

THE 14TH INTERNATIONAL WORKSHOP
ON THE DARK SIDE OF THE UNIVERSE

DSU
2018

25 - 29 June 2018

LAPTh, Annecy, France

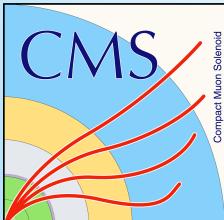


TOPICS INCLUDE: Dark matter, dark energy, cosmic rays, cosmology, gravitational waves, physics beyond the Standard Model



Dark Matter searches with mono-X and other exotic searches @LHC

Barbara Clerbaux
Université Libre de Bruxelles (ULB)
For the ATLAS and CMS Collaborations



Dark Matter searches

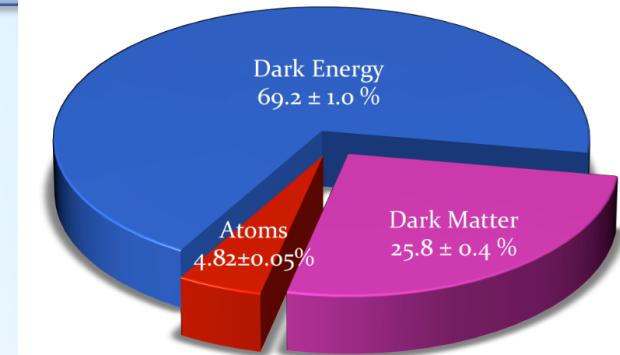
Abundant evidence for the presence of a dark sector :

Via its gravitational interactions :

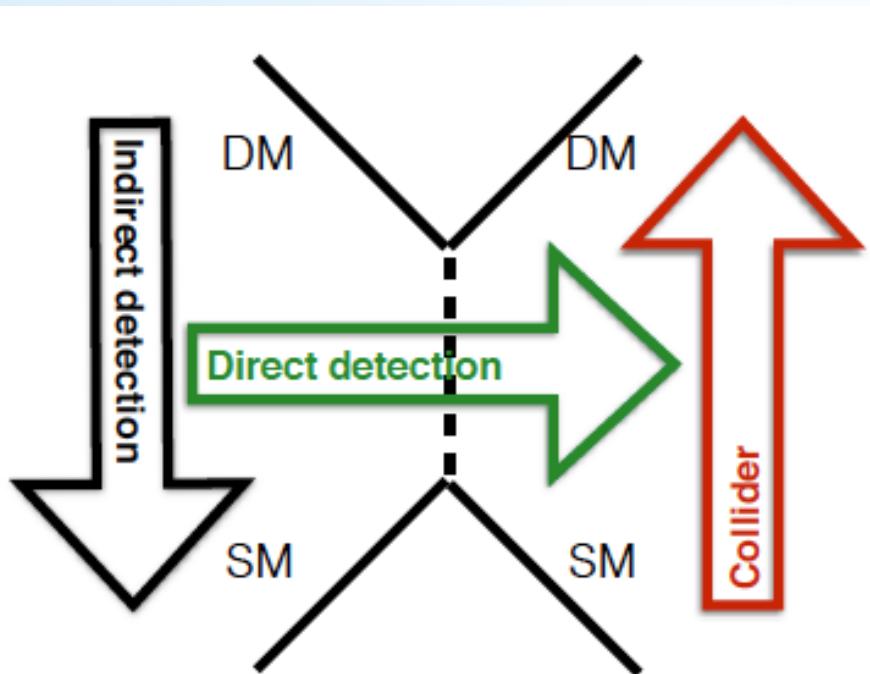
- Rotation curve from galaxies
- Weak lensing
- Cosmic microwave background measurement (CMB)

Composition Of The Universe

arXiv: 1502.01589



BUT the underlying nature of DM is still unknown



→ May be observed at proton-proton collider @LHC

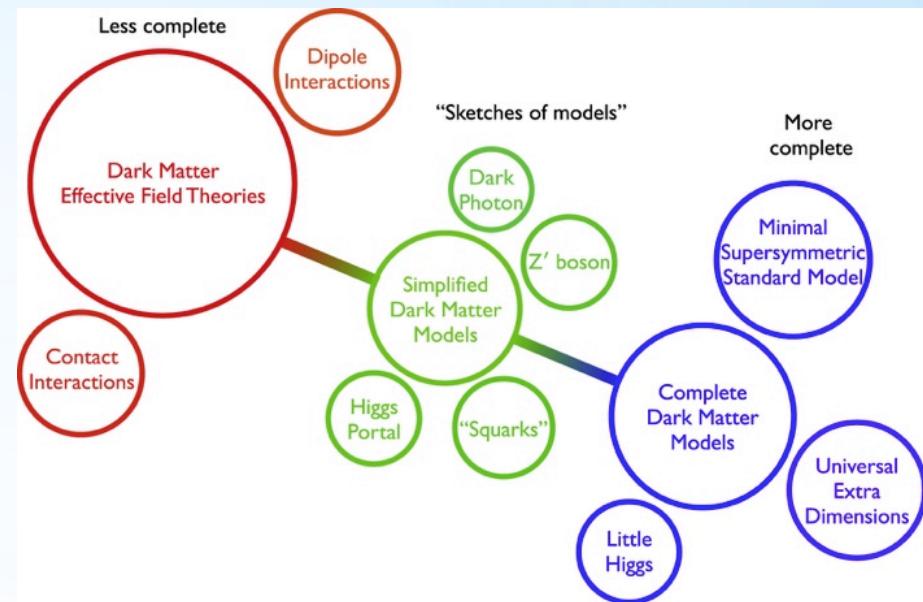
→ hunt for DM :

- Direct detection (LUX, XENON, SuperCDMS, CRESST)
- Indirect detection (Pamela, Fermi, AMS, IceCube)
- Production at Colliders

DM searches @LHC

What can we do at the LHC?

- Direct search for WIMP & mediator particles
- WIMP search in cascade decays
E.g, Neutralino in SUSY, Kaluza-Klein photon in UED
- Hidden/dark sector search



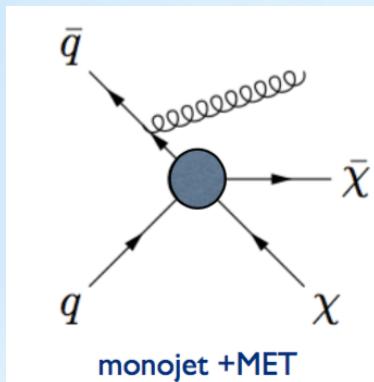
arXiv:1506.03116v3

2 talks :

- **Dark Matter searches with mono-X and other exotic searches @LHC** (mono-X searches, mediator searches and interpretation in simplified models) *(B. Clerbaux)*
- **Dark Matter searches in SUSY and other UV complete models @LHC** (DM searches in SUSY, long lived signatures and dark photons) *(F. Conventi)*

DM signatures @LHC

DM signal at colliders:

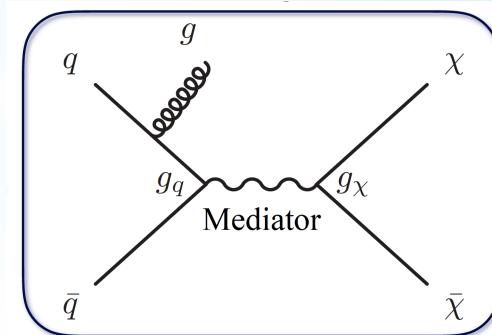
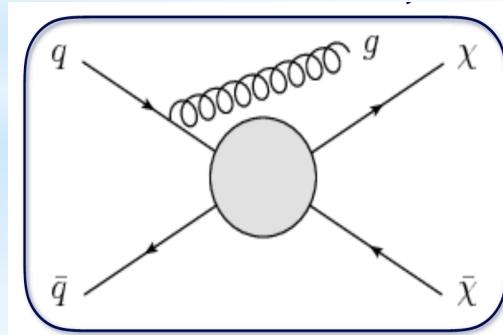


- DM particles would leave no trace in the detector
- Use Initial-State Radiation (ISR) to trigger events using recoiling SM objects **ISR : $X = \text{jet}/\text{photon}/W/Z$**
- → presence of a large amount of missing transverse energy (MET) → **spectacular events**

Interpretation :

- As much as possible model independent of DM processes
- Framework to compare with DD/ID experiments

From
Effective
Field
Theory...



... to
simplified
models

EFT - Contact interaction operators

- Described in terms m_X , cut-off scale
- Model-independent DD comparison
- Used in LHC Run 1 (8 TeV)

But invalid at large momentum transfer $Q^2 \sim M^*$

Via explicit mediator particles

- More complicated DD/ID comparison
- Used in LHC Run 2 (13 TeV)

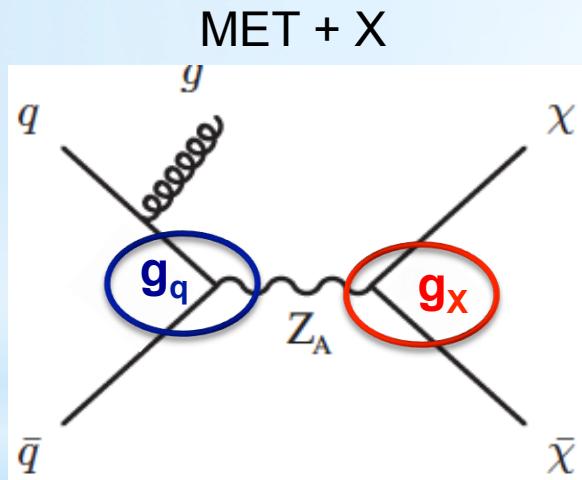
Simplified models

Mono-X signatures:

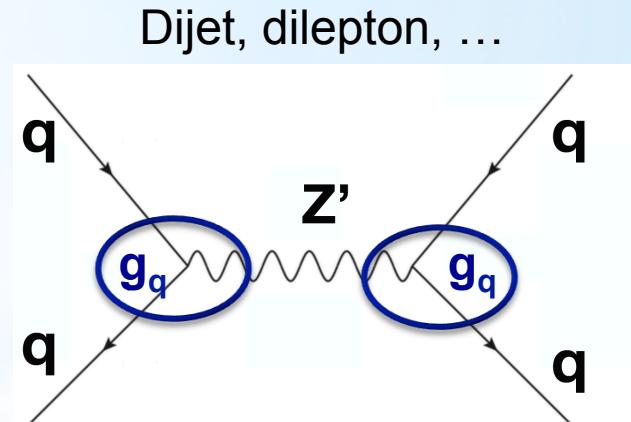
SM → mediator → DM

Resonant signatures:

SM → mediator → SM



→



→ Relevant parameters :

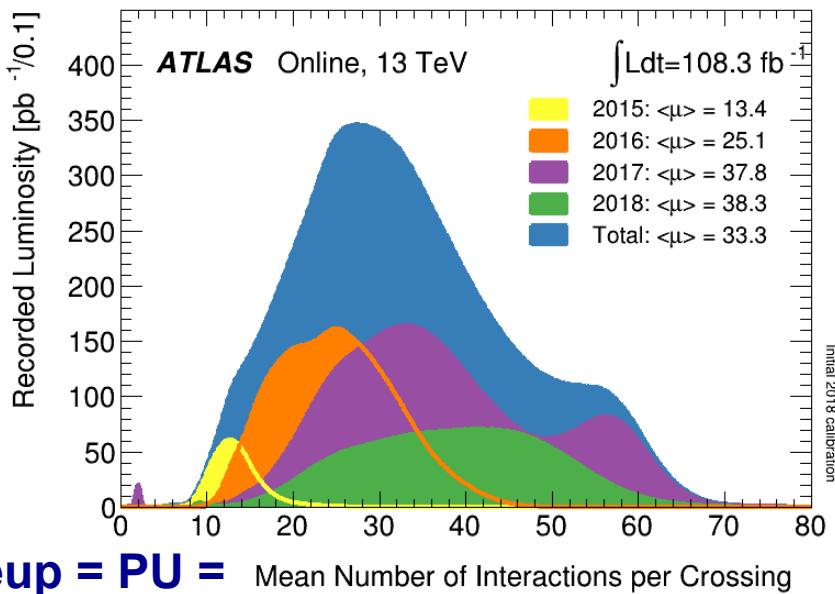
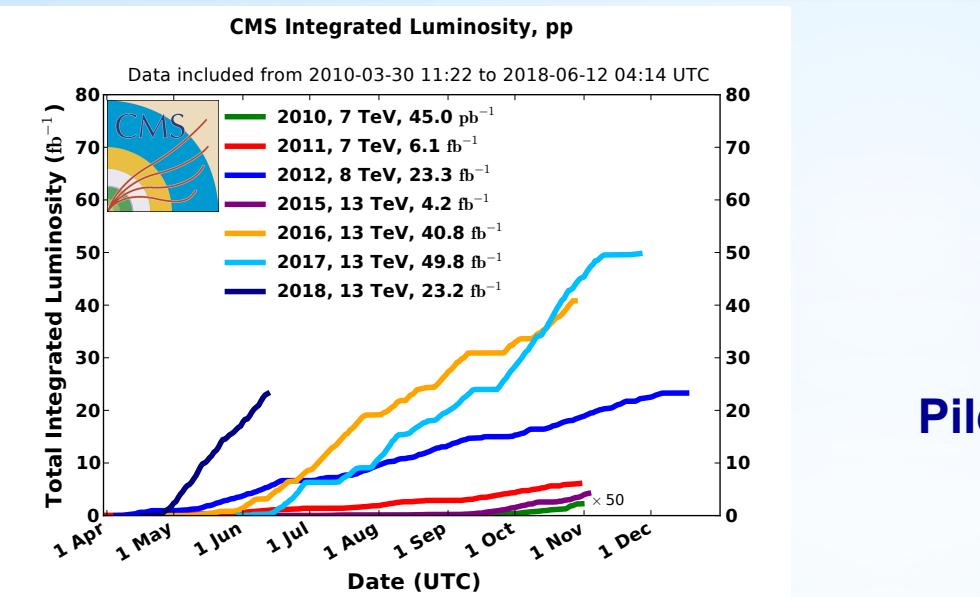
m_X , m_{med} , g_x and g_q

spin/parity of the mediator : scalar/pseudo-scalar or vector/axial-vector

→ See LHC DM working group

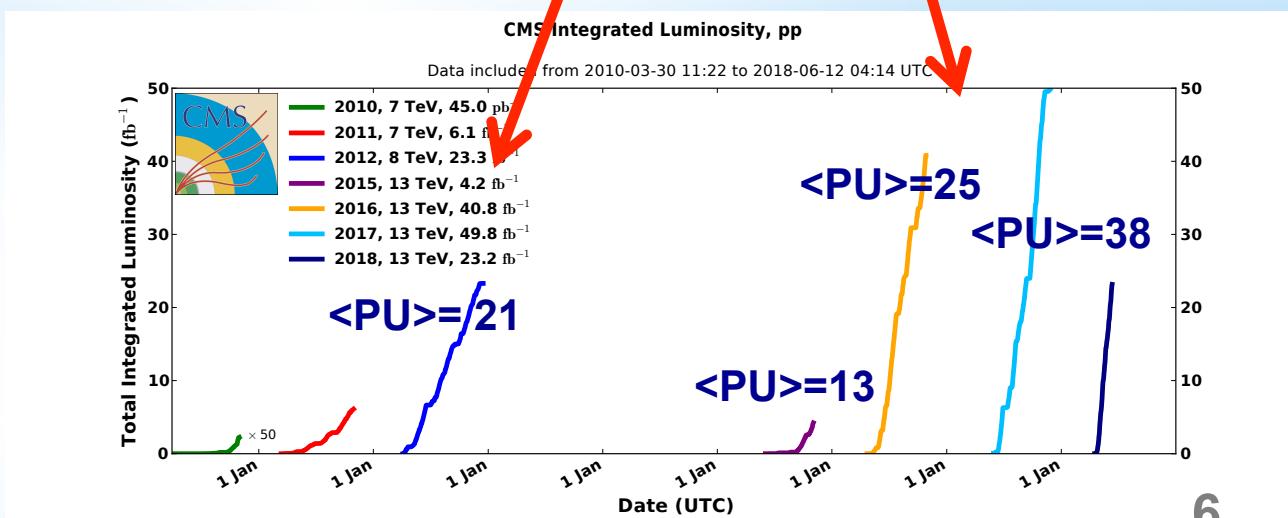
(arXiv:1507.00966, arXiv:1603.04156, arXiv:1703.05703)

