COLLIDER SEARCHES FOR DARK MATTER

YORAM ROZEN
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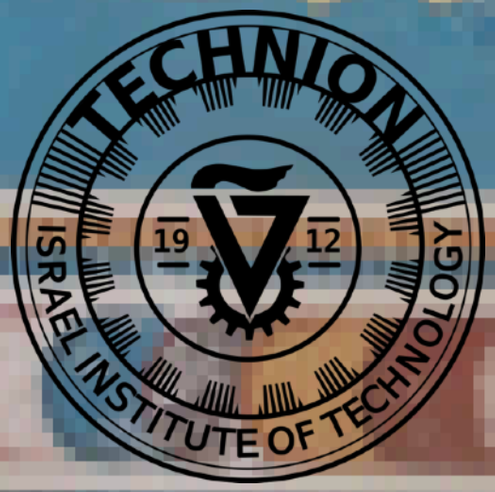
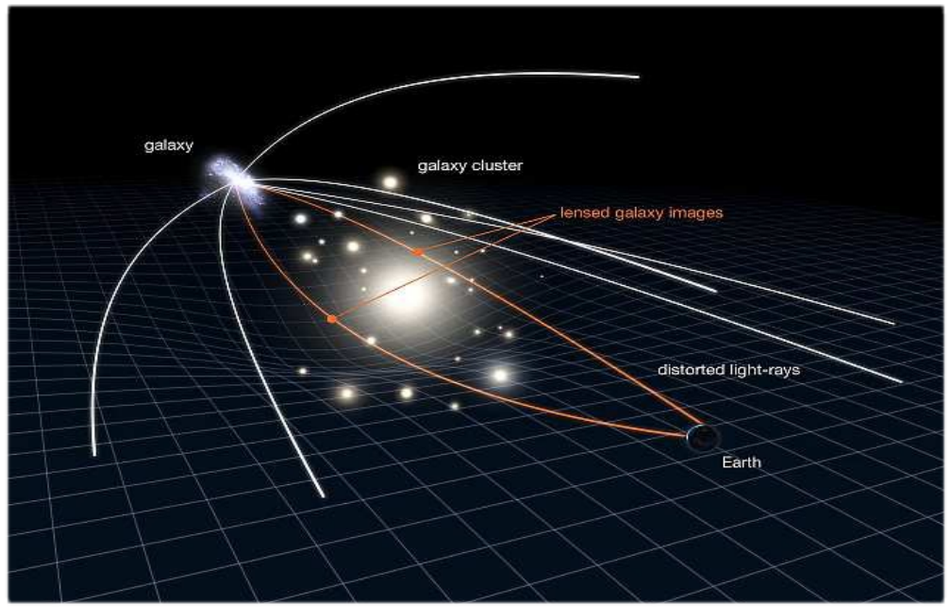
ON BEHALF OF THE ATLAS AND CMS COLLABORATIONS

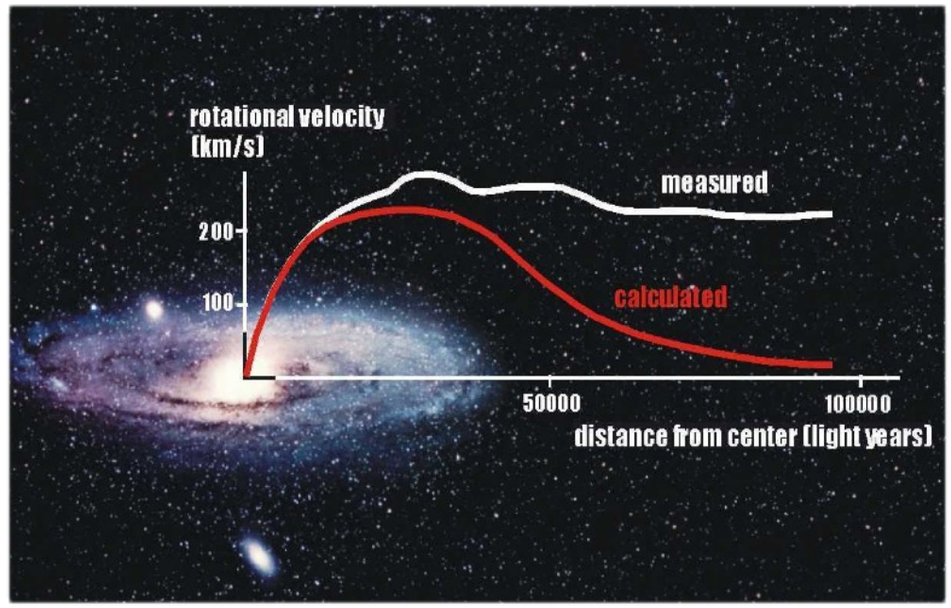


DM evidence

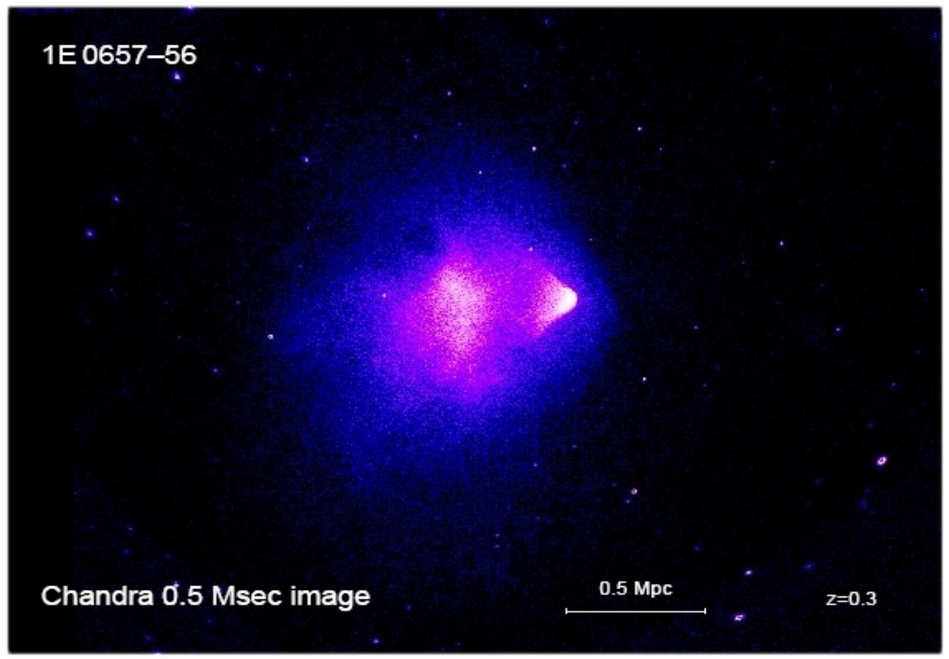
Gravitational lensing



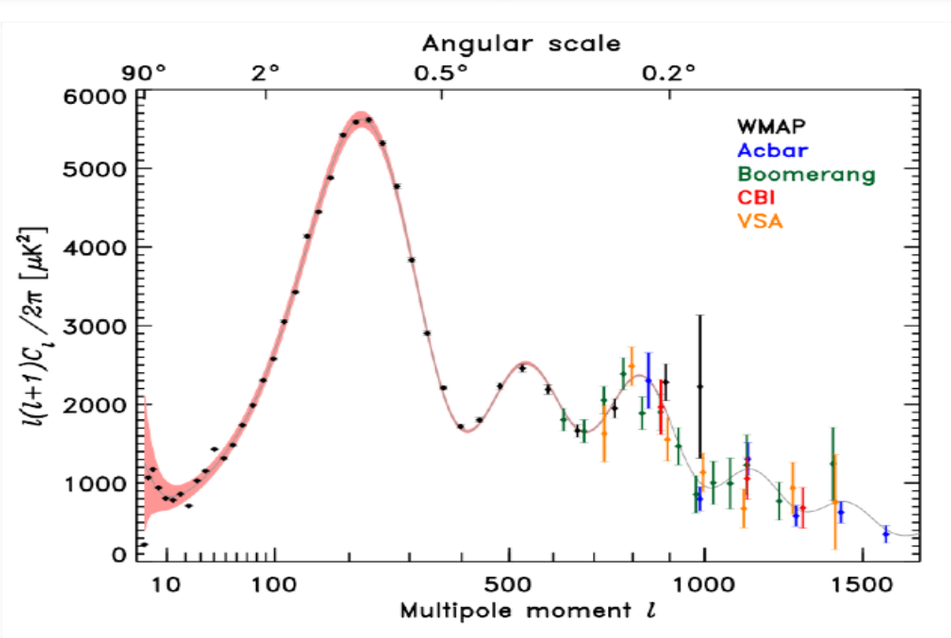
Galactic rotation curve



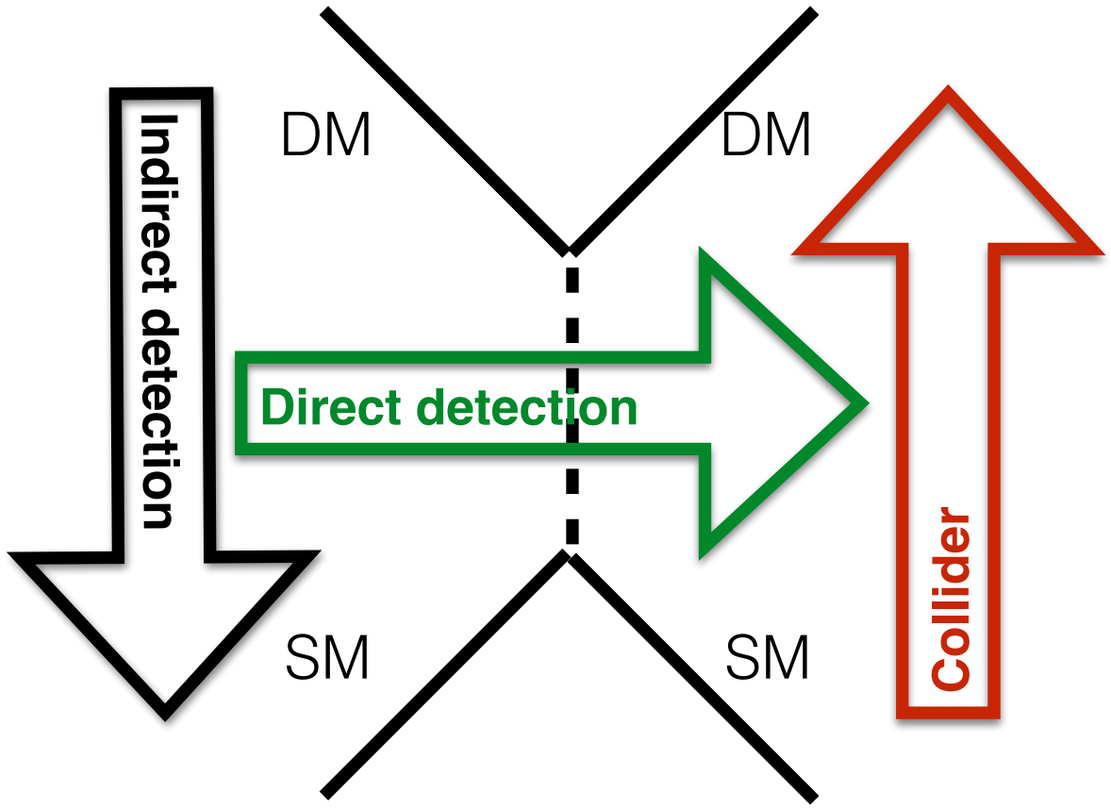
Bullet cluster - DM collision in galactic merger

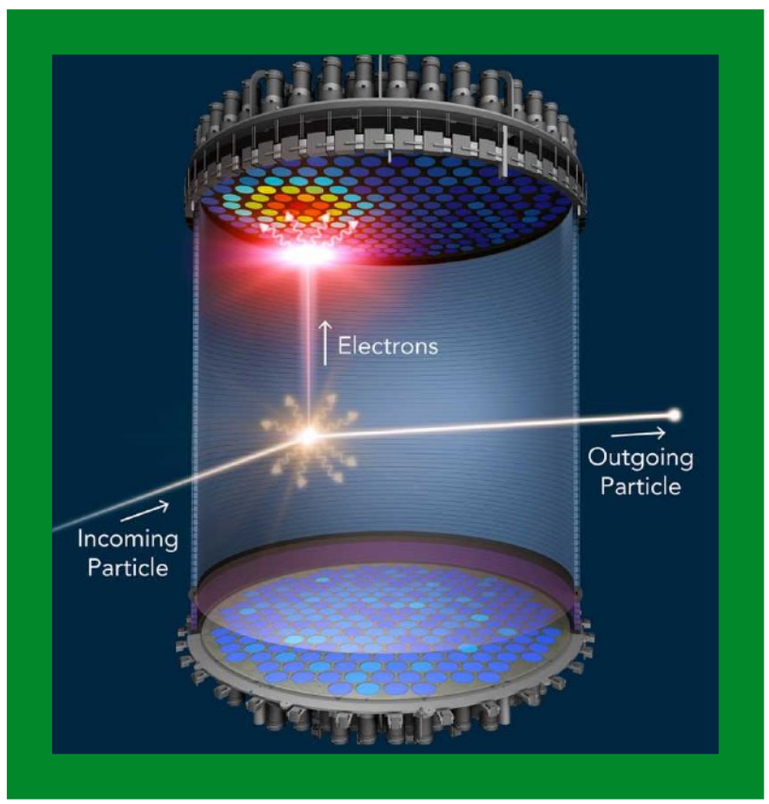


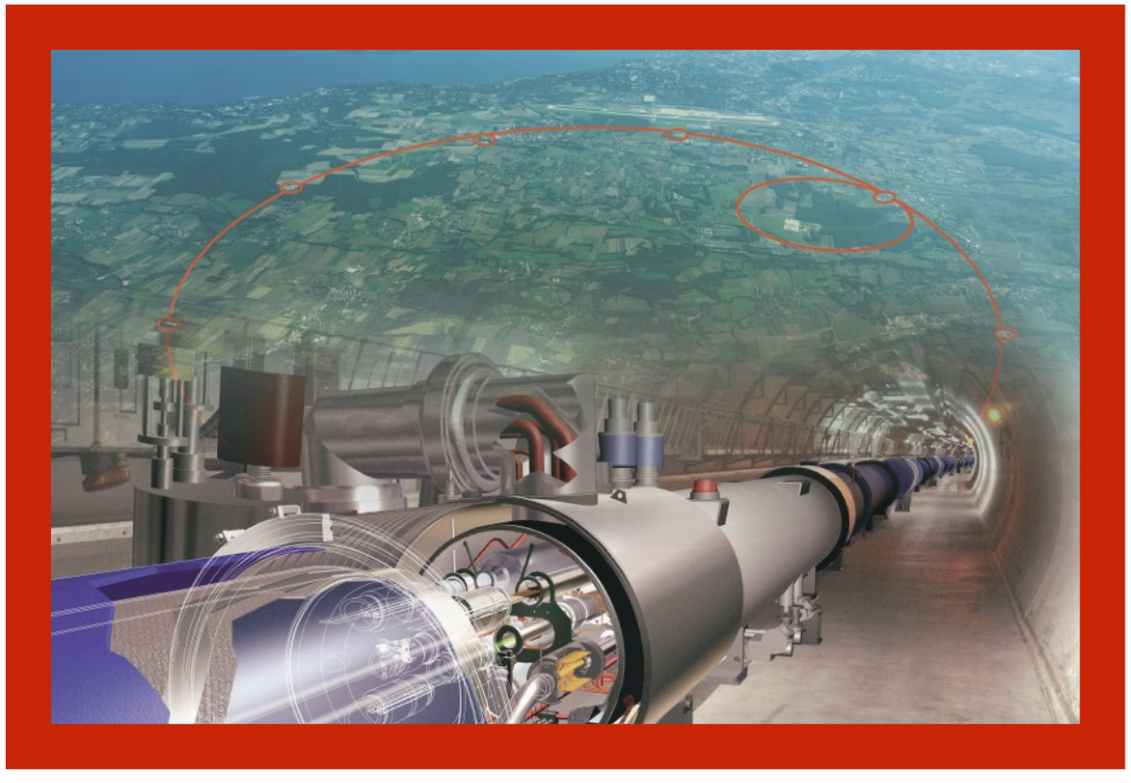
Cosmic Microwave Background



DM Search Methods

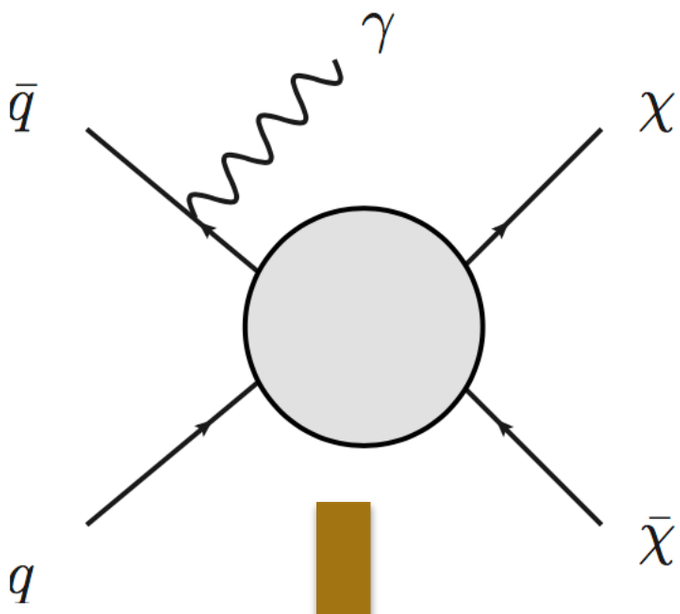




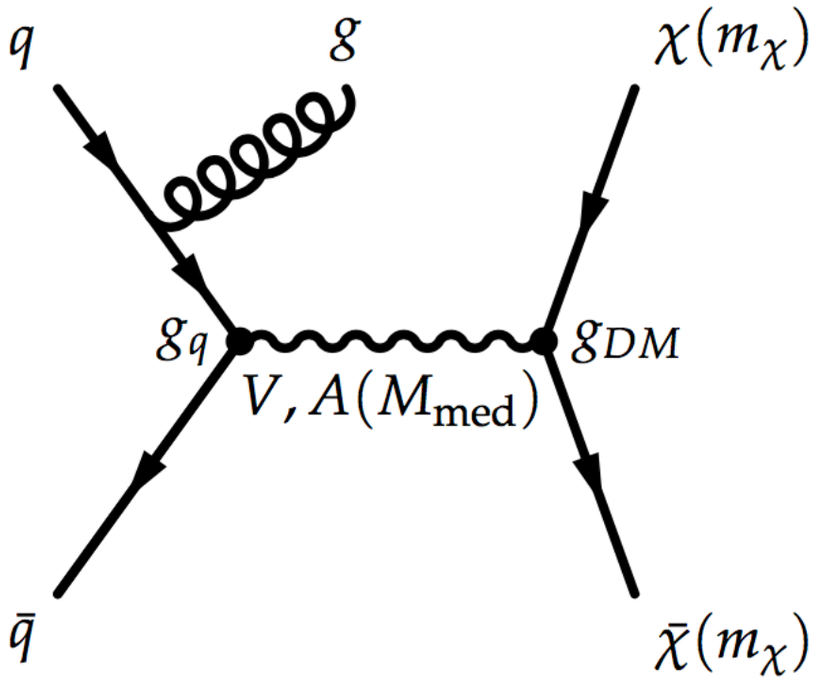


EFT -> Simplified Models

https://arxiv.org/abs/1507.00966



- 4 point interaction
- Valid if mediator mass much larger than momentum
  - Used for RUN1 but generally breaks at the LHC



Simplified models:

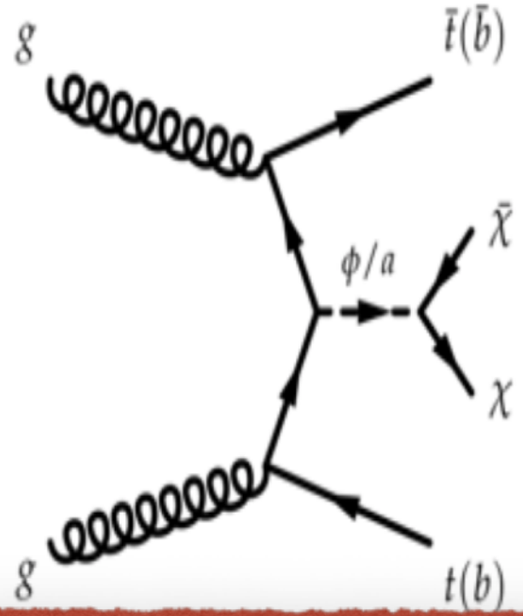
- Keep mediator information:
  mass, spin, coupling
- Can be a starting point to build a complete theory
- Colliders can search directly for the mediator
- Benchmark model for LHC RunII

$$\mathcal{L}_{\mathrm{vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$

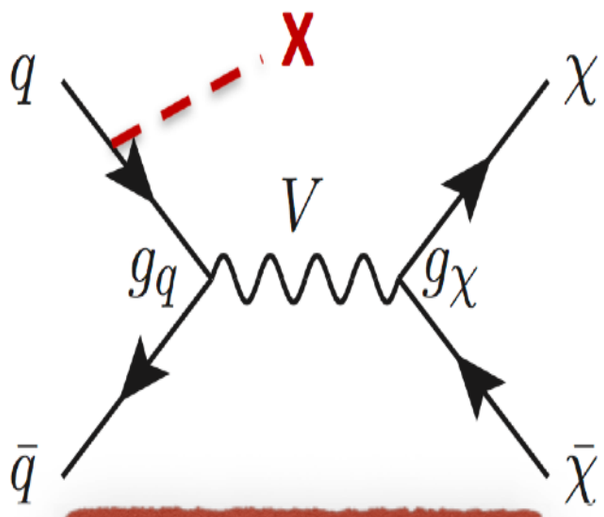
$$\mathcal{L}_{\mathrm{axial-vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu\gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu\gamma^5 \chi$$

