

Search for Dark Matter in pp Collisions with CMS

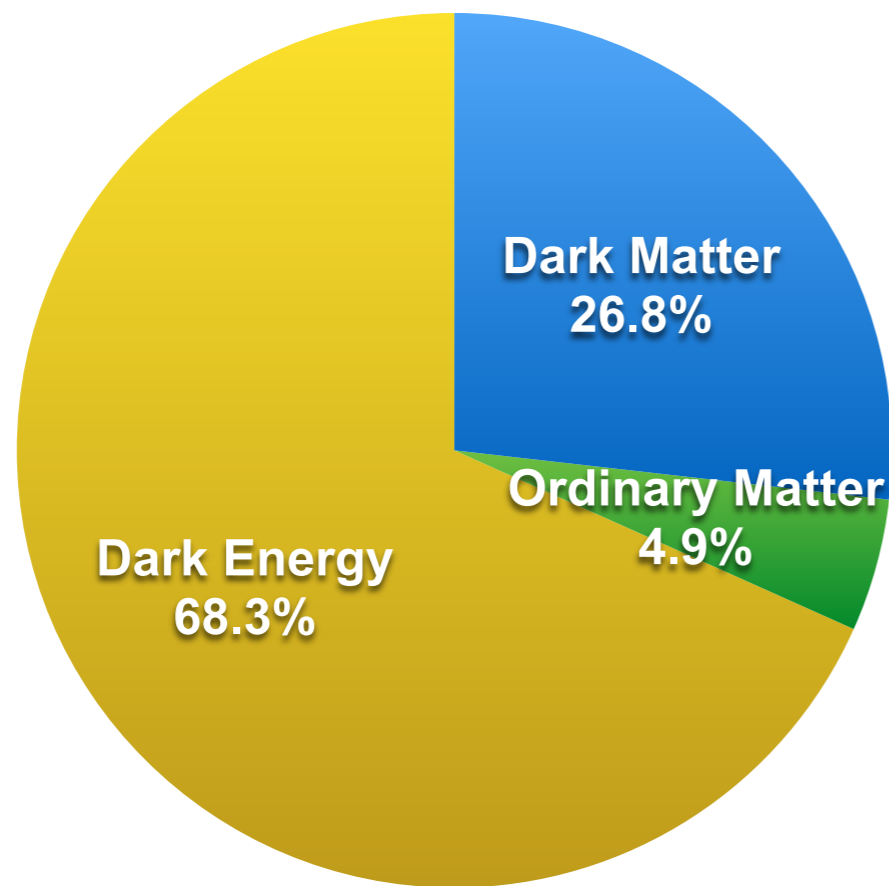
Shin-Shan Eiko Yu
National Central University, Taiwan
On behalf of the CMS Collaboration

5 August 2016

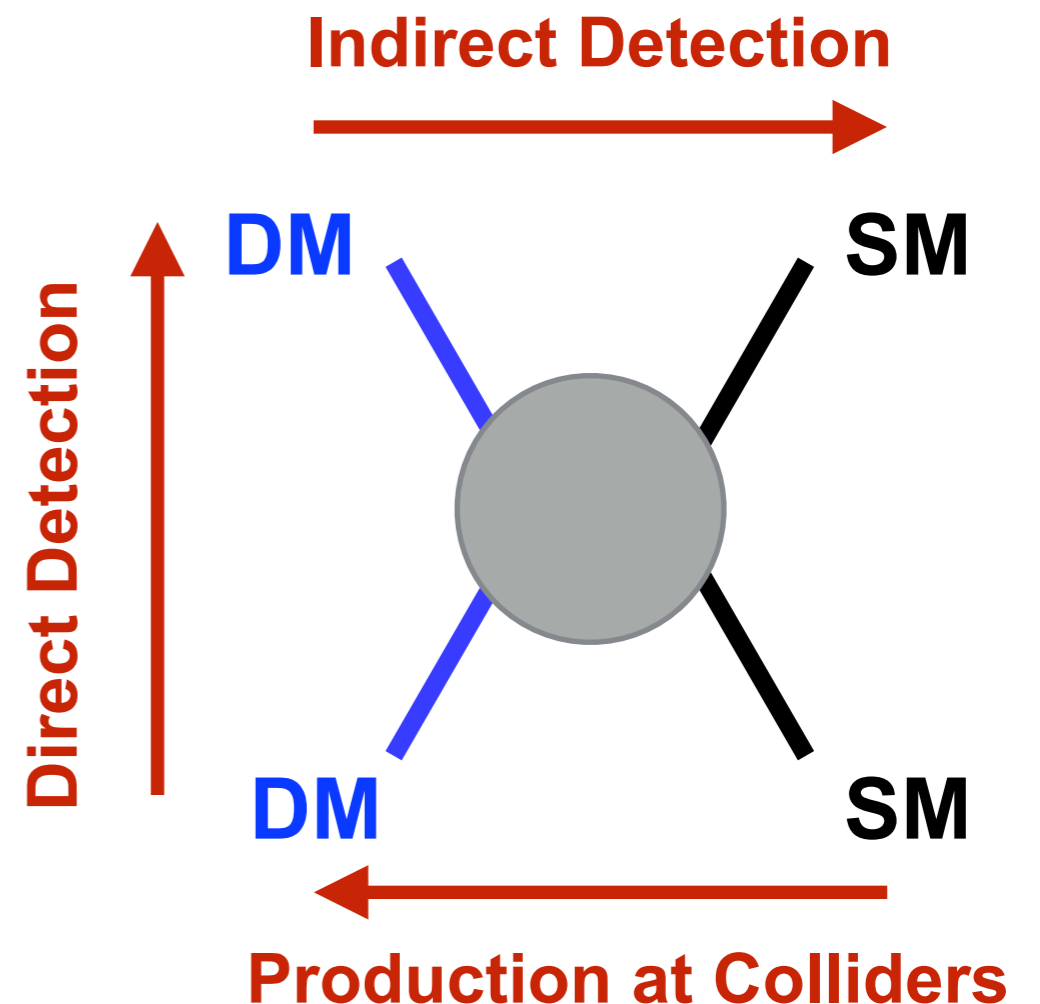
38th International Conference on High Energy Physics, Chicago

Why Dark Matter At LHC?

- Evidence of dark matter well established from astrophysical observations
 - The exact nature of DM is still unknown
- LHC provides a prime laboratory for production of DM
 - Can probe a wide range of DM/SM interaction types



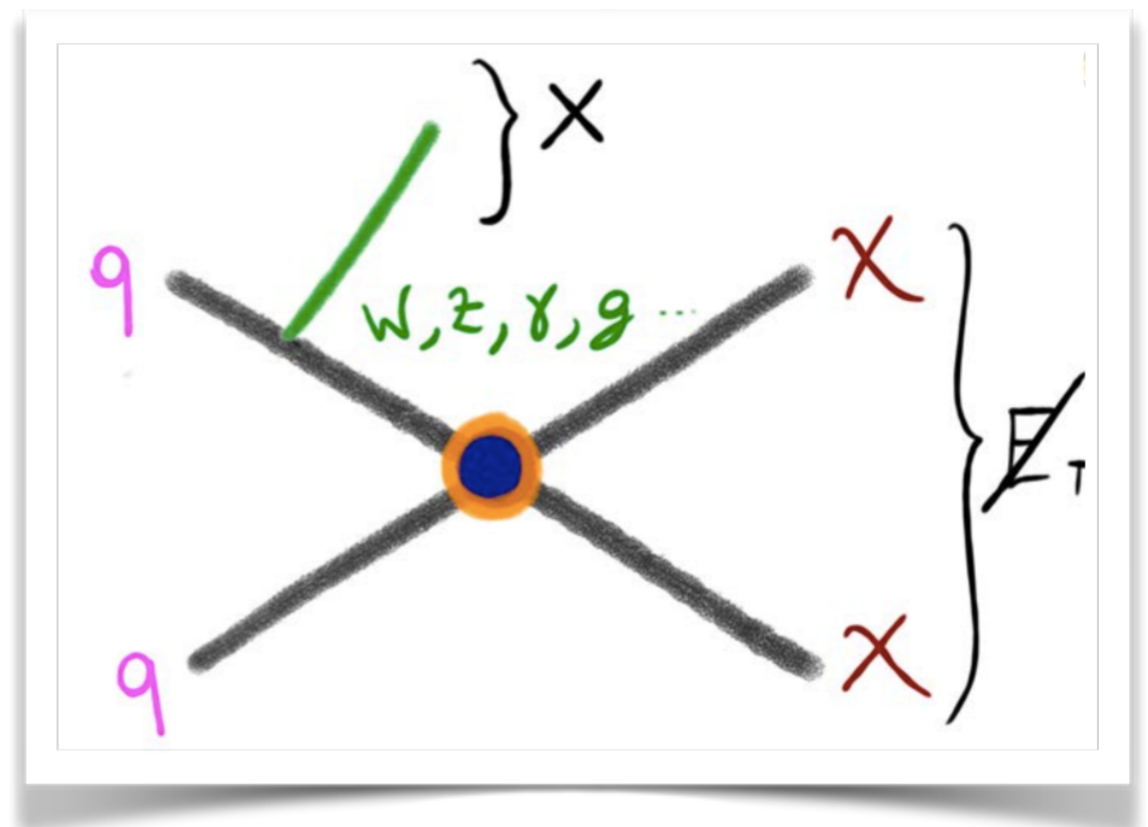
Matter/Energy Today



Searches For Dark Matter At LHC

- Typically look for $E_T^{\text{miss}} + X$
 - $X = \text{jet (g, q), } \gamma, W, Z, H, tt, bb, t$
- Use simplified models to interpret results (arXiv: [1507.00966](https://arxiv.org/abs/1507.00966))
 - DM particle is a Dirac fermion
 - DM particles are pair-produced
 - A new massive particle mediates the DM-SM interaction
 - Minimal flavor violation
 - Mediator has minimal decay width

- Minimal set of parameters
 - coupling structure, M_{MED} , m_{DM} , g_{SM} , g_{DM}



CMS 13 TeV Searches For Dark Matter

Focus of this talk

X	Dataset	CMS Documentation
jet or V (hadronic)	2016, 12.9 fb	EXO-16-037
photon	2016, 12.9 fb	EXO-16-039
Z (ll)	2015, 2.3 fb	EXO-16-010
Z (ll)	2016, 12.9 fb	EXO-16-038
Higgs (bb)	2015, 2.3 fb	EXO-16-012
Higgs (γγ)	2015, 2.3 fb	EXO-16-011
tt (semilep+had)	2015, 2.2 fb	EXO-16-005
t (hadronic)	2016, 12.9 fb	EXO-16-040

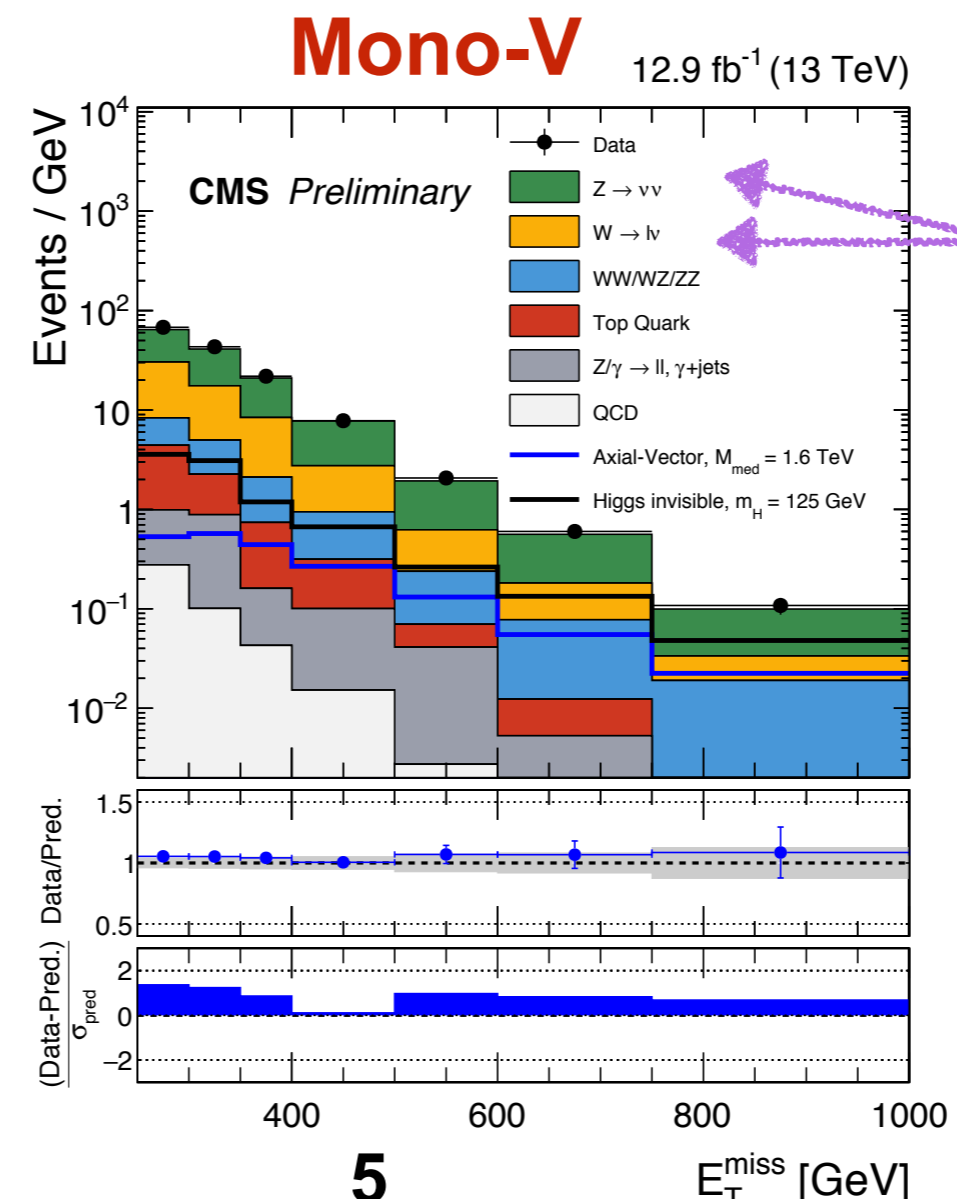
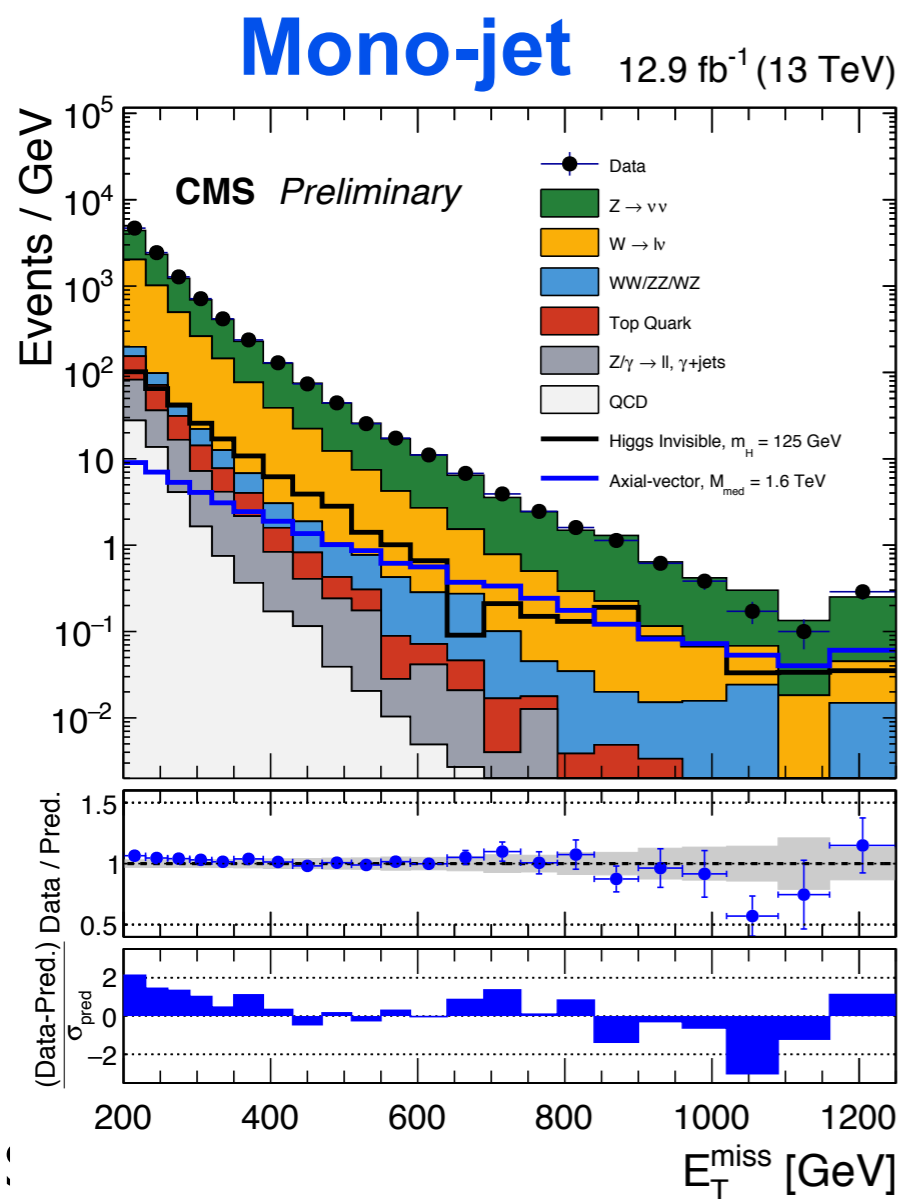
Previous Results

jet or V (hadronic)	2015, 2.3 fb	EXO-16-013
photon	2015, 2.3 fb	EXO-16-014
bb and tt	2015, 2.2 fb	B2G-15-007
t (hadronic)	2015, 2.3 fb	EXO-16-017

Mono-Jet/Jets/Hadronic W And Z

2016 data

- Look for large E_T^{miss} and ≥ 1 high- p_T jet, veto e, μ, τ, γ, b -jet
 - **Mono-V:** $p_{Tj1}^{\text{AK8}}, E_T^{\text{miss}} > 250$ GeV, mass 65-105 GeV, $\tau_{21} < 0.6$
 - **Mono-jet:** remaining events $p_{Tj1}^{\text{AK4}} > 100$ GeV, $E_T^{\text{miss}} > 200$ GeV
- Fit background and signal predictions to E_T^{miss} in data



