



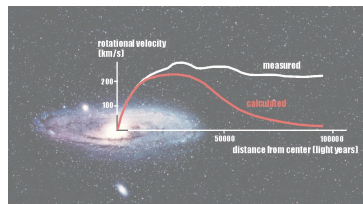
IPA 2018 - Cincinnati (OH)

# Dark Matter at the LHC

Giancarlo Panizzo

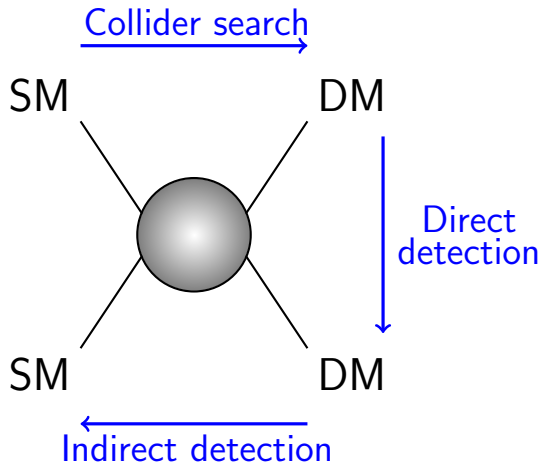
on behalf of

**ATLAS and CMS collaborations**



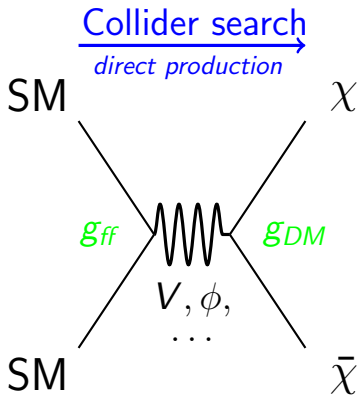
INFN di Trieste  
Gruppo collegato di Udine

# DM search paradigm and colliders



# DM search at LHC

simplified models

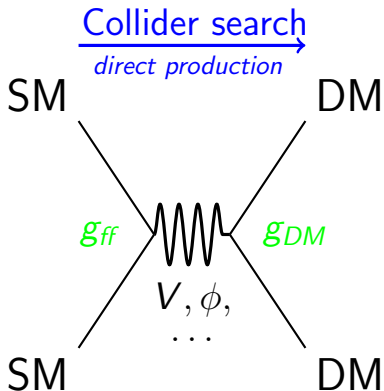


Collider search:

- Complete models: **SUSY**

# DM search at LHC

## simplified models

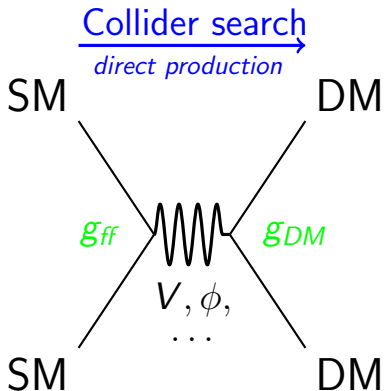


Collider search:

- Complete models: **SUSY**
- Assuming **simplified models**:
  - ▶ Mediator: vector/axial  
vector, scalar/pseudoscalar
  - ▶ fermionic dark matter

# DM search at LHC

## simplified models

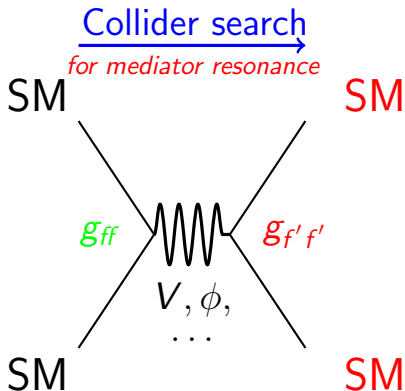


Collider search:

- Complete models: **SUSY**
- Assuming **simplified models**:
  - ▶ Mediator: vector/axial vector, scalar/pseudoscalar
  - ▶ fermionic dark matter
- Look for
  - ▶ DM direct production → transverse energy unbalance

# DM search at LHC

## simplified models

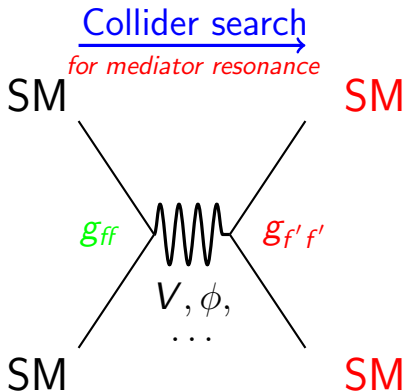


Collider search:

- Complete models: **SUSY**
- Assuming **simplified models**:
  - ▶ Mediator: vector/axial vector, scalar/pseudoscalar
  - ▶ fermionic dark matter
- Look for
  - ▶ DM direct production → transverse energy unbalance
  - ▶ Mediator → “exotic” resonances

# DM search at LHC

## simplified models



Collider search:

- Complete models: **SUSY**
- Assuming **simplified models**:
  - ▶ Mediator: vector/axial vector, scalar/pseudoscalar
  - ▶ fermionic dark matter
- Look for
  - ▶ DM direct production → transverse energy unbalance
  - ▶ Mediator → “exotic” resonances
- Categorized under signatures

- Heavy flavours
- Higgs
- Mono jets, mono  $W$ ,  $Z$
- Mono photon
- Others

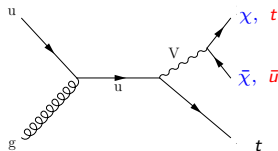


# DM with Heavy Flavours

vector mediator

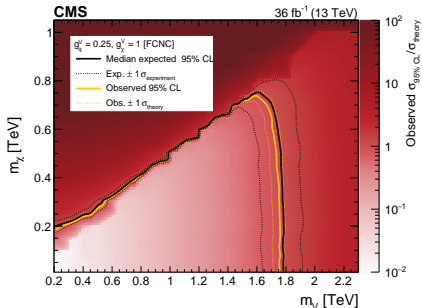
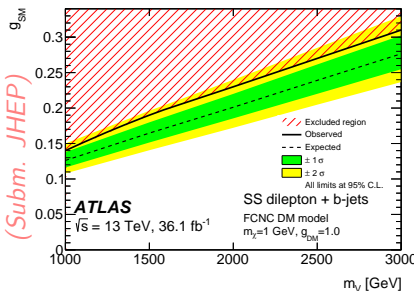
## Event selection

- $E_T^{\text{miss}} + \mathcal{L}$ . boosted top + jets
- two same sign  $\ell + (b)\text{jets}$



No excess found.

