Marco Trovato

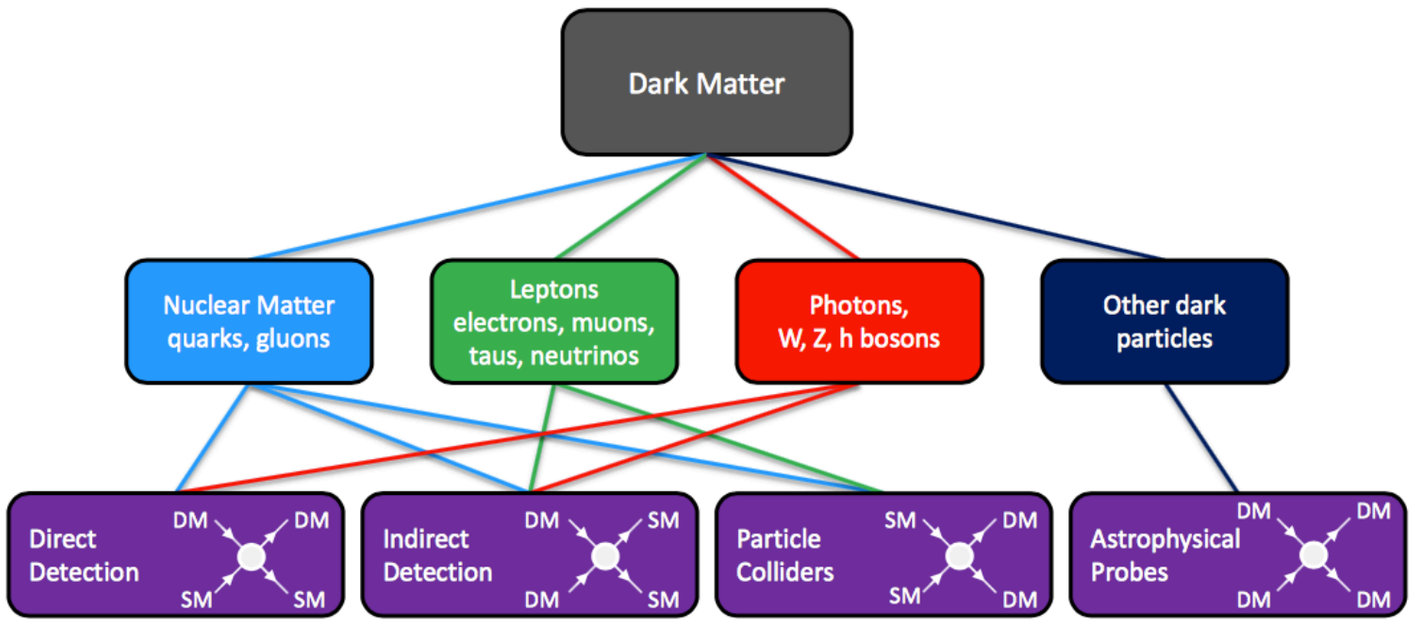
Northwestern University

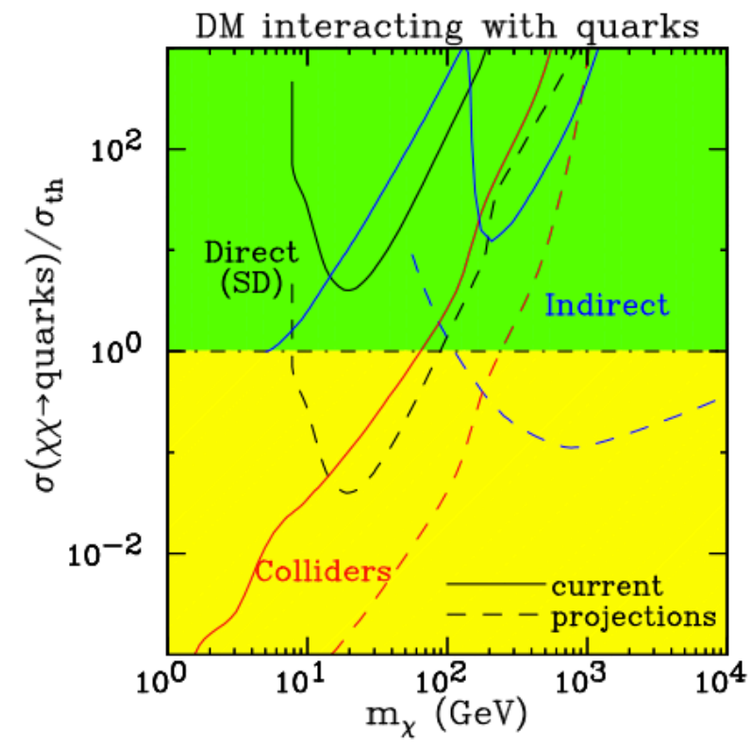
On Behalf of CMS and ATLAS

U.S. Cosmic Visions: New Ideas in Dark Matter
23-25 March 2017

Why DM at the LHC?

arXiv1310.8621 (2013)



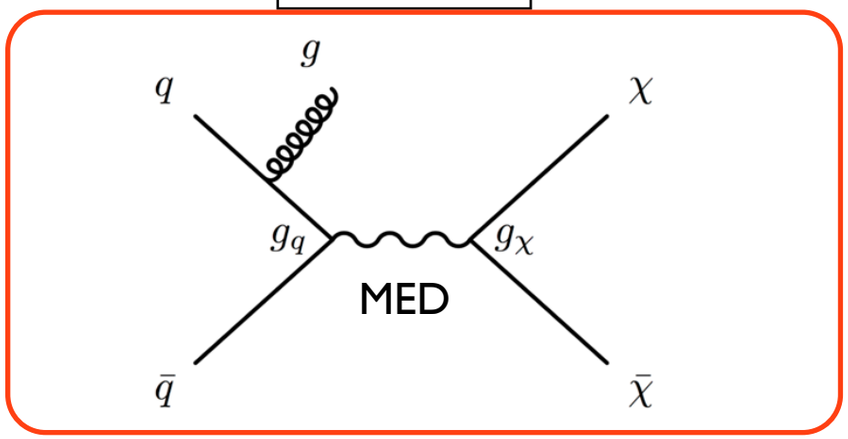


- Different experiments probe different (DM) parameter space
  - Colliders: low masses (~ 10 MeV?), Spin 0/1 (P +1/-1)
  - Direct Detection (DD): high masses (~10 GeV), Spin 0 (P +1), Spin 1 (P +1/-1)
  - Indirect Detection (ID): large range (100 GeV -...TeV), Spin 0 (P -1)
- A possible discovery will have to be cross checked in more than one experiment
  - different experiments are sensitive to different DM properties (ie: nature of the mediator)

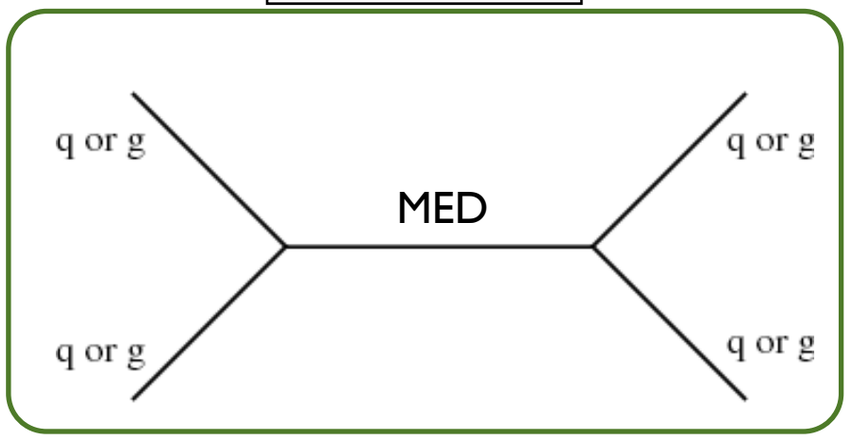
DM searches at the LHC

- Typical signatures:

MET + X



Resonances



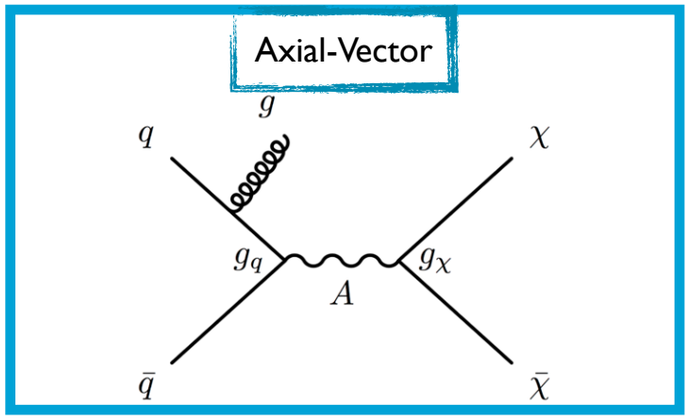
- Rely on simplified models *(arXiv: 1507.00966)* to interpret the results
  - Pair-produced DM Dirac fermions, χ
  - DM is stable on collider timescales
  - DM is non-interacting with the detector
  - Couplings: vector/axial/scalar/pseudo-scalar
  - Minimal Flavor violation
  - Minimal Decay width: couples only to SM and χ

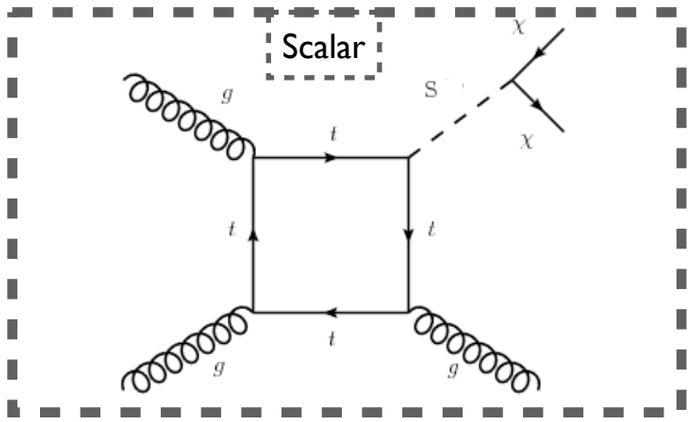
- Minimal set of parameters: g_q, g_χ, M_{MED}, M_χ

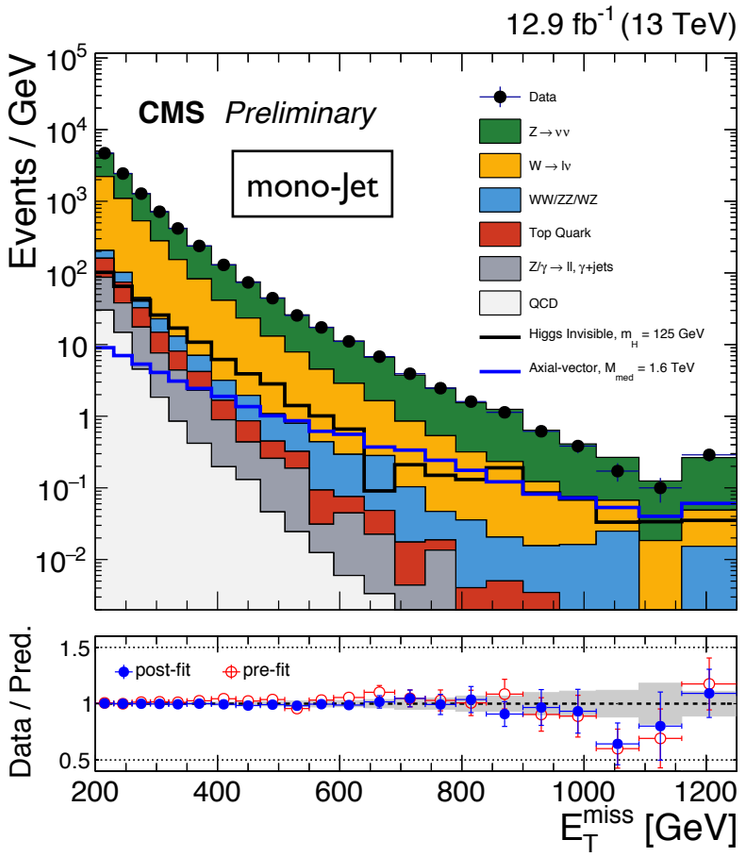
Mono-Jet/Mono-W/Z

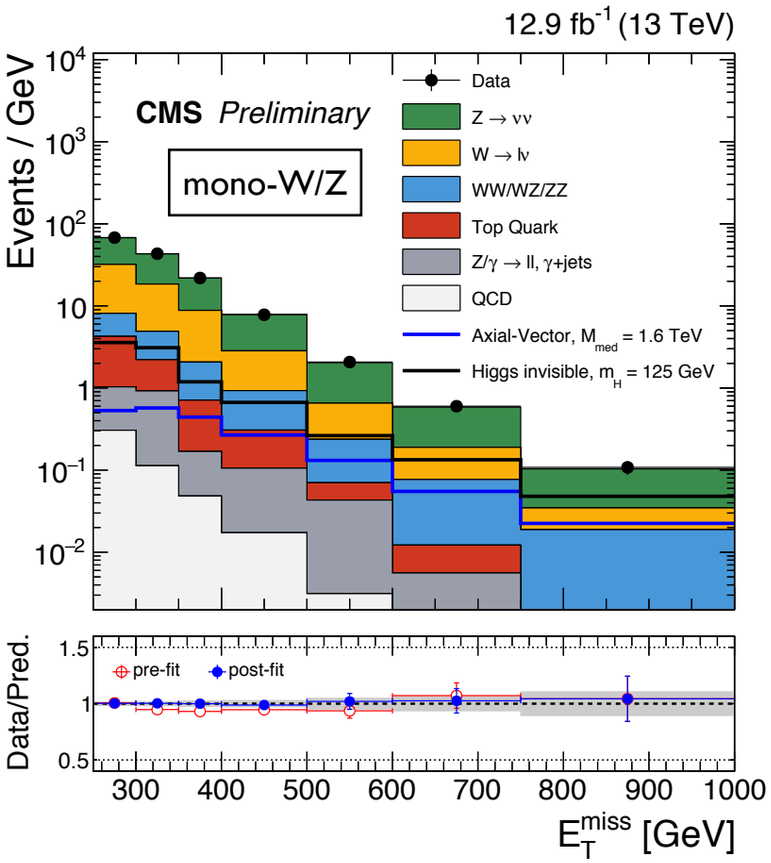
2016 ICHEP data

- Selection: MET>200 GeV, >= 1 jet, lepton/b/γ veto
- Categorization:
  - mono-W/Z: MET, p_T^{AK8} > 250 GeV, jet mass [65,105] GeV, τ_2/τ_1 < 0.6
    - τ_N are indicative of a N-prong decay
  - mono-jet: all other events w/ p_T^{AK4} > 100 GeV, MET>200 GeV
- Background and Signal predictions are fitted to data in MET
  - 5x2 control regions (CRs) plus 1x2 signal regions (SR) simultaneously fitted







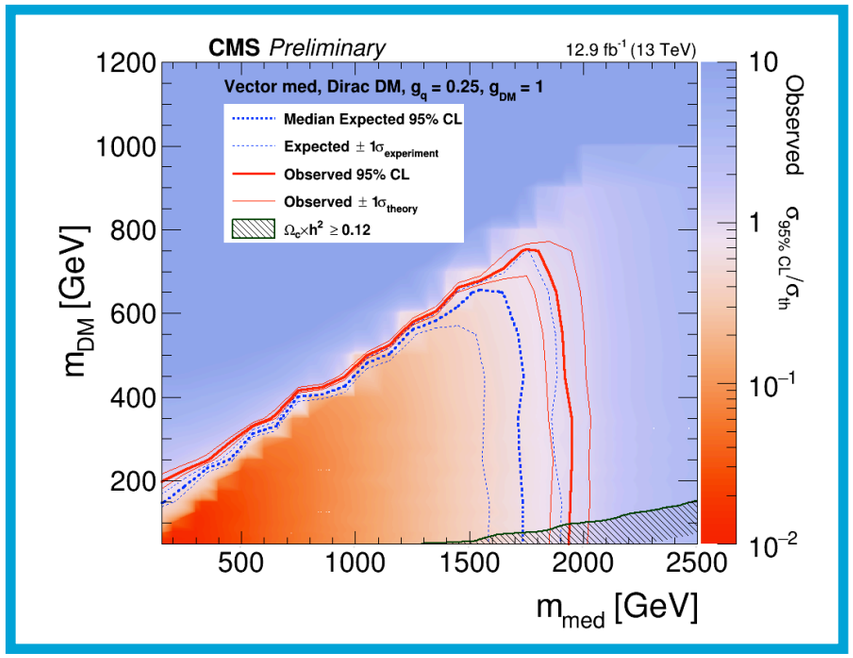


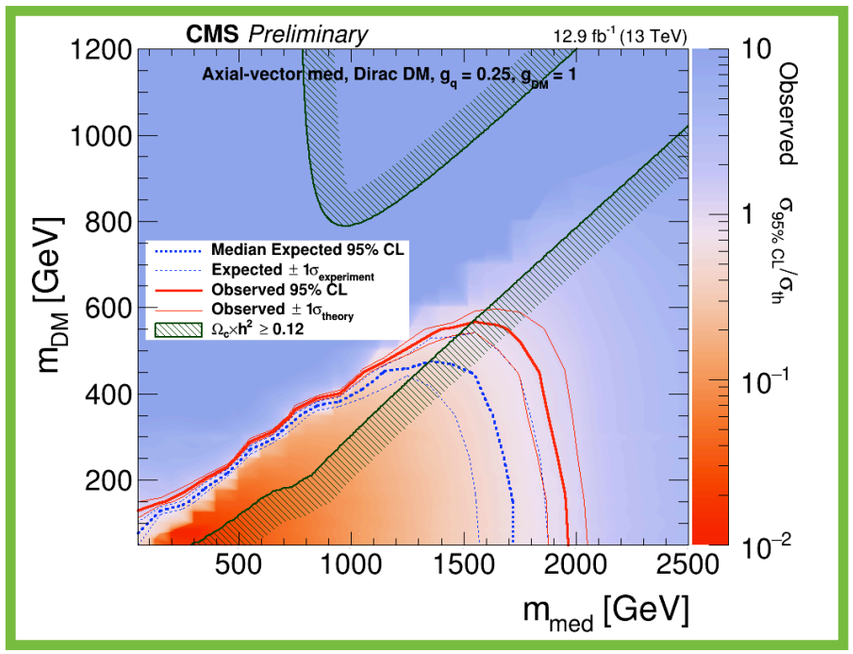
EXO-16-037

Mono-Jet/Mono-W/Z

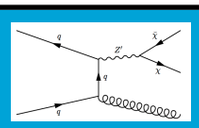
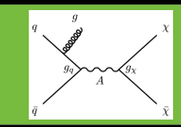
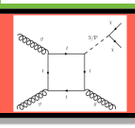
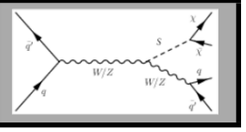
2016 ICHEP data

