings to quarks are expected for scalar mediators
⇒ study production in association with heavy flavor!

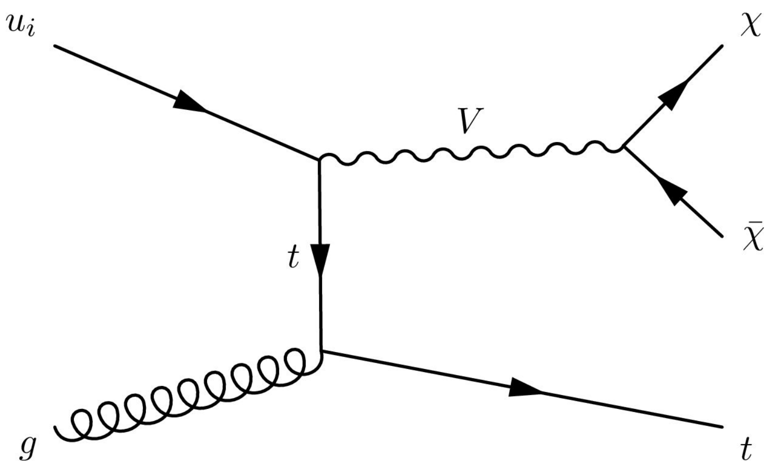


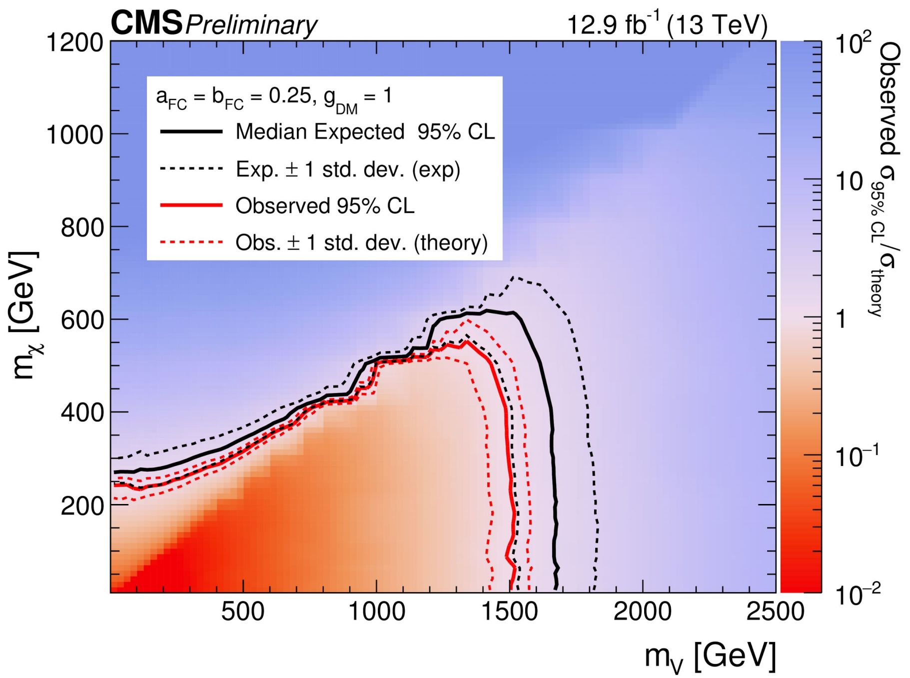


DM + top quark(s)

