Reconciling LHC DM and FIPs

P. Harris, J. Greaves, K. Pachal,
A.Boveia, C. Doglioni B. Gao, D. Pinna, E. Dreyer, G. Gustavino,
J. Krupa, R. Harris, D. Hayden, T. Hrynova, A. Kotwal, and J. Little

Overview

- There is interest in coming up with a way to compare DM bounds
  - LHC and PBC groups have chosen slightly different models
  - Wanted to see if we could translate between models
- This talk will be a recasting of models between benchmarks
  - For the LHC we will use Monojet(DM) results from end of Run 2
  - Interest in the LHC to transition the way we present results
  - We would like to present our results in terms of min coupling
    - This aligns more with the FIP(PBC) approach
    - Complicates presentation with direct detection
- These studies are in arxiv here : https://arxiv.org/abs/2206.03456
  - It might make sense to highlight this in a separate doc

LHC Default Models

- LHC has had 4 default models
  - Motivated by standard LHC signatures and comparison with ID/D
  - Additionally had benchmark coupling choices g_q=0.25 and g_{DM}=1.0

Spin 1

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q - g_\ell \sum_{\ell=e,\mu,\tau} Z'_\mu \bar{\ell}\gamma^\mu \ell\,,$$

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\gamma_5\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu\gamma_5 q - g_\ell \sum_{\ell=e,\mu,\tau} Z'_\mu \bar{\ell}\gamma^\mu\gamma_5 \ell$$

Spin 0

$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}}\phi\bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}q\,,$$

$$\mathcal{L}_{\text{pseudo-scalar}} = -ig_{\text{DM}}\phi\bar{\chi}\gamma_5\chi - ig_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}\gamma_5 q\,,$$

Only quark couplings guaranteed in interpretation

These remain the main ways to interpret DM at LHC

LHC Model Presentation

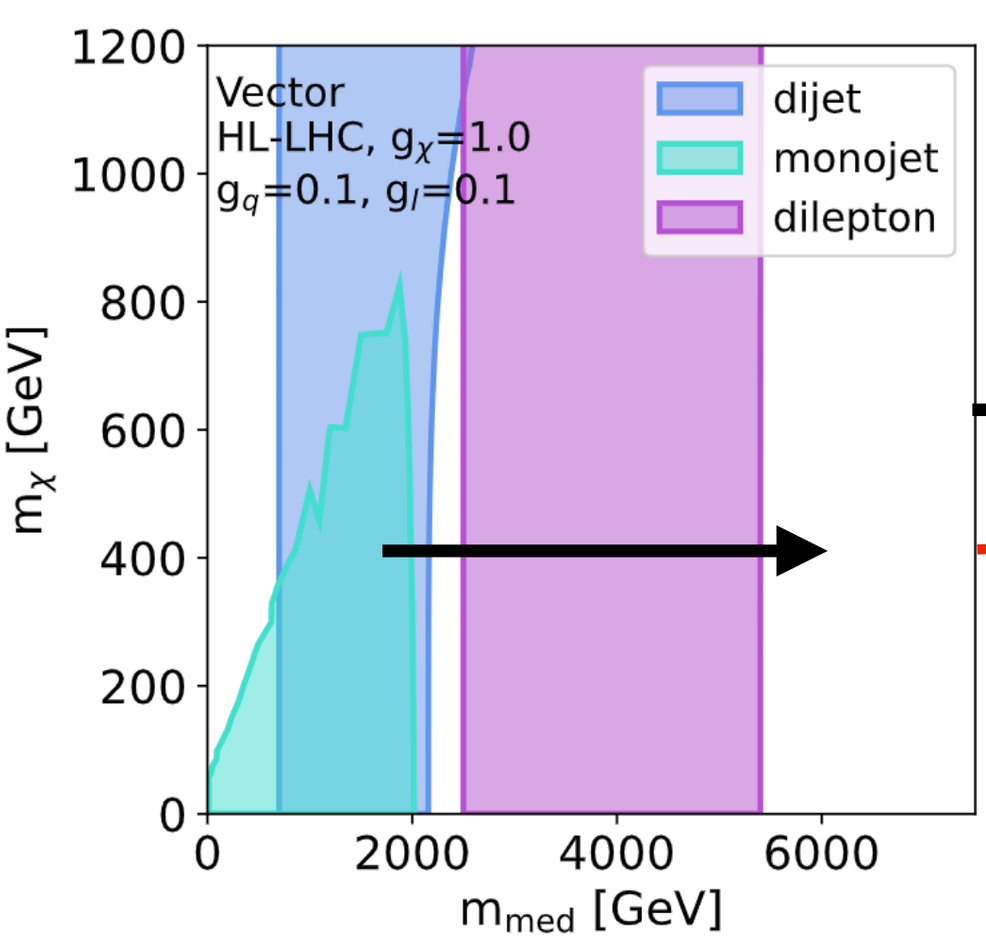
- Traditionally presented models in mass vs mass plane
  - With fixed couplings
  - Idea was to see how high a mass we could achieve

Fixed

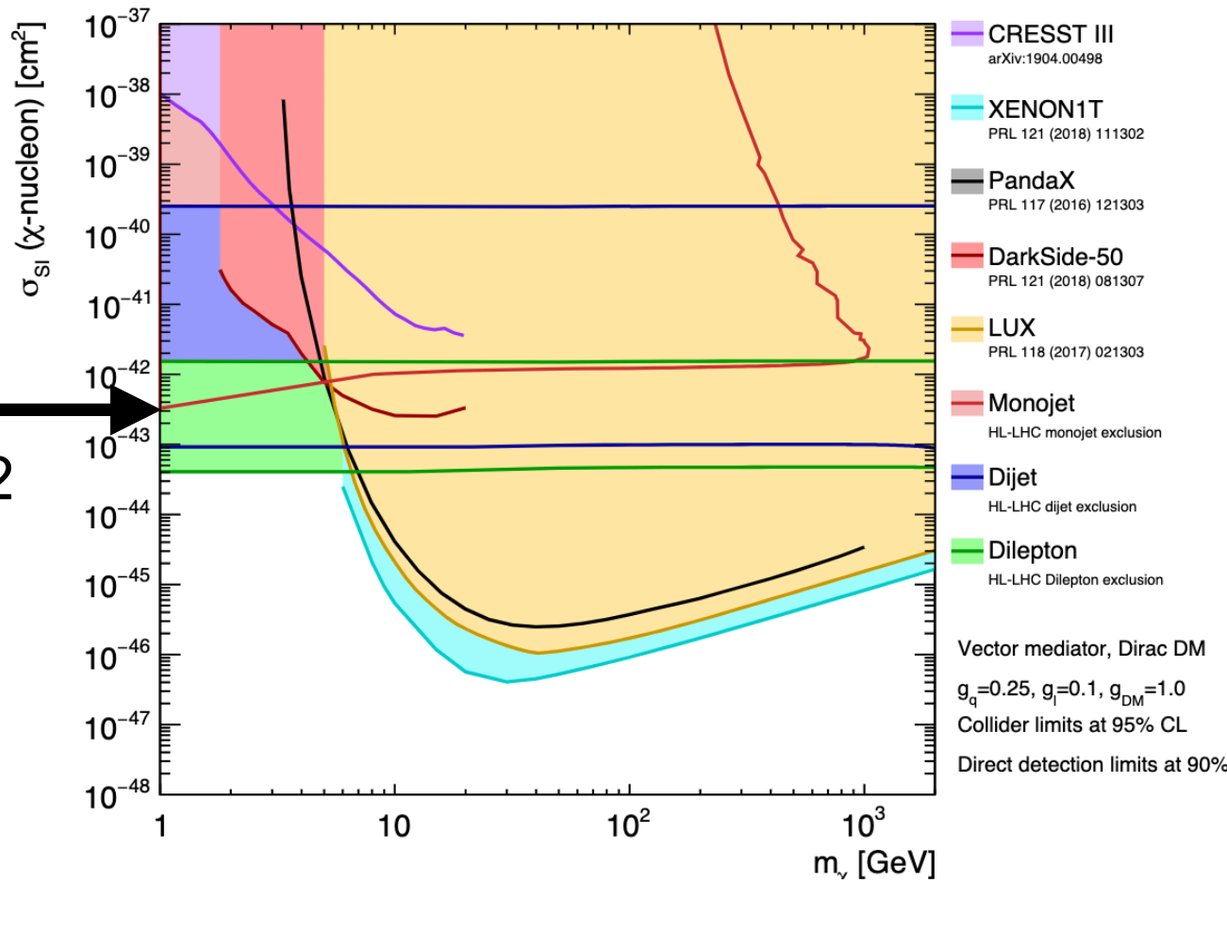
$$\sigma_{\rm SI} = \frac{f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}$$

Floated

Wanted to see how high we could go



Rotate π/2



Floating the couplings

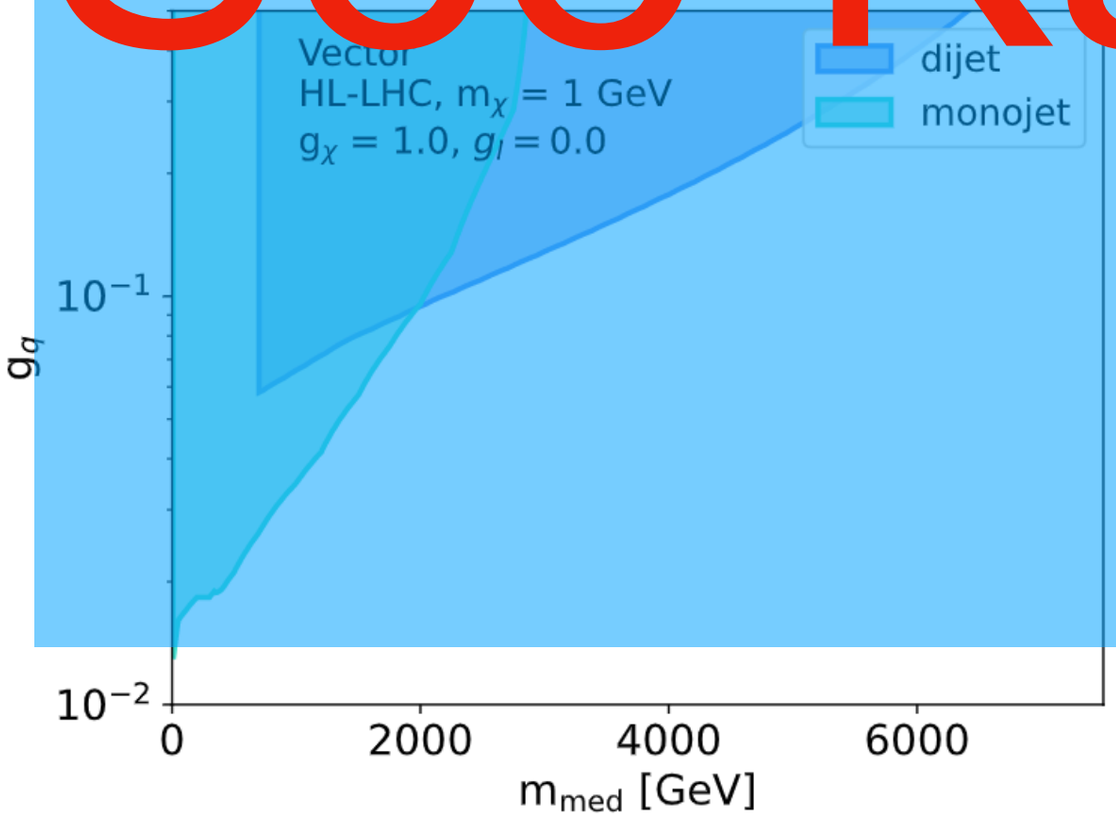
- Floating the couplings gives us a new set of bounds
  - In practice varying couplings doesn't change bounds much
  - However to make direct detection bounds coupling fixed
  - Monojet and dijet can probe couplings below $g_q = 0.1$

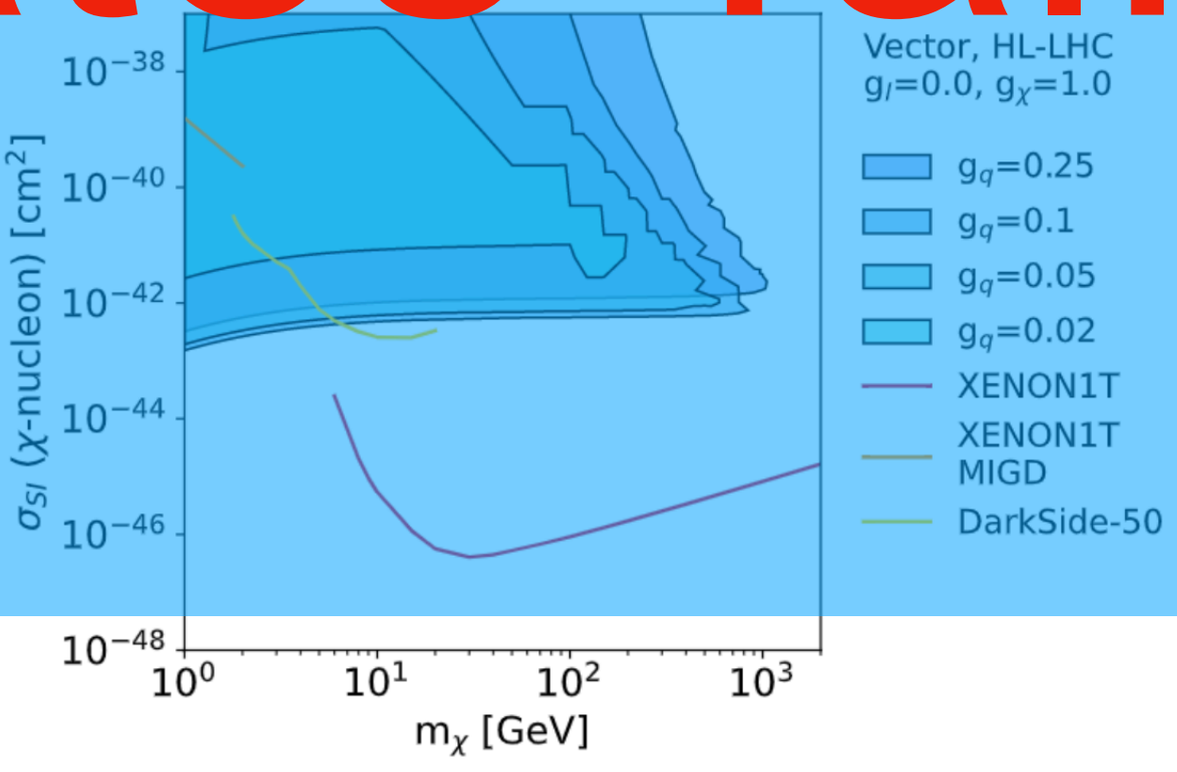
See Kates Talk

Fixing the Dark Matter Mass

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

Floating

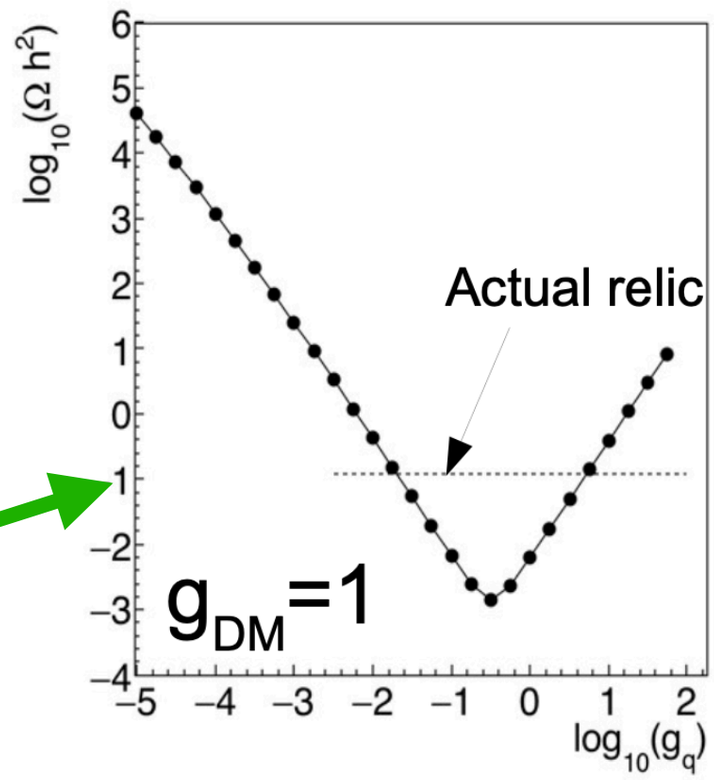




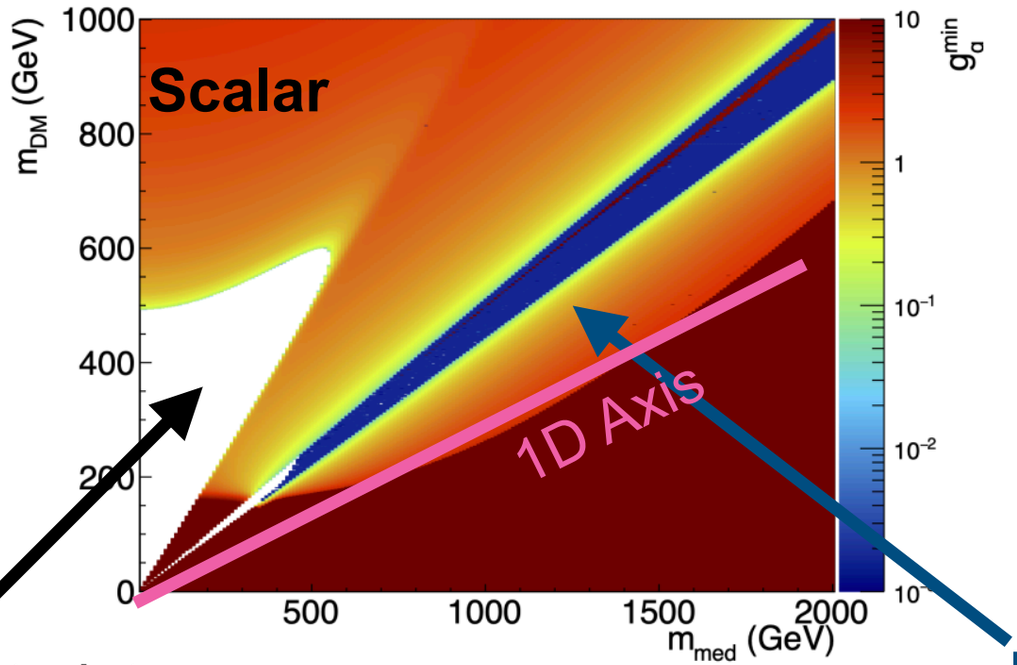
Minimum Coupling Scan

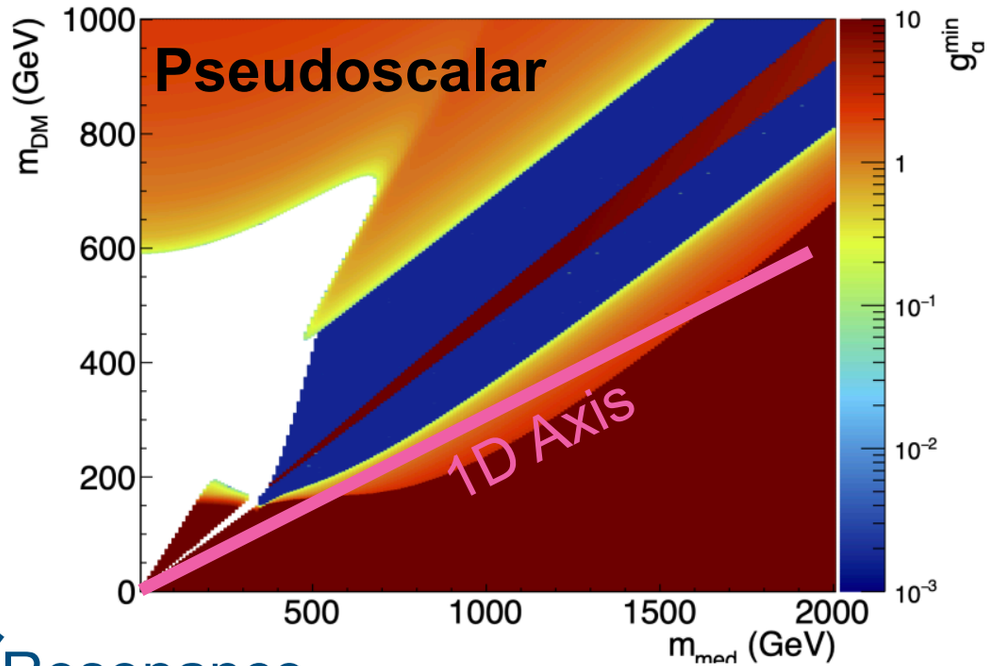
- As w/all simpified DM models there is a minimum coupling
- For the LHC models we can compute the relic density
  - Simplified models, so relic calculation is simplified
  - Compute relic density with MadDM
- We scan the full dark matter mass vs mediator mass
  - Useful to see

The Mininmum



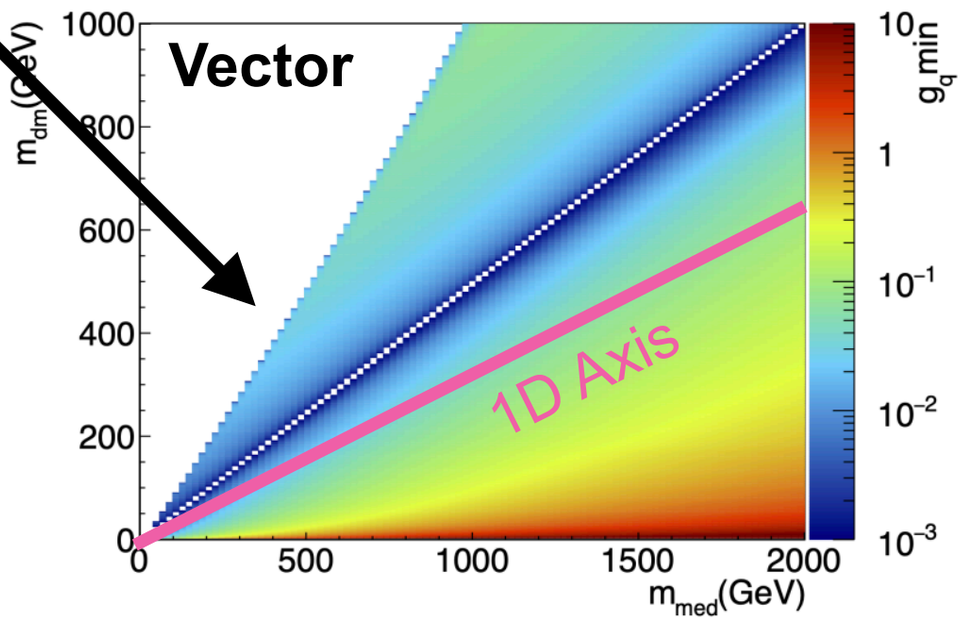
Relic Density Couplings

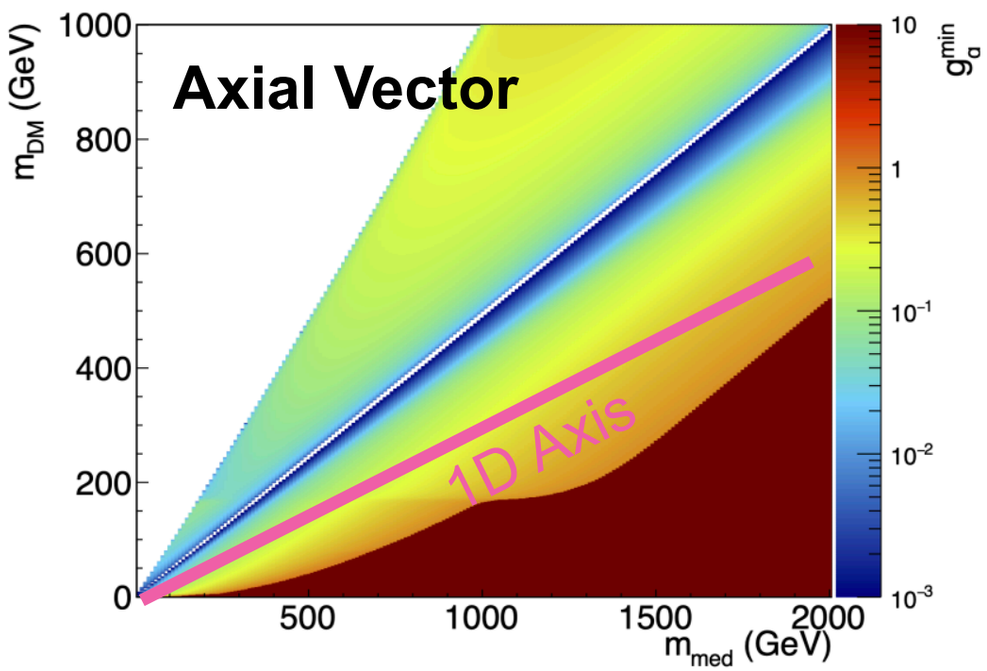




No Constraints

Resonance
(Loose Constraints)

