Dark Matter Searches at the LHC

Latest public results from ATLAS and CMS experiments

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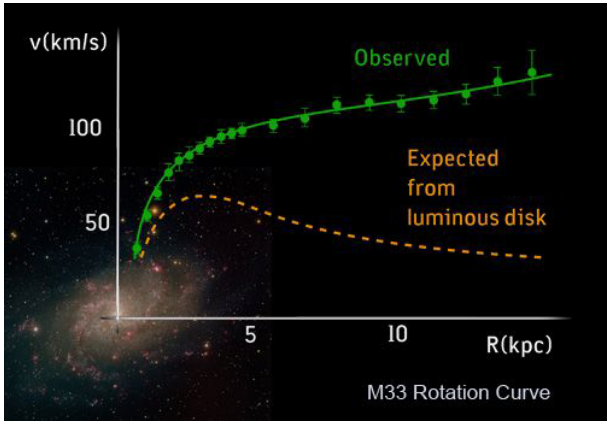
Introduction

- Multiple cosmological observation supports the existence of DM

- We know very little about DM
  - Have gravitational interaction
  - Charge/color neutral

- Searches for DM
  - Direct detection
    recoils of nuclei induced by DM
  - Indirect detection
    self-annihilation or decay of DM in outer space



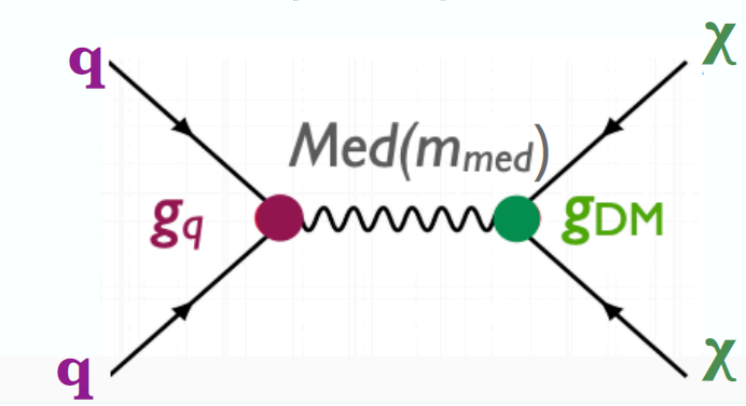
Galaxy rotation curve

Strong gravitational lensing effect

DM models searches at ATLAS/CMS

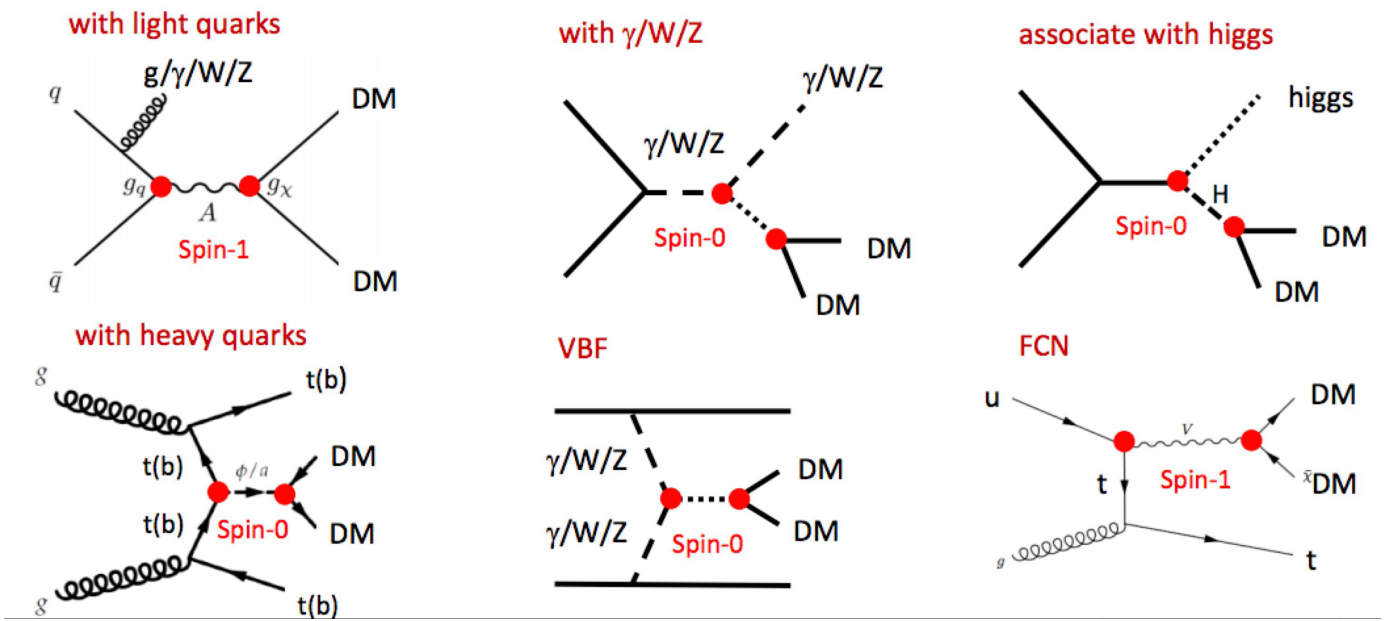
- LHC approach : produce DM through proton collisions

- Run-2 analyses follow simplified models suggested by ATLAS/CMS DM forum
  - ❑ Fermionic DM interacts with a mediator
  - ❑ Bosonic mediator couples to both DM and SM particles, could be a (pseudo) scalar or a (axial) vector
  - ❑ Model parameters include mediator mass/width, DM mass, mediator coupling to SM particle (quark) and to DM



Mono-X strategies for DM search

- DM has weak interaction with SM particles, it is not visible to ATLAS/CMS detectors, leading to large momentum imbalance (MET).
- mono-X strategies are widely investigated, where X could be a jet, vector boson, photon or top quark(s) or Higgs boson



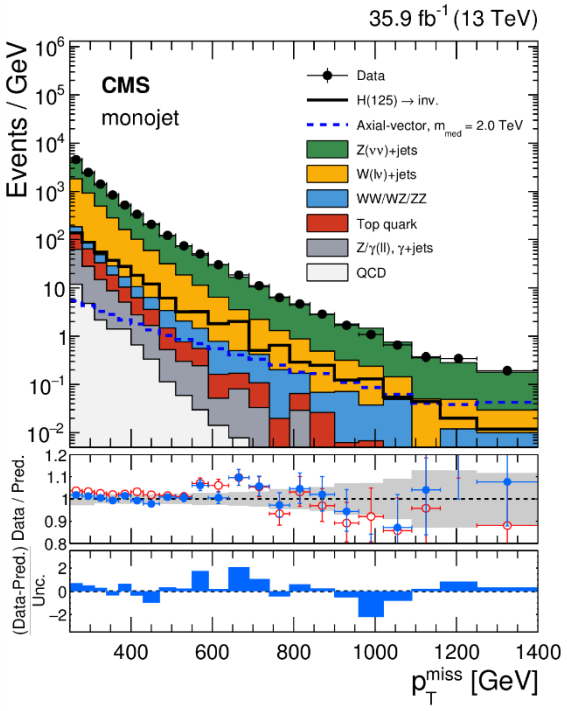
Outline

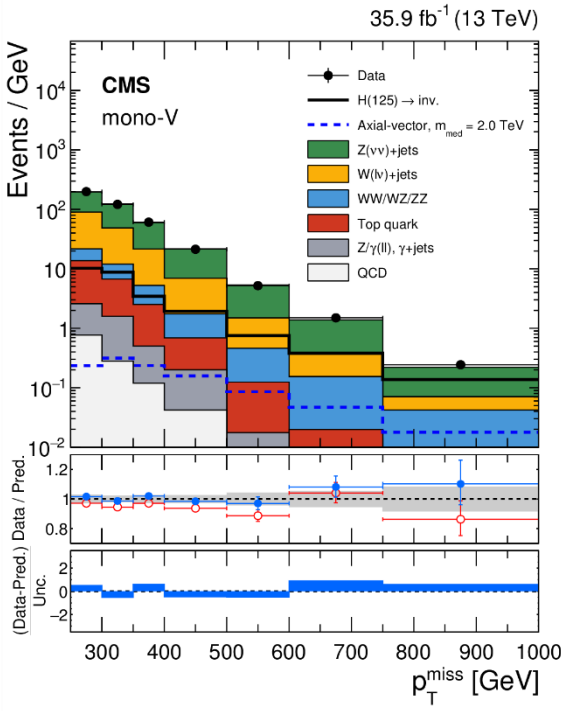
- Mono-X searches for dark matter
- Search for the mediator
- Higgs-related DM searches
  - Higgs as portal :
    search for invisible Higgs decay
  - Mono-Higgs

Mono-X searches for dark matter

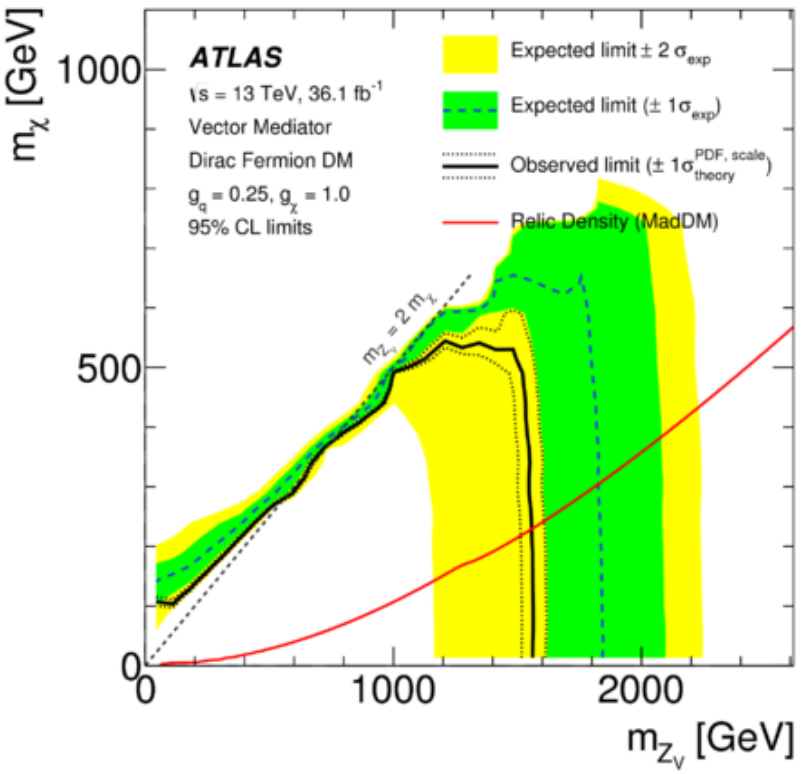
Mono-X search : mono-jet (W/Z)

- Event signatures
  - ❑ Large MET from mediator decays to DM
  - ❑ At least one high pT jet from ISR or a vector boson (hadronic decay)
  - ❑ No leptons/photons in the final state
- Dominant backgrounds are Z(vv)/W(lv)+jets

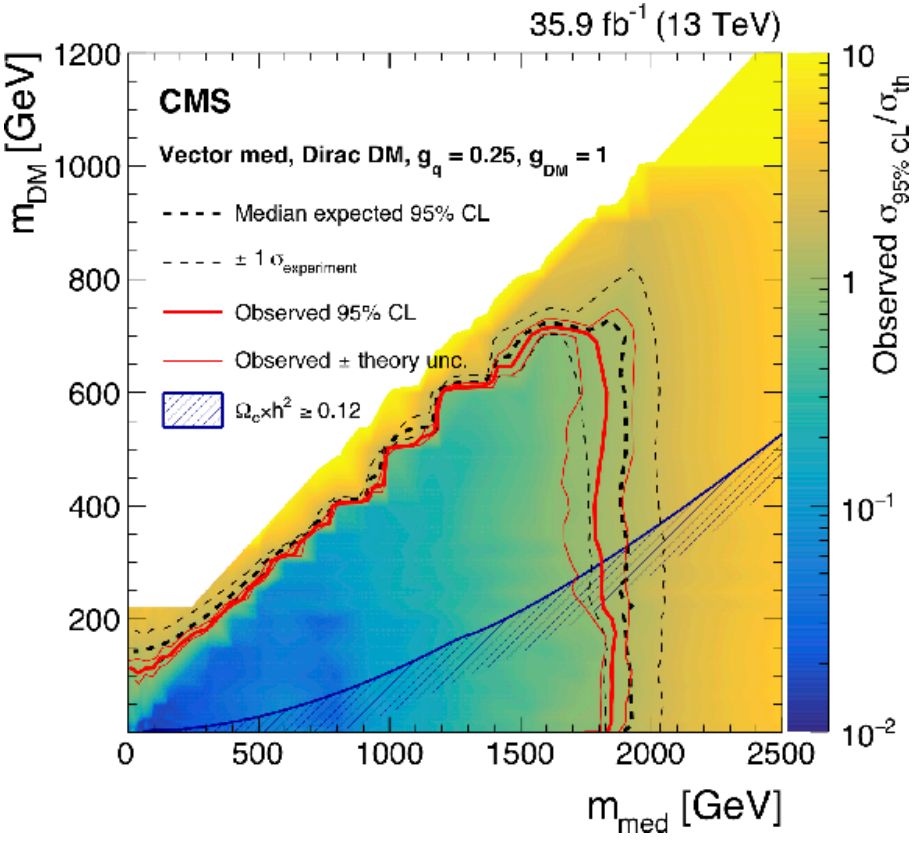




Mono-X search : mono-jet (W/Z)