90% of the total background

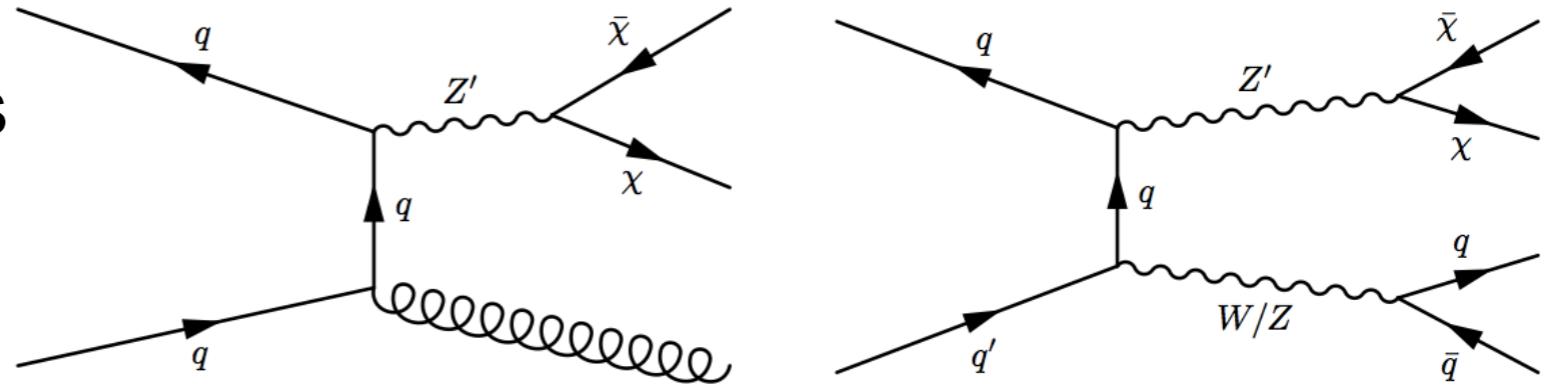
Modeled with 5 control regions ee/μμ/e/μ/γ

NLO QCD + EWK for the transfer factors

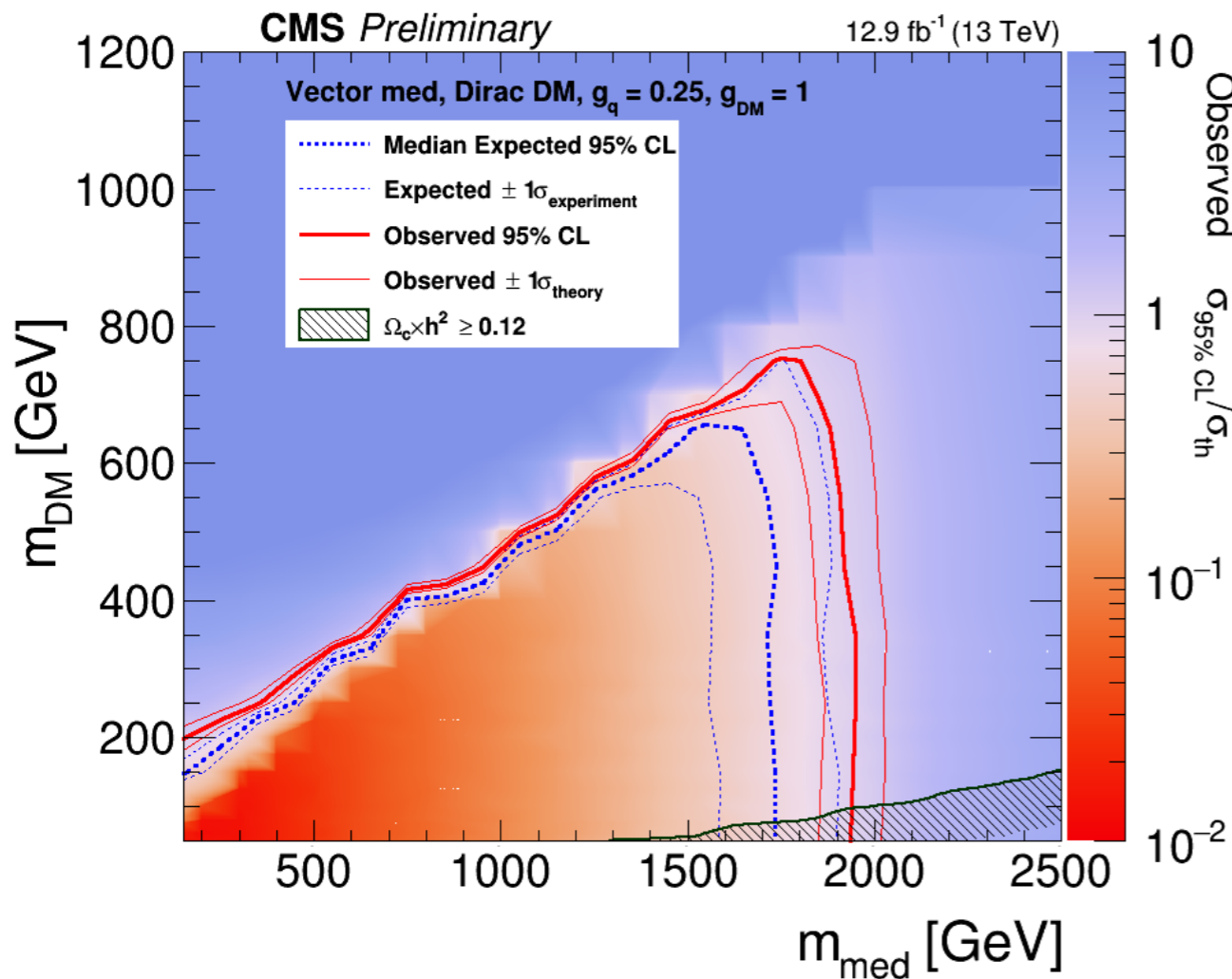
Mono-Jet/Jets/Hadronic W And Z

2016 data

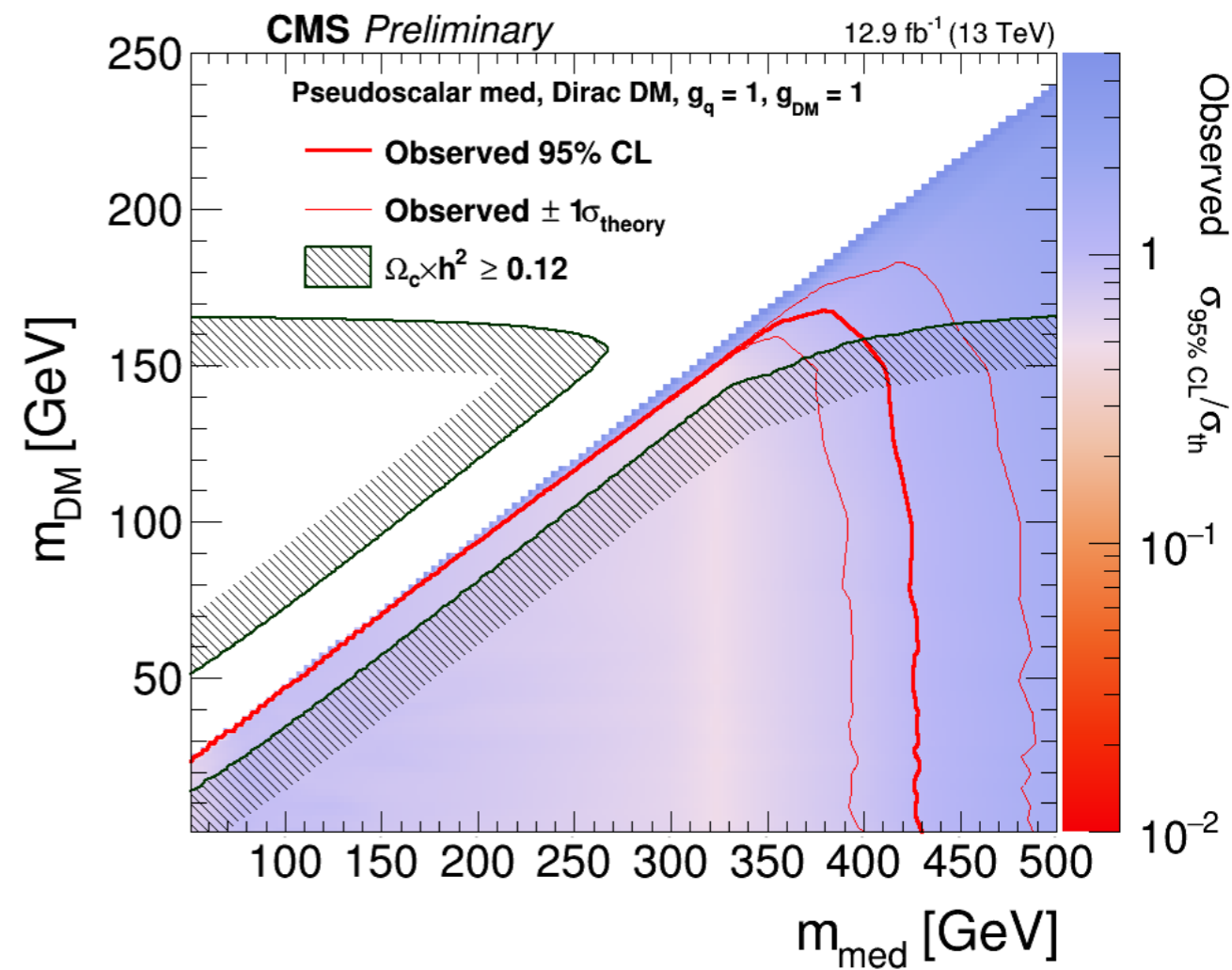
- No excess observed
- Vector/Axial mediator mass up to 1.95 TeV excluded
- (Pseudo) scalar mediator mass up to (430) 100 GeV



Vector Mediator



Pseudo-scalar Mediator

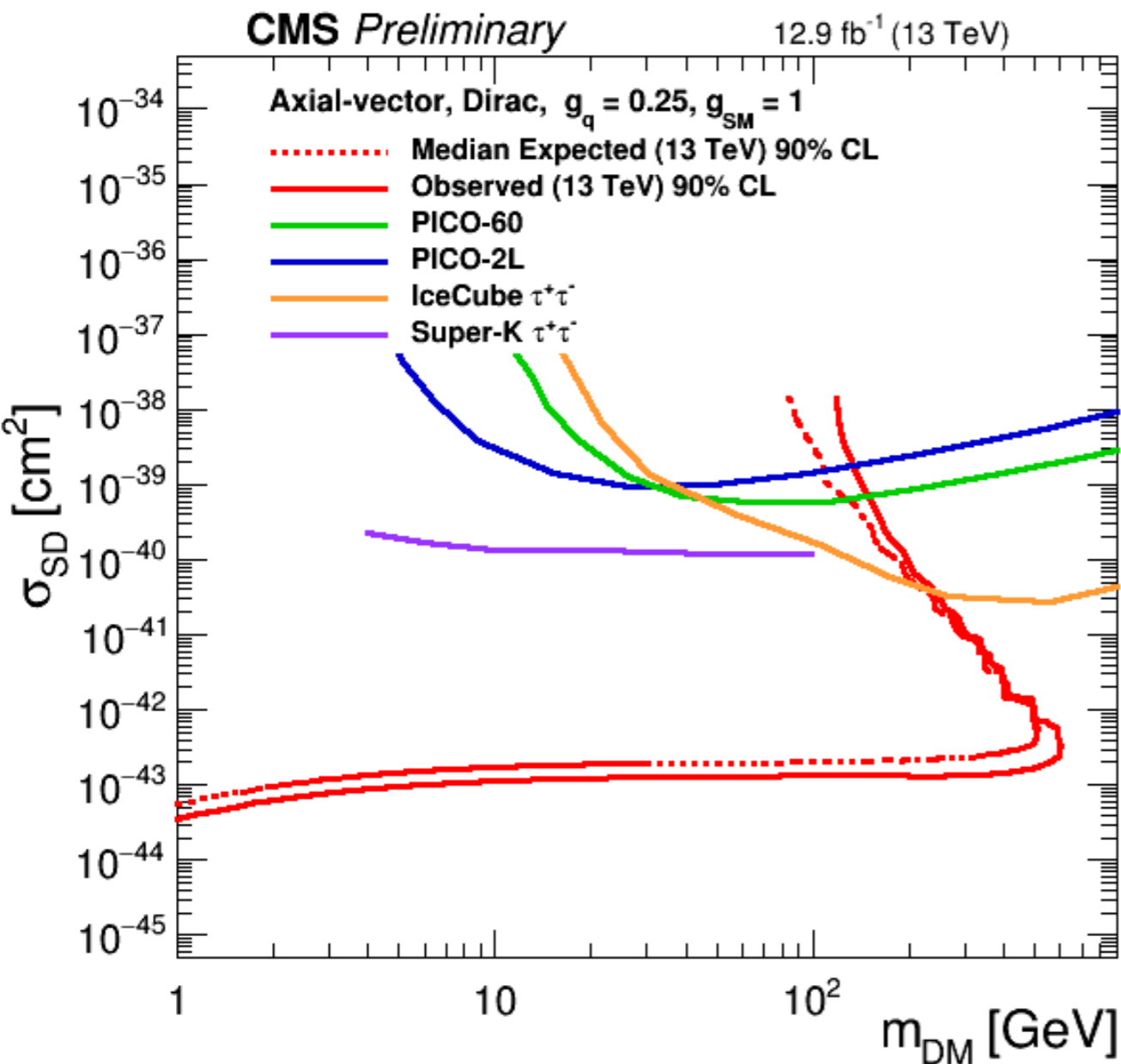


Mono-Jet/Jets/Hadronic W And Z

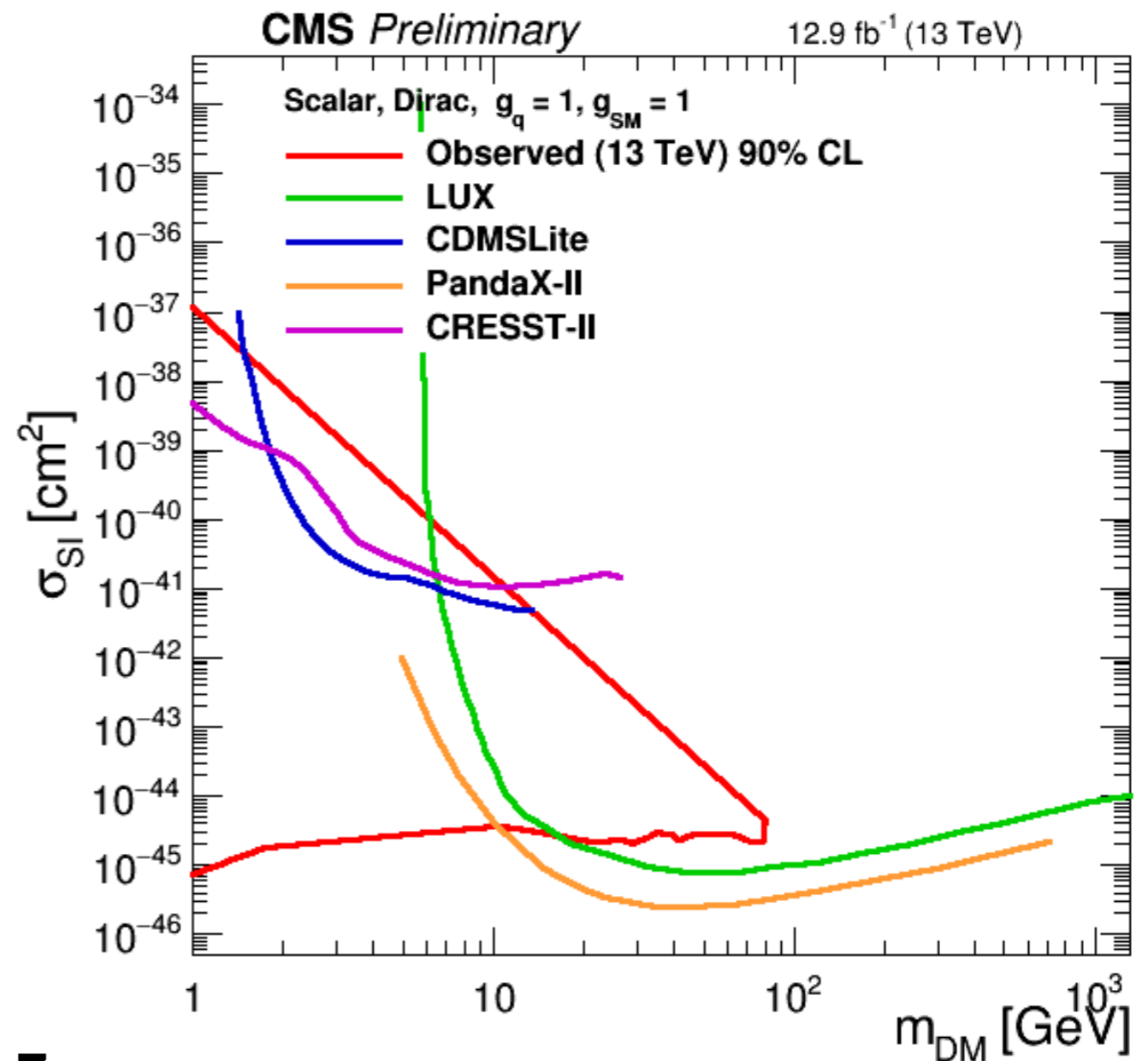
2016 data

- $\text{BR}(h(125) \rightarrow \text{invisible}) < 0.44$ (0.56 expected)
- Results recast to limits on SI/SD DM-nucleon scattering cross sections

