Recent Dark Matter Searches at CMS
PHENO 2022

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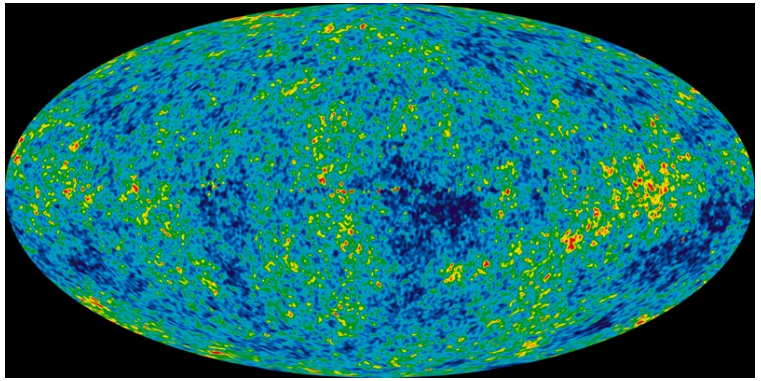
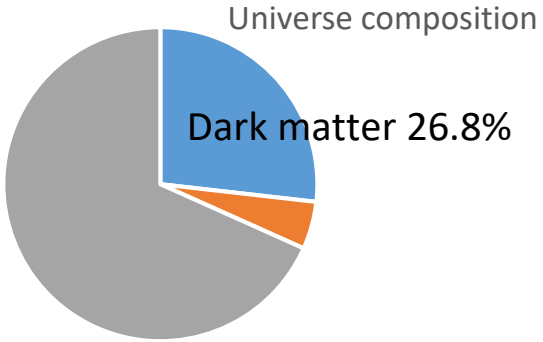
On behalf of CMS collaboration

Boston University

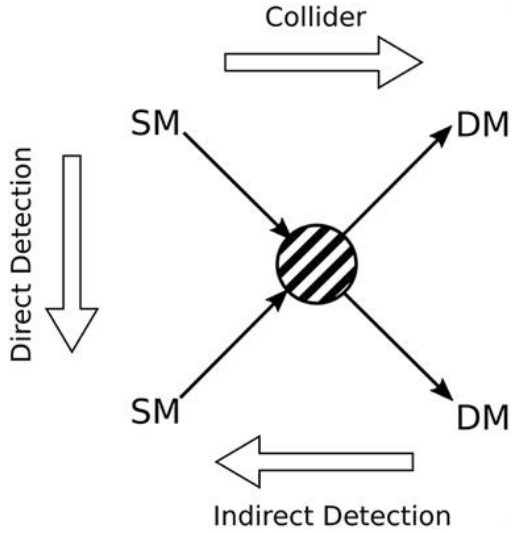
Dark matter search at LHC

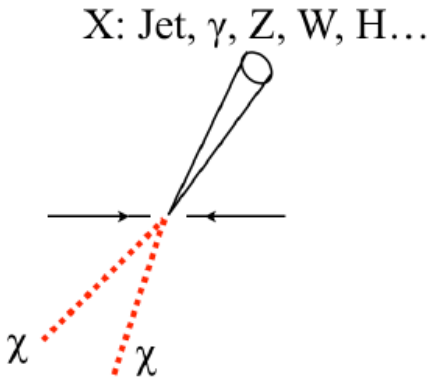
- Why search for dark matter (DM)?
  - Multiple evidence of DM from cosmology
  - WIMP being one of the favorite candidate





- Types of dark matter searches:
  - Direct search (DM annihilation)
  - Indirect search (DM-nucleon scattering)
  - **Collider search (DM produced in collider)**





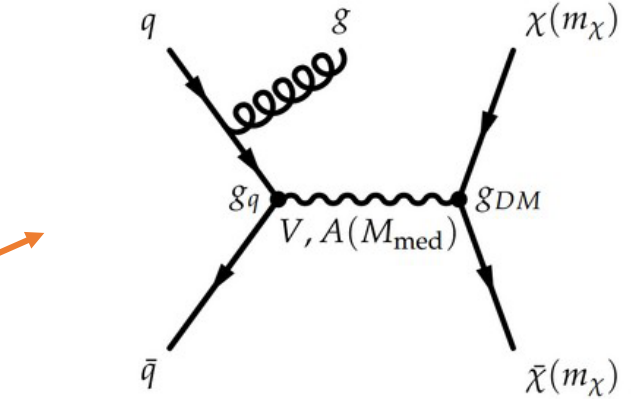
- How to detect DM on collider?
  - Look for missing transverse energy and recoiled SM particles (known as **mono-X** search)

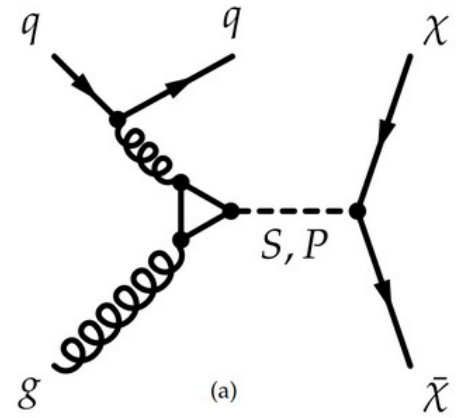
- **Talk organized in a few DM models followed by searches that are sensitive to them**

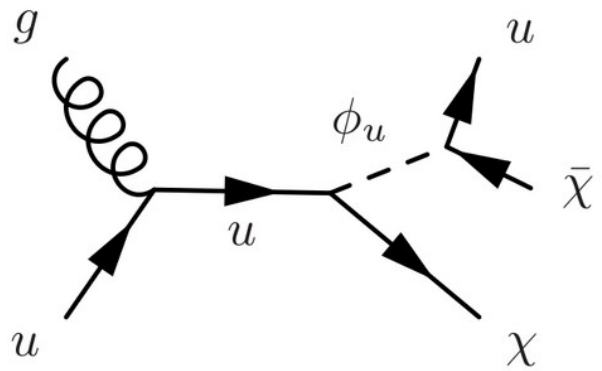
Benchmark Models and CMS searches

“Simplified Dark Matter Models” DOI: 10.1016/j.dark.2019.100371

- Serve as benchmark models for run-2 DM searches, balance between generality and completeness
- Assume Dirac Fermion DM particles produced through mediator particle
- The mediator can be:
  - colorless spin-1 mediator (vector or axial-vector)
  - colorless spin-0 mediator (scalar or pseudo-scalar mediator)
  - colored spin-0 mediator (t-channel coupling)
- We can probe them in MET + SM final states (mono-X):
  - **mono-jet**, **mono-V(had)** search
  - **mono-Z(ll)** search
- Or resonance of mediator in pure SM final state
  - **di-jet** resonant search
  - **di-lepton** resonant search







Mono-jet and mono-V(had) search

JHEP11(2021)153

Why is it important?

The most likely ISR: jet → Most stat power

Signal selection:

p_T^{miss}> 250 GeV + jet p_T> 100 GeV (250 GeV for mono-V categories)

Further split into 3 categories depending on the leading jet **properties** if it:

- is a narrow jet (anti-kt R=0.4) — Monojet
- is a fat jet (anti-kt R=0.8) passing tight selection — High-purity
- is a fat jet (anti-kt R=0.8) passing loose selection — Low-purity

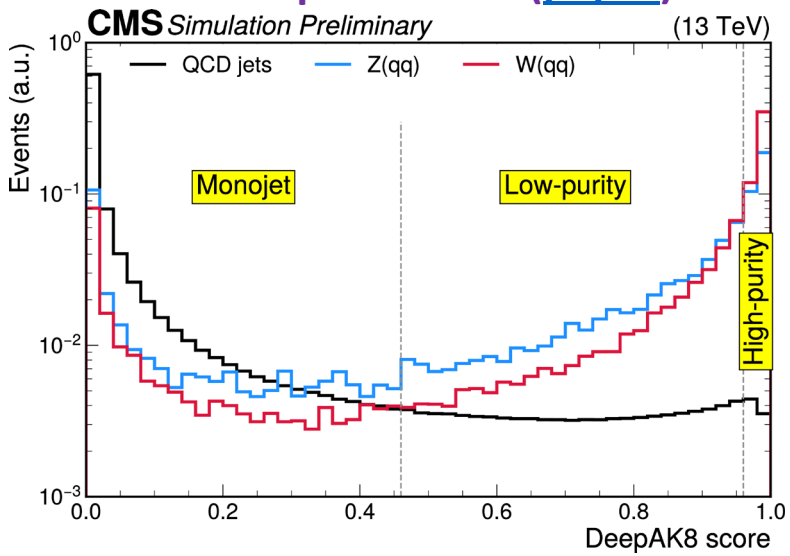
Mono-V category is particularly powerful for Higgs Portal Model (will introduce later)

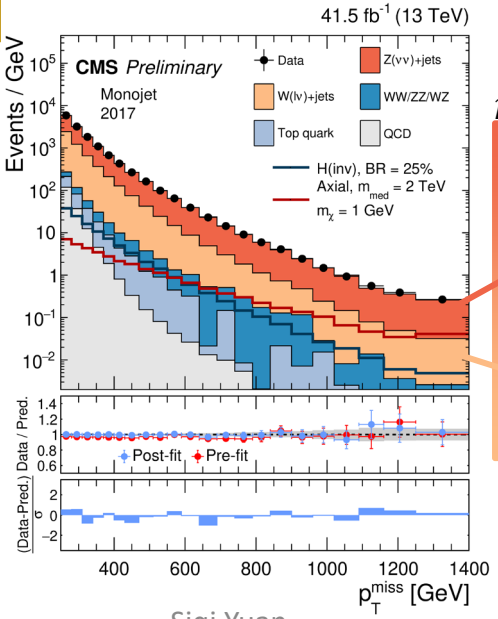
Main background estimation:

Simultaneous fit through SR and 5 CRs to estimate leading background normalization and shapes

- Z(vv)+jets: genuine p_T^{miss} and jets
- W(lv)+jets: fake with missing lepton

DeepAK8 score (paper)





p_T^{miss} faked from Z/W p_T

Main background:

- Z(νν)+jets
- W(lν)+jets (missing lepton)

Theoretically connected processes:

- Z(ll)+jets
- W(lν)+jets (detected lepton)
- γ+jets

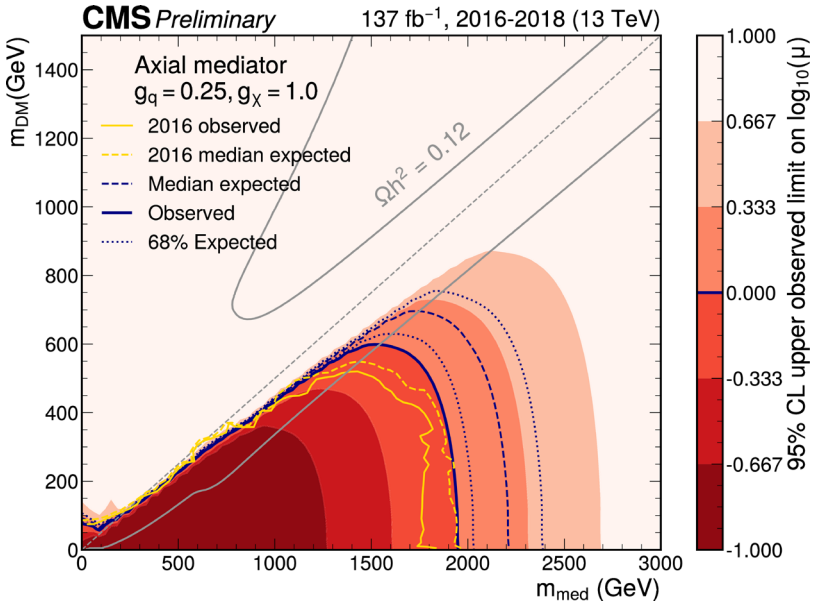
Define 5 Control Regions:

- 2e CR
- 2m CR
- 1e CR
- 1m CR
- γ CR

Exclusion limits on the "Simplified DM Models" from mono-jet/V

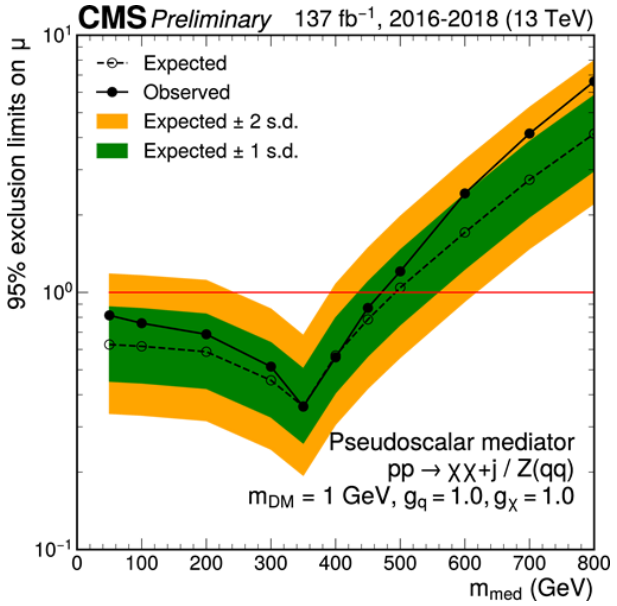
by analyzing 2017 and 2018 data, and combine with published 2016 data. **Integrated luminosity=137 $\mathbf{fb^{-1}}$**