LHC Search Strategy

DM production in association with SM particles

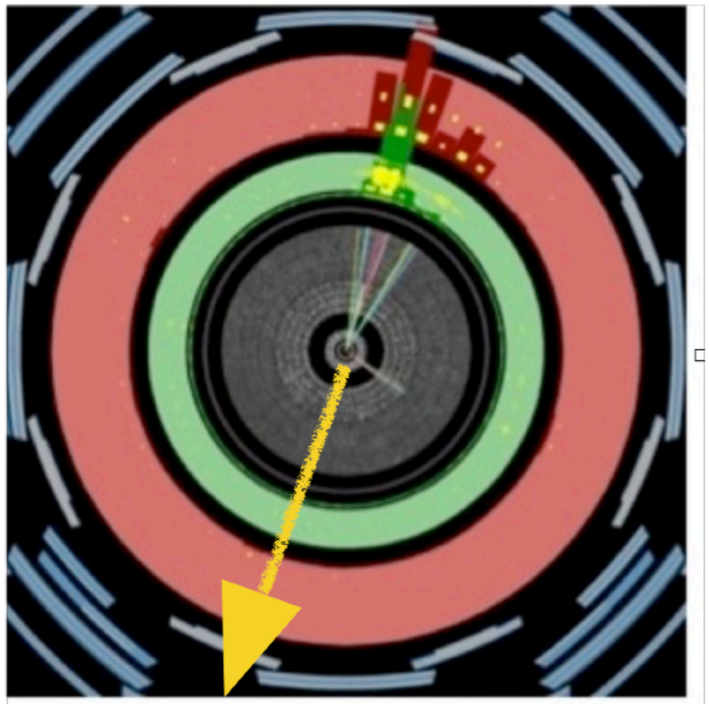


Associate production



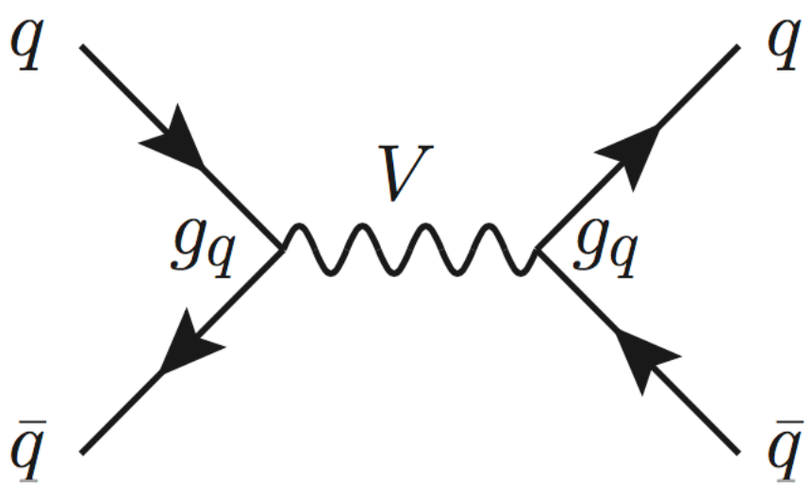
Mono-X

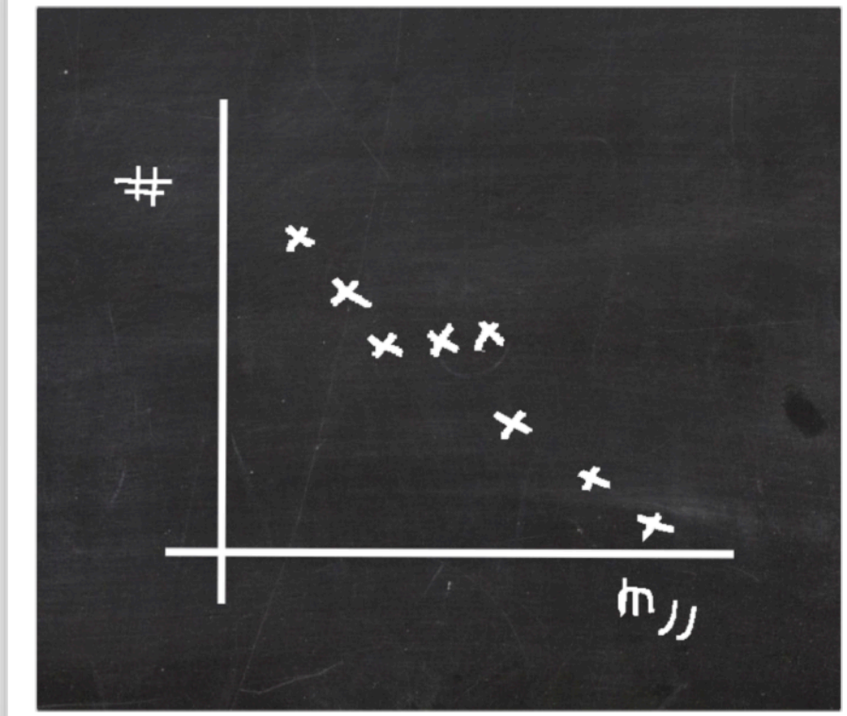
Mono Jet



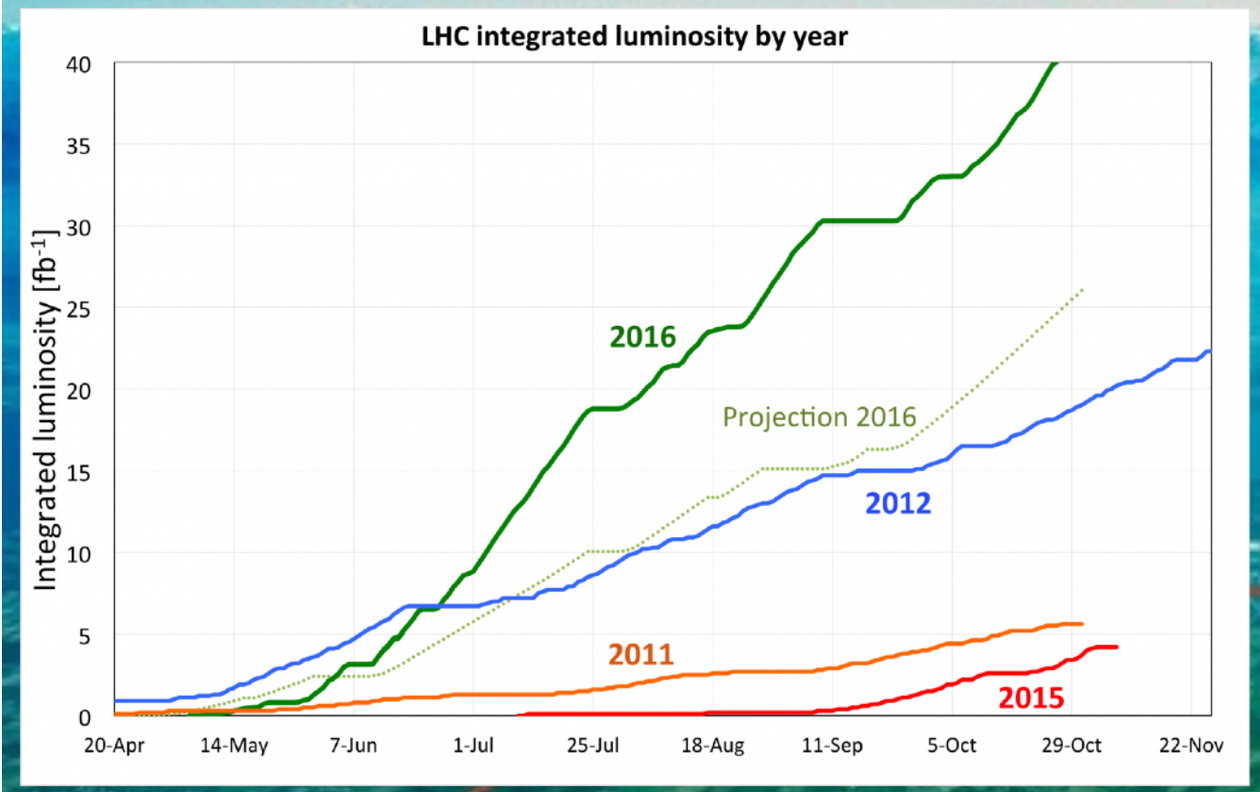
MET

WIMP-SM mediator search





LHC Status



Peak luminosity > 1.35×10^{34} $cm^{-2}s^{-1}$
about 40 fb^{-1} in both ATLAS and CMS

ATLAS

CMS

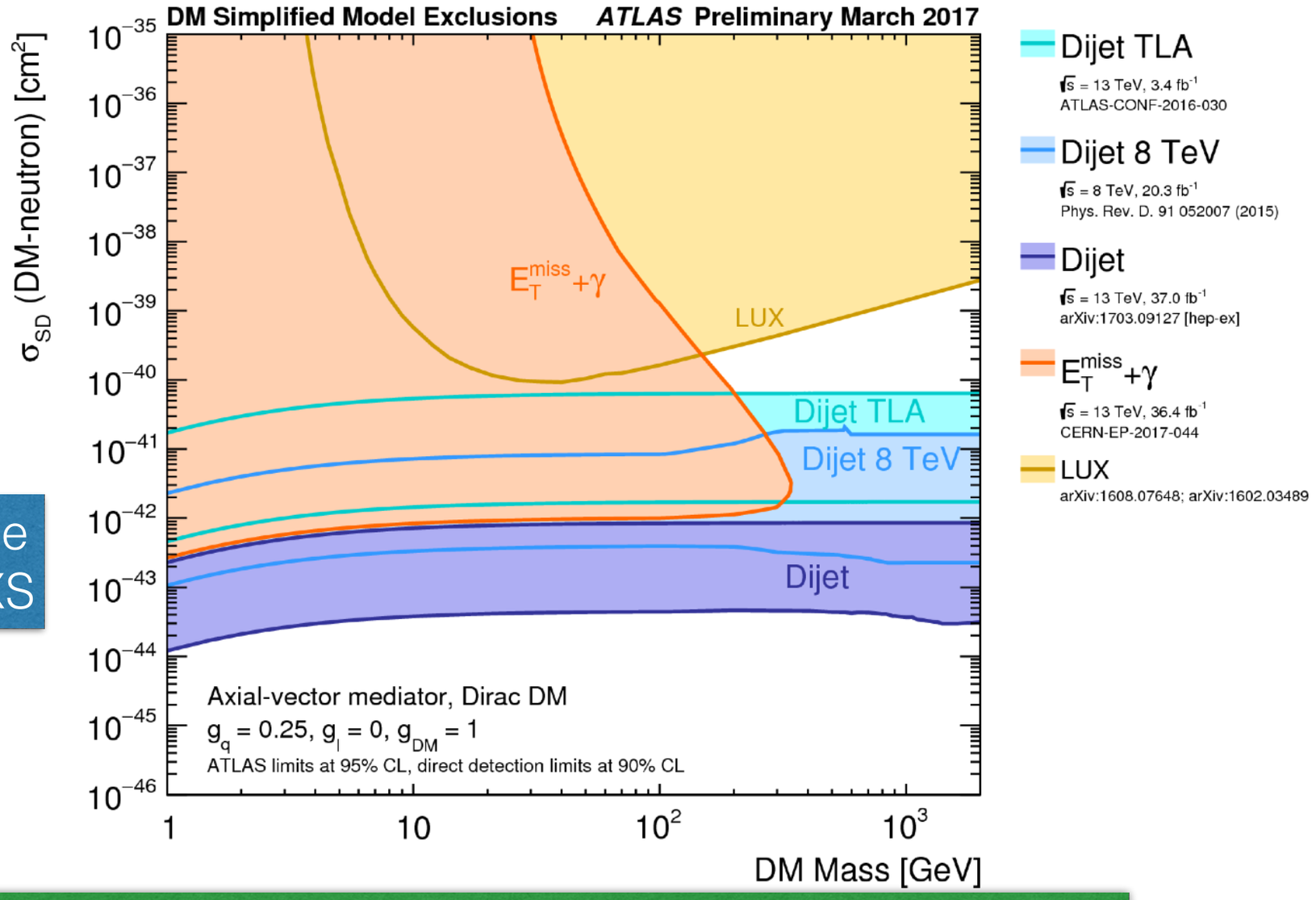
2017: beams are back in LHC from Friday 29th April

Plans: 45 fb^{-1} @13TeV

Coverage of LHC measurements

Mono-X: low DM sensitivity

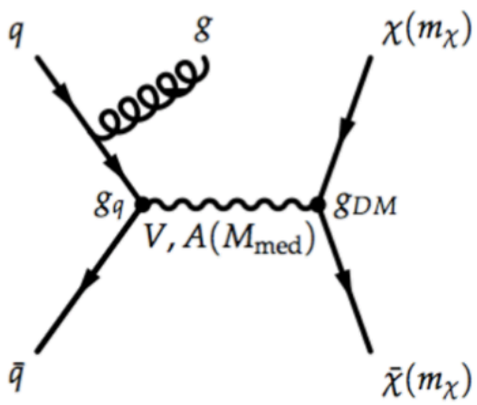
Dijet: large DM mass coverage
Sensitive to low DM-Neutron XS

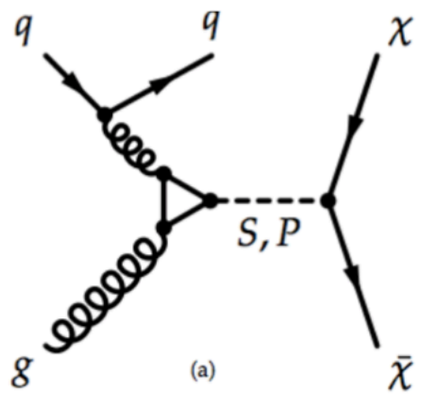


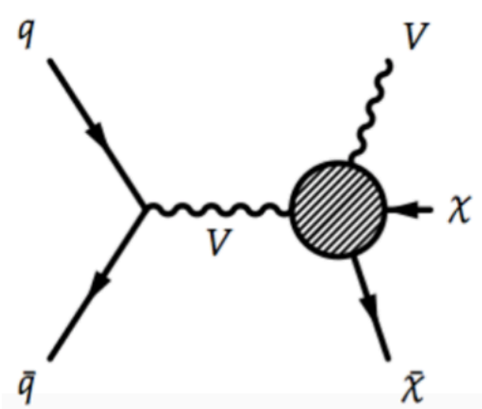
LHC complement direct detection experiments but is sensitive to the coupling

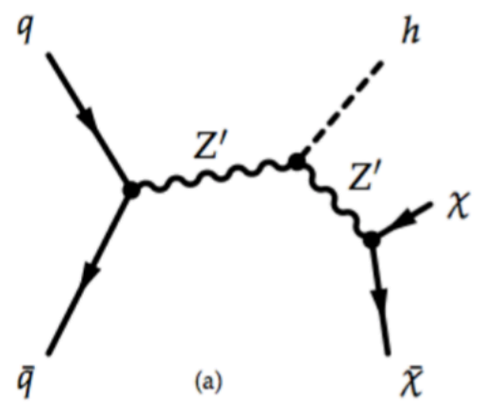
Mono X

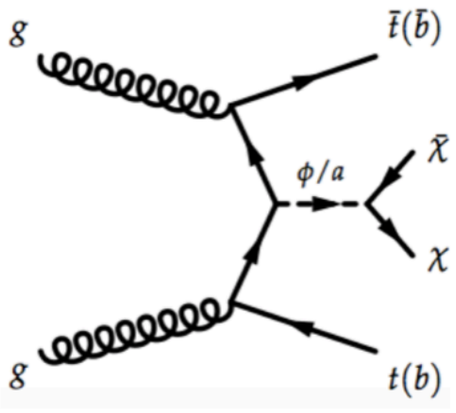
- Pair produced DM via massive mediator (scalar, pseudo- scalar, vector, axial-vector)
- X = visible particle to tag the DM: jet, photon, W/Z, Higgs, dijet (sometimes under associate production category)

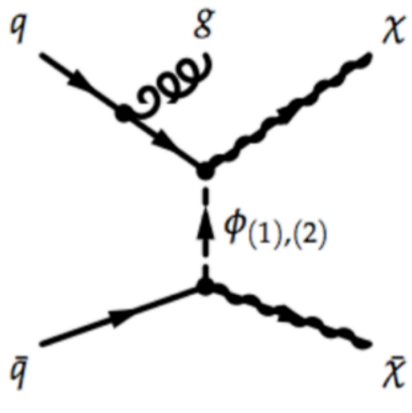


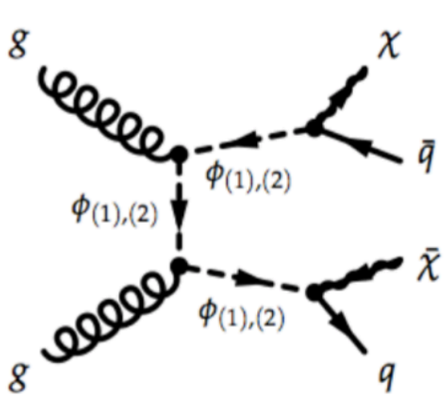








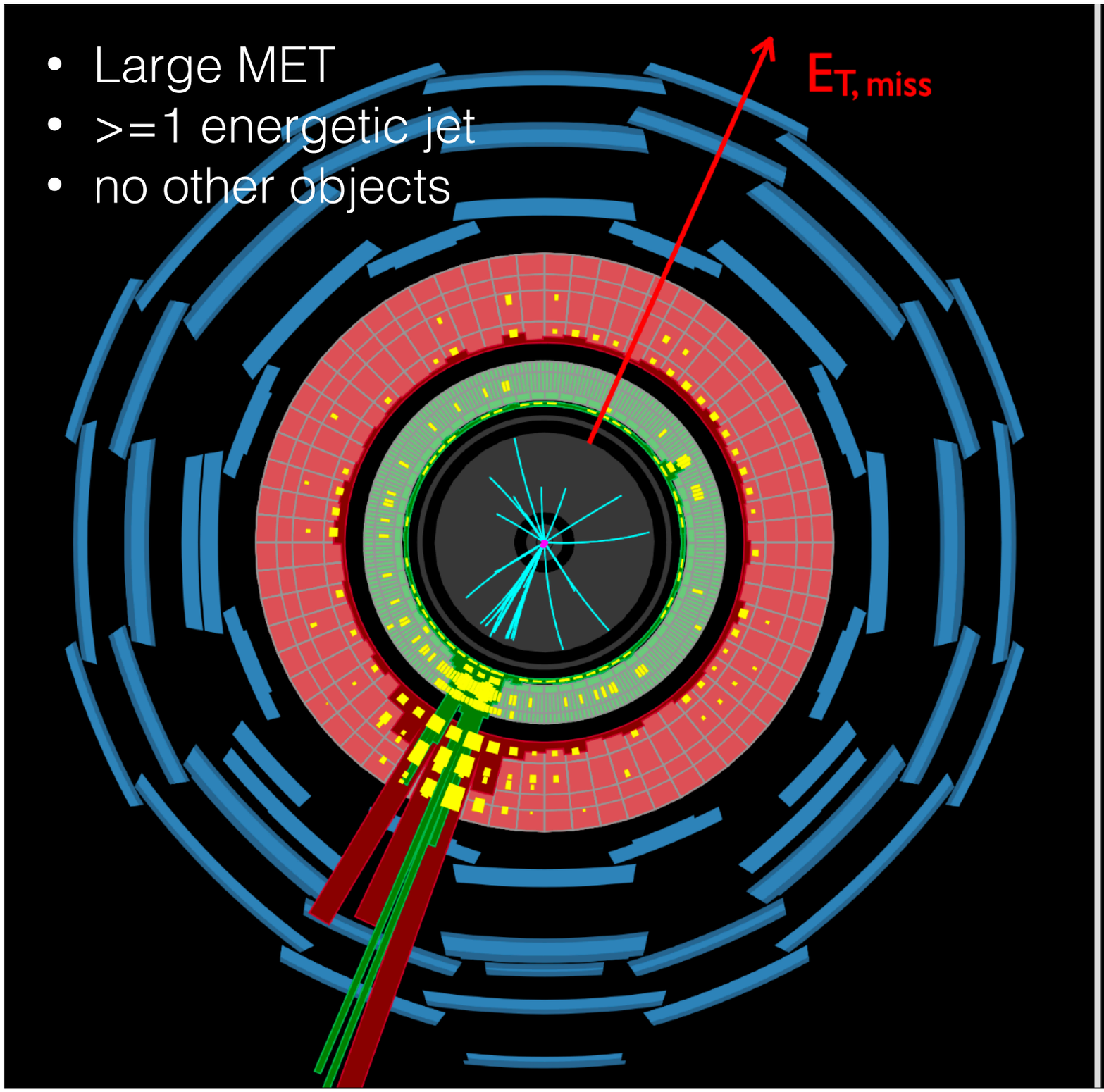


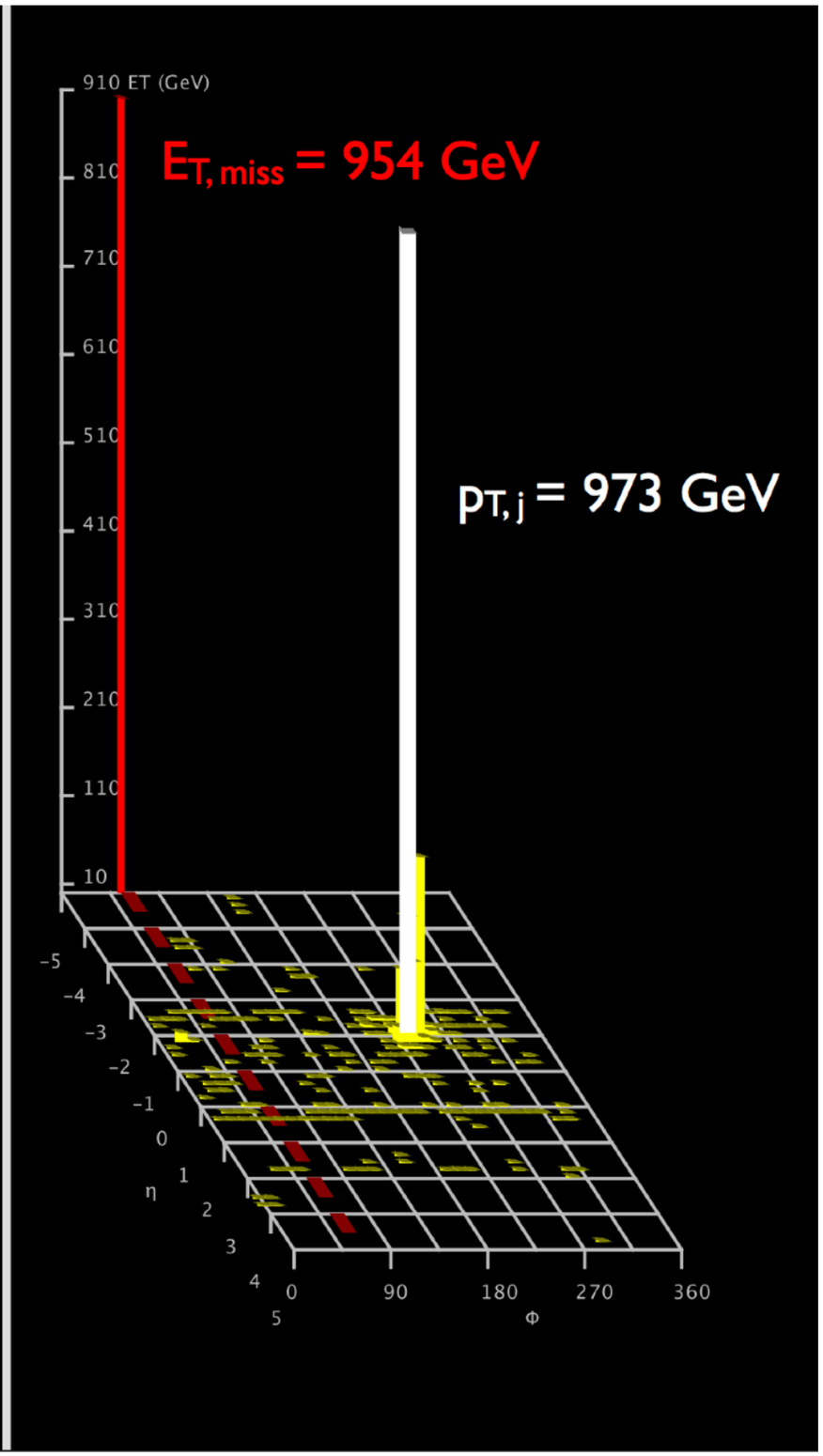


...

