Collider Dark Matter Searches

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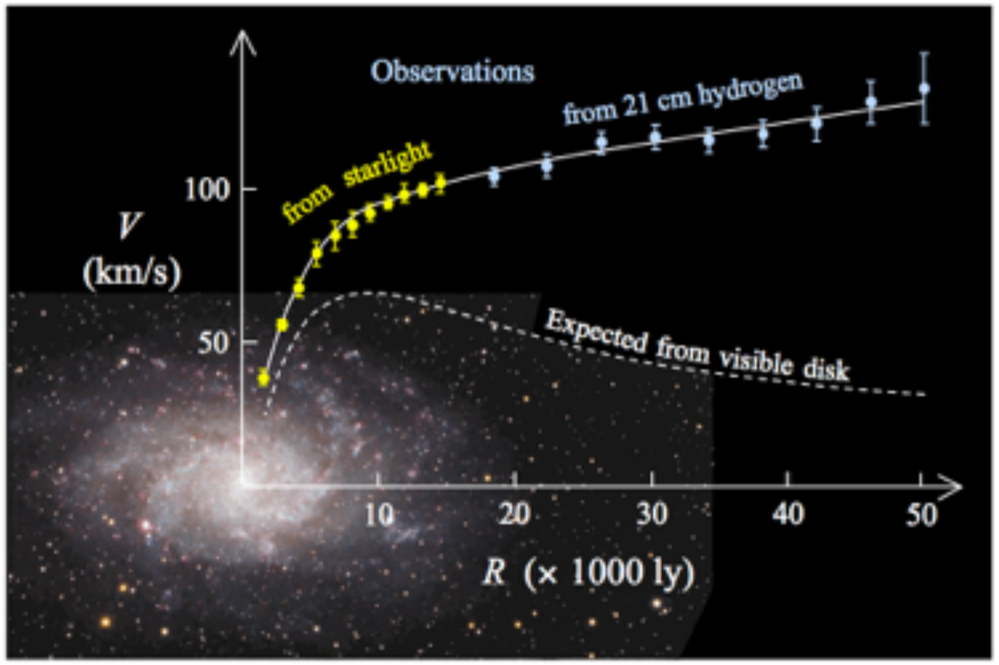
on behalf of the ATLAS and CMS collaborations

International Symposium on Higgs boson and BSM physics, Weihai, China, 15-19 August 2016

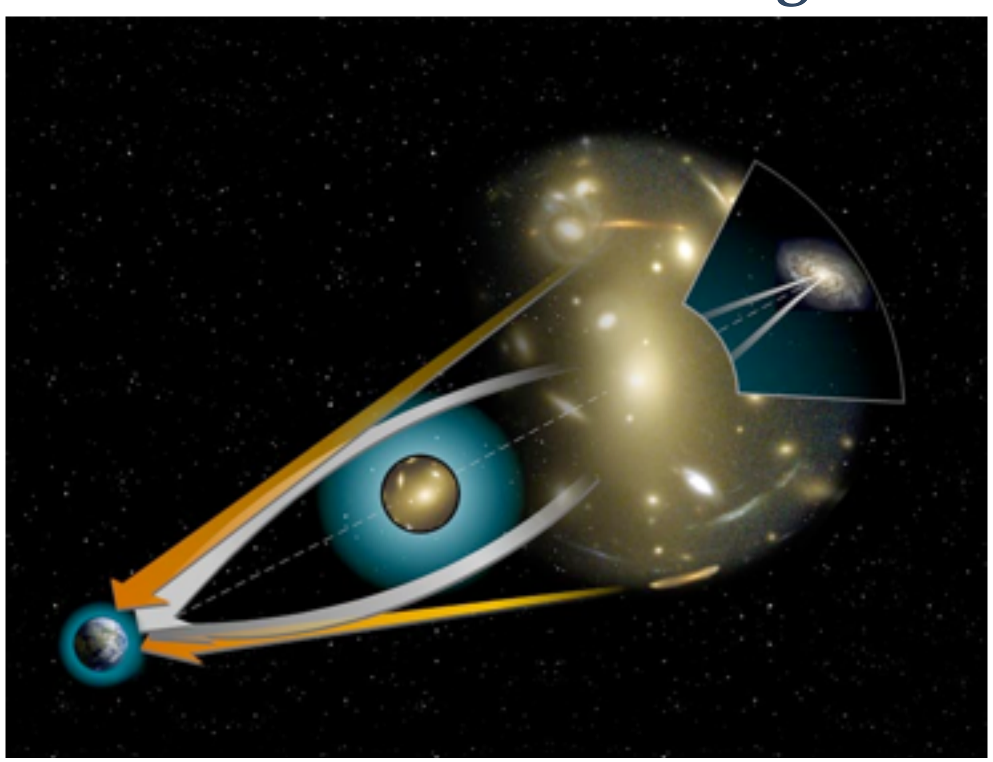
Evidence for Dark Matter

Galactic Rotation Curves

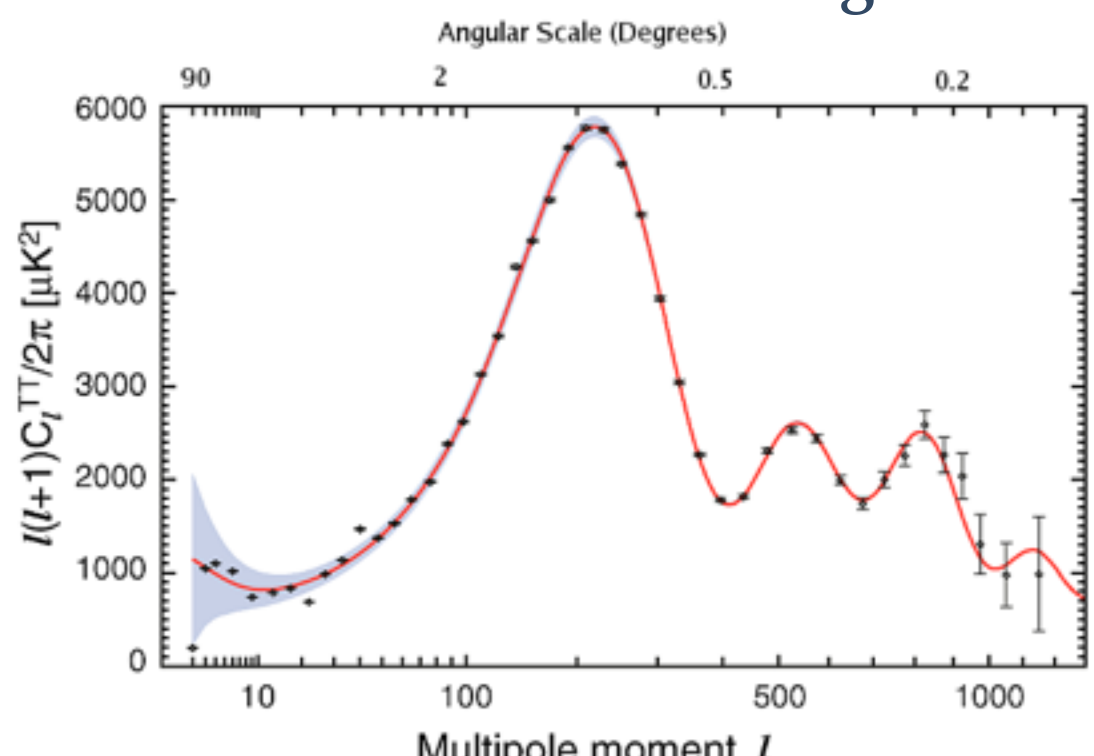


Bullet Clusters

Gravitational Lensing



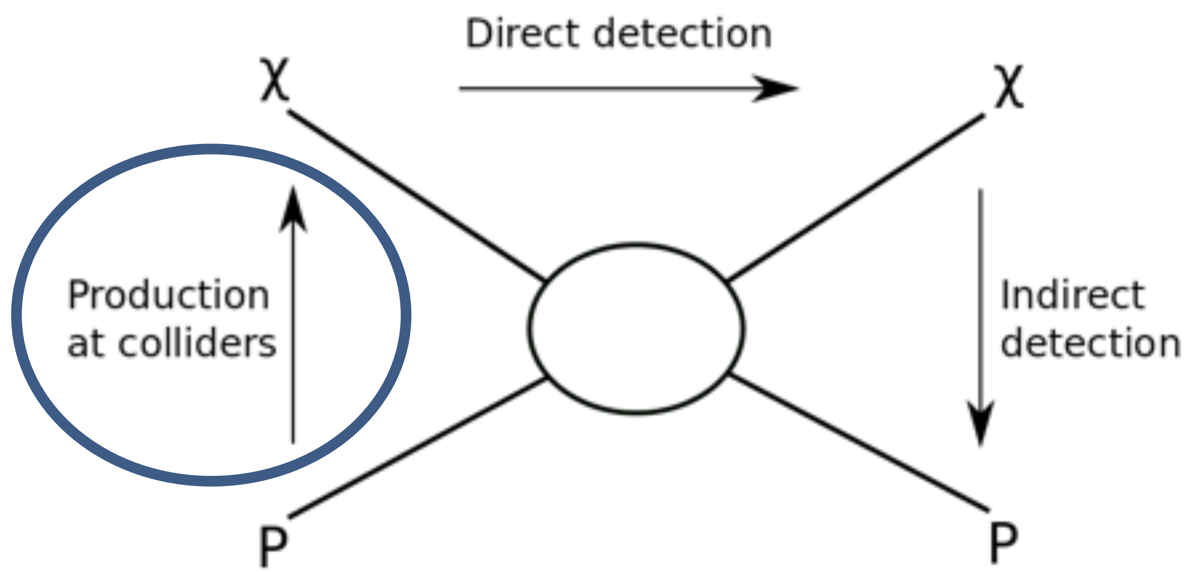
Radiation Cosmic Background



….and much more

Dark Matter Hunting

Three complementary approaches to dark matter detection



Detection at colliders possible if dark matter consist of a WIMP sector (very) weakly coupled to Standard Model

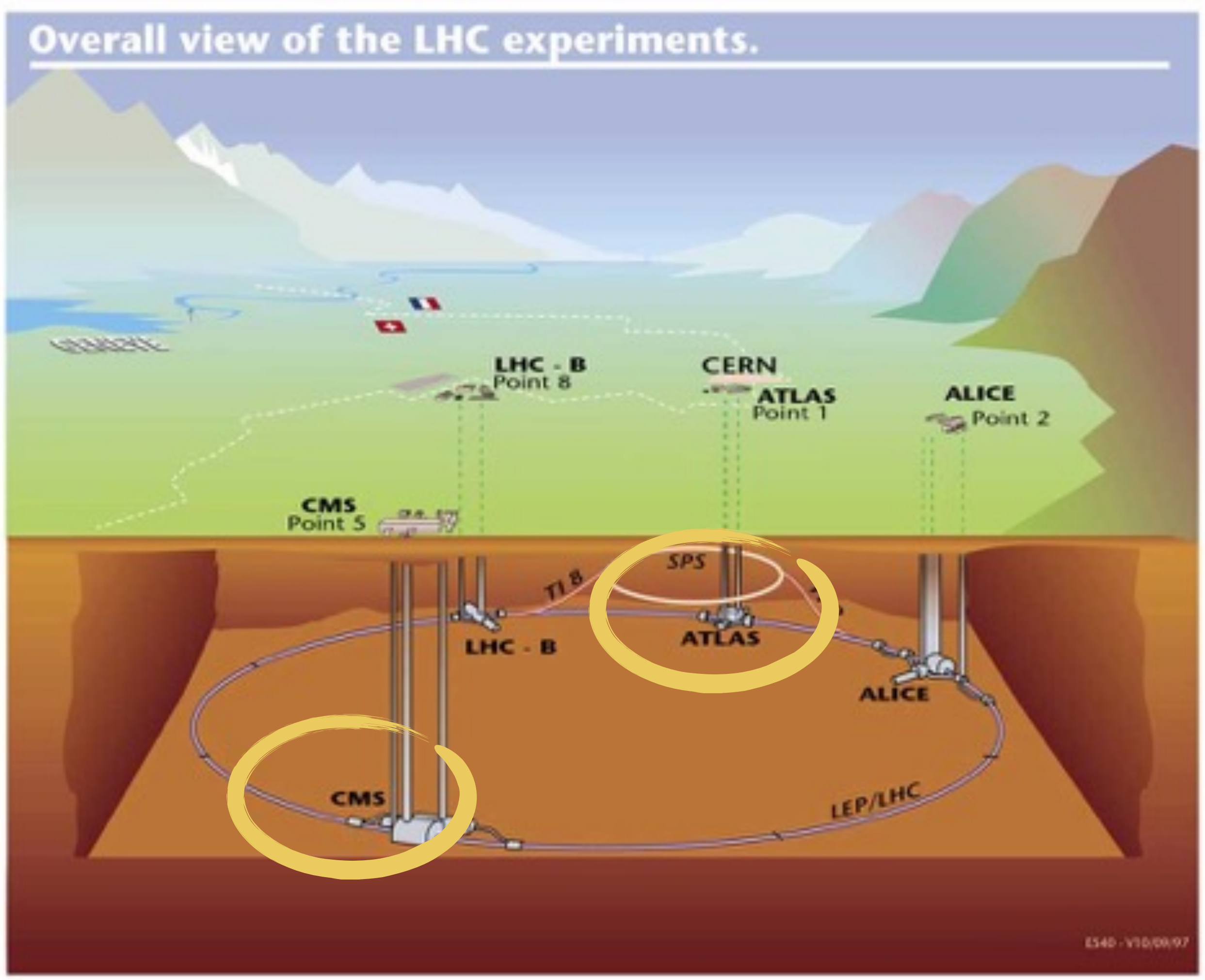
→ Consistent with experimental evidence

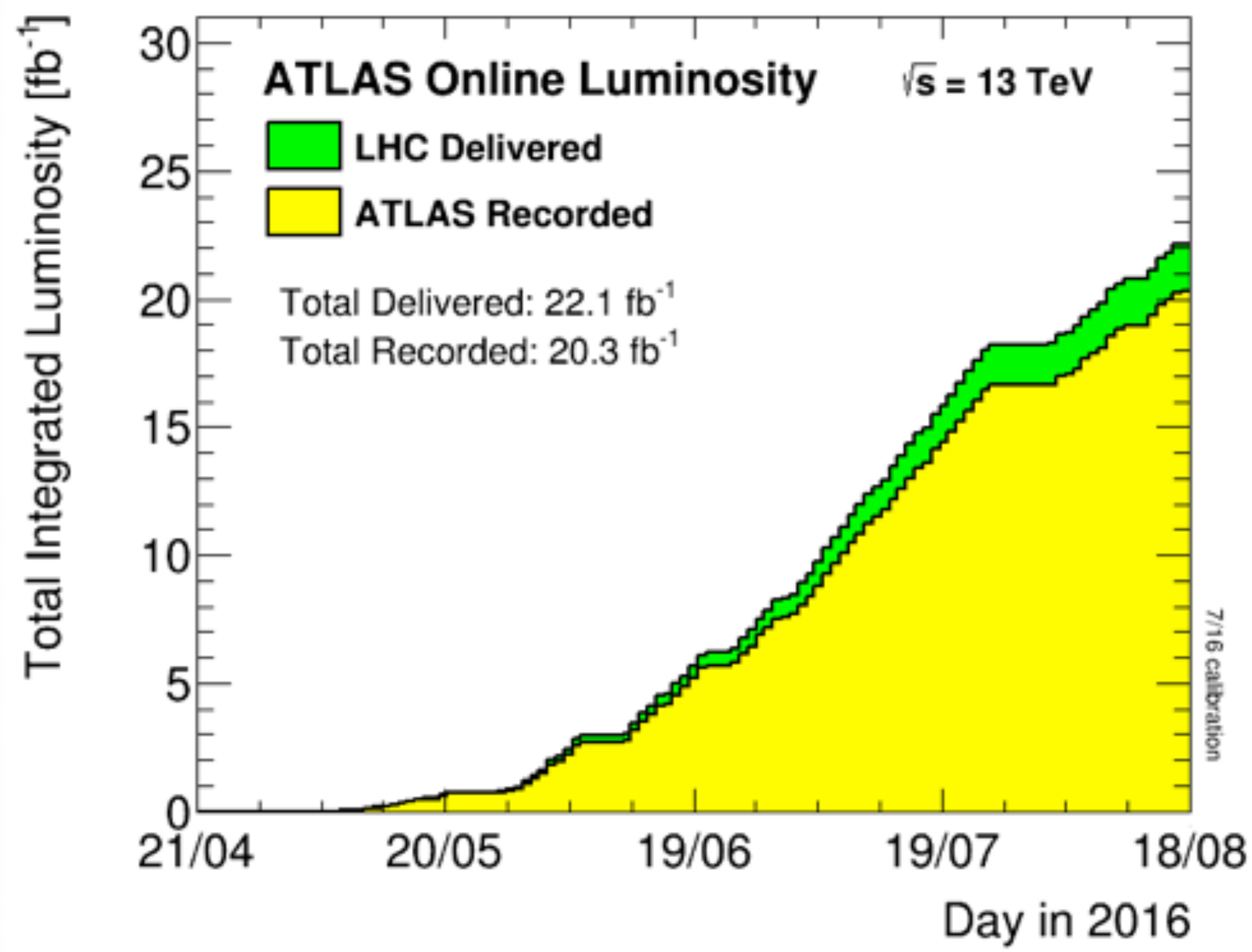
Dark Matter as a thermal relic of the early universe

The LHC

The Large Hadron Collider (LHC) accelerates and collides protons and heavy ions

- Operated between 2010 and 2012 at a centre-of-mass energy of the proton-proton collisions ($\sqrt{s}$) of 7 and 8 TeV → Run-I, ~5+20 fb^{-1} of data collected
- Since 2015 operating at $\sqrt{s}$=13 TeV → Run-II, ~20 fb^{-1} of data collected so far - collecting data right now!
- Collisions take place where experiments are located

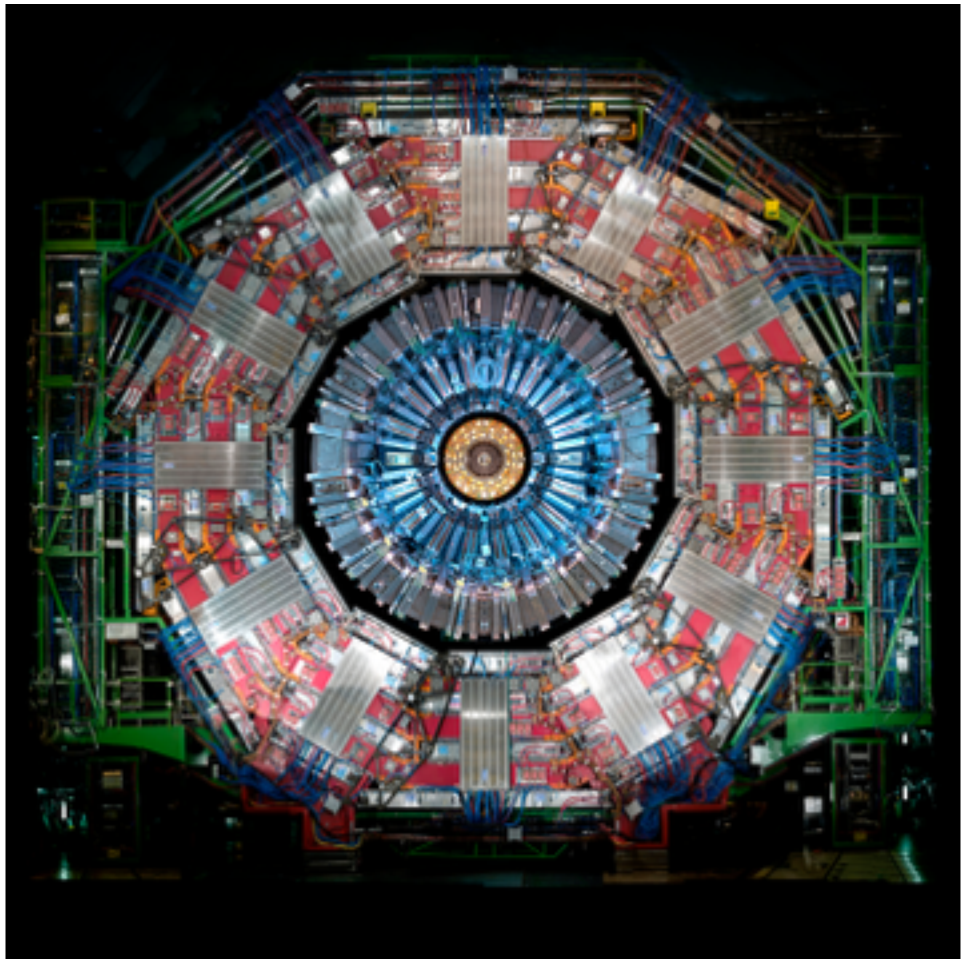


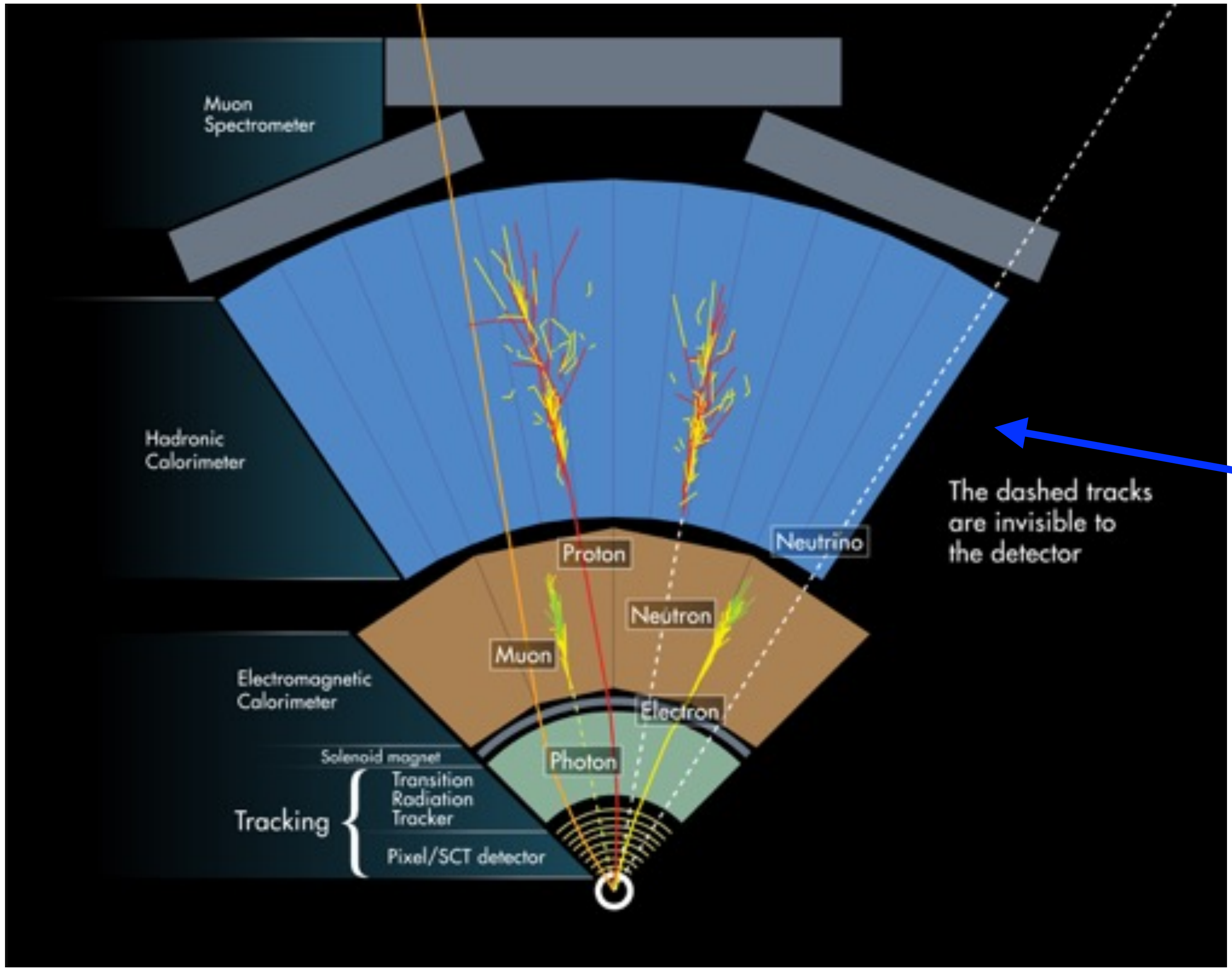


The ATLAS and CMS experiments

The ATLAS and CMS experiments are composed of different sub-systems

Particles resulting from the proton-proton collisions are identified by combining information from the sub-systems





Particles not interacting with the detector material:

Missing transverse energy

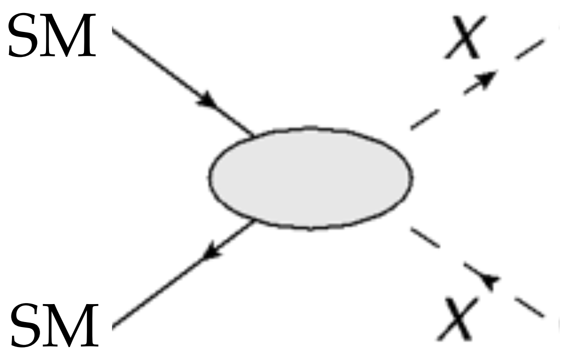
Exploit conservation of momentum in the transverse plane

$$E_{x(y)}^{miss} = -\sum_i E_{x(y)}^i$$

$$E_T^{miss} = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2}$$

Dark Matter Production

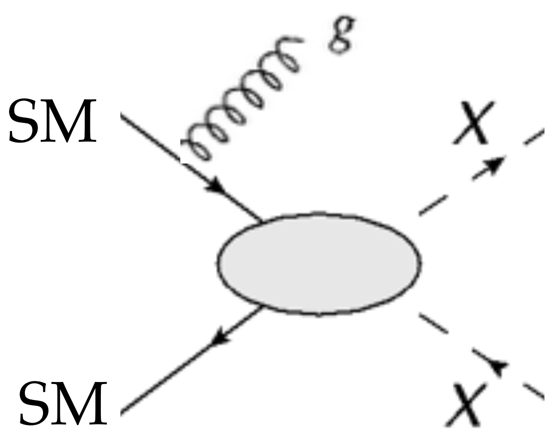
Mono-X signature



DM does not interact with the detector

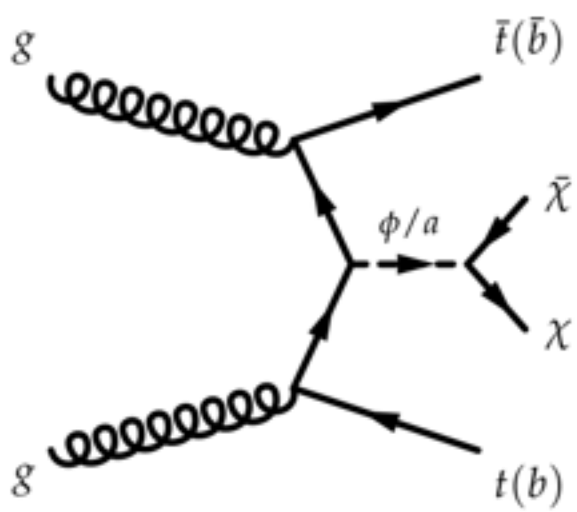
- Two **back-to-back invisible particles**
- Can't be detected

$\Rightarrow$ Consider signatures with **radiation of extra particles**:

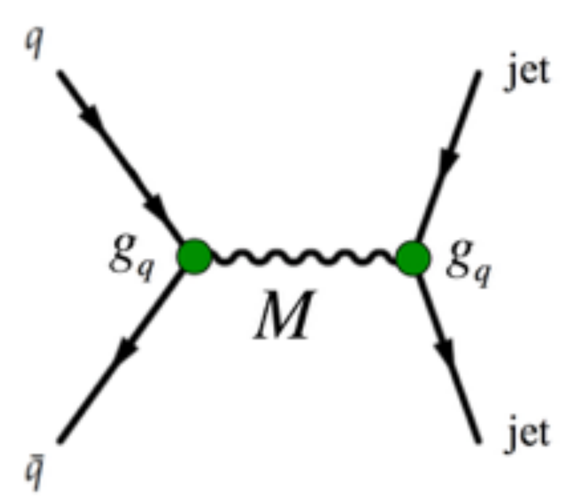


DM recoiling against a jet or a W/Z/γ

Associate Production



Search for mediators



Interpretation of the Results

- **Effective field theory** (EFT) **models** used for interpreting the results during **Run-1**
  - Valid if **transferred momentum much smaller than mediator mass**
  - Assumption breaks at the LHC
- Use mainly **simplified models** to interpret the results in **Run-2**
- Joint theory-experiment **LHC Dark matter forum** to
  - discuss and agree on **benchmark signal models**
  - Agree on how to **present the results**
  - arXiv:1507.00966

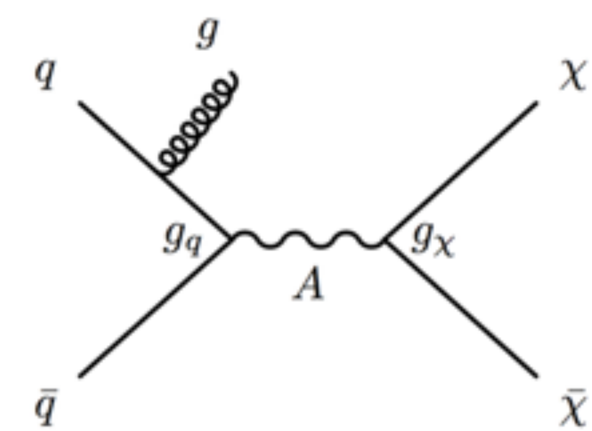
In this talk only Run-2 dark matter searches discussed in this talk,
but every search for R-conserving SUSY is de facto a search for dark matter candidates!

