Dark Sector & Dark Matter at LHC

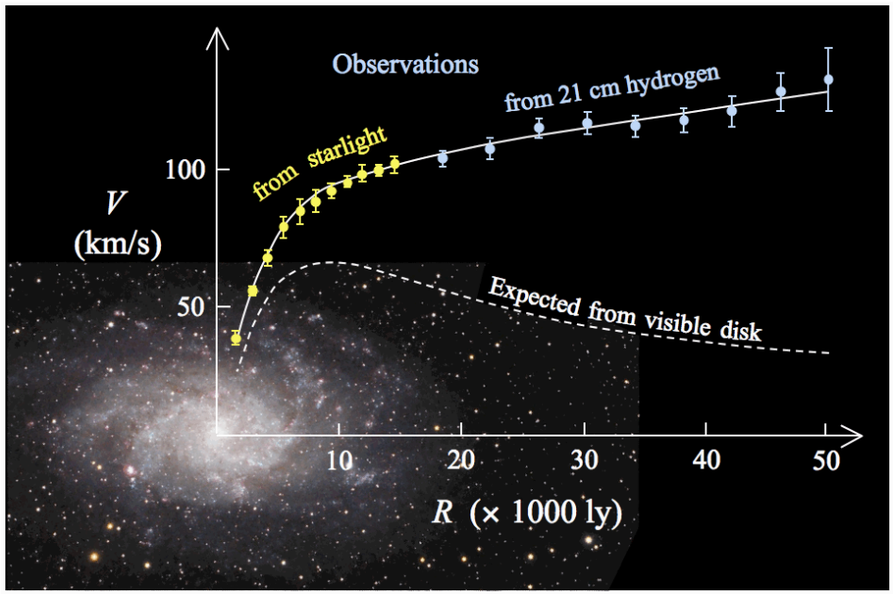
Adish Vartak [CERN]

On behalf of CMS, ATLAS & LHCb

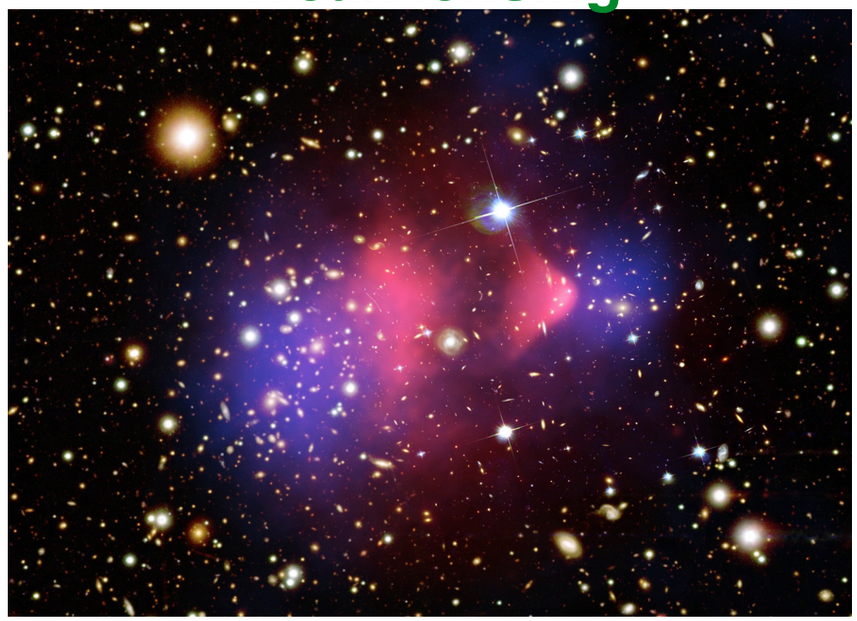
Dark Matter

Existence of dark matter known through its gravitational interactions

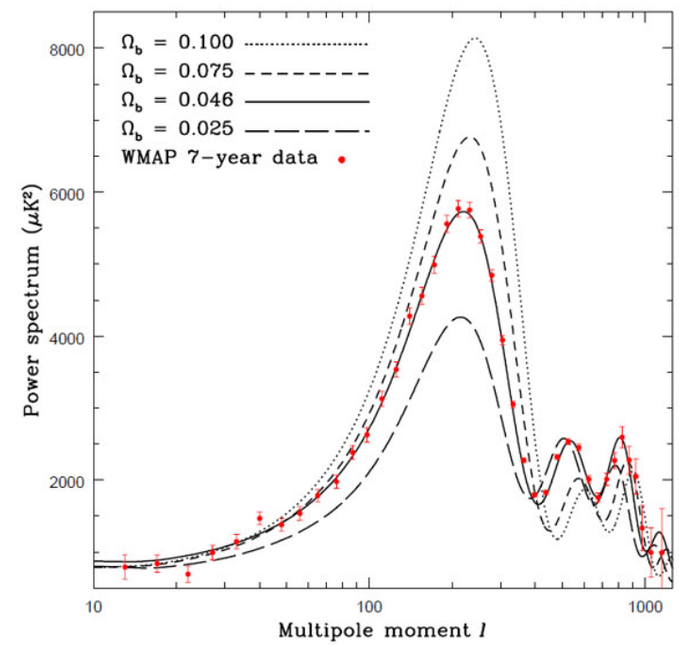
Galactic rotation



Weak lensing



CMB



But the underlying nature of dark matter (DM) remains unknown

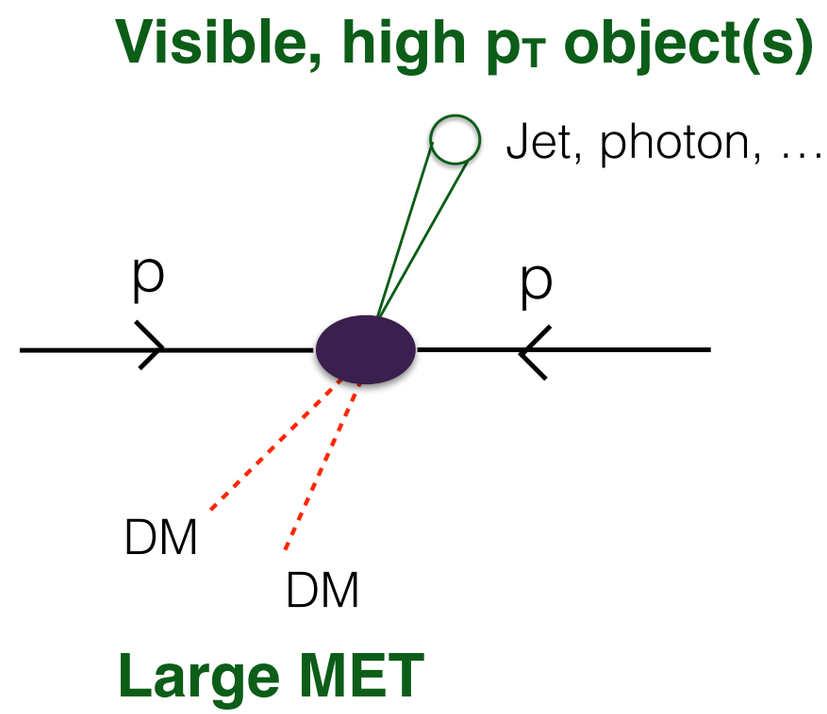
There is a well established case for weakly interacting DM particles (WIMPs)

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

DM Signatures @ LHC

MET+X Searches

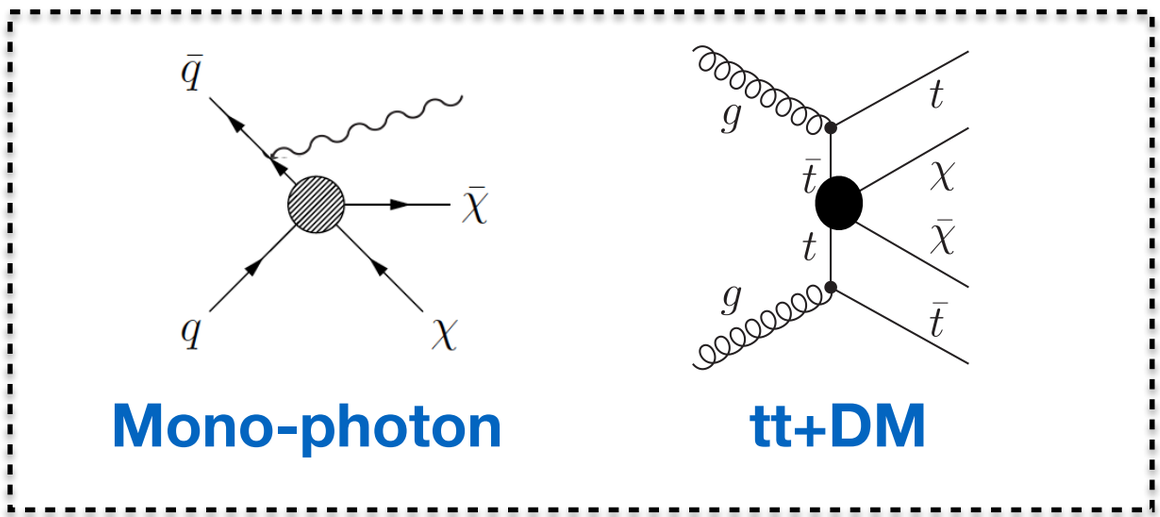
- DM particles would leave no trace in the detector
- But they may create a transverse momentum imbalance in the event (**MET**)
- To produce large MET, DM particles must recoil against some **high p_T, visible system "X"**



Wide range of possibilities for X

- X could be **gluon (jet), photon, W, Z, H, top, …**

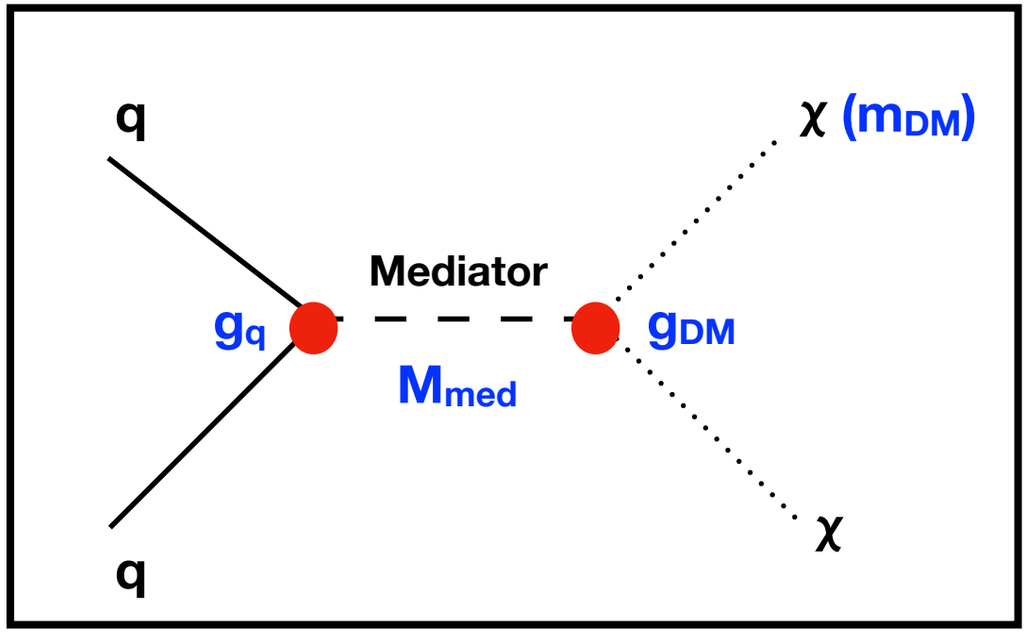
- ***This has led to a rich and diverse DM search program at the LHC***



Simplified Dark Matter Models

- Searches interpreted using generic ***'simplified models'***
- Assume **one pair of fermionic DM**, and a **massive boson** that mediates the interaction between DM and SM quarks

- **Parameters of the model :**
  - ➡ Spin/parity of the mediator
  - ➡ Mediator mass (M_{med})
  - ➡ DM mass (m_{DM})
  - ➡ Mediator coupling to quarks (g_q)
  - ➡ Mediator coupling to DM (g_{DM})

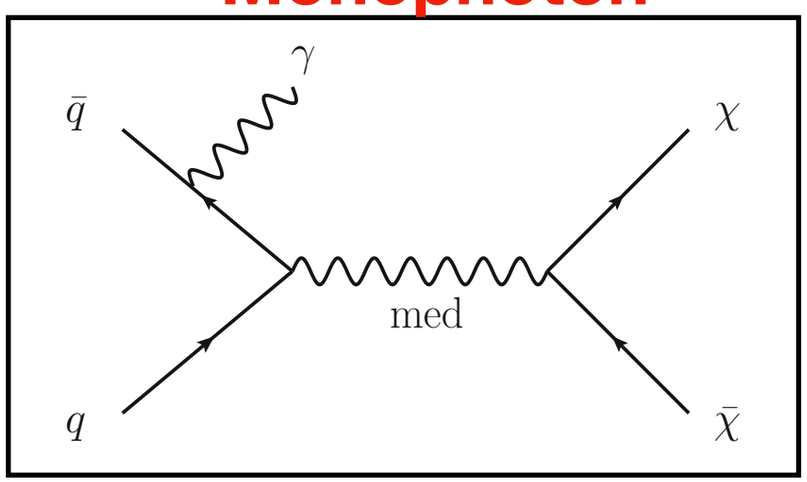


arXiv:1507.00966

Spin-1 Mediator

- Probed through several **ISR based MET+X searches**
- Look for MET + a high p_T photon, Z or jet