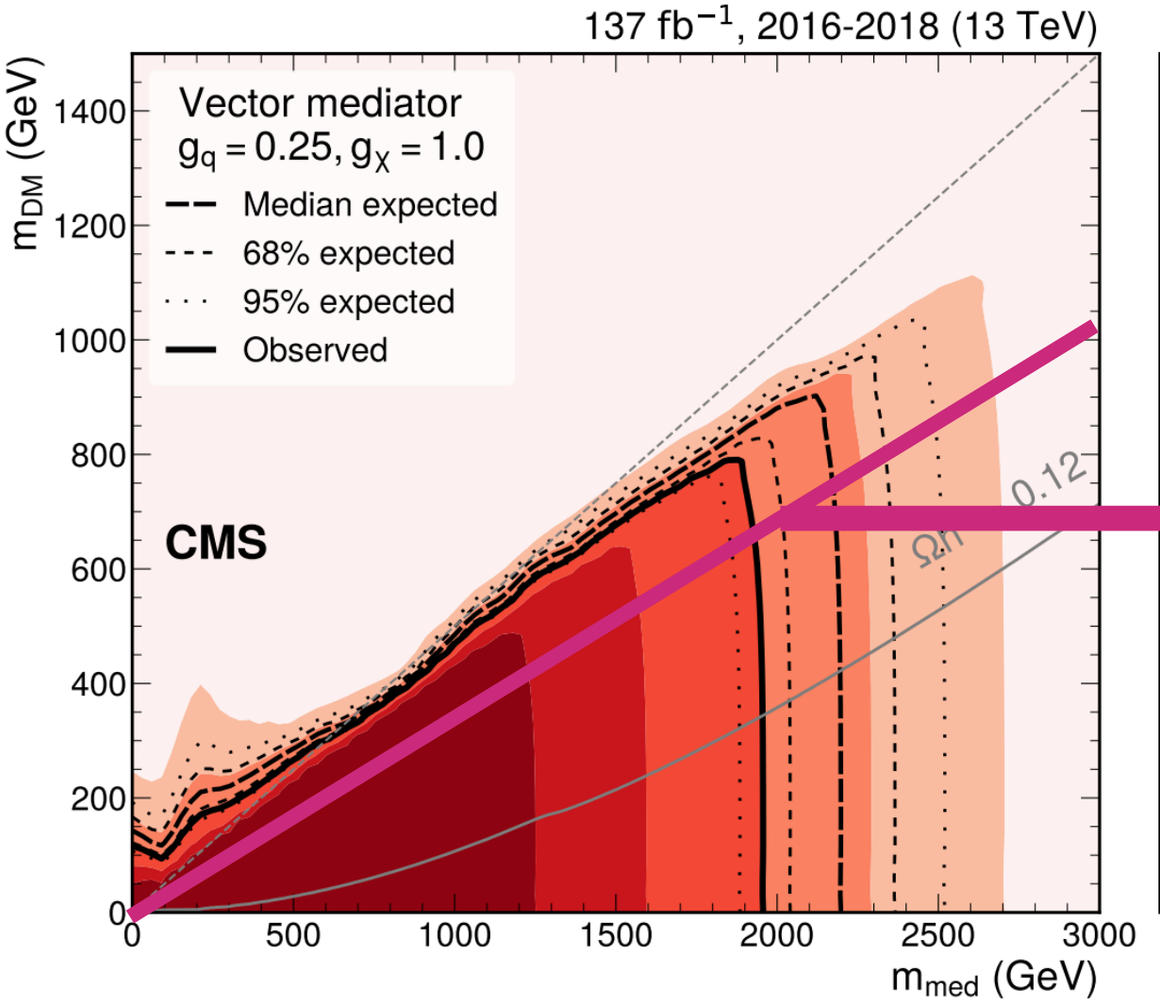


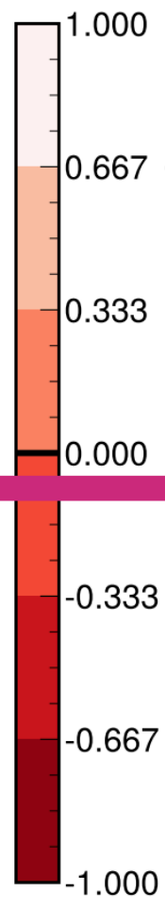


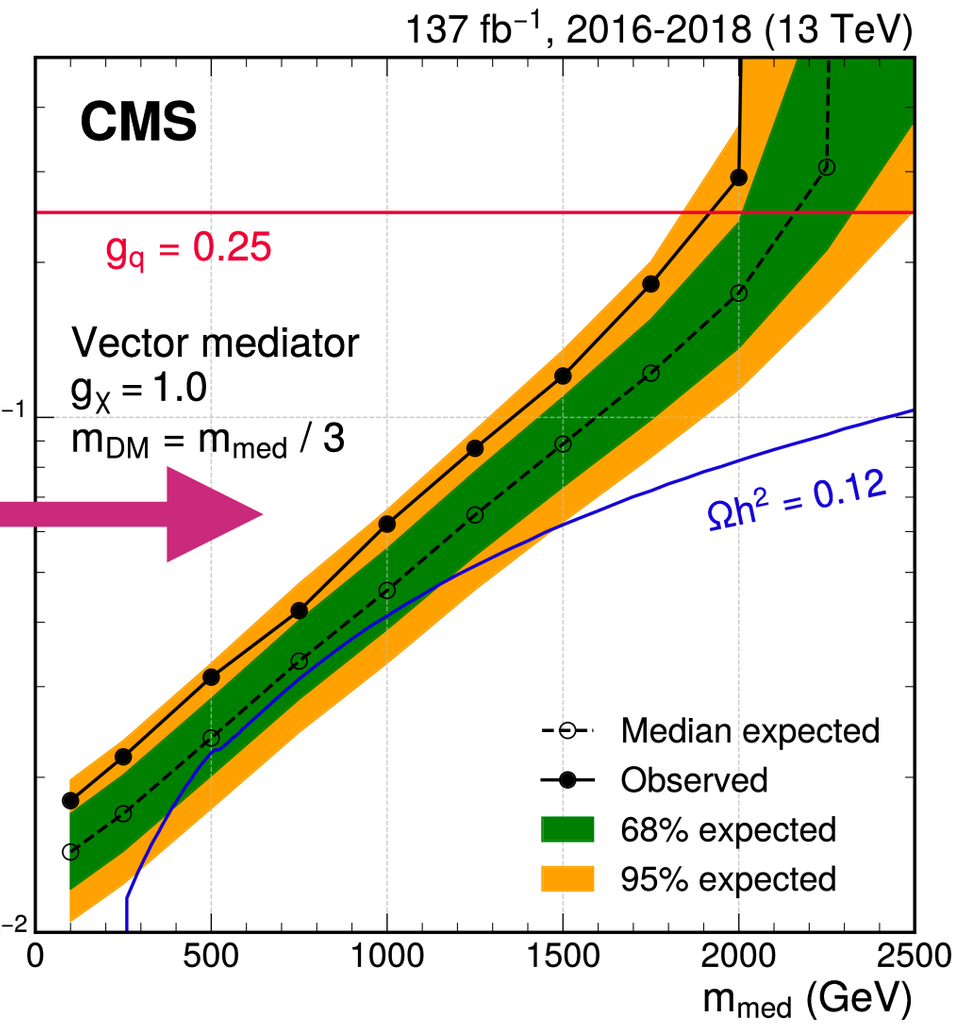
https://arxiv.org/pdf/2203.12035.pdf

Current (Vector) results

- Have been active efforts to harmonize results in DMWG
  - Added a lot of plots to allow for small coupling interpretations
- We are already presenting coupling scans on 1D axis







https://arxiv.org/abs/2107.13021

Coupling on y-axis shows overall sensitivity

PBC Models

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2)H^\dagger H$
Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

https://arxiv.org/pdf/1901.09966.pdf

FIP(PBC) Models

Like LHC DM WG present :

- spin-1 Vector (Dark Photon)
- spin-0 Scalar (Dark Higgs)
- spin-0 Psuedoscalar (ALP)

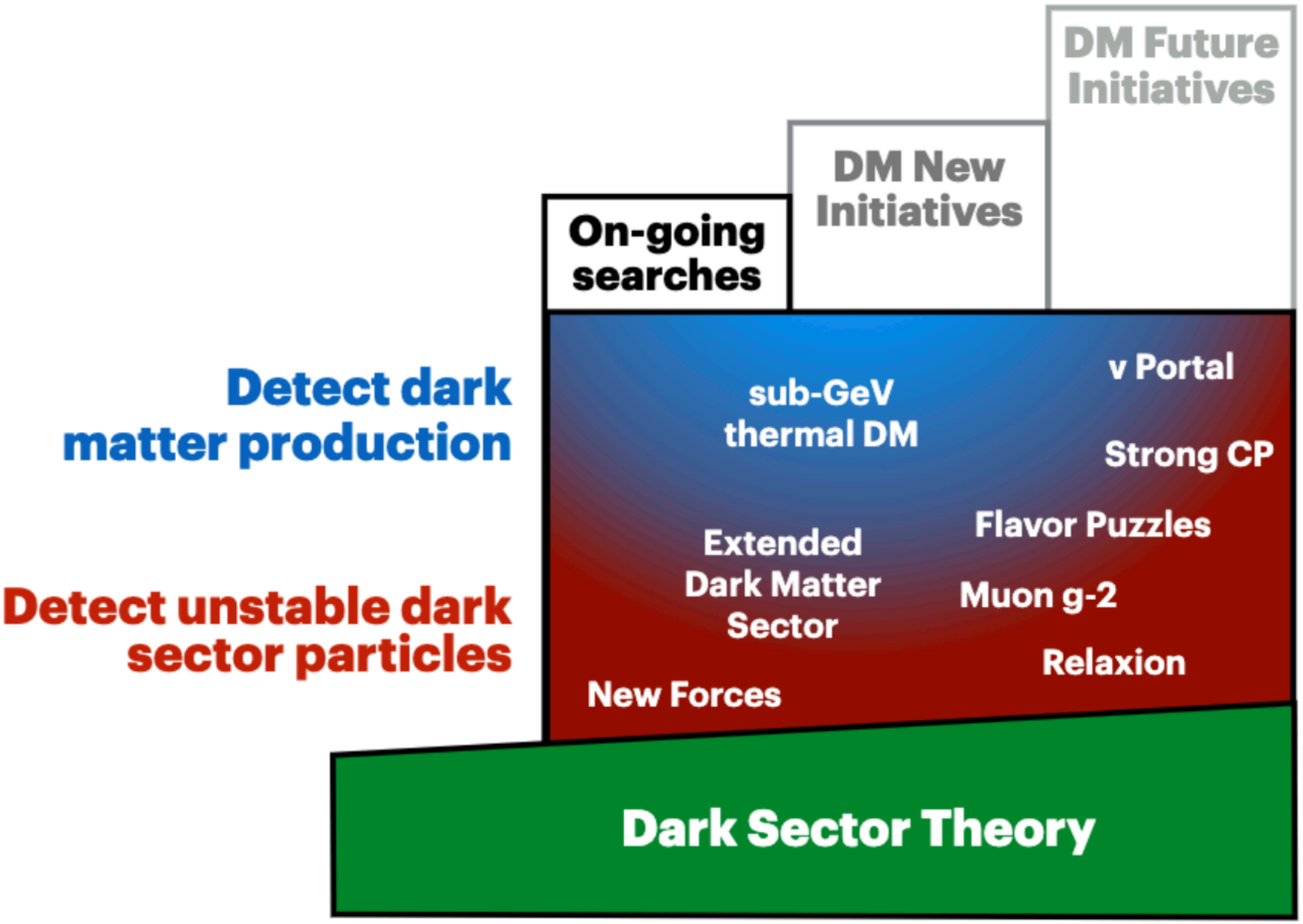
With FIP, Models are complete-ish

Also there is the Sterile Neutrino (we will not discuss)

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2)H^\dagger H$
Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

https://arxiv.org/pdf/1901.09966.pdf

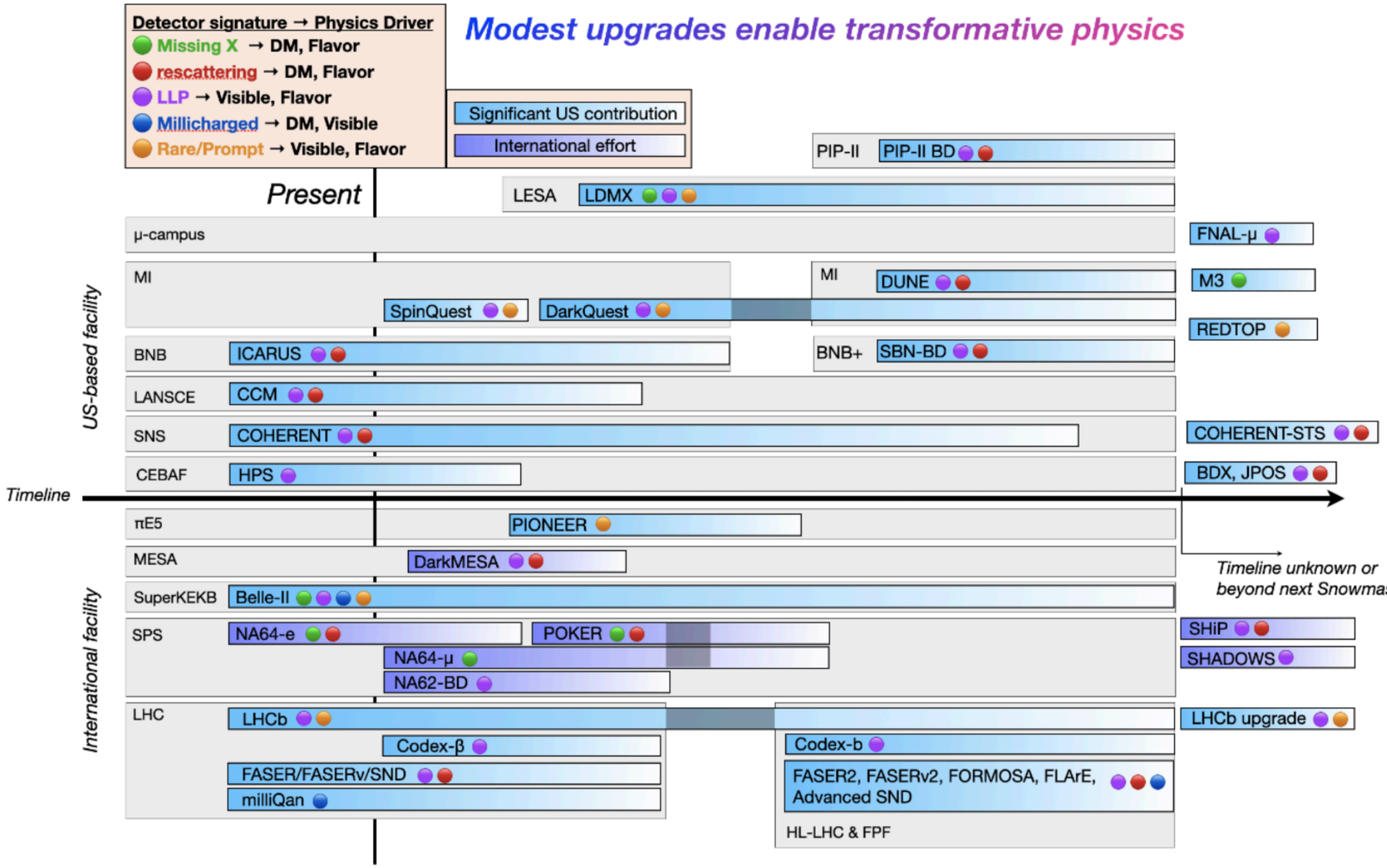
Light DM at Snowmass



This encompasses the models of the FIP with a US focus

Final Report to come out soon!

Goal of Snowmass

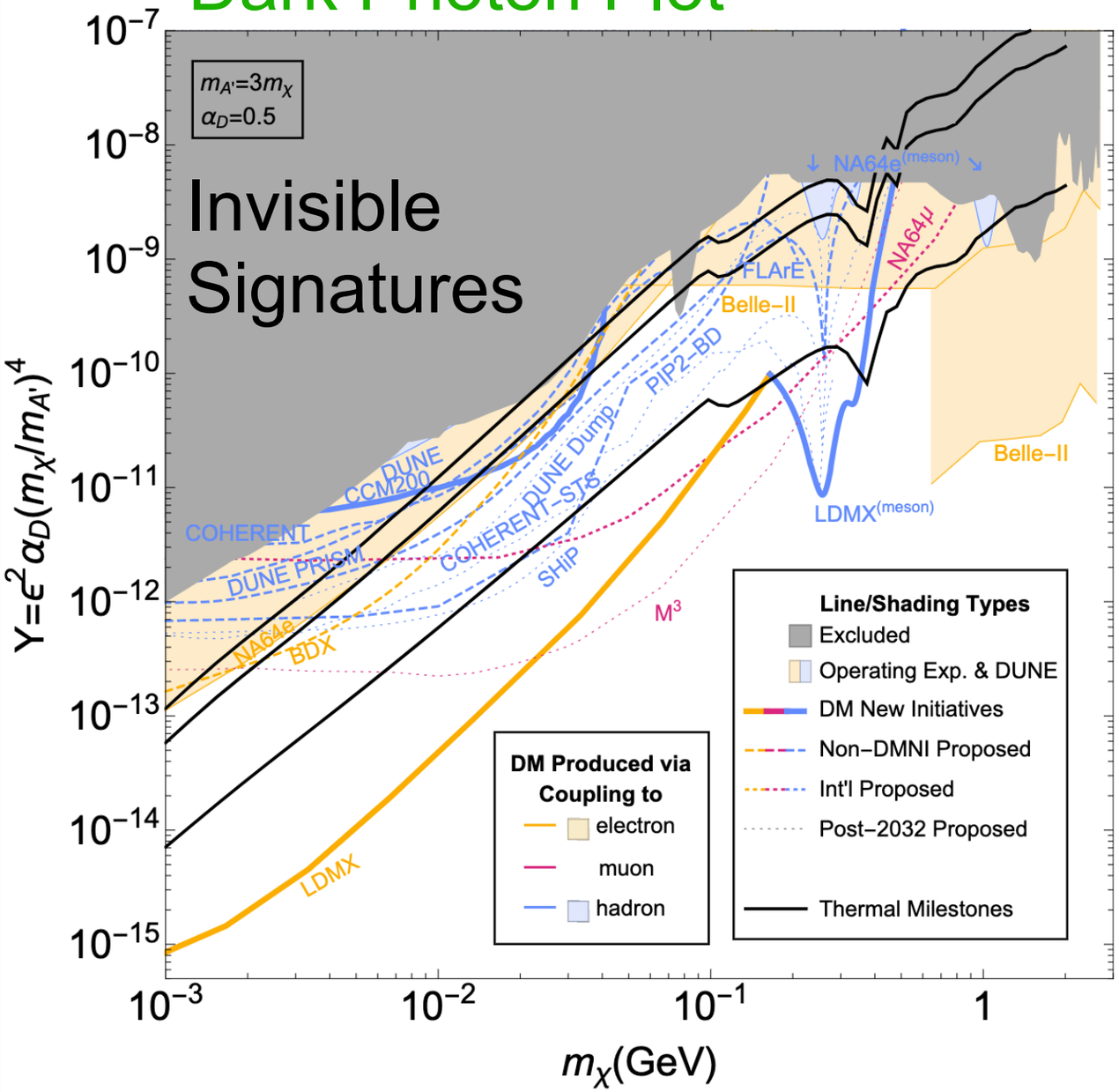


Bring awareness to the importance of Light Dark Matter

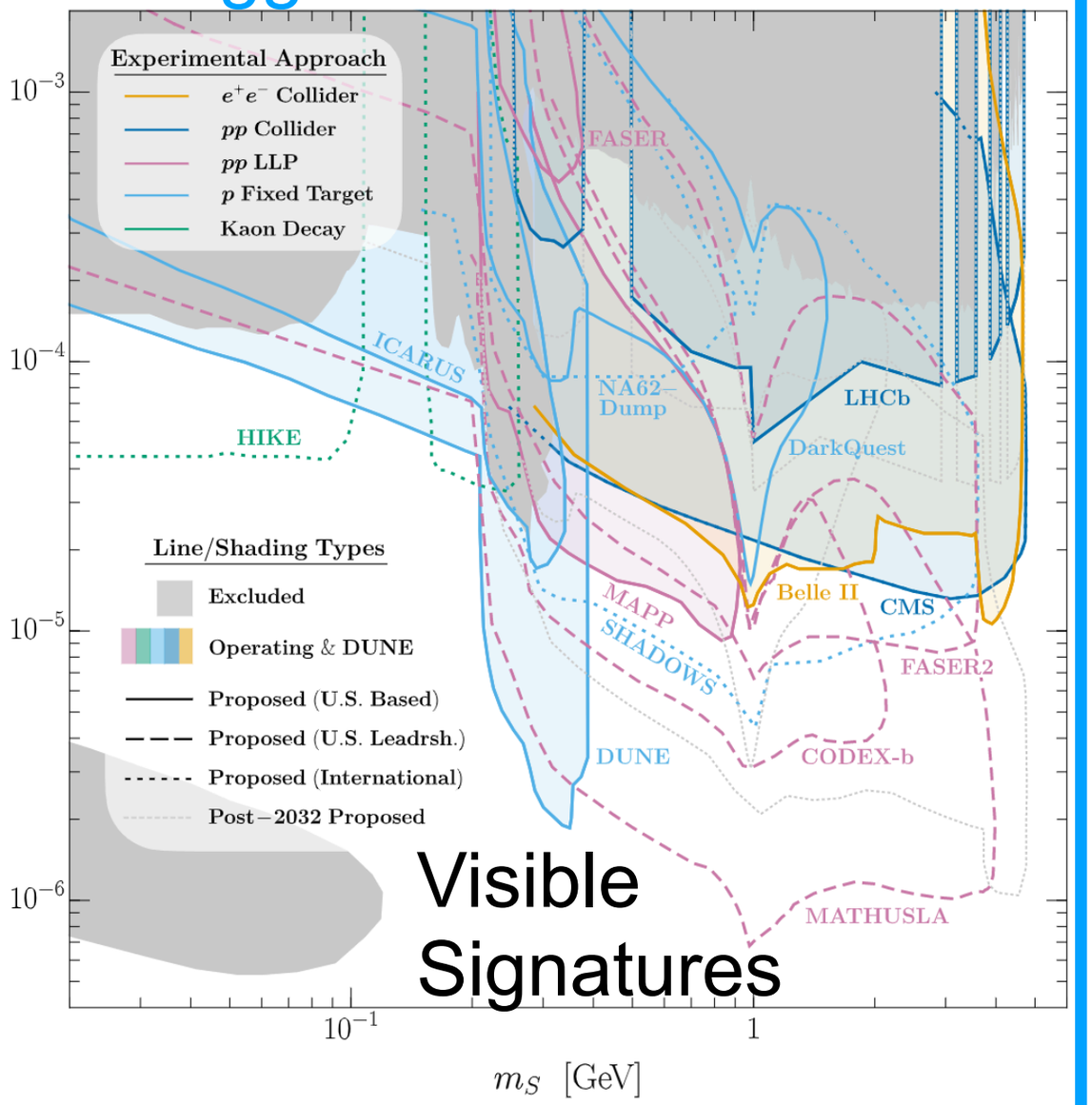
Recommend the development of modest experiments