Axial-vector Mediator



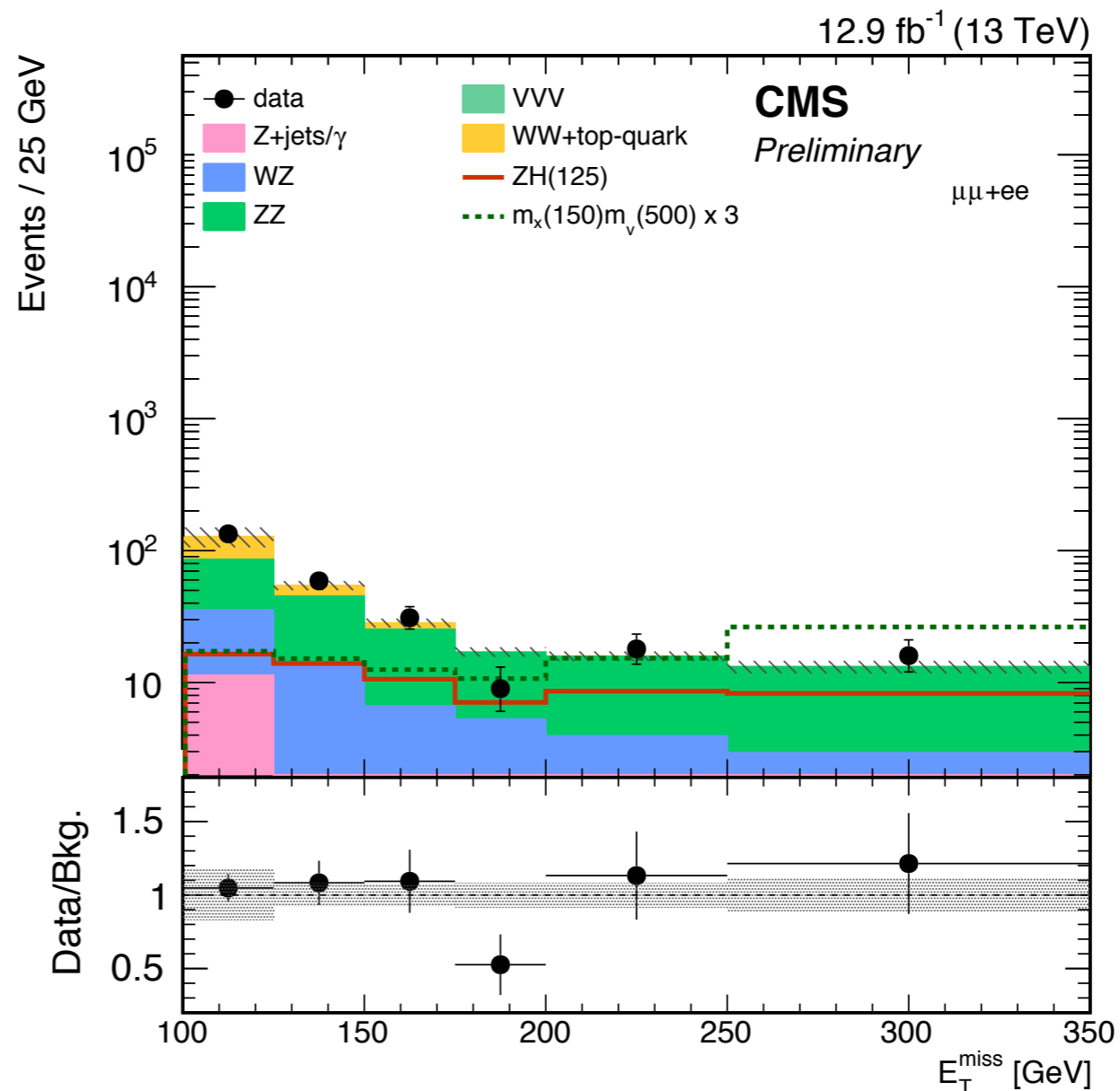
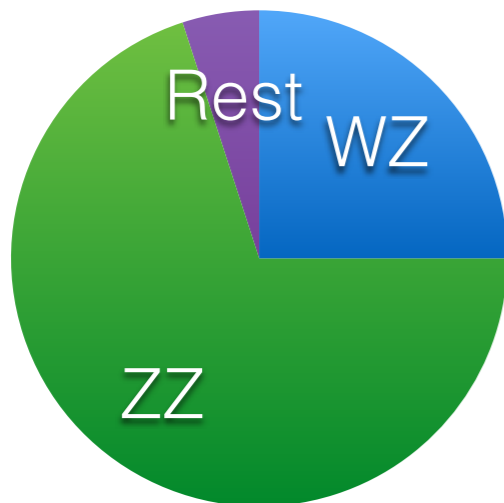
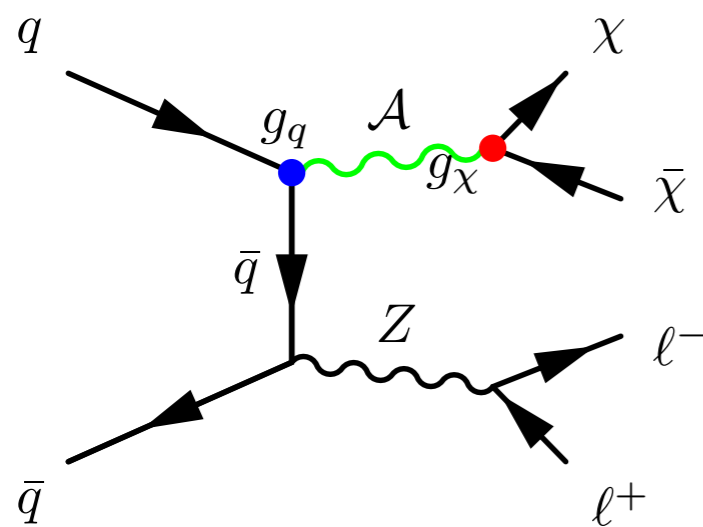
Scalar Mediator



Mono-Z (II)

2016 data

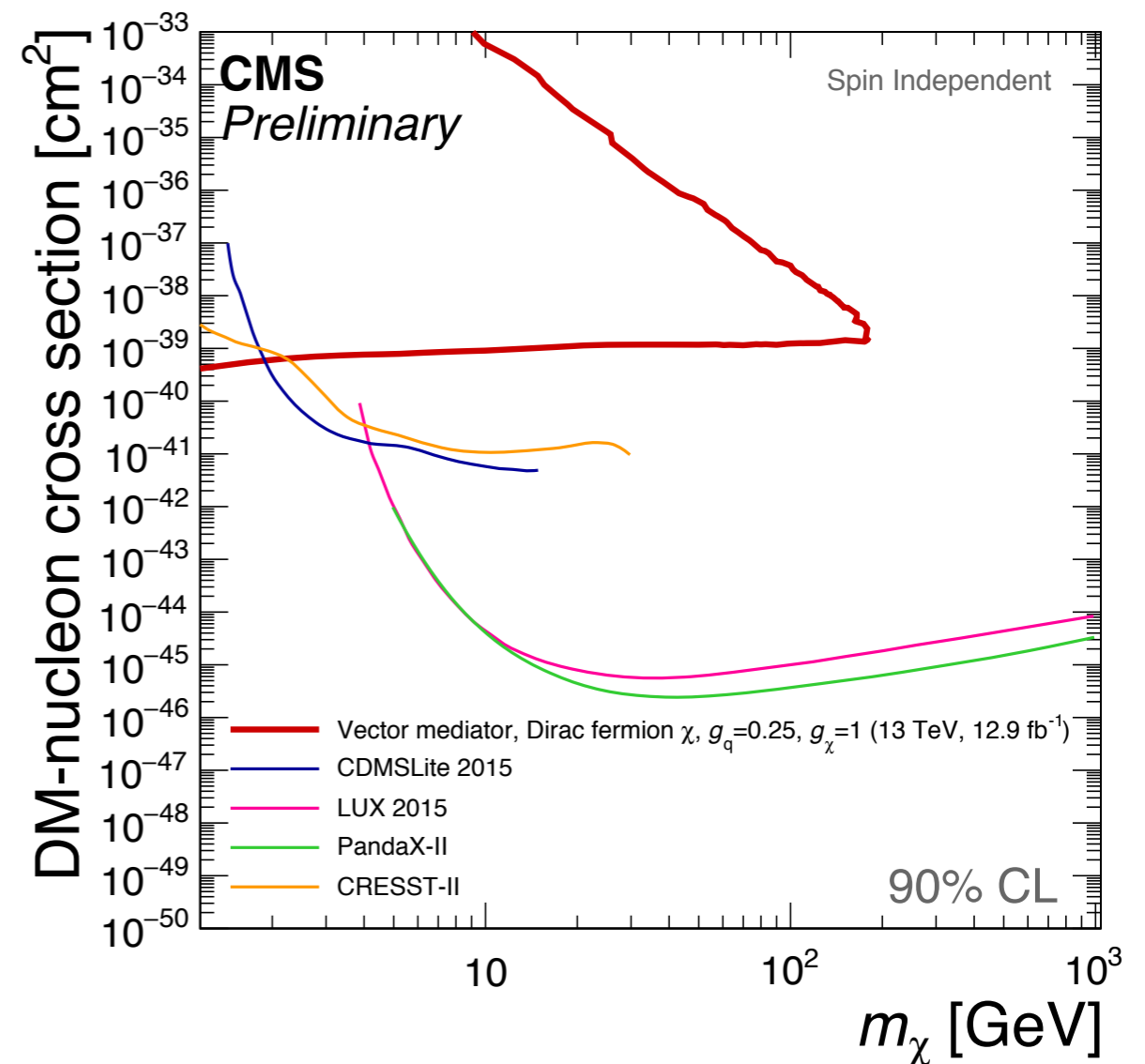
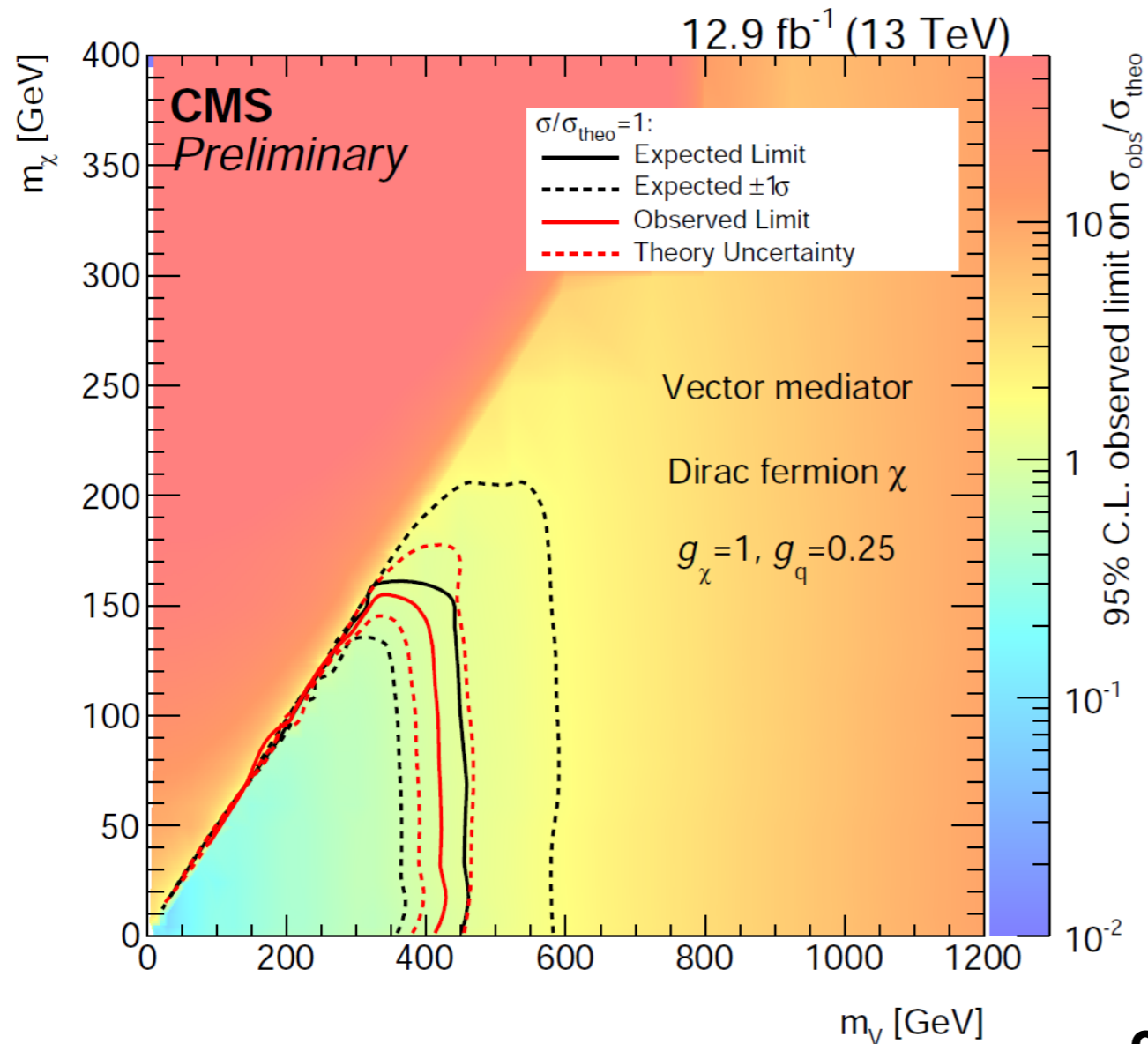
- Require $E_T^{\text{miss}} > 100$ GeV and $ee/\mu\mu$ with $p_{T^{\text{ll}}} > 60$ GeV, E_T^{miss} and $p_{T^{\text{ll}}}$ balance, veto extra e, μ, τ, b -jet, events with more than 1 jet
- ZZ/WZ background estimated with MC (with NNLO QCD and NLO EWK corrections), $tt, W, WW, tW, Z \rightarrow \tau\tau$ background estimated from the $e\mu$ data



Mono-Z (II)

2016 data

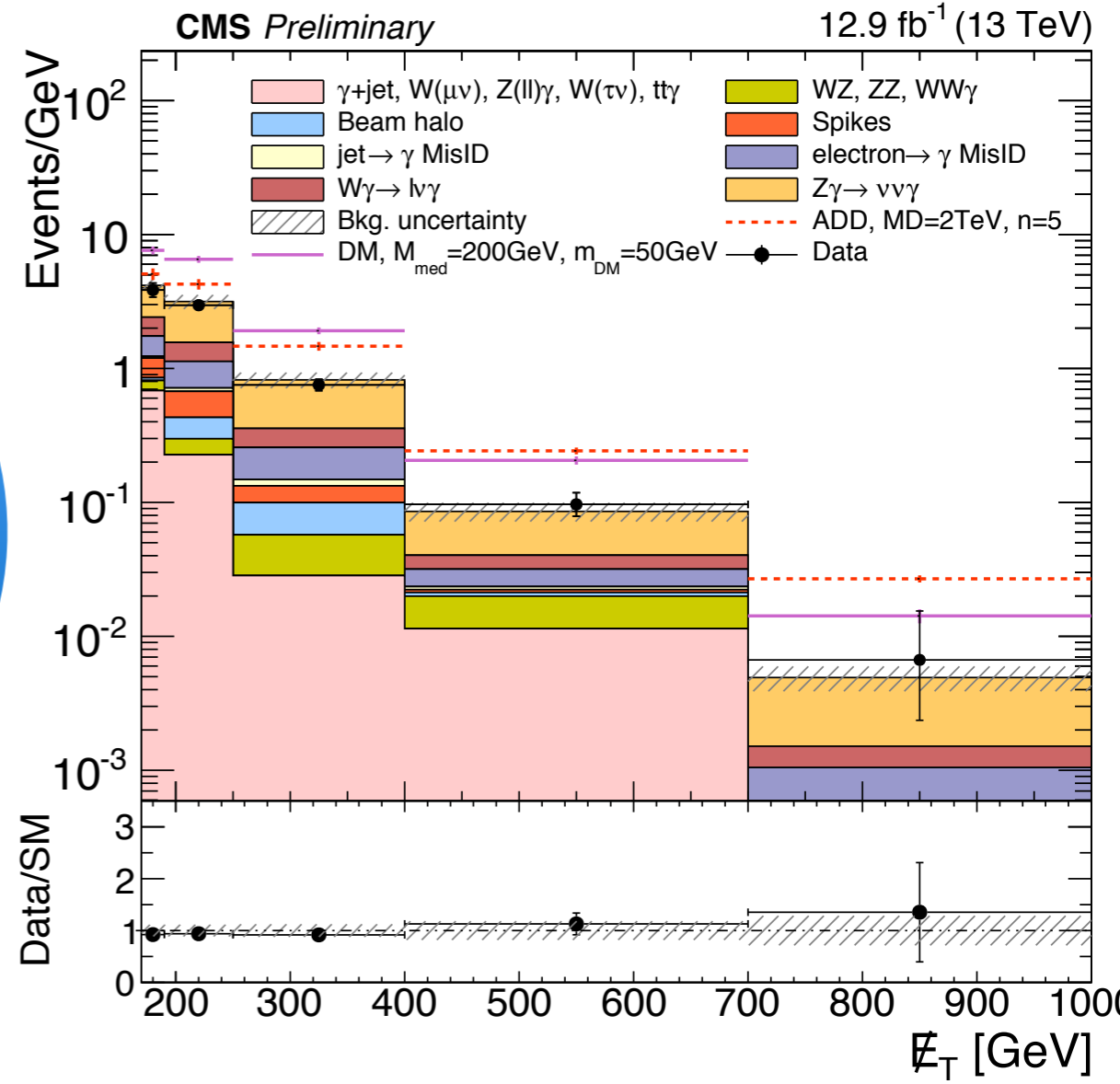
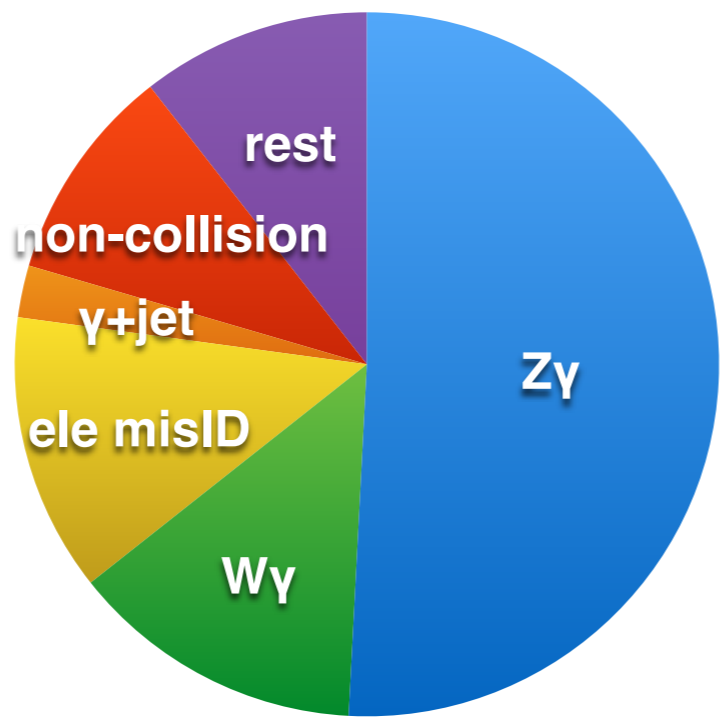
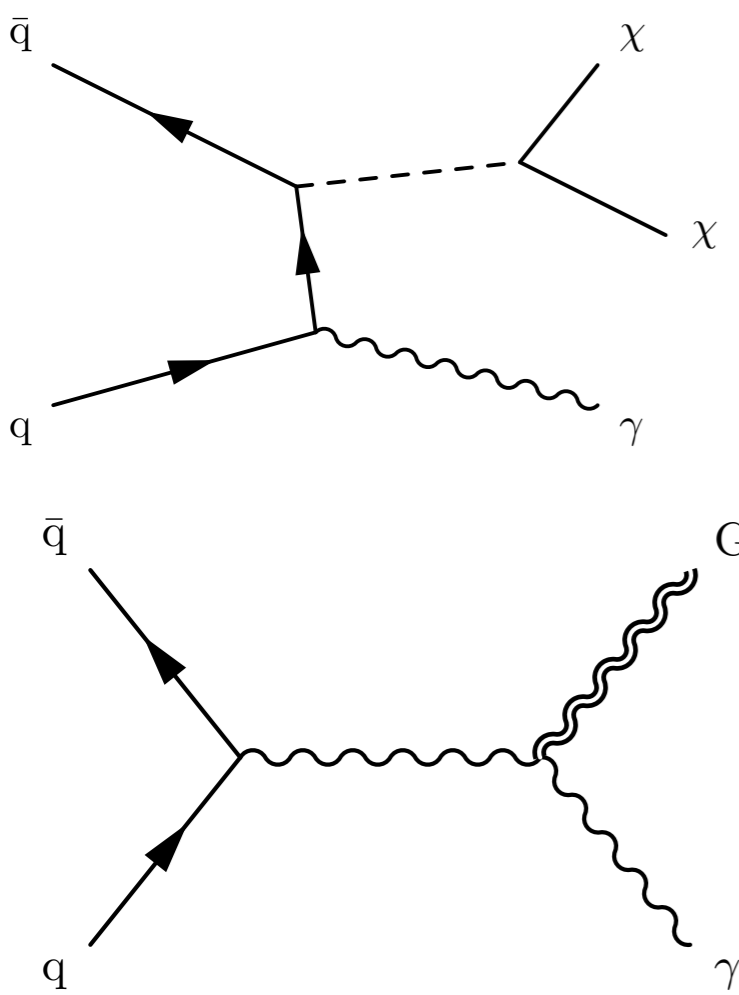
- No excess observed. Limits on cross section with 2D-scan of m_{DM} vs M_{MED} for vector/axial mediators
- $BR(h(125) \rightarrow \text{invisible}) < 0.86$ (0.70 expected), included $ggZh$
- See results of 2015 data in the backup slides