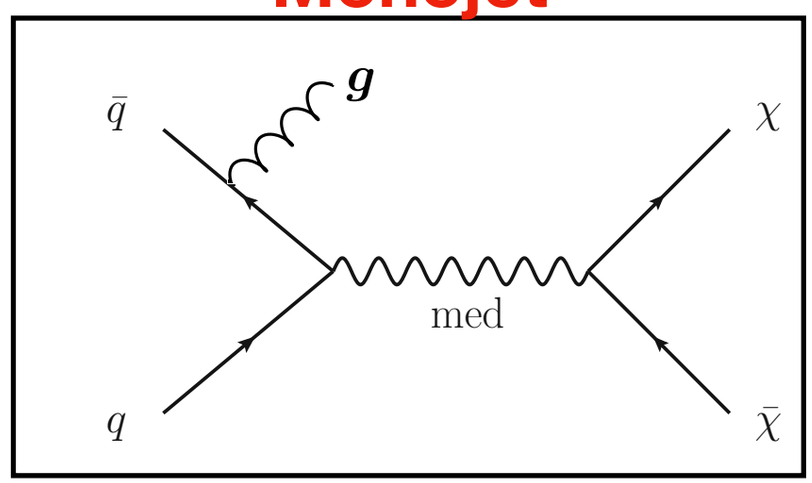
Monophoton



ATLAS (36 fb^{-1}) :
- EPJC 77 (2017) 393

CMS (12.9 fb^{-1}) :
- JHEP 10 (2017) 073

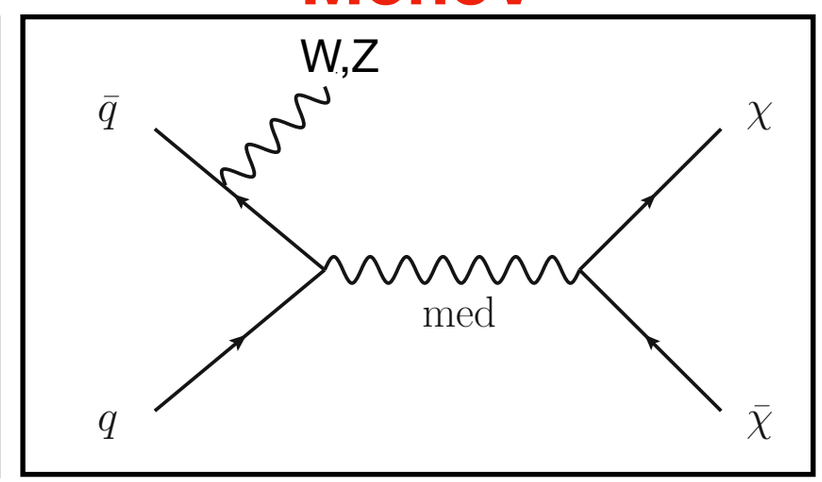
Monojet



ATLAS (36 fb^{-1}) :
- JHEP 01 (2018) 126

CMS Monojet (36 fb^{-1}) :
- PRD 97 (2018) 092005

MonoV



ATLAS Mono-Z(ll) (36 fb^{-1}) :
- PLB 776 (2017), 318

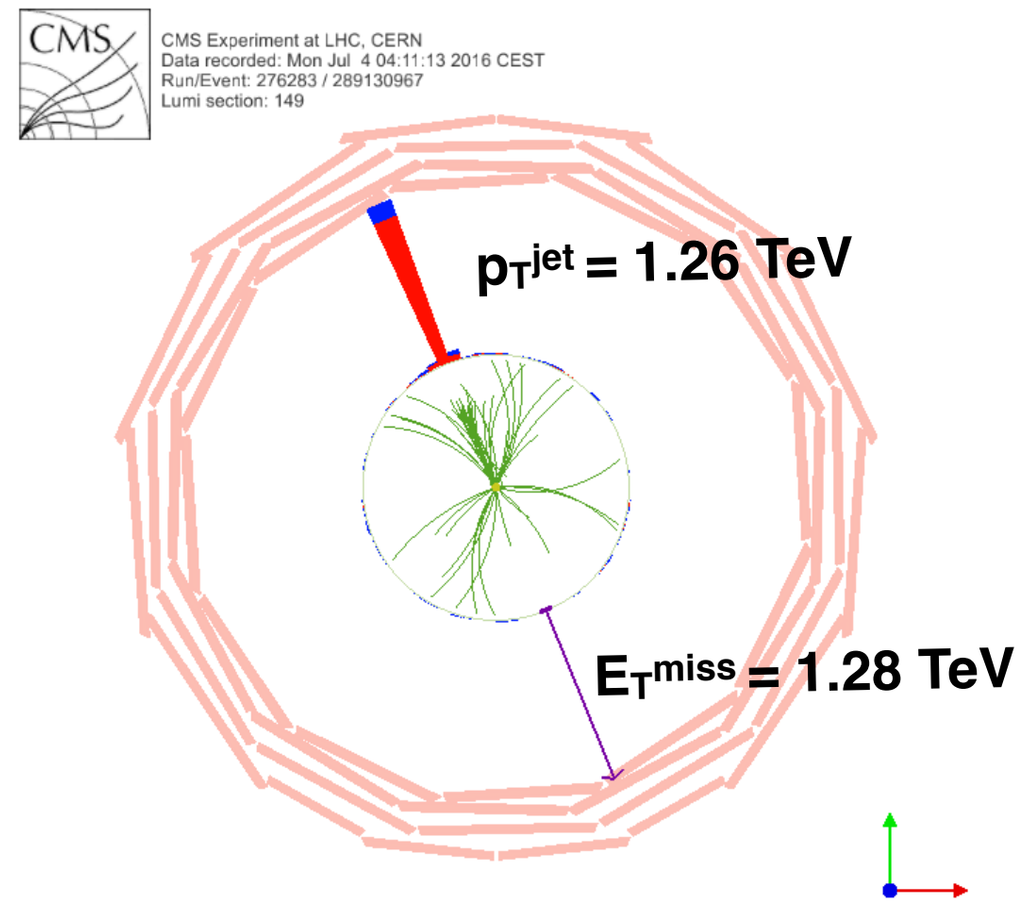
ATLAS Mono-V(had) (36 fb^{-1}) :
- ATLAS-CONF-2018-005

CMS Mono-Z(ll) (36 fb^{-1}) :
- EPJC 78 (2018) 291

CMS Mono-V(had) (36 fb^{-1}) :
- PRD 97 (2018) 092005

Monojet Search

Large 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)
  - ➡ $|\eta| < 2.4$
- Veto on events with leptons
  - ➡ Suppress backgrounds with genuine MET : W+jets, top

Main backgrounds

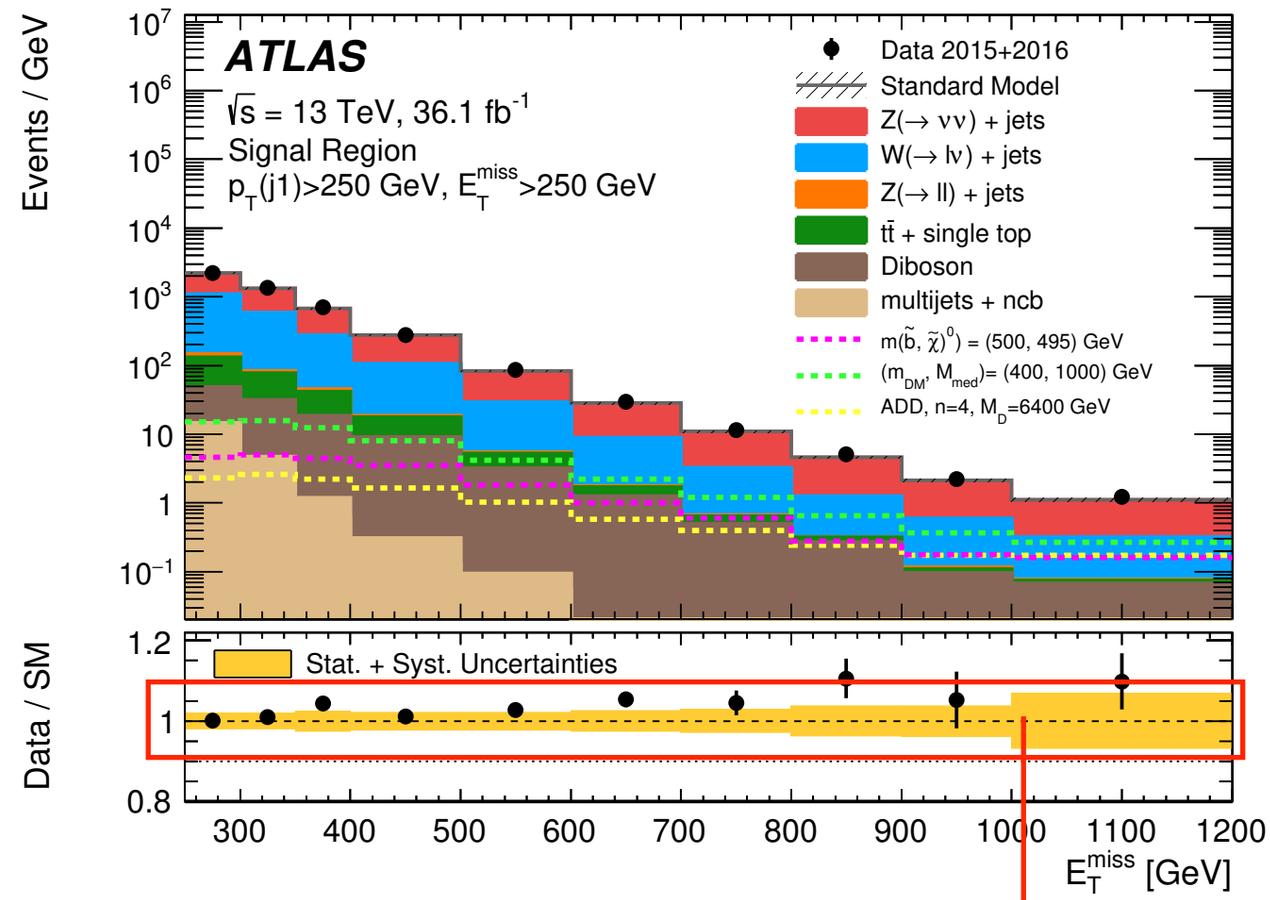
- ➡ Z(νν)+jets (~ 60%)
- ➡ W(lν)+jets where lepton is lost (~30%)
- ➡ Minor bkg : Top, dibosons, etc.

Monojet Analysis Strategy

- Signal has no mass peak or kinematic end-points (e.g. m_T)
- Use MET shape to extract signal
  - ➡ Signal has harder MET spectrum w.r.t. bkg
- **Need to precisely model the Z+jets, W+jets p_T spectrum**
- Multiple control regions in data constrain electroweak backgrounds
  - ➡ Z(ll)+jets events
  - ➡ W(lν)+jets
  - ➡ And γ+jets (in case of CMS)

