



# DM searches using missing $E_T$ ( $E_T^{miss}$ ) at LHC



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TeV Particle Astrophysics 2016, CERN

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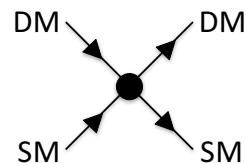
# Introduction

Strong evidences for the existence of Dark Matter (DM) from various astrophysical experiments.

## 3 complementary search strategies

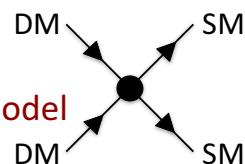
### – Direct detection (DD)

- ❑ DM-nucleus scattering
- ❑ Low-mass DM particles not probed yet
- ❑ Less sensitive to spin-dependent coupling



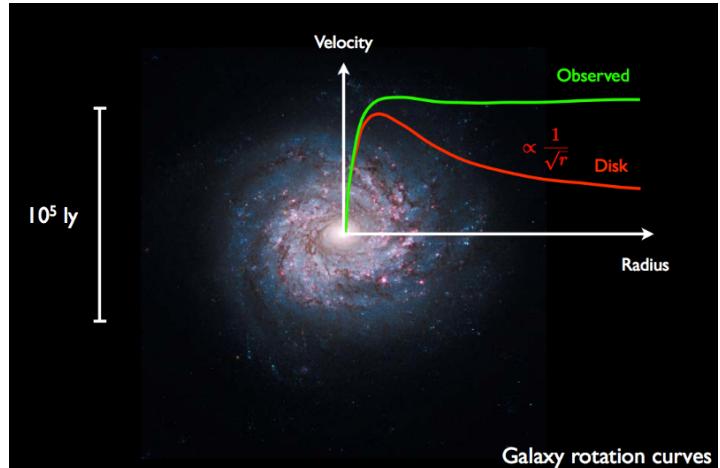
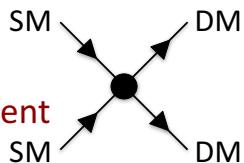
### – Indirect detection (ID)

- ❑ Observe annihilation products
- ❑ Low-mass DM particles not accessible
- ❑ Depends on DM density and annihilation model

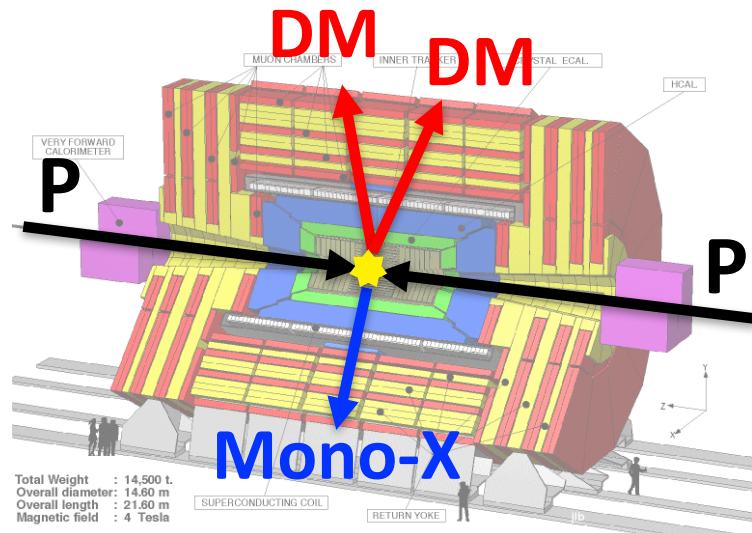


### – Production at colliders (PD)

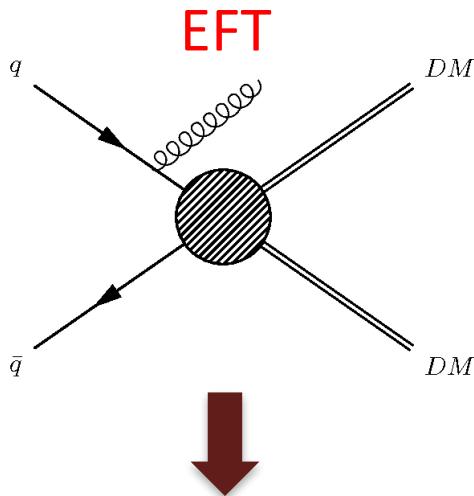
- ❑ Laboratory produced DM particles
- ❑ Sensitive to a wide mass range
- ❑ Both spin-dependent and spin-independent couplings



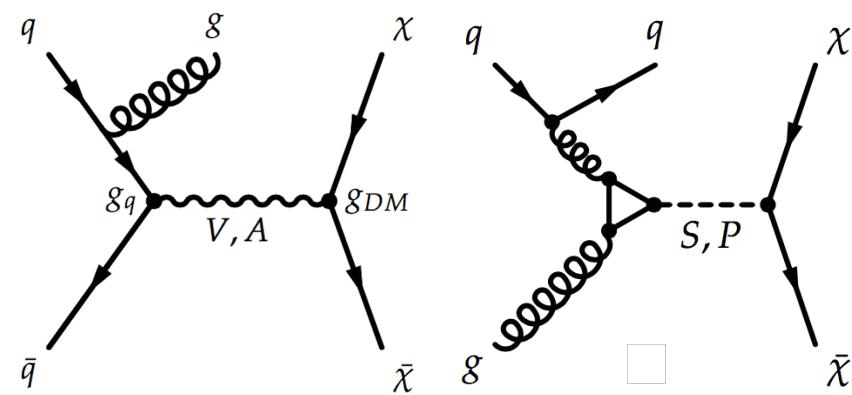
Need independent cross-checks!



# DM models at LHC



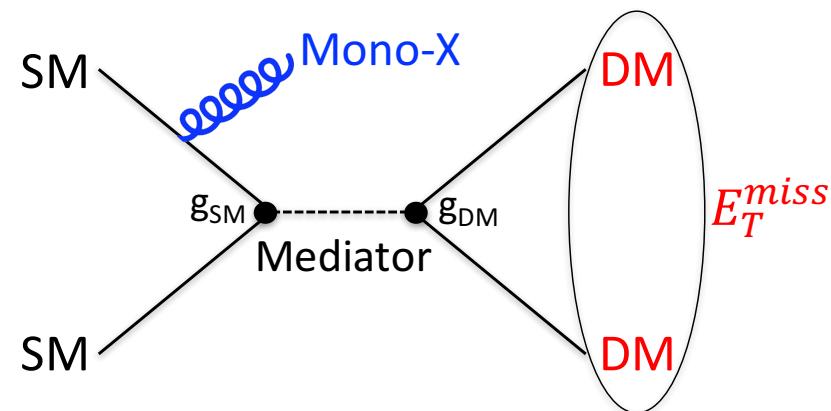
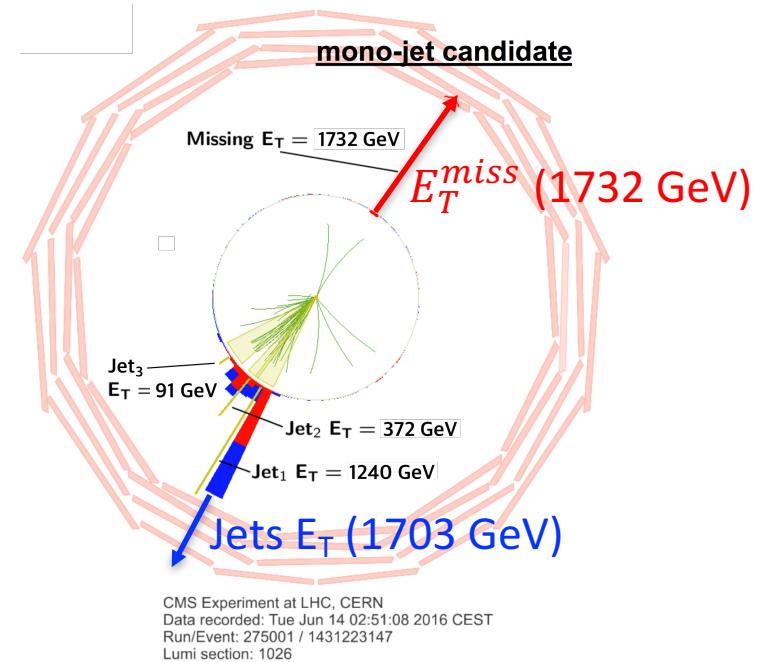
Simplified Model



- Run1 (7-8 TeV) : Effective Field Theories (EFT)
  - Contact Interactions between DM and SM
  - DM is pair-produced and light new particle
  - Mediators are very heavy
    - Invalid if mediator light enough to be resolved
  - 2 parameters: DM mass & interaction strength
- Run2 (13 TeV): Simplified Models
  - Suggested by ATLAS/CMS Dark Matter Forum
  - Fermionic DM particles interact a mediator
  - Bosonic mediator
    - Spin 0: scalar (S) / pseudo-scalar (PS)
    - Spin 1: vector (V) / axial-vector (AV)
    - coupling to both SM and DM particles
  - More parameters
    - Mediator mass ( $m_{\text{med}}$ ) and width, DM mass ( $m_{\text{DM}}$ ), couplings to SM ( $g_q$ ) and DM ( $g_{\text{SM}}$ ).

# Mono-X strategies for DM search

- Search for weakly-interacting massive particle (WIMP) as a Dark Matter pair at LHC
- DM particles cannot be detected by ATLAS and CMS detectors.
  - Large missing transverse energy ( $E_T^{miss}$ )
- SM particle recoiling against DM particles
  - Mono-X signature:
    - jet (g/q), heavy quarks (b/t), higgs or vector bosons ( $\gamma/W/Z$ )
- LHC searches focus on events with a SM particle(s) (Mono-X) with large  $E_T^{miss}$ :  $E_T^{miss} + \text{Mono-X}$ .

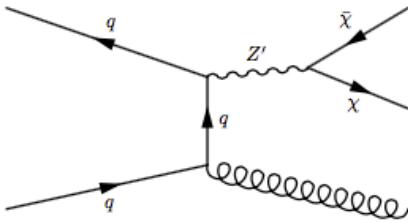


# LHC Dark Matter searches at 13 TeV

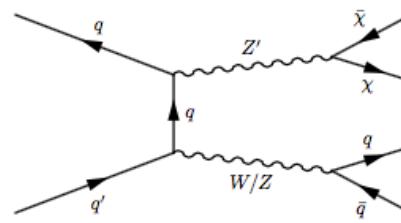
Analysis	Channel	ATLAS	CMS
$E_T^{miss} + \text{jet}$	Mono-jet	3.2 fb <sup>-1</sup> (2015)	12.9 fb <sup>-1</sup> (2016)
	$W/Z$ (hadronic)	3.2 fb <sup>-1</sup> (2015)	
$E_T^{miss} + Z$	( $Z \rightarrow \ell\ell$ )	13.3 fb <sup>-1</sup> (2015+2016)	12.9 fb <sup>-1</sup> (2016)
$E_T^{miss} + \gamma$	Photon	3.2 fb <sup>-1</sup> (2015)	12.9 fb <sup>-1</sup> (2016)
$E_T^{miss} + top$	$top$ (hadronic)	-	12.9 fb <sup>-1</sup> (2016)
$E_T^{miss} + b\bar{b}$	$b$ -jets	13.3 fb <sup>-1</sup> (2015+2016)	2.2 fb <sup>-1</sup> (2015)
$E_T^{miss} + t\bar{t}$	$t\bar{t}$ (hadronic)	13.3 fb <sup>-1</sup> (2015+2016)	2.2 fb <sup>-1</sup> (2015)
	$t\bar{t}$ (semi-leptonic)	13.2 fb <sup>-1</sup> (2015+2016)	
	$t\bar{t}$ (di-leptonic)	13.3 fb <sup>-1</sup> (2015+2016)	-
$E_T^{miss} + H$	( $H \rightarrow bb$ )	3.2 fb <sup>-1</sup> (2015)	2.3 fb <sup>-1</sup> (2015)
	( $H \rightarrow \gamma\gamma$ )	13.3 fb <sup>-1</sup> (2015+2016)	2.3 fb <sup>-1</sup> (2015)
	( $H \rightarrow ZZ \rightarrow 4\ell$ )	3.2 fb <sup>-1</sup> (2015)	-