Light DM at Snowmass

Dark Photon Plot



Dark Higgs Plot

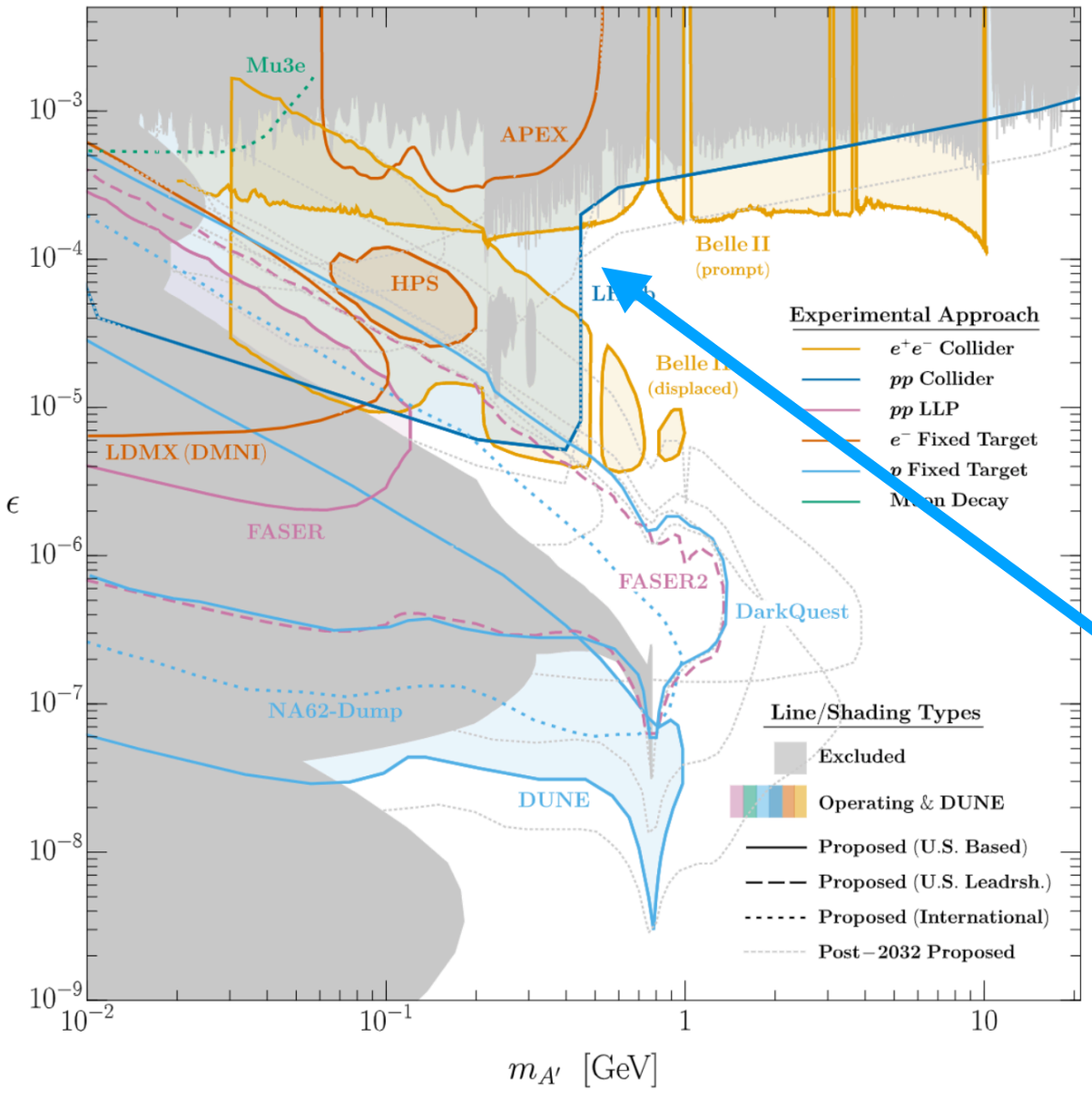


We will focus on invisible signatures for LHC to compare with

There are some cases that Light DM focuses not directly relavent

Future Connections

Weakly Coupled Dark Photons



Light DM considered g-2 models highlights specific final states

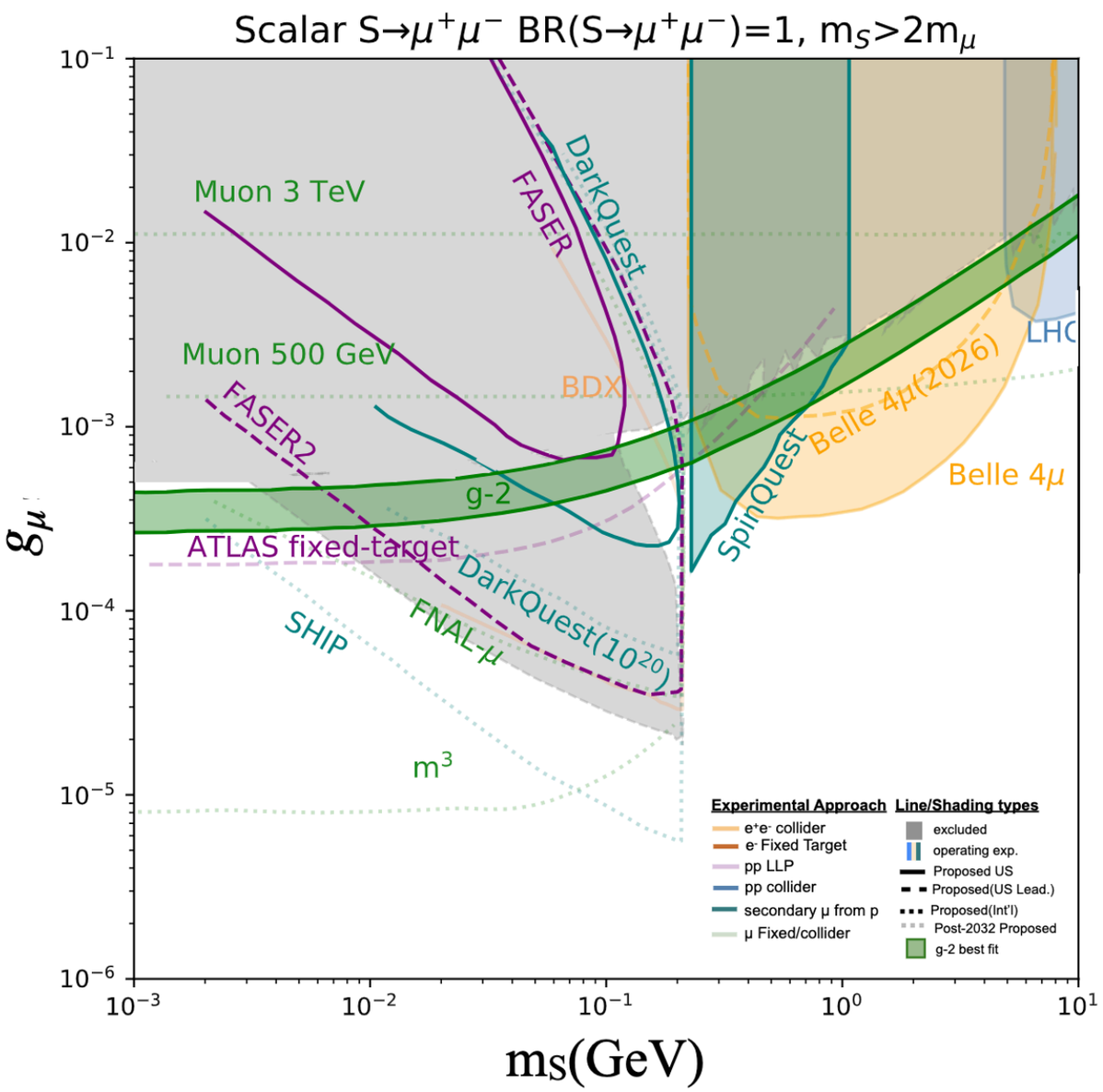
Effort to highlight weak coupled Dark Photon

Coupling weak enough to be long-lived

Potential to connect w/LL group

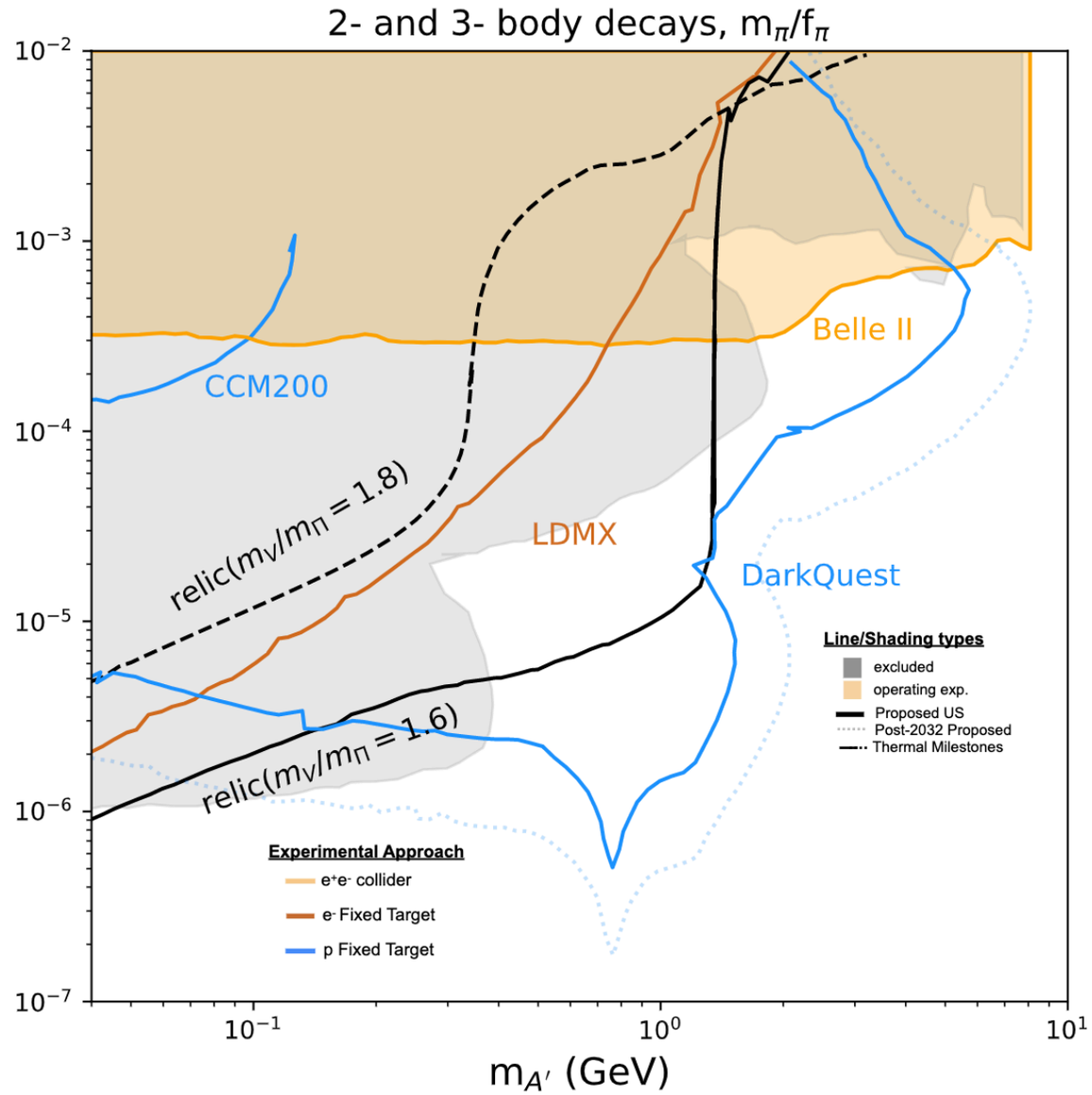
Other Highlights

Dark Scalar Coupling to Muons



Light DM considered g-2 models highlights specific final states

SIMP Dark Photon Model



Light DM considered g-2 models highlights specific final states

Comparisons w/PBC

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}}\, Z'_\mu\, \bar{\chi}\gamma^\mu\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu\, \bar{q}\gamma^\mu q - g_\ell \sum_{\ell=e,\mu,\tau} Z'_\mu\, \bar{\ell}\gamma^\mu \ell\,,$$

Adding Mixing with photon

$$g_q = g_\ell = \frac{\epsilon}{2e\cos\theta_W}$$

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

LHC Spin 1 results are very similar to Dark Photon in PBC
For the most part simple rescaling can allow for result comparisons

Dark Photon's have previously been discussed here https://indico.cern.ch/event/729789/

https://arxiv.org/pdf/1901.09966.pdf

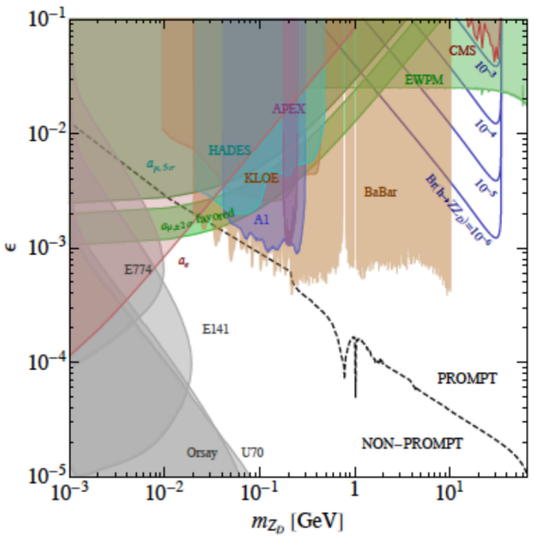
Actually Reconciling

- To reconcile the models we wanted a Madgraph Model
  - Started from here Dark Vector + Dark Higgs model here

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} - \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu} + g_{DM}\cos(\theta_a) Z_D \chi\chi + g_{DM}\sin(\theta_a) Z\chi\chi$$

We started with a Madgraph model with Dark Photon to SM couplings
Also, includes Dark Higgs

Adding DM terms to the model so we can probe invisible decays



D. Curtin et al. (Phys. Rev. D 90, 075004 (2014)

In the following slides we will recast the CMS monojet analysis and projections to Dark Photon
Just look at the invisible final state (LDMX/Belle bounds at low mass)

Analytic Form

- Additionally with model we can compare w/LHCDMWG
  - From the Lagrangian we can write

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} - \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu} + g_{DM}\cos(\theta_a) Z_D \chi\chi + g_{DM}\sin(\theta_a) Z\chi\chi$$

$$\begin{pmatrix} Z \\ Z_D \end{pmatrix} = \begin{pmatrix} \cos\theta_a & \sin\theta_a \\ -\sin\theta_a & \cos\theta_a \end{pmatrix} \begin{pmatrix} Z_0 \\ X \end{pmatrix}$$

Taking usual mixing scenario

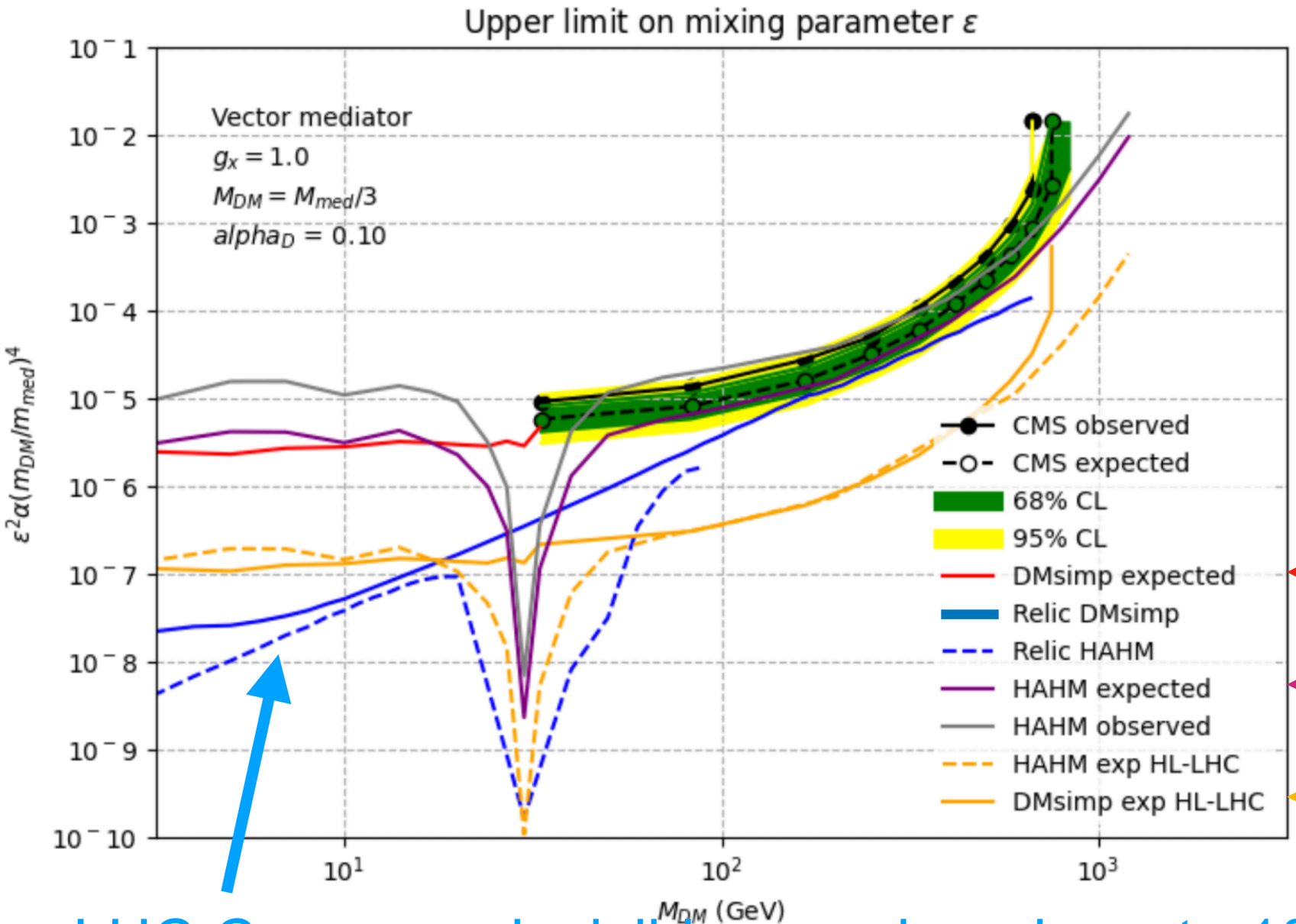
$$g_q = \frac{e\sin\theta_a}{2\tan\theta_w} \approx e\epsilon \frac{1}{\Delta_z - 1} \frac{\cos\theta_w}{2}$$

$$\Delta_z = \left(\frac{M_{z'}}{M_z}\right)^2$$

Master Formula Allows us to translate between the two

The Result

- LHC Monojet Analysis is in MadAnalysis
  - Relic density computed with MadDM (maps well)



LHCDMWG Default (DMSimp) scaled by $\epsilon e \frac{\cos\theta_W}{2}$

LHCDMWG Default

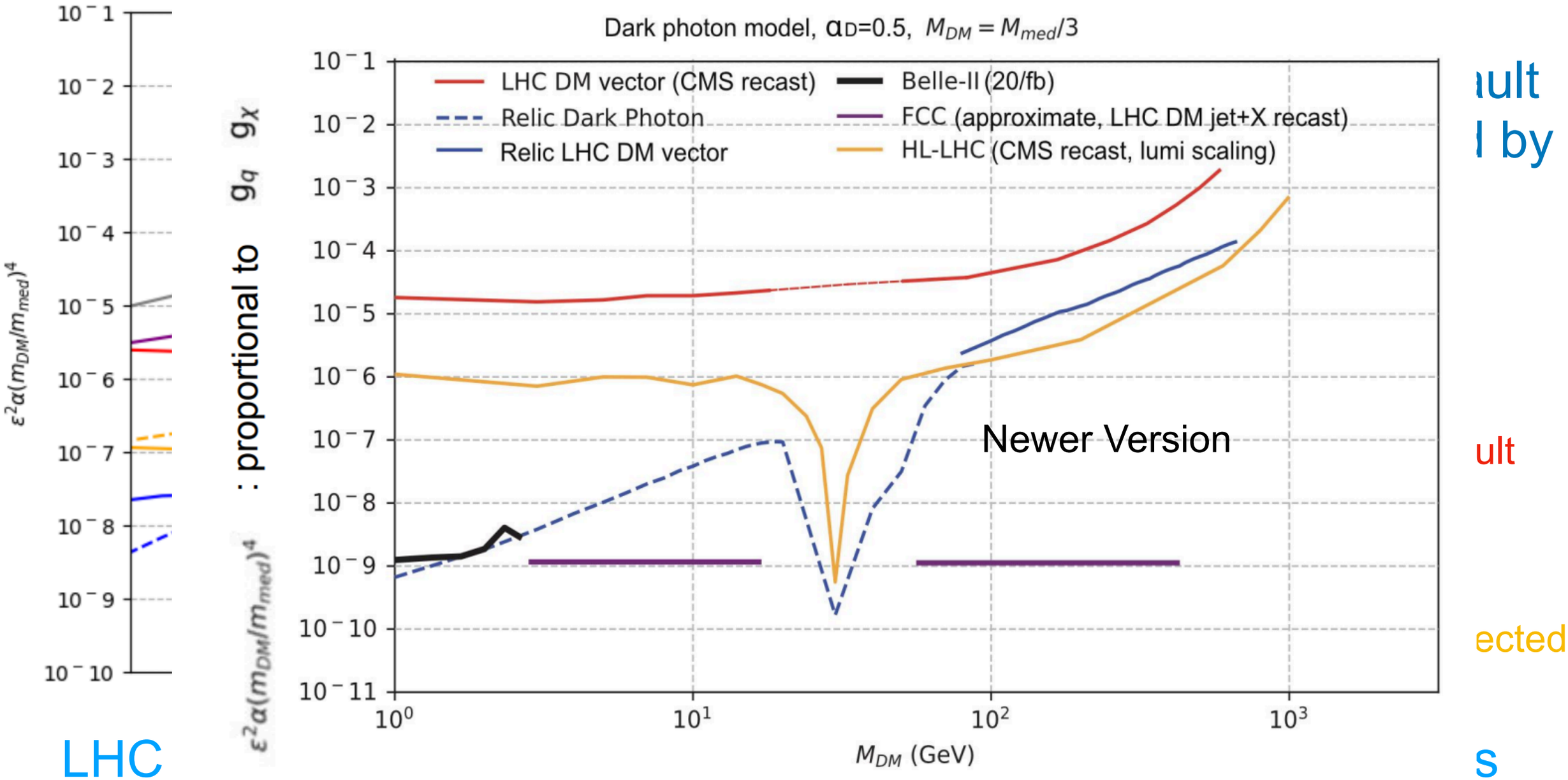
Dark Photon

LHCDMWG Projected

LHC Can cover invisible searches down to 10 GeV in DM mass

The Result

- LHC Monojet Analysis is in MadAnalysis
  - Relic density computed with MadDM (maps well)