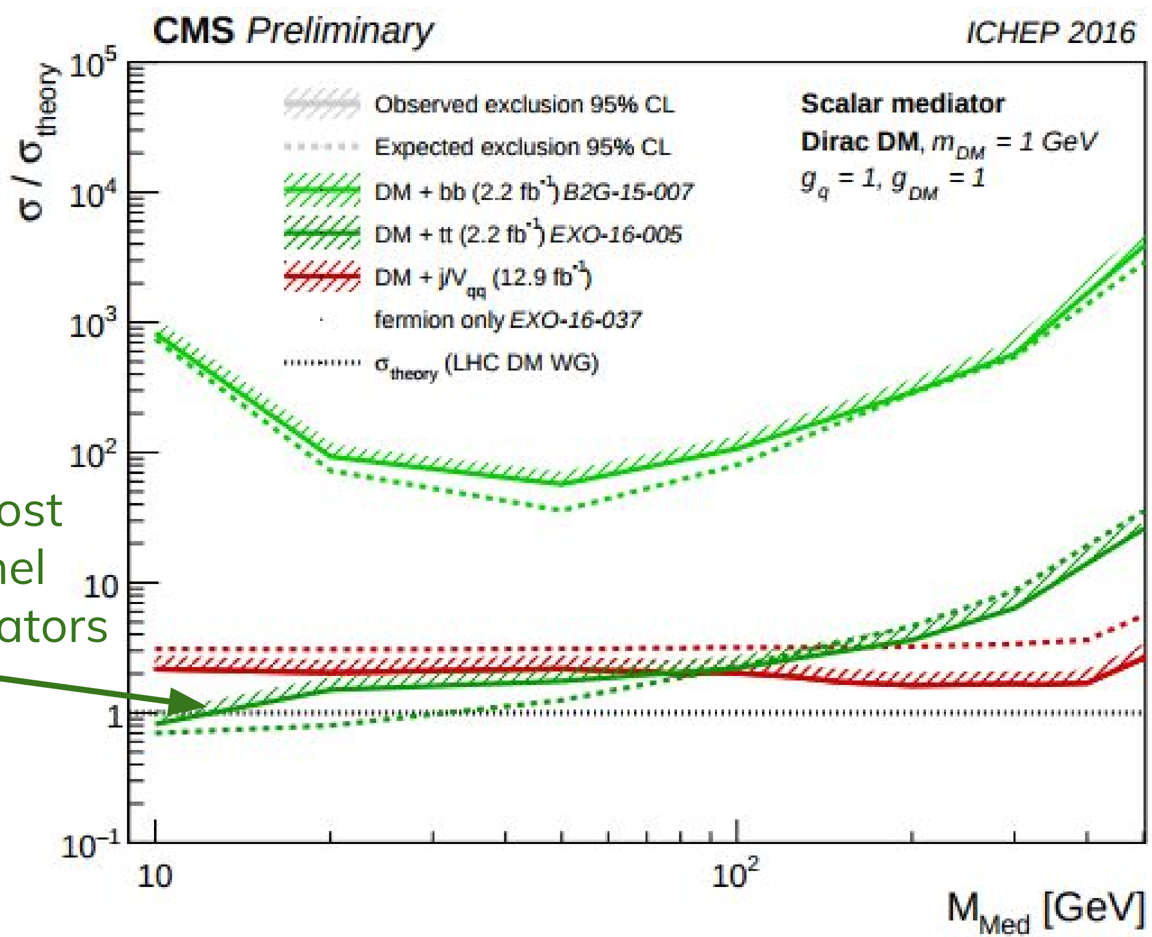
Both experiments analyze E_T^{miss} **+ tt production** in the fully hadronic, semi-leptonic, and dileptonic final states. The **fully hadronic** final state is the most sensitive to scalar mediators. **Top tagging** of large-R jets is employed.

CMS has also searched for a **single boosted top quark** that could be produced with a FCNC mediator.





DM + Heavy Flavor



DM+b(b) is also considered.

DM+tt is the most sensitive channel for scalar mediators at low mass.