Axial mediator



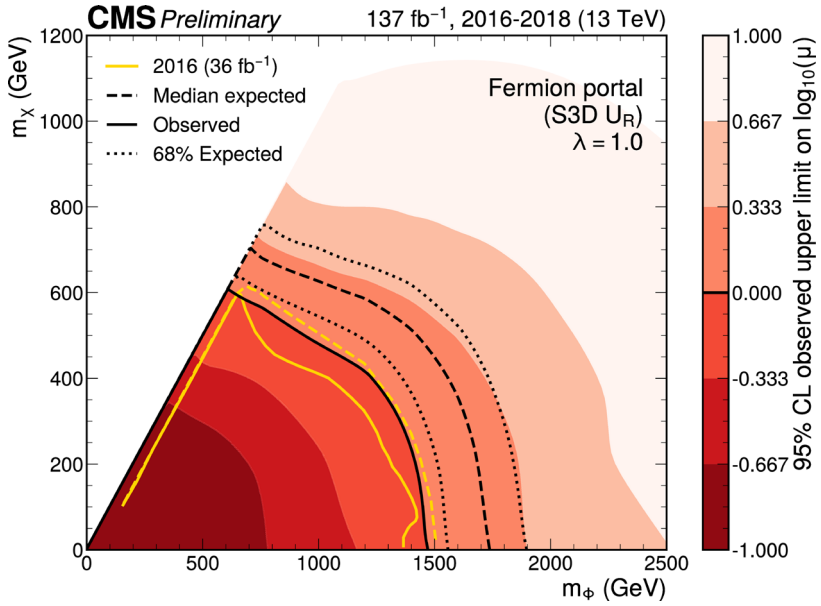
Probe m_{med}~2000 GeV

pseudo-scalar mediator



Probe m_{med}~470 GeV

t-channel mediator



Probe m_{med}~1500 GeV

little dependence on m_{DM}

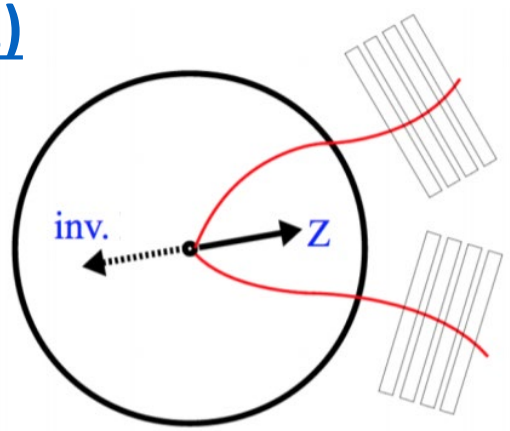
sensitivity mainly in the on-shell region

Other model interpretations: Higgs Portal, Extra Dimensions, Lepto-quark

Publishing simplified likelihood and MadAnalysis for reinterpretation (Hepdata)

Mono-Z (ll) search

Eur. Phys. J. C 81, 13 (2021)



Like mono-V but look for lepton pair decayed from Z boson (Smaller cross-sections but better background rejection power)

Signal Selection:

Select same-flavor opposite-sign lepton pairs that can reconstruct a Z boson, with p_T^{miss}> 250 GeV

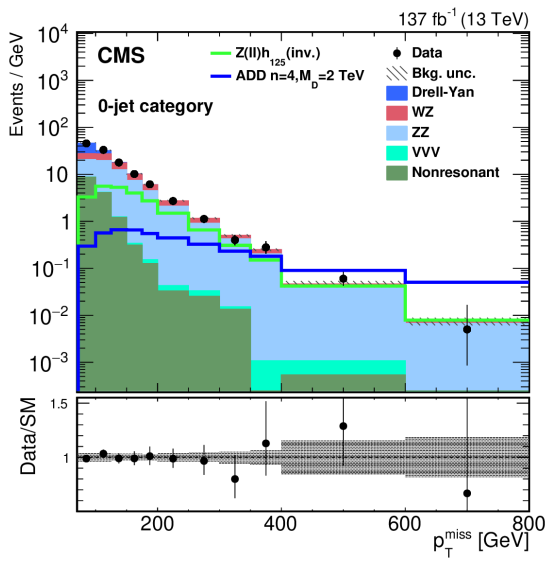
Background estimation:

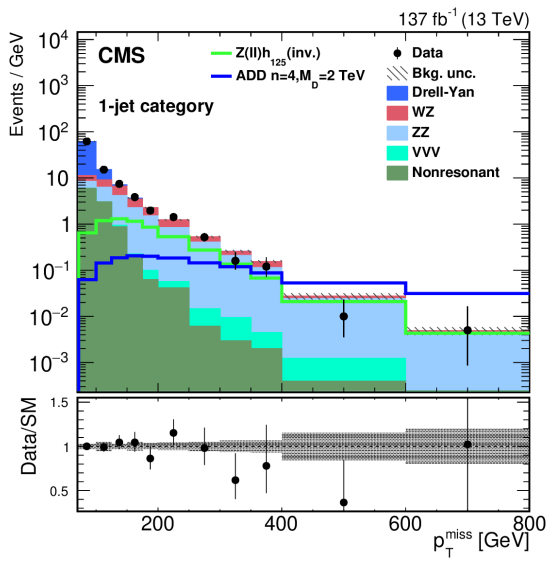
simultaneous fit across SR and CR to estimate each of:

- 3l CR for WZ events
- 4l CR for ZZ events
- Non-resonant (e+μ) CR for WW, tW, tt, $\tau\tau$
- DY CR from p_T^{miss} sideband

Highlight:

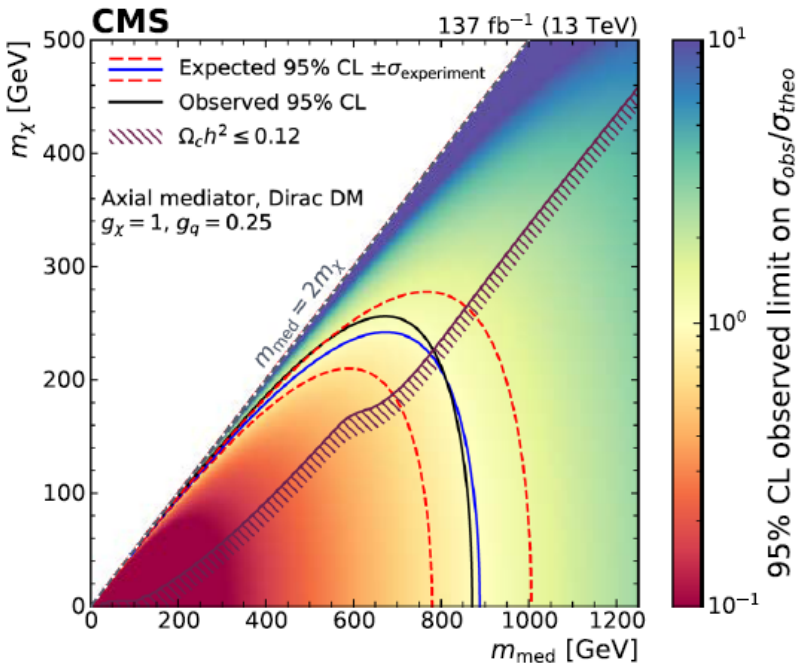
- **SR split into 0-jet and 1-jet categories to increase sensitivity**
- **Fit to p_T^{miss} for generic DM search, and fit to m_T specifically for the 2HDM+a model**





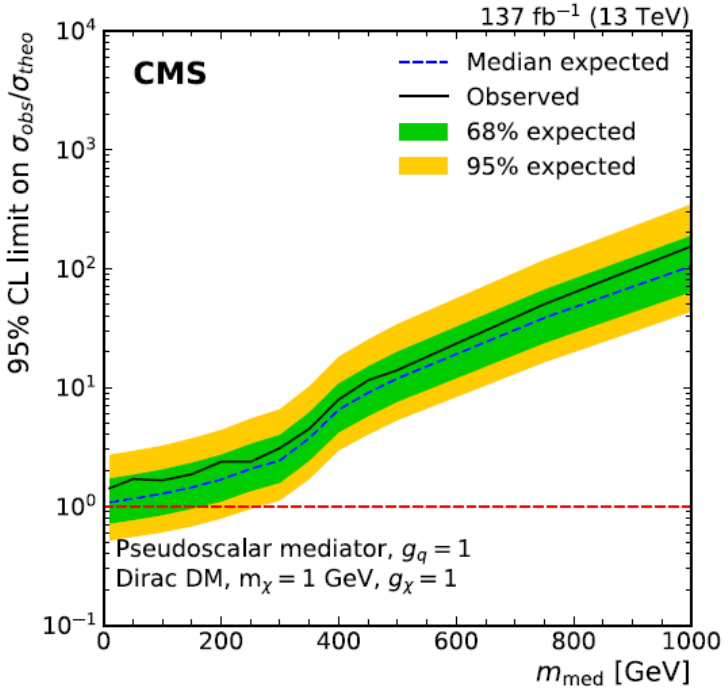
Exclusion limits on the "Simplified DM Models" from mono-Z(ll)

Axial mediator



Probe m_{med}~870 GeV

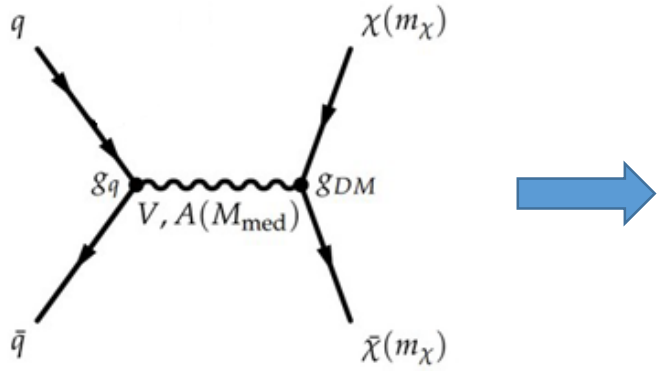
Pseudo-scalar mediator

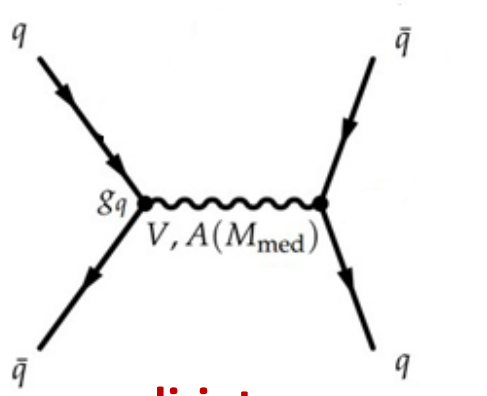


Not excluded area here yet

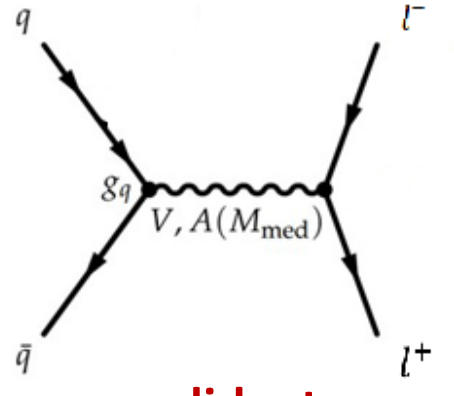
Less sensitive to these simplified DM models than mono-jet(V), **doesn't mean it's less sensitive in general!**
Check paper for other interpretations like Higgs portal model and 2HDM+a model

mediator resonance searches



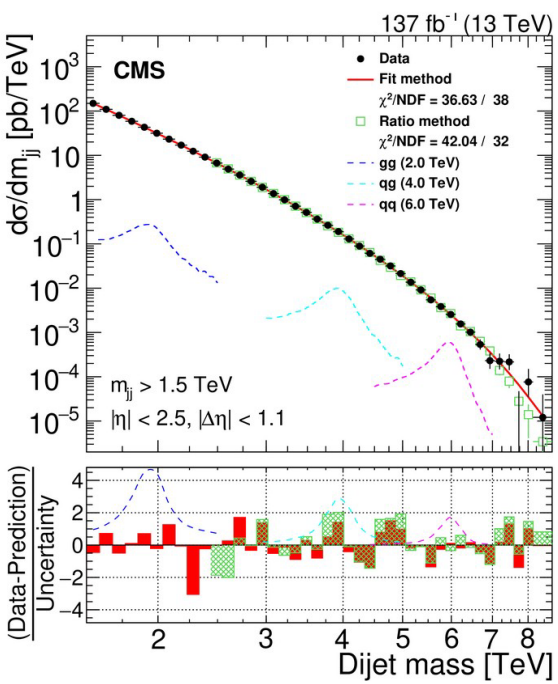


di-jet



di-lepton

- Mediator with both SM and DM couplings indicate existence of **di-quark-scattering** process, with possible extension to **di-lepton scattering**
- Search for **resonant bump on the invariant mass distributions**



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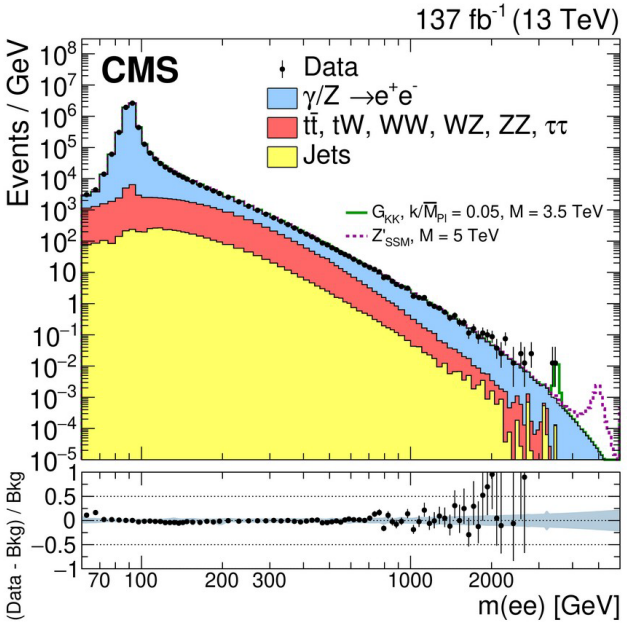