Limits on  $\sigma$  vs  $m_V/m_\chi/g_q$   
(FCNC)

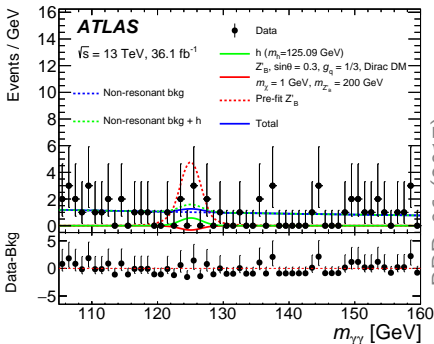
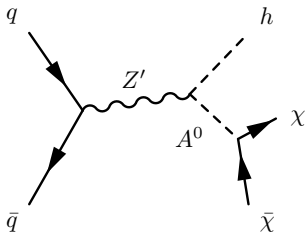


JHEP 06 (2018) 027

Different strategies for each  $h$  decay signature, on top of large  $E_T^{\text{miss}}$ :

### Analysis strategy

- $h \rightarrow \gamma\gamma$ : fit  $m_{\gamma\gamma}$

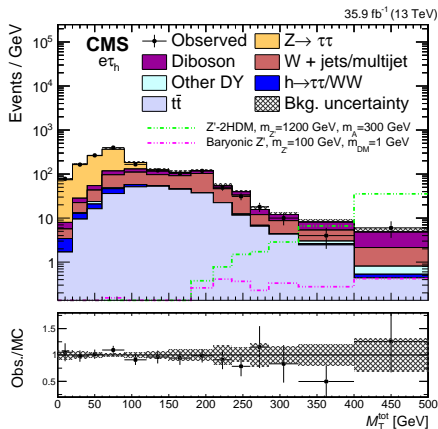
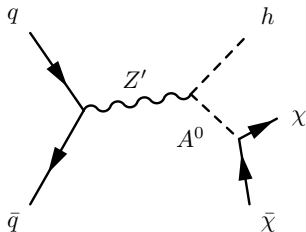


PRD 96 (2017)  
112004

Different strategies for each  $h$  decay signature, on top of large  $E_{\text{T}}^{\text{miss}}$ :

### Analysis strategy

- $h \rightarrow \gamma\gamma$ : fit  $m_{\gamma\gamma}$
- $h \rightarrow \tau\tau$ : fit  $m_{\text{T}}^{\text{tot}}$

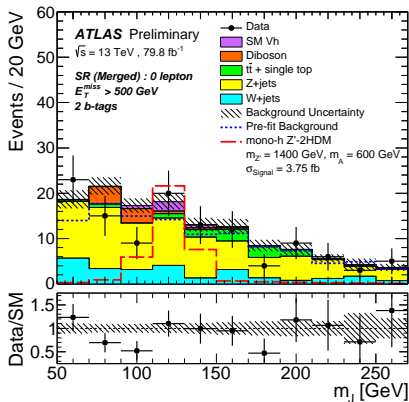
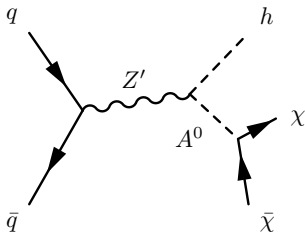


arXiv:1806.04771  
(Acpt. JHEP)

Different strategies for each  $h$  decay signature, on top of large  $E_T^{\text{miss}}$ :

### Analysis strategy

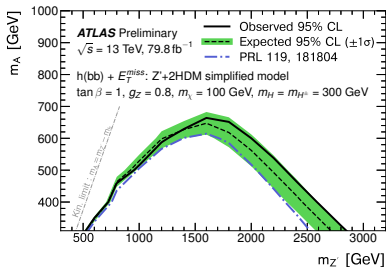
- $h \rightarrow \gamma\gamma$ : fit  $m_{\gamma\gamma}$
- $h \rightarrow \tau\tau$ : fit  $m_T^{\text{tot}}$
- $h \rightarrow b\bar{b}$ : fit  $m_{jj}/b\bar{b}/J$



# DM with Higgs

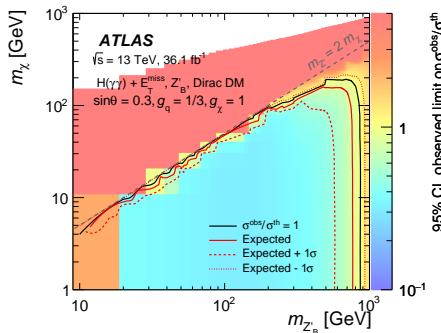
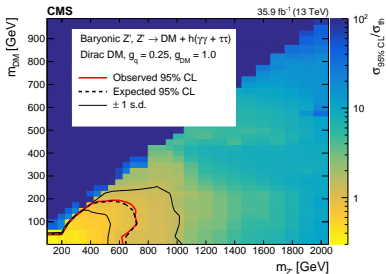
$h \rightarrow \text{SM}$  - results

ATLAS-CONF-2018-039



Good agreement with SM expectations.

Limits on  $\sigma/m_{Z'}$  vs  $m_\chi/m_A$

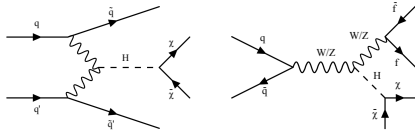


PRD 96 (2017) 112004

arXiv:1806.04771

# DM with Higgs

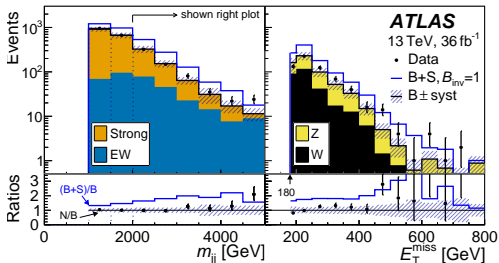
$h \rightarrow$  invisible



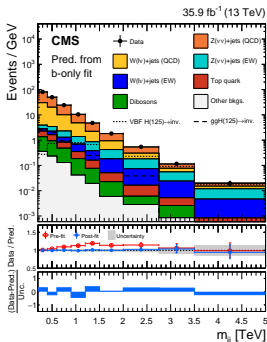
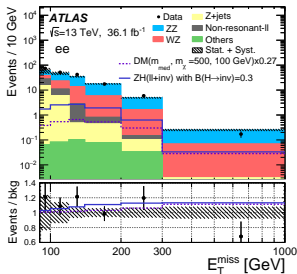
## Event selection

$E_T^{\text{miss}}$  + either:

- energetic jets
- $l^+l^-$



arXiv:1809.06682



PLB 776 (2017) 318

arXiv:1809.05937  
(Subm. PLB)

