Dark Matter Searches at the LHC

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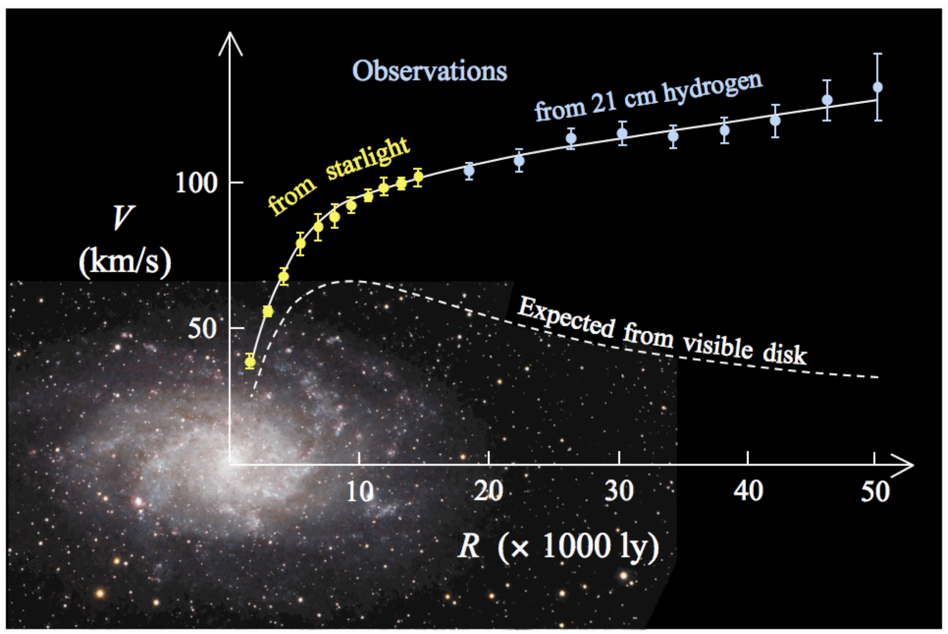
On behalf of CMS & ATLAS

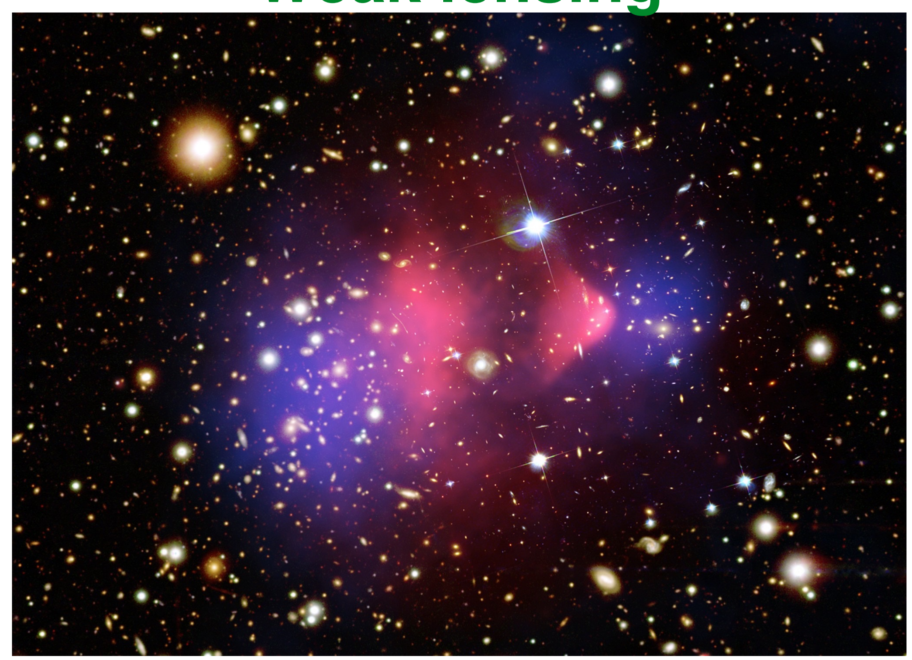
Dark Matter

Existence of dark matter known through its gravitational interactions

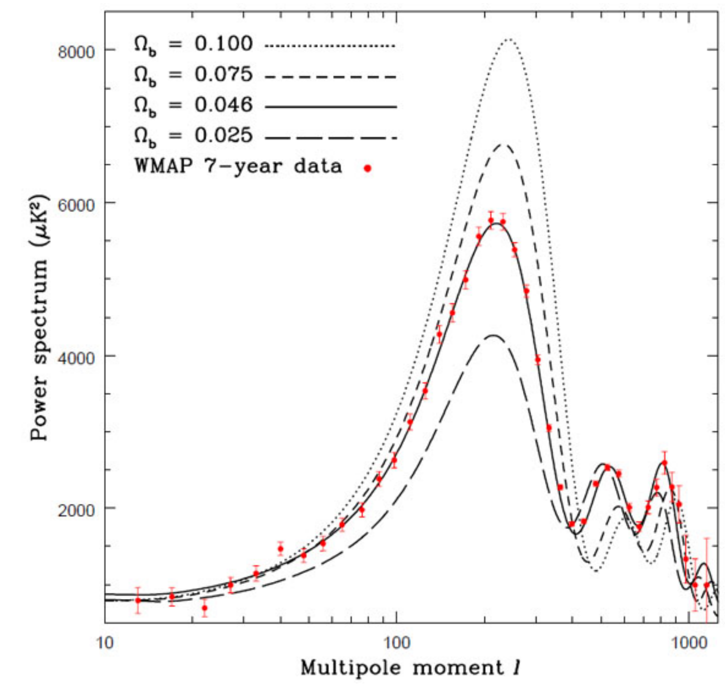
Galactic rotation



Weak lensing



CMB



Underlying nature of dark matter (DM) remains unknown

There is a well established case for weakly interacting DM particles (WIMPs)

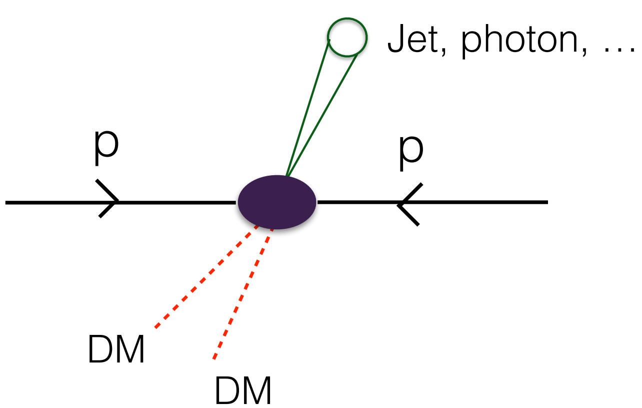
*Such particles may be **produced in high energy p-p collisions** at LHC!!*

DM Signatures @ LHC

How do we detect DM at the LHC ?

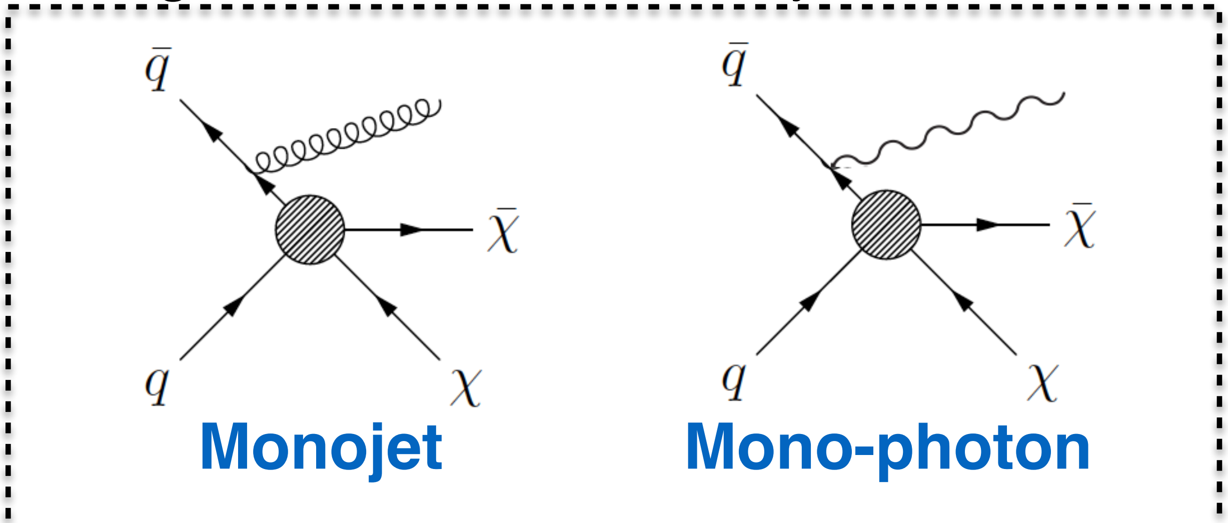
- DM particles leave no trace in the detector
- But they may create a transverse momentum imbalance in the event (MET)

DM pair recoils against a visible high p_T object



Substantial MET

- To produce significant MET, DM particles must recoil against some boosted system **"X"**
- **X** is typically some form of ISR
  - ➡ Gluon (jet), photon, W, Z
  - ➡ **"Mono-X"** or MET+X signatures



Overview of the Talk

- Quite a bit of discussion on the LHC DM searches yesterday
  - *See Francesco's talk on DM constraints from dijet, dilepton resonance searches*
  - *See Ren-Jie's talk on the study of DM-Higgs interactions*
  - *See Jeroen's talk on interpretations of DM & SUSY searches*

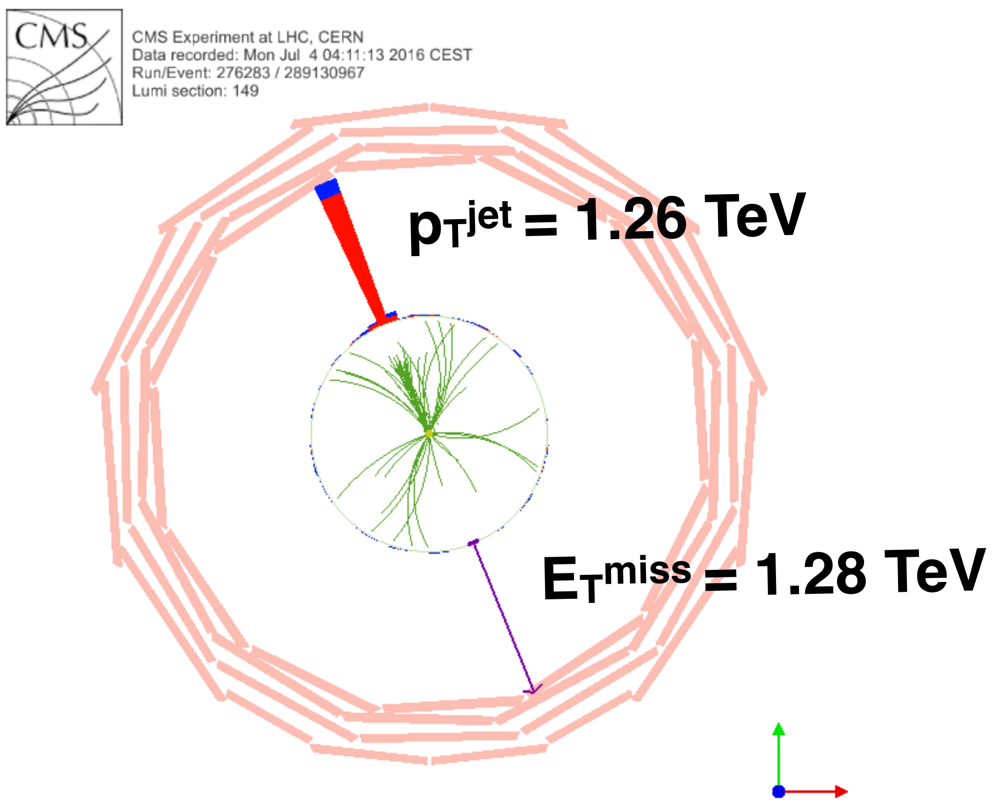
- In this talk I will focus on two key DM search channels at the LHC
  - Monojet : Important channel particularly for spin-1 mediators
  - tt+MET : Important channel for spin-0 mediators

Monojet Search at CMS & ATLAS

Large signal cross-section
Typically the most sensitive final state

Key features of event selection

- Large MET (250 GeV or more)
  - ➡ Driven by trigger thresholds
- At least one high p_T, central jet
  - ➡ p_T > 100 (250) GeV for CMS (ATLAS)
  - ➡ $|\eta| < 2.4$
- Remove fake MET from detector noise, non-collision bkg
  - ➡ For example : energy fraction of leading jet due to charged particles > 0.1
- Veto on events with leptons
  - ➡ Kills backgrounds with genuine MET such as W+jets and top



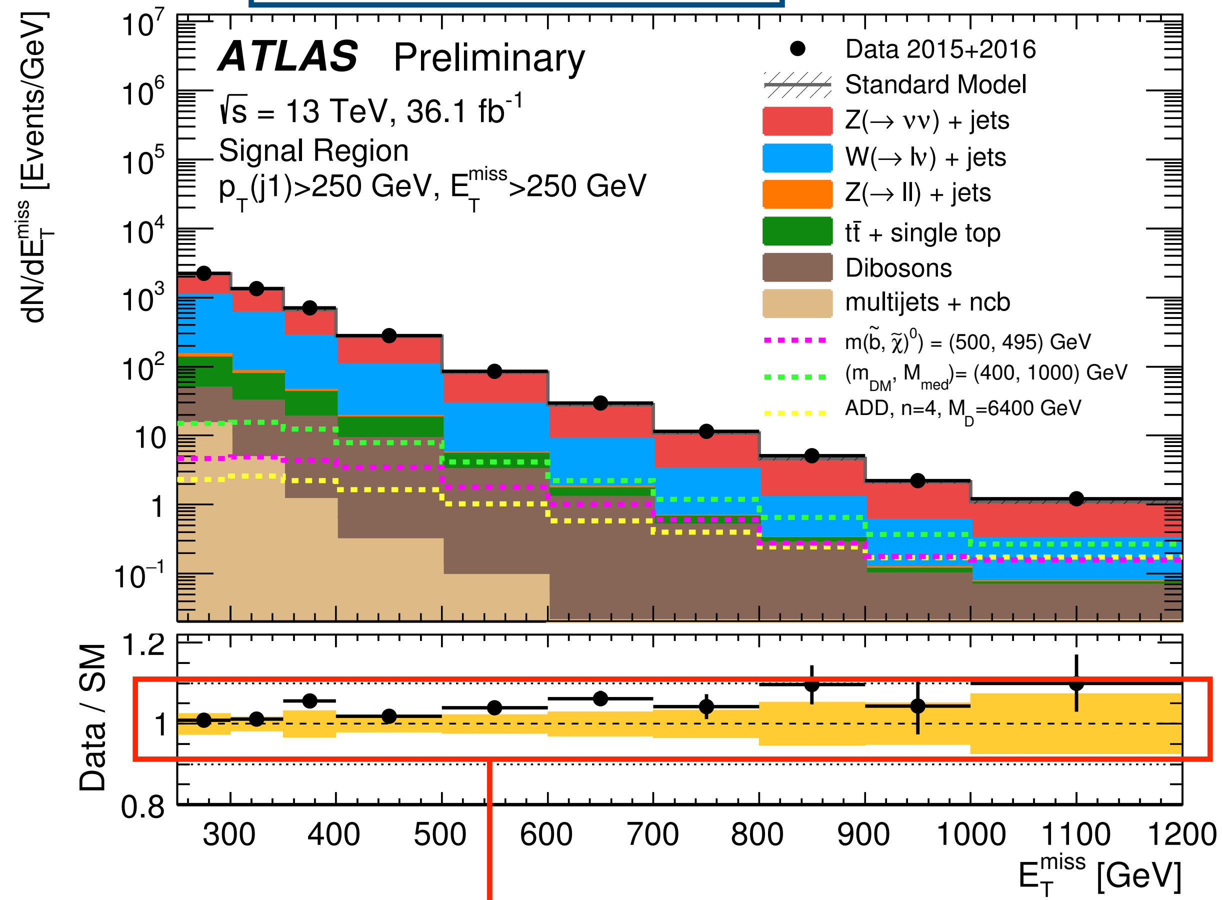
Main backgrounds

- ➡ Z(νν)+jets (~ 60%)
- ➡ W(lν)+jets where lepton is lost (~30%)
- ➡ Minor bkg : Top, dibosons, etc.

