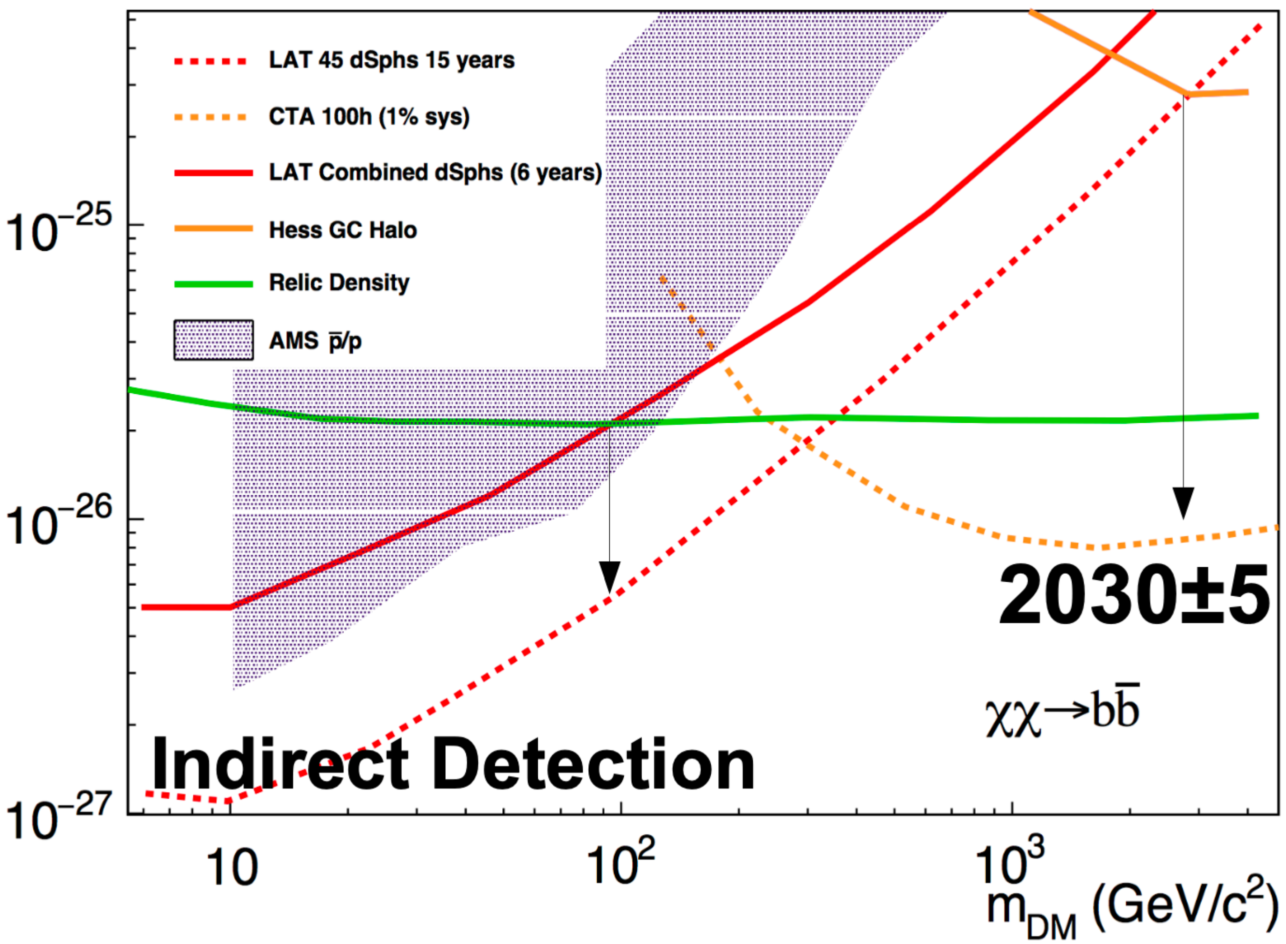
Phil Harris Lab@MIT