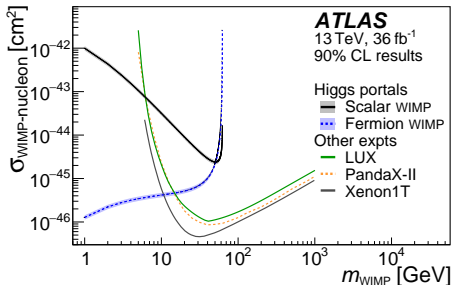
# DM with Higgs

## $h \rightarrow$ invisible - results

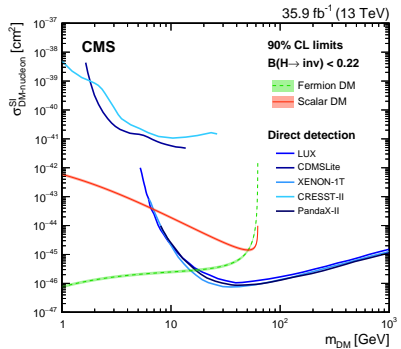
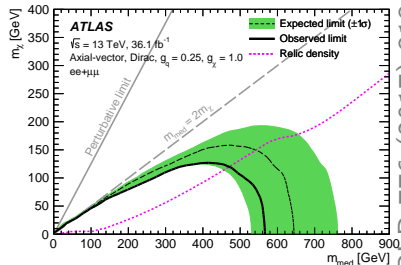
Results consistent with background only hypothesis.

Limits on  $\sigma_{SI}$  complement

DD experiments for  $m_\chi \lesssim m_h/2$



arXiv:1809.06682



PLB 776 (2017) 318

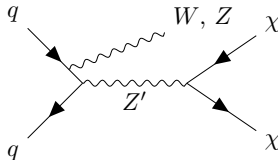
arXiv:1809.05937

(Subm. PLB)

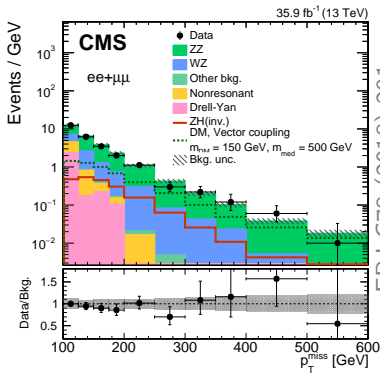
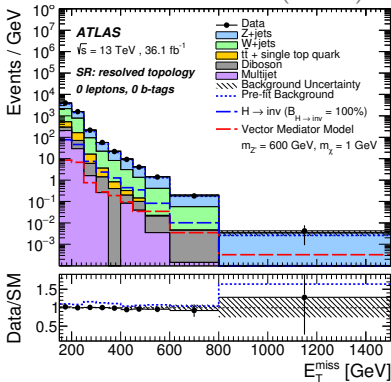
# Mono jet, mono $V$

DM produced in association with one

- energetic ISR jet
- Bosons  $W/Z$ , decaying hadronically/leptonically



arXiv:1807.11471 (JHEP)



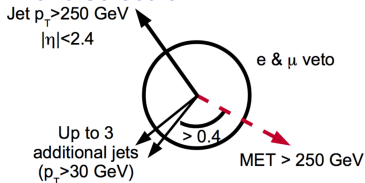
EPJ C78 (2018) 291



# Mono jet, mono $V$

JHEP 01 (2018) 126

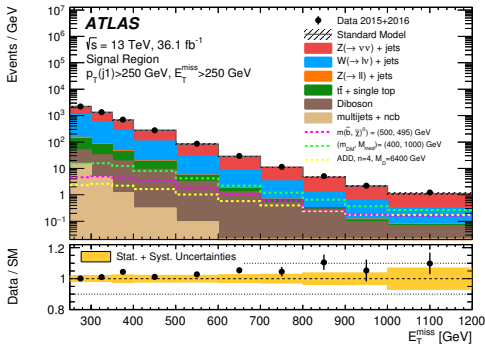
## Event selection



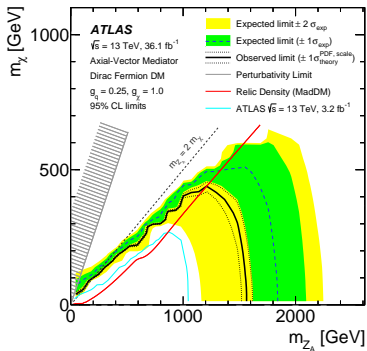
## Analysis strategy

- Fit  $V$ +jets,  $t\bar{t}$  in Control Regions
- Data driven estimation of multijet
- Likelihood fit in CR and SR

## Example from ATLAS



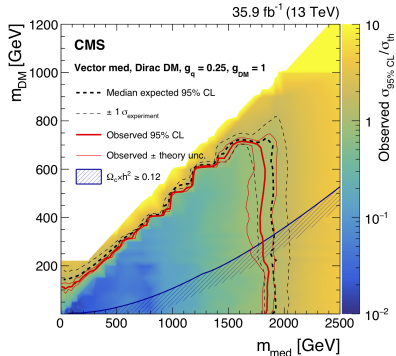
# Mono jet, mono $V$ results



Example Axial Vector  
 exclusions from ATLAS

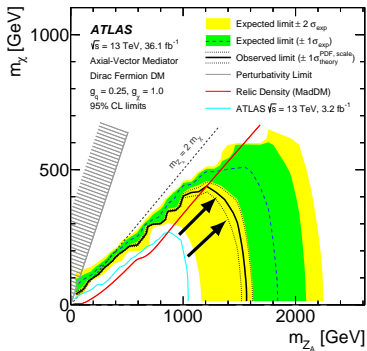
JHEP 01 (2018) 126

## Example Vector exclusions from CMS



PRD 97 (2018) 092005

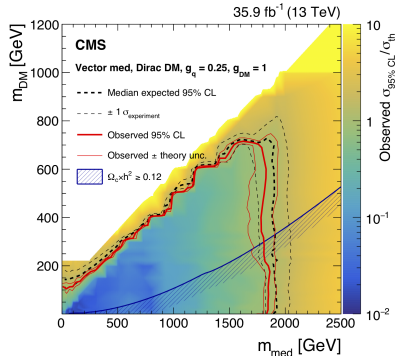
# Mono jet, mono $V$ results



Example Axial Vector  
 exclusions from ATLAS  
 From factor 10 in the  
 luminosity

JHEP 01 (2018) 126

## Example Vector exclusions from CMS



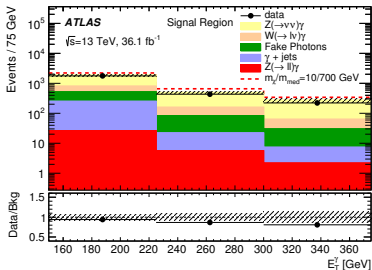
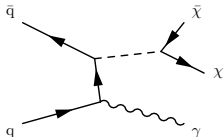
PRD 97 (2018) 092005