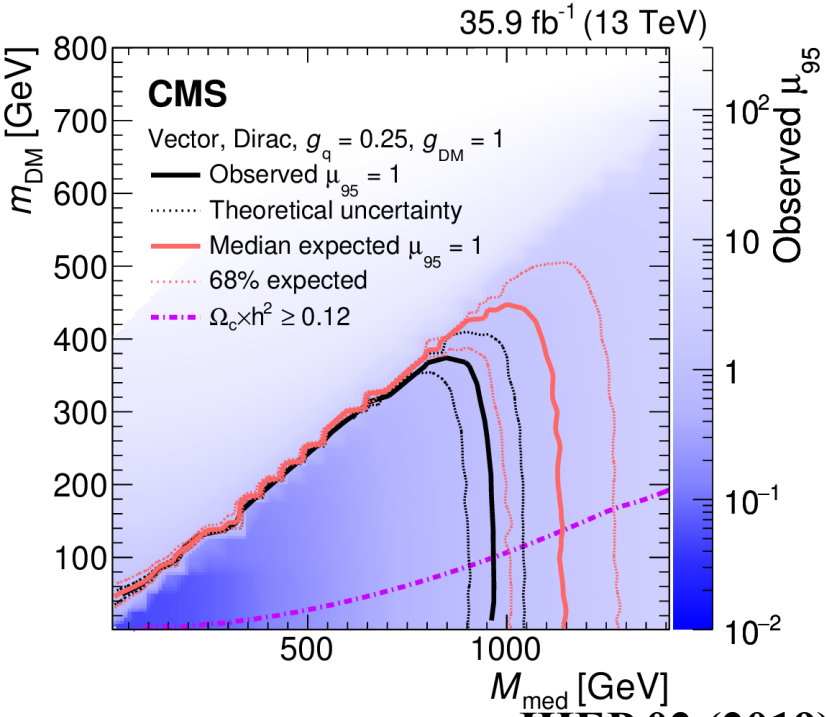
JHEP 01 (2018) 126

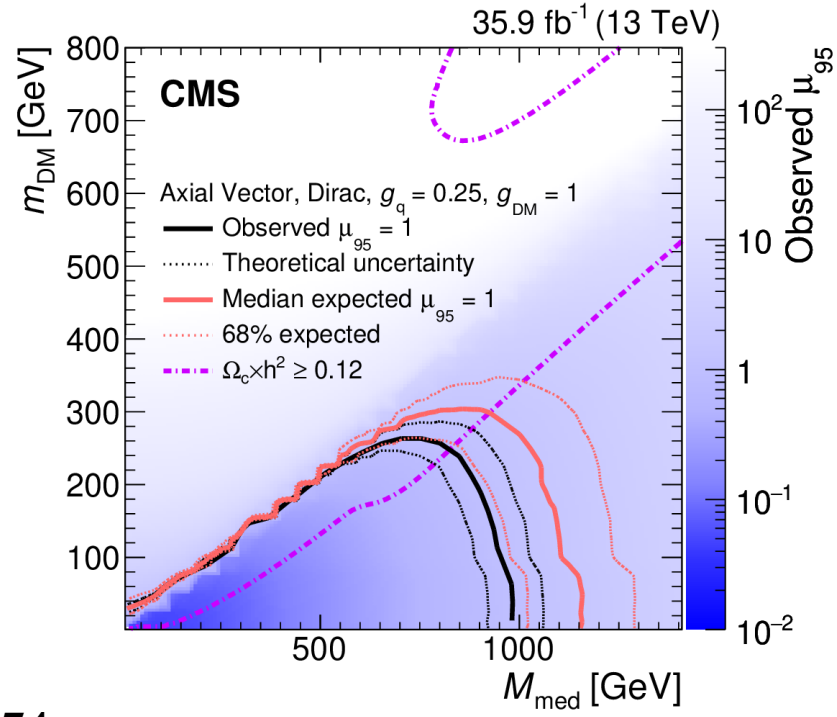


PRD 97 (2018) 092005

Mono-X search : mono-photon

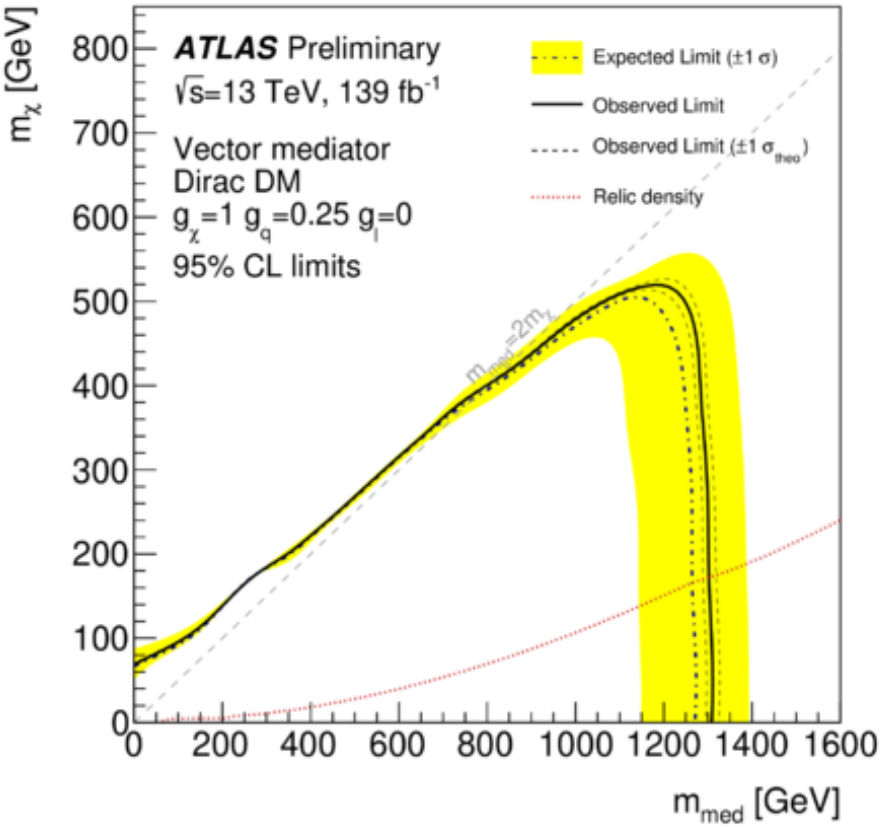
- Event signatures
  - ❑ Large MET from mediator decays to DM
  - ❑ High pT photon
  - ❑ No leptons to reject W(lv)+photon
- Dominant backgrounds are Z(vv)/W(lv)+photon

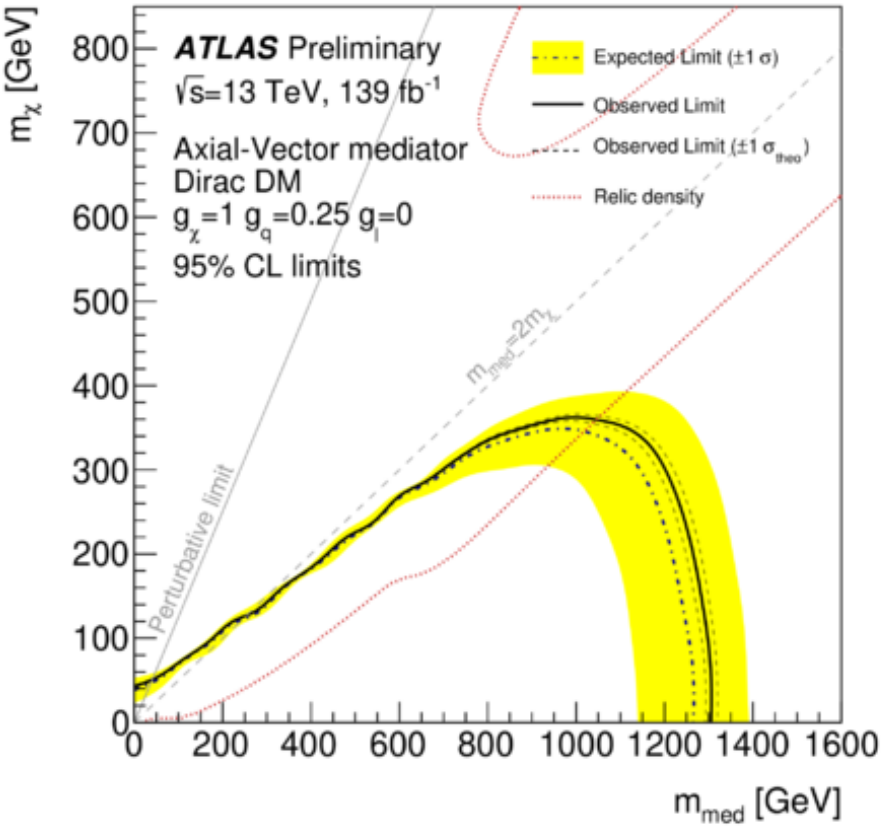




JHEP 02 (2019) 074

Mono-X search : mono-photon



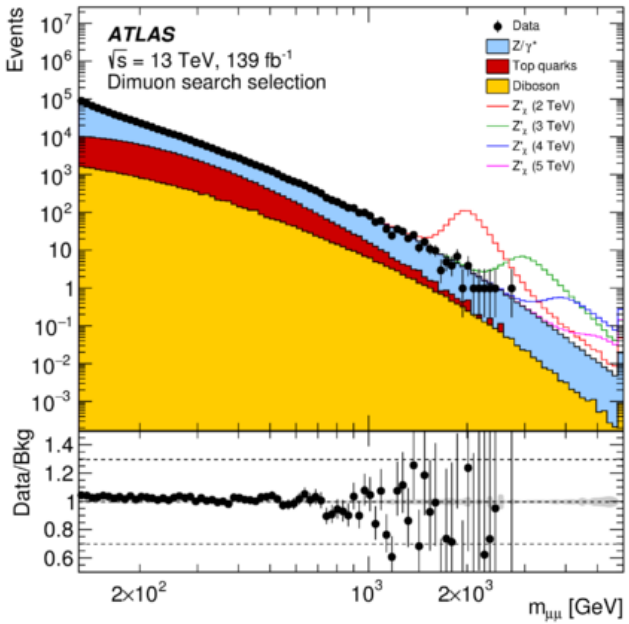


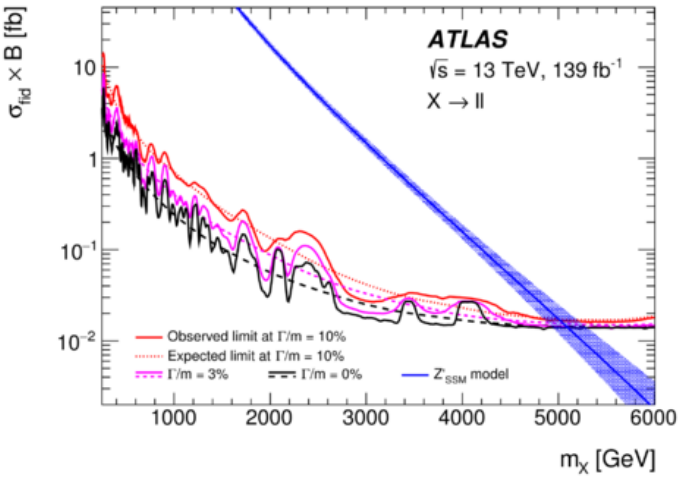
ATLAS-CONF-2020-020

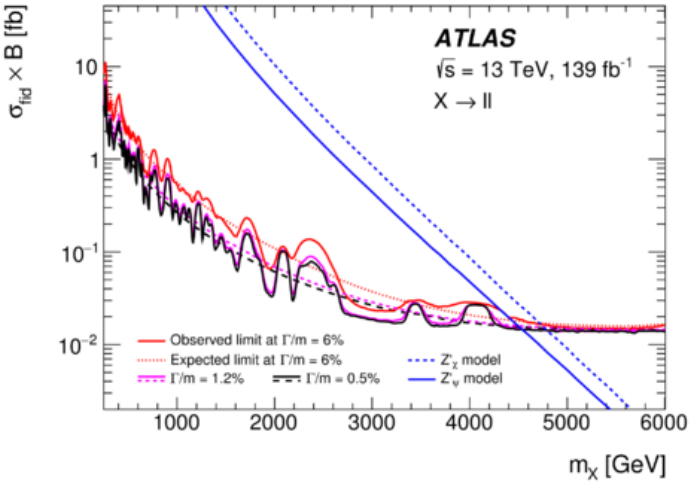
Search for the mediator

Search for the mediator : $\ell^+\ell^-$ resonances

- Di-electron/muon pair to search for resonance to identify high mass mediator
  - ❑ easy to trigger
  - ❑ strike signature from sharp peak in the mass spectrum