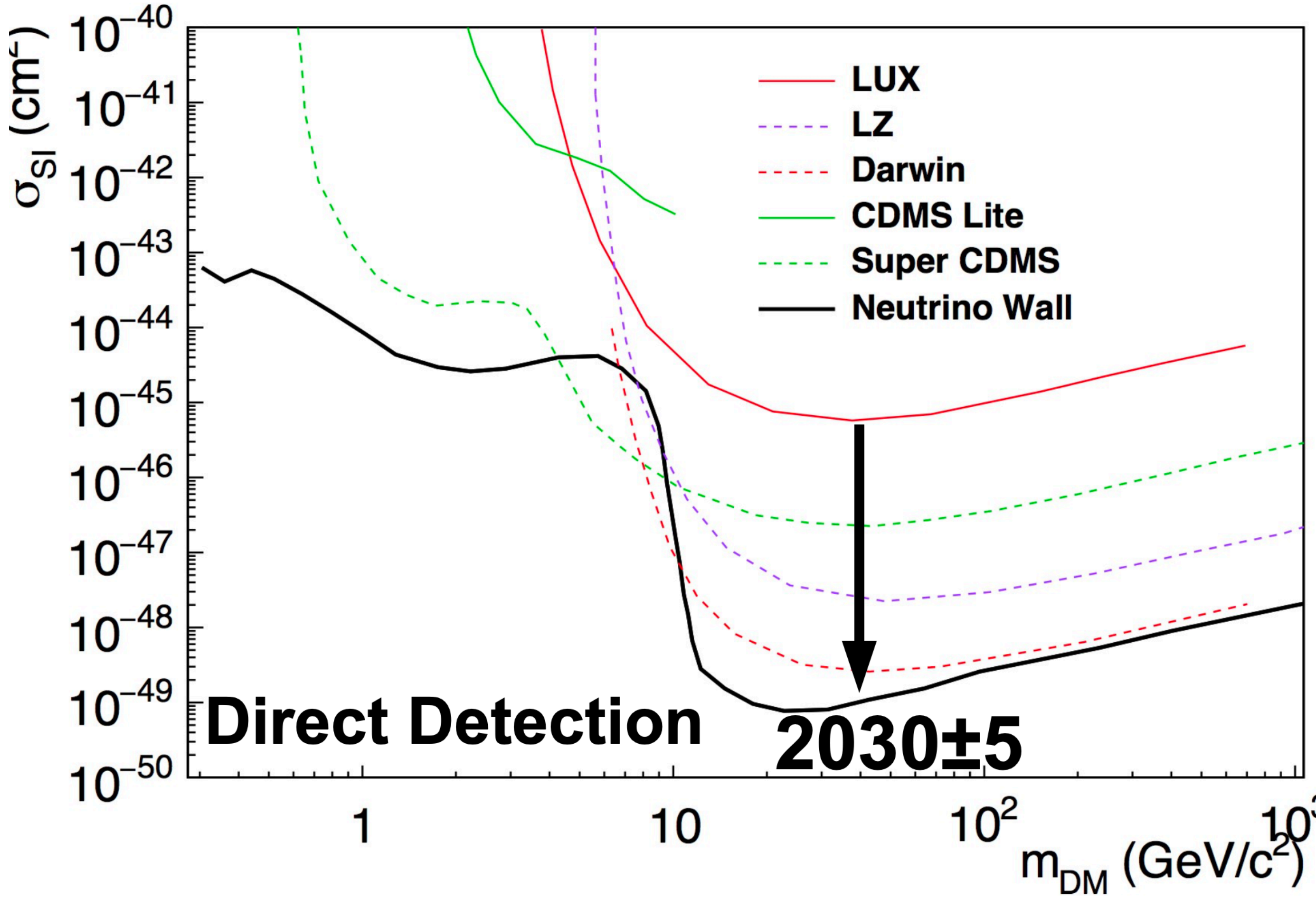
Accelerated AI Algorithms for Data-Driven Discovery