Monojet Analysis Strategy

- No mass peak or kinematic end-points (e.g. m_T)
- MET shape is the discriminant between signal and background
- Signal has a harder MET spectrum compared to the background
- **Main thrust of this analysis is accurate determination of the Z+jets (and W+jets) p_T spectrum**
- Multiple control regions employed in data
  - ➡ Z(ll)+jets events (dilepton events)
  - ➡ W(lν)+jets (single lepton events)
  - ➡ And γ+jets events in case of CMS

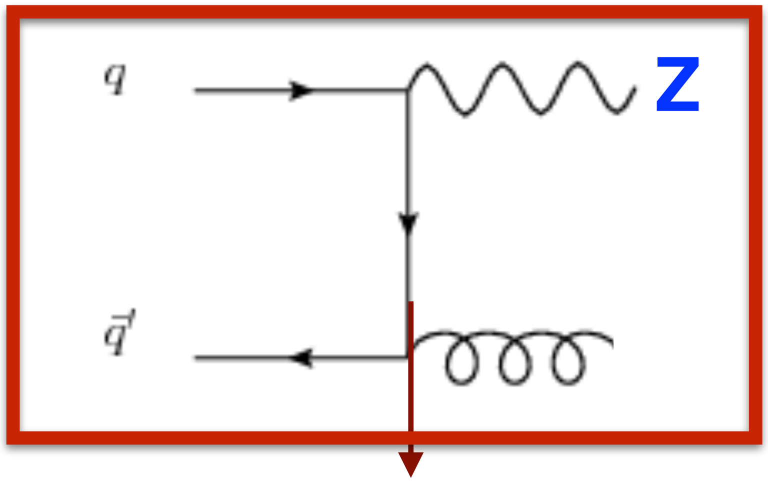
ATLAS-2017-060



- Background uncertainty constrained to
- **About 2% at MET ~ 250 GeV**
- **About 10% at MET ~ 1 TeV**
- ***Achieved by using precise predictions of the V+jets cross section ratios***

Control Regions In Monojet Analysis

$Z\rightarrow ll$



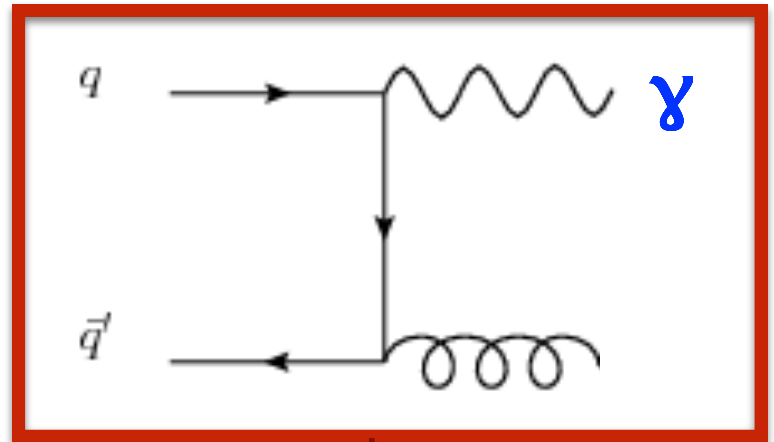
Same process as $Z\rightarrow\nu\nu$, same p_T spectrum

But statistically limited

$Z\rightarrow\mu\mu$ branching ratio ~3%

$Z\rightarrow\nu\nu$ branching ratio 20%

γ+jets (Used by CMS)

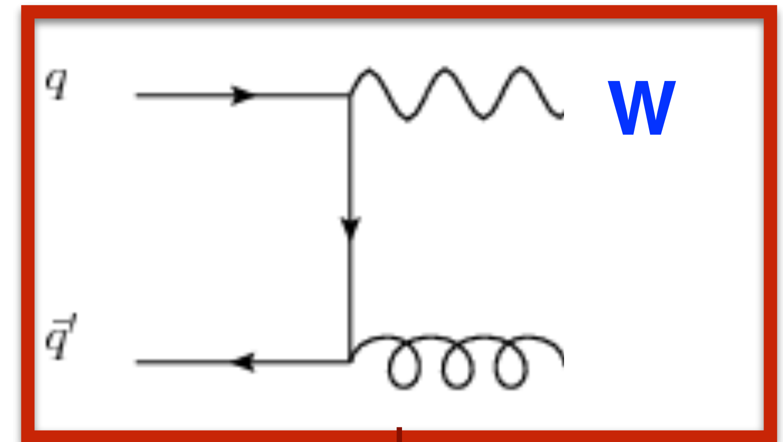


Similar p_T spectra to $Z\rightarrow\nu\nu$

Statistically rich

Event rate ~ $Z\rightarrow\nu\nu$ x 2

$W\rightarrow l\nu$



Similar p_T spectra to $Z\rightarrow\nu\nu$

Event rate ~ $Z\rightarrow\nu\nu$

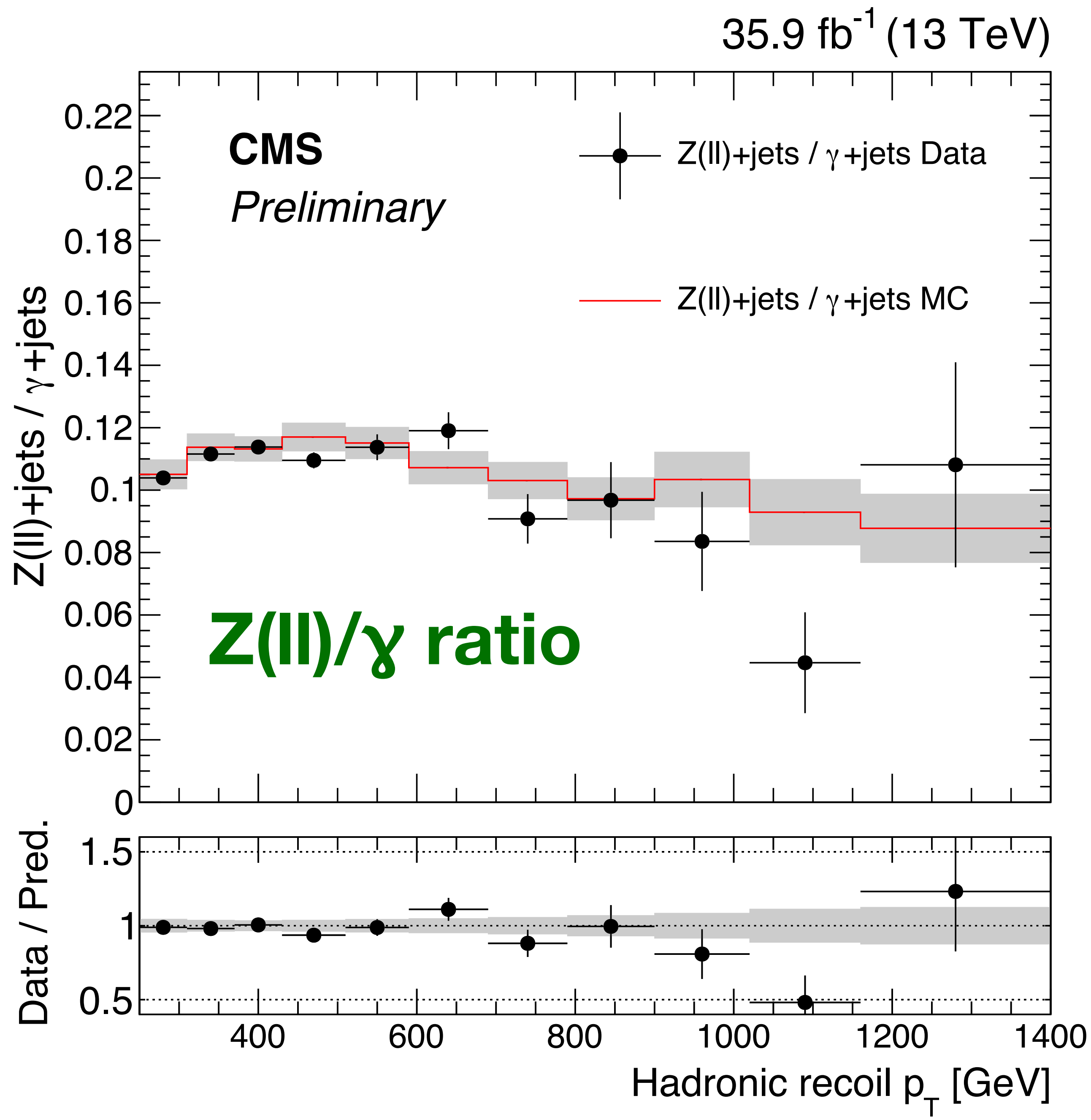
Also used to estimate W+jets background

How are these control regions tied to the electroweak backgrounds in signal region ?

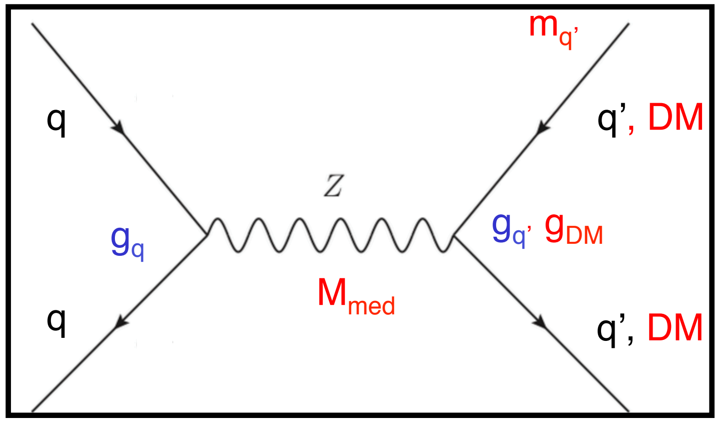
Electroweak Background Estimation

CMS-EXO-16-048

- Need precise estimates of Z/W and Z/ɣ cross section ratios to extrapolate from control regions to signal region
- Predictions for these ratios obtained at NLO in QCD and EWK corrections
- Theory uncertainties (e.g. QCD scale, PDF choice) largely cancel in the ratio leading to uncertainties at the level of a few percent
- Detailed theoretical estimates for Z/W and Z/ɣ ratios and uncertainties proposed by ***Lindert et al (arXiv: 1705.04664)***