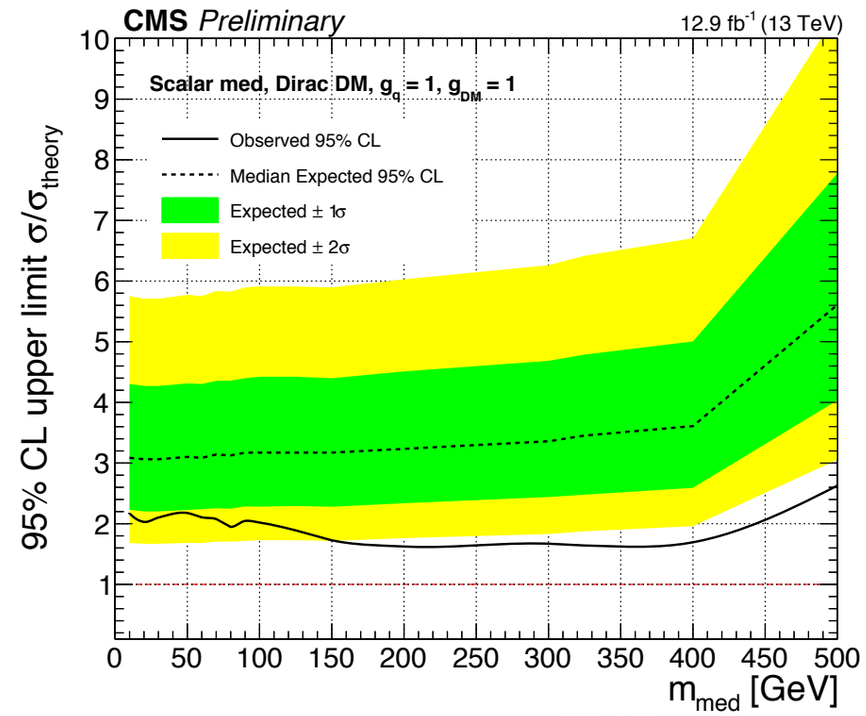
No excess observed





Exclusions (@ 95% CL) :

Model	M_{MED} (GeV)	M_X (GeV)	
Vector	<1950	<750	
Axial-Vector	<1950	<550	
Scalar	-	-	
Pseudo-Scalar	<430	<170	



couplings to fermions ONLY

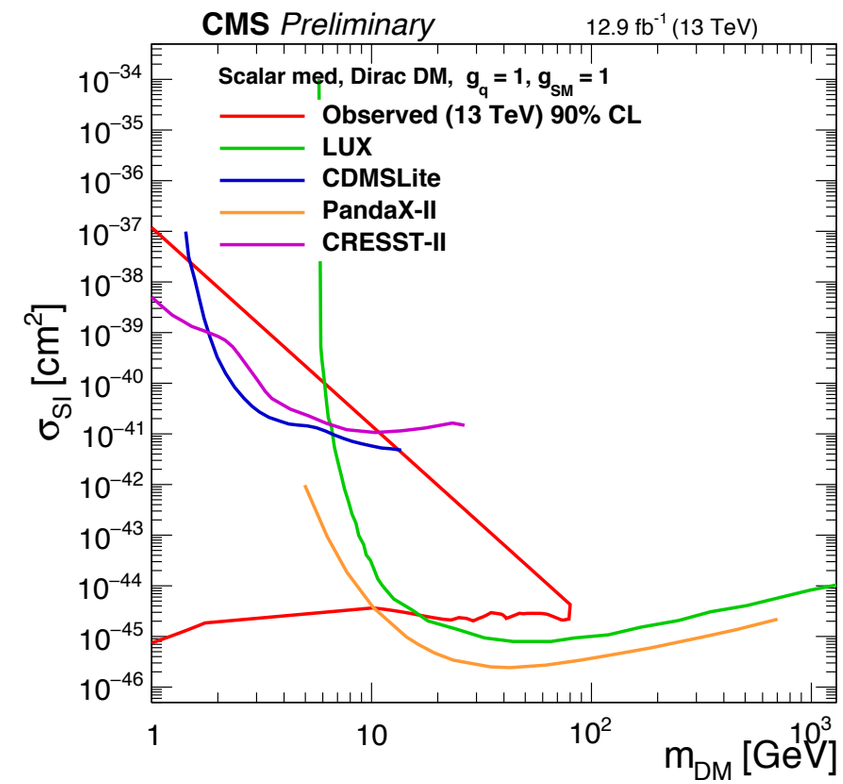
EXO-16-037

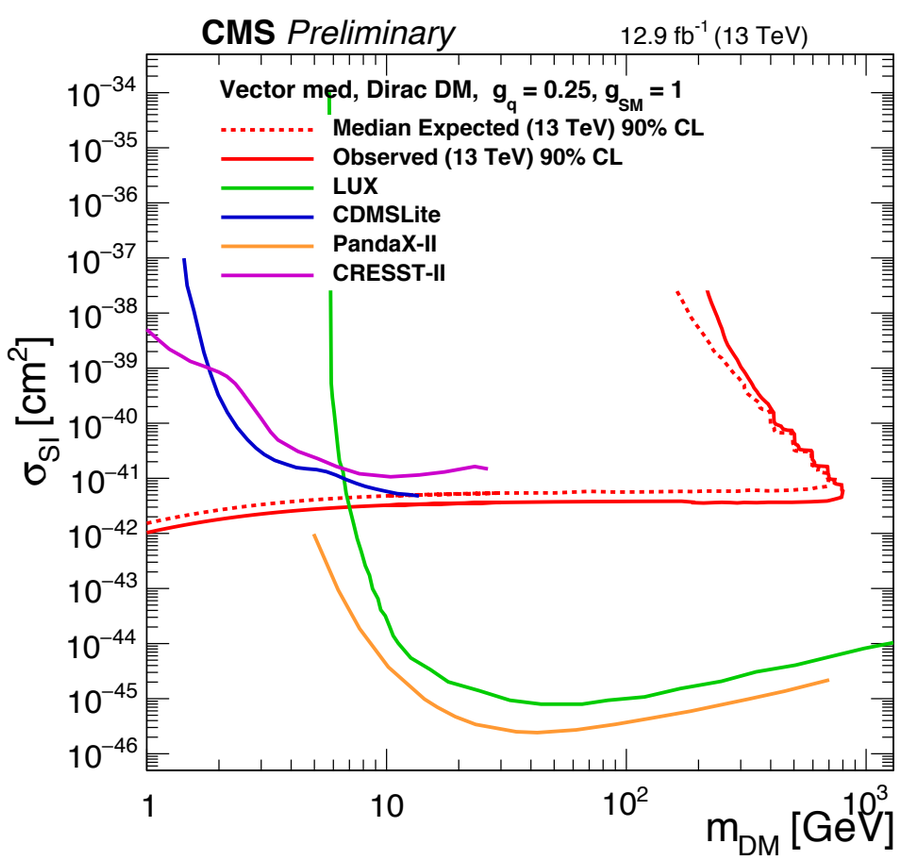
Mono-Jet/Mono-W/Z

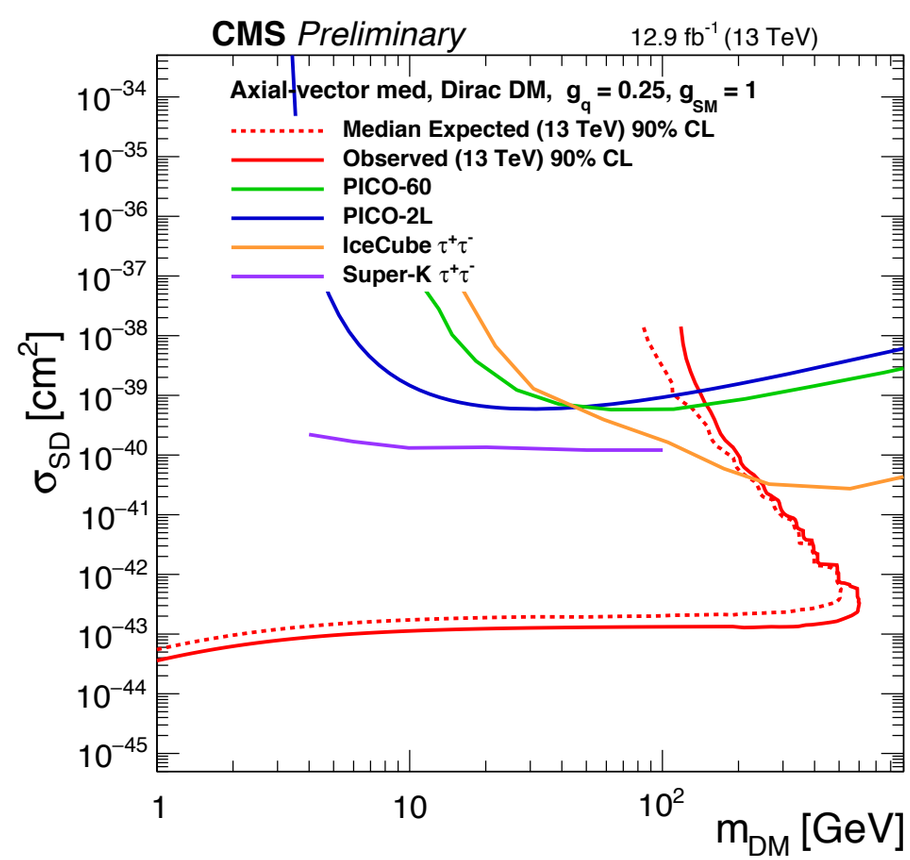
2016 ICHEP data

- Reinterpret as invisible Higgs:
  - BR < 0.44 (exp: 0.56)

- Recast to limits on SI/SD DM nucleon cross sections *(arXiv:1603.04156)*





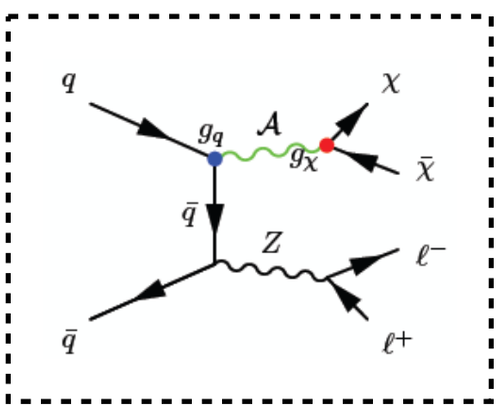


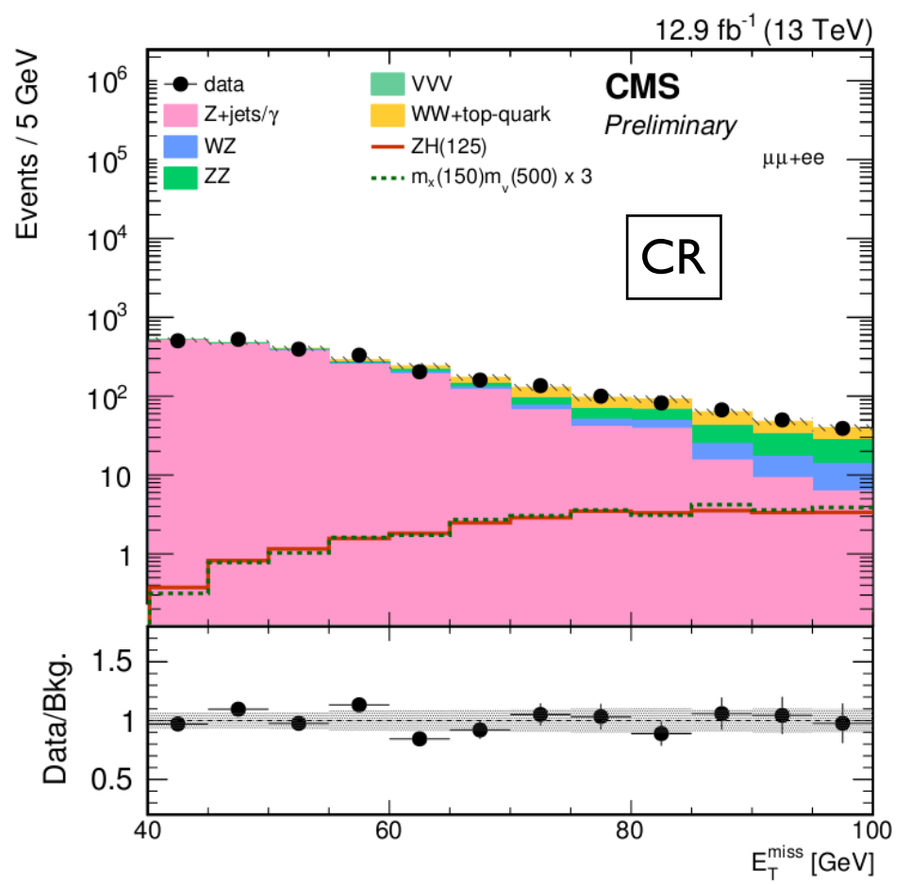
EXO-16-037

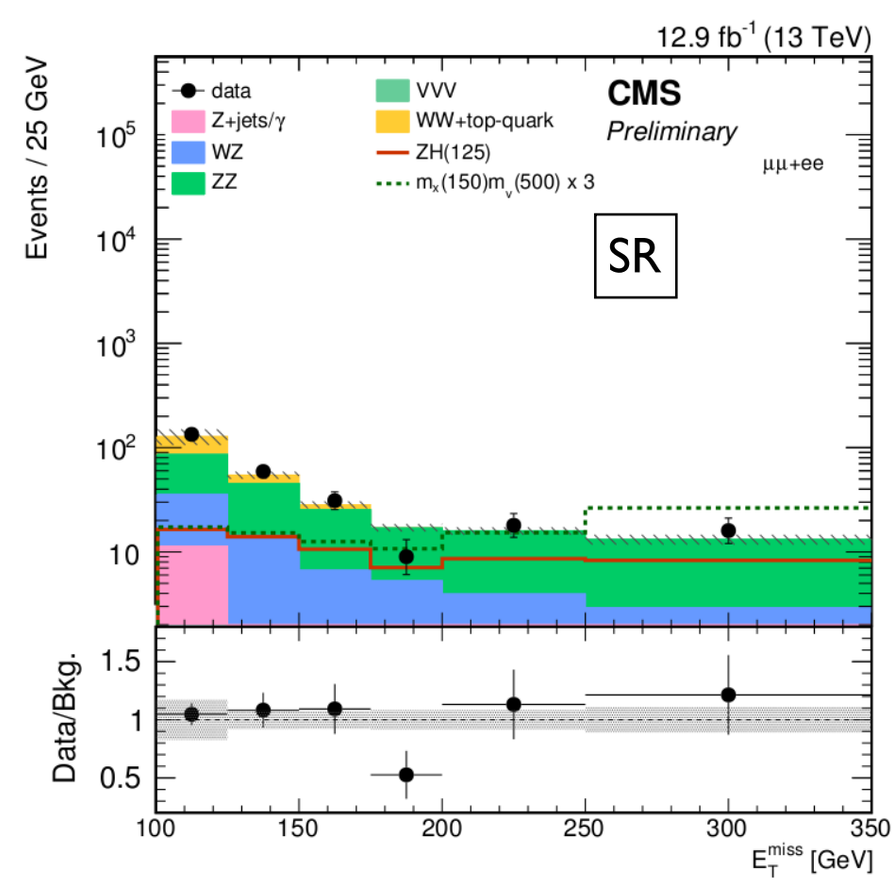
Mono-Z

2016 ICHEP data

- Selection: MET>100 GeV, $p_T^{ee/\mu\mu}$>60 GeV, $\Delta\varphi$(ee/μμ,MET)>2.8, $|p_T^{ee/\mu\mu}$ -MET$|/p_T^{ee/\mu\mu} < 0.4$, >1 jet/b/>2 lep veto
- Background and signal predictions are fitted to data in MET
  - background shapes from MC @ NLO
  - (pre-fit) normalization for :
    - WZ/ZZ: from MC @ NNLO-QCD, NLO-EWK
    - non-resonant background (WW, tt, tW, Z+jets) from eμ CR