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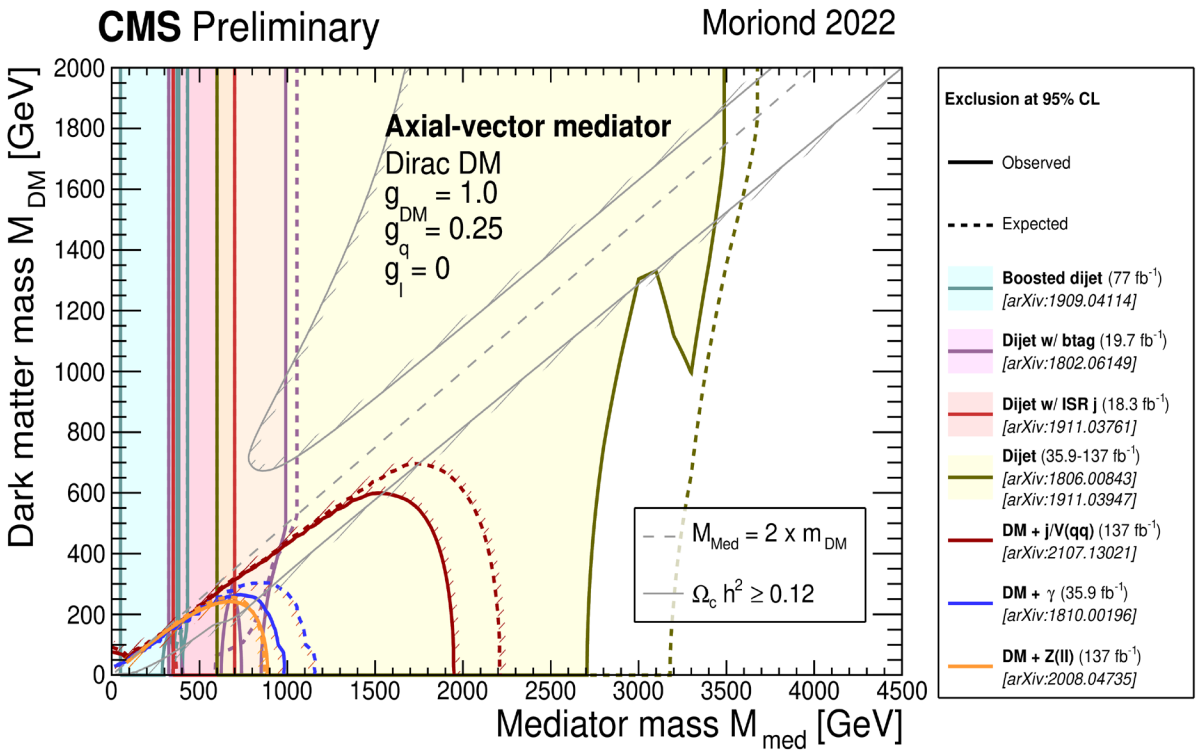
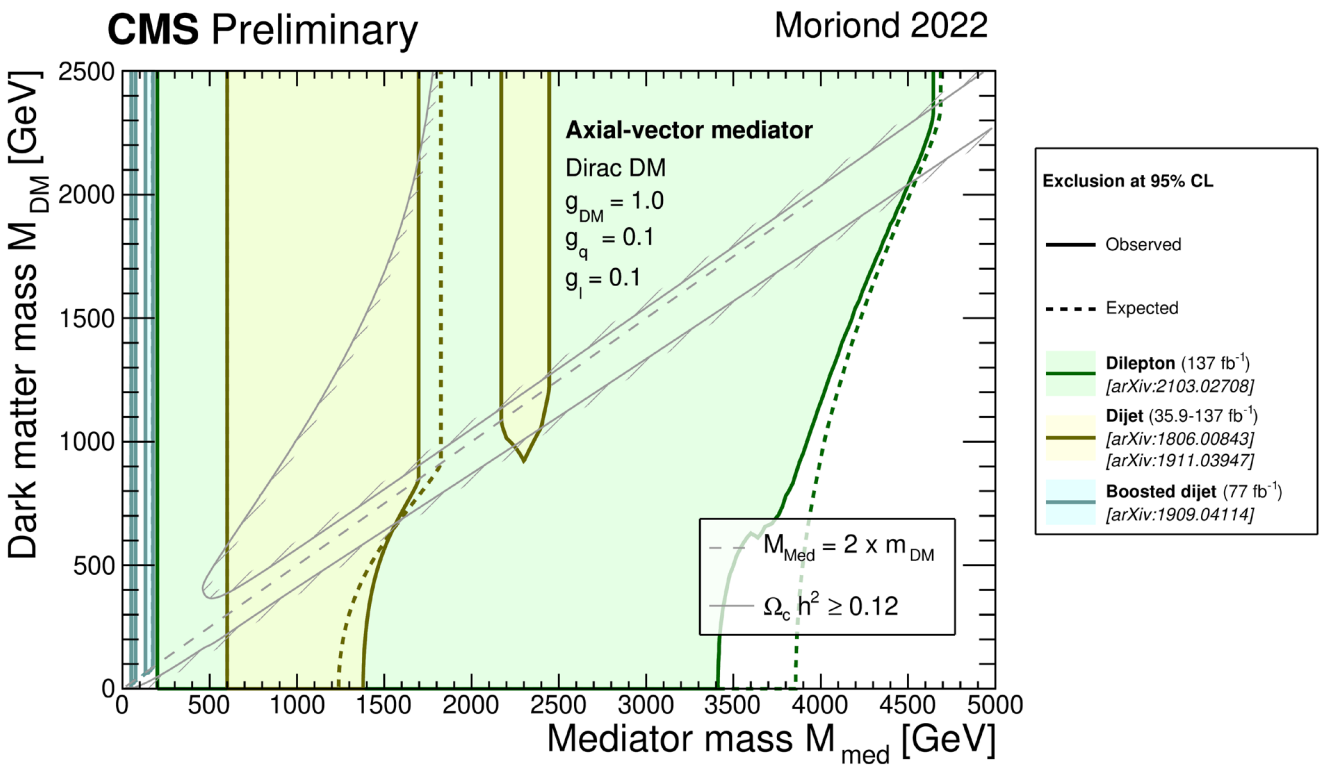
Limits from resonance searches

di-jet JHEP05(2020)033



di-lepton JHEP07(2021)208



Best constraint on $m_{med} - m_{DM}$ plane

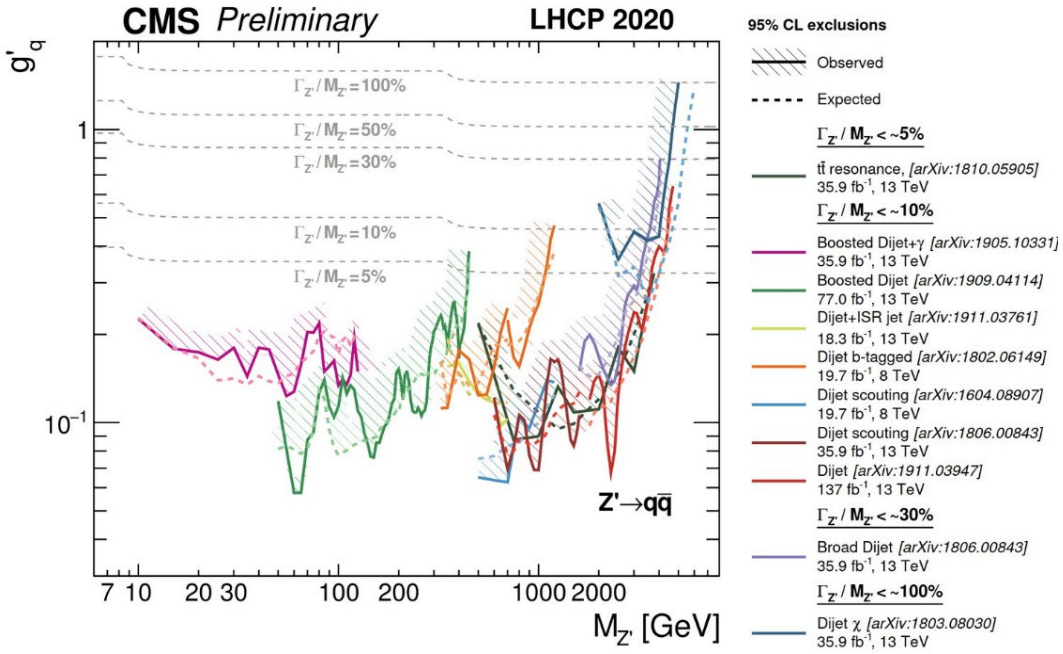
Even more powerful in the off-shell region

Limits depends on assumption on g_l

TeV level limits even for small g_l

Constrain on the couplings (g_q)

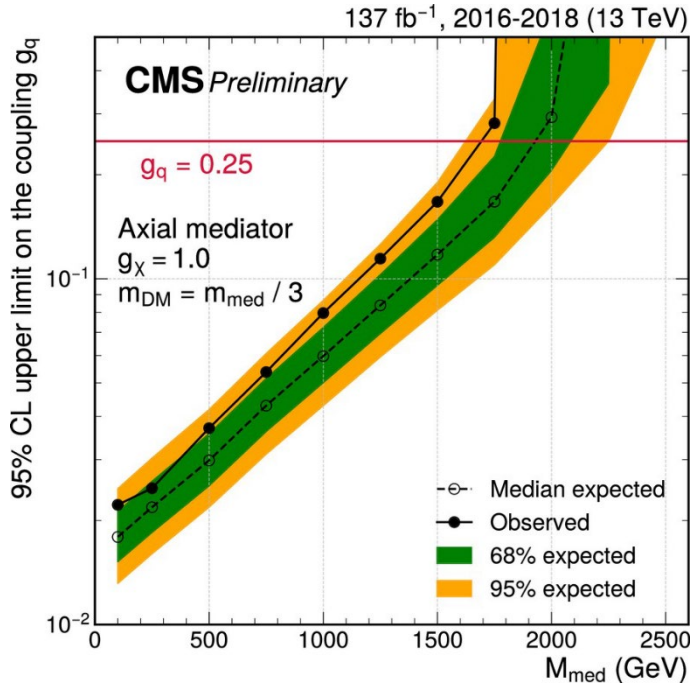
di-jet



Best probe down to 0.06

plot assumes pure hadronic decay. non-zero Br(Z'→DM) will lead to a factor of 2 increase

mono-jet



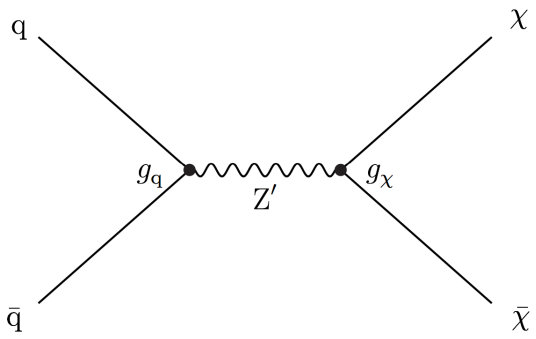
Best probe down to 0.02

Strongly coupled Dark Matter

Semivisible di-jet search

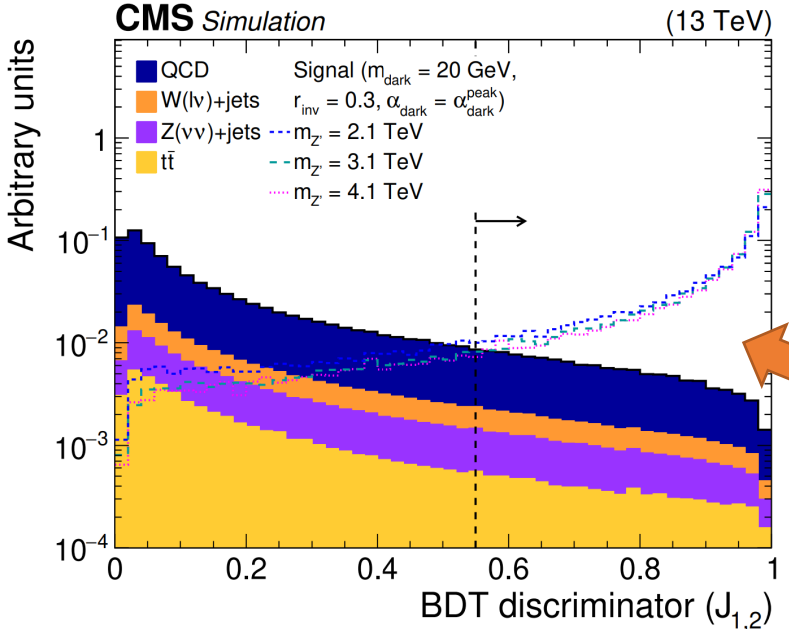
arXiv:2112.11125

- Hidden Sector has strong dynamics (like QCD)
- Include **stable and unstable dark hadrons**
- Unstable hard hadrons can decay to visible hadrons



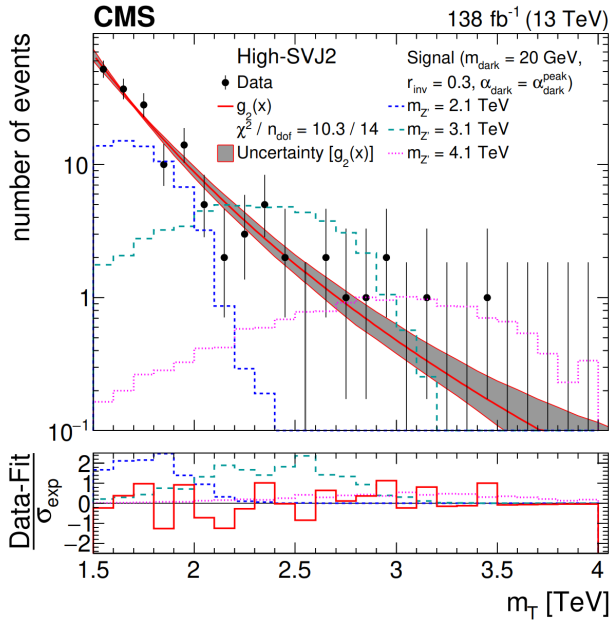
$$r_{\mathrm{Inv}} = \frac{\mathrm{N}_{\mathrm{stable}}}{\mathrm{N}_{\mathrm{stable}} + \mathrm{N}_{\mathrm{unstable}}}$$

$$r_{\mathrm{Inv}} = \begin{cases} 0 : \mathrm{monojet} \\ 1 : \mathrm{di-jet} \end{cases}$$