## Event selection

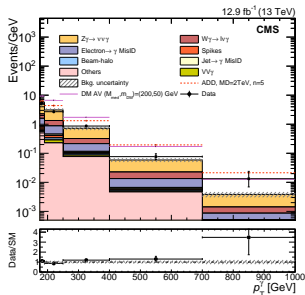
- Energetic photon  
+  $E_T^{\text{miss}}$

## Main backgrounds

- $t\bar{t}$ ,  $Z(\rightarrow \nu\bar{\nu})\gamma$ ,  
 $W(\rightarrow l\bar{\nu})\gamma$



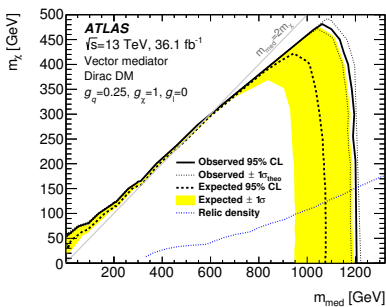
EPJ C77 (2017) 393



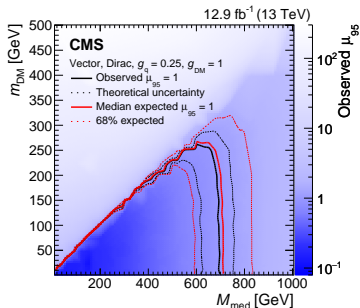
JHEP 10 (2017) 073

- Good Data/MC agreement (rare processes)

Results consistent with SM predictions. Set limits on mediator mass,  $m_\chi$



EPJ C77 (2017) 393

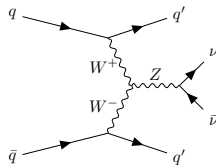
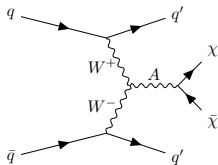


JHEP 10 (2017) 073

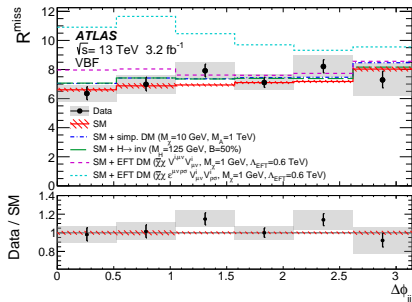
# Other indirect searches

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# Kinematic observables



Kinematic variables sensitive to BSM processes:



$$R^{\text{miss}} = \frac{\sigma_{\text{fid}}(p_{\text{T}}^{\text{miss}} + \text{jets})}{\sigma_{\text{fid}}(\ell^+\ell^- + \text{jets})}$$

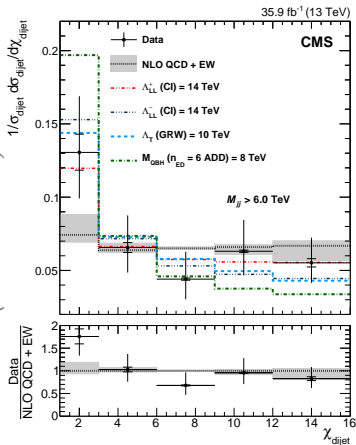
where SM main contributions are

$$(p_{\text{T}}^{\text{miss}} + \text{jets}) \simeq Z(\rightarrow \nu\bar{\nu}) + \text{jets}$$

$$(\ell^+\ell^- + \text{jets}) \simeq Z(\rightarrow \ell^+\ell^-) + \text{jets}$$

# Kinematic observables

Kinematic variables sensitive to BSM processes:



$$\chi_{\text{dijet}} = \frac{1 + \cos \theta^*}{1 - \cos \theta^*}$$

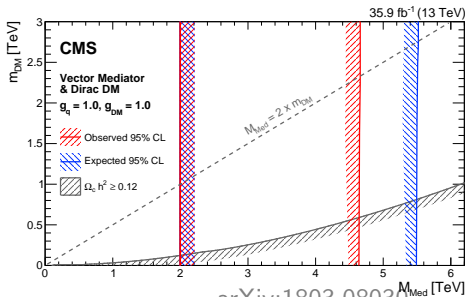
- $\theta^*$  polar scattering angle in the parton-parton center-of-mass (CM) frame
- BSM can give excess at small  $\chi_{\text{dijet}}$



# Kinematic observables

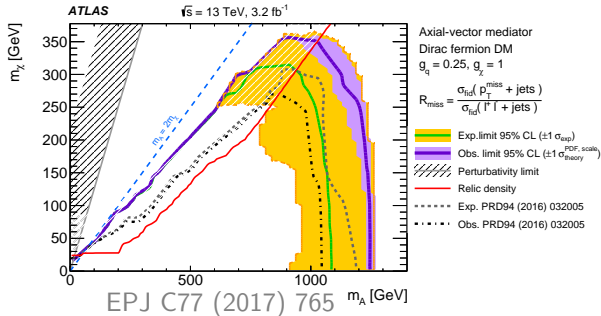
results

Nice agreement with expectations. Limits set on EFT models.



arXiv:1803.08030

ubm. EPJC)



# Summary and comparison to Direct Detection

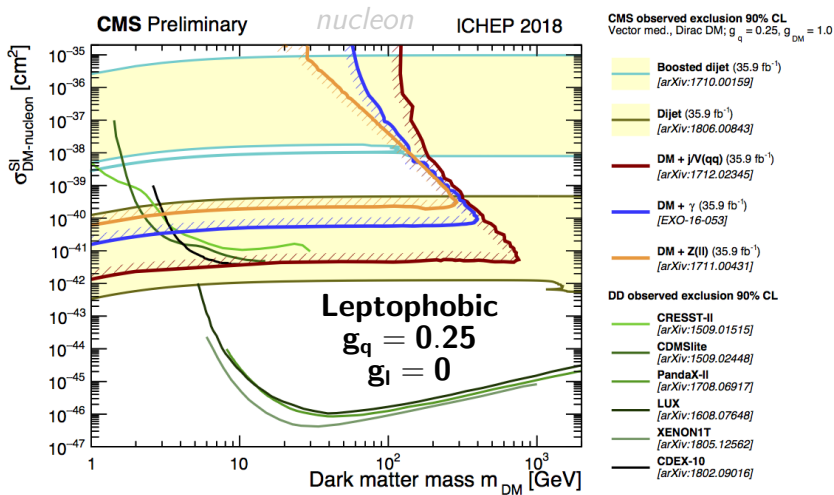
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# Comparison to direct detection