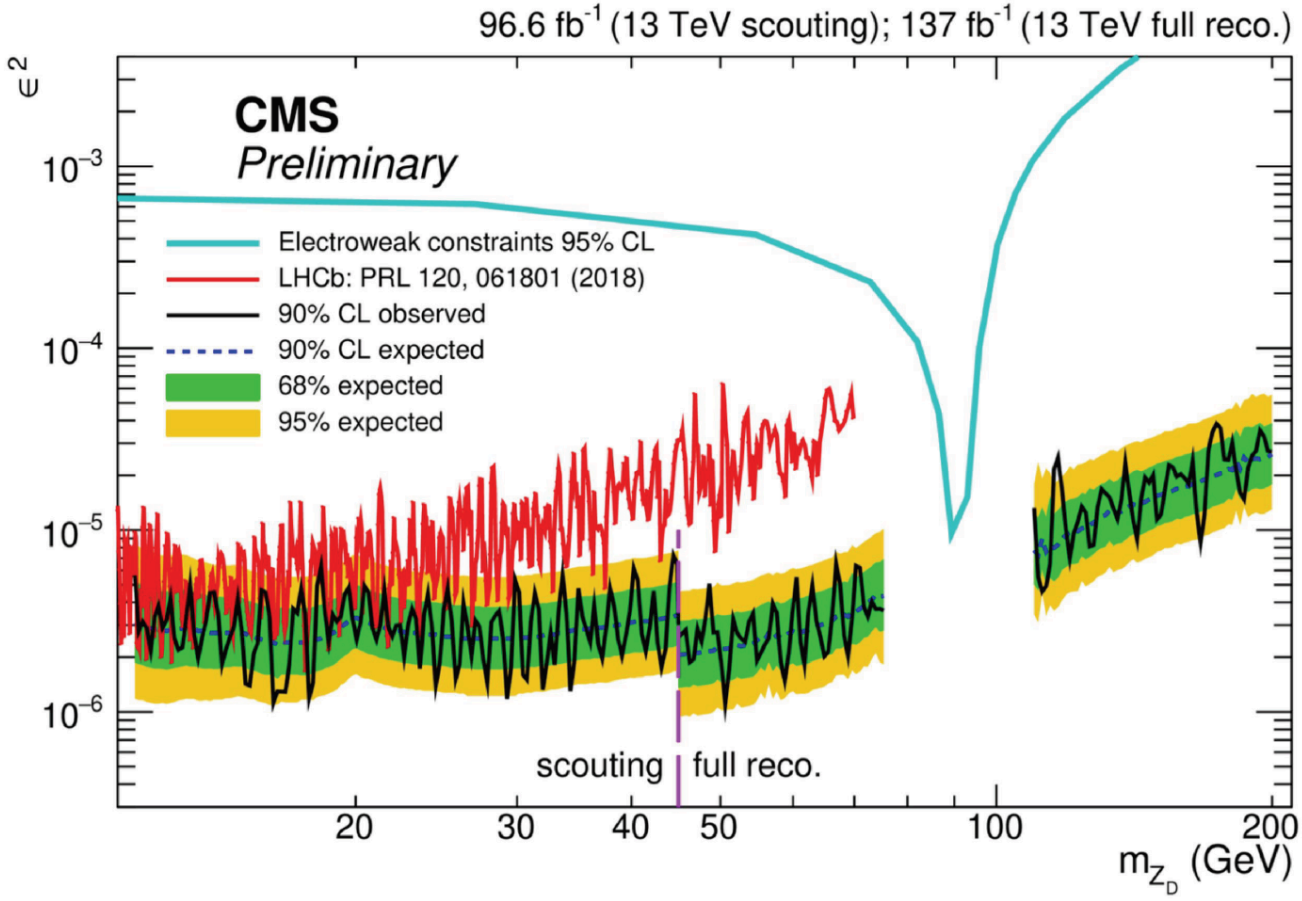






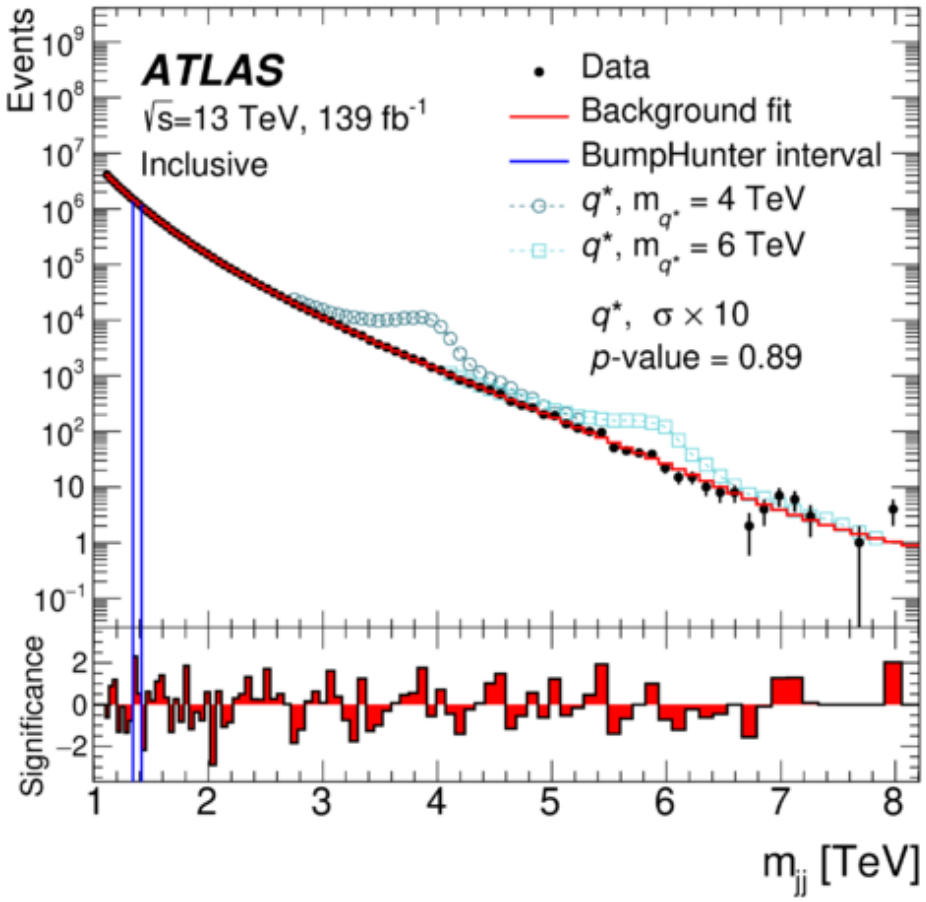
Phys. Lett. B 796 (2019) 68

Dark photon from low mass $\ell^+\ell^-$ resonances

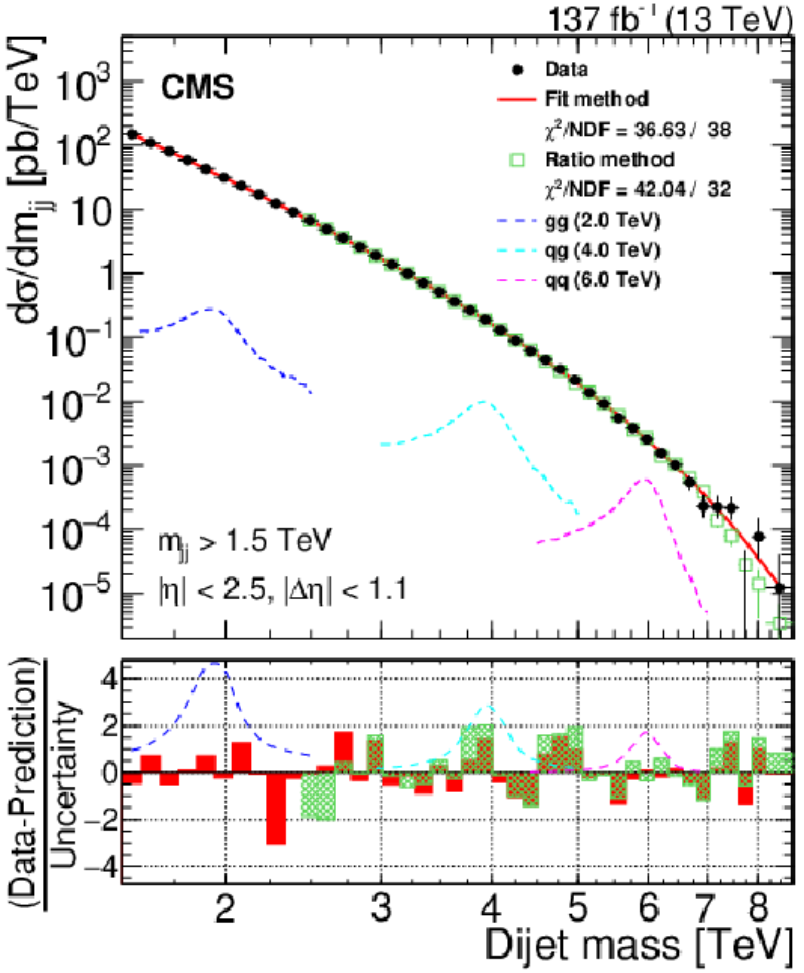


Phys. Rev. Lett. 124, 131802 (2020)