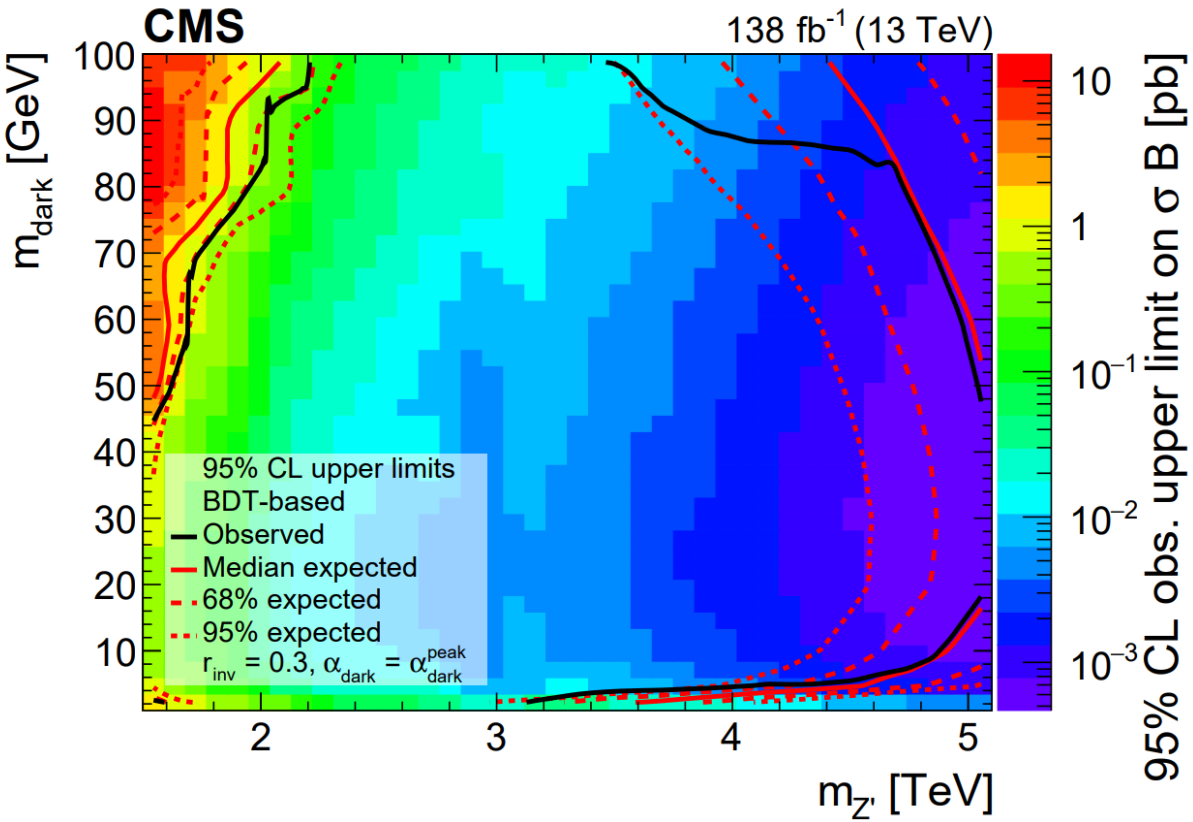
- **Event signature**: energetic di-jets
- Trigger based on high jet p_T or H_T
- Cut on low $\Delta\phi_{\mathrm{min}} = \min[\Delta\phi(p_{j1,j2}, p_T^{\mathrm{miss}})]$ and high $R_T = p_T^{\mathrm{miss}}/m_T$ to reduce background
- Utilize **BDT discriminator** to identify semivisible jets
- Final discriminator to fit: **di-jet transverse mass m_T**

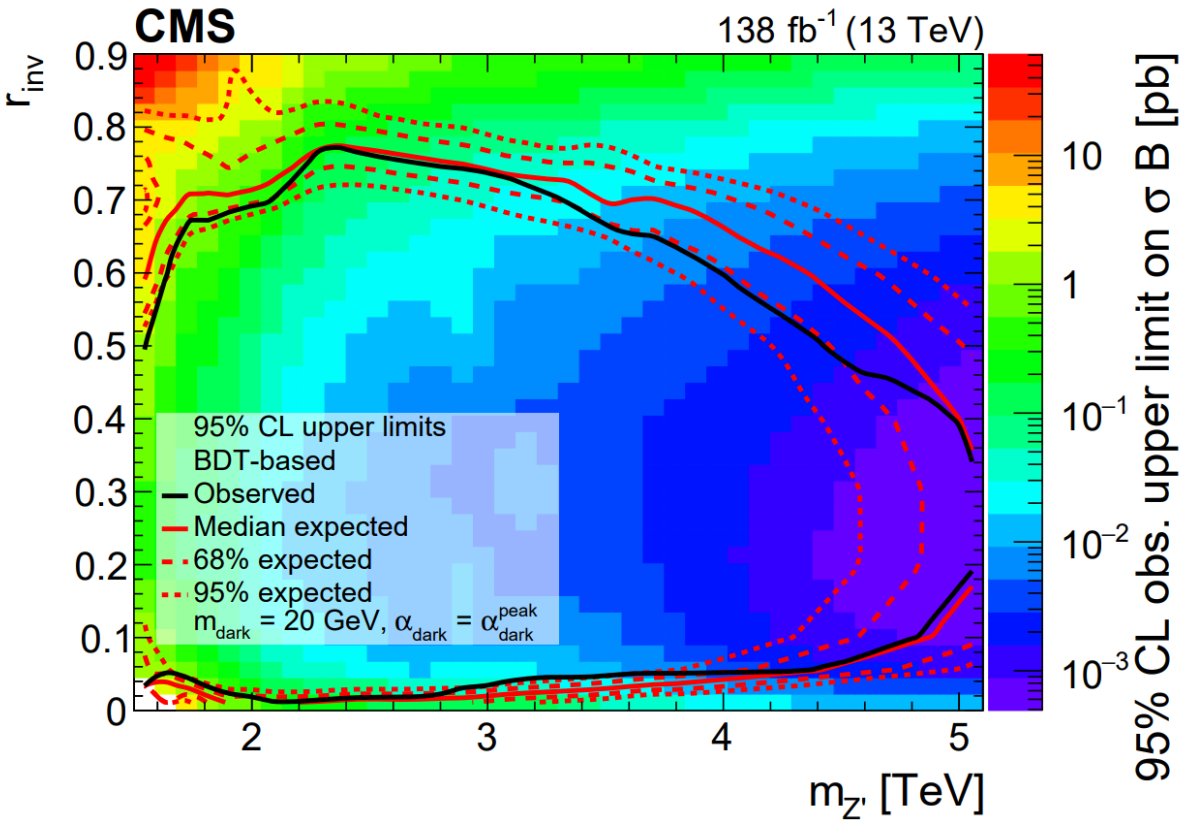
$$m_T^2 = m_{jj}^2 + 2p_T^{miss}(E_{T\,jj}^2 - p_{T\,jj}\cos\phi)$$



First collider search for DM from strongly coupled Hidden Sector

- Excluding $1.5 < m_{Z'} < 5.1$ TeV for $r_{\mathrm{Inv}} = 0.3$
- Excluding $0.01 < r_{Inv} < 0.77$ for $m_{DM} = 20\ GeV$





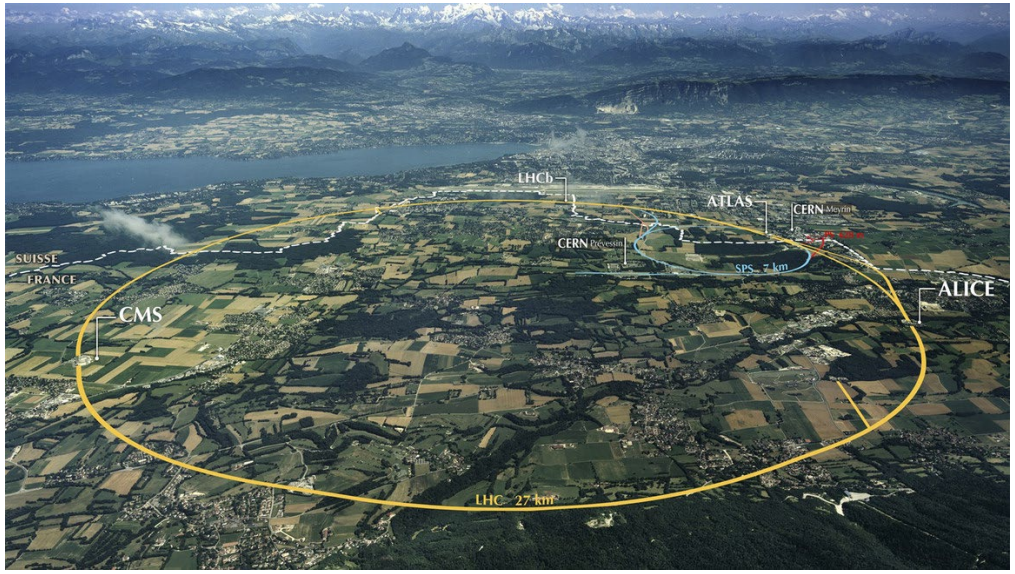
Summary

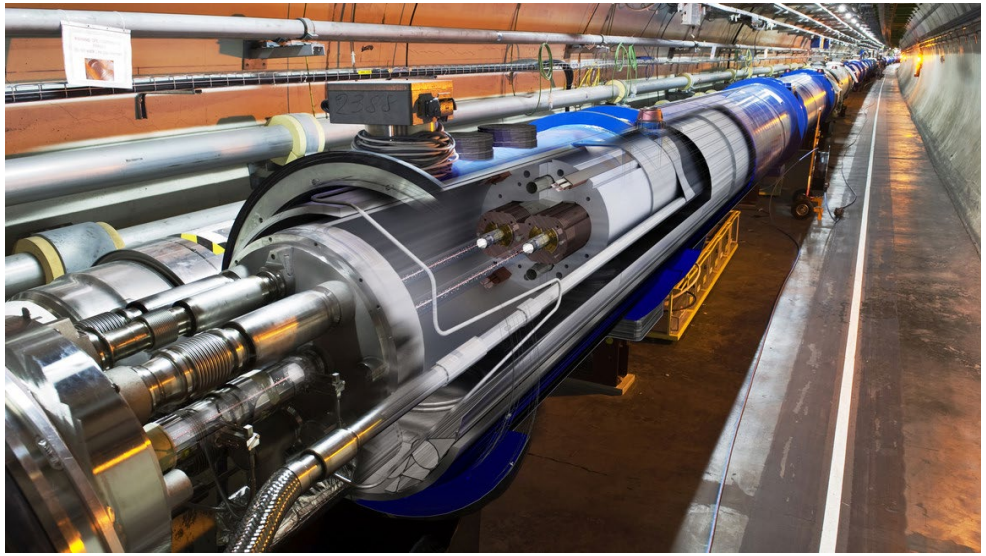
- Vast range of DM searches performed at CMS, complementing to each other
  - Showed **mono-jet** + **mono-V(had)**, **mono-Z(ll)**, **di-jet**, **di-lepton**, **semivisible jets**
- No obvious deviation from SM prediction
- Extending limits on BSM model parameters:
  - **Simplified models with (different types of) single mediator to DM**, **strongly coupled Hidden Sector**
- Analyses mentioned are also interpreted in other BSM models (i.e. not DM) such as **ADD**, **Higgs Portal, unparticle**, **lepto-quark**, refer to linked papers for more detail
- There are also searches targeting more complex models like **Extended Dark Sector** and **SUSY**, see all CMS public results

Backup

The LHC (Large Hadron Collider)

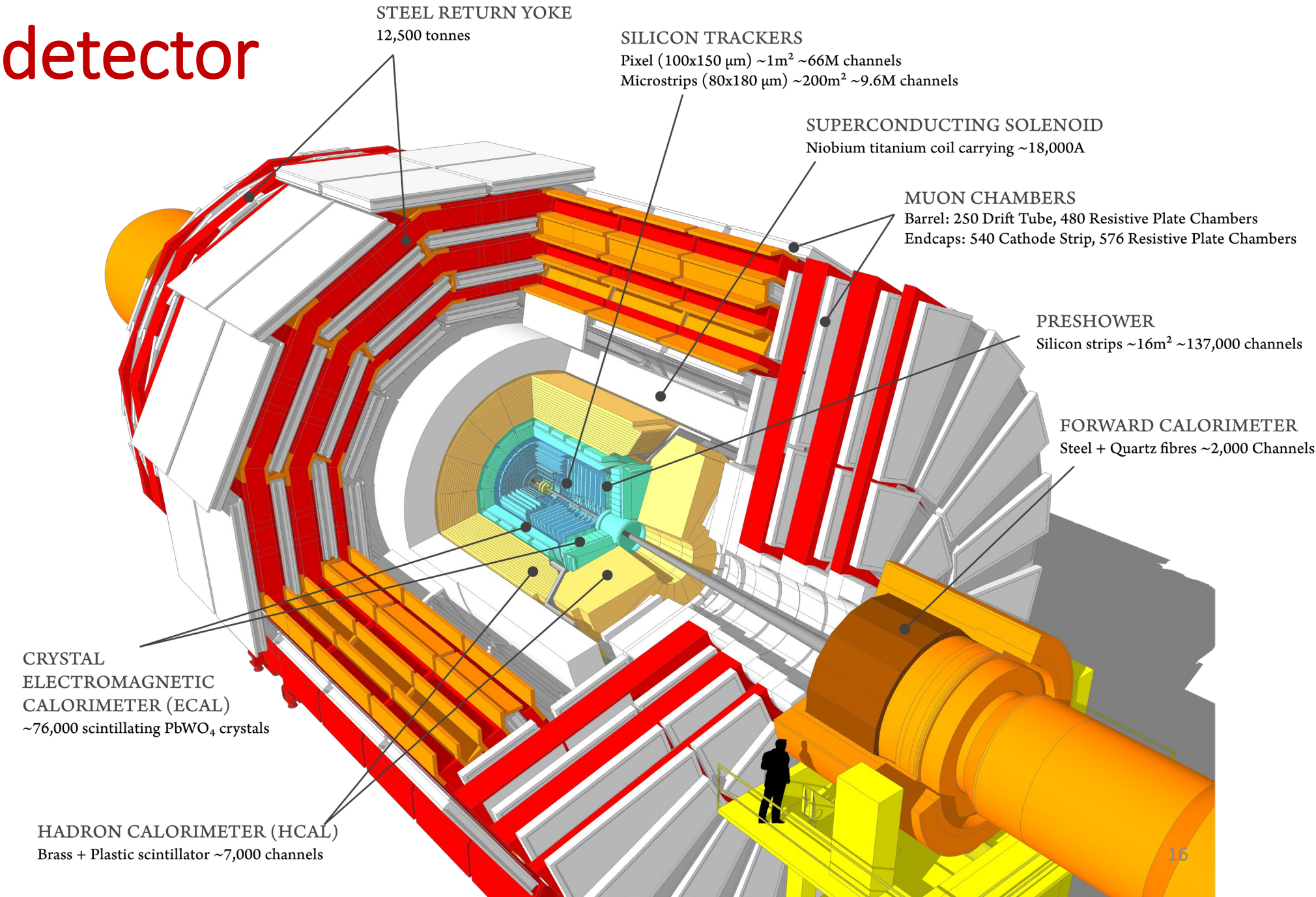
- The LHC is a large particle accelerator that accelerate protons/ions to near the speed of light
- Particles travel through a 27-km underground tunnel that consists super-conducting magnets and accelerating structures
- Bunches of particles traveling in opposite directions collide with each other every 25ns (at 40MHz) at the four collision points where the four detectors (CMS, ATLAS, LHCb, ALICE) are built