***Lindert et al* EPJC 77, 829 (2017)**

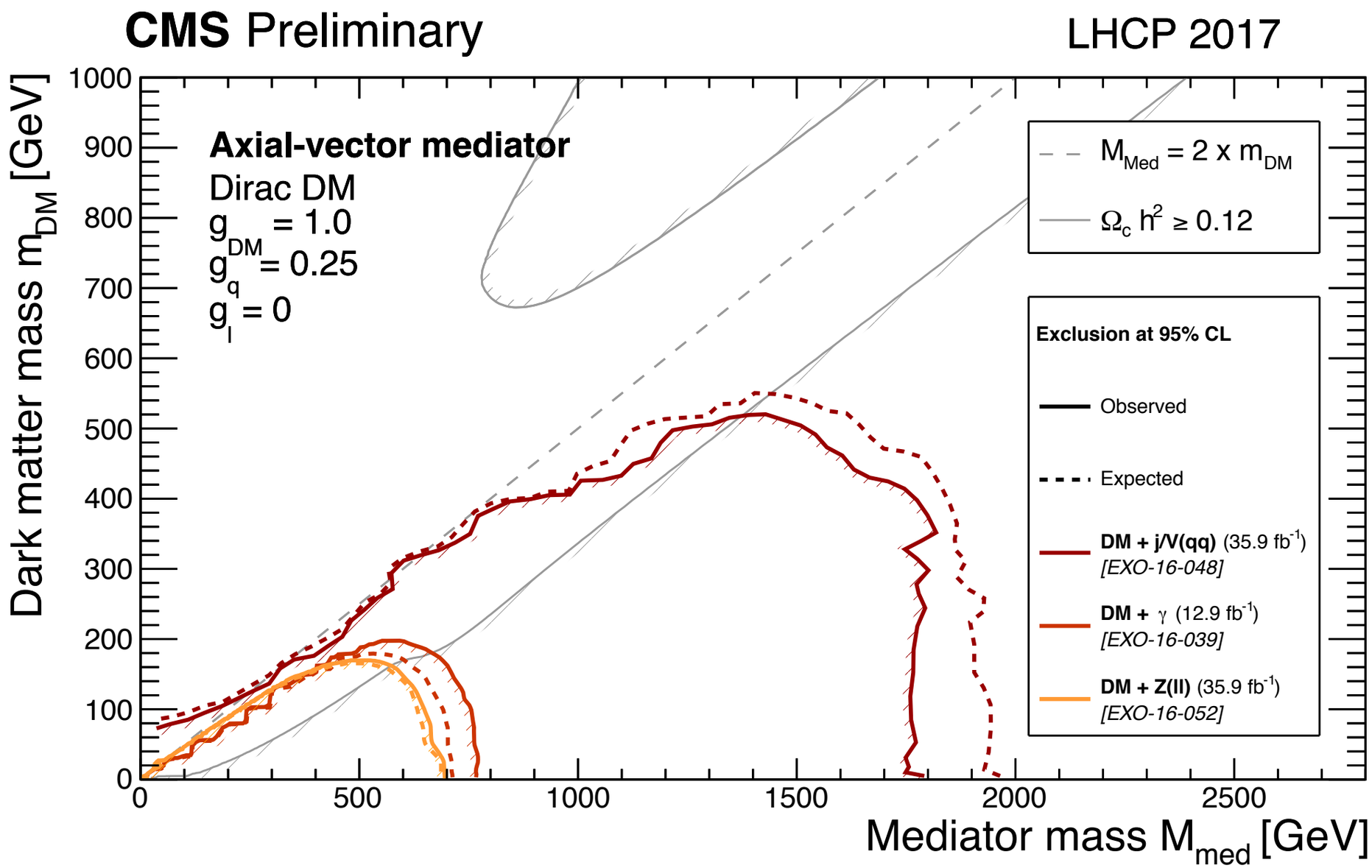
ATLAS : JHEP 01 (2018) 126



Background uncertainty constrained to

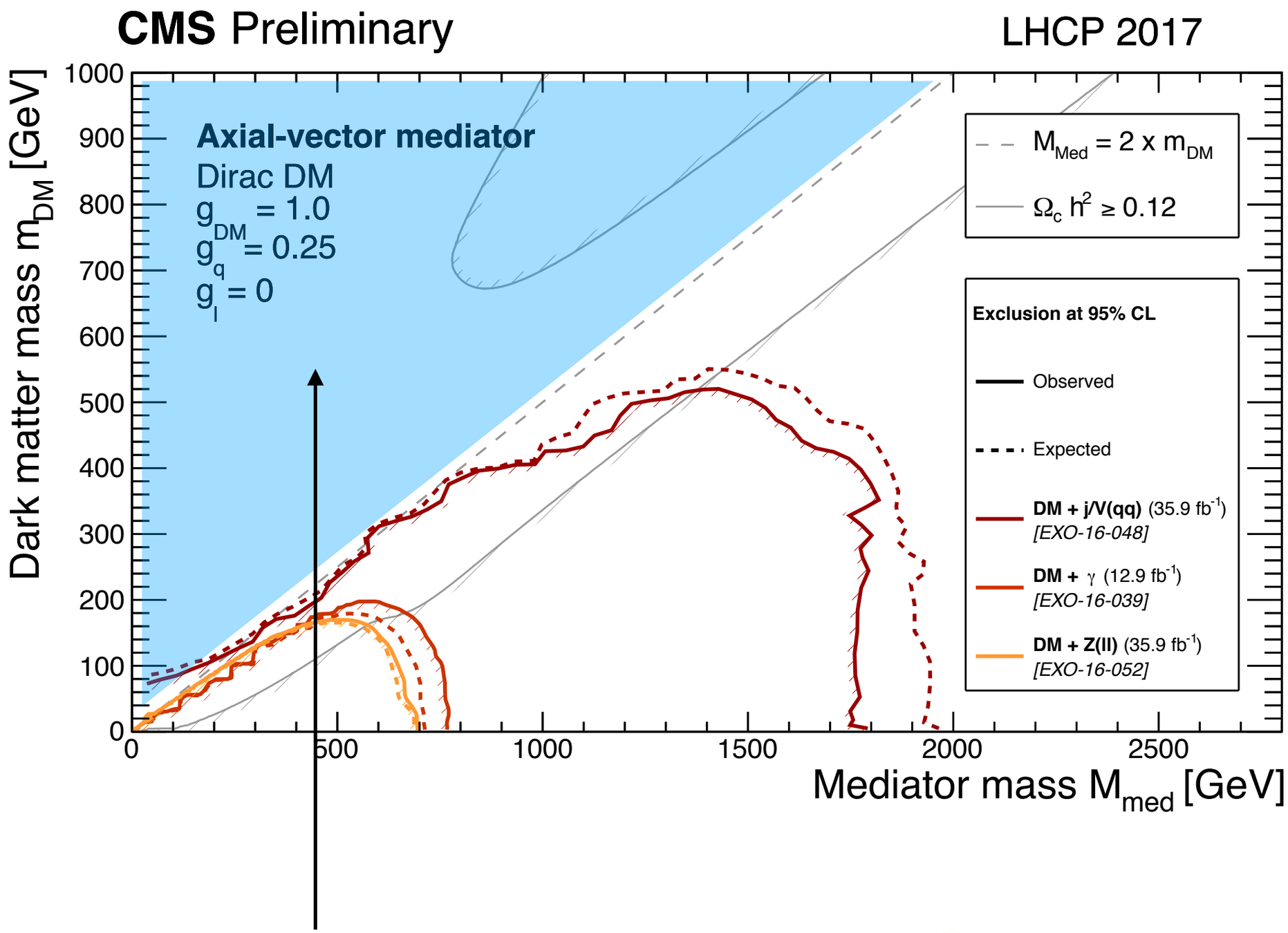
- **About 2% at MET ~ 250 GeV**
- **About 10% at MET ~ 1 TeV**
- *Similar for both ATLAS and CMS*

Limits for Spin-1 Mediator



Axial vector mediator masses up to 1.8 TeV excluded
Similar results for the vector mediator

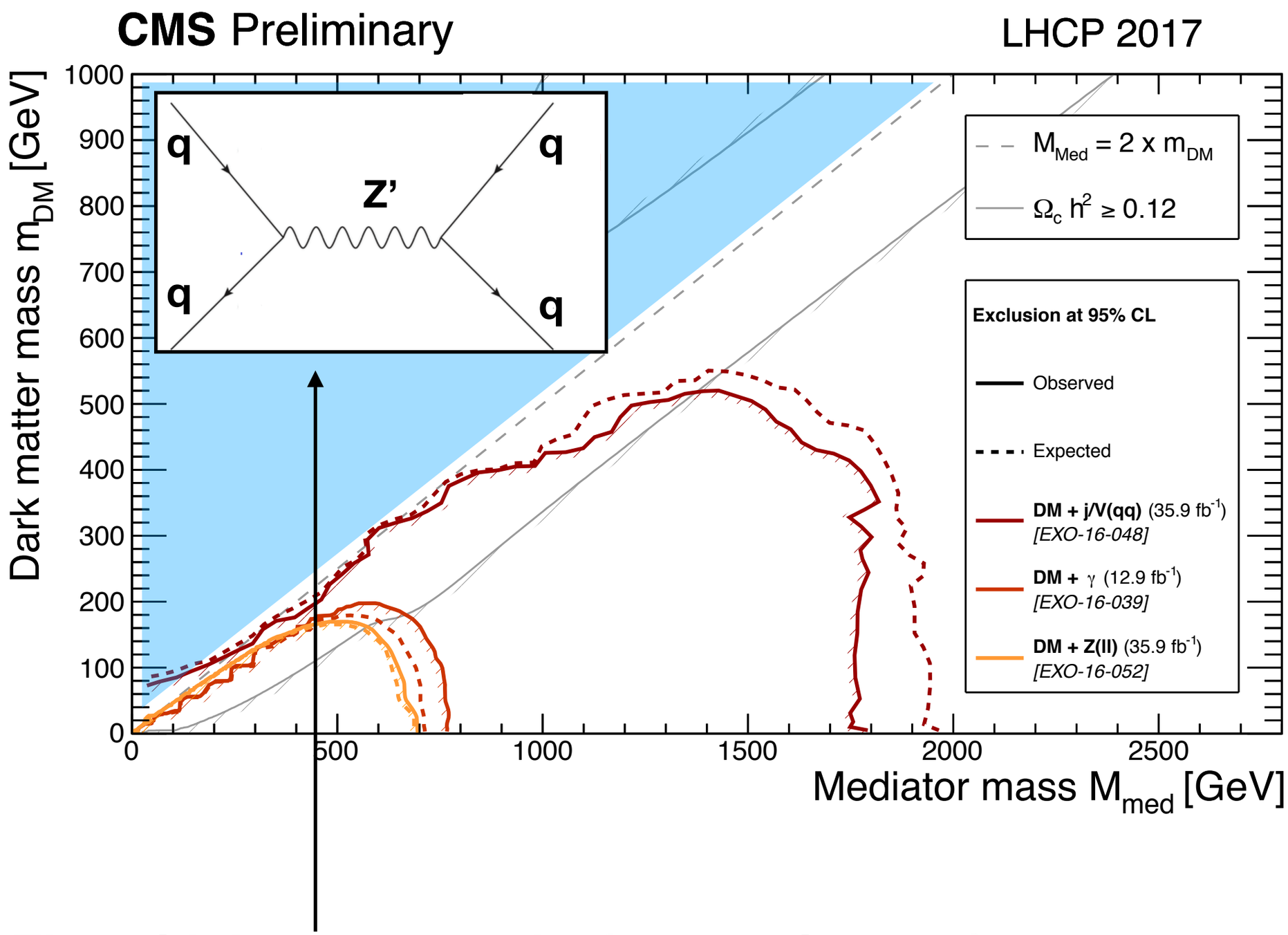
Limits for Spin-1 Mediator



MonoX searches not sensitive to the off-shell region ($M_{med} < 2\ m_{DM}$)

- Cross section is heavily suppressed

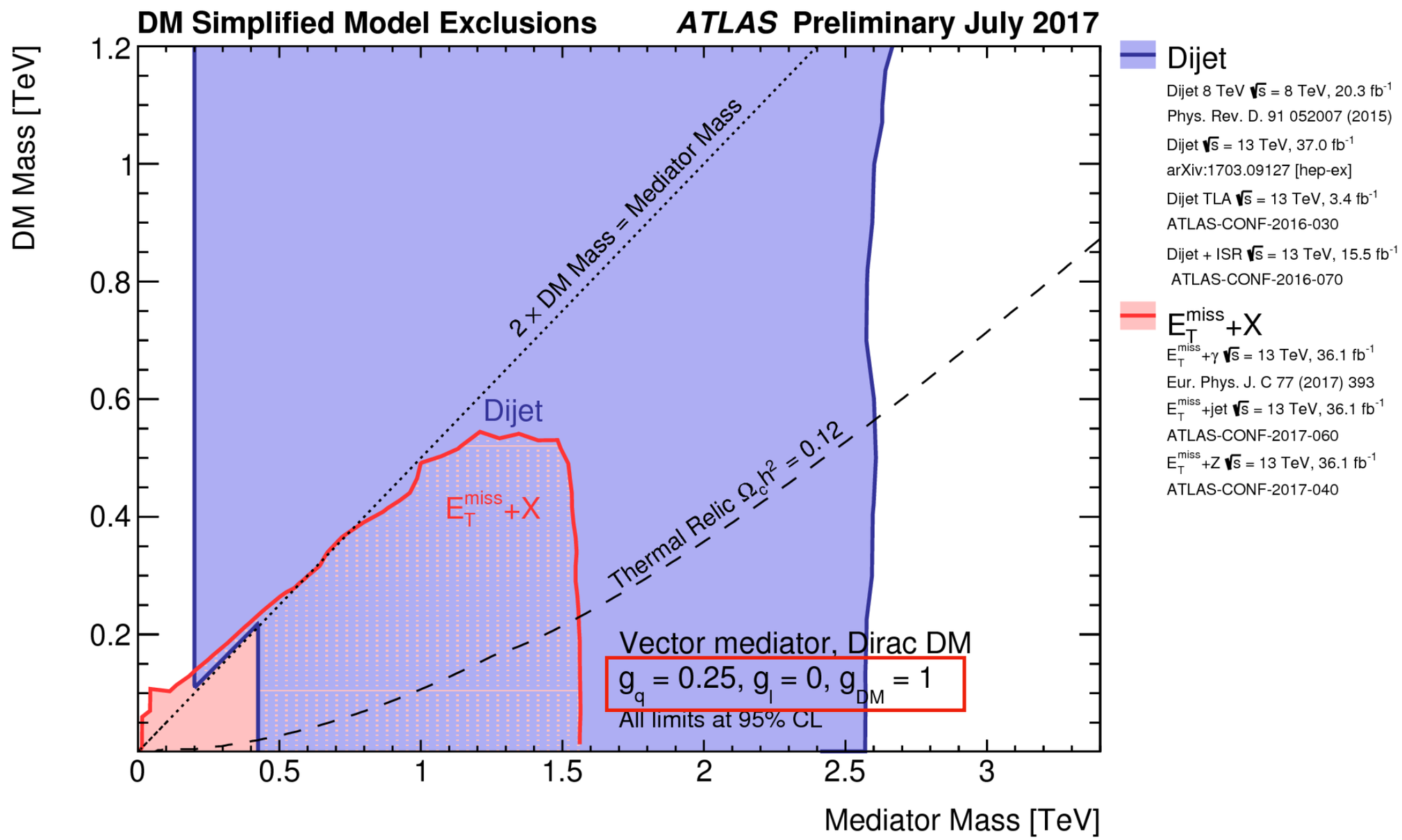
Limits for Spin-1 Mediator



But Z' could decay to quarks (or even leptons)

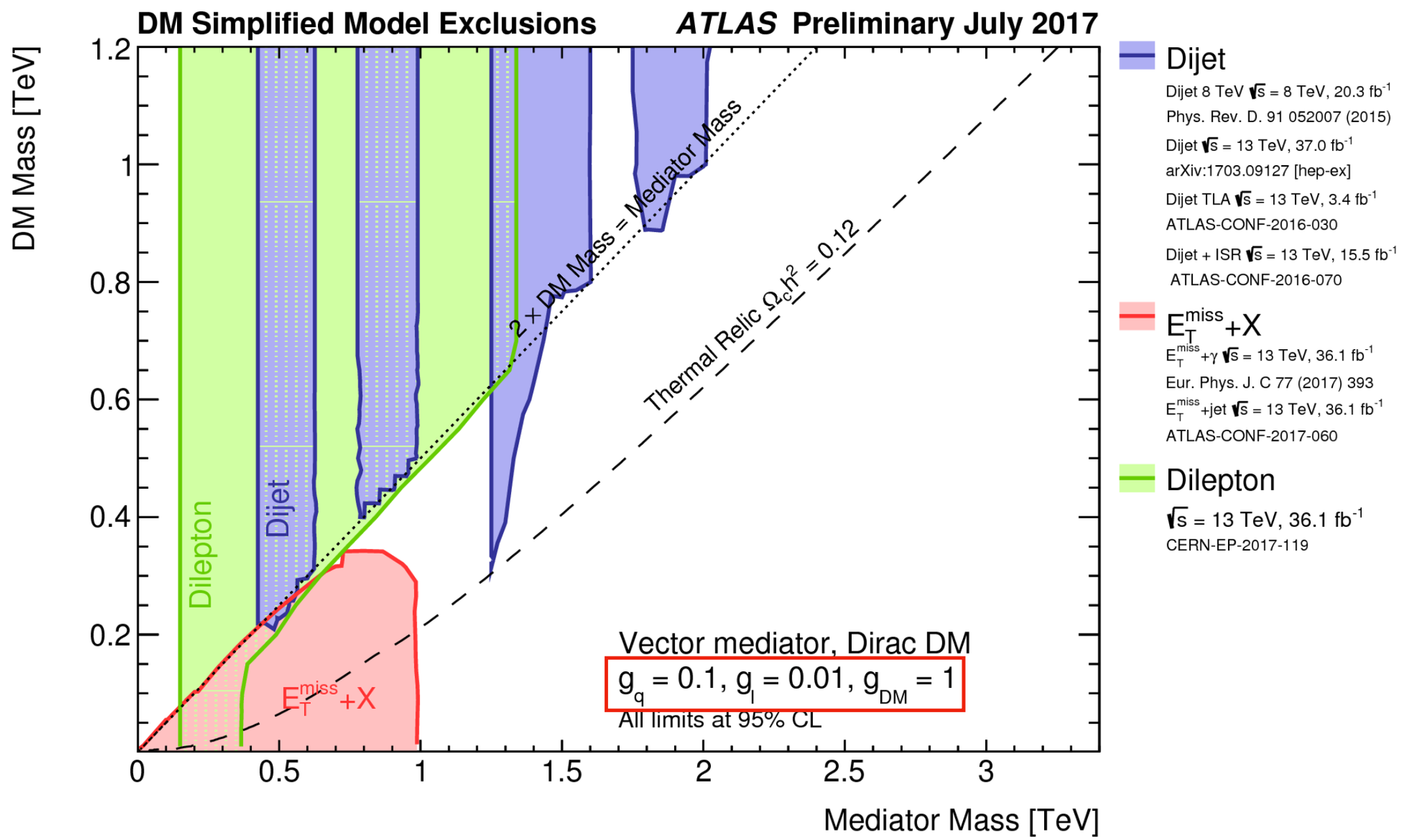
- *Derive constraints from searches looking for visible Z' decays*