# CMS Mono-jet & Mono-W/Z (hadronic)

spin-1 mediator (vector/axial-vector)

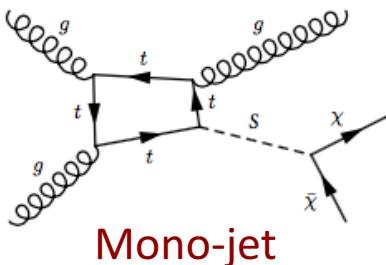


Mono-jet

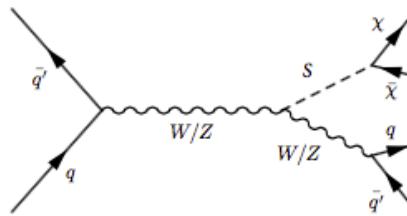


Mono-V

spin-0 mediator (scalar/pseudo-scalar)



Mono-jet

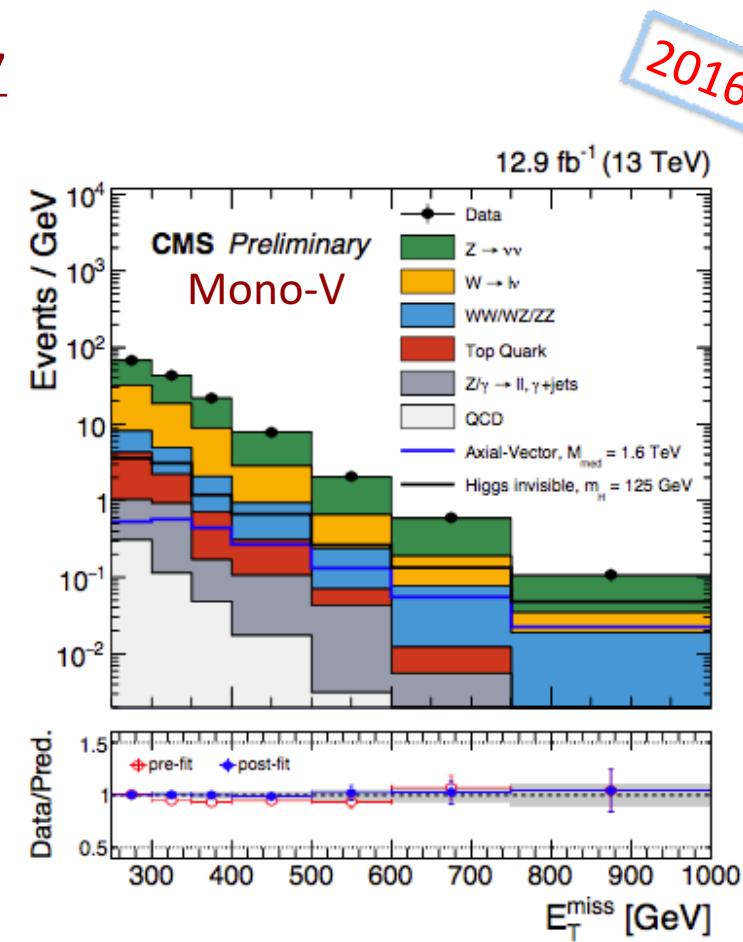
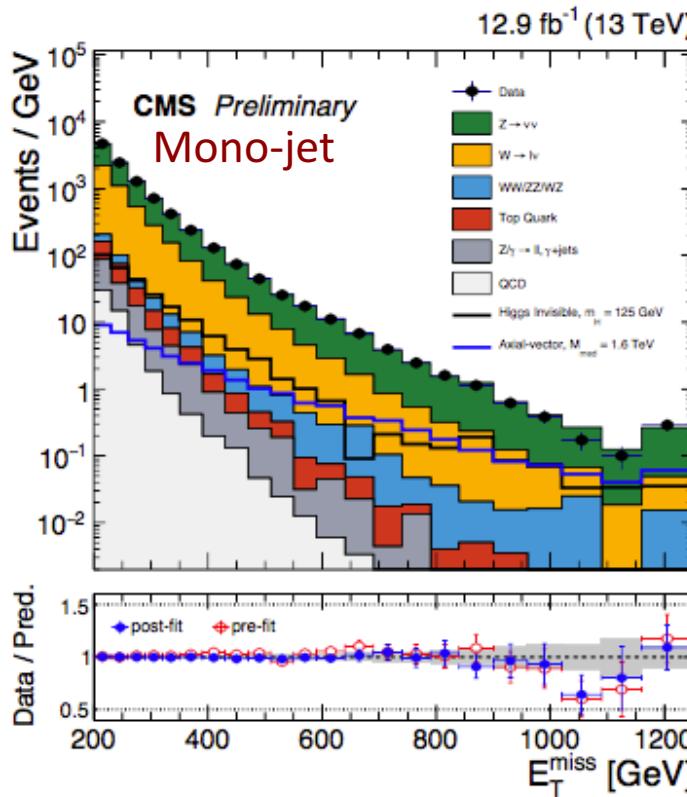


Mono-V

- Largest  $E_T^{miss}+X$  cross-section at LHC
- Experimental signature
  - Large  $E_T^{miss}$  from a spin 0 or 1 mediator decaying into DM particles
  - At least one high  $p_T$  jet from either QCD radiation or hadronically decaying W/Z-boson
    - Mono-jet channel:  $E_T^{miss} > 200$  GeV, leading jet  $p_T > 100$  GeV
    - Mono-V channel: highly boosted “fat jets” from W/Z:  $E_T^{miss}$  and leading jet  $p_T > 250$  GeV
  - No leptons ( $\mu, e, \tau$ ) or photons ( $\gamma$ )
  - Dominant SM backgrounds:  $Z(vv)+\text{jets}$  and  $W(\ell\nu)+\text{jets}$

# CMS Mono-jet & Mono-W/Z : $E_T^{miss}$

- $E_T^{miss}$  distributions in the mono-jet and mono-V signal regions
  - Compared with the fitted (post-fit) background expectations for various SM processes.
  - No significant excess
- Documentation: [CMS PAS EXO-16-037](#)



# CMS Mono-jet & Mono-W/Z : Limits

Scan parameters in  $m_{\text{med}}$  and  $m_{\text{DM}}$  plane.

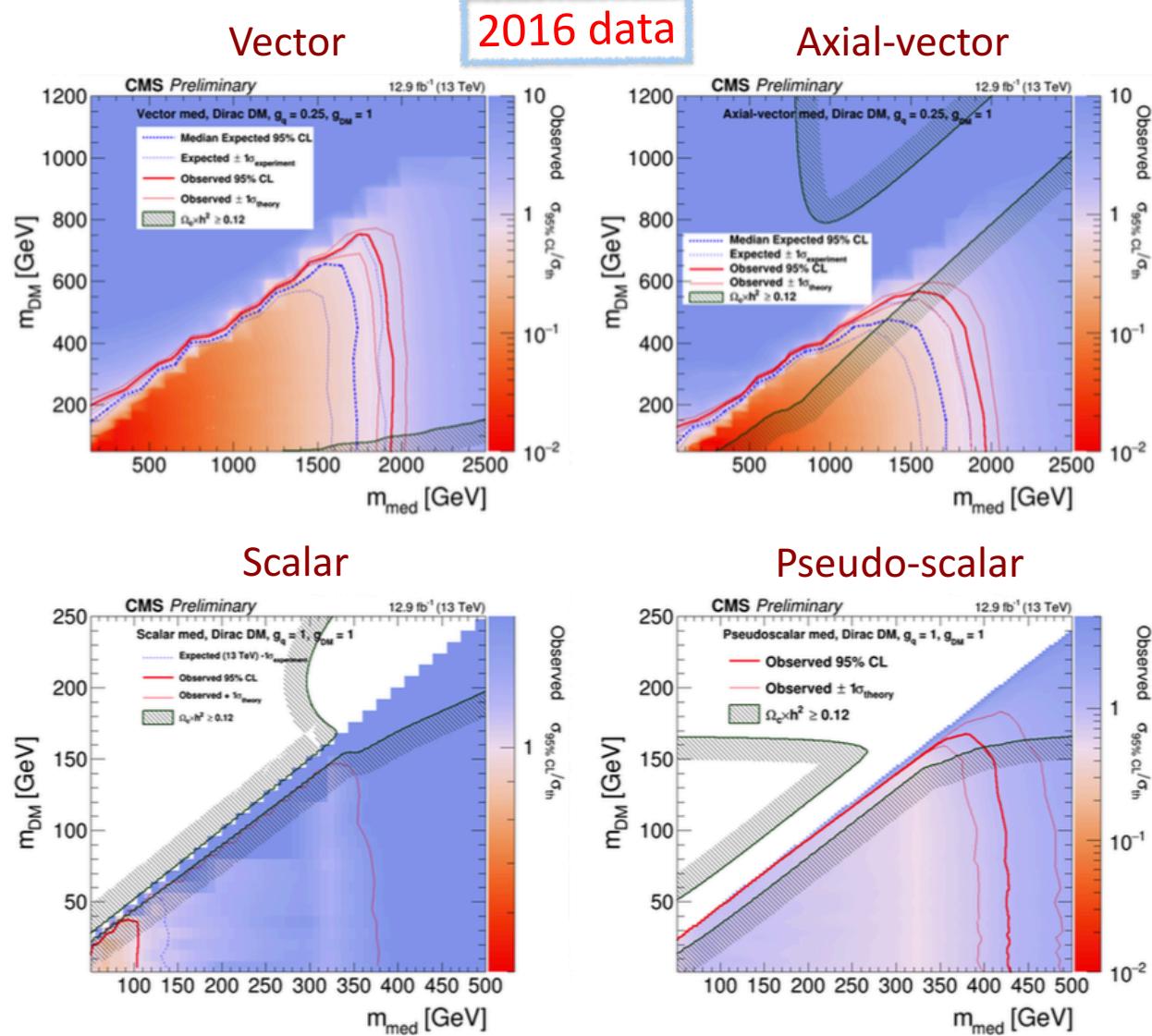
- Fixed  $g_q = 0.25, g_{\text{DM}} = 1$

Exclusion limits at 95% CL on the  $\mu = \sigma/\sigma_{\text{th}}$  in the  $m_{\text{med}}\text{-}m_{\text{DM}}$  plane assuming V/AV and S/PS mediators.

Red line: contour for the observed exclusion.

