

# Physics of Dark Sectors in CMS

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*On behalf of CMS*

*LHCP 2024, Boston*

# Dark Sector Paper in Numbers

[EXO-23-005 Public Page](#)

Submitted to Phys. Rept.

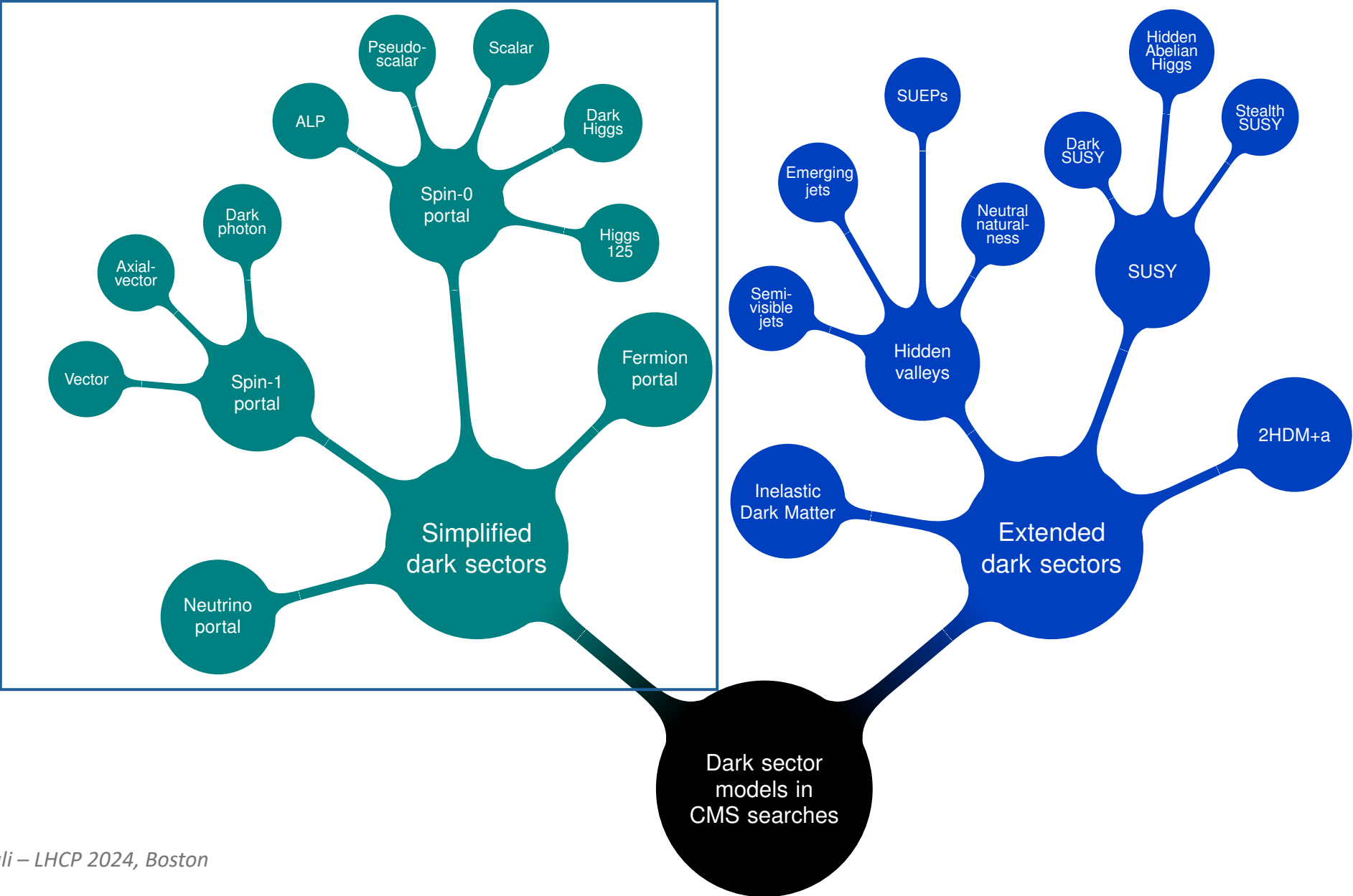
O(20) editors  
O(500) authors  
O(40) analysis

O(30) new  
interpretation and  
summary plots

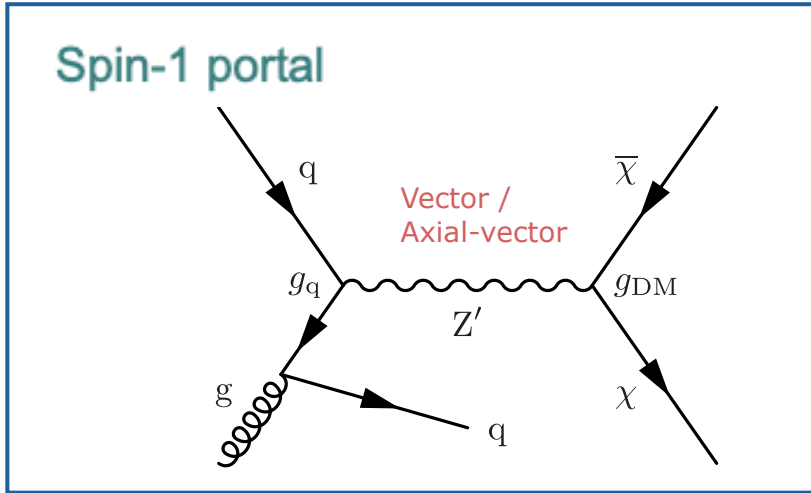
*Covered mass range from  $\sim 1$  GeV up to multiple TeV  
Coupling reach up to  $10^{-5}$*

<https://arxiv.org/abs/2405.13778>

# Introduction: Theoretical Framework

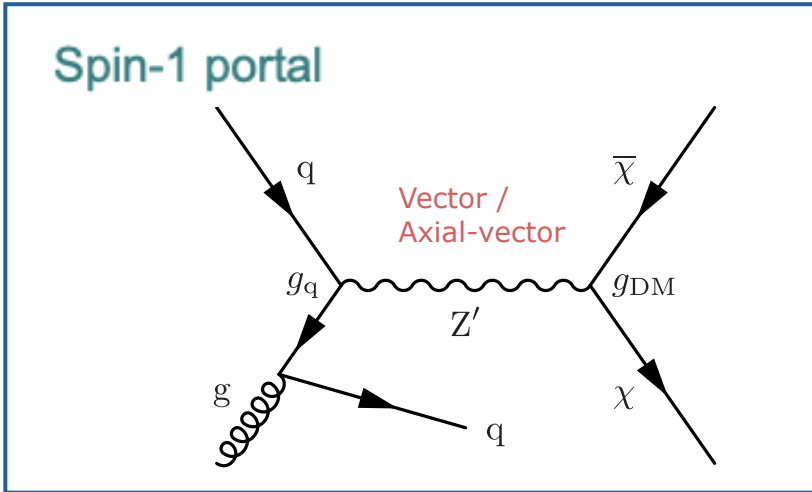


# Simplified Dark Sectors: Spin-1 V/AV

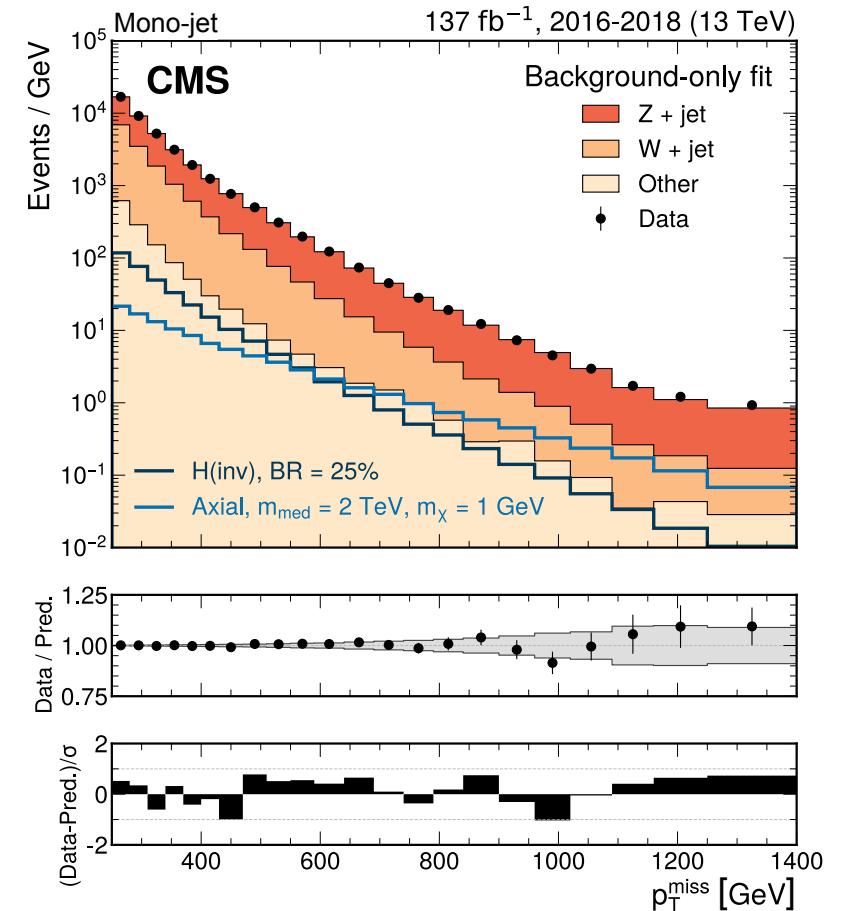


$$\mathcal{L}_{\text{vector}} \supset -g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi - g_q \sum_{\text{q}} Z'_\mu \bar{q} \gamma^\mu q - g_\ell \sum_{\ell} Z'_\mu \bar{\ell} \gamma^\mu \ell,$$

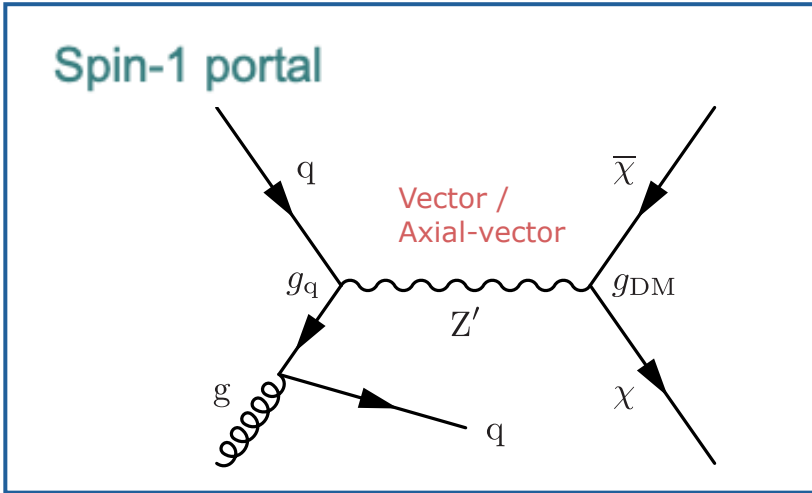
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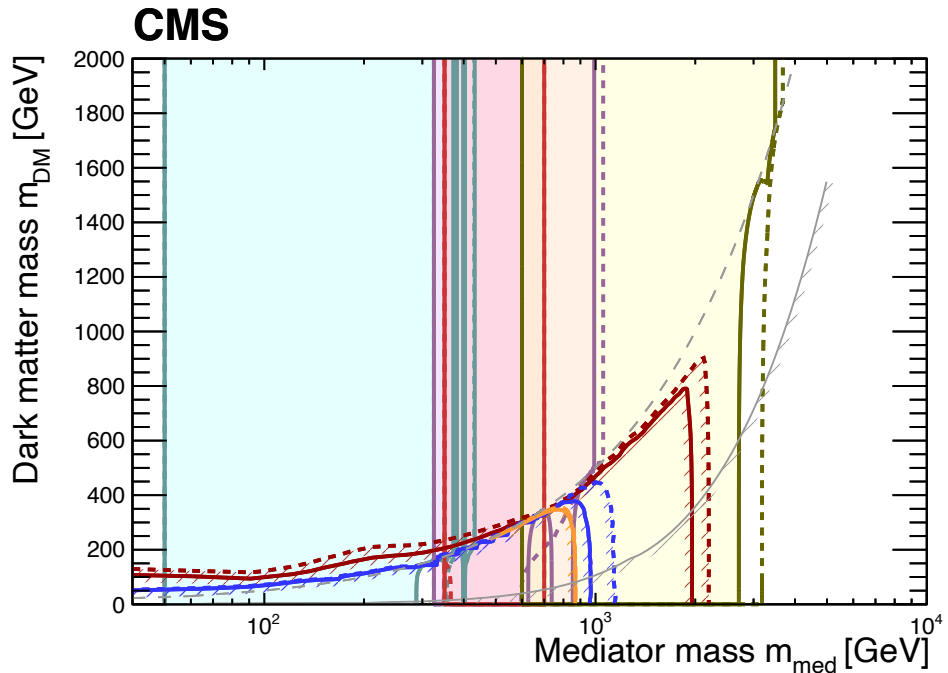
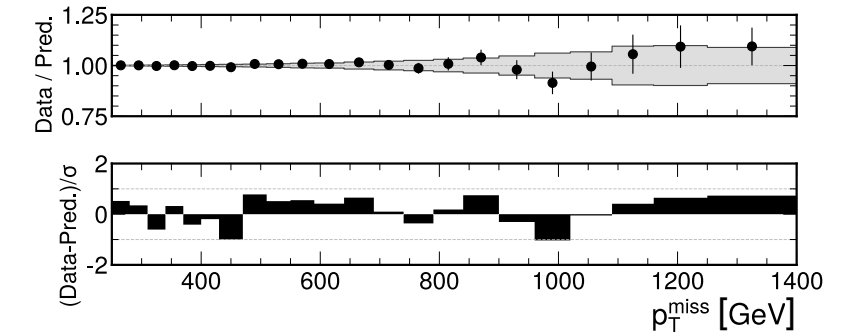
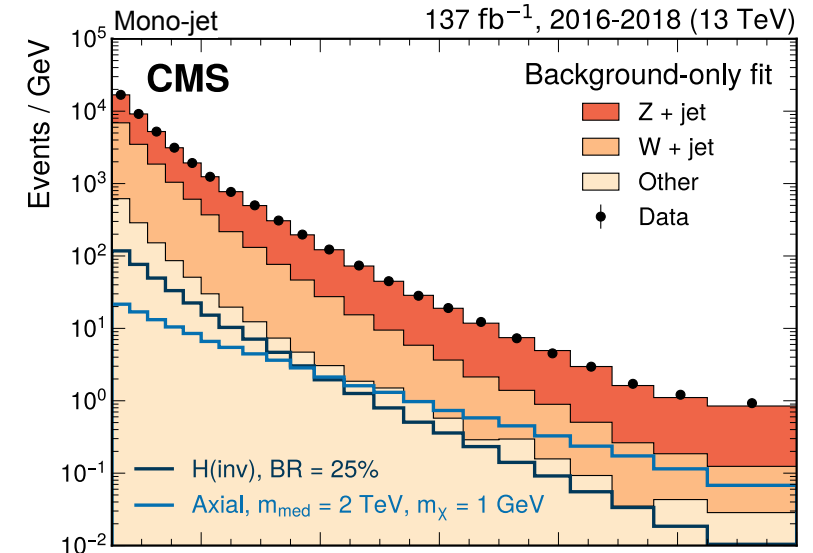
$$\mathcal{L}_{\text{vector}} \supset -g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi - g_q \sum_q Z'_\mu \bar{q} \gamma^\mu q - g_\ell \sum_\ell Z'_\mu \bar{\ell} \gamma^\mu \ell,$$