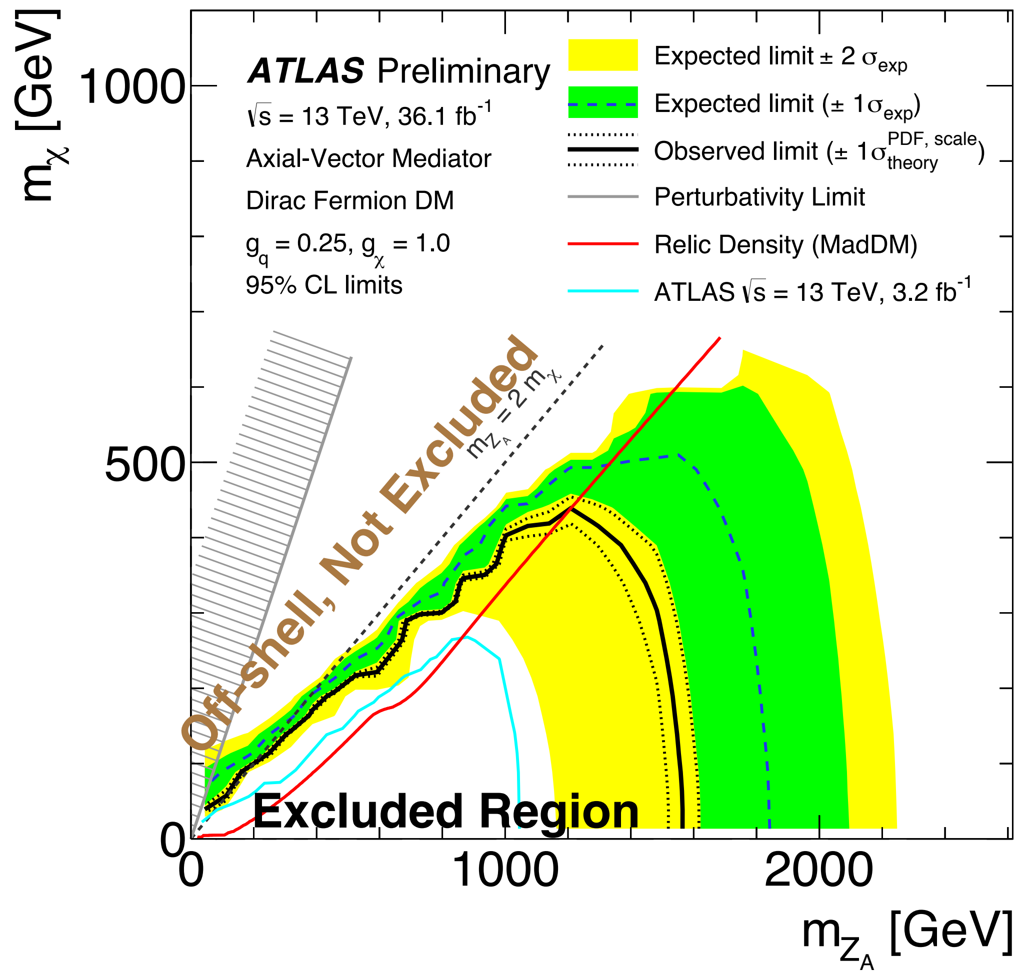


Monojet Results

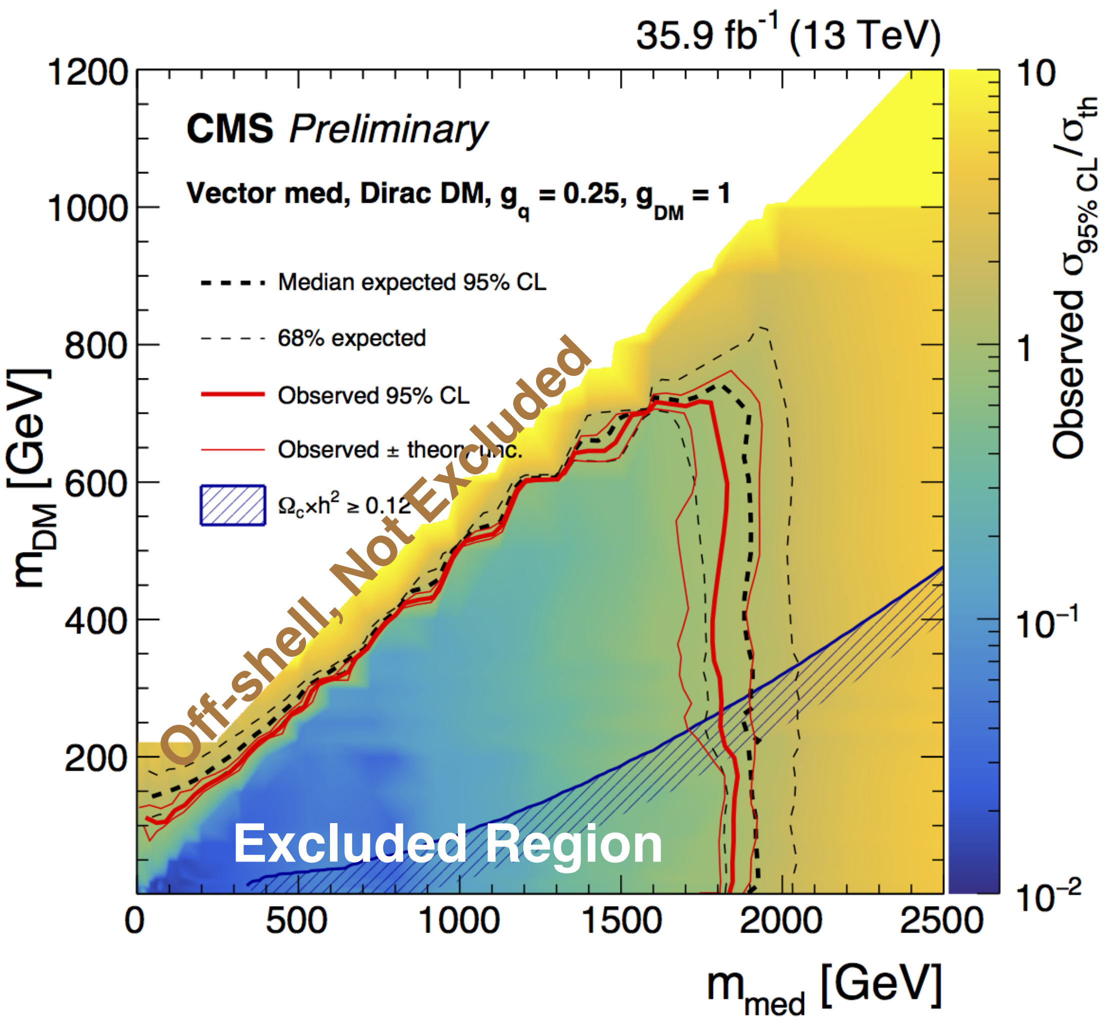


Spin-1 mediator (Vector or Axial-vector)
g_q = 0.25 ; g_{DM} = 1

ATLAS-2017-060



CMS-EXO-16-048



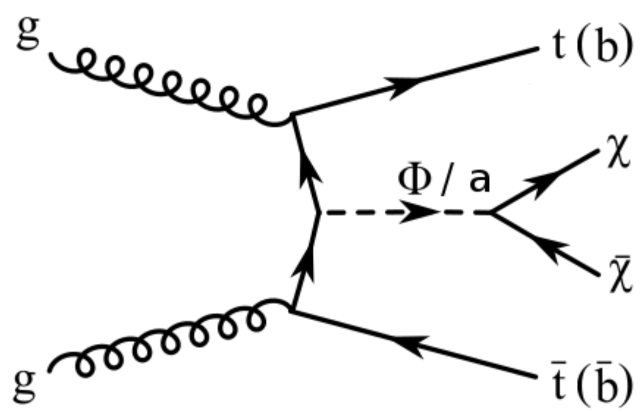
Spin-1 mediator masses up to ~2 TeV excluded

Spin-0 Mediators

- Also consider DM interactions mediated by scalar and pseudoscalar particles
- Require the interaction between spin-0 mediator and quarks to have the SM Yukawa structure (Minimal Flavor Violation)
- Coupling to quarks proportional to the quark mass (like the SM Higgs boson)
- Mediator couples preferentially to the top quark

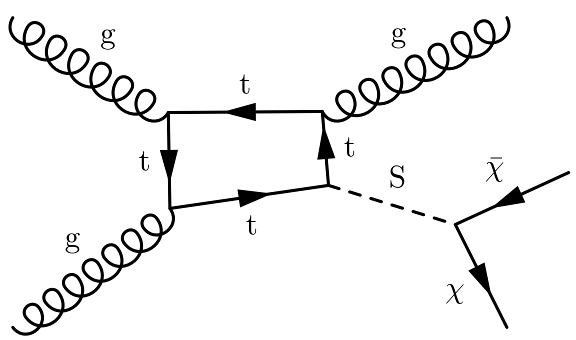
tt+DM Final State

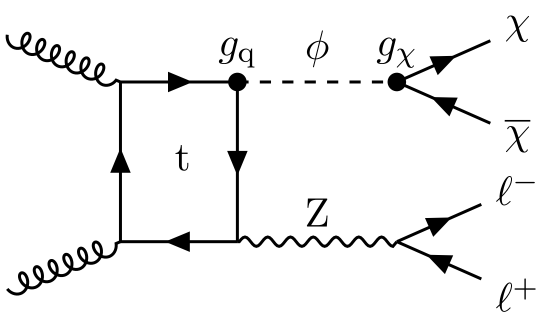
(Sensitive for spin-0 mediators)



Monojet or Mono-Z Final State

(Produced through gluon fusion)





CMS tt(2l)+DM Search

CMS-SUS-17-001

Event Selection

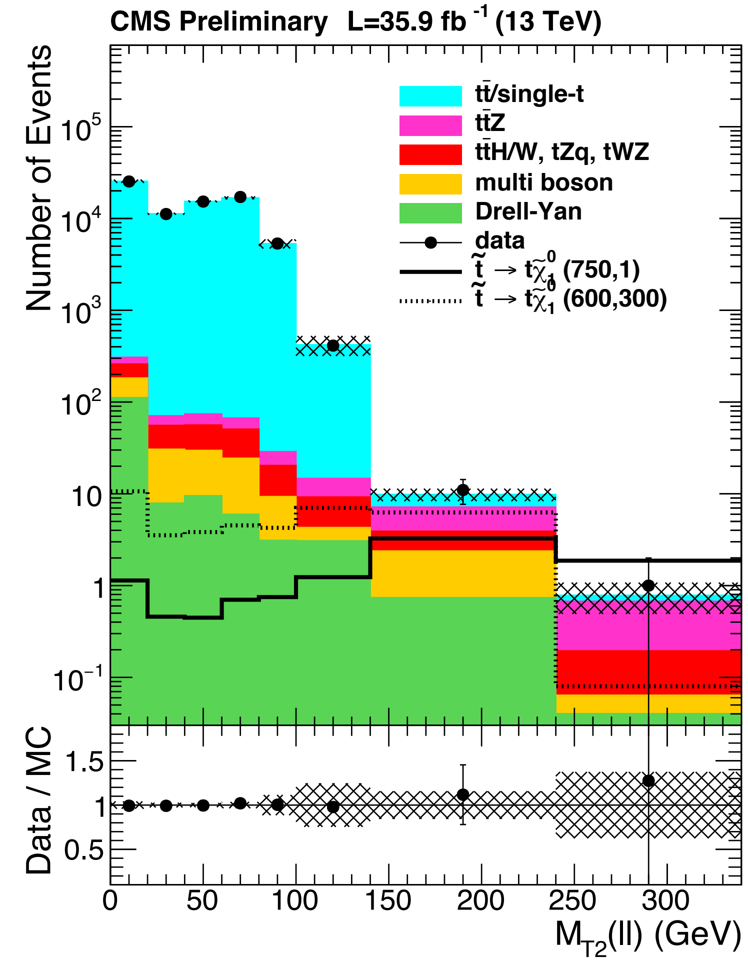
leptons	2 (e or μ), opposite charge
$m(ll)$	≥ 20
$\lvert M_Z - m(ll) \rvert$	$> 15\,\text{GeV}$, same flavor only
N_{jets}	≥ 2
N_{bjets}	≥ 1
$E_{\text{T}}^{\text{miss}}$	> 80 GeV
$E_{\text{T}}^{\text{miss}} / \sqrt{H_T}$	$> 5\,\text{GeV}^{1/2}$
$\cos\Delta\phi(E_{\text{T}}^{\text{miss}}, j_1)$	< 0.80
$\cos\Delta\phi(E_{\text{T}}^{\text{miss}}, j_2)$	< 0.96

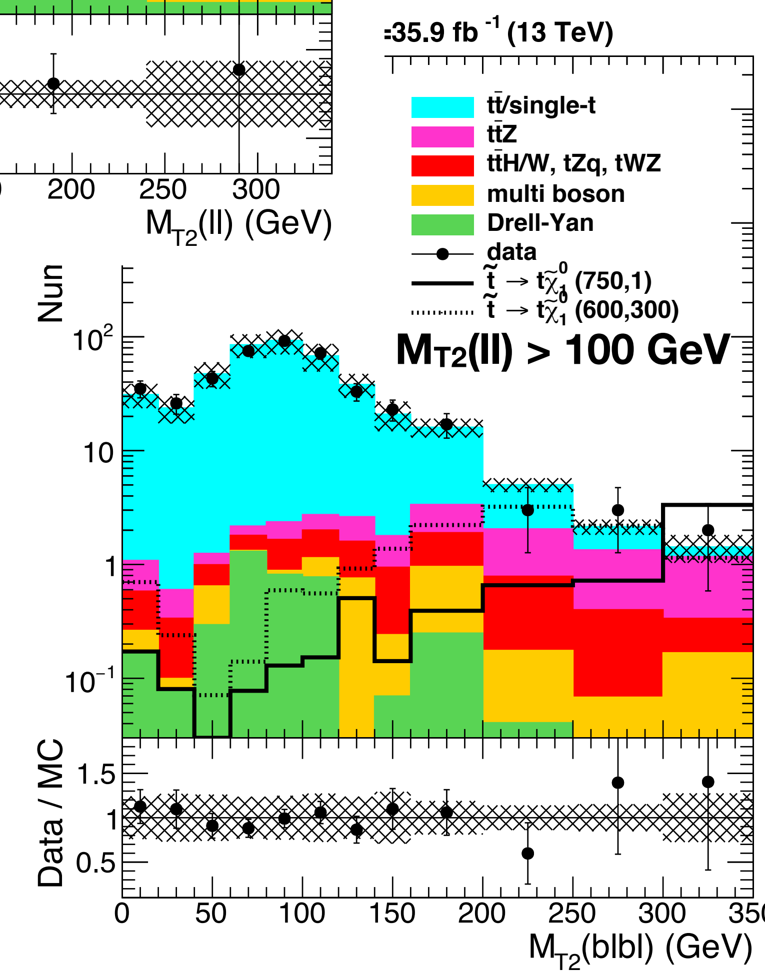
Main background : tt(2l)

- **Stransverse mass M_{T2}** key discriminant between signal and background

$$M_{T2}(\ell\ell) = \min_{\vec{p}_{\text{T1}}^{\text{miss}} + \vec{p}_{\text{T2}}^{\text{miss}} = \vec{p}_{\text{T}}^{\text{miss}}} \left(\max \left[M_T(\vec{p}_{\text{T}}^{\text{vis1}}, \vec{p}_{\text{T1}}^{\text{miss}}), M_T(\vec{p}_{\text{T}}^{\text{vis2}}, \vec{p}_{\text{T2}}^{\text{miss}}) \right] \right)$$

- Two kinematic end-points for the tt(2l) background
- M_{T2}(ll) ~ 80 GeV (W mass)
- M_{T2}(lblb) ~ 175 GeV (top mass)