Search for the mediator : di-jet resonance

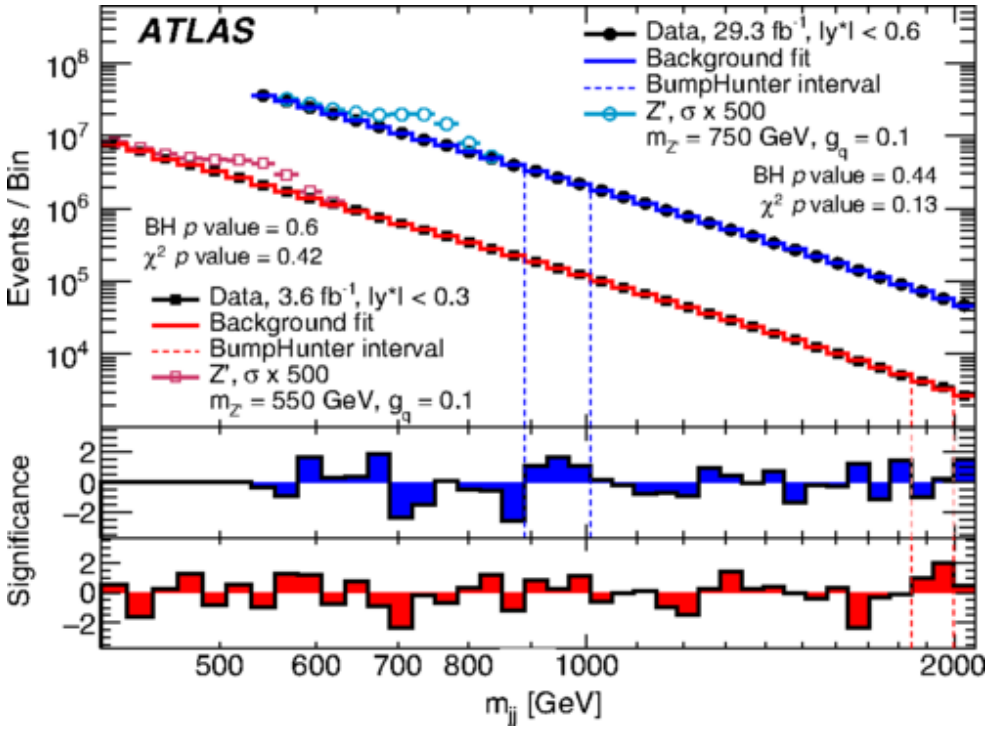


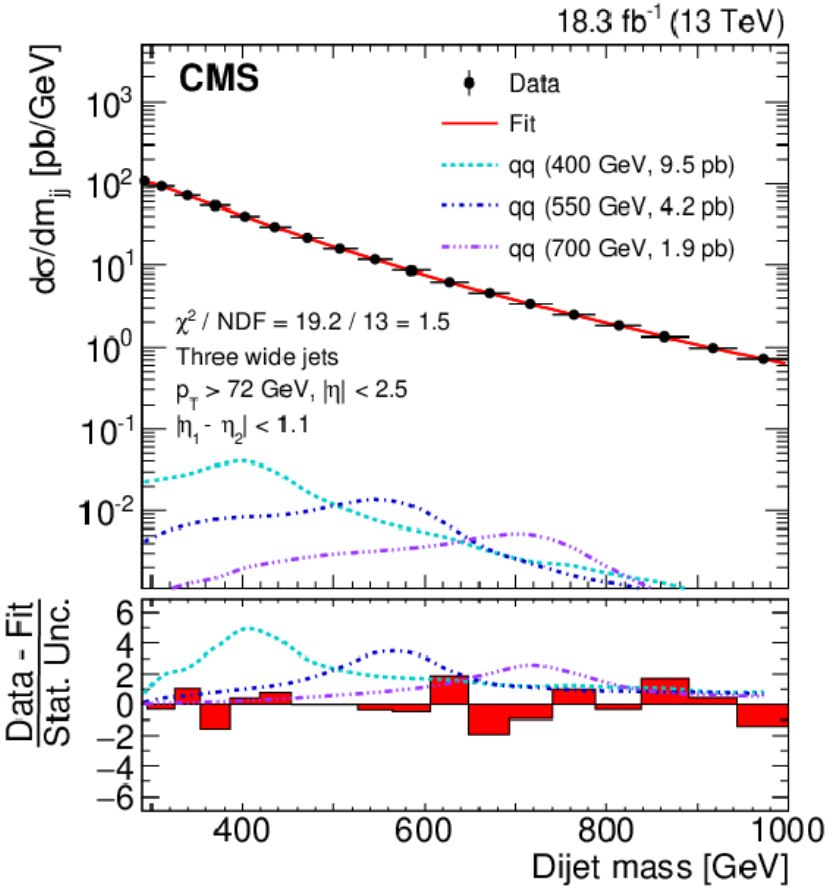
JHEP 03 (2020) 145



JHEP 05 (2020) 033

Search for the mediator : online di-jet

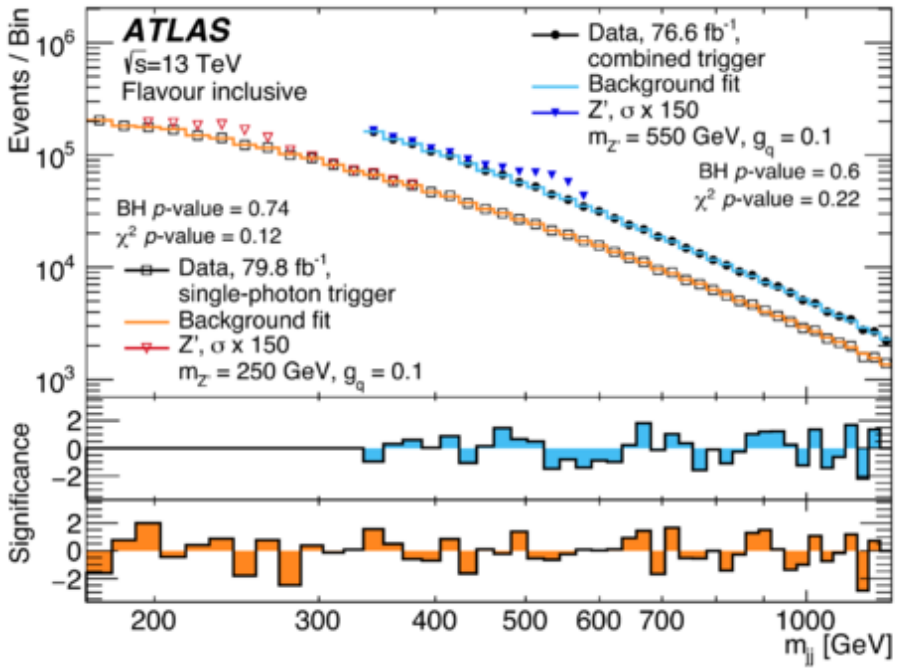


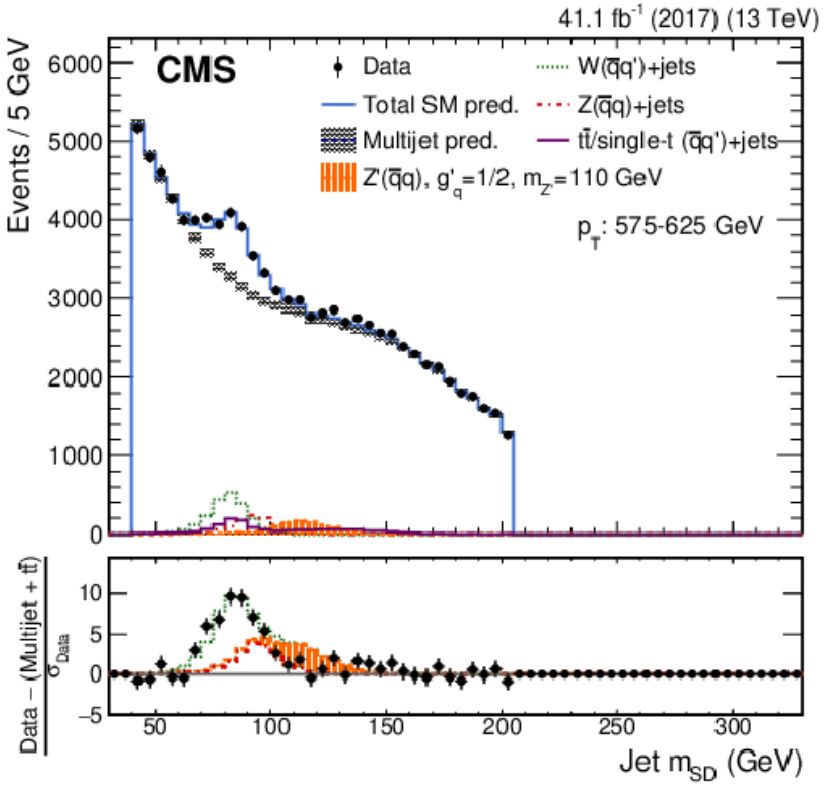


Phys. Rev. Lett. 121 (2018) 081801

Phys. Lett. B 805 (2020) 135448

Search for the mediator : recoiled with ISR



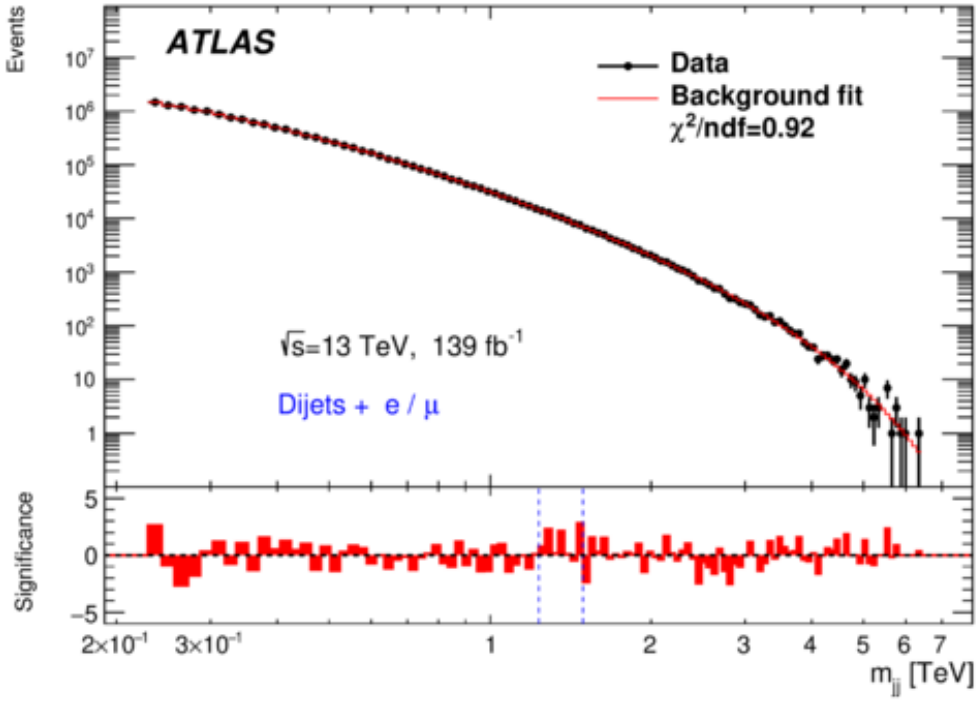


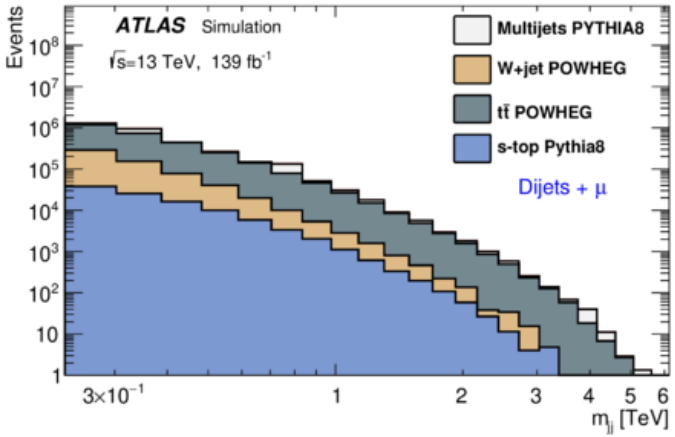
Phys. Lett. B 795 (2019) 56
Also see
Phys. Lett. B 788 (2019) 316
for jet/photon recoil

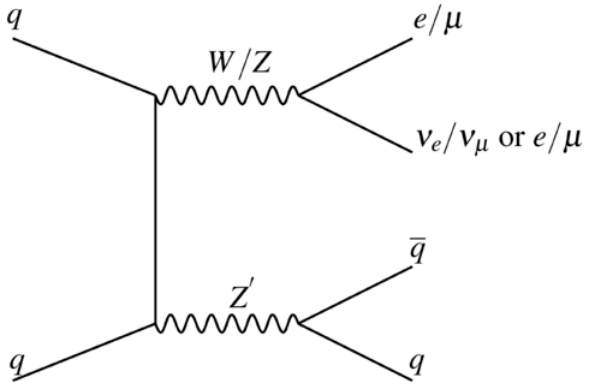
Phys. Rev. D 100 (2019) 112007
Also see
Phys. Rev. Lett. 123, 231803
for photon recoil

Search for the mediator : recoiled with W/Z

- W/Z associated production of the mediator can be triggered by leptons.
- The dominated by top backgrounds are top or V+jets processes.