Limits for Spin-1 Mediator



Constraints on Z' from visible and invisible decays

Limits for Spin-1 Mediator

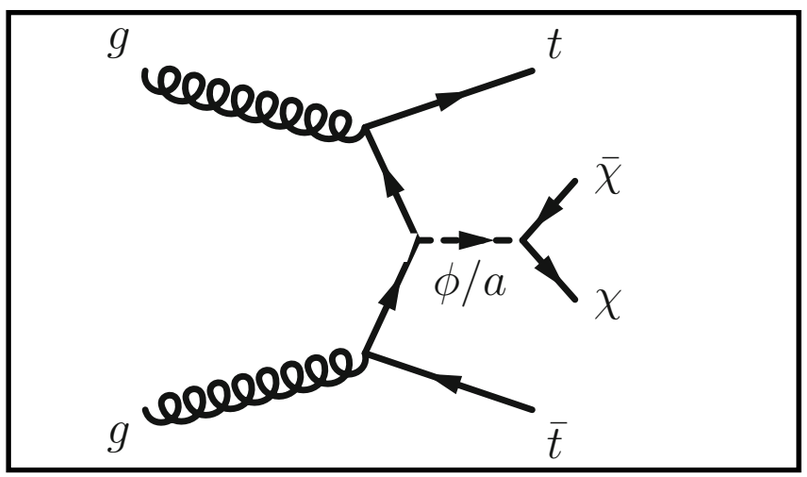


Constraints on Z' from visible and invisible decays

Spin-0 Mediator

- Interaction between spin-0 mediator and quarks required to have the SM Yukawa structure (Minimal Flavor Violation)
- Coupling to quarks proportional to the quark mass (like the SM Higgs boson)
- **Spin-0 mediator couples preferentially to the top quark**

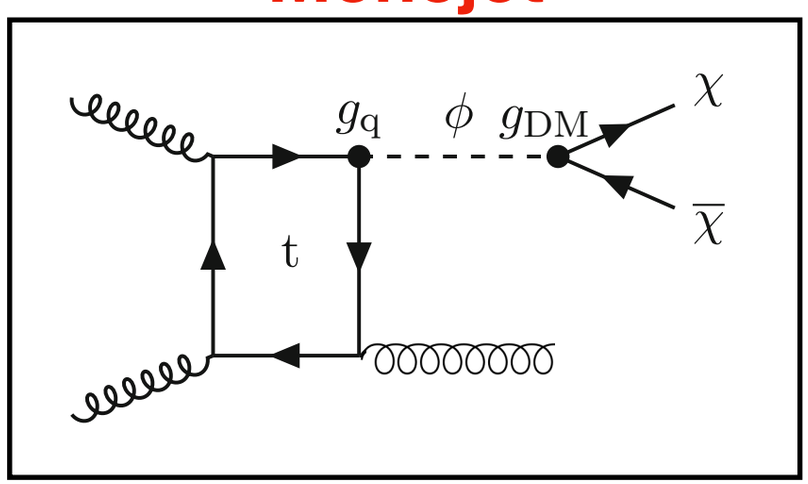
tt+DM



ATLAS :
- arXiv:1711.11520
- EPJC (2018) 78:18

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

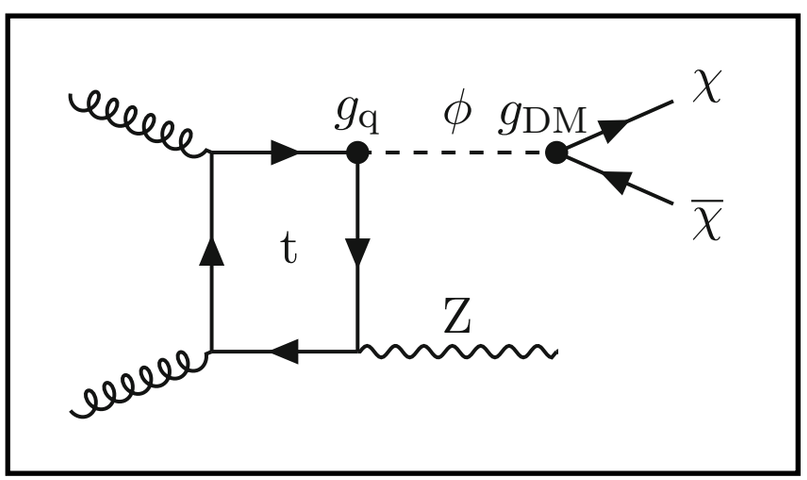
Monojet



ATLAS :
- JHEP 01 (2018) 126

CMS :
- PRD 97 (2018) 092005

Mono-Z



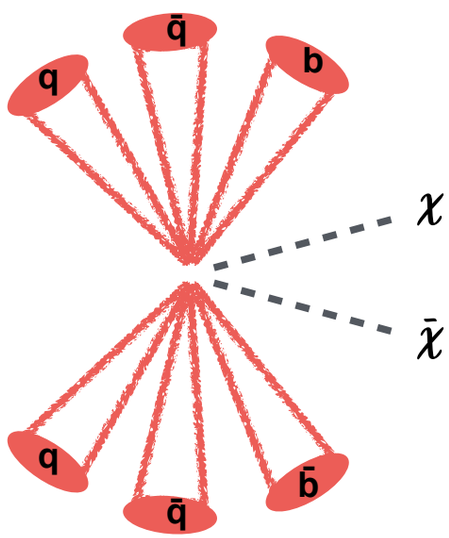
CMS Mono-Z(ll) :
- EPJC 78 (2018) 291

CMS Mono-V(had) :
- PRD 97 (2018) 092005

CMS tt+DM Search

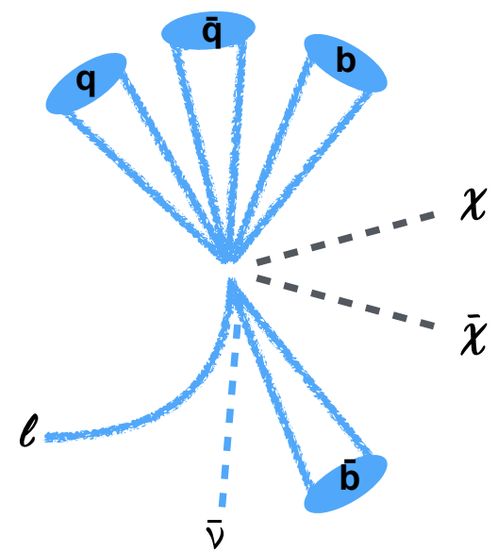
Combination of three final states

$t\bar{t}$(0l)+DM



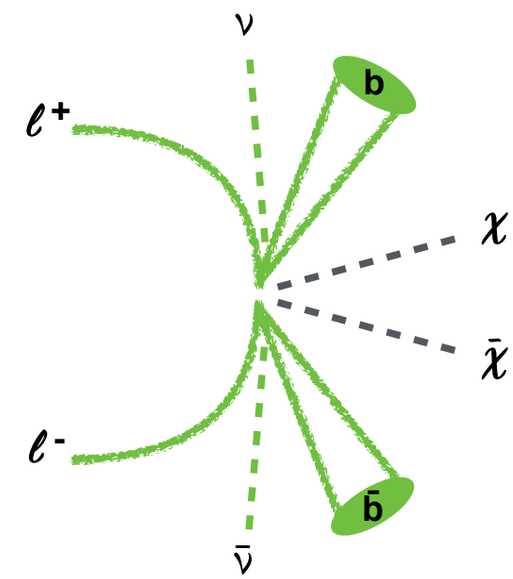
+

$t\bar{t}$(1l)+DM



+

$t\bar{t}$(2l)+DM



- MET > 200 GeV
- At least 4 jets,1 b-jet
- **Main bkg : tt(1l) where lepton is lost**

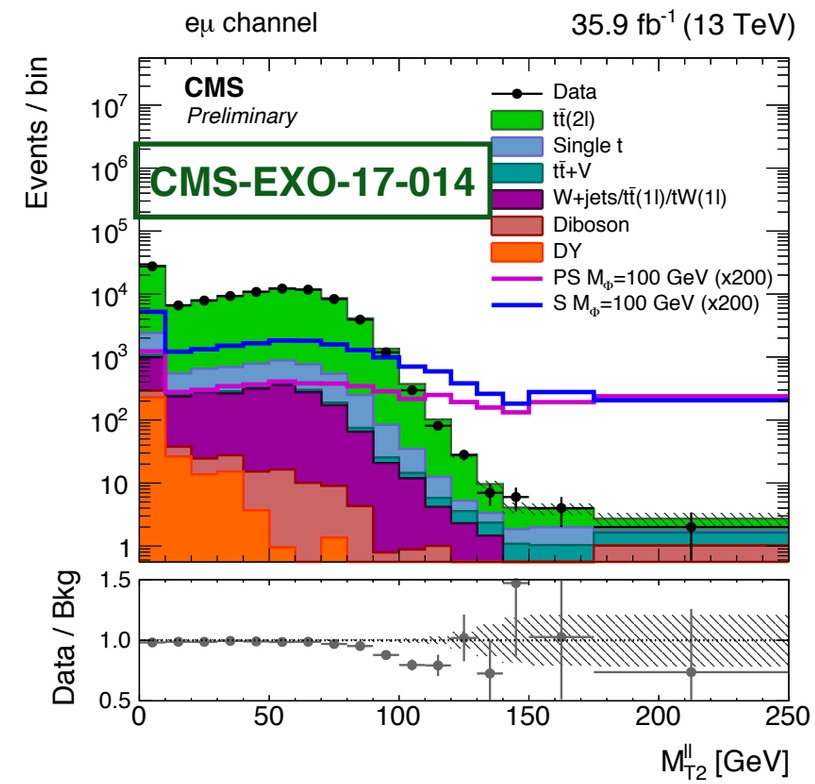
- MET > 160 GeV, m_T>160 GeV
- At least 3 jets,1 b-jet
- **Main bkg : tt(2l) where one lepton is lost**

- MET > 50 GeV
- At least 2 jets, 1 b-jet
- **Main bkg : tt(2l) irreducible**

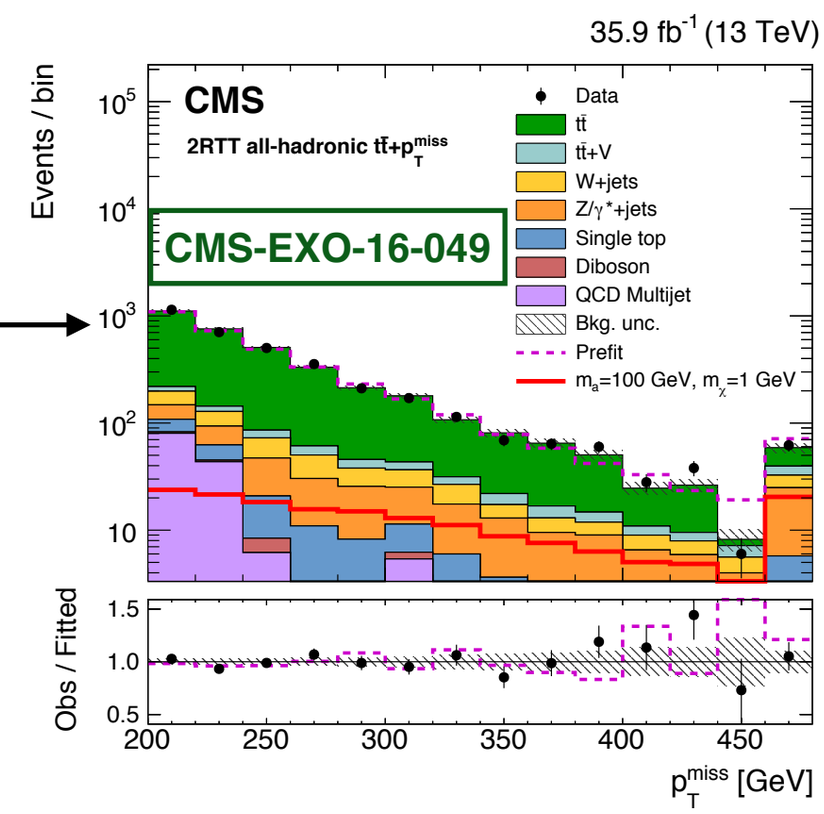
MET contribution also from neutrinos

tt+DM Analysis Strategy

- Suppress top background in each channel using dedicated discriminating variables
- **Resolved top tagger (RTT)** in **0-lep** channel
  - Identify jet triplets from top decays
  - Two event categories : 0/1 & 2 RTT
- **Stransverse mass variables M_{T2}^{W} and $M_{T2}(ll)$** used in **1-lep** and **2-lep** channels