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$$\mathcal{L}_{\text{vector}} \supset -g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi - g_q \sum_q Z'_\mu \bar{q} \gamma^\mu q - g_\ell \sum_\ell Z'_\mu \bar{\ell} \gamma^\mu \ell,$$



**Vector mediator**

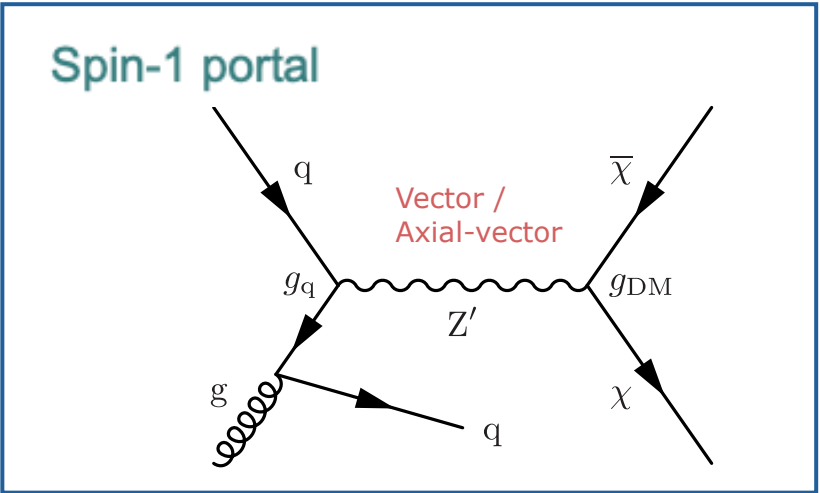
Dirac DM

$g_{\text{DM}} = 1.0$

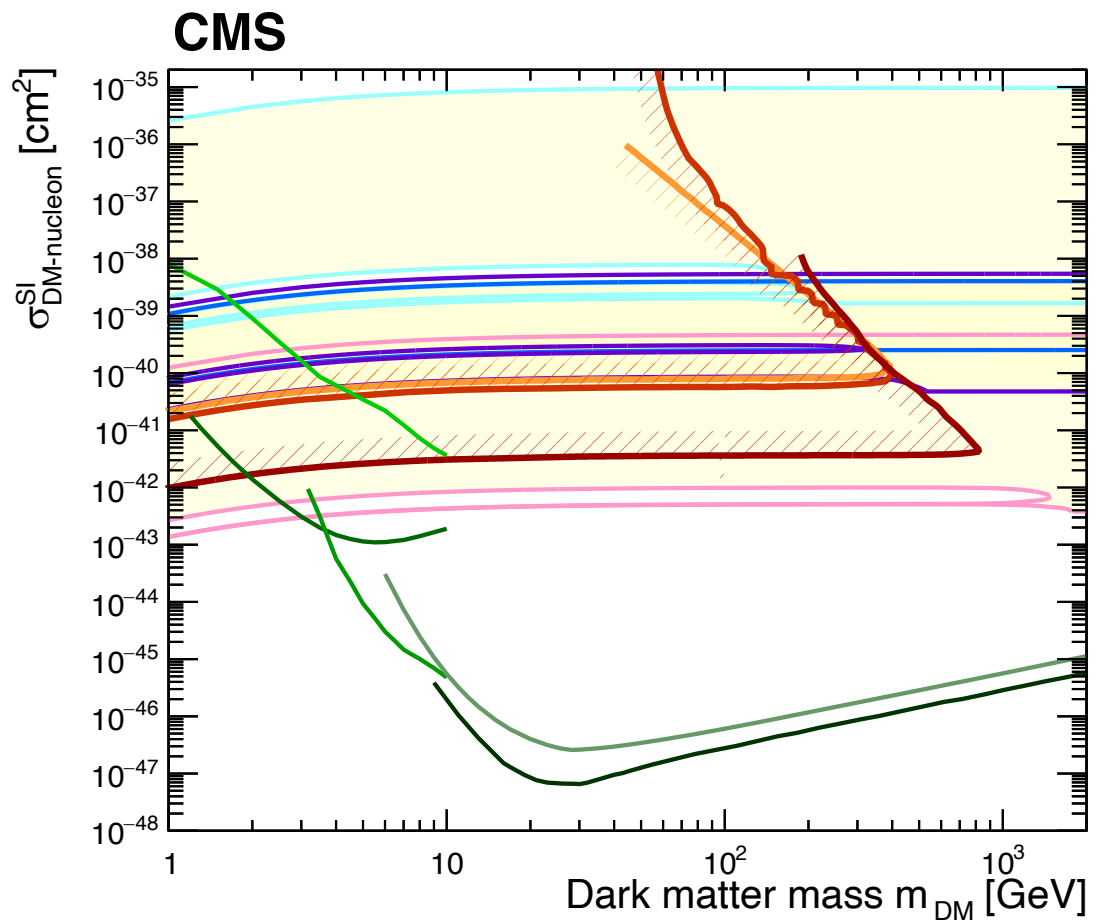
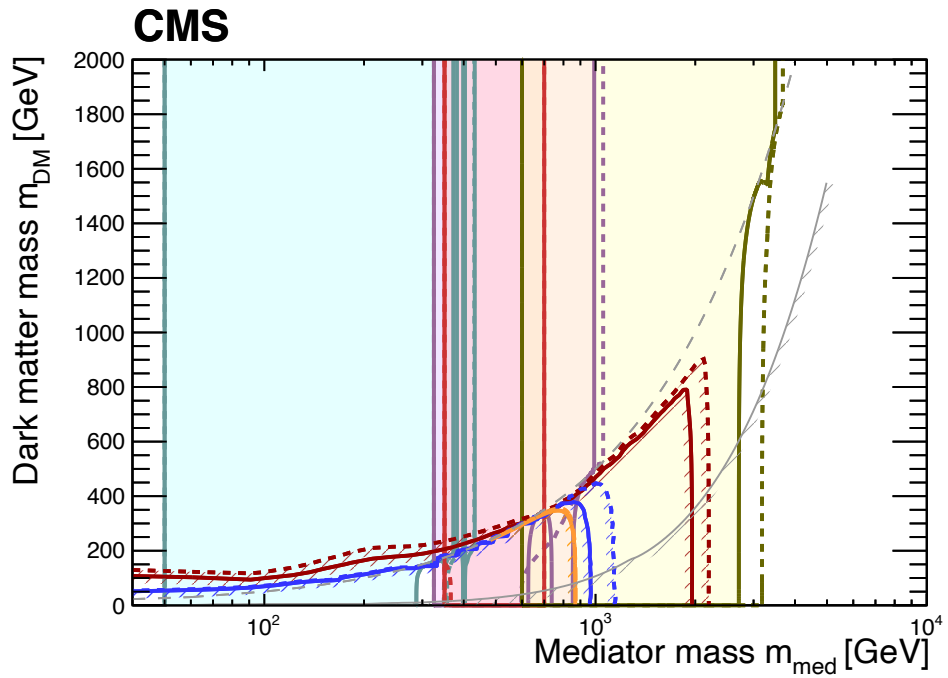
$g_q = 0.25$

$g_\ell = 0$

# Simplified Dark Sectors: Spin-1 V/AV



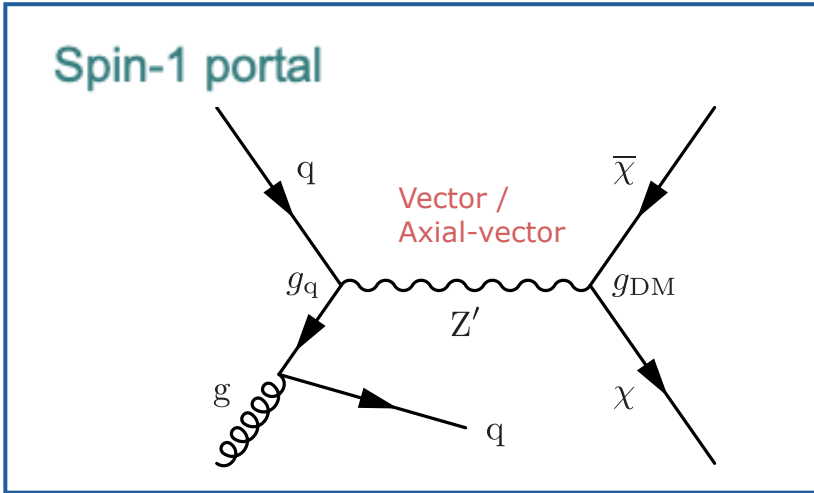
$$\mathcal{L}_{\text{vector}} \supset -g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi - g_q \sum_q Z'_\mu \bar{q} \gamma^\mu q - g_\ell \sum_\ell Z'_\mu \bar{\ell} \gamma^\mu \ell,$$



- CMS observed exclusion 90% CL**  
Vector med., Dirac DM;  $g_q = 0.25, g_{\text{DM}} = 1.0$
- **Boosted dijet** (77 fb<sup>-1</sup>)  
Phys. Rev. D 100 (2019) 112007
  - **Dijet+ISR j** (18.3 fb<sup>-1</sup>)  
Phys. Lett. B 805 (2020) 135448
  - **b-tagged dijet** (19.7 fb<sup>-1</sup>)  
Phys. Rev. Lett. 120 (2018) 201801
  - **Dijet** (137 fb<sup>-1</sup>)  
JHEP 05 (2020) 033
  - **DM + Z<sub>ll</sub>** (137 fb<sup>-1</sup>)  
Eur. Phys. J. C 81 (2021) 13
  - **DM +  $\gamma$**  (35.9 fb<sup>-1</sup>)  
JHEP 02 (2019) 074
  - **DM + jV<sub>qq</sub>** (137 fb<sup>-1</sup>)  
JHEP 11 (2021) 153
- DD observed exclusion 90% CL**
- **CRESST-III**  
Phys. Rev. D 100 (2019) 102002
  - **DarkSide-50**  
Phys. Rev. D 107 (2023) 063001
  - **PandaX-4T**  
Phys. Rev. Lett. 130 (2023) 021802
  - **XENONnT**  
Phys. Rev. Lett. 131 (2023) 041003
  - **LZ**  
Phys. Rev. Lett. 131 (2023) 041002