The LHC



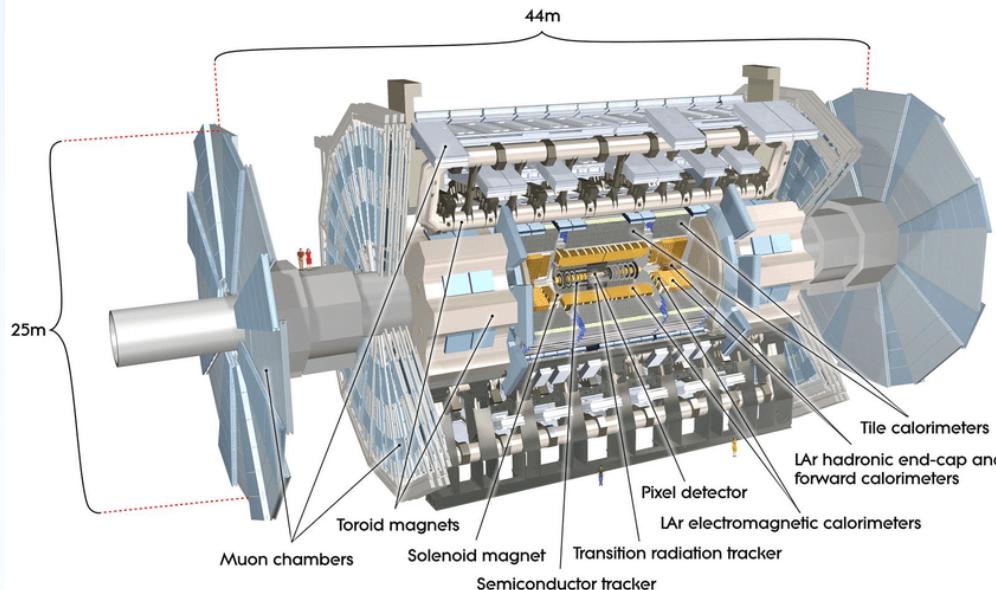
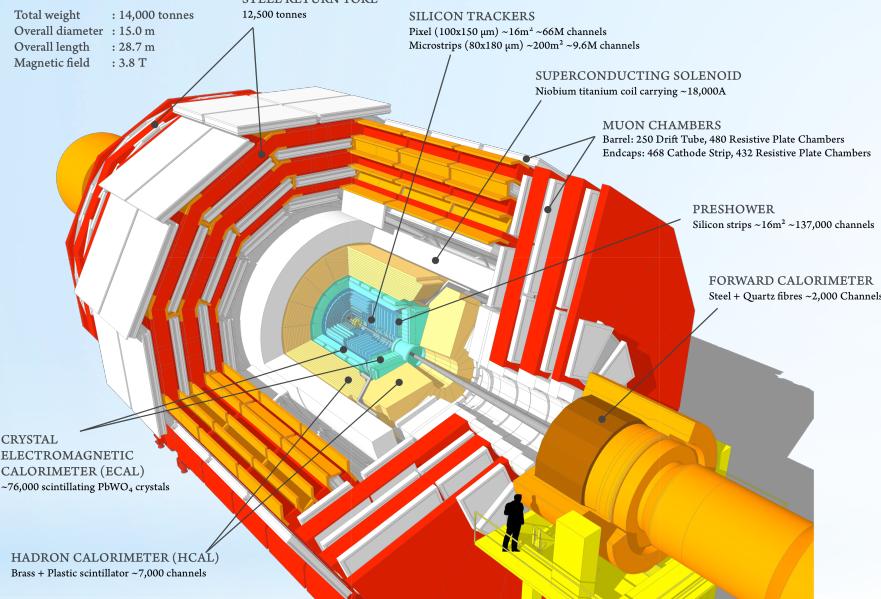
Analyses presented in this talk mainly use the data collected in :

- 2015+2016 (ATLAS)
 $L=36.1/\text{fb}$
- 2016 (CMS)
 $L=35.9/\text{fb}$
- $\sqrt{s}=13 \text{ TeV}$



The ATLAS/CMS detectors

CMS DETECTOR



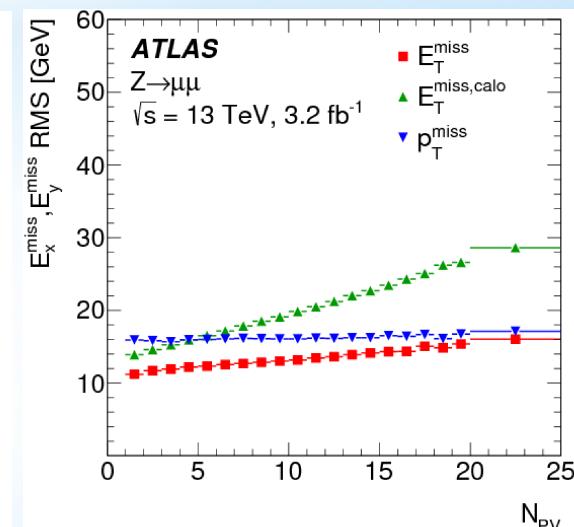
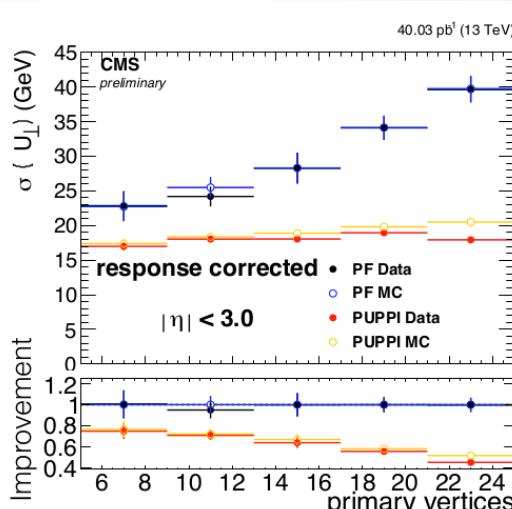
High precision multipurpose detectors

Particle identification: electrons, muons, photons, charged hadrons, neutral hadrons

Object performance at high pile-up:

Pile-up affects the event reconstruction:
MET, jet E and resolution, isolation, ...

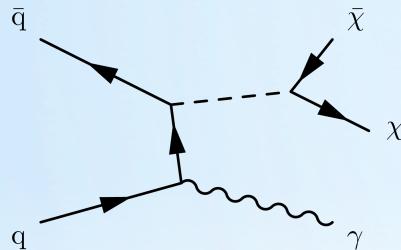
→ Sophisticated techniques deployed
e.g. weight particle momenta according
to the probability of not having pileup
activity around it (PUPPI)



Overview of DM searches @LHC

- Spin-1 mediator probed via several ISR based MET+X searches:

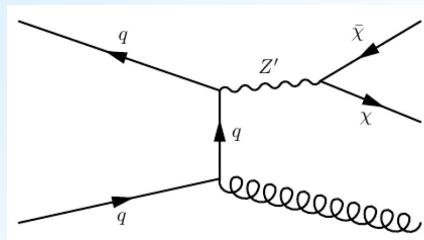
Monophoton



EPJC 77 (2017) 393

JHEP 10 (2017) 073 (13/fb)

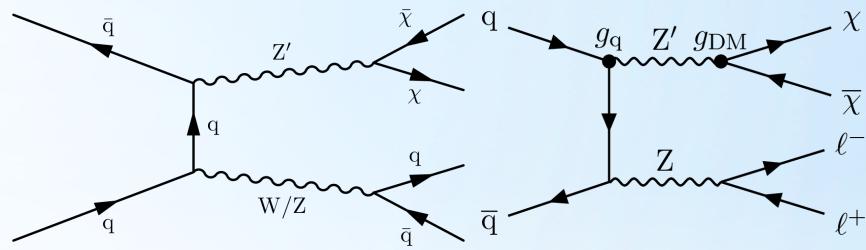
Monojet



JHEP 01 (2018) 126

PRD 97 (2018) 092005

MonoV



ATLAS-CONF-2018-005

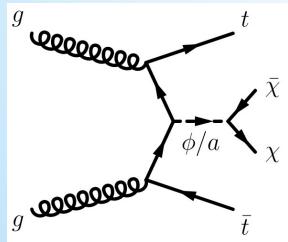
PRD 97(2018) 092005

PLB 776 (2017) 318

EPJC 78 (2018) 291

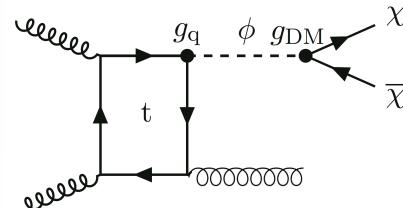
- Spin-0 mediator probed via large coupling to top (bottom) :

tt+DM, bb+DM



EPJC 78 (2018) 18
ArXiv:1711.11520

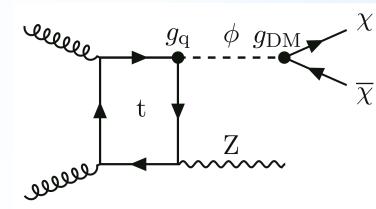
Monojet



CMS-EXO-16-049, CMS-EXO-17-014
PRD 97 (2018) 032009

JHEP 01 (2018) 126
PRD 97 (2018) 092005

MonoV



PRD 97(2018) 092005
EPJC 78 (2018) 291

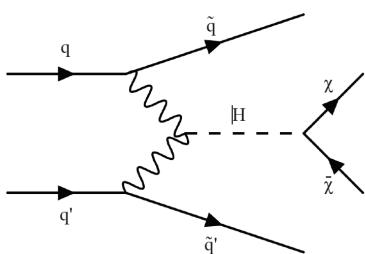


L=36/fb

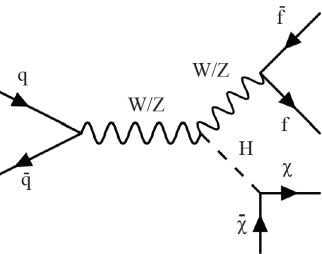
Overview of DM searches@LHC

Higgs portal to the dark sector
H to invisible

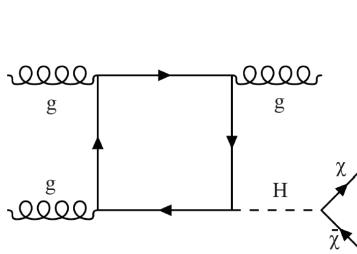
VBF+MET



Mono-V



Monojet

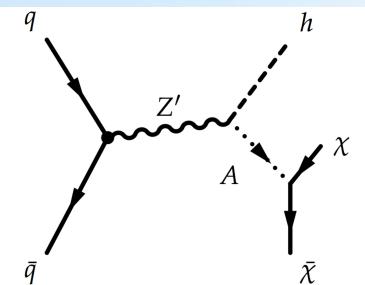


CMS 13 TeV $H \rightarrow$ Inv Combination:
CMS-PAS-HIG-17-023

ATLAS 8 TeV $H \rightarrow$ Inv Combination:
JHEP11(2015) 206

ATLAS 13 TeV:
Mono-Z(II) EPJC 78 (2018) 291
Mono-V(qq) ATLAS-CONF-2018-005

Mono-H



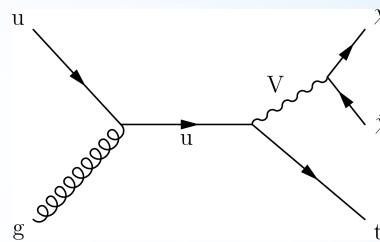
$H \rightarrow bb$:

PRL 119 (2017) 181804,
CMS-PAS-B2G-17-004

$H \rightarrow \gamma\gamma, \tau\tau$:

PRD 96 (2017) 112004
CMS-PAS-EXO-16-055

Mono-t

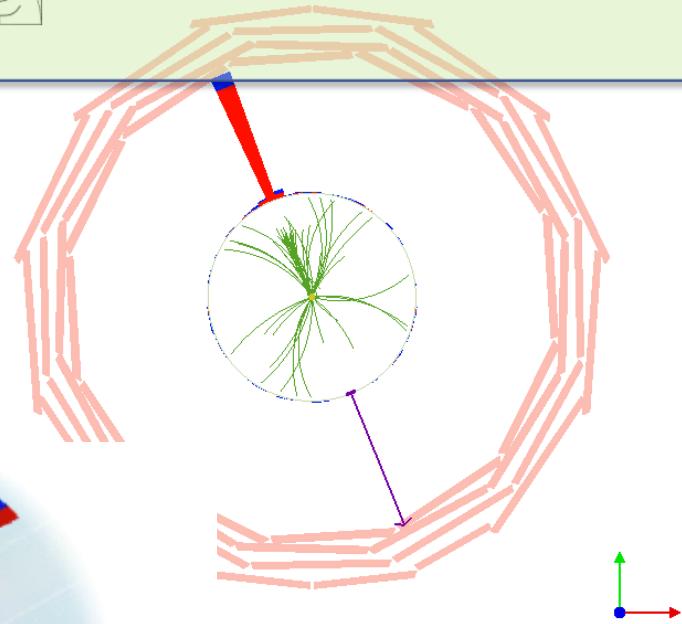


EPJC 78 (2018) 18
CMS-PAS-EXO-16-051
(arXiv:1801.08427)