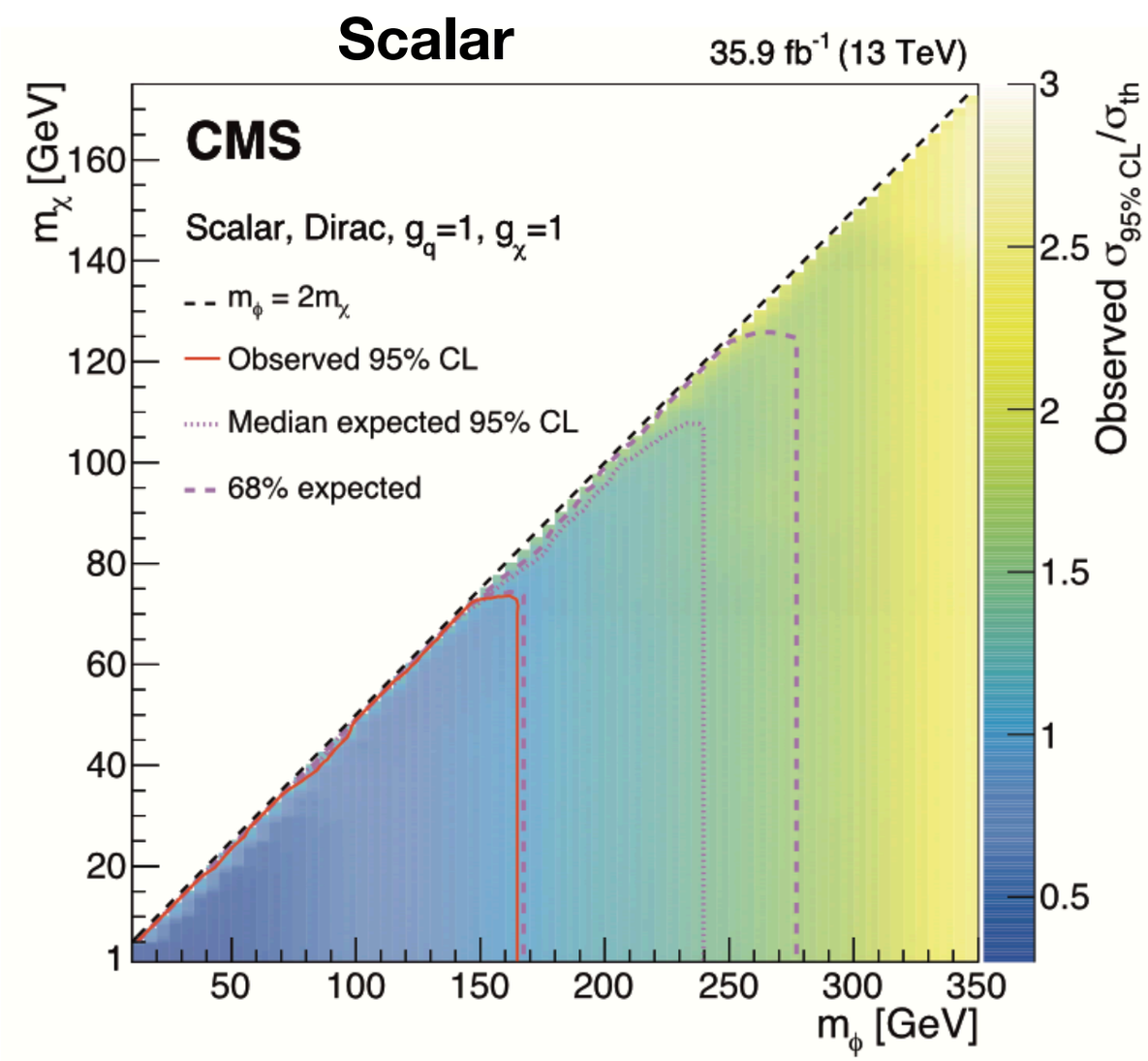
- Fit the MET distribution in data to extract signal
- Dedicated control regions used to constrain W, Z, top backgrounds

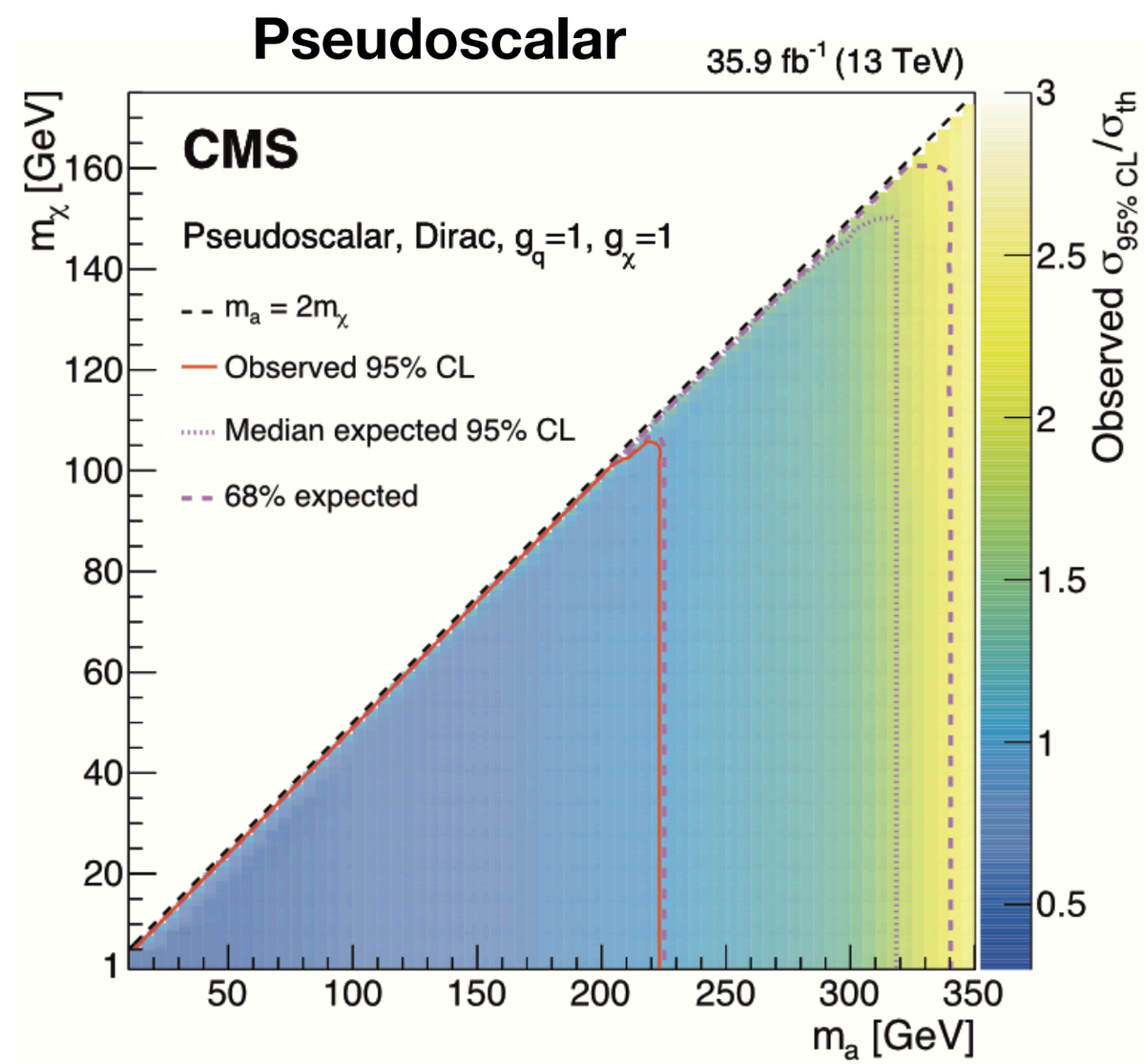


tt+DM Results

Combined results of the 3 channels

CMS-EXO-16-049





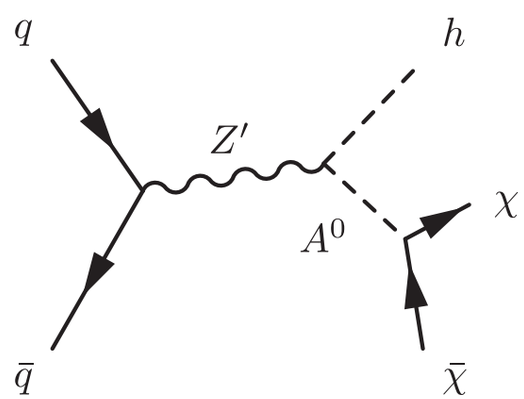
Masses up to 160 GeV excluded

Masses up to 220 GeV excluded

DM + X→had

DM produced with hadronically decaying heavy boson

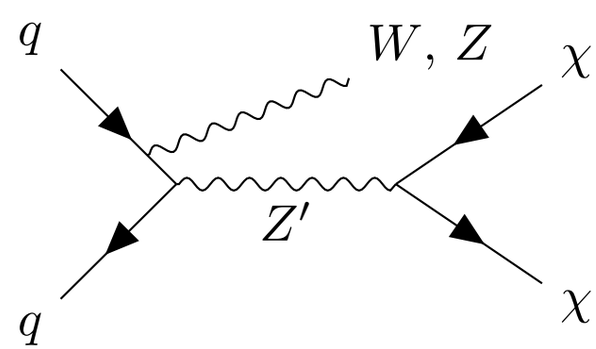
Mono-H(bb)



ATLAS (H→bb):
- PRL 119, 181804 (2017)

CMS (H→bb) :
- CMS-B2G-17-004

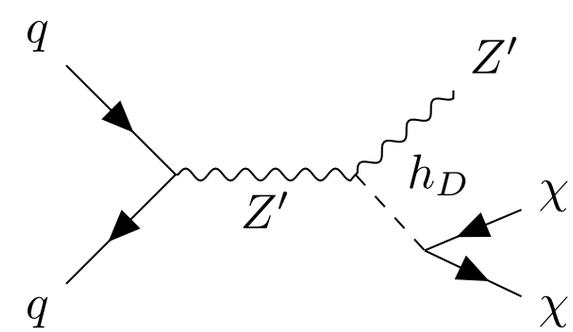
Mono-V(qq)



ATLAS :
- ATLAS-CONF-2018-005

CMS :
- PRD 97 (2018) 092005

Mono-Z'(qq)



ATLAS :
- ATLAS-CONF-2018-005

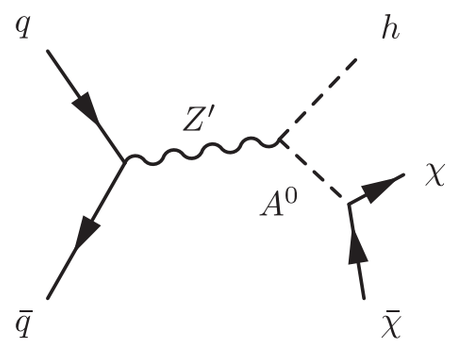
- Look for events with large MET (~200 GeV), and
- Hadronic decays of X(=H, V, Z') into two resolved jets or a single fat-jet
- Use jet substructure techniques to identify 2-prongs in a fat jet

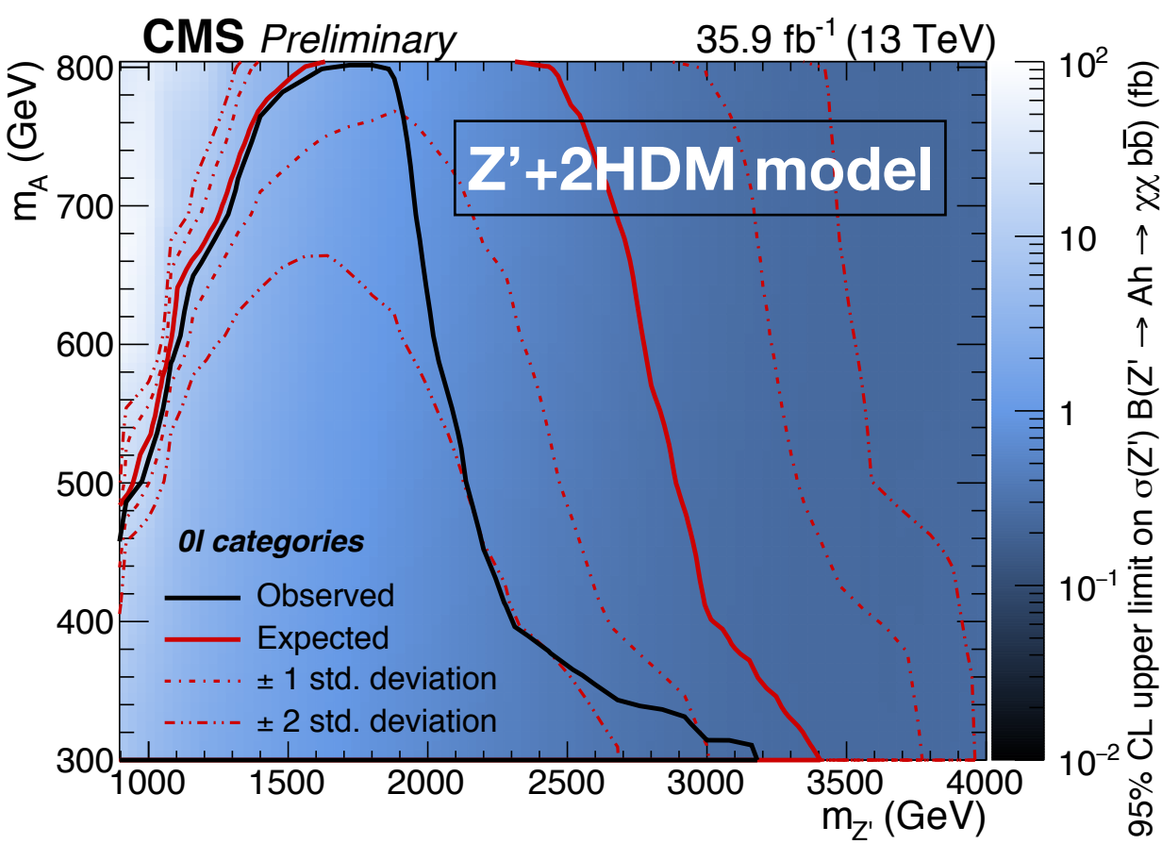
DM + X→had

DM produced with hadronically decaying heavy boson

Mono-H(bb)