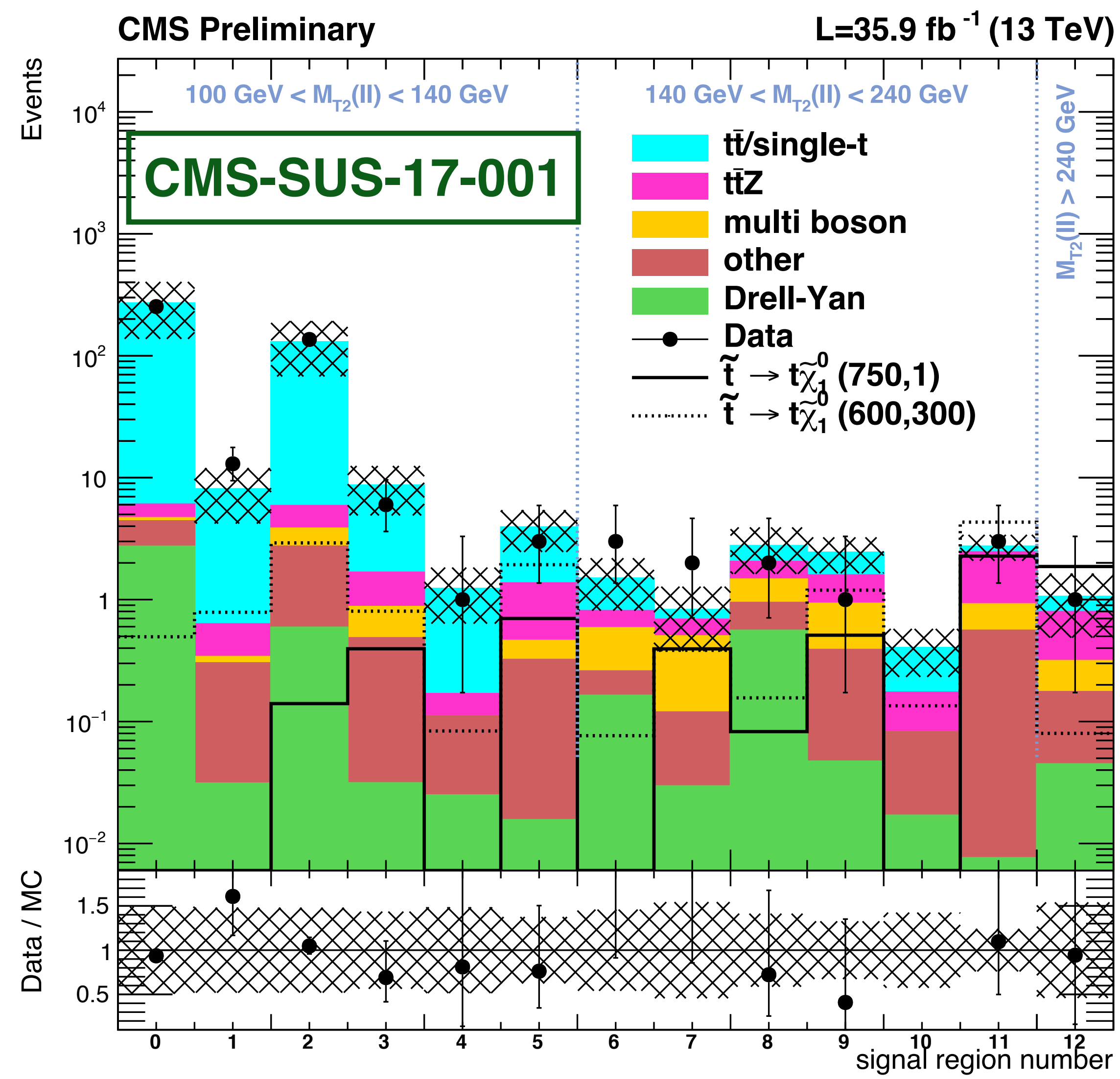
CMS tt(2l)+DM Search

Analysis performed in bins of M_{T2}(ll), M_{T2}(lblb) and MET

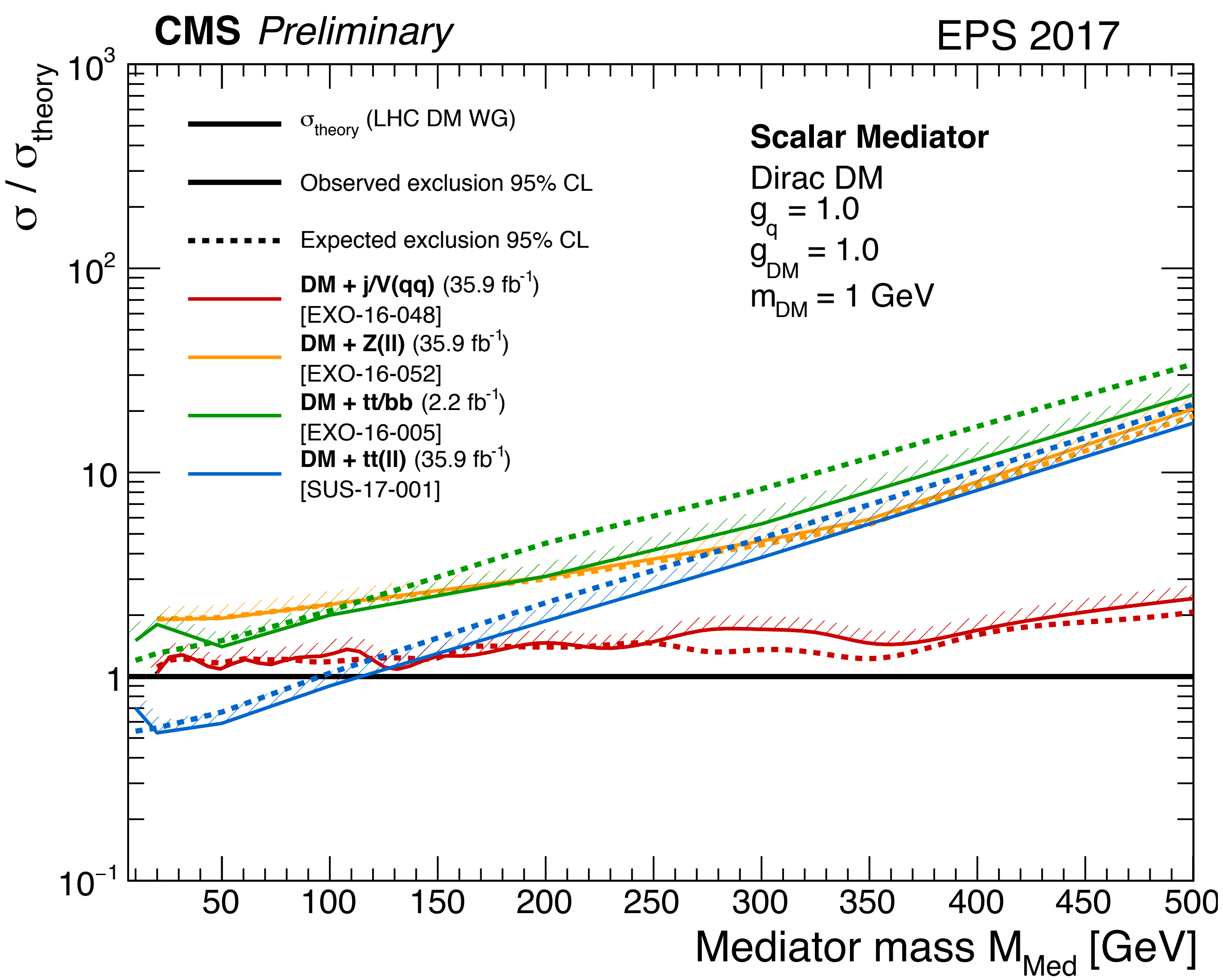
$M_{T2}(b\ell b\ell)$ (GeV)	E_T^{miss} (GeV)	$100 \leq M_{T2}(\ell\ell) < 140$ GeV	$140 \leq M_{T2}(\ell\ell) < 240$ GeV	$M_{T2}(\ell\ell) \geq 240$ GeV
0 – 100	80 – 200	SR0	SR6	SR12
	≥ 200	SR1	SR7	
100 – 200	80 – 200	SR2	SR8	
	≥ 200	SR3	SR9	
≥ 200	80 – 200	SR4	SR10	
	≥ 200	SR5	SR11	

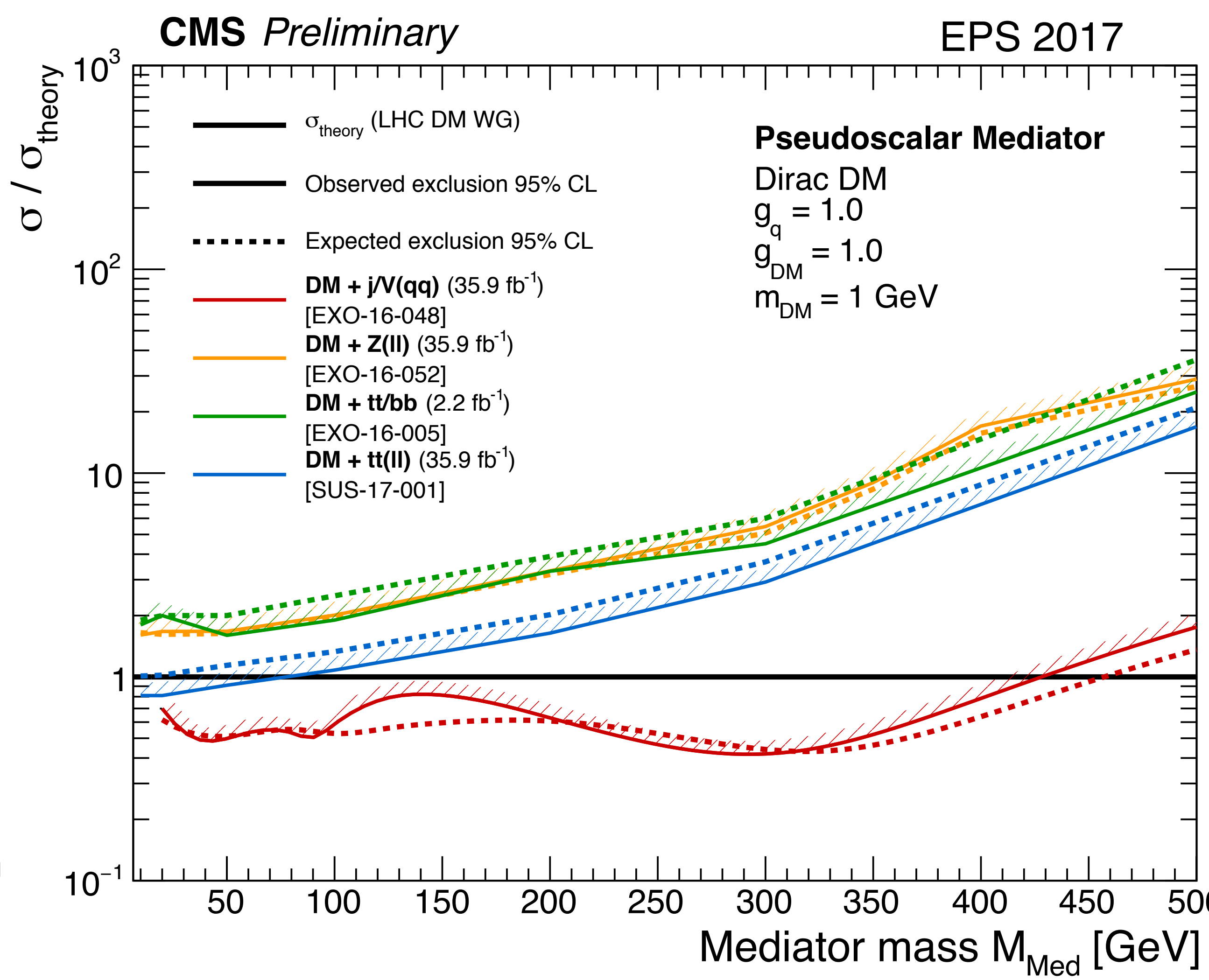
Important Backgrounds

- **tt(2l) background** estimated from simulation
  - ➡ Validated in a control region having a 3rd, non-isolated lepton
- **ttZ(vv) background** important at high M_{T2}(ll)
  - ➡ Normalization obtained from events with three isolated leptons : tt(semi-leptonic) + Z(ll)
  - ➡ Validated using a control sample of ttɣ events



Spin-0 Mediator Results From CMS





- **Scalar mediator masses up to 100 GeV excluded by the tt(2l)+DM search**
- **Monojet provides stronger limits for pseudoscalar mediator**
  - **Masses up to 400 GeV excluded**

ATLAS tt+DM Semi-leptonic Search

Some key discriminating variables
Transverse mass (m_T) : Kills W+jets, tt(1l)

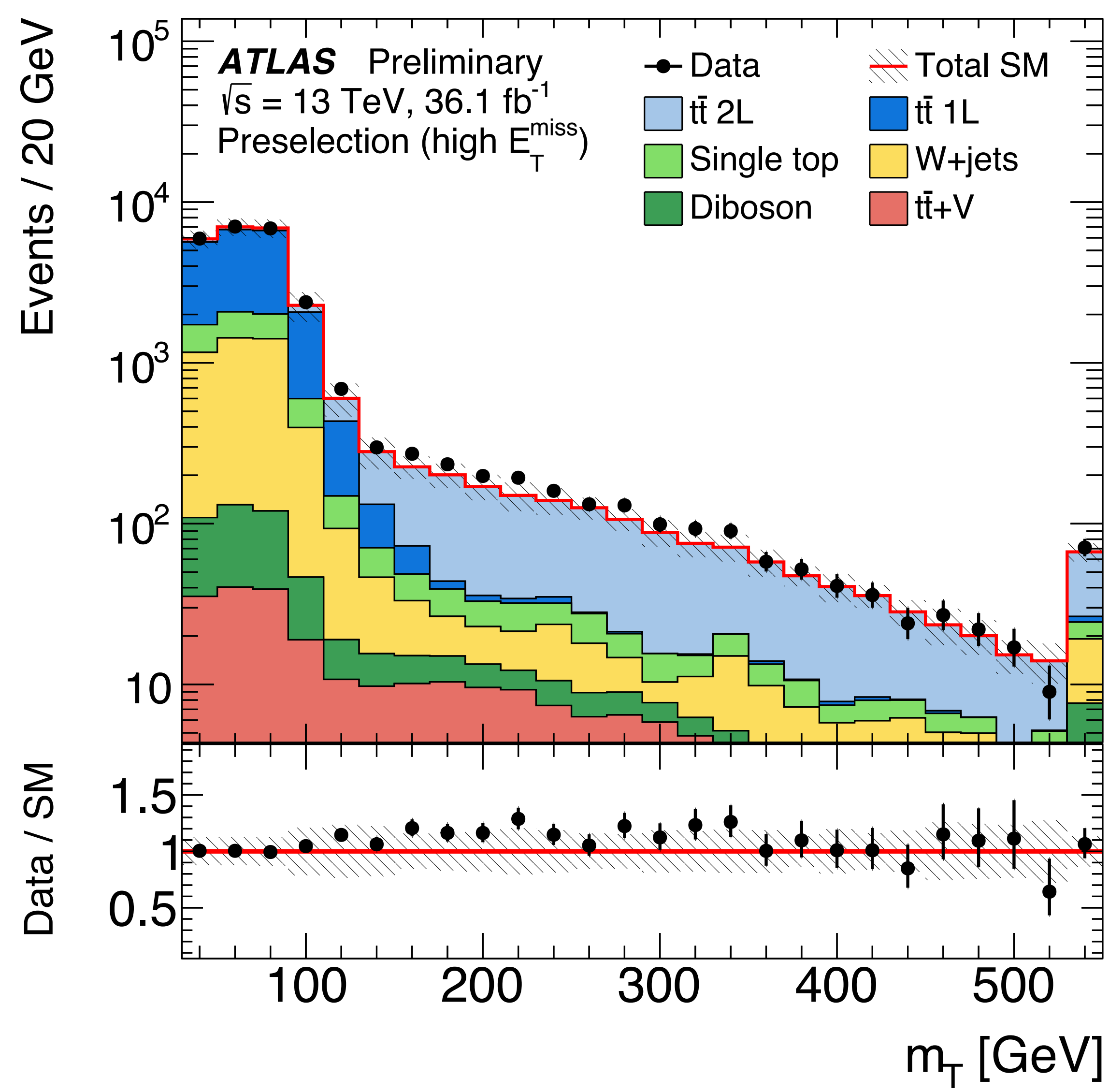
tt+DM semi-leptonic final state

- Exactly 1 lepton (e,μ) in the event
- Substantial MET (at least 230 GeV)
- Four or more jets
- One or more b-jets
- At least 1 reconstructed top candidate with mass > 130 GeV