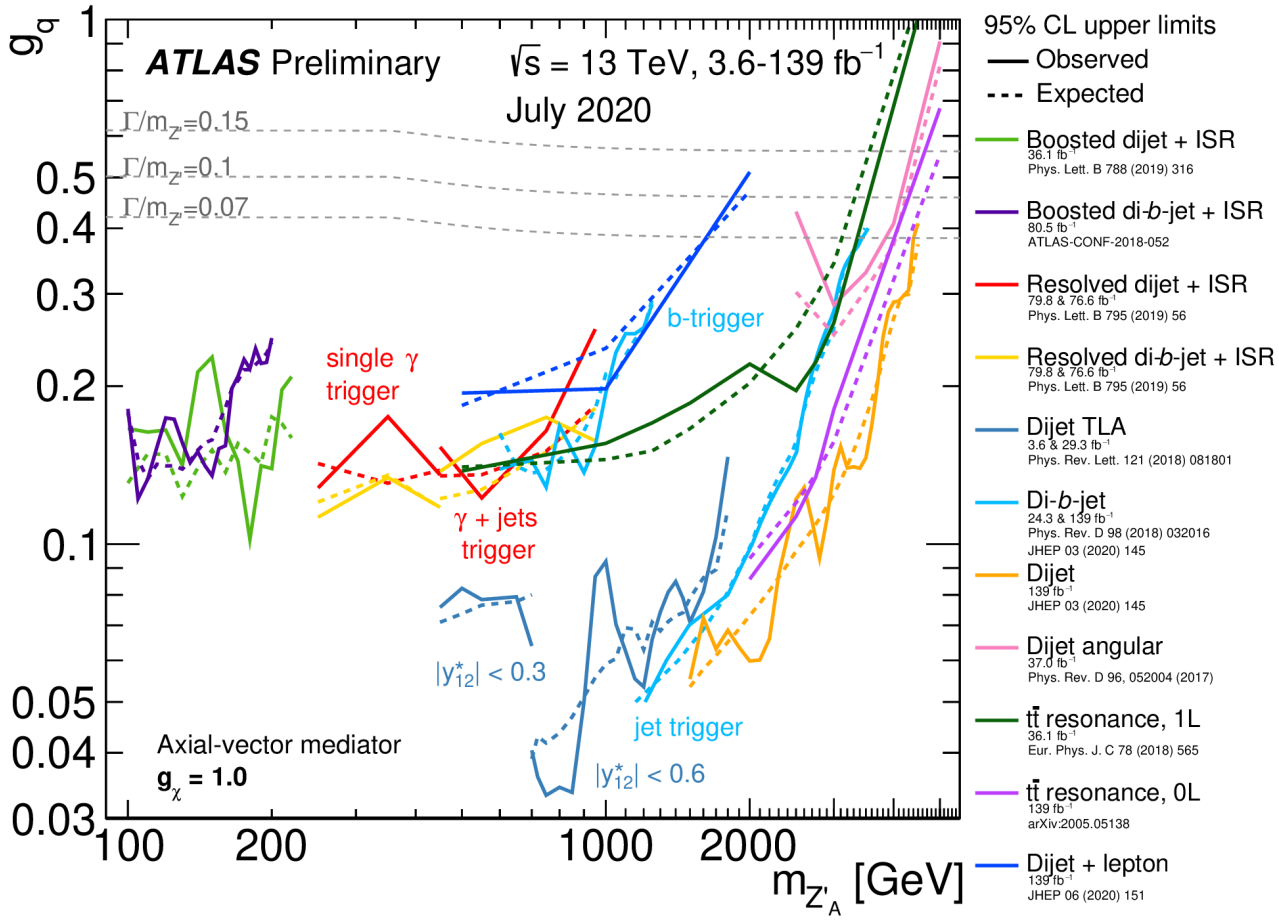






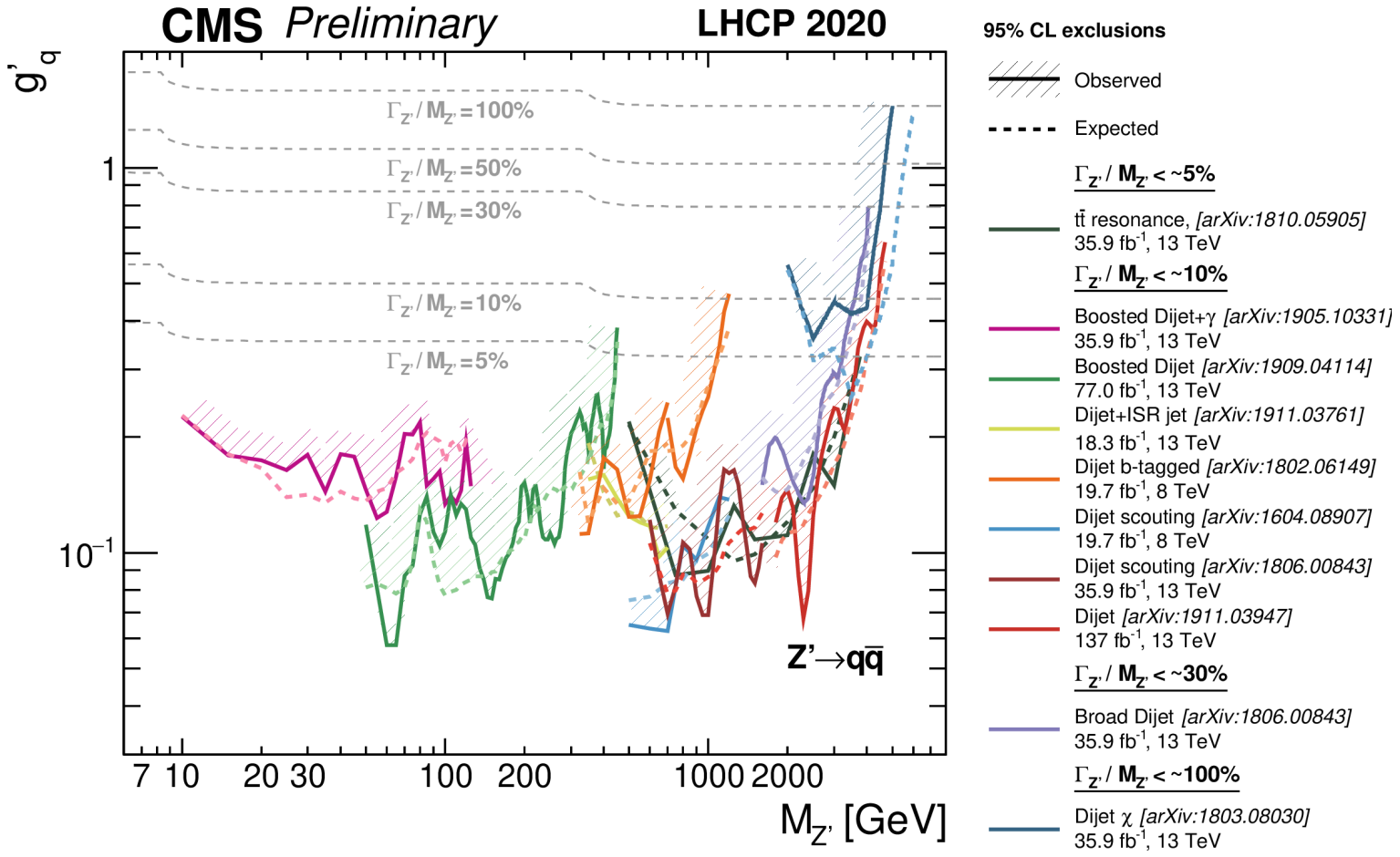
JHEP 06 (2020) 151

Search for the mediator : summary



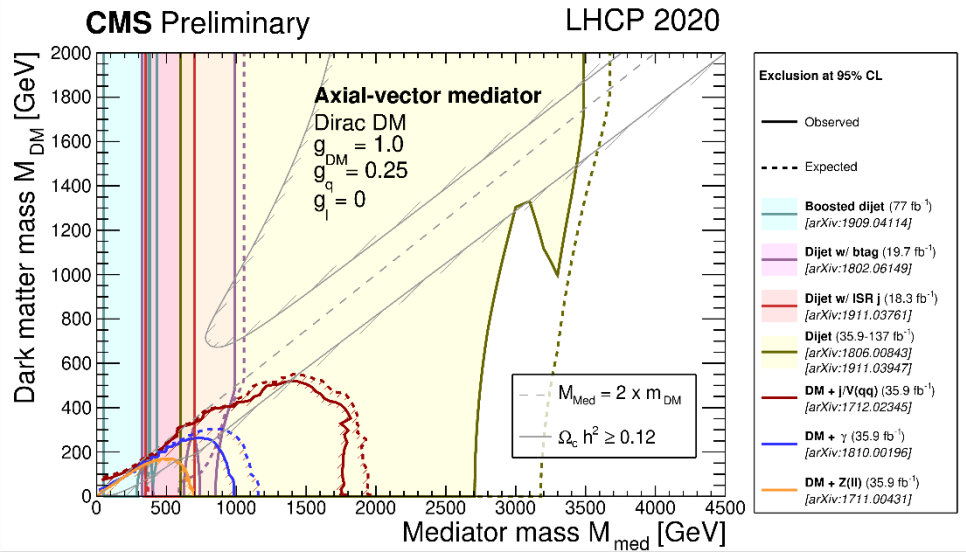
ATL-PHYS-PUB-2020-021

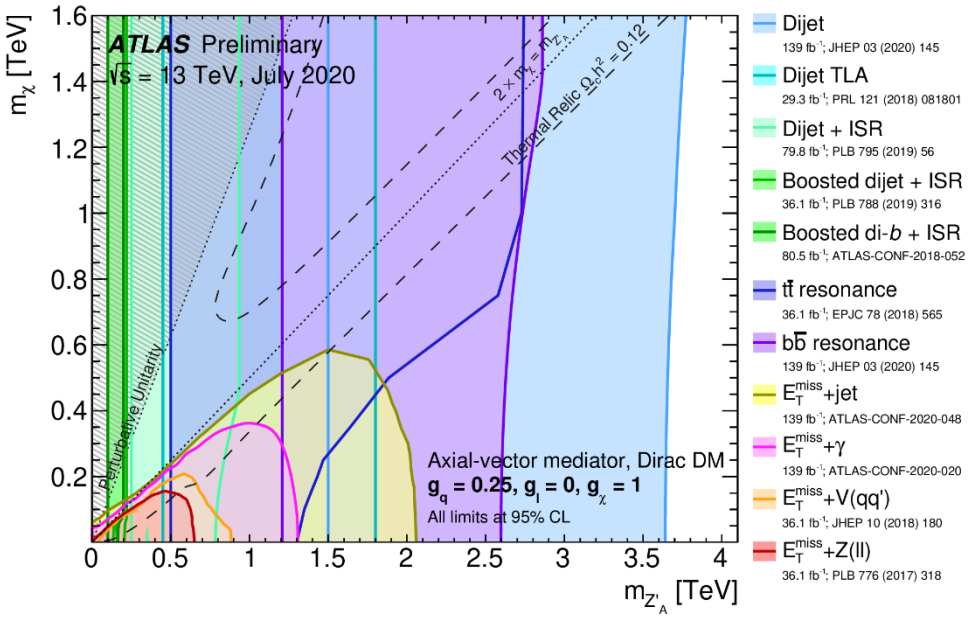
Search for the mediator : summary



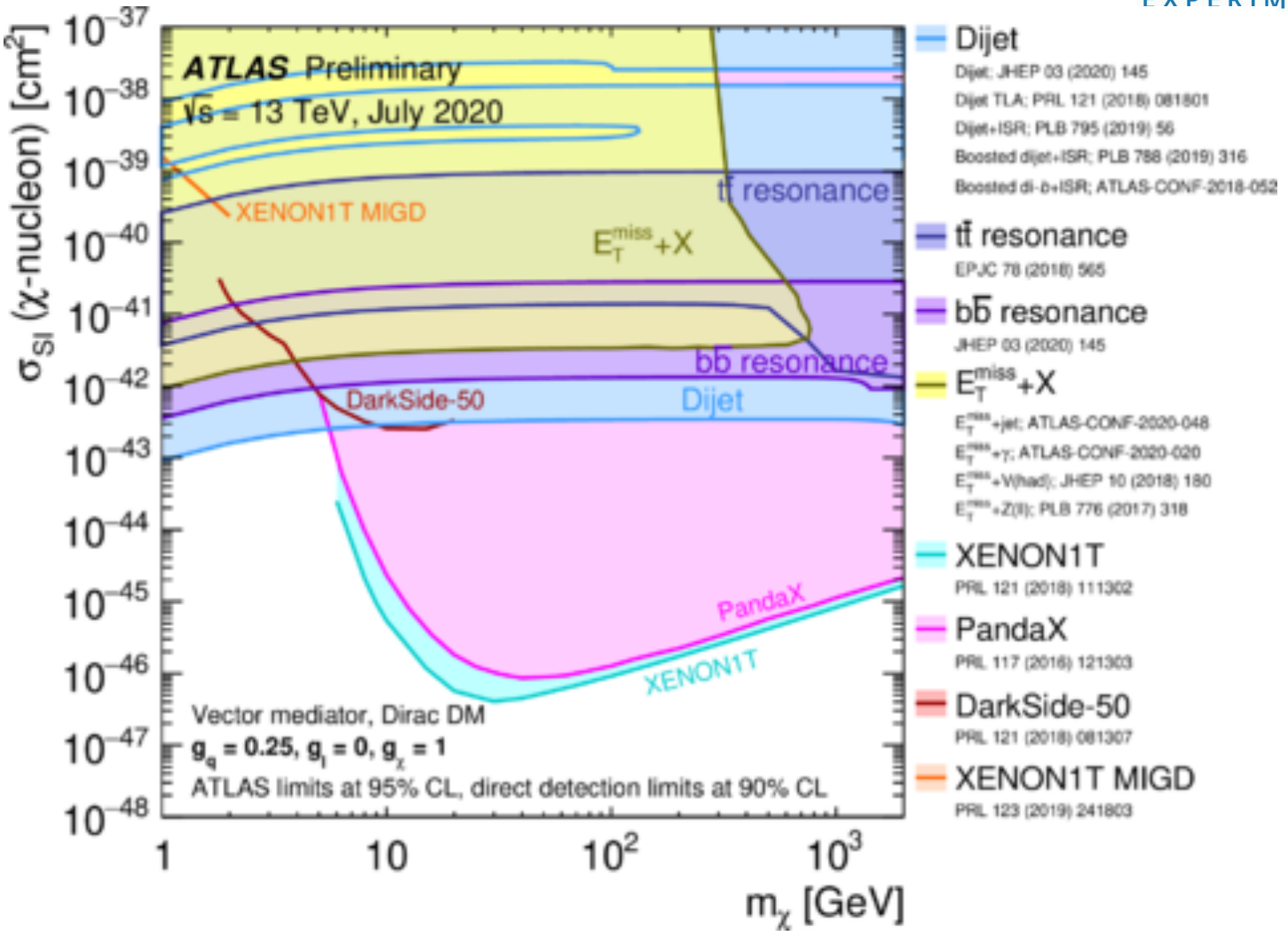
CMS Summary Twiki

Summary : mediator and DM





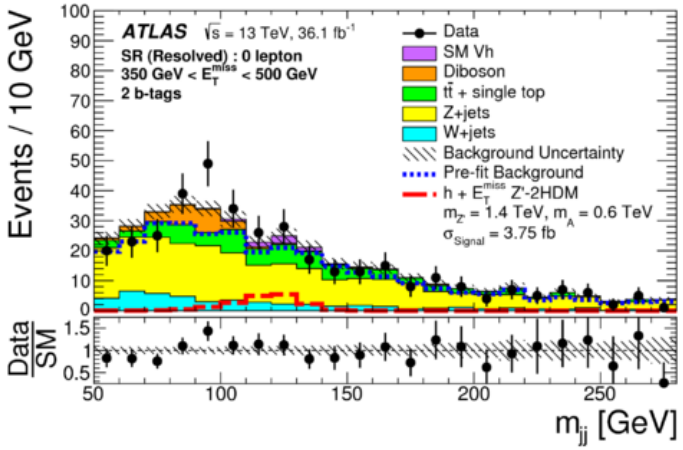
Summary : comparing with direct detection

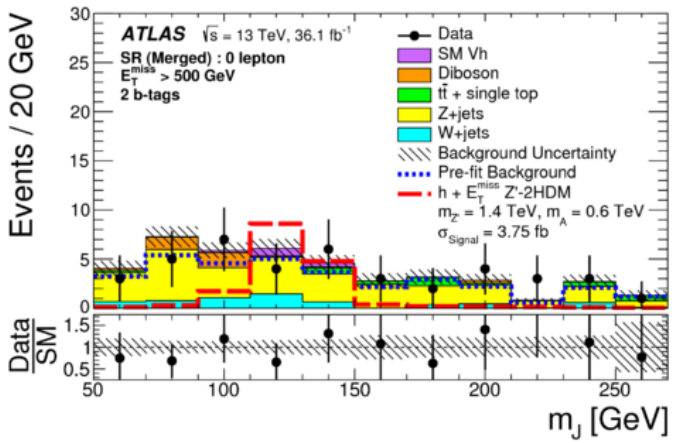


Higgs and Dark Matter

Mono-X search : mono Higgs

- DM recoils against the Higgs boson
  - Most of the sensitivity coming from Higgs decay to bottom quarks
  - Higgs to diphoton/WW/ZZ can also contribute
  - Different Higgs reconstruction according to MET (boost of Higgs) in signal efficient region

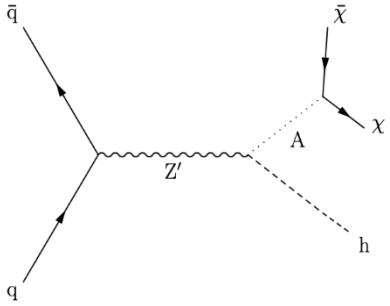


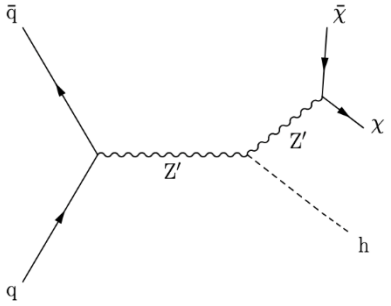


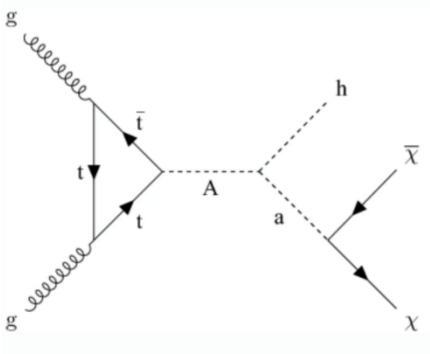
Phys. Rev. Lett. 119 (2017) 181804

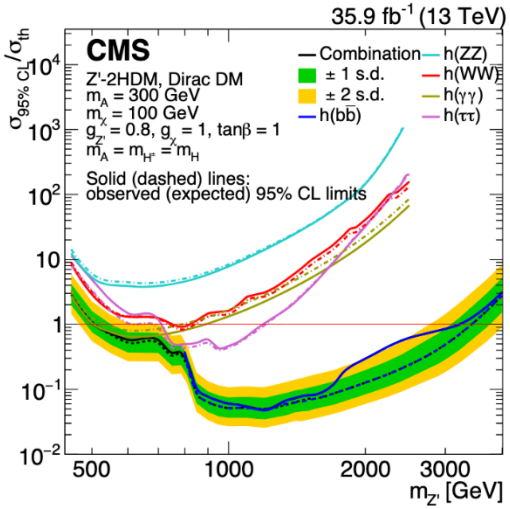
Mono-X search : mono Higgs

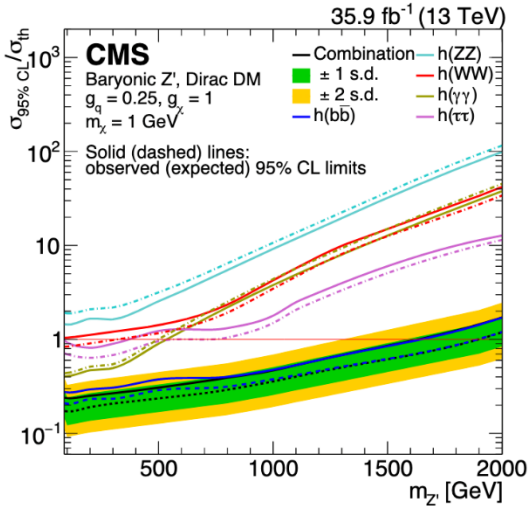
- Three models are considered :
  Z'-2HDM, baryonic Z' and 2HDM+a

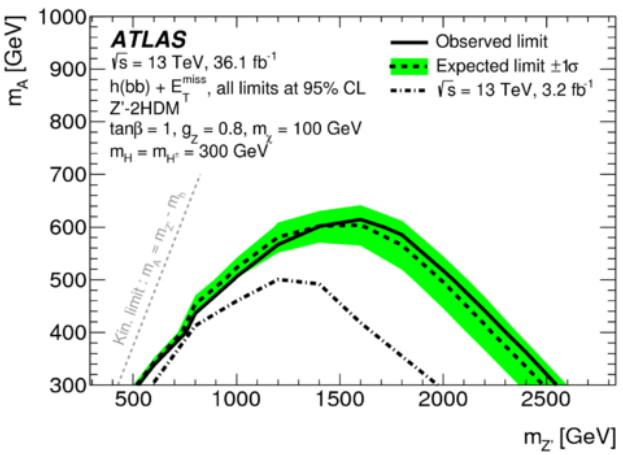










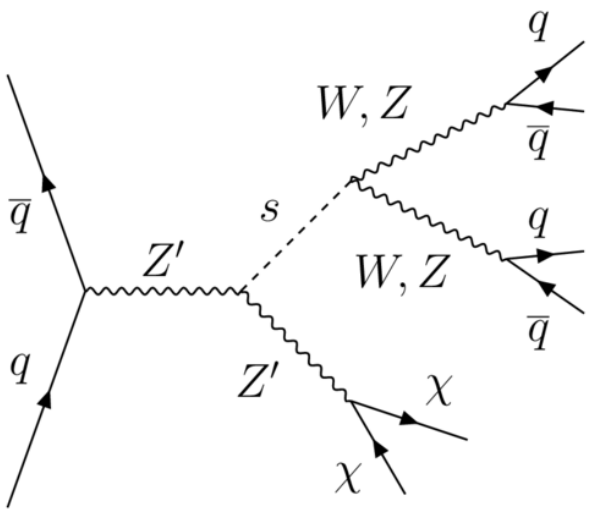


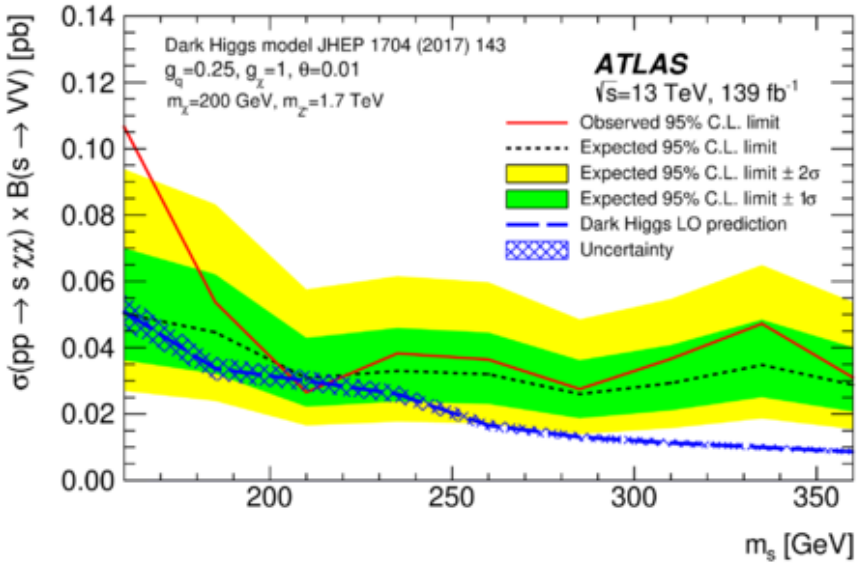
JHEP 03 (2020) 025

Phys. Rev. Lett. 119 (2017) 181804

Mono-X search : mono Heavy scalar

- New dark sector Higgs(s) recoils against DM
  - Primary decay mode to WW/ZZ for large mass
  - Use **T**rack **A**ssisted **R**eclustered (TAR) jets to improve jet mass and substructure resolution
  - Require four prong jets using N-subjetiness
- Excess observed at 160GeV