Mono - jet

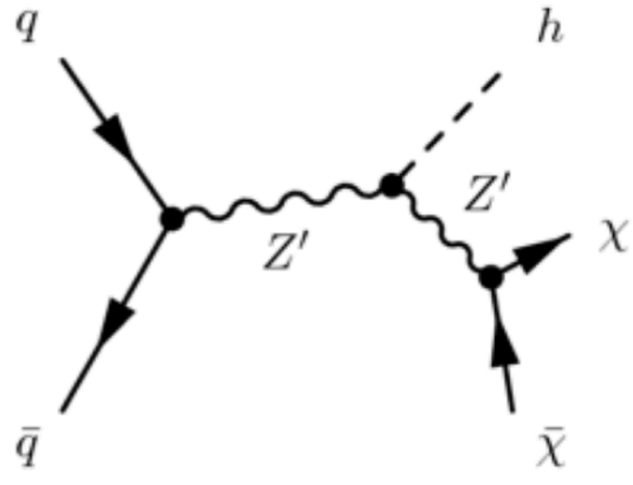
- Large MET
- >=1 energetic jet
- no other objects





Mono Higgs (bb)

DM couples to Higgs in many models
(e.g. Z' vector mediator, leptophobic model)

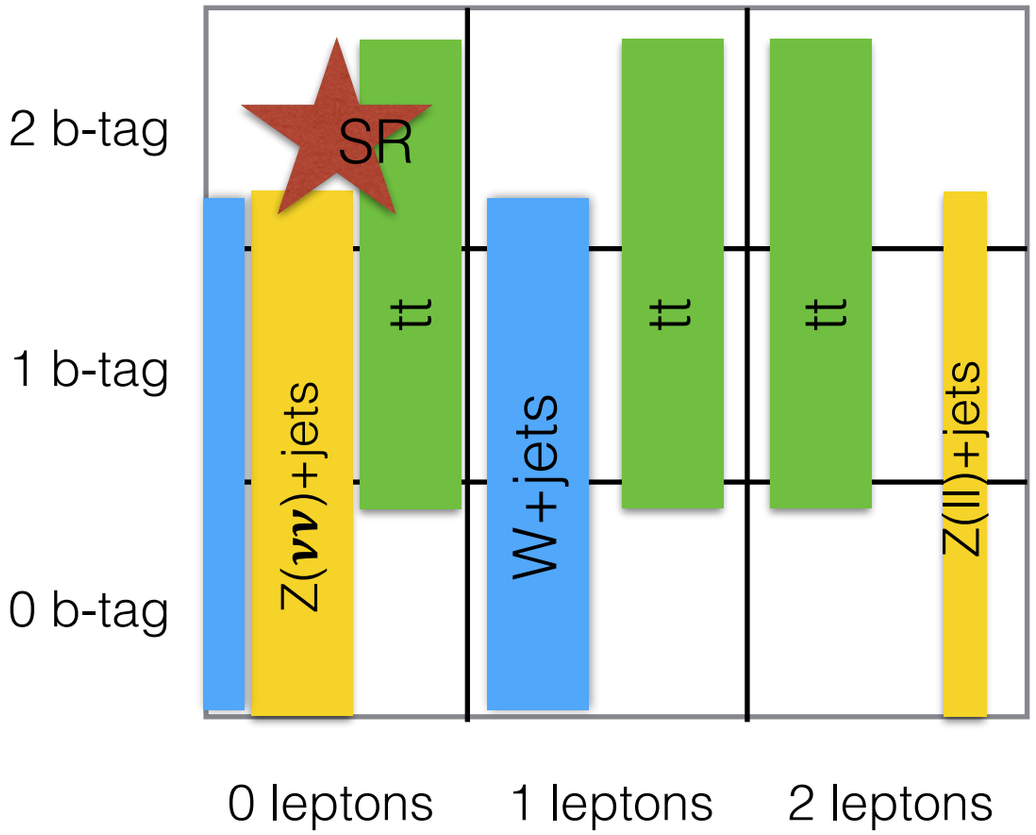


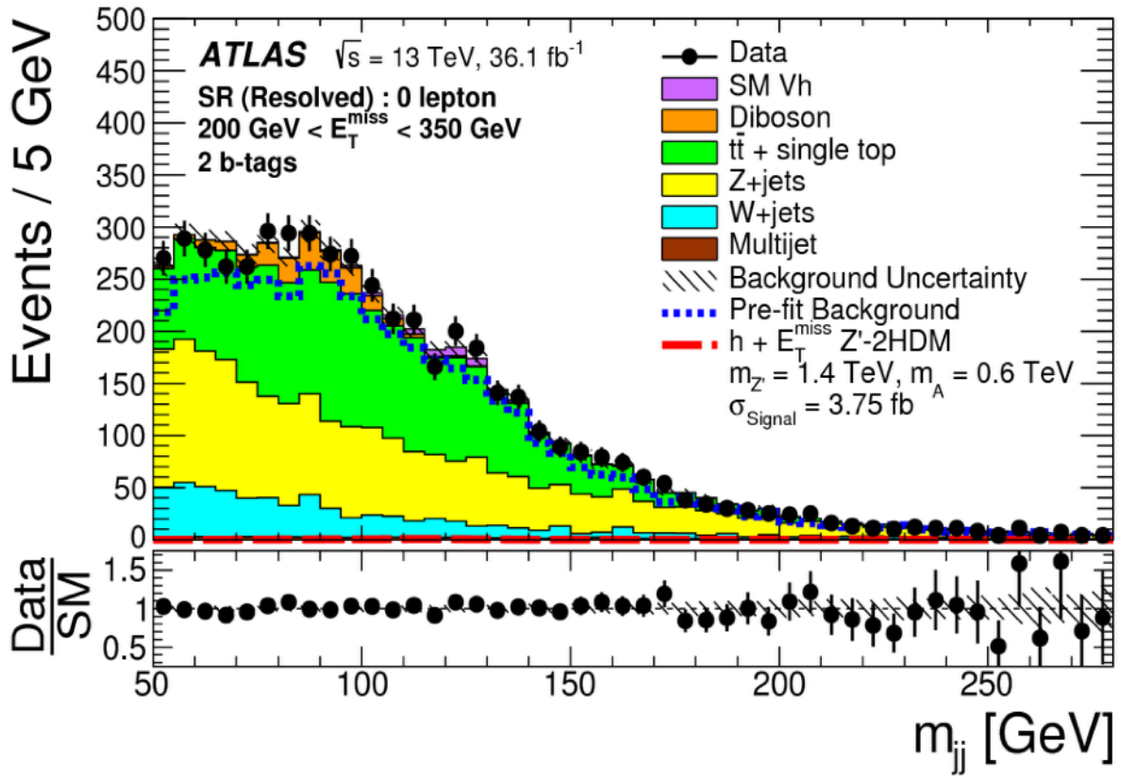
Probing the Higgs coupling to the mediator

H➛bb (as it is the largest Br)
Two scenarios:

1. High MET (>500 GeV) ➛ merged b-jets
2. Low MET (<500 GeV) ➛ two resolved b-jets

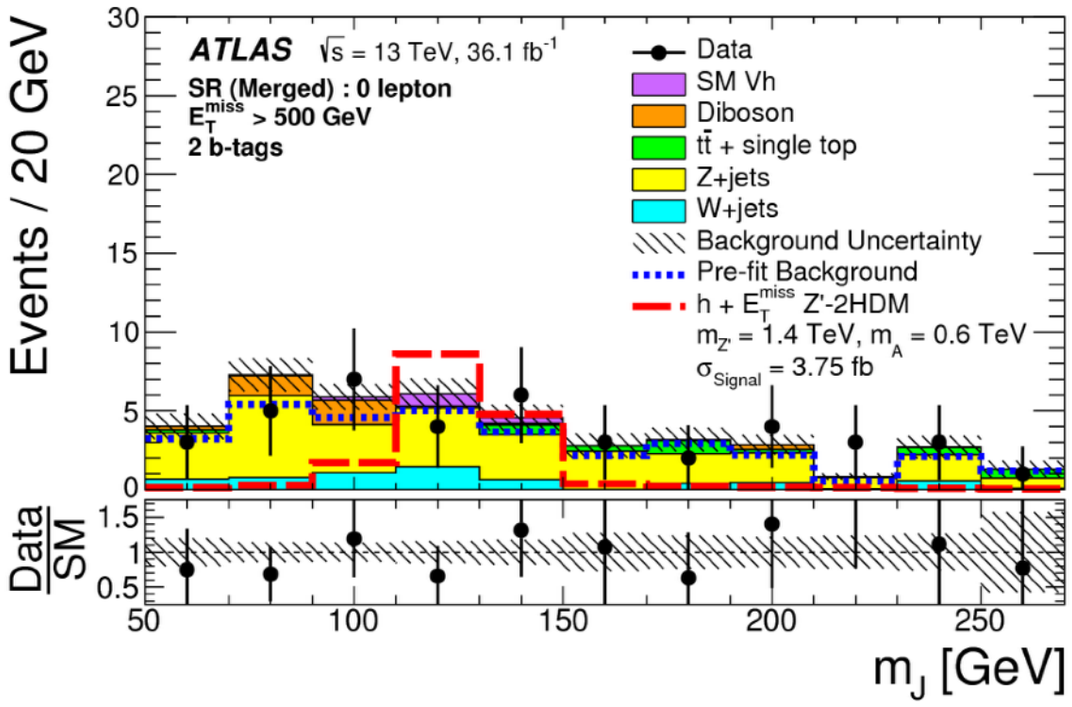
Background estimation: Data driven
leptonic/b-tagged CRs

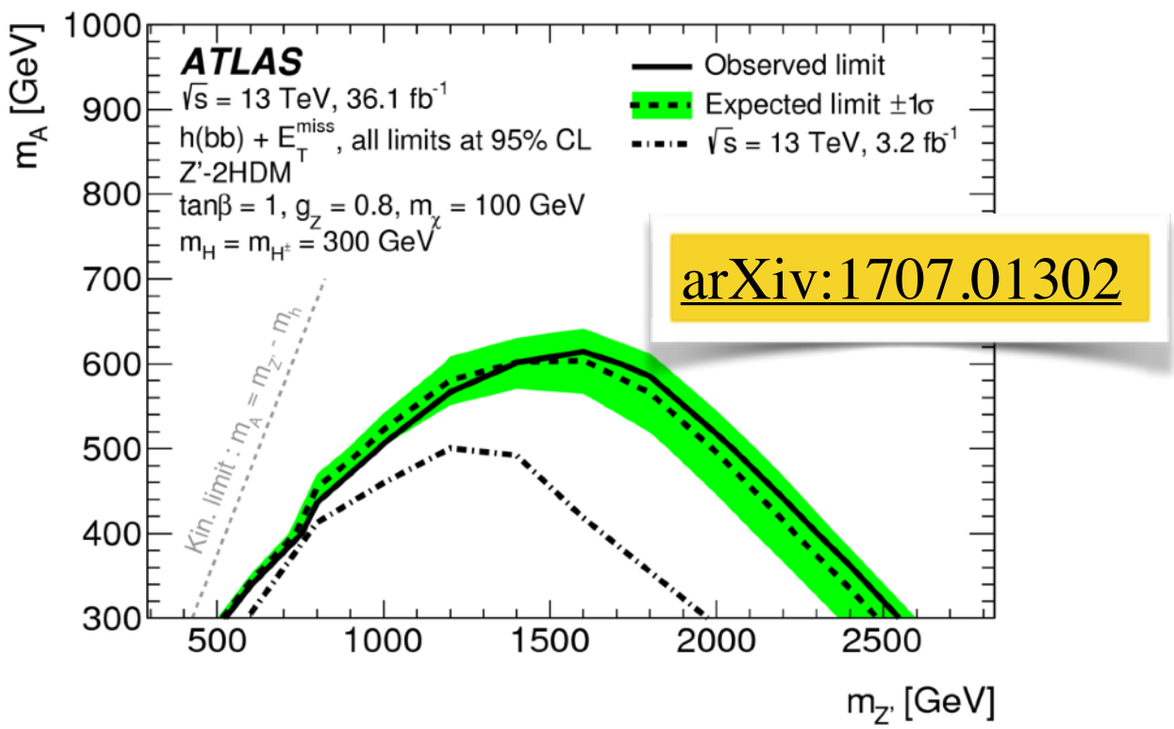




arXiv:1707.01302

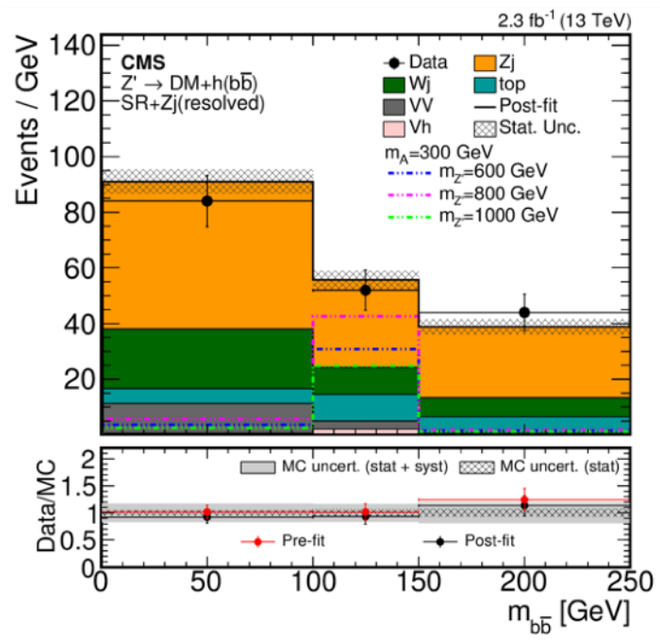
Mono Higgs (bb)

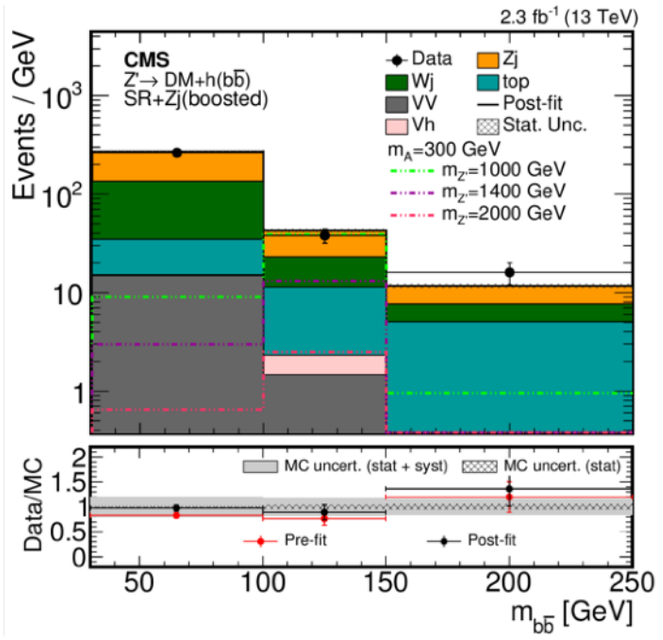


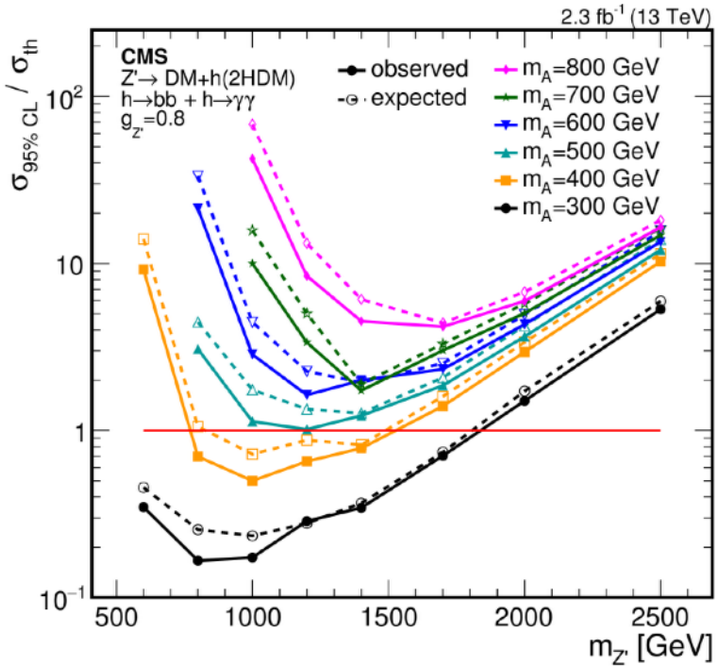


arXiv:1707.01302

A similar analysis by CMS (CMS-EXO-16-012 ; CERN-EP-2017-027)

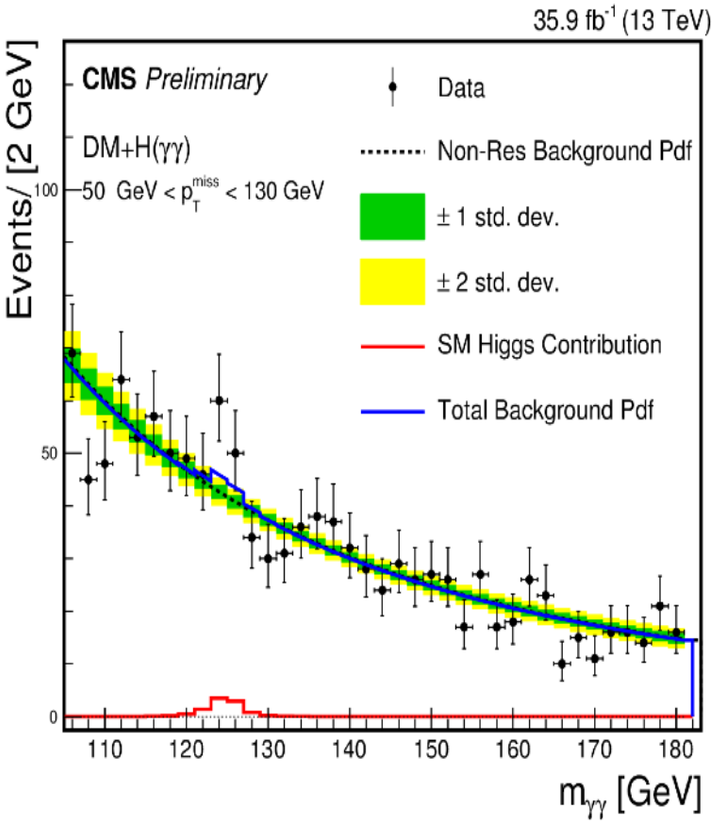


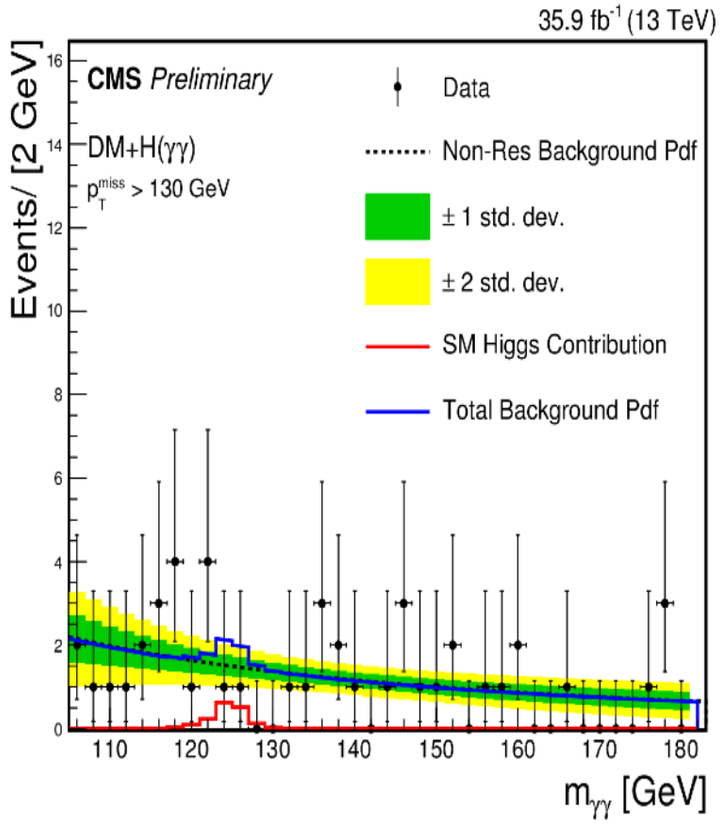


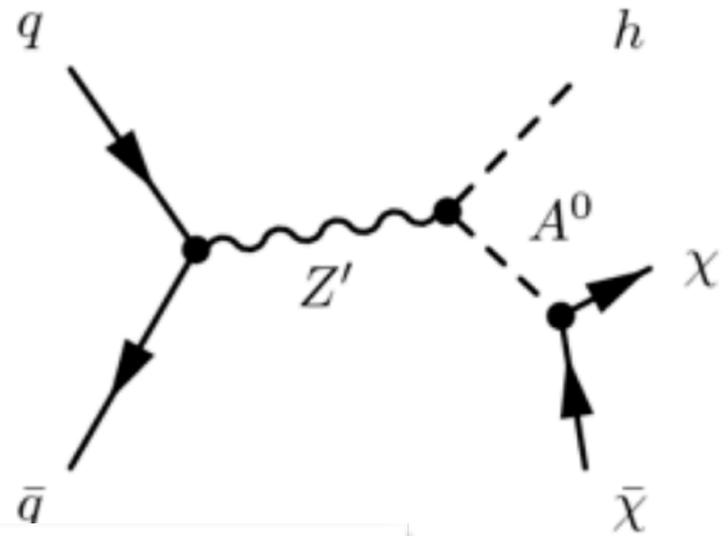


Mono Higgs ($\gamma\gamma$)