Main backgrounds

- ➡ W(lν)+jets
- ➡ tt(1l)
- ➡ tt(2l) with one lost lepton

- Suppressed using additional kinematic discriminating variables



ATLAS-CONF-2017-037

ATLAS tt+DM Semi-leptonic Search

tt+DM semi-leptonic final state

- Exactly 1 lepton (e,μ) in the event
- Substantial MET (at least 230 GeV)
- Four or more jets
- One or more b-jets
- At least 1 reconstructed top candidate with mass > 130 GeV

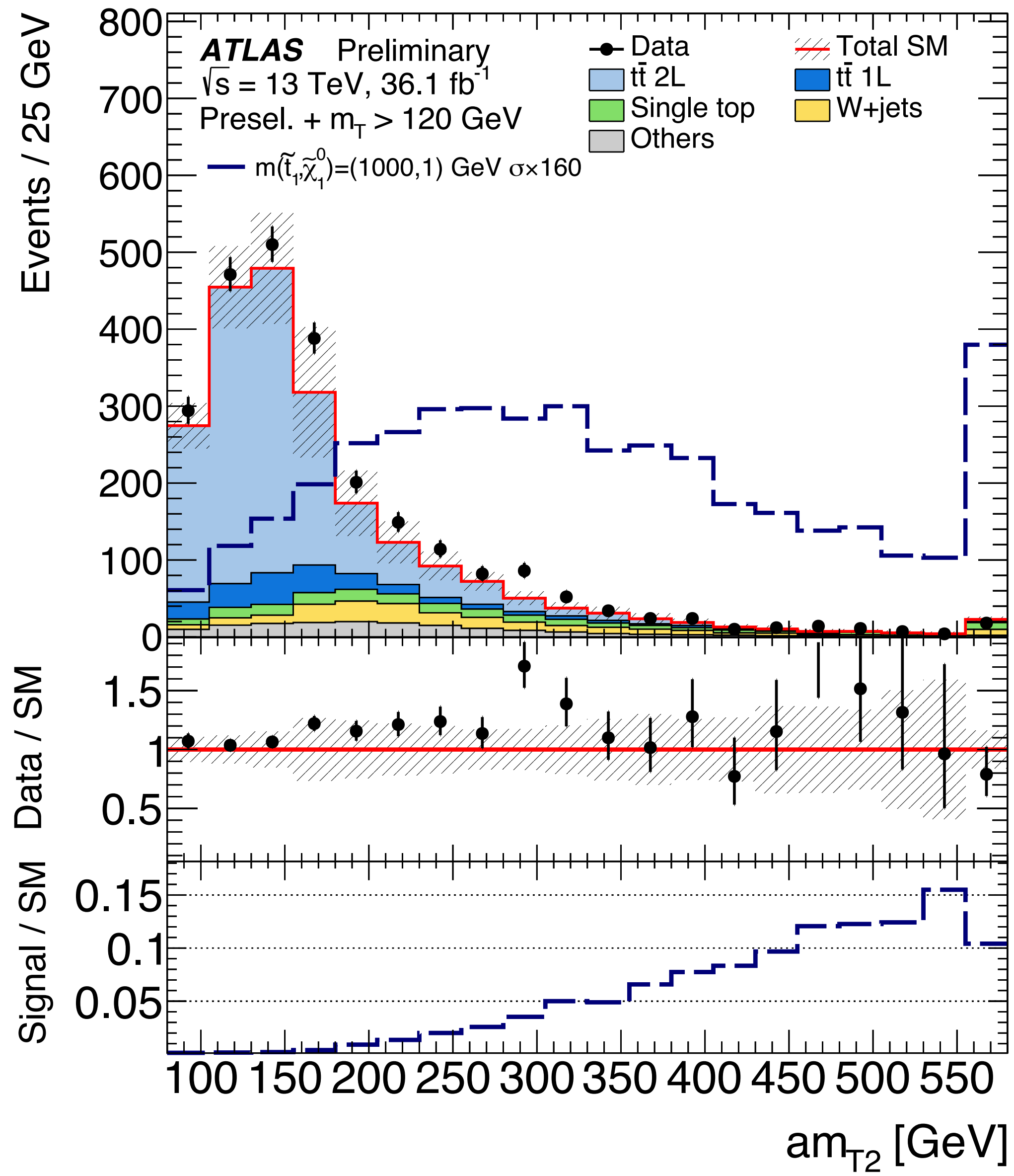
Main backgrounds

- ➡ W(lν)+jets
- ➡ tt(1l)
- ➡ tt(2l) with one lost lepton

- Suppressed using additional kinematic discriminating variables

Some key discriminating variables

Asymmetric m_{T2} : Kills tt(2l) bkg



ATLAS-CONF-2017-037

tt+DM Semi-leptonic Analysis

Event Selection : ATLAS-CONF-2017-037

Signal region	DM_low_loose	DM_low	DM_high
Preselection	high-E_T^{miss} preselection		
Number of (jets, b-tags)	$(\geq 4, \geq 1)$	$(\geq 4, \geq 1)$	$(\geq 4, \geq 1)$
Jet p_T [GeV]	$> (60, 60, 40, 25)$	$> (120, 85, 65, 25)$	$> (125, 75, 65, 25)$
b-tagged jet p_T [GeV]	> 25	> 60	> 25
E_T^{miss} [GeV]	> 300	> 320	> 380
m_T [GeV]	> 120	> 170	> 225
$H_{T,sig}^{miss}$	> 14	> 14	–
am_{T2} [GeV]	> 140	> 160	> 190
$m_{top}^{reclustered}$ [GeV]	–	> 130	> 130
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	> 0.8	> 1.2	> 1.2
$\|\Delta\phi(jet_i, \vec{p}_T^{miss})\|$	> 1.4	> 1.0	> 1.0
$\|\Delta\phi(j_{1,2}, \vec{p}_T^{miss})\|$		> 0.4	
m_{T2}^{τ} based τ-veto [GeV]		> 80	
exclusion technique	cut-and-count	cut-and-count	cut-and-count

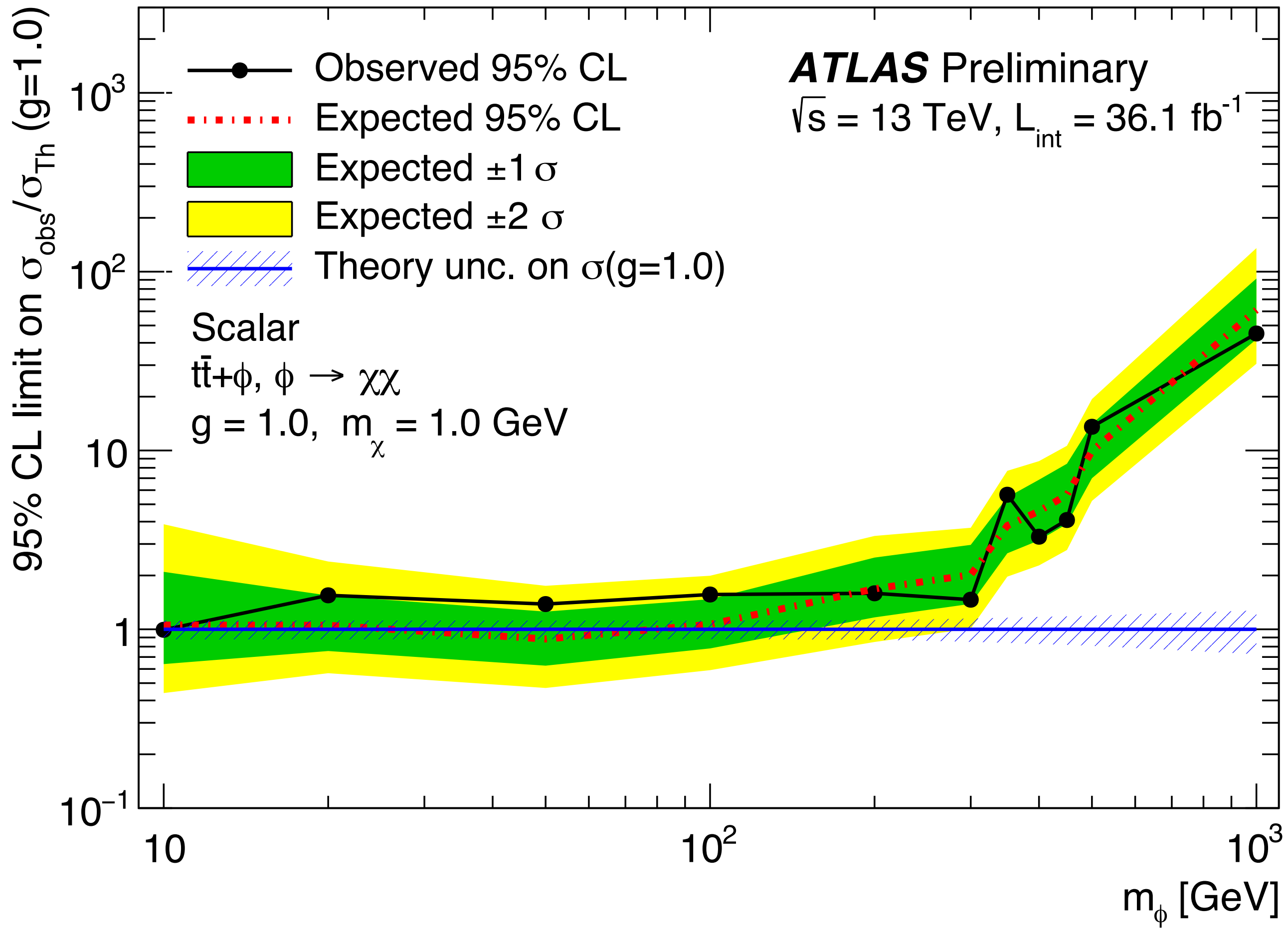
Key backgrounds estimated from dedicated control regions

- tt(2l) CR obtained by inverting the am$_{T2}$ requirement
- W+jets CR obtained by inverting the m$_T$ cut
- ttZ CR obtained by requiring 3 leptons in the event