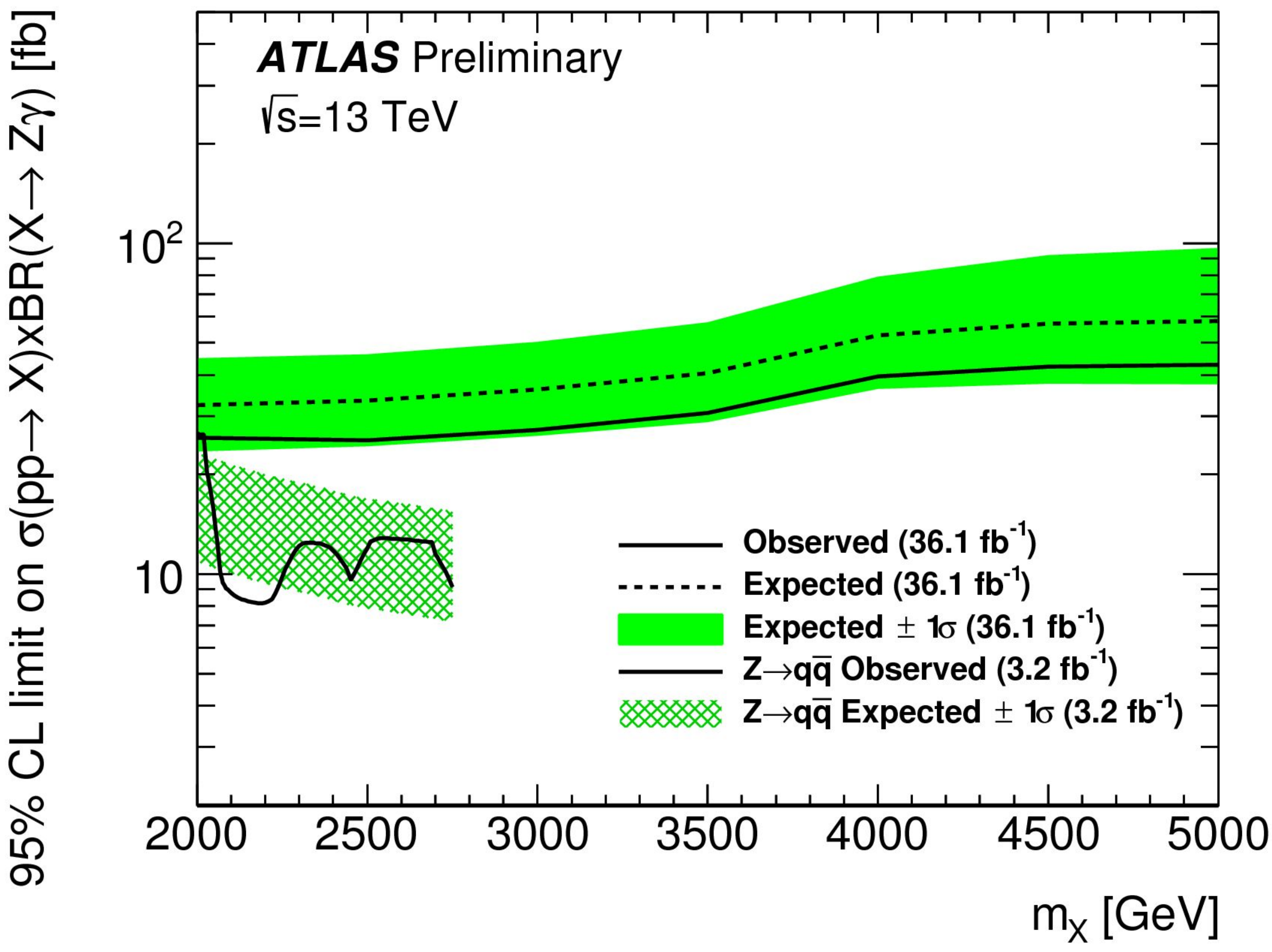
Mono-jet/W/Z

Conclusions

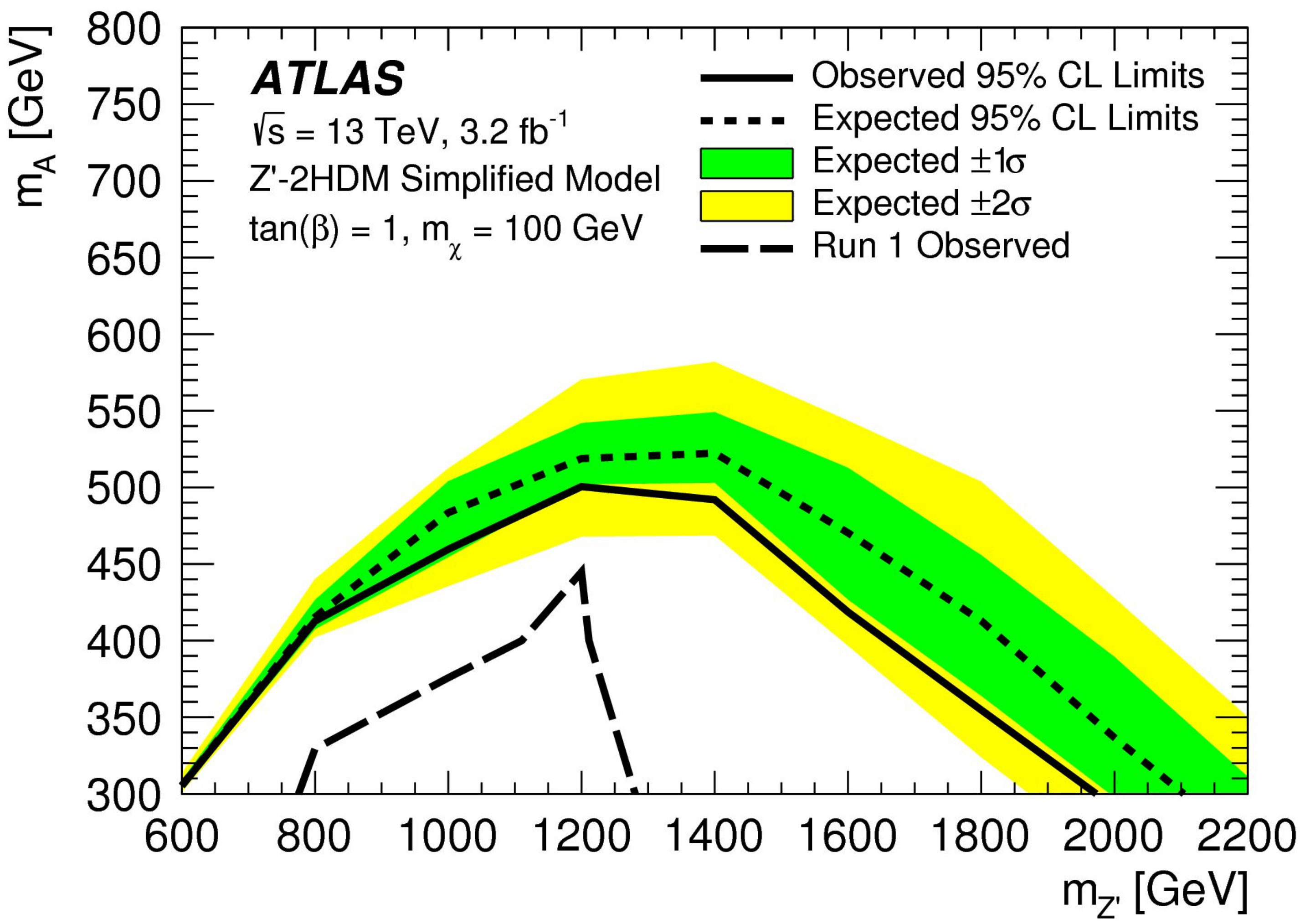
- In Run-2, focus is on simplified models.
  - Allows comparison with other DM searches and with relic density constraints.
- Mono-X final states are sensitive to DM production at the LHC. Several searches in 13 TeV data performed by ATLAS and CMS.
  - No significant excesses seen.
  - DM exclusions are complementary to direct detection experiments.