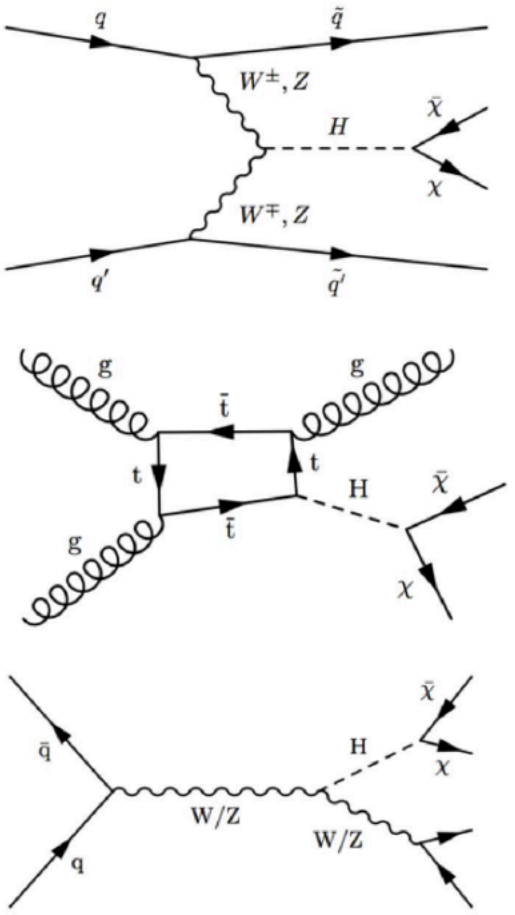




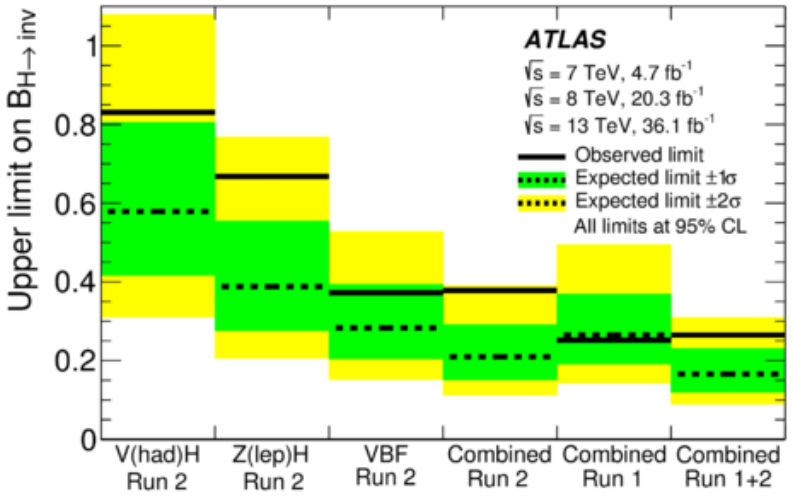
ATLAS-2020-036

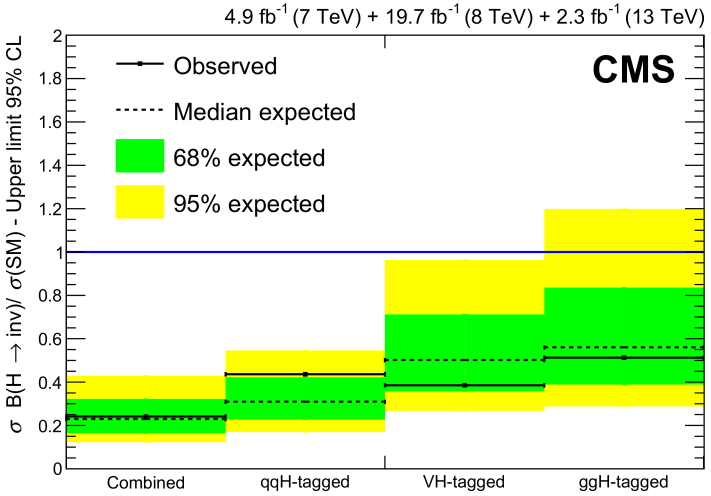
Invisible Higgs decay : Higgs as a DM portal

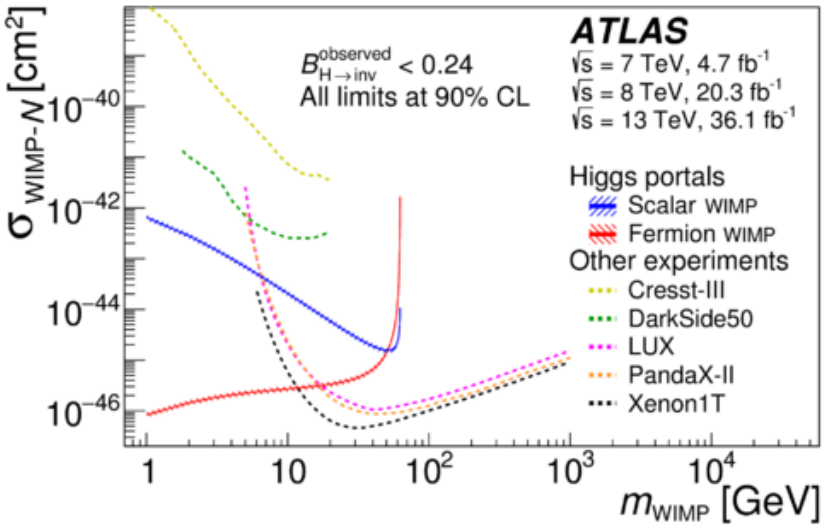
- Assume Higgs is a portal to DM
  - ❑ SM predict invisible Higgs decay BR ~ 0.1%
- Several ways to tag
  - ❑ VBF Higgs invisible decay
  - ❑ Reinterpretation of mono-jet
  - ❑ Associated production with W/Z
- VBF gives the most sensitivity
  - ❑ Search in bins of m_{jj}

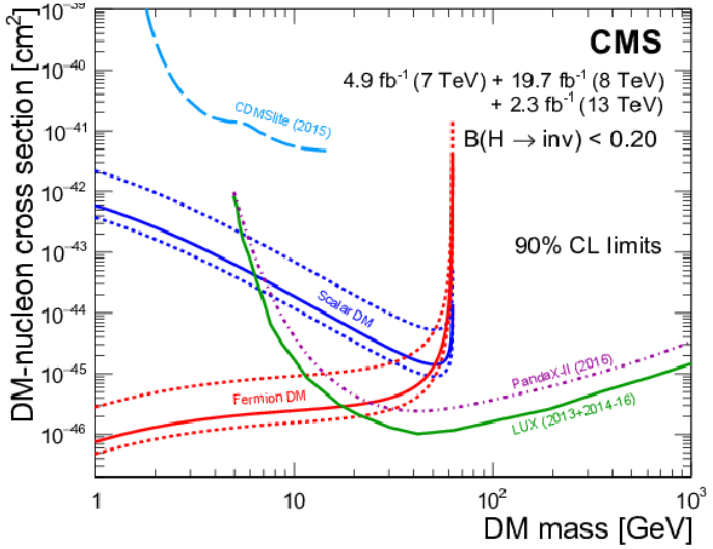


Invisible Higgs decay : Higgs as a DM portal







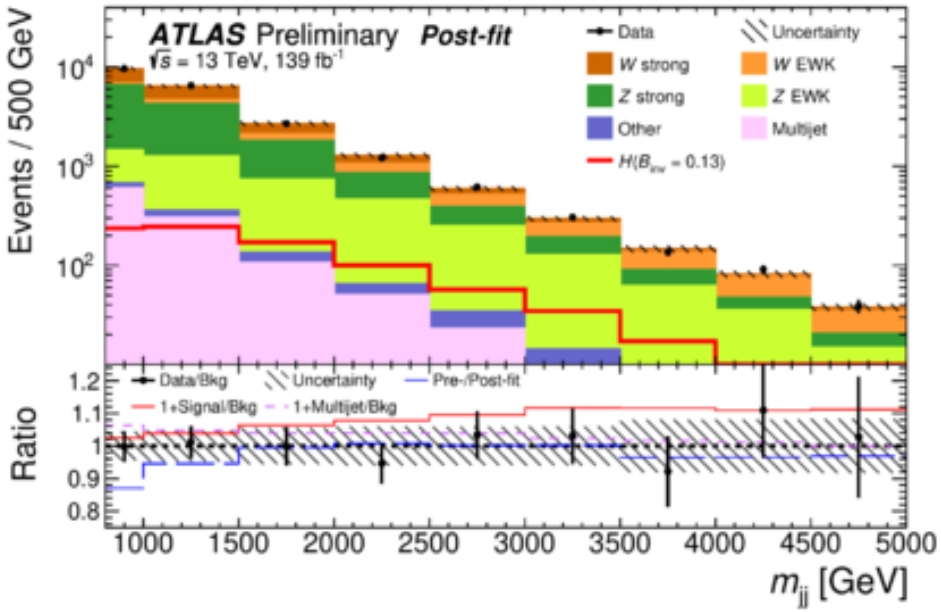


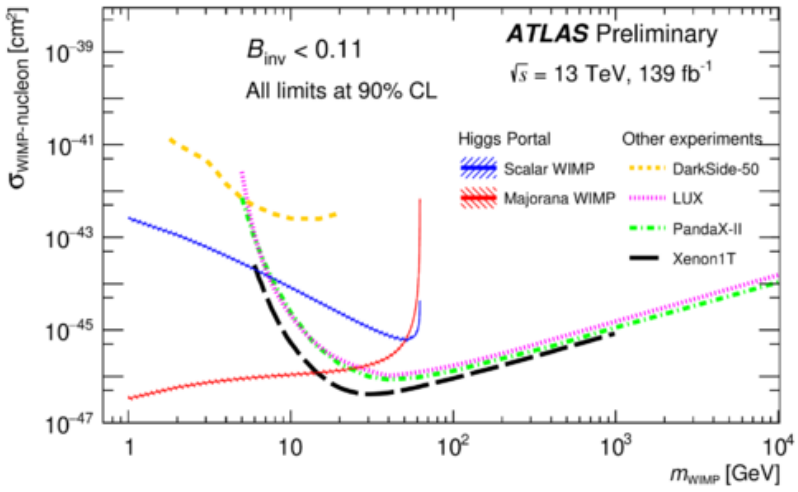
Phys. Rev. Lett. 122 (2019) 231801

Phys. Lett. B 793 (2019) 520

Invisible Higgs decay : full Run-2 VBF analysis

- VBF analysis in ATLAS updated to full Run-2 data
- Additional bins in m_{jj} and phi_{jj} are included to gain statistics
- Sensitivity is improved by a factor of 2
  comparing with previous analysis with 36 fb^{-1} data
- Constraint invisible branching ratio to be less than 0.11





ATLAS-CONF-2020-008

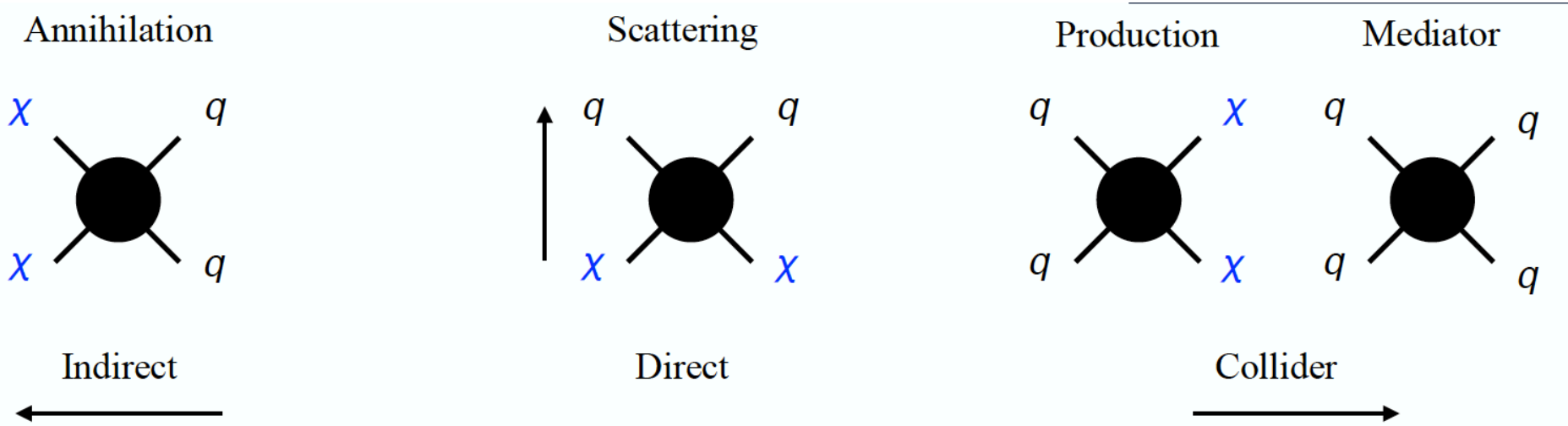
Summary

- DM is very active in ATLAS/CMS
  - A wide range of analyses provide constraints on DM at the LHC
  - Results with full Run-2 data ongoing
  - Higgs boson to Invisible and MET based signatures are key to DM search at CMS

- Combination with different analyses and different experiments are crucial to get a full picture
  (need to be careful about model/parameter dependency)