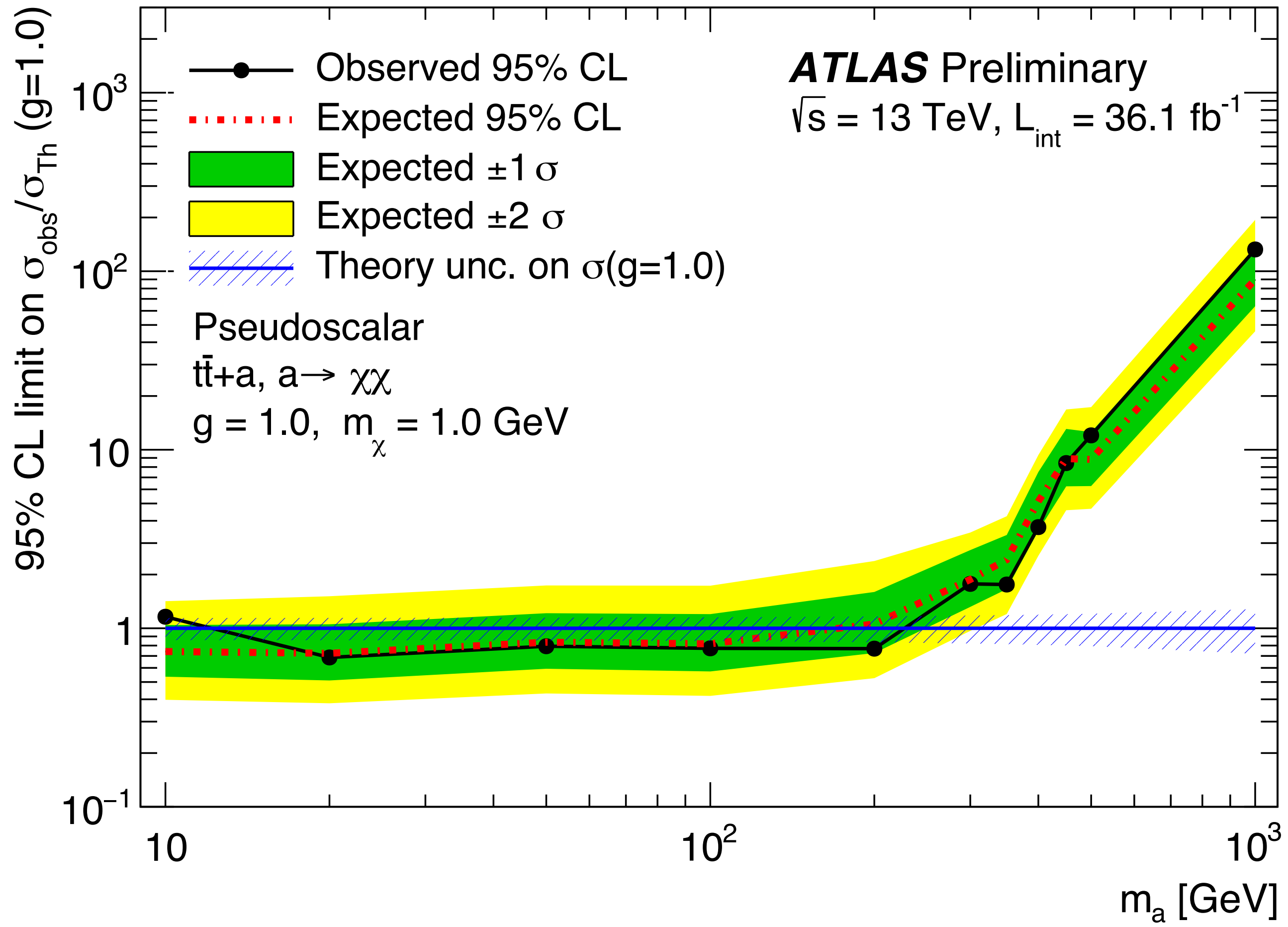
tt+DM Semi-leptonic Results

ATLAS-CONF-2017-037

Scalar Mediator



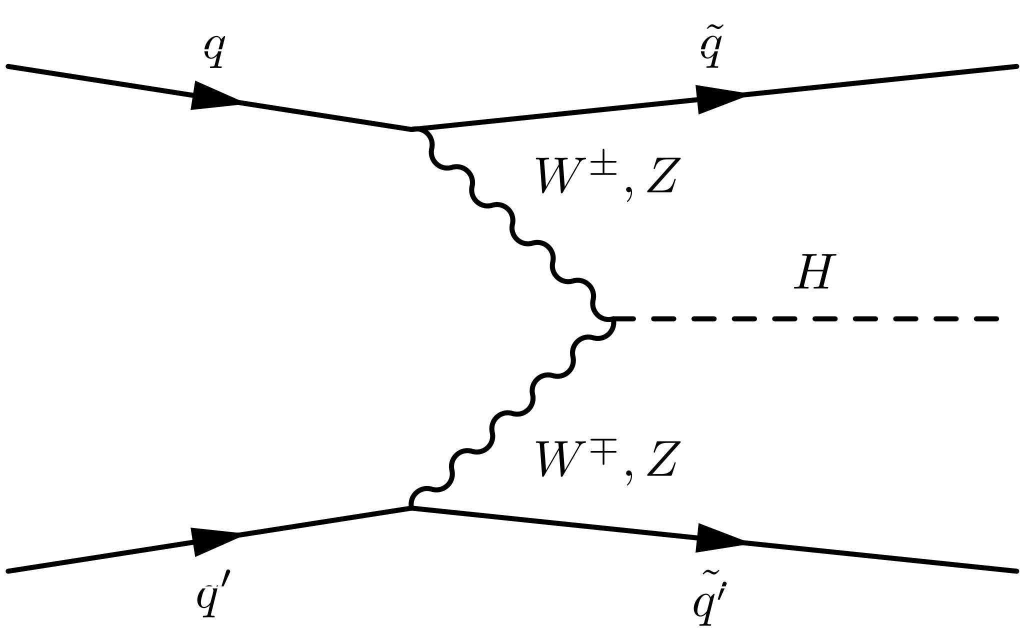
Pseudoscalar Mediator



Pseudoscalar masses up to 220 GeV excluded

Higgs Boson As a Dark Matter Portal

- Very small invisible branching ratio of the Higgs boson in SM (~0.1%)
- But if Higgs boson couples to DM & $m_{DM} < m_H/2$ it will decay invisibly
- Unlike the scalar simplified models discussed so far, the **Higgs boson also couples directly to the W & Z bosons**
- This opens up new final states
- **VBF+MET is the most sensitive channel probing invisible Higgs decays**

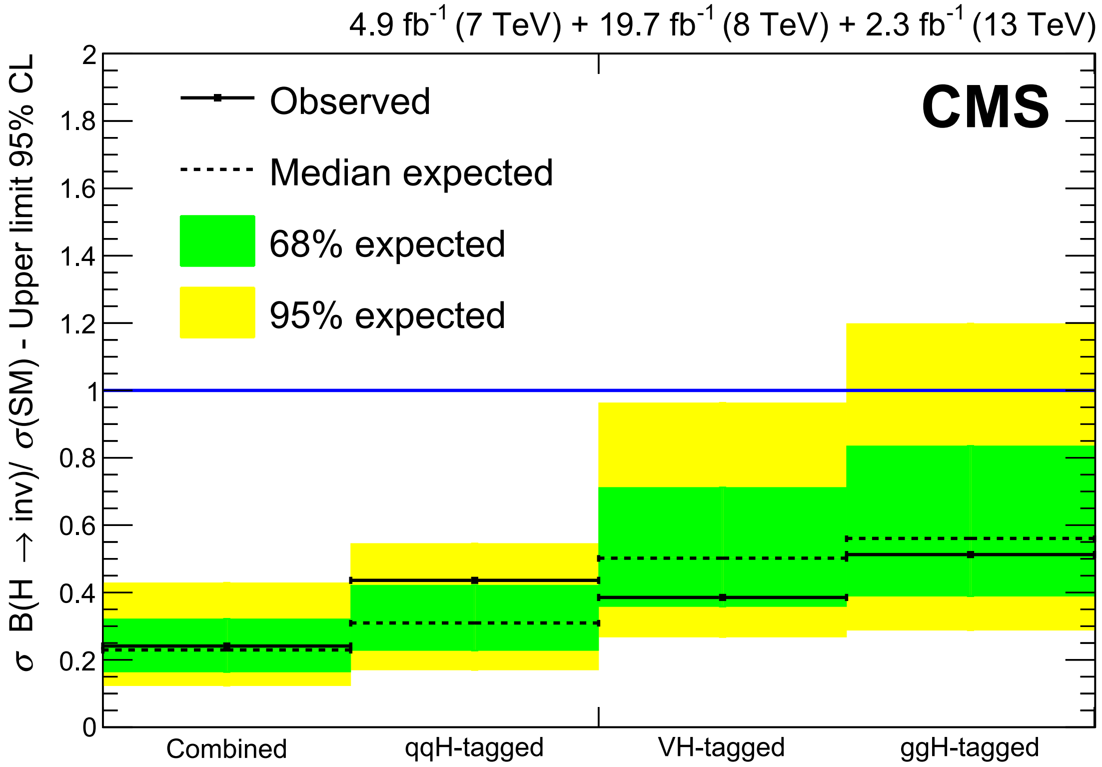


See R. Wang's talk for more details

Higgs → Invisible Combination

- Limit on H→inv BR obtained from a combination of several final states
- Limit dominated by the VBF+MET search
- Monojet (gluon fusion) and mono-V(Higgsstrahlung) final states also included

CMS H(inv) Combination



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ATLAS H(inv) Combination

Channels	Upper limit on BR($h \to$ inv.) at the 95% CL					
	Obs.	−2 std. dev.	−1 std. dev.	Exp.	+1 std. dev.	+2 std. dev.
VBF h	0.28	0.17	0.23	0.31	0.44	0.60
$Z(\to \ell\ell)h$	0.75	0.33	0.45	0.62	0.86	1.19
$V(\to jj)h$	0.78	0.46	0.62	0.86	1.19	1.60
Combined Results	0.25	0.14	0.19	0.27	0.37	0.50

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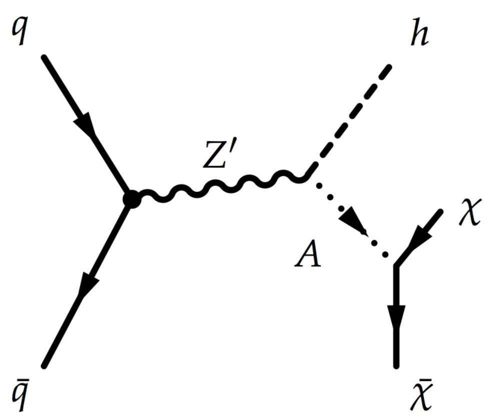
Limit on H(inv) BR

- **24% (CMS)**
- **25% (ATLAS)**
- **23% (ATLAS visible+invisible combined fit)**