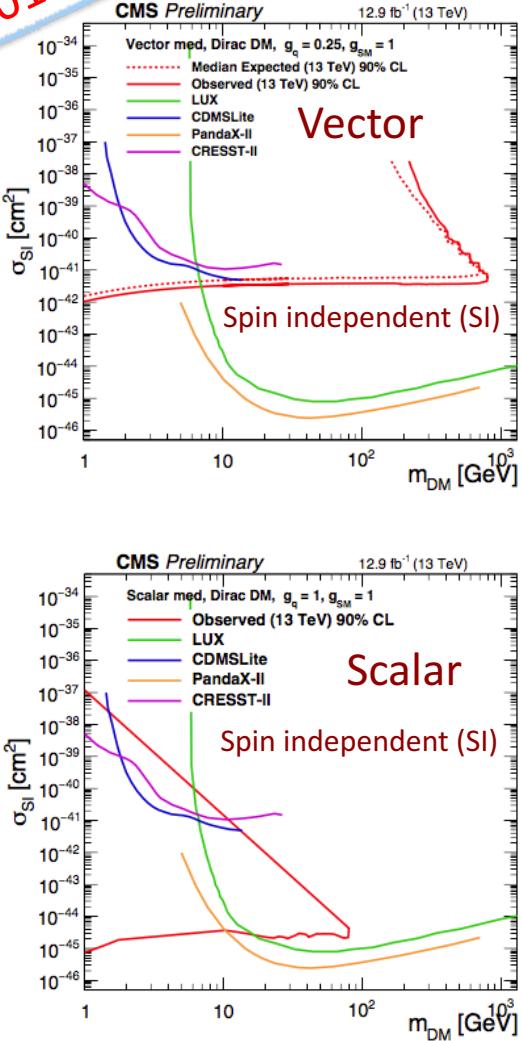
- Excludes models with V/AV mediators for  $m_{\text{med}} < 2$  TeV
- S (PS) mediator mass up to 100 (430) GeV

Dark Green line: cosmological constraints from the WMAP and Planck experiments



# CMS Mono-jet & Mono-W/Z : Limits

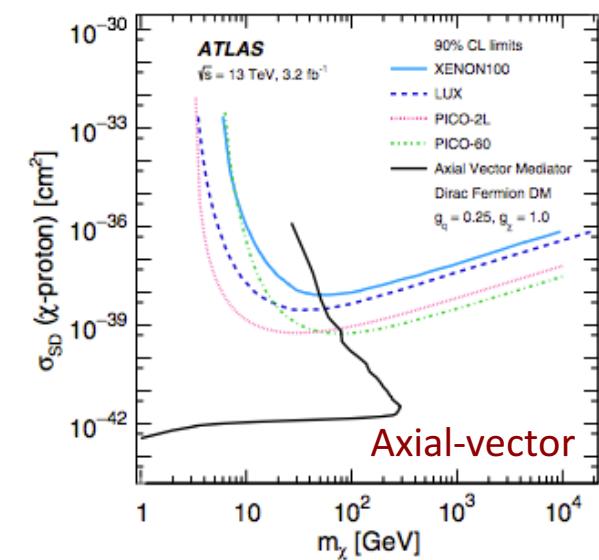
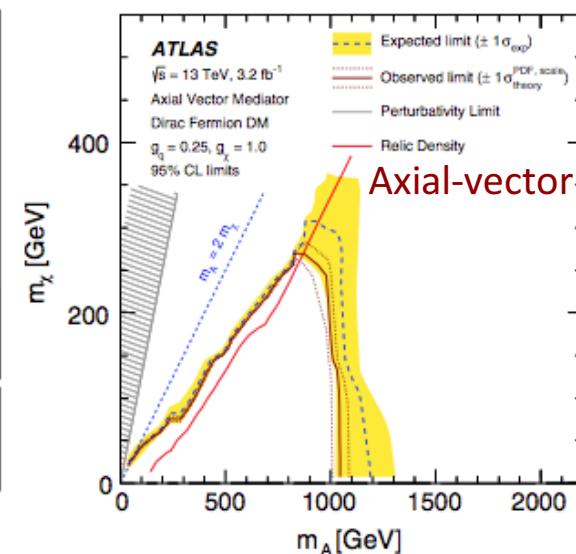
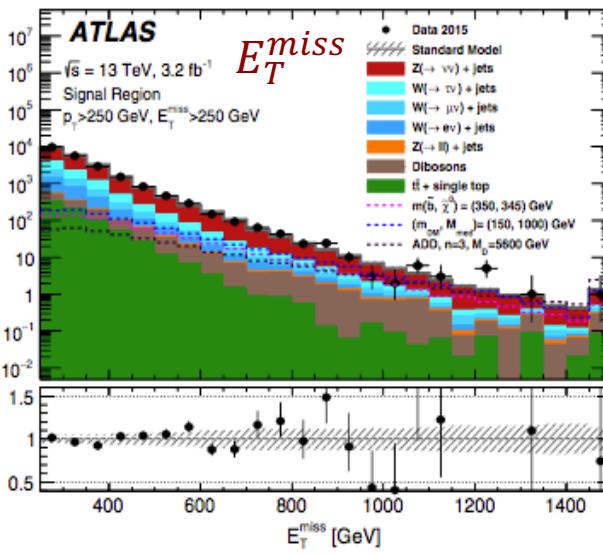
2016 data



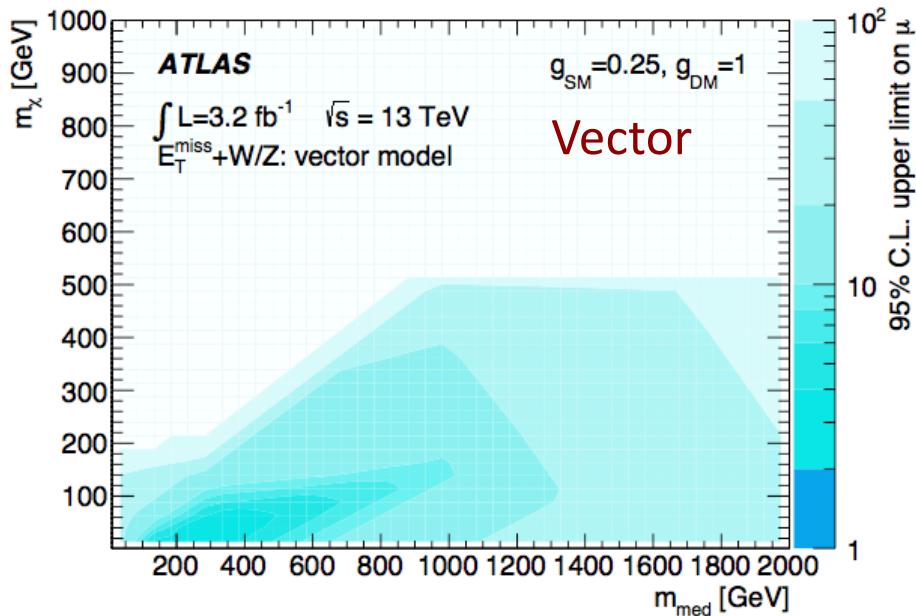
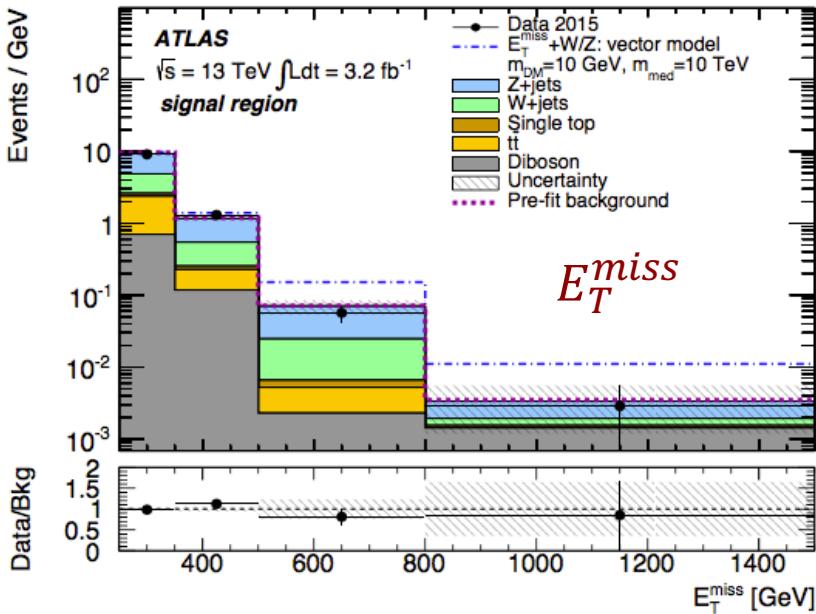
- Exclusion limits at 90% CL in the  $m_{DM}$ - $\sigma_{SI/SD}$  plane assuming for V/AV and S/PS mediator models
- The solid (dotted) red line:
  - Contour for the observed (expected) exclusion using  $12.9 \text{ fb}^{-1}$  of 13 TeV data
- Limits comparisons
  - Vector and scalar mediators
    - CDMSLite, LUX, PandaX-II and CRESST-II experiments
  - Axial-vector mediator
    - PICO-2L, PICO-60, IceCube and Super-Kamiokande experiments
  - Pseudo-scalar mediator
    - LimitFermi-LAT

# ATLAS Mono-jet

- Good agreement with post-fit SM background estimation in  $E_T^{miss}$  distribution
- 95% CL exclusion contours in the  $m_{med}$ - $m_{DM}$  plane.
  - Limit on axial mediators  $m_{med} < 1$  TeV
- Comparison of limits from DD experiments on the spin-dependent WIMP-proton scattering cross section in simplified model with axial-vector couplings.
- Results with  $3.2 \text{ fb}^{-1}$  of 2015 data published in PRD
  - [Phys. Rev. D94 032005](#)



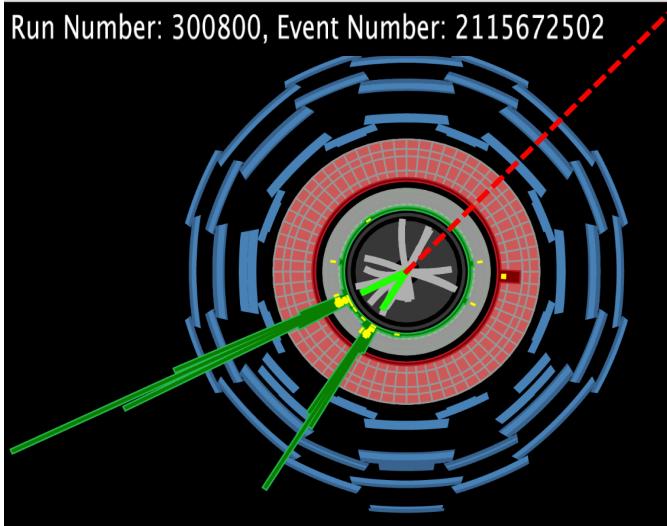
# ATLAS Mono-W/Z (hadronic)