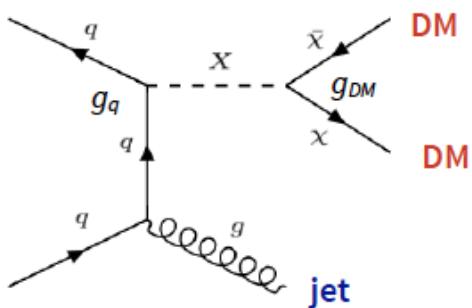
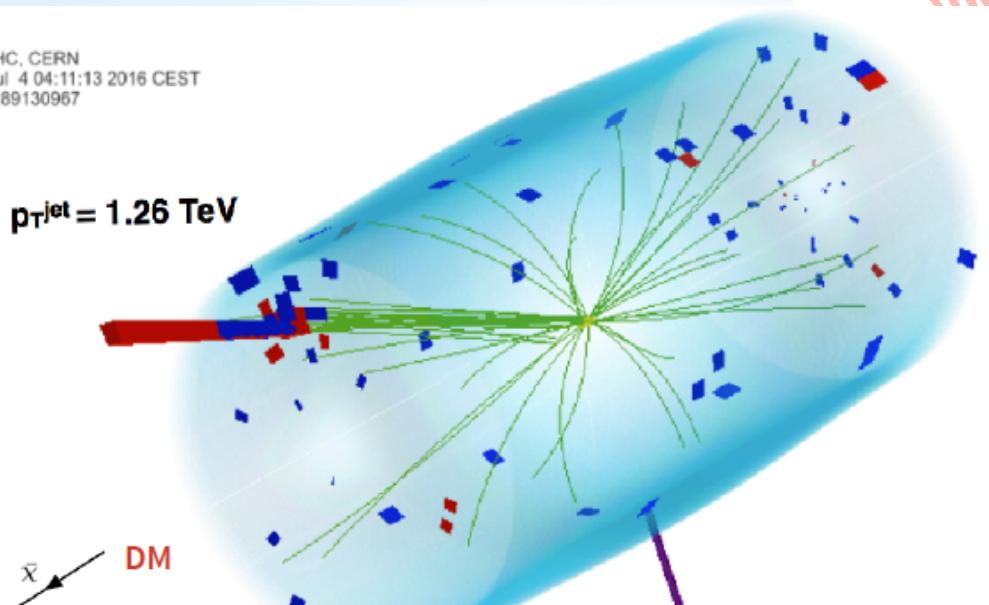
Mono-jet searches



CMS Experiment at LHC, CERN
Data recorded: Mon Jul 4 04:11:13 2016 CEST
Run/Event: 276283 / 289130967
Lumi section: 149



CMS Experiment at LHC, CERN
Data recorded: Mon Jul 4 04:11:13 2016 CEST
Run/Event: 276283 / 289130967
Lumi section: 149



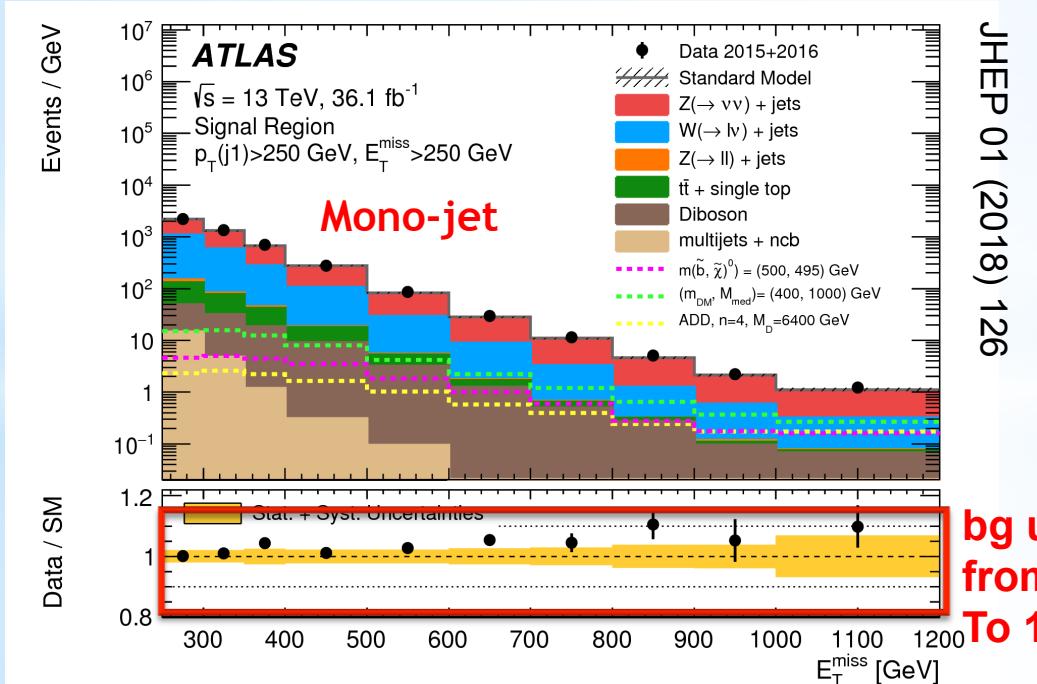
Large MET!

**Spectacular
Events**

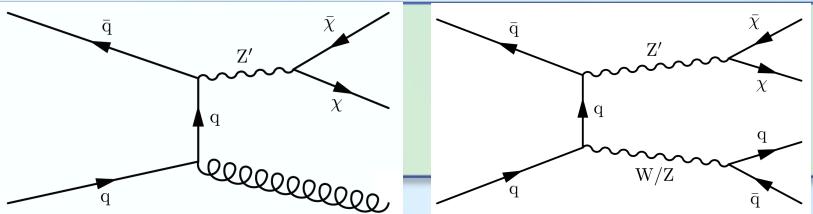
Mono-jet searches

Mono-jet selection: (trigger caloMET>90 GeV)

- MET>250 GeV, no leptons
- $p_T(\text{jet1})>250 \text{ GeV}$, $|\eta|<2.4$
- Njets ($p_T>30 \text{ GeV}$) ≤ 4 , $\Delta\phi(\text{jet}, \text{MET})>0.4$



- **Signal extraction based on the MET distribution**
- Main backgrounds: Z(vv)+jets (60%) & W(lv)+jets (30%)
 - Well modelled from control regions in data : Z($\mu\mu, ee$)+jets, W($\mu\nu, e\nu$)+jets, γ +jets (CMS)
 - Simultaneous fit to signal and control regions

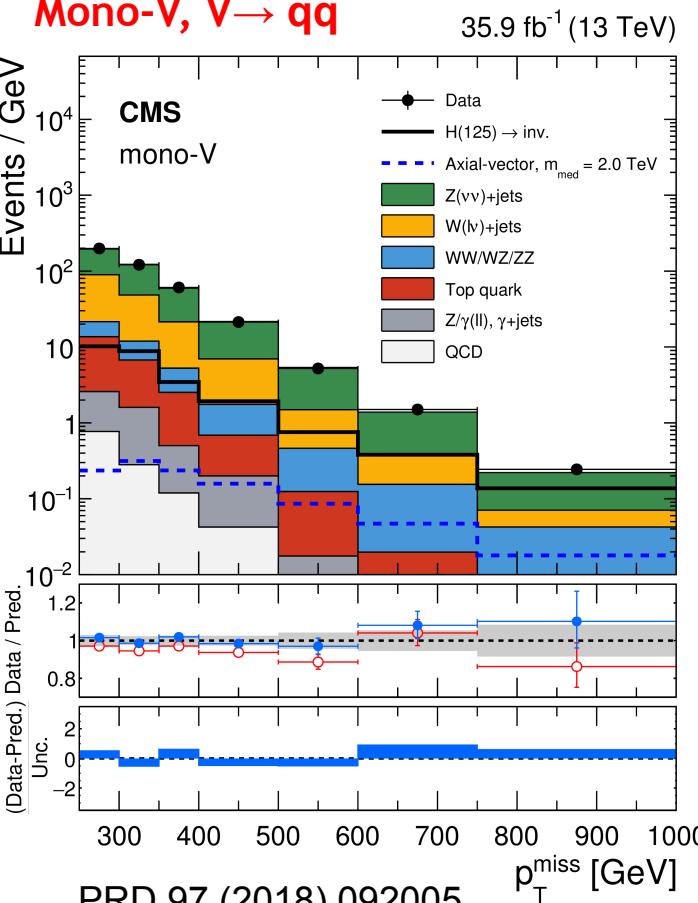


Similar final state as boosted monoV, $V \rightarrow qq$, where jet substructure is used for identification

Mono-V event selection:

- $R=0.8$ jet $p_T>250 \text{ GeV}$
- $m(\text{jet}) \sim m_{W/Z}$, 2-prong

Mono-V, $V \rightarrow qq$

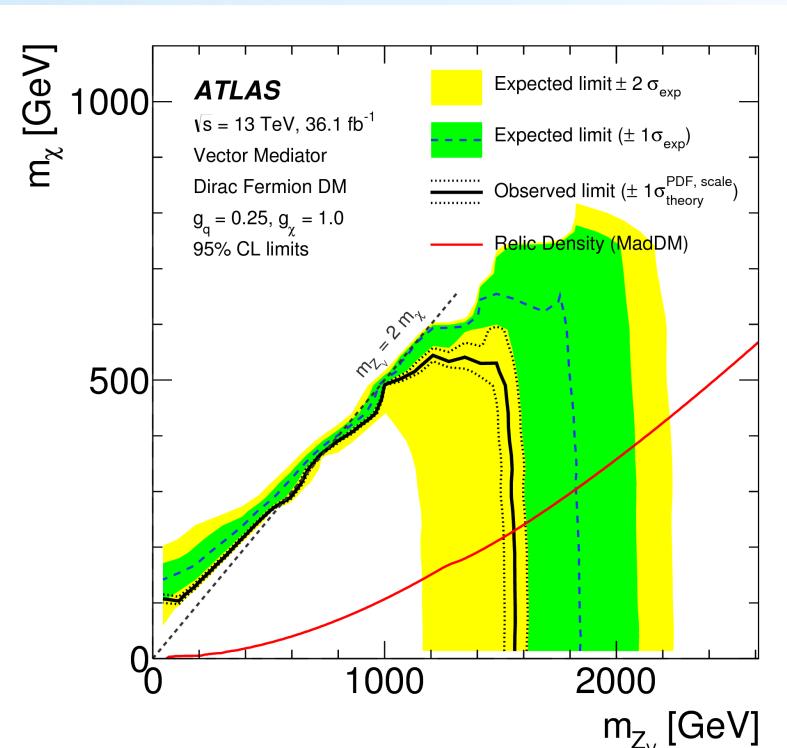


Mono-jet: DM interpretation

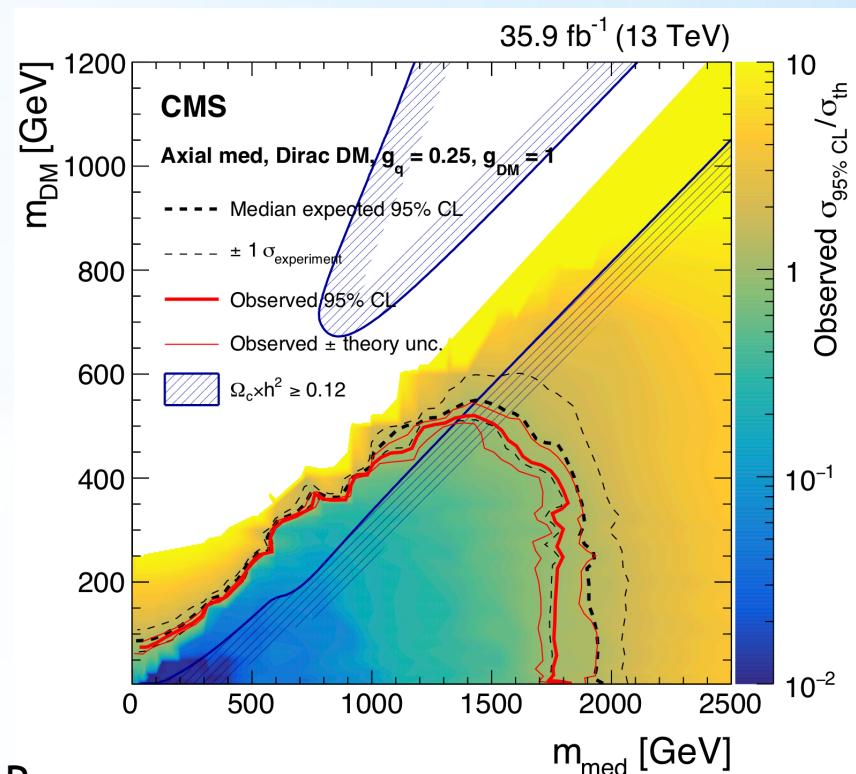
95% C.L. upper limits obtained in the (M_χ, M_{med}) plane:

Suppose Dirac Fermion DM, $g_x=1$ and $g_q=0.25, g_l=0$

Vector mediator :



Axial-vector mediator :



Expected relic density : consistent with the WMAP measurements (i.e. $\Omega h^2 = 0.12$), in this model.

For vector and axial-vector interactions :

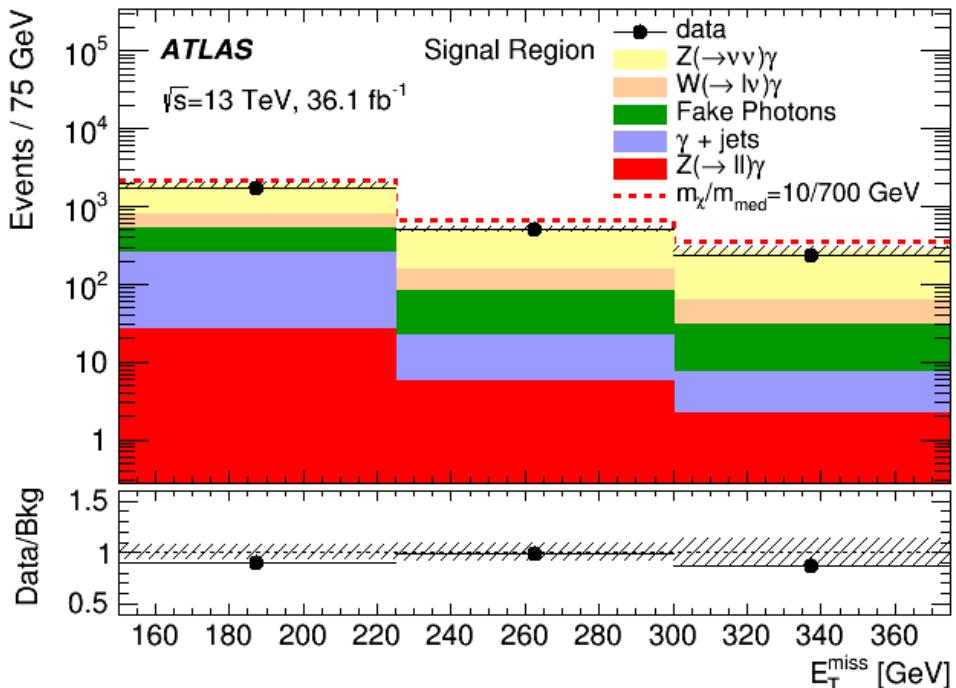
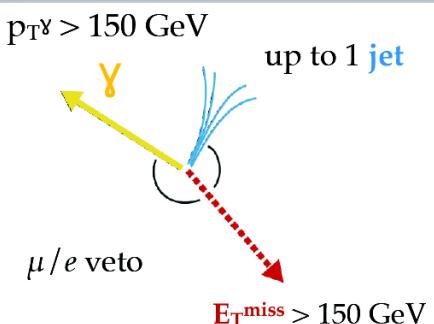
- Mediator masses are excluded up to 1.6-1.8 TeV
- DM masses are excluded up about 500 GeV