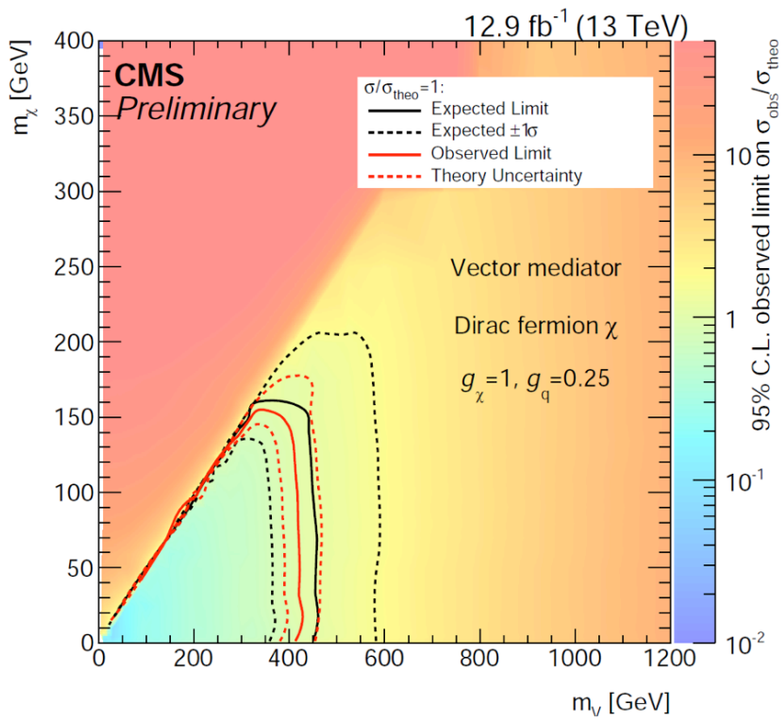


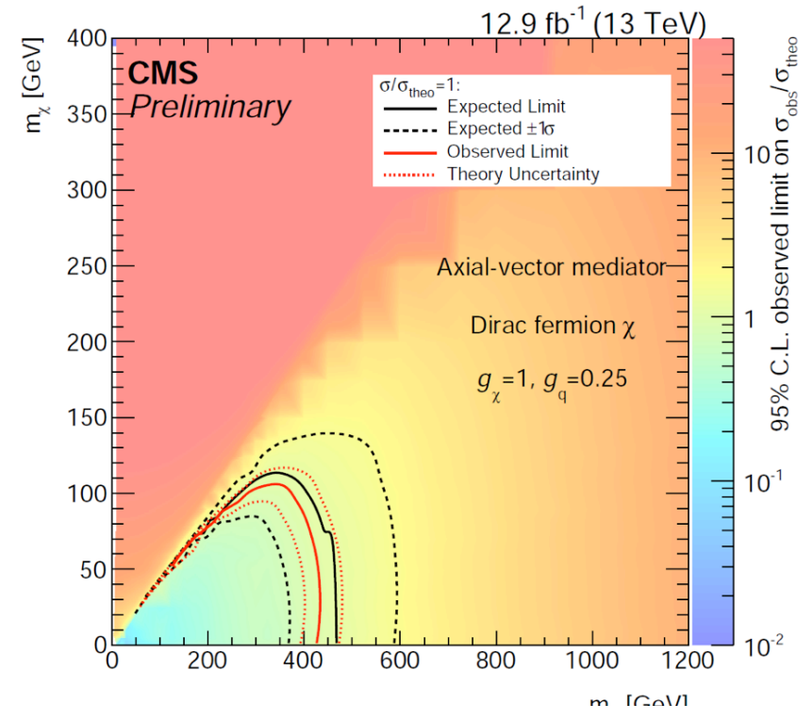
EXO-16-038

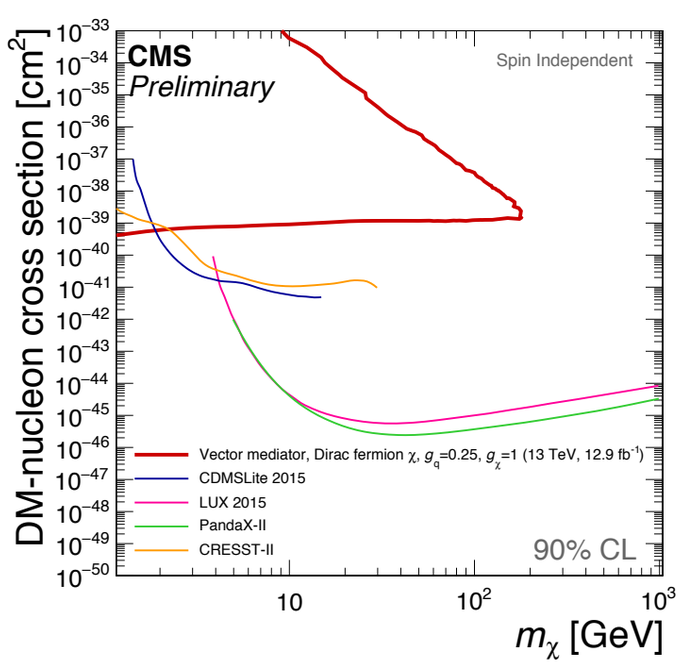
Mono-Z

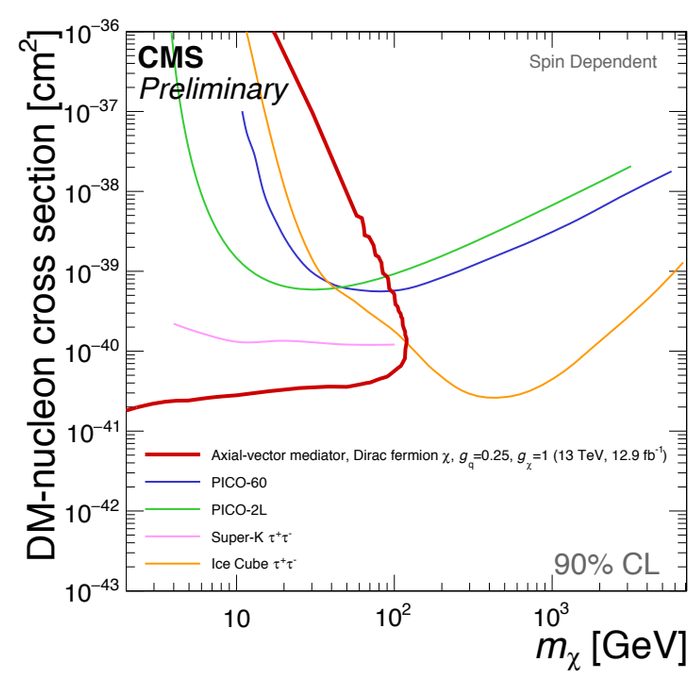
2016 ICHEP data

- No observed excess: M_{MED} <~400 GeV excluded (vector/axial)
- Recast to limits on SI/SD DM nucleon cross sections







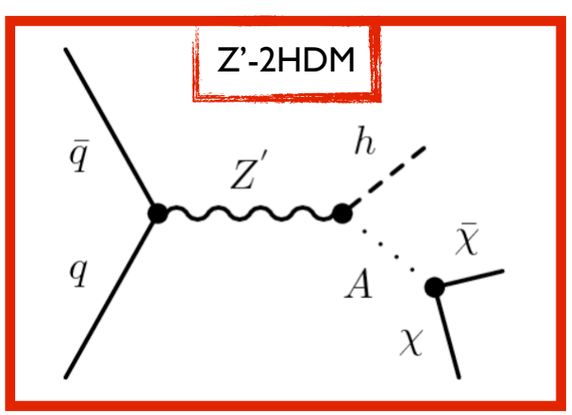


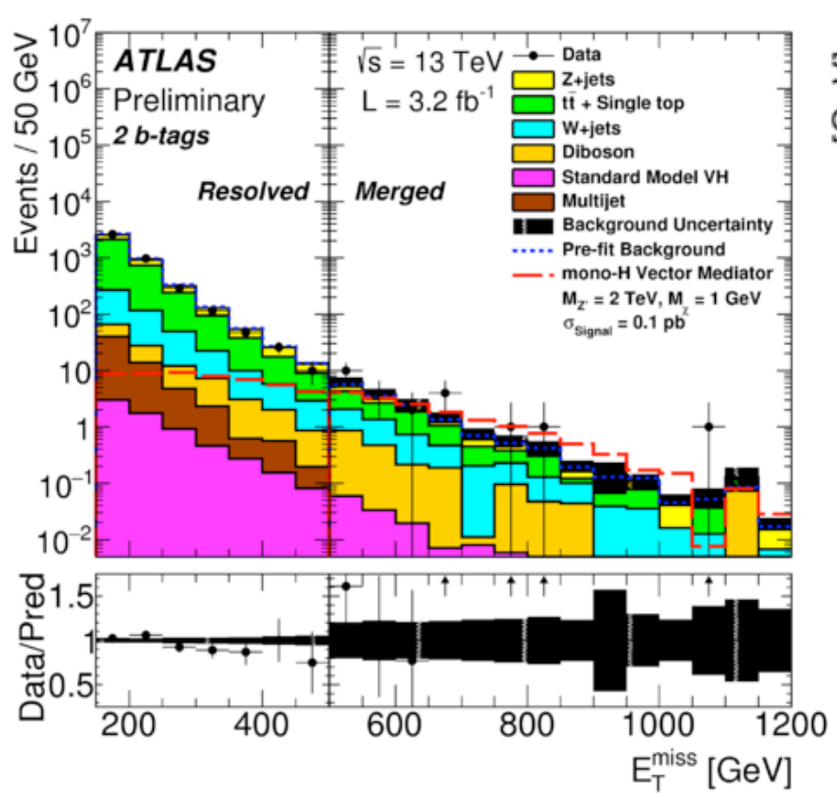
EXO-16-038

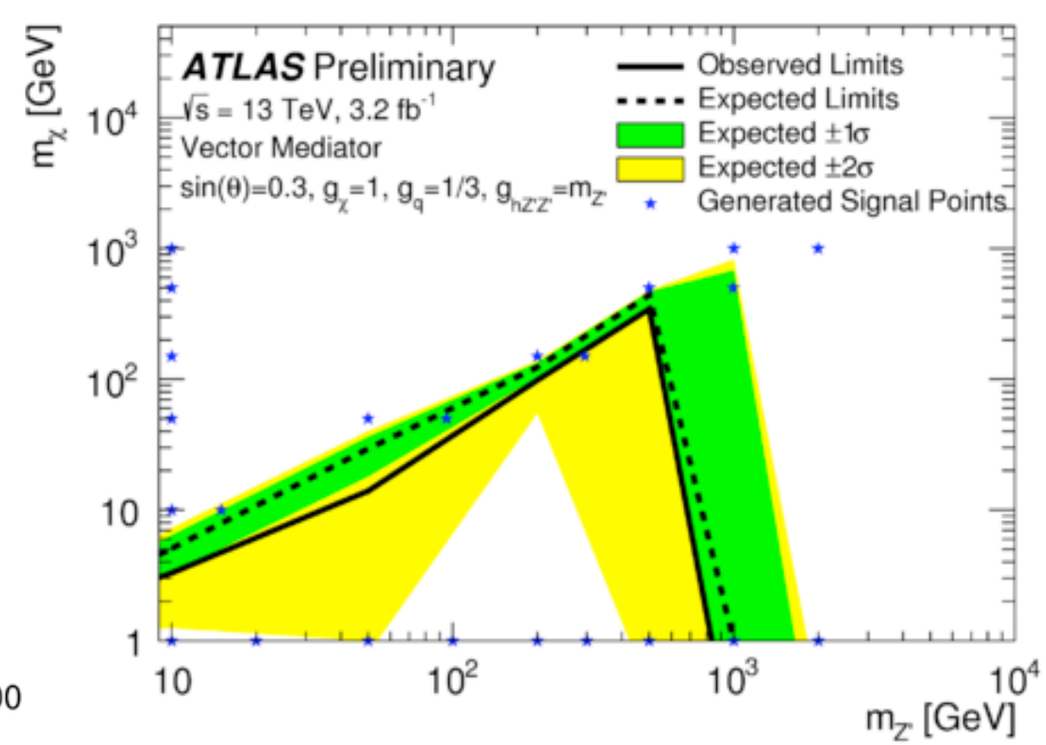
Mono-H(bb)

2015 data

- Selection: MET>150 GeV, lepton veto
- Categorization
  - resolved: MET<500, at least two R=0.4 jets;
  - boosted: MET>500, at least one R=1.0 jets w/ at least two track-jets (R=0.2)
    - substructure variables (e.g: τ_2/τ_1) use to further reject multijet/top background
- Background and signal predictions are fitted to data in di-jet mass
  - W/Z+jets, multi-jet backgrounds initially estimated from dedicated CRs
  - Other backgrounds from simulation
- No observed excess: M_{MED} <~ 0.7 TeV excluded (vector)





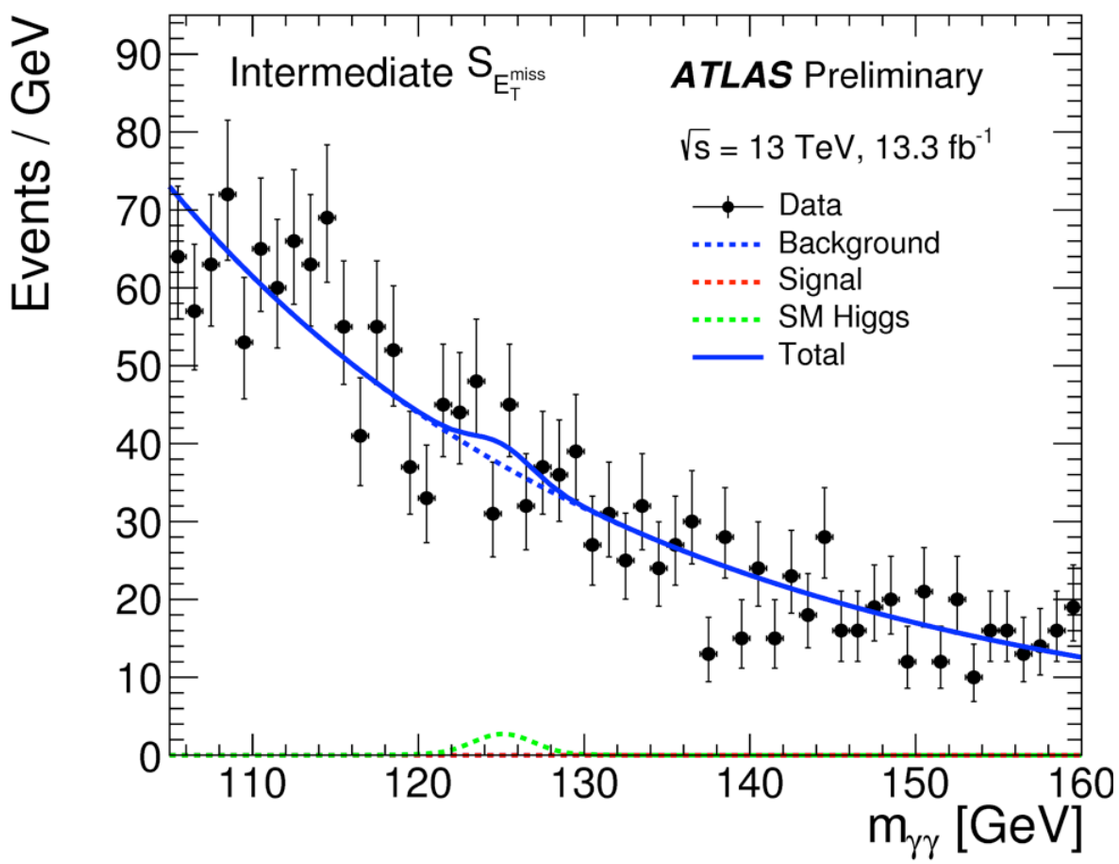


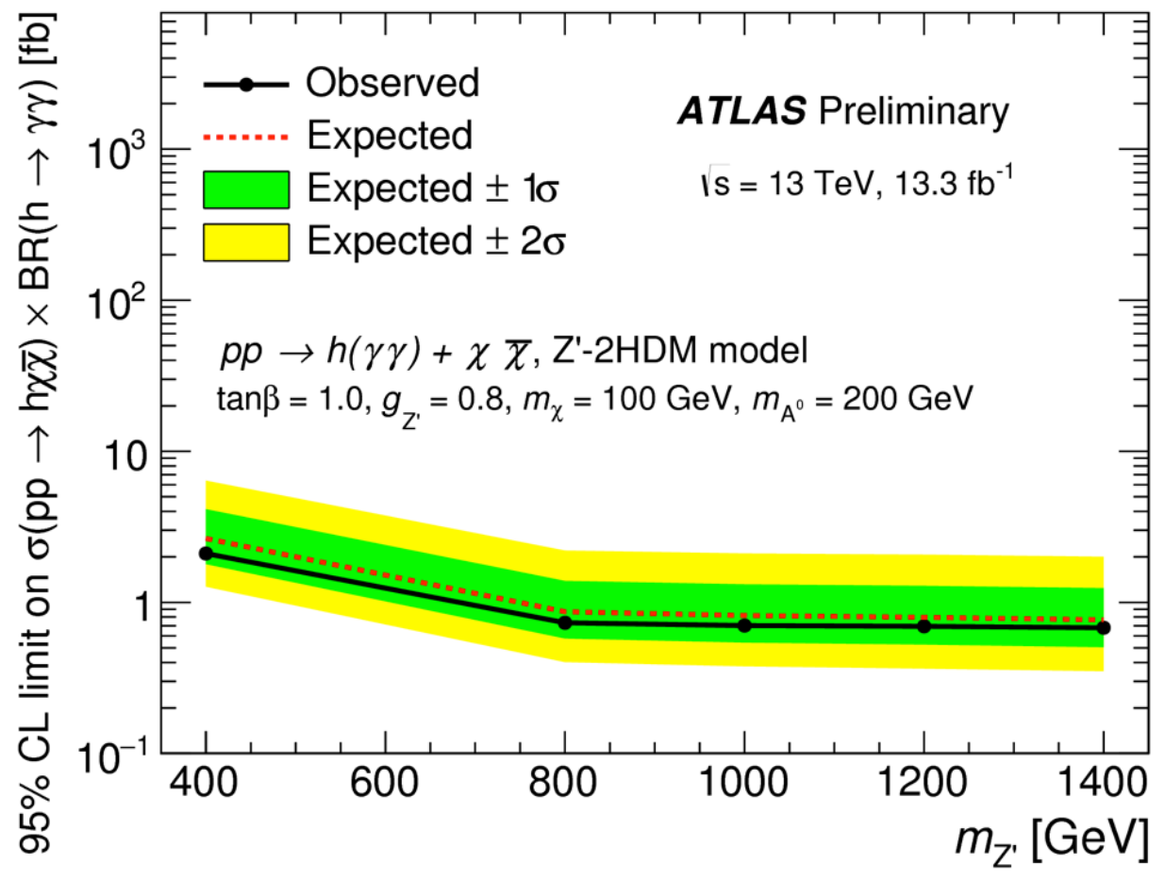
ATLAS-CONF-2016-019

Mono-H(γγ)