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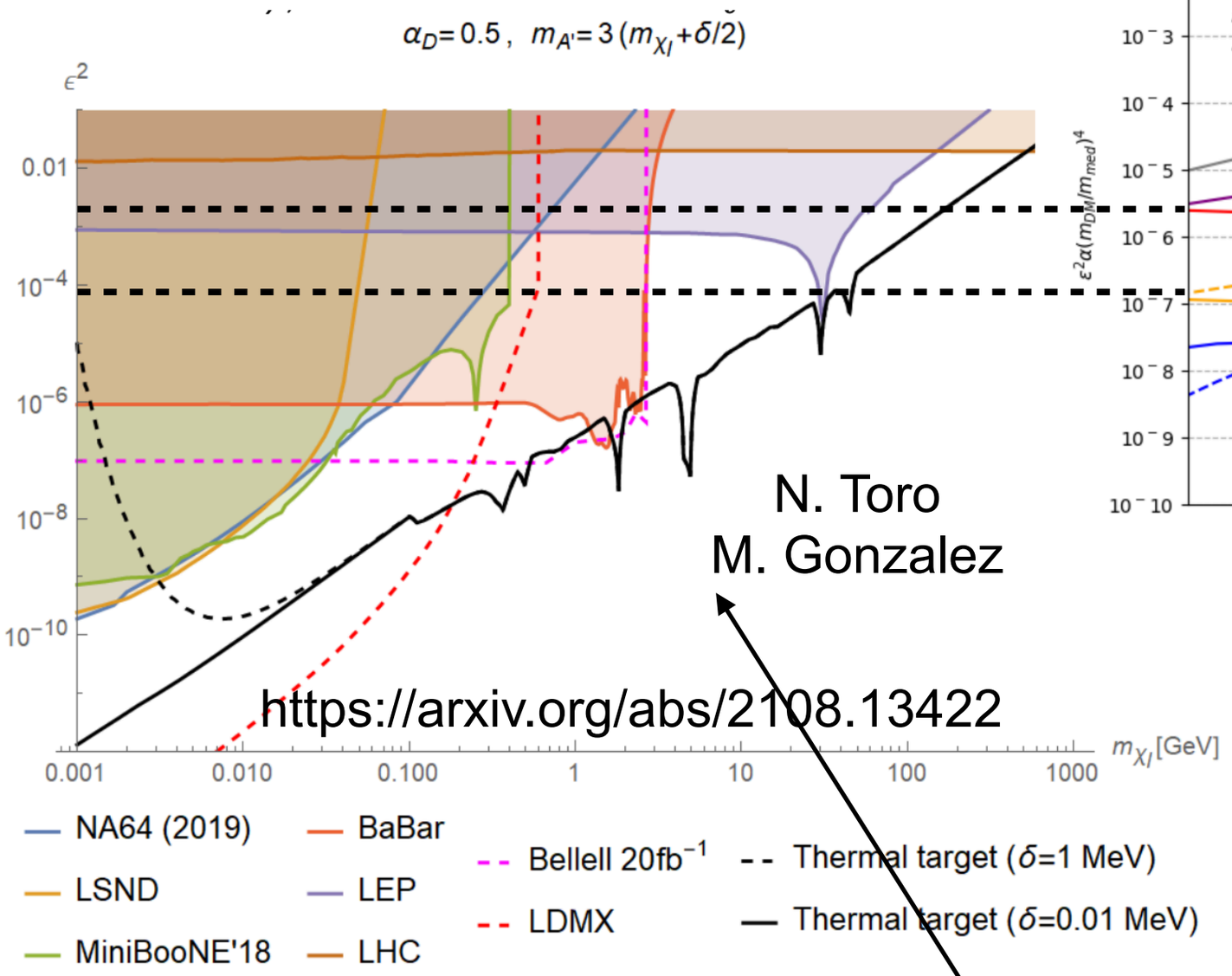
LHC

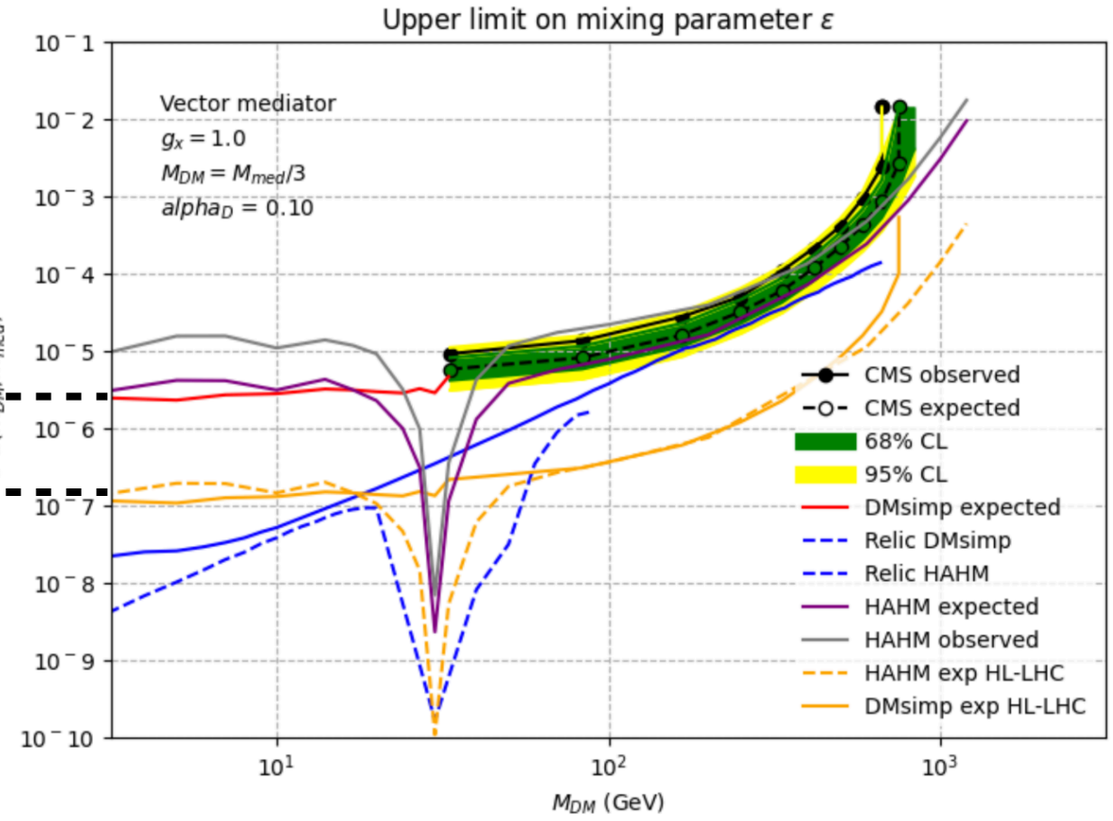
Check of Some Params

Relic calculations match pretty closely with other calculations



N. Toro
M. Gonzalez

https://arxiv.org/abs/2108.13422

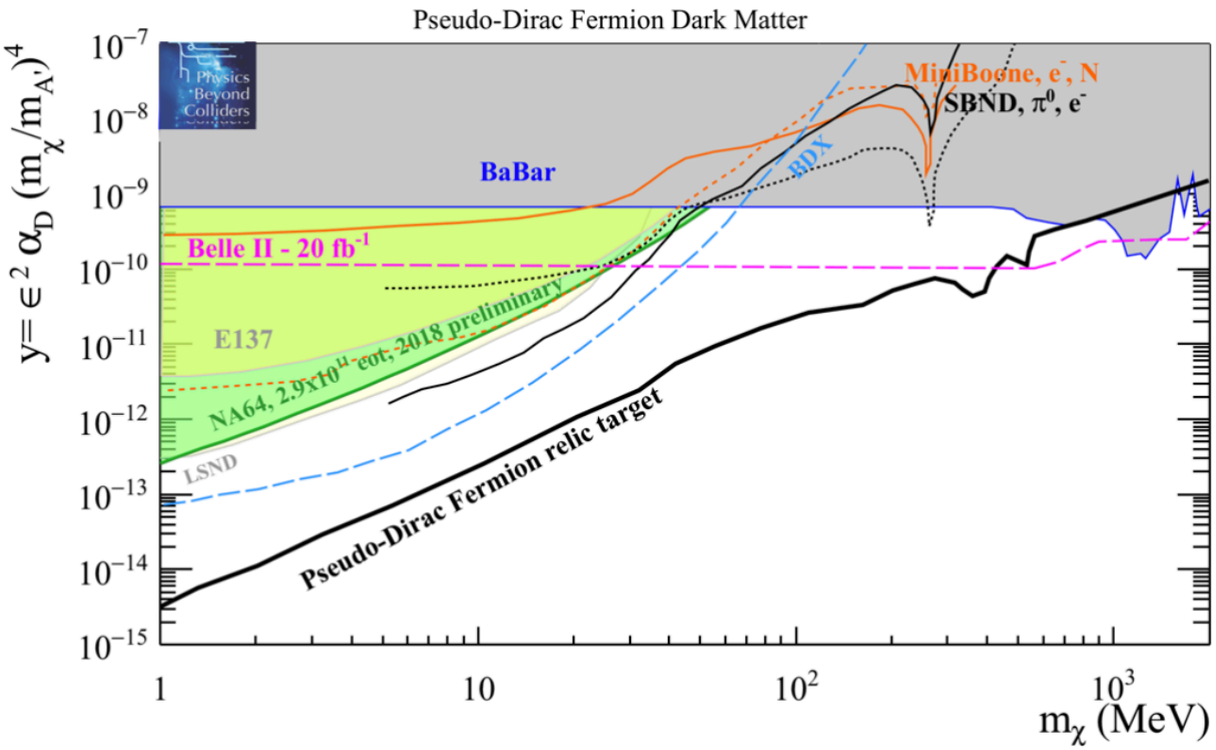


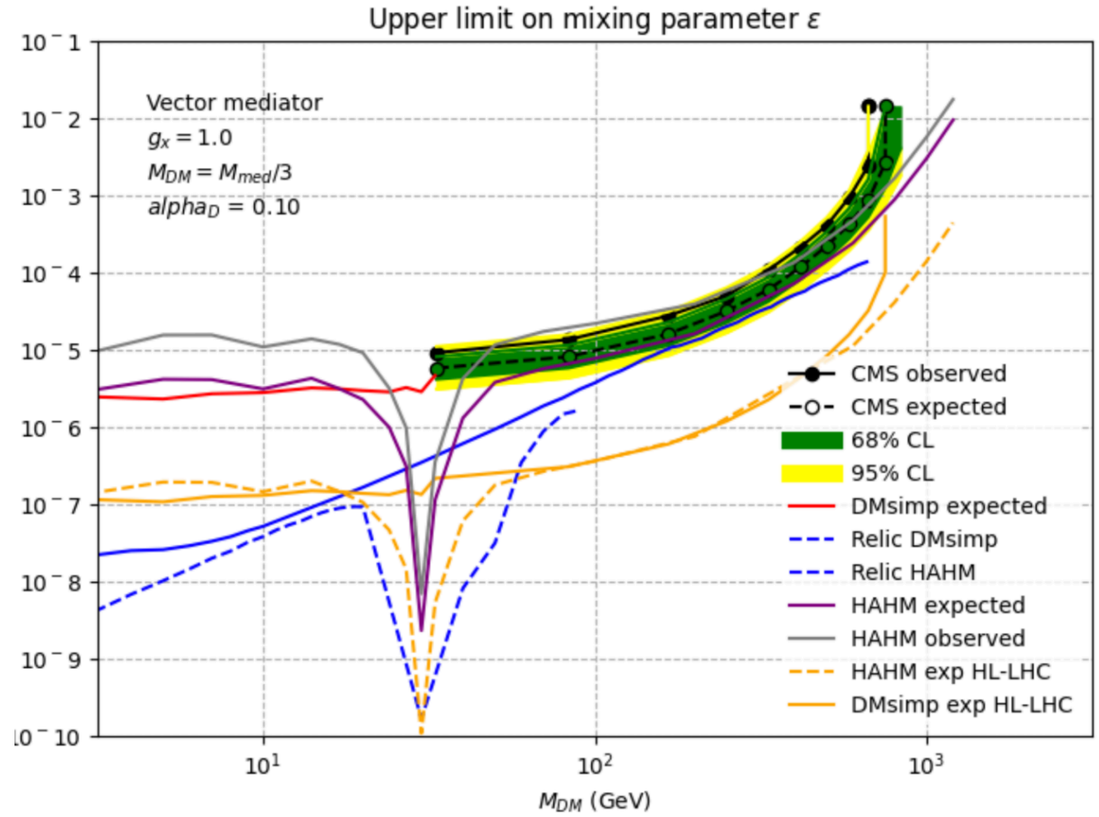
Bounds from LHC appear stronger than on left plot

Cross Check

Now Connecting them

Appears that w can now connect plots into one





LHC is complemntary

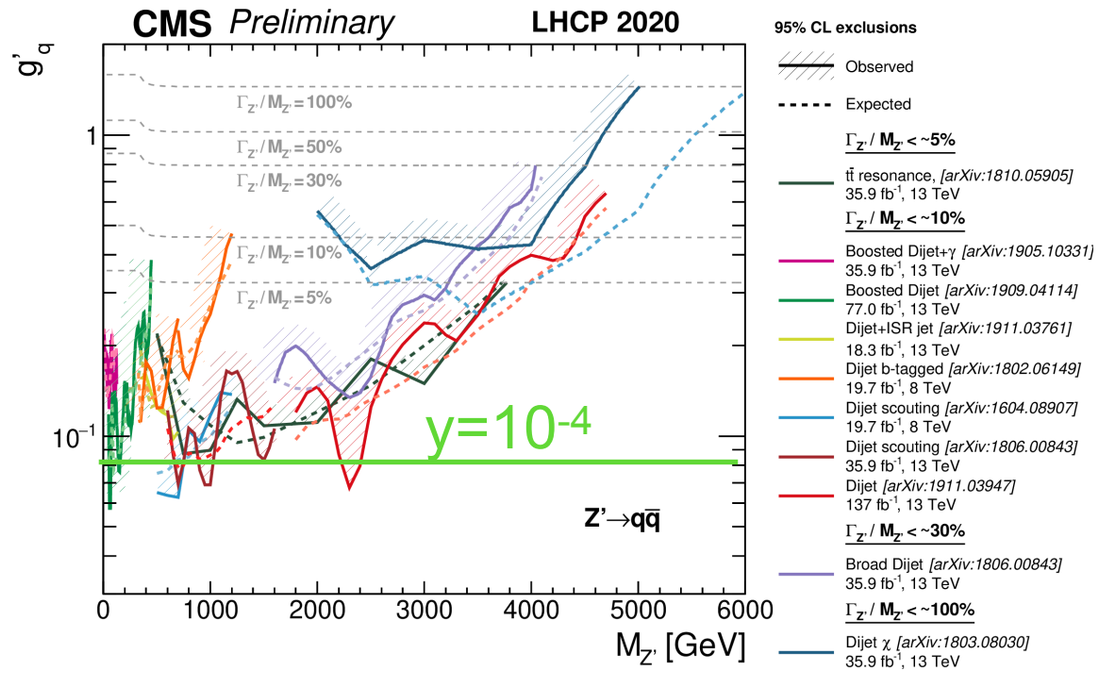
Similar goals on similar timesales

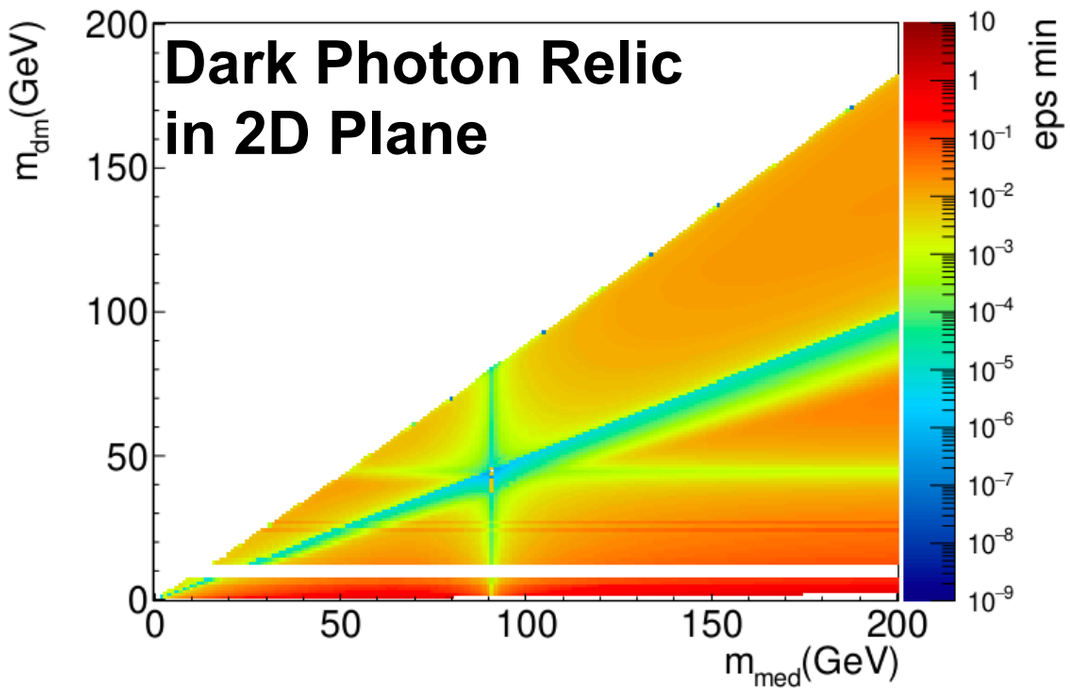
LHC goes left when mediator mass gets larrger

Note Also that as $\frac{m_{DM}}{m_{med}}$ gets larger LHC DM searches are the only game in town

Additional Plots

- With Madgraph model we have some flexibility
  - MG mode has the full Higgs to dark photon couplings
    - Can envision adding the Higgs/Dark Higgs bounds
  - Visible searches provide bounds for heavy DM
- Since g_q=0.01-0.1 maps y=10^{-7}-10^{-4} include jets/lepton bounds
  - y > 10^{-4} we have largely excluded this up to 2 TeV





Comparisons w/PBC

$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}}\,\phi\bar{\chi}\chi - g_q\,\frac{\phi}{\sqrt{2}}\sum_{q=u,d,s,c,b,t} y_q\,\bar{q}q$$

Enforcing a mixing with the Higgs
Higgs to Invisible dominates bounds (adds VBF channel)

$$g_q = -\sin\theta$$

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2)H^\dagger H$
Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N LHN$

DMWG presents results as a scalar w/o Higgs mixing

This eliminates the ϕ to SM vector boson coupling

However, Higgs to invisible is presented with Singlet Mixing model

https://arxiv.org/pdf/1901.09966.pdf

Singlet Mixing Model

$$\mathcal{L} \supset -y_{\mathrm{DM}}\, s\, \bar{\chi}\chi - \mu\, s\, |H|^2$$

What if we make a complete singlet scalar model?

Observed mass eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

With vector boson interactions it will mix w/Higgs

$$\mathcal{L} \supset -y_{\mathrm{DM}} \left(\sin\theta\, h_1 + \cos\theta\, h_2\right) \bar{\chi}\chi$$

Higgs to Invisible

$$+ \left(\cos\theta\, h_1 - \sin\theta\, h_2\right) \left(\frac{2M_W^2}{v} W_\mu^+ W^{-\mu} + \frac{M_Z^2}{v} Z_\mu Z^\mu - \sum \frac{m_f}{v} \bar{f} f \right)$$

Standard LHC Model w/MC….

To Map to PBC models
We need to fix DM coupling
and take it very large

Singlet Mixing Model

$$\mathcal{L} \supset -g_{\rm DM}\, s\bar{\chi}\chi - \mu s|H|^2$$

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With vector boson interactions it will mix w/Higgs

$$\mathcal{L} \supset -g_{\rm DM}(\sin\theta\, h_1 + \cos\theta\, h_2)\,\bar{\chi}\chi$$

Higgs to Invisible

$$+(\cos\theta\, h_1 - \sin\theta\, h_2)\left(\frac{2M_W^2}{v} W_\mu^+ W^{-\mu} + \frac{M_Z^2}{v} Z_\mu Z^\mu - \sum_f \frac{m_f}{v}\bar{f}f\right)$$

Singlet Mixing Model

$$\mathcal{L} \supset -g_{\mathrm{DM}}\, s\, \bar{\chi}\chi - \mu s |H|^2$$

What if we make a complete singlet scalar model?

Observed mass eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

Modified Higgs Vector Boson Couplings

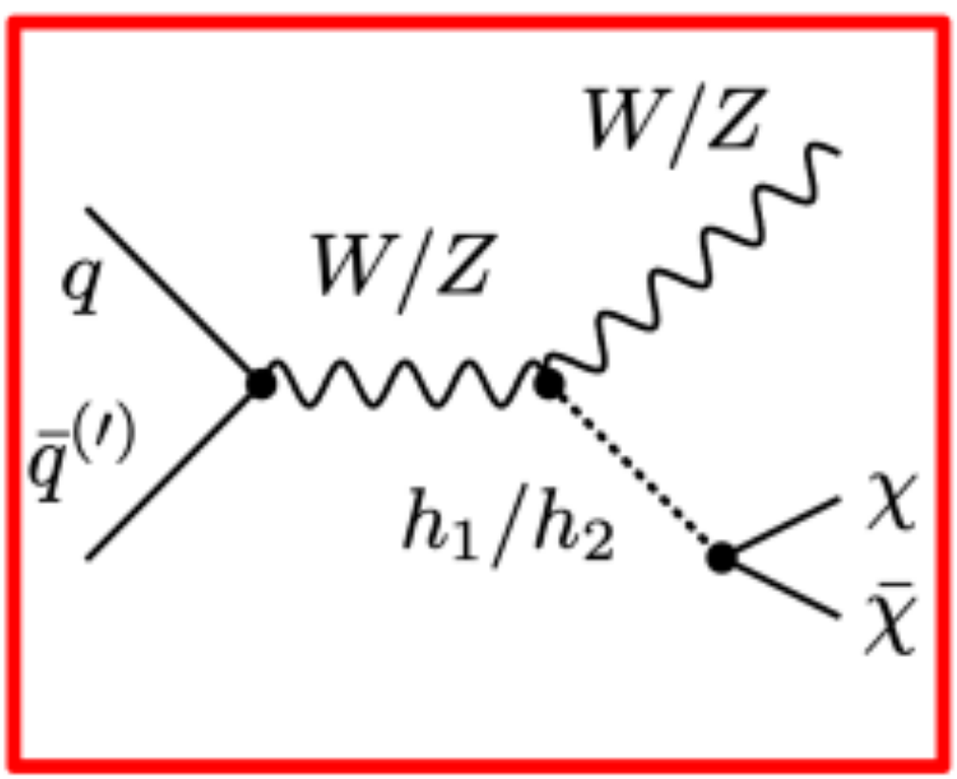
$$\mathcal{L} \supset -g_{\mathrm{DM}} (\sin\theta\, h_1 + \cos\theta\, h_2)\, \bar{\chi}\chi$$

$$+ (\cos\theta\, h_1 - \sin\theta\, h_2) \left(\frac{2M_W^2}{v} W_\mu^+ W^{-\mu} + \frac{M_Z^2}{v} Z_\mu Z^\mu - \sum_f \frac{m_f}{v} \bar{f} f \right)$$