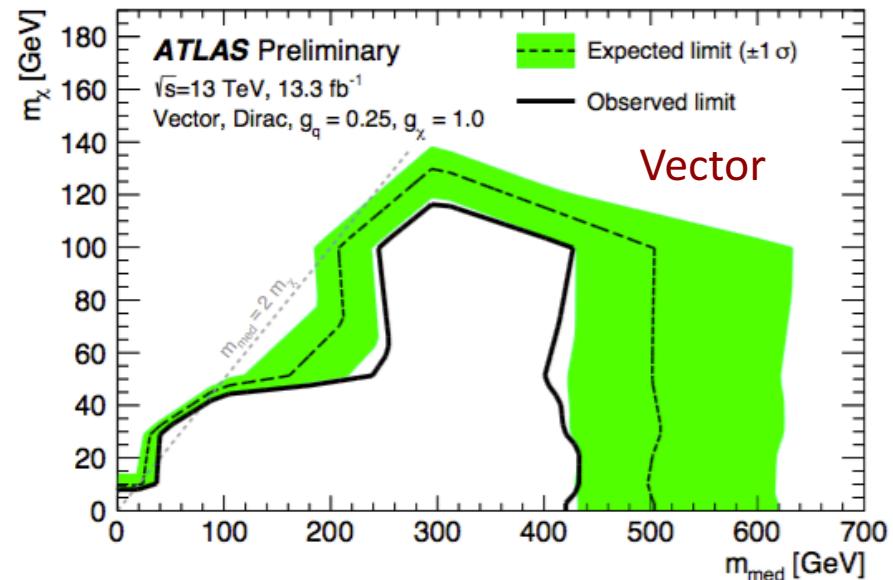
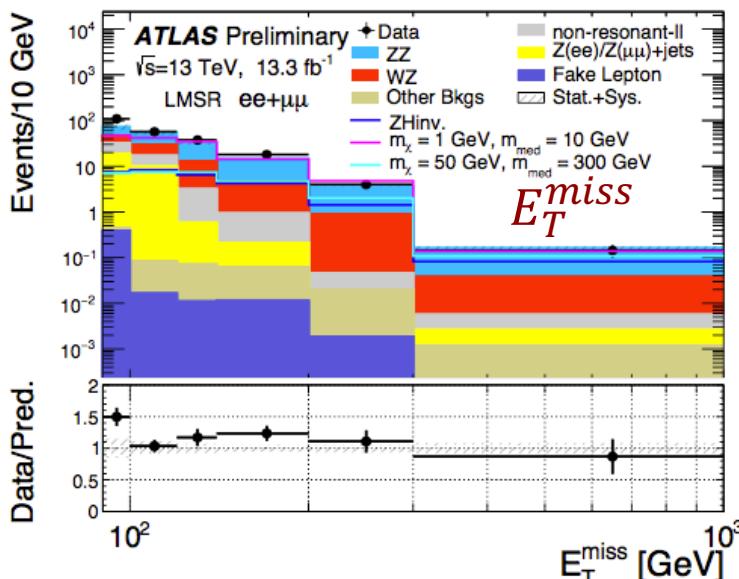
- $E_T^{\text{miss}} > 250 \text{ GeV}$  and at least one large-R jet with  $p_T > 200 \text{ GeV}$
- No reconstructed electron or muon
- Observed limit on the signal strength ( $\mu$ ) of the vector-mediated simplified model in the plane of the  $m_{\text{DM}}-m_{\text{med}}$ 
  - White areas: Upper limit at  $\mu \geq 100$
- Documentation: [arXiv:1608.02372](https://arxiv.org/abs/1608.02372)

# ATLAS Mono-Z( $\rightarrow \ell\ell$ )

2015+2016 data



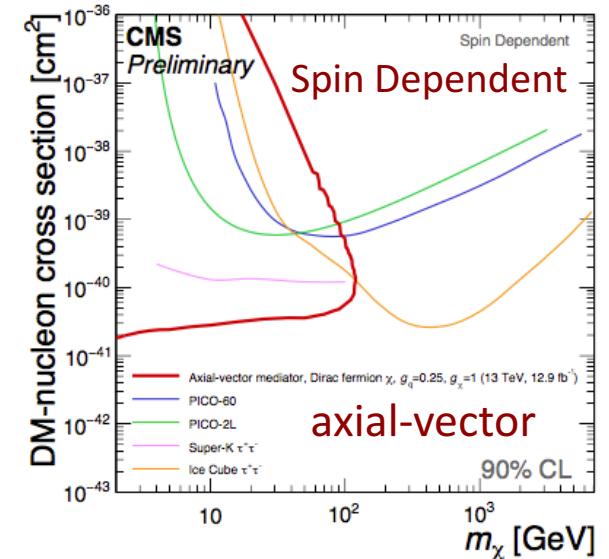
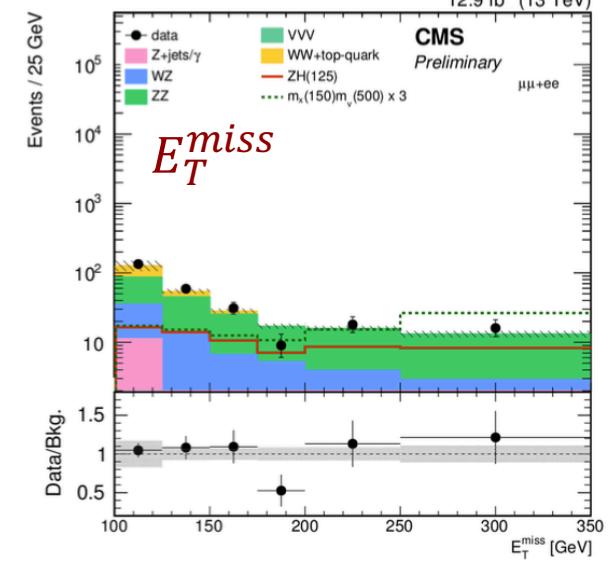
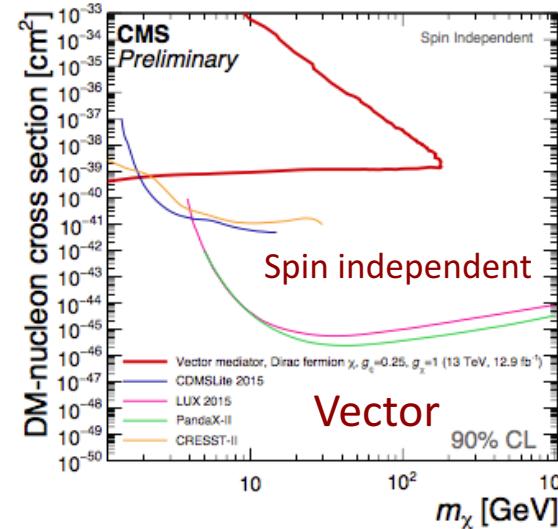
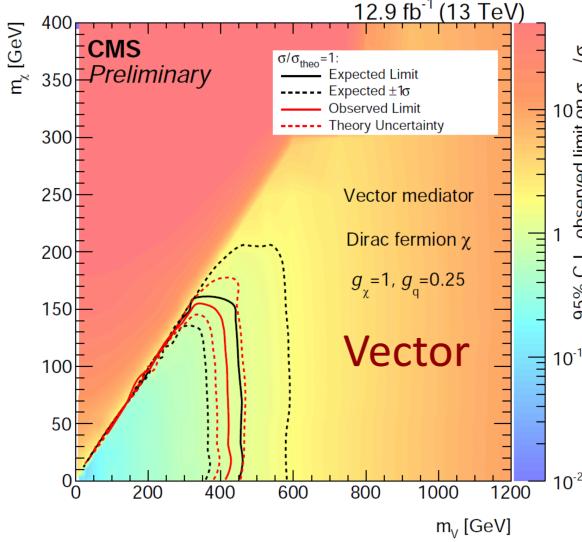
- $E_T^{miss} > 90$  GeV and leading (sub-leading) electron or muon  $p_T > 30$  (20) GeV
- Set limit on the vector mediator decaying to DM particles
  - Vector mediators for  $m_{med} < 0.4$  TeV
- Documentation: [ATLAS-CONF-2016-056](#)

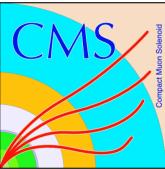


# CMS Mono-Z( $\rightarrow \ell\ell$ )

2016 data

- Events with  $E_T^{miss} > 100$  GeV and lepton  $p_T > 25/20$  GeV (electrons),  $> 20$  GeV (muons)
- Main background
  - $ZZ \rightarrow \nu\nu + \ell\ell$  irreducible
- Vector/axial-vector mediator decays to DM particles
  - Excluded the V/AV mediators for  $m_{med} < 0.4$  TeV
- Documentation: [CMS PAS EXO-16-038](#)

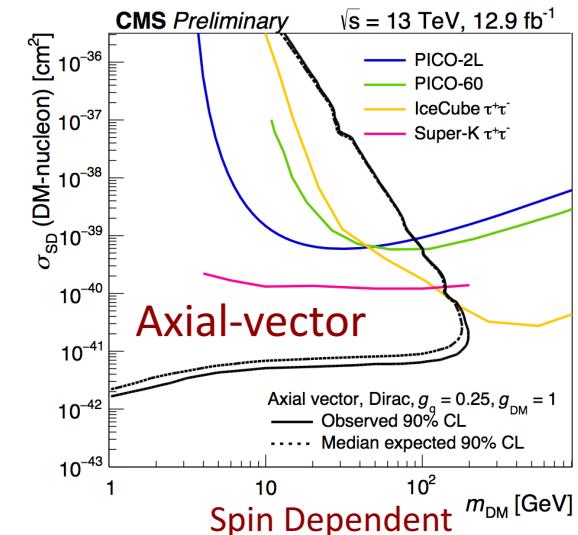
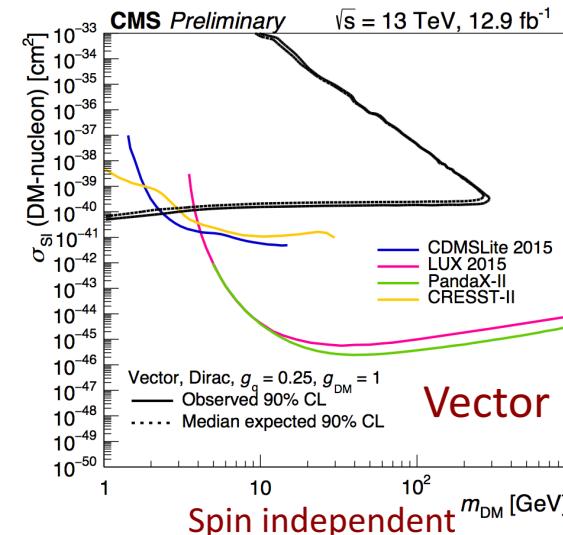
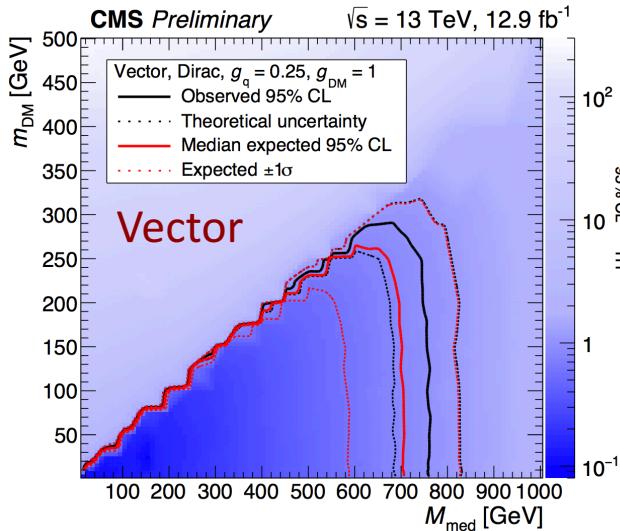
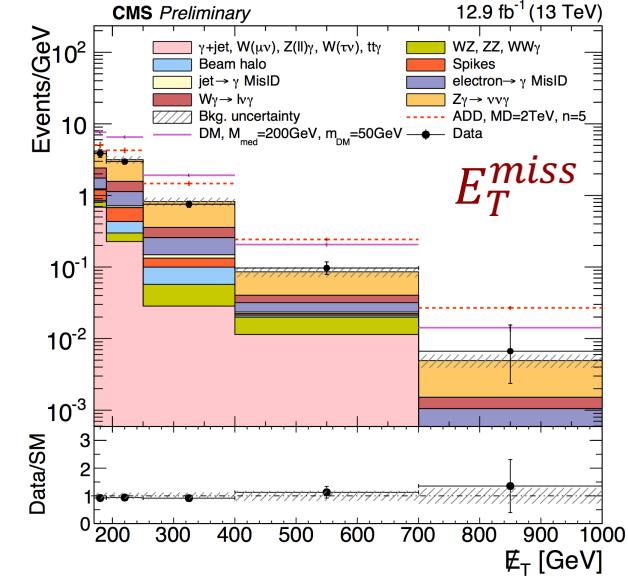