Prospects of DM at Colliders

P. Harris w/ Contributions from Many

Other Exp: Driving Bounds

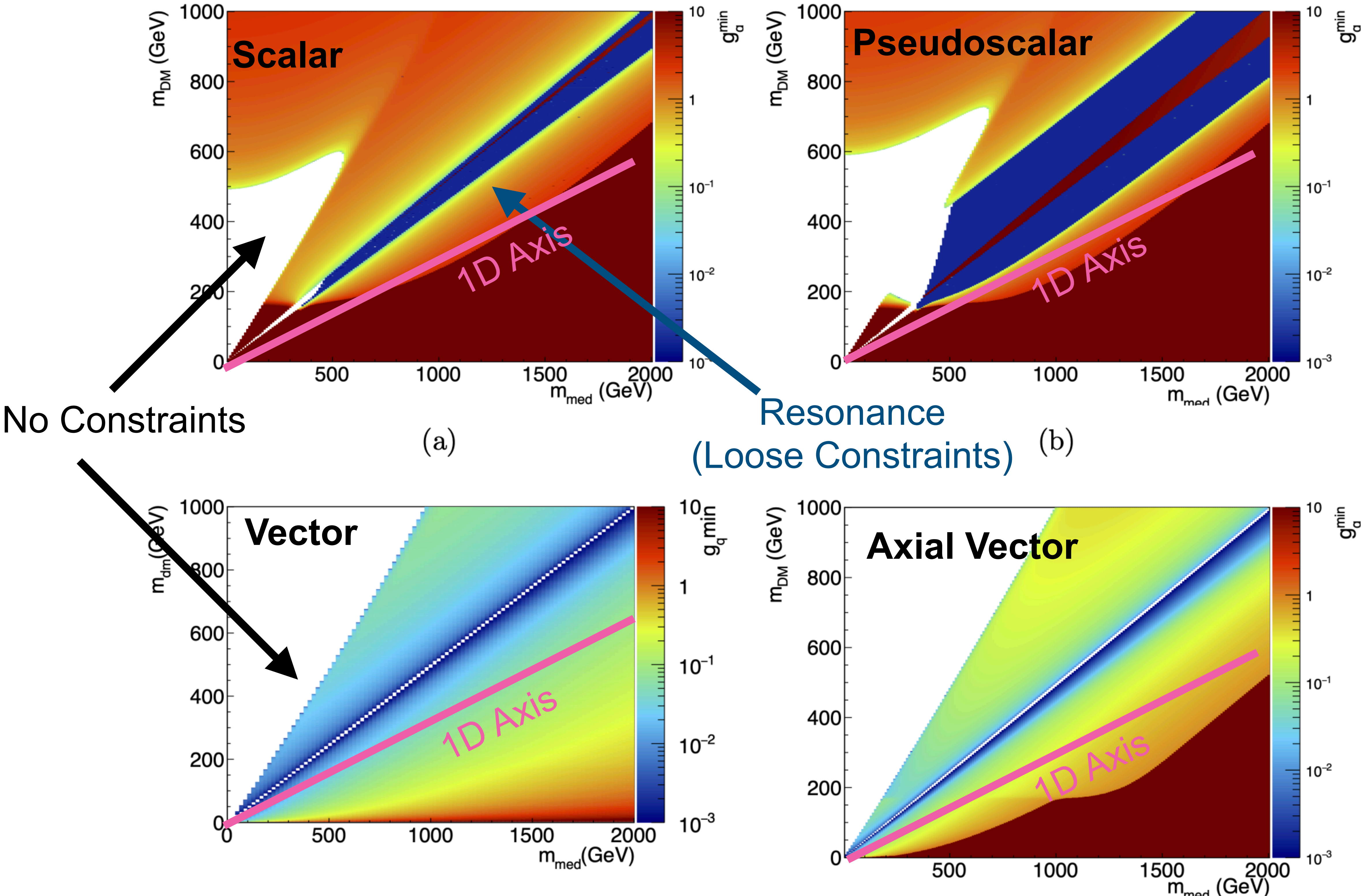