Mono-X Signatures

ATLAS mono-jet search

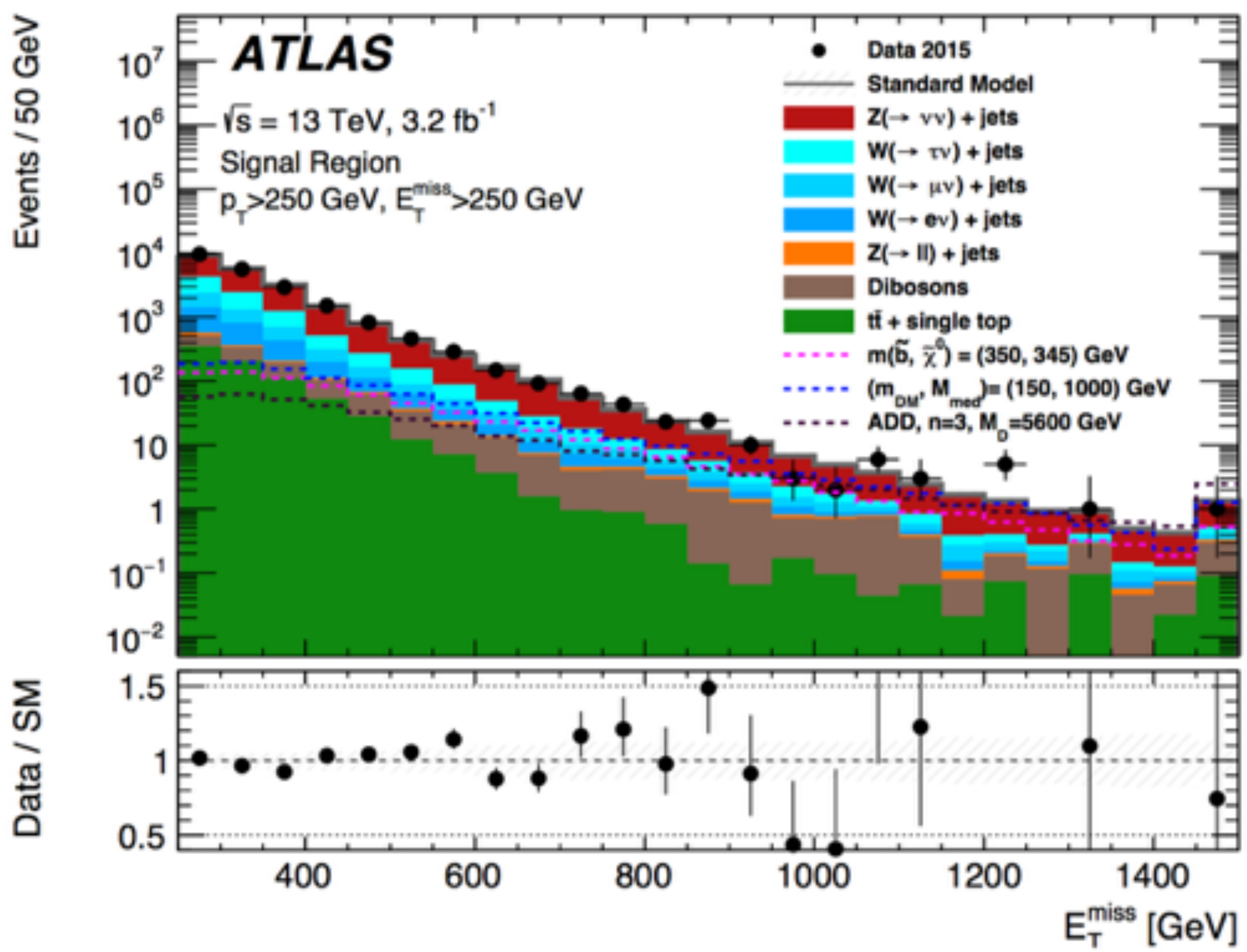
Select **initial state radiation (ISR) jet recoiling against DM candidates**

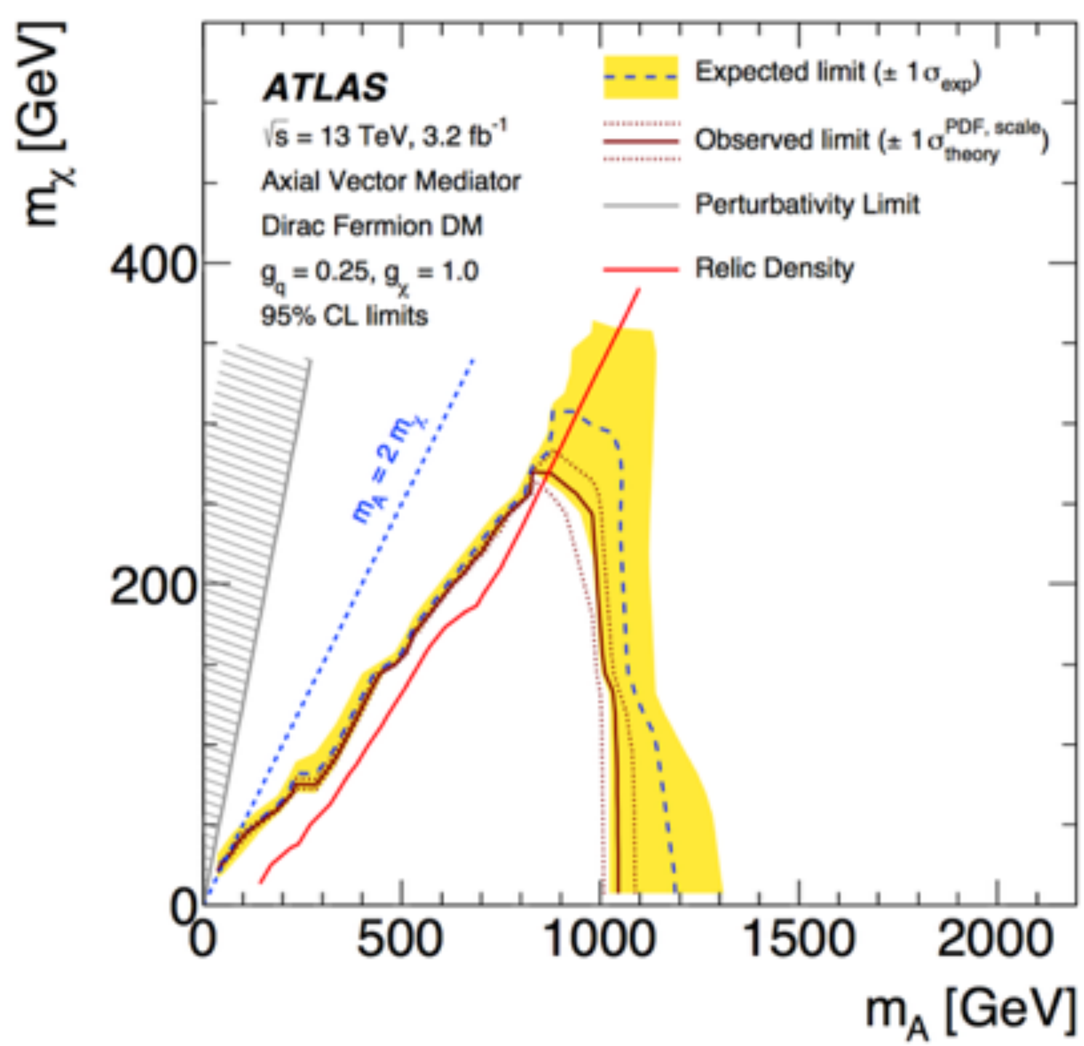
- **Axial-vector mediator** coupling to quarks and DM
- Most powerful search at hadron colliders
- Select events with at least one jet and large E_T^{miss}



Main background: Z→$\nu\nu$ + jets

arXiv:1604.07773



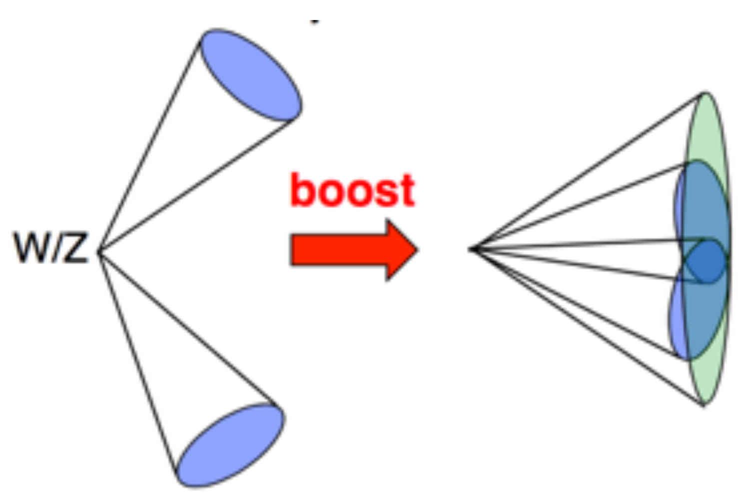


ATLAS mono-V (hadronic) search

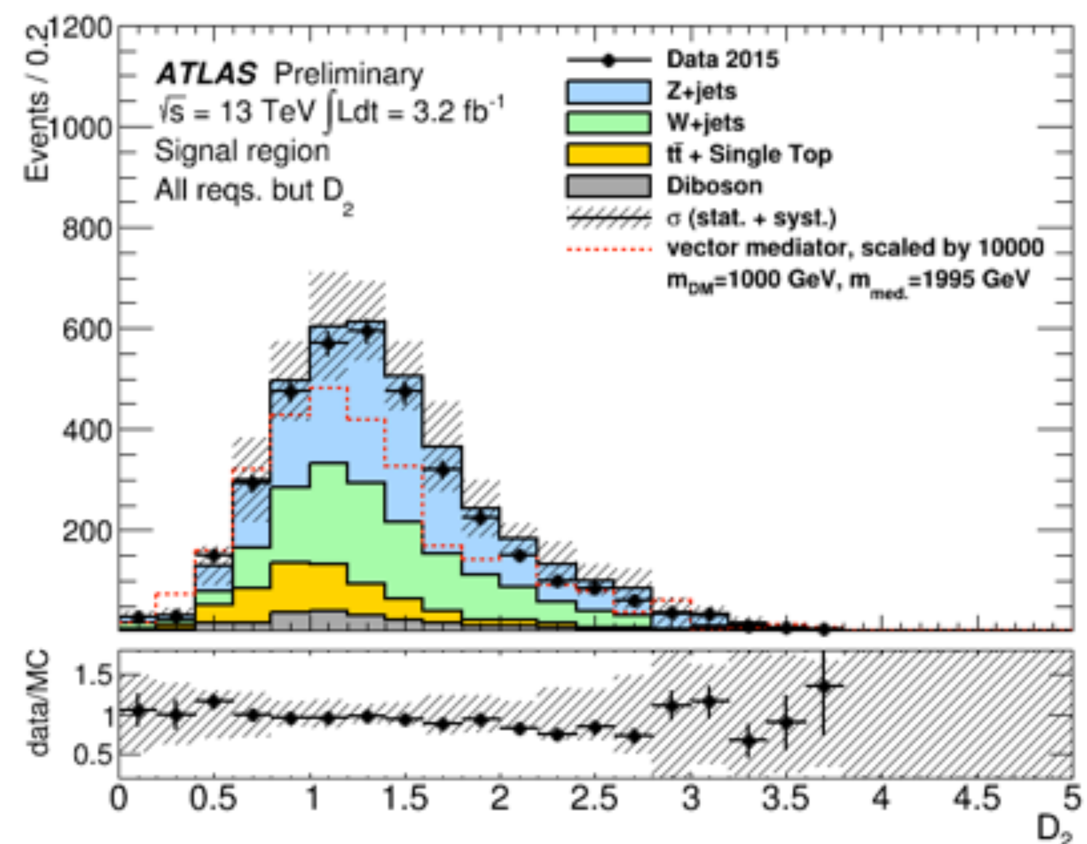
Simplified model with vector mediator and EFT model $ZZ\chi\chi$

(considering only jets with p_T lower than mediator mass for EFT models)

- Consider hadronic decays of W and Z bosons (larger BR)
- Construct "large jets" starting from "small jets"
  → exploit sub-structure to distinguish W from Z



Substructure



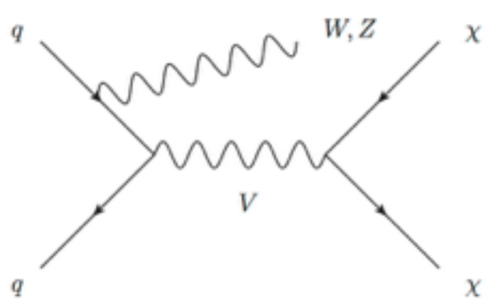
arXiv:1608.02372

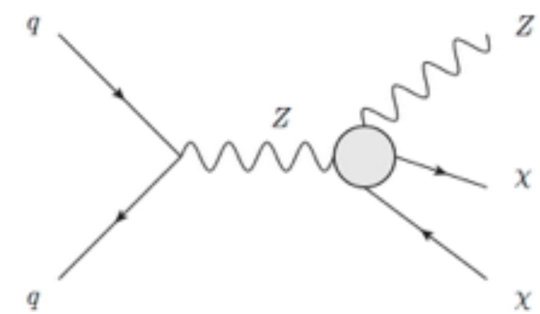
ATLAS mono-V (hadronic) search

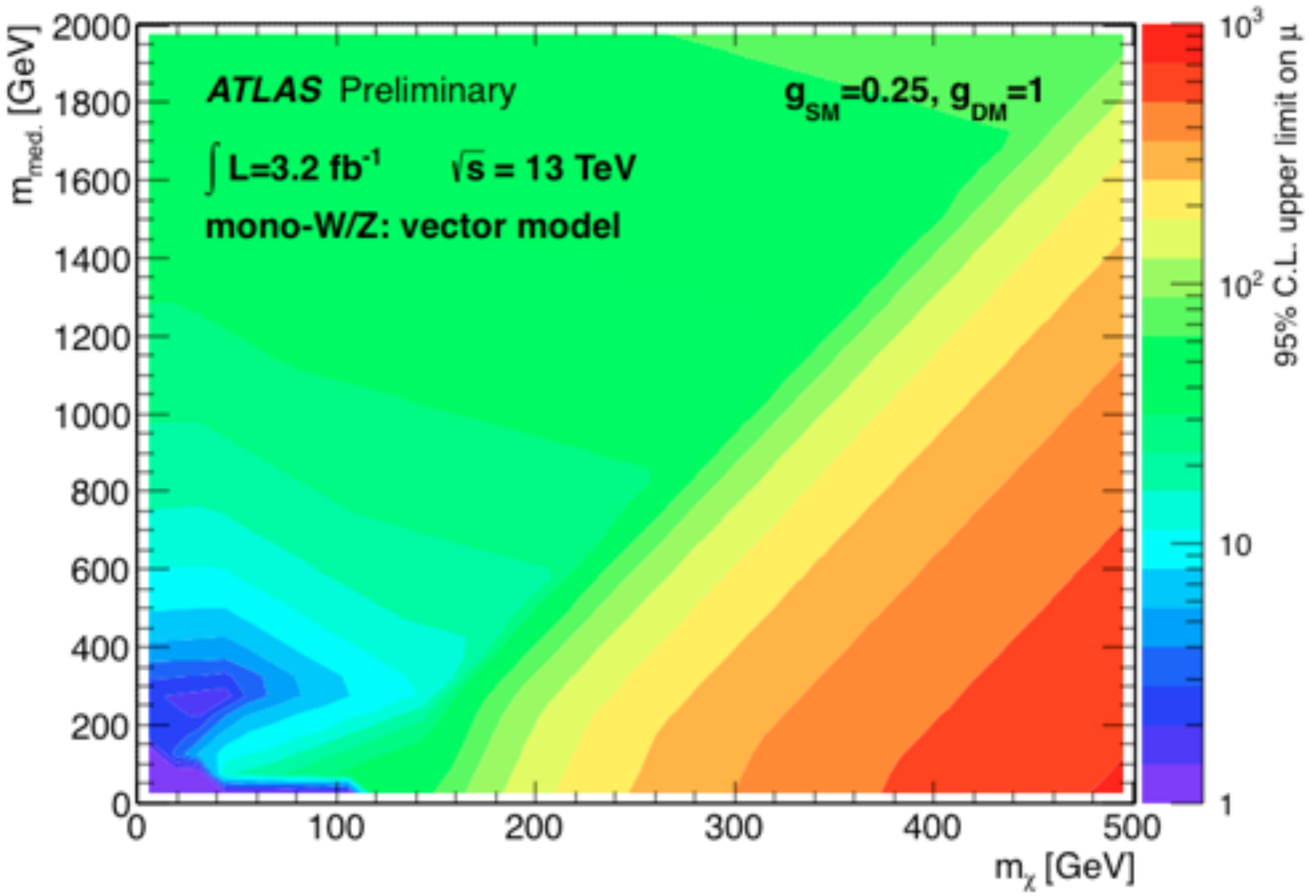
arXiv:1608.02372

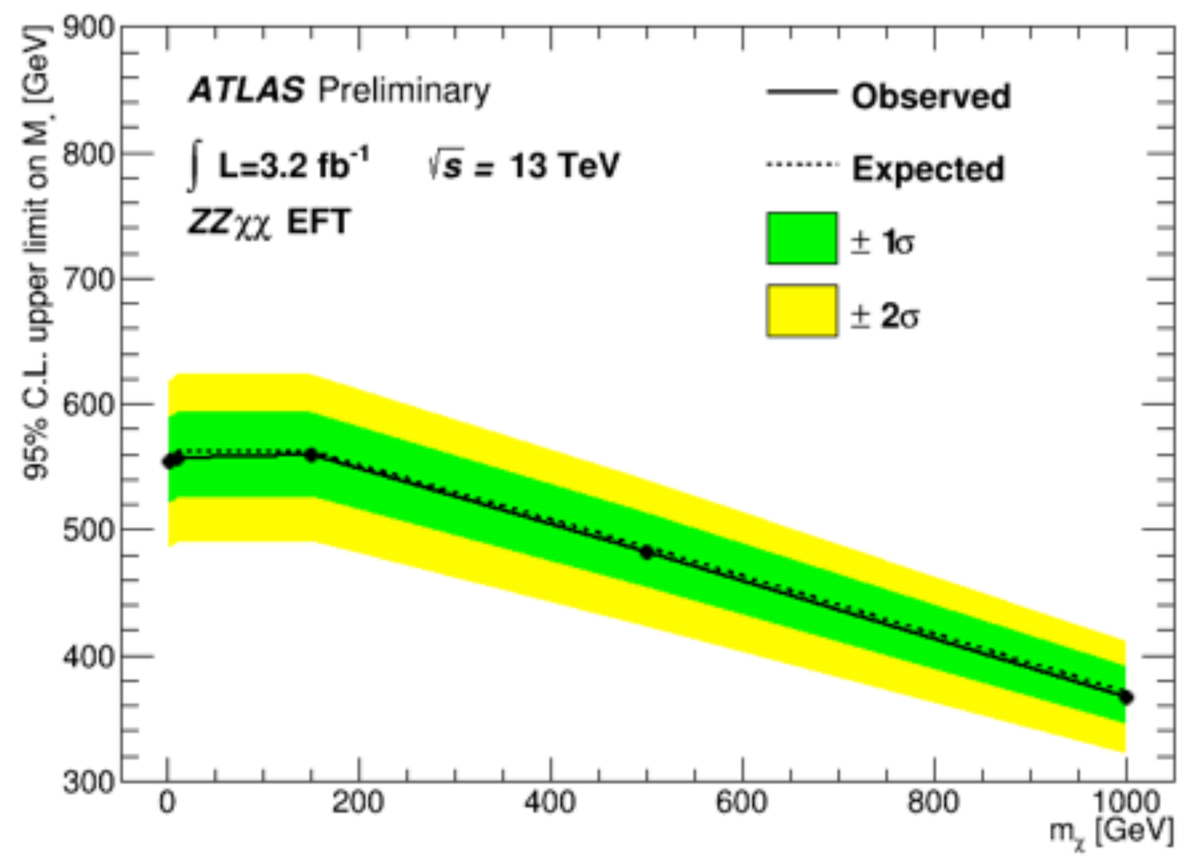
Simplified model with vector mediator and EFT model $ZZ\chi\chi$

- **Simplified model**: limit on **signal strength in dark matter - mediator mass plane**
- **EFT model**: limit in **dark matter mass - EFT mass scale**



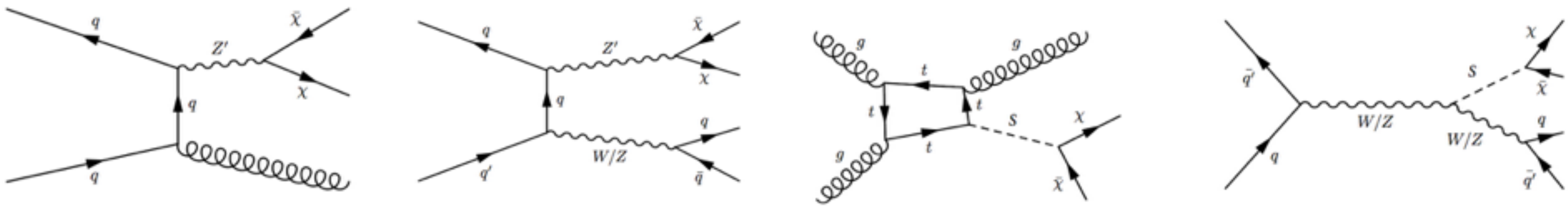






CMS mono-jet and mono-V (hadronic) search

Spin-1 or spin-0 mediators coupling to **quarks** and **DM**



ISR jet or W/Z boson recoiling against DM candidates

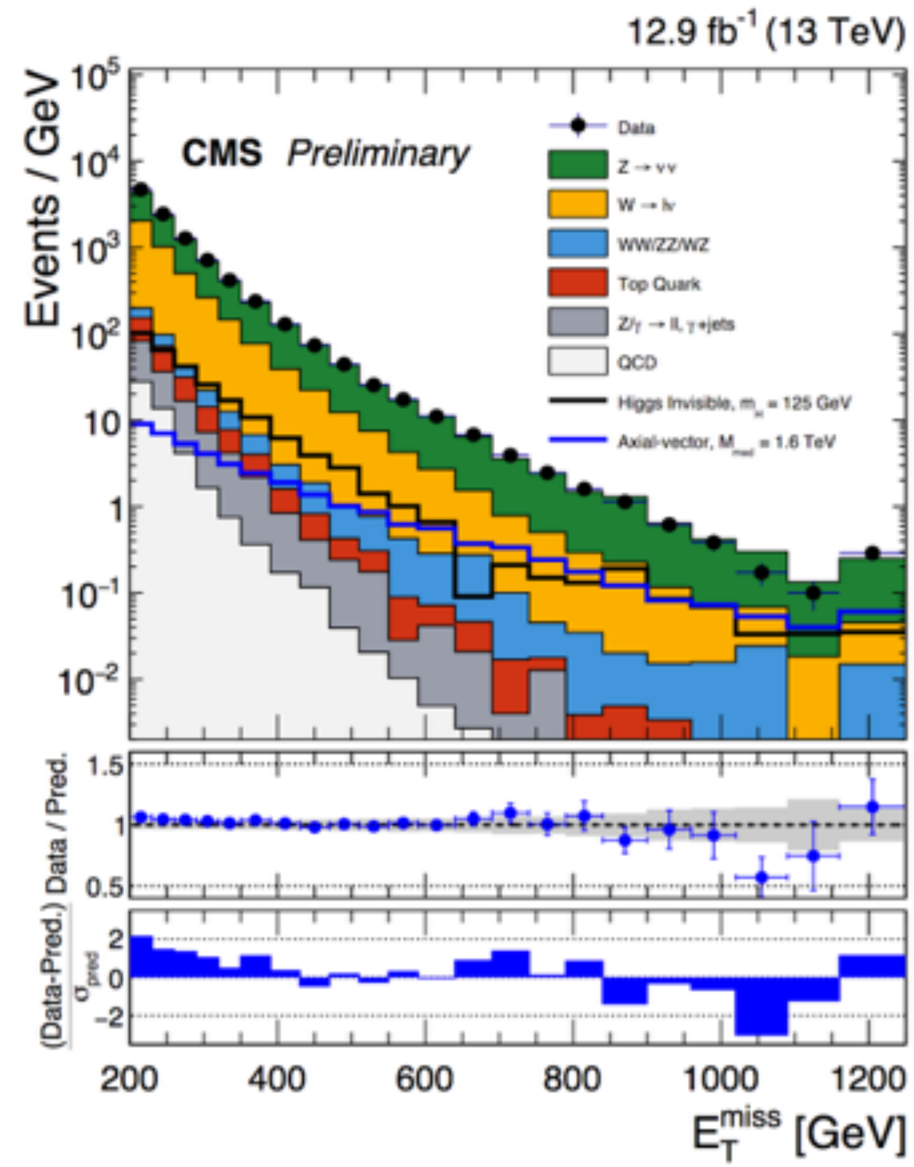
- Hadronic decays of energetic W and Z bosons