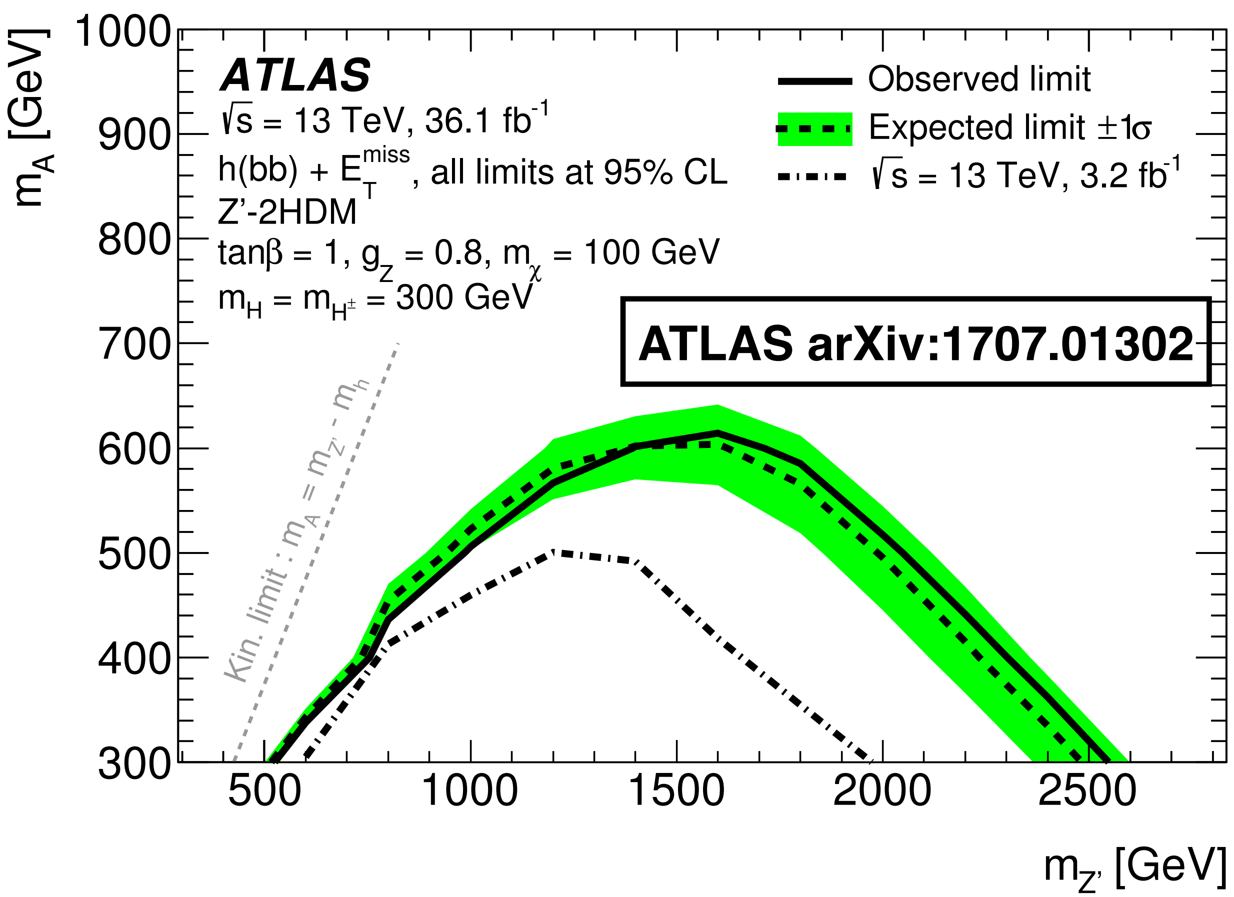
Other DM Models & Searches

Mono-H and mono-top signatures also searched for

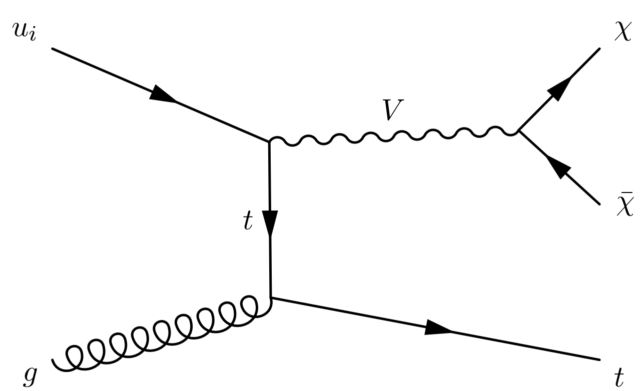
ATLAS mono-H(bb) search



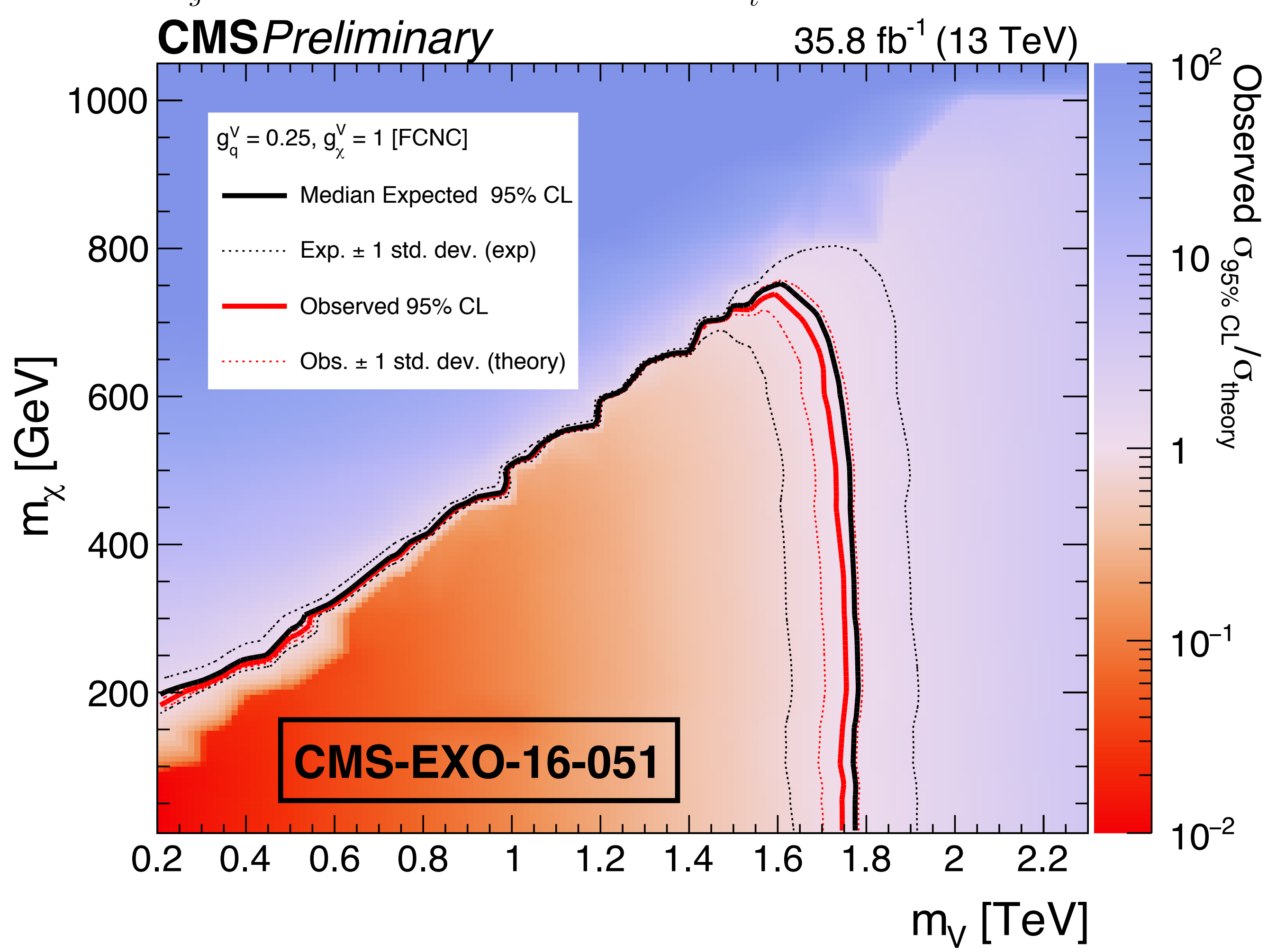
Z'-2HDM model



CMS mono-top search

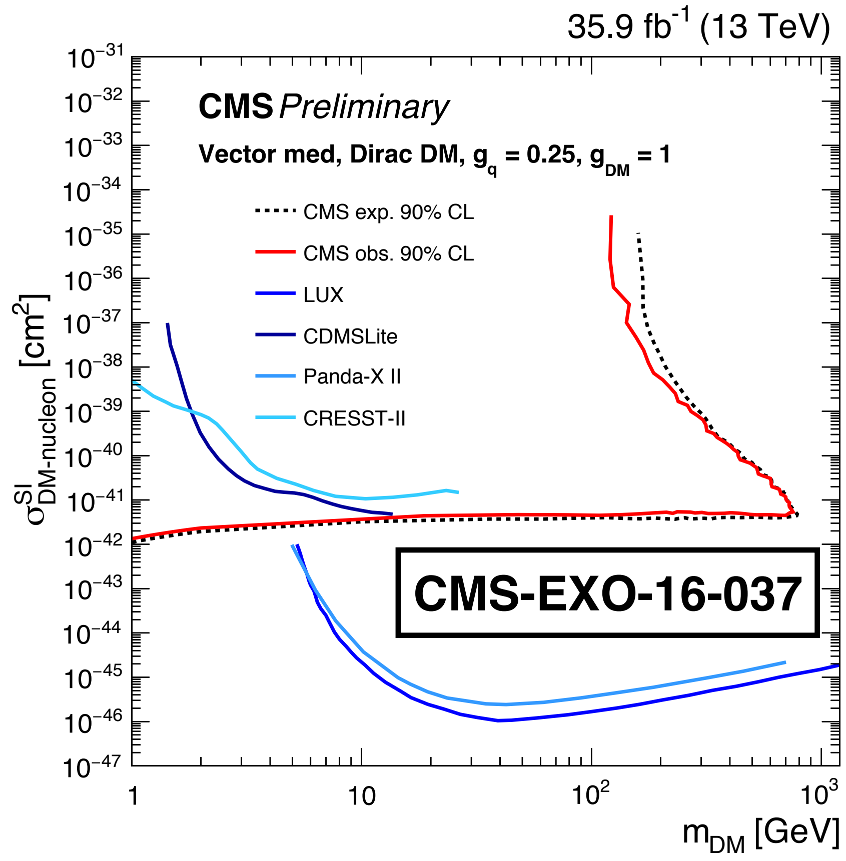


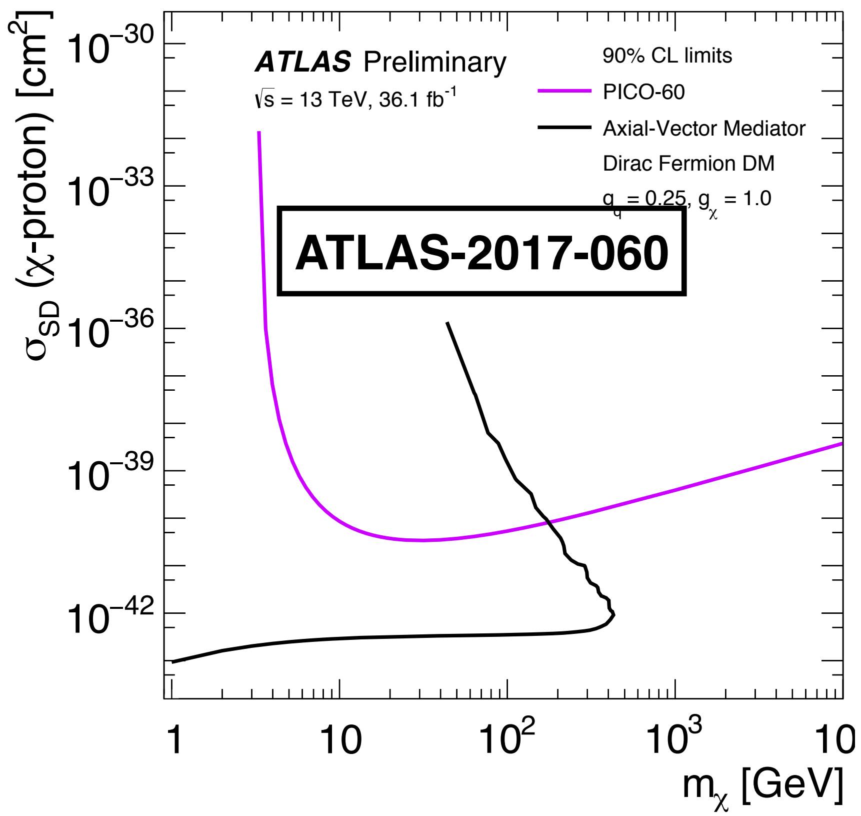
Mono-top from FCNC

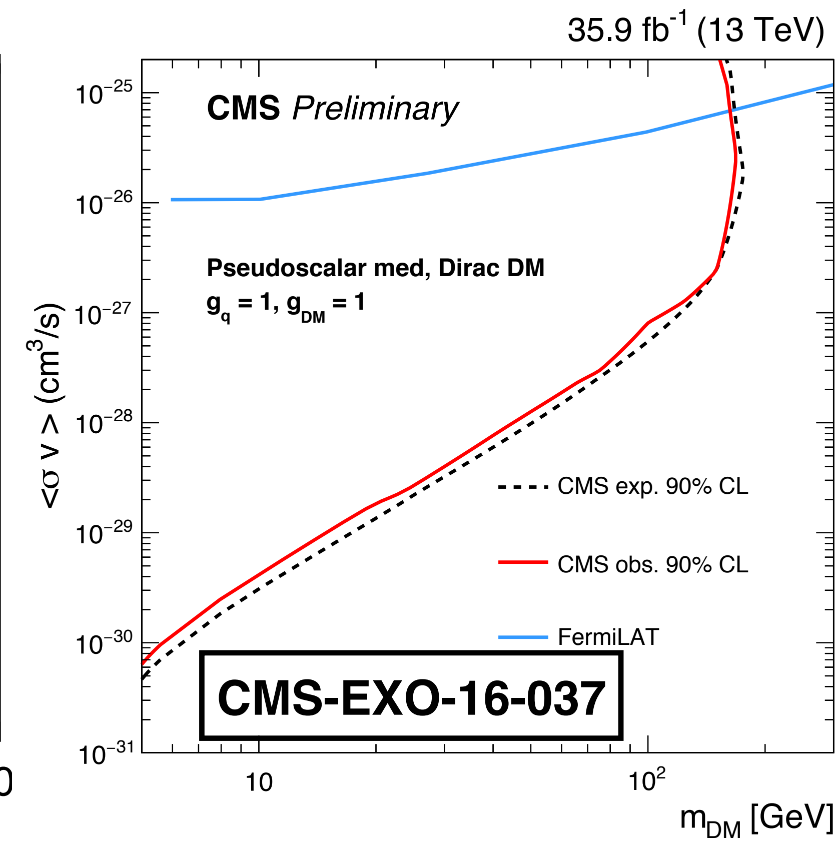


Comparison With Direct and Indirect DM Searches

Collider results recast into limits on the DM-nucleon cross section







- **Note that LHC limits depend on the model assumptions (e.g. choice of couplings)**
- **For vector mediator LHC searches provide complementarity at low DM masses (below 5 GeV)**
- **For axial-vector mediator LHC limits most sensitive for DM masses up to a few 100 GeV**
- **For pseudoscalar mediator there are no constraints from direct searches**

Concluding Remarks

- CMS and ATLAS are pursuing a wide ranging program to search for dark matter
- Collider DM searches mostly complementary to the direct detection experiments
- An exhaustive set of final states probing different types of dark matter interactions have been looked at
- Spin-1 mediators with masses up to 2 TeV have been excluded
- Searches targeting spin-0 mediators (scalar in particular) just starting to be sensitive
  - ➡ Will benefit most from more data

Backup

CMS Mono-Z($\ell\ell$) Search

Target DM signal produced in association with χ or a Z

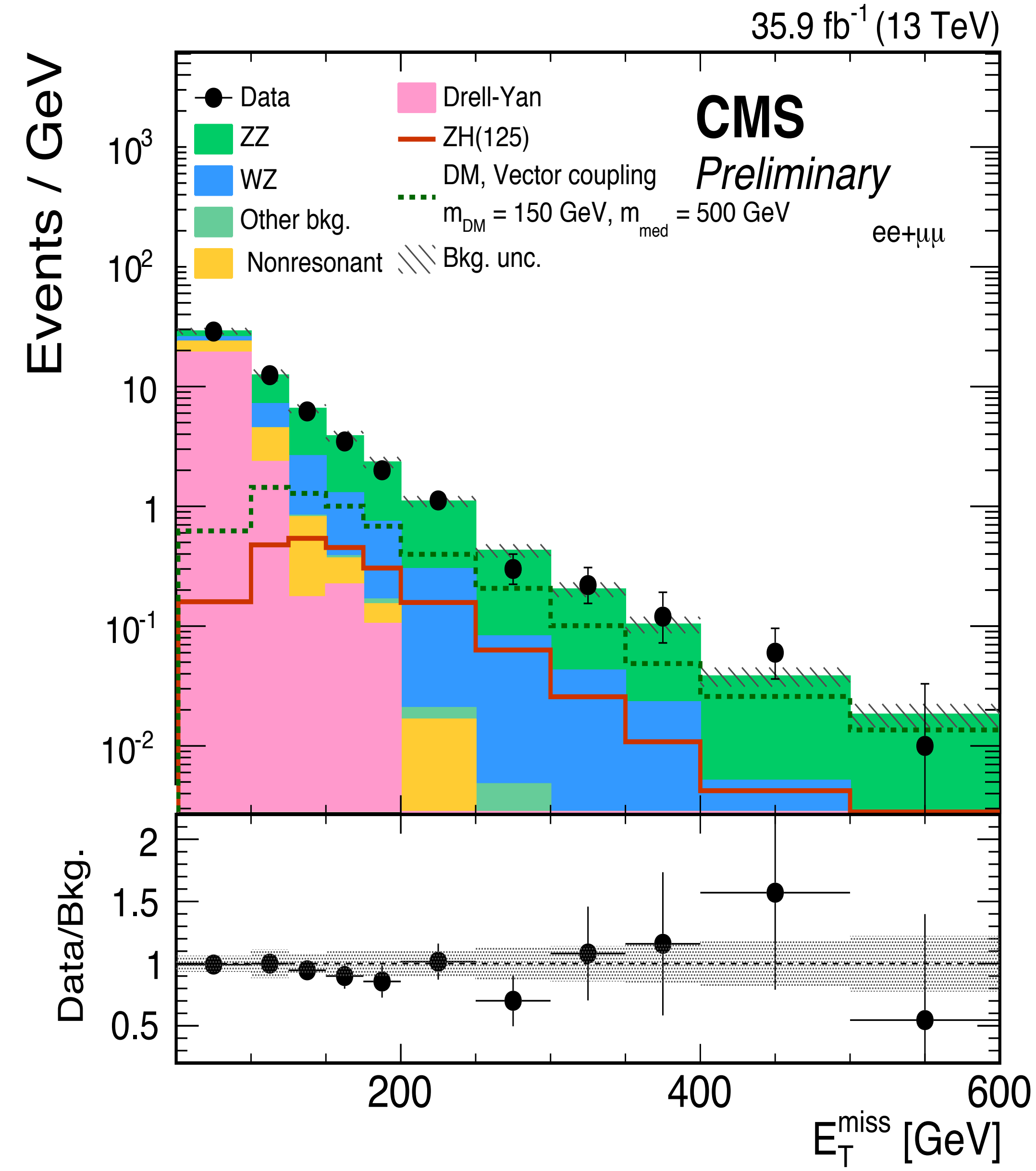
CMS-EXO-16-052

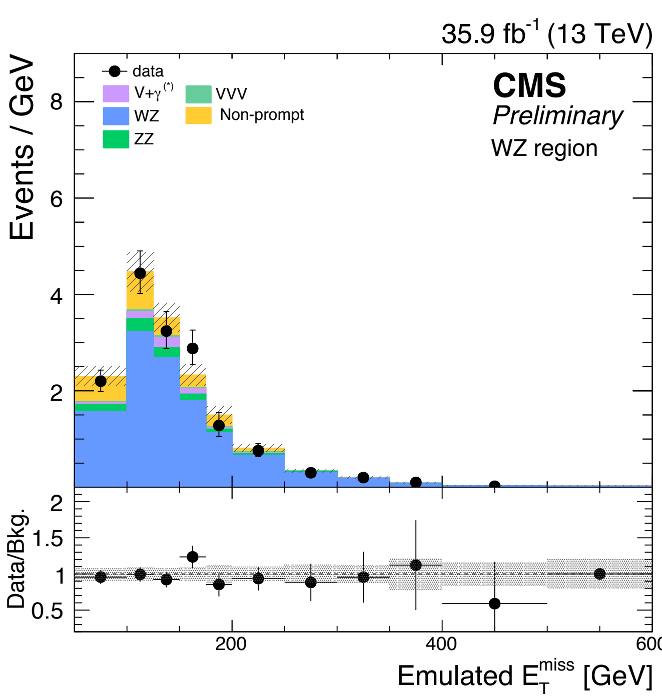
Key features of event selection

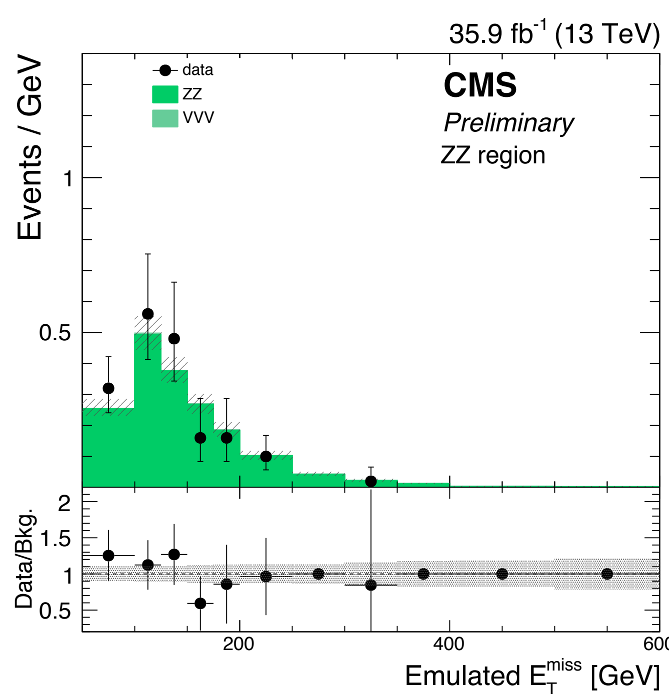
- Select events with well-identified Z(ee), Z(μμ) candidates : $|m_{ll} - m_Z| < 15$ GeV
- At least 100 GeV MET in the event
- At most 1 jet with $p_T > 30$ GeV
- Third lepton veto
- b-jet veto