2015+2016 ICHEP data

- Selection: MET>150 GeV, p_T^{γ} > 25 GeV, $M_{\gamma\gamma}$ in [105,160] GeV
- 4 Categories defined based on $p_T^{\gamma\gamma}$ and MET significance
- Background predictions are fitted to data in $M_{\gamma\gamma}$
  - one fit per region
  - major backgrounds: SM γγ, γ+jet, Wγ/γγ, Higgs
    - normalization/shape of Higgs $m_{\gamma\gamma}$ from MC



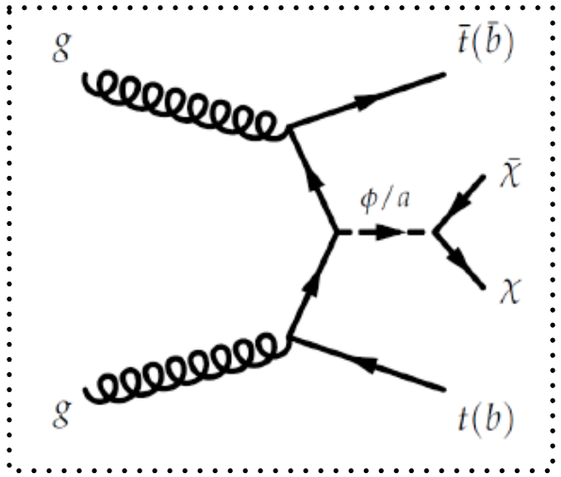


ATLAS-CONF-2016-087

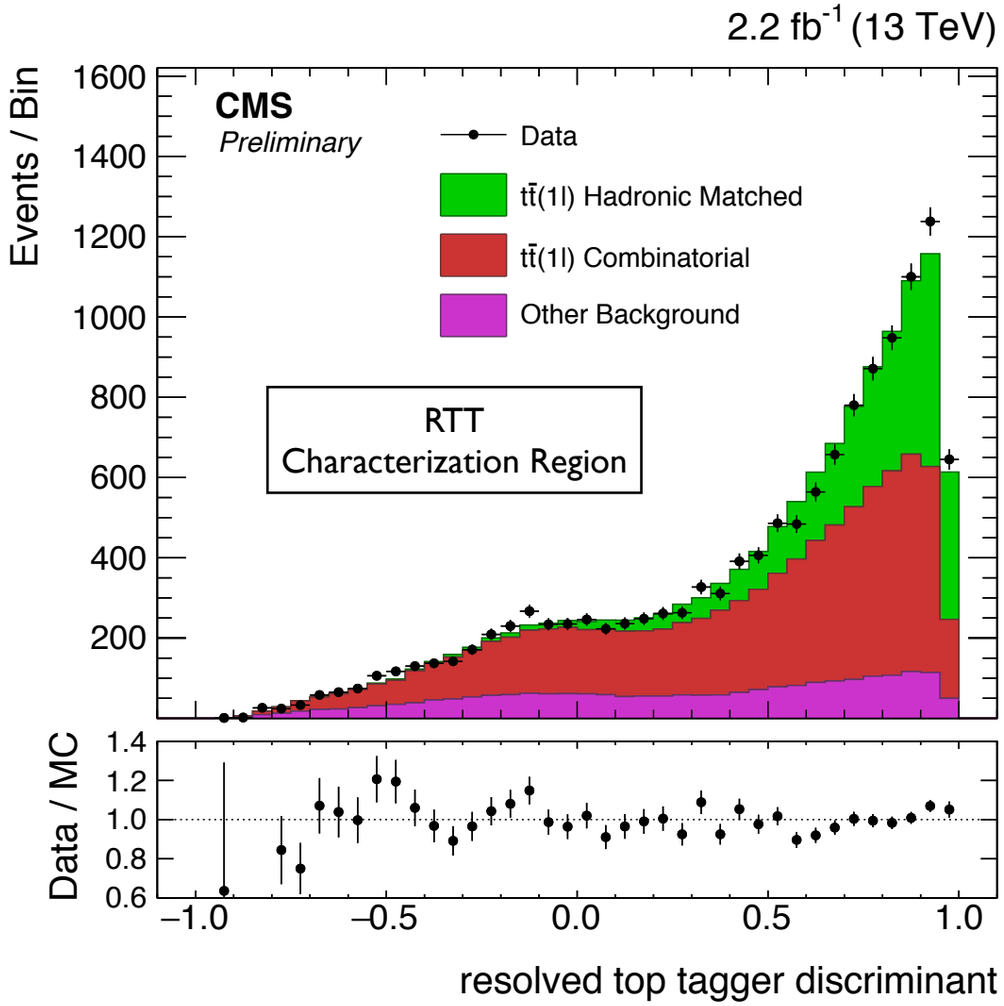
tt+DM

2015 data

- Direct probe for Yukawa couplings of spin-0 mediators



- Selection:
  - all-hadronic: MET>200
  - semi-leptonic: MET>160 GeV
  - di-leptonic: MET>50 GeV
  - all channels: b-tag and min Δφ(jet,MET) requirements
  - leptonic channels: leptons are identified is pT>30 GeV
- All-hadronic/semi-leptonic (EXO-16-005)
  - Dominant background: SM ttbar with one less hadronic top
  - Categorization: employ a resolved top tagger (RTT) to improve the significance of the search
- Di-leptonic (EXO-16-028):
  - Major background: SM ttbar

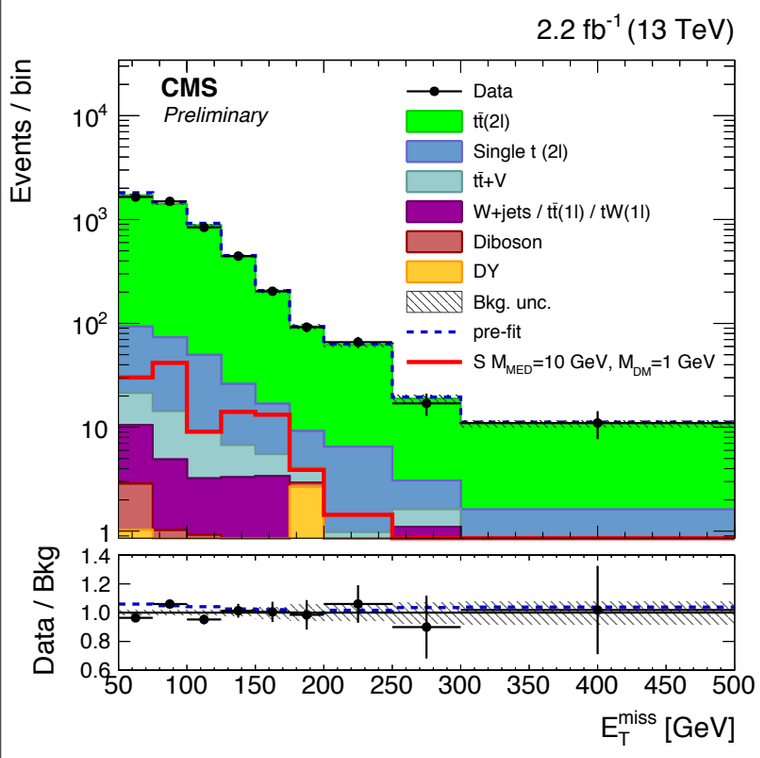


tt+DM

2015 data

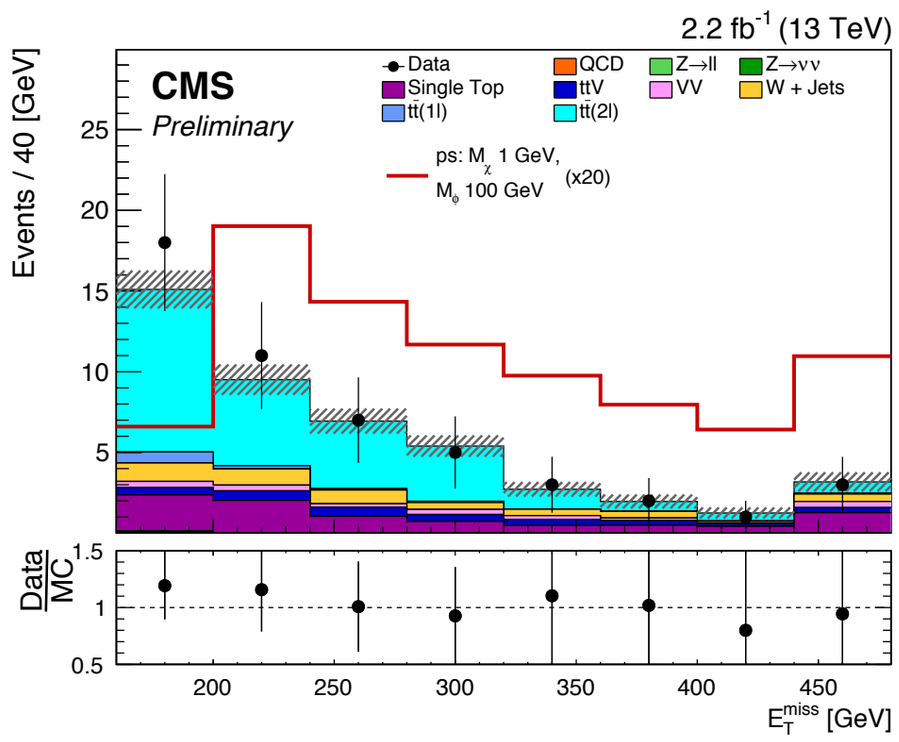
- Signal and background fitted to data in MET
  - All-hadronic/semi-leptonic: simultaneously fitting 3 SRs + 9 CRs,
  - di-leptonic: simultaneously fitting 3 SRs
    - Drell-Yan and fake-lepton backgrounds estimated from CRs,
    - other backgrounds from MC

di-leptons



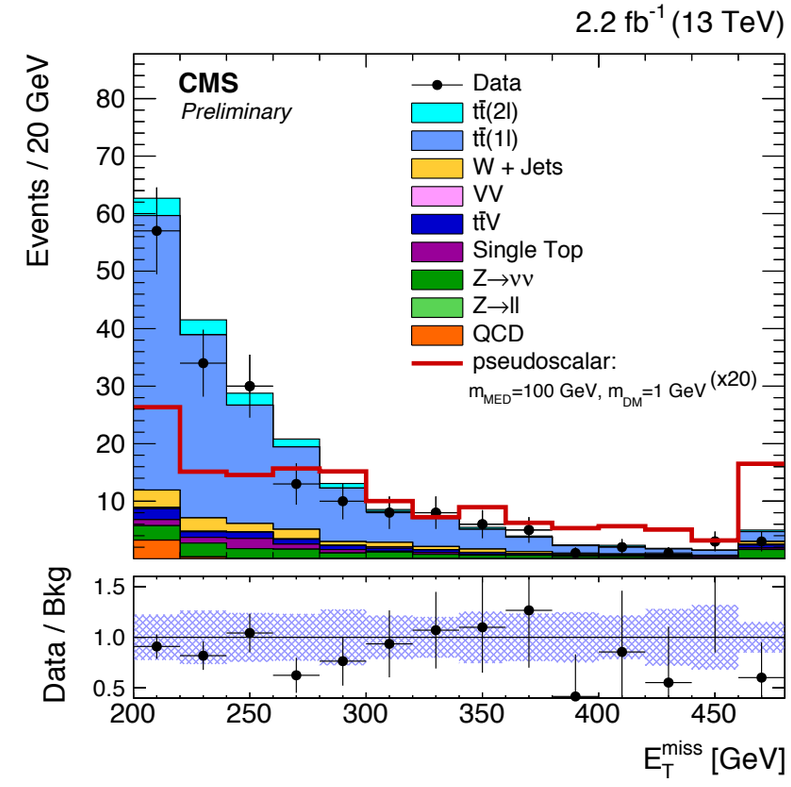
EXO-16-028

semi-leptonic



EXO-16-005

all-hadronic
(double top tagged)

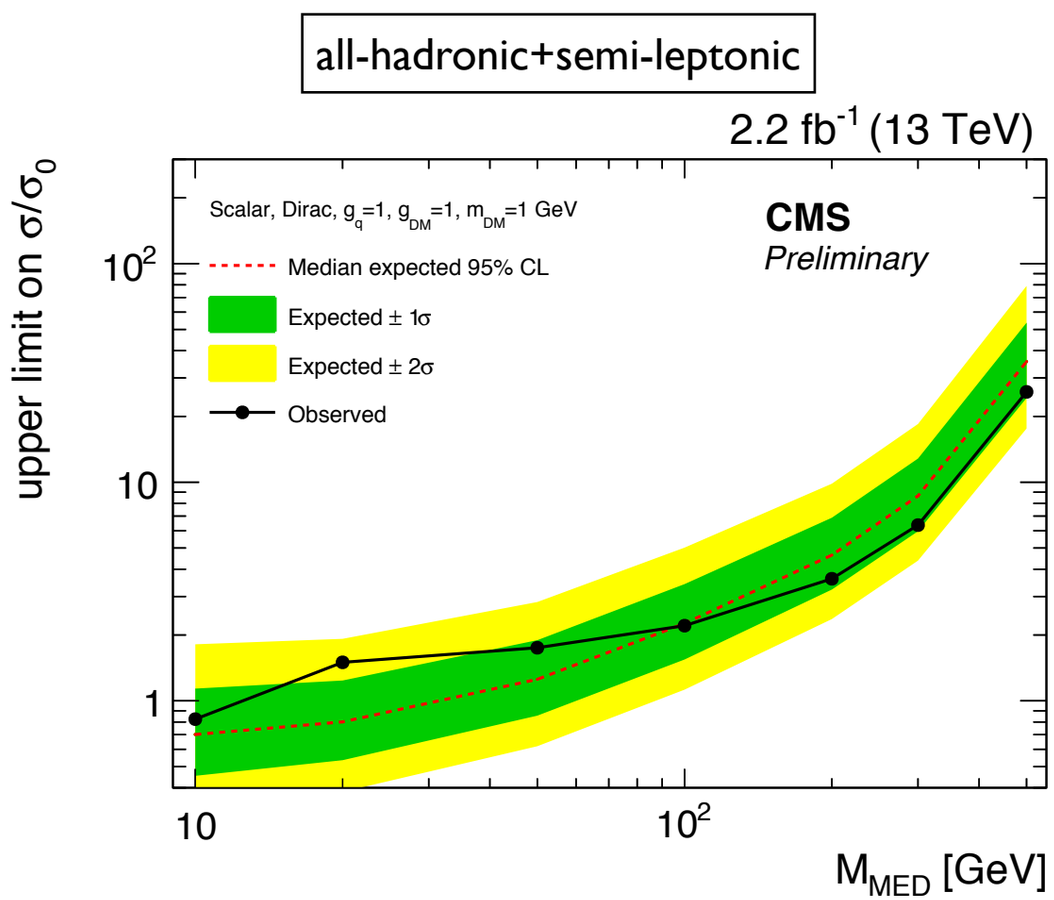


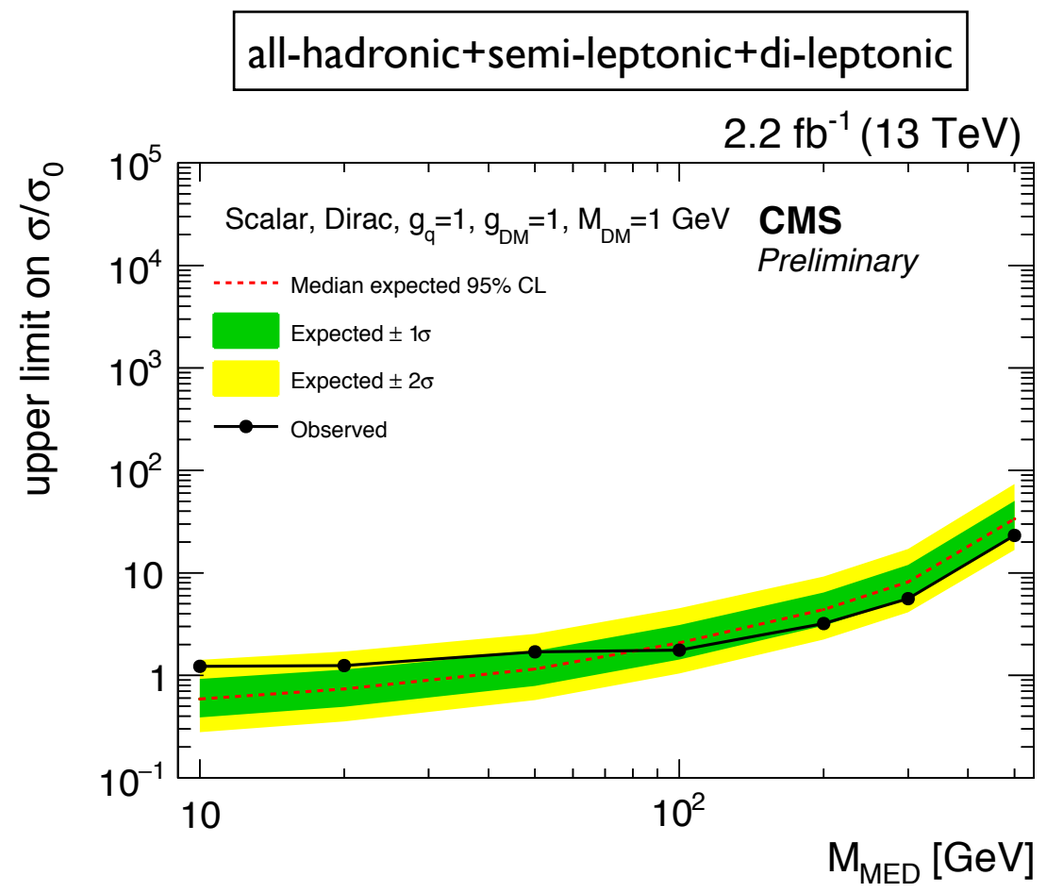
EXO-16-005

tt+DM

2015 data

- First expected exclusion of low-mass scalar mediators
  - Observed exclusion for M_{MED}=10 GeV, M_X=1 GeV (g_{SM}=g_{DM}=1) in all-hadronic/semi-leptonic only
  - Expected/Observed exclusion improved/worsened when adding di-leptonic
    - cause: upward data fluctuations in low-MET region