Separate jets from **g** and jets from **W/Z** bosons

- R=0.4 VS R=0.8 anti-K_T jets
- Jet mass
- Jet substructure (subjetness)

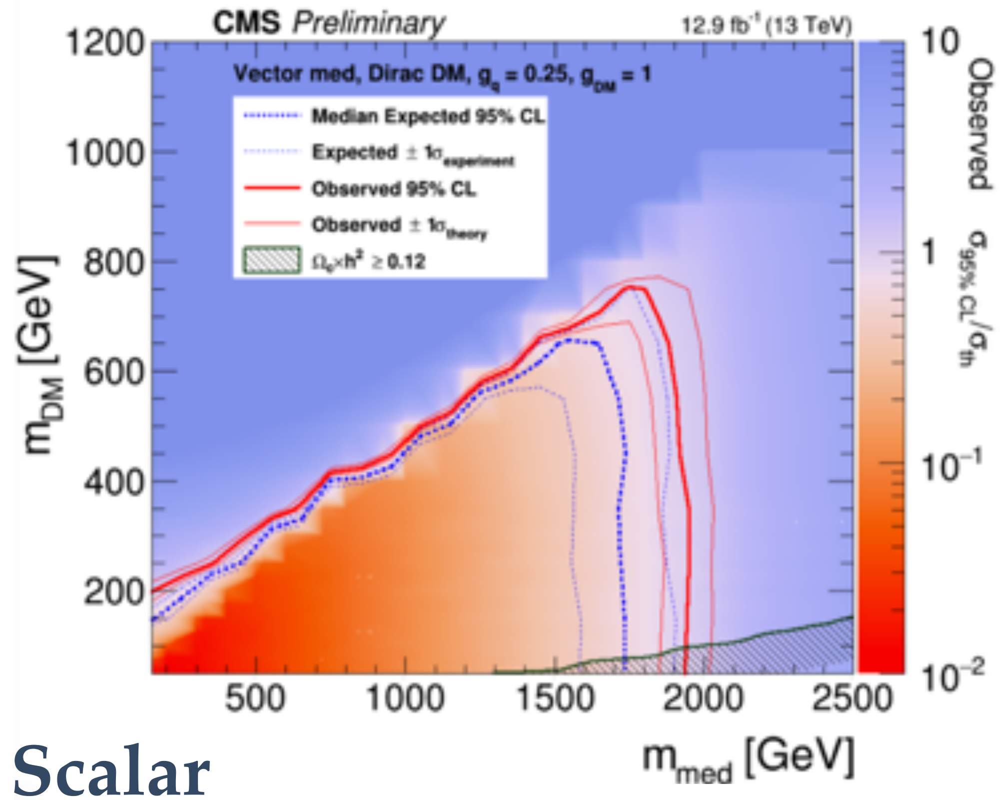
Main backgrounds **Z→**$\nu\nu$ and **W→l**ν **+ jets** normalised in γ+jets region

CMS-PAS-EXO-16-037

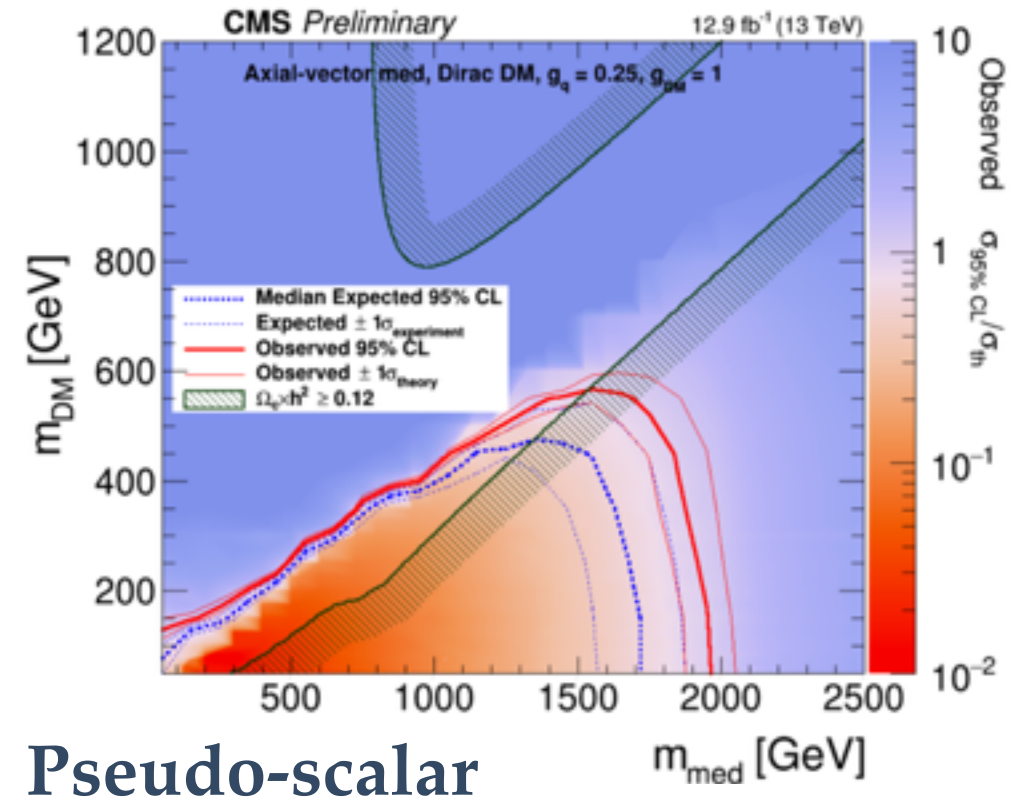


CMS mono-jet and mono-V (hadronic) search

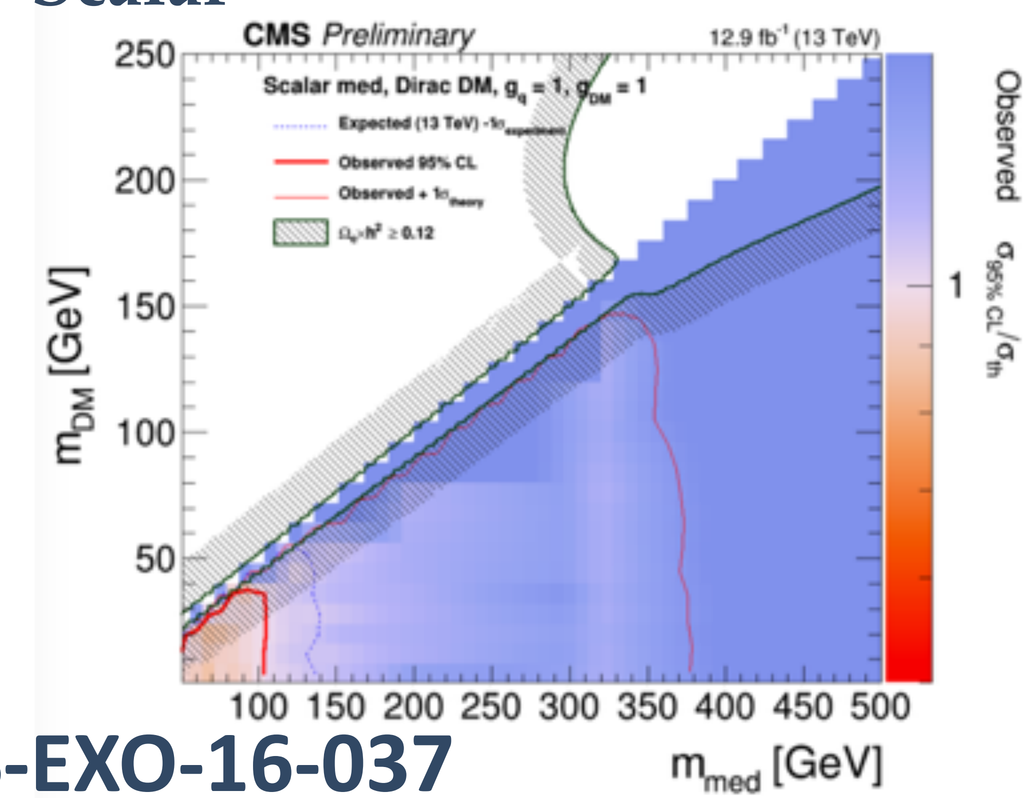
Vector



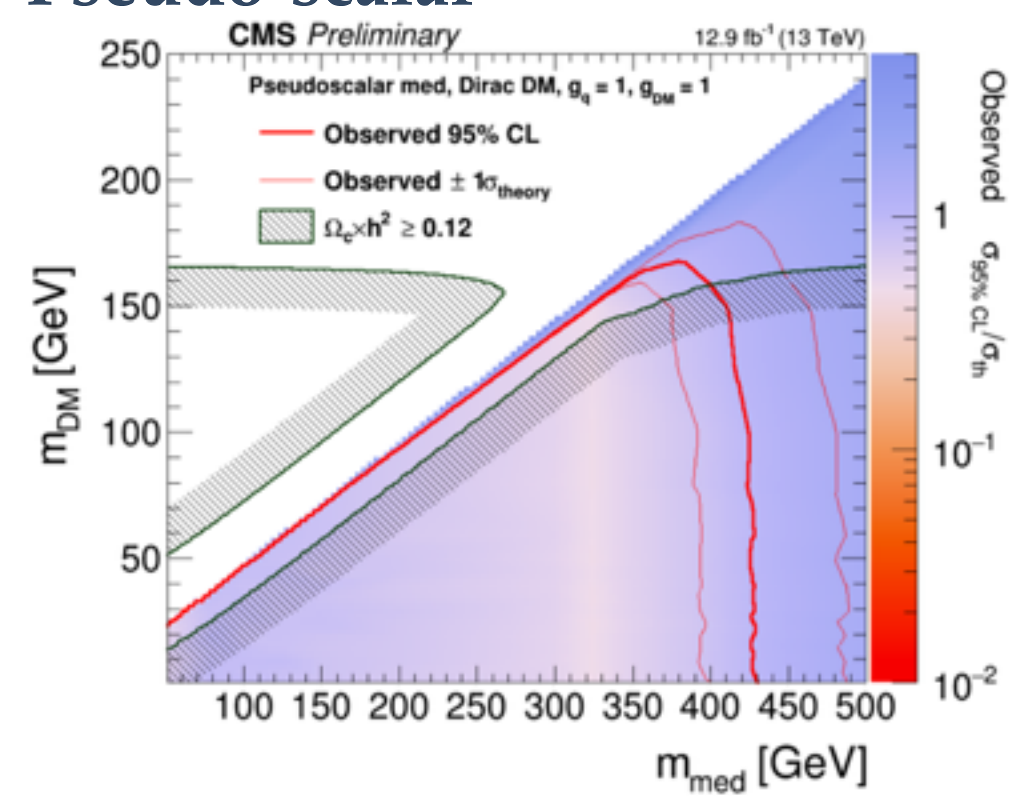
Axial-vector



Scalar



Pseudo-scalar

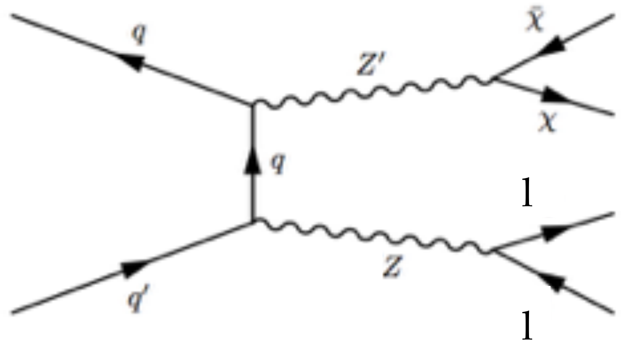


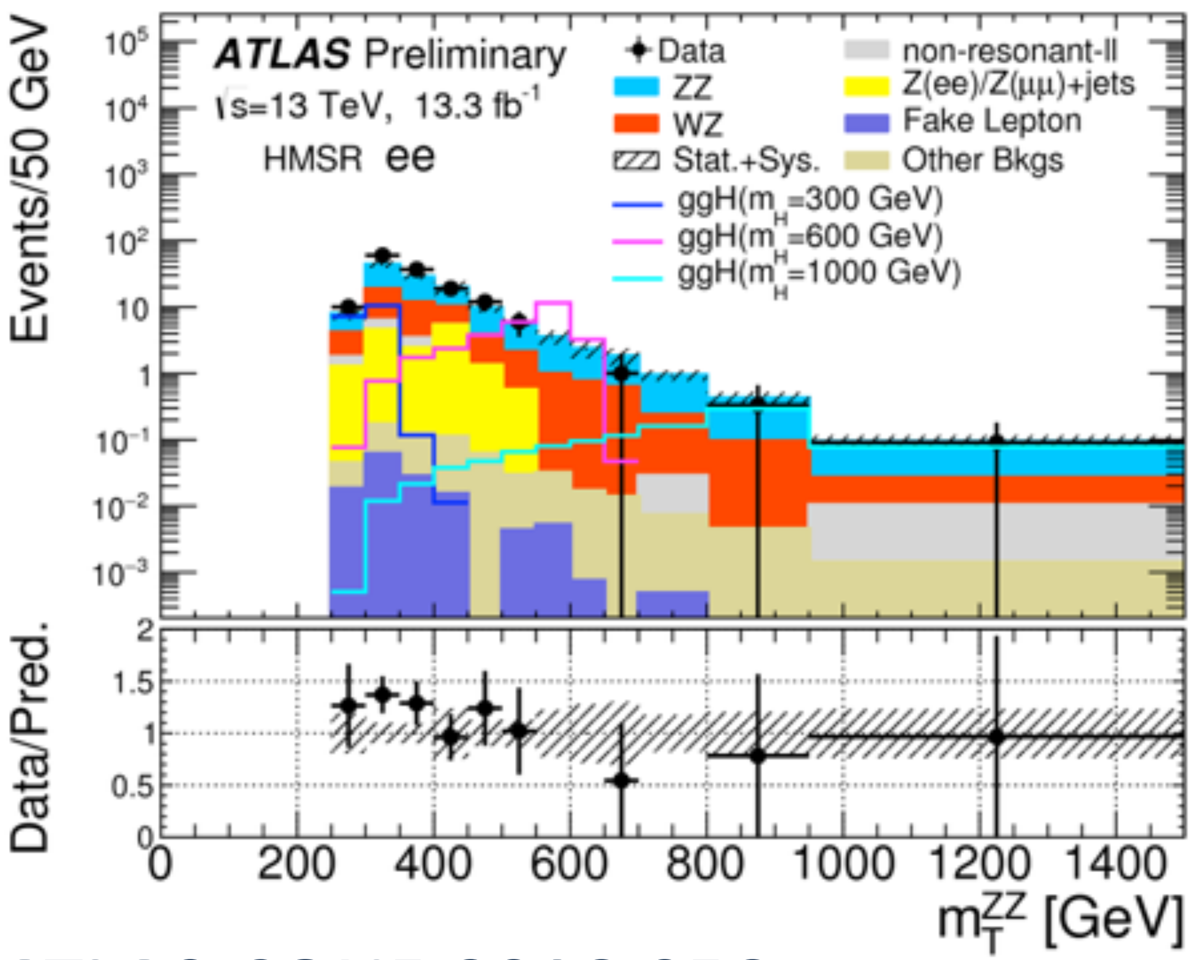
CMS-PAS-EXO-16-037

ATLAS and CMS mono-Z(ll) search

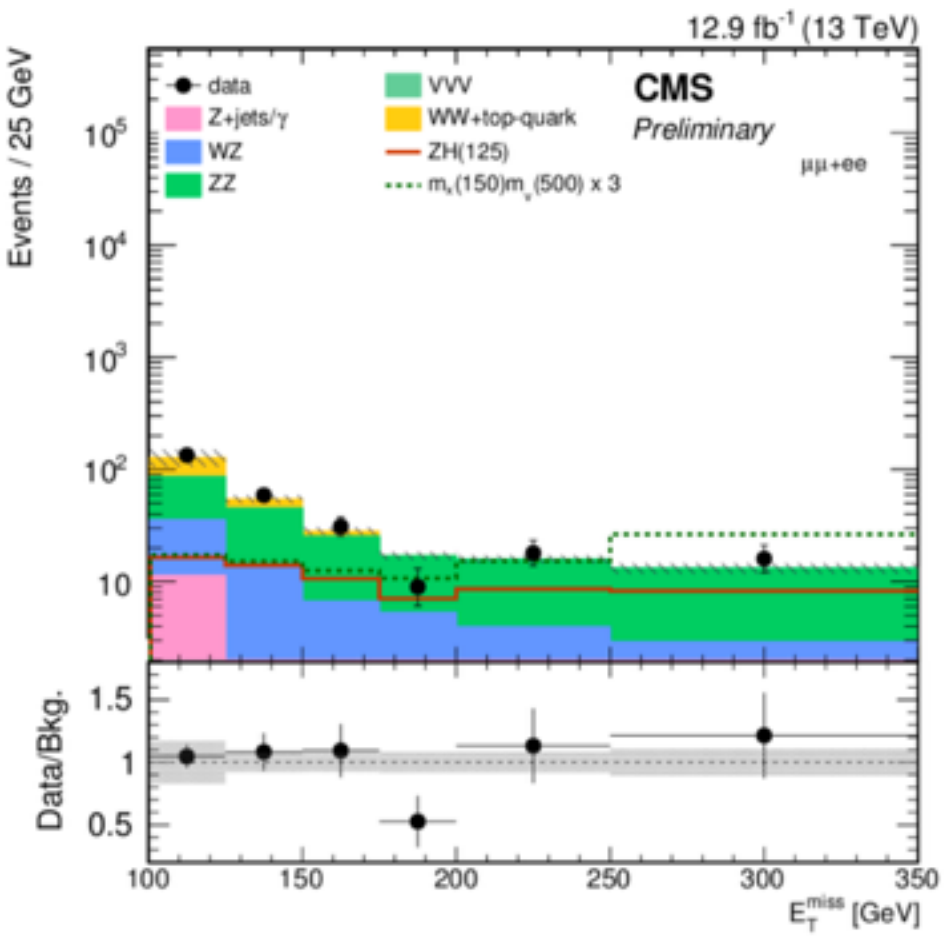
Simplified model of dark matter production with vector mediator

- Z decaying into **electron** or **muon** pairs
- Select events with lepton pairs and large E_T^{miss}
- **Main background: ZZ→$\nu\nu$ll**