Bonus

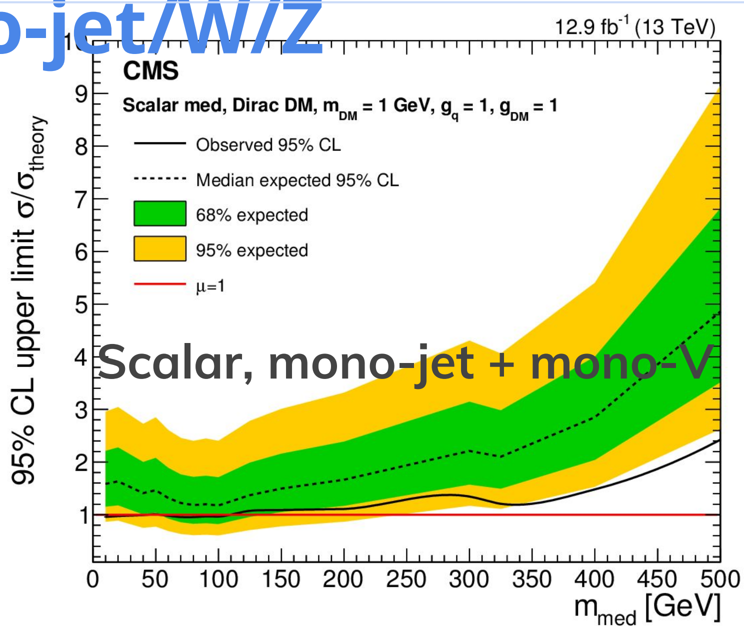
Mono-photon limits on Zγ resonance

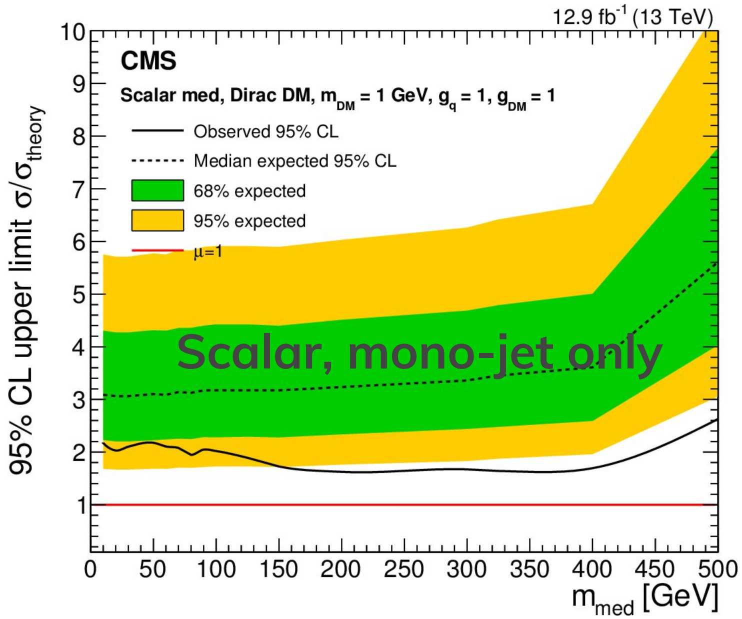


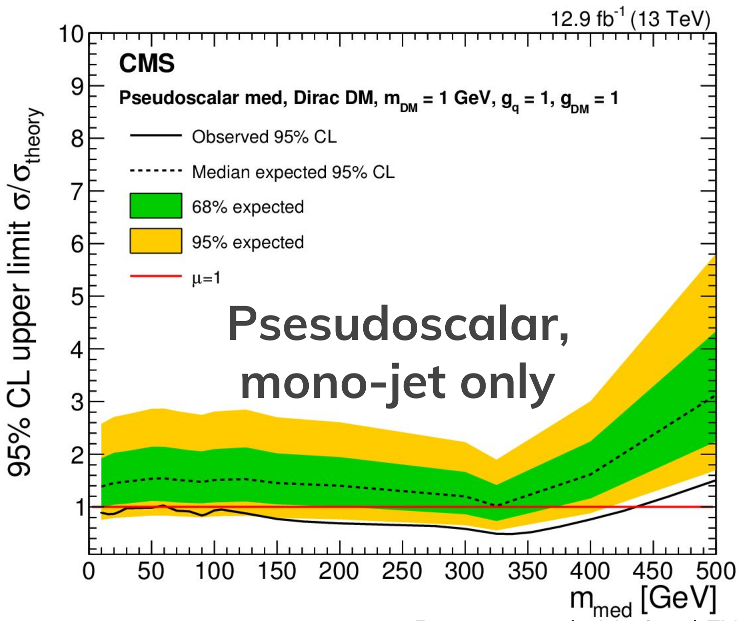
Mono-H(bb) limit on Z'+2HDM



Spin-0 mediator exclusions by CMS Mono-jet/W/Z