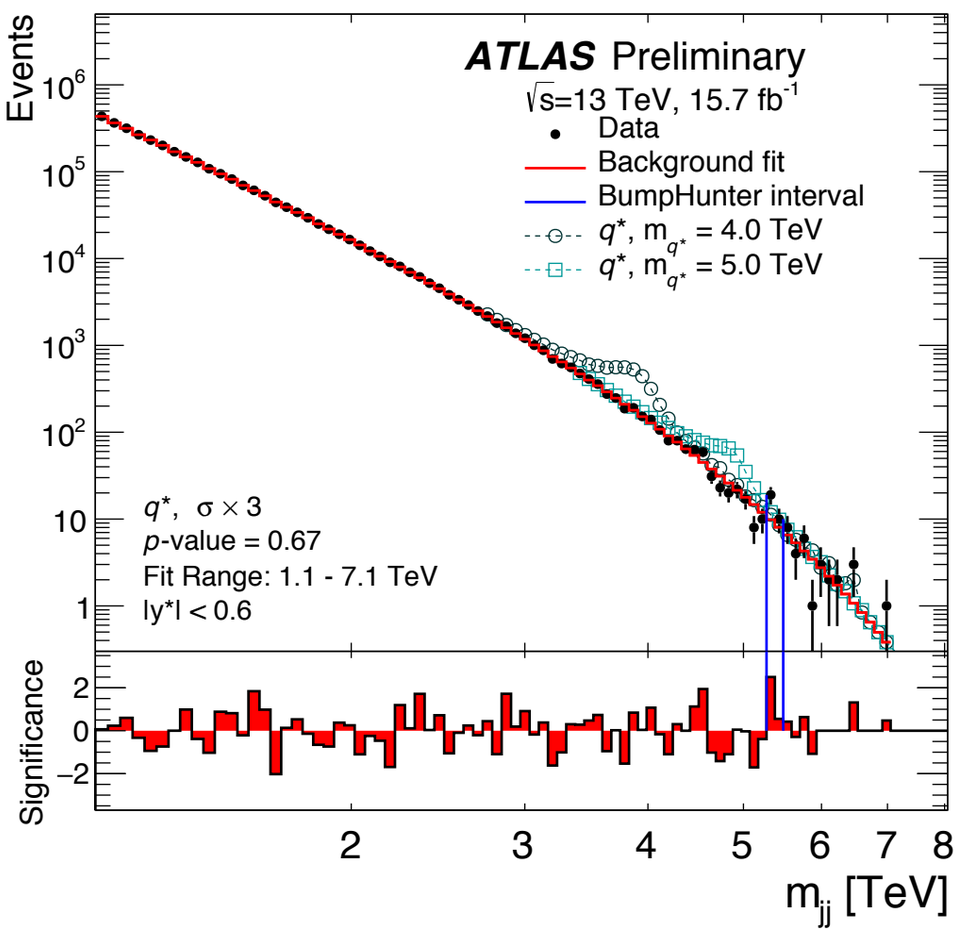


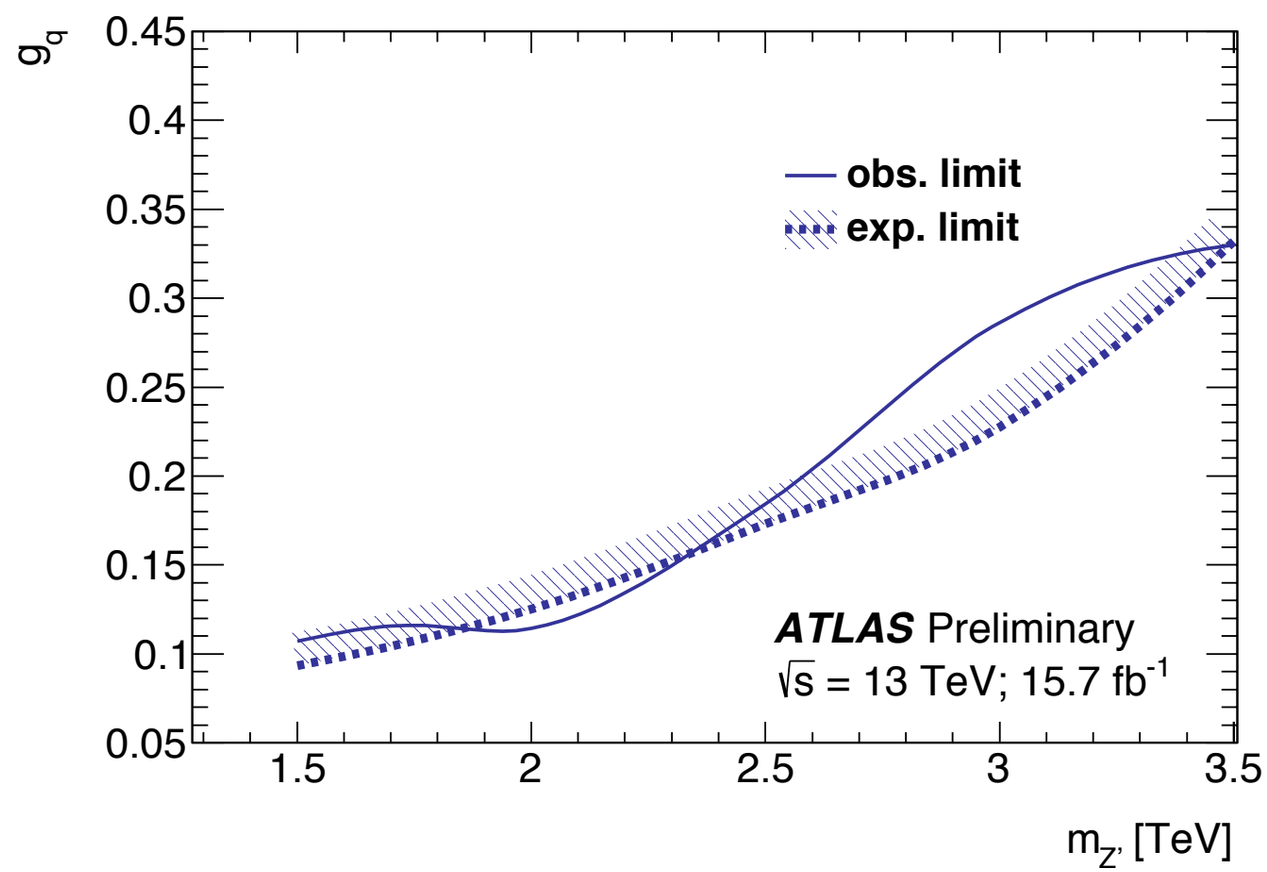
EXO-16-028

Dijet searches (high mass)

2015+2016 ICHEP data

- Selection: two energetic jets (P_T>440, 60 GeV) w/ small rapidity separation, veto on extra jets
- Background and signal predictions fitted to data in di-jet mass
  - a proper functional form (cross-checked in simulation) is used for the SM background
- Exclusions down to $M_{Z'}$ ~ 1.5 TeV
  - w/ trigger level analyses ("TLA") mass reach extended down to ~0.5 TeV (ATLAS-CONF-2016-030)



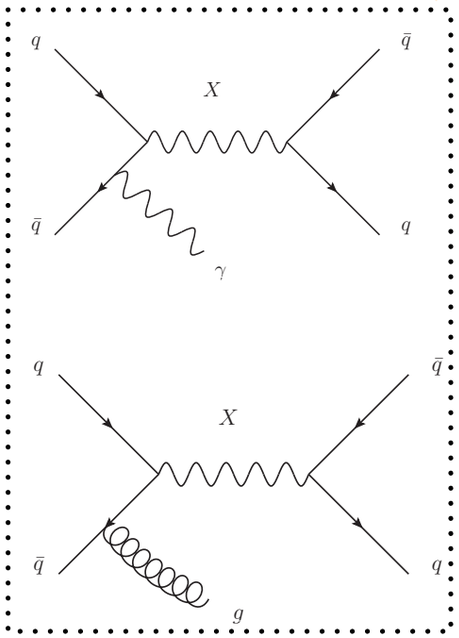


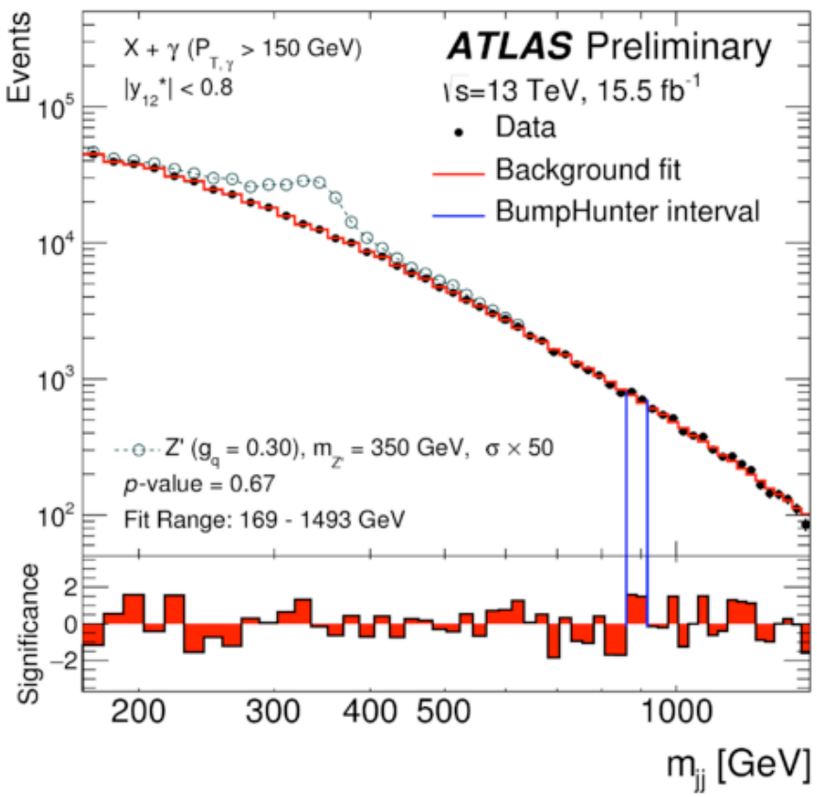
ATLAS-CONF-2016-069

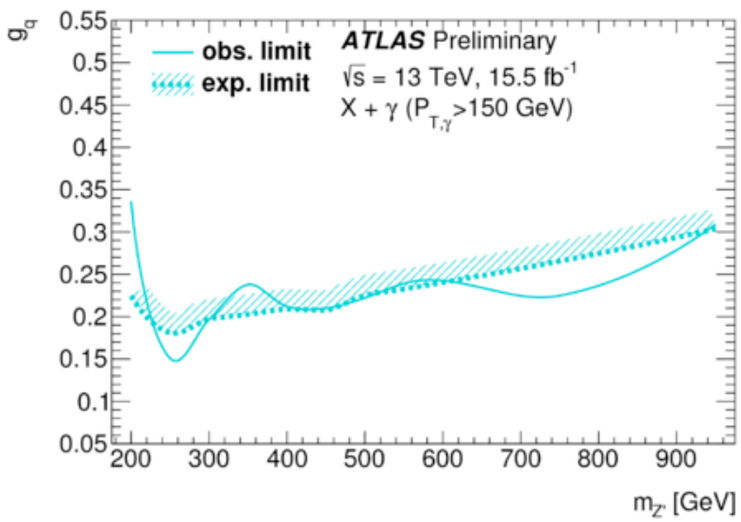
Dijet searches (low mass)

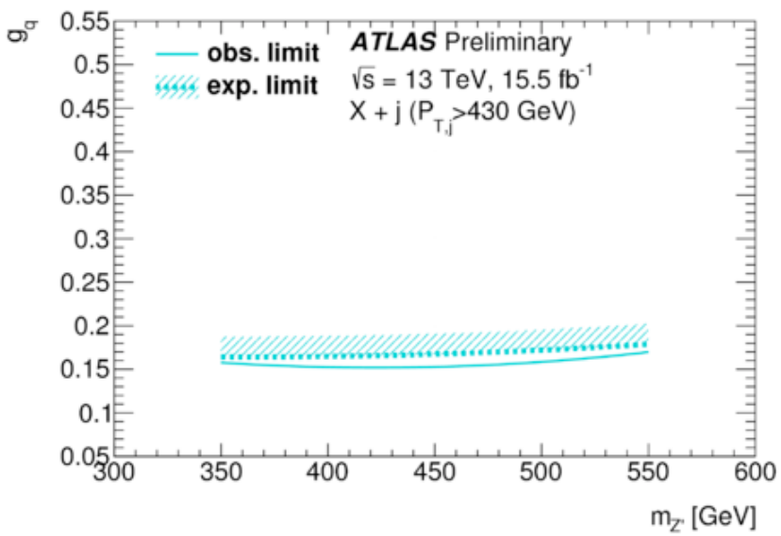
2015+2016 ICHEP data

- Look for resonance recoiling against high-P_T γ/jet
  - X+γ: E_T^{γ} > 150 GeV, two jets w/ P_T>25 GeV and small rapidity separation
  - X+j: P_T^{J} > 430 GeV, two extra jets w/ P_T>25 GeV and small rapidity separation
- Exclusions down to:
  - $M_{Z'}$ ~ 200 GeV (X+γ),
  - $M_{Z'}$ ~ 350 GeV (X+j)
    - inefficiencies at MZ' < 350 GeV are due to jet merging