Mono-Photon

2016 data

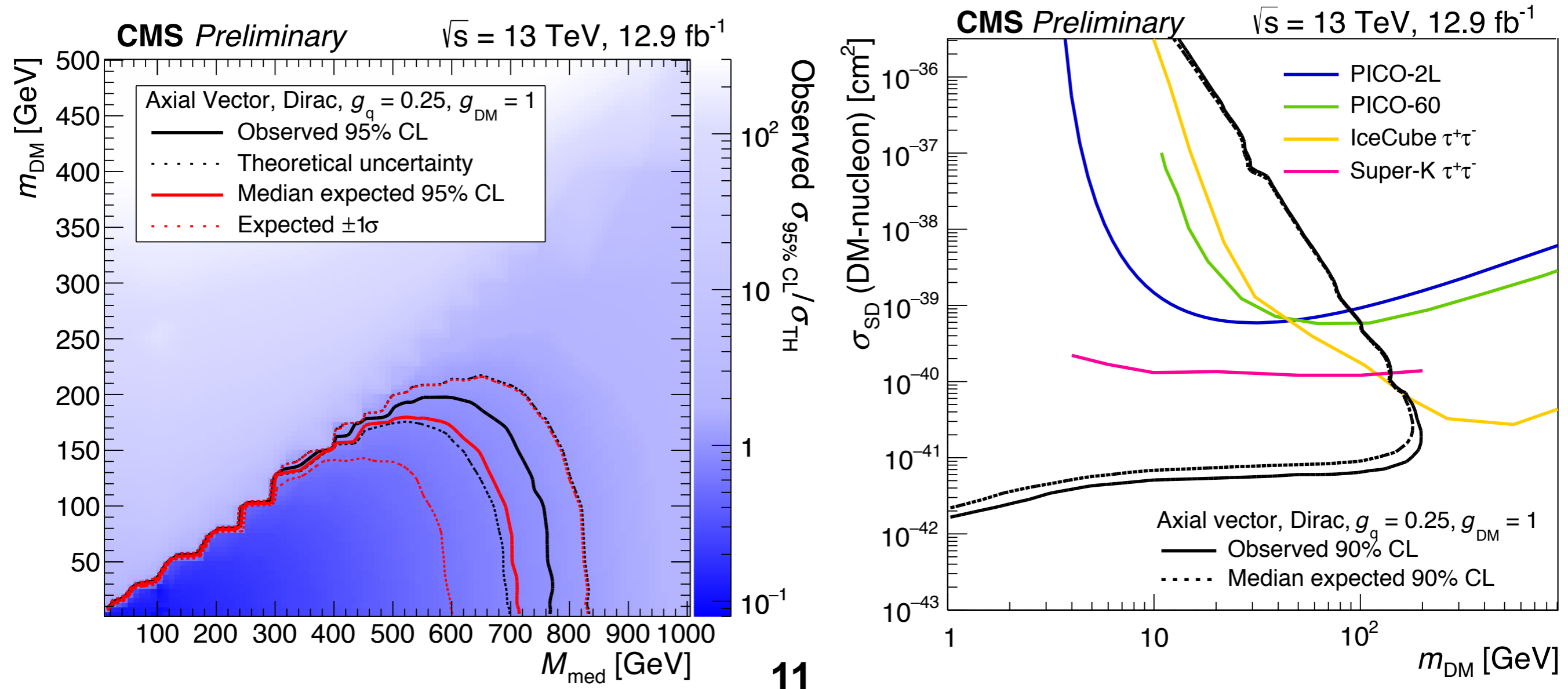
- Look for events with $E_T^{\text{miss}} > 170$ GeV and ≥ 1 central photon with $p_T > 175$ GeV, veto e, μ
- $Z(\nu\nu)\gamma$ and $W(l\nu)\gamma$ estimated using MC with NNLO QCD (DYRES) +NLO EWK corrections, misID and non-collision background estimated from data



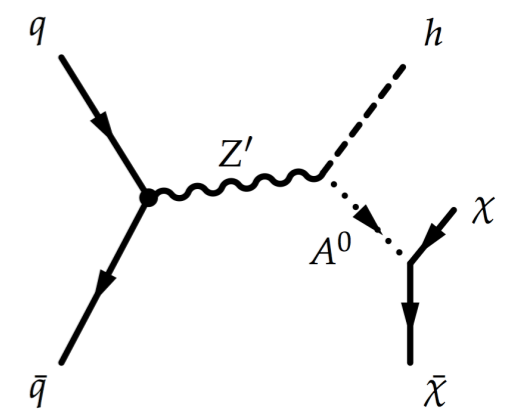
Mono-Photon

2016 data

- No excess observed, set limits on DM and ADD LED graviton
 - Mediator mass up to 760 GeV excluded (vector/axial vector)
 - Dim-7 EFT scale Λ up to 620 GeV excluded
 - ADD LED $M_D > 2.44$ to 2.60 TeV for $n=3$ to $n=6$ extra dimension



Mono-Higgs (bb, $\gamma\gamma$)



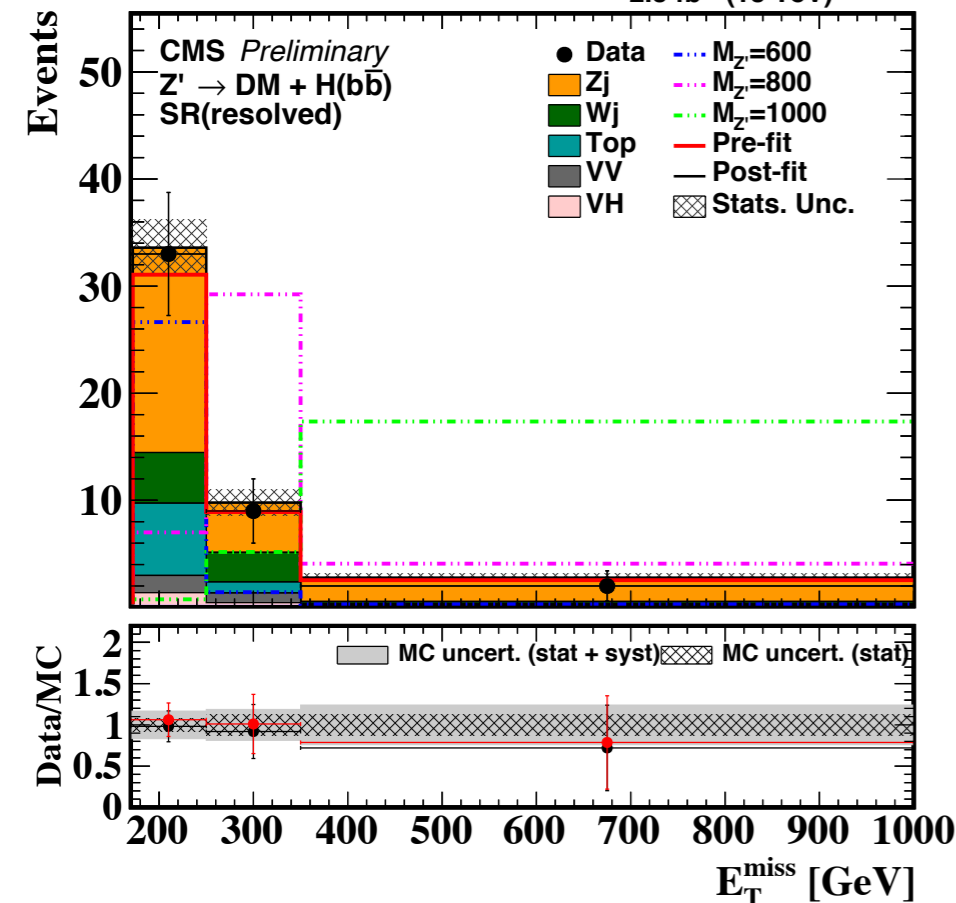
- Higgs \rightarrow bb

- Resolved: 2 AK4 b-tagged jets, $p_T^{bb} / E_T^{\text{miss}} > 150 / 170$ GeV
- Boosted: 1 AK8 jet with subjets b-tagged, $p_T^j / E_T^{\text{miss}} > 200$ GeV

- Higgs \rightarrow $\gamma\gamma$: $E_T^{\text{miss}} > 105$ GeV, $p_T^{\gamma\gamma} > 90$ GeV, $p_T^{\gamma^1} (p_T^{\gamma^2}) / m^{\gamma\gamma} > 0.5$ (0.25)

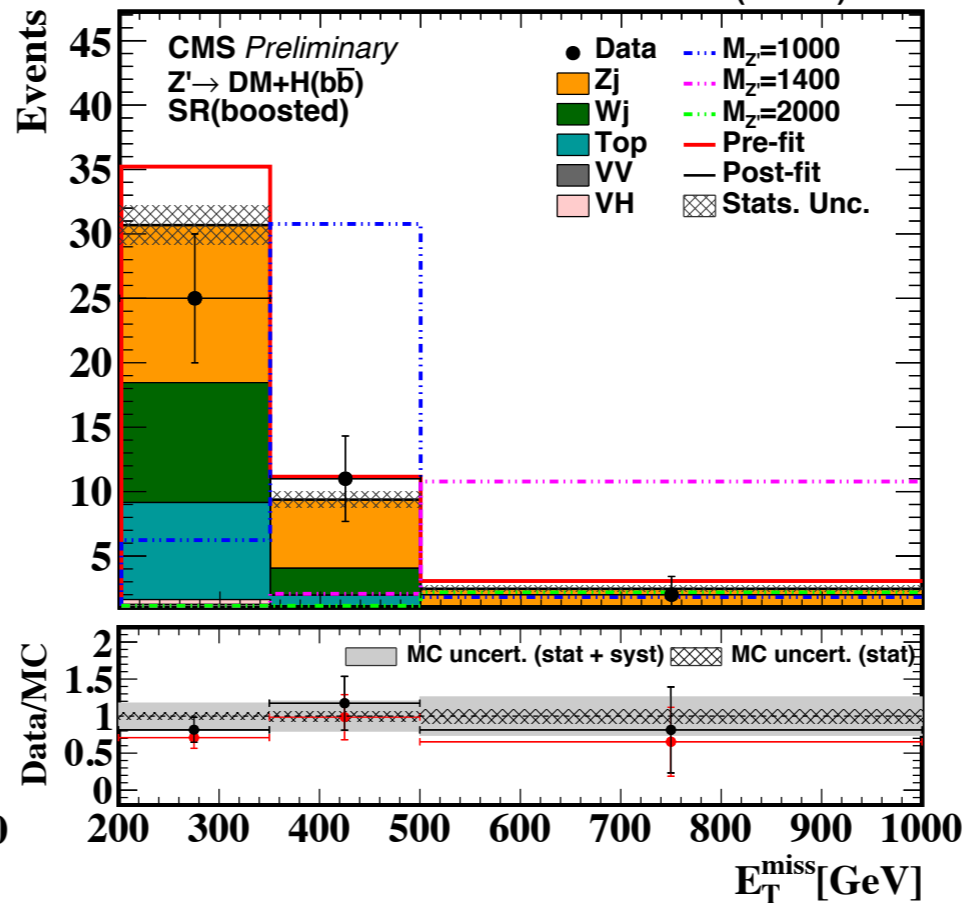
H \rightarrow bb Resolved

2.3 fb⁻¹ (13 TeV)



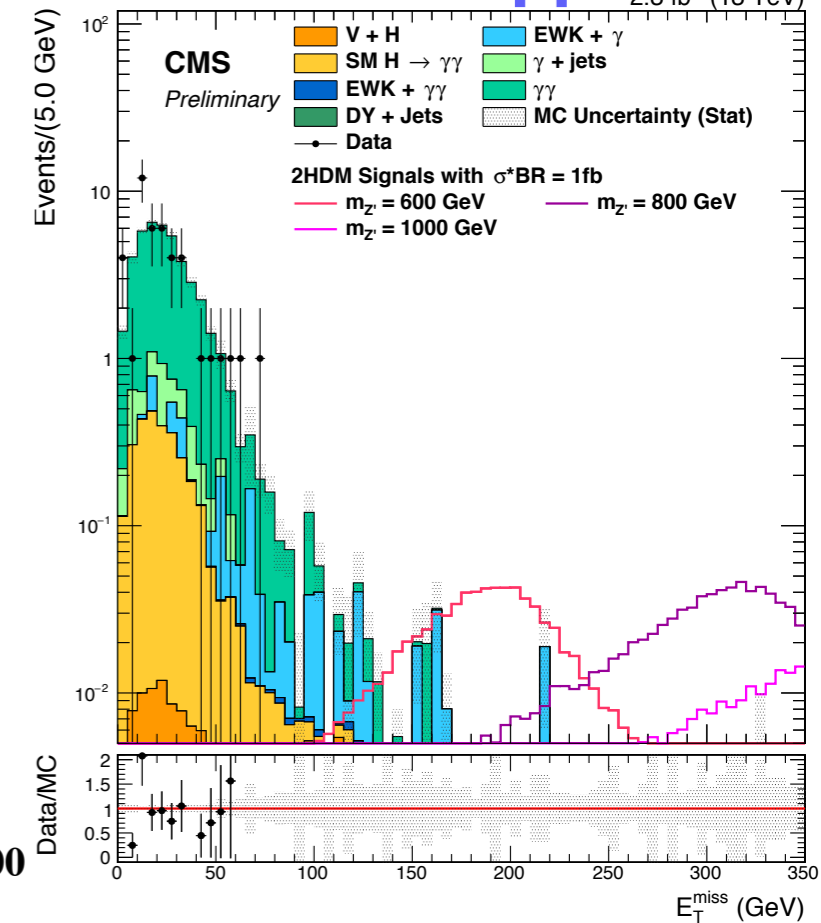
H \rightarrow bb Boosted

2.3 fb⁻¹ (13 TeV)