Mono-photon searches

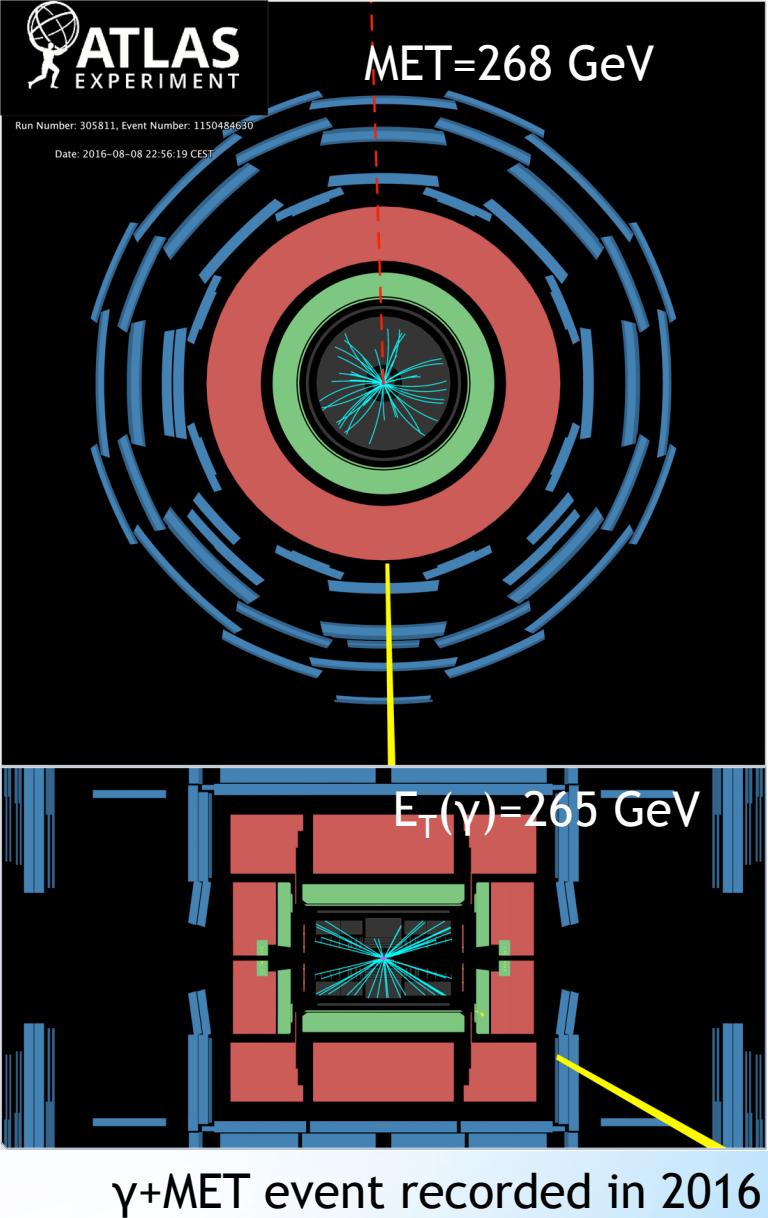
Selection:

(Trigger Single $\gamma E_T > 140$ GeV)

- $E_T(\gamma) > 150$ GeV, $|\eta| < 2.37$
- MET > 150 GeV
- $\Delta\phi(\text{photon, MET}) > 0.4$
- Njets ($p_T > 30$ GeV, $|\eta| < 4.5$) ≤ 1



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



Main backgrounds: $(Z \rightarrow \nu\nu) + \gamma$ and $(W \rightarrow l\nu) + \gamma$

It is estimated from $(Z \rightarrow ll) + \gamma$ and $(W \rightarrow \mu\nu) + \gamma$ Control Regions (CR)
where the MET includes the corresponding charged lepton(s)

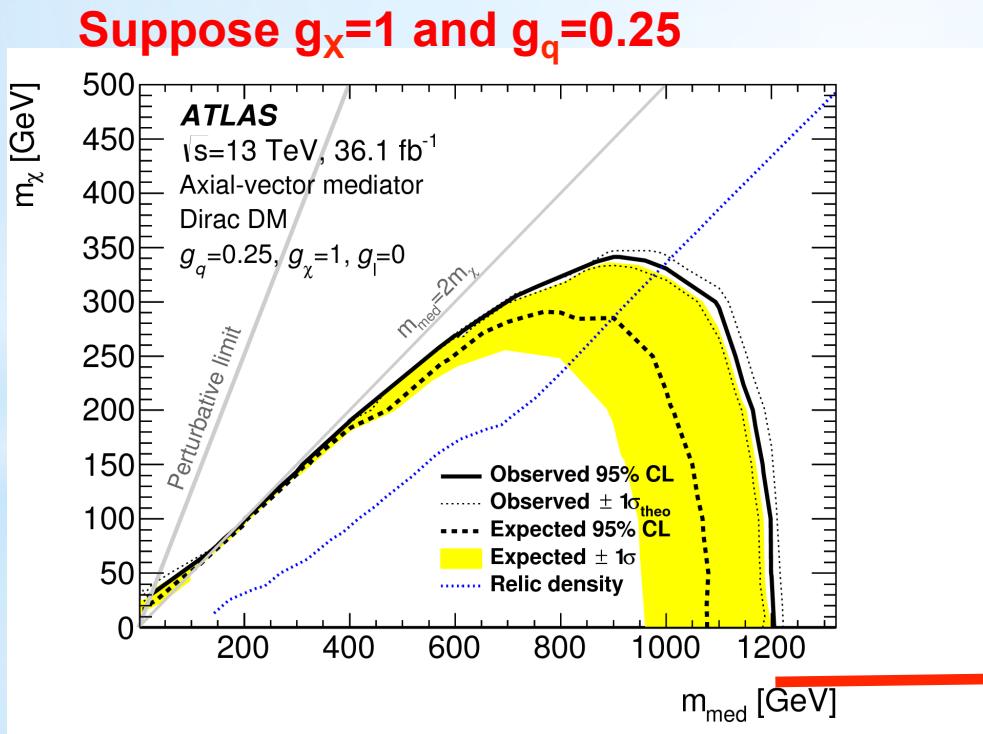
Mono-photon: DM interpretation

95% C.L. upper limits obtained in the (M_χ, M_{med}) plane:

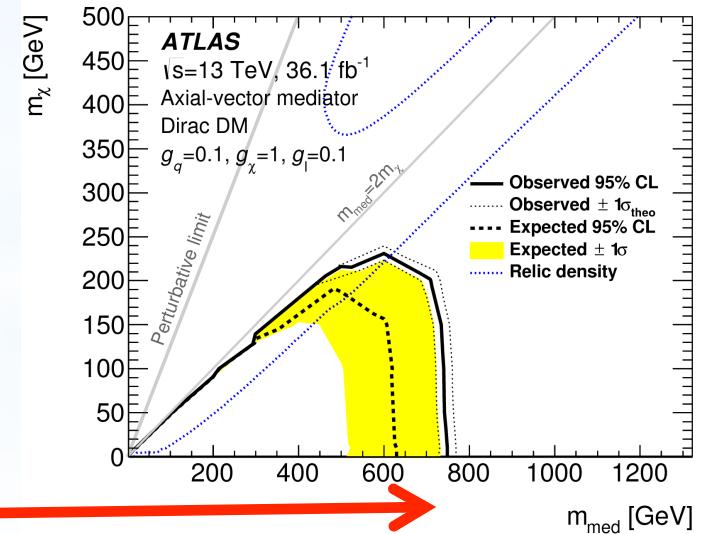
Eur. Phys. J. C 77 (2017) 393

axial-vector interactions

Suppose $g_x=1$ and $g_q=0.25$



axial-vector interactions
And if we suppose
 $g_x=1$ and $g_q=0.1$



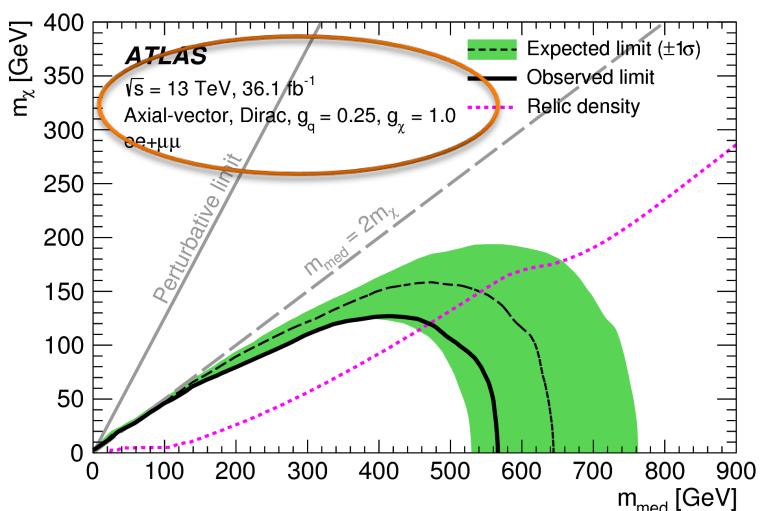
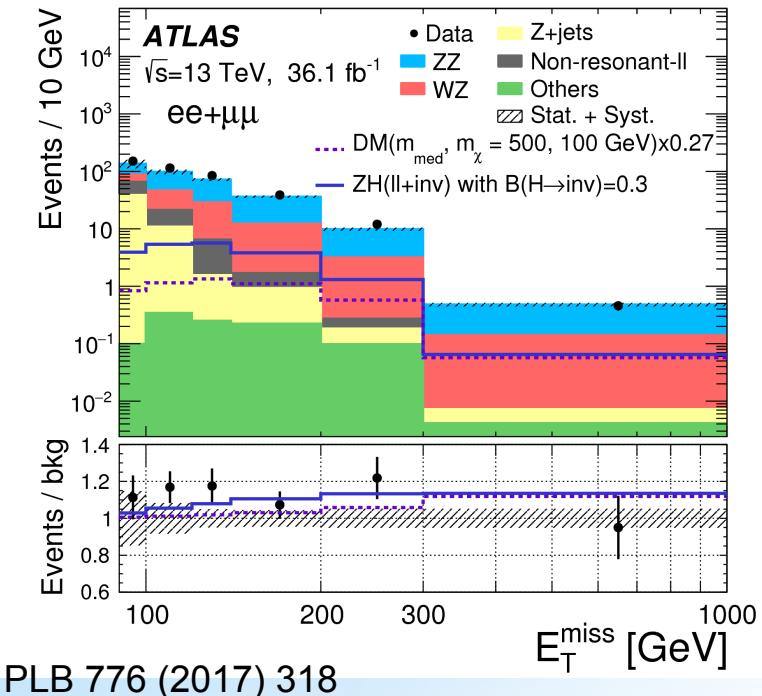
Limits are highly dependent on the choice of the couplings

For vector and axial-vector interactions :

- Mediator mass excluded up to 1.2 TeV
- DM mass excluded up to 350-500 GeV

→ Lower sensitivity compared to mono-jet (factor $\alpha_{\text{QED}} \ll \alpha_s$)

Mono-Z searches, $Z \rightarrow ll$

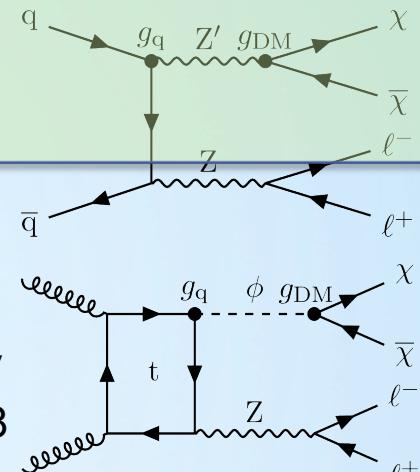
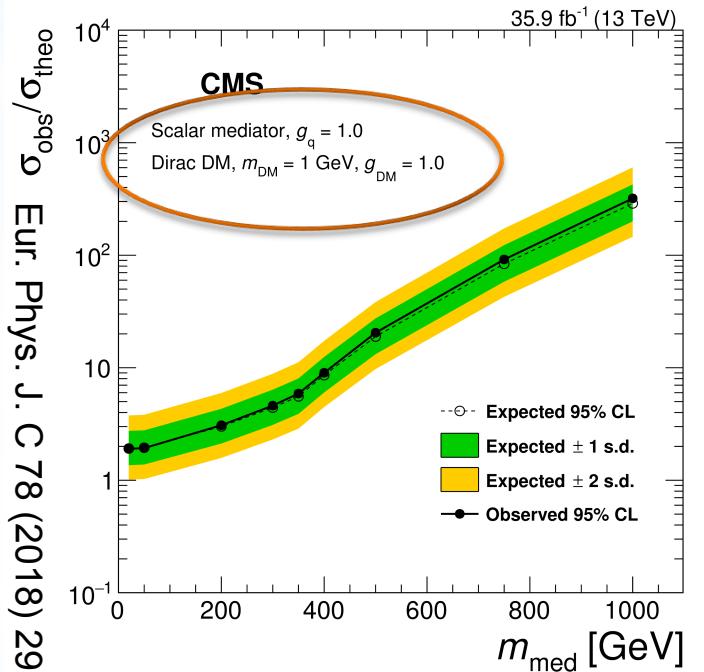


Selection:
(dilepton trigger)

- 2 OS leptons $p_T > 30/20 \text{ GeV}$
- $76 < m_{ll} < 106 \text{ GeV}, \Delta R(l,l) < 1.8$
- MET > 90 GeV, MET/H_T > 0.6
- $\Delta\phi(ll, \text{MET}) > 2.7, \text{Nb-jets} = 0$

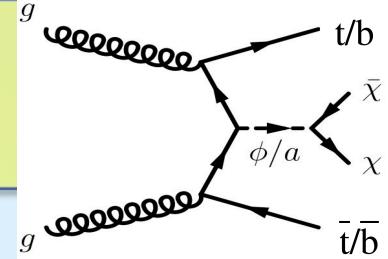
Main bg : ZZ and WZ

Low sensitivity to scalar mediators:



Limits are expressed in terms of the ratio of the excluded cross-section to the nominal cross-section for a coupling assumption of $g = g_q = g_\chi = 1$