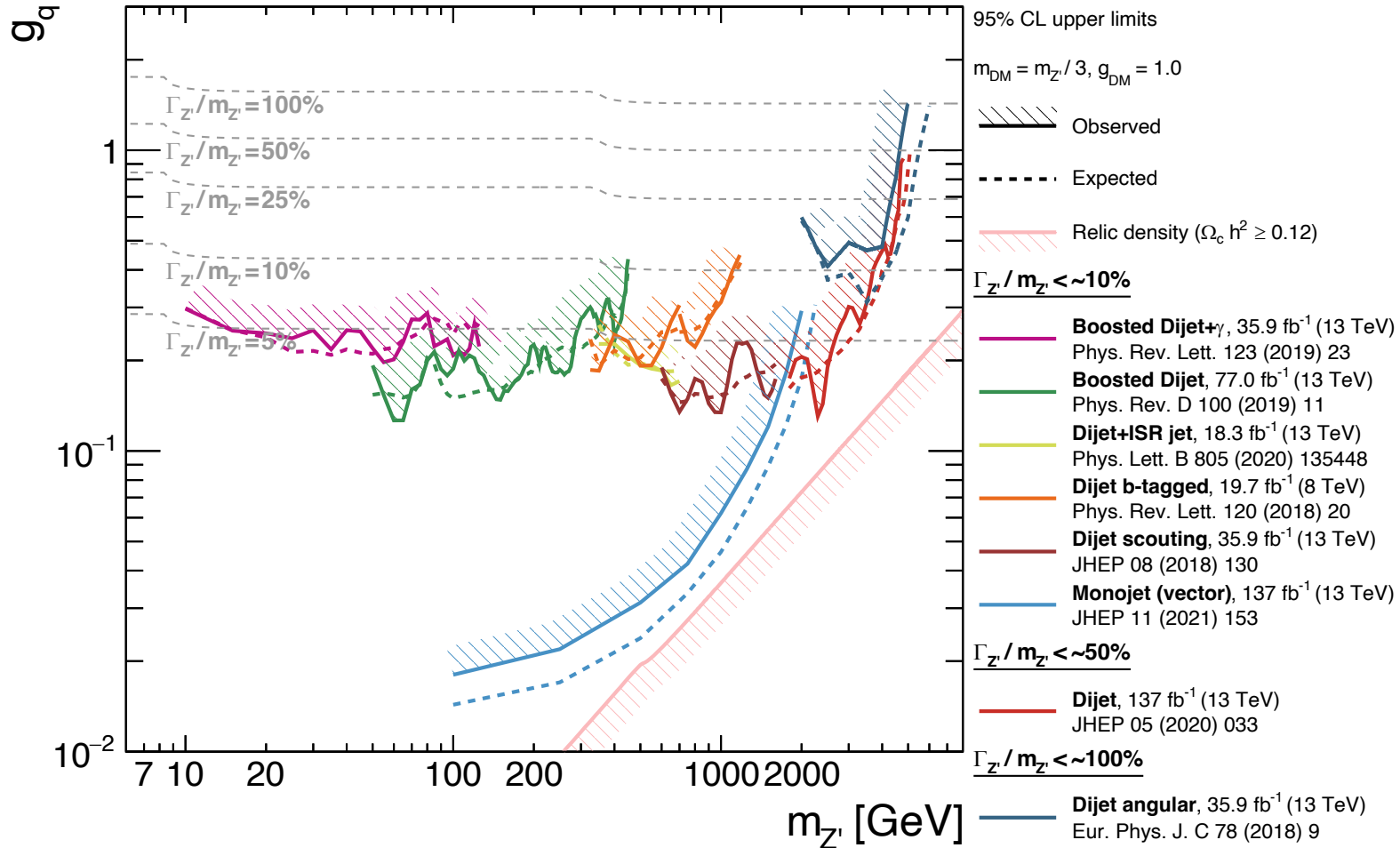


# Simplified Dark Sectors: Spin-1 V/AV

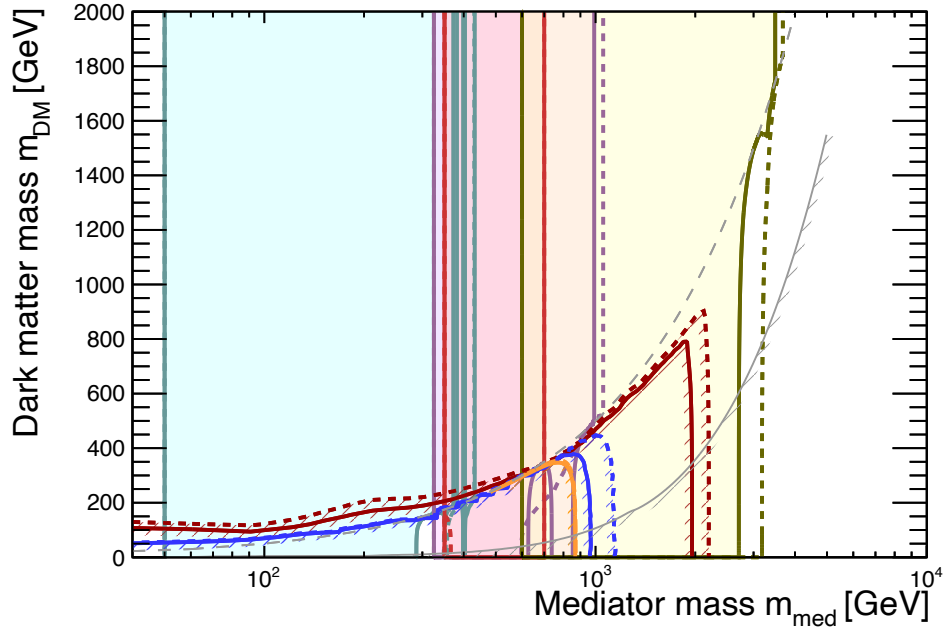


$$\mathcal{L}_{\text{vector}} \supset -g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi - g_q \sum_q Z'_\mu \bar{q} \gamma^\mu q - g_l \sum_l Z'_\mu \bar{l} \gamma^\mu l,$$

CMS

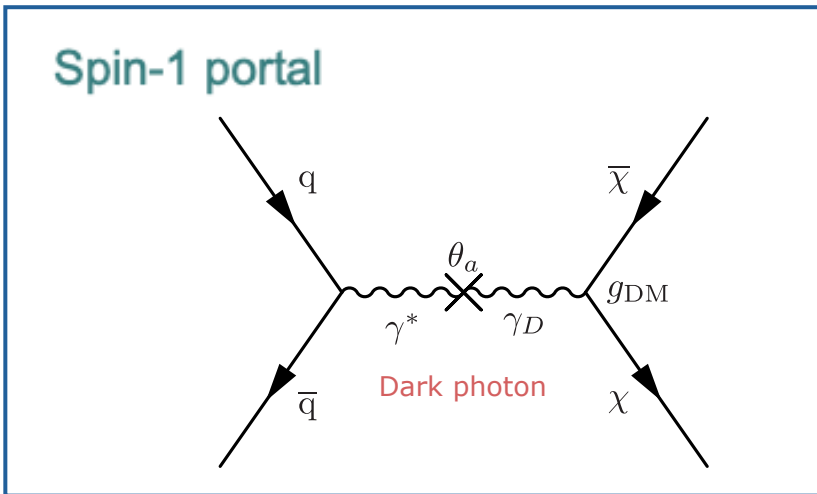


CMS



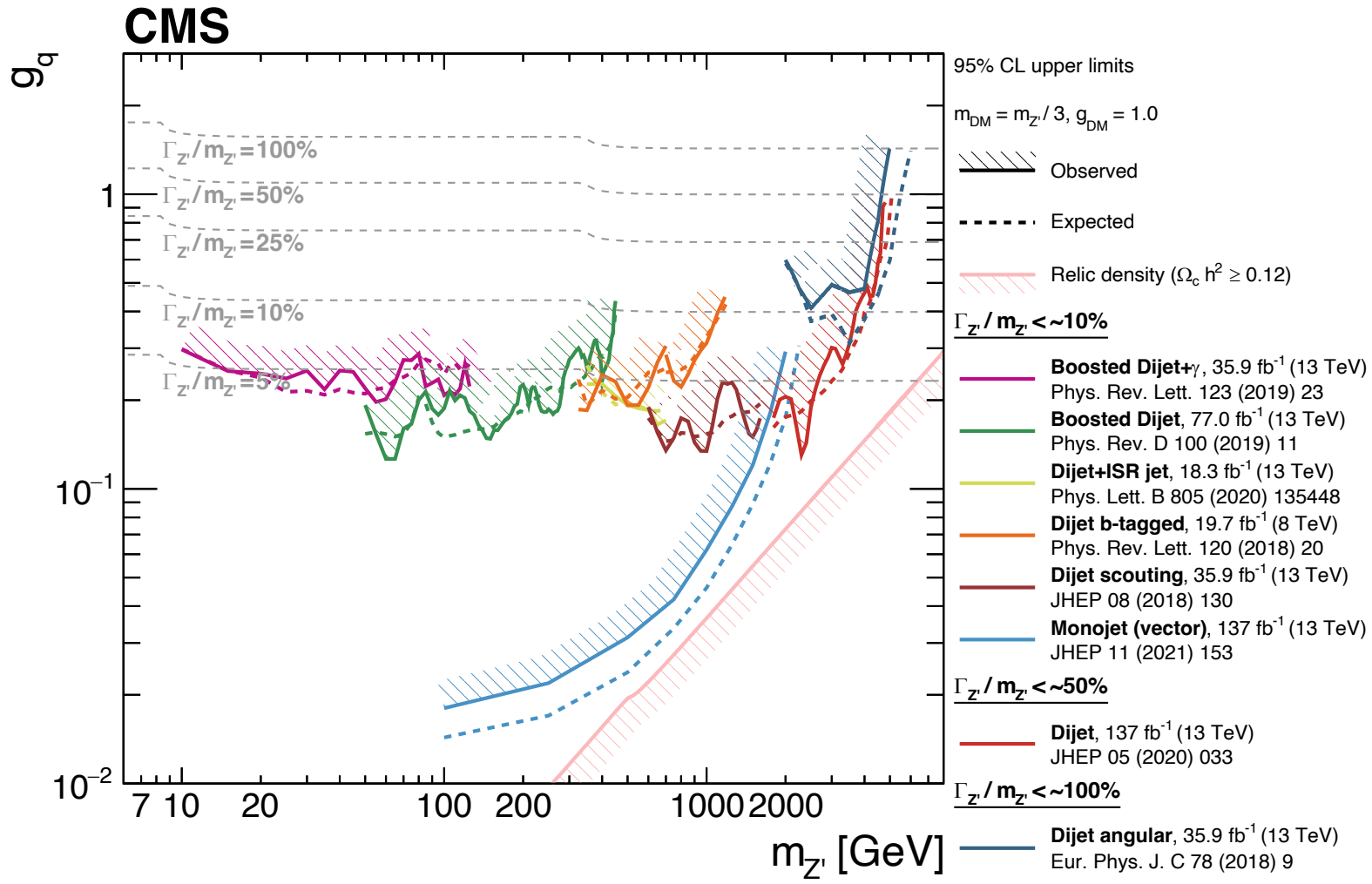
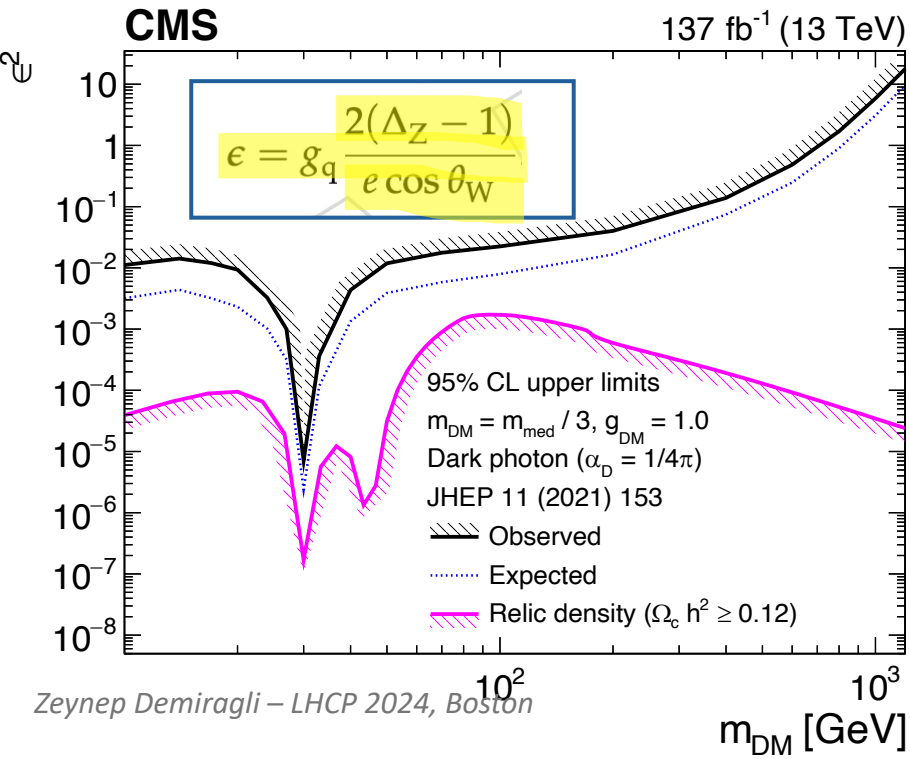