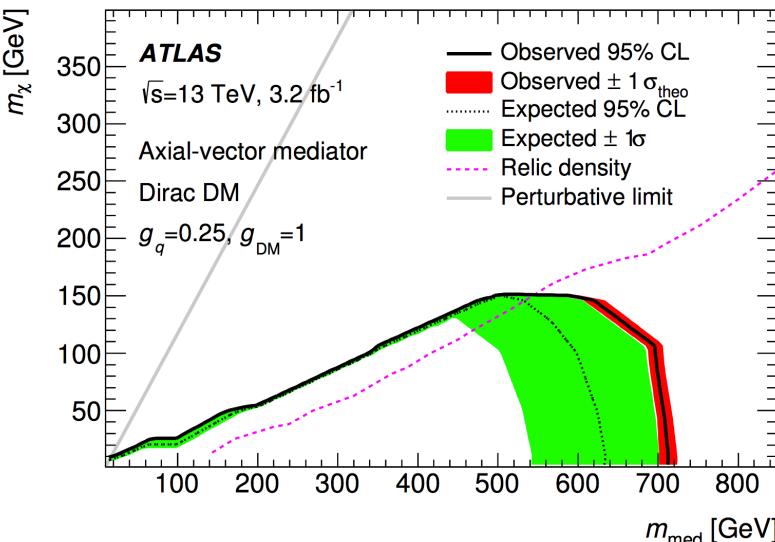
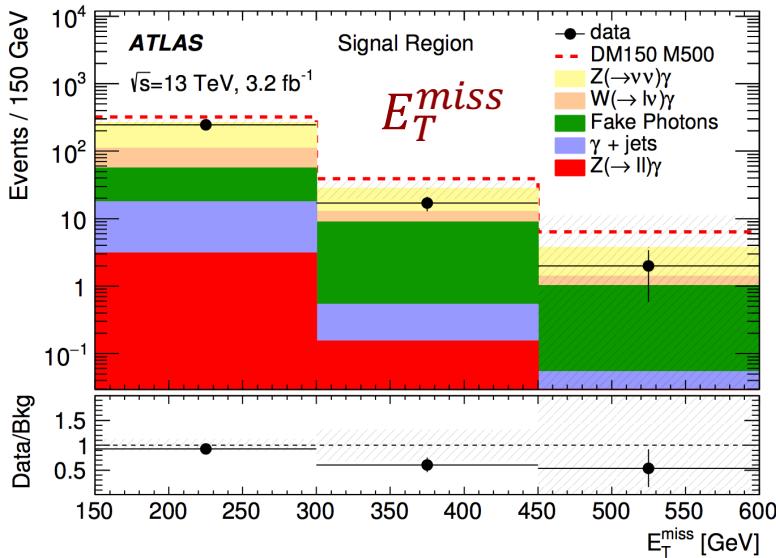
# CMS Mono-photon

2016 data

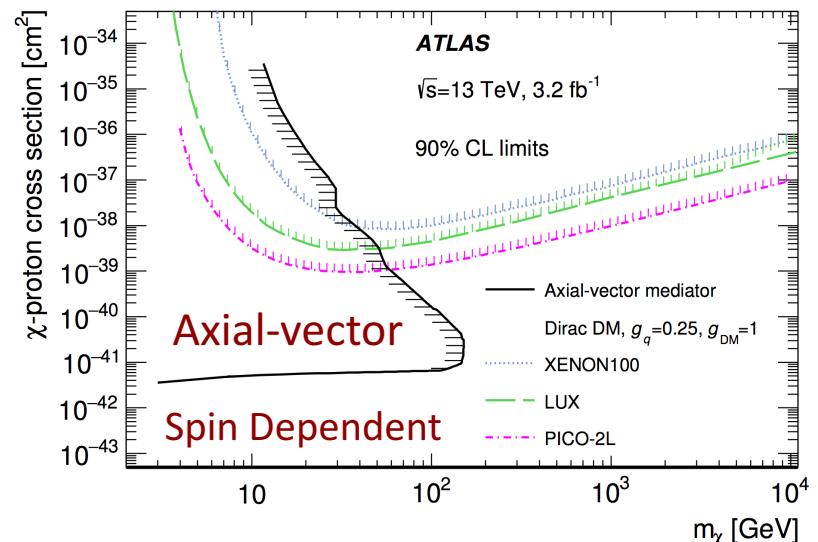
- Events with  $E_T^{miss} > 170$  GeV and at least one photon with  $p_T > 175$  GeV
- No electron or muon to reject  $W(\ell\nu) + \gamma$  process
- Dominant SM backgrounds:
  - $Z(vv) + \gamma$  and  $W(\ell\nu) + \gamma$
- Vector/axial-vector mediator  $m_{med} < 760$  GeV excluded
- Documentation: [CMS PAS EXO-16-039](#)



# ATLAS Mono-photon



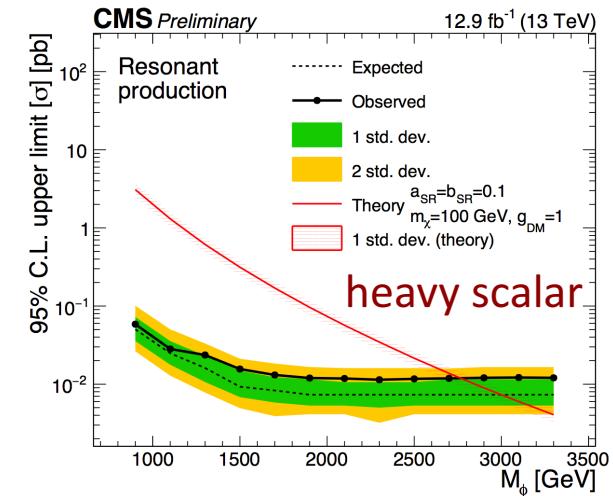
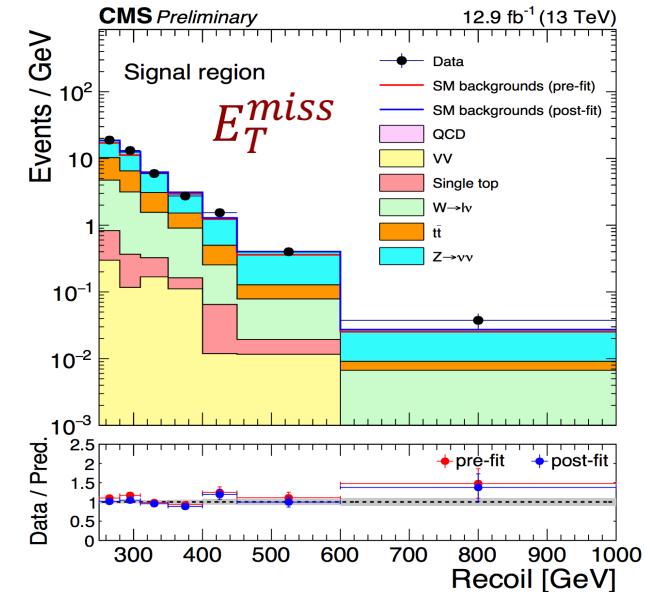
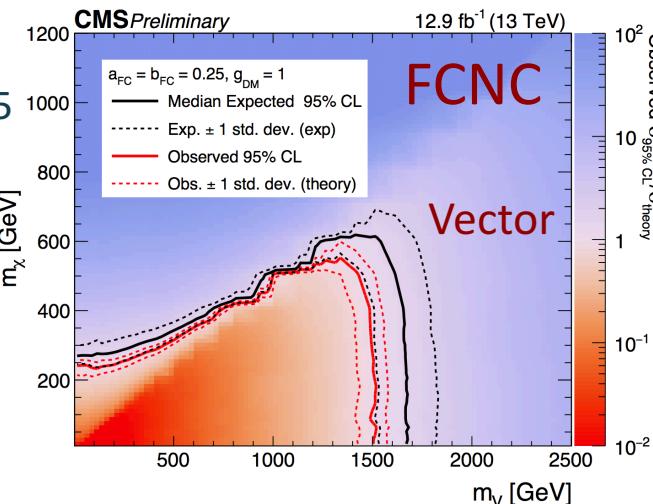
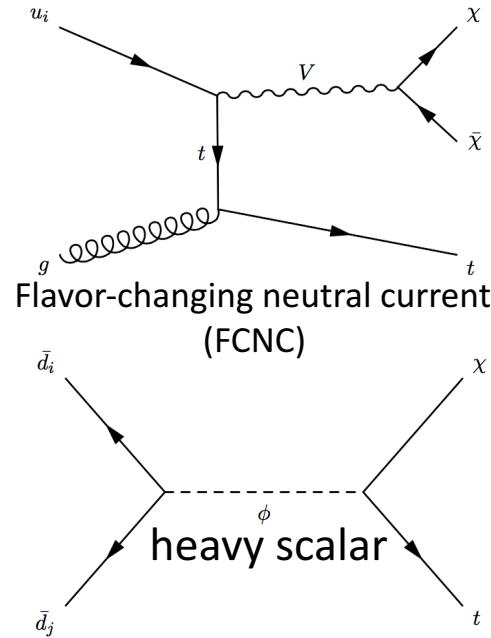
- $E_T^{\text{miss}} > 150 \text{ GeV}$  and leading photon  $p_T > 150 \text{ GeV}$
- Veto electron or muon
- Axial-vector mediator  $m_{\text{med}} < 700 \text{ GeV}$  and DM  $m_{\text{DM}} < 150 \text{ GeV}$  excluded
- Publication: [JHEP 06 \(2016\) 059](#)



# CMS Mono-top (hadronic)

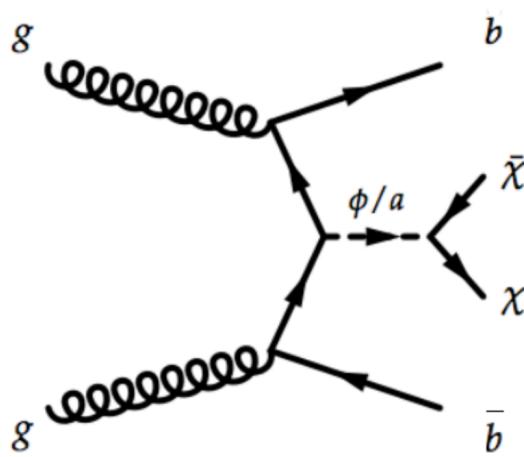
2016 data

- Sensitive to scalar and pseudo-scalar couplings
- $E_T^{\text{miss}}$  and boosted fat jet  $p_T > 250 \text{ GeV}$
- Subjet b-tagging required
- Dominant backgrounds are  $Z+jets$  and  $t\bar{t}$
- No significant excess and exclude
  - FCNC Mediator  $m_{\text{med}} < 1.5 \text{ TeV}$
  - Charged scalar  $< 2.7 \text{ TeV}$
- Documentation:
  - [CMS PAS EXO-16-040](#)