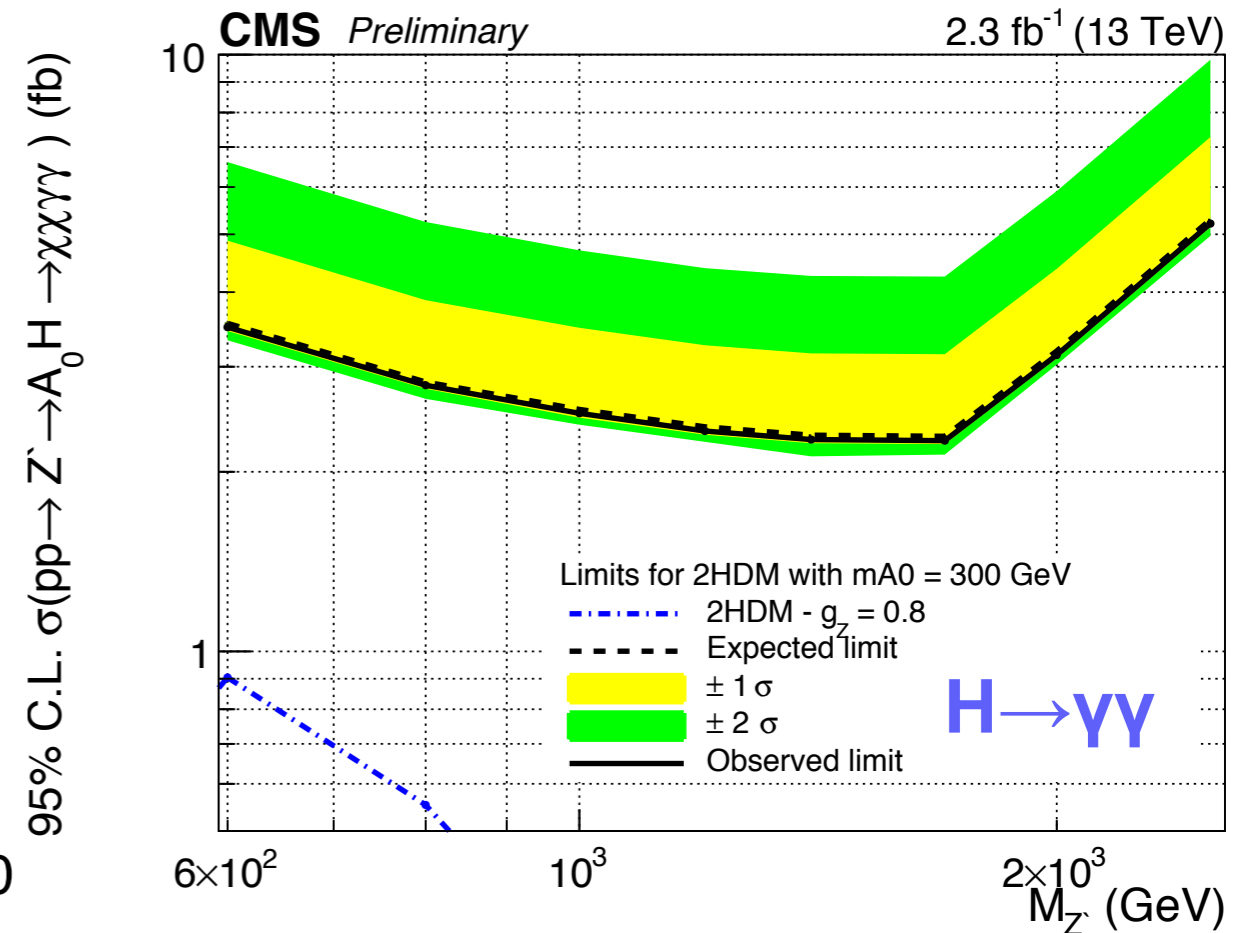
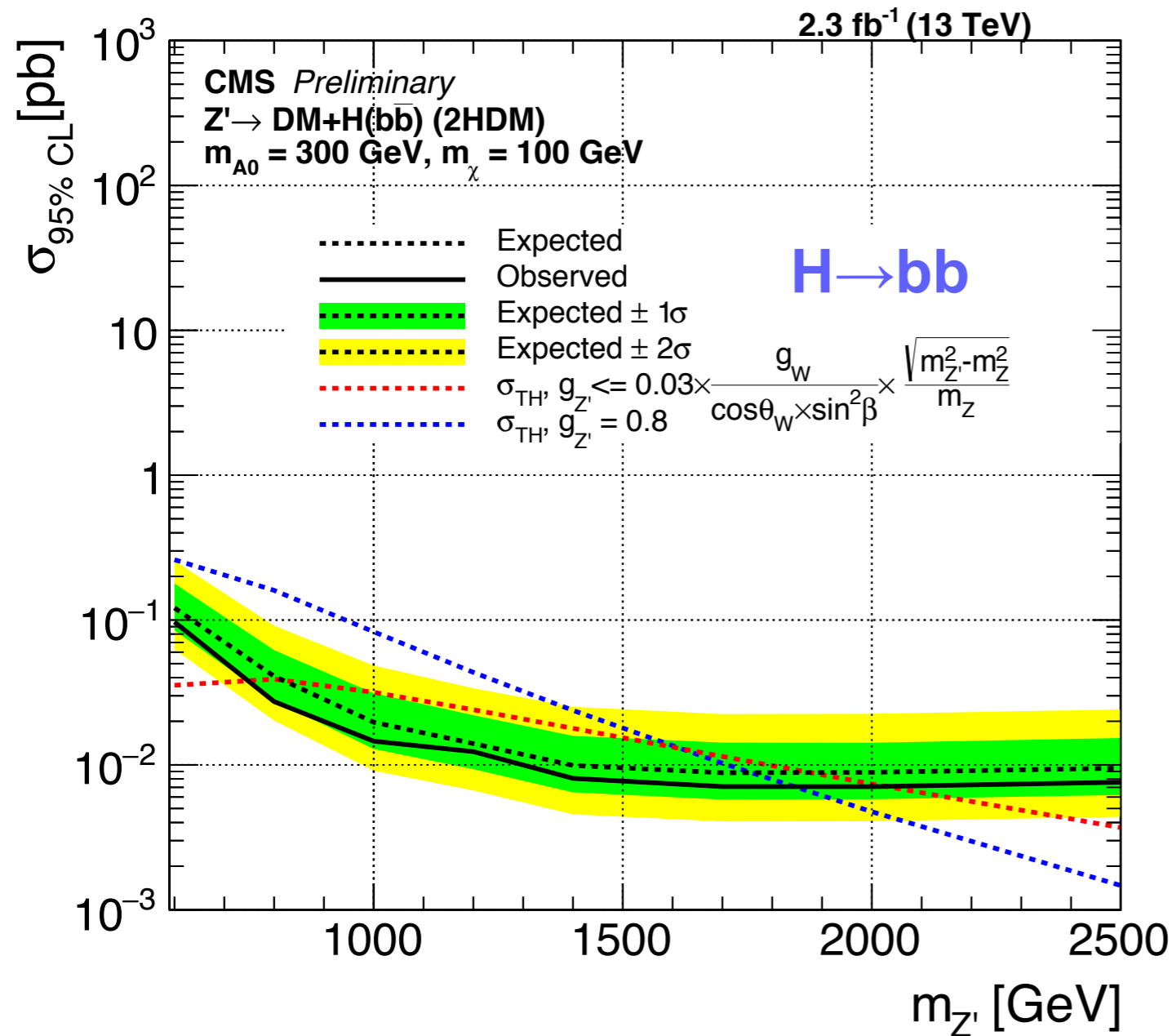
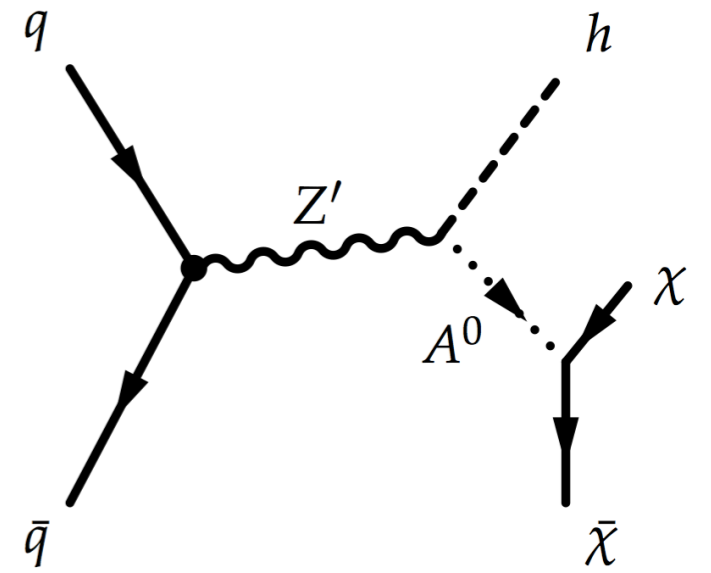
H \rightarrow $\gamma\gamma$

2.3 fb⁻¹ (13 TeV)



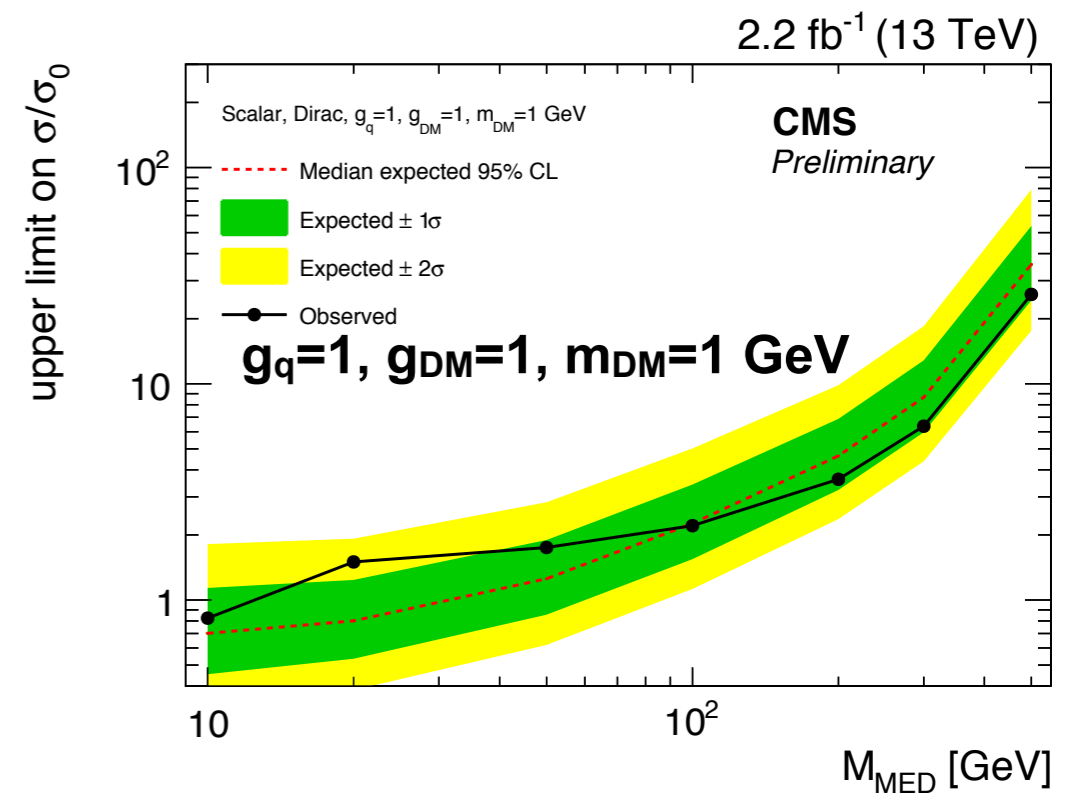
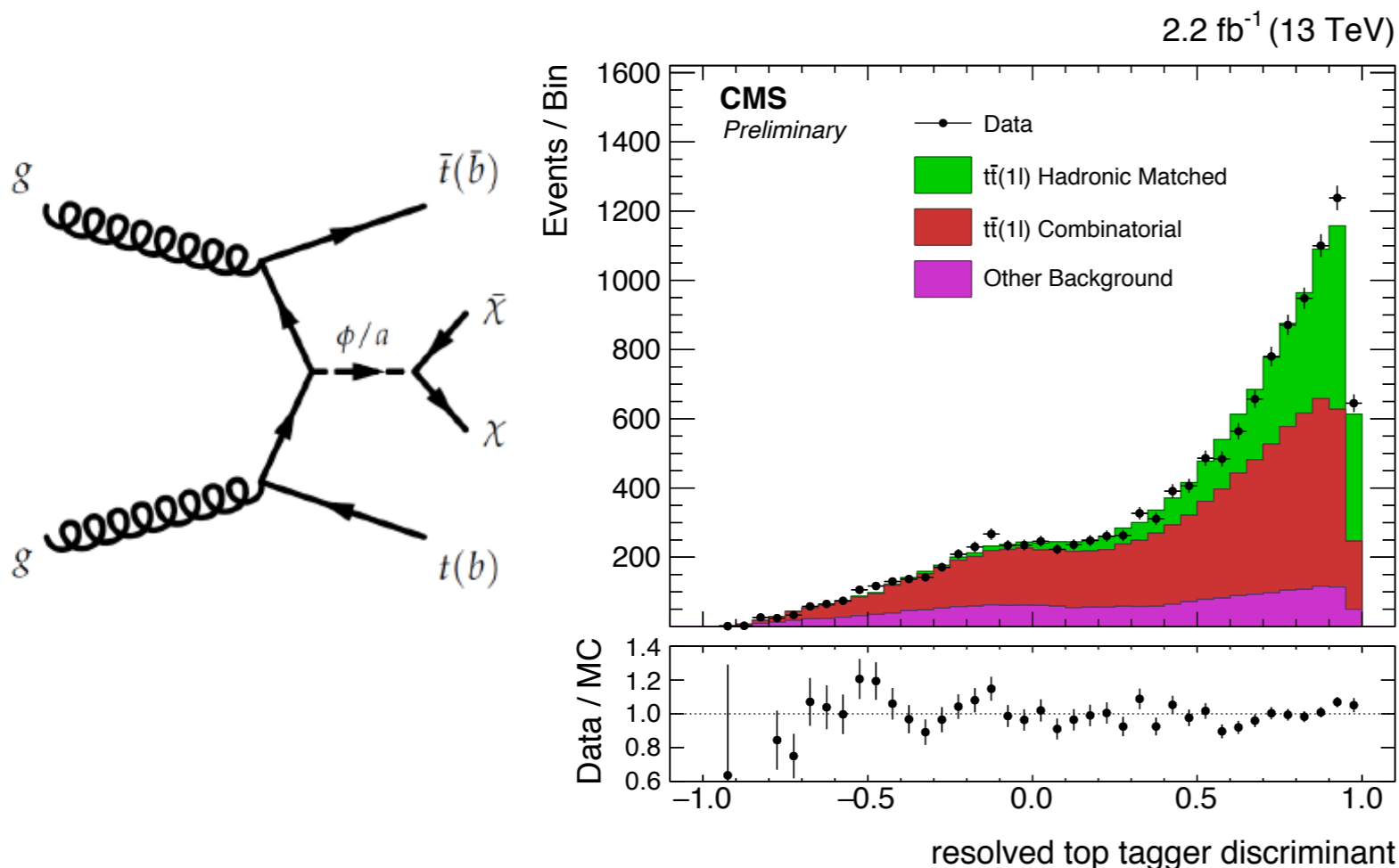
Mono-Higgs (bb, $\gamma\gamma$)

- No excess observed, set limits on Type-2 2HDM
 - Excluded $M_{Z'}=600$ (768) GeV to 1863 (2036) GeV with $g_z=0.8$ (formula)



Mono-tt

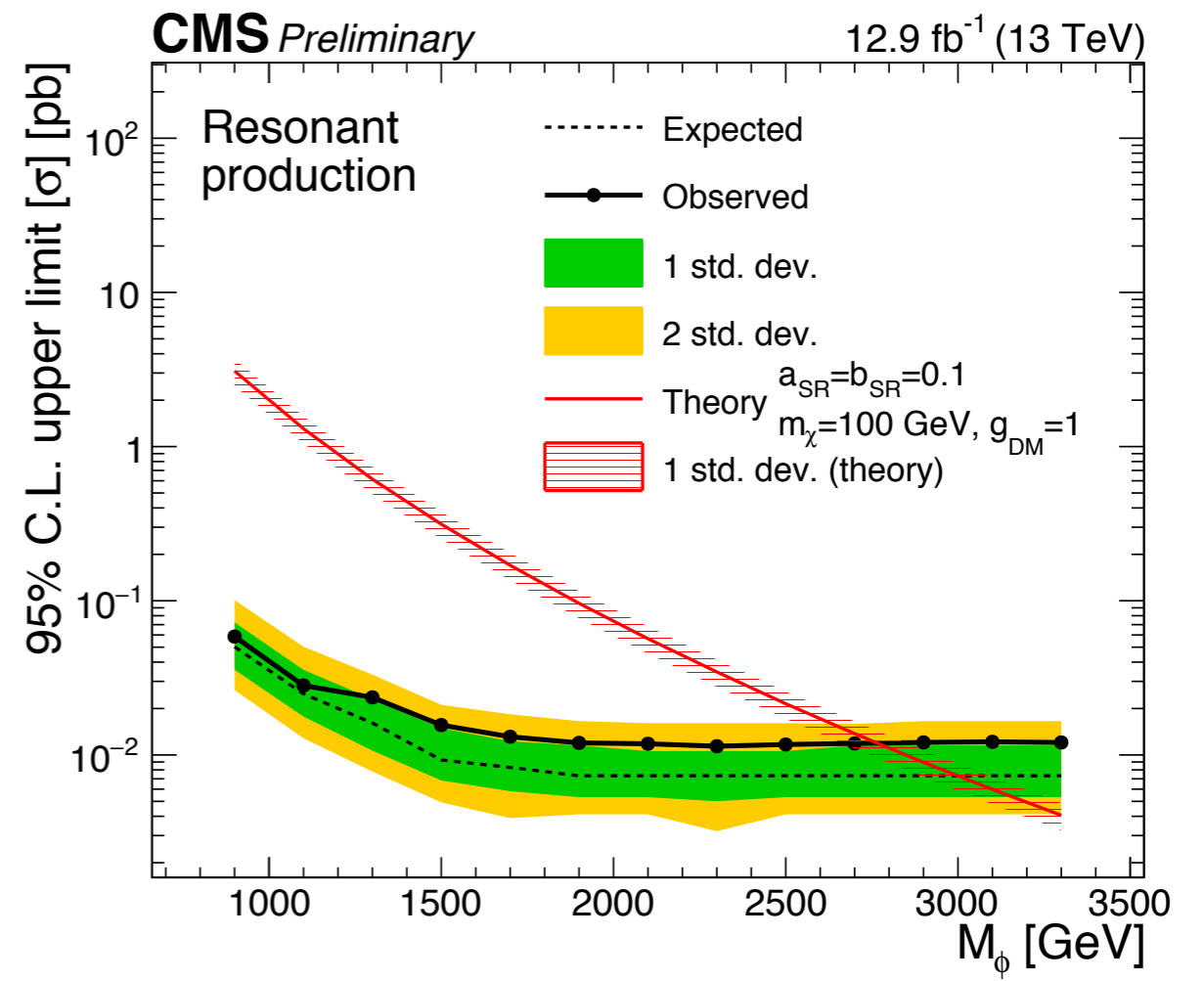
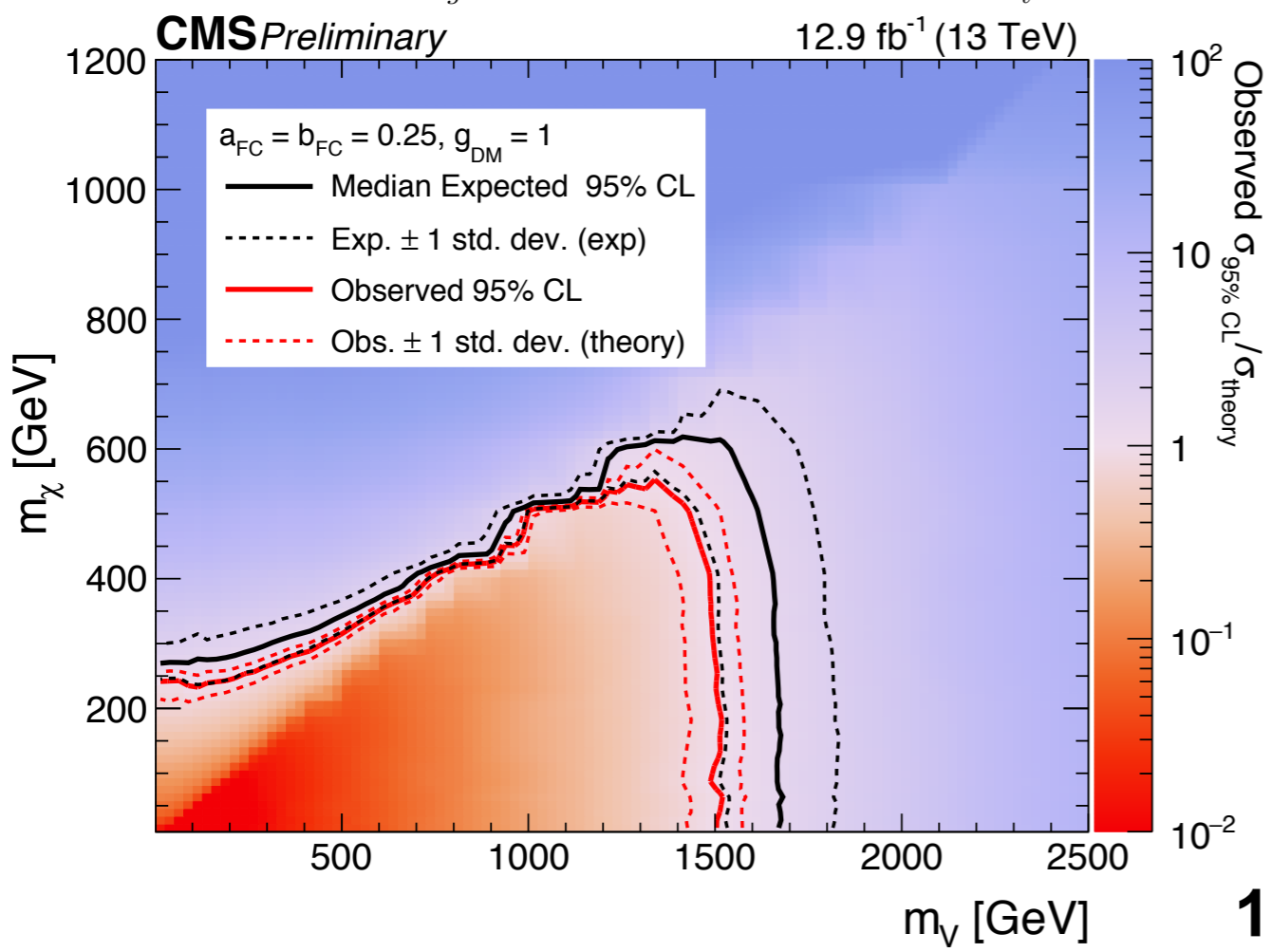
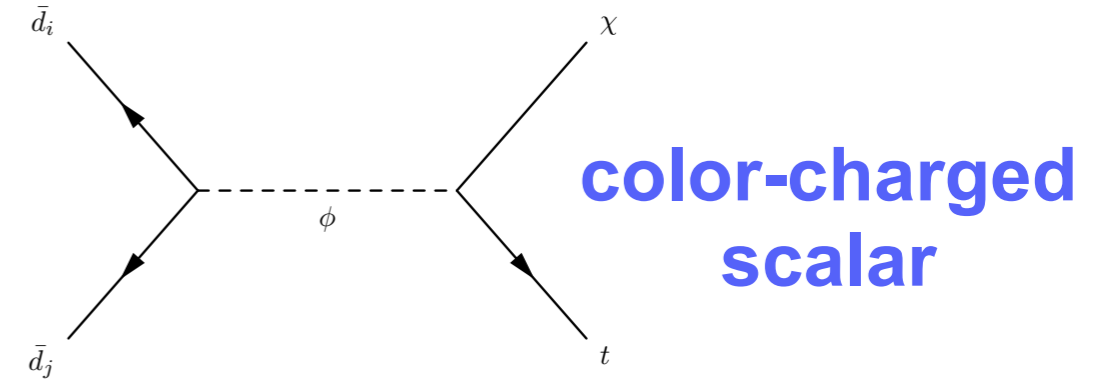
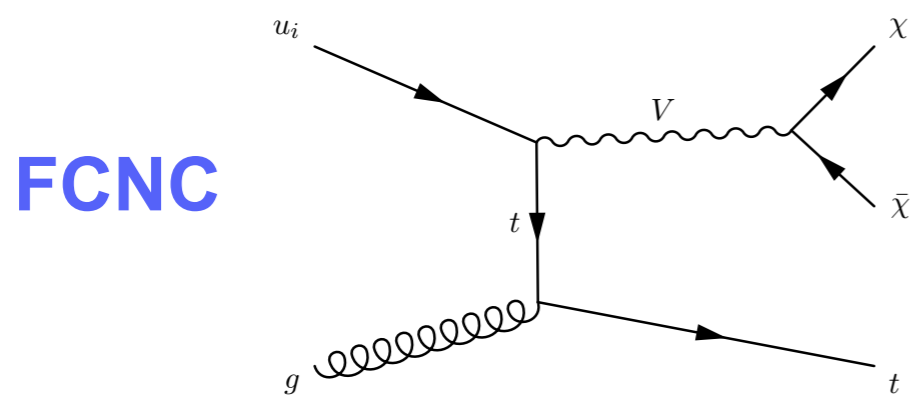
- Hadronic (semileptonic) channel with $E_T^{\text{miss}} > 200$ (160) GeV
- Major background from $t\bar{t}$ events with one less hadronic top
 - Apply resolved-hadronic-top tagger to the hadronic channel and categorize events based on the number of top tags, b-tagged jets, and $\Delta\Phi(\text{jet}, E_T^{\text{miss}})$, up to 30% improvement
- No excess observed, limits on scalar/pseudoscalar mediators