# Simplified Dark Sectors: Spin-1 Dark Photon

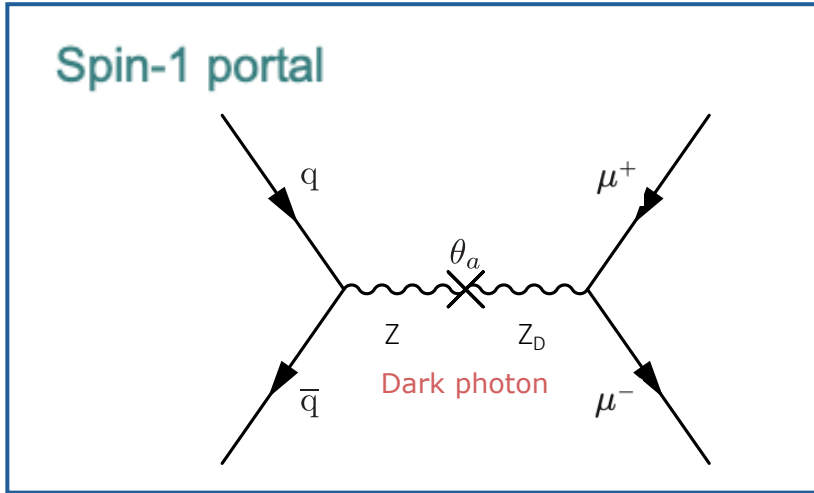


$$\mathcal{L} \supset g_{\text{DM}} \cos \theta_a A'_\mu \bar{\chi} \gamma^\mu \chi + g_{\text{DM}} \sin \theta_a A_\mu \bar{\chi} \gamma^\mu \chi$$

$$\sin \theta_a \approx \epsilon \frac{\sin \theta_W}{\Delta_Z - 1}$$

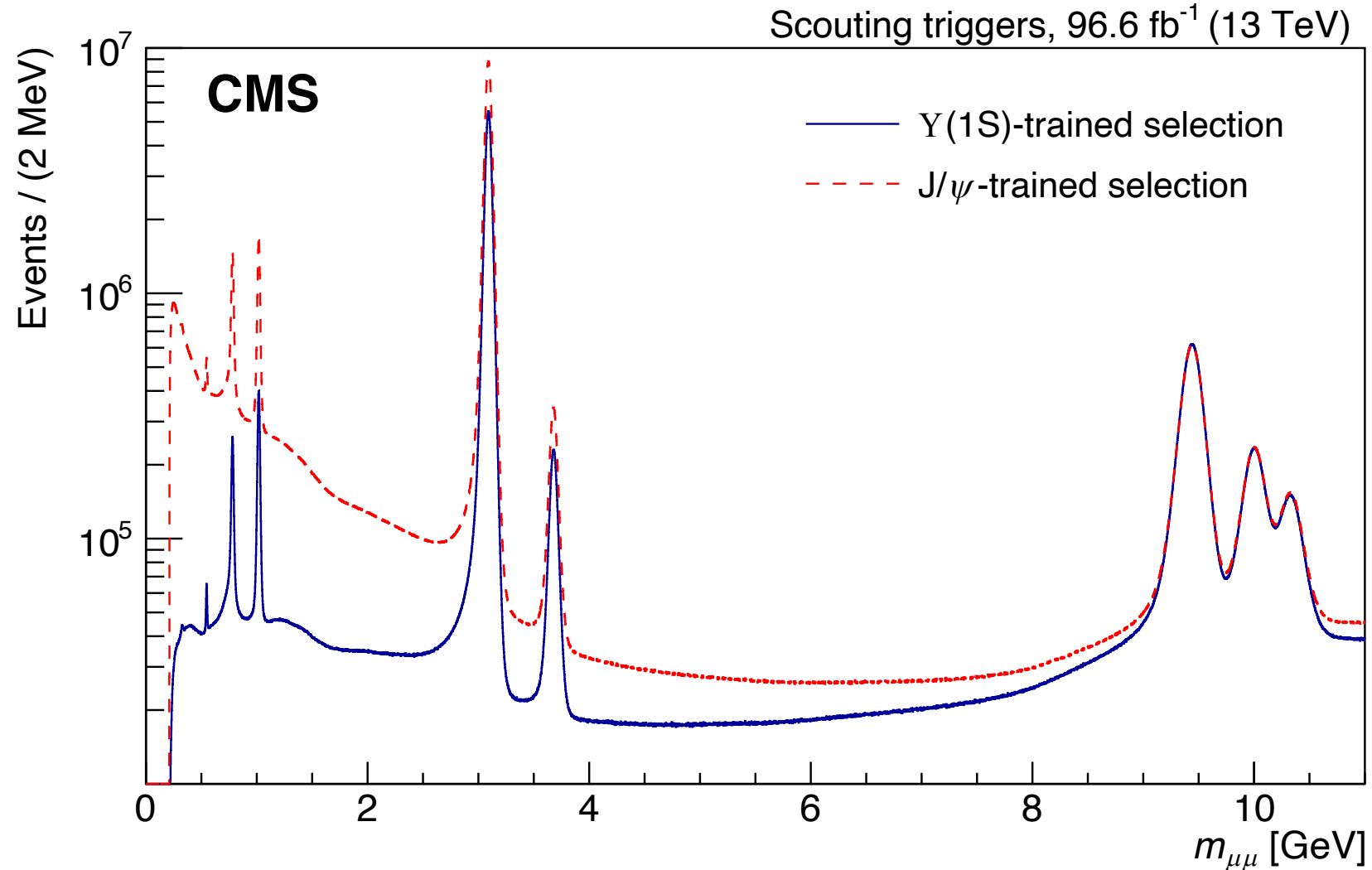


# Simplified Dark Sectors: Spin-1 Dark Photon

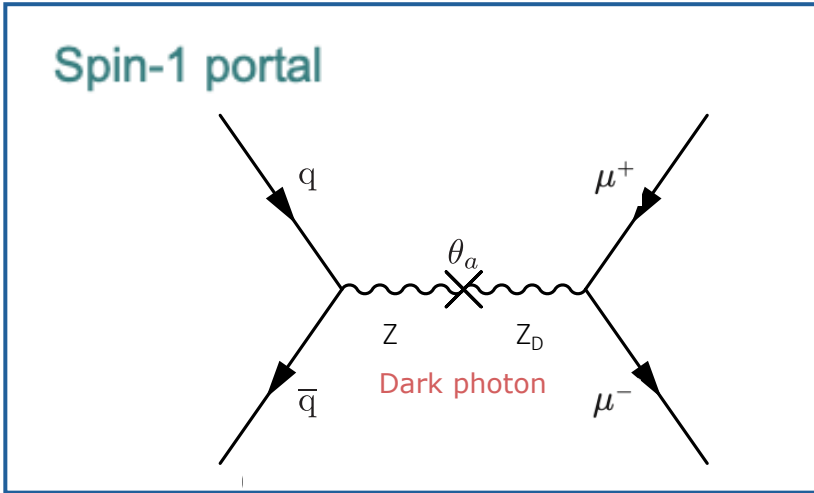


Resonant mediator search bounds are driven by dilepton

Data scouting program and dedicated selection trainings enables access to the  $\sim 1$  GeV Dark Photons!



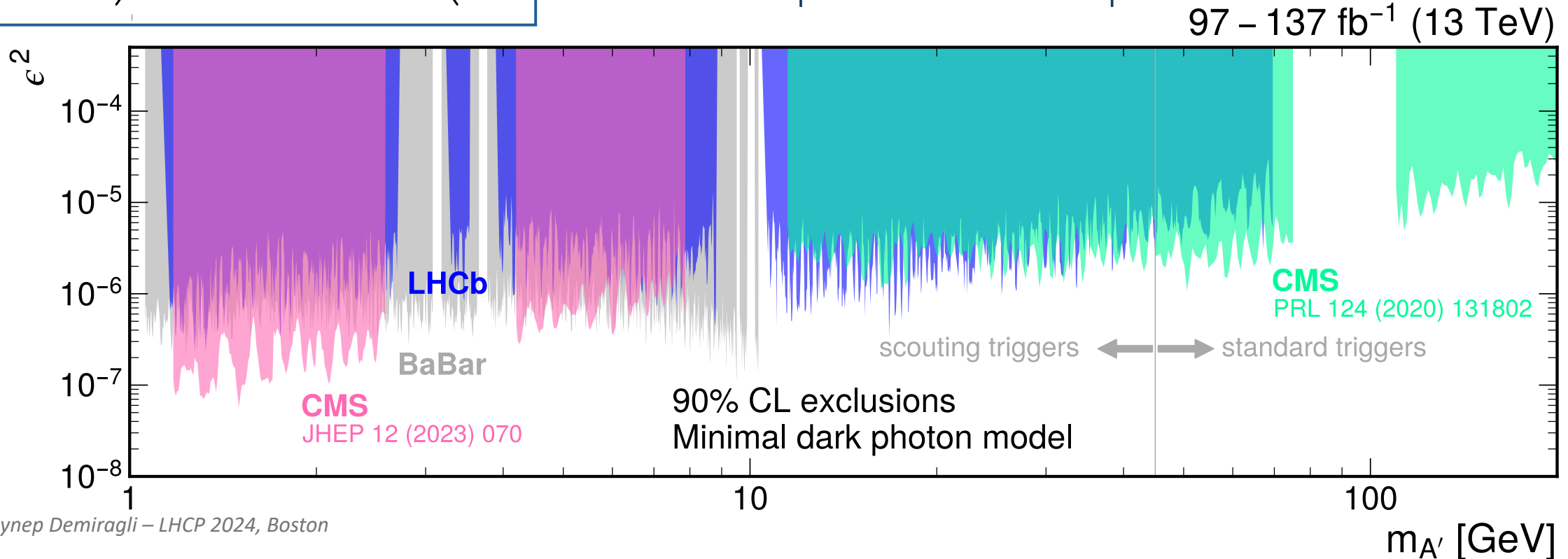
# Simplified Dark Sectors: Spin-1 Dark Photon



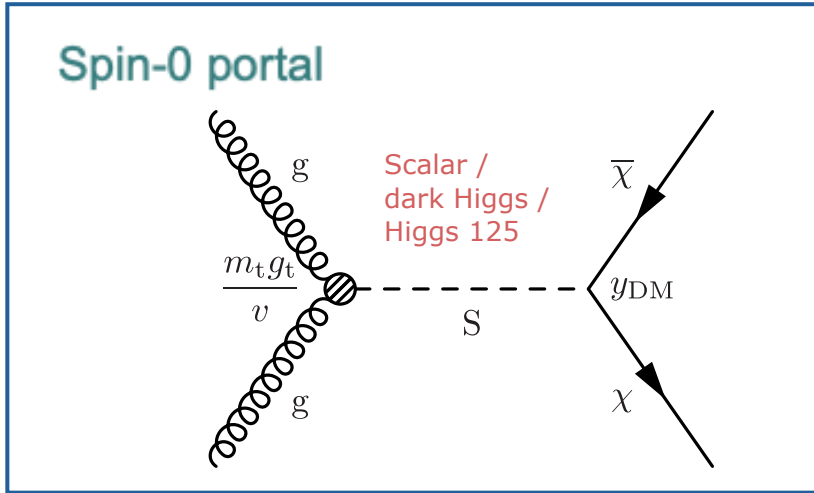
Dark sector bounds are often presented in terms of the mixing parameter  $\epsilon$ .

$$\sin \theta_a \approx \epsilon \frac{\sin \theta_W}{\Delta_Z - 1}$$

Similar or stronger exclusions in a wide range of dark photon masses compared to other experiments.



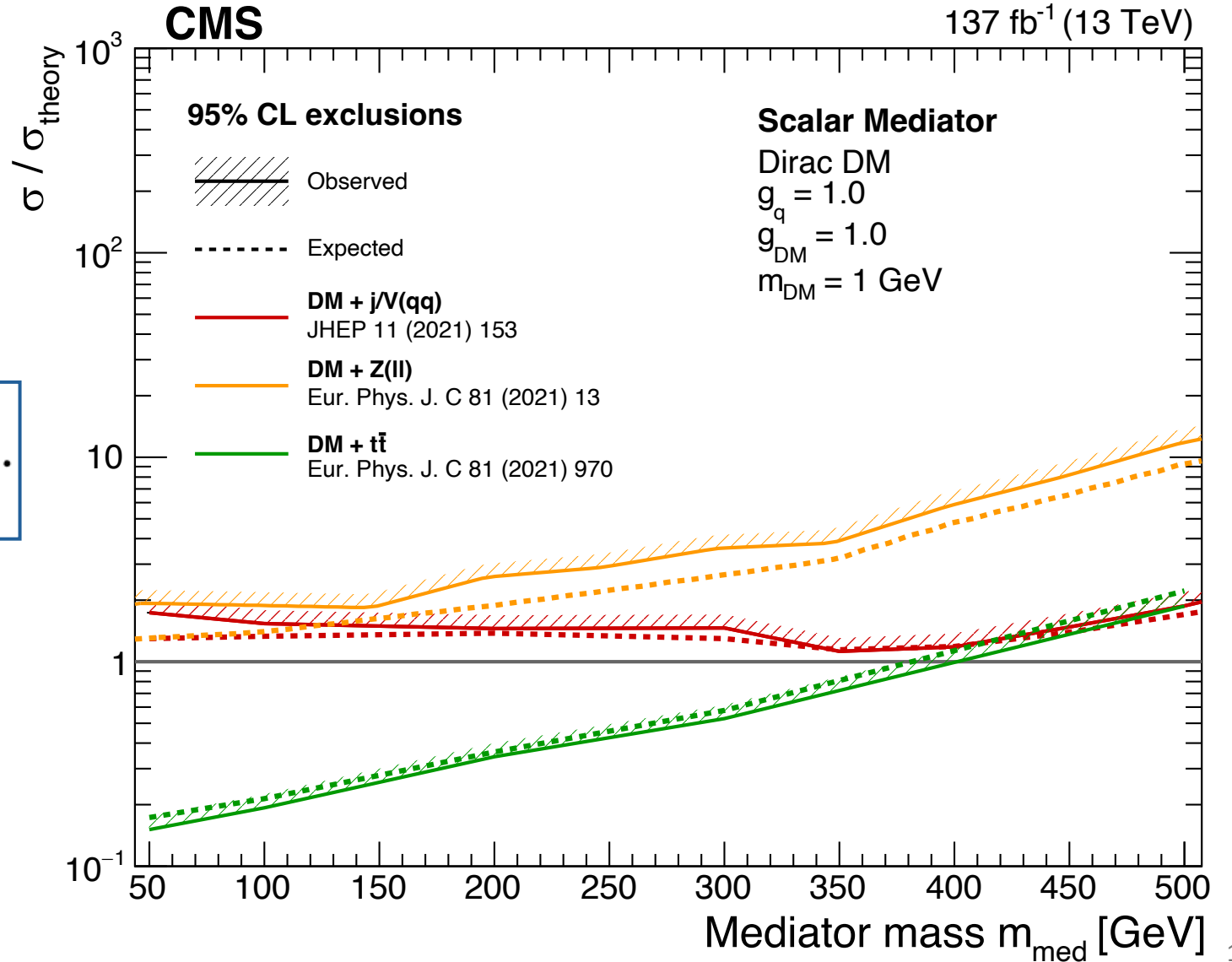
# Simplified Dark Sectors: Spin 0 – Scalar



$$\mathcal{L} \supset g_q \frac{S}{\sqrt{2}} \sum_q y_q q \bar{q} + y_{DM} S \bar{\chi} \chi + \dots$$

The scalar portal assumes mass-dependent Yukawa couplings between the mediator  $S$  and the SM particles.