Similarly but using a cleaner mode H ➛ $\gamma\gamma$

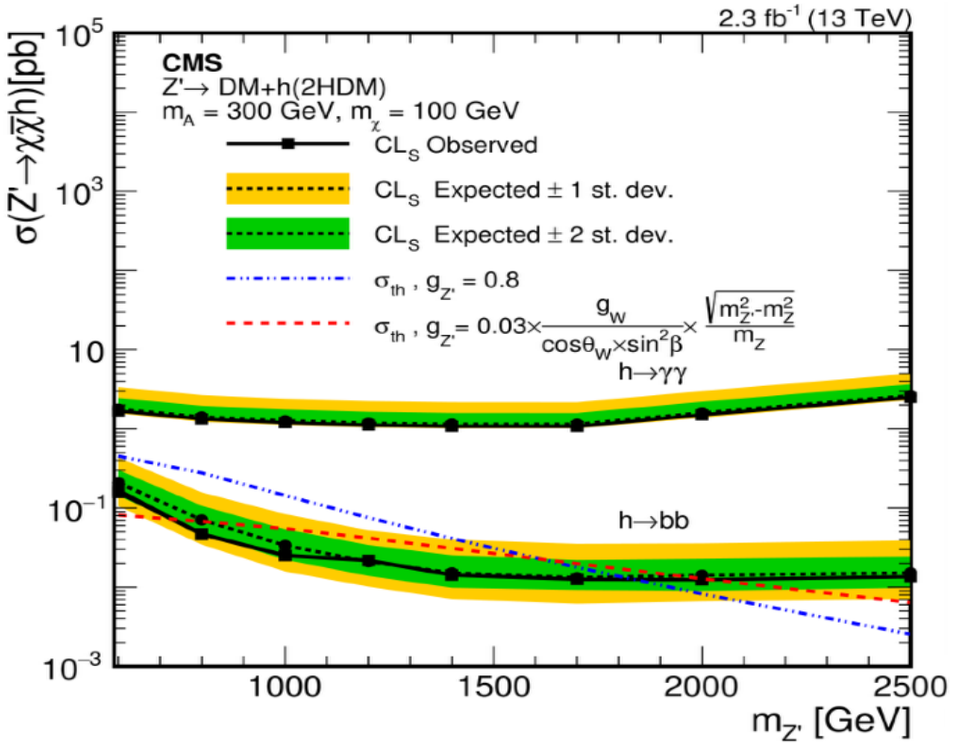






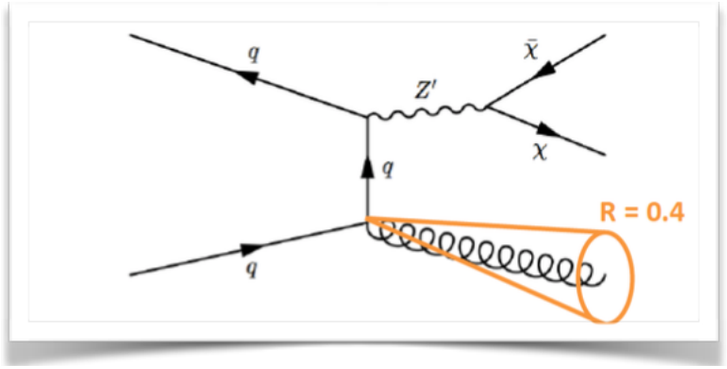
CMS-PAS-EXO-054

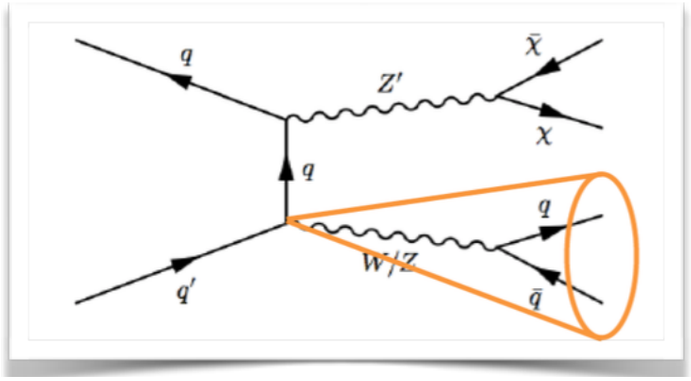
Also by ATLAS arXiv:1706.03948



Mono - jet

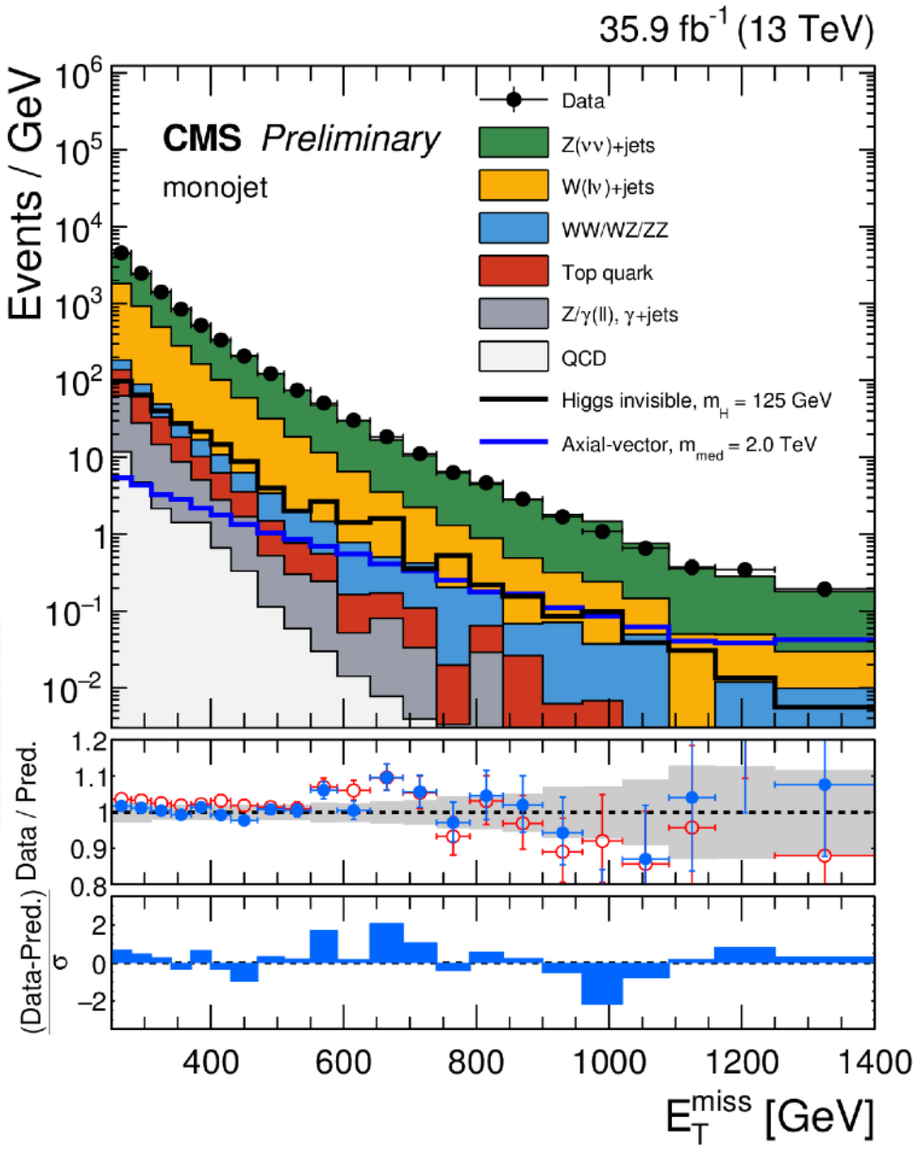
- Large MET
- >=1 energetic jet
- no other objects

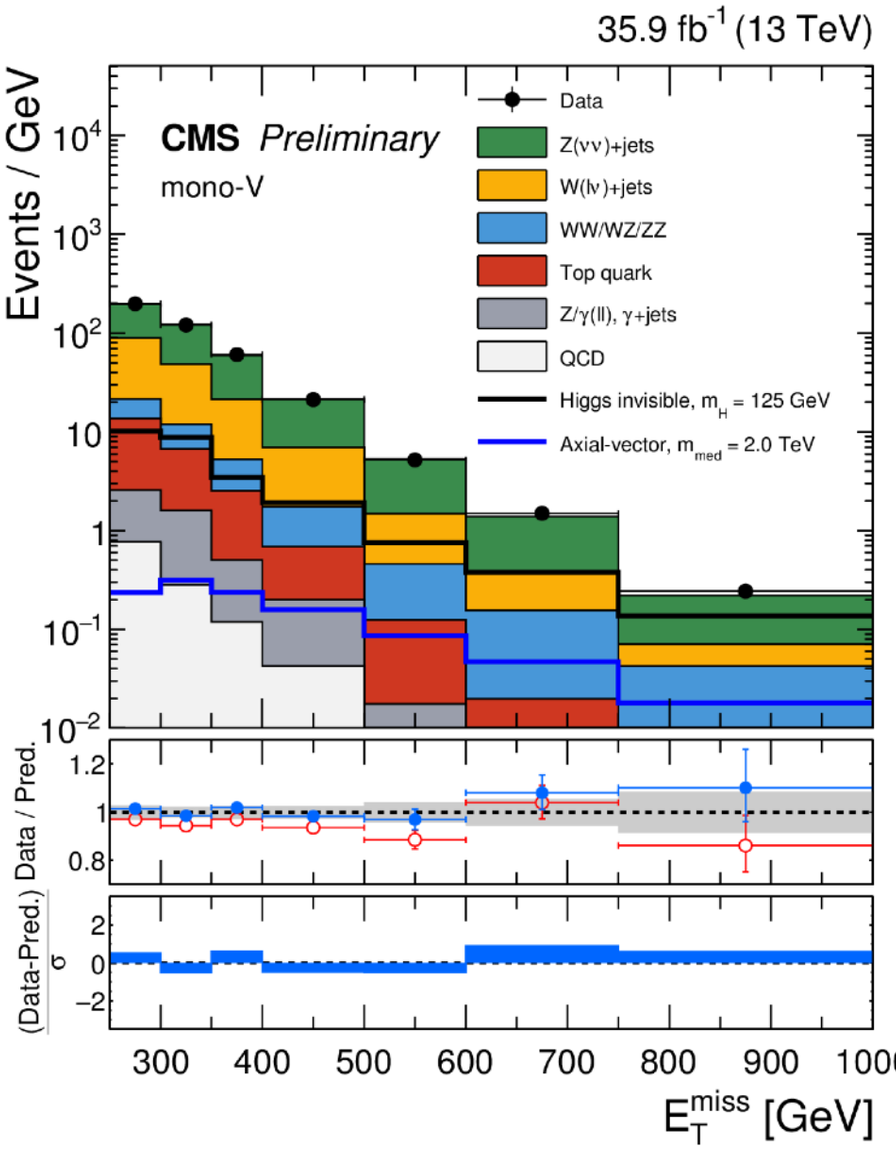




SM Backgrounds:
Z(vv)+jets,
W(lv)+jets
VV, top, QCD, etc

Data-driven estimation:
Likelihood fit in control regions





CMS EXO-16-048

Mono - jet

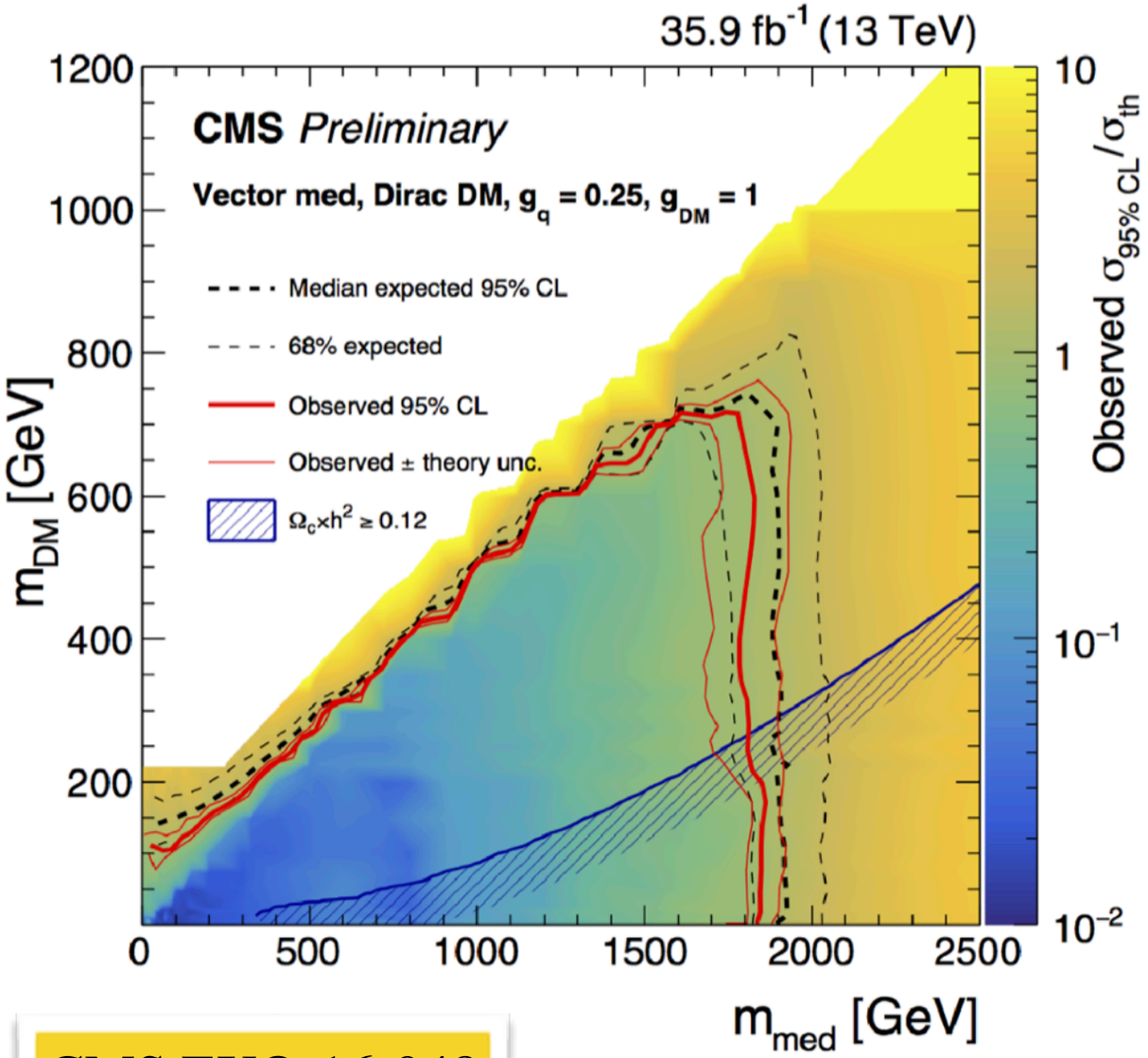
With g_q=0.25, g_{DM}=1.0

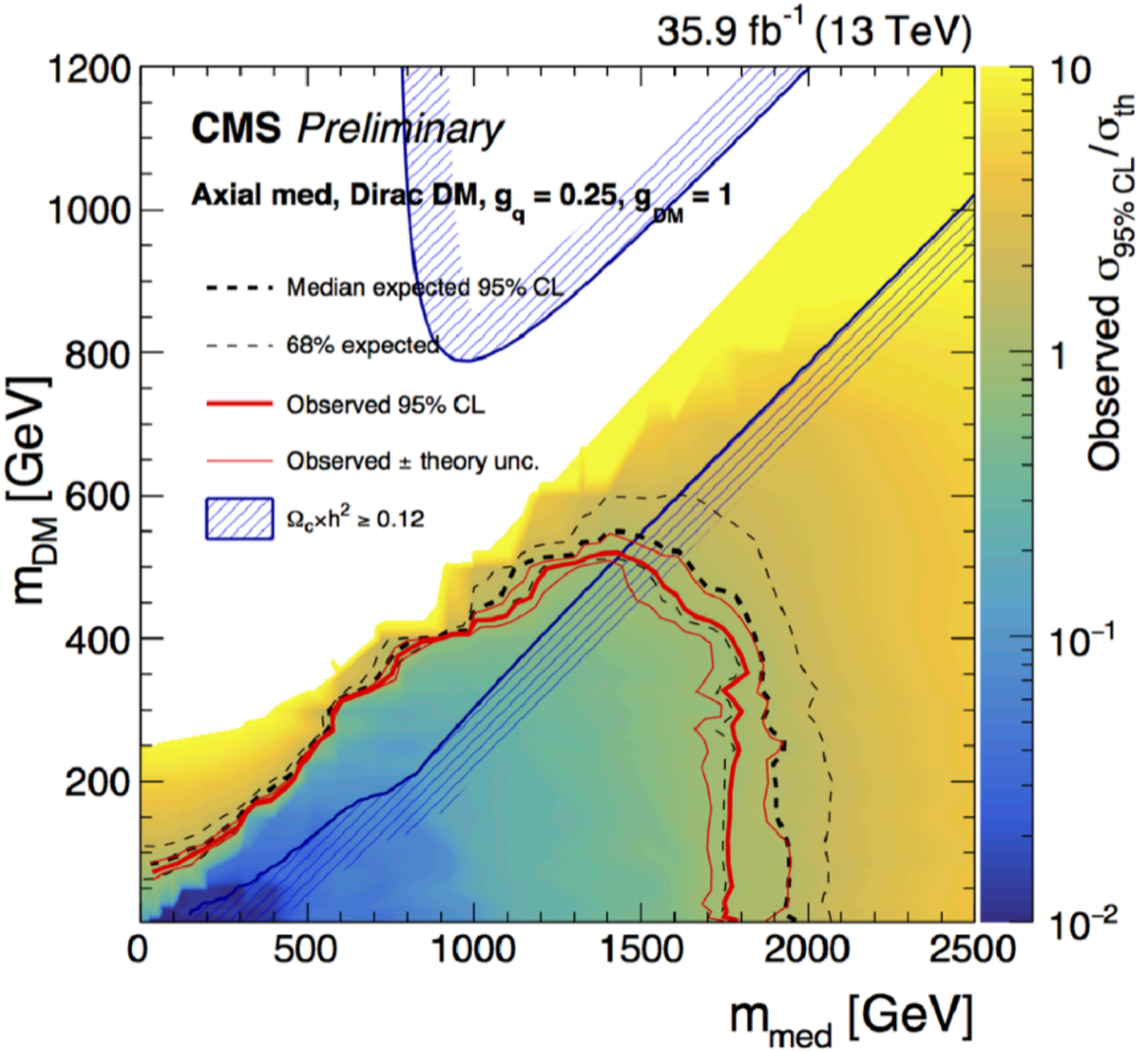
Current constraints:

– DM mass~600GeV

– mediator mass~2TeV

Similar results from ATLAS:
ATLAS-CONF-2017-060
arXiv:1707.03263

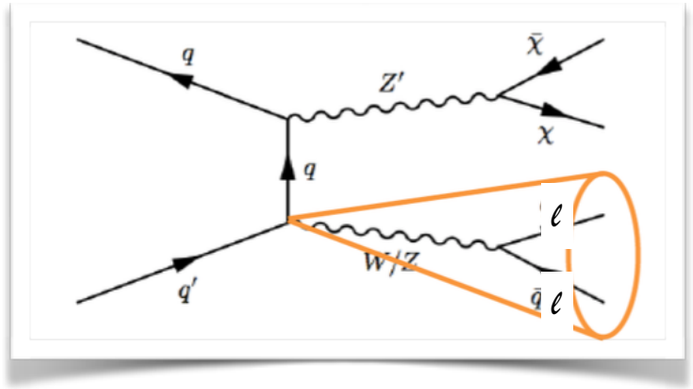


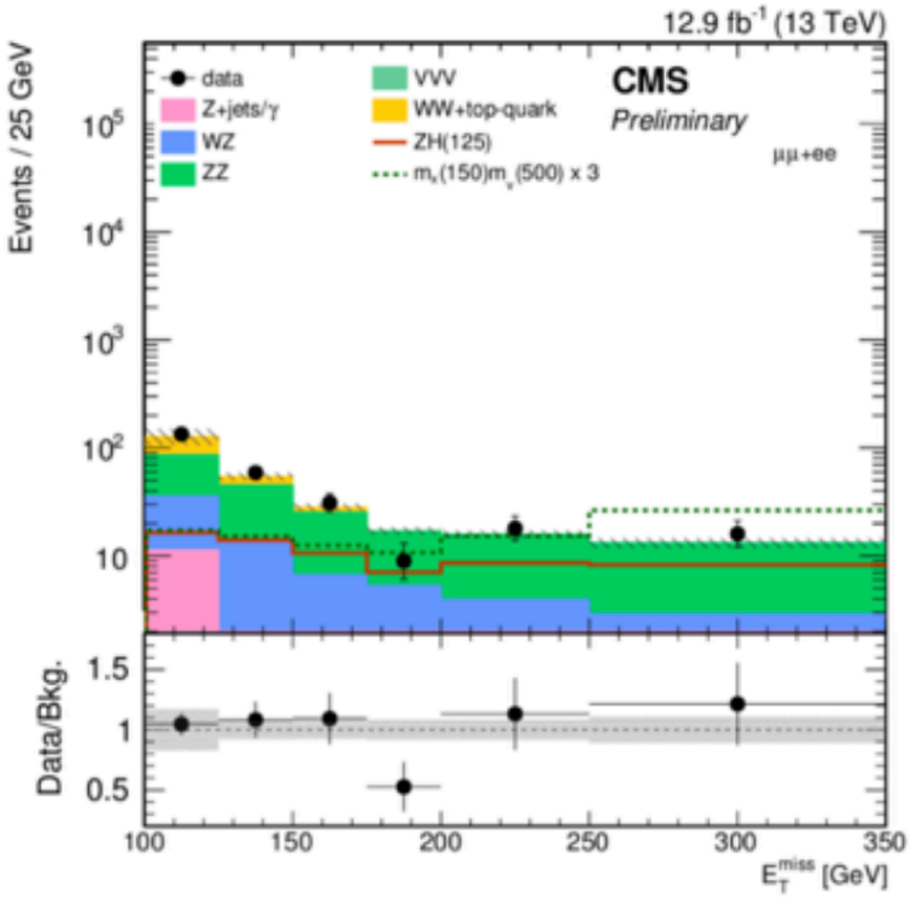


CMS EXO-16-048

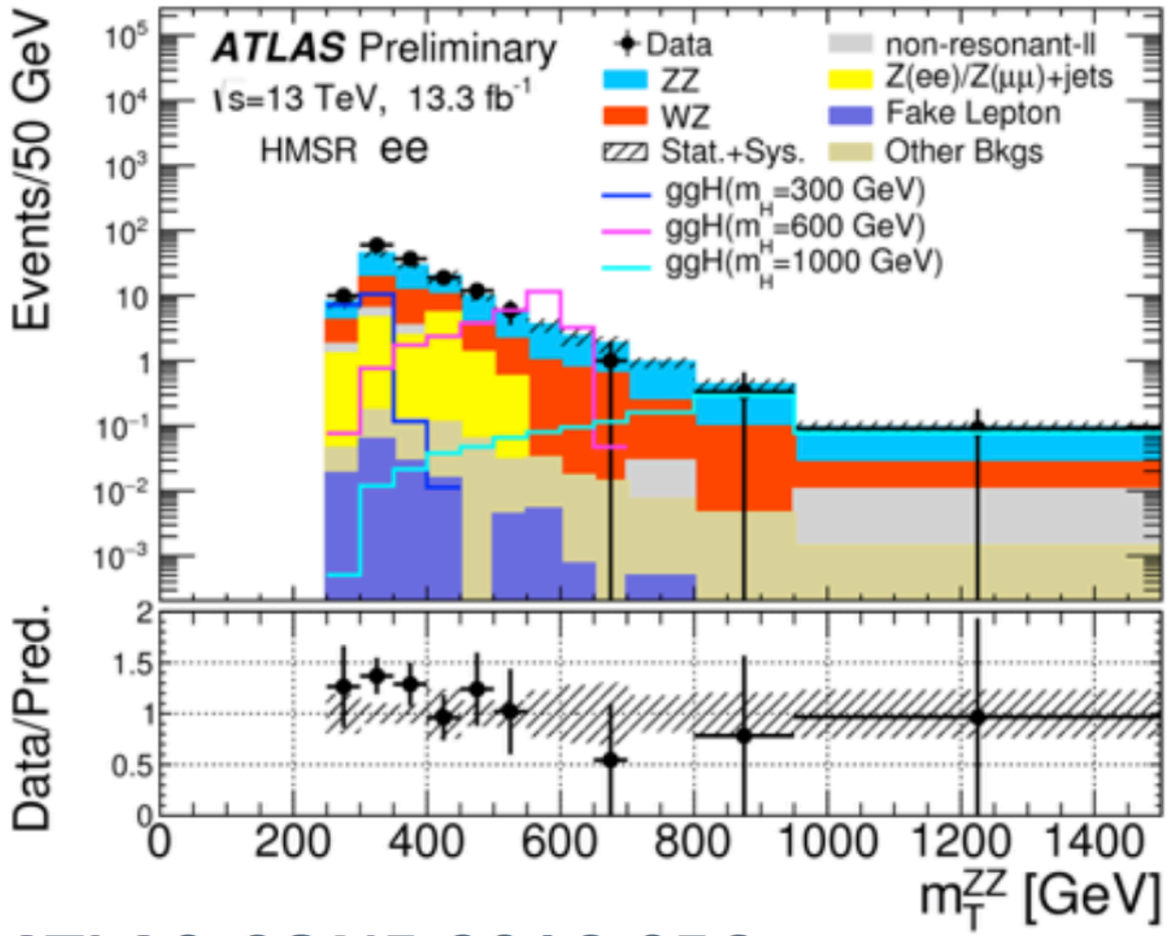
Mono - ~~jet~~ Z(ll)

- Similar physics Z➛ll (rather than qq)
- Lepton pair + MET
- Background: mostly ZZ➛ll$\nu\nu$





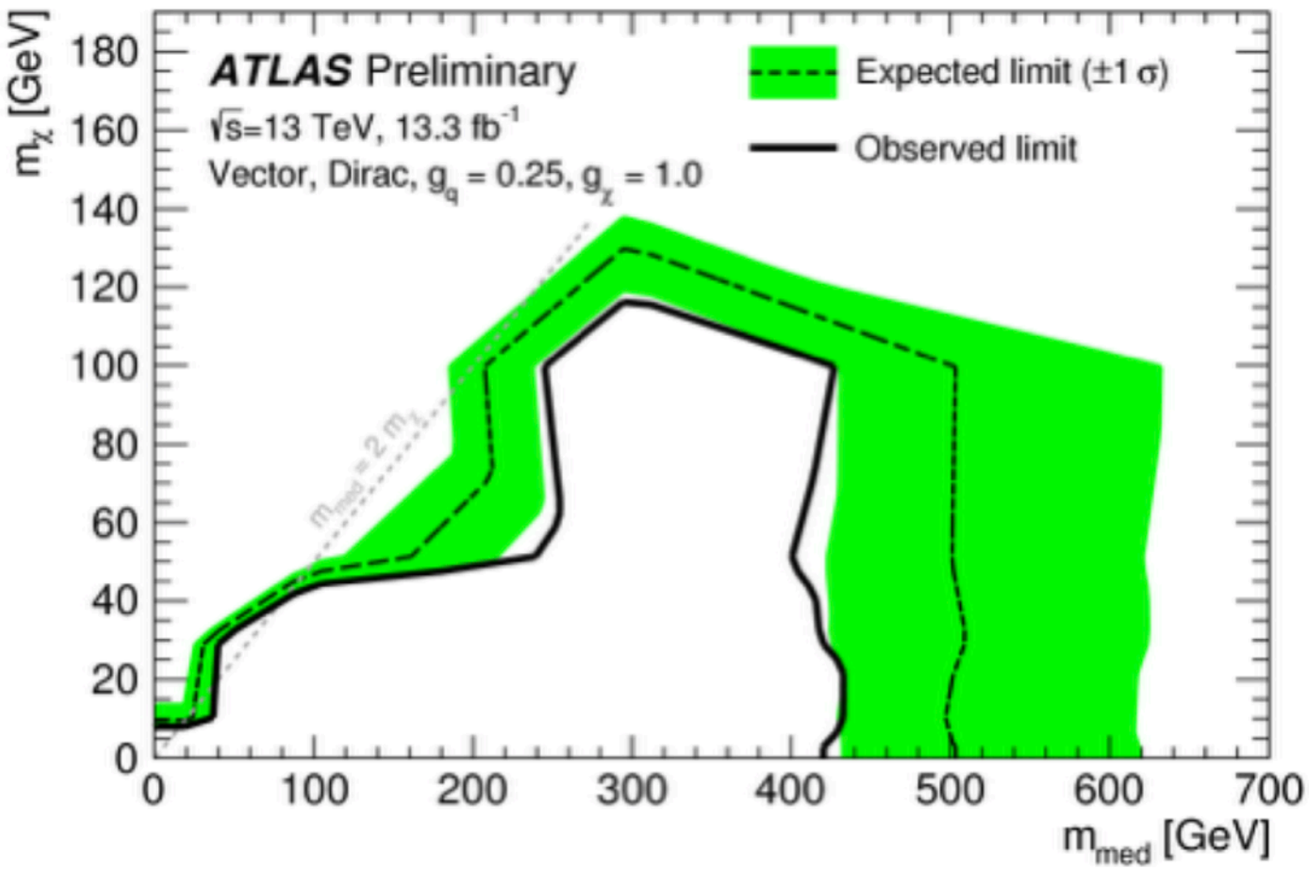
CMS-PAS-EXO-16-038



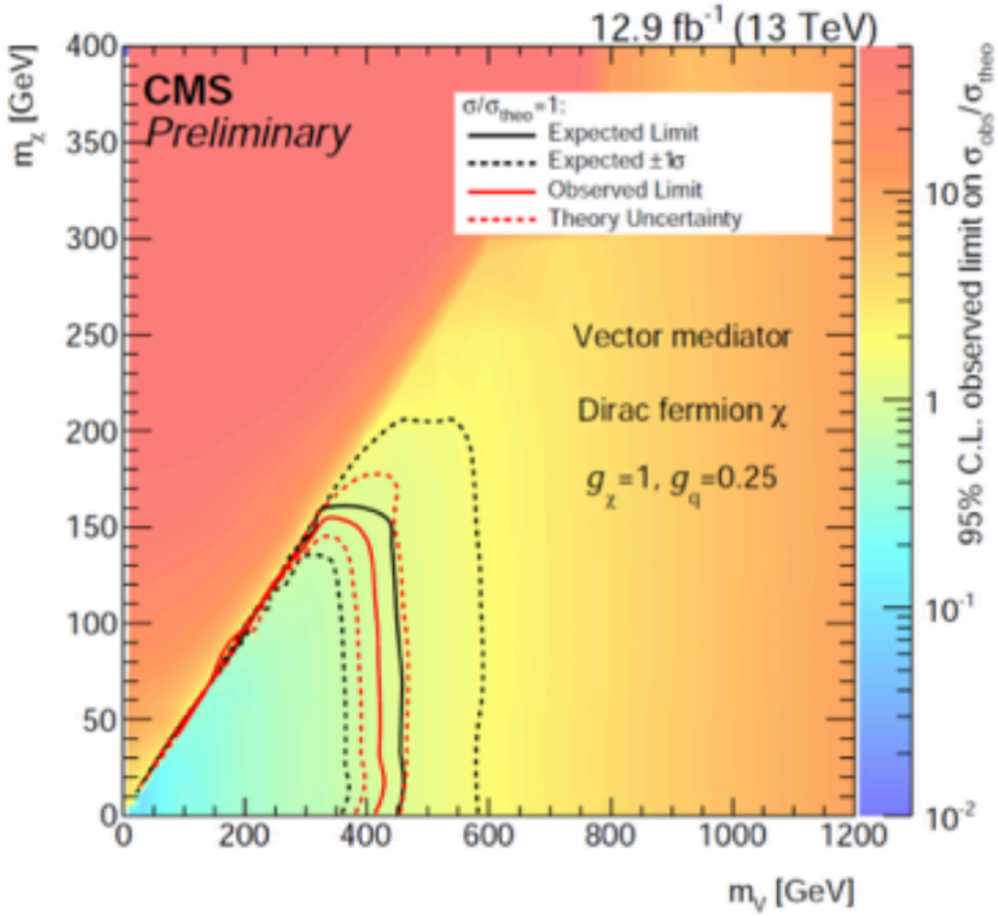
ATLAS-CONF-2016-056

Mono - Z(ll)

using simplified models with vector mediator for DM production

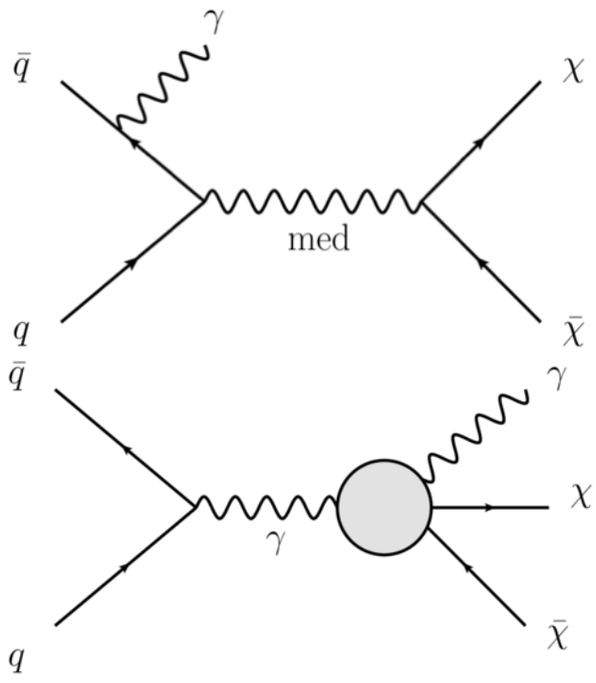


ATLAS-CONF-2016-056



CMS-PAS-EXO-16-038

Mono - photon



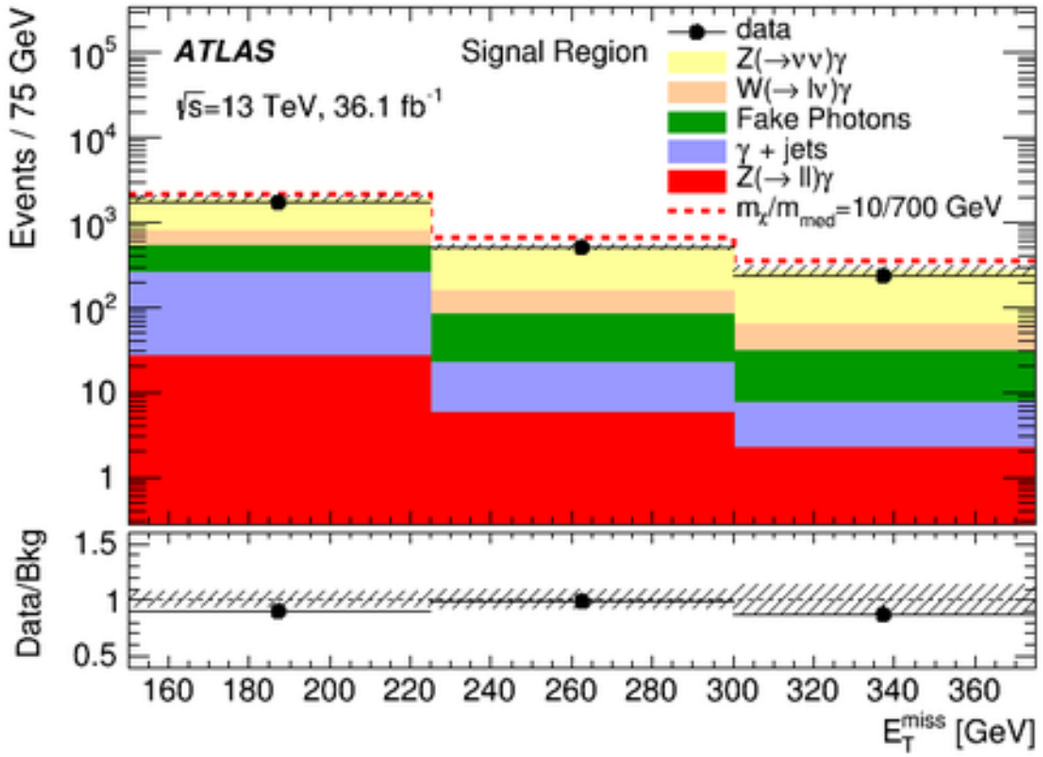
Smaller XS and Bkg than mono-jet

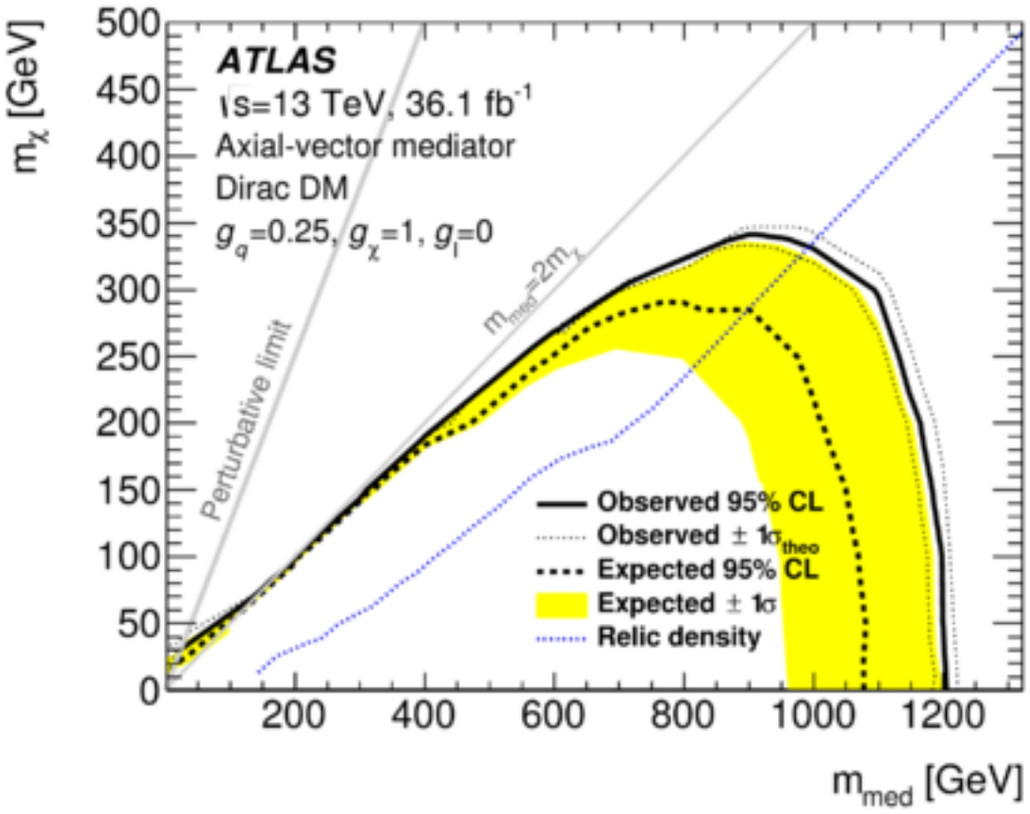
Selection: Photon+ MET

Main Bkg: Z($\nu\nu$)+$\boldsymbol{\gamma}$

Bkg estimation: CR with leptons

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

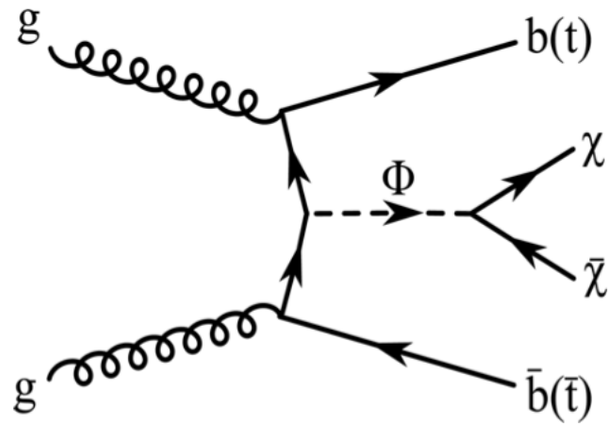




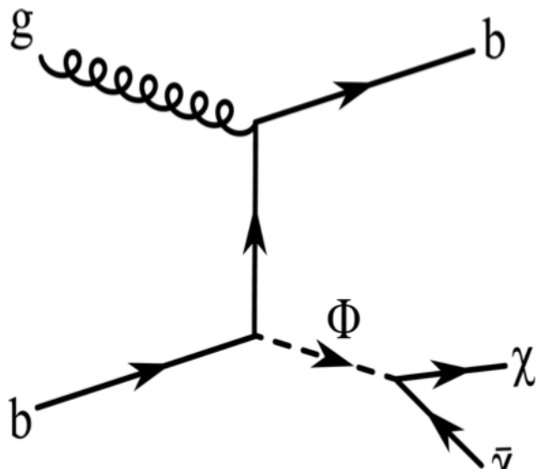
Similar analysis by CMS (13 fb^{-1}): CMS-PAS-EXO 16-039

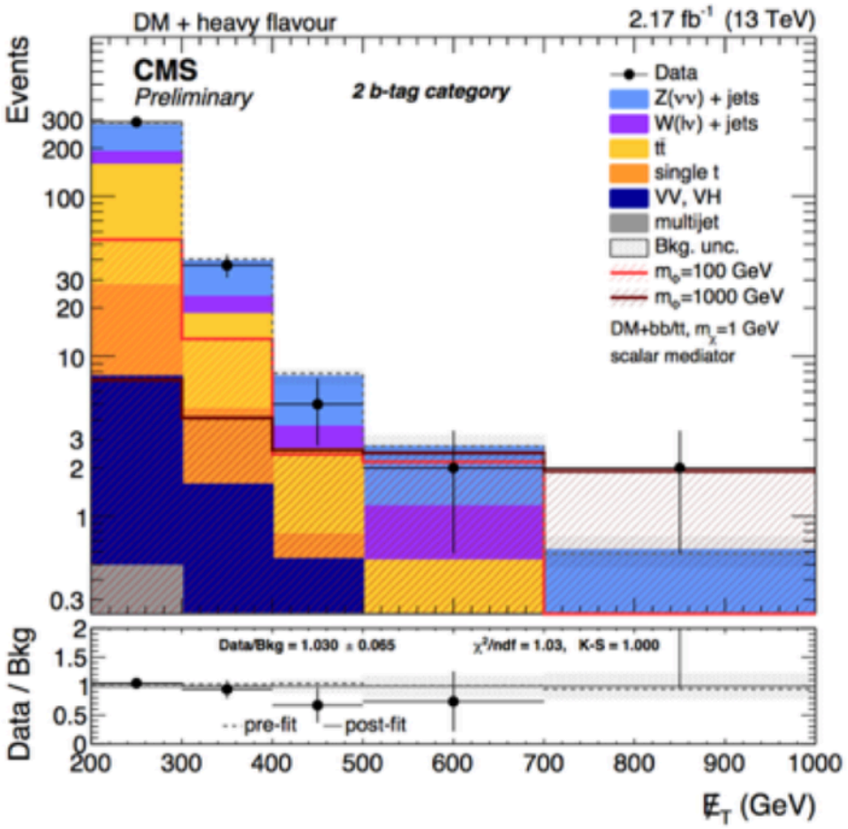
DM+HF (Associate production)

Sensitive to scalar and pseudo-scalar interaction
Favored if Yukawa like coupling