Backup slides

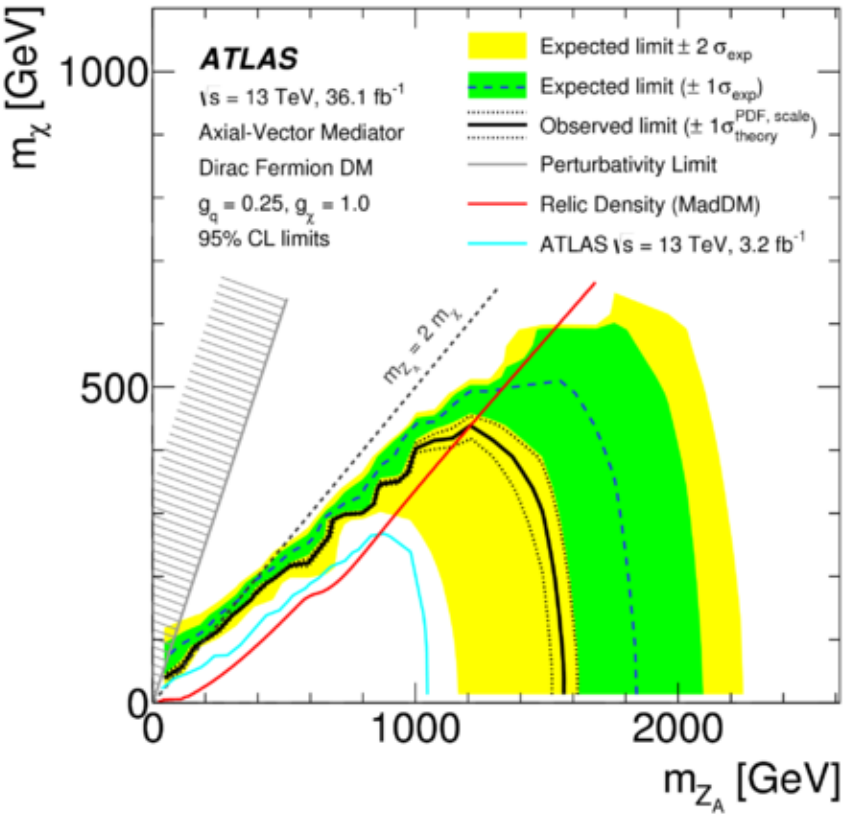
Dark matter searches

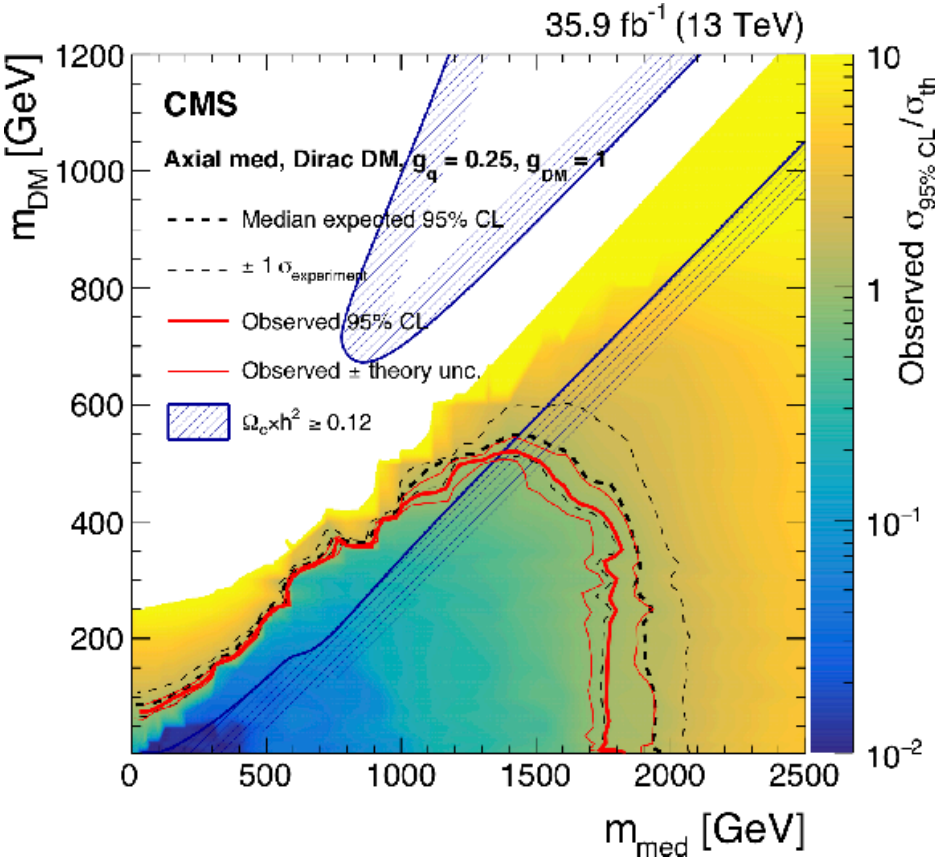


- Indirect detection experiments search for the products of the self-annihilation or decay of DM in outer space
  - AMS at International space station

- Direct detection experiments aim to observe low-energy recoils of nuclei induced by interactions with DM
  - Requires underground experiments
    Deep Underground Science and Engineering Laboratory
    China Jinping Underground Laboratory

Mono-Jet


ATLAS
√s = 13 TeV, 36.1 fb-1
Axial-Vector Mediator
Dirac Fermion DM
gq = 0.25, gχ = 1.0
95% CL limits
Expected limit ± 2 σexp
Expected limit (± 1σexp)
Observed limit (± 1σtheoryPDF, scale)
Perturbativity Limit
Relic Density (MadDM)
ATLAS √s = 13 TeV, 3.2 fb-1
mZA = 2 mχ
mχ [GeV]
mZA [GeV]
0
500
1000
0
1000
2000


35.9 fb-1 (13 TeV)
CMS
Axial med, Dirac DM, gq = 0.25, gDM = 1
Median expected 95% CL
± 1 σexperiment
Observed 95% CL
Observed ± theory unc.
Ωch2 ≥ 0.12
mDM [GeV]
mmed [GeV]
Observed σ95% CL/σth
200
400
600
800
1000
1200
0
500
1000
1500
2000
2500
10
1
10-1
10-2

Top(s) + MET

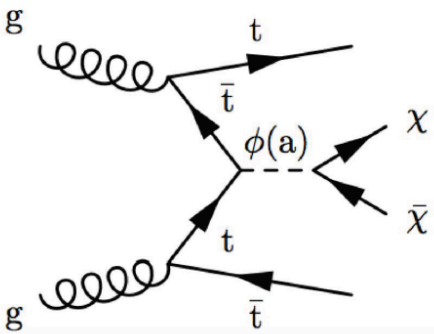
- Scalar/pseudoscalar mediators with Yukawa-like couplings to SM fermions
  - top couplings dominate

scalar

$$\mathcal{L}_\phi \supset g_\chi \phi \bar{\chi}\chi + \frac{g_q \phi}{\sqrt{2}} \sum_f (y_f \bar{f} f),$$

pseudoscalar

$$\mathcal{L}_a \supset i g_\chi a \bar{\chi}\gamma^5 \chi + \frac{i g_q a}{\sqrt{2}} \sum_f (y_f \bar{f} \gamma^5 f),$$



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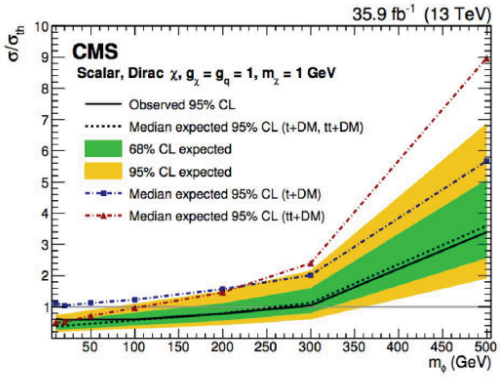

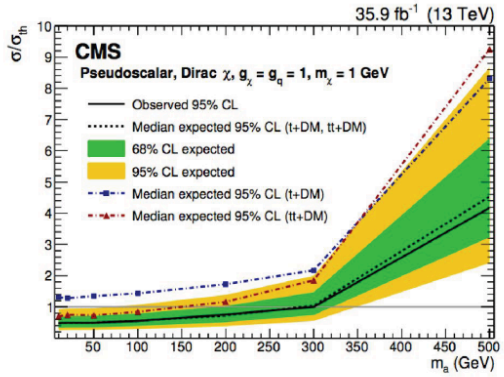

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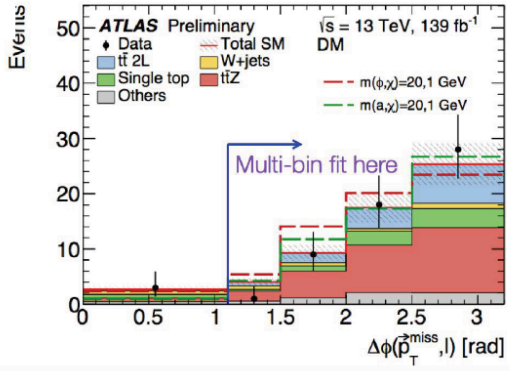
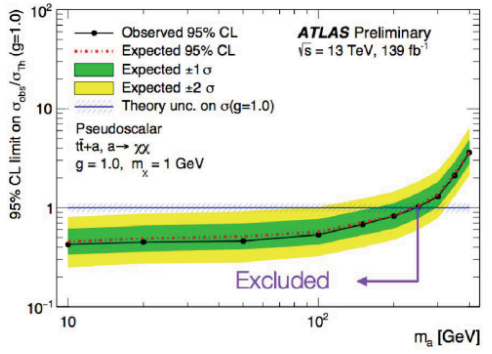
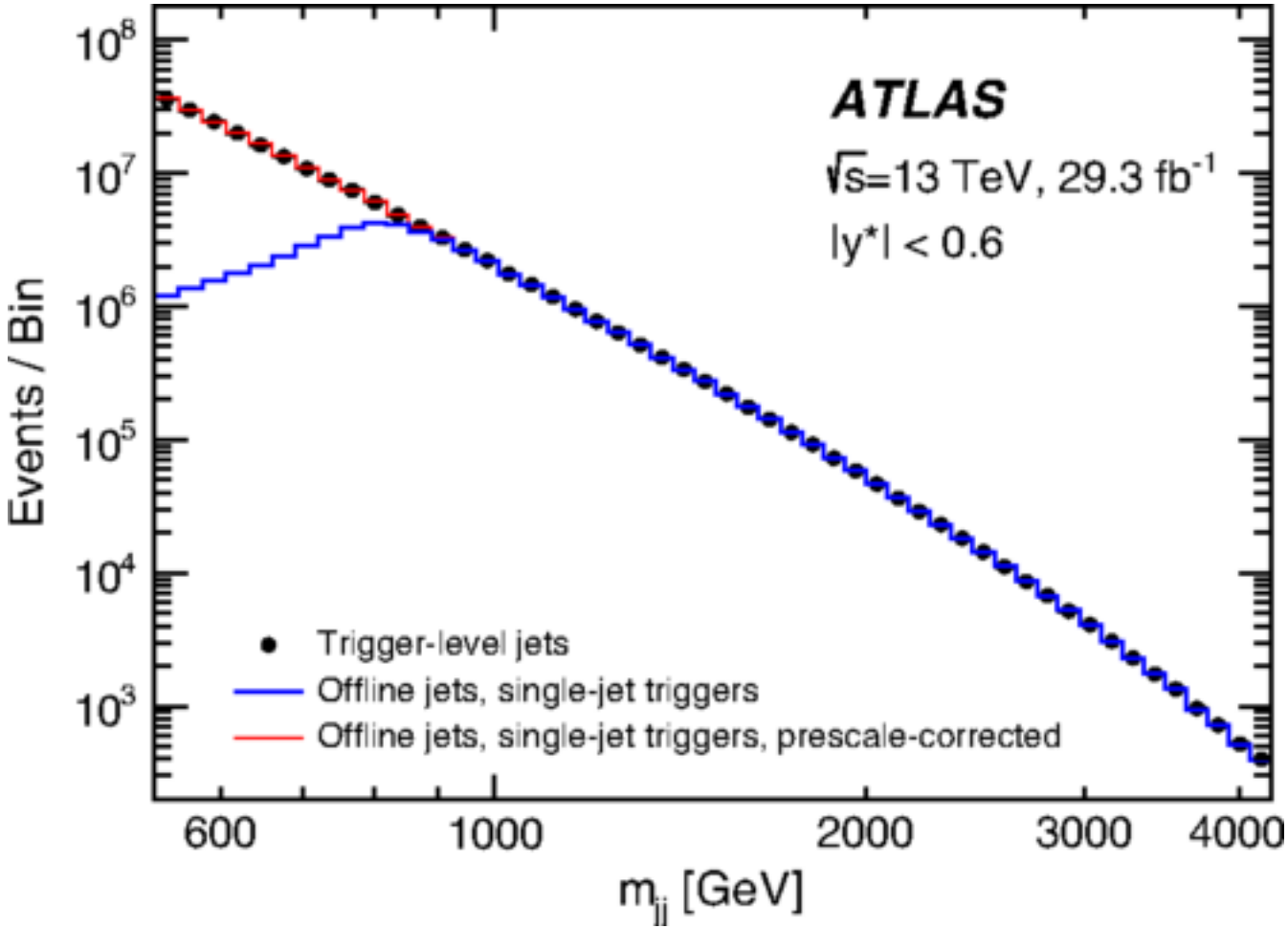
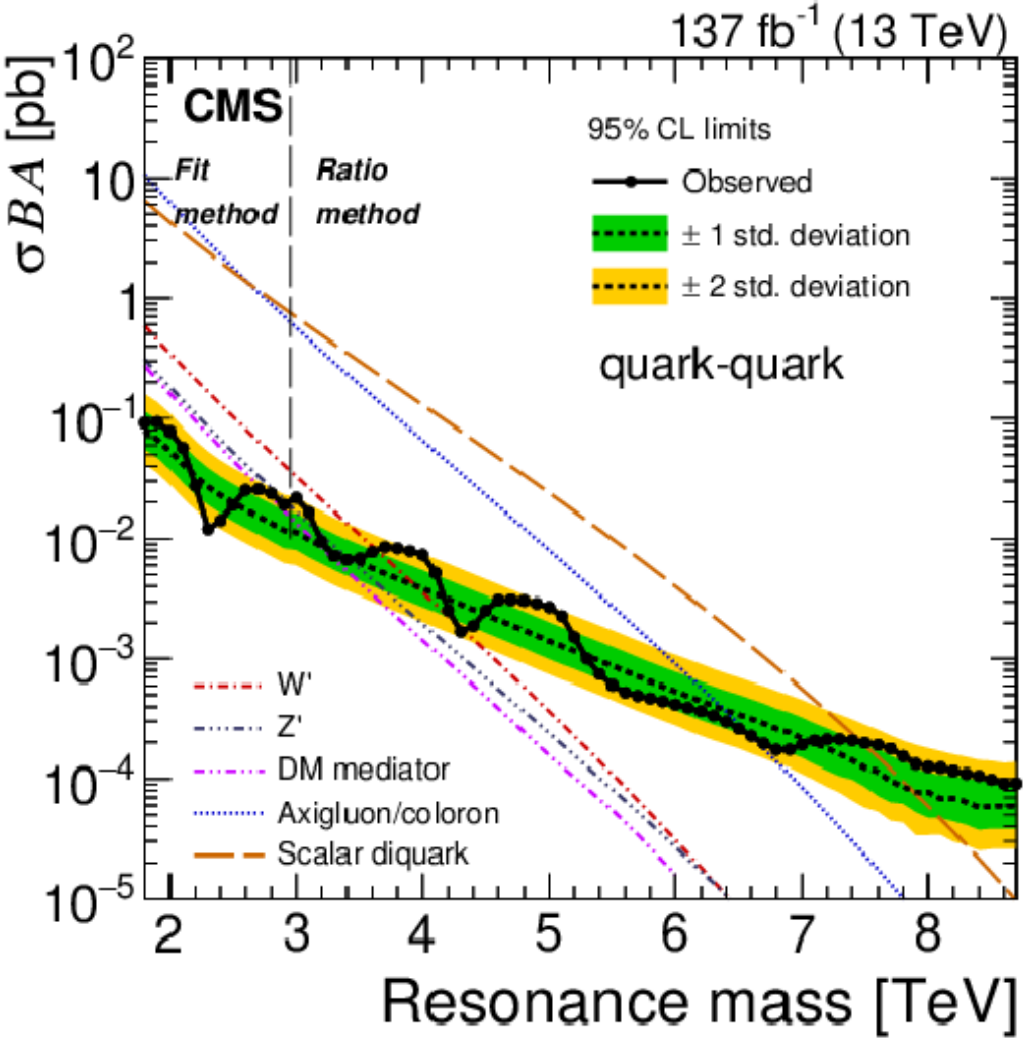