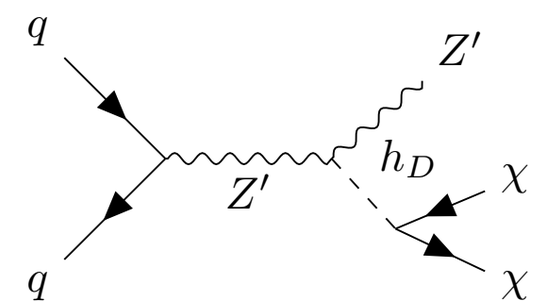
CMS-B2G-17-004

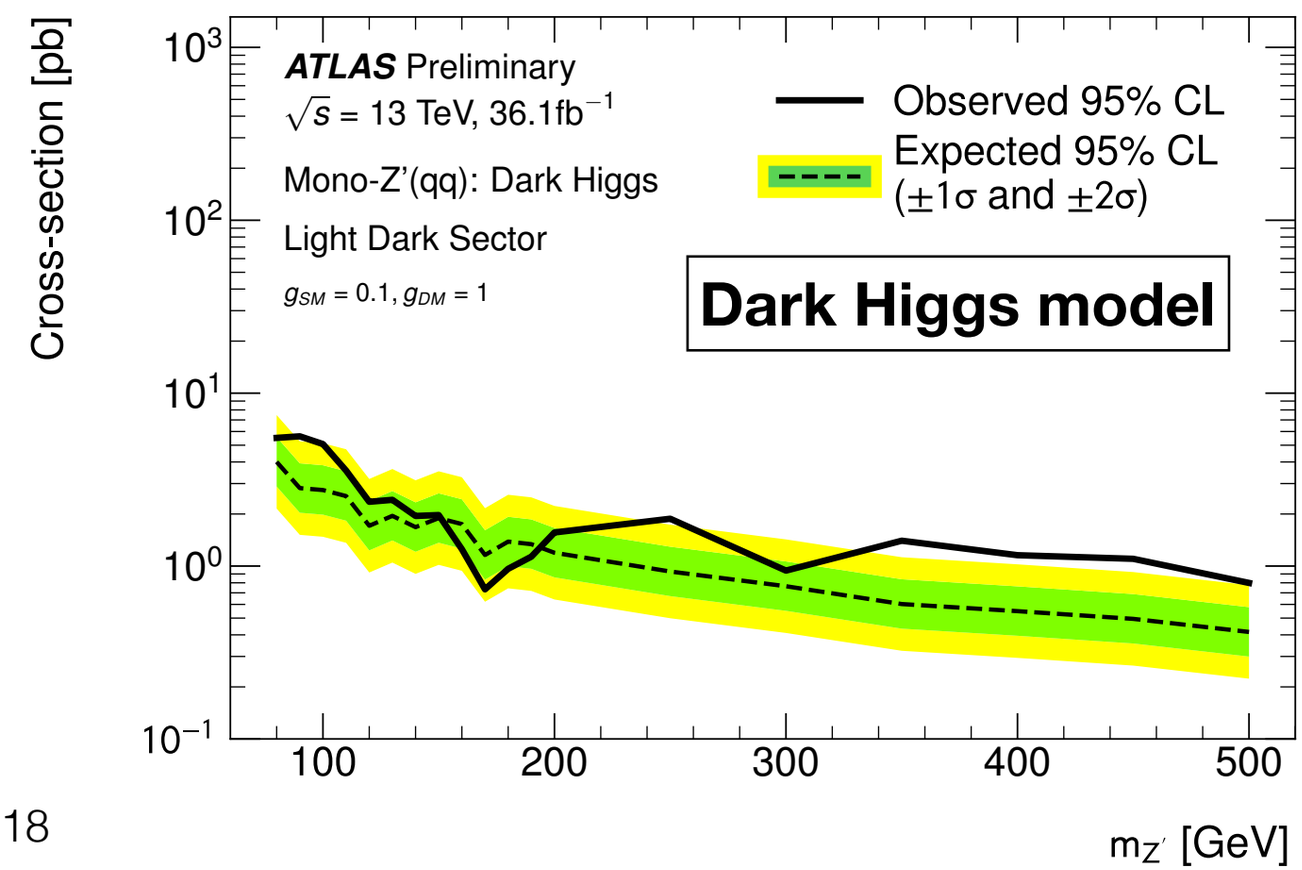




Mono-Z'(qq)

ATLAS-CONF-2018-005

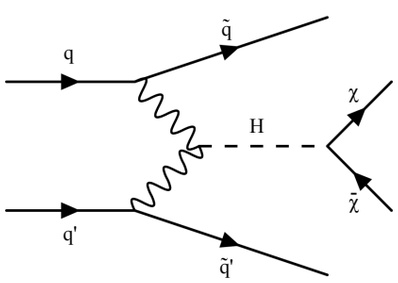




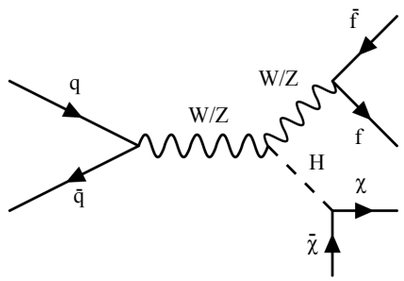
Higgs Portal to the Dark Sector

- We still don't know a lot about the 125 GeV Higgs boson
- Limit on BR(H→BSM) is 34% (Run-1 Higgs measurements : JHEP 08 (2016) 045)
- Plenty of room for the Higgs boson to couple to a new hidden, dark sector

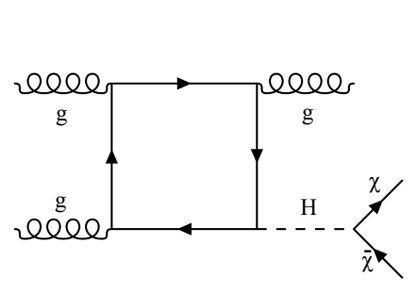
H decay to invisible particles



VBF+MET



Mono-V



Monojet

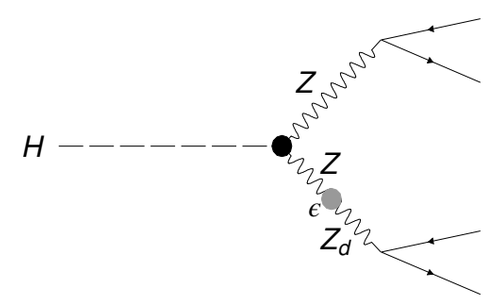
CMS 13 TeV H→inv combination : CMS-HIG-17-023

ATLAS 8 TeV H→inv combination : JHEP11 (2015) 206

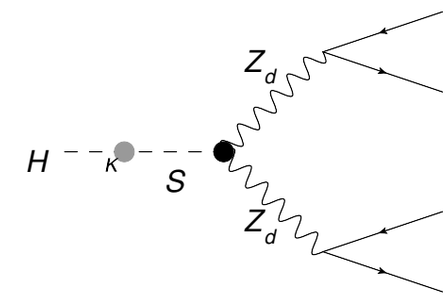
ATLAS 13 TeV

- **Mono-Z(ll) : EPJC 78 (2018) 291**
- **Mono-V(qq) : ATLAS-CONF-2018-005**

H decay to dark photons



H→Z Z_d



H→ Z_d Z_d

ATLAS-CONF-2018-005 (Submitted to JHEP)

VBF H→Invisible

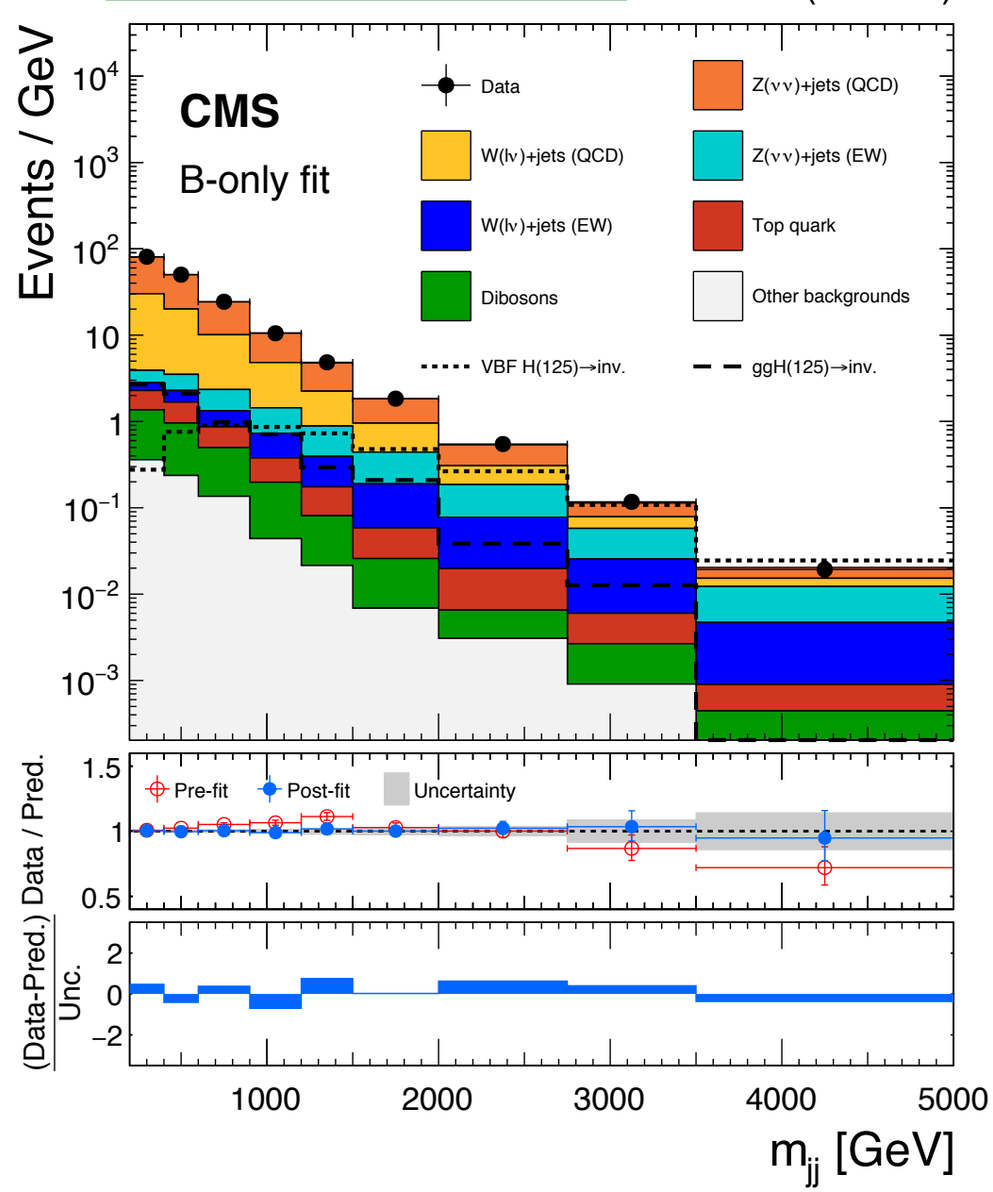
Most sensitive channel to look for H→inv

- **VBF signature:** two jets with large η-gap & dijet mass
- Start with some loose VBF requirements on two leading jets
  - ➡ $|\Delta\eta_{jj}| > 1.0$ $|\Delta\phi_{jj}| < 1.5$
  - ➡ $m_{jj} > 200$ GeV
  - ➡ $p_T(j_1) > 80$ GeV, $p_T(j_2) > 40$ GeV
- Require large MET > 250 GeV
- Lepton veto to suppress W+jets, top bkg.

Main backgrounds : Z(vv)+jets, W(ℓv)+jets

Fit to the dijet mass spectrum

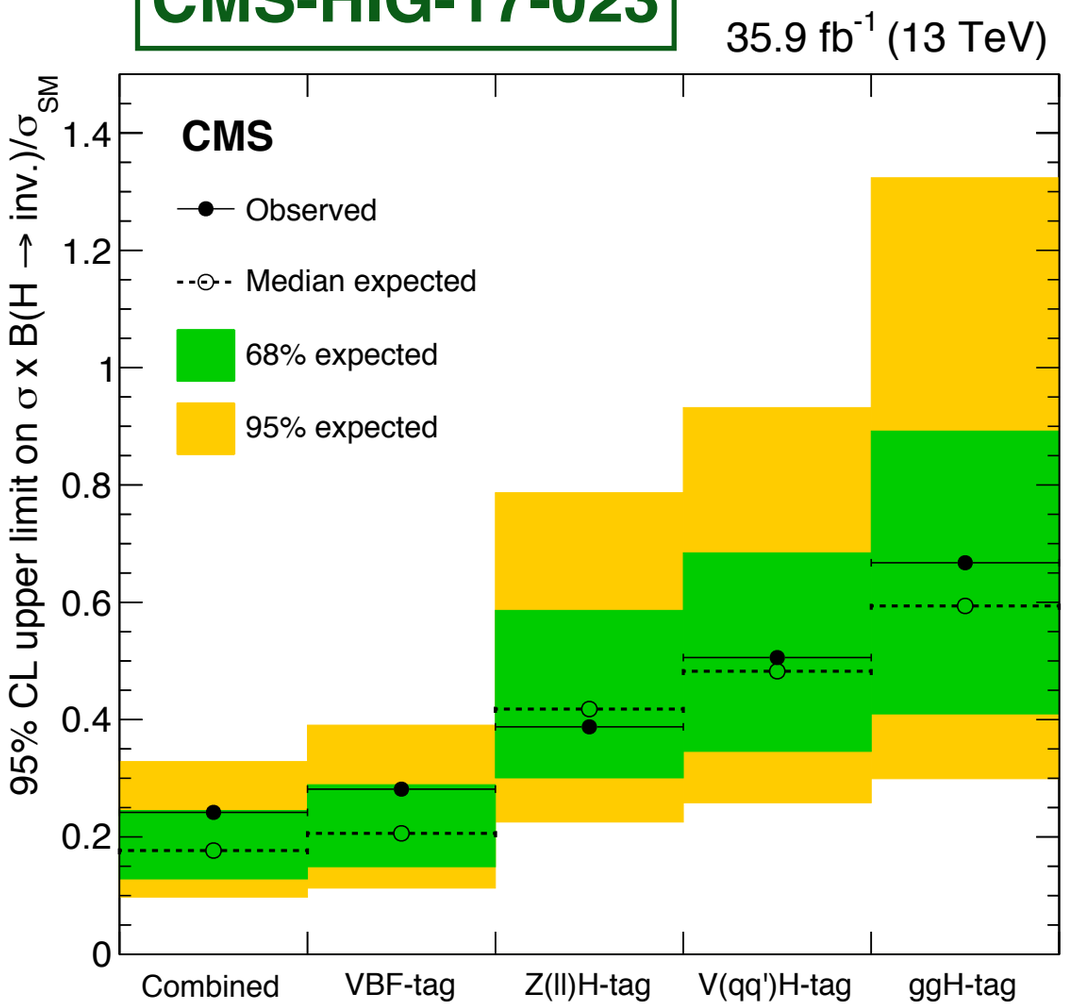
CMS-HIG-17-023



95% CL limit on BR(H→inv)
Obs (Exp) : 0.28 (0.21)