Mono-Jet background normalizations

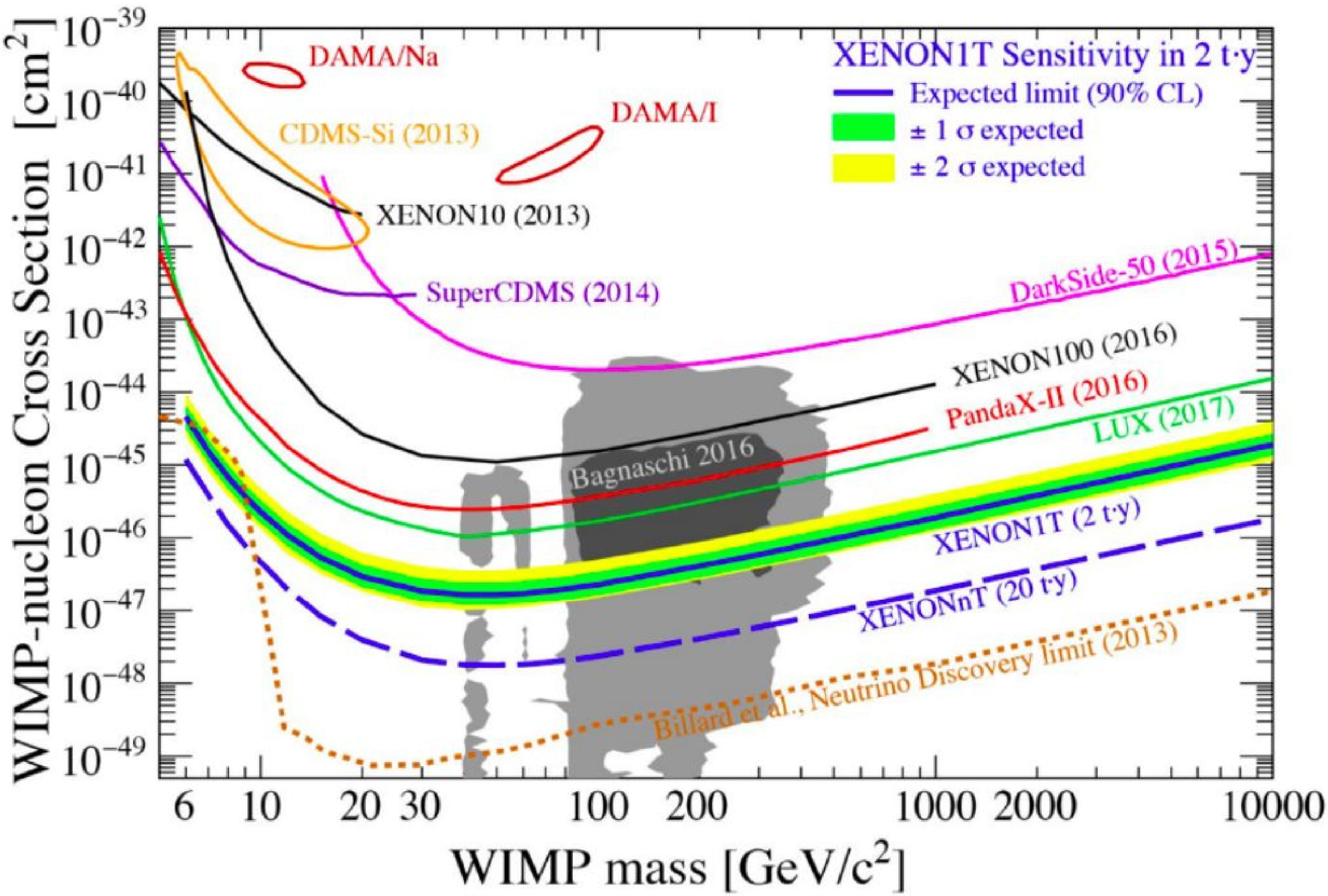
	ATLAS			CMS				
	1e	1μ	2m	1e	1μ	2e	2μ	1γ
Z➪νν+jets		✓		✓	✓	✓	✓	✓
Z➪μμ+jets			✓	✓	✓	✓	✓	✓
Z➪ee+jets				✓	✓	✓	✓	✓
Z➪ττ+jets	✓			✓	✓	✓	✓	✓
W➪μν+jets		✓		✓	✓			
W➪eν+jets	✓			✓	✓			
W➪τν+jets	✓			✓	✓			