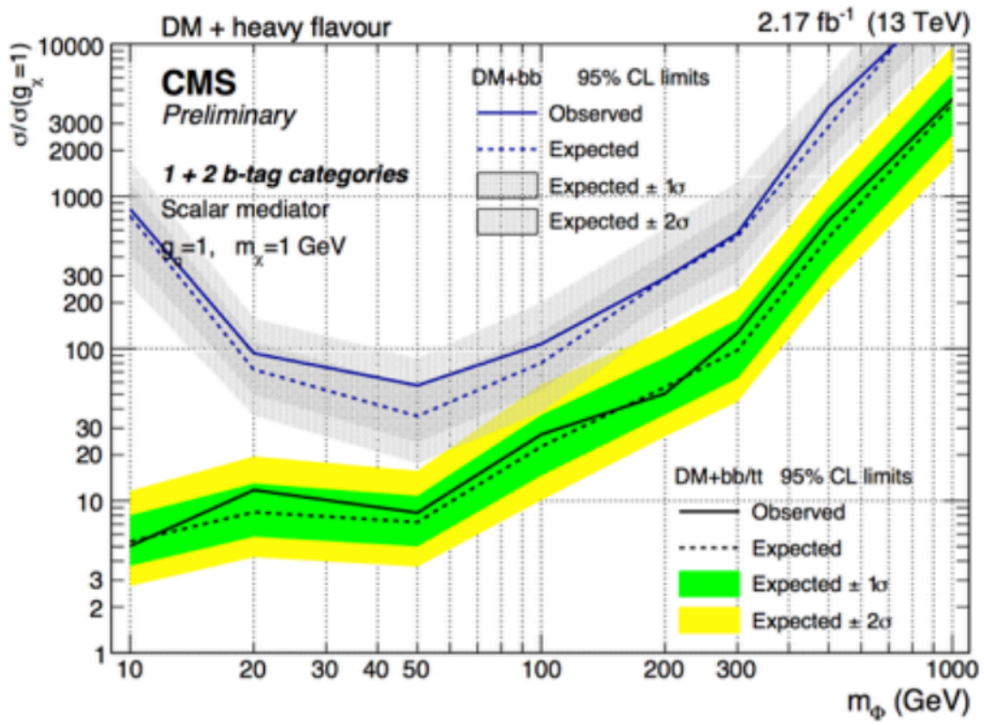


b-jet + MET



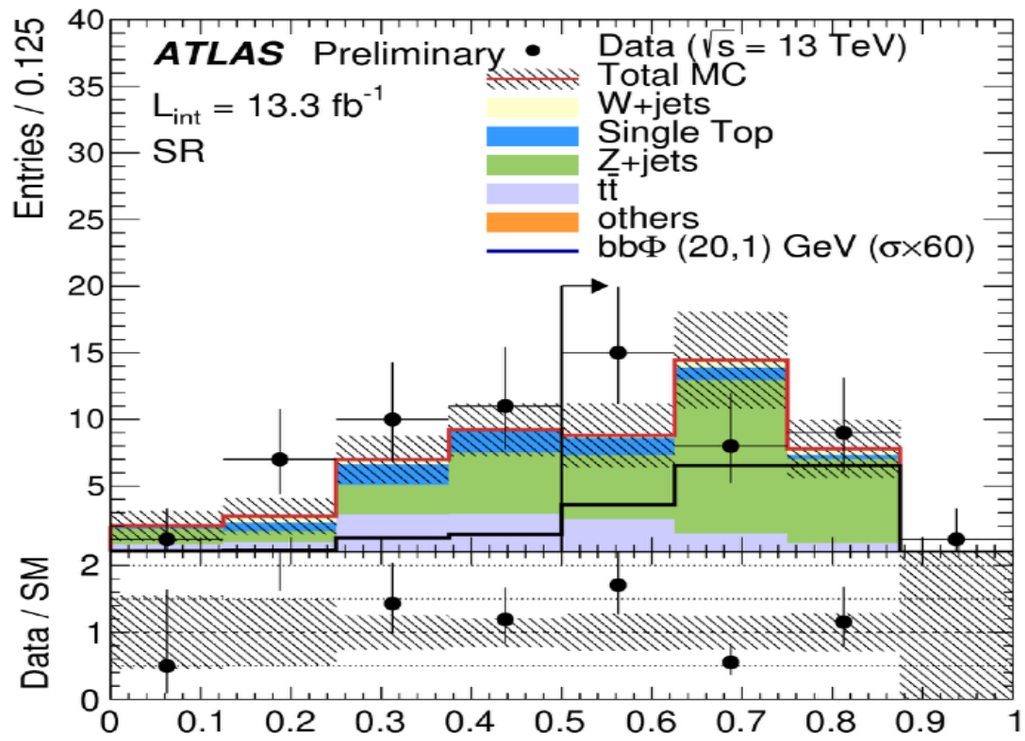


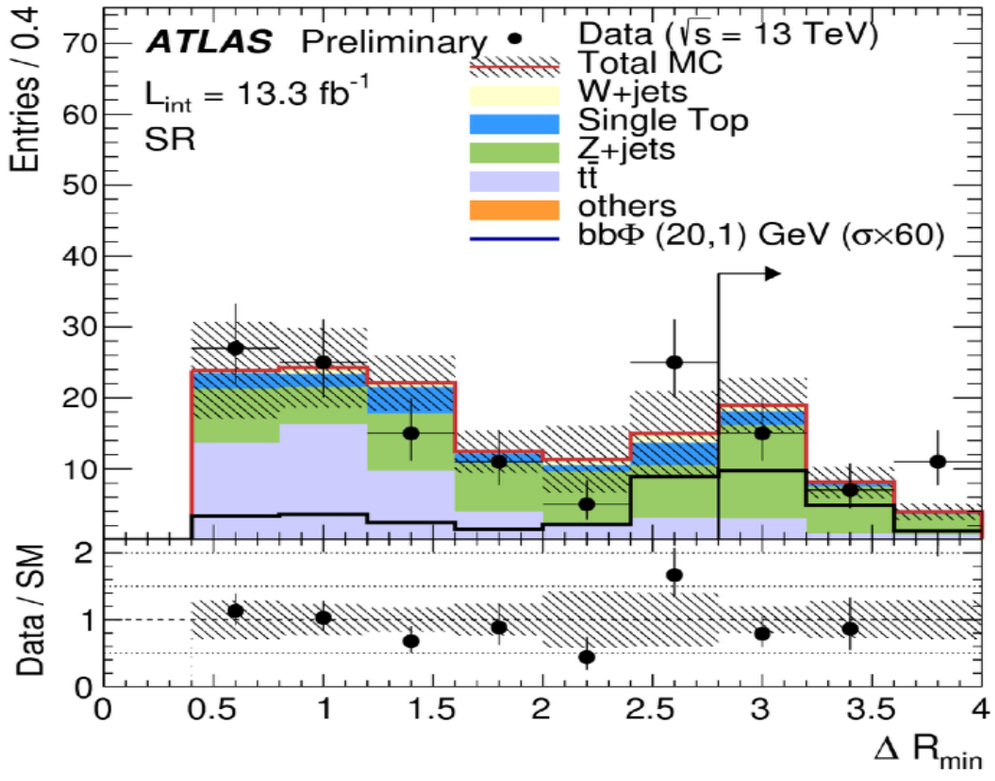
CMS-PAS-B2G-15-007

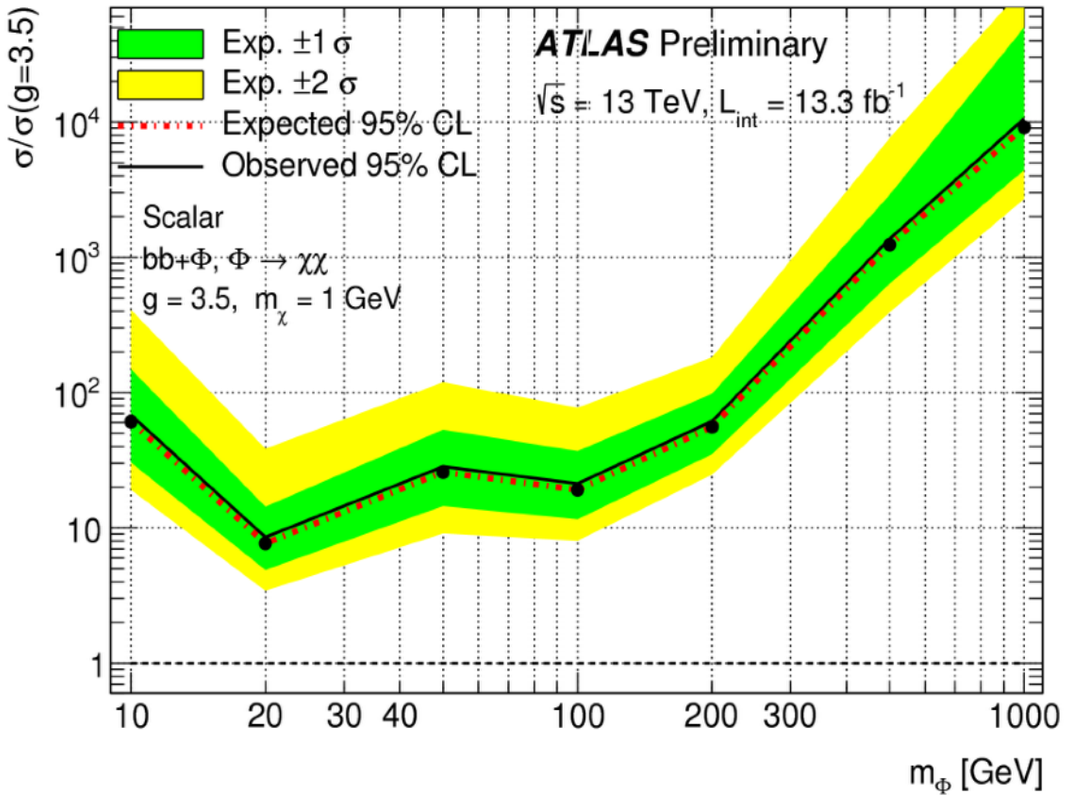


ATLAS DM+bb

Selection:
b-jets +MET
kinematical/geometrical variables
BG: mostly Z+jets
estimated using leptonic control regions

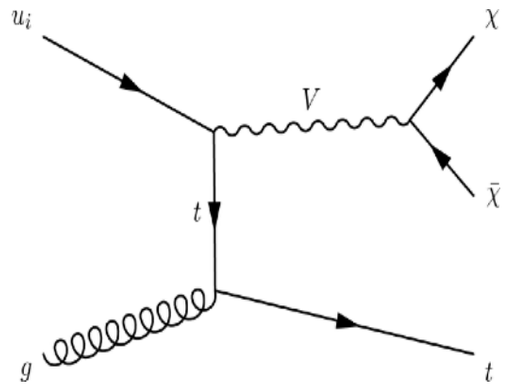


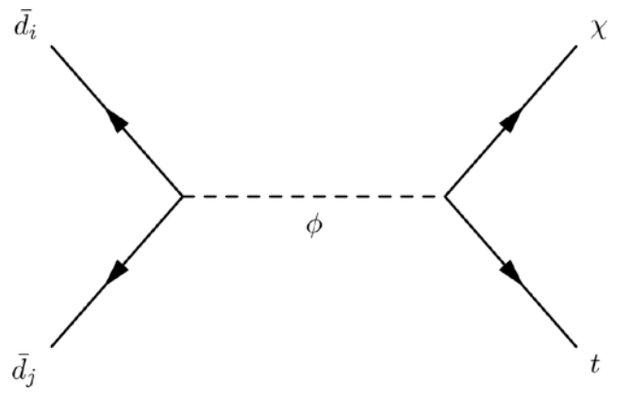


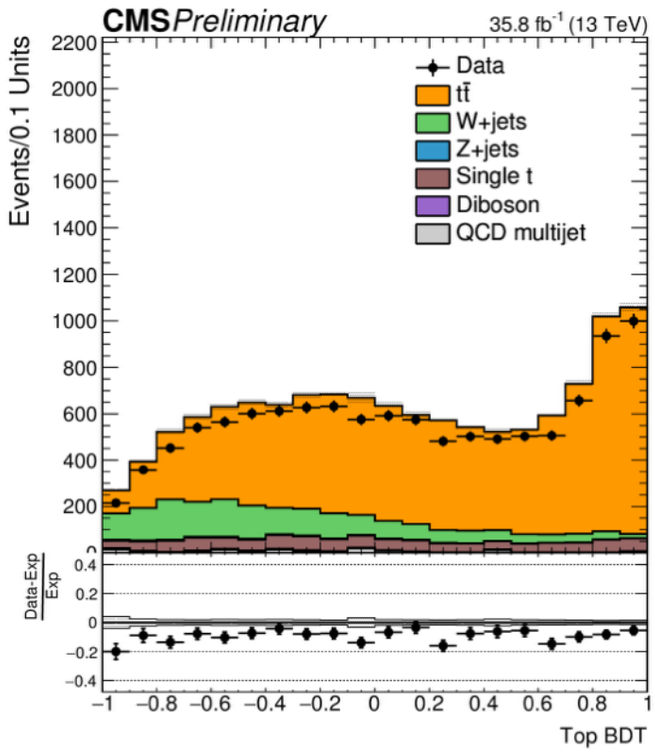


CMS DM+t (boosted) [CMS-PAS-EXO-051]

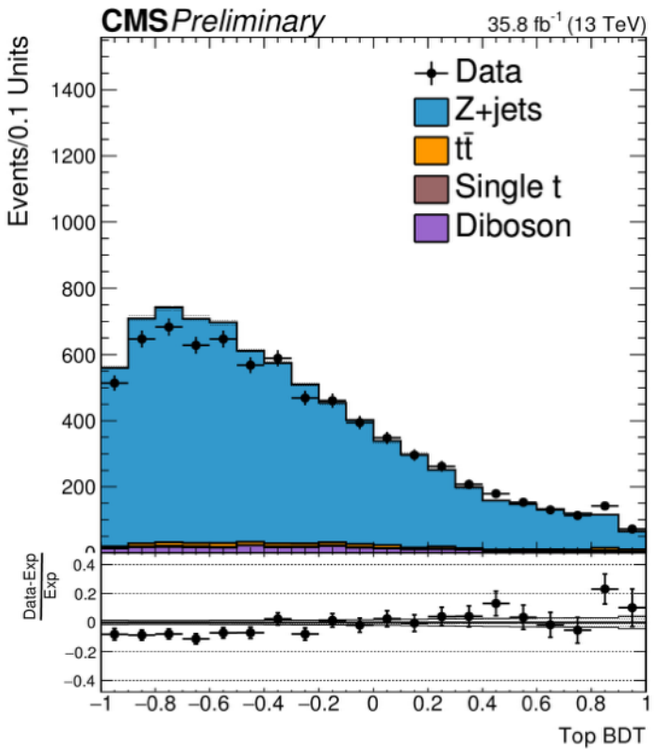
Using a MVA (BDT) for boosted top tagging





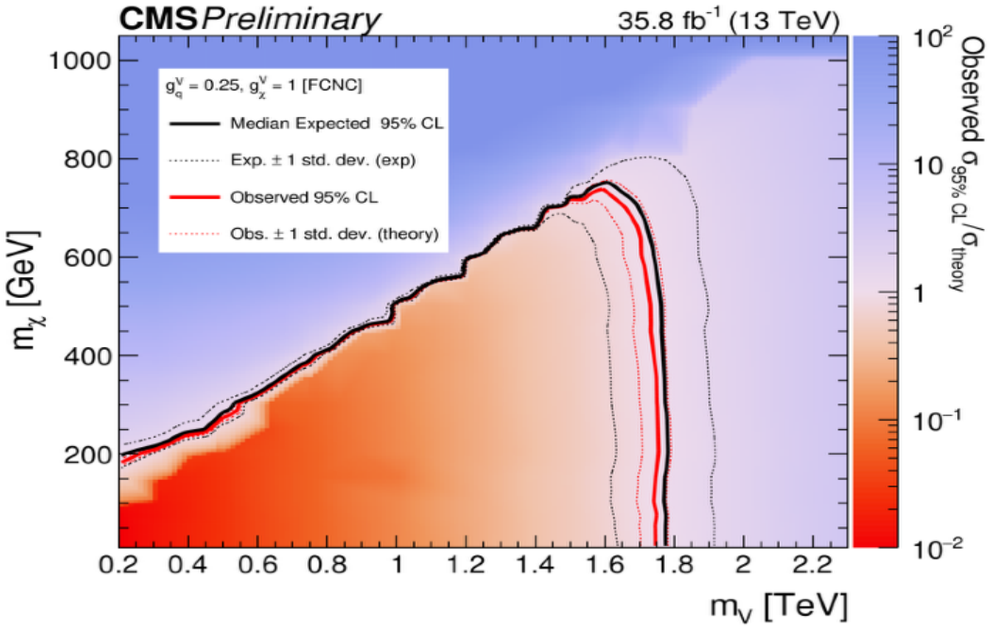


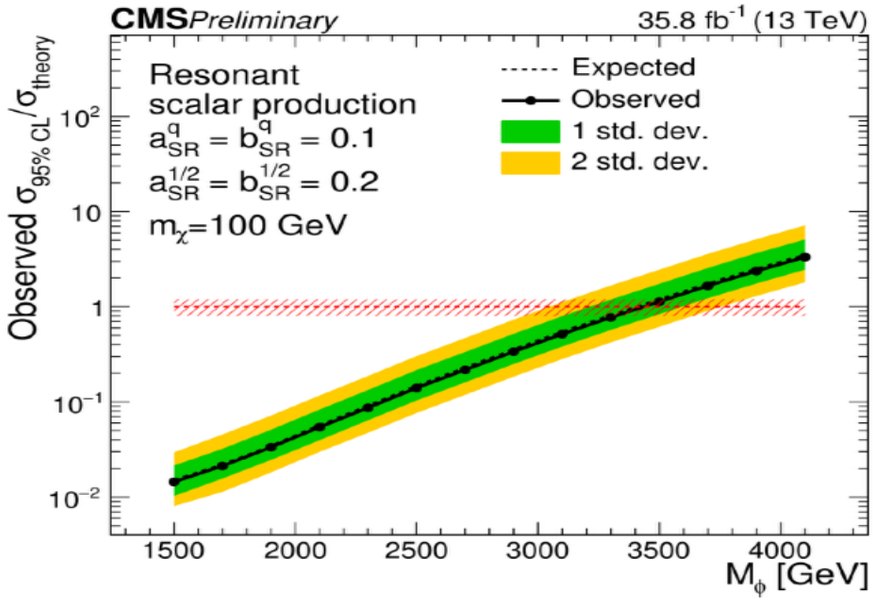
(a) Single muon $t\bar{t}$ selection



(b) $Z \rightarrow \mu\mu$ selection

Validation plots



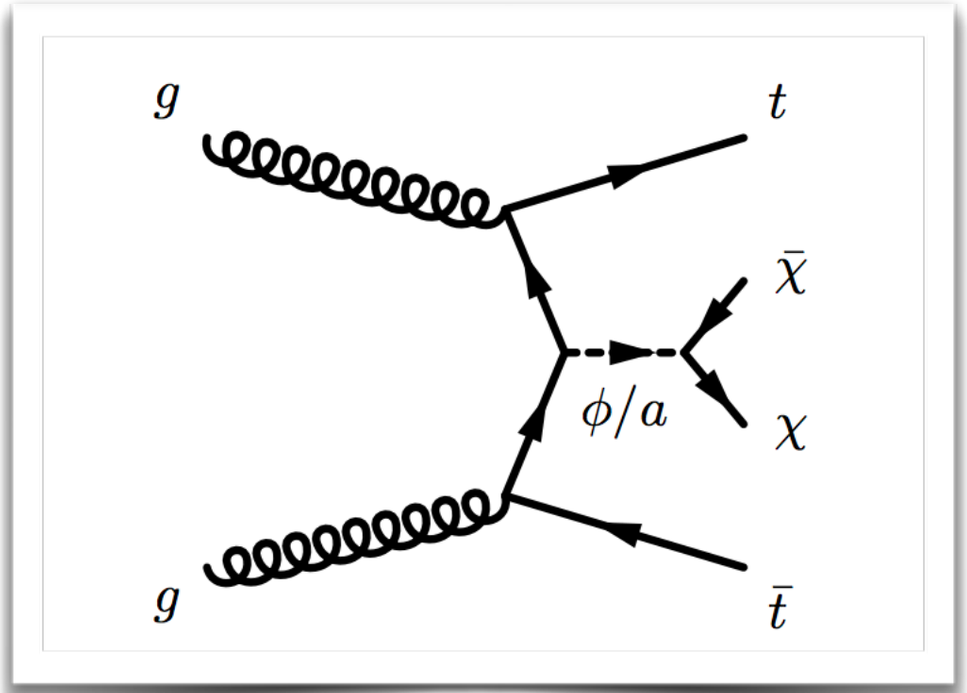


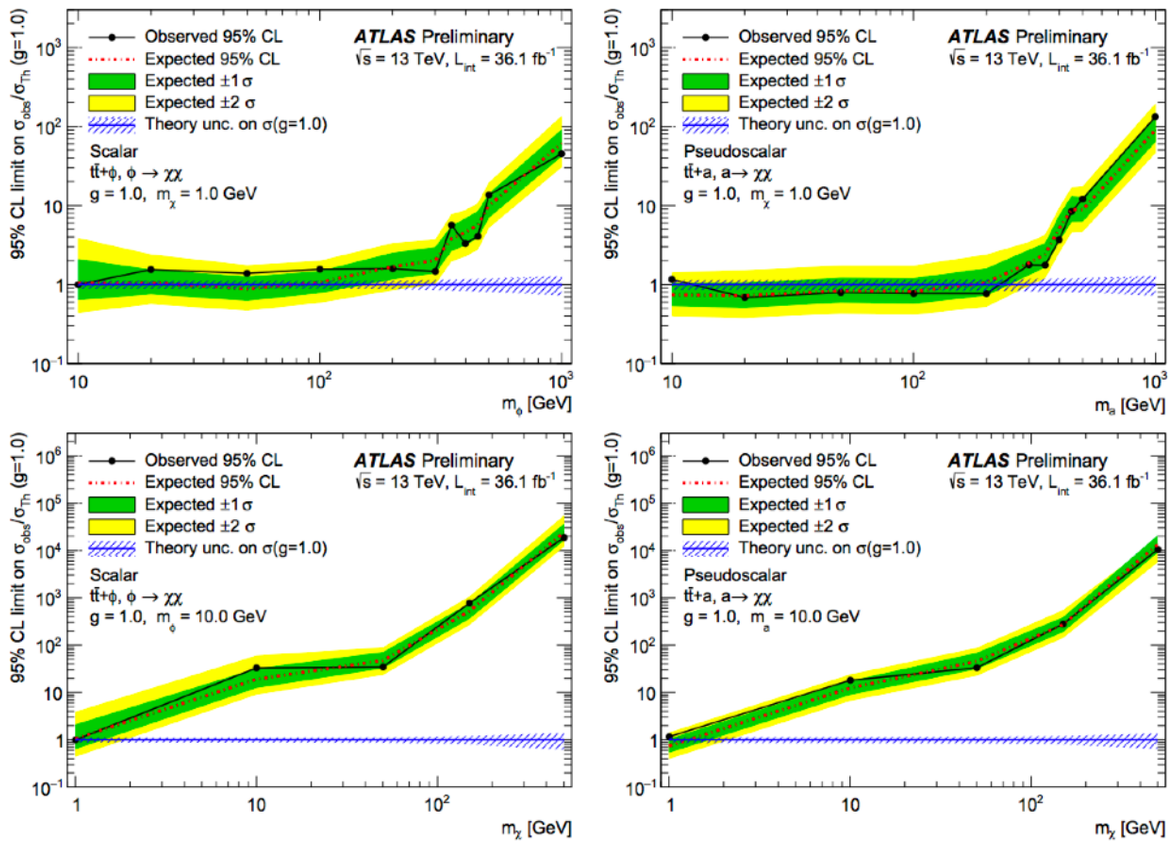
ATLAS DM+tt

3 channels forth decays
- Full had (0-lep)
- Full lep (2-lep)
- Mixed (1-lep)

tt environment➛ background mostly from tt events; V+jets (channel dependent)