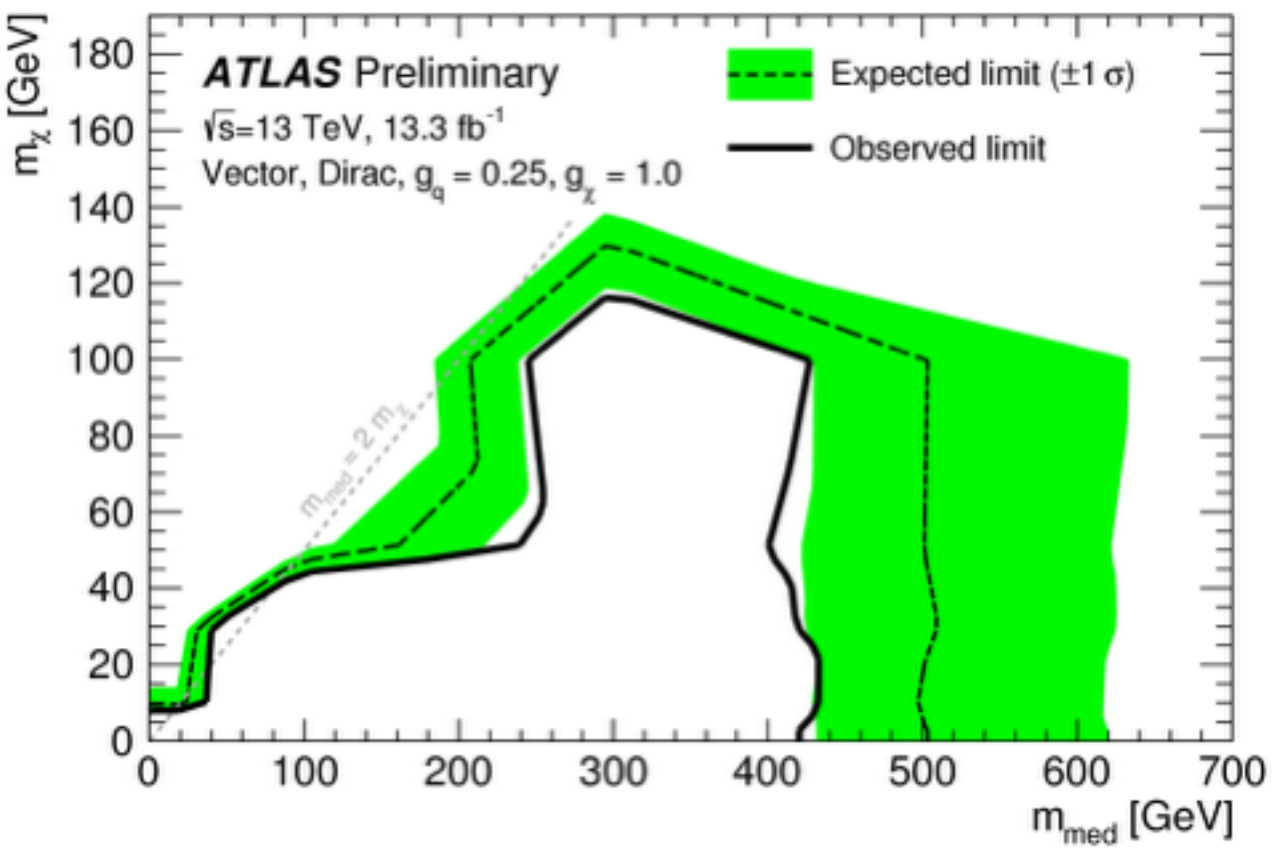
ATLAS-CONF-2016-056



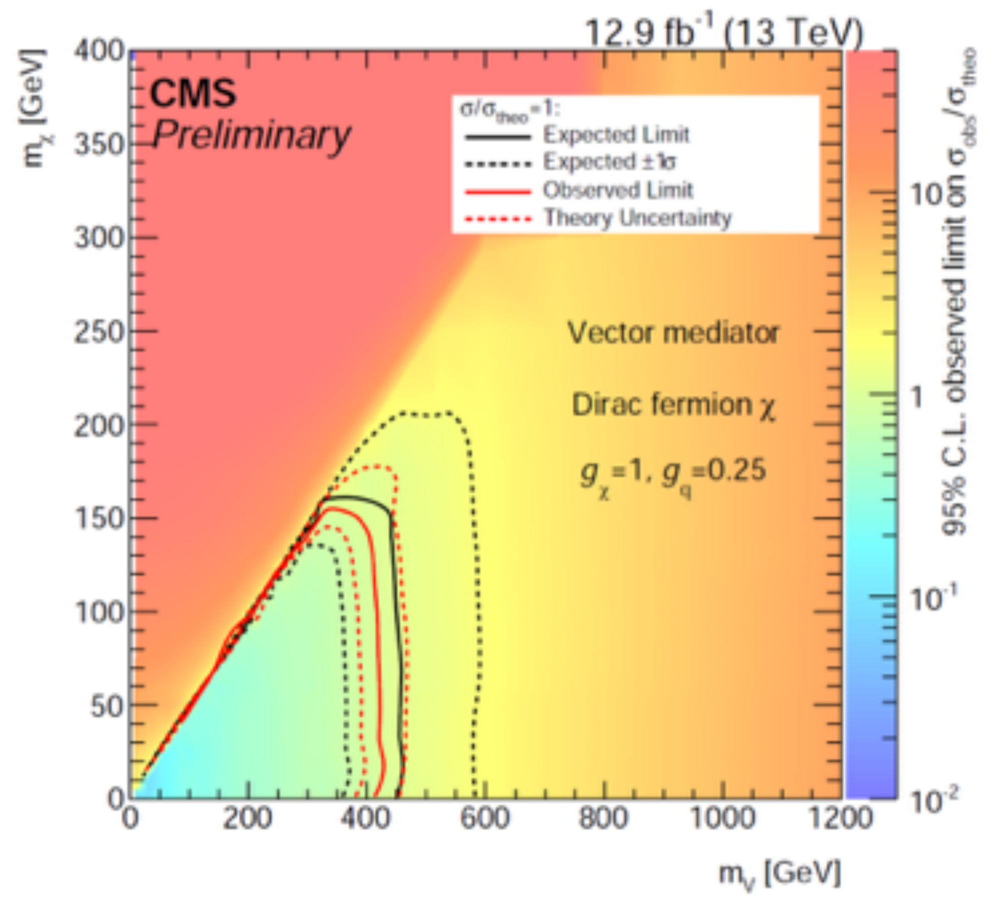
CMS-PAS-EXO-16-038

ATLAS and CMS mono-Z(ll) search

Simplified model of dark matter production with vector mediator



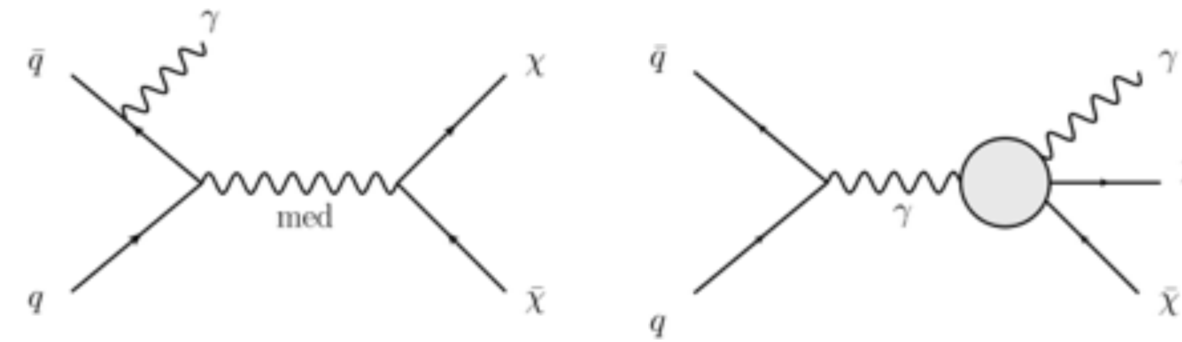
ATLAS-CONF-2016-056



CMS-PAS-EXO-16-038

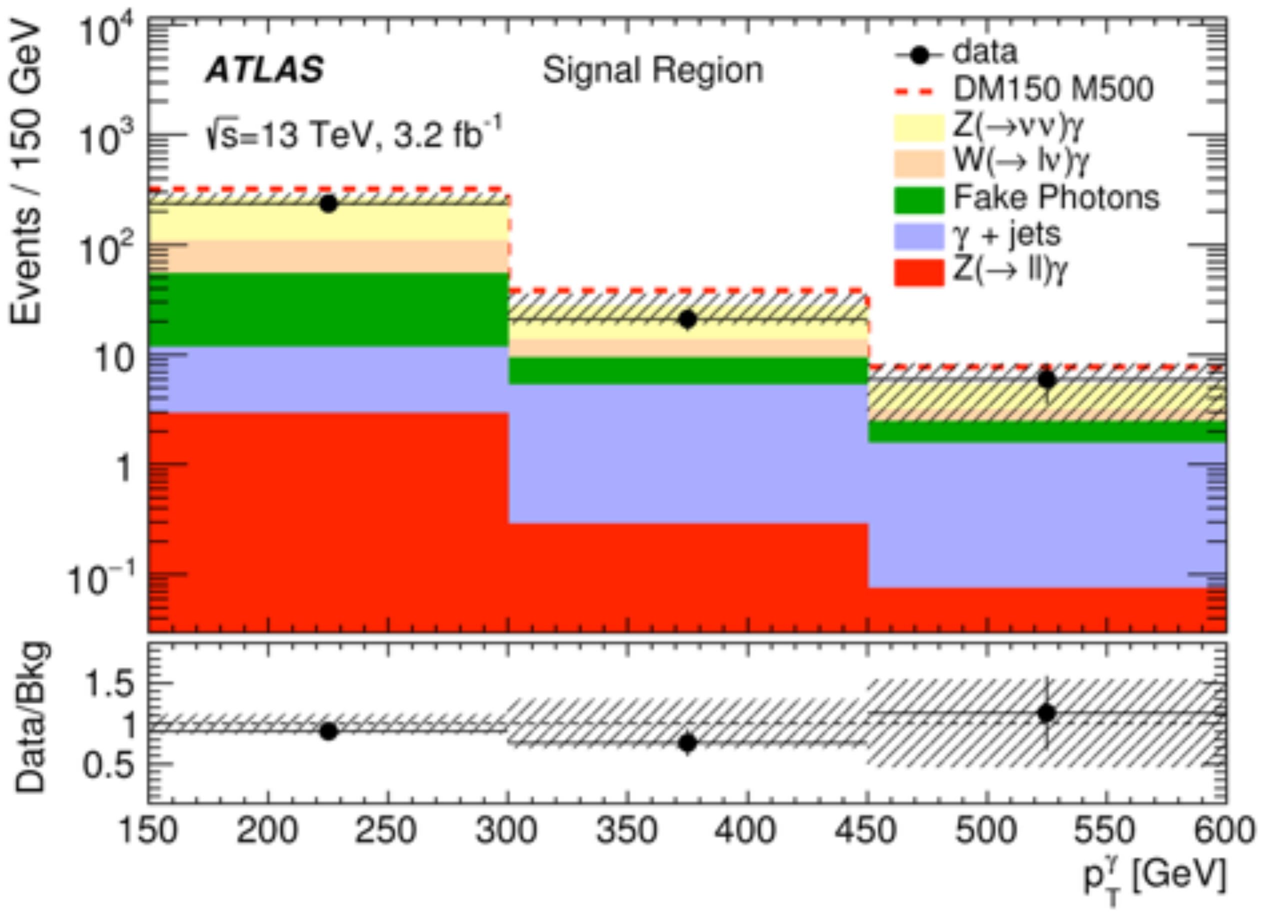
ATLAS and CMS mono-γ searches

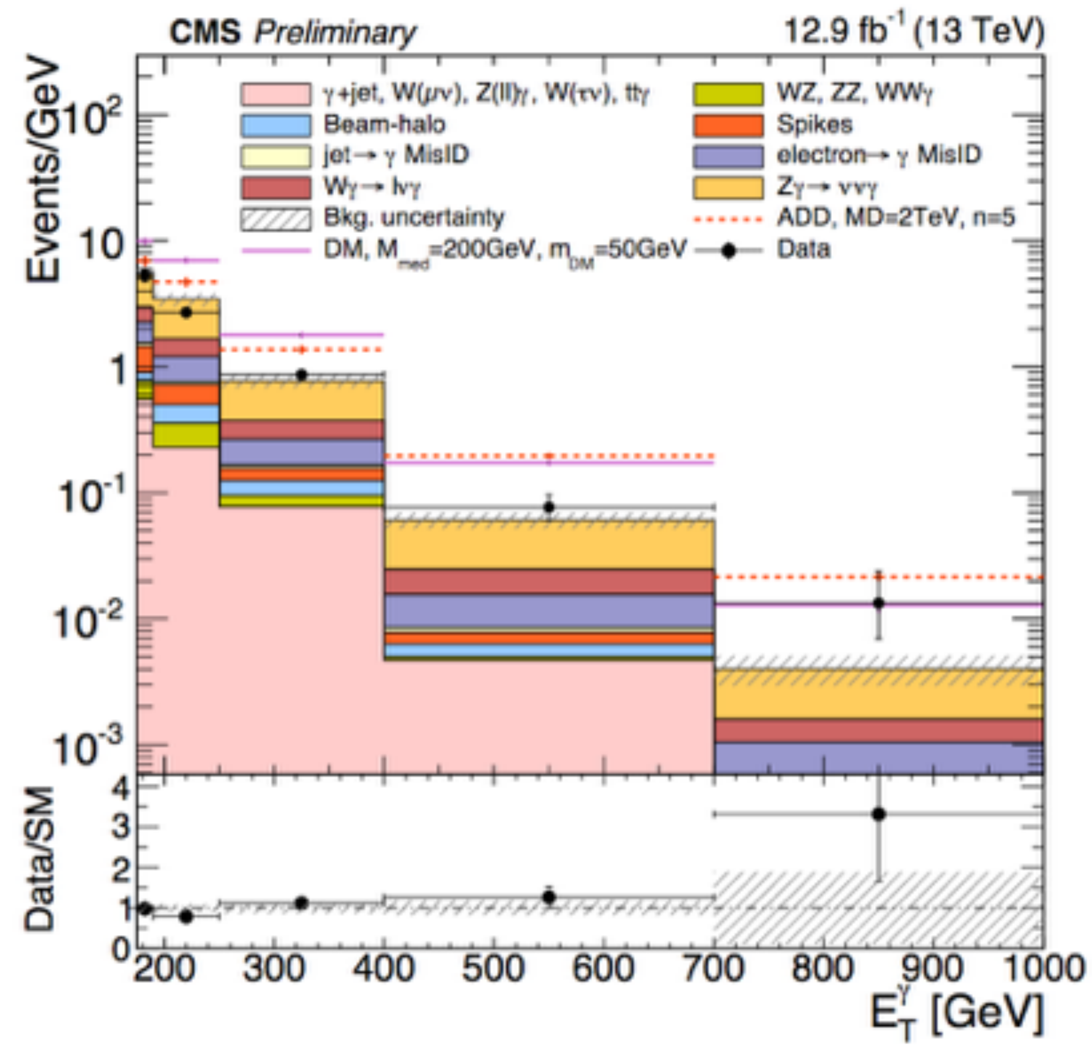
Simplified models and EFT model $\gamma\gamma\chi\chi$



Clean signal but low cross section

- Select events with high p_T isolated γ and large E_T^{miss}
- Main background: $Z(\rightarrow \upsilon\upsilon)+\gamma$

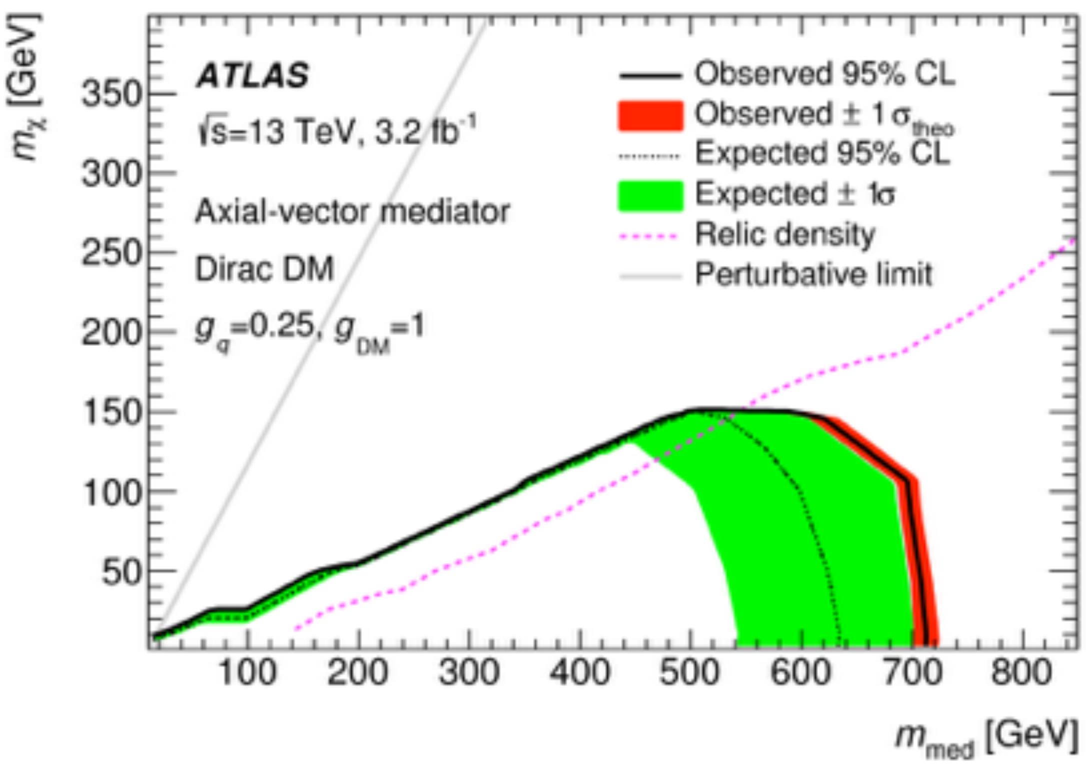


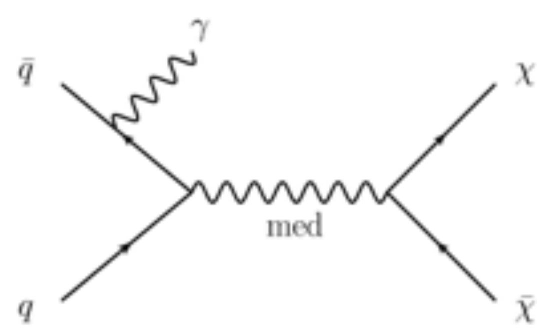


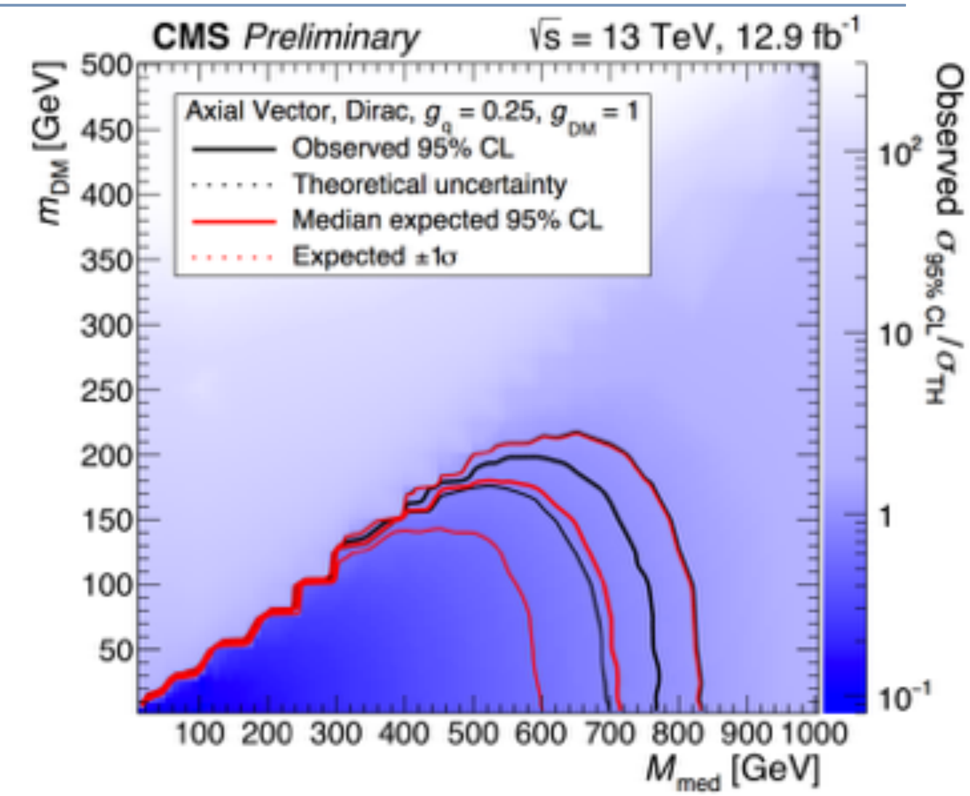
ATLAS: JHEP06 (2016) 059

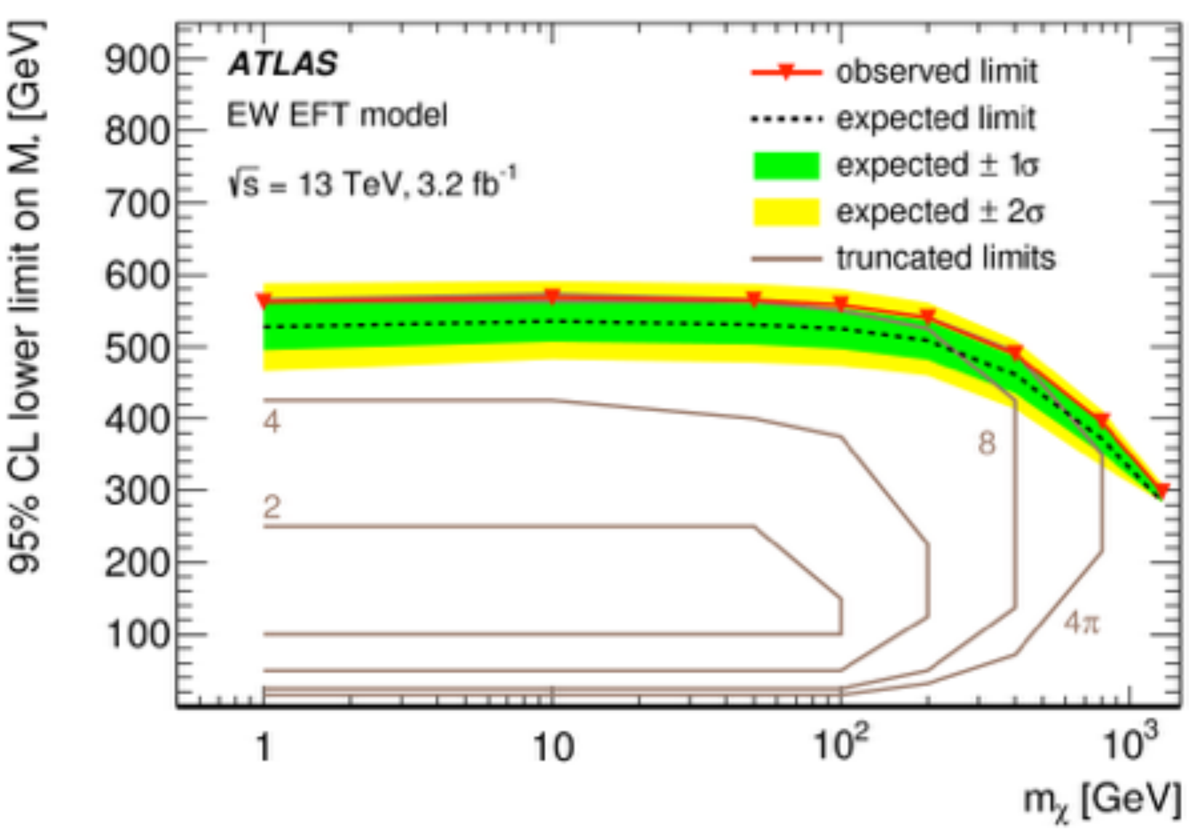
CMS-PAS-EXO 16-039

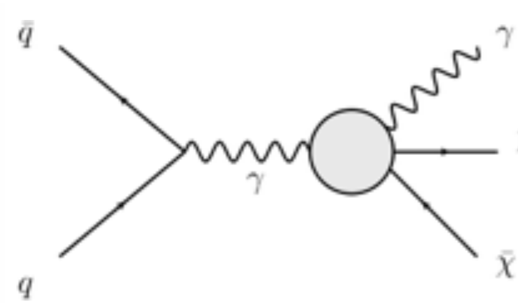
ATLAS and CMS mono-γ searches











ATLAS

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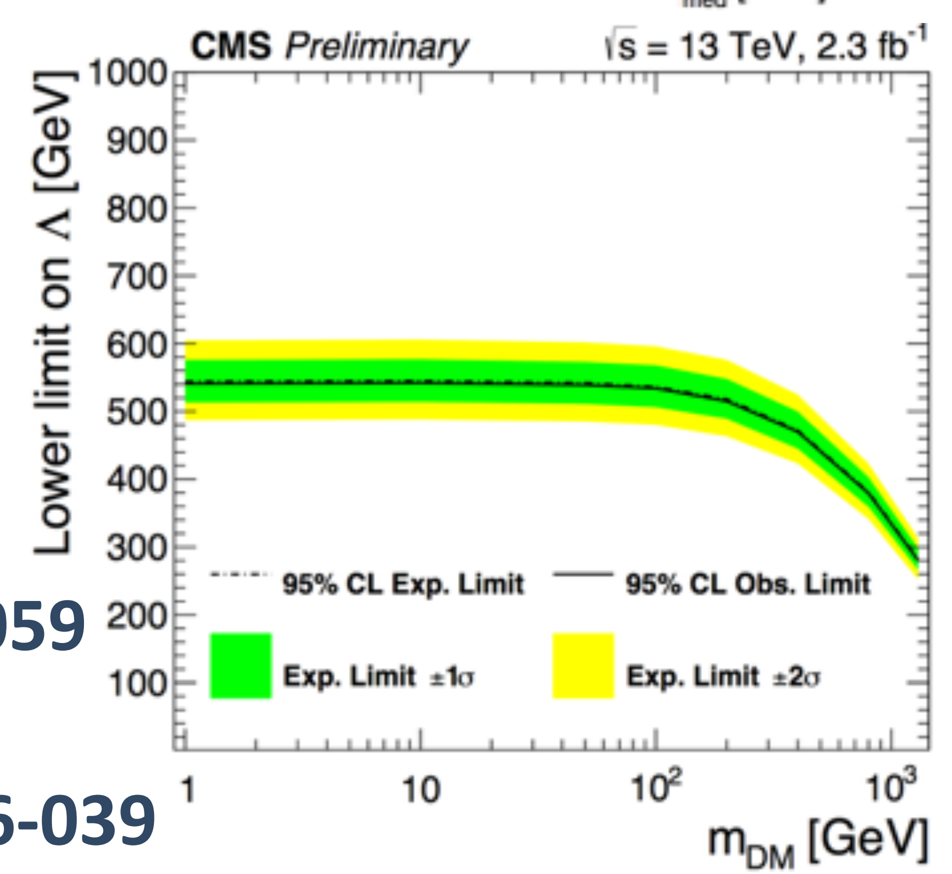


CMS-PAS-EXO 16-039

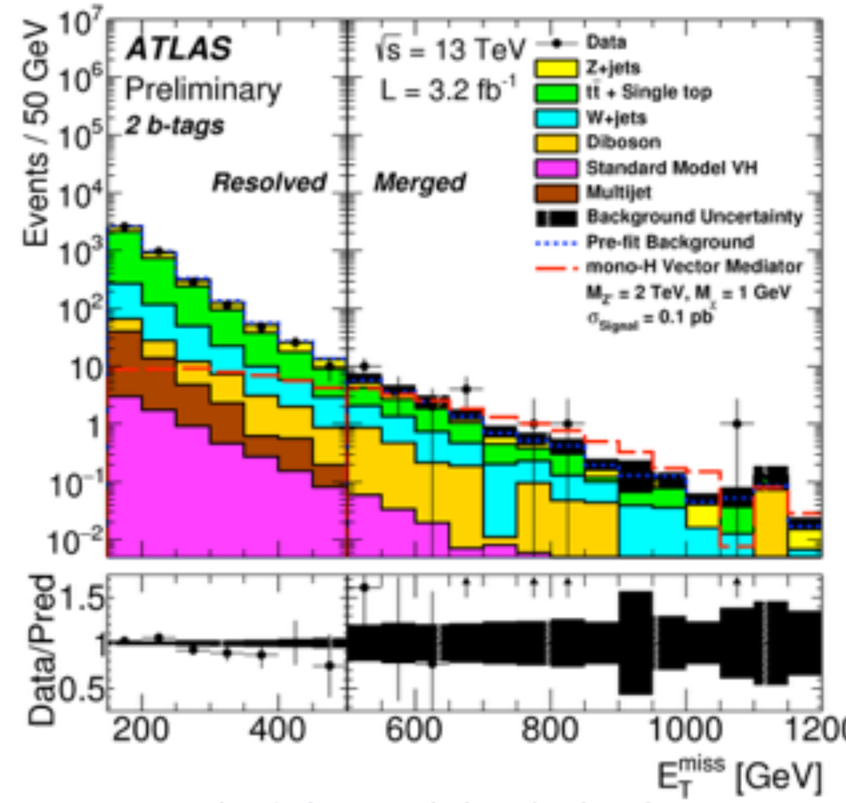
ATLAS and CMS mono-h search, h→bb

Dark matter coupling to **Higgs boson**, e.g. in Z' leptophobic models

- Higgs radiation suppressed
- **Probe coupling of Higgs boson to mediator**

h→bb dominant decay mode

- **Resolved or merged b-jets depending on E_T^{miss}**
- **look for resonance m(bb) or m(B) ~m(h)**



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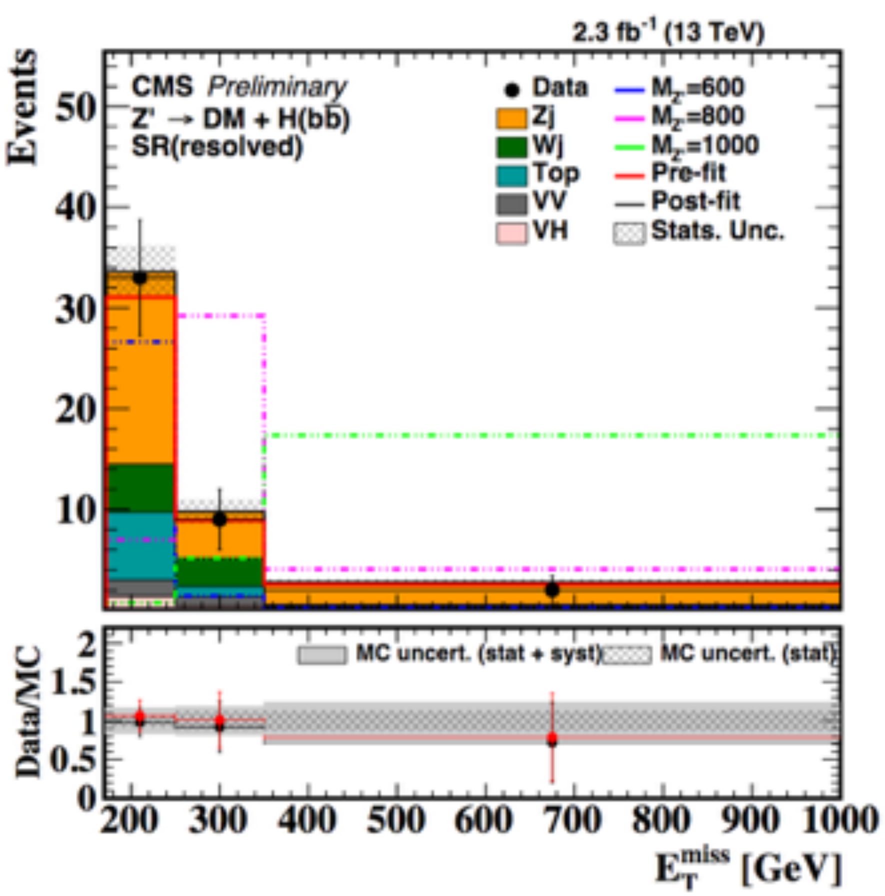
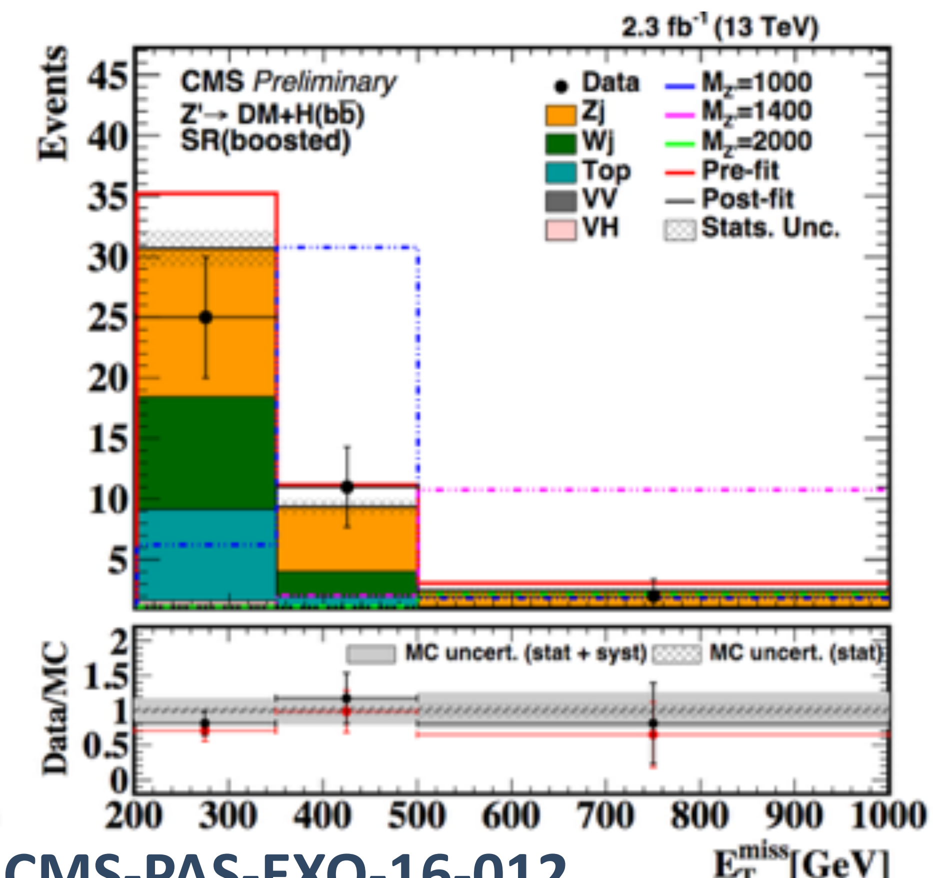
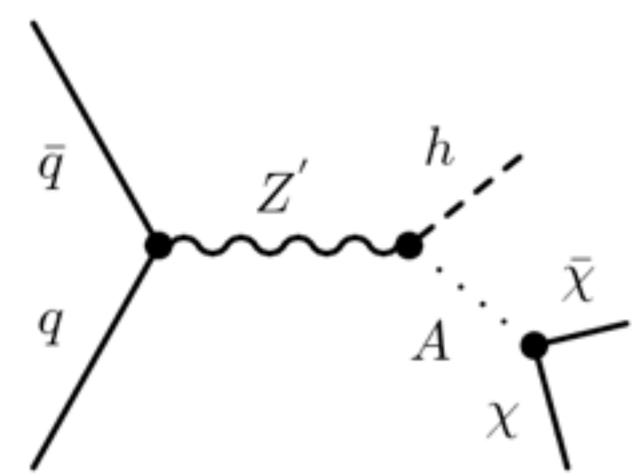
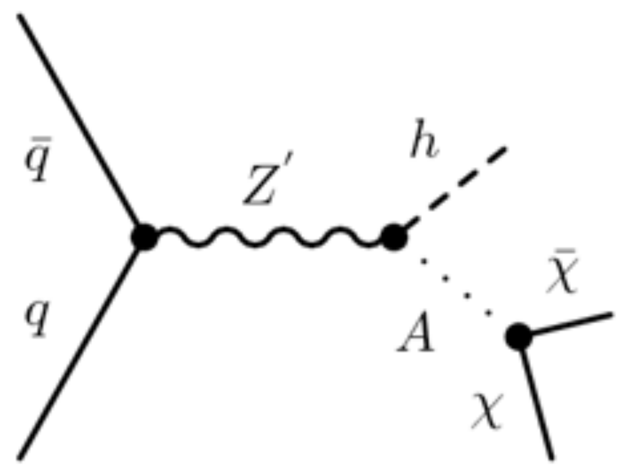