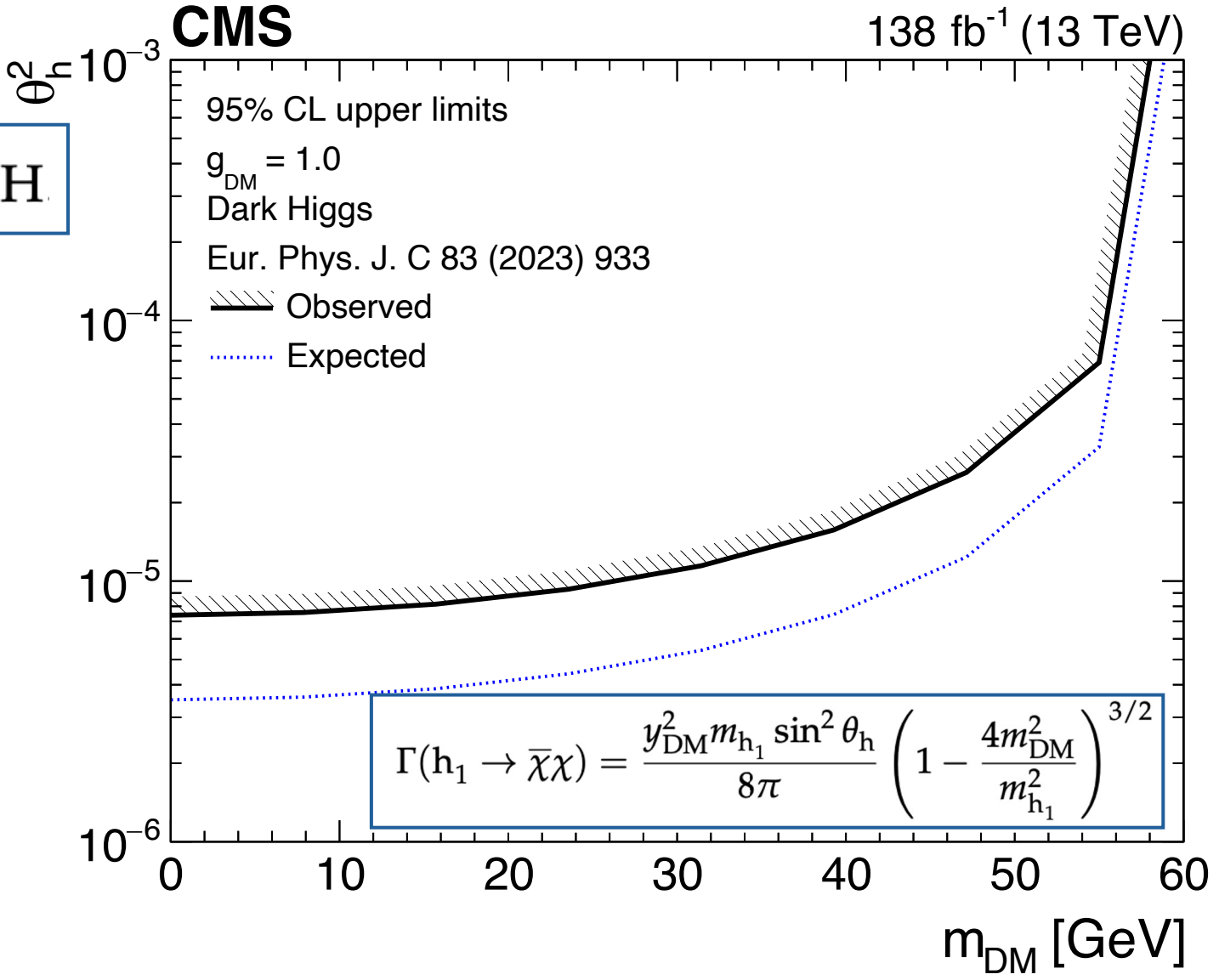
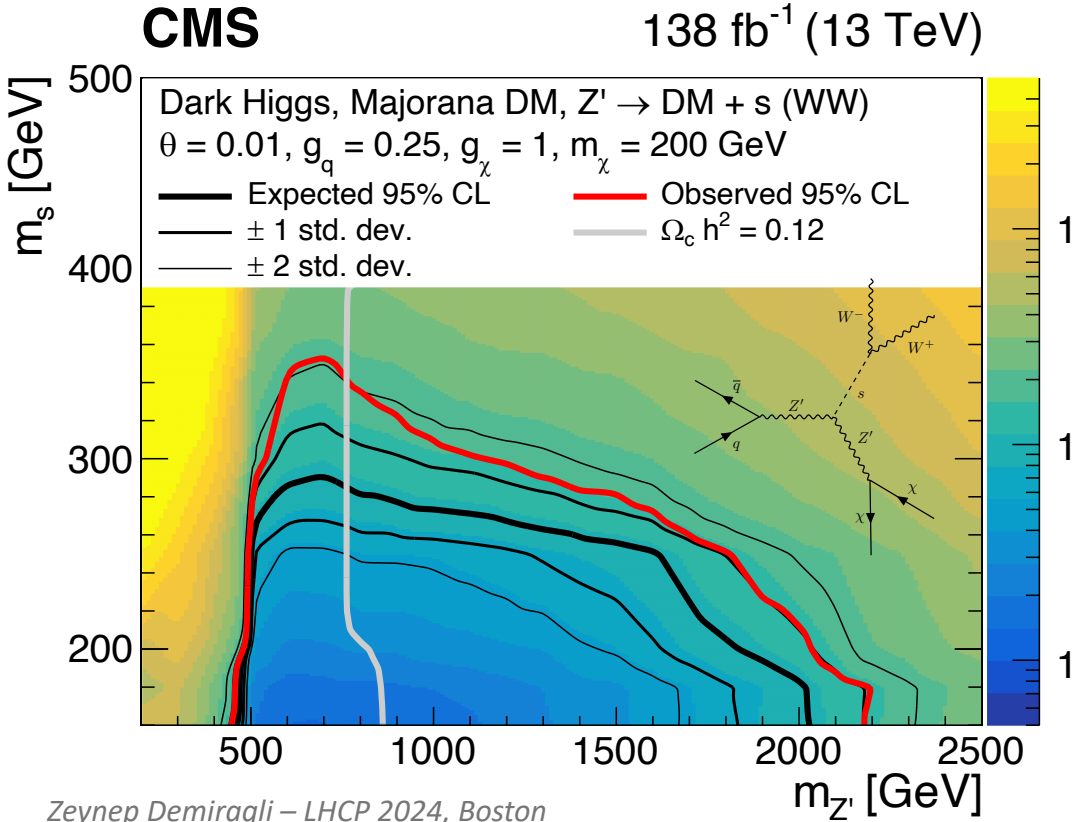
- Heavy-flavor-induced processes drive the production of the scalar mediator



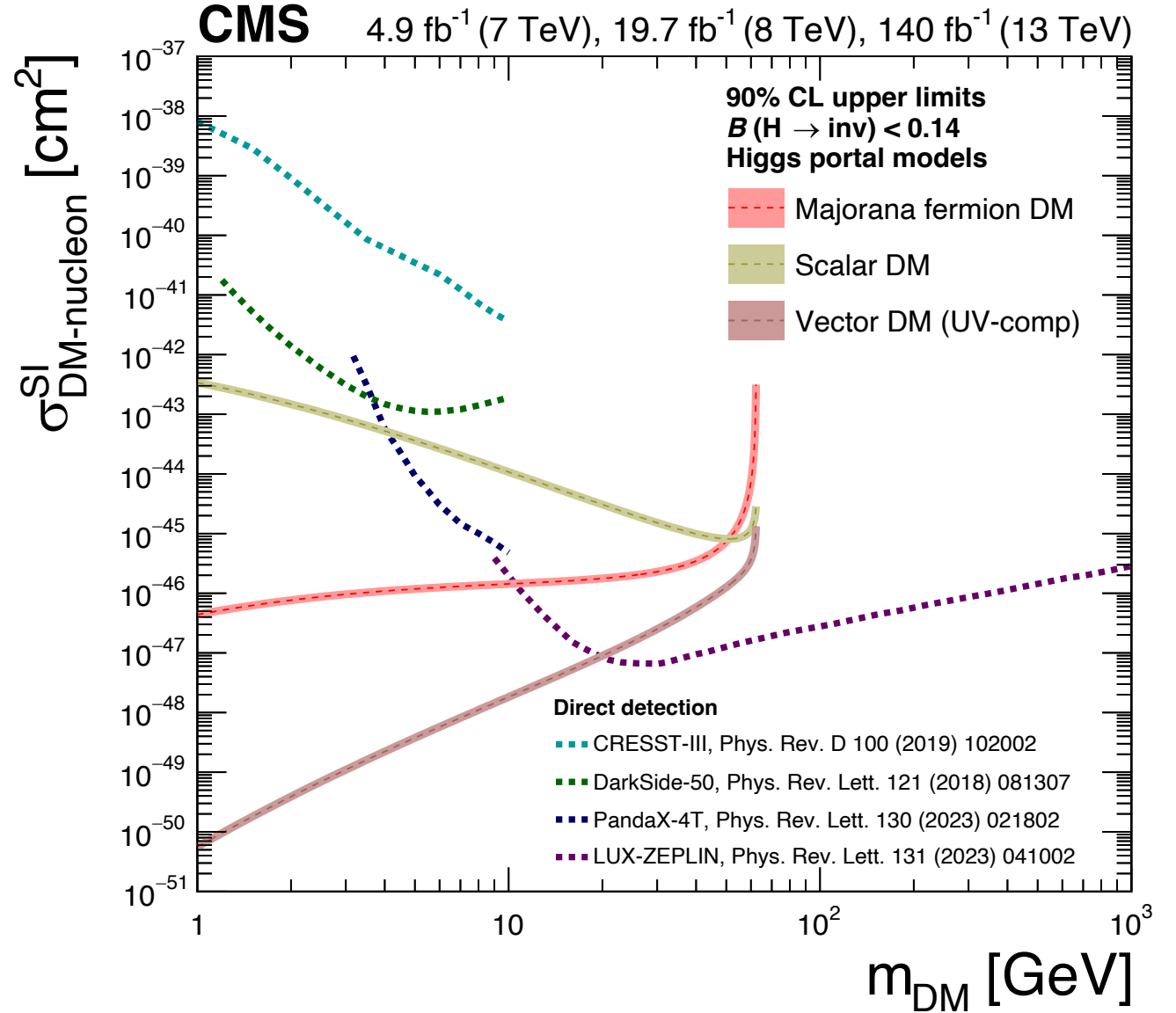
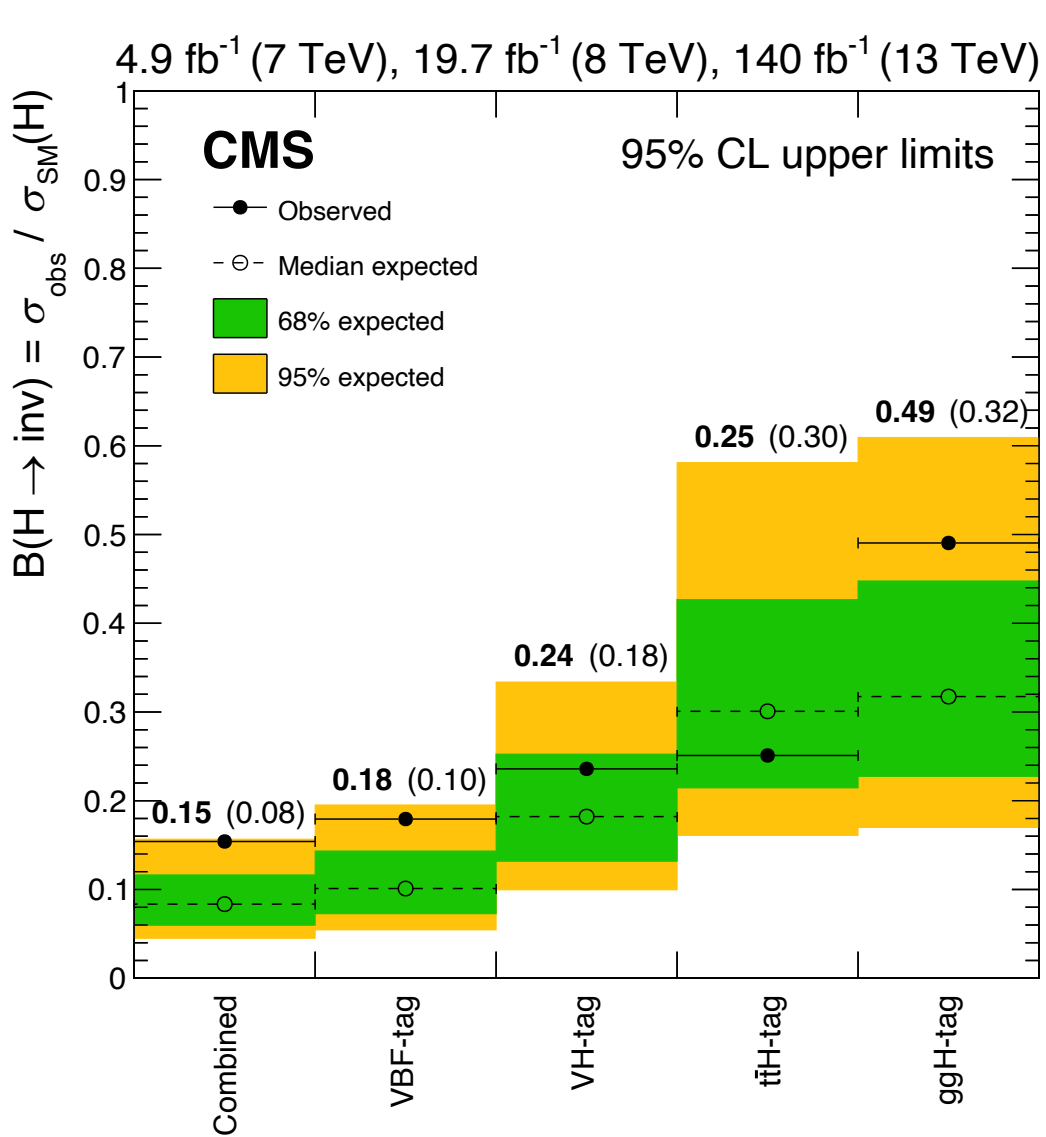
# Simplified Dark Sectors: Spin 0 – Dark Higgs