Mono-Top

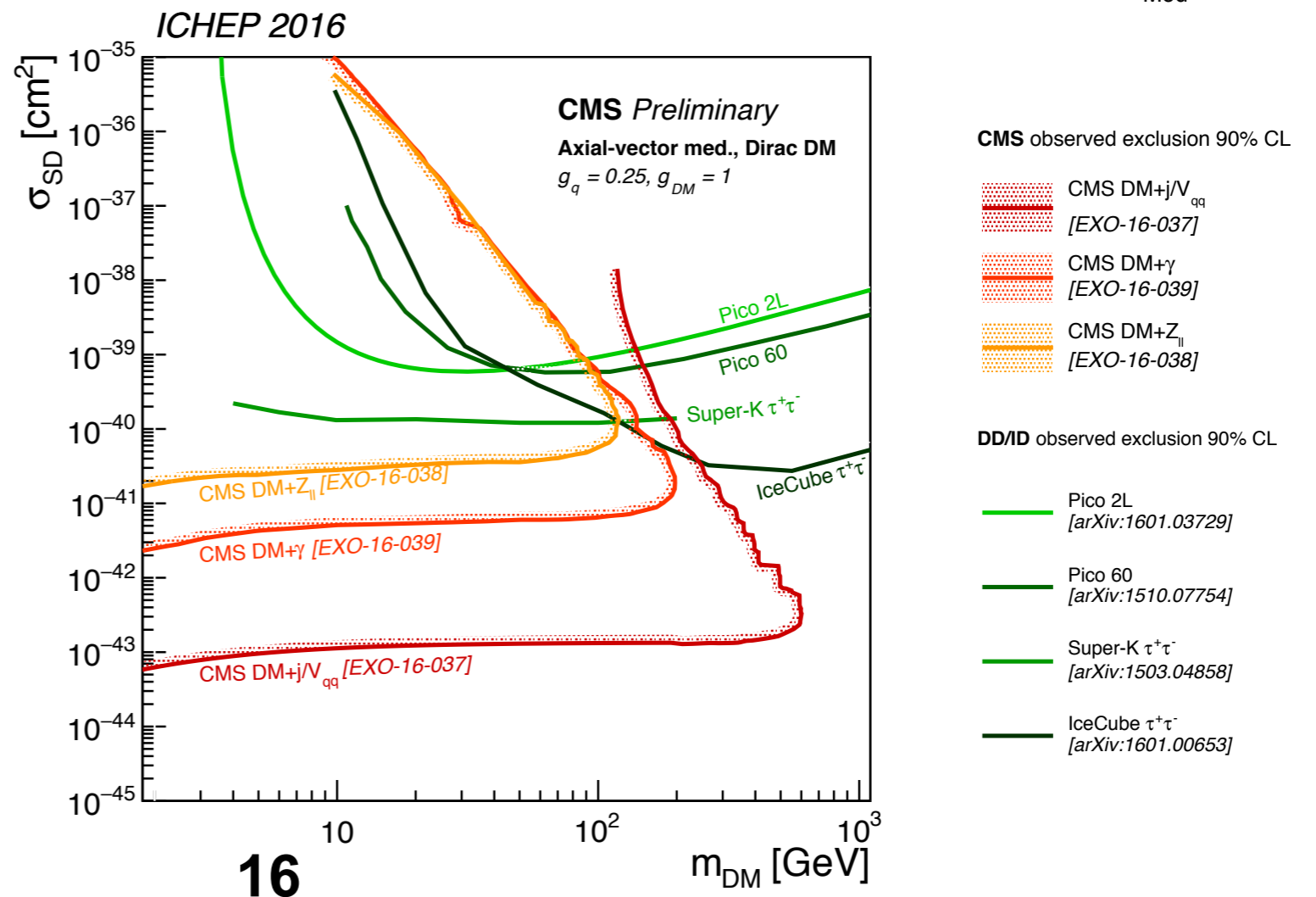
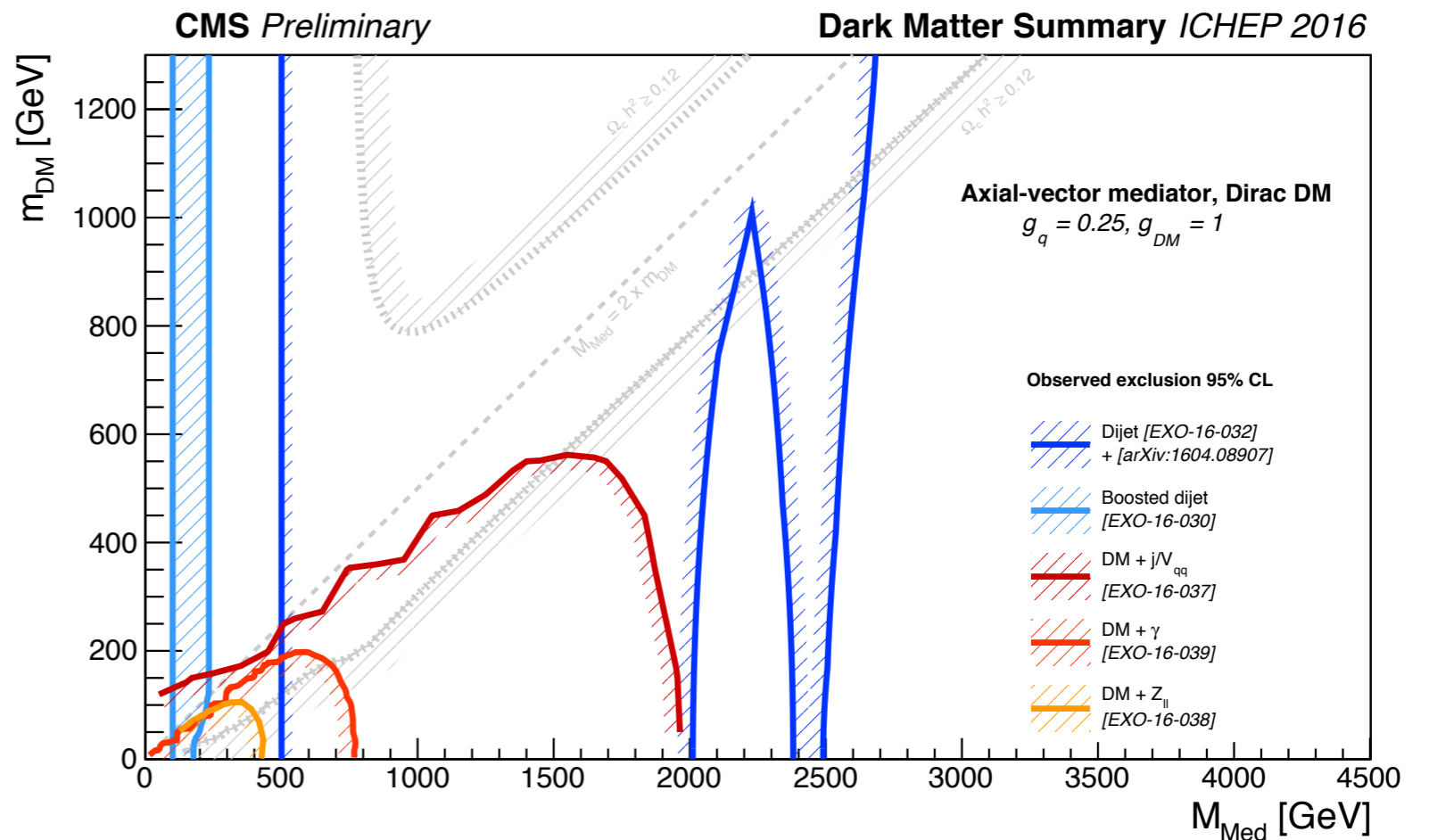
2016 data

- p_{Tj}^{CA15} and $E_T^{\text{miss}} > 250$ GeV, mass 110-210 GeV, τ_{32} , subjet b-tag
- Use PUPPI for pileup removal: JHEP10(2014)059
- FCNC vector up to 1.5 TeV, charged scalar 0.9-2.7 TeV excluded



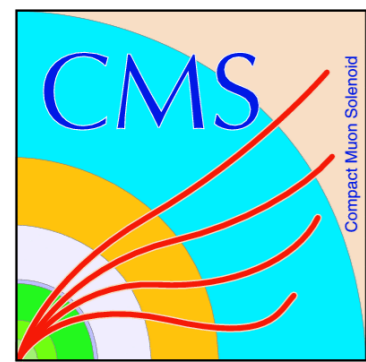
Summary Of Mono-X And Dijet Searches

- Fix $g_q=0.25$ and $g_{DM}=1$
- Reinterpret dijet searches with resolved and boosted jets
- Cover the off-shell region



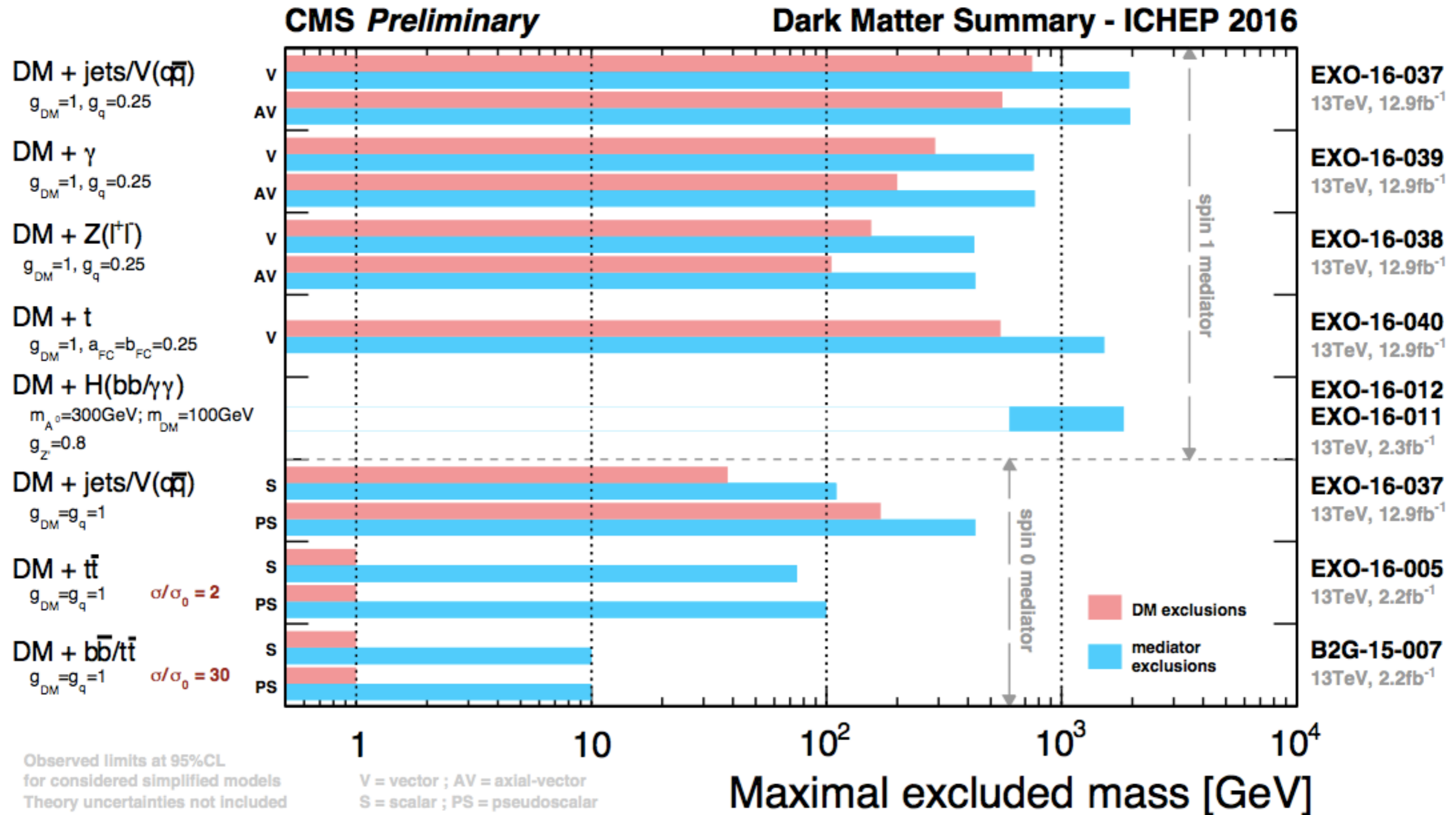
Conclusion And Outlook

- CMS searches for dark matter have been performed with various mono-X final states
 - Results with 2016 data from mono-jet/photon/Z/top
 - First results from mono-Higgs and mono-tt (hadronic)
- No sign of excess yet
 - Provide limits on simplified models and EFTs
 - Results were recast in terms of nucleon-DM scattering cross section
- Expect updates with the full 2016 data and combinations of different mono-X channels