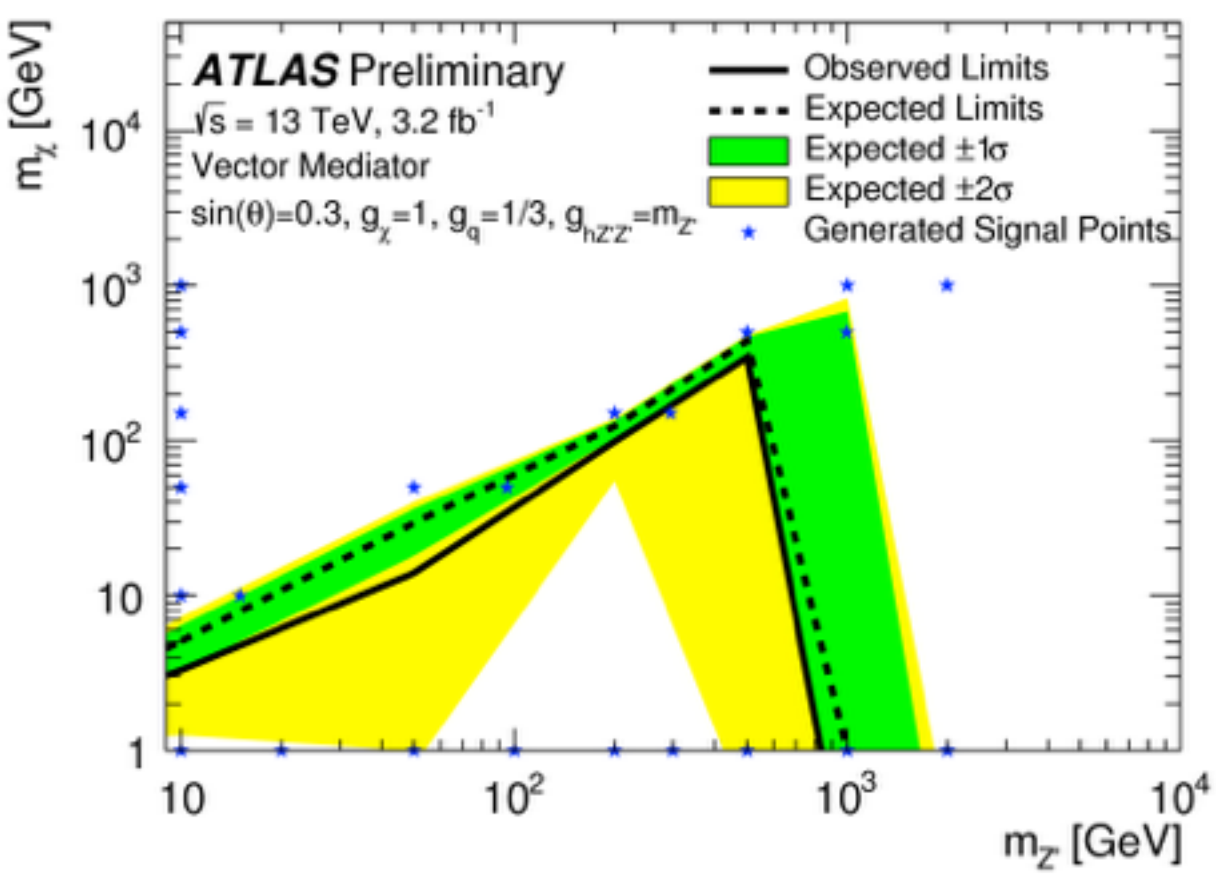
CMS-PAS-EXO-16-012



ATLAS and CMS mono-h searches, h→bb



ATLAS-CONF 2016-019



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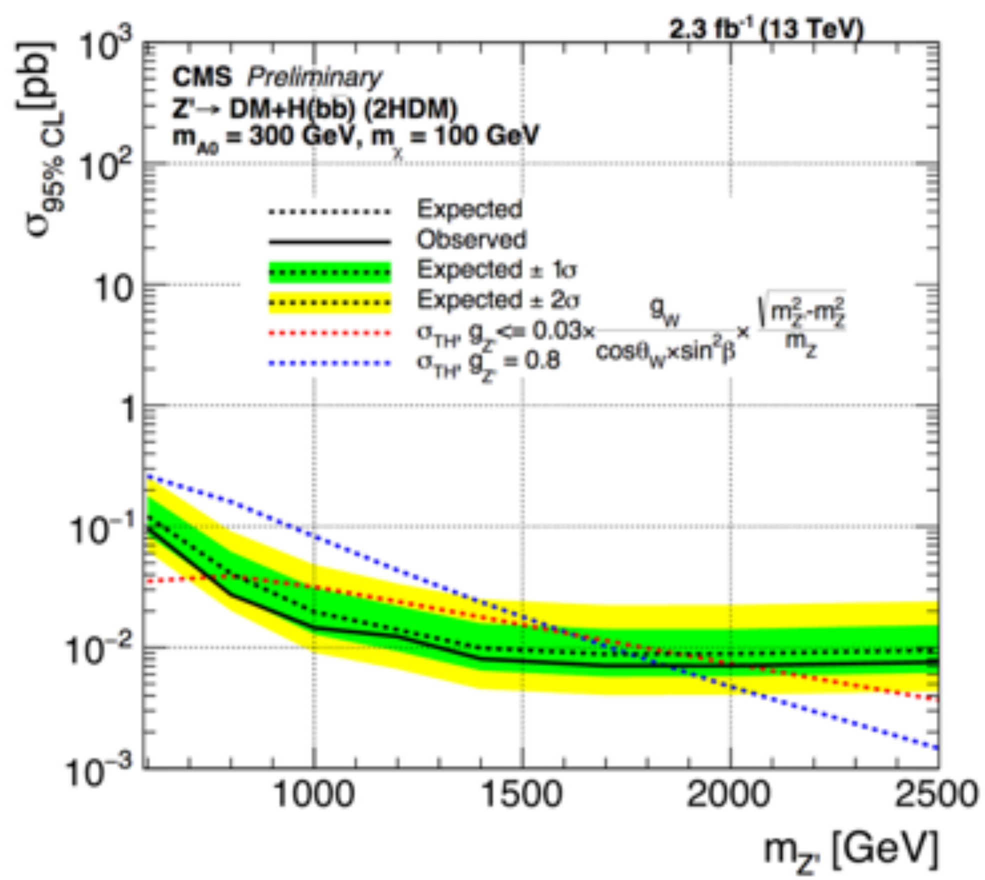
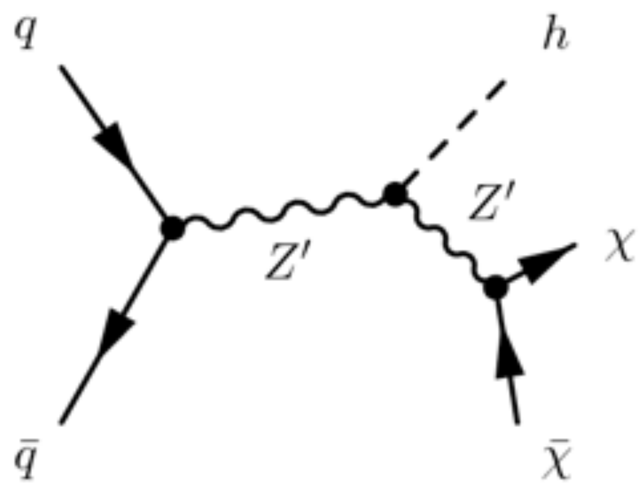
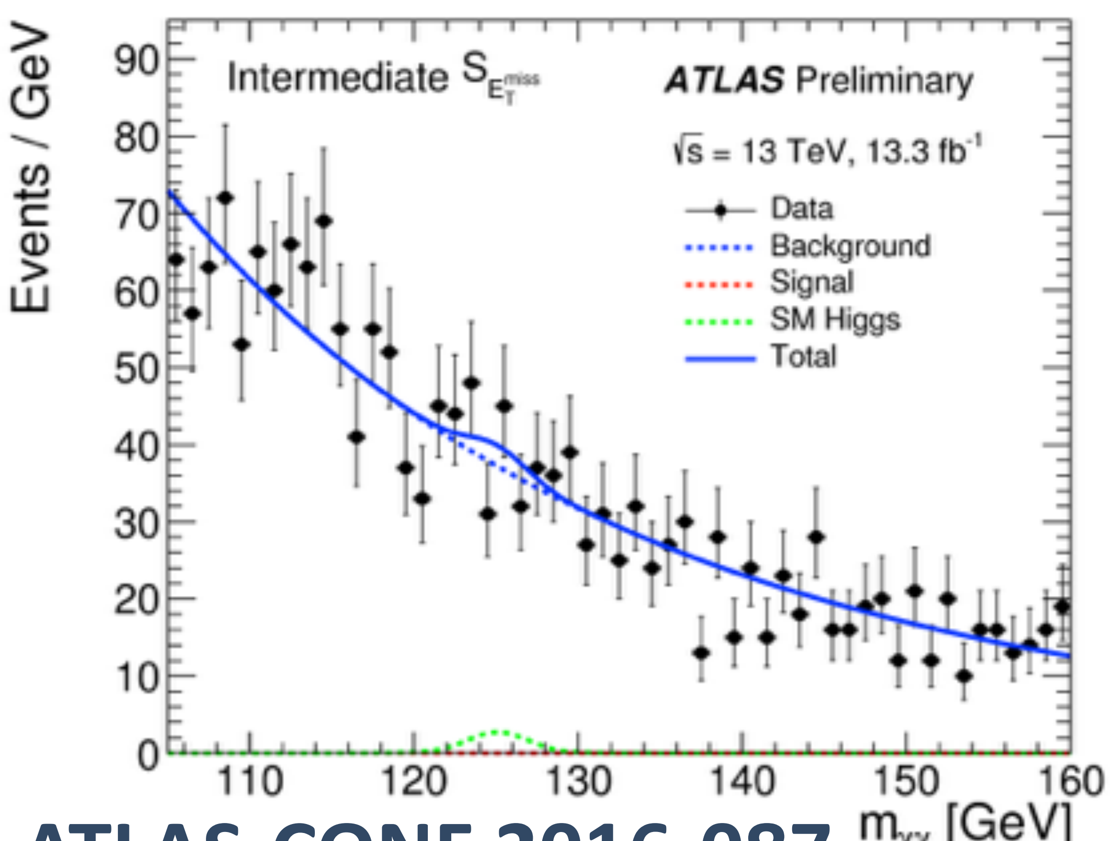


ATLAS and CMS mono-h search, h→γγ

h→γγ low BR but clean signal

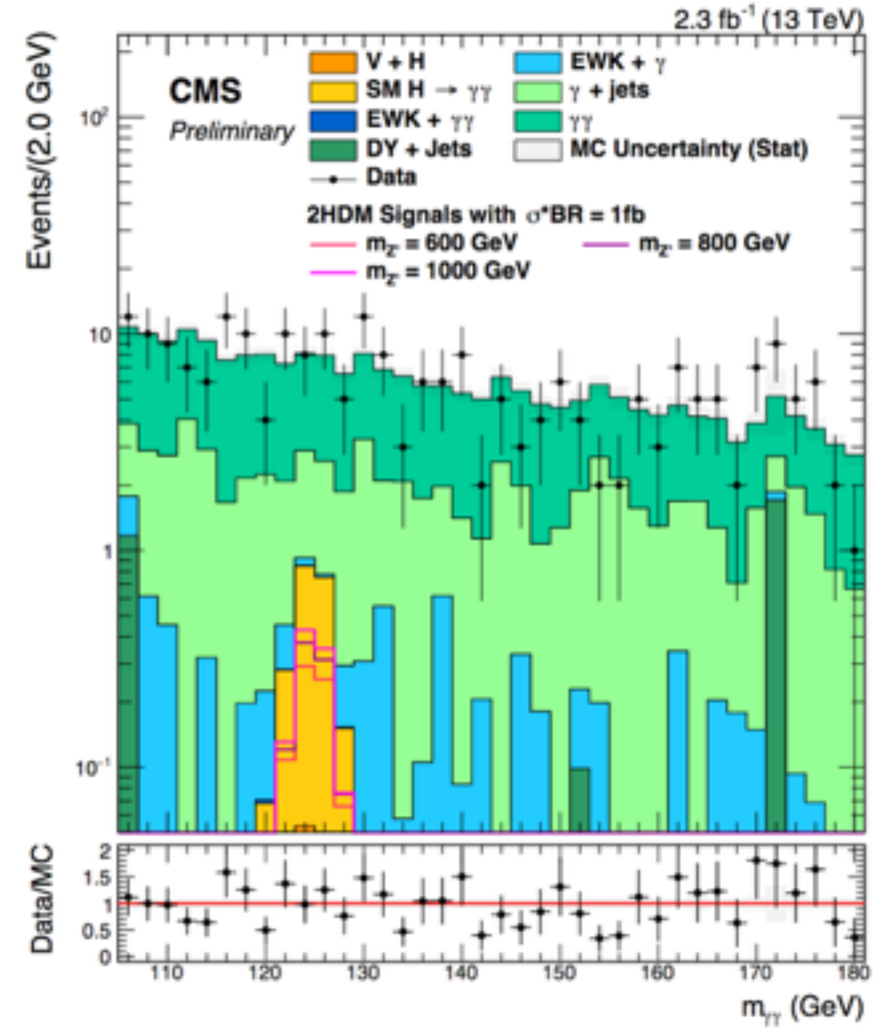
look for resonances m(γγ)~m(h)