H→Invisible Results

CMS-HIG-17-023



95% CL limit on BR(H→inv)
Obs (Exp) : 0.24 (0.18)

8 TeV 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

JHEP11 (2015) 206

95% CL limit on BR(H→inv)
Obs (Exp) : 0.25 (0.27)

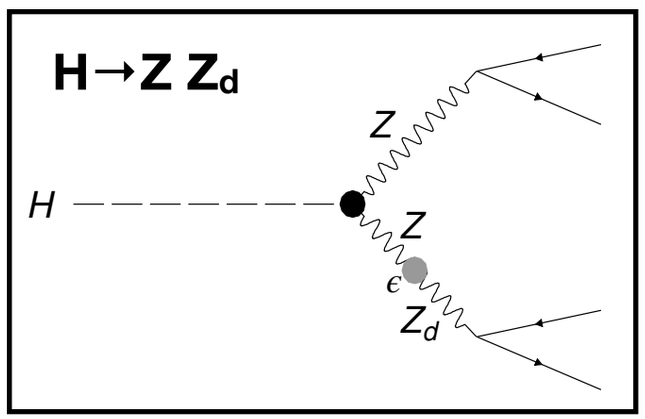
ATLAS 13 TeV BR(H→inv) results

Channel	Obs.	Exp.	+1 std. dev.	-1 std. dev
MET+Z(ll)	0.67	0.39	0.56	0.28
MET+V(qq)	0.83	0.58	0.81	0.42

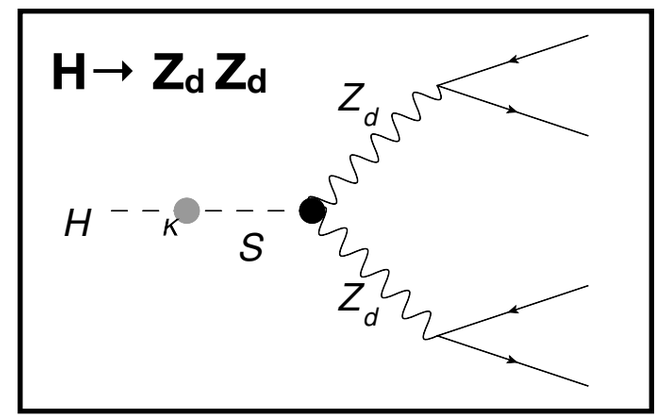
H Decays to Dark Photon

Dark photon : New U(1) gauge symmetry of dark sector

Talks to SM through kinetic mixing → $\frac{1}{2}\frac{\epsilon}{\cos\theta}\hat{Z}_{D\mu\nu}\hat{B}^{\mu\nu}$



Z_d mixes with Z



H mixes with dark Higgs

- **Select 4-lepton events : 4μ, 2e2μ, 4e**
- **H candidate** : $115 < m_{4l} < 130$ GeV
- **Z candidate (m_{12})** :$50 < m_{12} < 106$ GeV
- **Z_d candidate (m_{34})** : $12 < m_{34} < 115$ GeV
- **Fit m_{34} distribution**

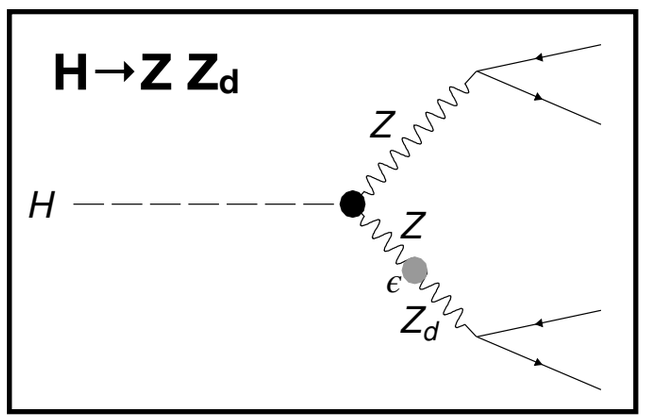
- **$15 < m_{Zd} < 60$ GeV : 4μ, 2e2μ, 4e**
- **$1 < m_{Zd} < 15$ GeV : 4μ**
- **H(4l) candidate** : $120 < m_{4l} < 130$ GeV
- **Z_d candidates** : $m_{34} / m_{12} > 0.85$
- **Fit average m_{ll} distribution**

(ATLAS) arXiv:1802.03388

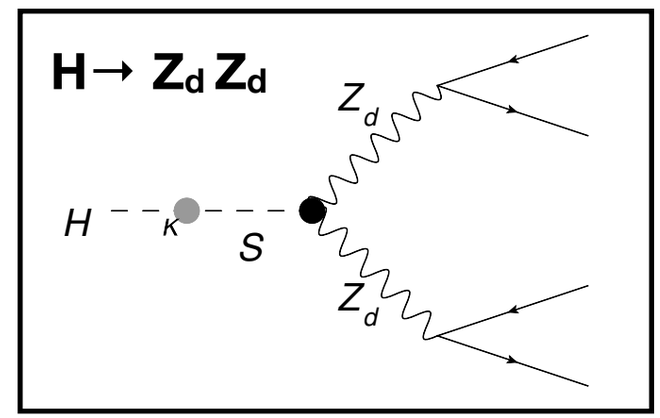
H Decays to Dark Photon

Dark photon : New U(1) gauge symmetry of dark sector

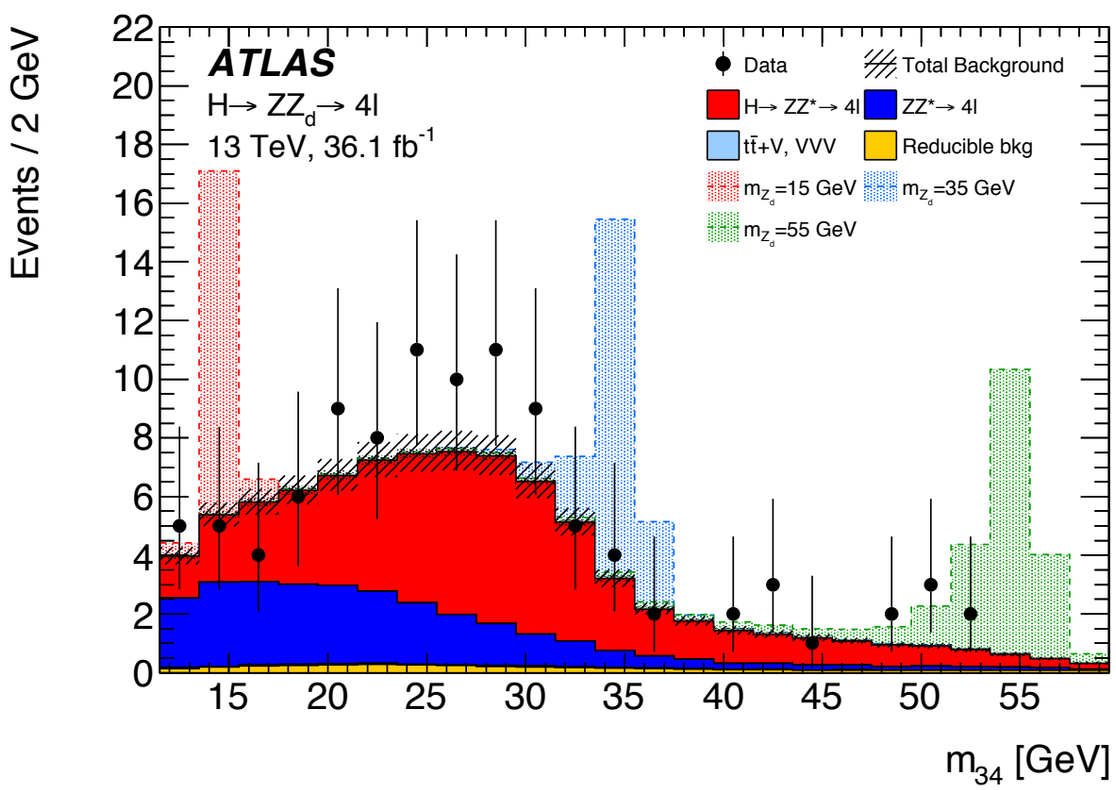
Talks to SM through kinetic mixing → $\frac{1}{2}\frac{\epsilon}{\cos\theta}\hat{Z}_{D\mu\nu}\hat{B}^{\mu\nu}$