## $Z'$ -like model interpretation

Spin independent

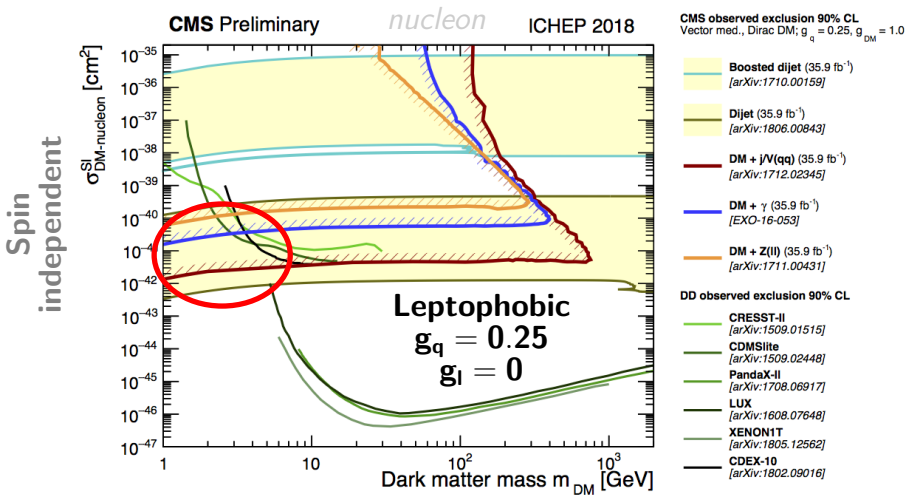


Example from CMS



# Comparison to direct detection

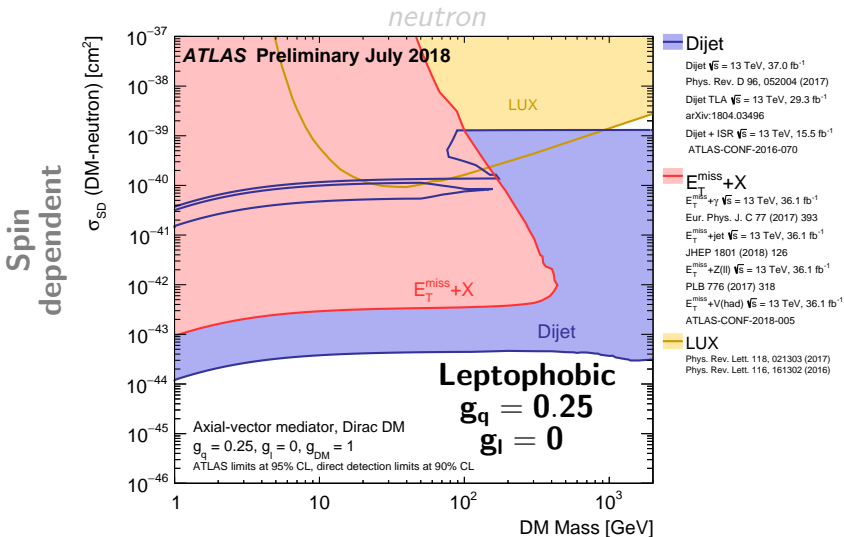
## $Z'$ -like model interpretation



Example from CMS

# Comparison to direct detection

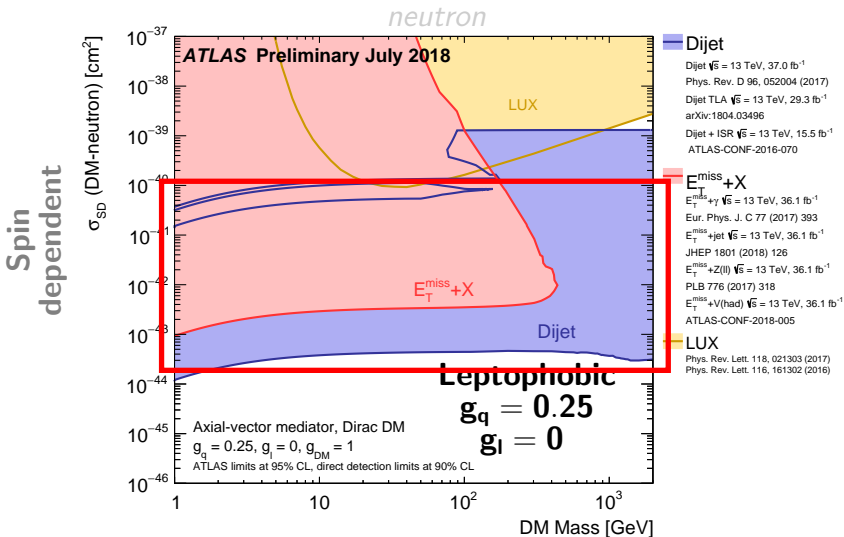
## $Z'$ -like model interpretation



*Example from ATLAS*

# Comparison to direct detection

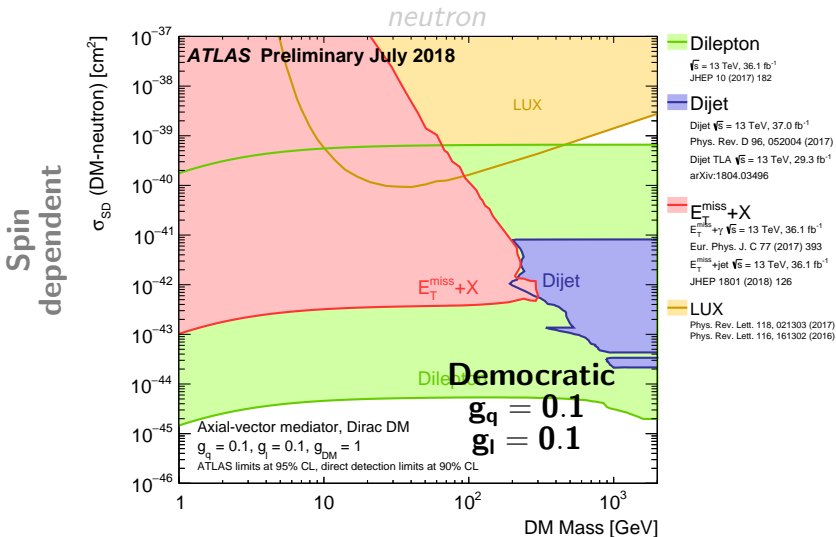
## $Z'$ -like model interpretation



*Example from ATLAS*

# Comparison to direct detection

## $Z'$ -like model interpretation



*Example from ATLAS*

- Large LHC program for Dark Matter searches
- 2015-16 data extended search reach, first  $79.8 \text{ fb}^{-1}$  analysis shown
- No DM signals found so far
- Be ready for more results, LHC is still taking data!