New scalar mediator with similar properties with Higgs

$$\mathcal{L} \supset -y_{\text{DM}} H_D \bar{\chi} \chi + (\mu H_D + \lambda H_D^2) H^\dagger H.$$

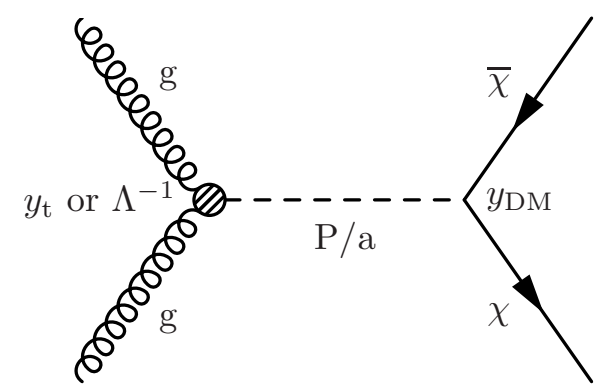


# Simplified Dark Sectors: Spin 0 – SM Higgs



# Simplified Dark Sectors: Spin 0 - PS & ALP

Spin-0 portal



$$\mathcal{L} \supset -ig_q \frac{P}{\sqrt{2}} \sum_q y_q q \gamma^5 \bar{q} - iy_{DM} P \bar{\chi} \gamma^5 \chi$$

$$\mathcal{L}_\gamma \supset \frac{c_\gamma}{4\Lambda} a F_{\mu\nu} \tilde{F}^{\mu\nu},$$

$$\mathcal{L}_g \supset \frac{4\pi\alpha_S c_g}{\Lambda} a G_{i,\mu\nu} \tilde{G}_i^{\mu\nu},$$

$$\frac{c_g}{\Lambda} = g_q/v.$$

Pseudoscalar and scalar have similar sensitivities at the LHC, but:

- DD bounds have PS-mediator suppressed: depends on the square of the velocity of the DM
- ID bounds have the sensitivity to PS-mediator DM annihilation is enhanced.

The ALP portal and the PS portal can be directly translated between each other!

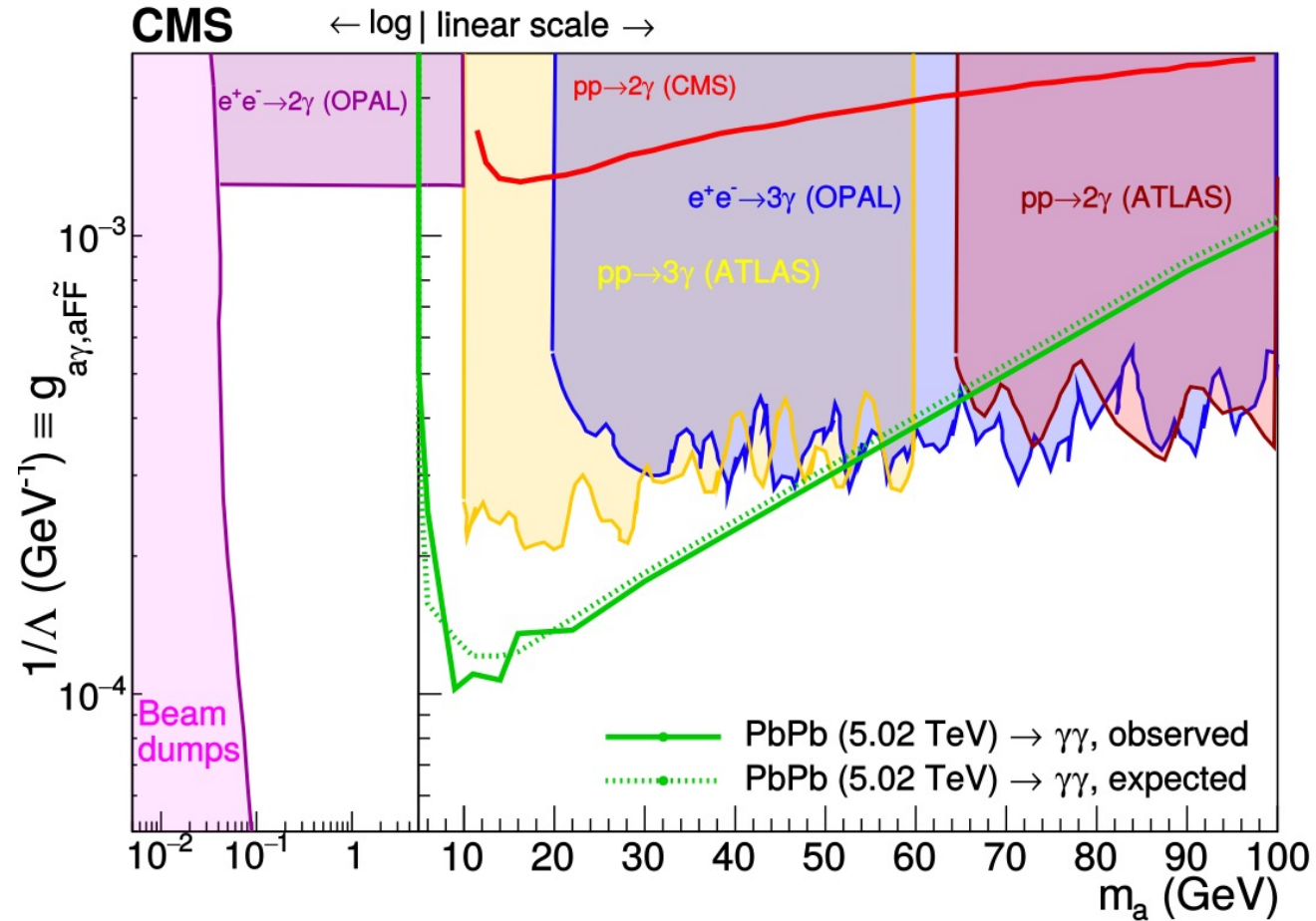
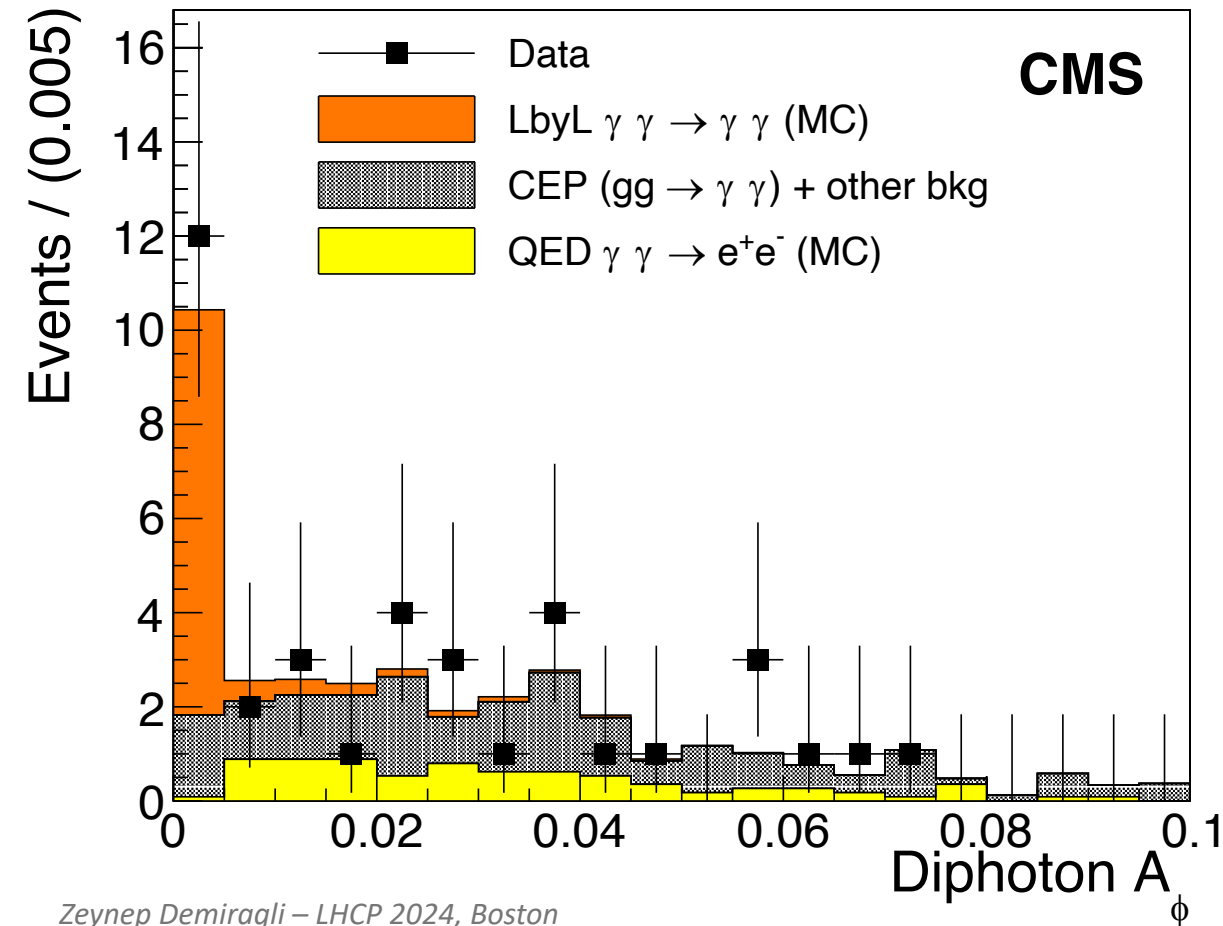


# Simplified Dark Sectors: ALP Sensitivity

ALPS that couple to photons in PbPb Ultraperipheral Collisions:

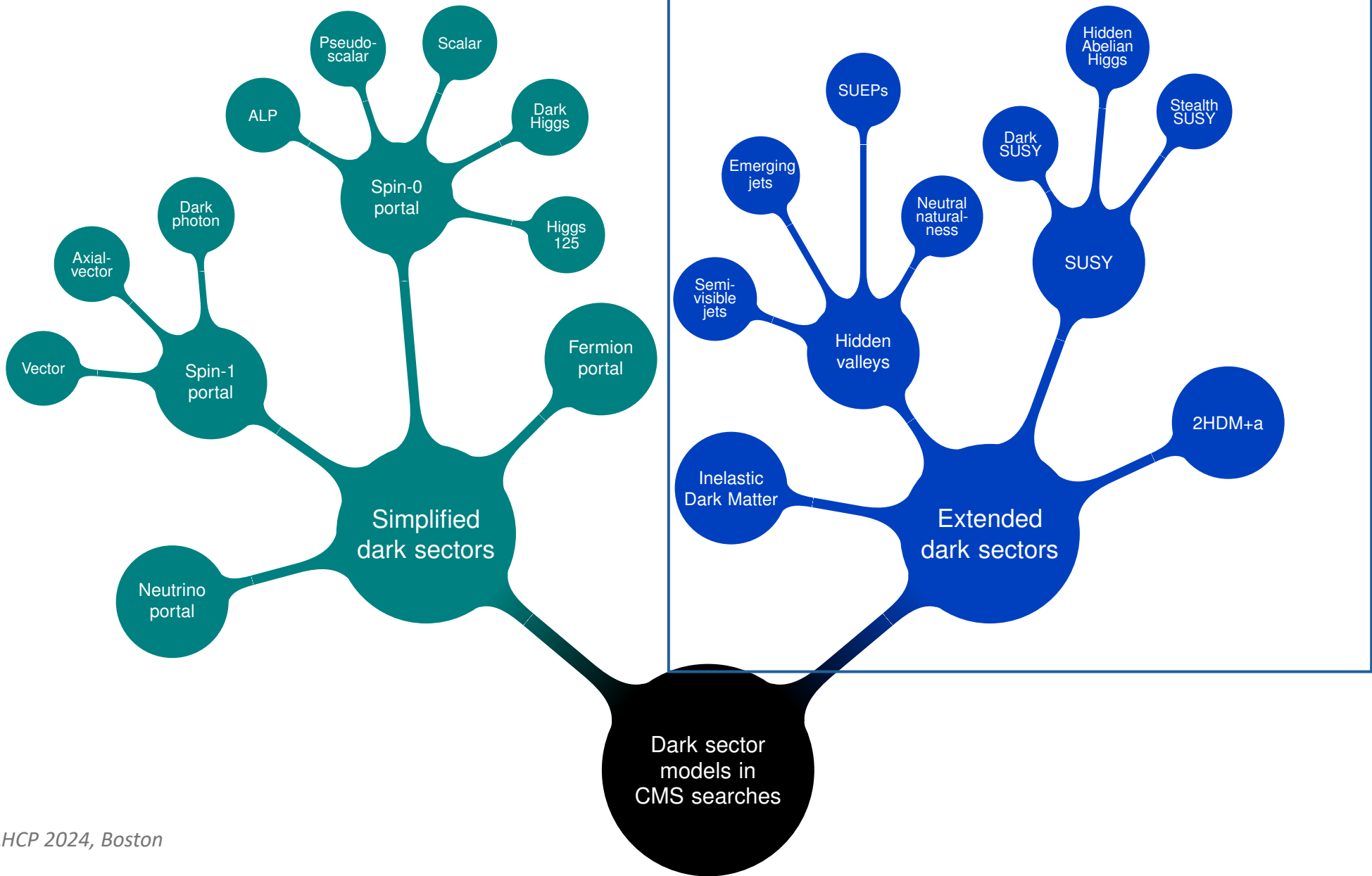
- The production of an ALP ( $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ ) would modify the rate of ( $\gamma\gamma \rightarrow \gamma\gamma$ )

PbPb 390  $\mu\text{b}^{-1}$  (5.02 TeV)



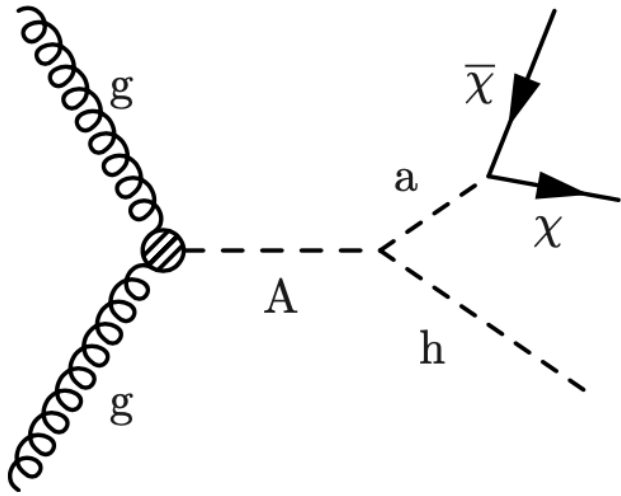
But *nature* could be more complicated ...

# Introduction: Theoretical Framework



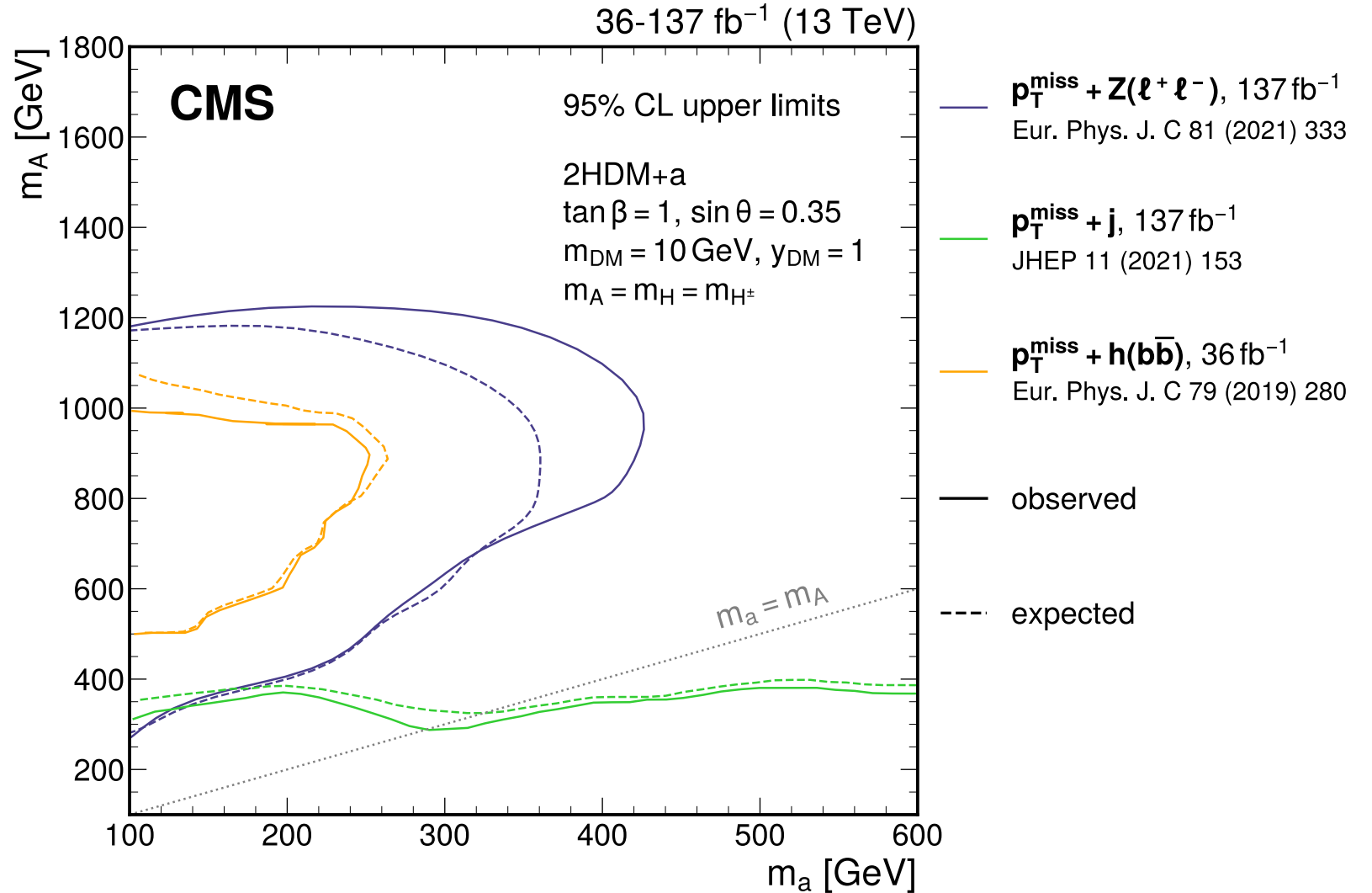
# Extended Dark Sectors: 2HDM+a

Ultra-violet complete and renormalizable



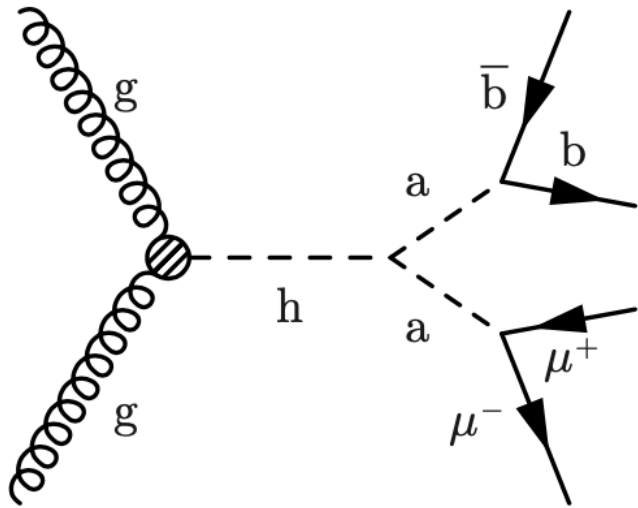
Assumes SM Higgs boson is part of an extended Higgs sector with two complex Higgs doublets

14 independent parameters..  
but reduce to 5 free parameters



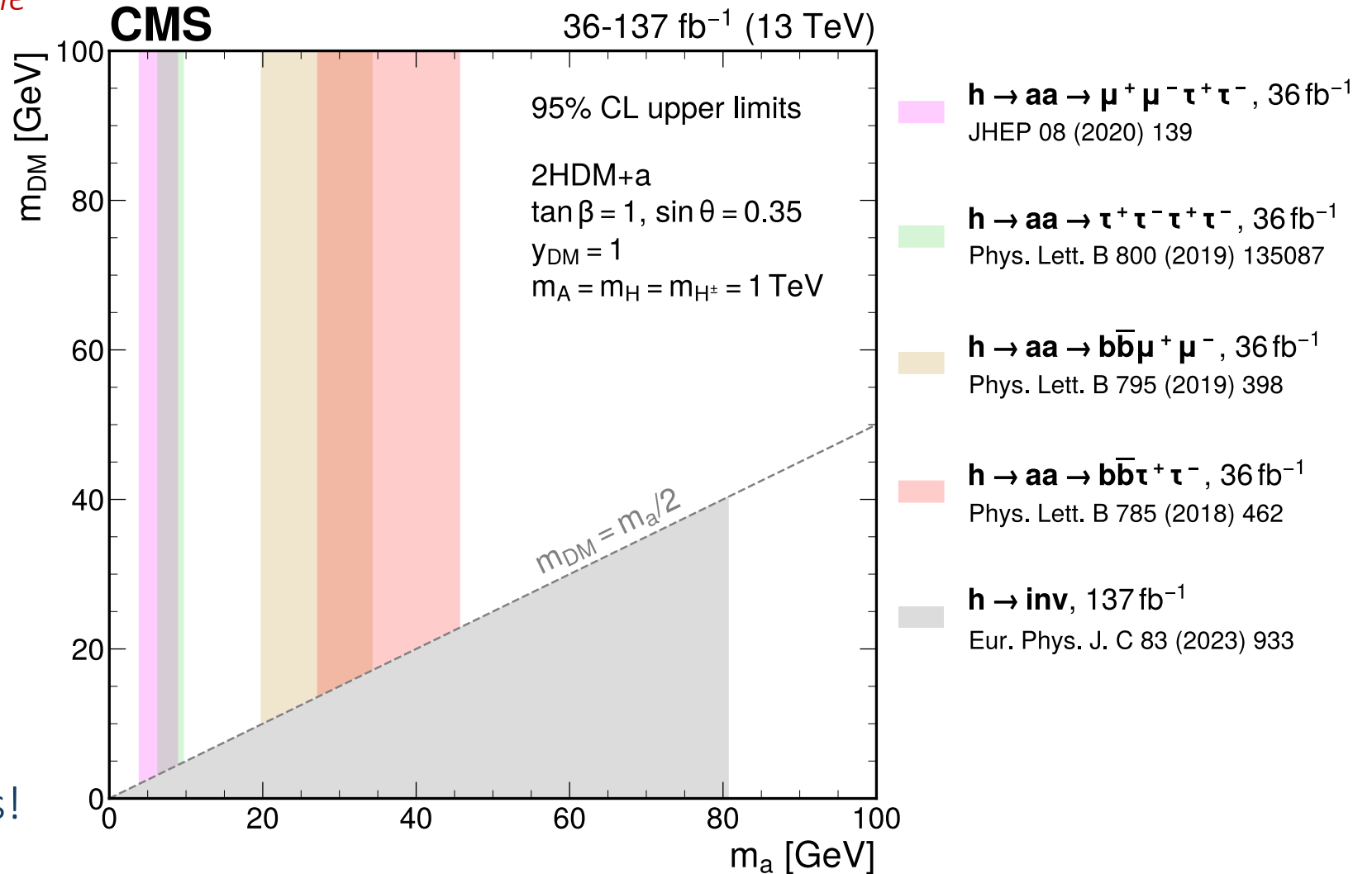
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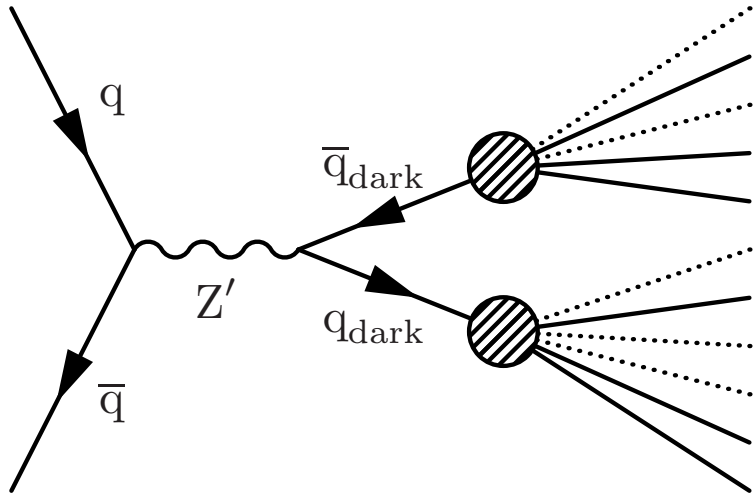


The exotic decay  $h \rightarrow aa$  is possible for very low  $m_a$ :

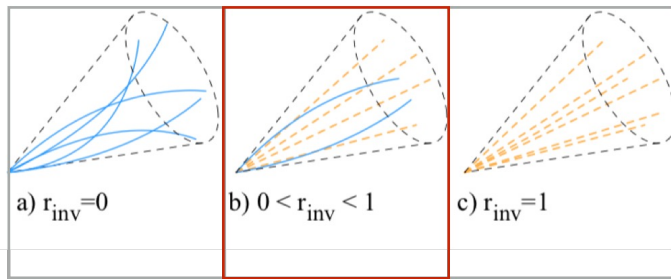
- including invisible, semi-visible, and visible final states!