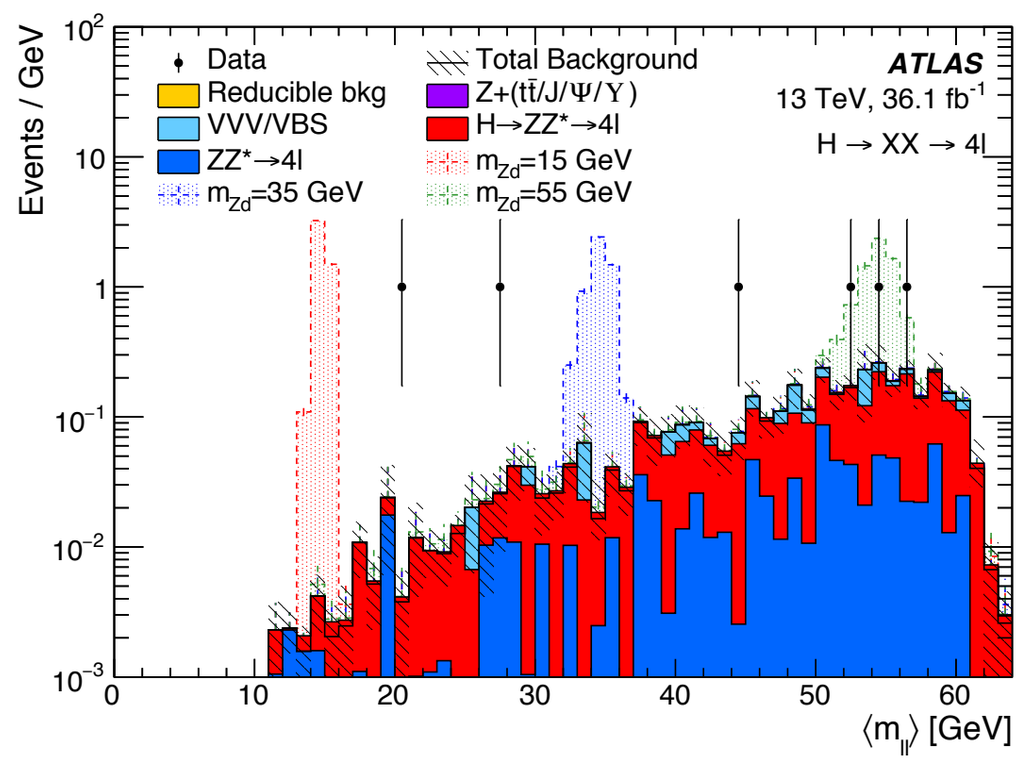


Z_d mixes with Z



H mixes with dark Higgs



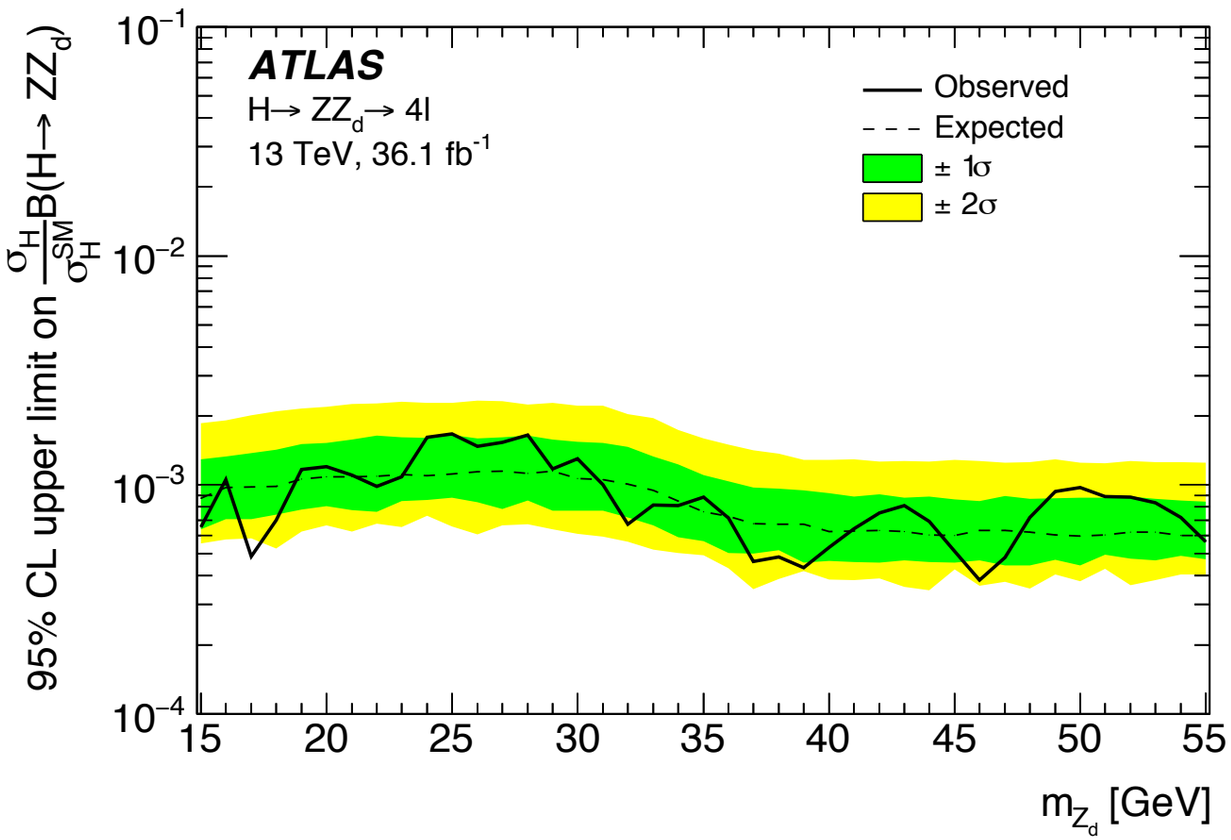


(ATLAS) arXiv:1802.03388

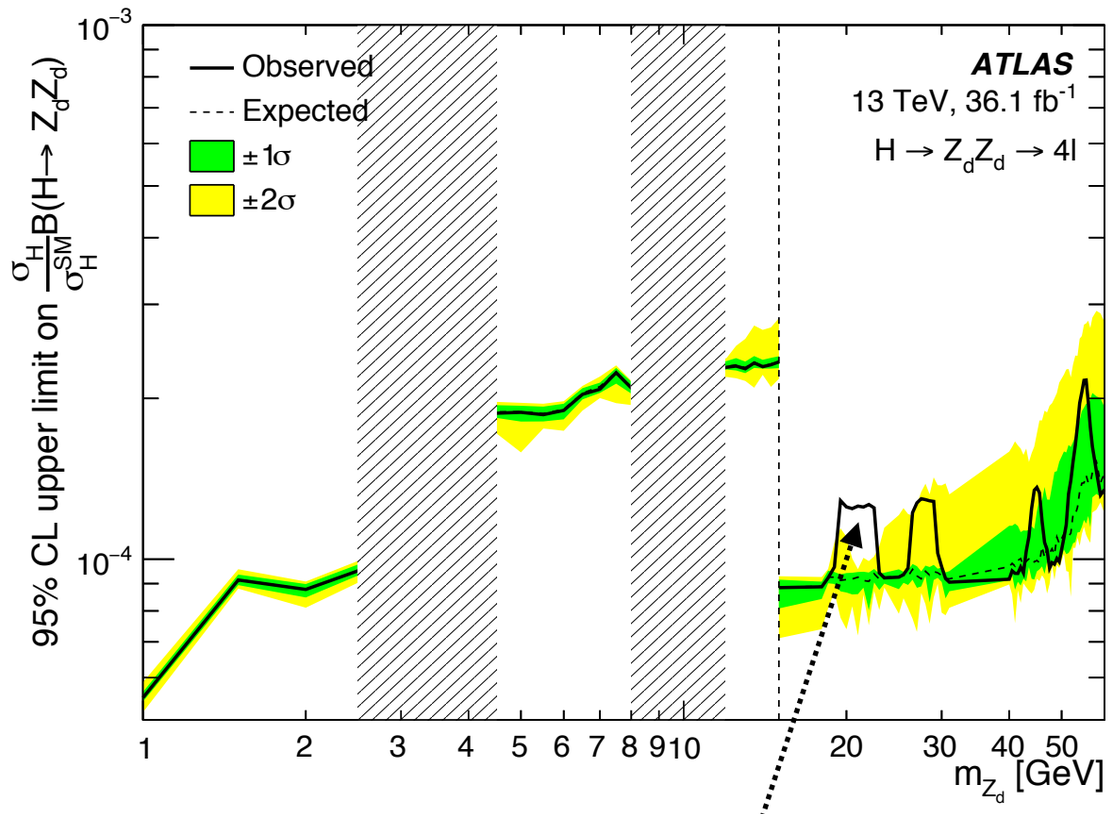
$H \rightarrow Z_{(d)} Z_d$ Results

(ATLAS) arXiv:1802.03388

$H \rightarrow Z\, Z_d$

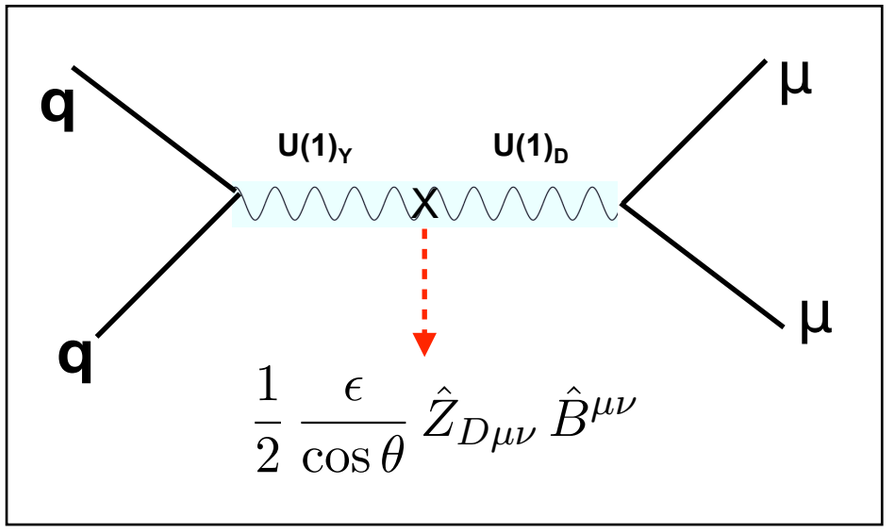


$H \rightarrow Z_d\, Z_d$



3.2σ excess (global sig. 1.9σ) in $H \rightarrow Z_d\, Z_d$ search for $m_{Zd} \sim 20$ GeV due to a single event observed in data

Dark Photon Search at LHCb



Salient Features

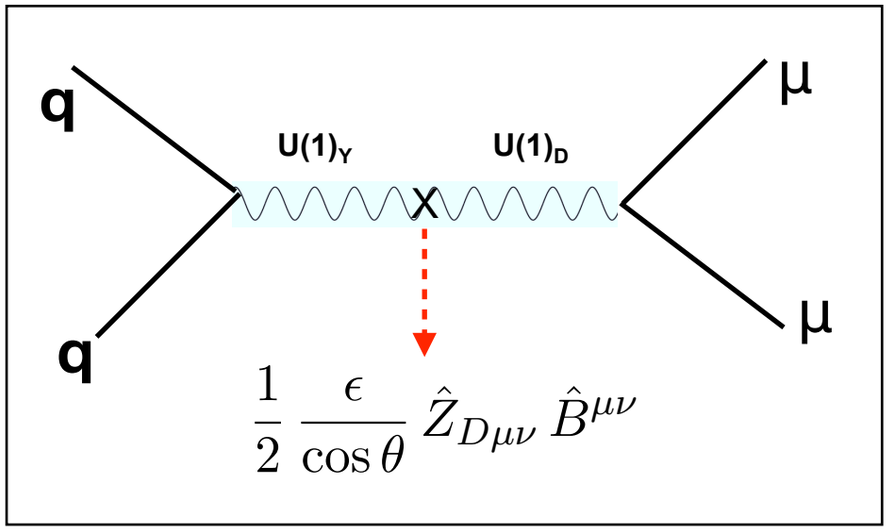
Interaction of Z_d with SM fermions is similar to Z/γ (x-sec suppressed by ϵ^2)

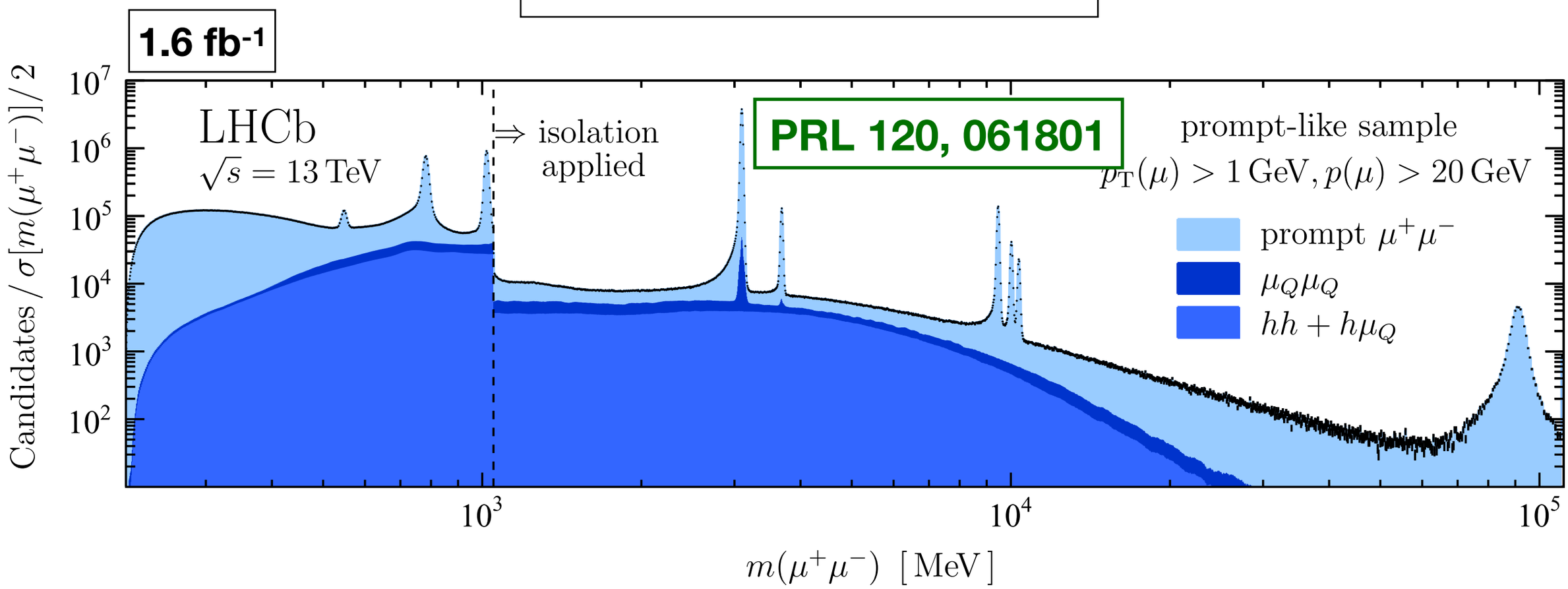
Assuming Z_d decays only to SM, its width (lifetime) depends on ϵ

- Prompt regime : $\epsilon > 10^{-3}$
- Displaced regime : $\epsilon < 10^{-4}$ … O(1mm) $c\tau$ for sub-GeV dark photons

Look for a bump in prompt & displaced dimuon events

Dark Photon Search at LHCb



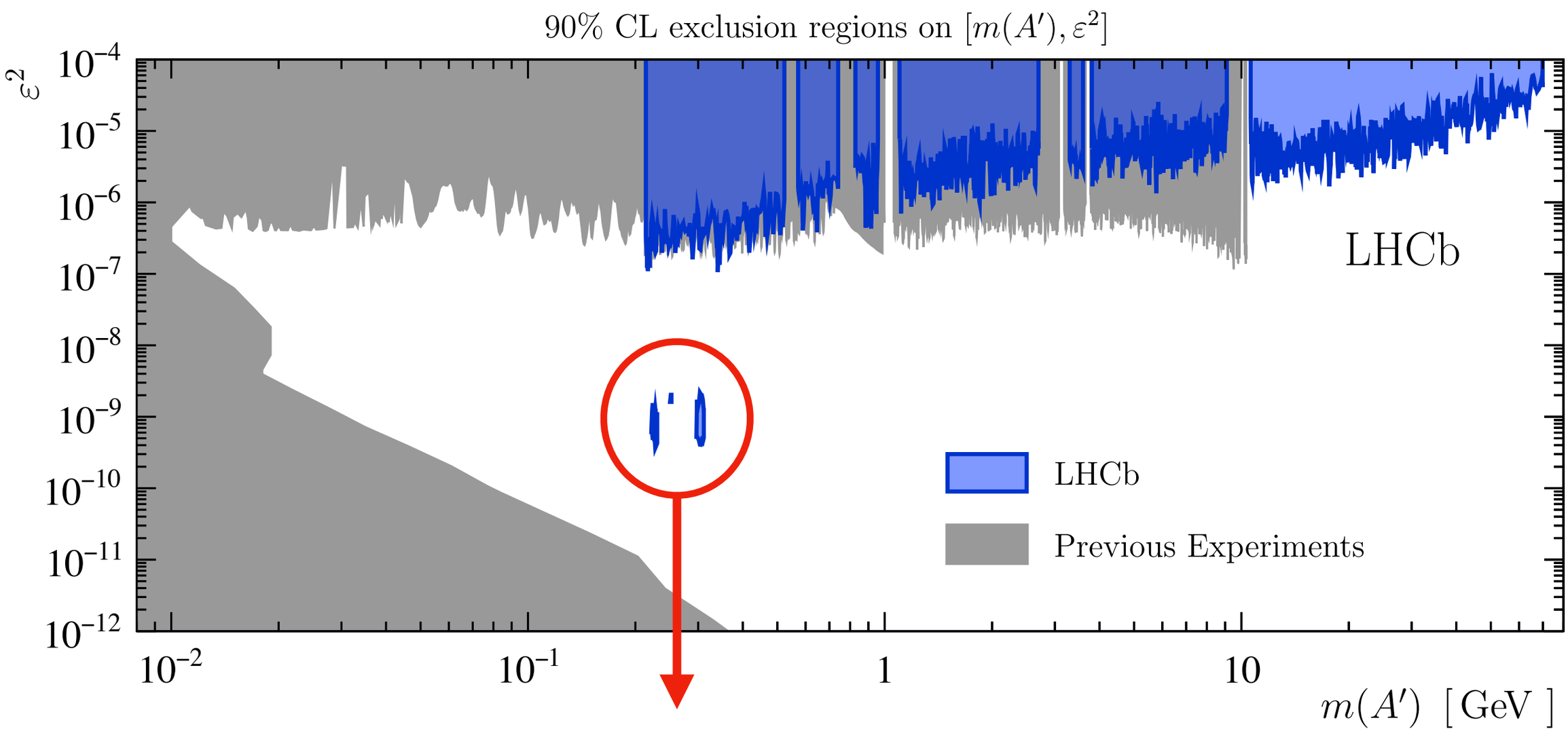


Prompt dimuon distribution in data

Dark Photon Limits

Getting competitive with BaBar below 10 GeV

Best limits on dark photons above 10 GeV



Sensitivity to long-lived dark photons

Summary

- Extensive, on-going program at LHC searching for dark matter and, in general, a hidden dark sector
- Searches span a broad spectrum of final states and signal models
  - Could not cover all of them in this talk
  - See talks from ***S. Ahuja (CMS), J. Frost (ATLAS) F. Redi (LHCb)***
- The canonical MET+X searches continue to expand their reach with more data
- At the same we are exploring new DM models and signatures

Thank you for your attention!