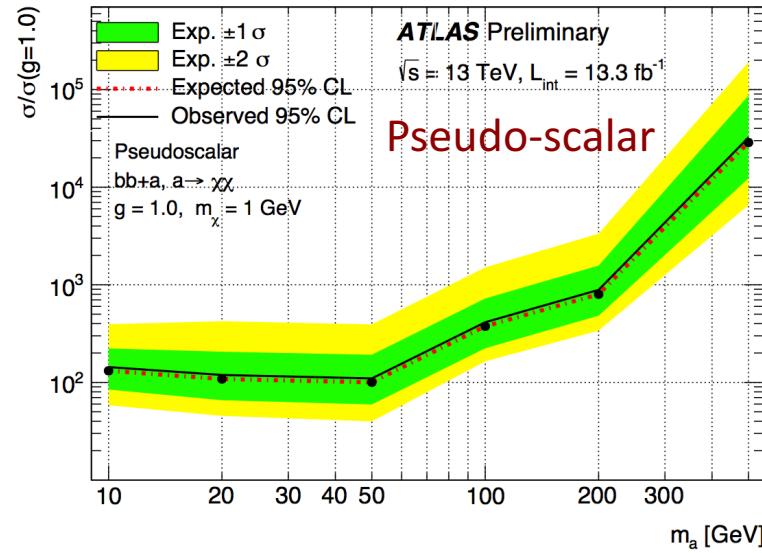
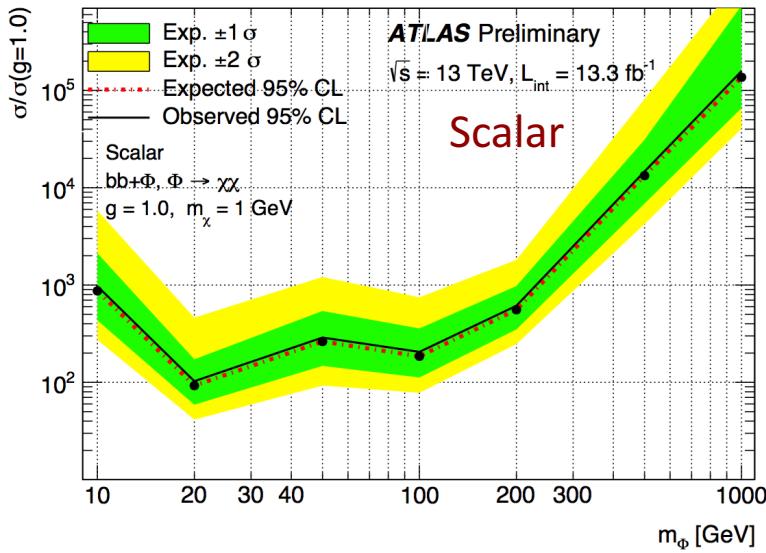


# ATLAS Mono- $b\bar{b}$

2015+2016 data



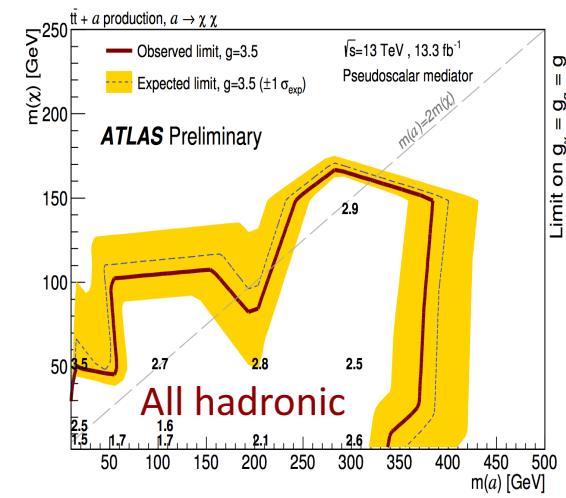
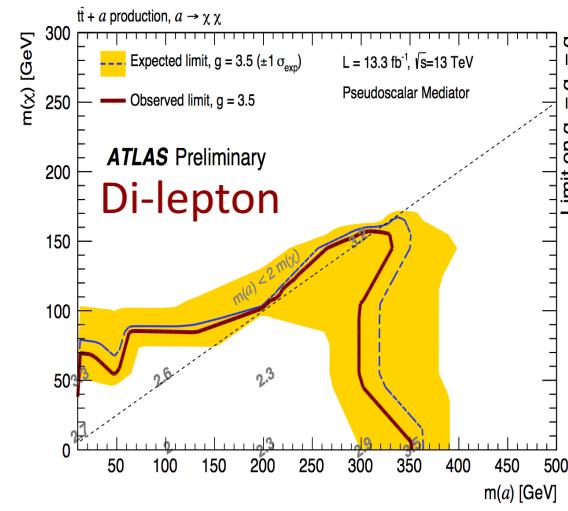
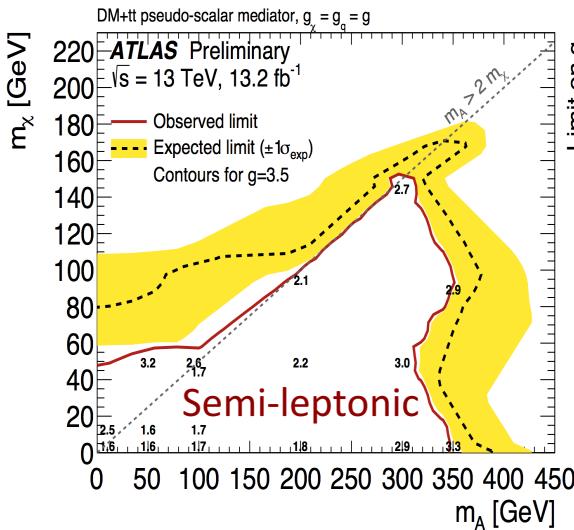
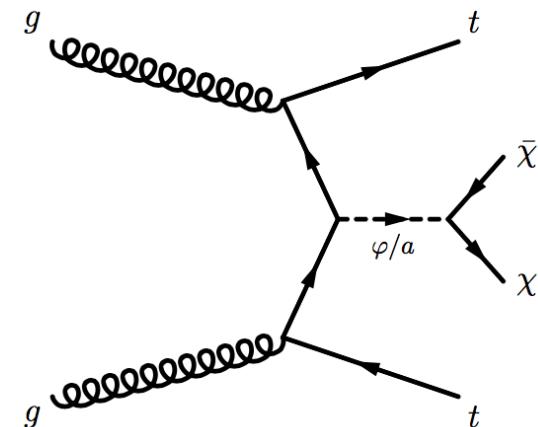
- $E_T^{miss} > 150$  GeV and leading jet  $p_T > 100$  GeV
- $N_{jet}=2$  and two b-tags required
- Spin 0 mediator decays to a DM pair
  - Mediator is either scalar or pseudo-scalar
  - Assuming a specific DM mass of 1 GeV
  - Best observed upper limit on the signal strength
    - Mediator mass: 20 GeV.
- Documentation: [ATLAS-CONF-2016-019](#)



# ATLAS Mono- $t\bar{t}$

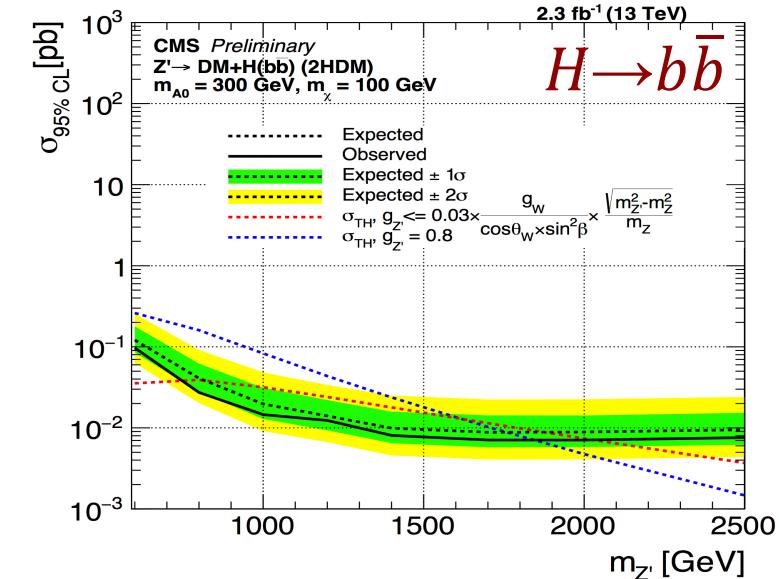
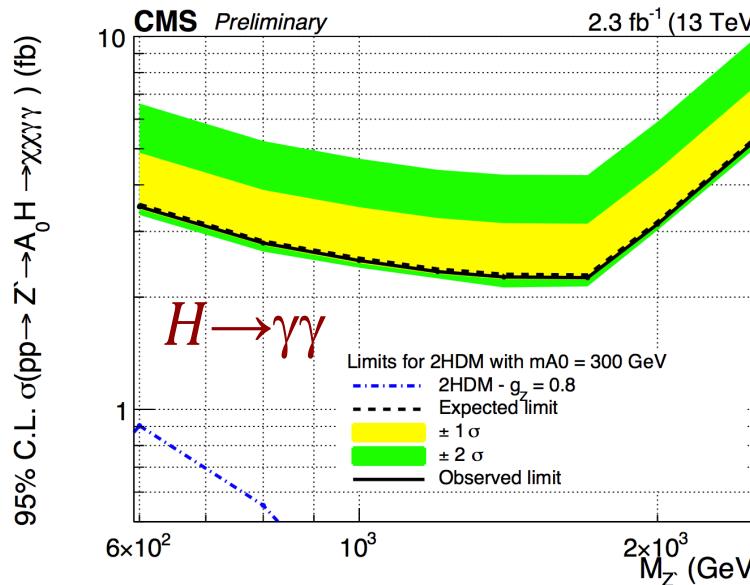
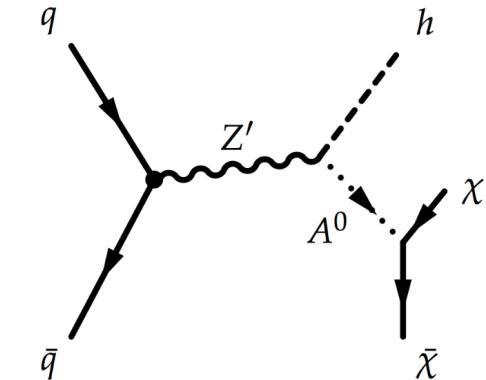
2015+2016 data

- Events with  $E_T^{miss} + t\bar{t}$  in three  $t\bar{t}$  decay channels are analyzed with  $13.3 \text{ fb}^{-1}$  data.
- Scalar and Pseudo-scalar mediators are interpreted with coupling  $g_{DM} = 3.5$ 
  - Limit on the S/PS mediator  $m_{med} < 350 \text{ GeV}$
- Documentations:
  - [ATLAS-CONF-2016-050](#), [ATLAS-CONF-2016-076](#),  
[ATLAS-CONF-2016-077](#)