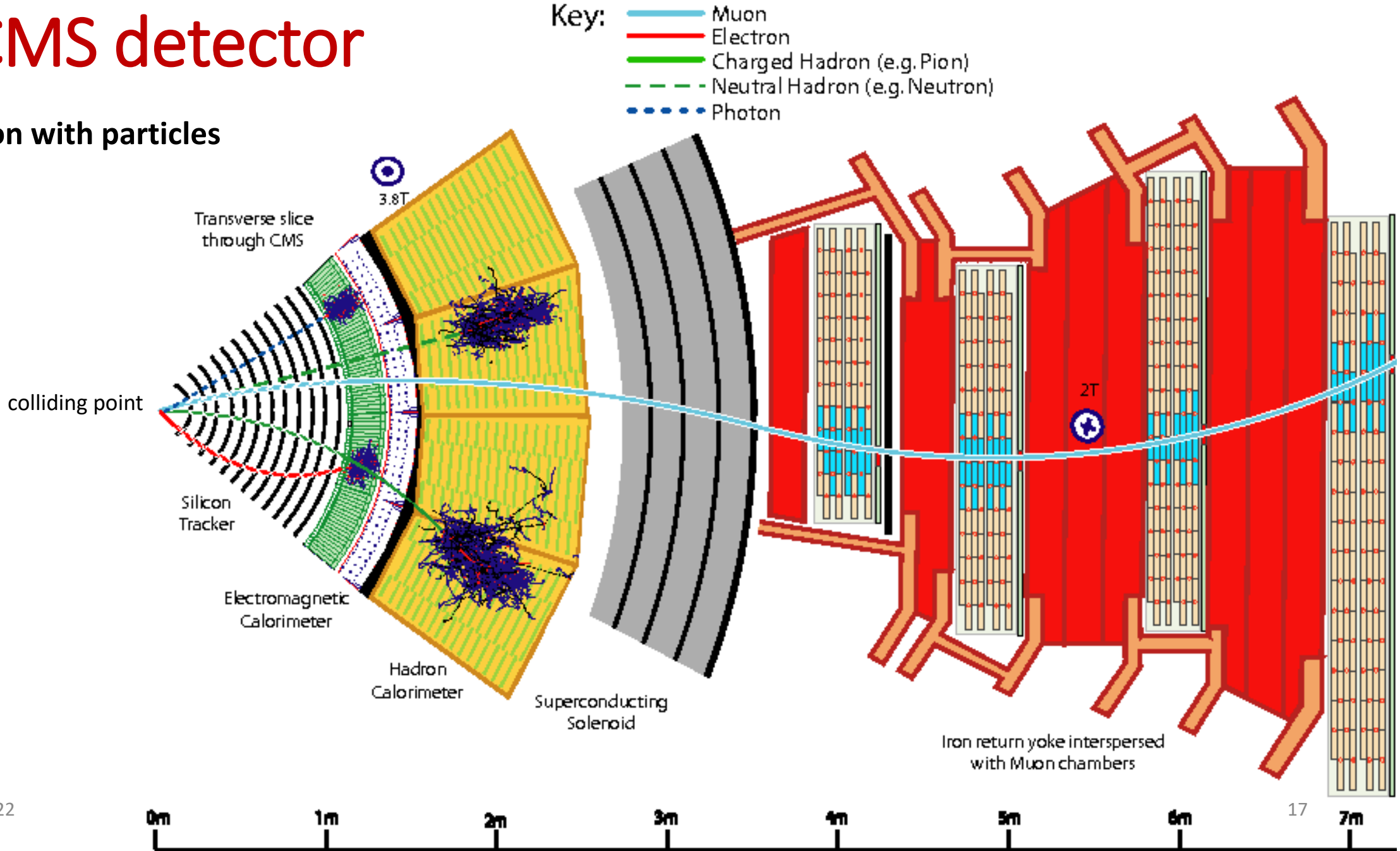
The CMS detector

Detector layout

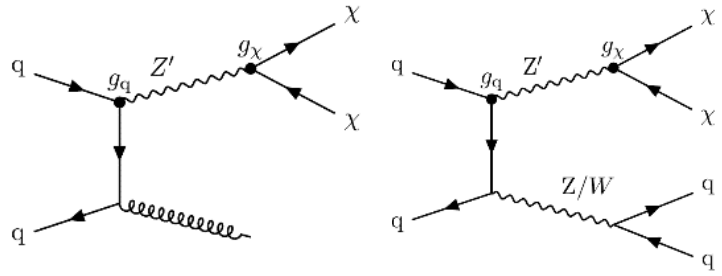


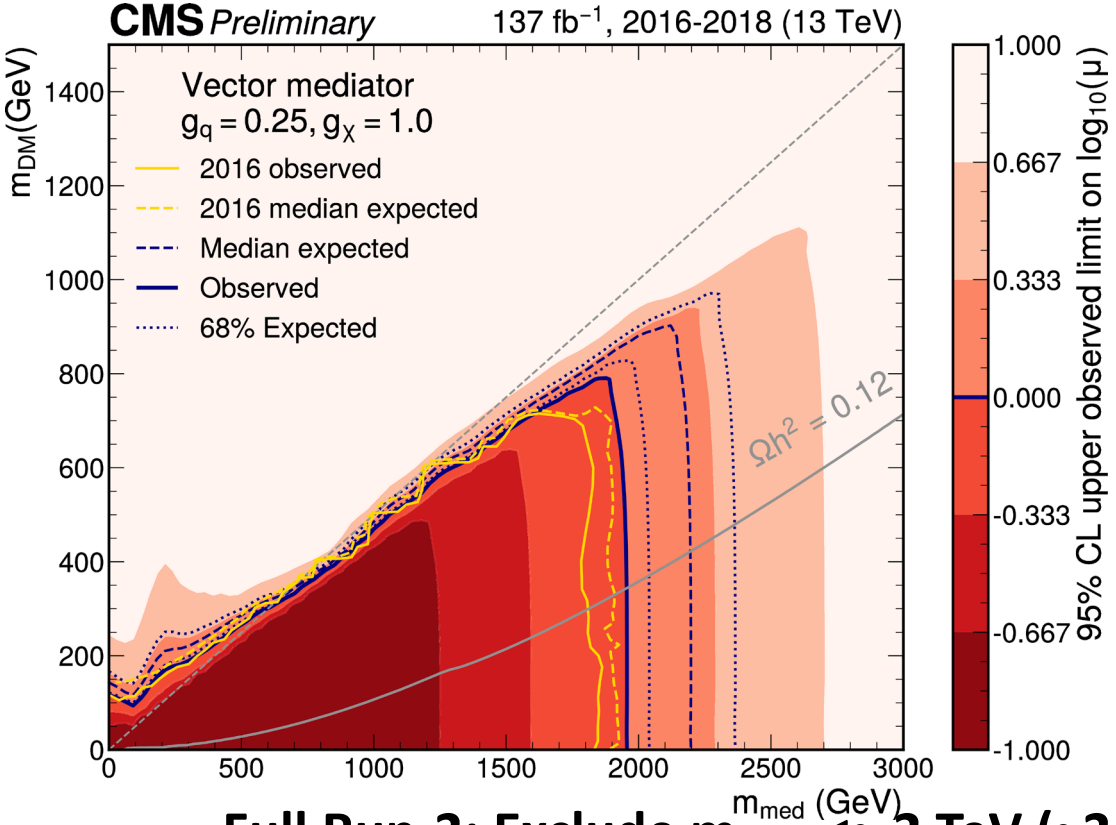
The CMS detector

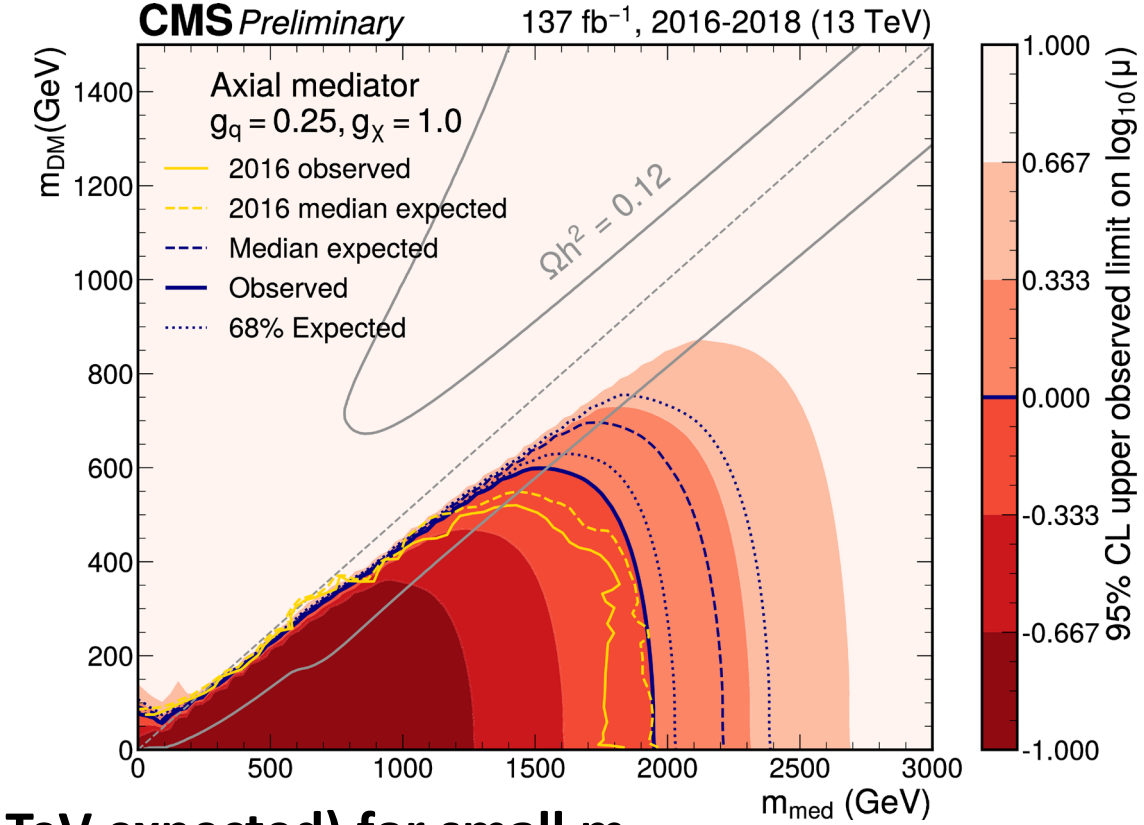
Interaction with particles



Model interpretation
Simplified DM model: Spin-1 mediator



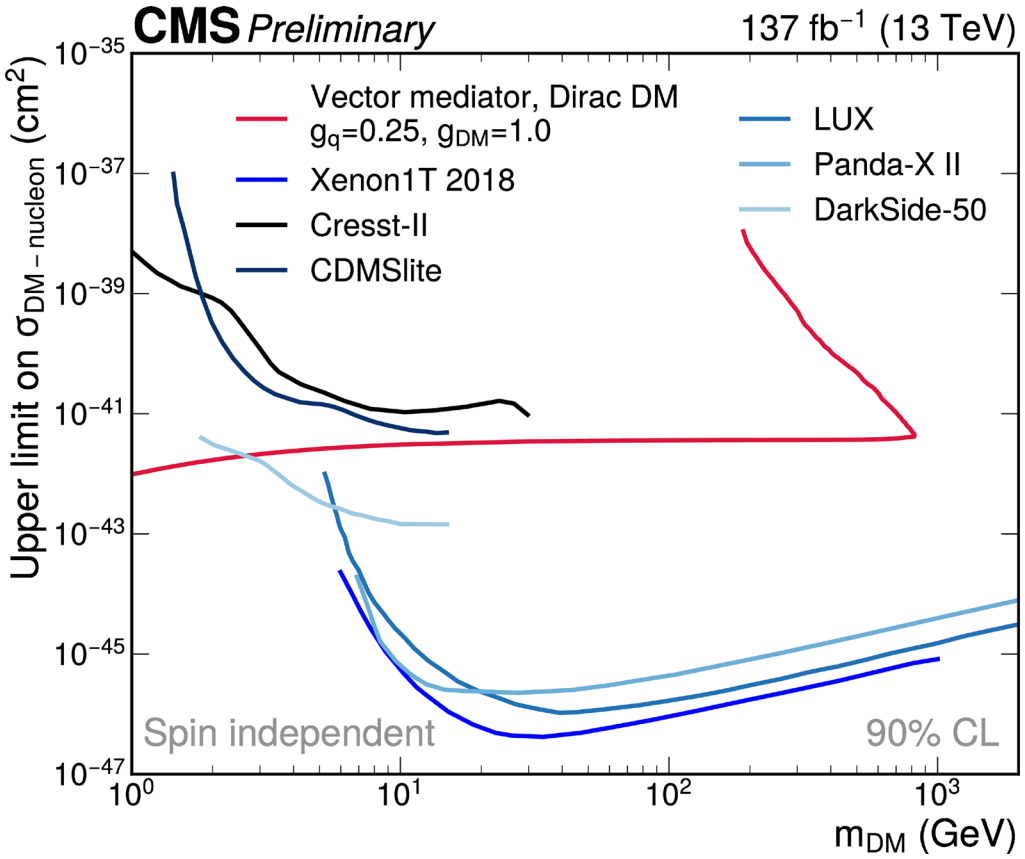


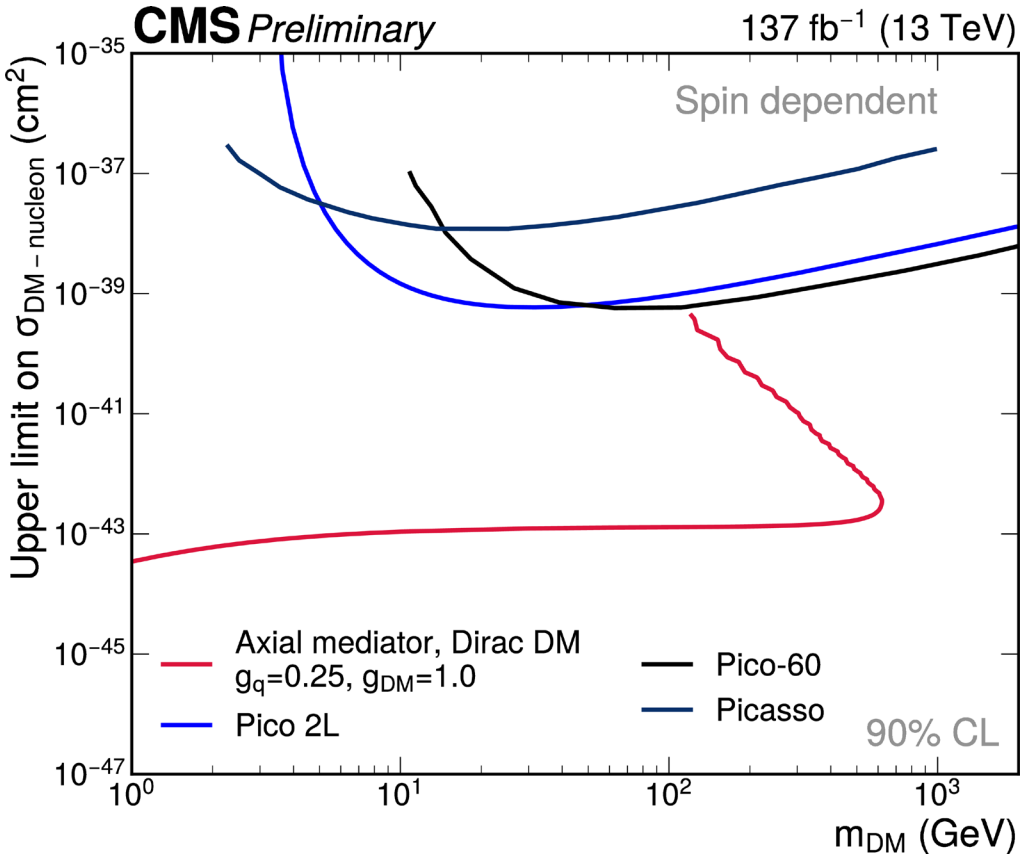


Full Run-2: Exclude m_{med} <≈ 2 TeV (≈2.2 TeV expected) for small m_{DM}

improvement relative to 2016 by ≈ 200 GeV in m_{med} (≈ 300 GeV expected)

Comparison of simplified model constrains to direct detection experiments



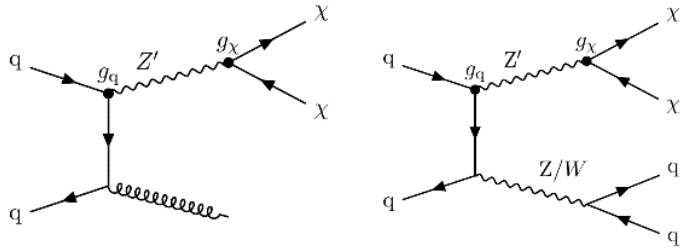


Point-to-point conversion from $m_{\mathrm{med}} - m_{\mathrm{DM}}$ countour to $\sigma_{\mathrm{DM-nucleon}} - m_{\mathrm{DM}}$ plane