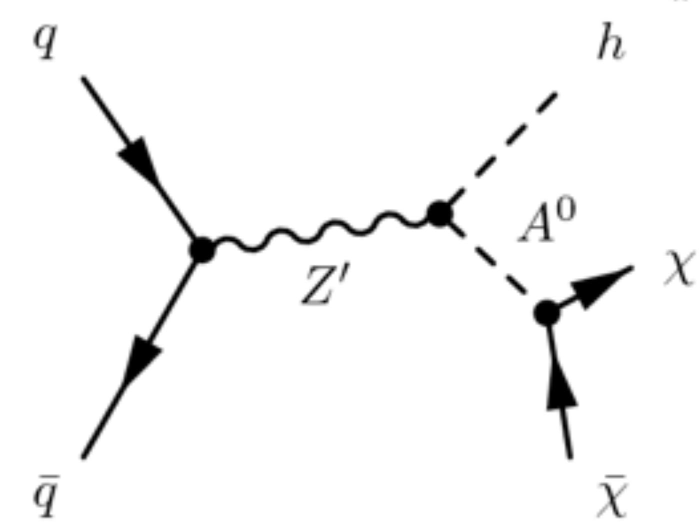




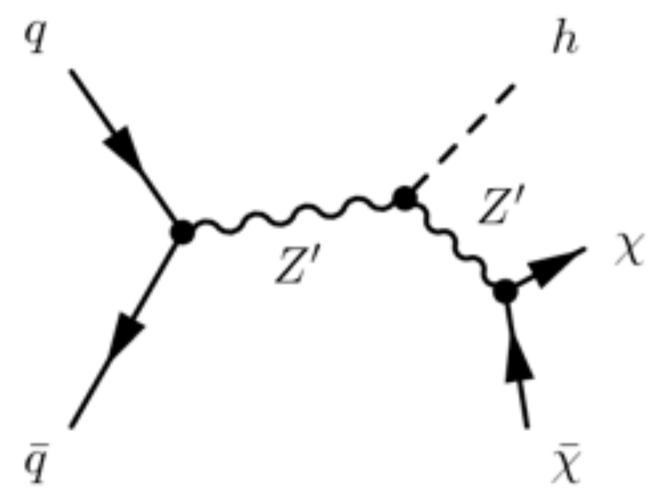
ATLAS-CONF 2016-087

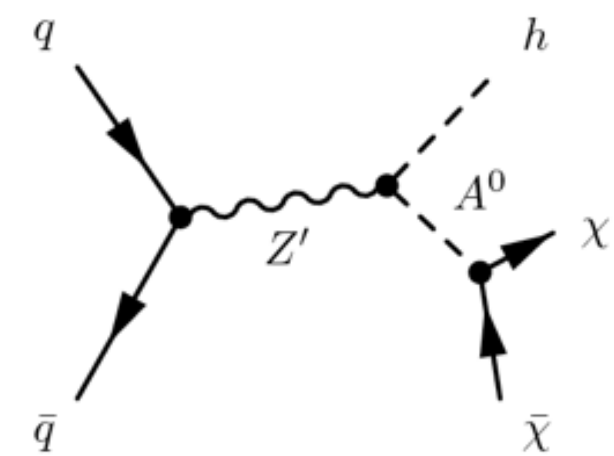
CMS-PAS-EXO-16-011

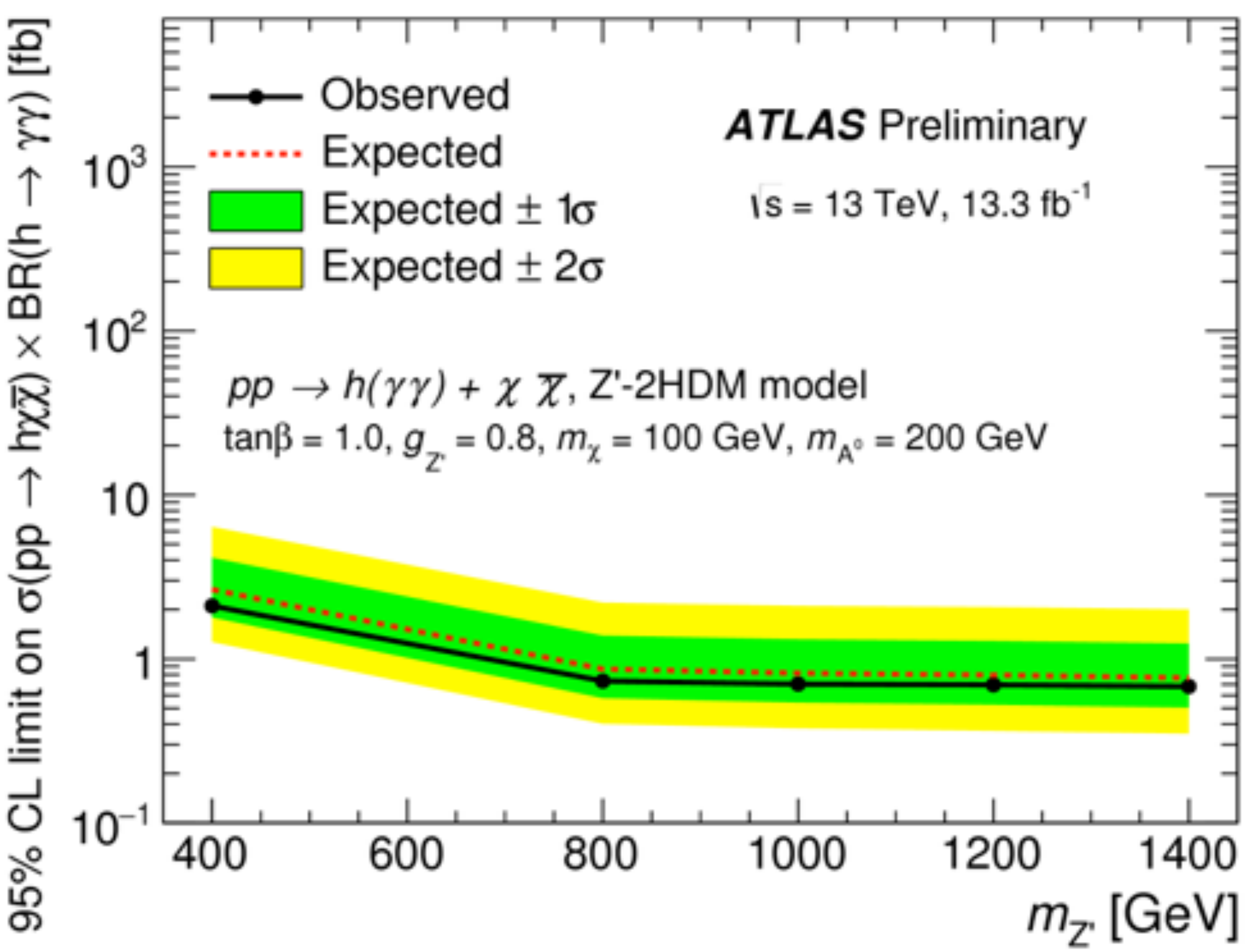


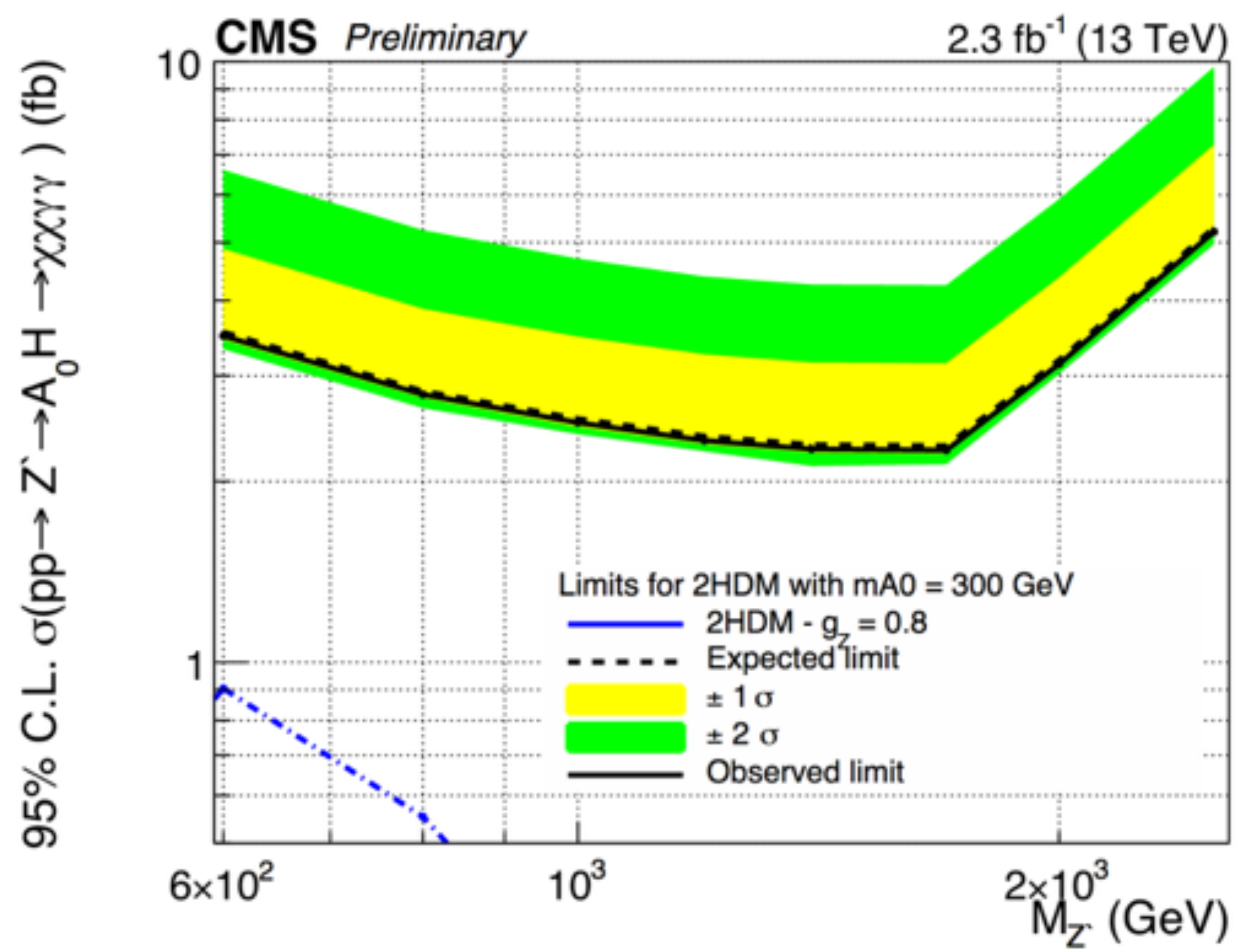


ATLAS and CMS mono-h search, h→$\gamma\gamma$









ATLAS-CONF 2016-087

CMS-PAS-EXO-16-011

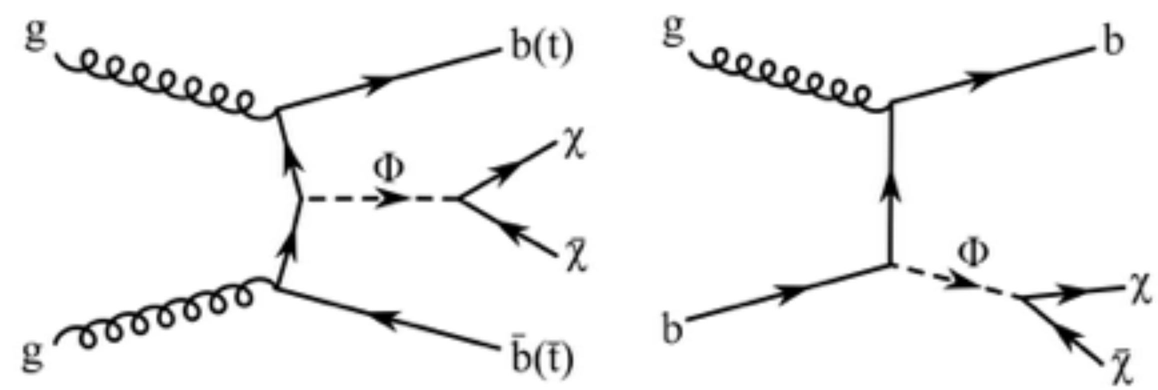
Associate Production

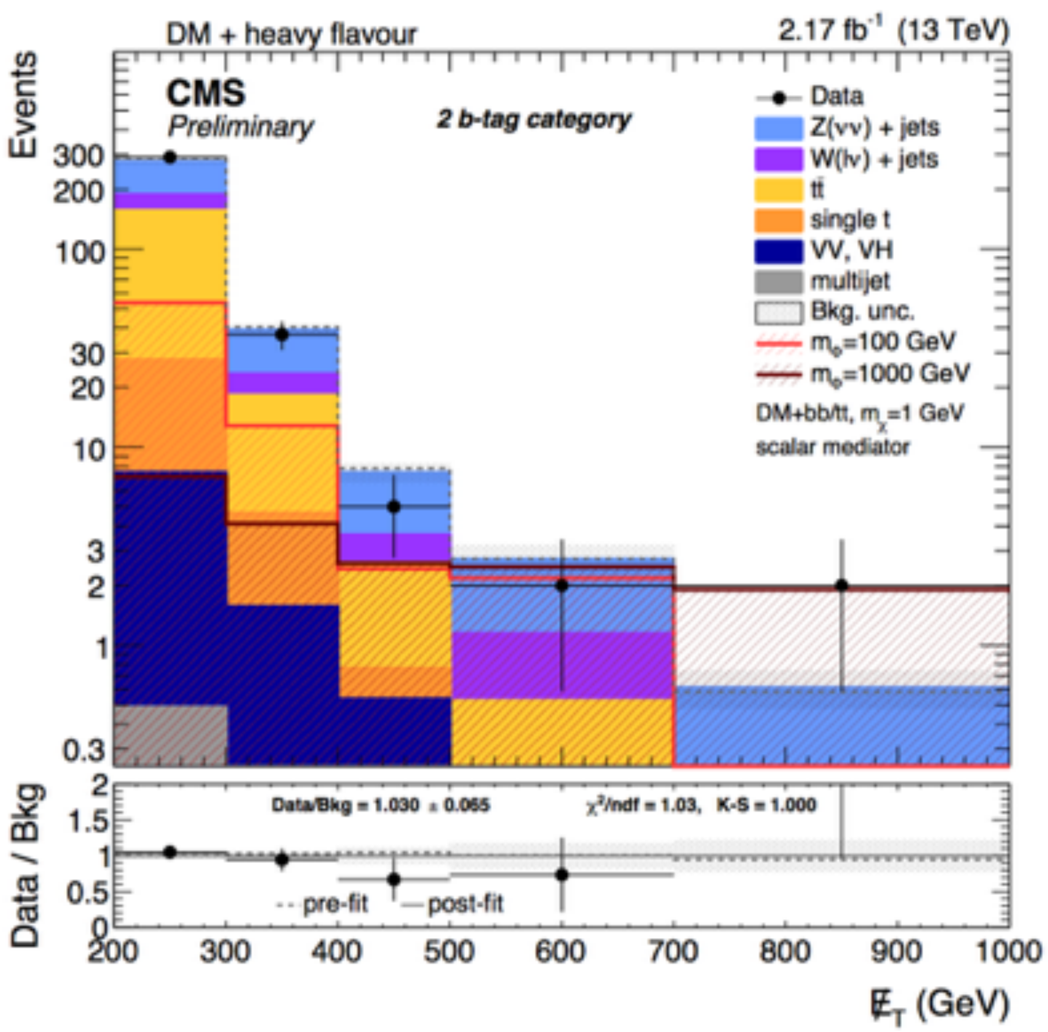
CMS search for DM plus heavy quarks

Search for **dark matter** produced in association with **top or bottom quarks**

- Favoured if couplings are Yukawa-like
- Scalar or pseudo-scalar mediators

Final state: **b-jets plus E_T^{miss}**





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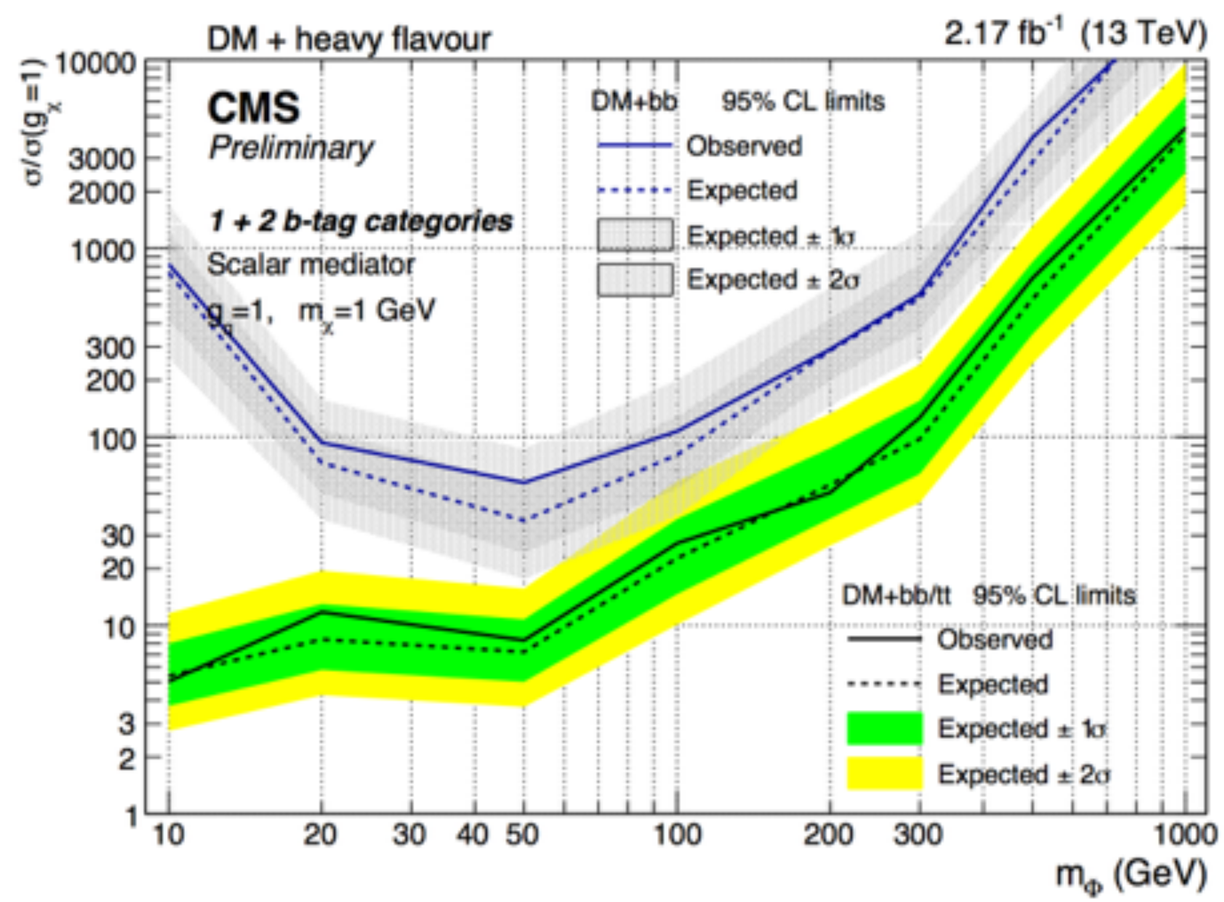
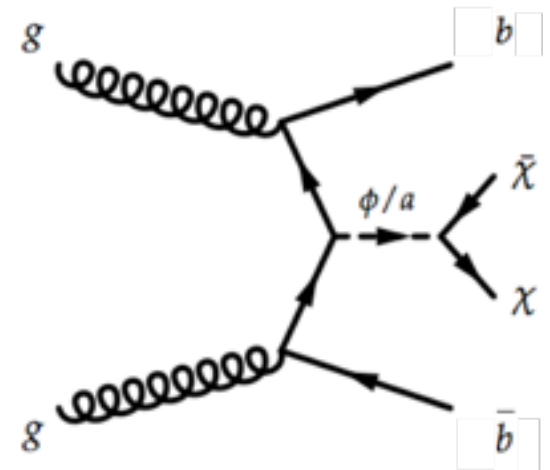
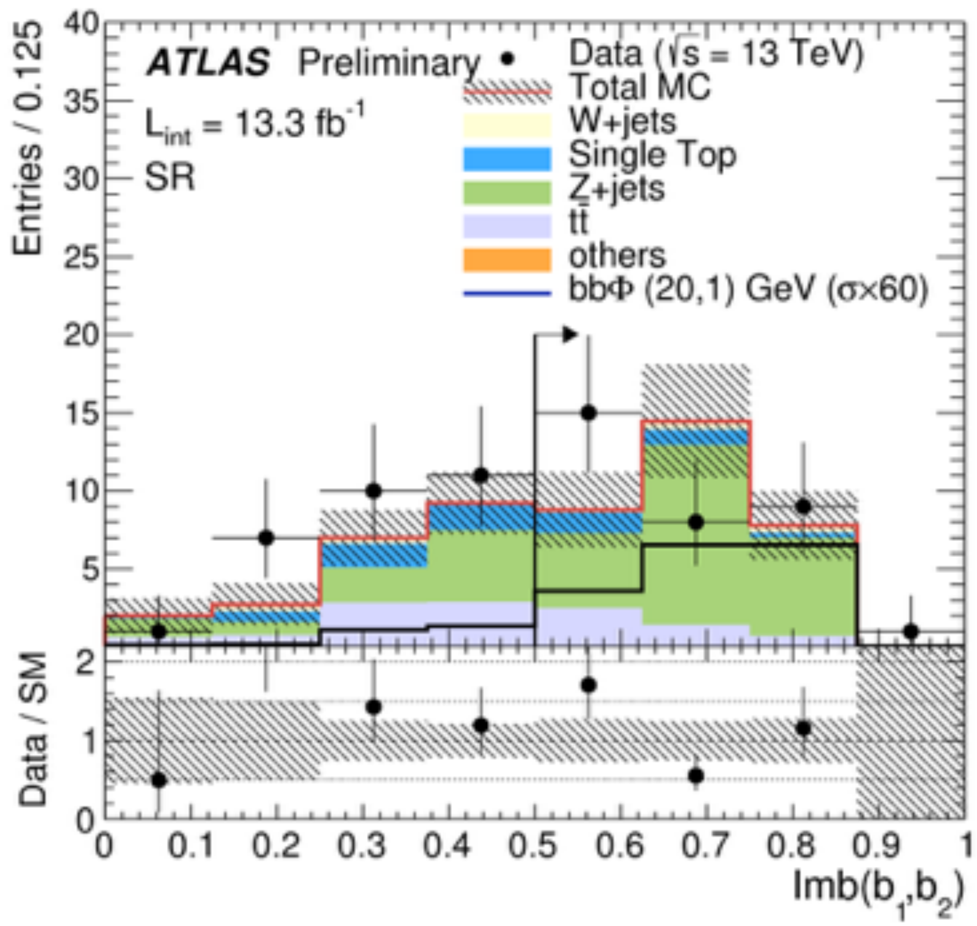


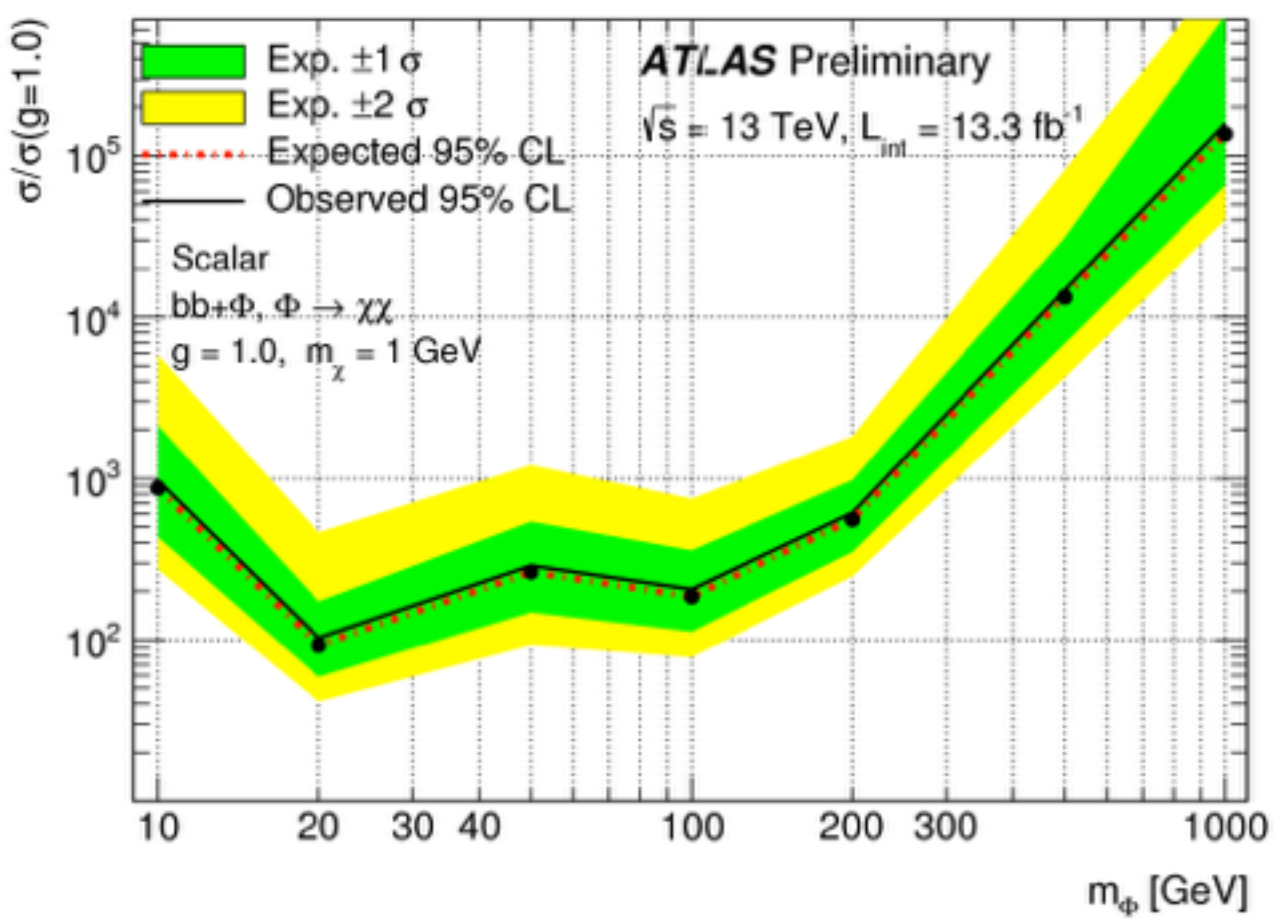
ATLAS search for DM plus b-quarks

Search for **dark matter** produced in association with **bottom quarks**

- Select events with **b-jets plus E_T^{miss}**
- Low jet multiplicity





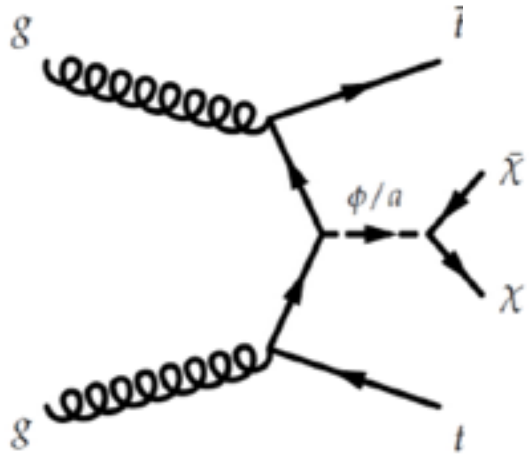


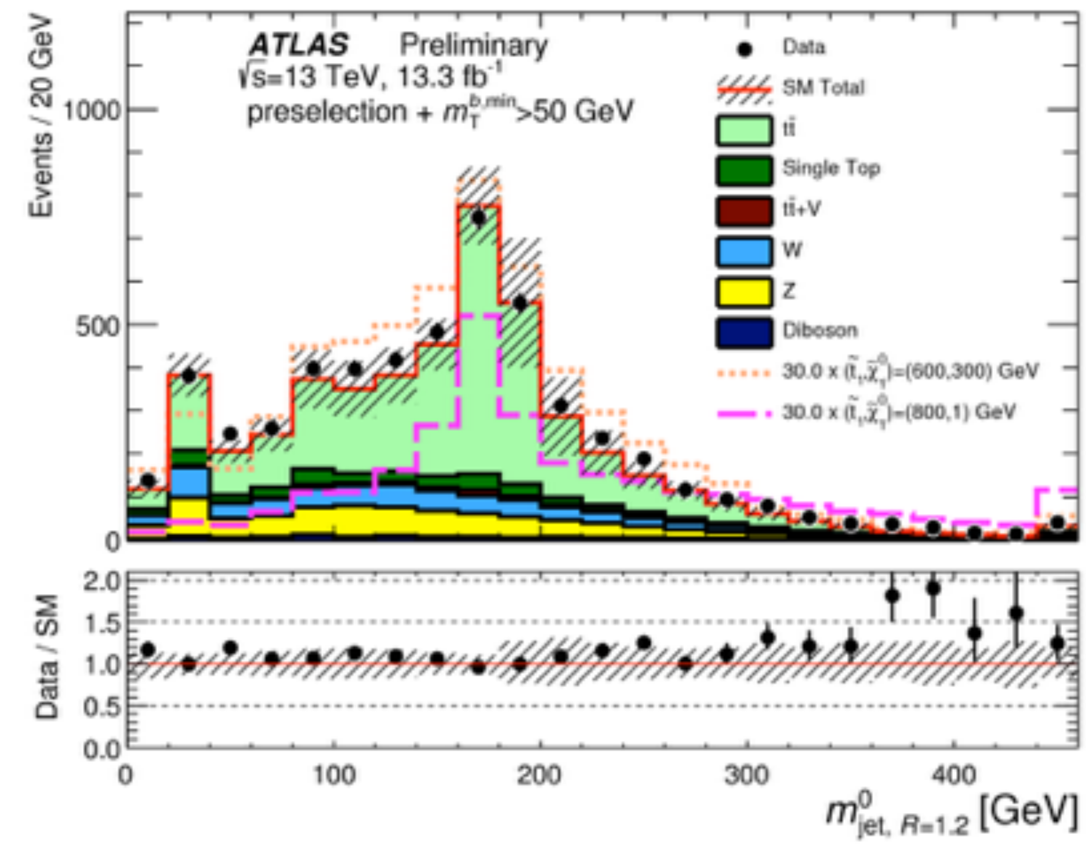
ATLAS-CONF 2016-068

ATLAS search for DM plus top pairs

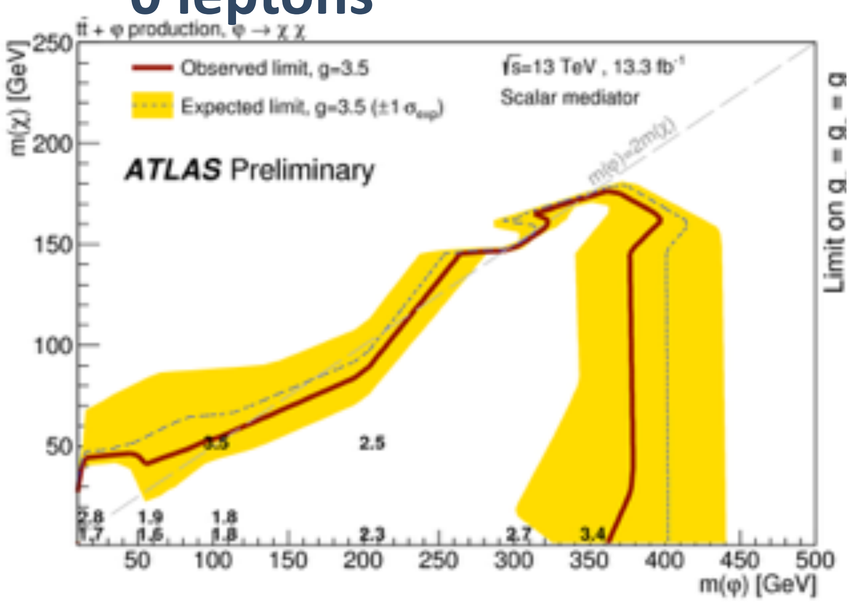
Search for **dark matter** produced in association with **top quarks**

- Hadronic, semi-leptonic and di-leptonic decays
- Selections optimised separately



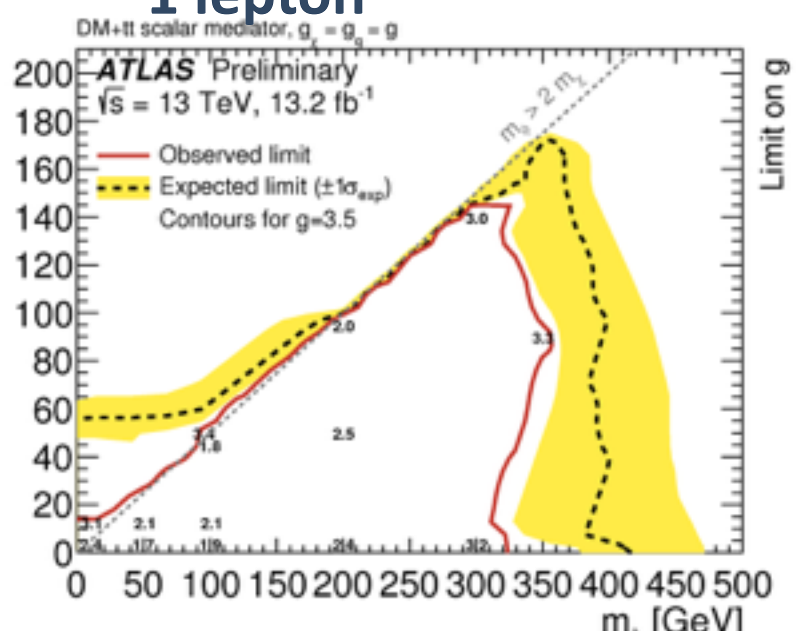


0 leptons

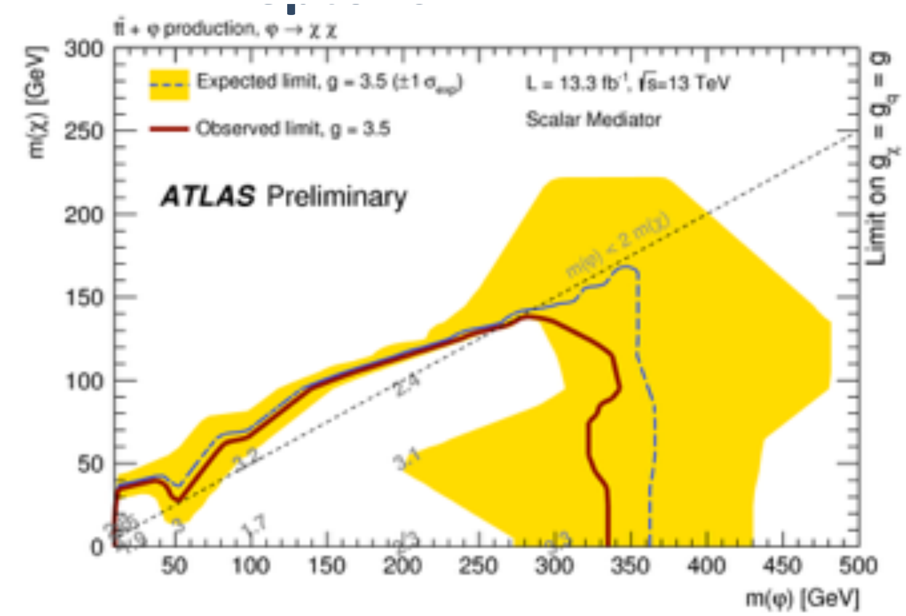


ATLAS-CONF 2016-077

1 lepton



ATLAS-CONF 2016-050

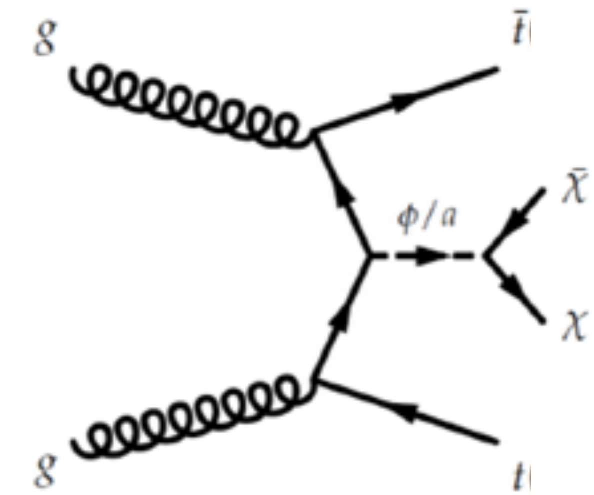


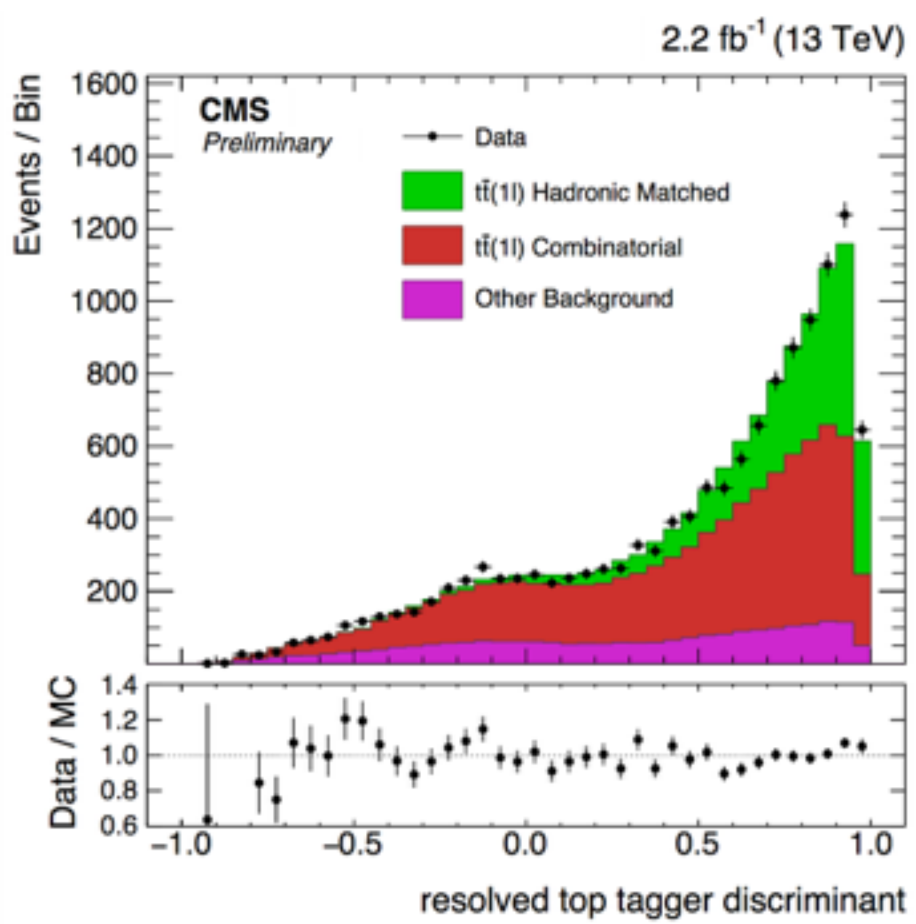
ATLAS-CONF 2016-076

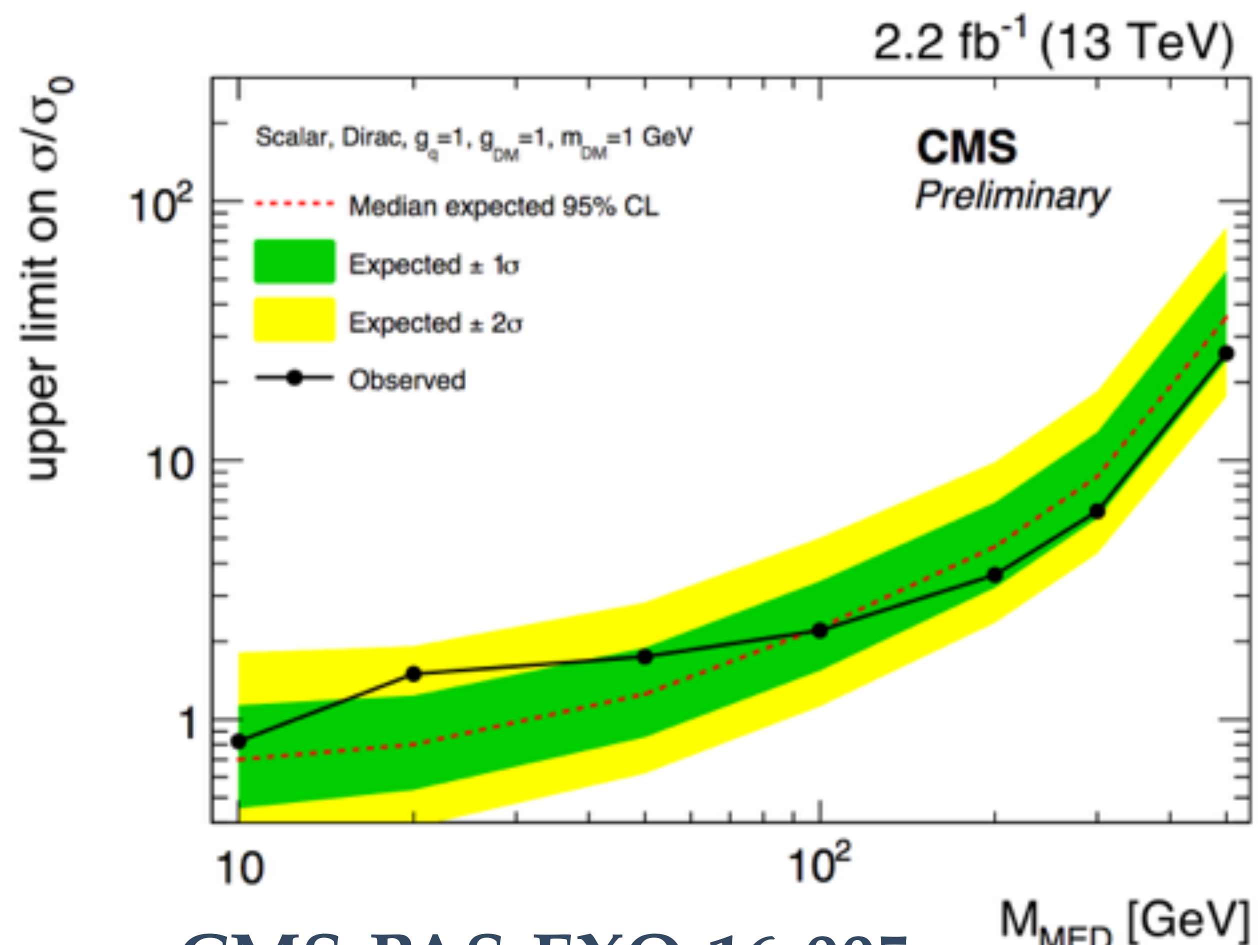
CMS search for DM plus top pairs

Search for **dark matter** produced in association with **top quarks**

- Hadronic and semi-leptonic decays
- Background dominated by top pairs
- Use top tagger and optimise selections based on number of top tags and b-jets