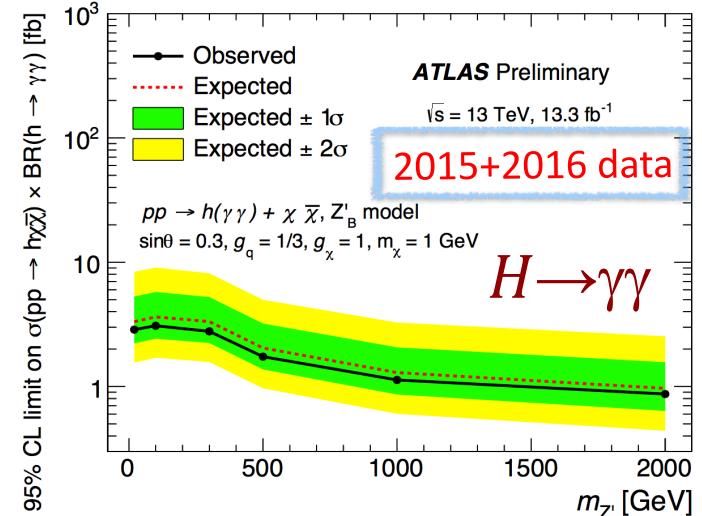
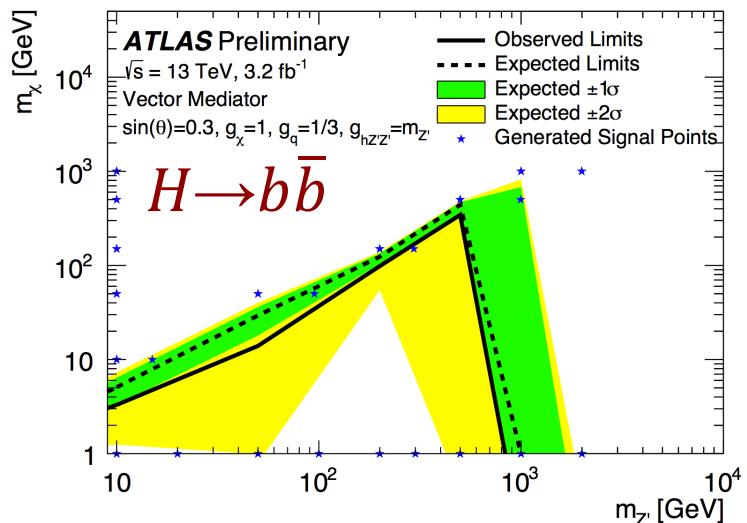
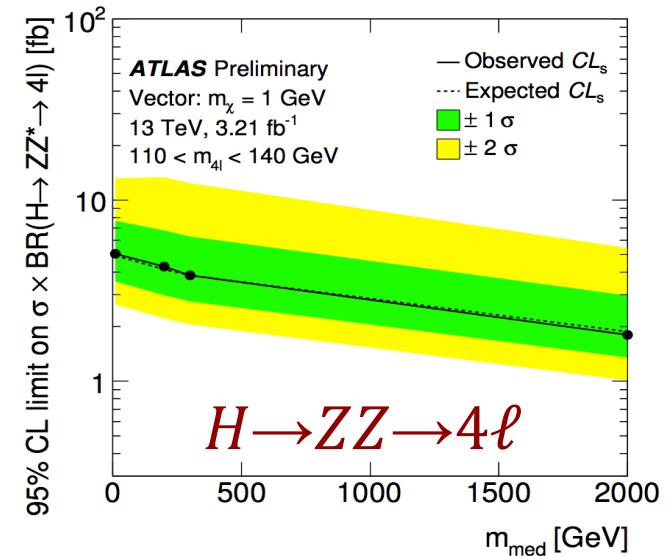
# CMS Mono- $H(\rightarrow b\bar{b}, \gamma\gamma)$

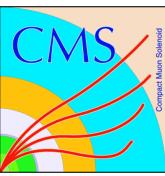
- Higgs mixing with new dark mediators
- $H \rightarrow b\bar{b}$  : Largest cross-section for Higgs+DM
  - Resolved jet (b-tagging):  $p_T$  of  $b\bar{b} > 150$ ,  $E_T^{miss} > 170$  GeV
  - Boosted jet (subjet b-tagging) :  $E_T^{miss}$
- $H \rightarrow \gamma\gamma$  :  $E_T^{miss} > 105$  GeV,  $p_T$  of  $\gamma\gamma > 90$  GeV
- No excess observed, limits set on Type-2 2HDM
  - Excluded  $m_{Z'}$  range 600-1863 GeV assuming  $g_z = 0.8$
  - Using constrained  $g_z$  excluded  $m_{Z'}$  768-2036 GeV
- Documentation: [CMS PAS EXO-16-011](#), [CMS PAS EXO-16-012](#)



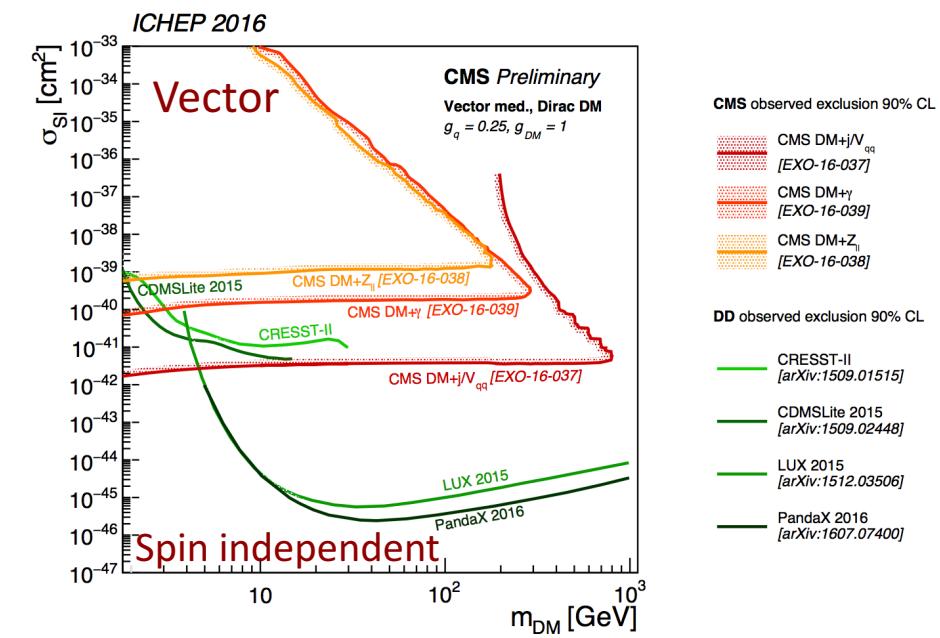
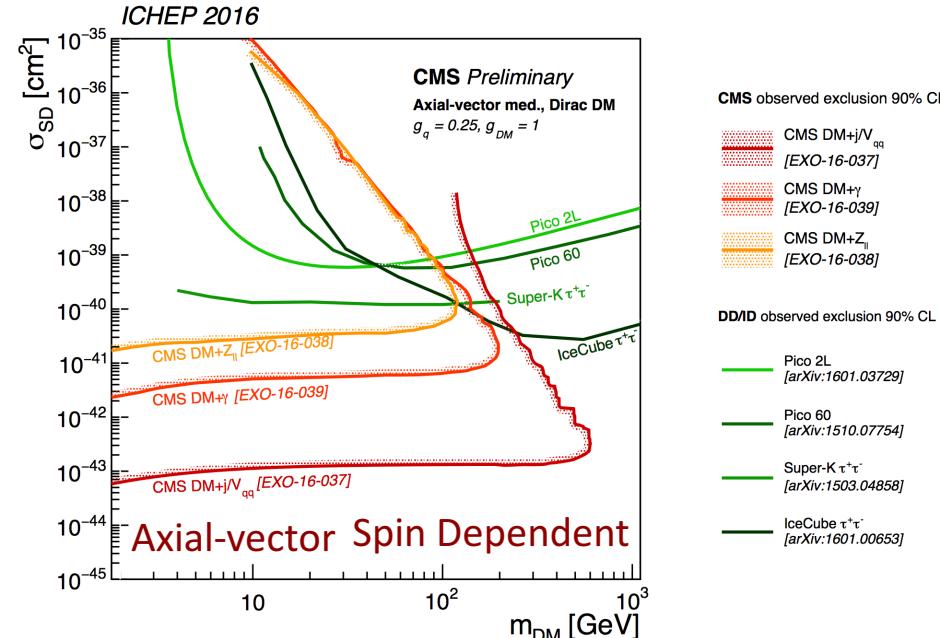
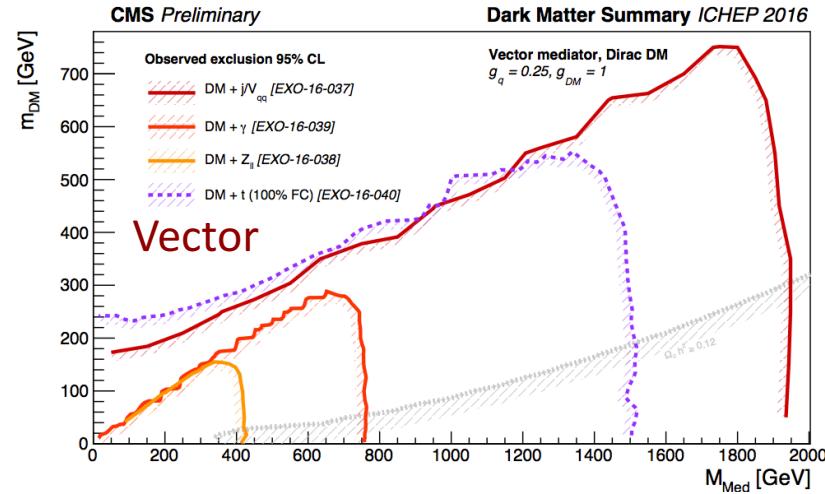
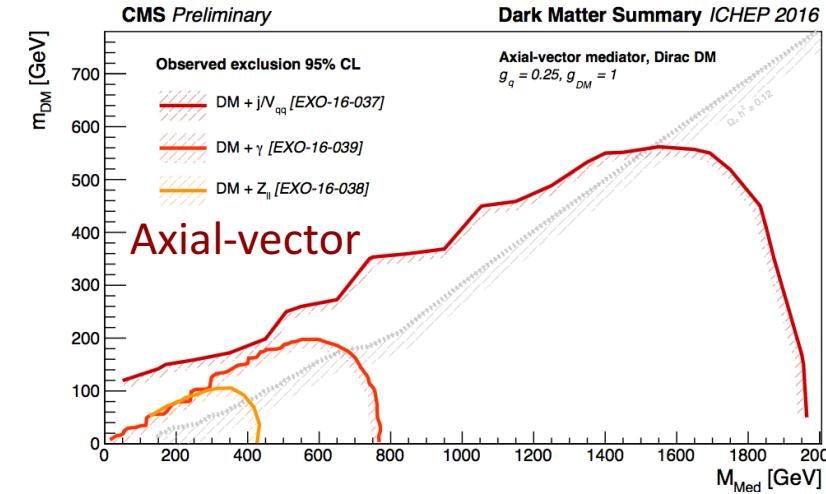
# ATLAS Mono- $H$ ( $\rightarrow ZZ \rightarrow 4\ell$ , $b\bar{b}$ , $\gamma\gamma$ )

- $H \rightarrow b\bar{b}$ 
  - $E_T^{\text{miss}} > 150 \text{ GeV}$ , 2 b-tagged jets
- $H \rightarrow \gamma\gamma$ 
  - $E_T^{\text{miss}} > 100 \text{ GeV}$ ,  $\geq 2$  photons with  $m_{\gamma\gamma}$  in 105-160 GeV
- $H \rightarrow ZZ \rightarrow 4\ell$ 
  - Leading lepton  $p_T > 20, 15, 10 \text{ GeV}$
  - $50 < m_{12} < 106 \text{ GeV}$ ;  $12 < m_{34} < 115 \text{ GeV}$
- Set limit on vector mediator  $m_{\text{med}} < 0.9 \text{ TeV}$