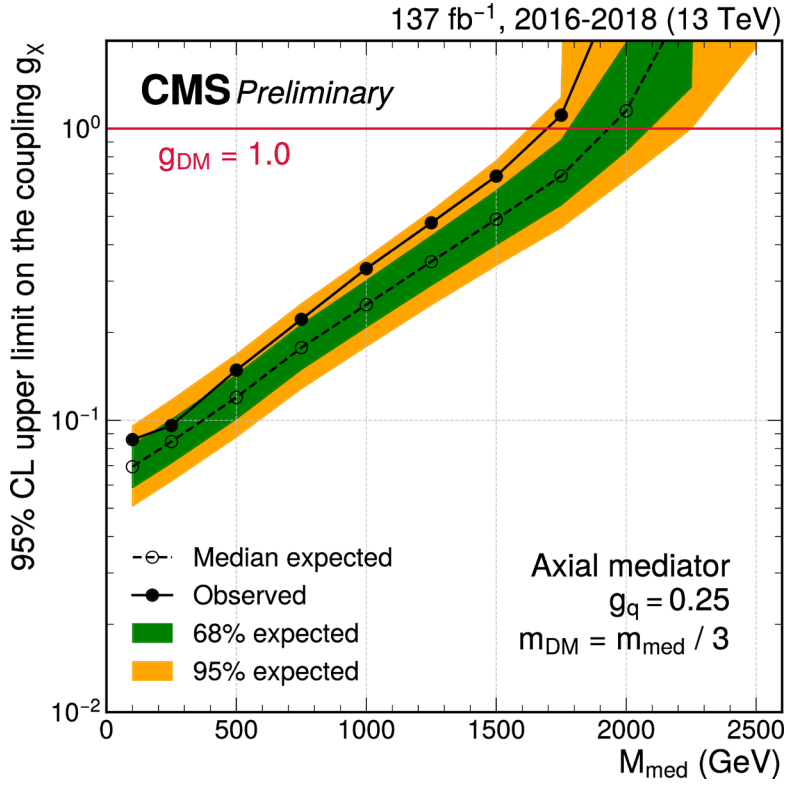
Show stronger limit at small m_{DM} for $\sigma_{\mathrm{spin\ independent}}$ up to $m_{\mathrm{DM}} = 1\mathrm{TeV}$ for $\sigma_{\mathrm{spin\ dependent}}$

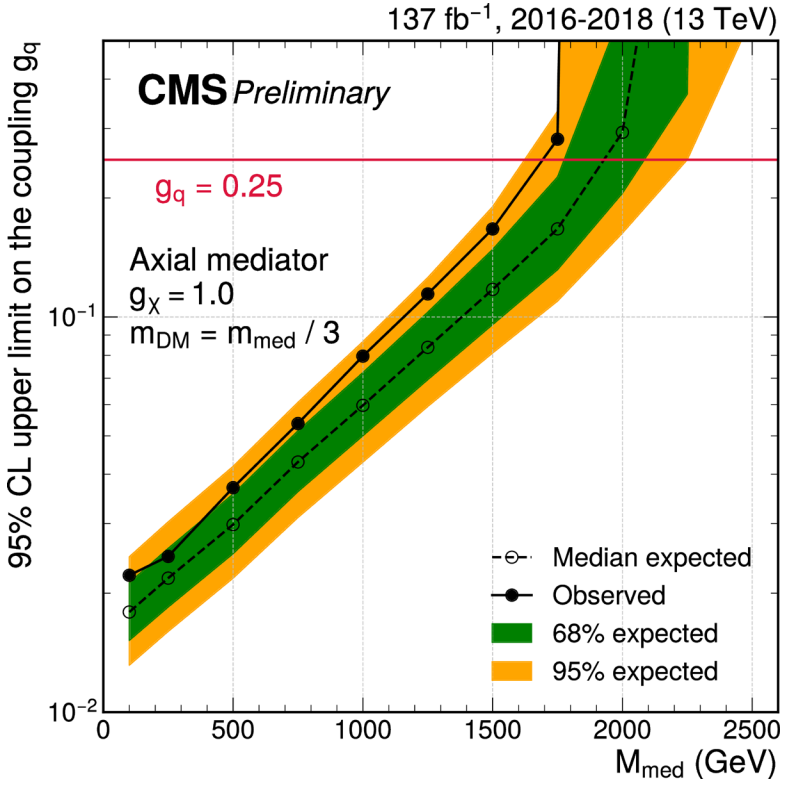
Note that the **red lines** are subject to specific choice of couplings

Simplified DM model: Spin-1 mediator coupling limit



1D scan of mediator mass with $m_{DM} = \frac{m_{med}}{3}$

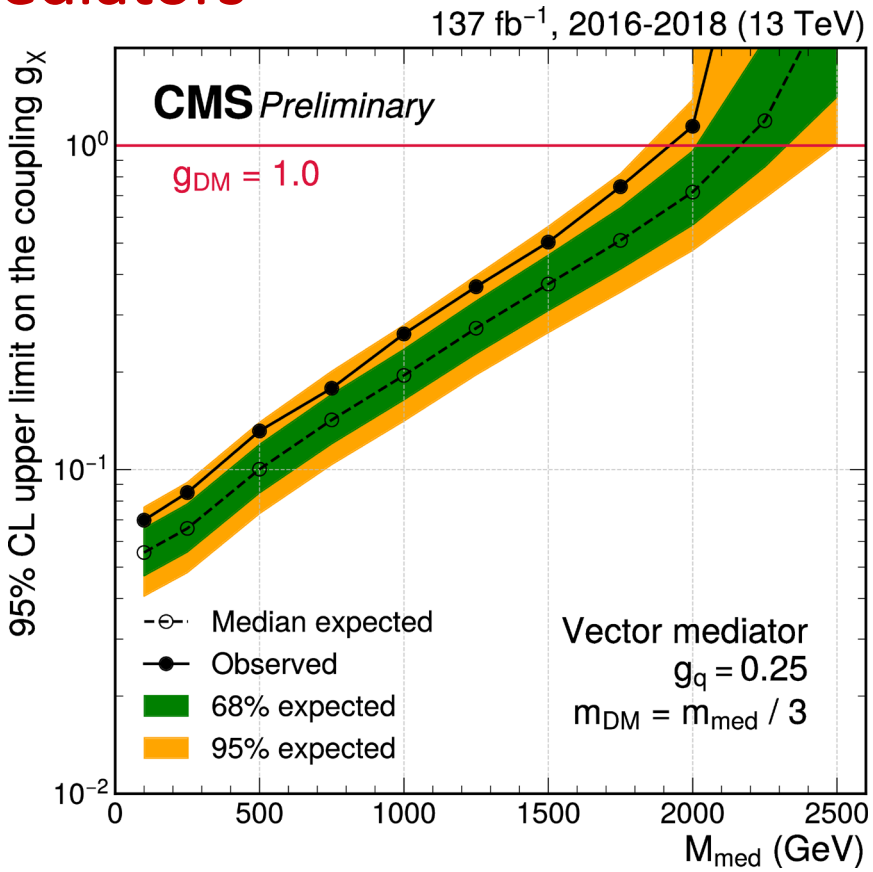


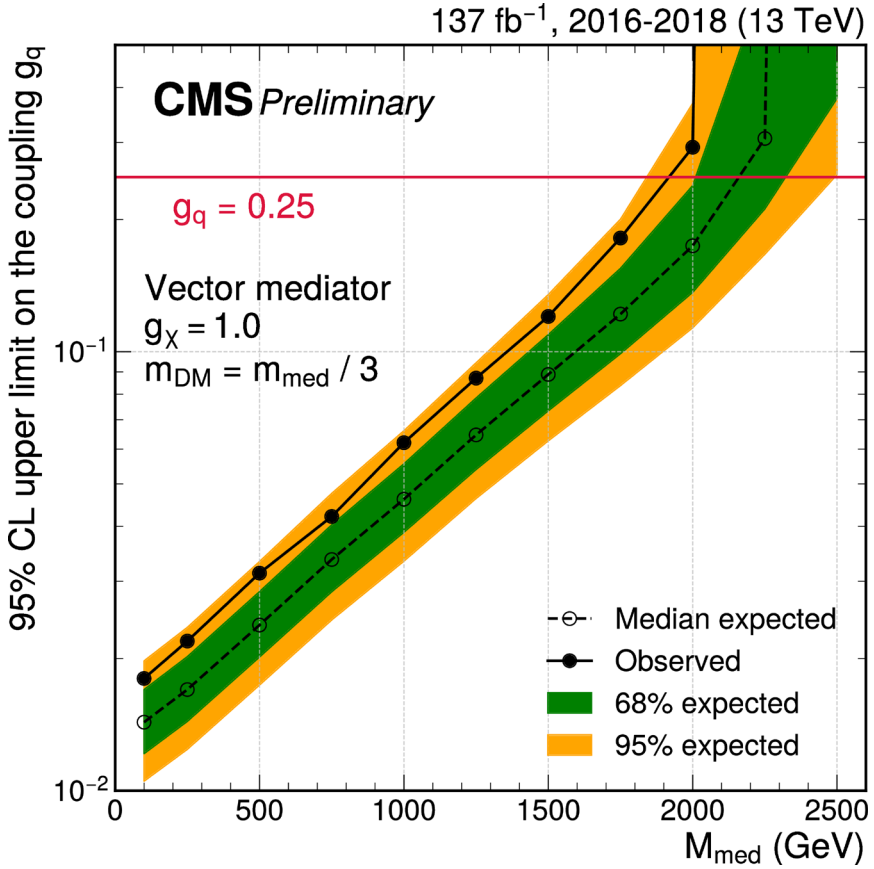


More than one additional order of magnitude in coupling limit approached compared to the nominal limit with 2D contour

Same plots with vector mediators in backup

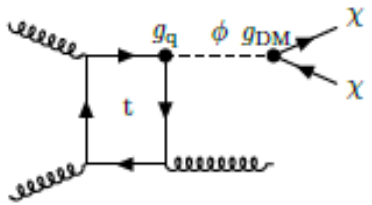
Simplified DM model: Spin-1 mediator coupling limit for vector mediators