Mono-H(bb) background normalizations

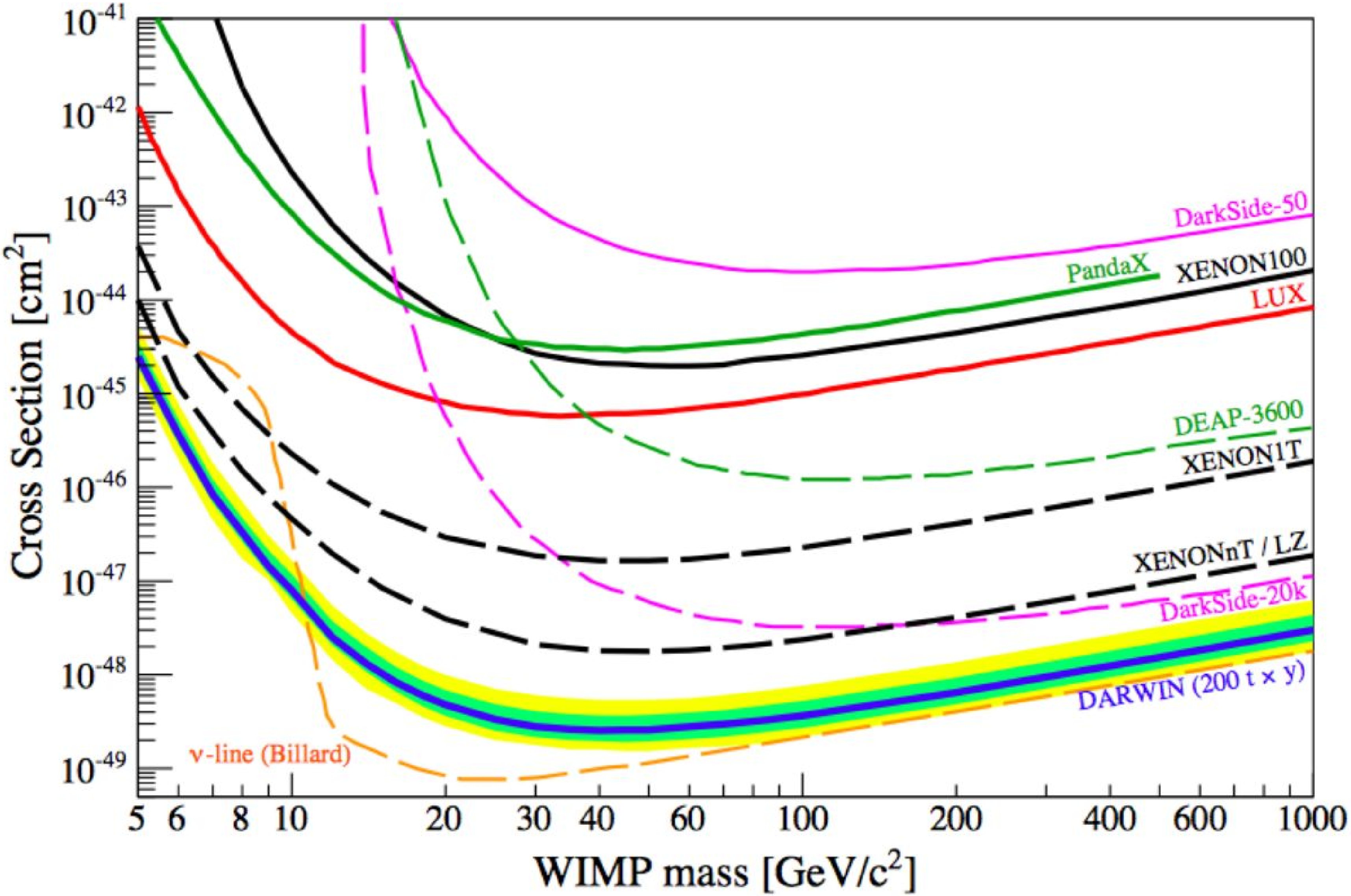
<table>
<tr><th></th><th>CMS (resolved)</th><th>CMS (boosted)</th><th>ATLAS</th></tr>
<tr><td>Z+jets</td><td colspan="2">Mass sideband</td><td>Mass shape fit and 2l CR</td></tr>
<tr><td>W+jets</td><td>1l+0j CR</td><td rowspan="2">1l CR</td><td rowspan="2">1mu CR</td></tr>
<tr><td>Top</td><td>1l+1j CR</td></tr>
</table>

XENON(1/n)T Sensitivity

See talk by T. Marrodan Undagoitia in VHEPU session



DARWIN Sensitivity



DARWIN, JCAP 1611 (2016) no.11, 017, arXiv:1606.07001