EXO-16-049	dark matter particles produced in association with a top quark pair	Submitted to PRL
EXO-16-055	dark matter produced in association with a Higgs boson decaying to $\gamma\gamma$ or $\tau^+\tau^-$	Accepted by JHEP
EXO-16-046	new physics in dijet angular distributions using proton-proton collisions and constraints on dark matter and other models	Submitted to EPJC
EXO-16-051	dark matter in events with energetic, hadronically decaying top quarks and missing transverse momentum	JHEP 06 (2018) 027
EXO-16-048	new physics in final states with an energetic jet or a hadronically decaying $W$ or $Z$ boson and transverse momentum imbalance	PRD 97 (2018) 092005
EXO-16-052	new physics in events with a leptonically decaying $Z$ boson and a large transverse momentum imbalance in proton-proton collisions	EPJC 78 (2018) 291
EXO-17-001	low mass vector resonances decaying into quark-antiquark pairs in proton-proton collisions	JHEP 01 (2018) 097
EXO-16-039	new physics in the monophoton final state in proton-proton collisions	JHEP 10 (2017) 073
EXO-16-005	dark matter produced in association with heavy-flavor quark pairs in proton-proton collisions	EPJC 77 (2017) 845
EXO-16-012	associated production of dark matter with a Higgs boson decaying to $b\bar{b}$ or $\gamma\gamma$	JHEP 10 (2017) 180
HIG-17-023	invisible decays of a Higgs boson produced through vector boson fusion	Submitted to PLB

EXOT-2016-37	invisible Higgs boson decays in vector boson fusion	Submitted to PLB
EXOT-2016-16	new phenomena in events with same-charge leptons and $b$ -jets	Submitted to JHEP
EXOT-2016-23	dark matter in events with a hadronically decaying vector boson and missing transverse momentum	Submitted to JHEP
SUSY-2016-16	top-squark pair production in final states with one lepton, jets, and missing transverse momentum	JHEP 06 (2018) 108
EXOT-2016-27	dark matter and other new phenomena in events with an energetic jet and large missing transverse momentum	JHEP 01 (2018) 126
SUSY-2016-18	dark matter produced in association with bottom or top quarks; 0, 2 leptons	EPJC 78 (2018) 18
HIGG-2016-28	invisibly decaying Higgs boson or dark matter candidates produced in association with a Z boson	PLB 776 (2017) 318
EXOT-2016-03	Measurement of detector-corrected observables sensitive to the anomalous production of events with jets and large missing transverse momentum	EPJC 77 (2017) 765
AT-C-2018-039	Dark Matter Produced in Association with a Higgs Boson Decaying to $b\bar{b}$ $79.8 \text{ fb}^{-1}$	ATLAS-CONF-2018-039
HIGG-2016-18	dark matter in association with a Higgs boson decaying to two photons	PRD 96 (2017) 112004
EXOT-2016-32	dark matter in final states containing an energetic photon and large missing transverse momentum	EPJC 77 (2017) 393





Backup

ԲԱՅԿՐԱԾ



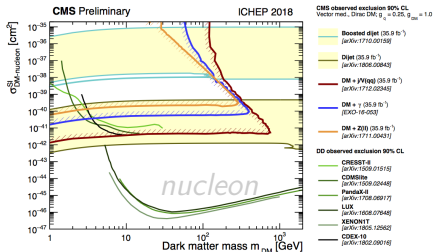
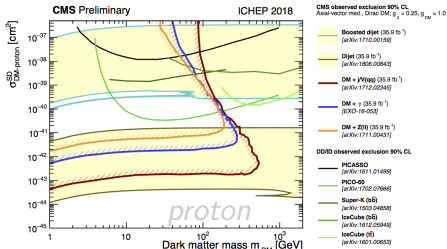


# Comparison to direct detection

## $Z'$ -like model interpretation

Spin dependent

Spin independent



Leptophobic  
 $g_{\text{q}} = 0.25$   
 $g_{\text{l}} = 0$

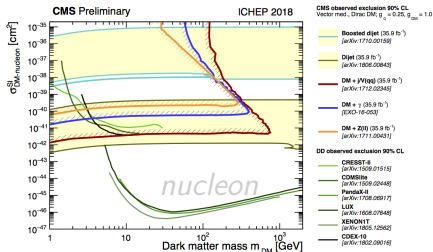
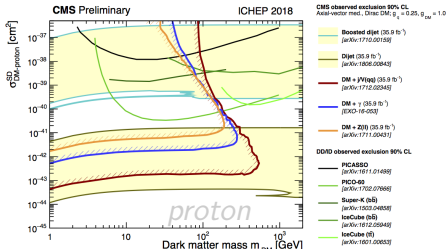


# Comparison to direct detection

## $Z'$ -like model interpretation

Spin dependent

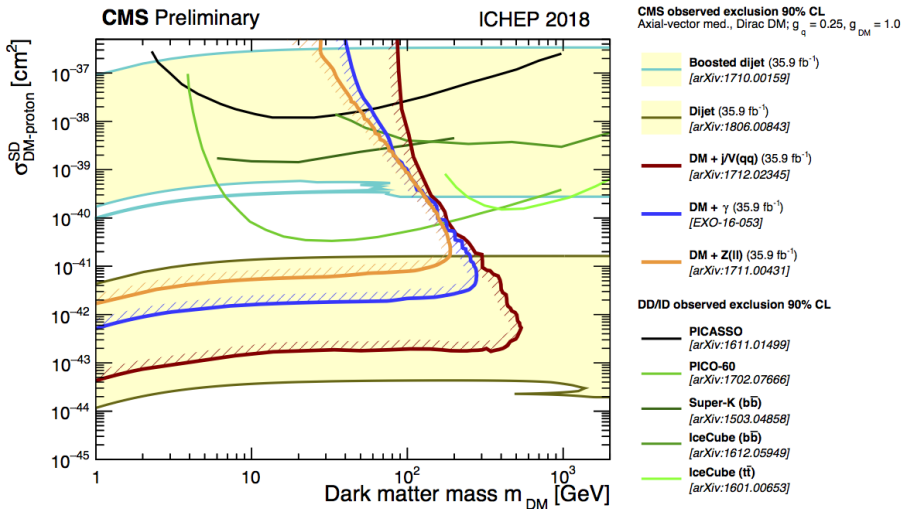
Spin independent



Leptophobic  
 $g_q = 0.25$   
 $g_l = 0$

# Comparison to direct detection

## $Z'$ -like model interpretation



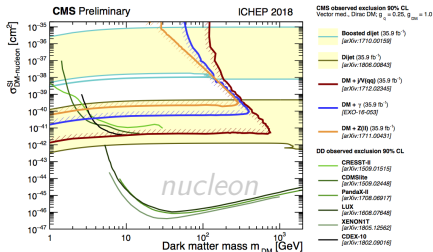
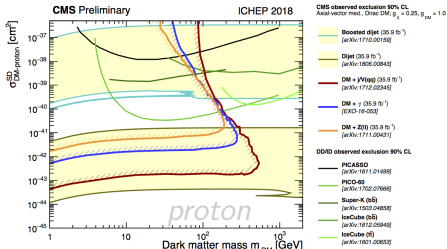