Future Experiments in other domains have clear benchmarks

With current DM searches, we aim to complement these

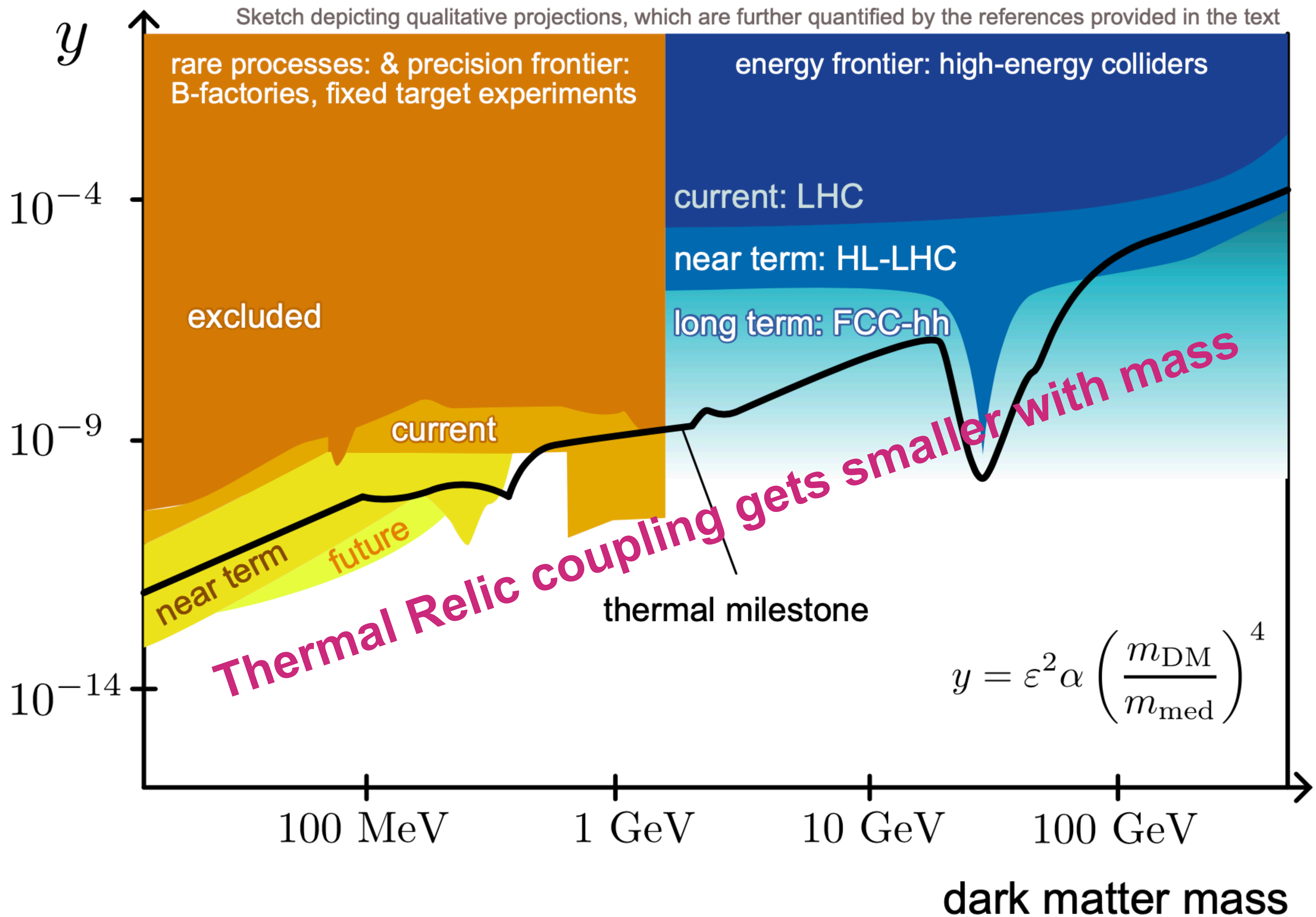