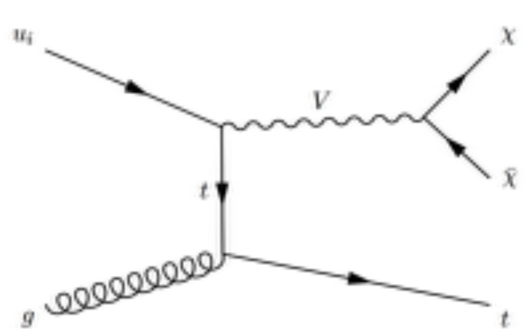
CMS-PAS-EXO-16-005

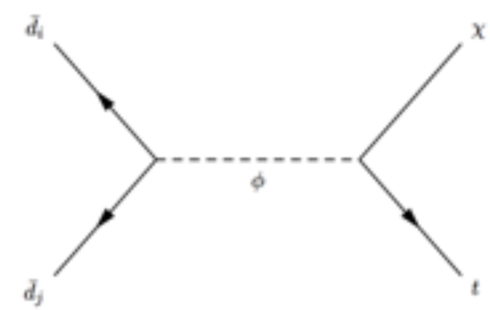
CMS search for DM plus boosted tops

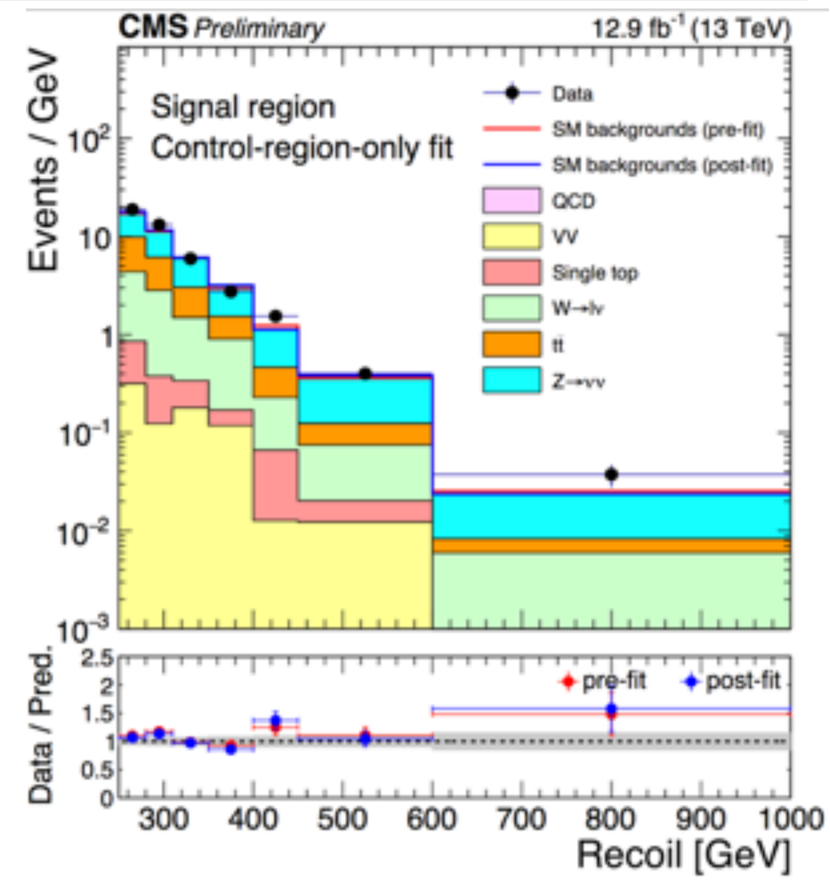
FCNC production of mono-top

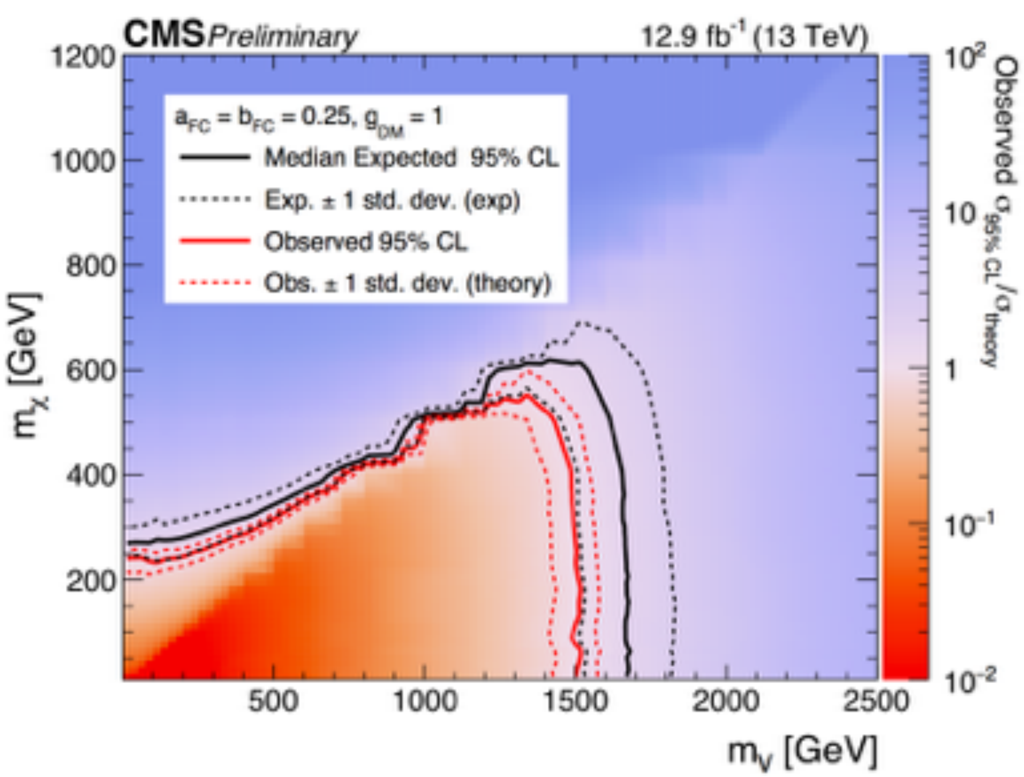
Boosted single **top** decaying hadronically → reconstructed as **single “fat” jet**

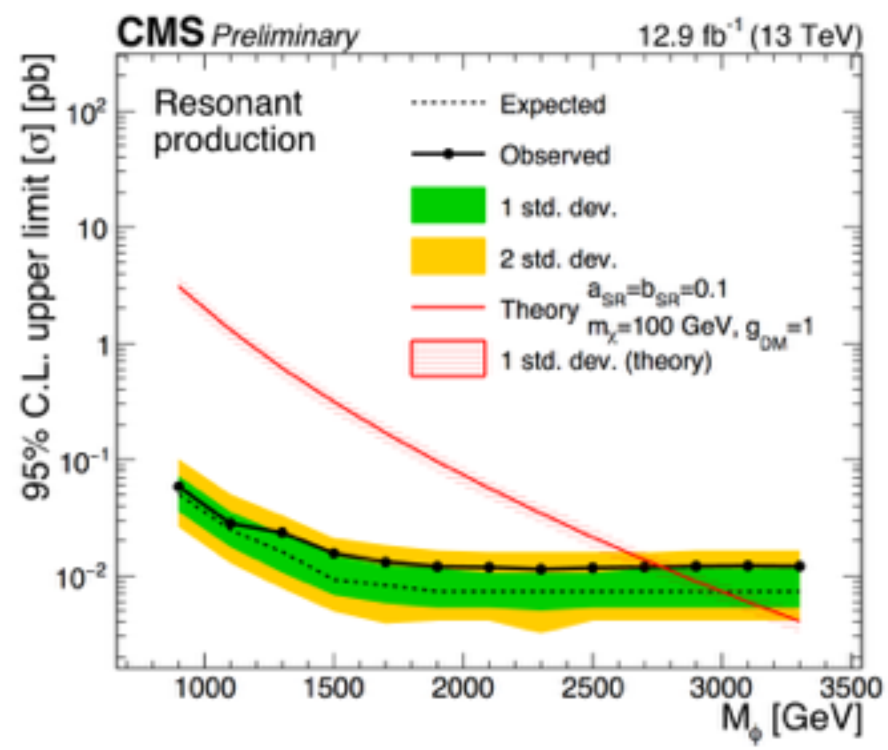
- jet mass plus substructure
- b-tagging in sub-jets









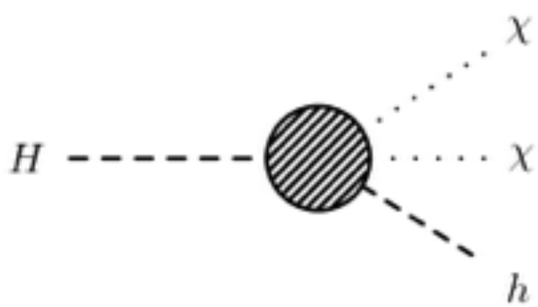


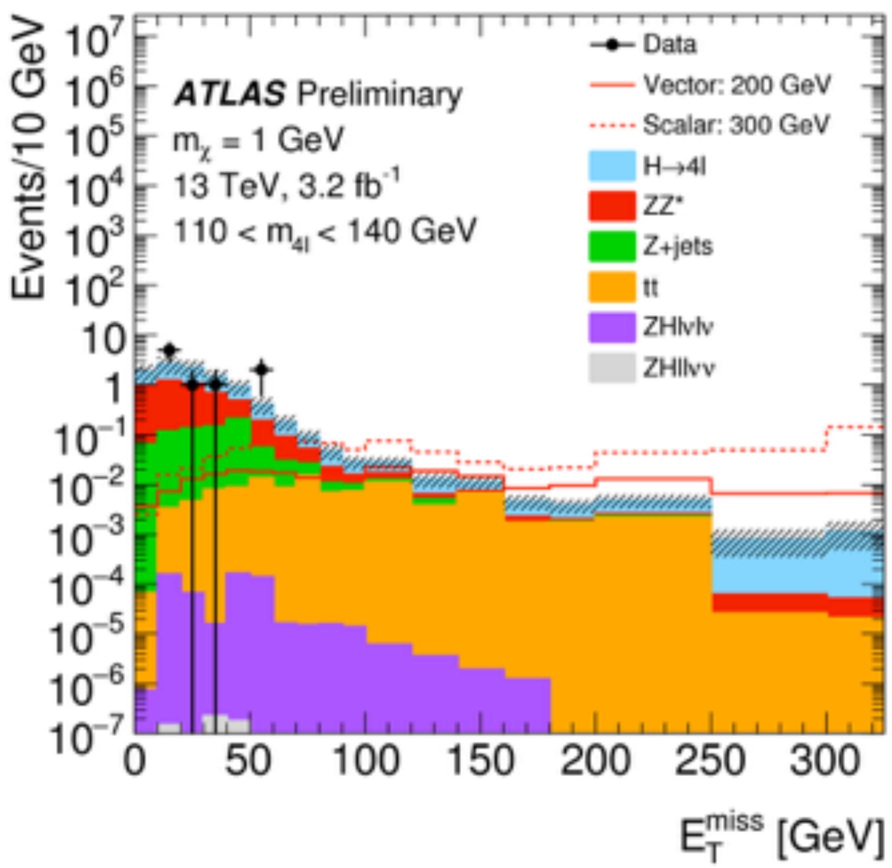
CMP PAS EXO-16-040

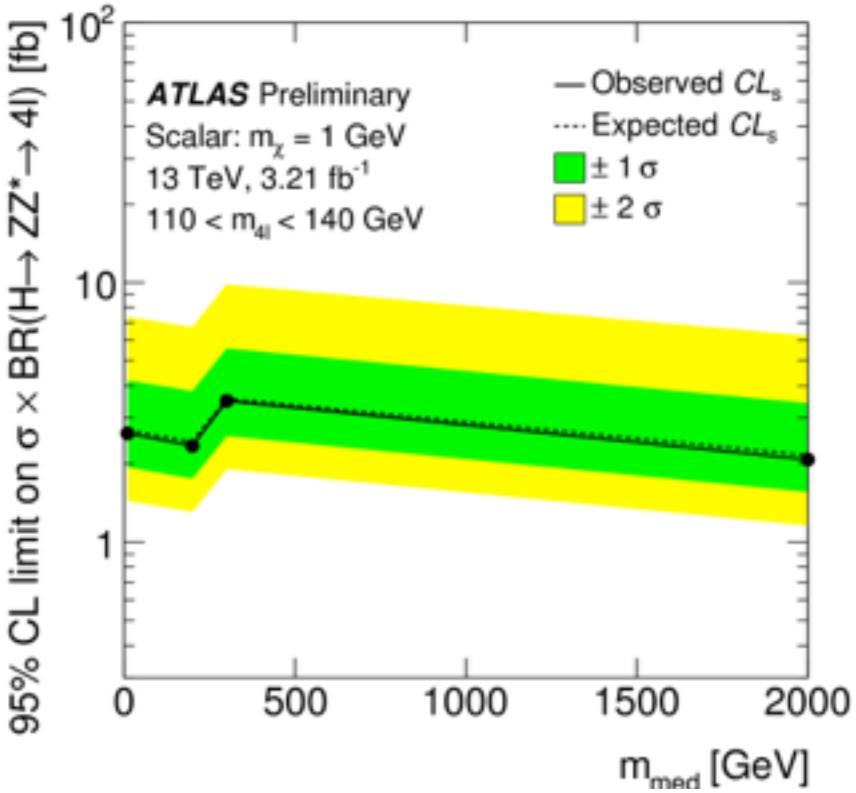
ATLAS h DM search, h→4l

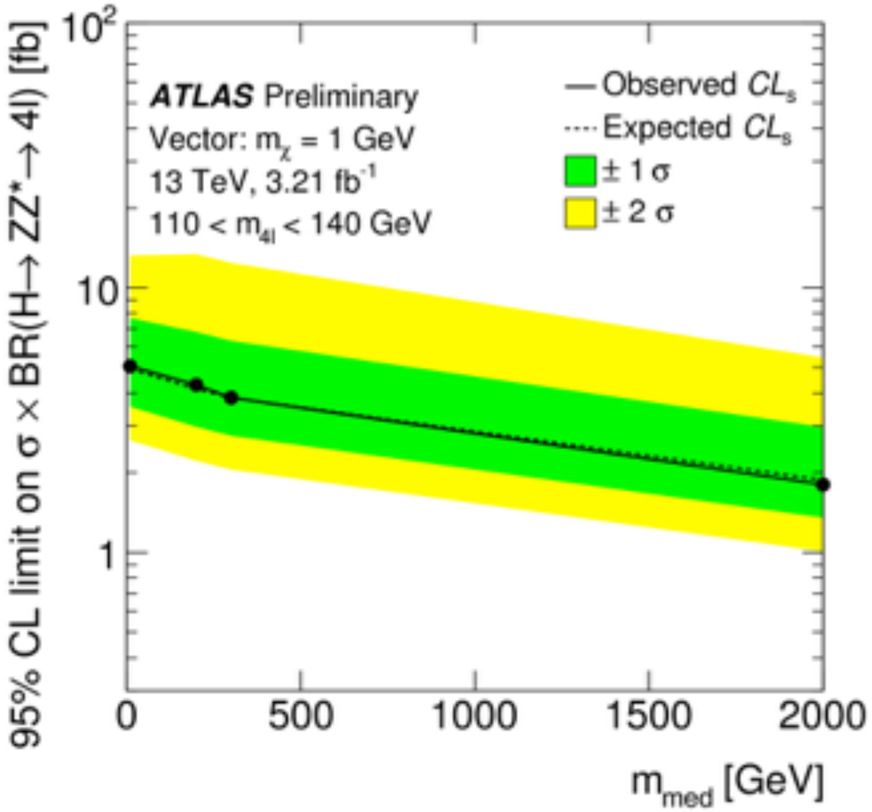
Higgs boson produced in association with dark matter