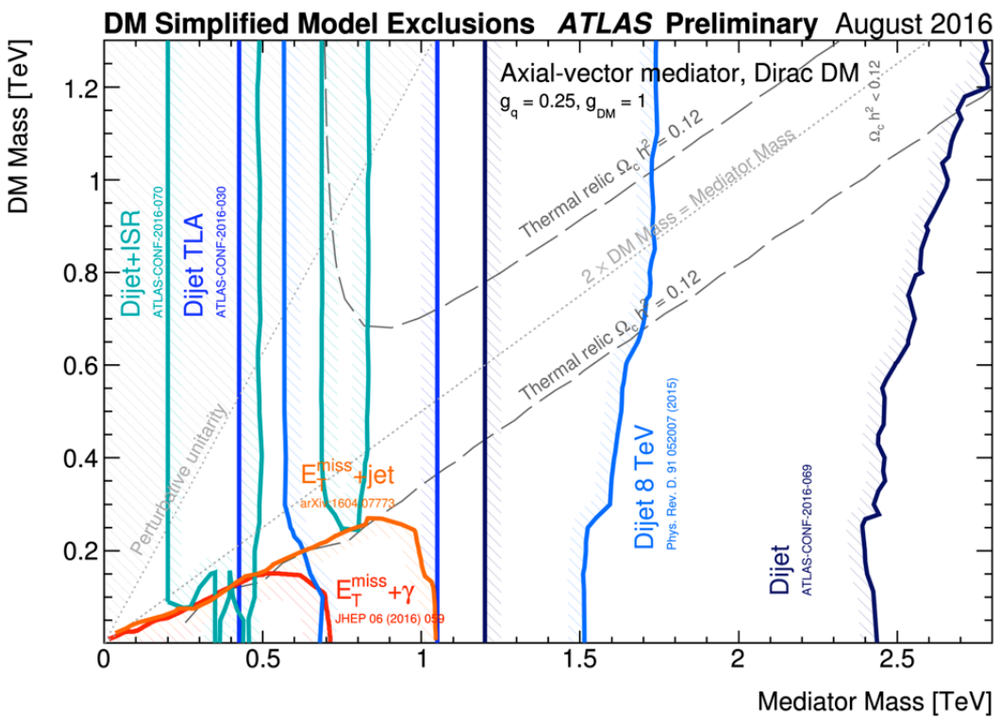


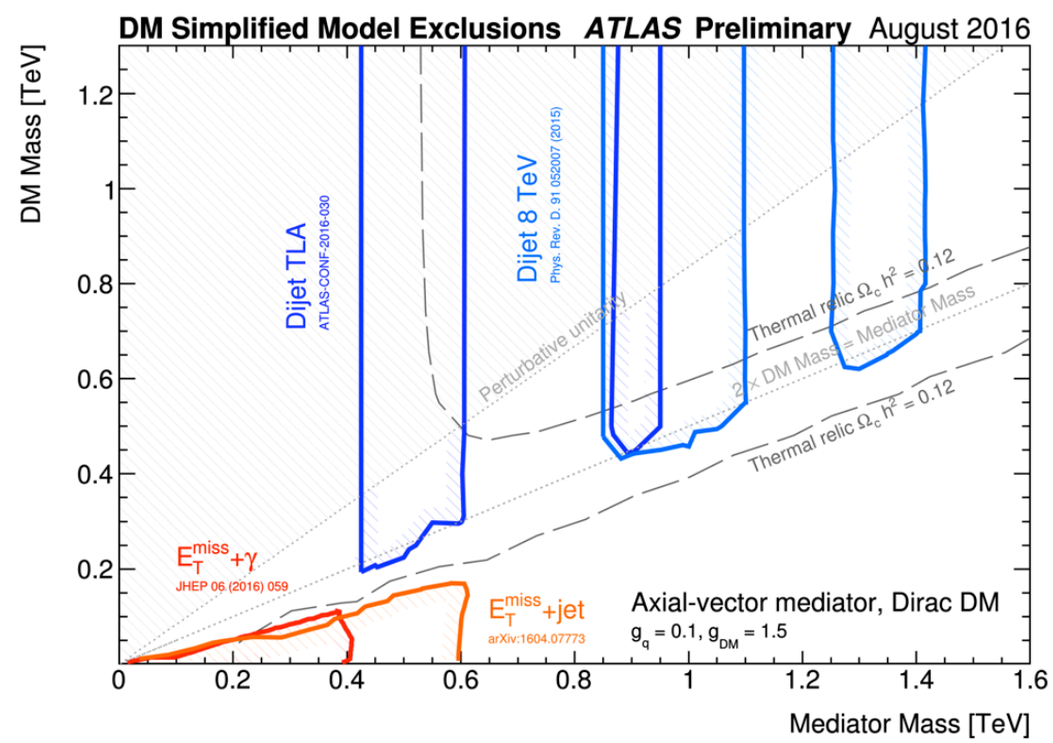
ATLAS-CONF-2016-070

ATLAS DM Summary

2015+2016 ICHEP data

- lepto-phobic Z' **dijet** results reinterpreted in terms of DM spin-1 mediators
  - Z' width depends on (M_{MED}, M_X)
- and compared to complementary **MET+X** results





Summary page

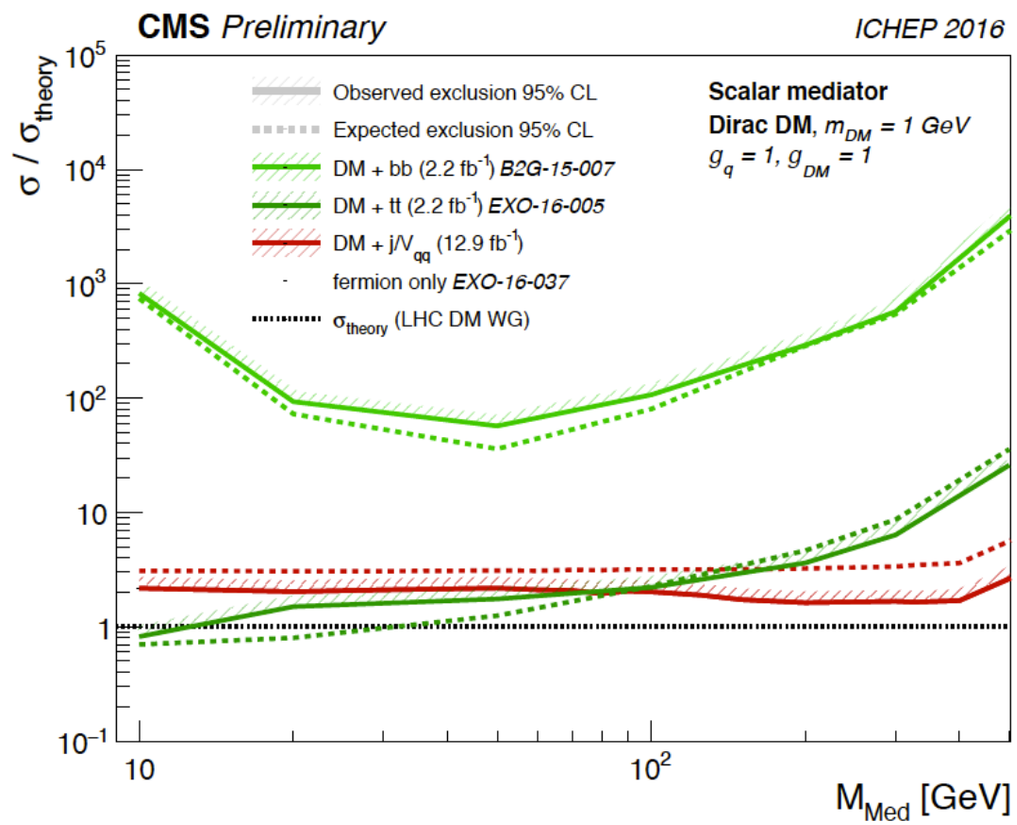
Dijet limits are very strong for (relatively) large g_q, complementary to MET+X limits at lower g_q

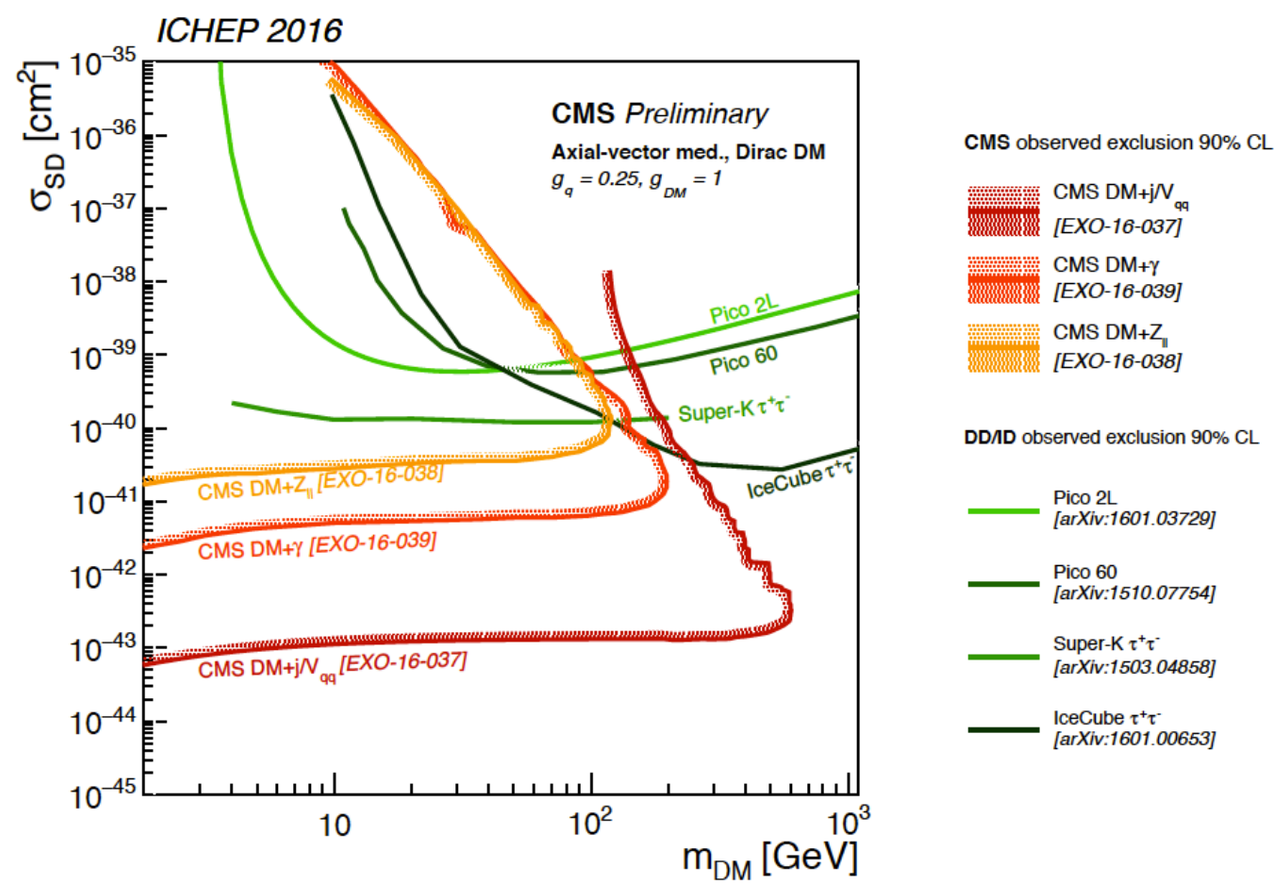
CMS DM Summary

2015+2016 ICHEP data

- Mono-Jet and tt+DM (all-hadronic/semileptonic) compared in term of scalar/pseudo-scalar models
- Recast of (MET+X) M_{MED} Vs M_X limits in terms of DM-nucleon cross sections

CMS-DP-2016/057





Collider results provide the most stringent limits up to Mχ ~100 GeV

Conclusions

- Remarkable amount of results at colliders:
  [see backup for more]
  - from MET+X searches
  - and recast of resonance searches
- Results explored new phase space
  - Multi-TeV spin-1 mediators
  - Low-Mass spin-0 mediators
- Re-interpretation in terms of DM-nucleon cross sections confirmed the complementarity between colliders and DD(/ID) experiments
- Unfortunately no signs of DM yet... :-(
- Hunt continues with way more data :-)

- backup

List of CMS/ATLAS DM searches

K. Hahn Aspen 2017 talk

X	Dataset	Documentation
jet or hadronic V	2016, 12.9 fb-1	EXO-16-037, 1703.01651
photon	2016, 12.9 fb-1	EXO-16-039
Z(ll)	2016, 12.9 fb-1	EXO-16-038
Higgs (γγ)	2015, 2.3 fb-1	EXO-16-011
Higgs (bb), with γγ combo	2015, 2.3 fb-1	EXO-16-012
tt (hadronic, semileptonic)	2015, 2.2 fb-1	EXO-16-005
tt (dileptonic + tt combination)	2016, 2.2 fb-1	EXO-16-028
t hadronic	2016, 12.9 fb-1	EXO-16-040
bb	2015, 2.2 fb-1	B2G-15-007

Not really X	Dataset	Documentation
dijets	2016, 12.9 fb-1	EXO-16-032, 1611.03568
boosted dijets	2016, 2.7 fb-1	EXO-16-030
dijets	2016, 27+36 fb-1	EXO-16-056

S. Schramm 2016 Moriond talk

Summary

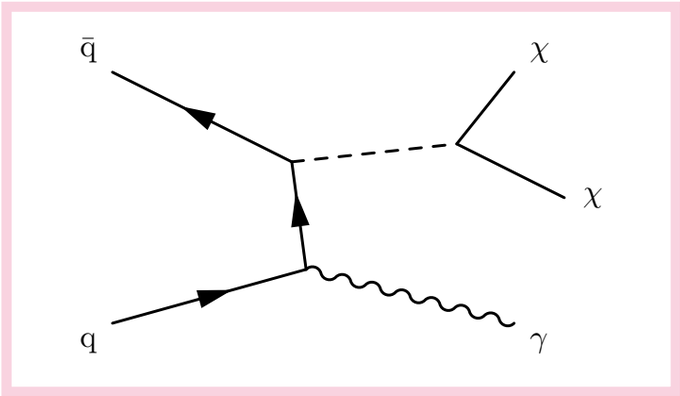
Analysis summary table

ATLAS EXPERIMENT
UNIVERSITÉ DE GENÈVE

Analysis	Dataset	Public link	
Production search:			
E_T^{miss}+jet	2015	Paper: EXOT-2015-03	
$E_T^{miss}+\gamma$	2015	Paper: EXOT-2015-05	
E_T^{miss}+Z($\to \ell\ell$)	2015+2016	Note: ATLAS-CONF-2016-056	new!
E_T^{miss}+W/Z($\to qq$)	2015	Paper: EXOT-2015-08	new!
E_T^{miss}+H($\to bb$)	2015	Note: ATLAS-CONF-2016-019	
E_T^{miss}+H($\to \gamma\gamma$)	2015+2016	Note: ATLAS-CONF-2016-087	new!
E_T^{miss}+H($\to \ell\ell\ell\ell$)	2015	Note: ATLAS-CONF-2015-059	
E_T^{miss}+b-jets	2015+2016	Note: ATLAS-CONF-2016-086	new!
$E_T^{miss}+t\bar{t}$ (0ℓ)	2015+2016	Note: ATLAS-CONF-2016-077	new!
$E_T^{miss}+t\bar{t}$ (1ℓ)	2015+2016	Note: ATLAS-CONF-2016-050	new!
$E_T^{miss}+t\bar{t}$ (2ℓ)	2015+2016	Note: ATLAS-CONF-2016-076	new!
Mediator search:			
Dijet	2015+2016	Note: ATLAS-CONF-2016-069	new!
Trigger-level dijet	2015	Note: ATLAS-CONF-2016-030	
Dijet+ISR	2015+2016	Note: ATLAS-CONF-2016-070	new!
Summary plots:			
Mediator searches	2015+2016	Plot: Summary plot page	new!
Search combination	2015+2016	Plot: Summary plot page	new!

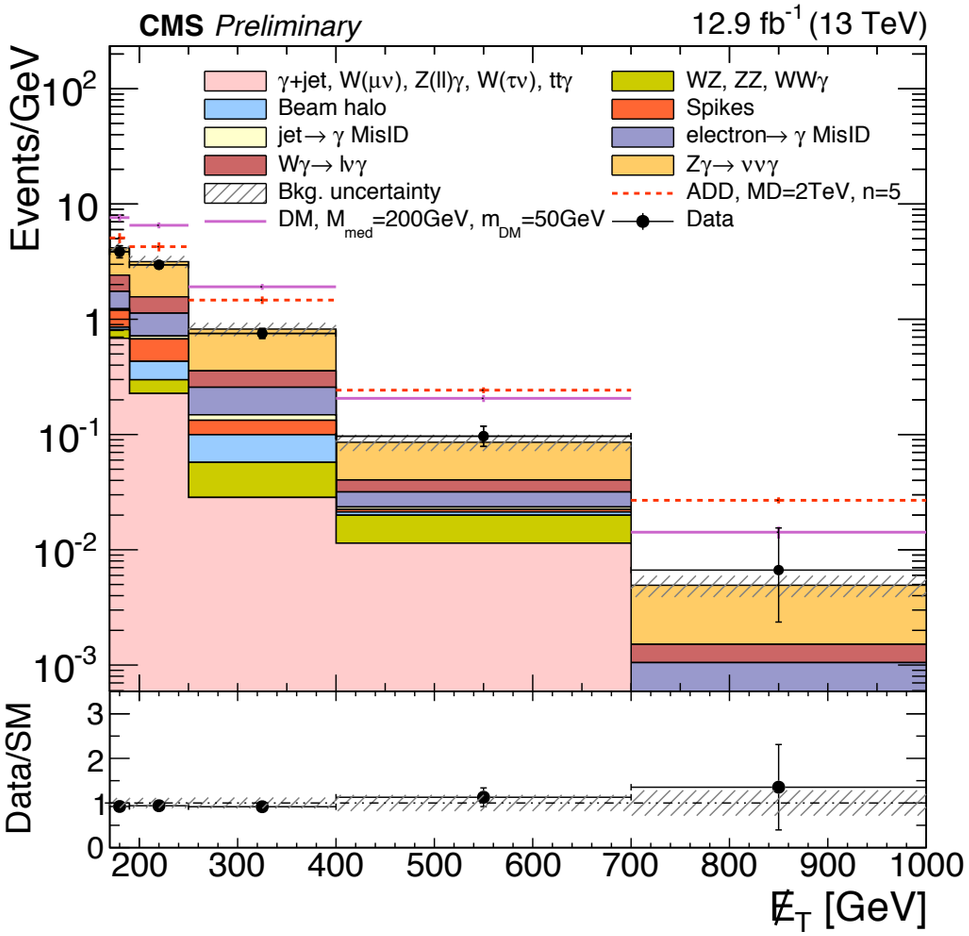
Mono-Photon

ICHEP 2016 data



- Selection: MET>170 GeV, p_T^{γ} > 175 GeV, $\Delta\varphi(\gamma,\text{MET})>2$, veto e/μ