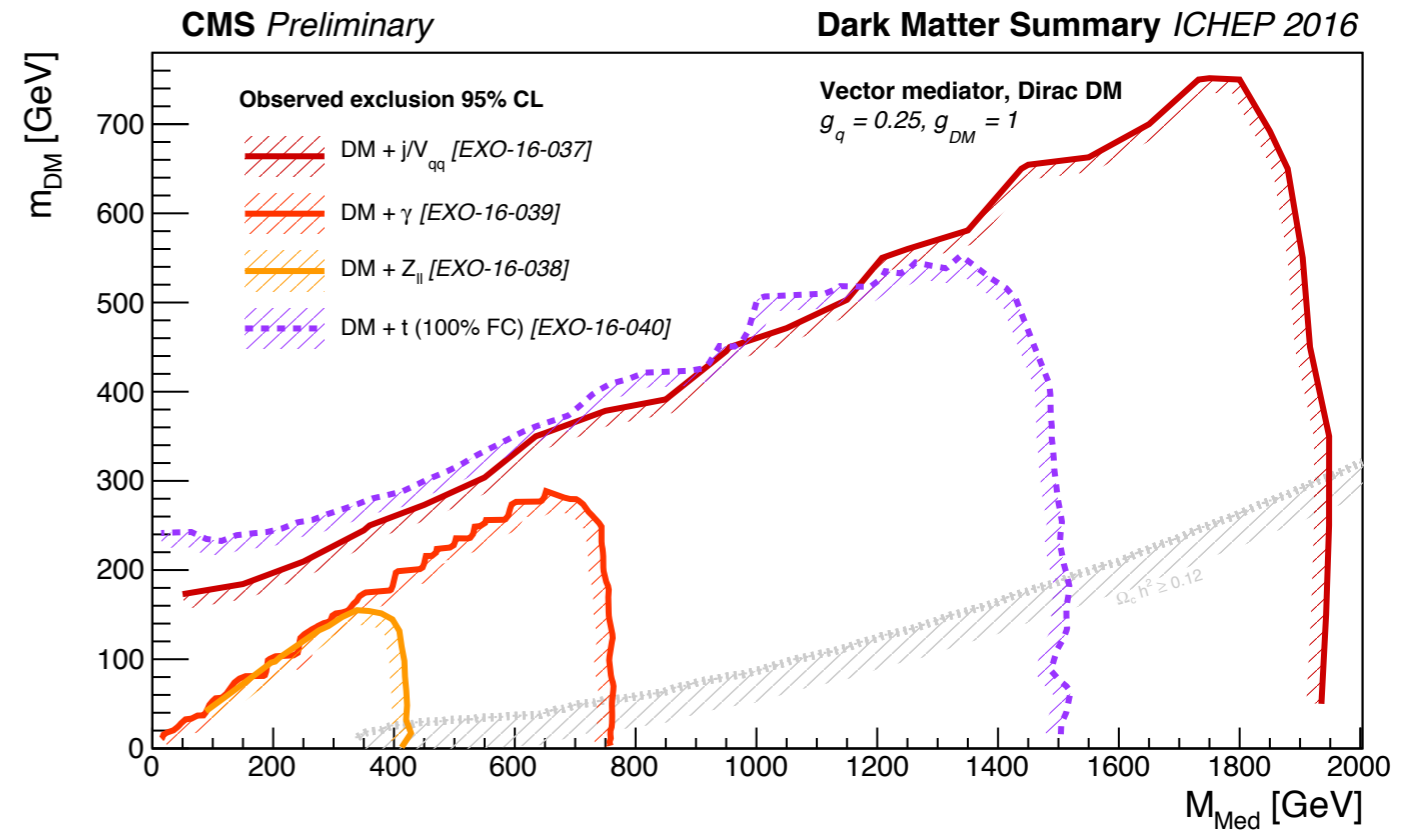
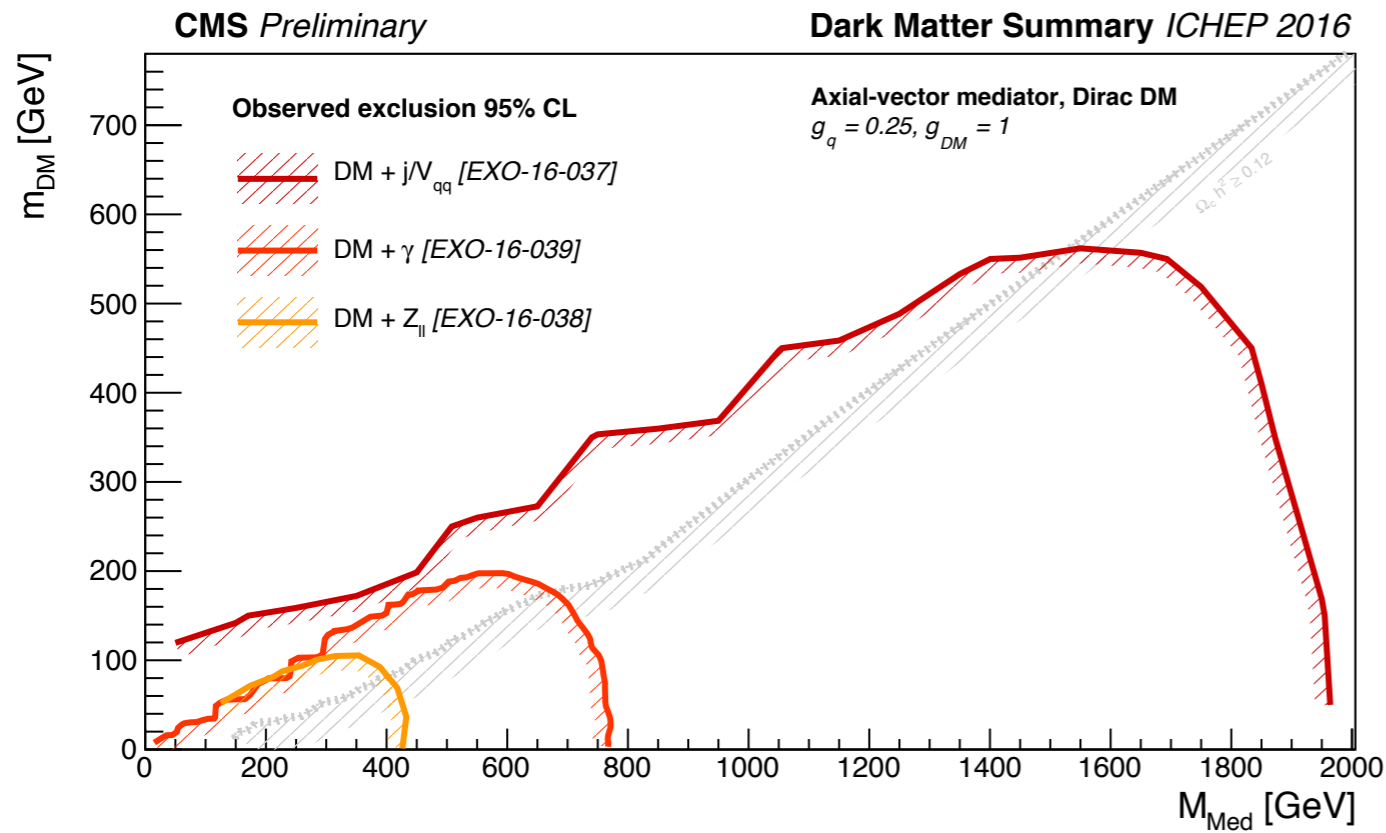


Backup Slides

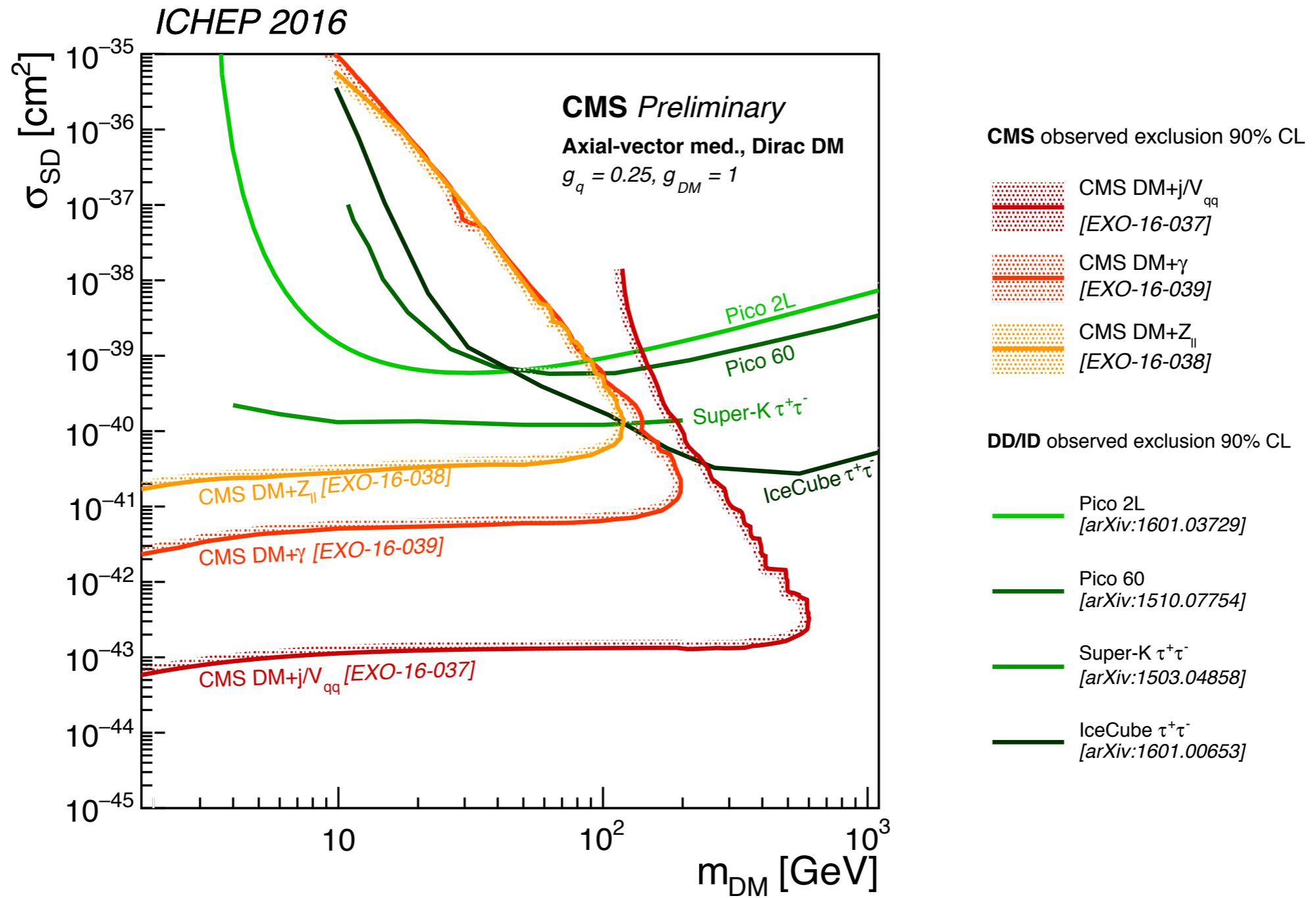
Summary Of All Mono-X Channels



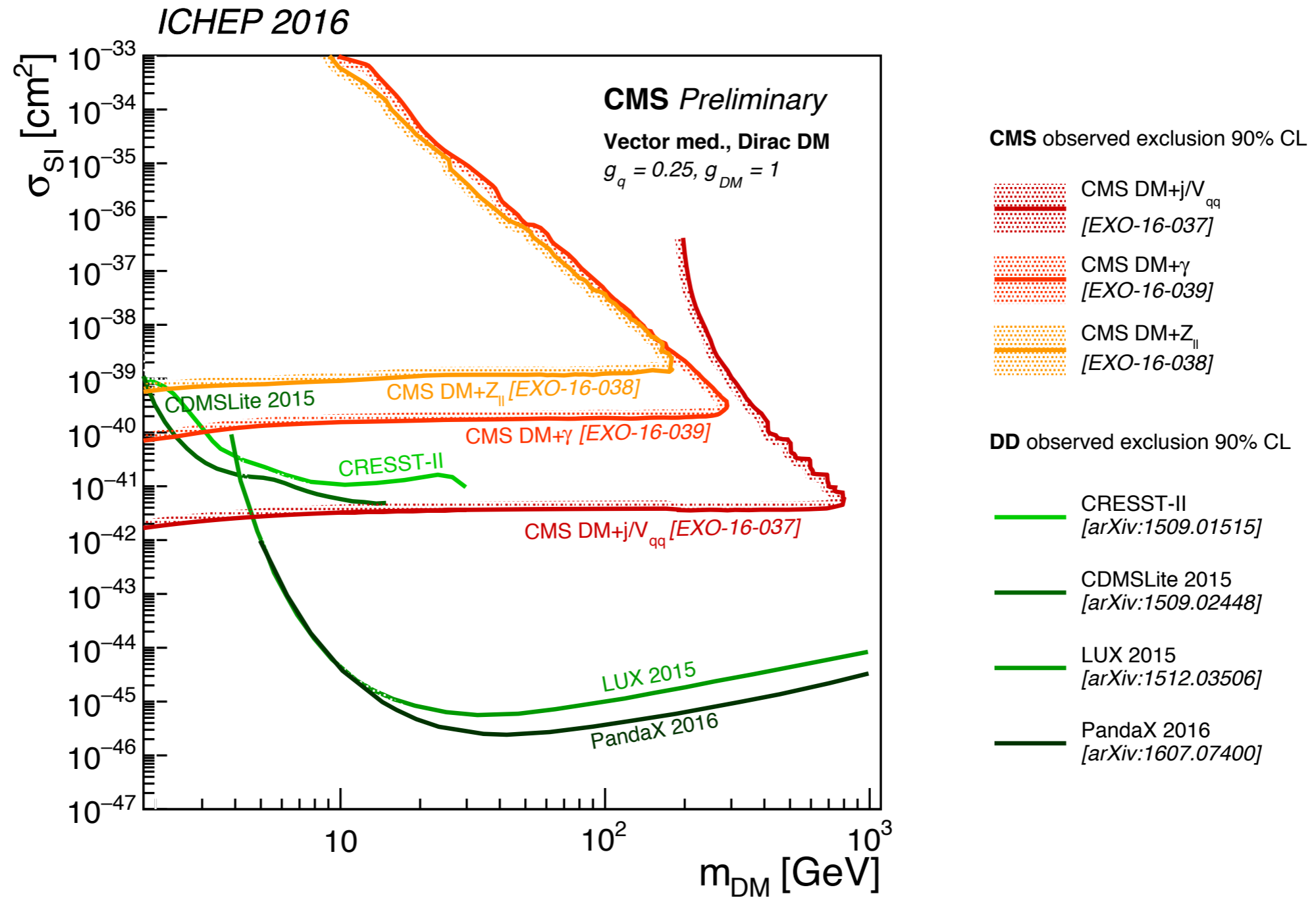
Summary Of Mono-X For Vector/Axial



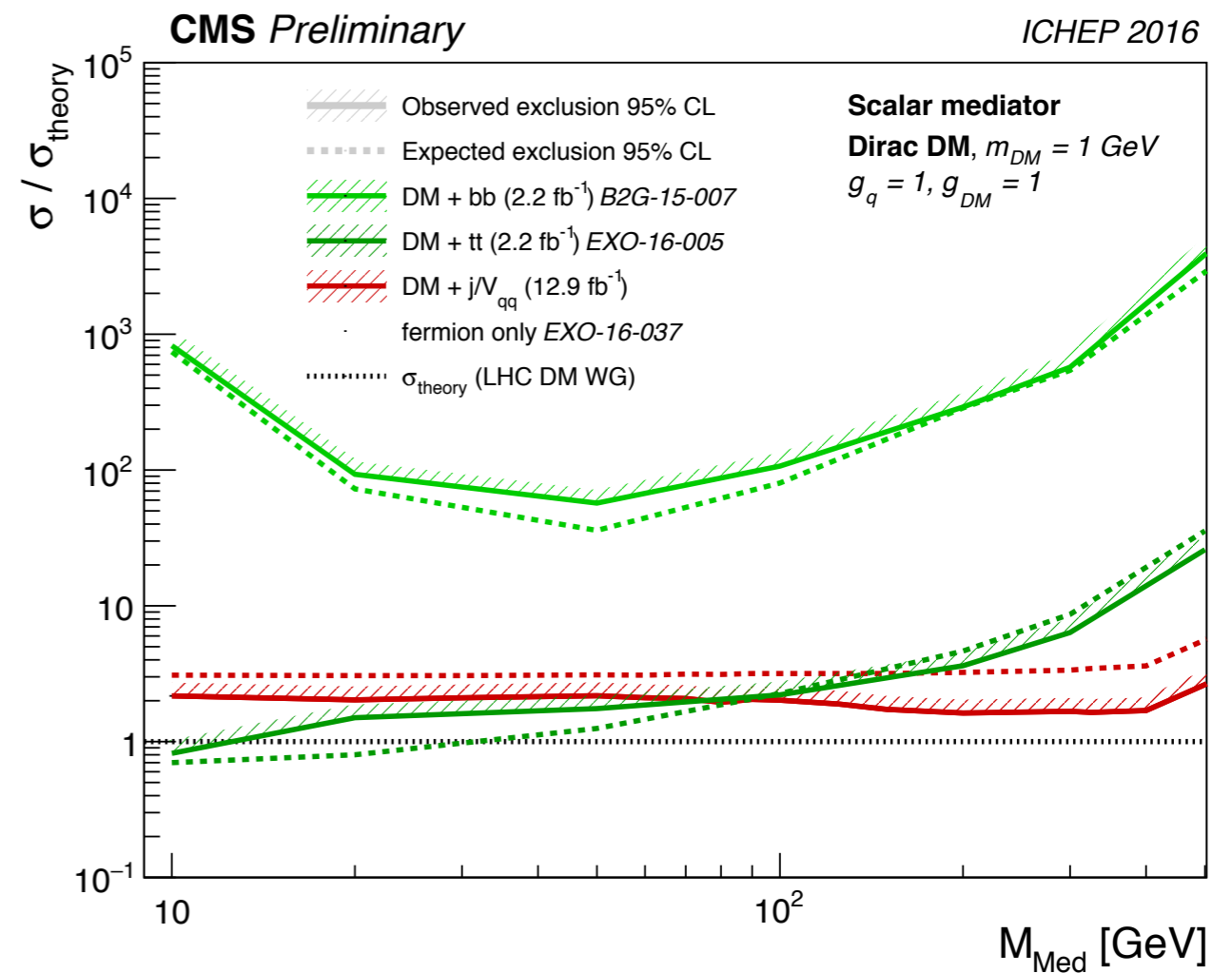
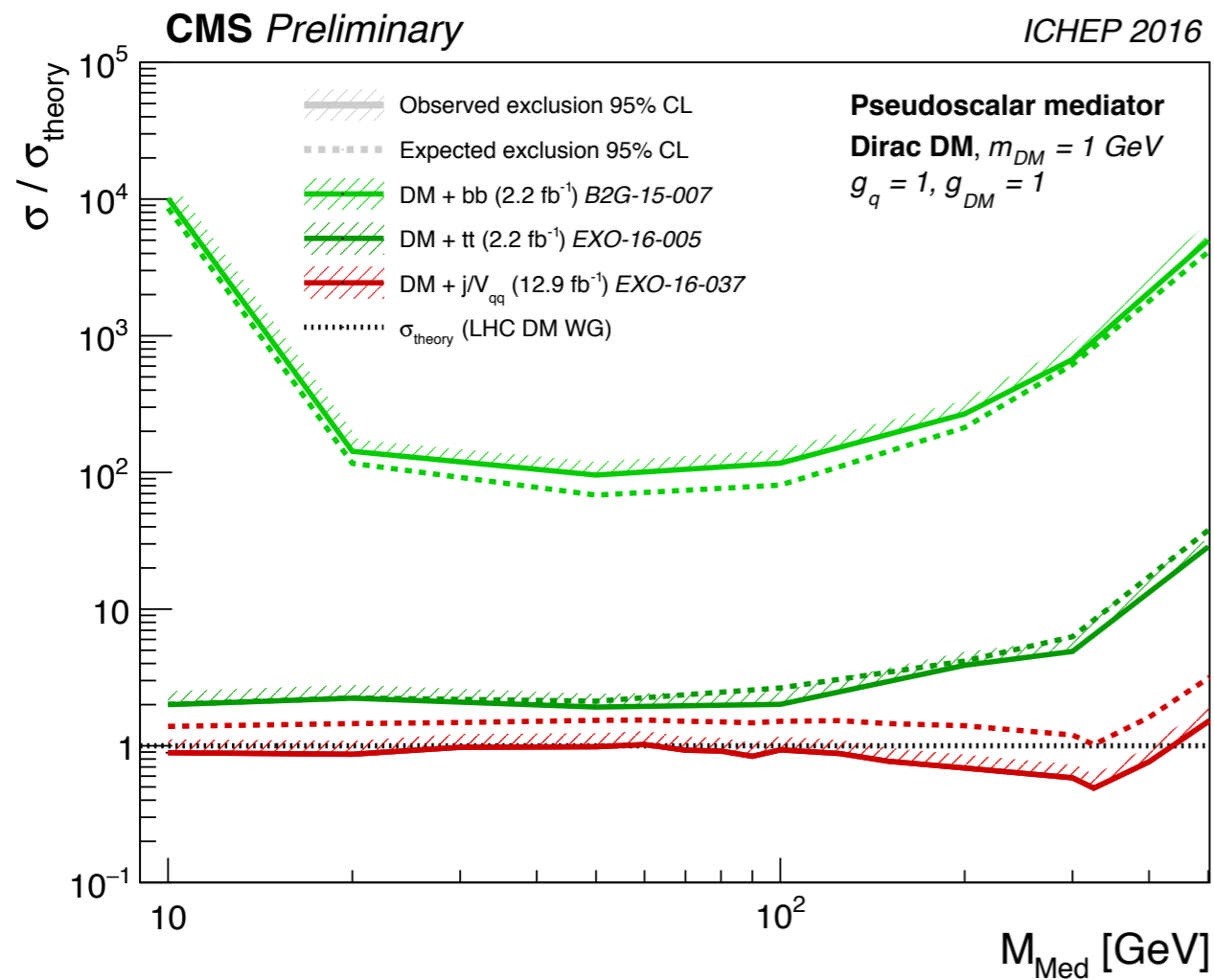
Summary Of Limits On SD Cross Sections