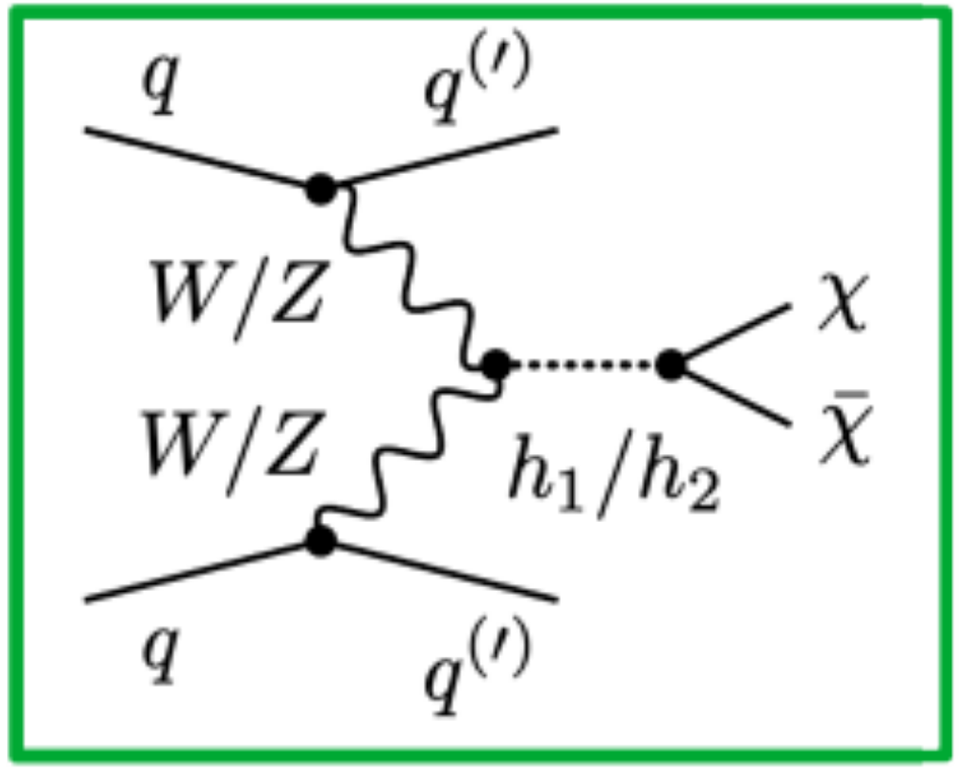
Details of Model Here

What are the scale of Modifications?

$$\Gamma(h_1 \to \chi\bar{\chi}) = \frac{g_{\mathrm{DM}}^2 \sin^2\theta\, m_{h_1}}{8\pi}\left(1 - \frac{4m_\chi^2}{m_{h_1}^2}\right)^{3/2}$$



Higgstrahlung



VBF Higgs to invisible

https://arxiv.org/pdf/1607.06680.pdf

What Drives Constraints

$$\Gamma(h_1 \to \chi\bar{\chi}) = \frac{g_{\rm DM}^2 \sin^2\theta\, m_{h_1}}{8\pi}\left(1 - \frac{4m_\chi^2}{m_{h_1}^2}\right)^{3/2}$$

Higgs to invisible bounds puts constraints a 10% bound equates to $\sin\theta < 0.002$ (note $g_{\rm DM} = 1.0$)

Higgs boson coupling of 10% bound equates to

$$1 - \cos\theta < 0.1 \to \sin\theta < 0.3$$

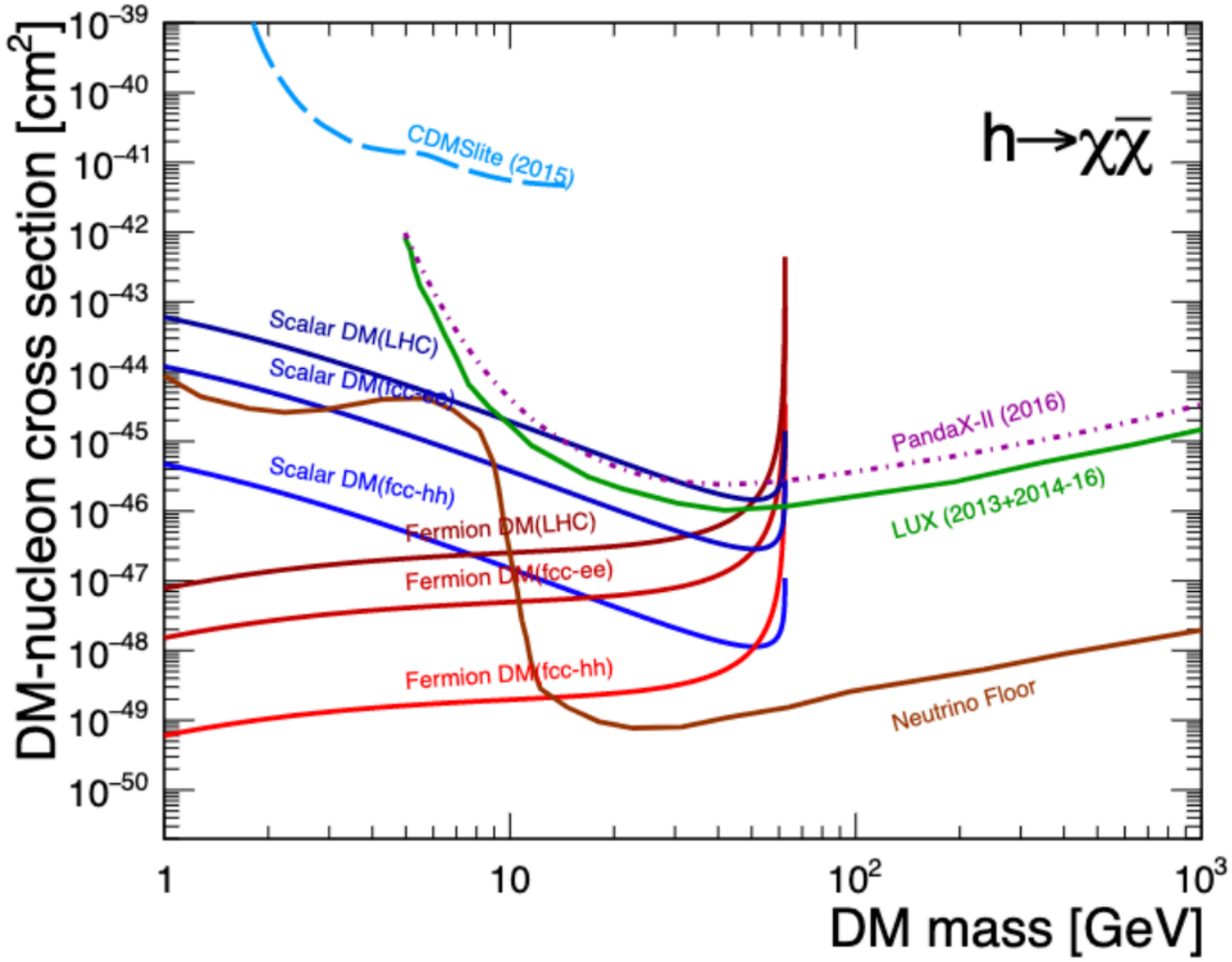
Both invisible decay and Couplings play a critical role

This model is effectively the same as the PBC model

Typically take $g_{\rm DM} = y_{\rm DM}$ makes Higgs to invisible less sensitive

Propagating Bounds

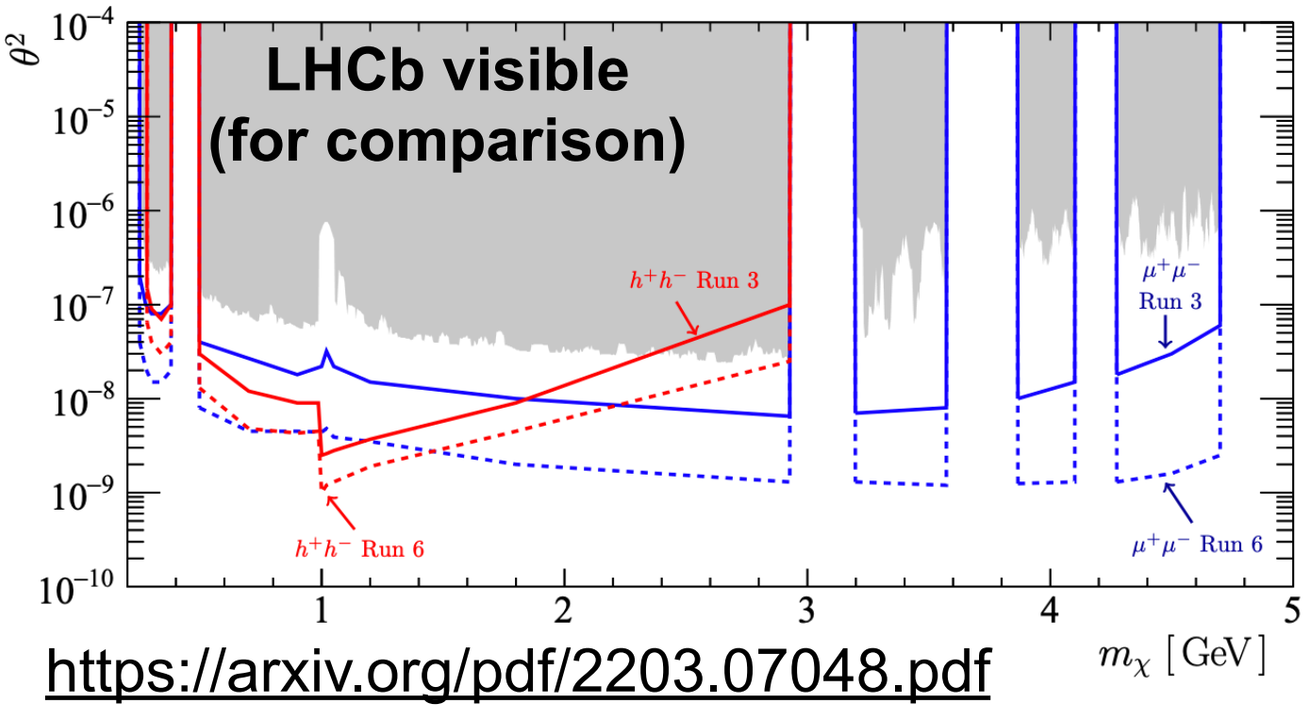
- Higgs to invisible Bounds
  - Current LHC H(inv) > 0.1
  - Future LHC H(inv) >0.02
  - FCC-ee H(inv) > 0.005
  - FCC-hh H(inv) > 0.0001



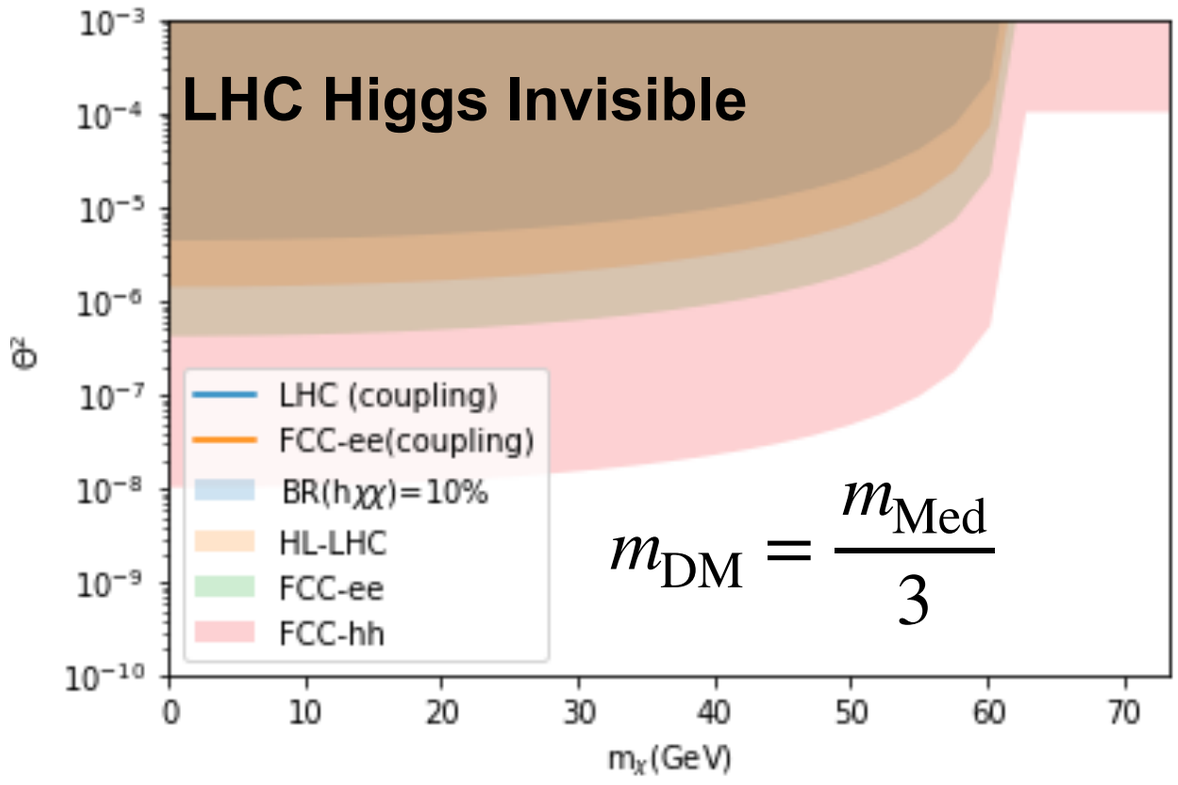
- Current projections of Higgs to invisible similar to Direct Detection
  - Sensitivities comaprable in the low DM mass region
  - LHC exceed neutrino floor for light DM

Comparing Standard Plot

- Often the scalar portal is presented in terms of θ^2
  - LHC bounds have clear and large sensitivity

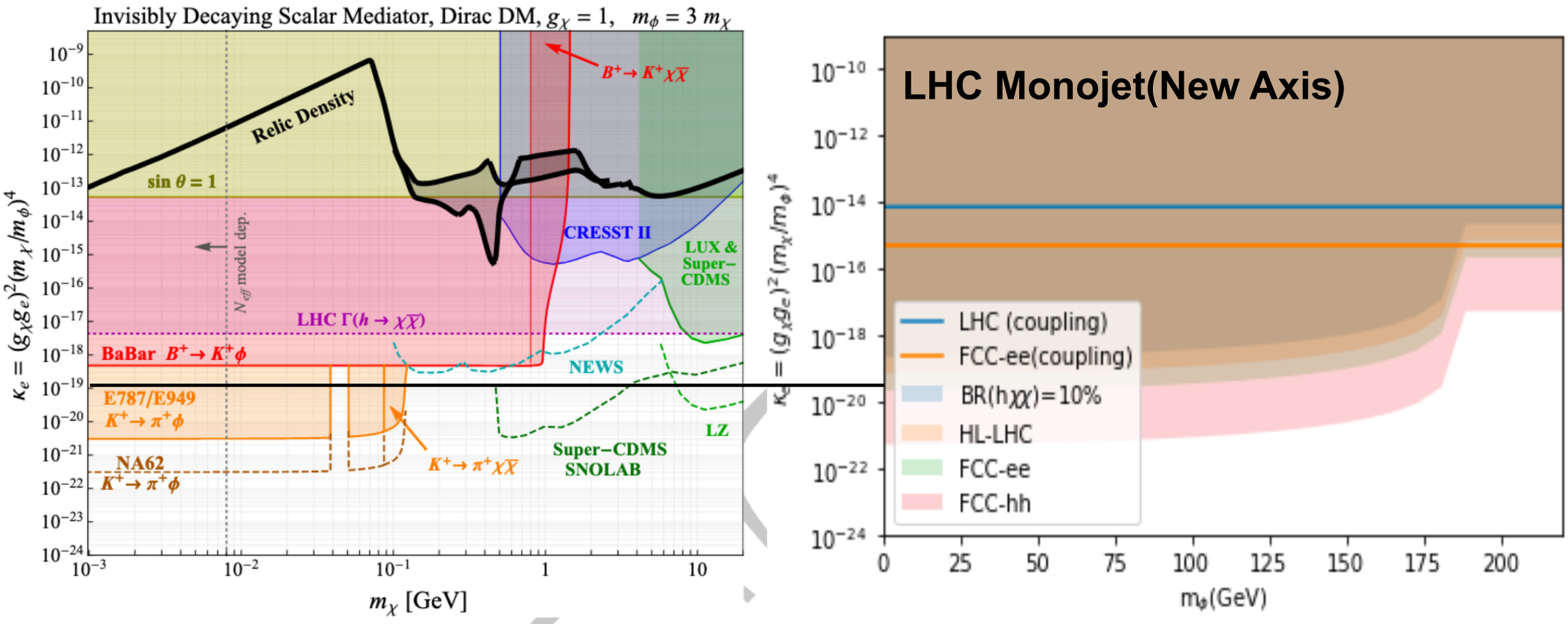


https://arxiv.org/pdf/2203.07048.pdf



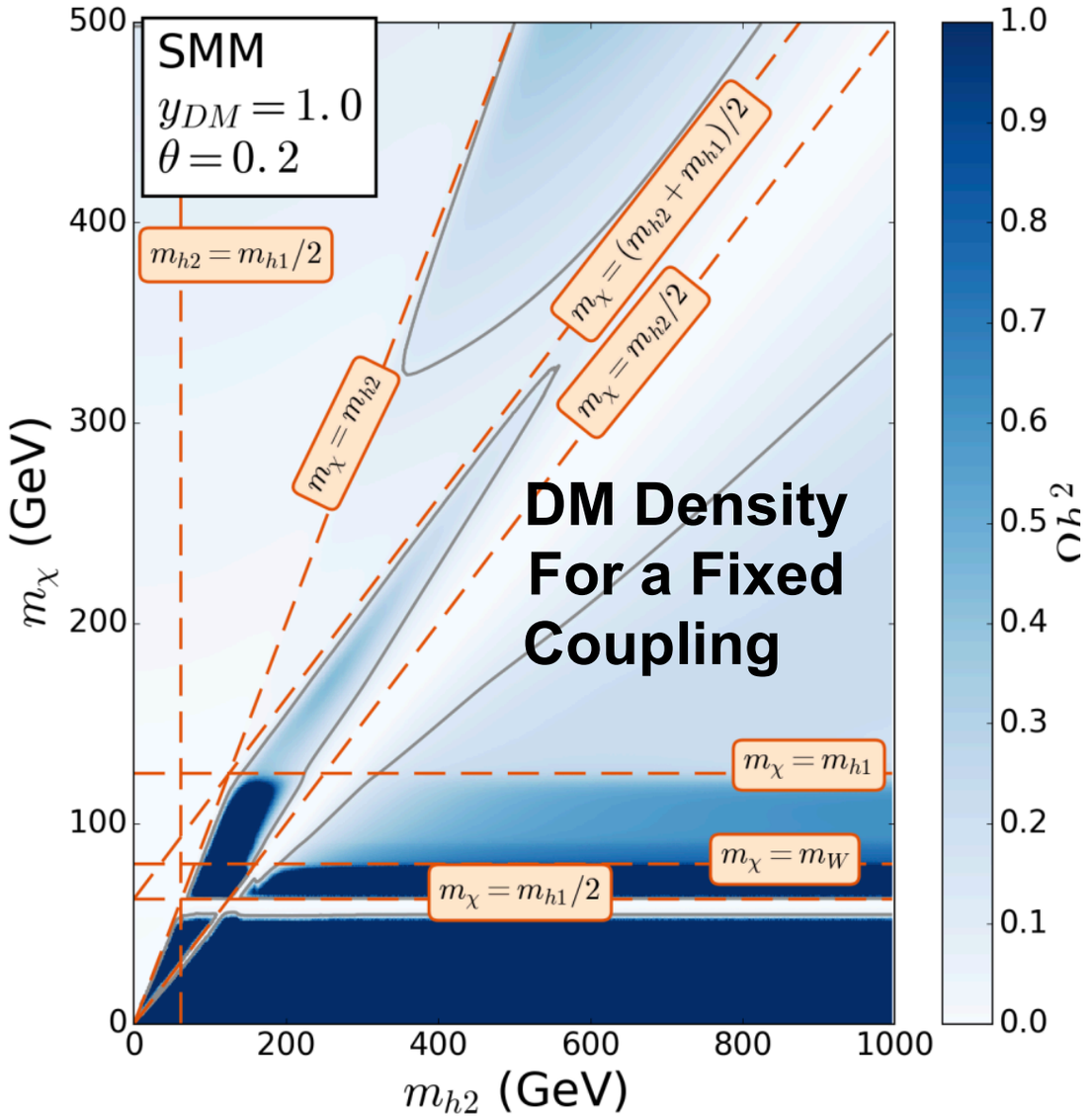
- Bounds for Monojet(invisible) comparable to visible bounds
  - Covers a variety of important final states

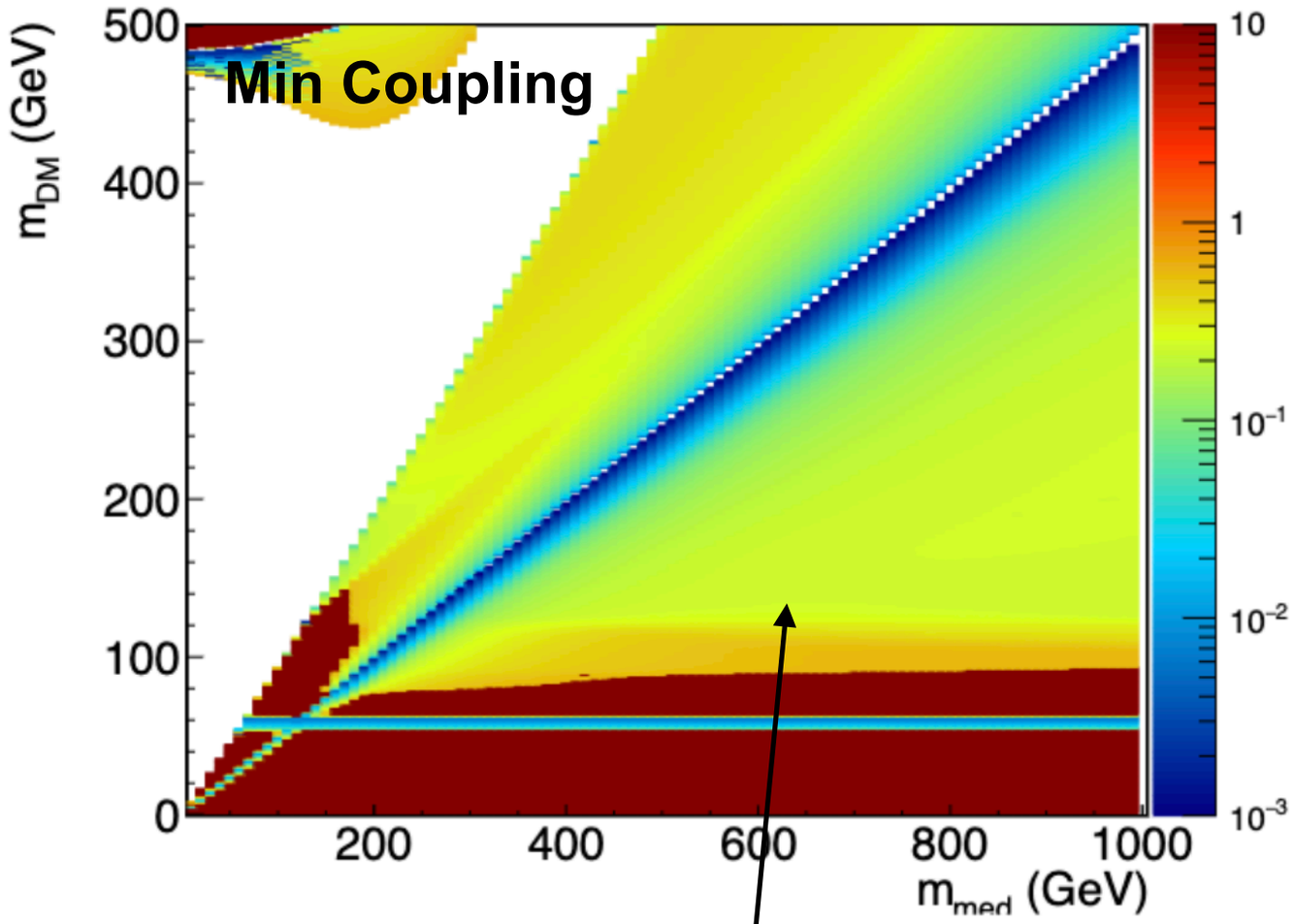
Scalar DM Bounds



- LHC Higgs to invisible dominates the scalar DM bounds
  - Additionally Higgs couplings bounds also impact bounds
  - Overall extends sensitivity beyond range of light DM models

Relic Density





- Overall minimum coupling bound is very large
  - Mostly constrained by a 5% Higgs coupling measurement
  - A 5% Higgs coupling bound is an equivalent bound on $\sin\theta < 0.1$

Comparisons w/PBC

$$\mathcal{L}_{\text{pseudo-scalar}} = -ig_{\text{DM}}\phi\bar{\chi}\gamma_5\chi - ig_q\frac{\phi}{\sqrt{2}}\sum_{q=u,d,s,c,b,t} y_q\bar{q}\gamma_5 q\,,$$