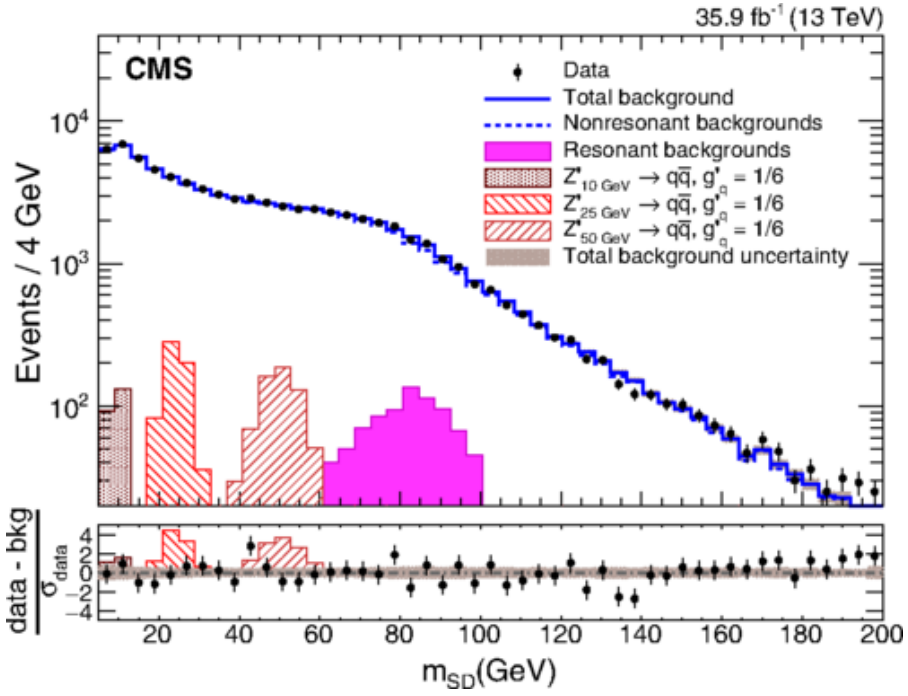
Event rate : online(trigger) v.s. offline

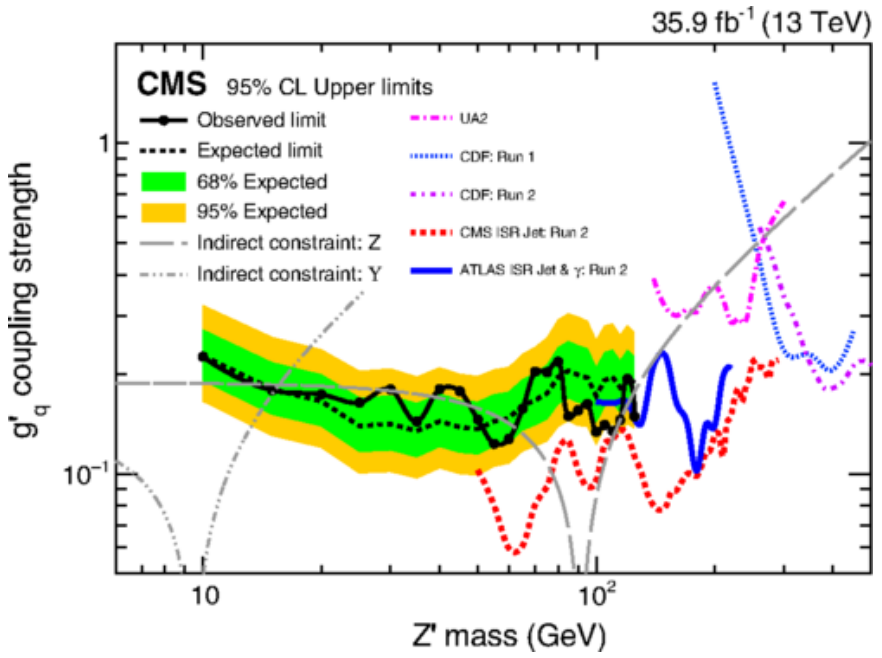


CMS Full-Run2 dijet search

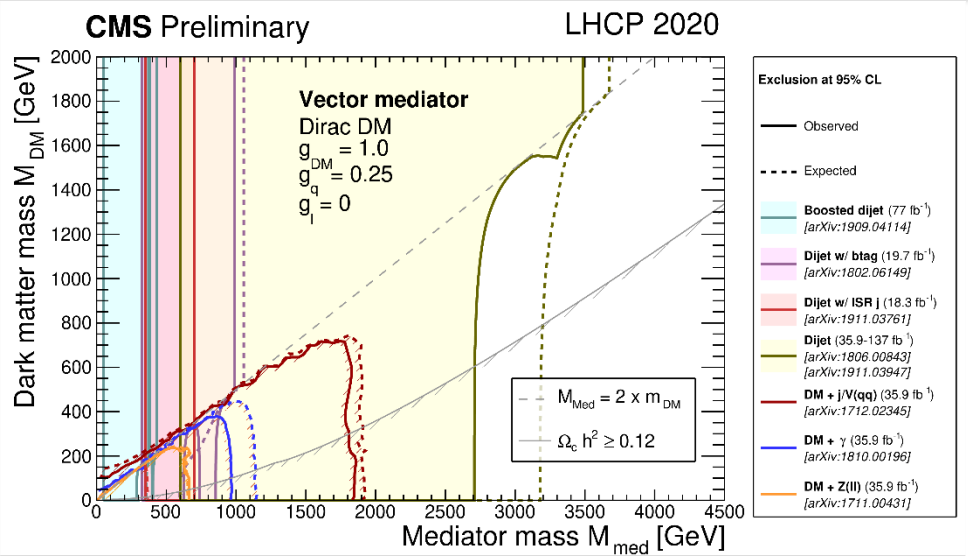


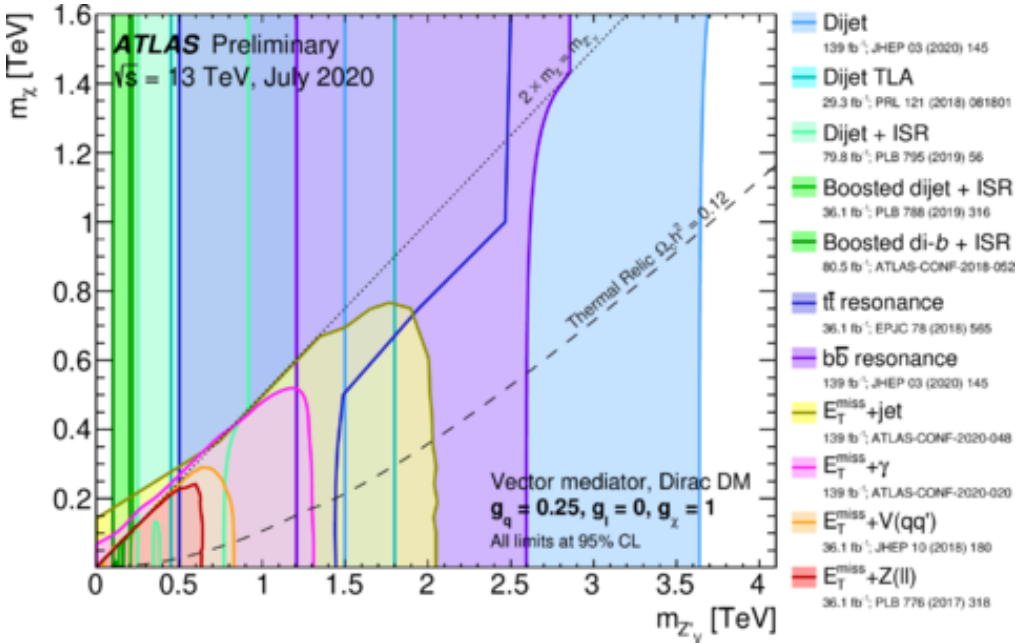
Recoil with a photon in CMS analysis



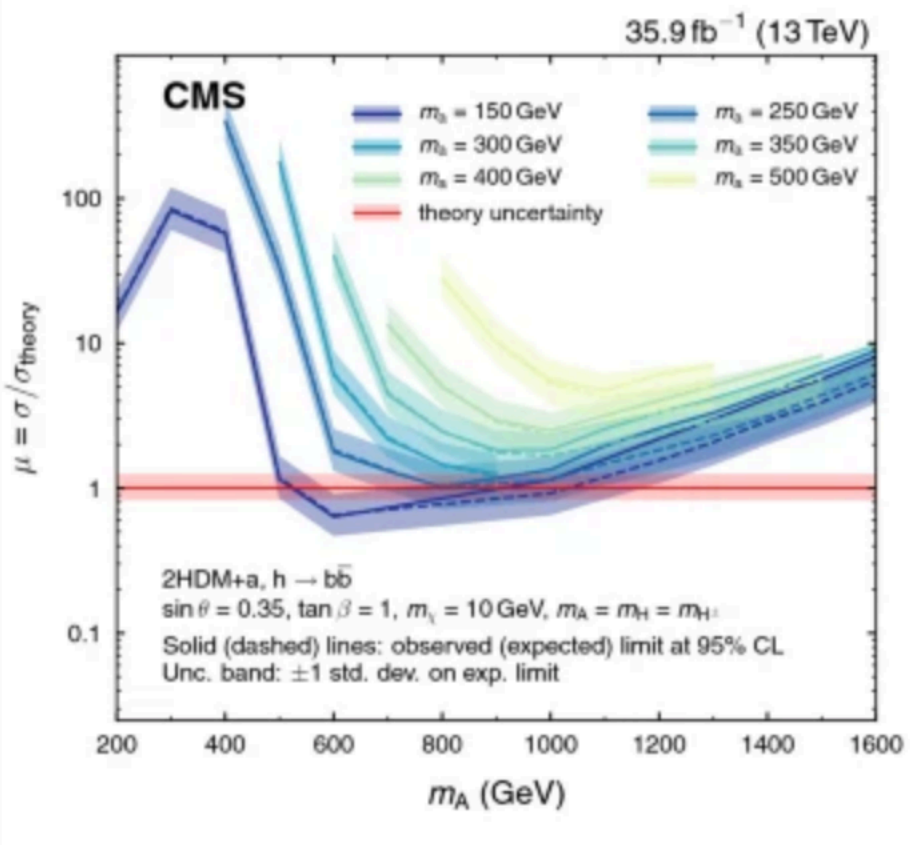


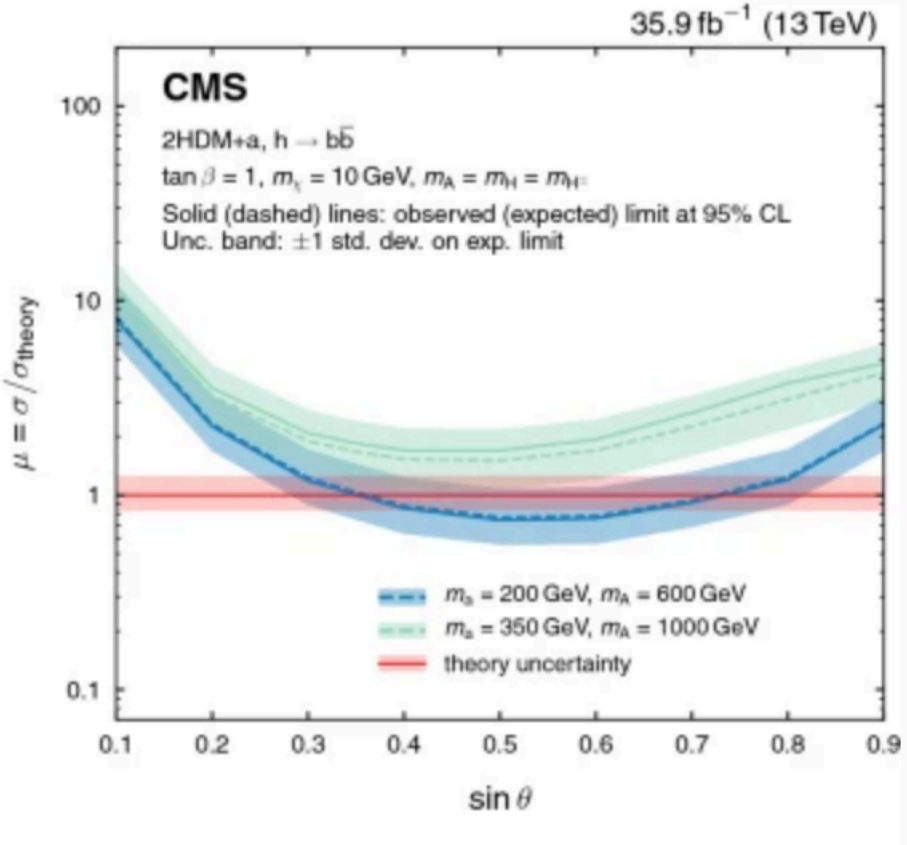
Summary : mediator and DM





Mono-Higgs


35.9 fb^{-1} (13 TeV)
CMS
m_a = 150 GeV
m_a = 250 GeV
m_a = 300 GeV
m_a = 350 GeV
m_a = 400 GeV
m_a = 500 GeV
theory uncertainty
2HDM+a, h → bb̄
sin θ = 0.35, tan β = 1, m_χ = 10 GeV, m_A = m_H = $m_{H^\pm}$
Solid (dashed) lines: observed (expected) limit at 95% CL
Unc. band: ±1 std. dev. on exp. limit
$\mu = \sigma/\sigma_{theory}$
m_A (GeV)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Solid (dashed) lines: observed (expected) limit at 95% CL
Unc. band: ±1 std. dev. on exp. limit
m_a = 200 GeV, m_A = 600 GeV
m_a = 350 GeV, m_A = 1000 GeV
theory uncertainty
$\mu = \sigma/\sigma_{theory}$
sin θ