Summary Of Limits On SI Cross Sections



Summary For Scalar/Pseudo-Scalar



Re-Interpretation Of Dijet Searches

$$(g'_B)^2 = \frac{g_B^2}{2} \left(1 + \sqrt{1 + 4 \frac{\Gamma_{DM}}{\Gamma(g_B)}} \right)$$

$$\begin{aligned} \sigma_0(g_B) &= \sigma_{DM}(g'_B, g_{DM} = 1, m_{DM}) \\ &= \frac{(g'_B)^4}{\Gamma_q(g'_B) + \Gamma_{DM}} \frac{C}{M_{med}^4} \\ \rightarrow \frac{g_B^4}{\Gamma(g_B)} &= \frac{(g'_B)^4}{\Gamma_q(g'_B) + \Gamma_{DM}} \\ \rightarrow (g'_B)^2 &= \frac{g_B^2}{2} \left(1 + \sqrt{1 + 4 \frac{\Gamma_{DM}}{\Gamma(g_B)}} \right), \end{aligned}$$

$$\begin{aligned} \Gamma_V^{\chi\bar{\chi}} &= \frac{g_{DM}^2 M_{med}}{12\pi} \left(1 - 4 \frac{m_{DM}^2}{M_{med}^2} \right)^{1/2} \left(1 + 2 \frac{m_{DM}^2}{M_{med}^2} \right), \\ \Gamma_{AV}^{\chi\bar{\chi}} &= \frac{g_{DM}^2 M_{med}}{12\pi} \left(1 - 4 \frac{m_{DM}^2}{M_{med}^2} \right)^{3/2}, \\ \Gamma_V^{q\bar{q}} &= \frac{g_q^2 M_{med}}{4\pi} \left(1 - 4 \frac{m_q^2}{M_{med}^2} \right)^{1/2} \left(1 + 2 \frac{m_q^2}{M_{med}^2} \right), \\ \Gamma_{AV}^{q\bar{q}} &= \frac{g_q^2 M_{med}}{4\pi} \left(1 - 4 \frac{m_q^2}{M_{med}^2} \right)^{3/2}, \end{aligned}$$

How To Translate (Vector)

In general, the SI DM-nucleon scattering cross section takes the form

$$\sigma_{\text{SI}} = \frac{f^2(g_q)g_{\text{DM}}^2\mu_{n\chi}^2}{\pi M_{\text{med}}^4}, \quad (4.1)$$

where $\mu_{n\chi} = m_n m_{\text{DM}} / (m_n + m_{\text{DM}})$ is the DM-nucleon reduced mass with $m_n \simeq 0.939 \text{ GeV}$

For the vector mediator,

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

and hence

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

How To Translate (Scalar)

In general, the SI DM-nucleon scattering cross section takes the form

$$\sigma_{\text{SI}} = \frac{f^2(g_q) g_{\text{DM}}^2 \mu_{n\chi}^2}{\pi M_{\text{med}}^4}, \quad (4.1)$$

where $\mu_{n\chi} = m_n m_{\text{DM}} / (m_n + m_{\text{DM}})$ is the DM-nucleon reduced mass with $m_n \simeq 0.939 \text{ GeV}$

For the simplified model with scalar mediator exchange we follow the recommendation of ATLAS/CMS DM Forum [1] and assume that the scalar mediator couples to all quarks (like e.g. the SM Higgs). In general the formula for $f(g_q)$ is

$$f^{n,p}(g_q) = \frac{m_n}{v} \left[\sum_{q=u,d,s} f_q^{n,p} g_q + \frac{2}{27} f_{\text{TG}}^{n,p} \sum_{Q=c,b,t} g_Q \right]. \quad (4.4)$$

these values, we find that numerically

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

and therefore the size of a typical cross section is

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

How To Translate (Axial-Vector)

For the axial-vector mediator, the scattering is SD and the corresponding cross section can be written as

$$\sigma_{\text{SD}} = \frac{3 f^2(g_q) g_{\text{DM}}^2 \mu_{n\chi}^2}{\pi M_{\text{med}}^4}. \quad (4.7)$$

In general $f^{p,n}(g_q)$ differs for protons and neutrons and is given by

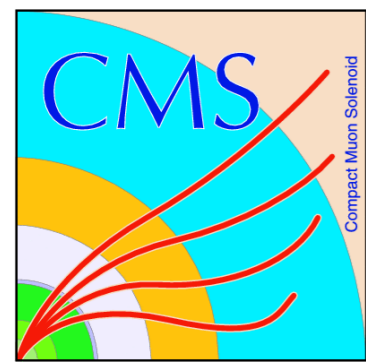
$$f^{p,n}(g_q) = \Delta_u^{(p,n)} g_u + \Delta_d^{(p,n)} g_d + \Delta_s^{(p,n)} g_s, \quad (4.8)$$

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

$$f(g_q) = 0.32 g_q, \quad (4.9)$$

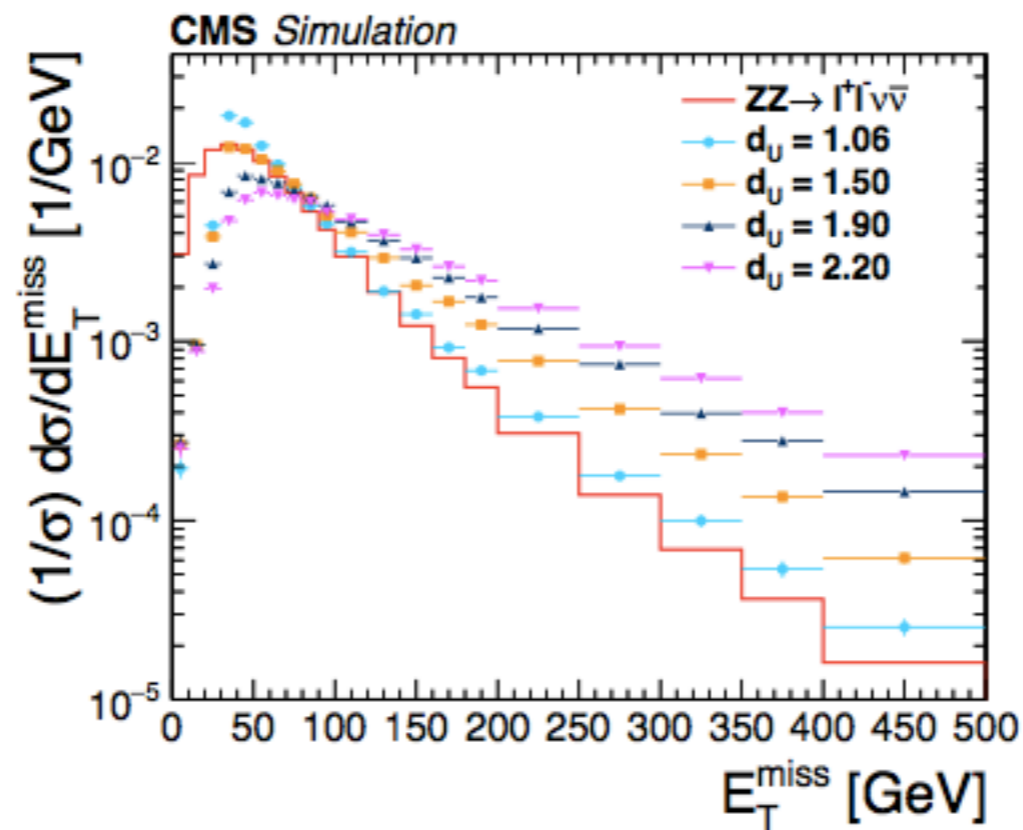
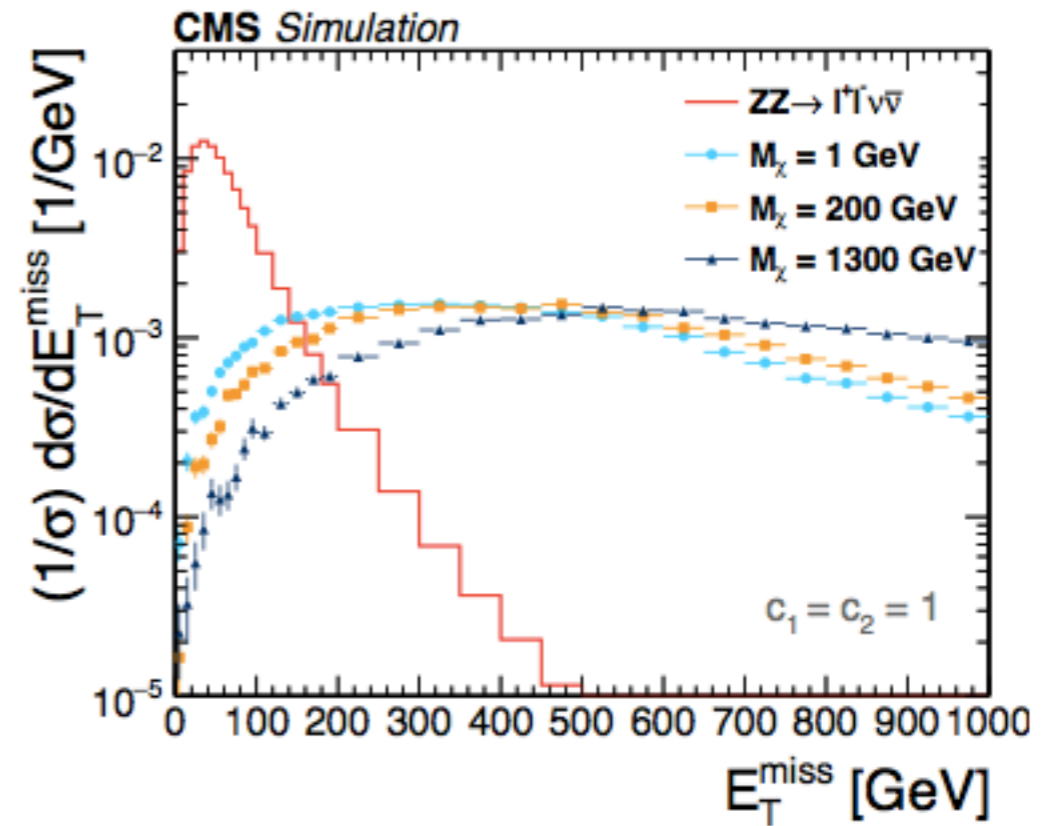
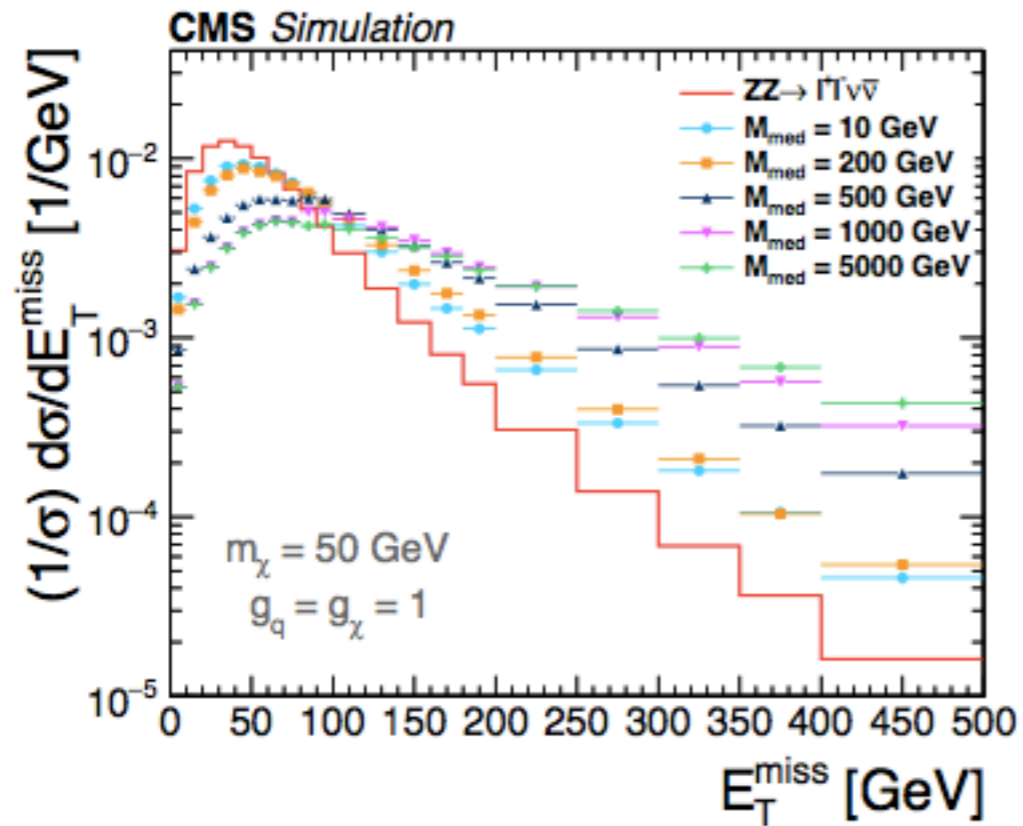
and thus

$$\sigma^{\text{SD}} \simeq 2.4 \times 10^{-42} \text{ cm}^2 \cdot \left(\frac{g_q g_{\text{DM}}}{0.25} \right)^2 \left(\frac{1 \text{ TeV}}{M_{\text{med}}} \right)^4 \left(\frac{\mu_{n\chi}}{1 \text{ GeV}} \right)^2. \quad (4.10)$$

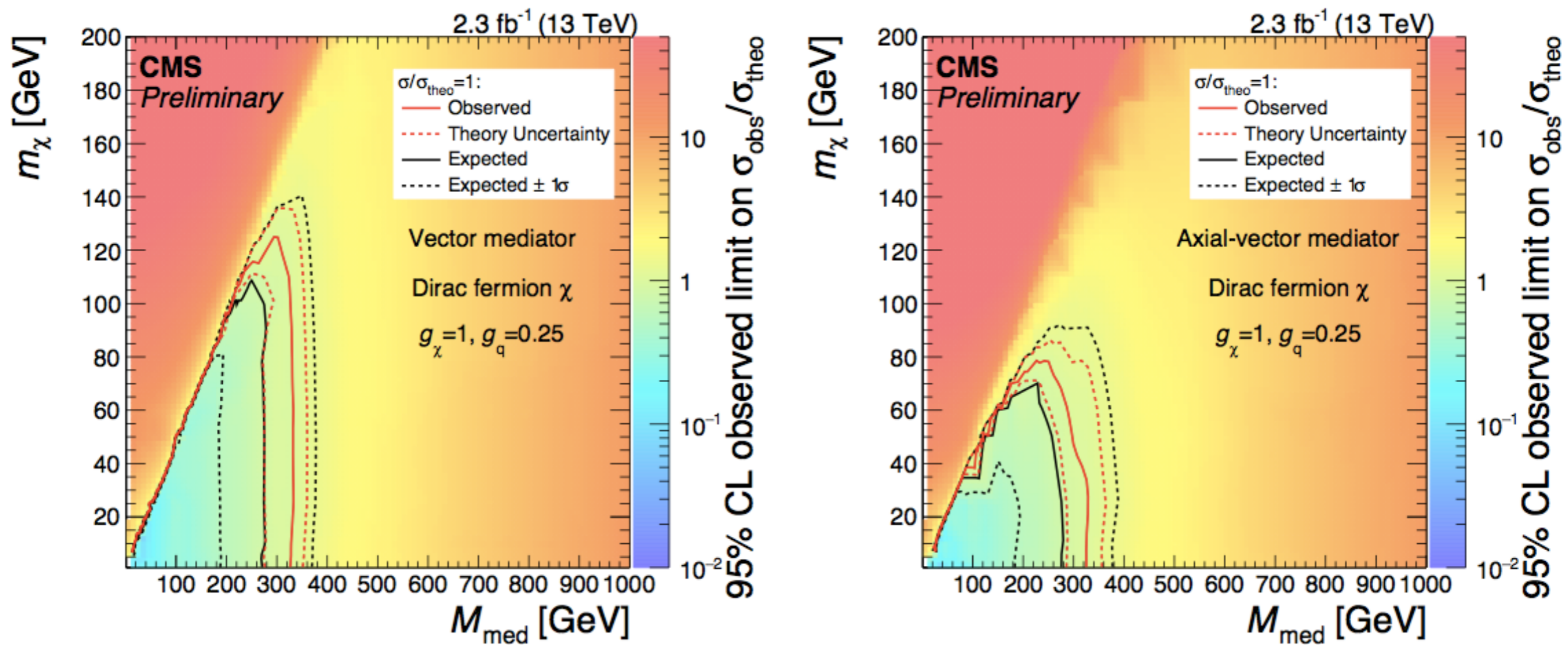


Mono-Z

Comparison Of Kinematics



Mono Z 2015 Data: Limits 2D Scan



Mono Z 2015 Data: Limits 2D Scan