Pseudoscalar mediator again similar
Interpretation of couplings also similar

$$g_q = \frac{v}{f_a}$$

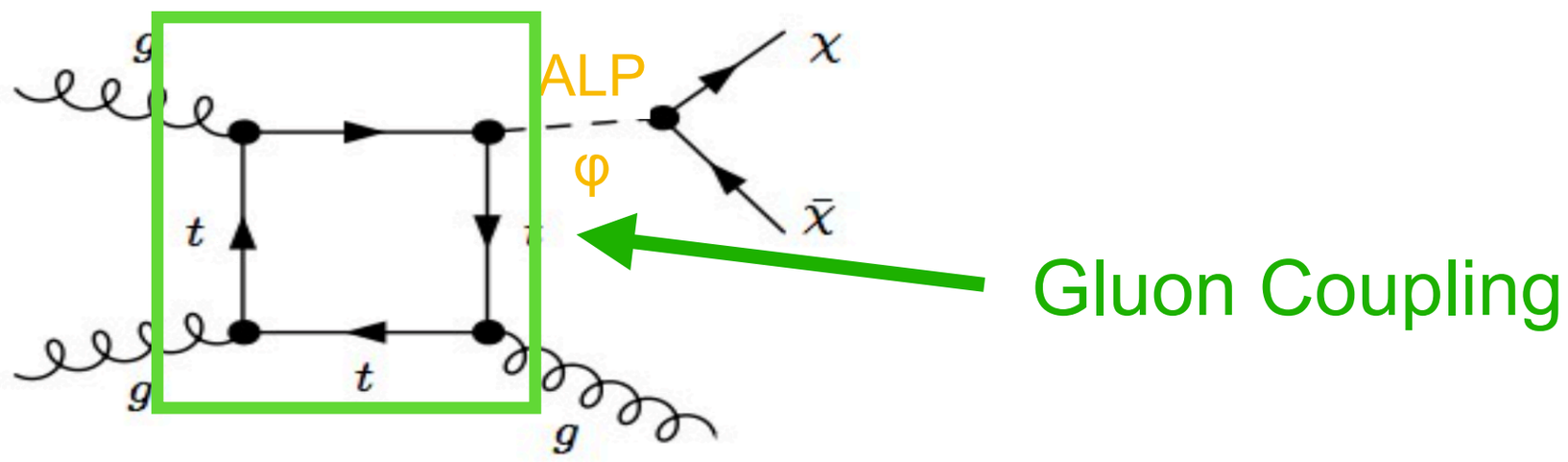
Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2)H^\dagger H$
Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N LHN$

DMWG tends to present pseudoscalar results in two ways:
- A single mediator (as a simplified model)
- A mediator within a 2HDM

https://arxiv.org/pdf/1901.09966.pdf

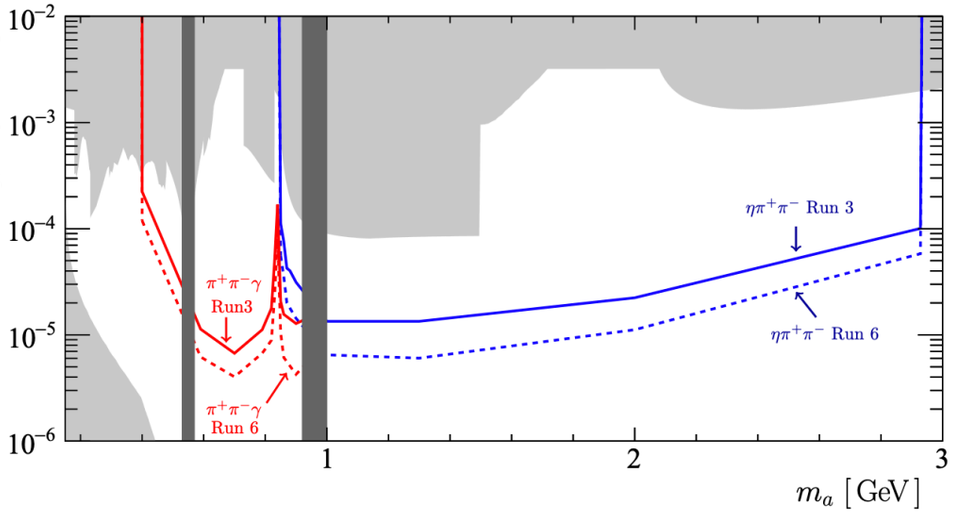
Axion Portal is a recast

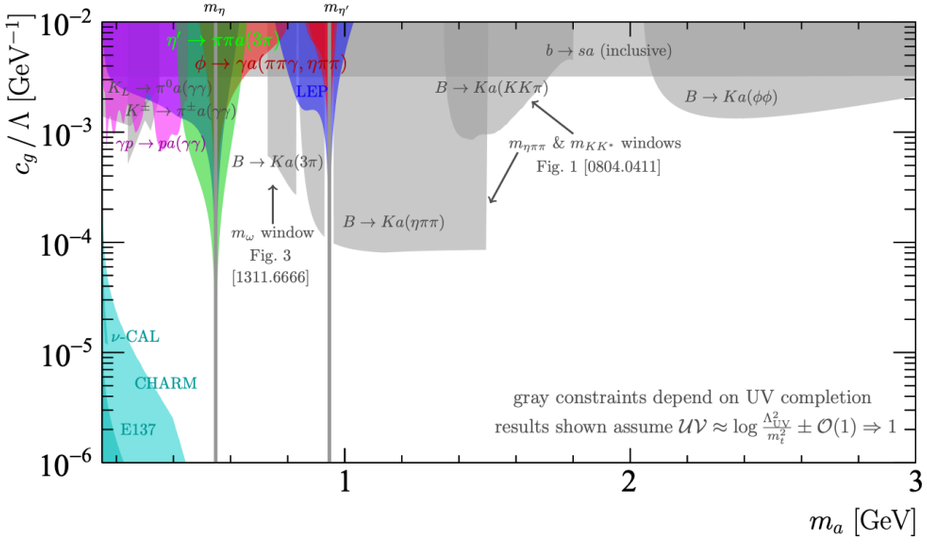
- We can translate directly into the axion like portal
  - Governed by one formula $\frac{c_g}{\Lambda} = \frac{g_q}{v}$
  - Assumes Gluon coupling comes from a yukawa loop
  - Also LHC model assumes yukawa coupling(not need)
    - Photon coupling not considered in this setup
- With the model used by LHC DM WG gluon coupling is a loop

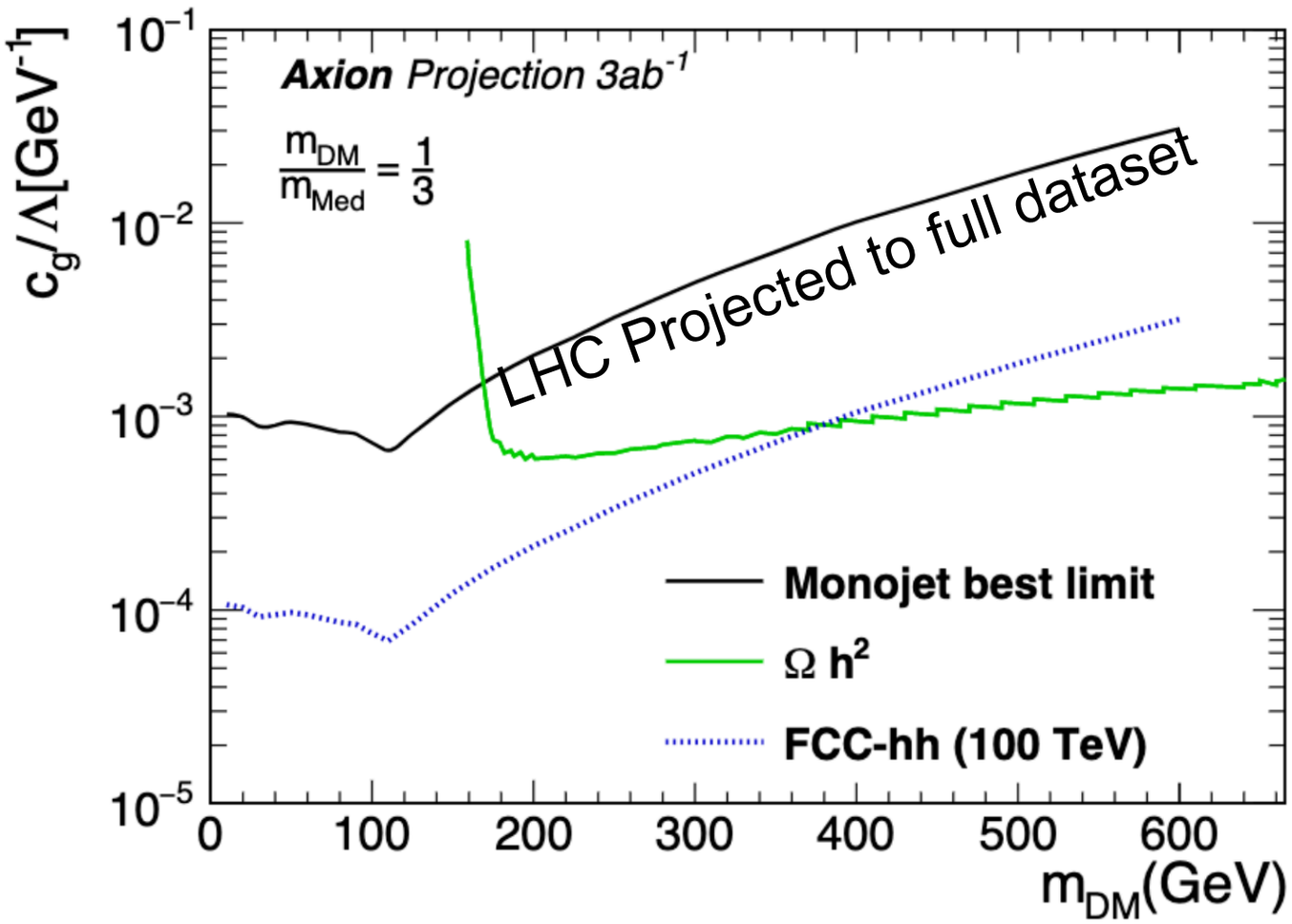


Axion Portal result

- Bounds written in ALP notation are quite strong
  - Relic density bound exists whend mediator mass is higher







LHCDMWG & FIP

- The LHC is the only collider in town above 10 GeV
  - There is a lot it can say about Dark Matter
    - Particular in context of Higgs and heavy mediators
  - LHCDMWG is the forum for DM interpretations of the LHC
- Light Dark Sector group focuses on specific models
  - There is a large overlap of these models with LHC DM WG
  - **We now have a model to enable Dark Photon Interpretations**
  - **Reconciled ALP and Dark Higgs Portals**
    - Madgraph models exist for both
  - Part of a greater dark sectors effort underway
- New interpretations/models will motivate new directions at LHC

Thanks!

Comparisons w/PBC

PBC doesn't consider Axial Vector model
(Indeed this model has many constraints on is)

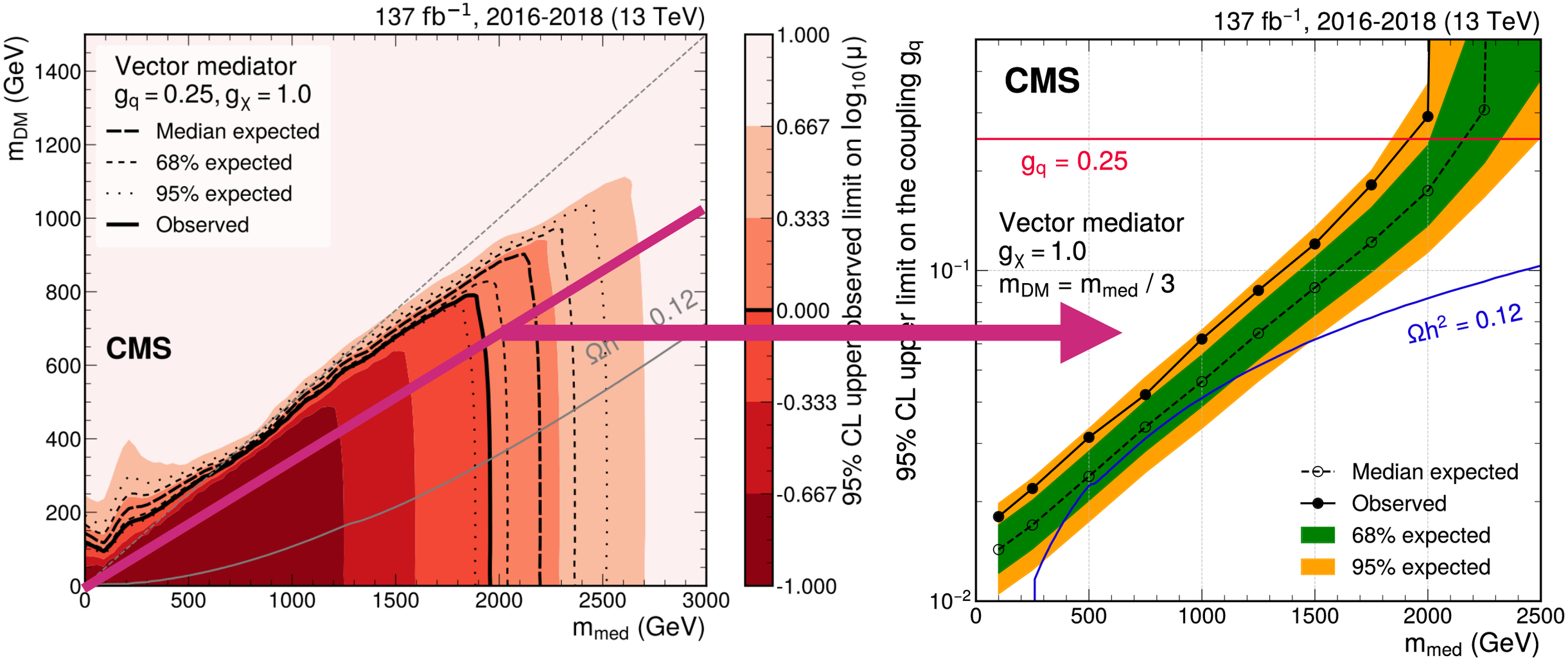
Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2)H^\dagger H$
Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

Currently Sterile Neutrino not a topic in LHCDMWG, but could be considered in future results

https://arxiv.org/pdf/1901.09966.pdf

Presenting (Vector) results

- Have been active efforts to harmonize results in DMWG
  - Added a lot of plots to allow for small coupling interpretations

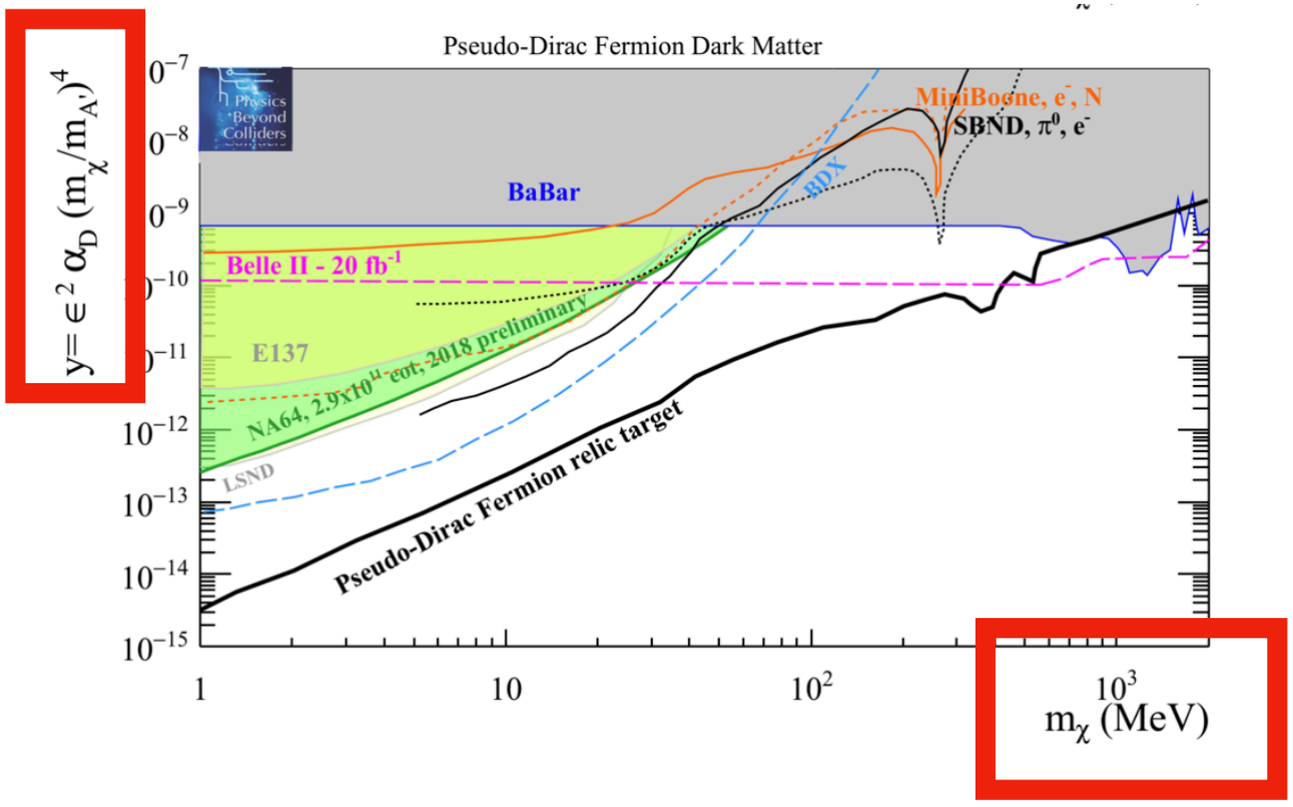


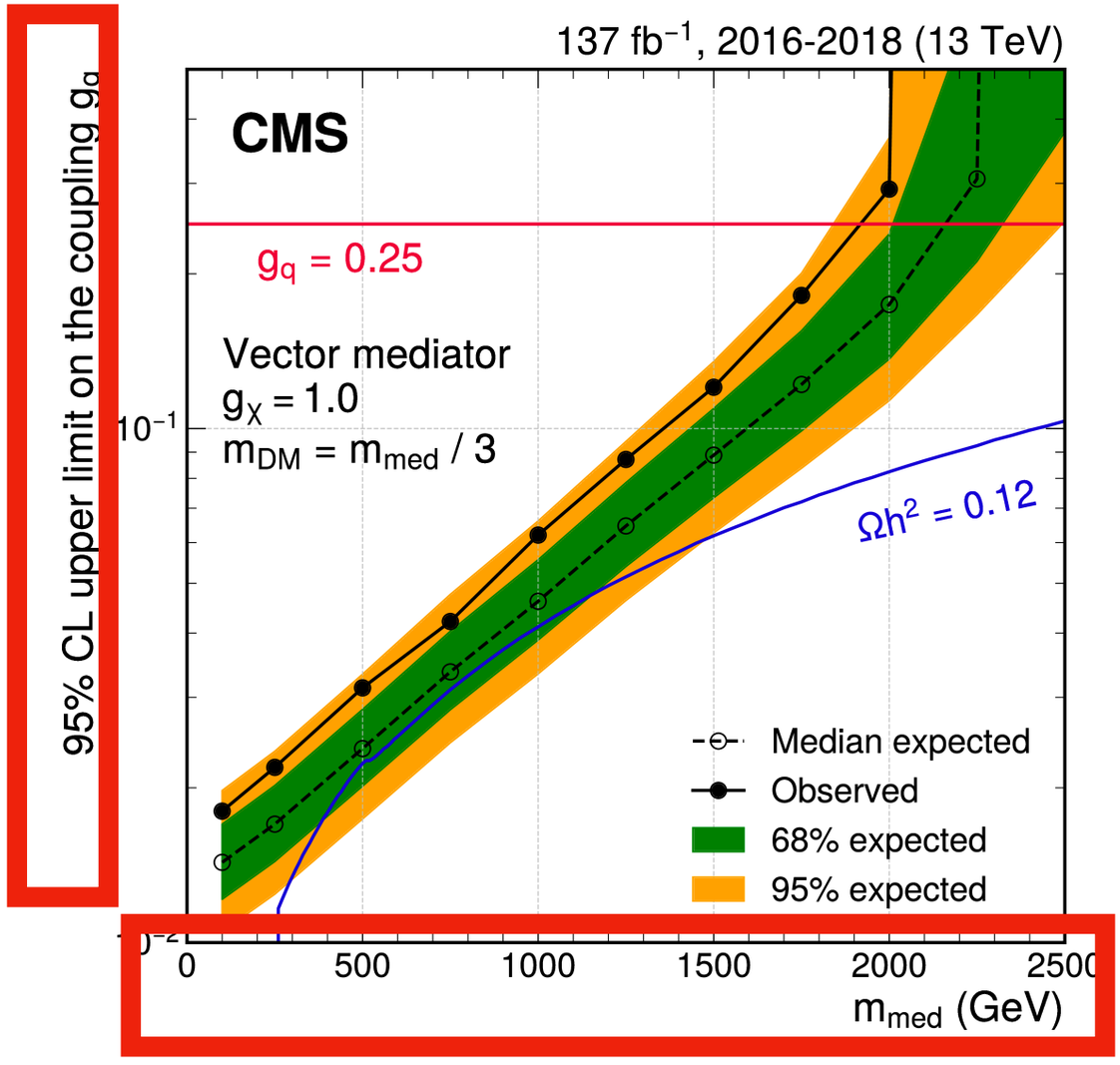
https://arxiv.org/abs/2107.13021

Coupling on y-axis shows overall sensitivity

Comparing w/PBC

- Results are often presented on very different axes
  - Despite the different axes the models are very similar
  - It is possible to connect these plots in a coherent way

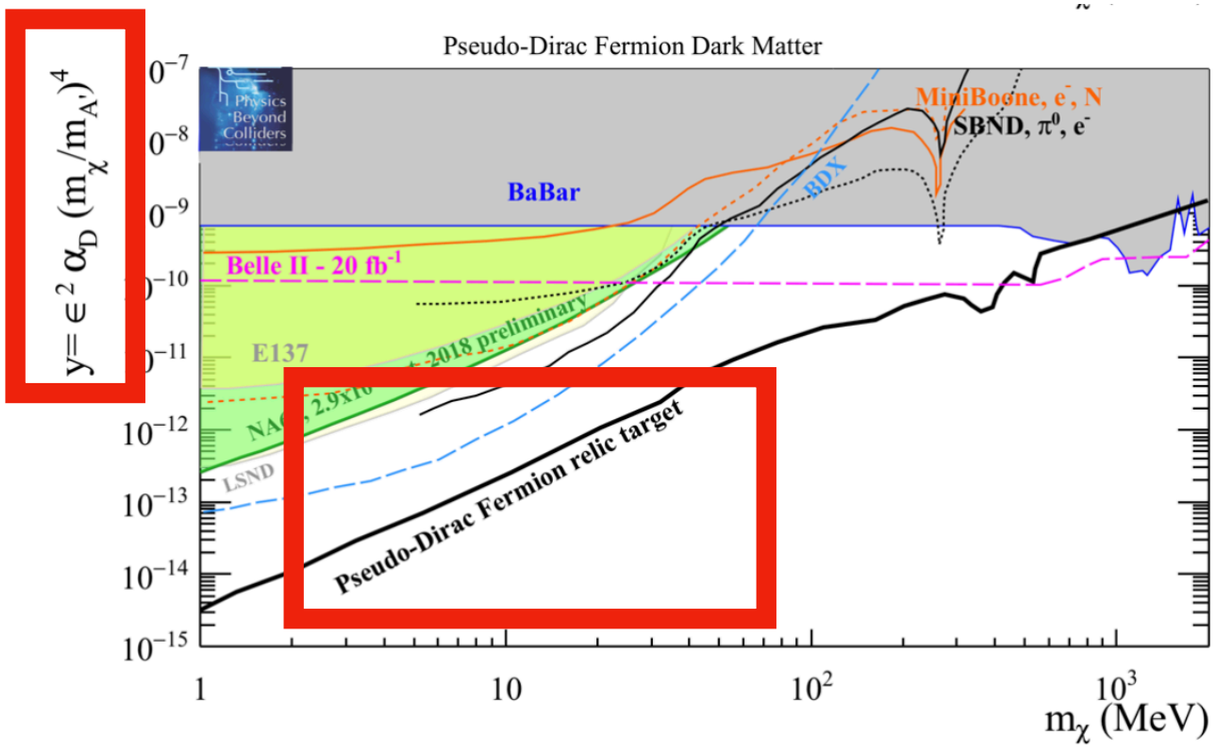




One important note is that for fixed α_D the relic bound $\propto \frac{\epsilon}{m_{A'}} \propto \frac{g_q}{m_{med}}$