- Major backgrounds:
  - Z(νν)+jets, W(lν)+jets:
    - estimated from simulations with NNLO QCD +NLO corrections
    - cross-checked in Z(ll)/W(μν) CRs
  - (e/jets->)γ MisID and non collisional background:
    - estimated from CRs or SR sidebands

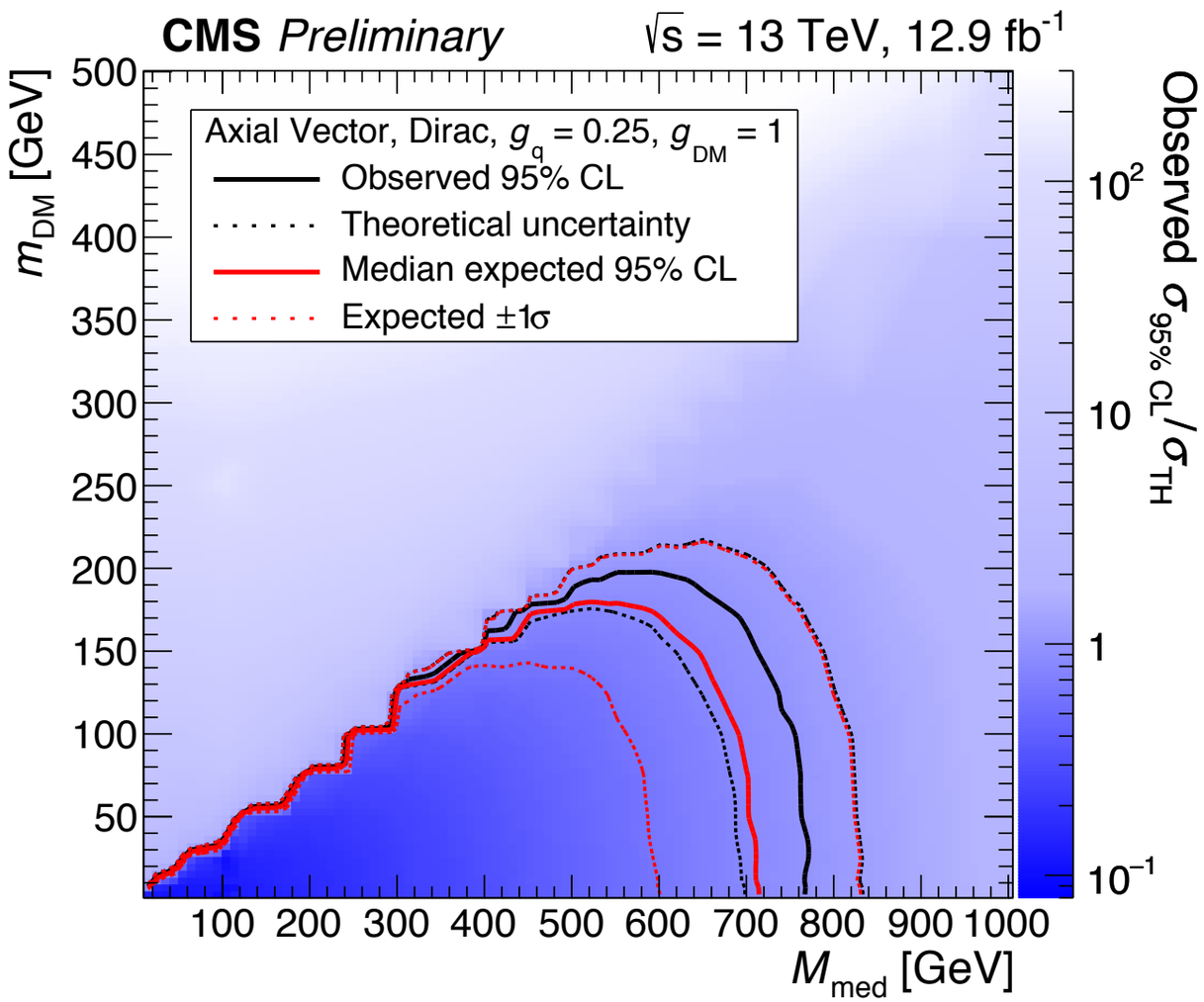


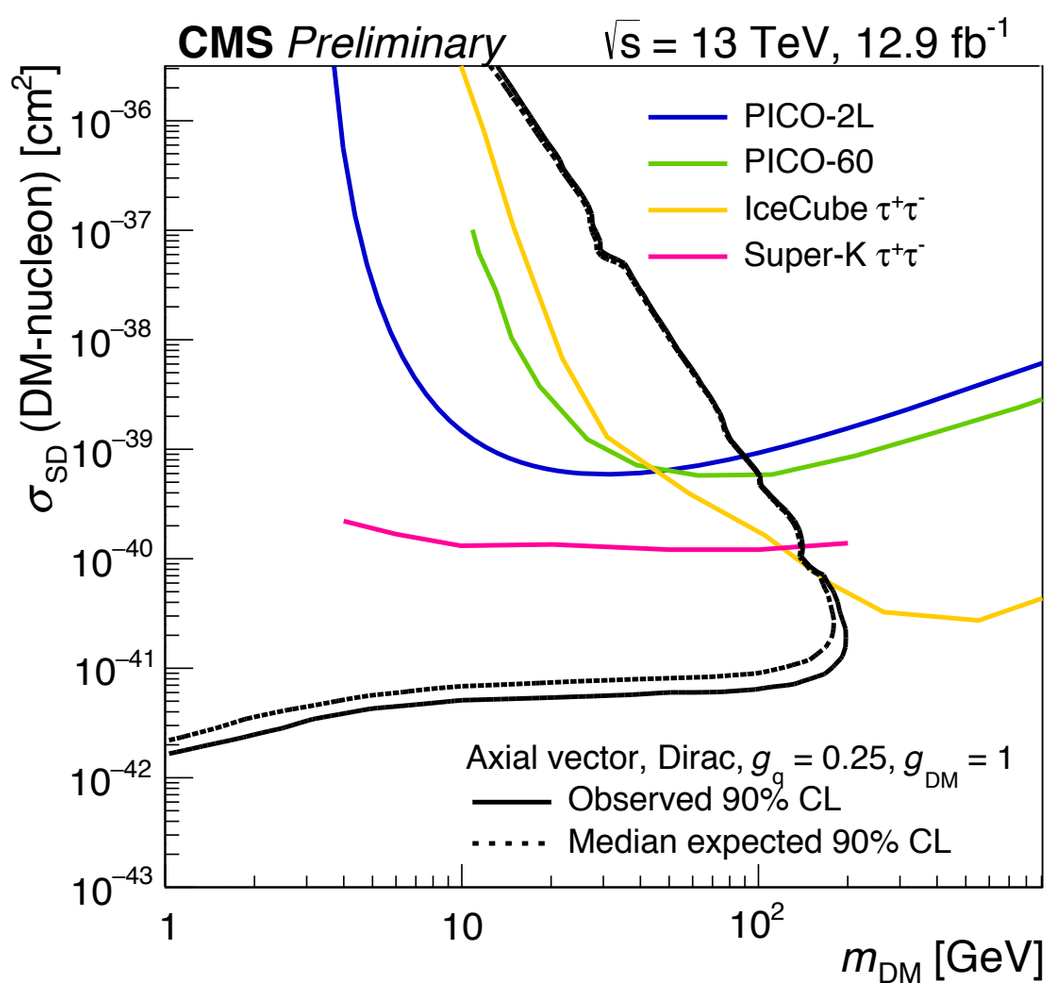
- Counting experiment to extract a potential excess

Mono-Photon

ICHEP 2016 data

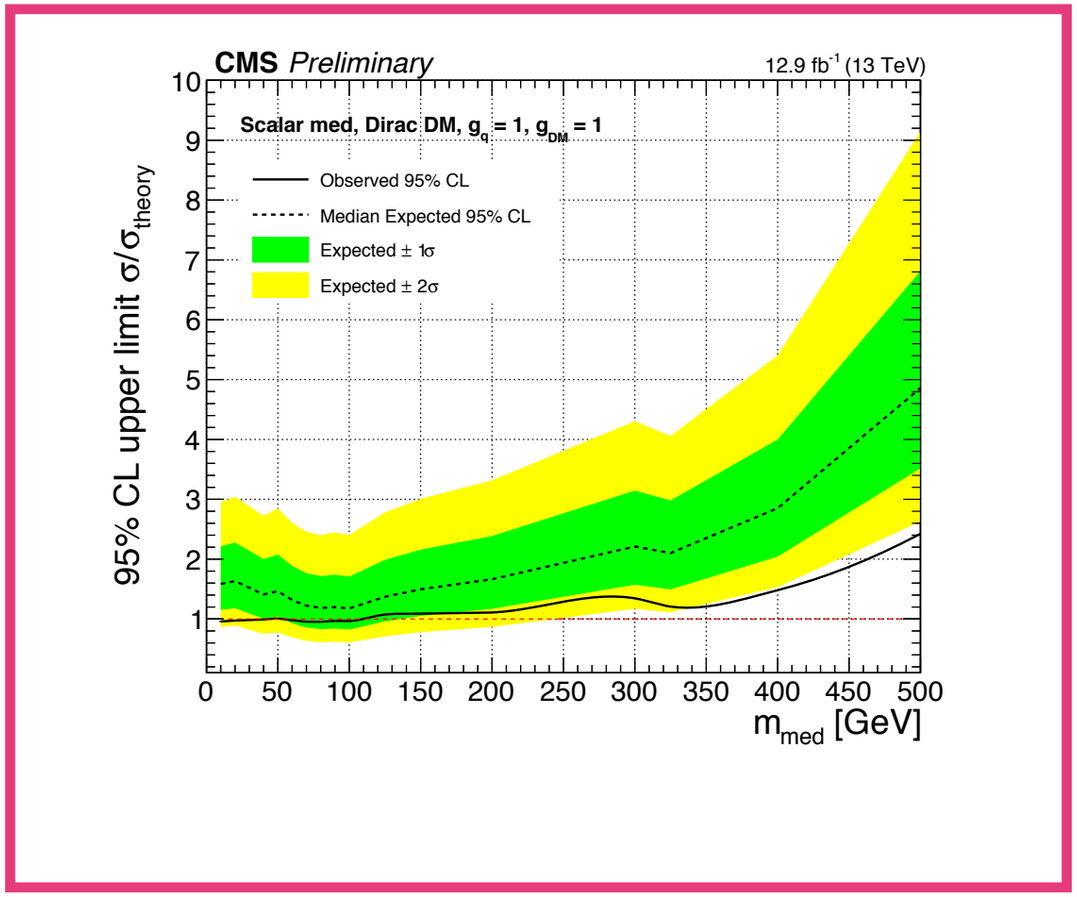
- No excess observed
- M_{MED}<760 GeV, M_X<200 GeV excluded (vector/axial)
  - Results used also to set limits on various ADD extra dimension scenarios
- Recast limits on SI/SD of DM-nucleon cross sections and compare to DD results





Mono-Jet/Mono-W/Z

2016 ICHEP data

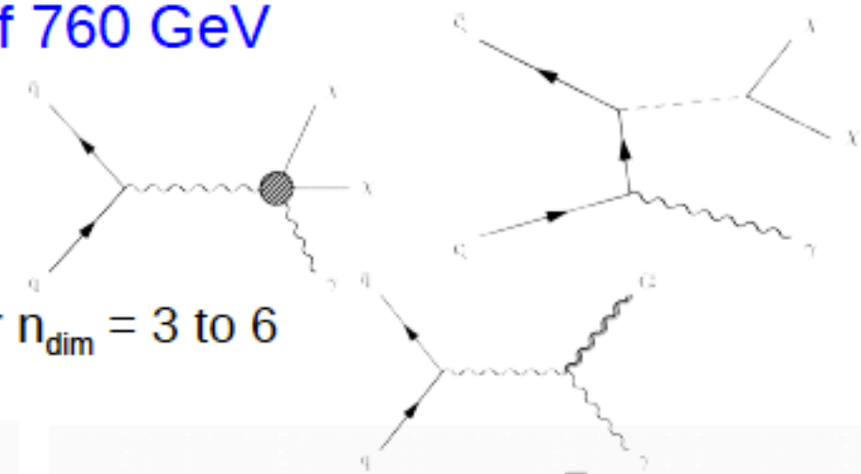


EXO-16-037

couplings to fermions and bosons

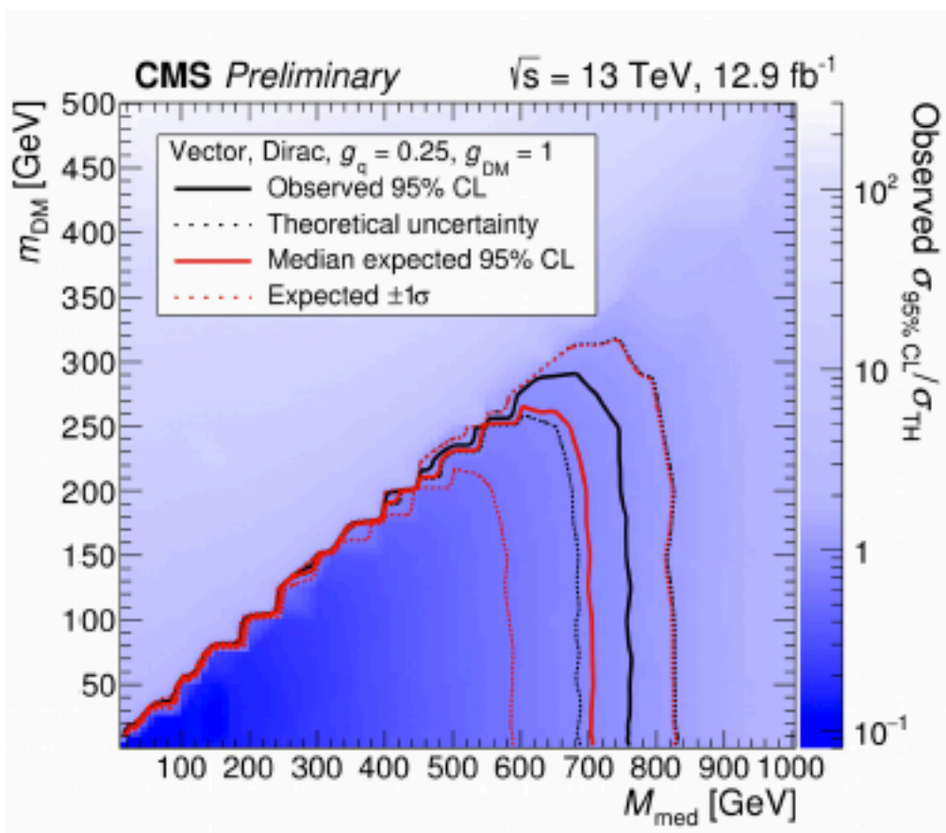
mono-photon

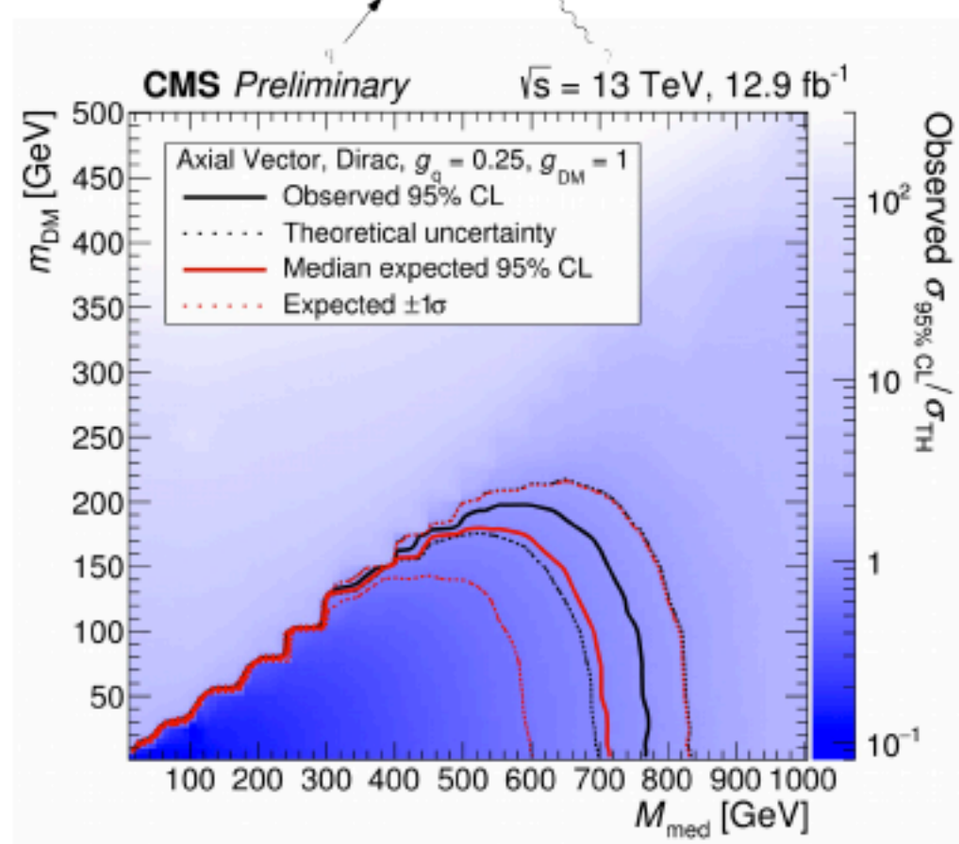
Limits for vector/axial mediator of 760 GeV



Also:

- Dim-7 EFT scale up to 620 GeV
- ADD LED M_D > 2.44 to 2.60 TeV for n_{dim} = 3 to 6





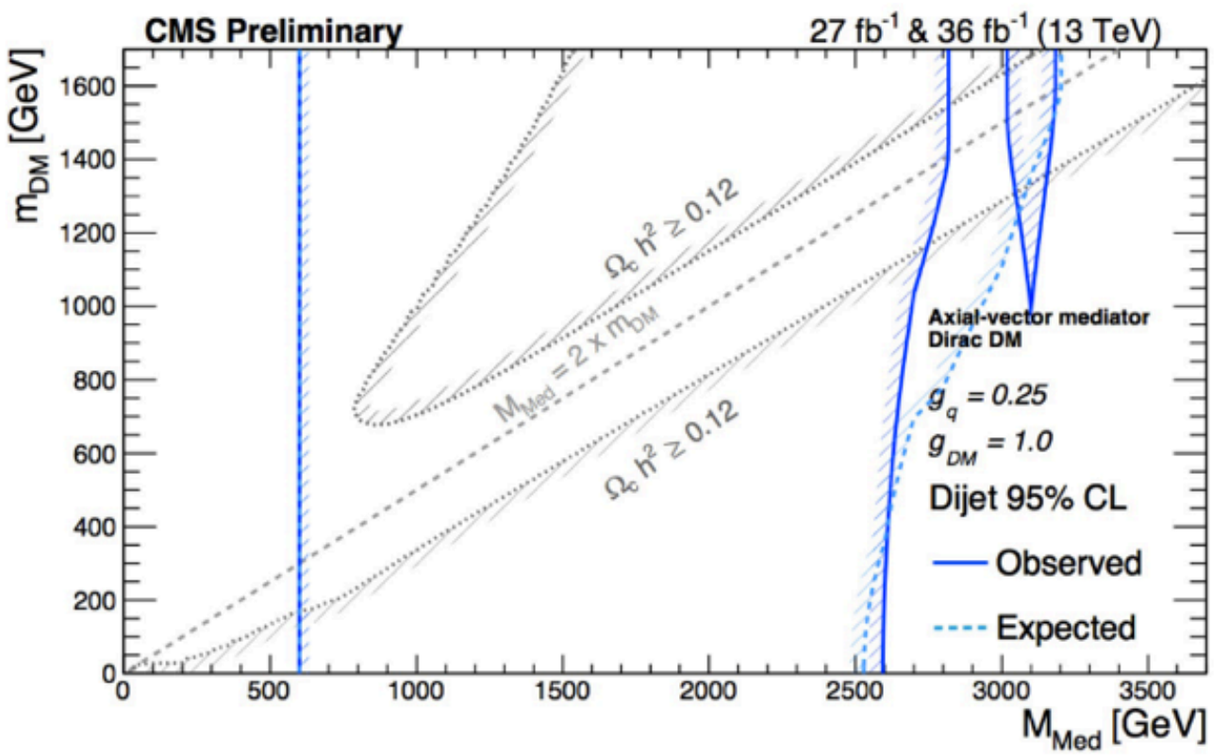
Update: DM Mediator Search w/ Dijets

A combination of :

- Low-mass (0.6-1.6 TeV) search with 26 fb-1 using data scouting
- High-mass (> 1.6 TeV) search with 36 fb-1

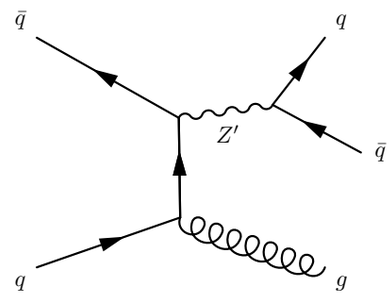
Model-independent search for excess in dijet mass spectrum

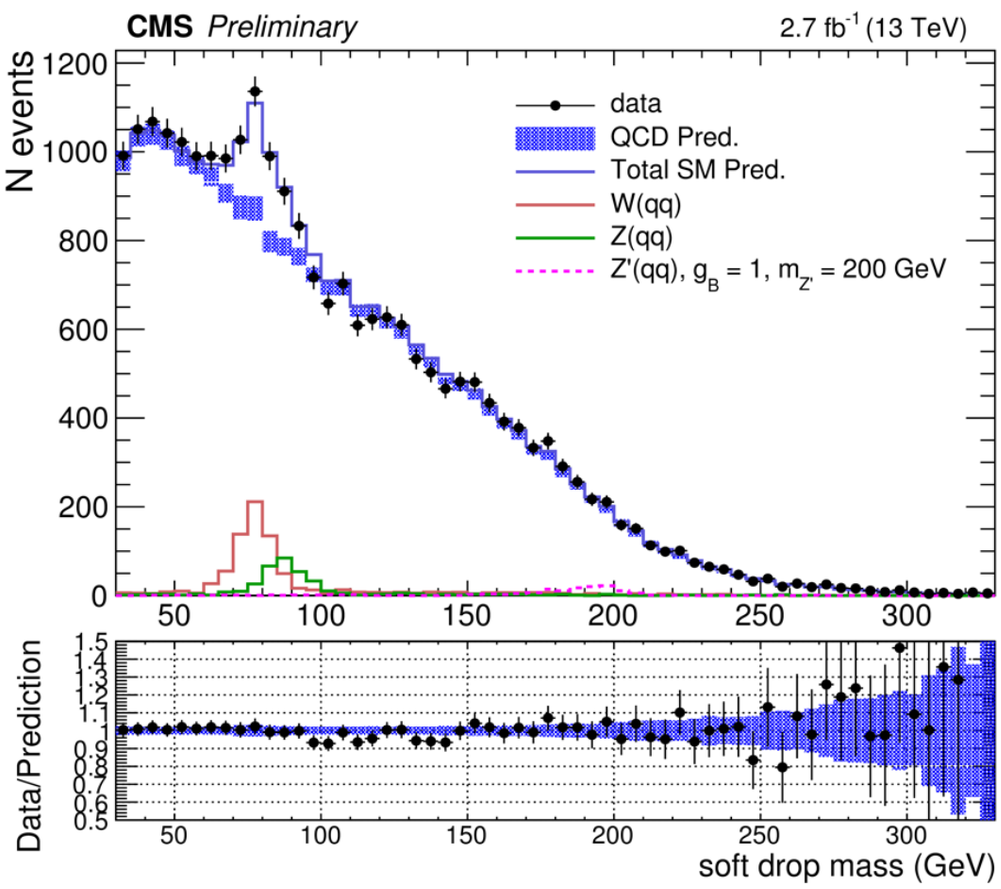
- Sensitive to wide range of BSM, including DM
- AV mediators excluded between 0.6 – 2.6 TeV

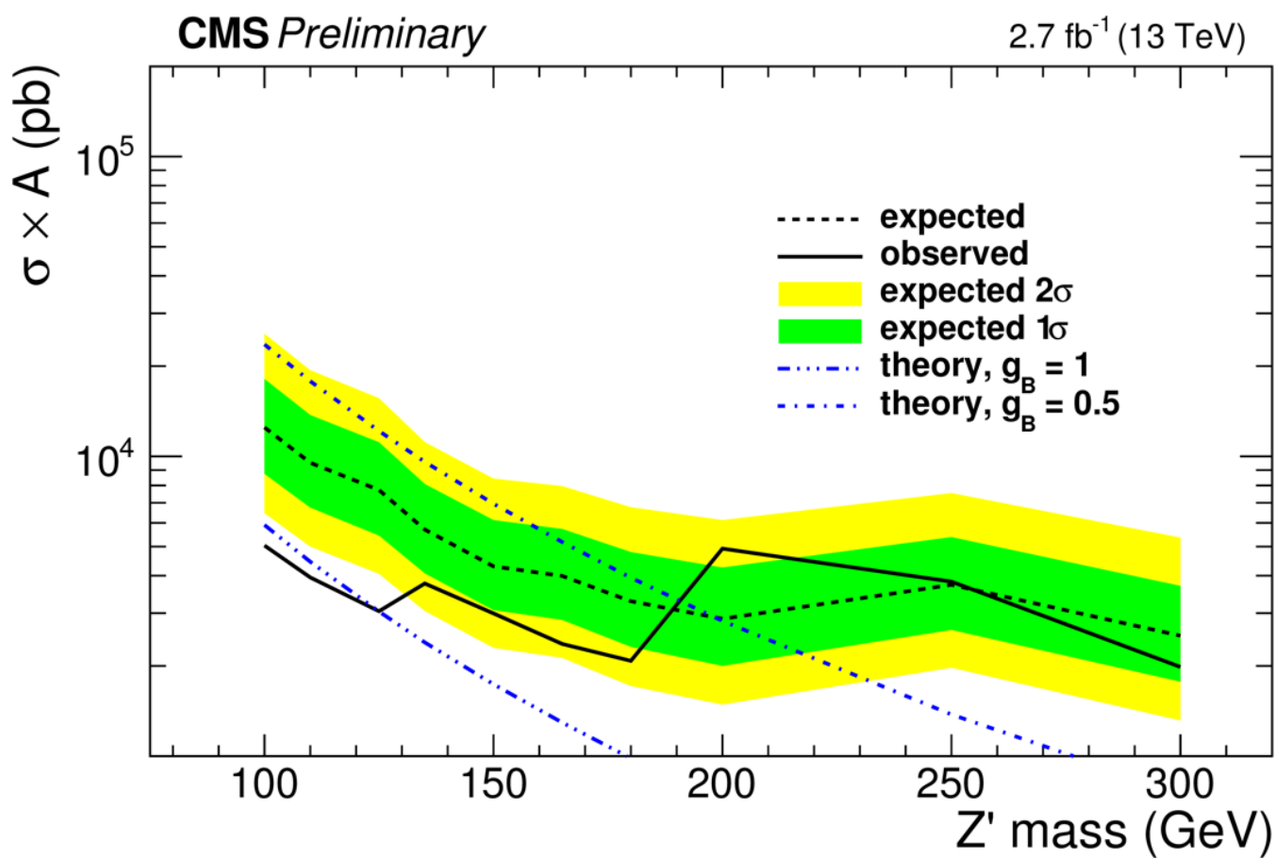


Dijet (low mass)

2015 data





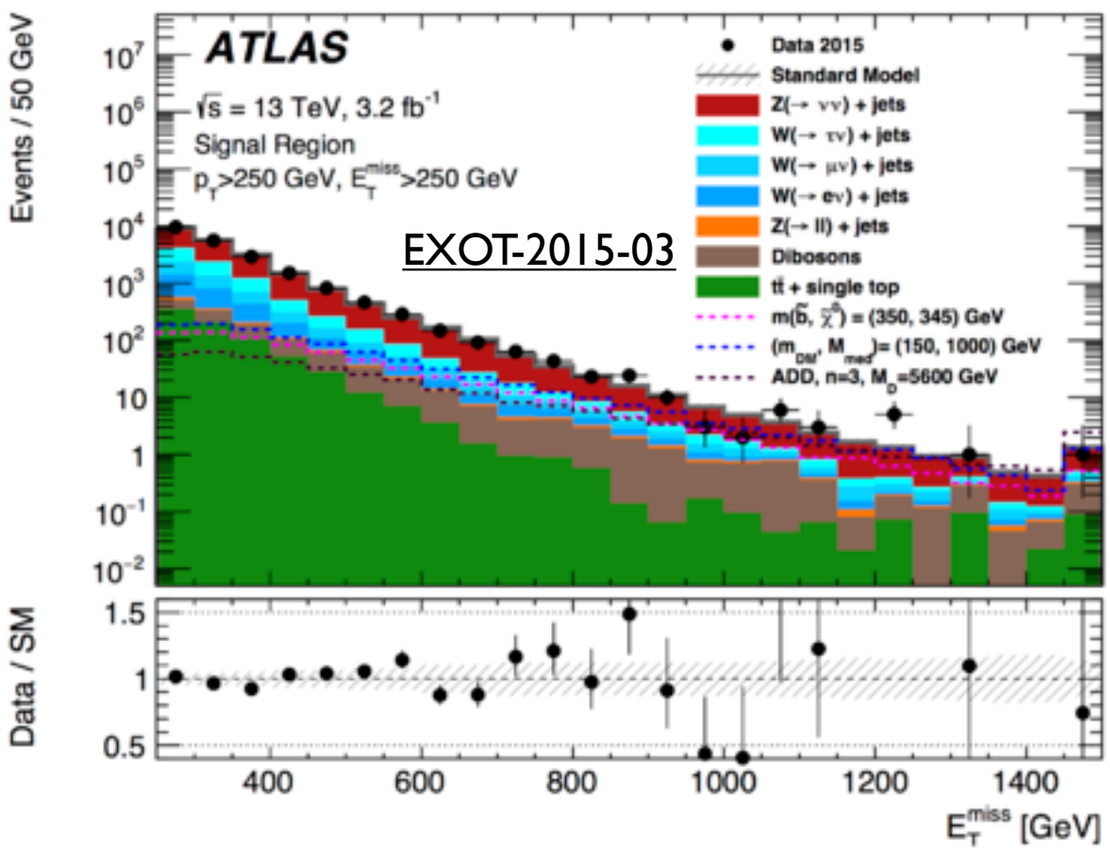


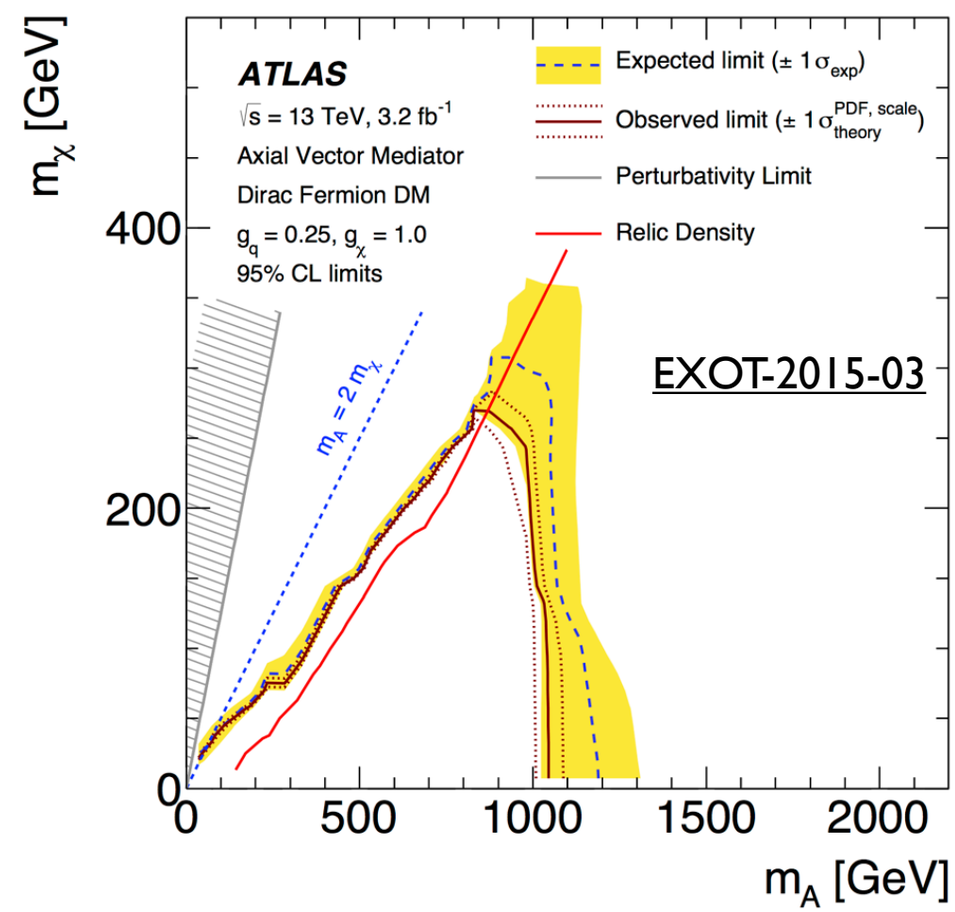
EXO-16-030

Mono-Jet/Mono-W/Z

2015 Data

- Selection: MET>200 GeV, >= 1 jet, lepton veto
  - additional cut to remove events with instrumental MET
- Categorization in several inclusive+exclusive SRs by varying the MET cut from 250 GeV to 700 GeV
- No observed excess:
  - axial-vector model: Mmed< 1 TeV, Mchi<250 GeV excluded @ 95% CL
  - data used for exclusion limits of other models (extra spatial dimensions, SUSY)





Recast (M_{MED}, $M\chi$) to nucleon-DM xsec (*arXiv:1603.04156*)

$$\sigma_{\rm SI} = \frac{f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4} ,$$

Vector

$$f(g_q) = 3 g_q ,$$

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2 .$$

Scalar

$$f(g_q) = 1.16 \cdot 10^{-3} g_q ,$$

and therefore the size of a typical cross section is

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-43}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{1}\right)^2 \left(\frac{125\,{\rm GeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2 .$$

Recast (M_{MED}, $M\chi$) to nucleon-DM xsec (*arXiv:1603.04156*)

$$\sigma_{\rm SD} = \frac{3\, f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}\,. \qquad f^{p,n}(g_q) = \Delta_u^{(p,n)}\, g_u + \Delta_d^{(p,n)}\, g_d + \Delta_s^{(p,n)}\, g_s$$

Under the assumption that the coupling g_q is equal for all quarks, one finds

$$f(g_q) = 0.32\, g_q\,,$$

and thus

$$\sigma^{\rm SD} \simeq 2.4 \times 10^{-42}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2\,.$$

Axial-vector