Considering both **scalar** and **vector mediators**









ATLAS-CONF 2015-059

Search for Mediators

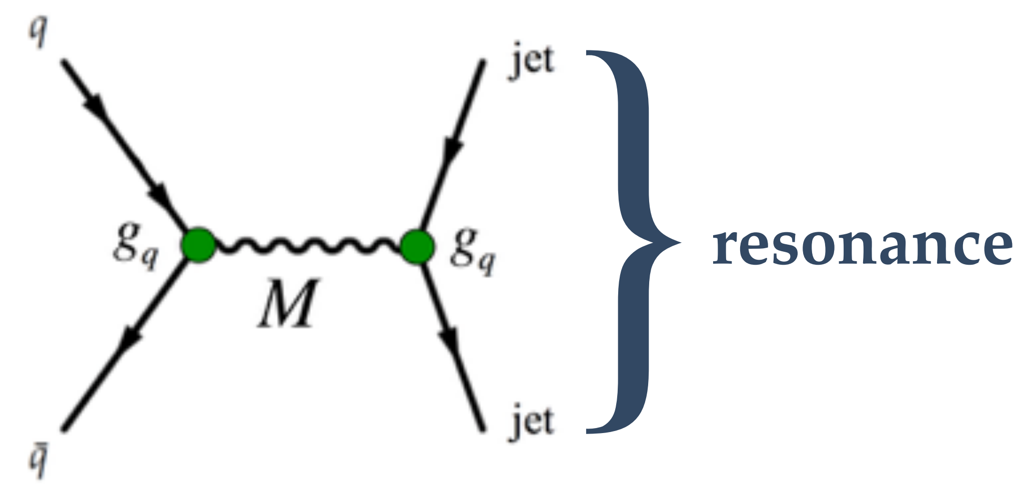
ATLAS searches for mediators

Look for **mediators decaying into quarks**

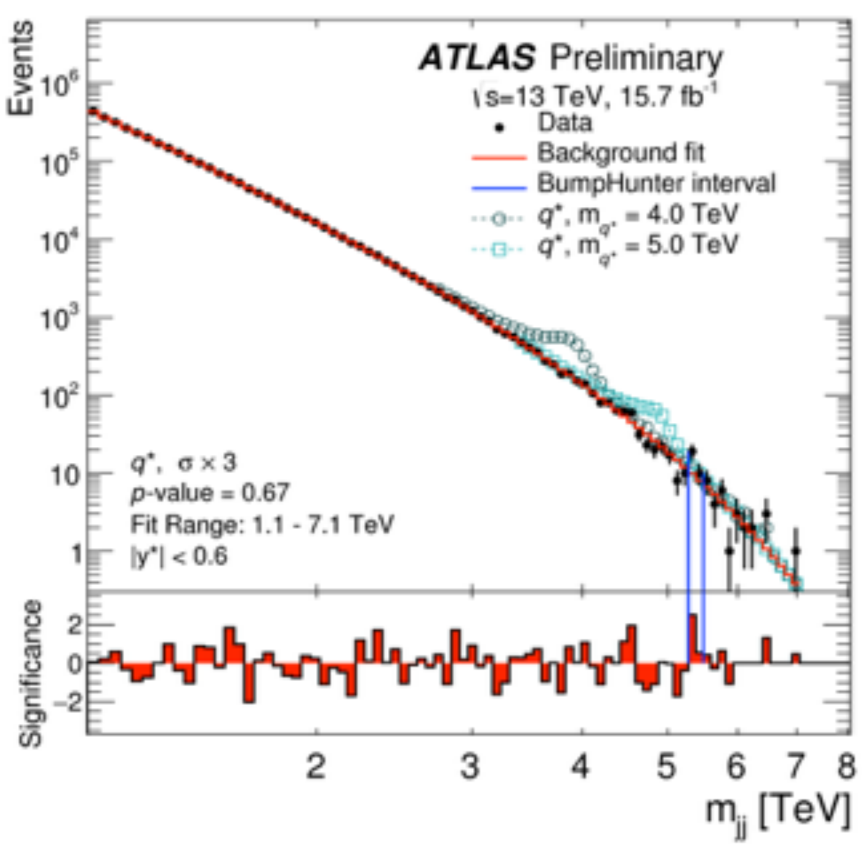
→**Dijet resonances**

Complementary approach to searches for DM candidates

Three distinct searches addressing **different mass range**

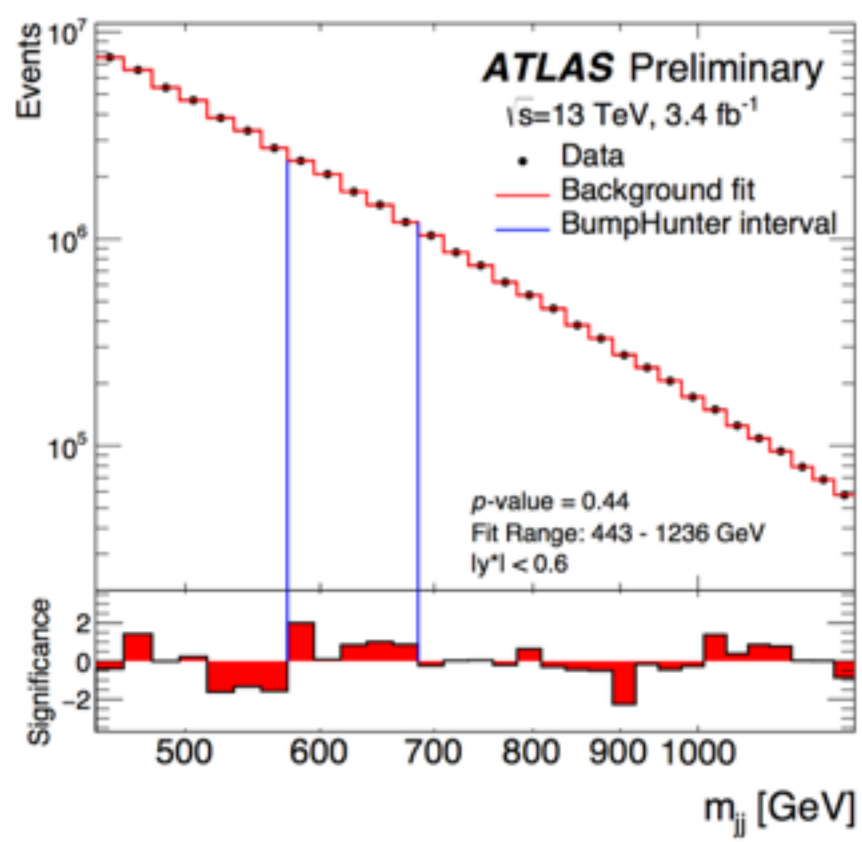


Probing range above 1.5 TeV



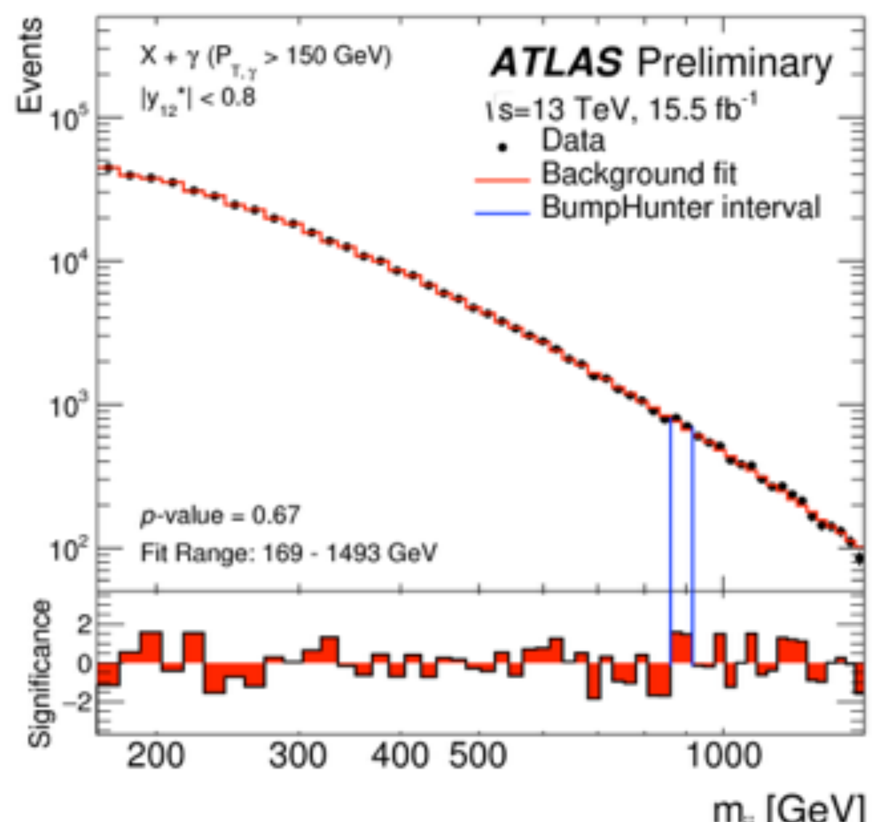
ATLAS-CONF 2016-069

Extend sensitivity with trigger-level objects



ATLAS-CONF 2016-030

Select ISR photon or jet to probe lower masses



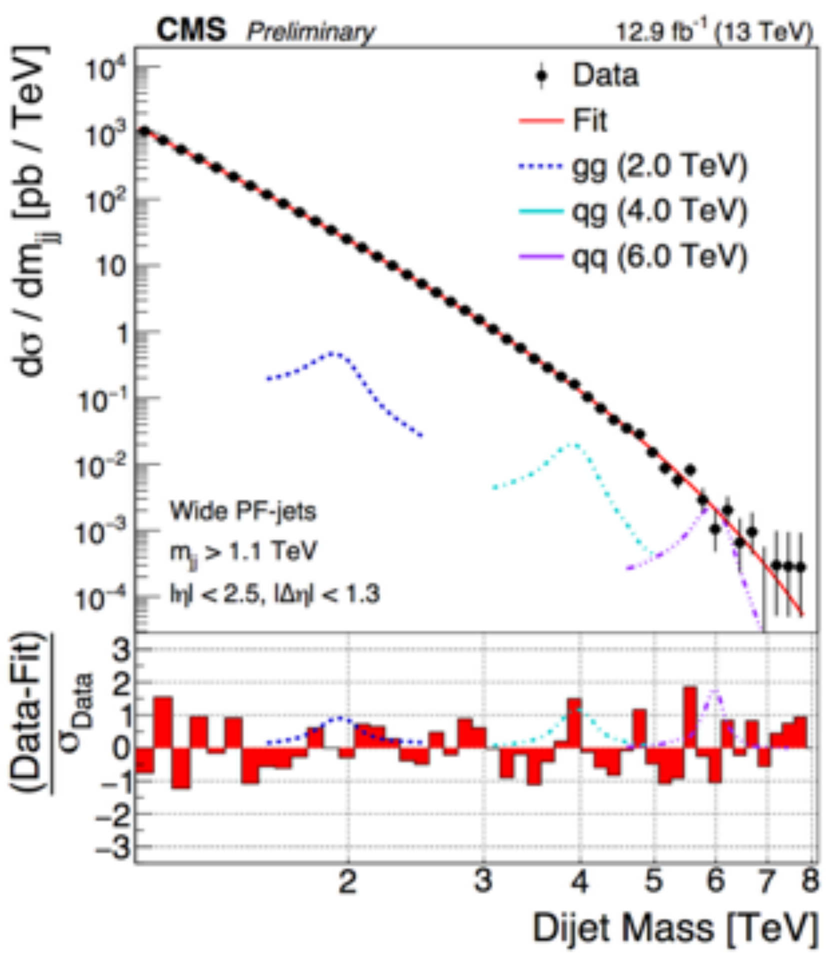
ATLAS-CONF 2016-070

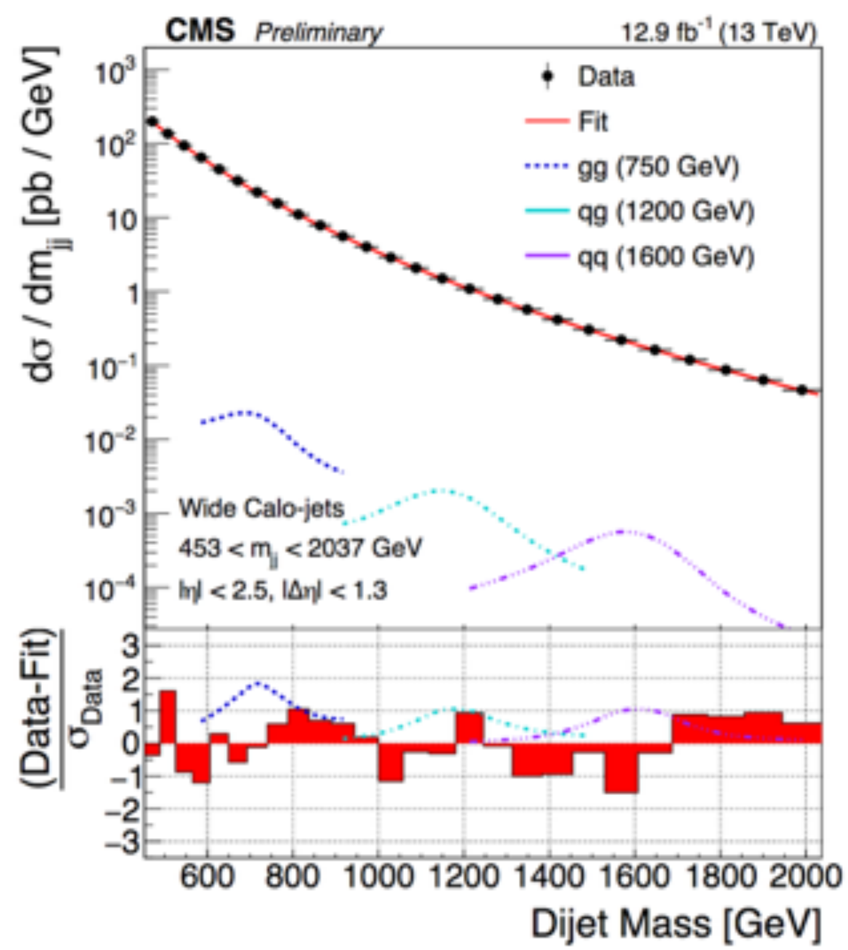
CMS searches for mediators

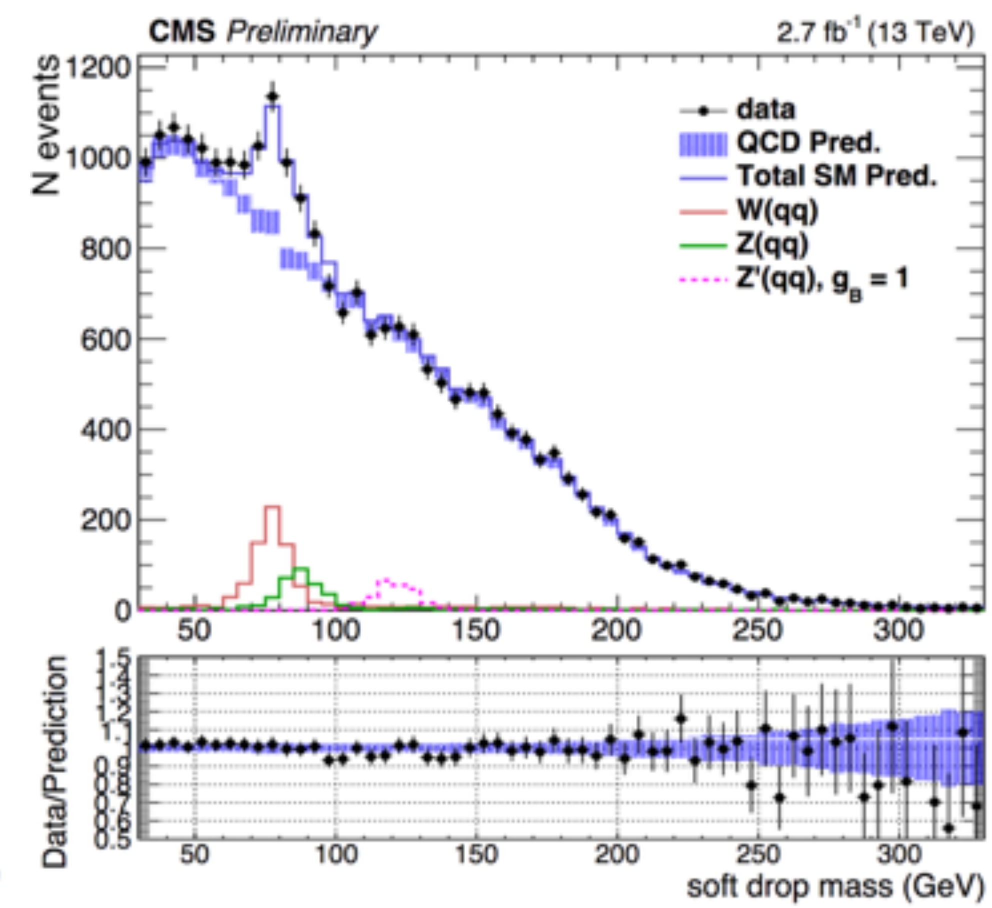
Probing range above 1.1 TeV

Extend sensitivity with trigger-level objects

Select ISR jet to probe lower masses



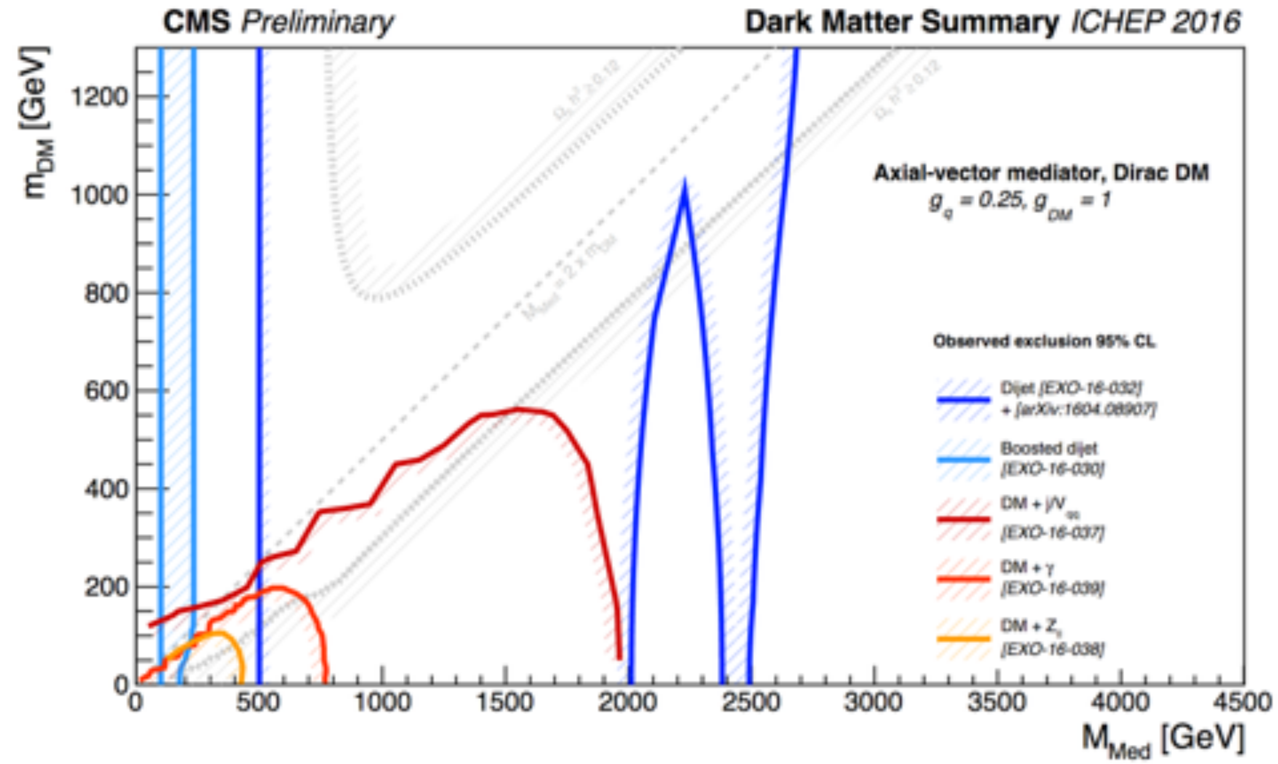


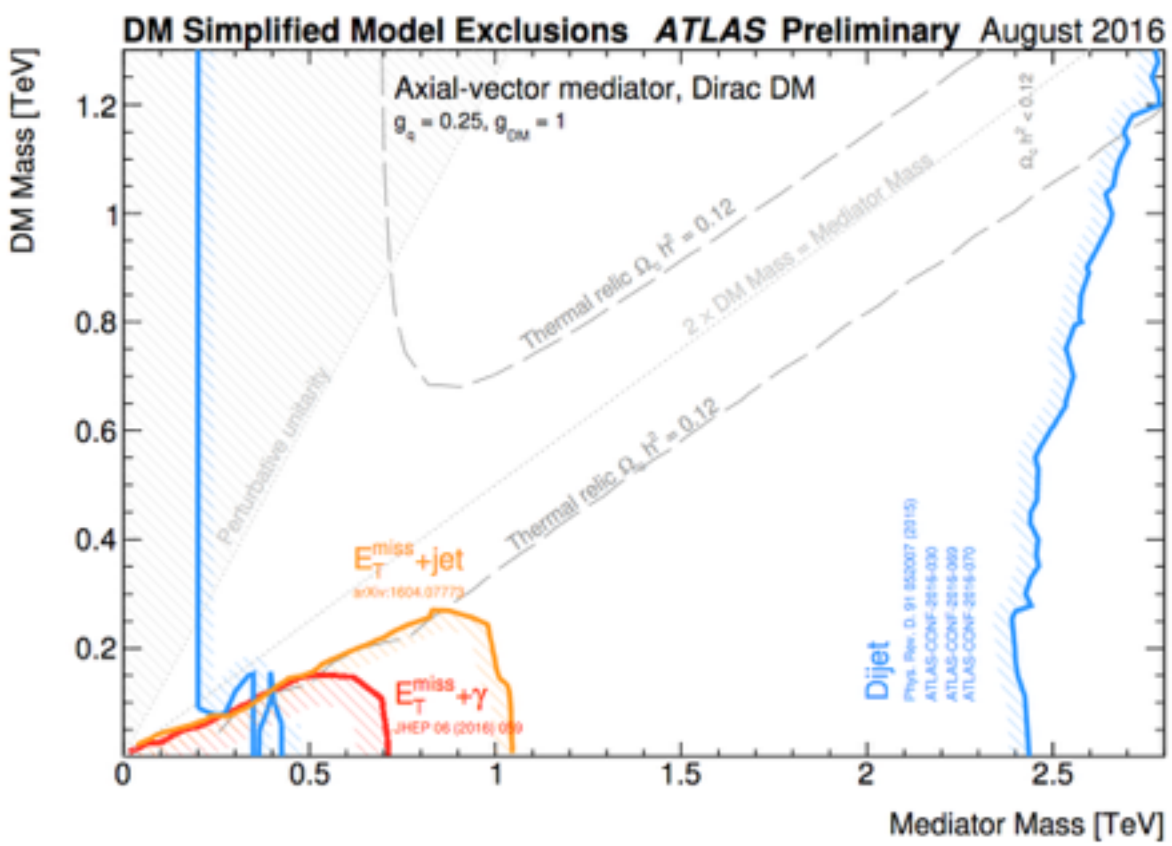


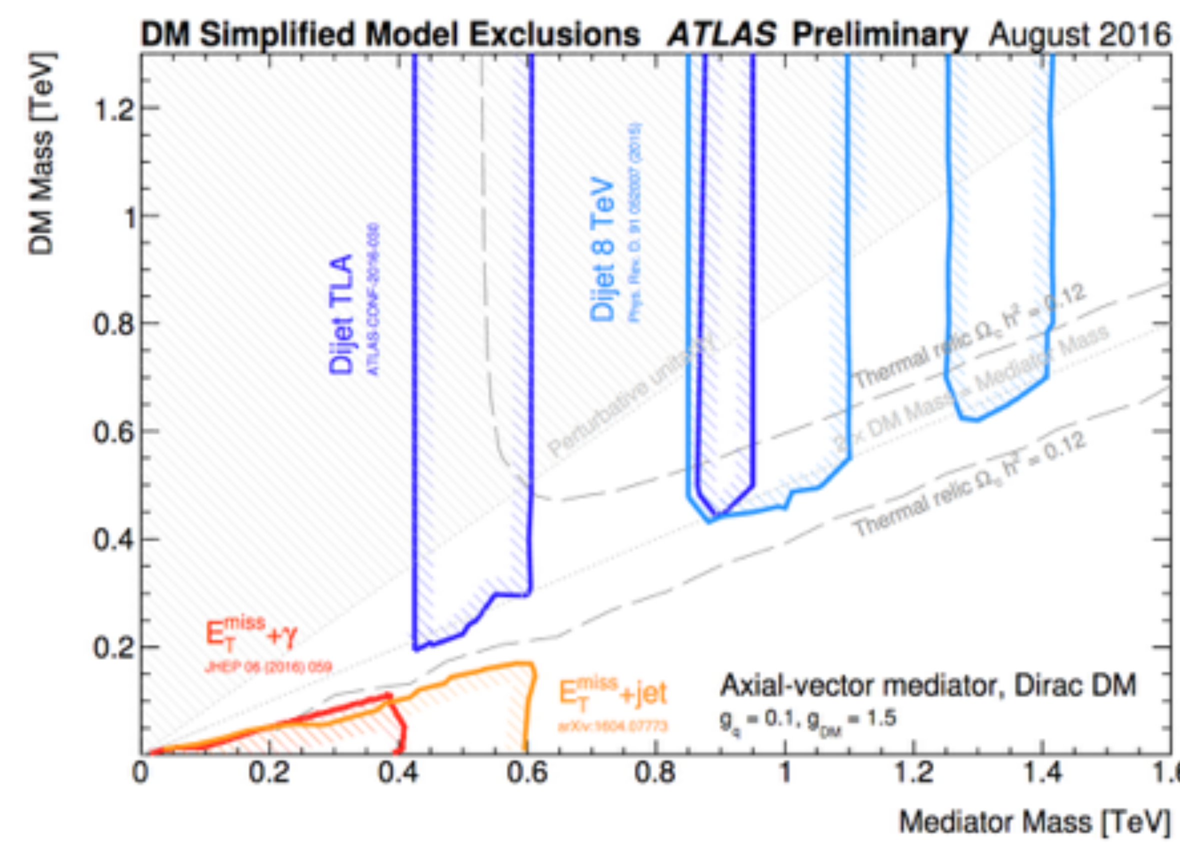
CMS-PAS-EXO-16-032

CMS-PAS-EXO-16-030

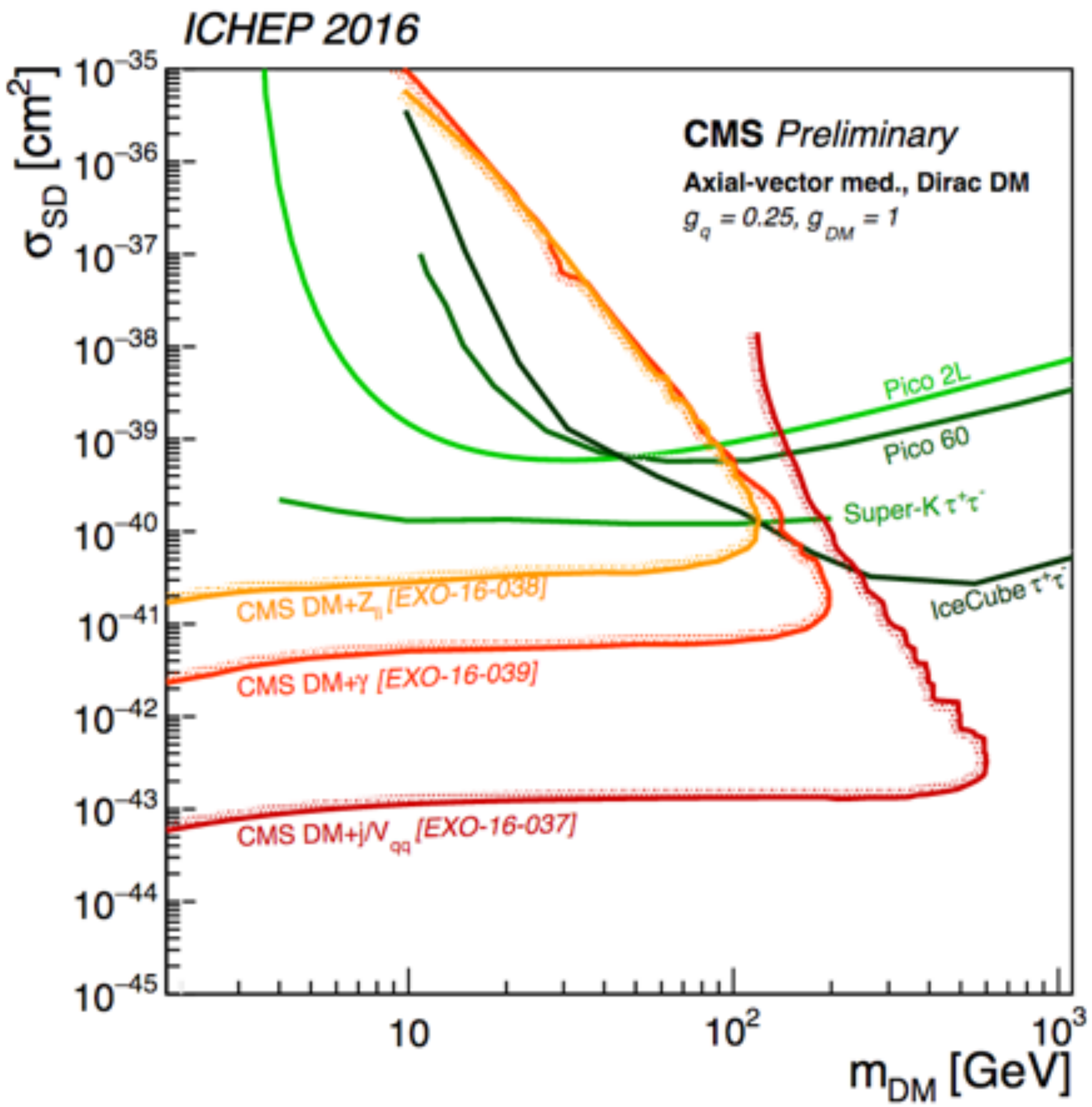
Summary of Searches

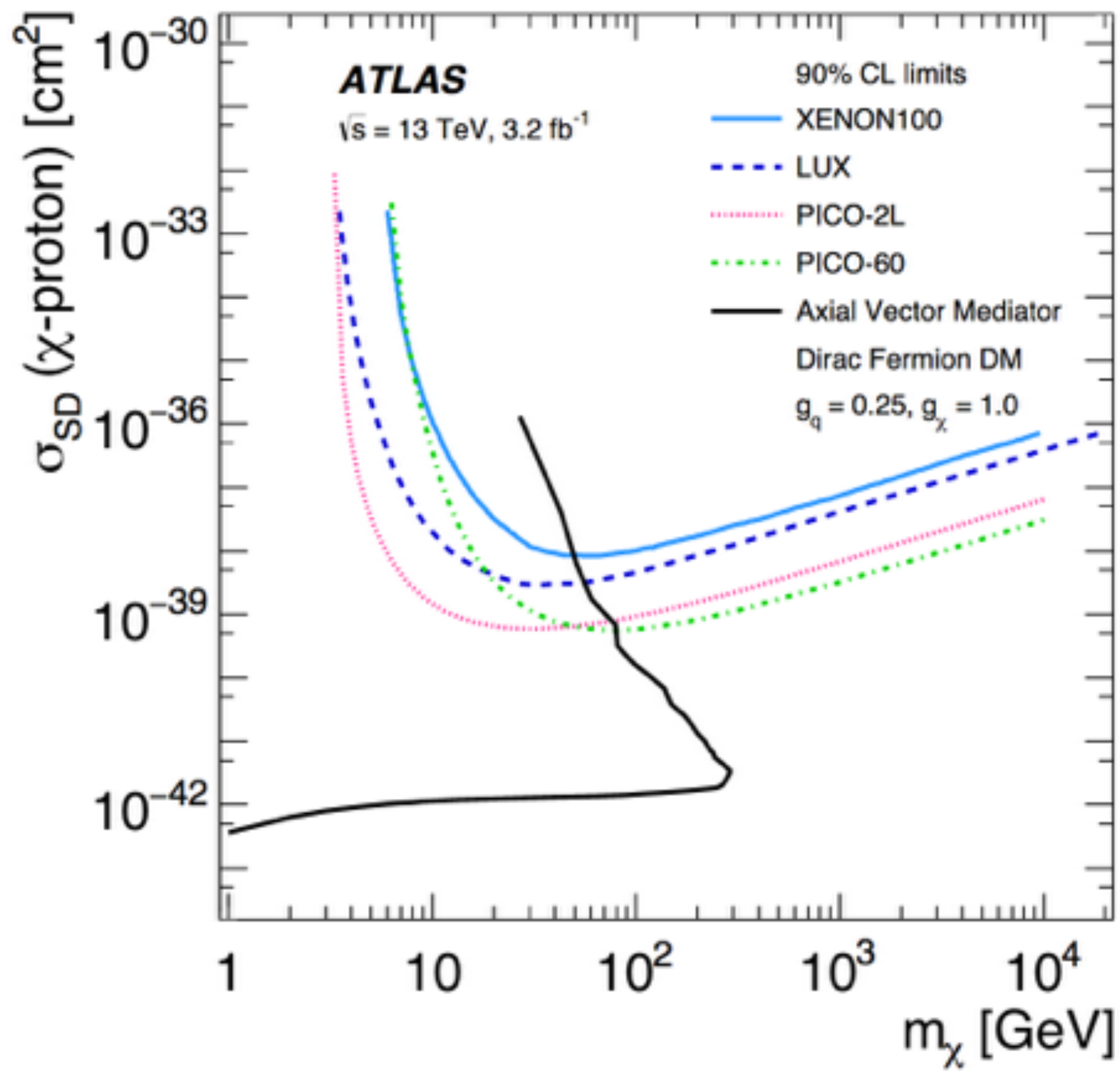






Comparison with Direct Detection Searches





Conclusions

- Many searches for dark matter from the ATLAS and CMS experiments
    - Complementary to direct and indirect detection searches
- Looking for dark matter candidates through mono-X analyses and produced association
- Looking for mediators through resonances of di-jets
- No excess over the SM prediction observed, results interpreted in terms of exclusion limits in the context of simplified models and effective field theories

Back-Up

Truncation

In the case of the model of $\gamma\gamma\chi\bar{\chi}$ interactions, lower limits are placed on the effective mass scale M_* as a function of m_χ, as shown in Fig. 8. The EFT is not always valid, so a truncation procedure is applied [75]. In this procedure, the scale at which the EFT description becomes invalid (M_{cut}) is assumed to be related to M_* through $M_{\mathrm{cut}} = g^* M_*$, where g^* is the EFT coupling. Events having a centre-of-mass energy larger than M_{cut} are removed and the limit is recomputed.

ATLAS: JHEP06 (2016) 059