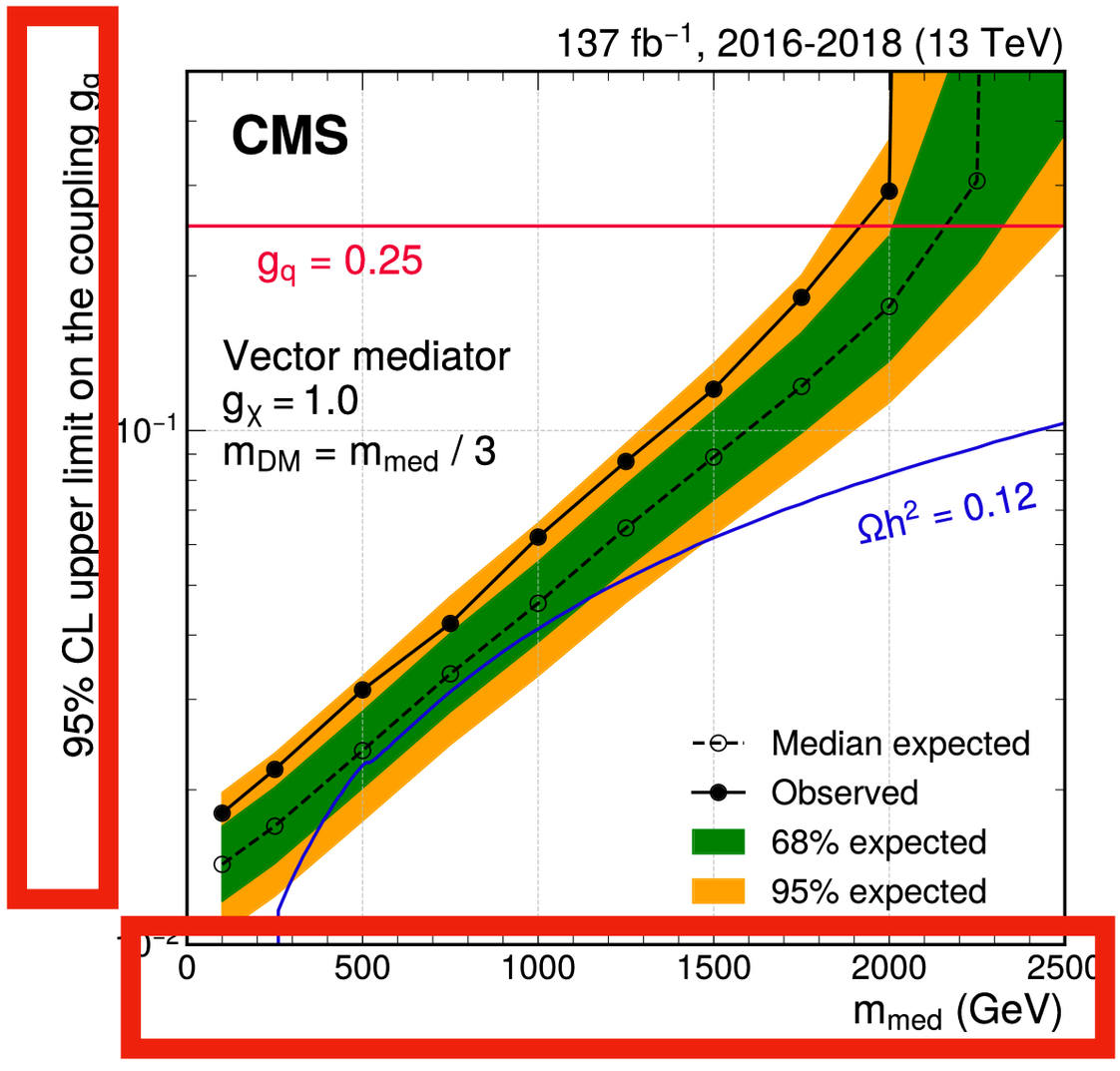
Comparing w/PBC

- Results are often presented on very different axes
  - Despite the different axes the models are very similar
  - It is possible to connect these plots in a coherent way



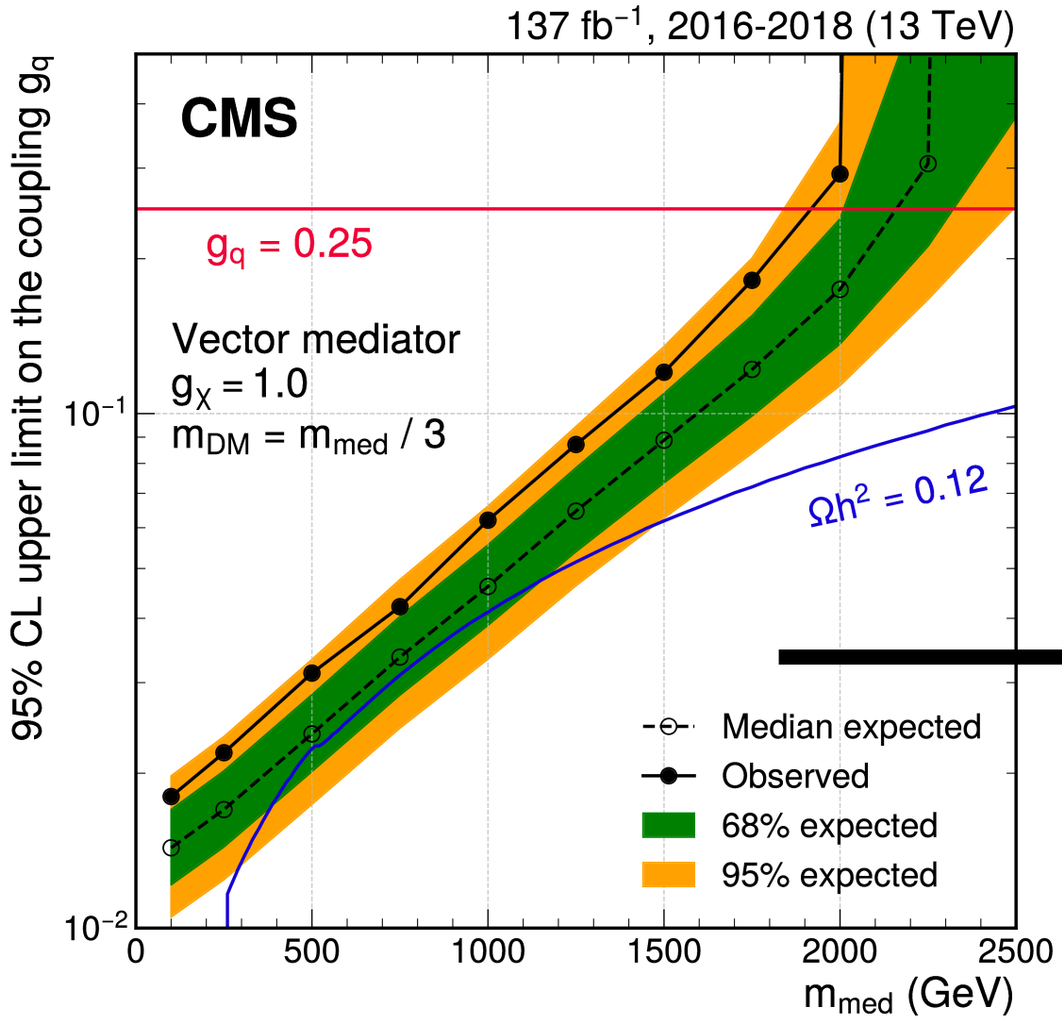
PBC tends to use Pseudo-Dirac DM instead of DM

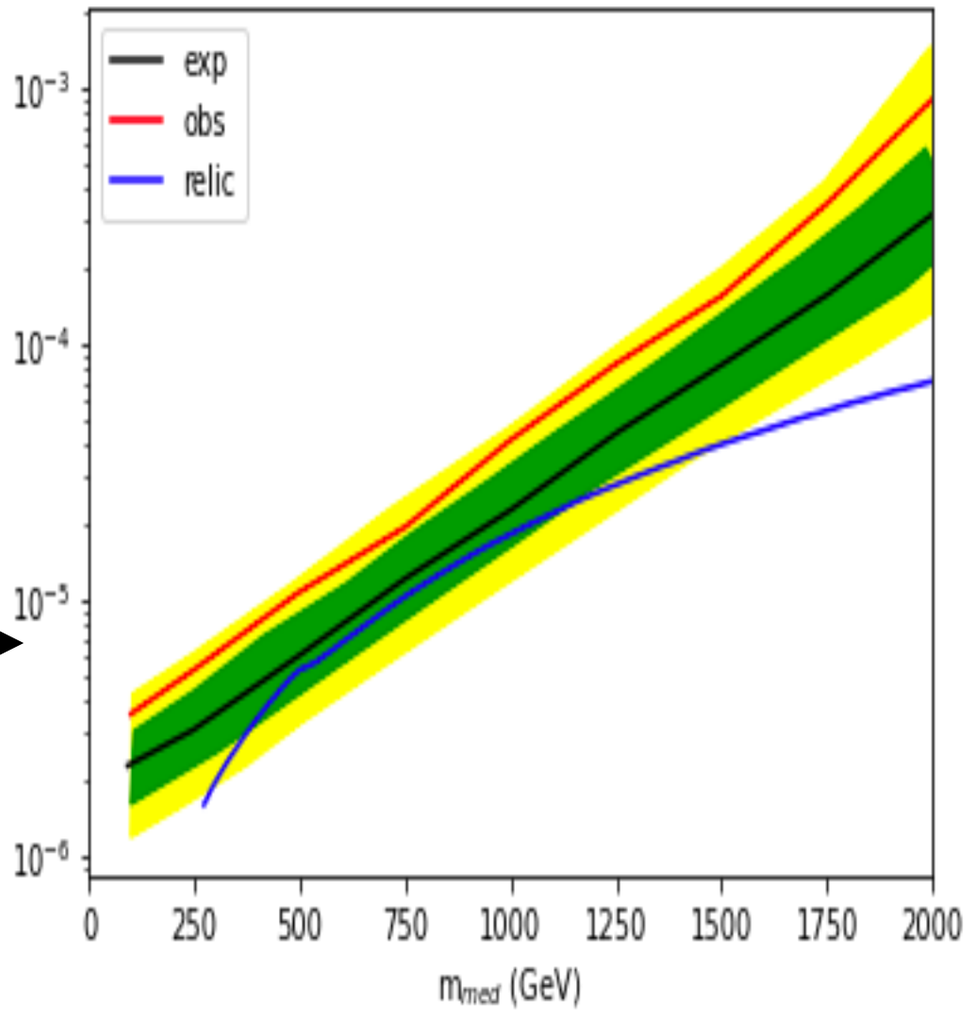
Pseudo-Dirac avoids direct detection DM bounds



Trying to reconcile plots

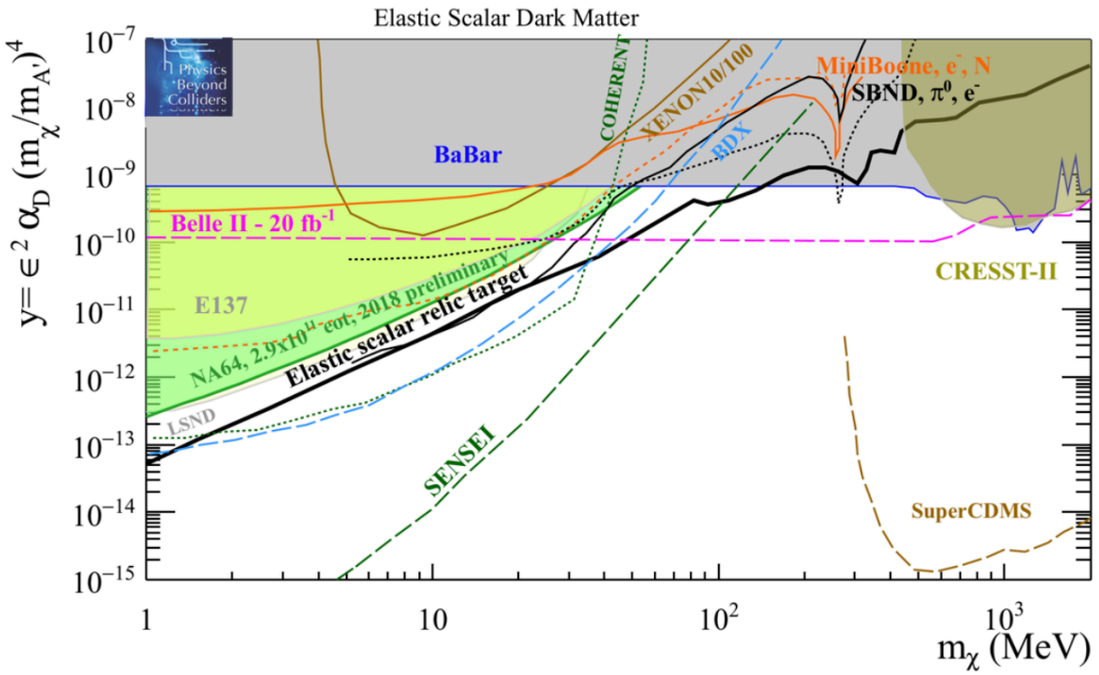
- A quick comparison of the plots gives a translation
  - y-axis bounds in coupling can be translated
  - Change in bounds is 4 orders of magnitude

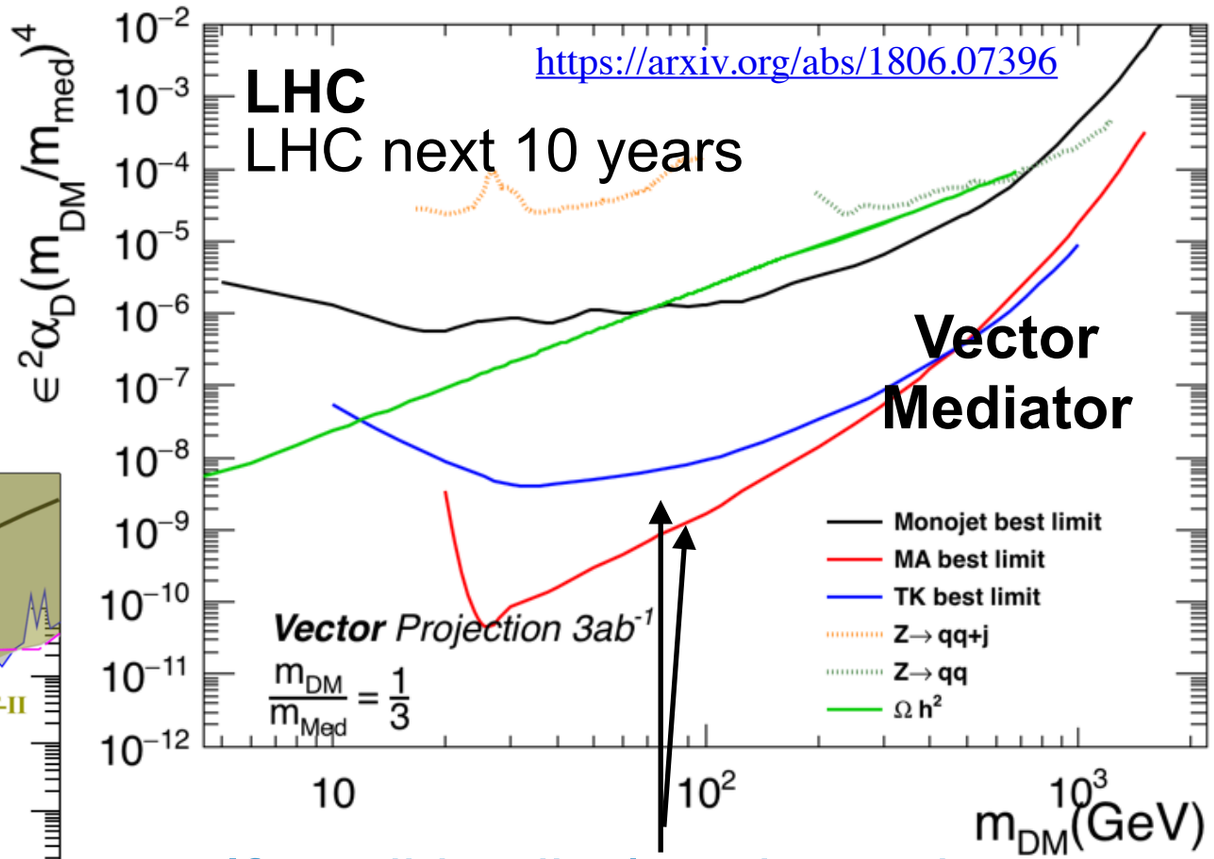




An Attempt to reconcile

One Plot





If we did a displaced search
using inelastic DM model

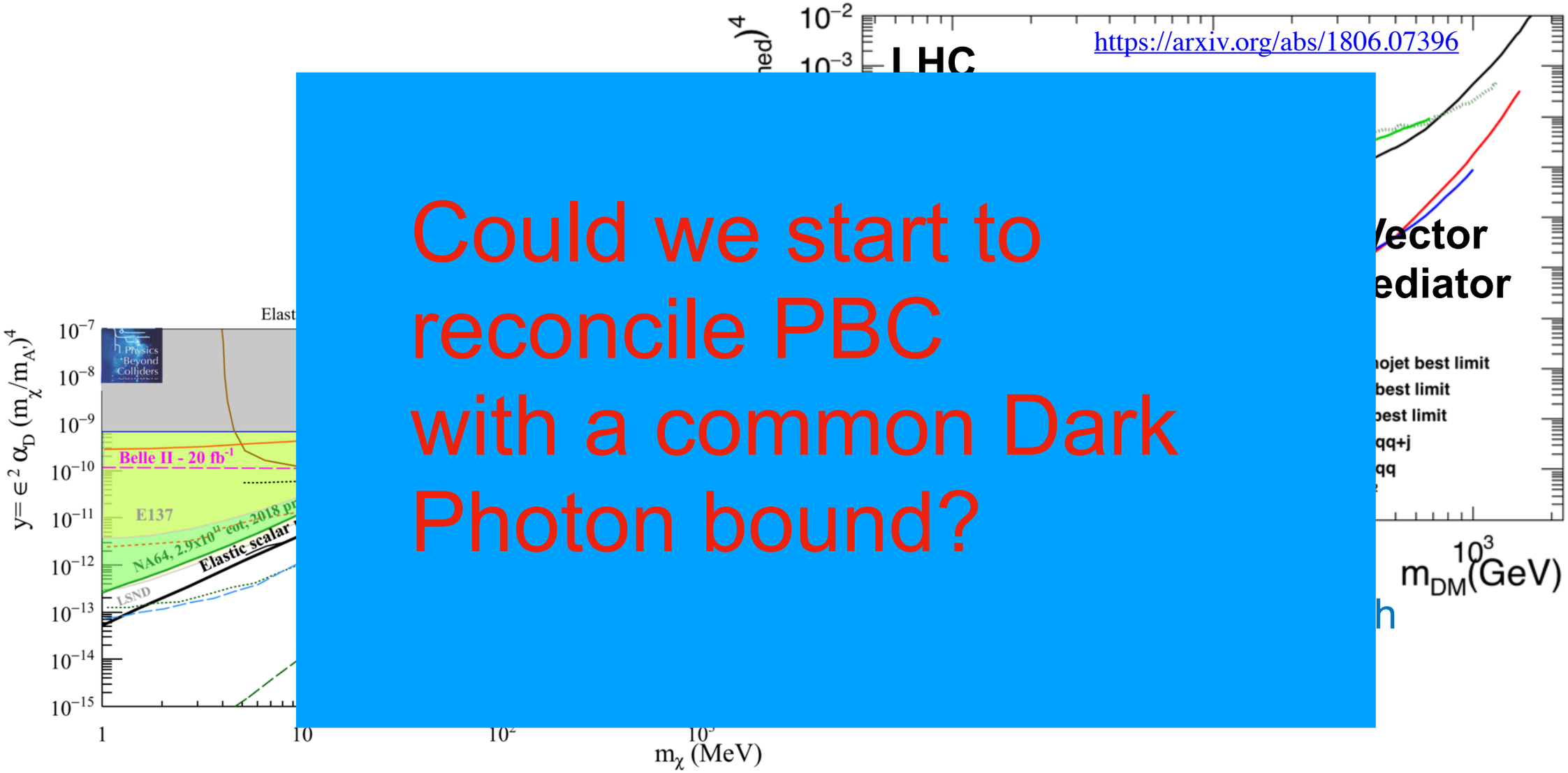
Weakly Coupled

Light Dark Matter

An Attempt to reconcile

One Plot

Could we start to reconcile PBC with a common Dark Photon bound?