Heavy q pair + DM



If Yukawa-like coupling → high sensitivity to Spin-0 mediator

Three final states for tt+DM analysis:

tt(0l) + DM : MET>200 GeV, at least 4 jets, 1b-jet

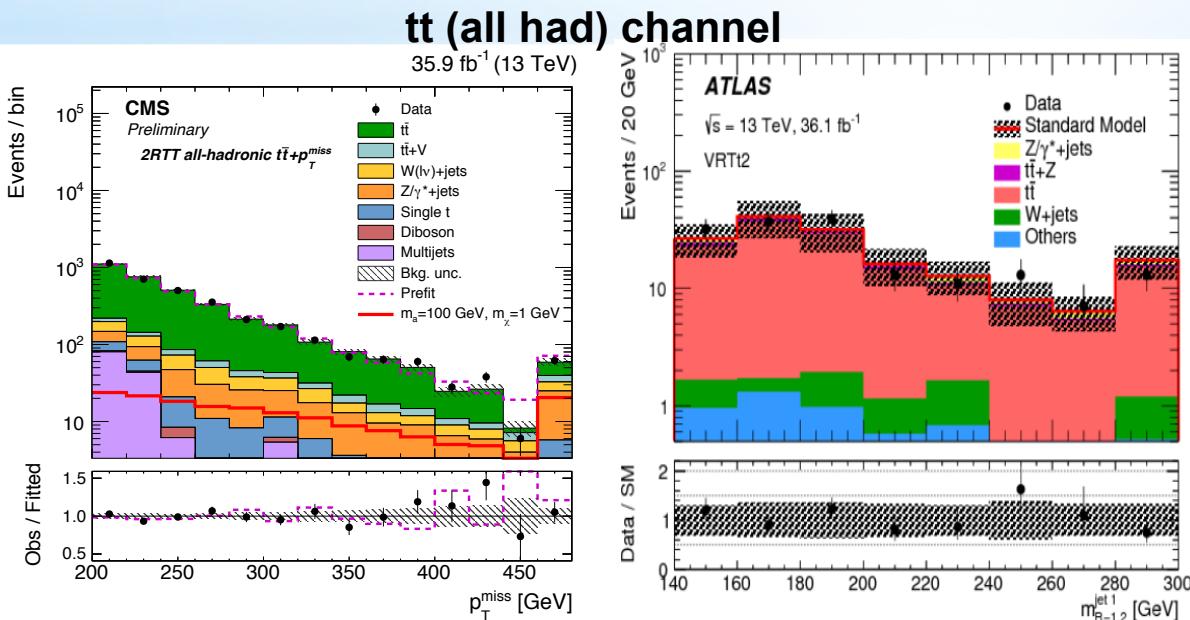
tt(1l) + DM : MET>160 GeV, M_T>160 GeV, at least 3 jets, 1b-jet

tt(2l) + DM : MET>50 GeV, at least 2 jets, 1b-jet

Main background : top-antitop production, tt+Z and Z+jets, constrained from several CR

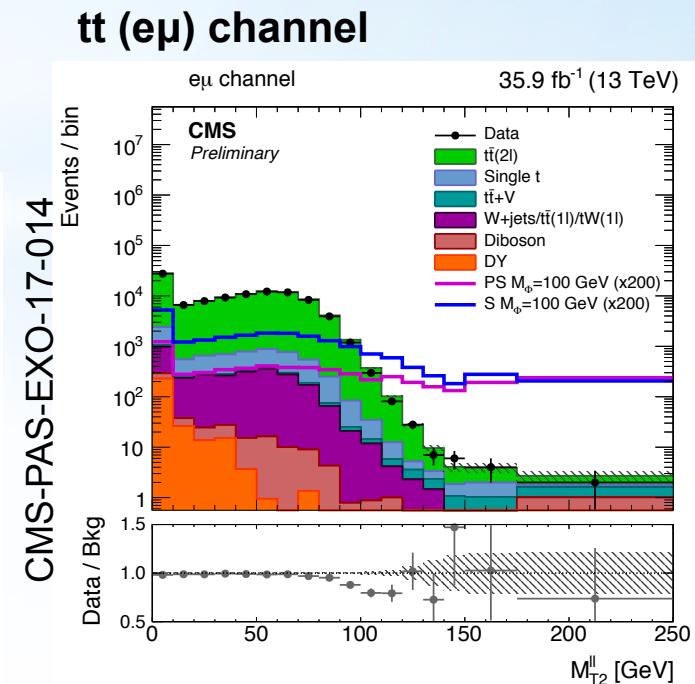
Resolved top tagger (RTT) in 0-lep channel

- Identify jet triplets from top decays
- Two event categories : 0/1 & 2 RTT



CMS-PAS-EXO-16-049

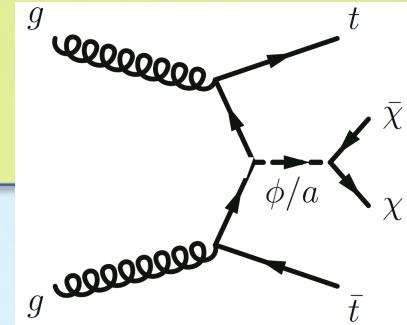
EPJC 78 (2018) 18



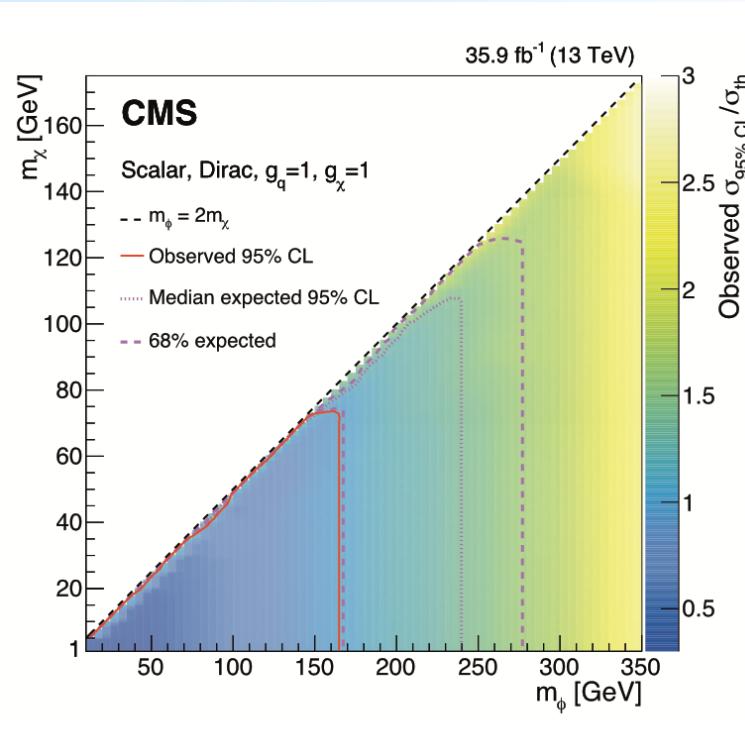
$$M_{T2}^{ll} = \min_{\vec{p}_{T1}^{\text{miss}}, \vec{p}_{T2}^{\text{miss}} = \vec{p}_T^{\text{miss}}} \left(\max \left[M_T \left(\vec{p}_T^{\ell_1}, \vec{p}_{T1}^{\text{miss}} \right), M_T \left(\vec{p}_T^{\ell_2}, \vec{p}_{T2}^{\text{miss}} \right) \right] \right)$$

DM+tt : Limits plots

Combination of the 3 decay channels
(all hadronic, semileptonic, fully leptonic)

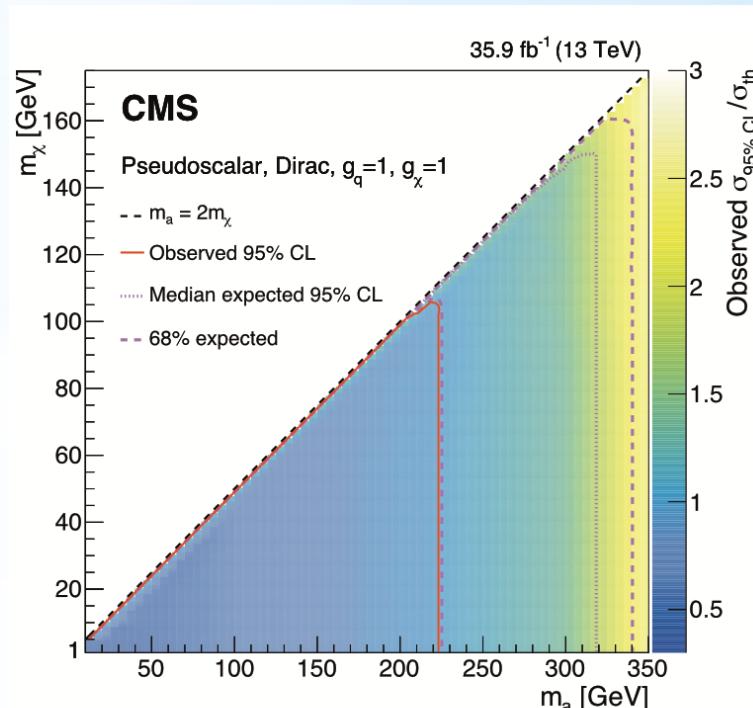


Scalar mediator :



→ Scalar mediator masses excluded up to 160 GeV

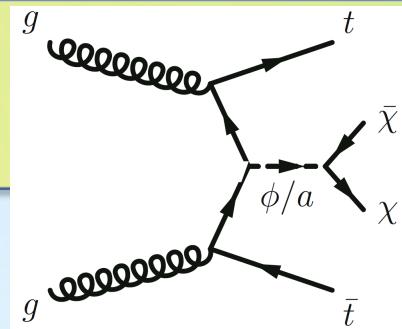
Pseudo-scalar mediator :



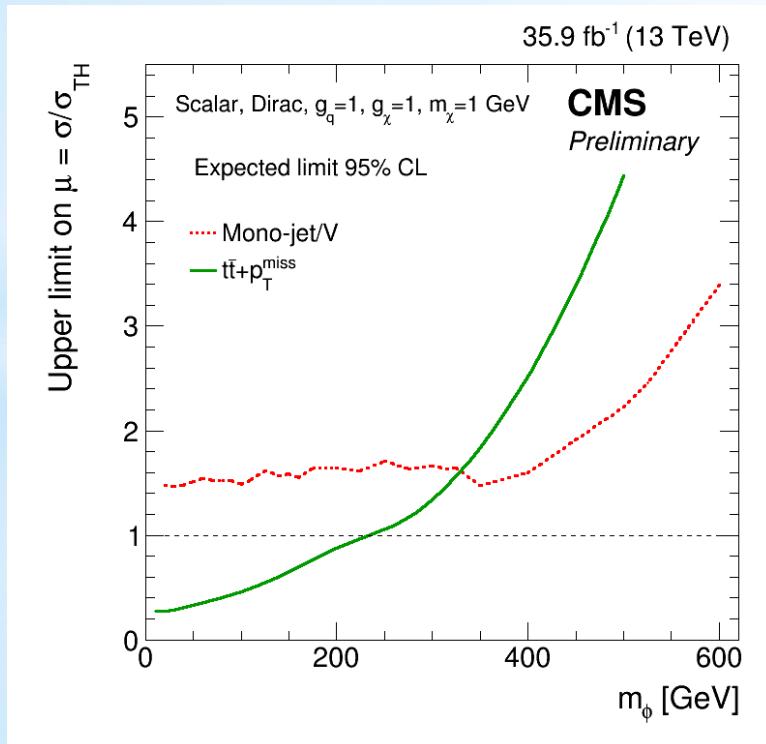
→ Pseudo-scalar mediator masses excluded up to 220 GeV

DM+tt : Limits plots

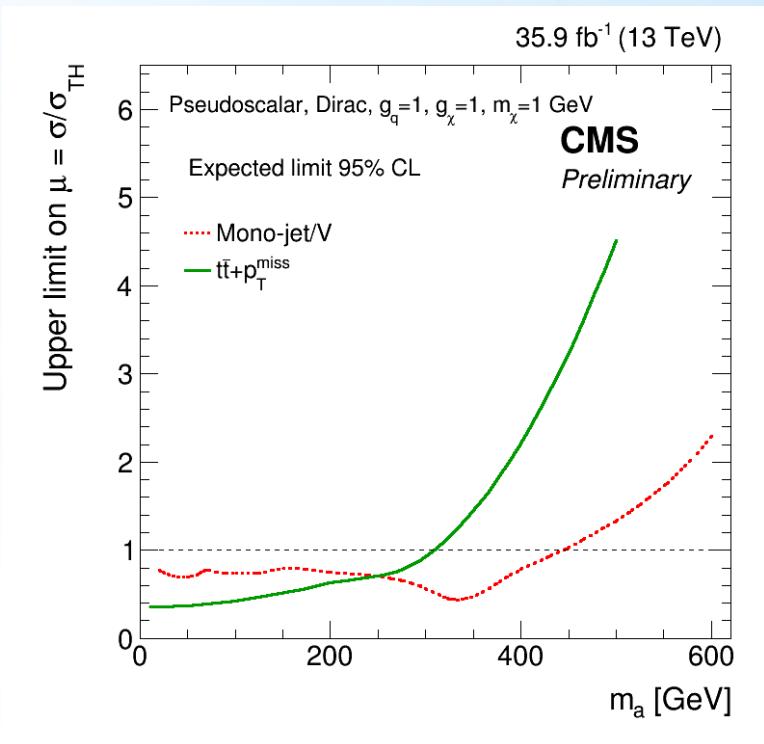
The tt+DM 2016 result gives the strongest limit at low mass for collider spin0-mediated DM



Scalar mediator :



Pseudo-scalar mediator :