# Comparison to direct detection

## $Z'$ -like model interpretation

Spin dependent

Spin independent

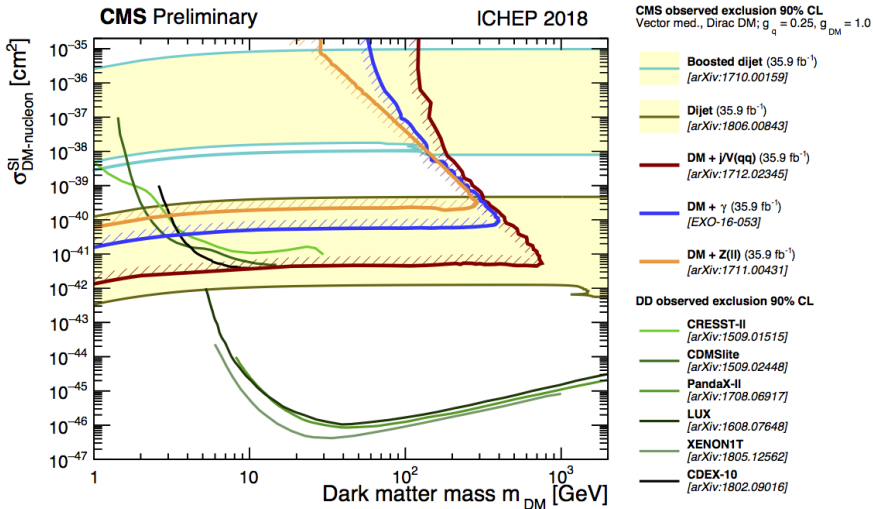


Leptophobic  
 $g_q = 0.25$   
 $g_l = 0$



# Comparison to direct detection

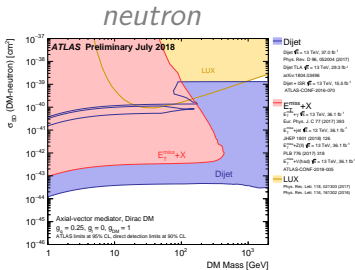
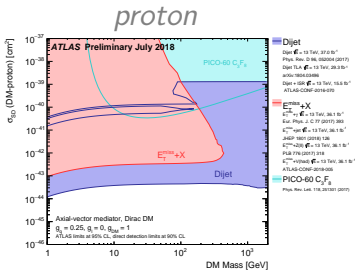
## $Z'$ -like model interpretation



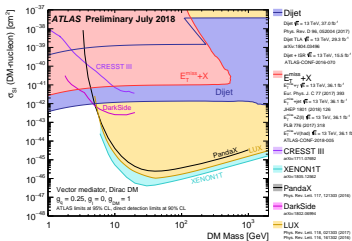
# Comparison to direct detection

## $Z'$ -like model interpretation

Spin dependent



Spin independent



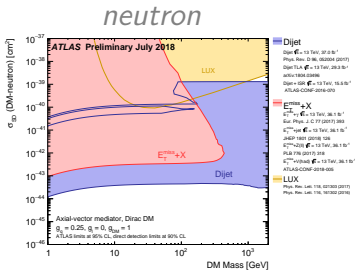
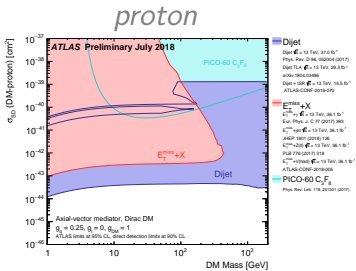
Leptophobic  
 $g_q = 0.25$   
 $g_l = 0$

*nucleon*

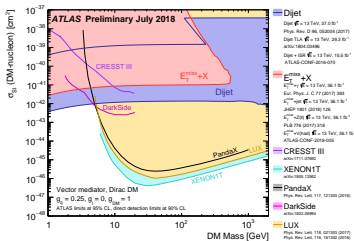
# Comparison to direct detection

## $Z'$ -like model interpretation

Spin dependent



Spin independent

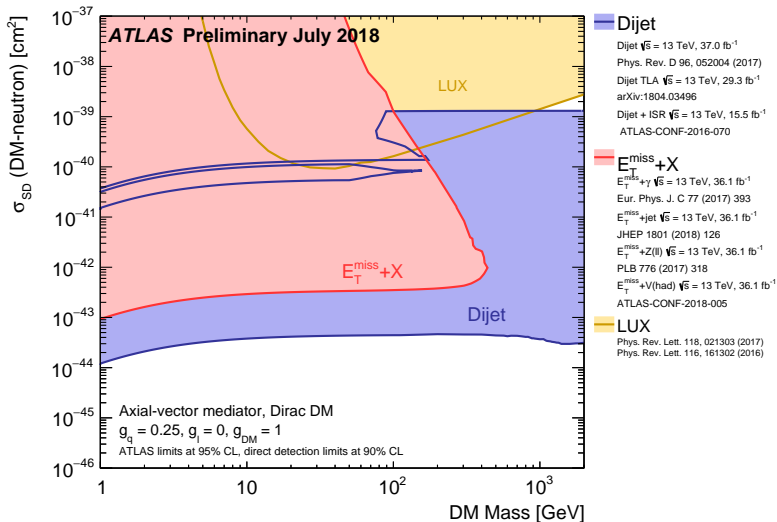


Leptophobic  
 $g_q = 0.25$   
 $g_l = 0$

*nucleon*

# Comparison to direct detection

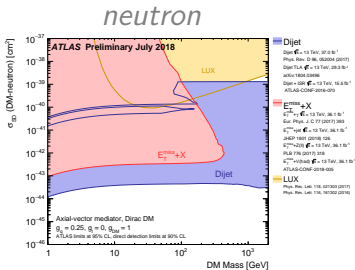
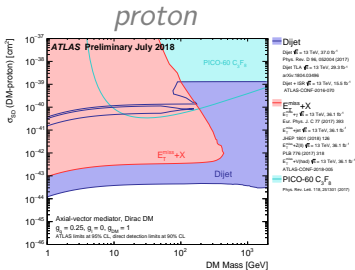
## $Z'$ -like model interpretation