# Extended Dark Sectors: Hidden Valleys

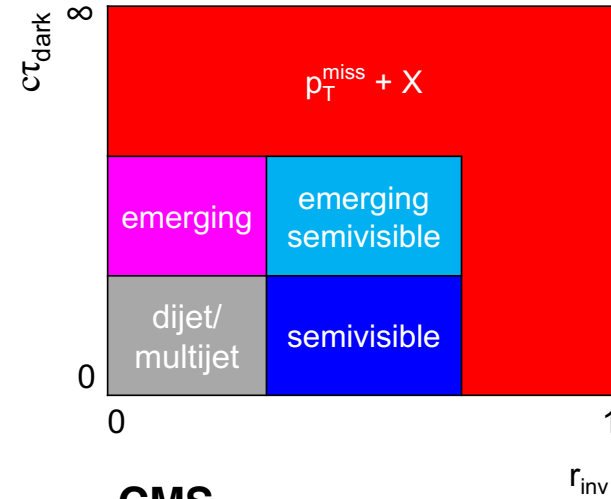


$$r_{inv} = \left\langle \frac{N \text{ stable dark hadrons}}{N \text{ dark hadrons}} \right\rangle$$



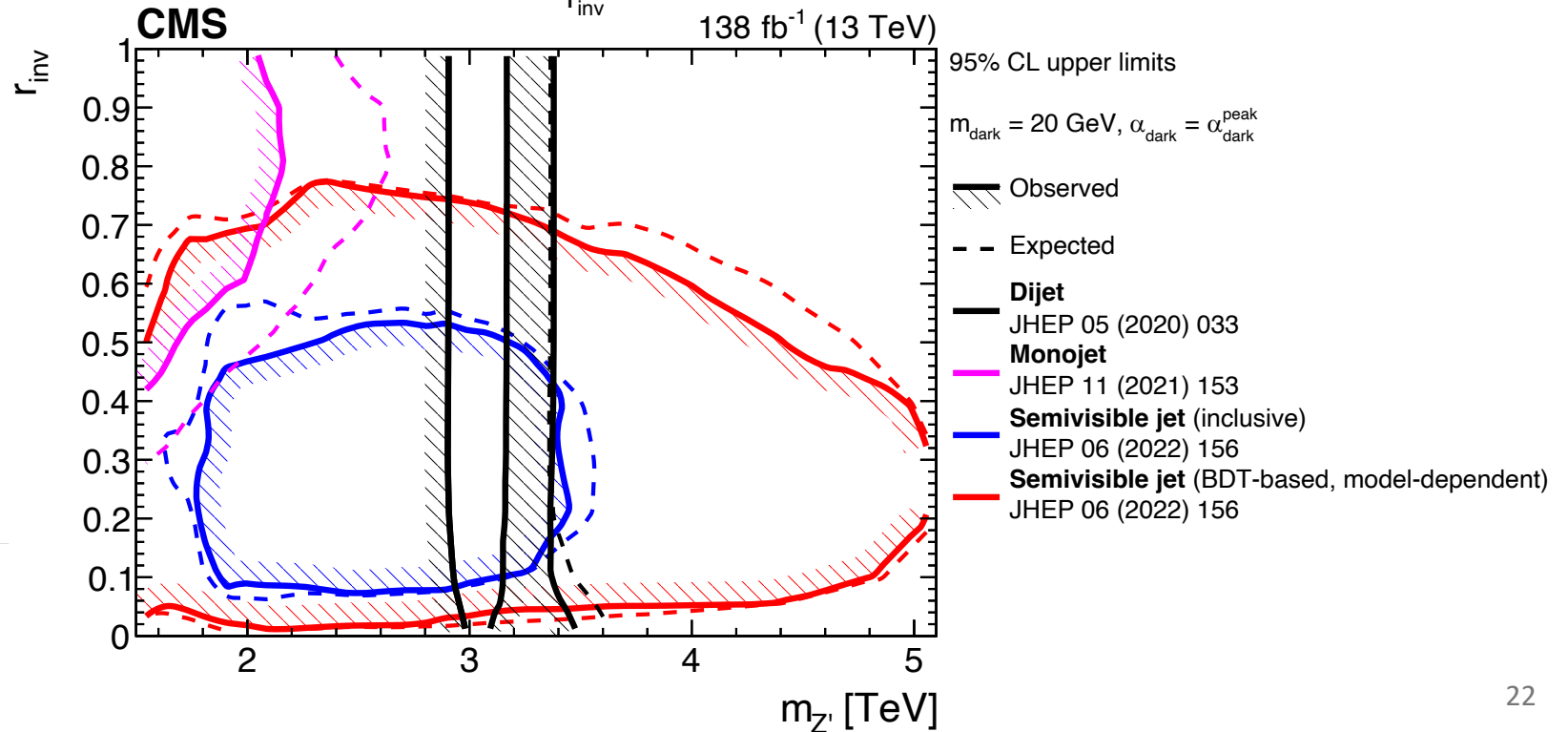
dijet-like

monojet-like

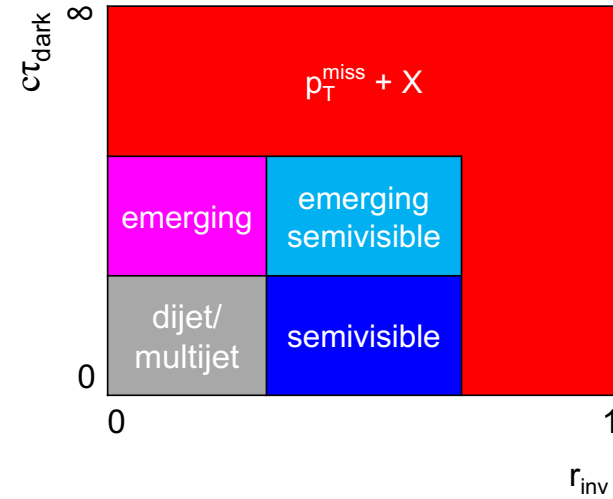
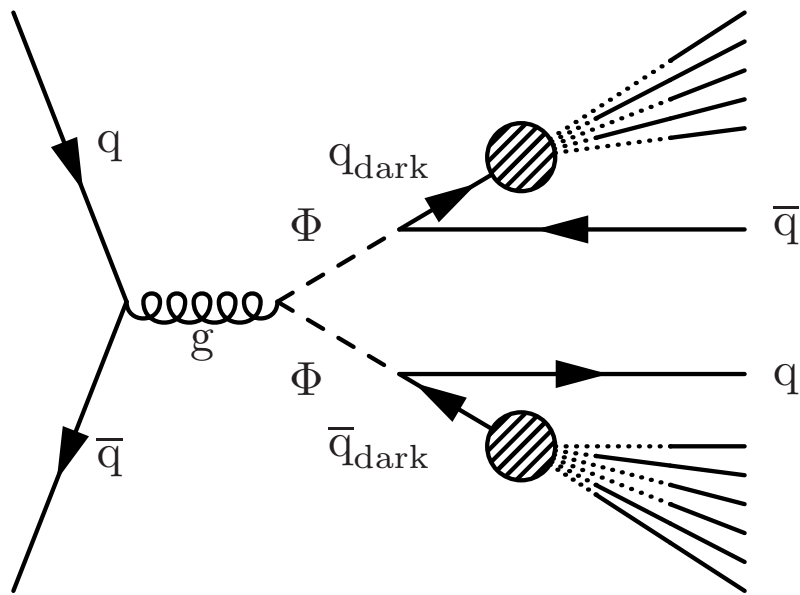
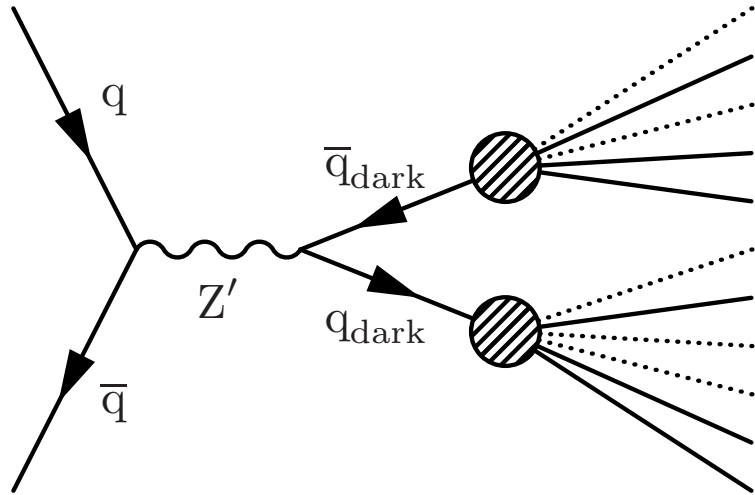


Simple strongly coupled DS with  $N_{c_{\text{dark}}} = 2$  and  $N_{f_{\text{dark}}} = 2$  connected via  $Z'$

➤ Production of stable hadrons can be suppressed leading to an invisible fraction

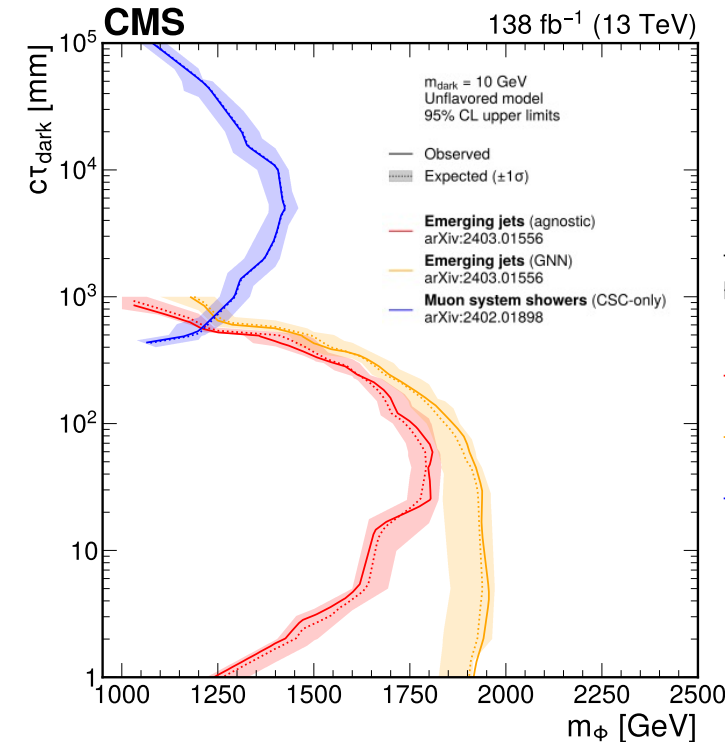
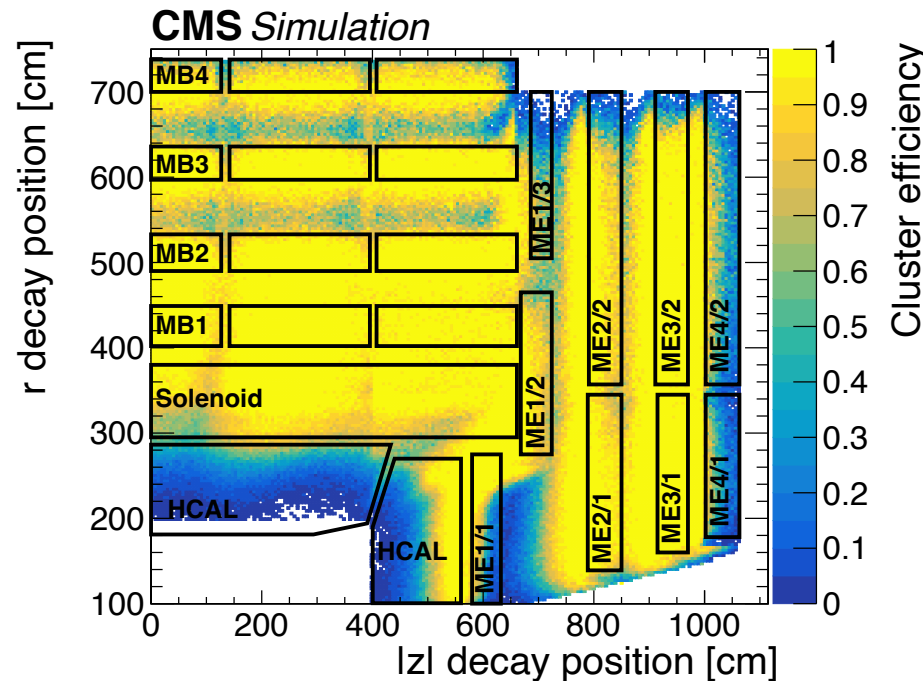


# Extended Dark Sectors: Hidden Valleys



Dark mesons can travel long distances before decaying into SM particles.

- Unique analysis technique: using the muon detector as a sampling calorimeter to identify showers produced by the decays of LLPs





# Conclusion