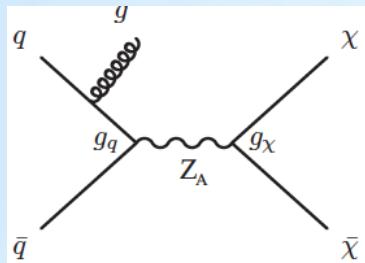


Green line (tt+DM) from CMS-PAS-EXO-16-049

Red line (Mono-jet/V) from Phys. Rev. D97 (2018) 092005

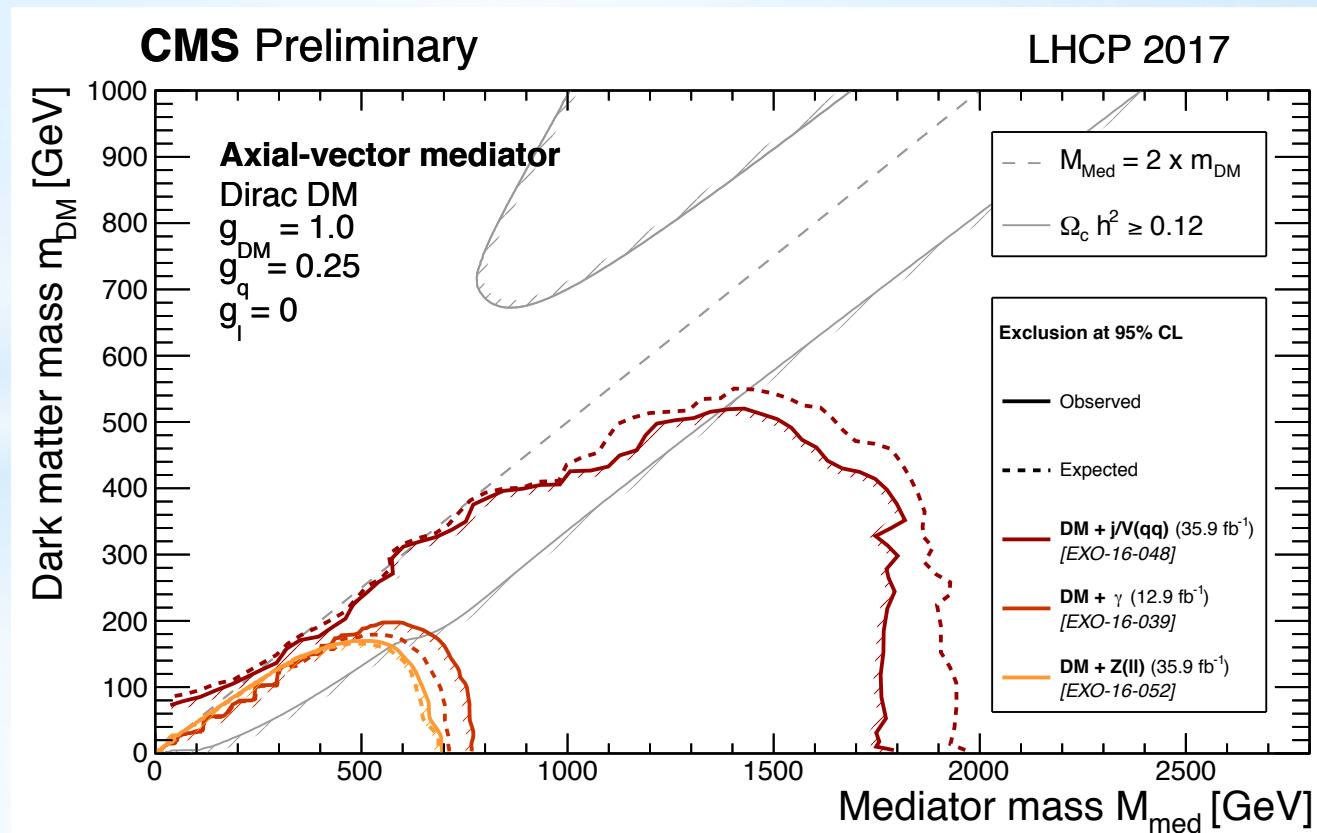
Combined plots :

Limit for spin 1 mediator with mono-jet, mono-photon, mono-Z(ll) results
(here axial-vector mediator)



**Mono-X
searches :**

No sensitivity to
the off-shell
region ($2M_\chi > M_{\text{med}}$)
due to the small
cross section

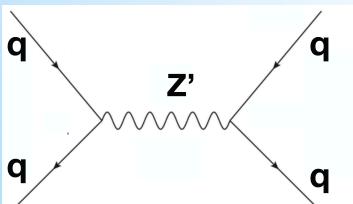
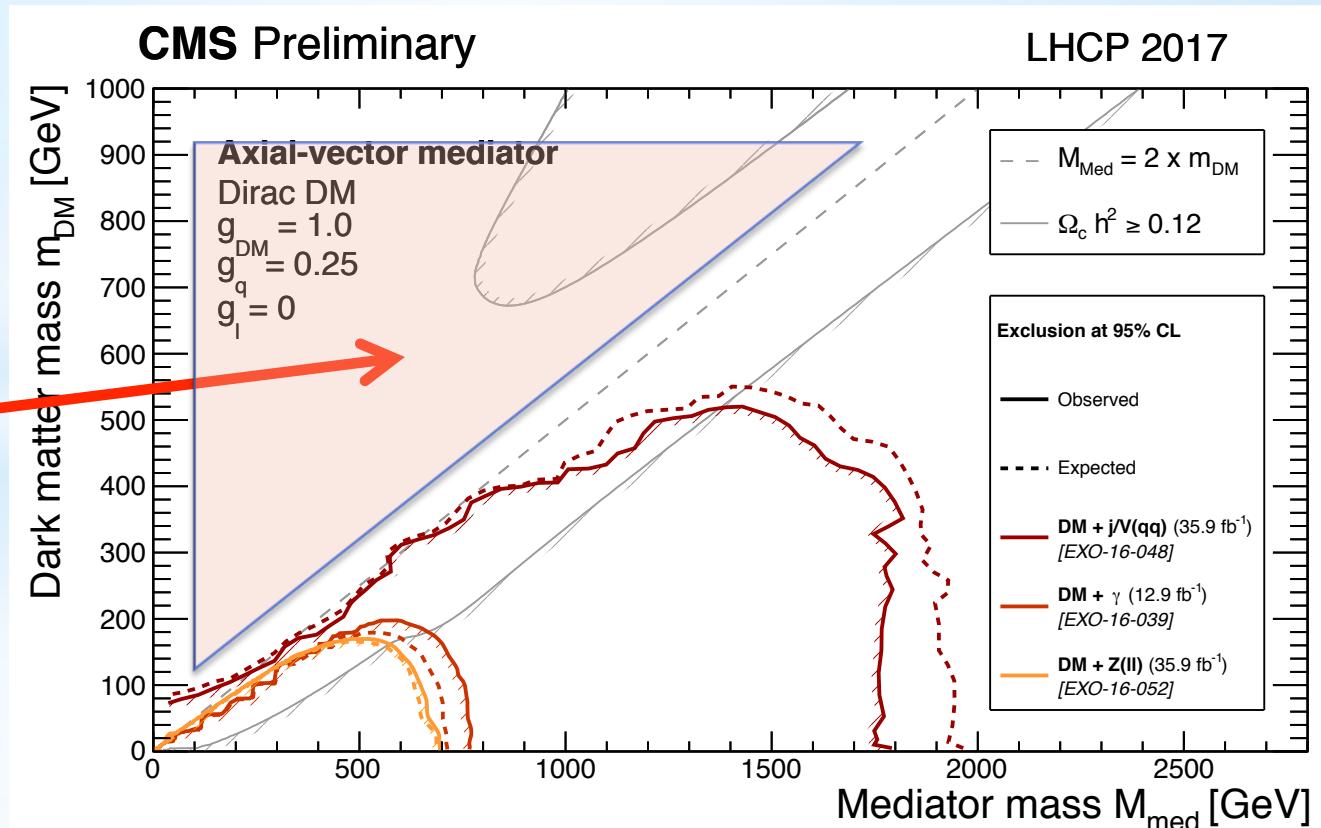


Combined plots :

Limit for spin 1 mediator with mono-jet, mono-photon, mono-Z(ll) results
 (here axial-vector mediator)

Mono-X
 searches :

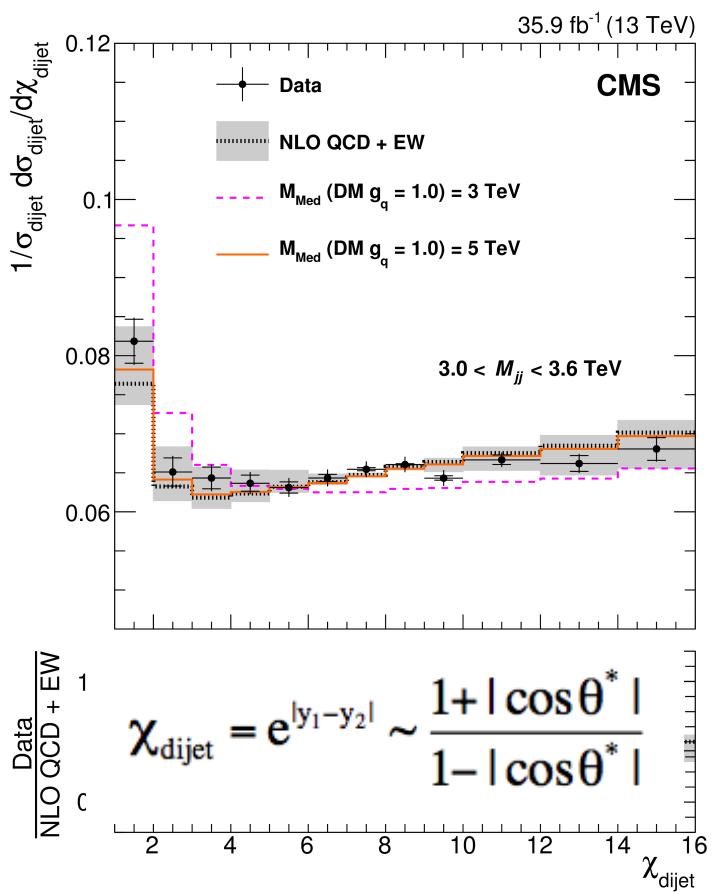
No sensitivity to
 the off-shell
 region ($2M_X > M_{\text{med}}$)
 due to the small
 cross section



There : can use constraints from Z' decay to qq or ll
 → mediator searches

Dijet/dilepton searches

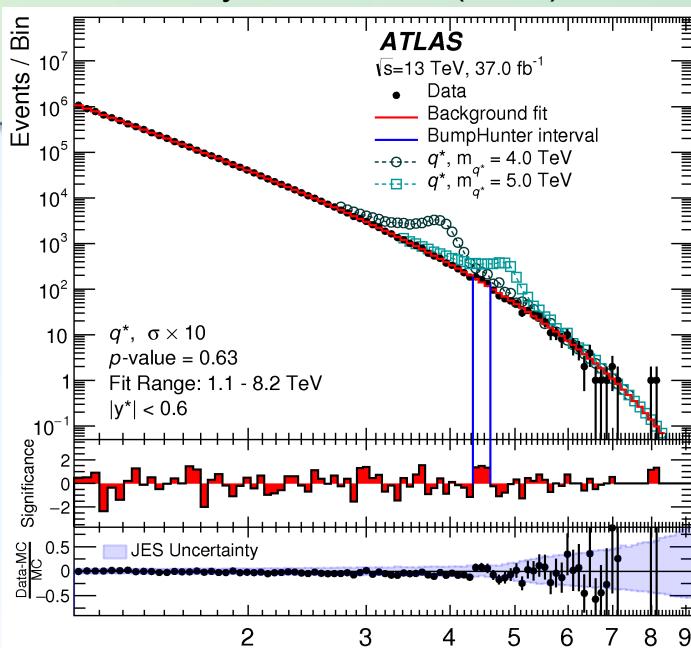
Dijet angular analysis:
 the angular distributions are fit
 for different dijet mass bins
 New physics signal at low $X(\text{dijet})$



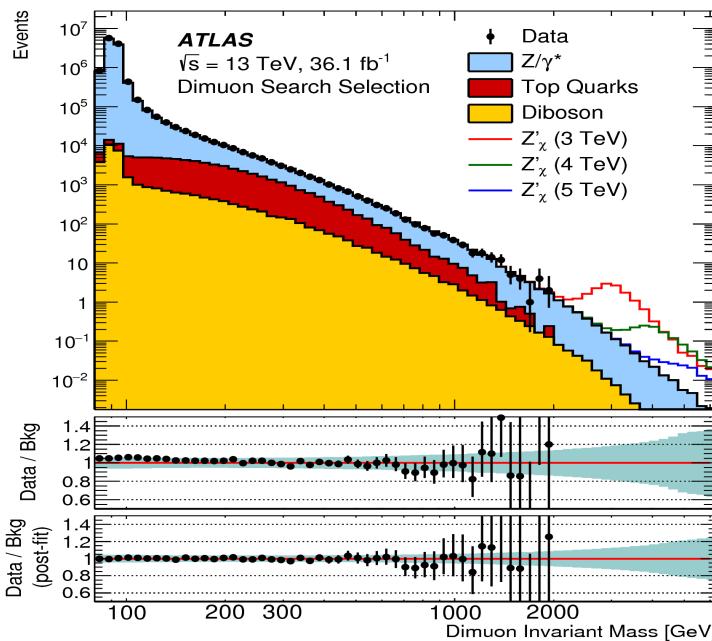
CMS-PAS-EXO-16-046 (arXiv:1803.08030)

**Standard
searches →
at high mass**

Dijet at low mass
 JHEP 01 (2018) 097
 CMS EXO-17-001



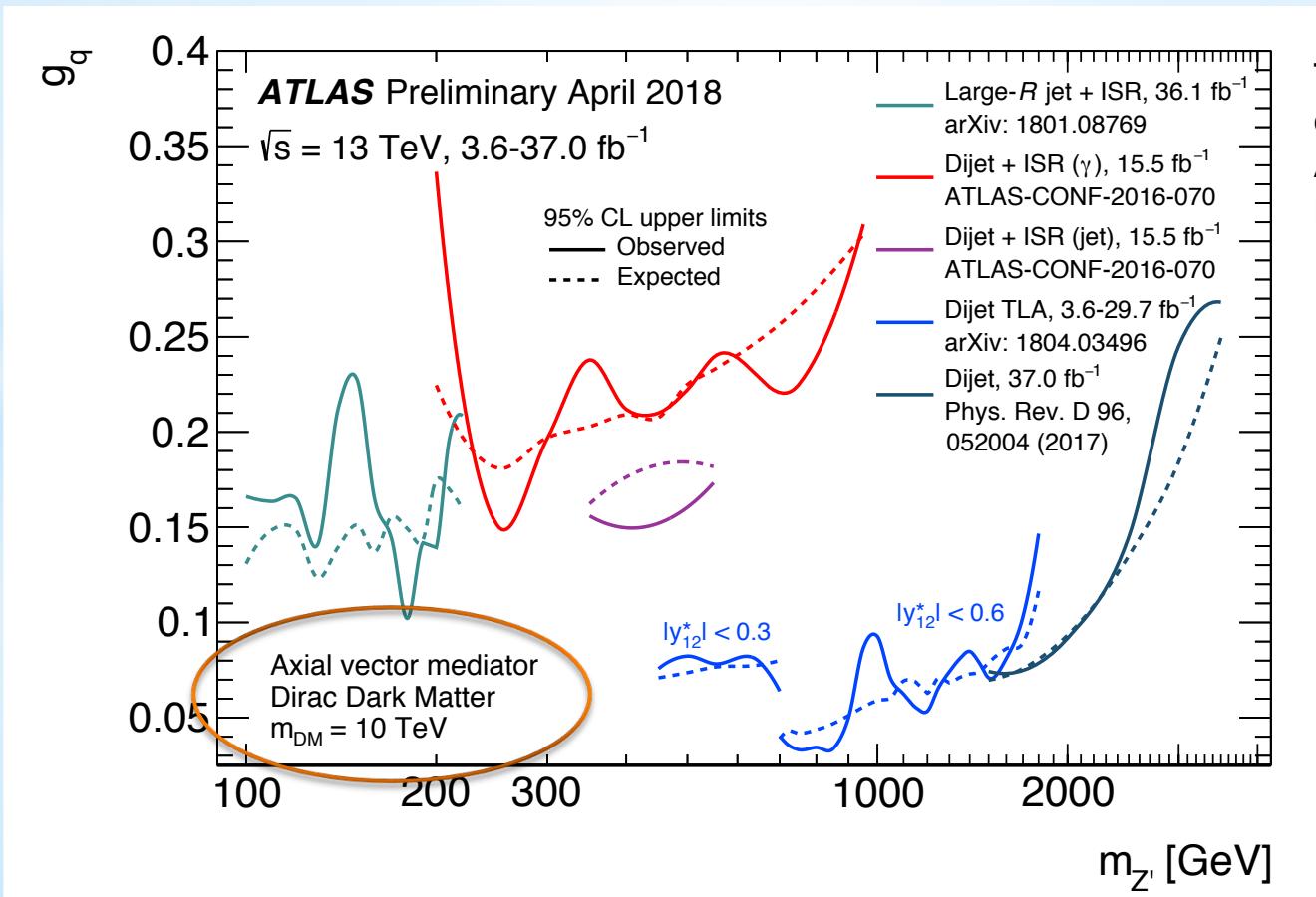
Dilepton searches :