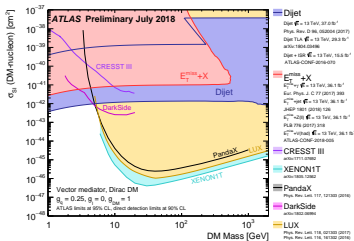
# Comparison to direct detection

## Z'-like model interpretation

Spin dependent



Spin independent

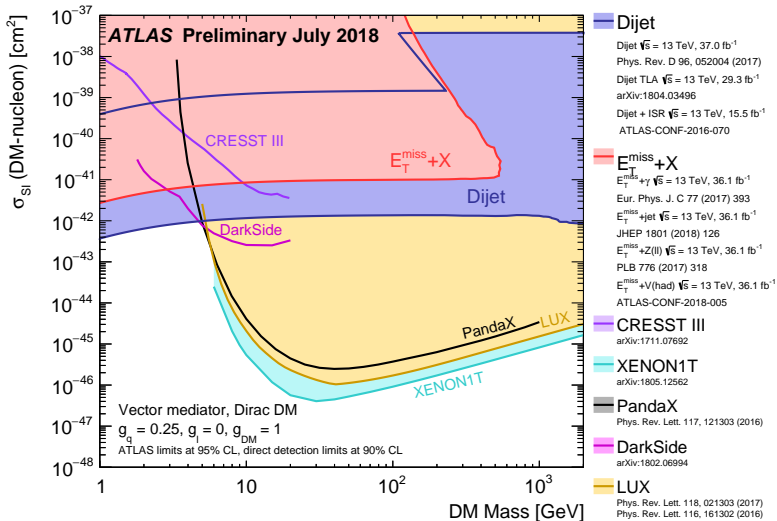


Leptophobic  
 $g_q = 0.25$   
 $g_l = 0$

*nucleon*

# Comparison to direct detection

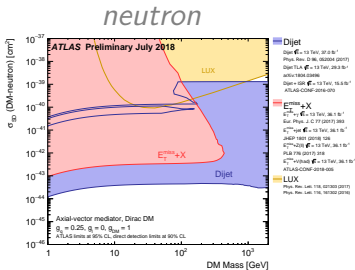
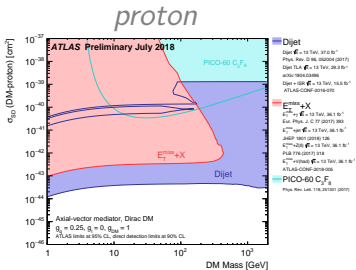
## $Z'$ -like model interpretation



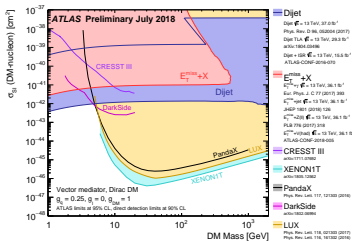
# Comparison to direct detection

## Z'-like model interpretation

Spin dependent



Spin independent



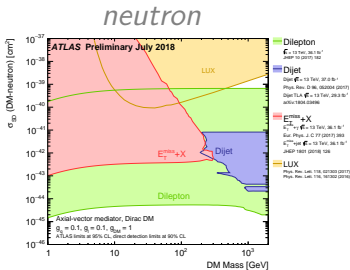
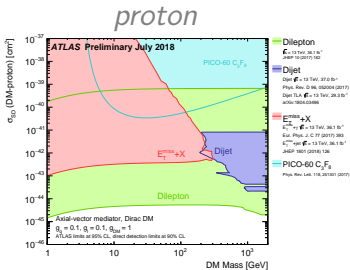
Leptophobic  
 $g_q = 0.25$   
 $g_l = 0$

*nucleon*

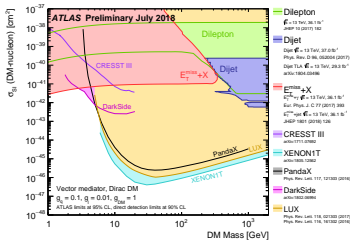
# Comparison to direct detection

## $Z'$ -like model interpretation

Spin dependent



Spin independent



Democratic  
 $g_q = 0.1$   
 $g_l = 0.1$

*nucleon*



# DM with Heavy Flavours

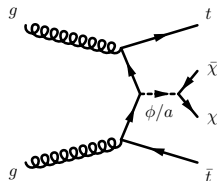
## scalar mediator

### Event selection

- $b$ -jets +  $\{0, 1, 2\} \ell$

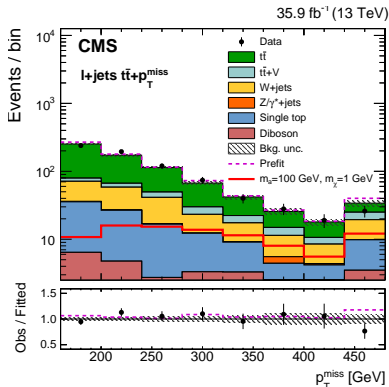
### Main backgrounds

- $t\bar{t}$ ,  $V$ + jets



### Analysis strategy

- Tag  $b$ -,  $t$ - quarks (e.g. “Resolved Top Tagger” for CMS)
- Simultaneous max-likelihood fit of  $E_T^{\text{miss}}$  distribution



arXiv:1807.06522  
 (Subm. PRL)

# DM with Heavy Flavours

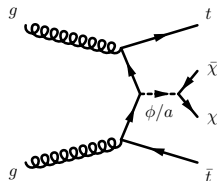
## scalar mediator

### Event selection

- $b$ -jets +  $\{0, 1, 2\} \ell$

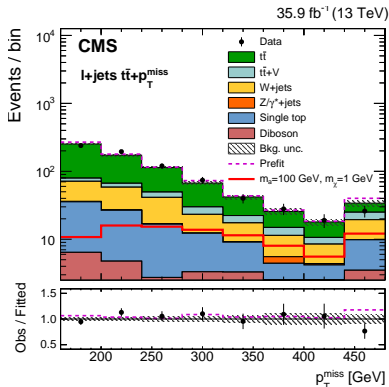
### Main backgrounds

- $t\bar{t}$ ,  $V$ + jets



### Analysis strategy

- Tag  $b$ -,  $t$ - quarks (e.g. “Resolved Top Tagger” for CMS)
- Simultaneous max-likelihood fit of  $E_T^{\text{miss}}$  distribution
- Good Data/MC agreement

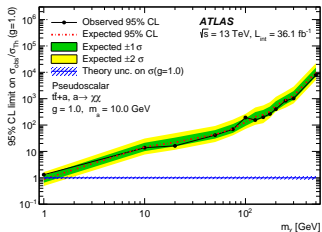
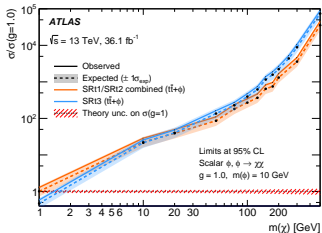


arXiv:1807.06522  
 (Subm. PRL)

# DM with Heavy Flavours

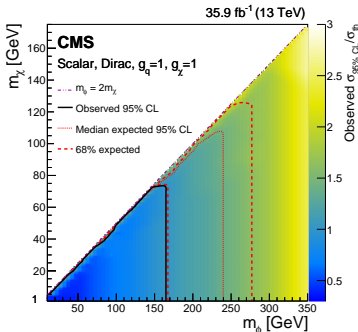
## scalar mediator - results

EPJC 78 (2018) 18



JHEP 06 (2018) 108

No excess found.  
Limits on  $\sigma$  vs  $m_{\phi/a}/m_{\chi}$



arXiv:1807.06522  
(Subm. PRL)