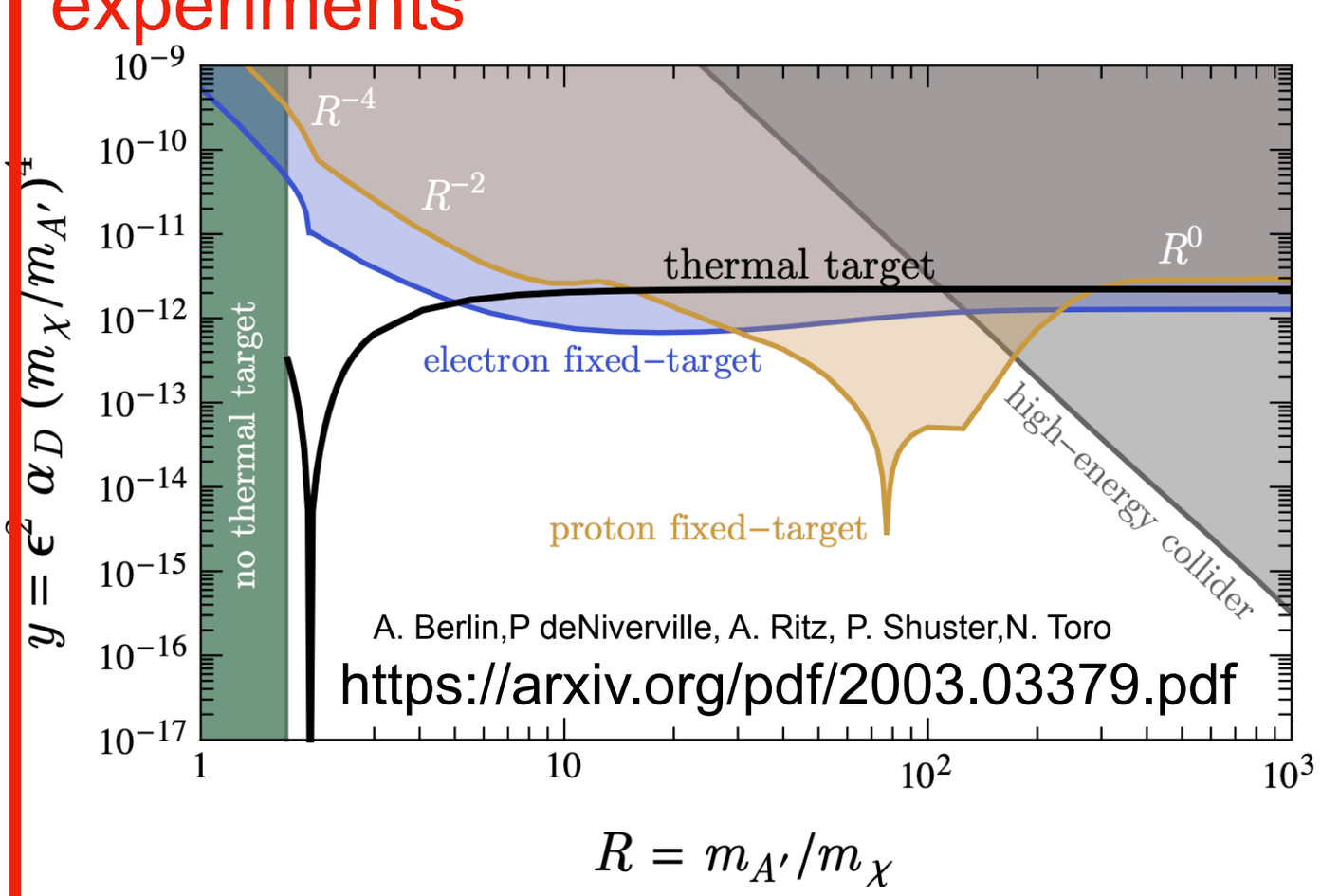
Weakly Coupled

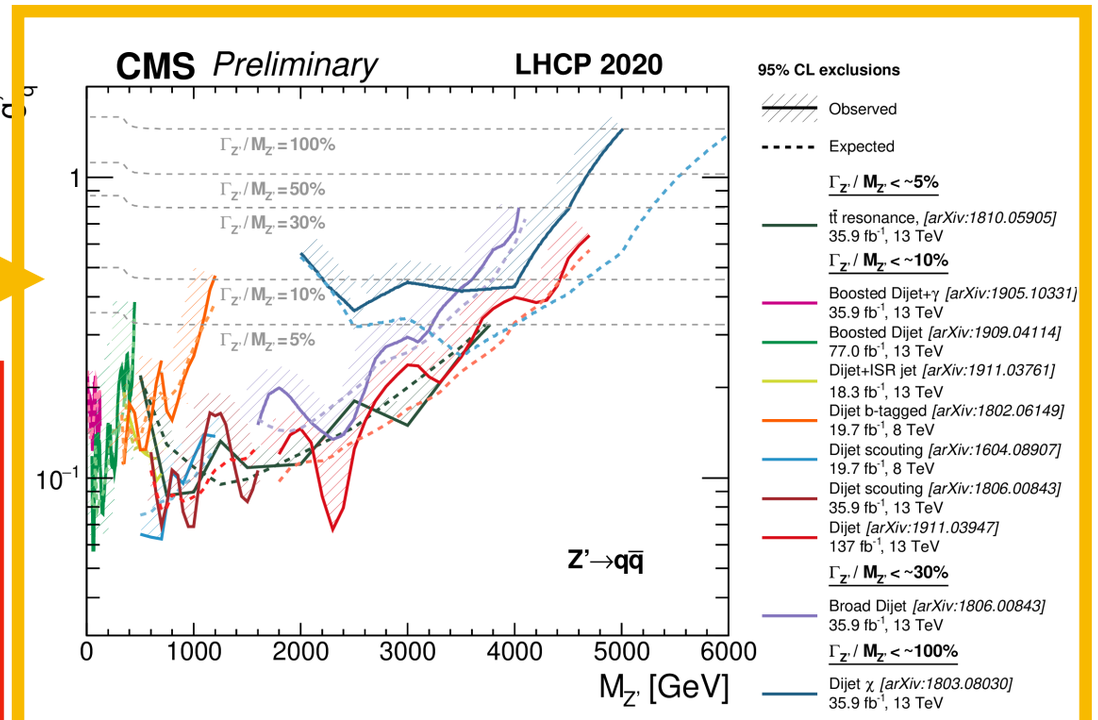
Light Dark Matter

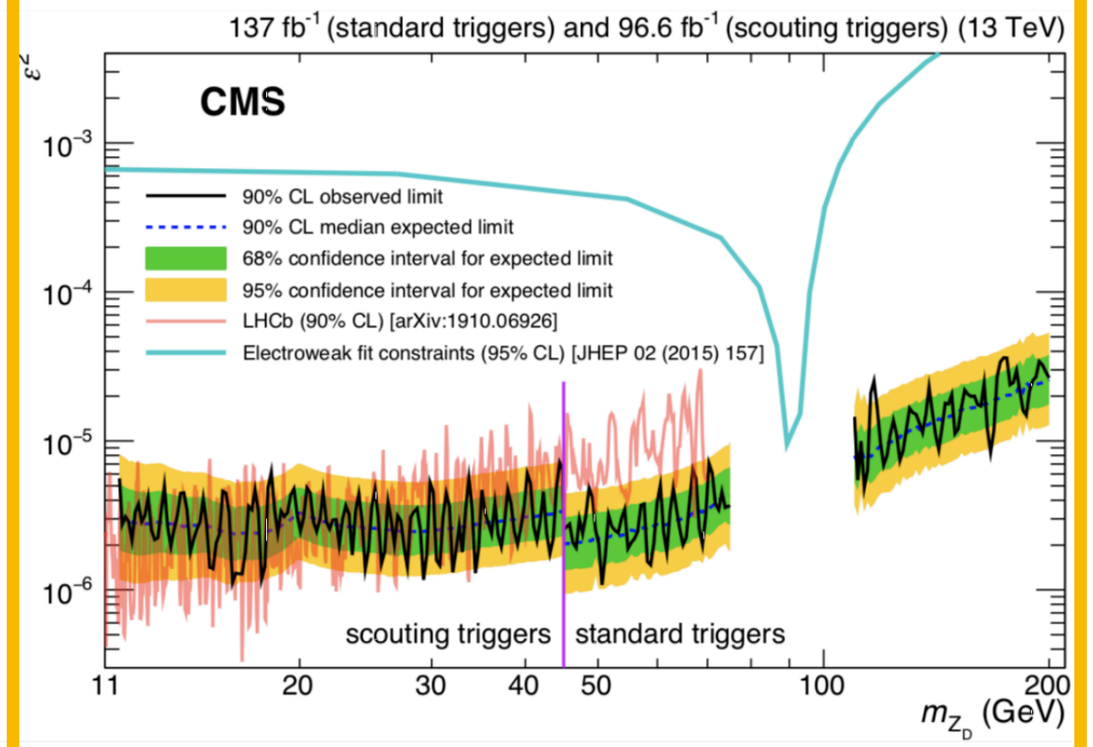
Other Points to keep in mind

Visible Results for Quark and Lepton final states can be added into the mix

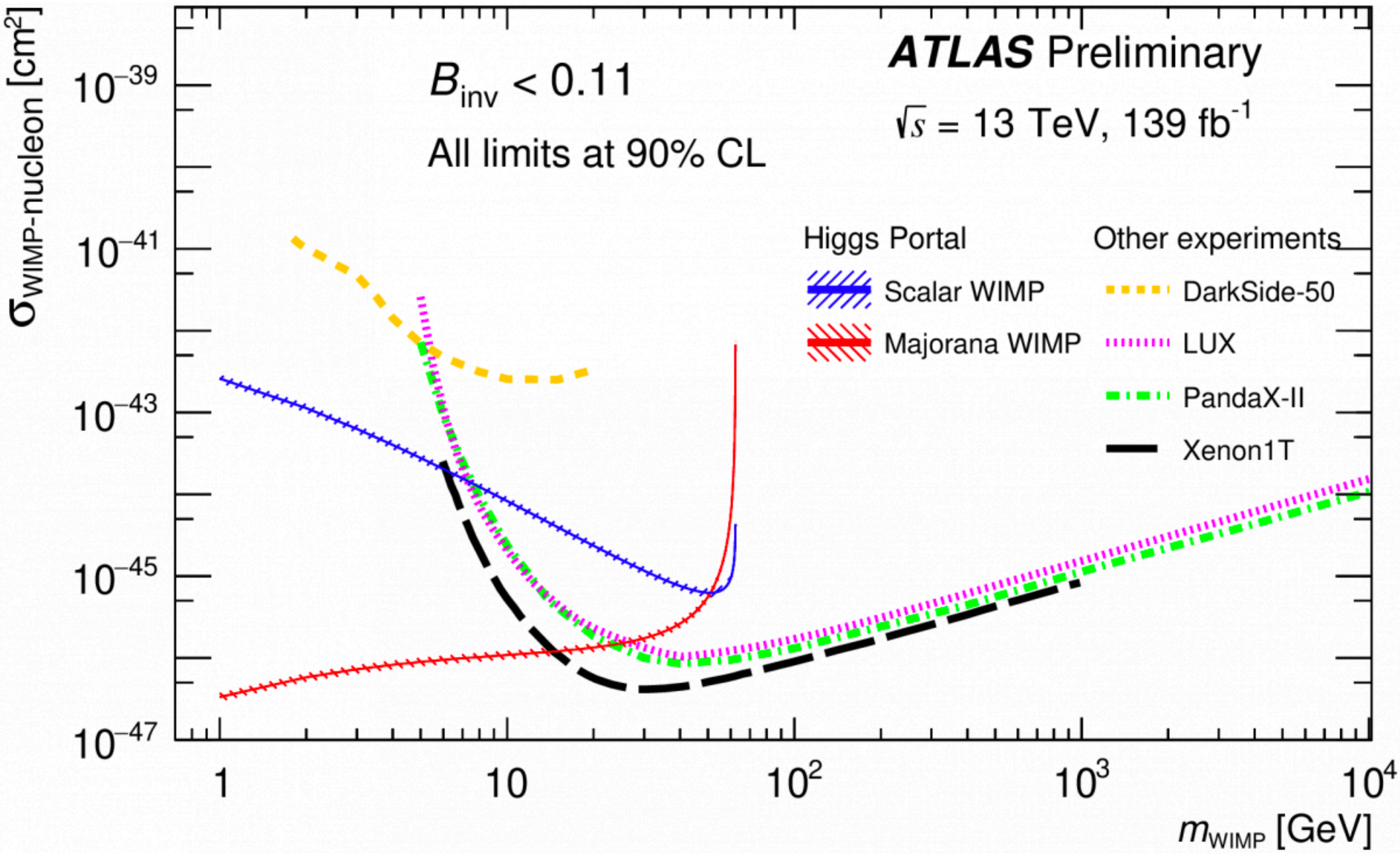
There are other ways to present LHC results on the same plot w/light DM experiments







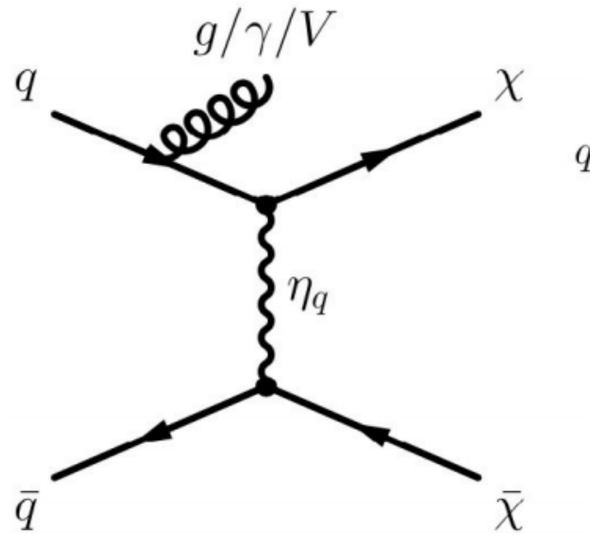
Higgs To Invisible



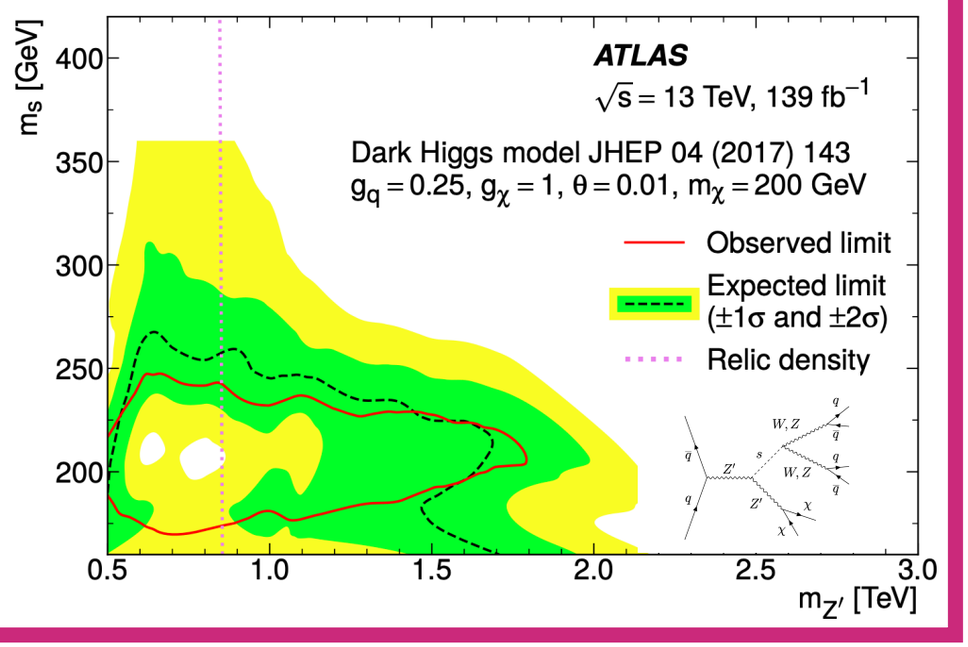
Future DMWG Work

- Currently actively pursuing t-channel interpretation
  - Both ATLAS/CMS release t-channel interpretations
  - Aiming to centralize the presentation
- Recently, a number of dark Higgs analyses have emerged
  - This could be a topic of future work
- Number of other options: Long lived/Neutrino Portal….

$$\mathcal{L} \supset g_{q\chi} \sum_{i=1,2} (\bar{Q}_{L,i}\eta_{L,q_i} + \bar{u}_{R,i}\eta_{R,u_i} + \bar{d}_{R,i}\eta_{R,d_i})\chi + \text{h.c.}$$



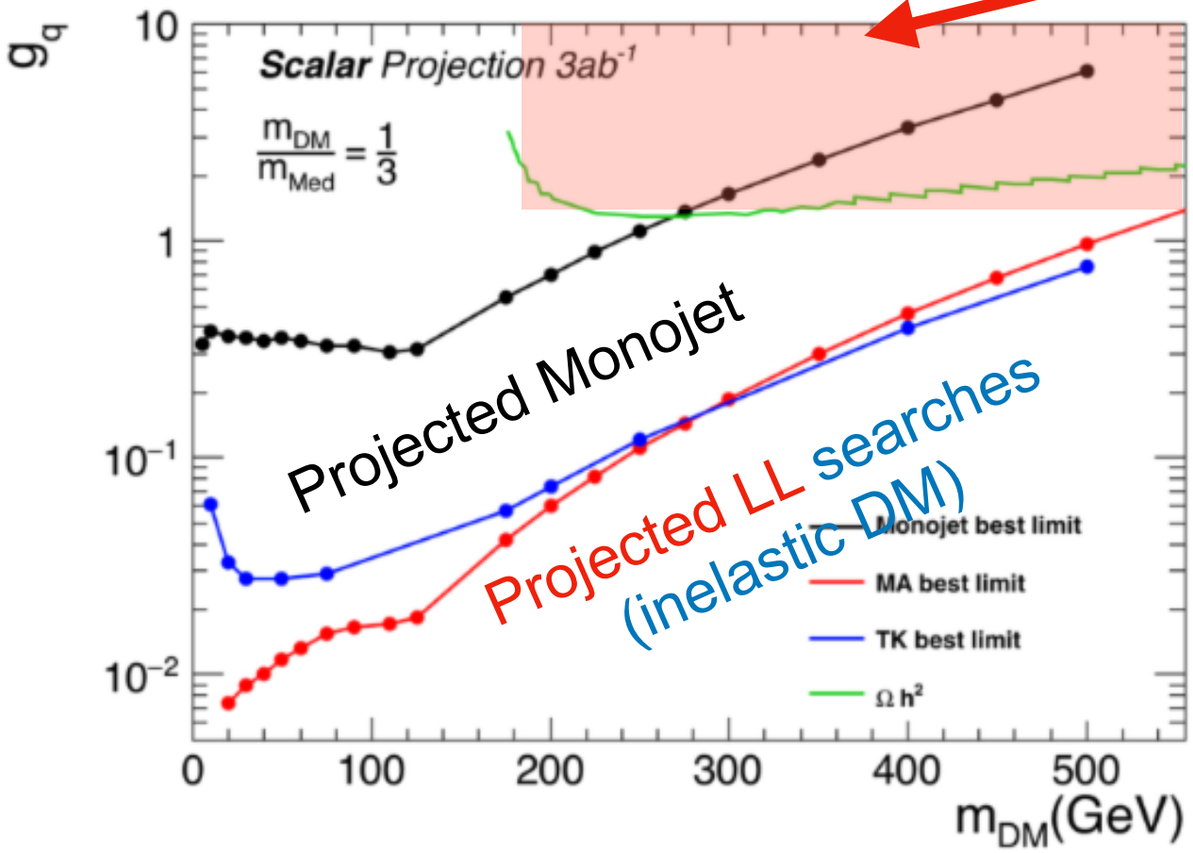
t-channel Mediator

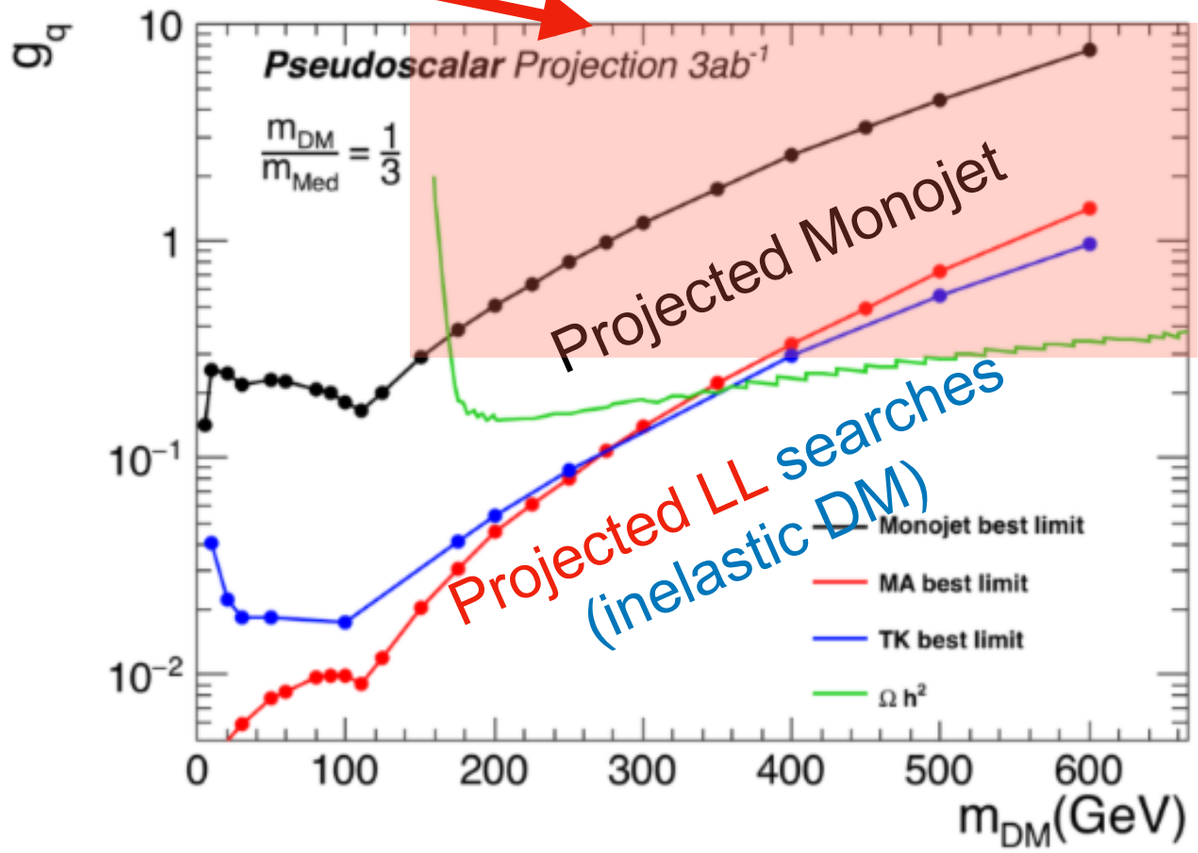


Scalar/Pseudoscalar

- Heavy (pseudo)scalar models contend w/ relic bounds
  - Addition of Higgs to invisible also complicates this
  - Its very hard to have a scalar/ALP without heavier objects
    - Typically need a 2HDM or Higgs Mixing

Region that would not overclose DM

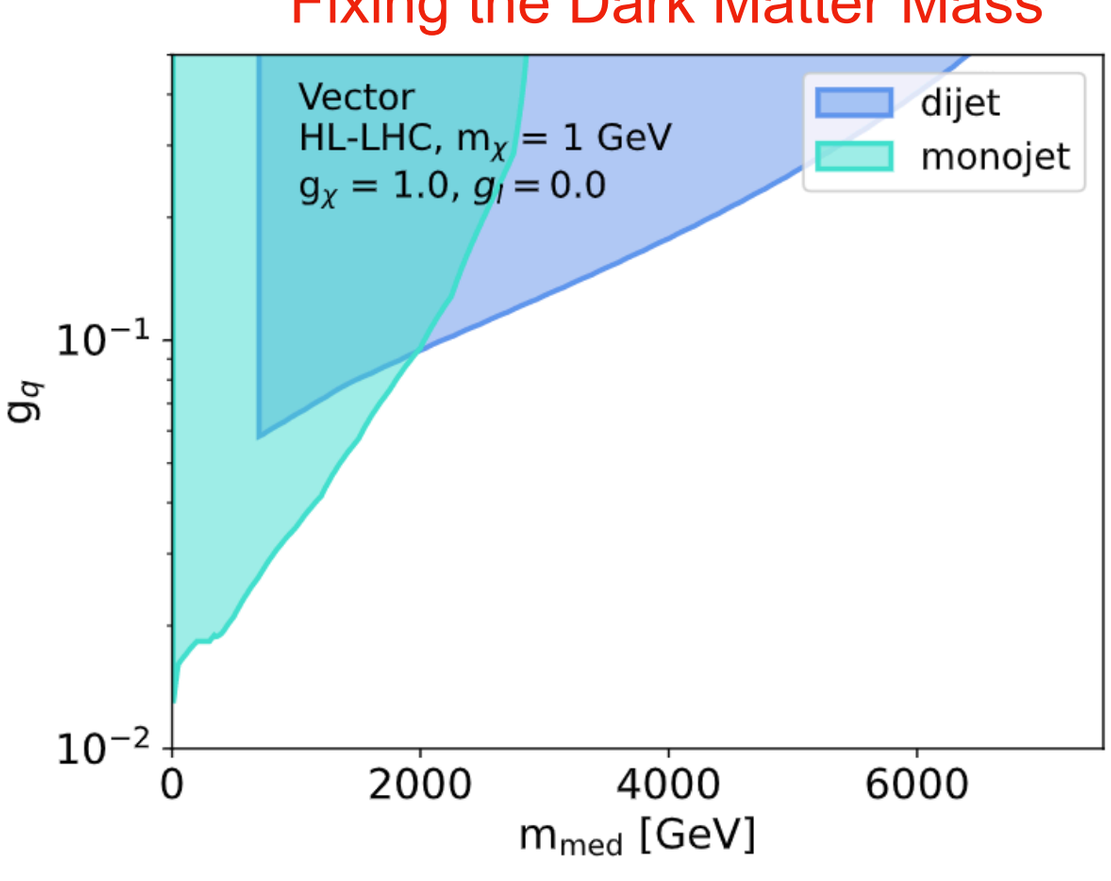




Floating the couplings

- Floating the couplings gives us a new set of bounds
  - In practice varying couplings doesn't change bounds
  - However to make direct detection bounds coupling fixed
  - Monojet and dijet can probe couplings below $g_q = 0.1$

Fixing the Dark Matter Mass



Float

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

Fix