CMS-PAS-EXO-16-047
 JHEP 10 (2017) 182

Dijet summary

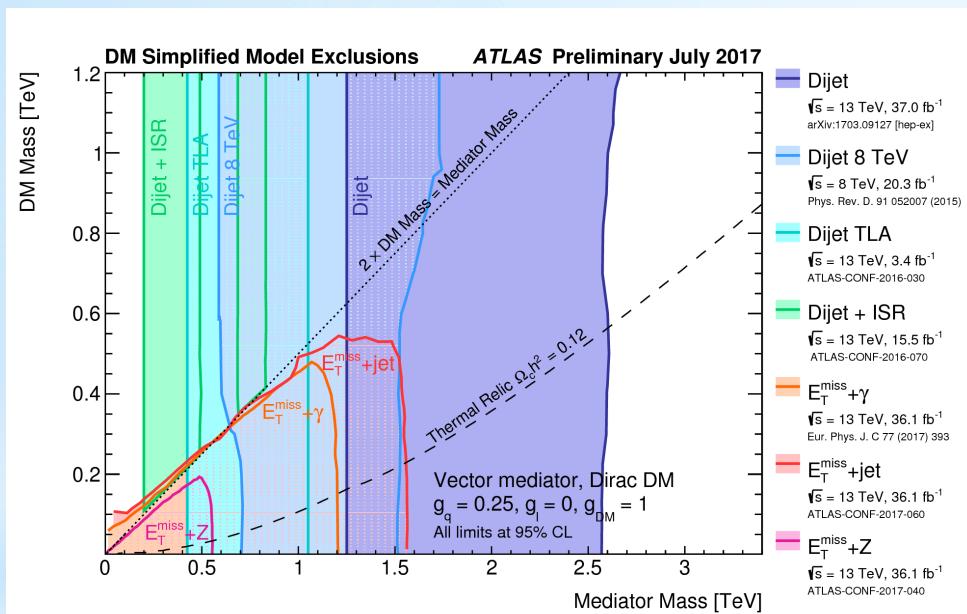
- Summary plot of bounds in the coupling-mediator mass plane from dijet searches using 2015 and 2016 data
- Limits on universal coupling (between leptophobic Z' and quarks)
- $m_{DM}=10 \text{ TeV}$



TLA=trigger level
object analysis (ATLAS)
Also called
Data scouting (CMS)

Similar plot exists for CMS

Combining Mono-X and mediator searches

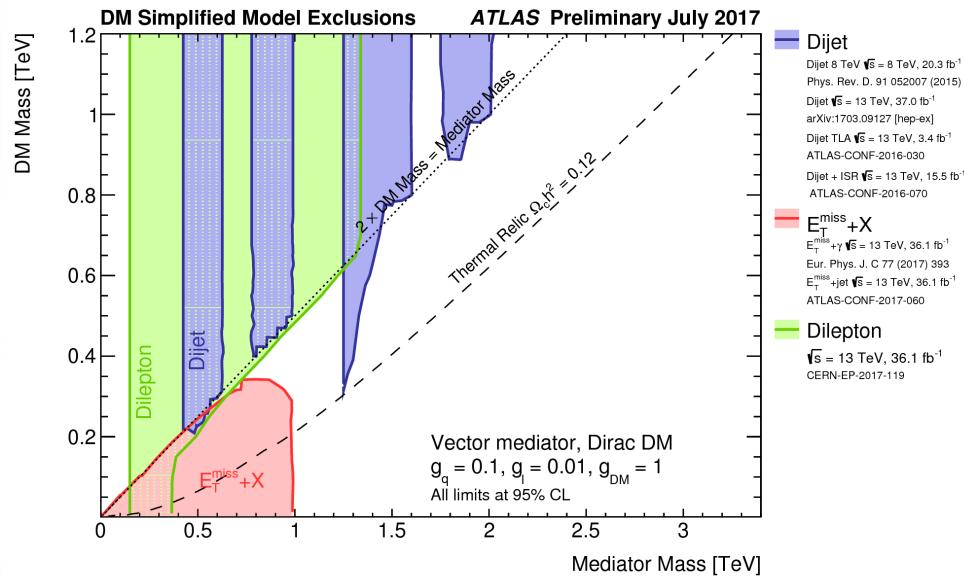


The coupling values determine the interplay between DM and resonance searches

→ For vector mediator,
 $g_q=0.25, g_x=1$ and $g_l=0$,
mediator masses down to
~50 GeV* and up to 2.5 TeV
are excluded

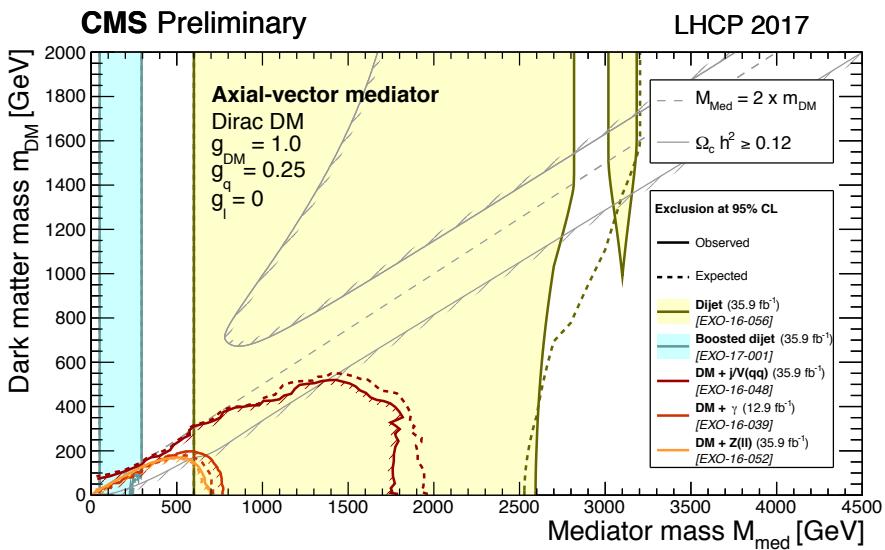
* CMS, JHEP 01 (2018) 097)

- For vector mediator, $g_q=0.1, g_x=1$ and $g_l=0.1$
- Strong constraints from dilepton search if $g_l > 0$ →
- Dijet and mono-X constraints weaken when $g_q = 0.25 \rightarrow 0.1$



Combining Mono-X and mediator searches

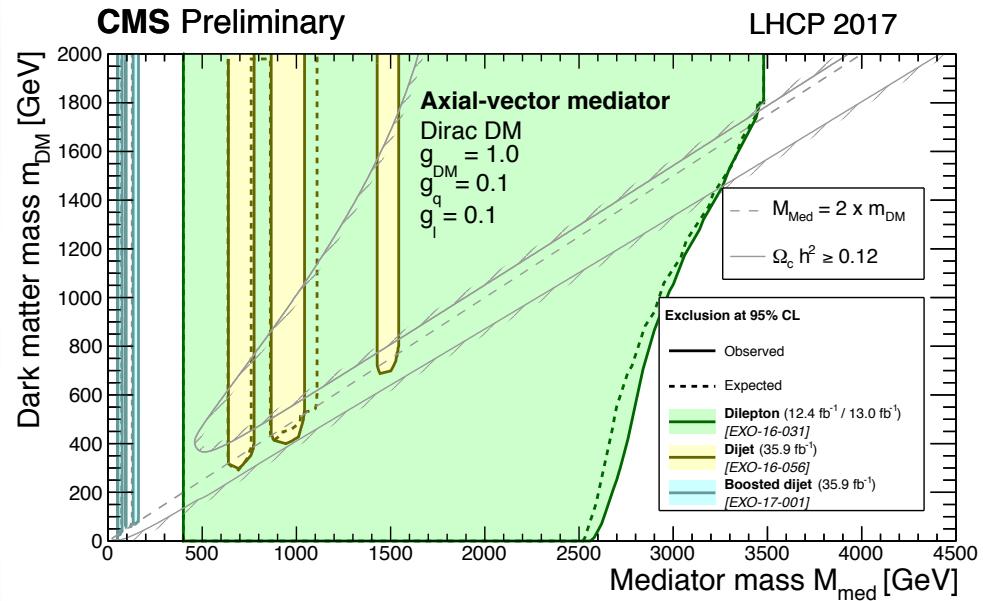
Same plot for axial-vector mediator:



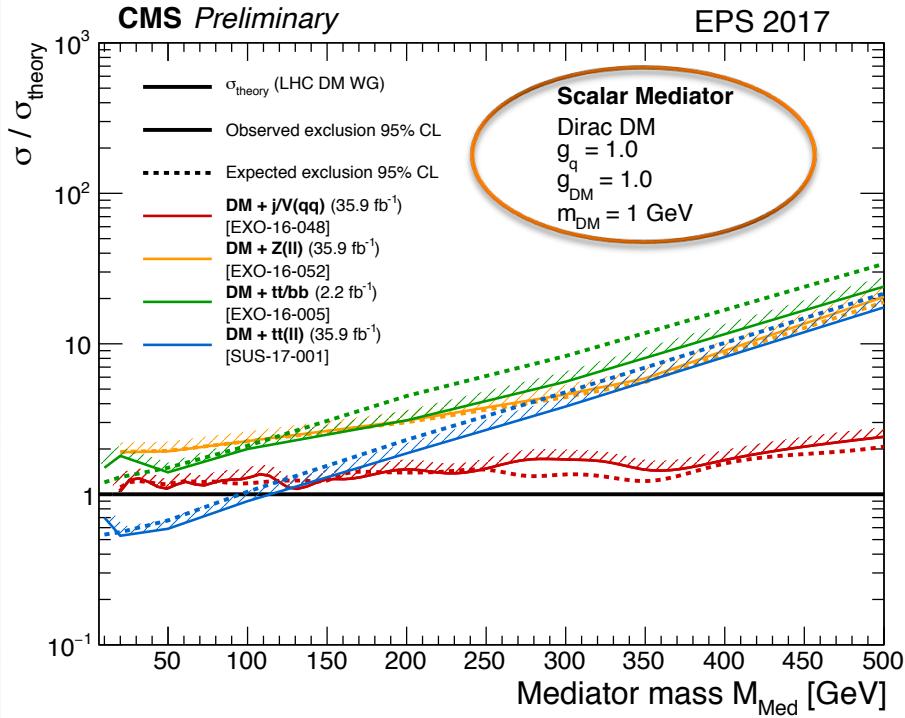
→ For axial-vector mediator,
 $g_q=0.25$, $g_x=1$ and $g_l=0$

For axial-vector mediator,
 $g_q=0.1$, $g_x=1$ and $g_l=0.1$

→



Combining Mono-X and mediator searches

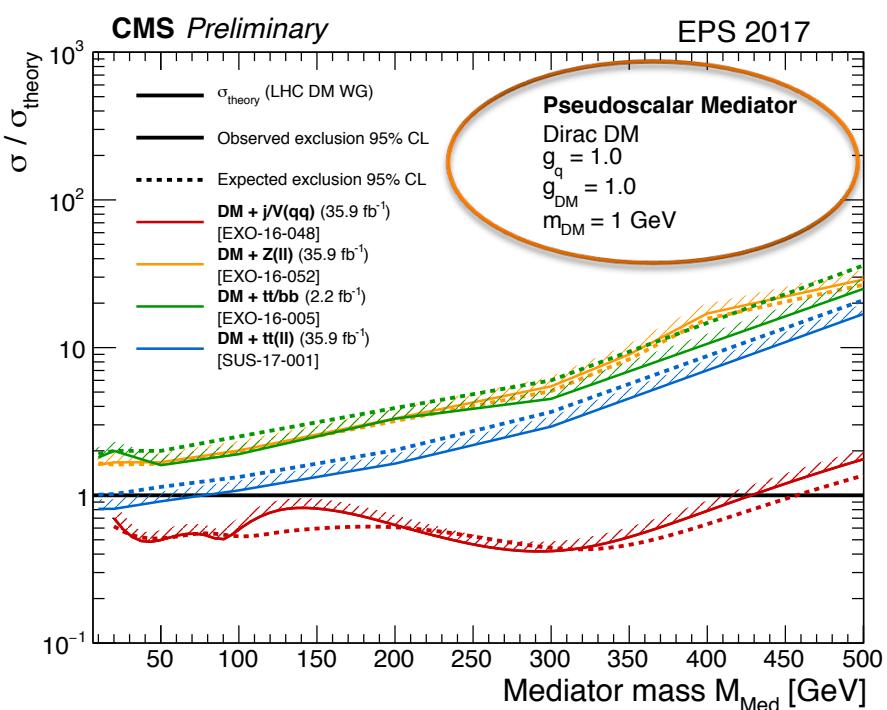


Limits are expressed in terms of the ratio of the excluded cross-section to the nominal cross-section for a coupling assumption of $g = g_q = g_x = 1$
And $m_{DM}=1 \text{ GeV}$

(to be updated with new $t\bar{t}+\text{DM}$ analysis,
CMS-PAS-EXO-16-049, see slide 18)