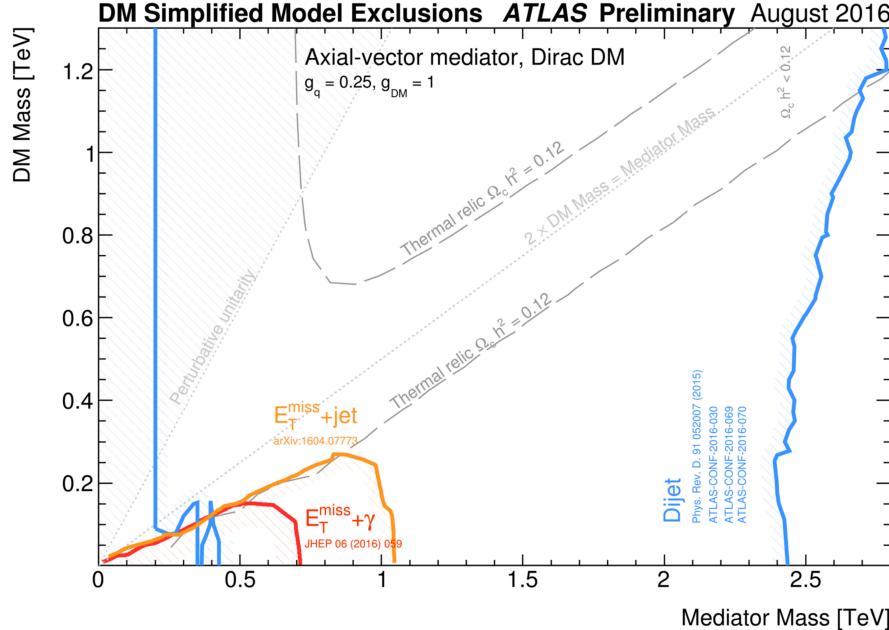




# Summary of mono-X searches from CMS



# Summary of mono-X searches from ATLAS



- Regions in a  $m_{\text{med}} - m_{\text{med}}$  plane excluded at 95% CL by ATLAS DM searches ( $E_T^{\text{miss}} + X$  & Dijet)
  - One possible interaction between the SM and DM
  - Lepto-phobic axial-vector mediator
  - DM coupling  $g_{\text{DM}} = 1.0$  and quark coupling  $g_q = 0.25$  universal to all flavors.

Model	$\ell, \gamma$	Jets†	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$
DM	Axial-vector mediator (Dirac DM)	0 e, $\mu$	$\geq 1 j$	Yes 3.2
	Axial-vector mediator (Dirac DM)	0 e, $\mu$ , 1 $\gamma$	1 j	Yes 3.2
	$ZZ\chi\chi$ EFT (Dirac DM)	0 e, $\mu$	1 J, $\leq 1 j$	Yes 3.2
	<b><math>m_A</math></b> <b>1.0 TeV</b>	$g_q=0.25, g_\chi=1.0, m(\chi) < 250 \text{ GeV}$		1604.07773
	<b><math>m_A</math></b> <b>710 GeV</b>	$g_q=0.25, g_\chi=1.0, m(\chi) < 150 \text{ GeV}$		1604.01306
	<b><math>M_*</math> 550 GeV</b>	$m(\chi) < 150 \text{ GeV}$		ATLAS-CONF-2015-080

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

# Concluding remarks

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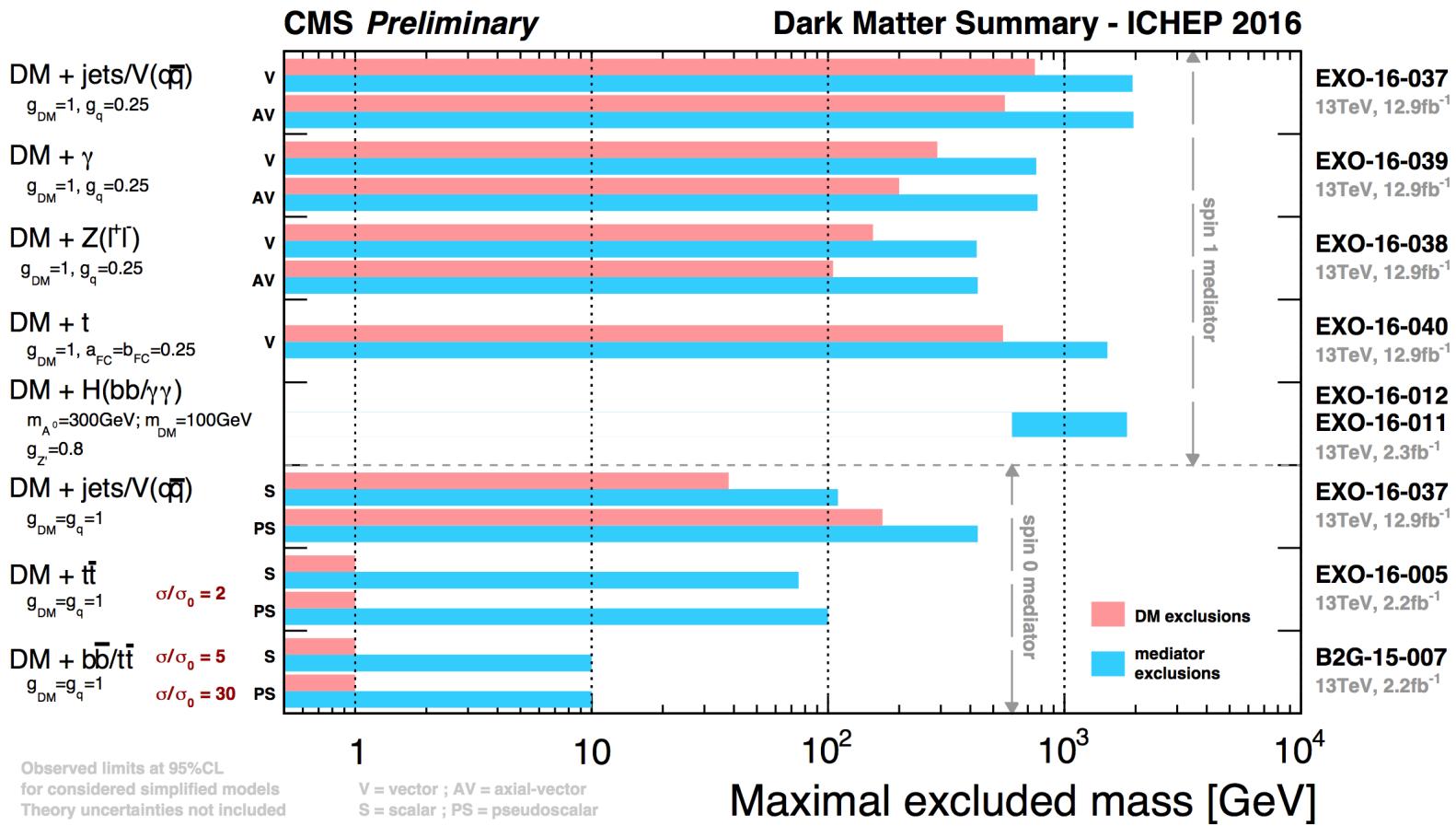
- DM search is one of key physics programs at ATLAS and CMS.
- LHC DM analyses focused on the WIMP search based on the simplified models.
  - Mono-X strategy : used a large  $E_T^{miss}$  by DM and SM particle (Mono-X) recoiling against DM
    - Mono-X: Jet,  $\gamma$  /  $W/Z$ , top,  $b\bar{b}$ ,  $t\bar{t}$ , Higgs
- No significant excess yet over the SM background and set limit on the  $m_{med}$  and  $m_{DM}$ 
  - Data set up to  $13 \text{ fb}^{-1}$  of data at 13 TeV.
  - Vector/Axial-vector mediator,  $m_{med} < 2 \text{ TeV}$
  - (Pseudo) scalar mediator,  $m_{med} < 100$  (430) GeV
  - **Provided an important complementary check with DD and ID experiments.**
  - **Upcoming Dark Matter Working Group meeting**, 19-20 September
    - Review on the ICHEP results at ATLAS and CMS
    - Refinements to the DM Forum menu of models that alter the signals and search design
- More than  $30 \text{ fb}^{-1}$  of full 2016 data will be collected by the end of this year
  - Stay tuned for the new updates on DM searches at LHC.

# Backup slides

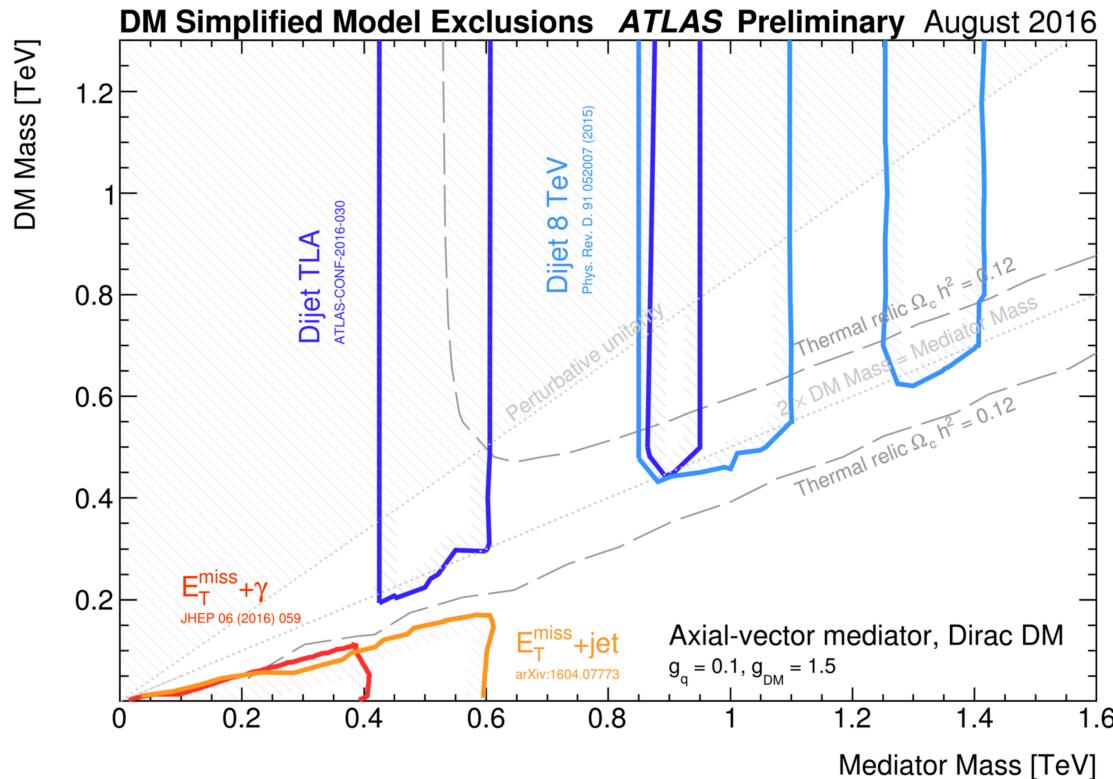
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# CMS Maximal/minimal reach of DM searches

- Mediator mass (blue bar) and DM mass (red bar)
- The limits represent 95% CL observed exclusions and they are only applicable to the model and coupling choices indicated next to the bars.



# ATLAS other couplings: $g_{\text{SM}}=0.1$ , $g_{\text{DM}}=1.5$



- Exclusions computed for  $g_{\text{DM}} = 1.5$  and  $g_q = 0.1$  universal to all flavors.
  - $Z'$  decays to quarks suppressed in favour of a higher branching ratio to DM particles, reducing the sensitivity of di-jet searches to this scenario.
- The mono-jet and mono-photon exclusion regions obtained by rescaling, using acceptance and cross-section information from samples simulated at truth-level