Estimation using data driven techniques in control regions



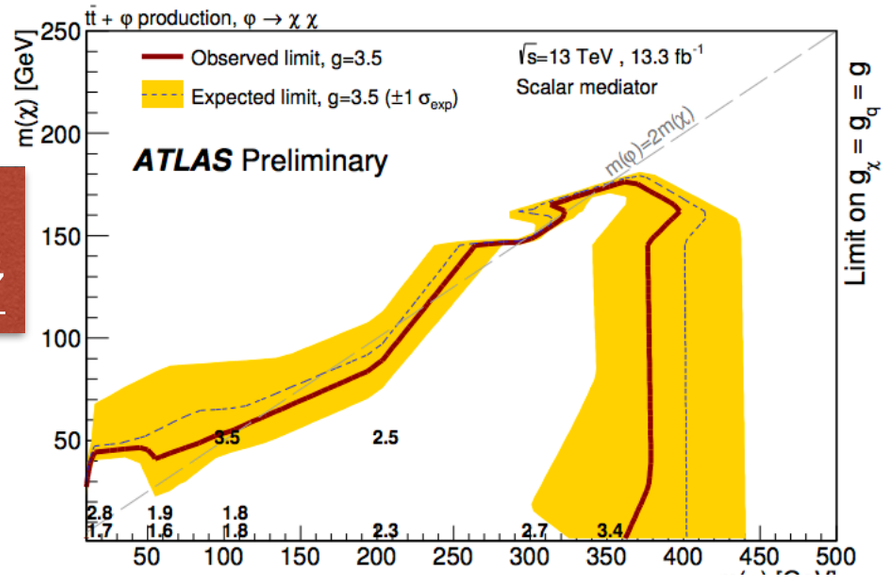


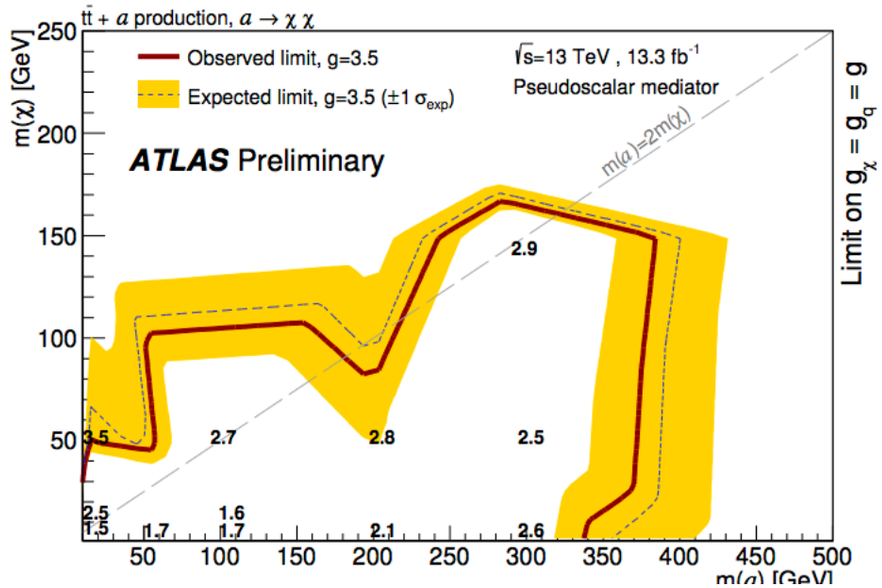
1 lepton analysis ATLAS-CONF-2017-037

Scalar and PseudoScalar mediator
Only sensitive to low mediator mass

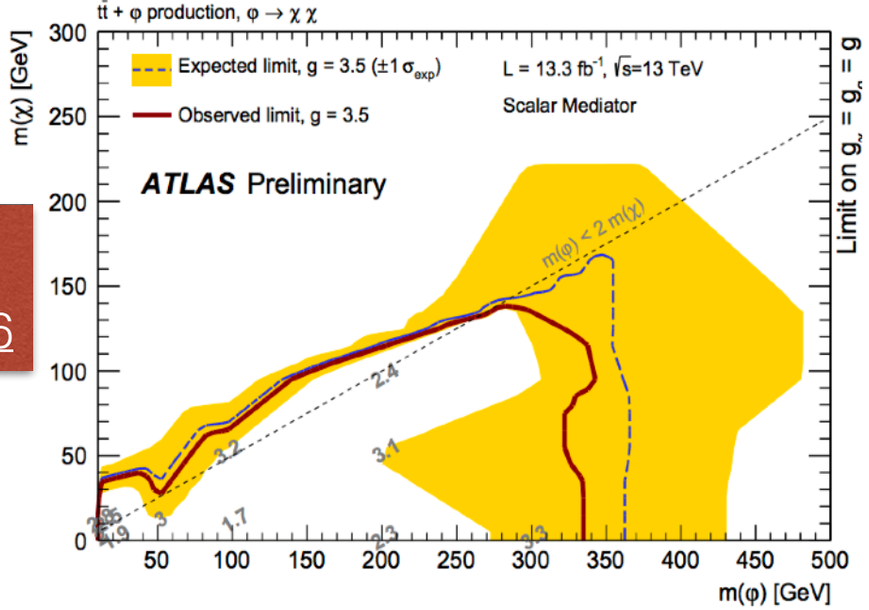
ATLAS DM+tt

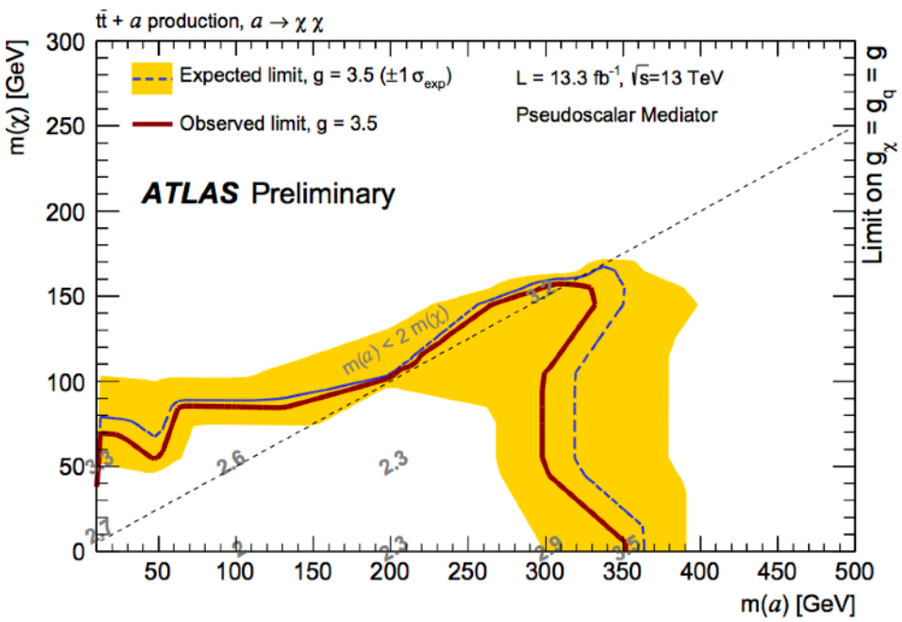
0 lepton analysis
ATLAS-CONF-2016-077





2 lepton analysis
ATLAS-CONF-2016-076

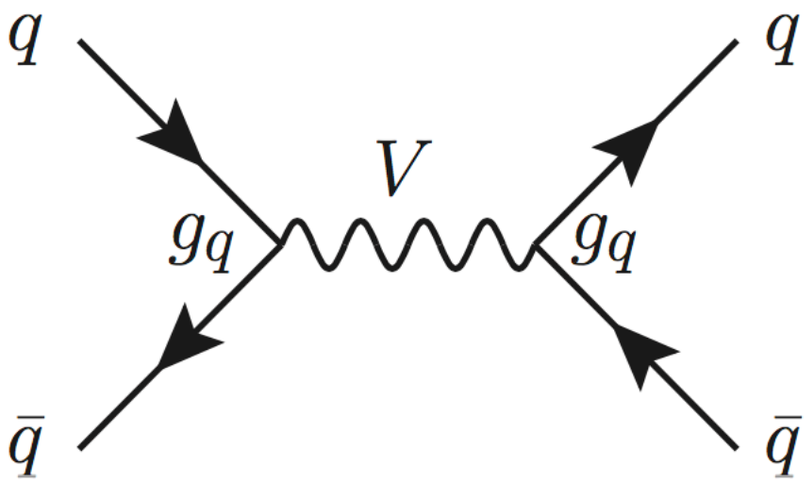




Mono X Results from the LHC

"X"	Expt	Run 1 (20 fb-1 @8TeV)	Run 2 (36 fb-1 @13TeV)
≥1 jet	ATLAS CMS	EPJC 75 (2015) 299 EPJC 75 (2015) 235	ATLAS-CONF-2017-060 CMS-PAS-EXO-16-048
≥2jet	CMS	JHEP 12 (2016) 088	
Photon	ATLAS CMS	PRD 91 (2015) 012008 PLB 755 (2016) 192	arXiv:1704.03848 CMS-PAS-EXO-16-039
W(lν)	ATLAS CMS	JHEP 09 (2014) 037 PRD 91 (2015) 092005	
Z(ll)	ATLAS CMS	PRD 90 (2014) 012004 PRD 93 (2016) 052011	ATLAS-CONF-2016-056 CMS-PAS-EXO-16-052
W,Z (qq)	ATLAS CMS	PRL112 (2014) 041802 JHEP 12 (2016) 083	Phys. Lett. B 763 (2016) 251 CMS-PAS-EXO-16-037
H(bb)	ATLAS CMS	PRD 93 (2016) 072007	arXiv:1707.01302 CMS-PAS-EXO-16-012
H($\gamma\gamma$)	ATLAS CMS	PRL115 (2015) 131801	arXiv:1706.03948 CMS-PAS-EXO-16-054
tt or t	CMS	JHEP 06 (2015) 121	ATLAS-CONF-2016-077(076) CMS-PAS-EXO-16-051
bb	CMS		ATLAS-CONF-2016-086 CMS-PAS-B2G-15-017
t/b jet	ATLAS CMS	EPJC 75 (2015) 92	CMS-PAS-EXO-16-005

Mediator search

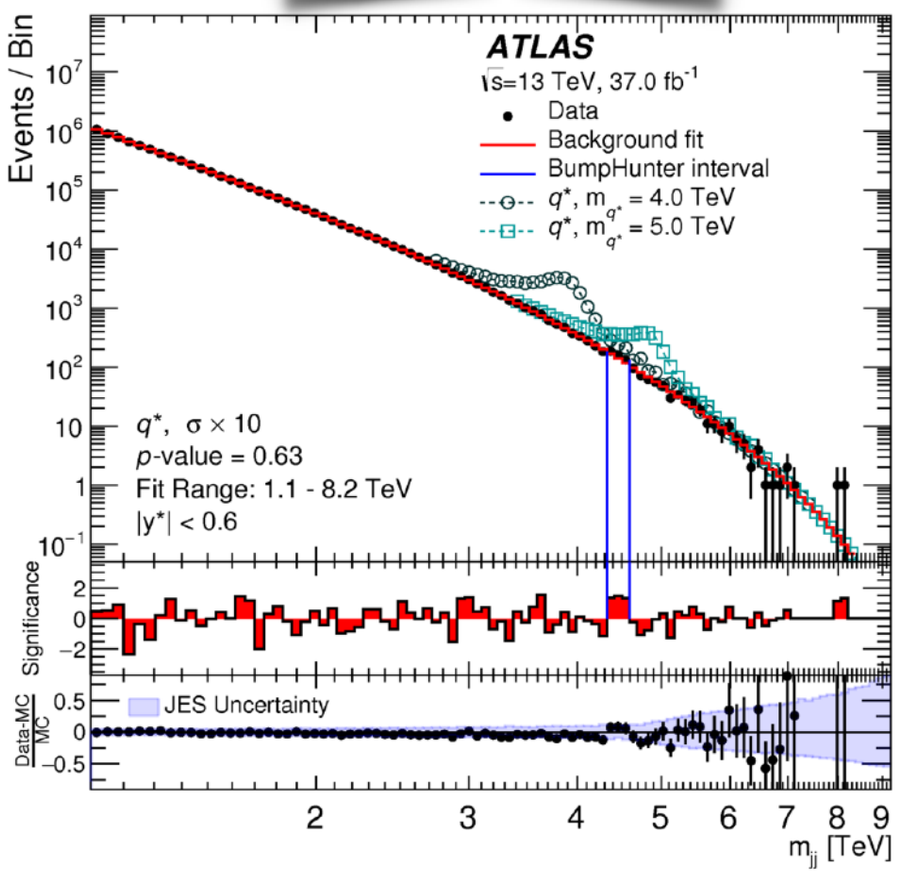


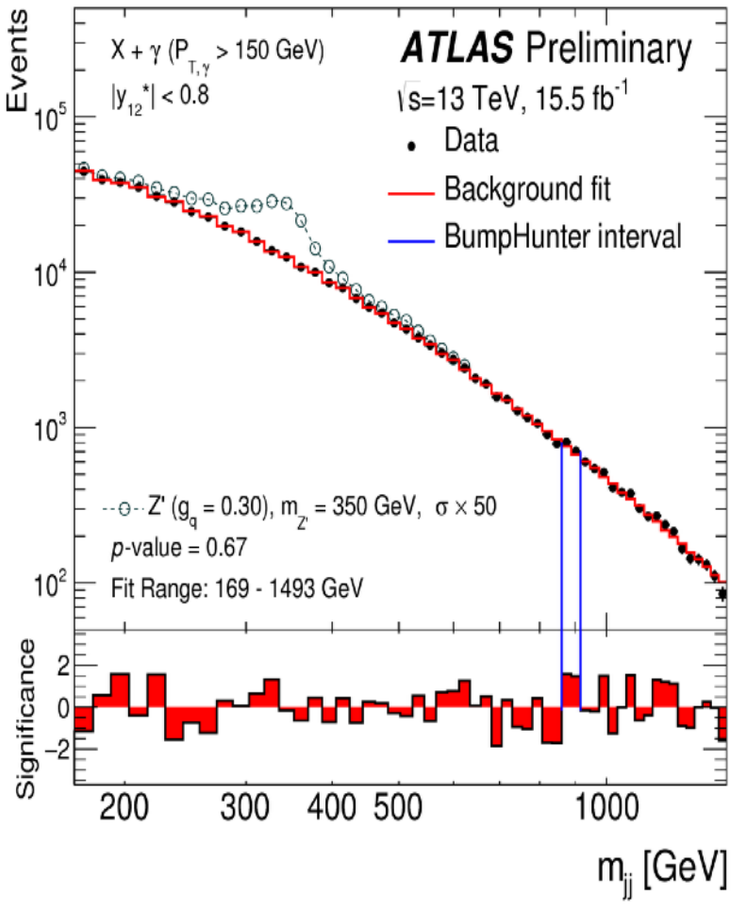
Di-jet invariant mass ➔ resonance ➔ bump hunting