← For scalar mediator

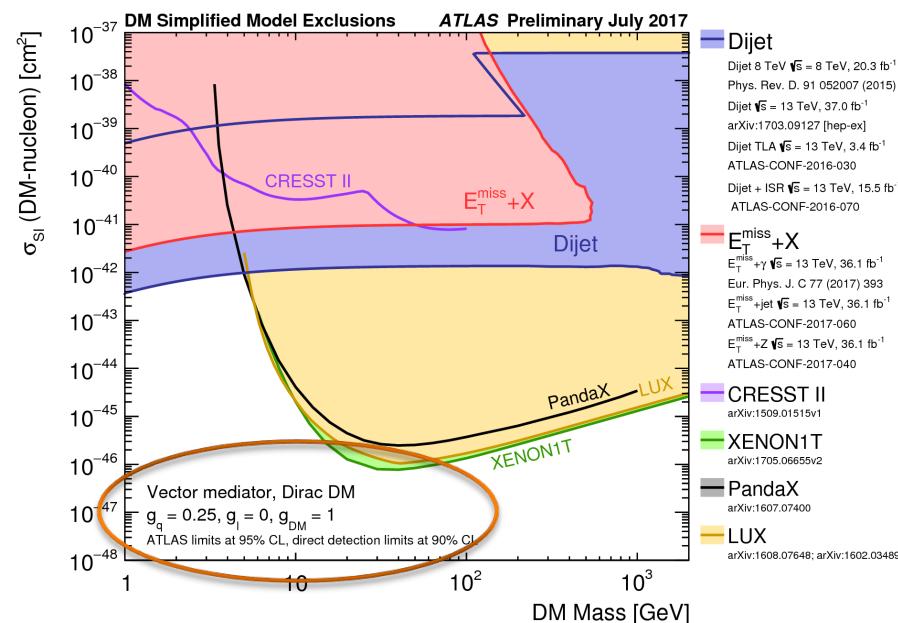
For pseudo-scalar mediator



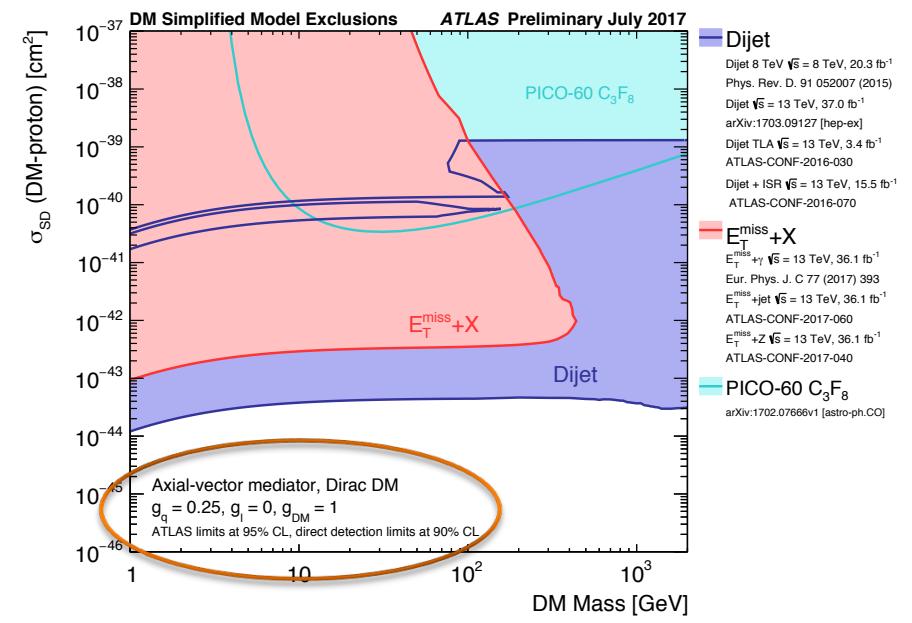
Comparison with DD experiments

95% C.L. upper limits obtained in the (M_X, M_{med}) plane
are translated to 90% CL upper limits to compare to DD experiments

Spin-independent σ_{SI} DM-nucleon
cross section vs DM mass



Spin-dependent σ_{SD} DM-nucleon
cross section vs DM mass



Exist also for $g_q = 0.1$, $g_l = 0.01$, and $g_{\text{DM}} = 1$

Complementarity between LHC and DD experiments

Under the model assumptions: (comparison is model dependent!)

- We are sensitive at low DM (~ 5 GeV) for σ_{SI} (DM-nucleon)
- We have about 3 orders of magnitude better sensitivity for σ_{SD} (DM-nucleon)

Hadronic Mono-top

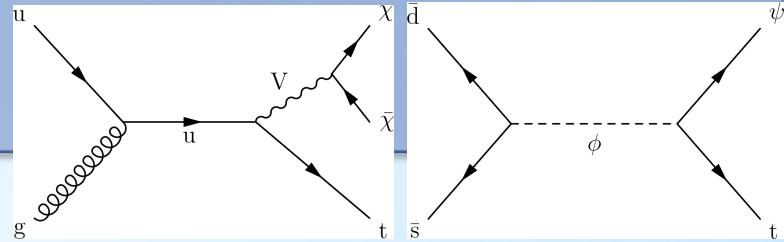
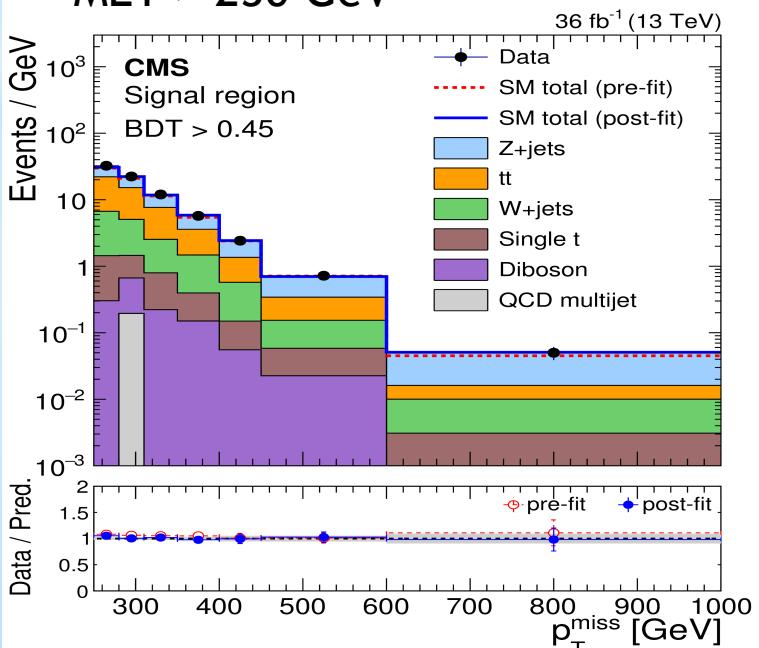
Extensions of simplified models:

DM recoils against a single top quark

- Flavor-changing simplified model or
- Colored charged scalar

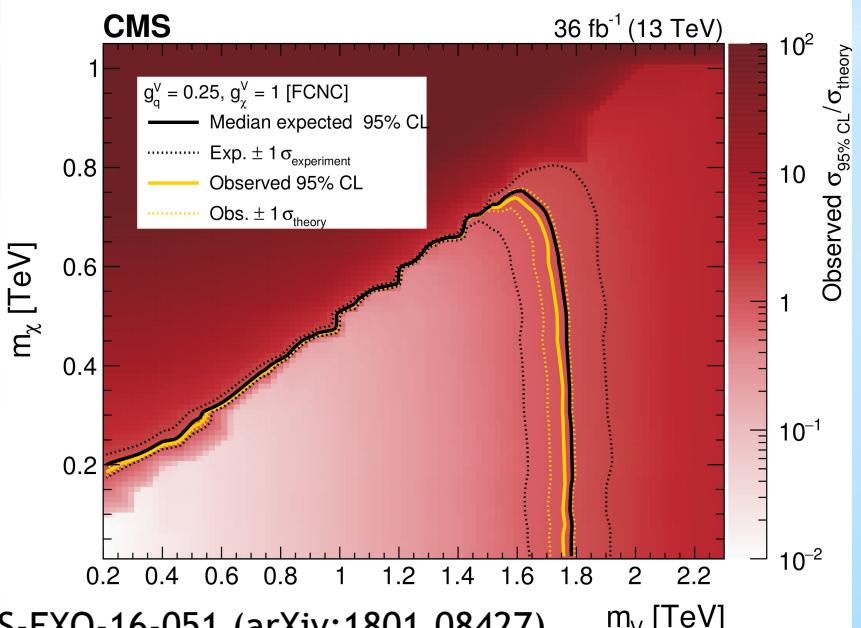
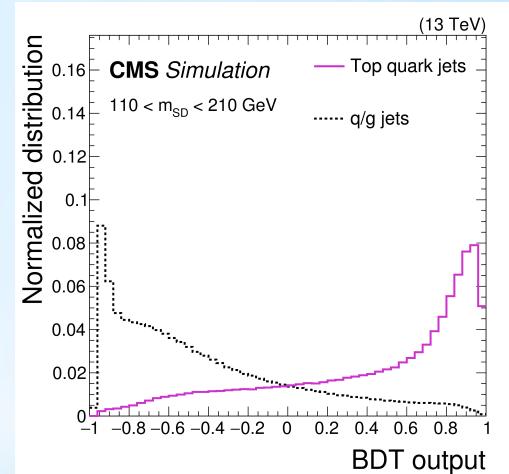
Final state - hadronically decaying boosted top quarks:

- N-subjettiness & top-tagger
- 1 b-subjet, CA15 jet $p_T > 250$ GeV
- $100 < m_j < 210$ GeV,
- MET > 250 GeV



BDT to discriminate
Top-jet to q/g jet

Extract signal
strength from fit
to MET in 2 BDT bins



Mono-Higgs searches

Extensions of the scalar models:

DM may interact with SM through H sector

Search for mono-Higgs with

$H \rightarrow bb$ and $H \rightarrow \gamma\gamma, \tau\tau$

Two benchmark models:

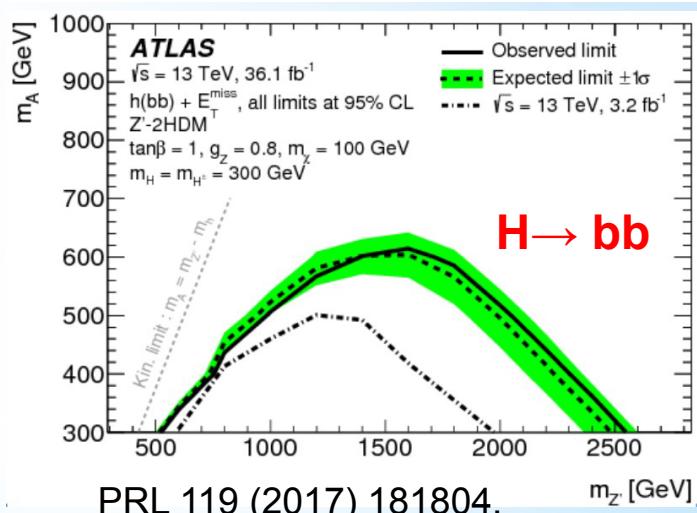
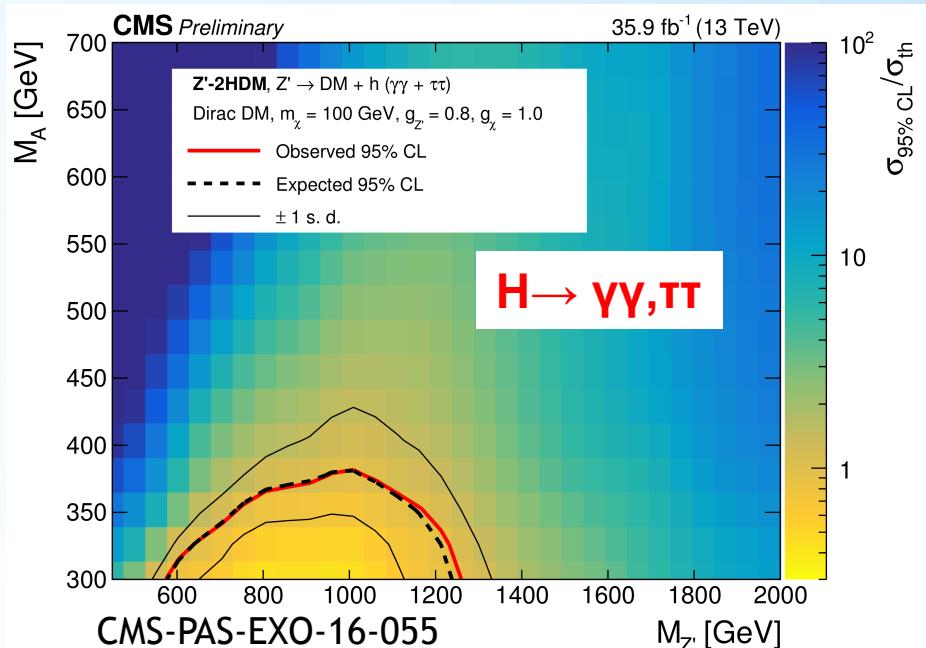
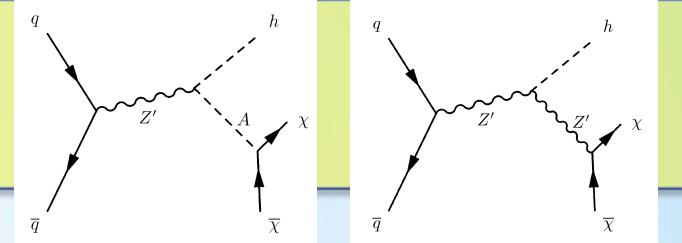
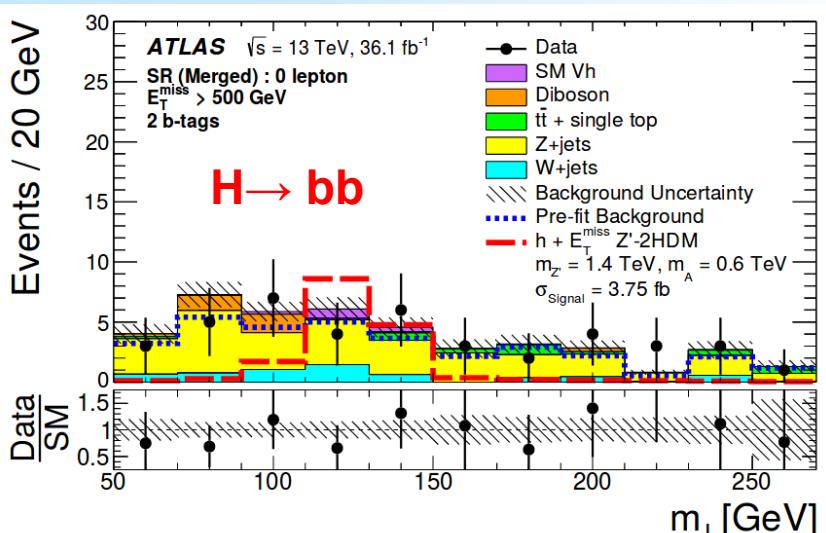
Z'-2HDM (resonant) & baryonic Z'

$H \rightarrow \gamma\gamma$: excellent mass resolution (<2%)

Use MET inside Higgs mass window

$H \rightarrow \tau\tau$: consider $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ final states

$H \rightarrow bb$: largest branching fraction (~60%)
but poor mass resolution (~10%)



Summary

Wide range of on-going DM searches at the LHC :

- Searches span a broad spectrum of final states and signal models
- This talk covered mainly the mono-X searches and the interpretation in terms of simplified models

Mono-jet (γ , Z) search excludes :

- Mediator mass up to 1.6-1.8 (1.2, 0.7) TeV
- DM mass up to 0.5 (0.3-0.5, ~0.2) TeV
for vector and axial-vector interactions
($g_x=1$ and $g_q=0.25$)

Using simplified models to interpret the data :

LHC searches complement DD experiments for DM mass < O(10) GeV

Strong LHC limits for spin-dependent DM-nucleon cross section

Summary

Results presented today :
Based on 2015 and 2016 data → 36 /fb

Many more data to analyze

2017 → 46 /fb

2018 → 60-80/fb expected

2016+2017+2018 → about 150 /fb expected

- Gain sensitivity to various searches
- Expected legacy papers on the full Run2 dataset