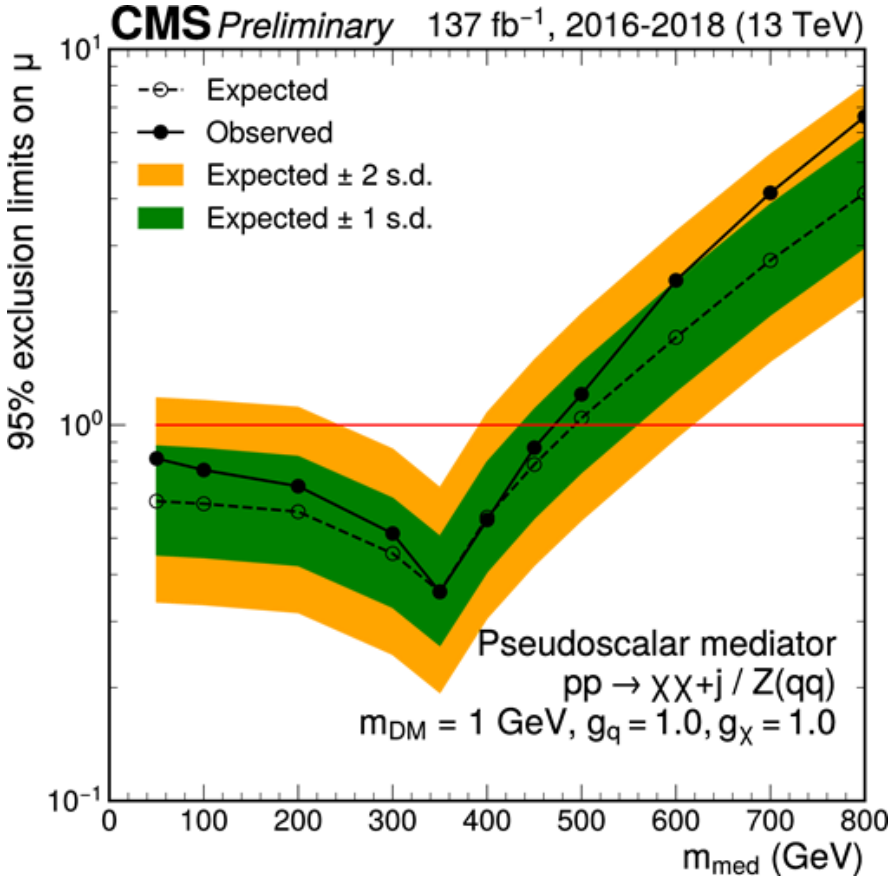


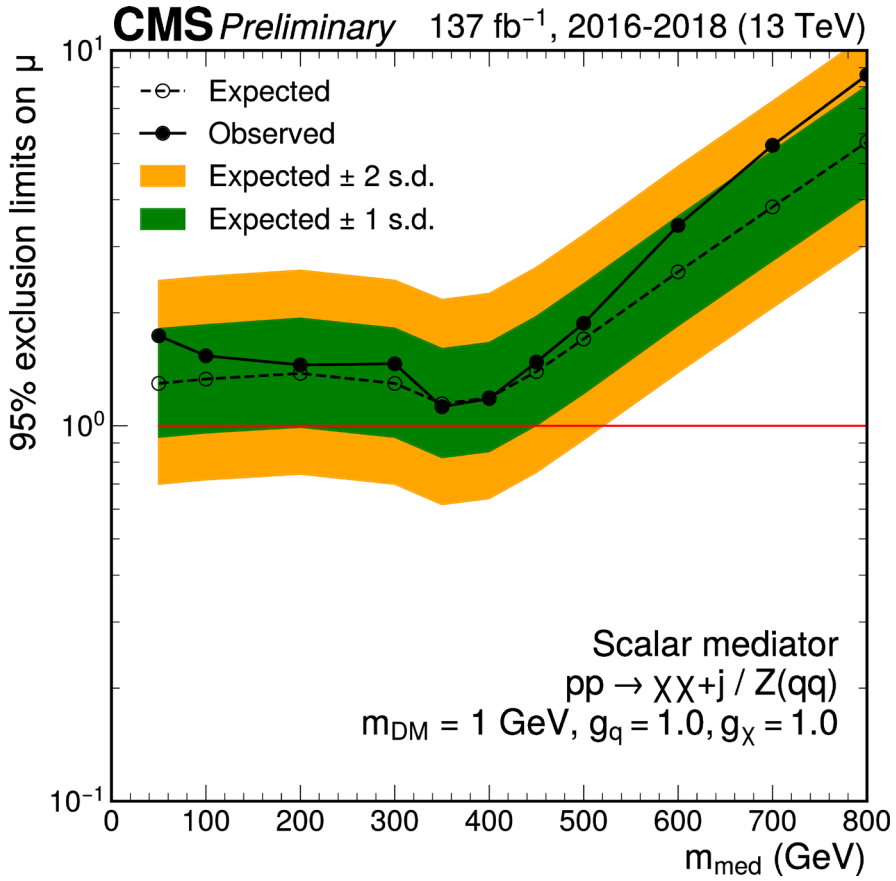


same plots with axial vector mediators

Simplified DM model: Spin-0 mediator





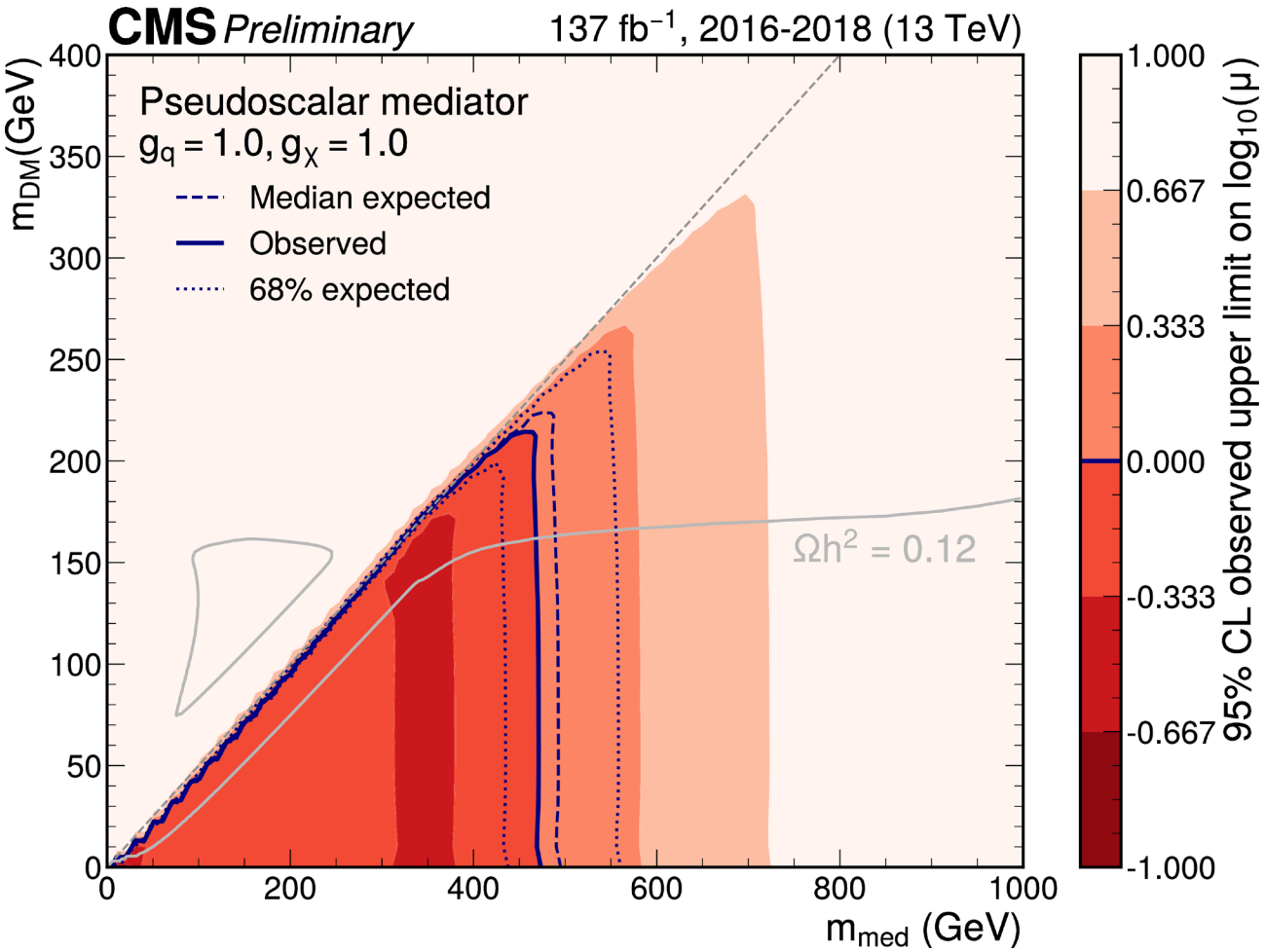


Exclude m_{med} < 480 GeV (460 exp)
(60 GeV improvement (20 exp))

Exclusion around μ≈1.15-1.2 (1.0-1.1)

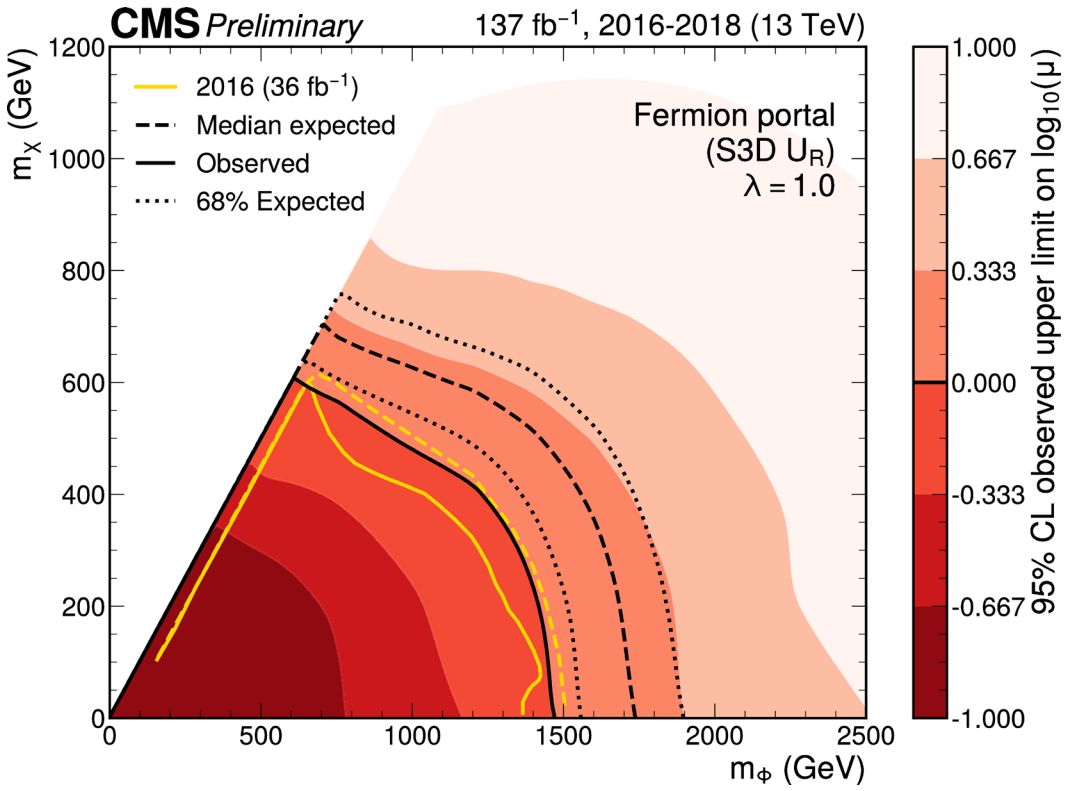
There is also 2D limit contour on the m_{med}-m_{DM} plane in backup

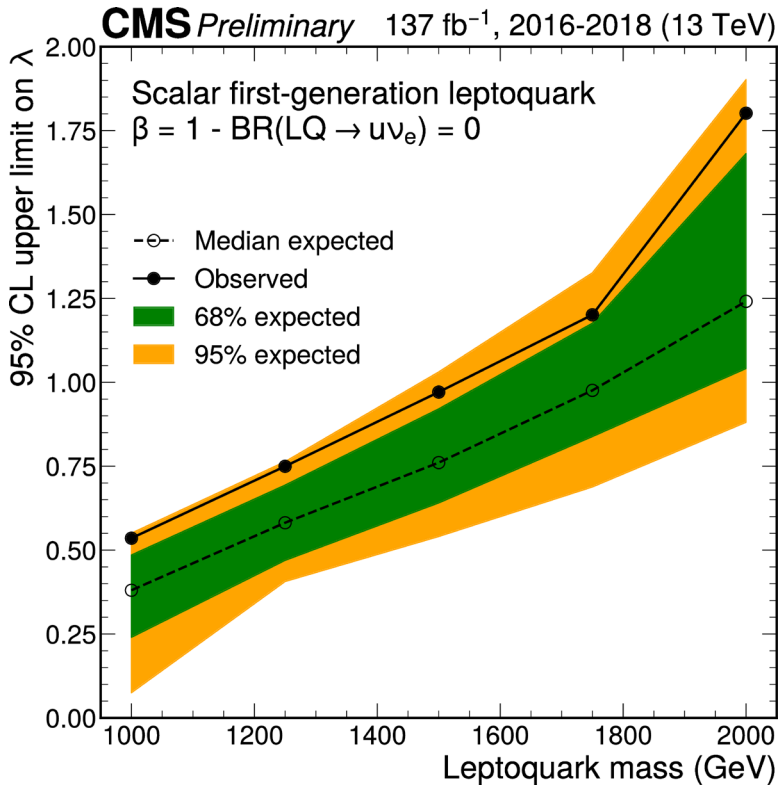
Two-dimensional exclusion in the simplified DM model with pseudoscalar mediator



Fermion portal DM and LQ(qv)