To get the low mass we need ISR photon or jet to fire the trigger

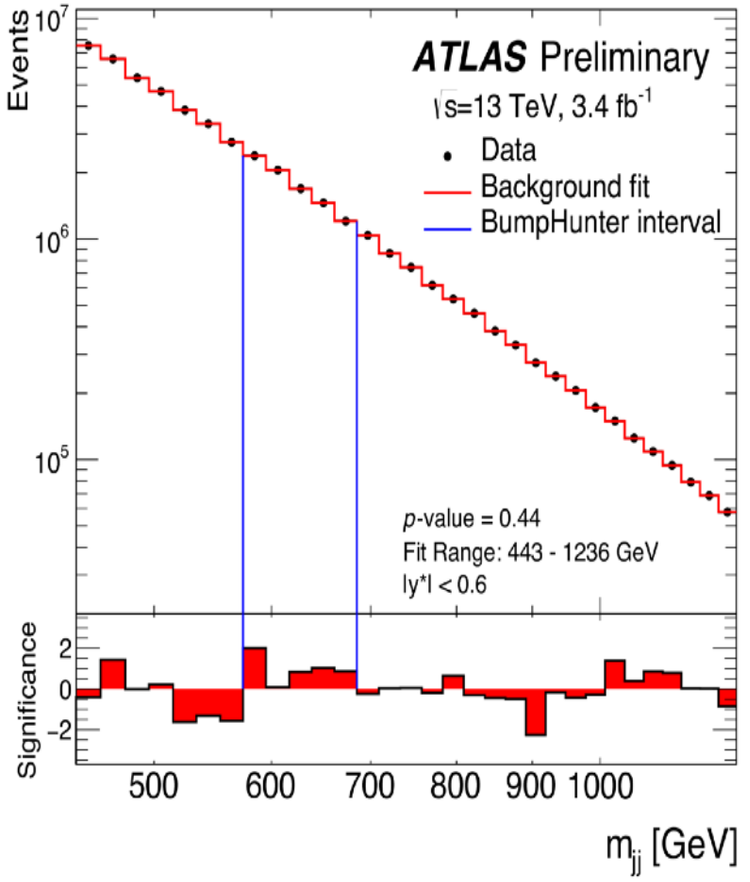
Trigger constrains search to >1 TeV

arXiv:1703.09127

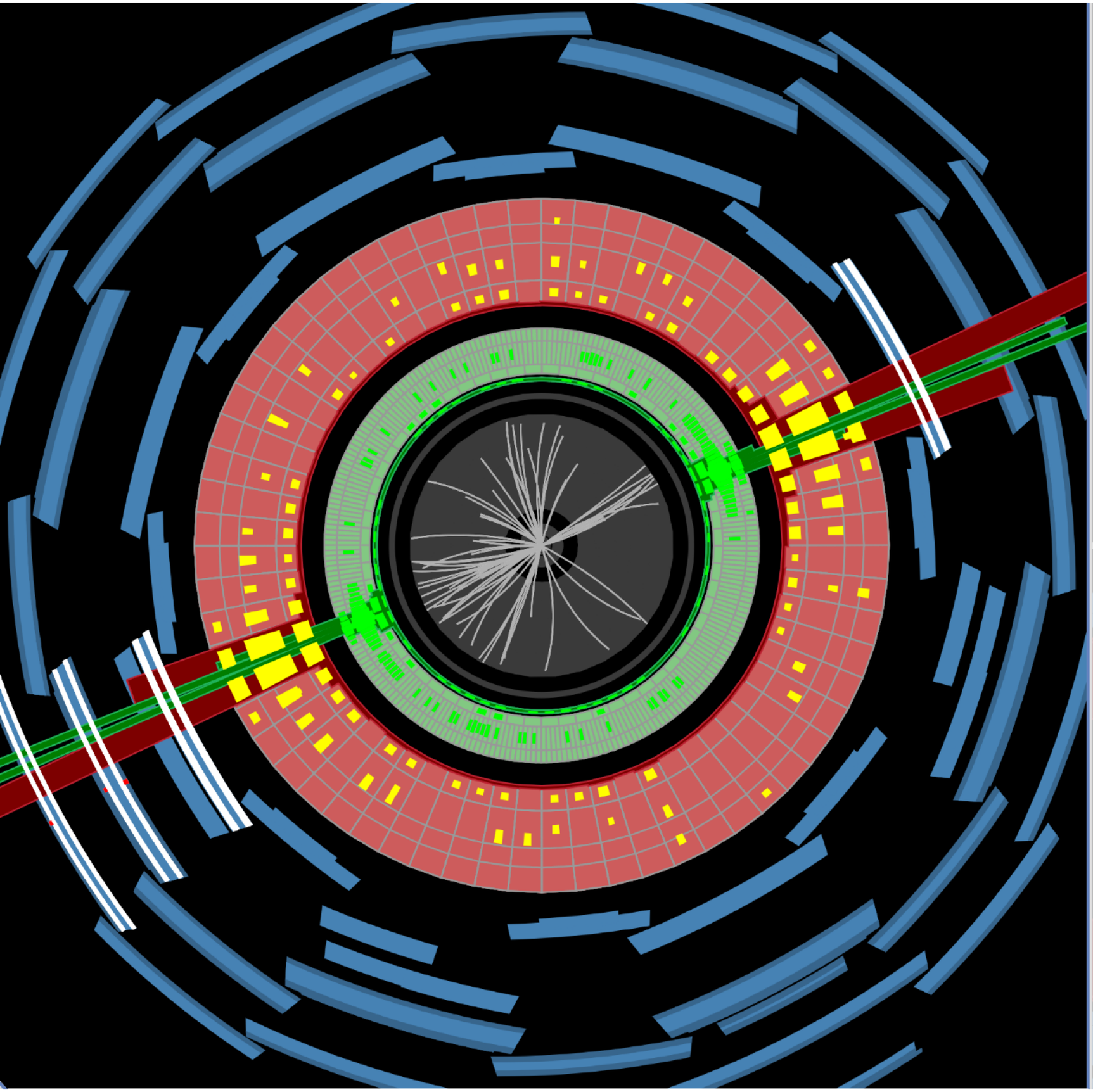


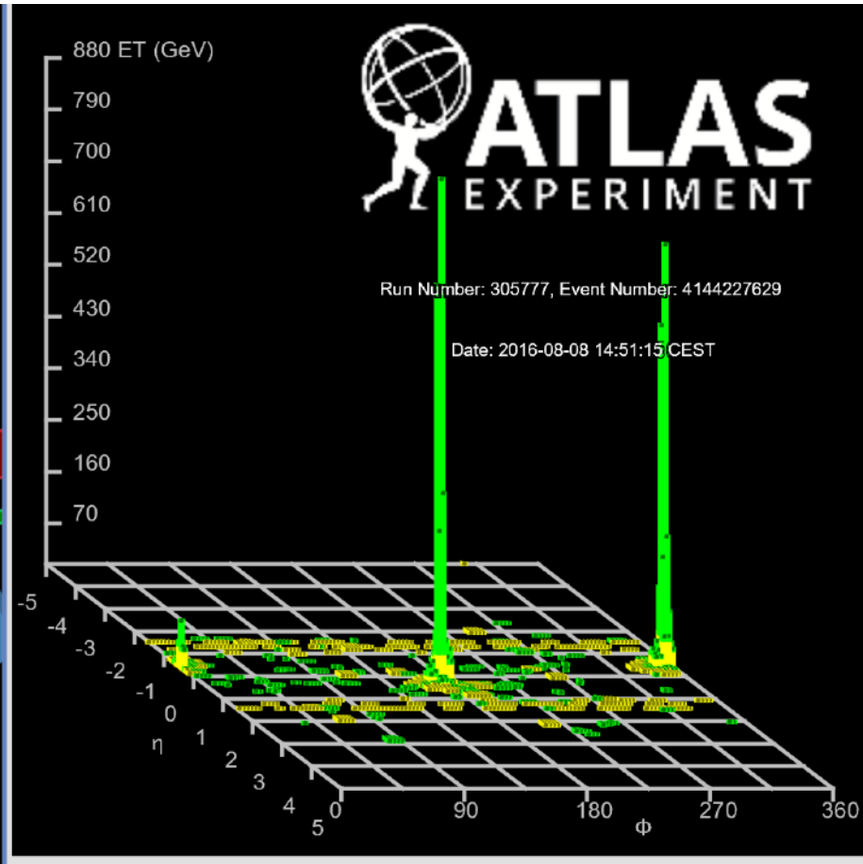


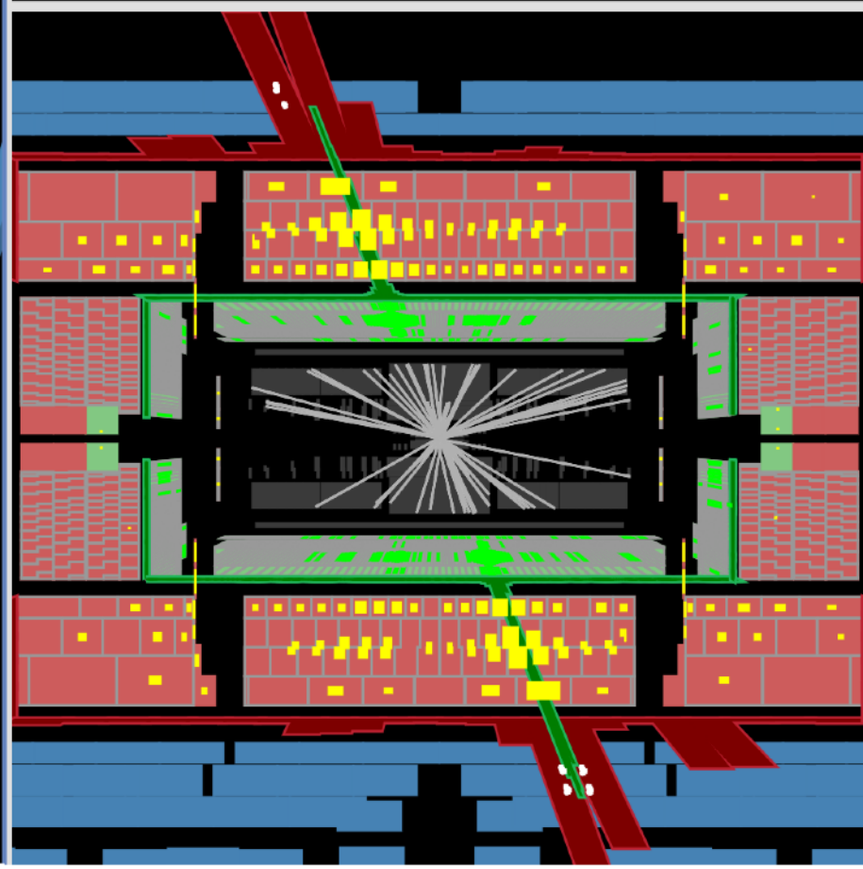
ATLAS-CONF-2016-030



ATLAS-CONF-2016-070

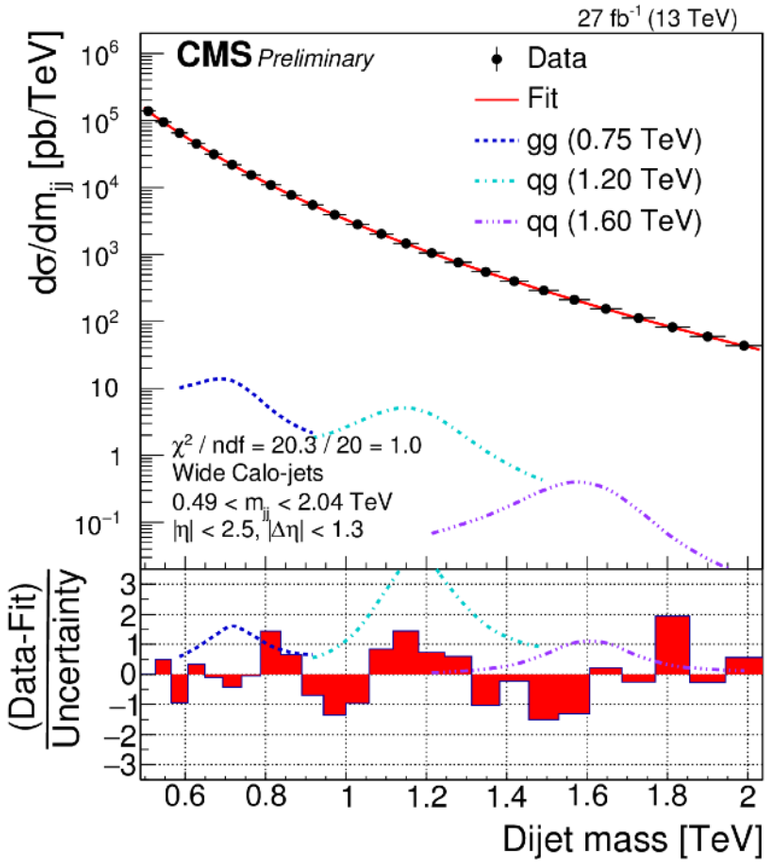


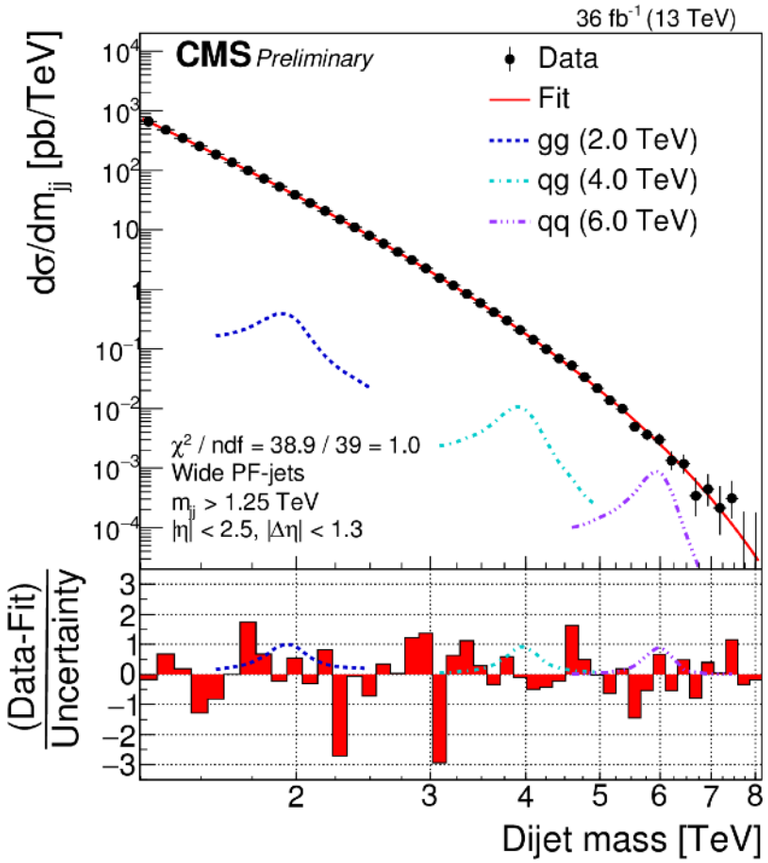

880 ET (GeV)
790
700
610
520
430
340
250
160
70
ATLAS
EXPERIMENT
Run Number: 305777, Event Number: 4144227629
Date: 2016-08-08 14:51:15 CEST
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
0
90
180
270
360
Φ

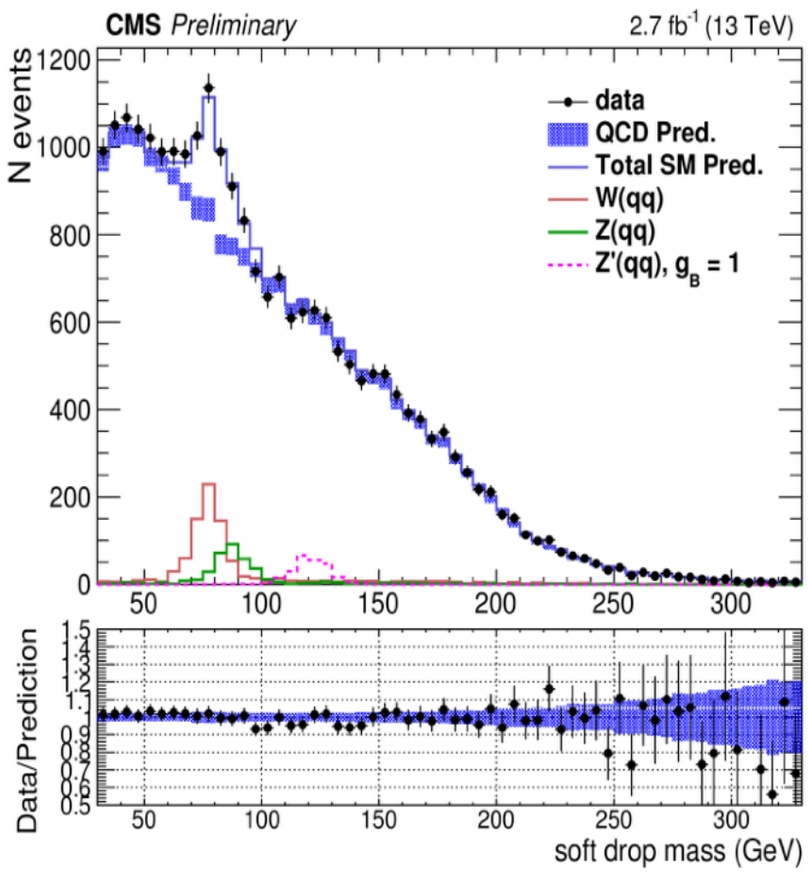


Mediator search

Similar analyses by CMS



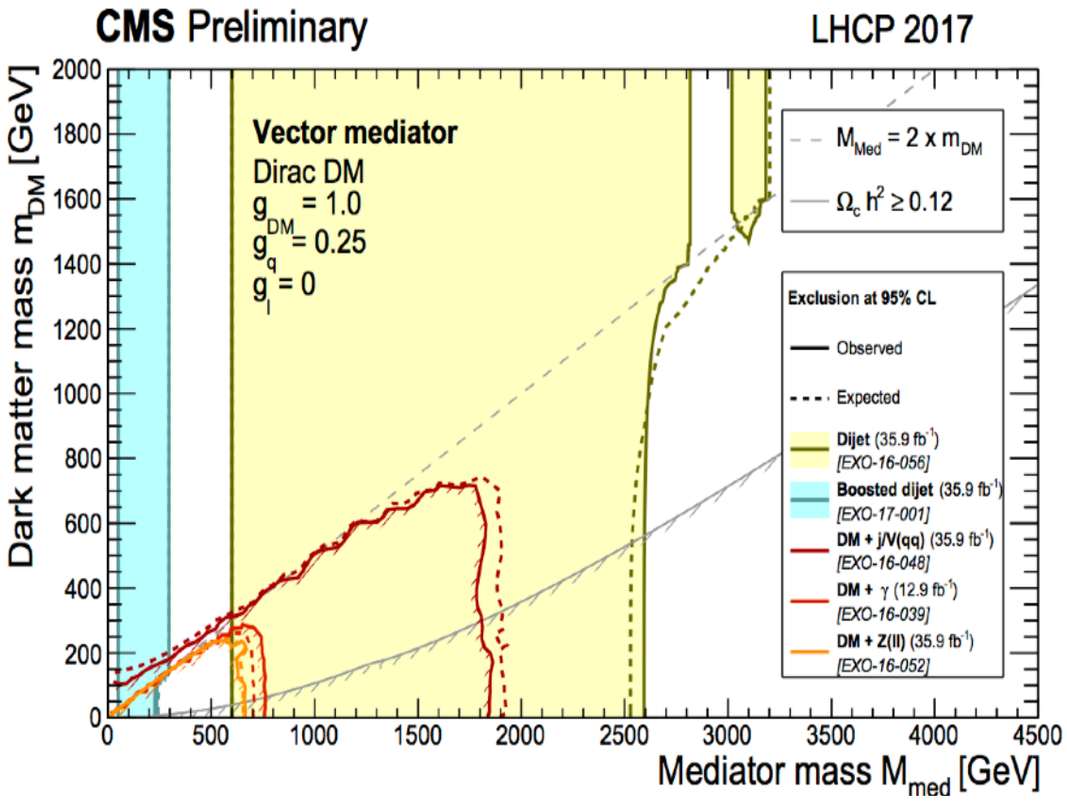


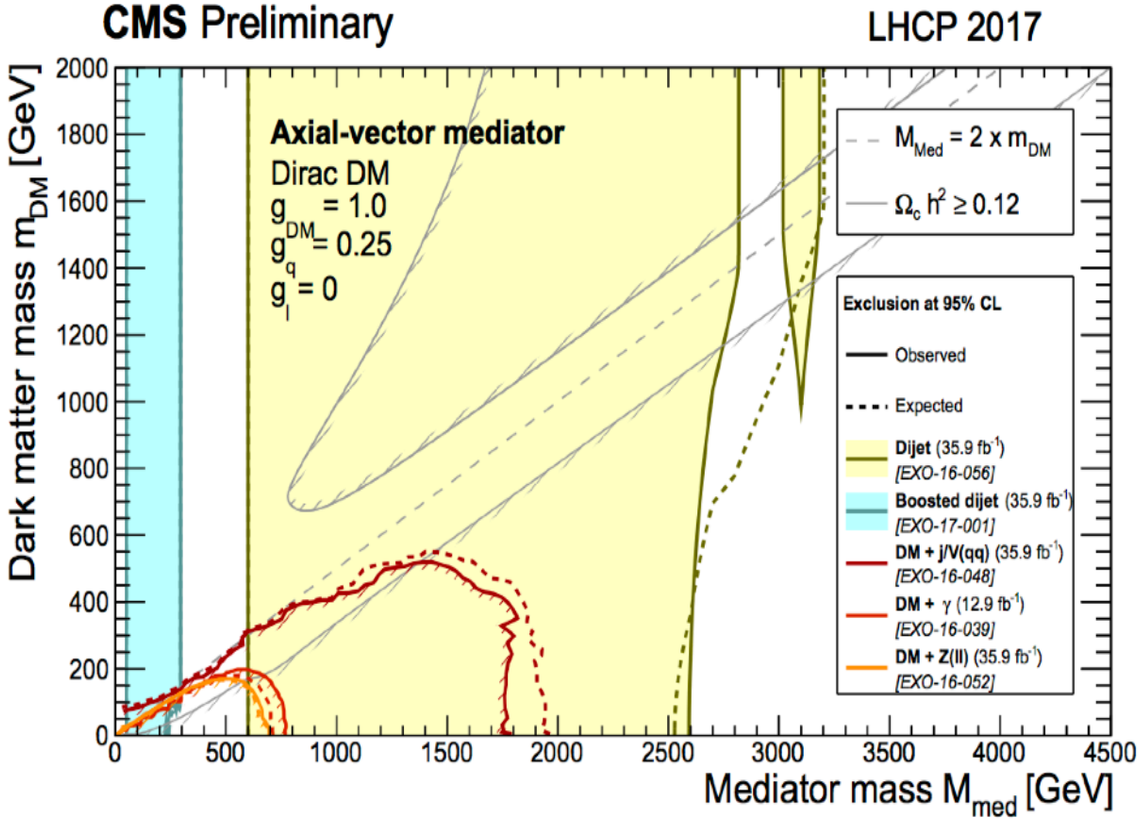


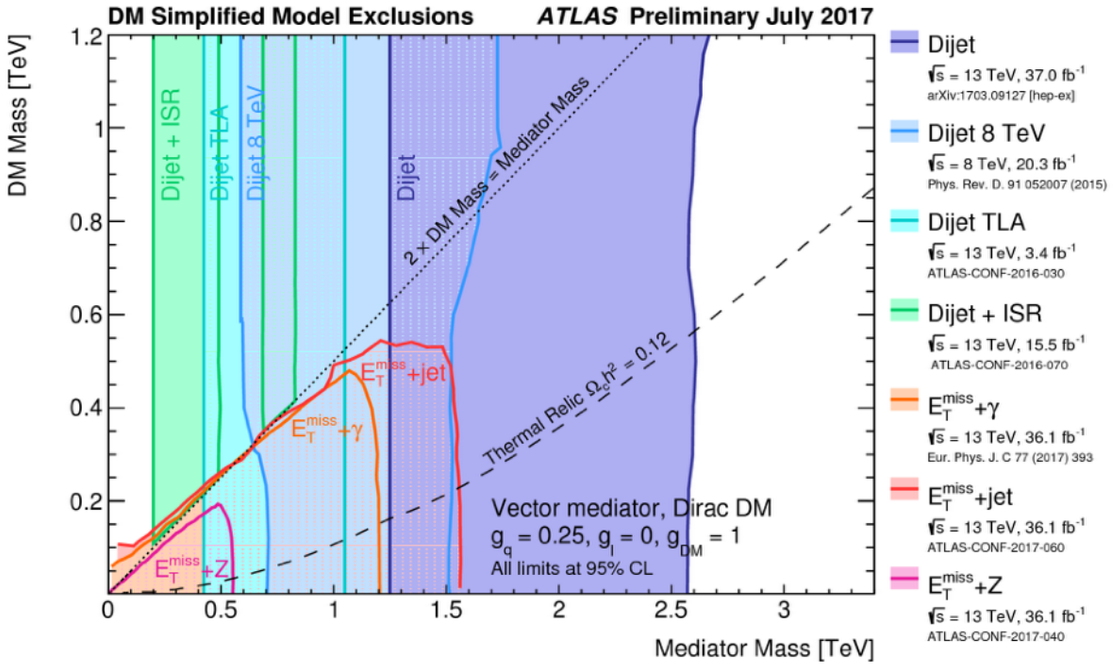
CMS-PAS-EXO-16-056

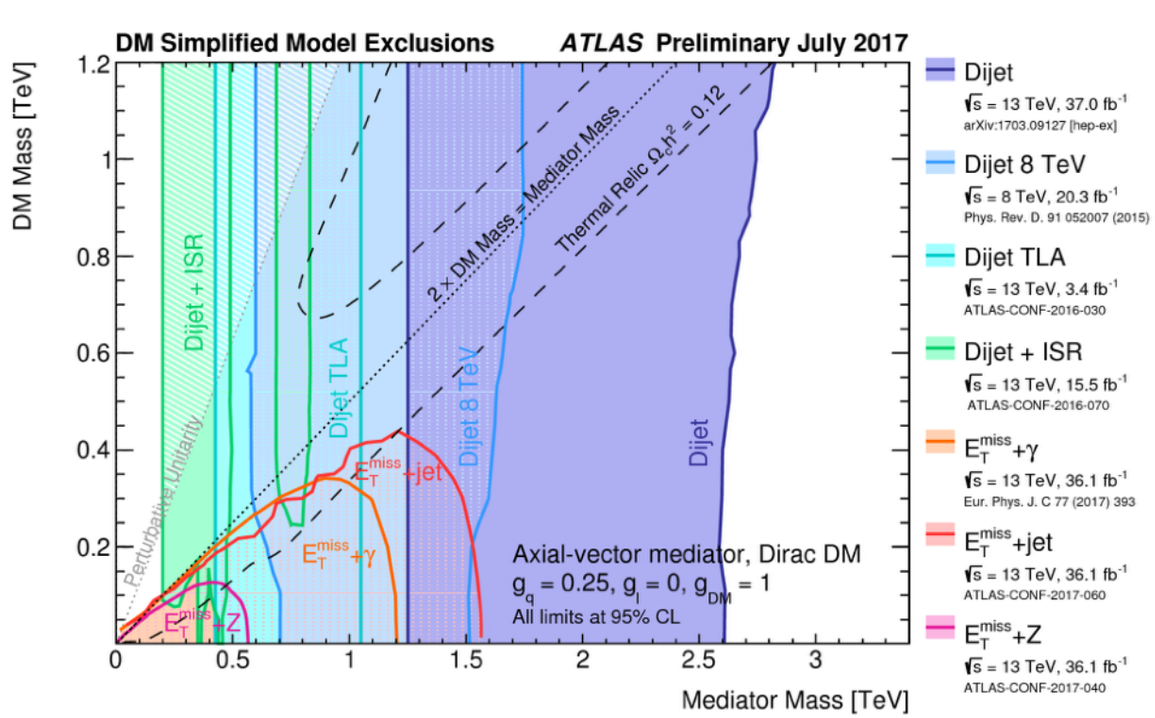
CMS-PAS-EXO-16-030

Summary of searches









Shown for one common set of coupling but limits are strongly dependent on choice of coupling

Conclusion

- Extensive search for DM at the LHC
- complementary to direct searches
- No excess over the SM was found but the results are interpreted as exclusion limits in the framework of simplified models and effective field theories.