Main backgrounds : Z(νν)Z($\ell\ell$), W(ℓν)Z($\ell\ell$)

- Estimated using ZZ(4l), WZ(3l**ν**) control regions
- Use ZZ/WZ x-sec ratio to constrain the uncertainty on the ZZ background







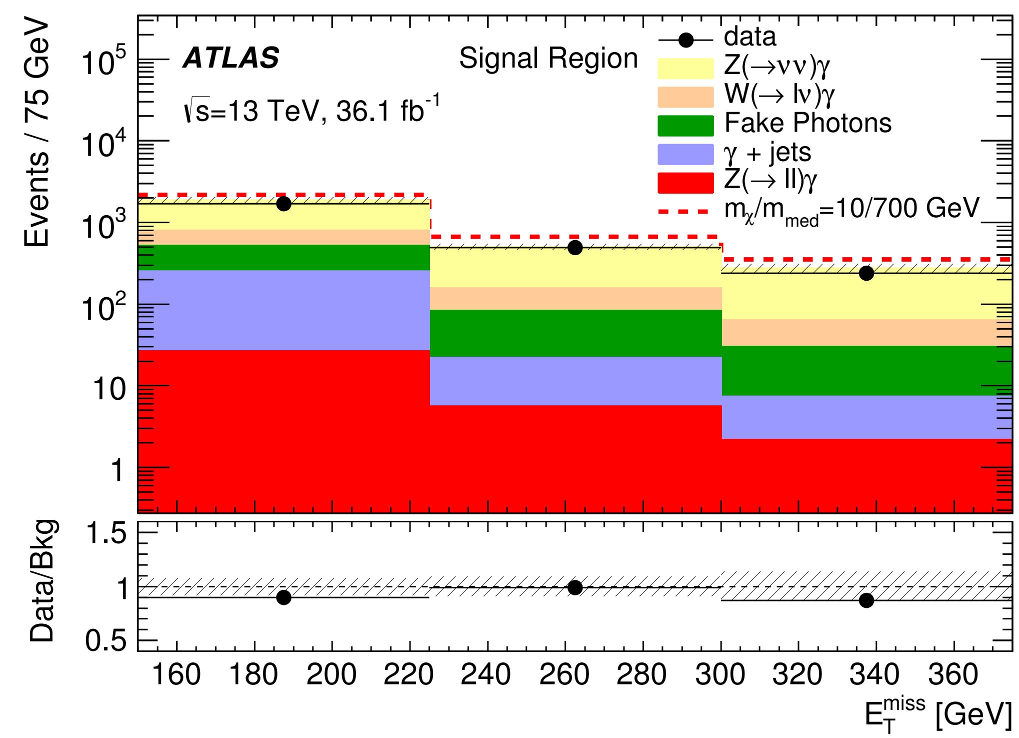
ATLAS Mono-γ Search

Target DM signal produced in association with γ

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

Key features of event selection

- Photon p_T > 150 GeV; $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$
- At least 150 GeV MET in the event
- Non-collision bkg suppressed by :
    - Photon cleaning cuts , $|z|_\gamma < 0.25$ m
- Lepton veto
- At most 1 jet with p_T > 30 GeV
- $\Delta\phi$(jet, MET) > 0.4 ; $\Delta\phi(\gamma$, MET) > 0.4
- MET/sqrt($\sum E_T$) > 8.5 $GeV^{1/2}$

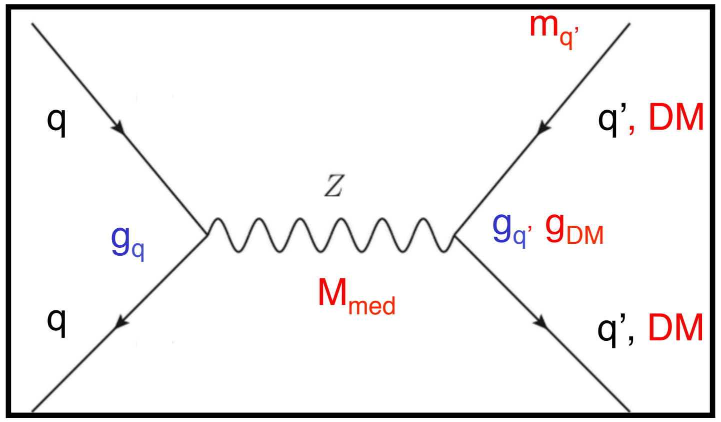


Main backgrounds :

- Largest background : Z(νν)γ
- 2nd largest : W(ℓν)γ (lost lepton, or electron faking photon)
- Estimated from a combined fit of several CRs
    - ➡ Single muon, dimuon, dielectron, low MET γ+jets

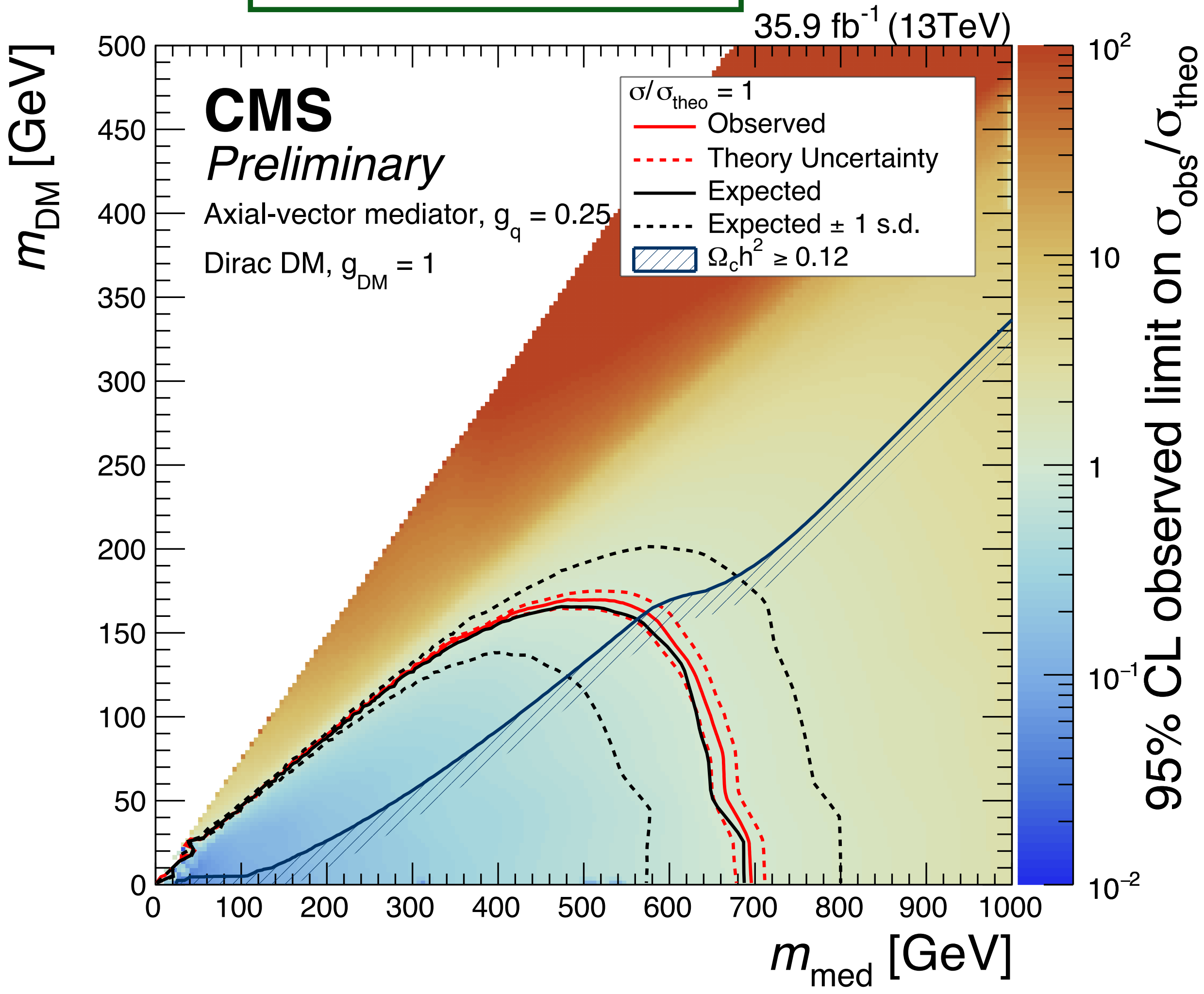
	SRI1	SRI2	SRI3	SRE1	SRE2
Observed events	2400	729	236	1671	493
Fitted Background	2600±160	765±59	273±37	1900±140	501±44
$Z(\to \nu\nu)\gamma$	1600±110	543±54	210±35	1078±89	342±41
$W(\to \ell\nu)\gamma$	390±24	109±9	33±4	282±22	75±8
$Z(\to \ell\ell)\gamma$	35±3	7.8±0.8	2.2±0.4	27±3	5.7±0.7
γ + jets	248±80	22±7	5.2±1.0	225±80	17±6
Fake photons from electrons	199±40	47±11	13±3	152±28	34±8
Fake photons from jets	152±22	37±15	$9.7^{+10}_{-9.7}$	115±24	27±9
Observed events in 1muCR	1083	343	116	740	227
Observed events in 2muCR	254	86	27	168	59
Observed events in 2eleCR	181	59	21	122	38
Observed events in PhJetCR	5064	5064	5064	5064	5064

Mono-Z(ll) & Mono-γ Results



Spin-1 mediator (Vector or Axial-vector)
$g_q = 0.25$; $g_{DM} = 1$

CMS-EXO-16-052



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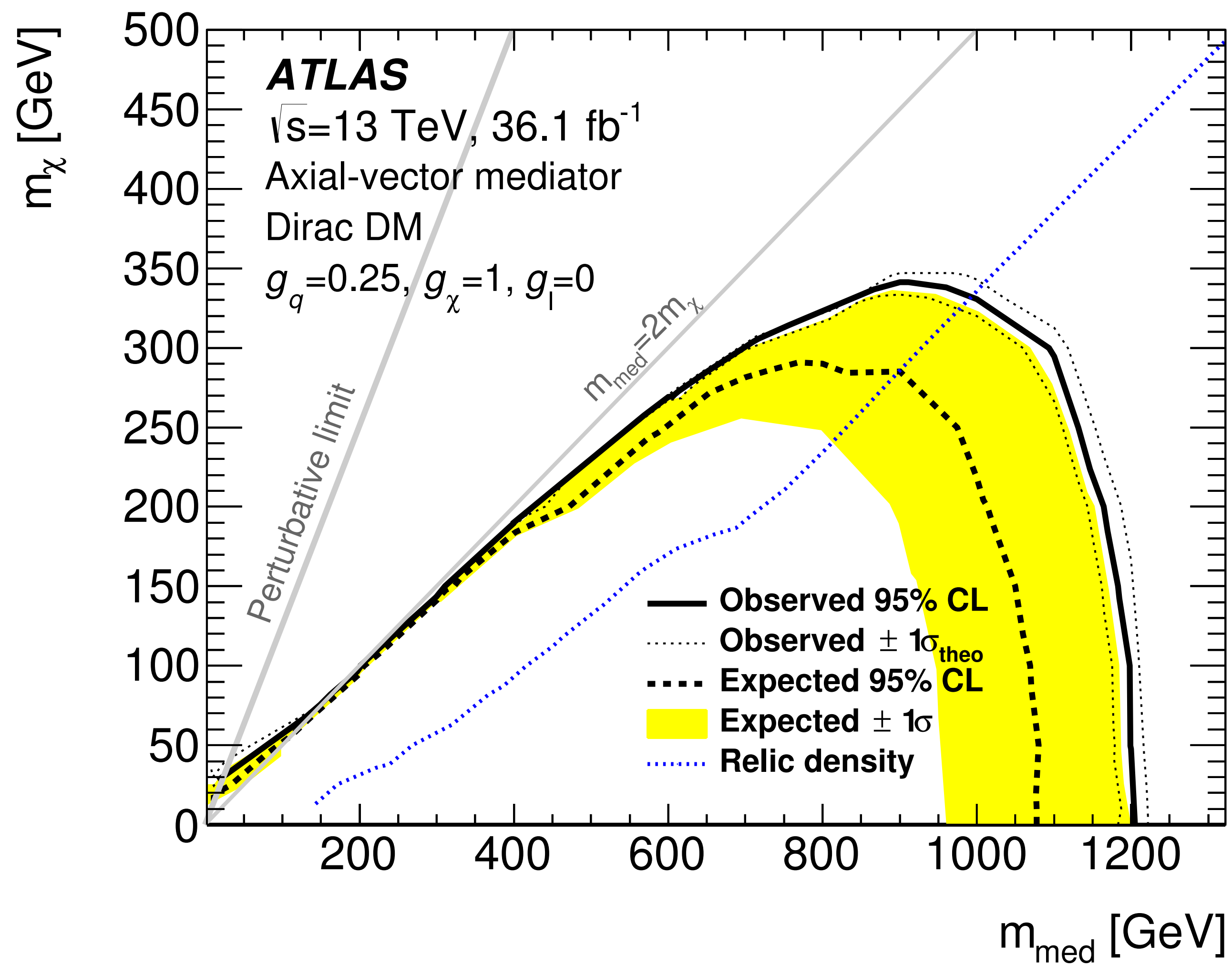

Mono-Z search excludes spin-1 mediators with masses up to 700 GeV
Mono-γ search excludes spin-1 mediators with masses up to 1.2 TeV