Both cases: Single, pair and t channel production





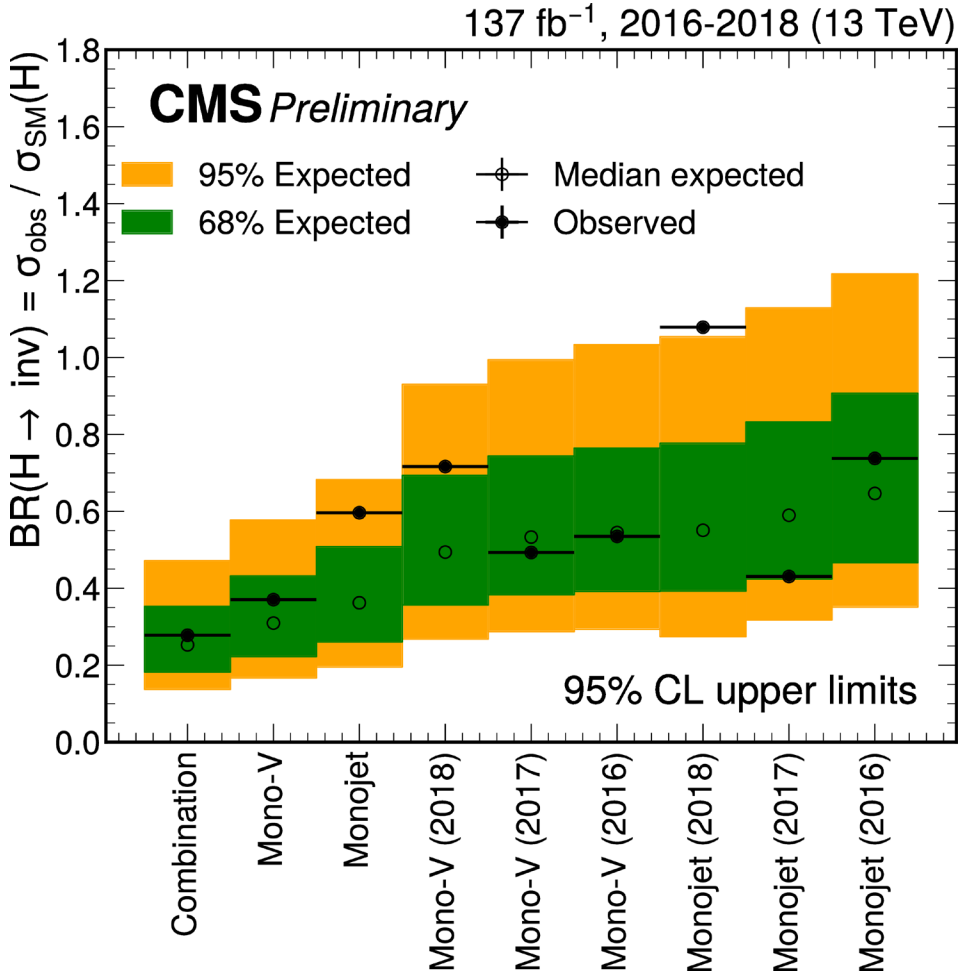
Max exclusion around 1.5 TeV for m_Φ

New interpretation, not done in '16

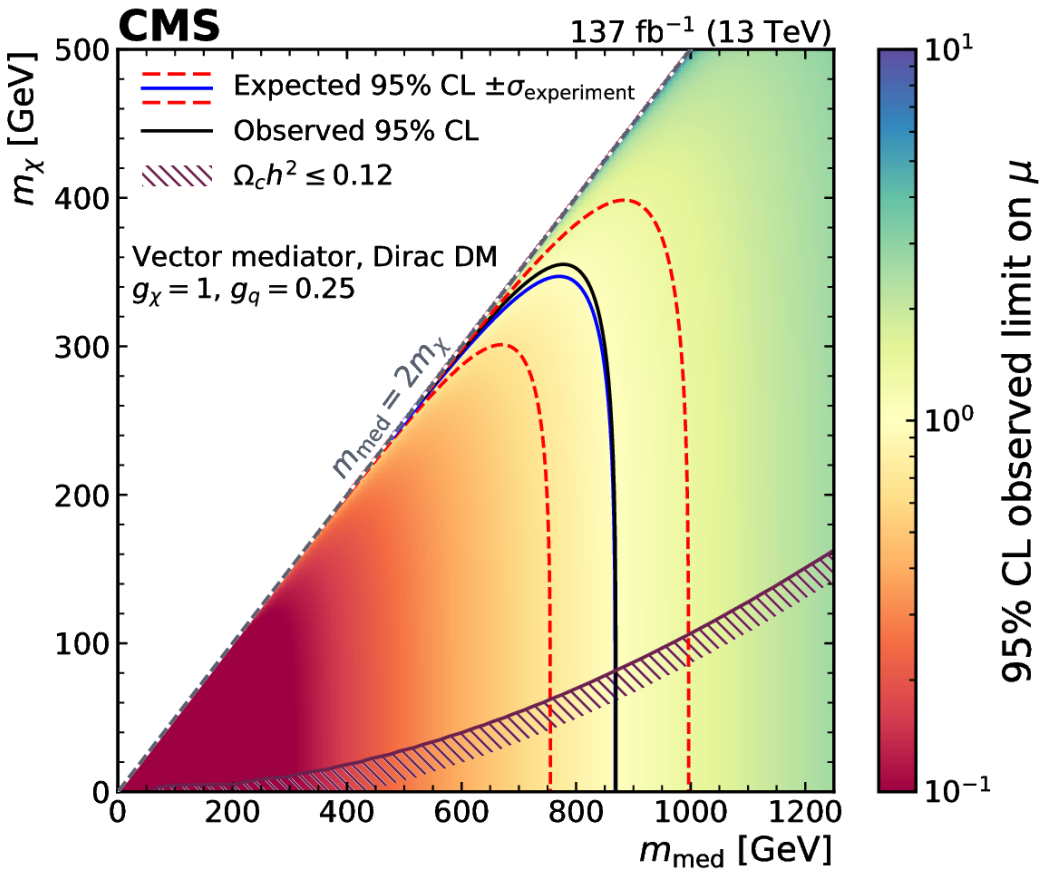
low MLQ: λ → 0, pair prod alone is excluded

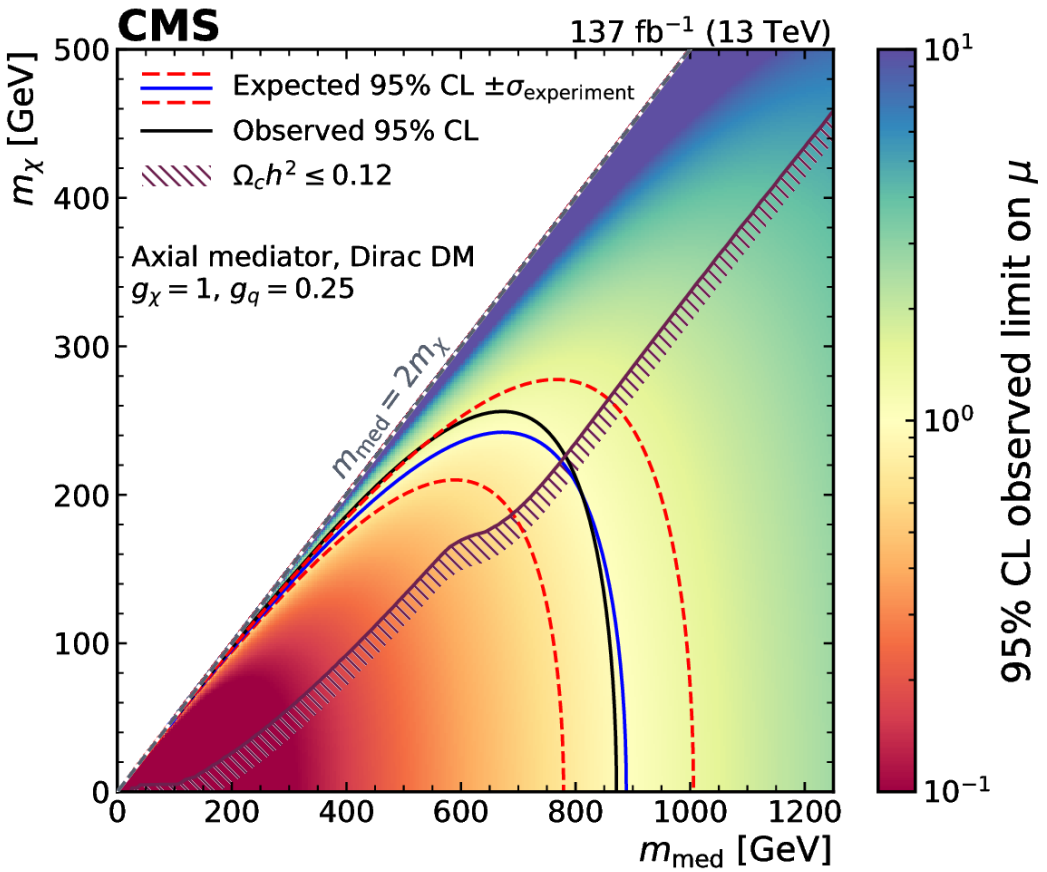
higher MLQ: single prod. dominates, exclude λ=1

Higgs invisible model (fine-binned information)

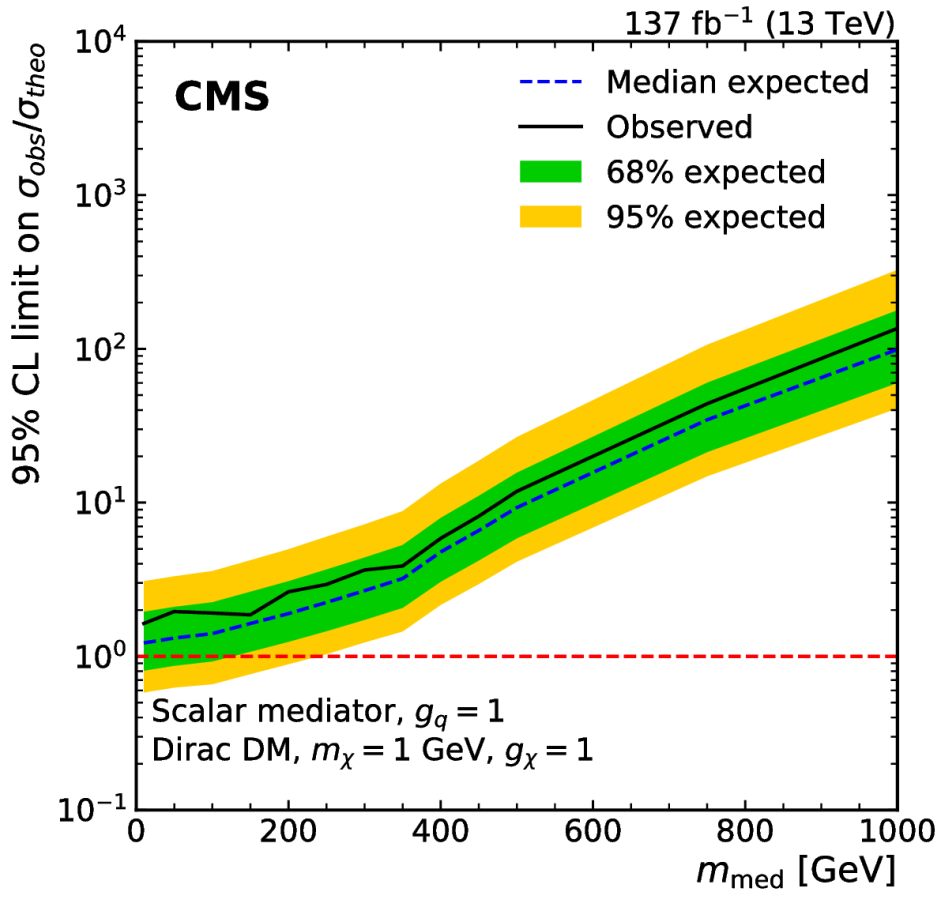


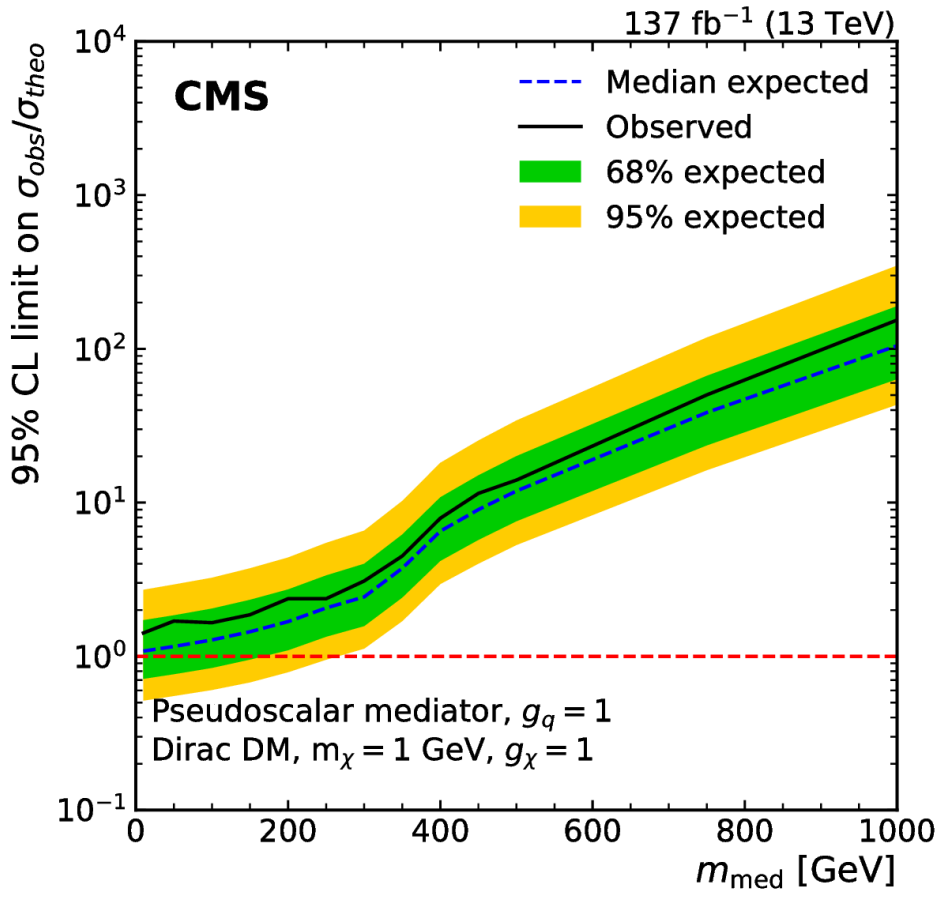
mono-Z DM Simp spin-1 limits





mono-Z DM Simp spin-0 limits





di-lepton spin-1 limits