Relic: Driving Bounds



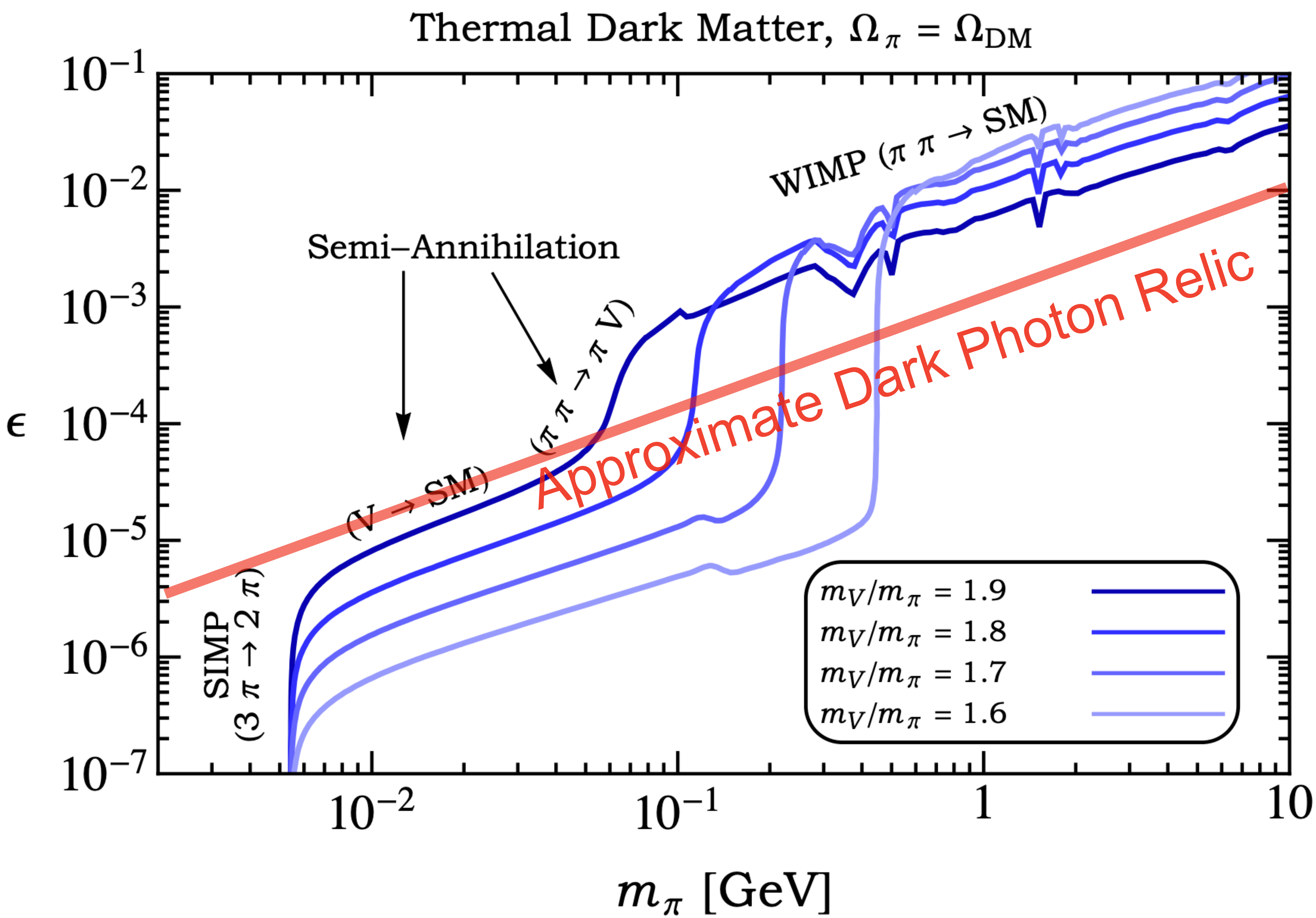
arxiv:2203.12035

We can do the same for the relic bounds

Driving Factors

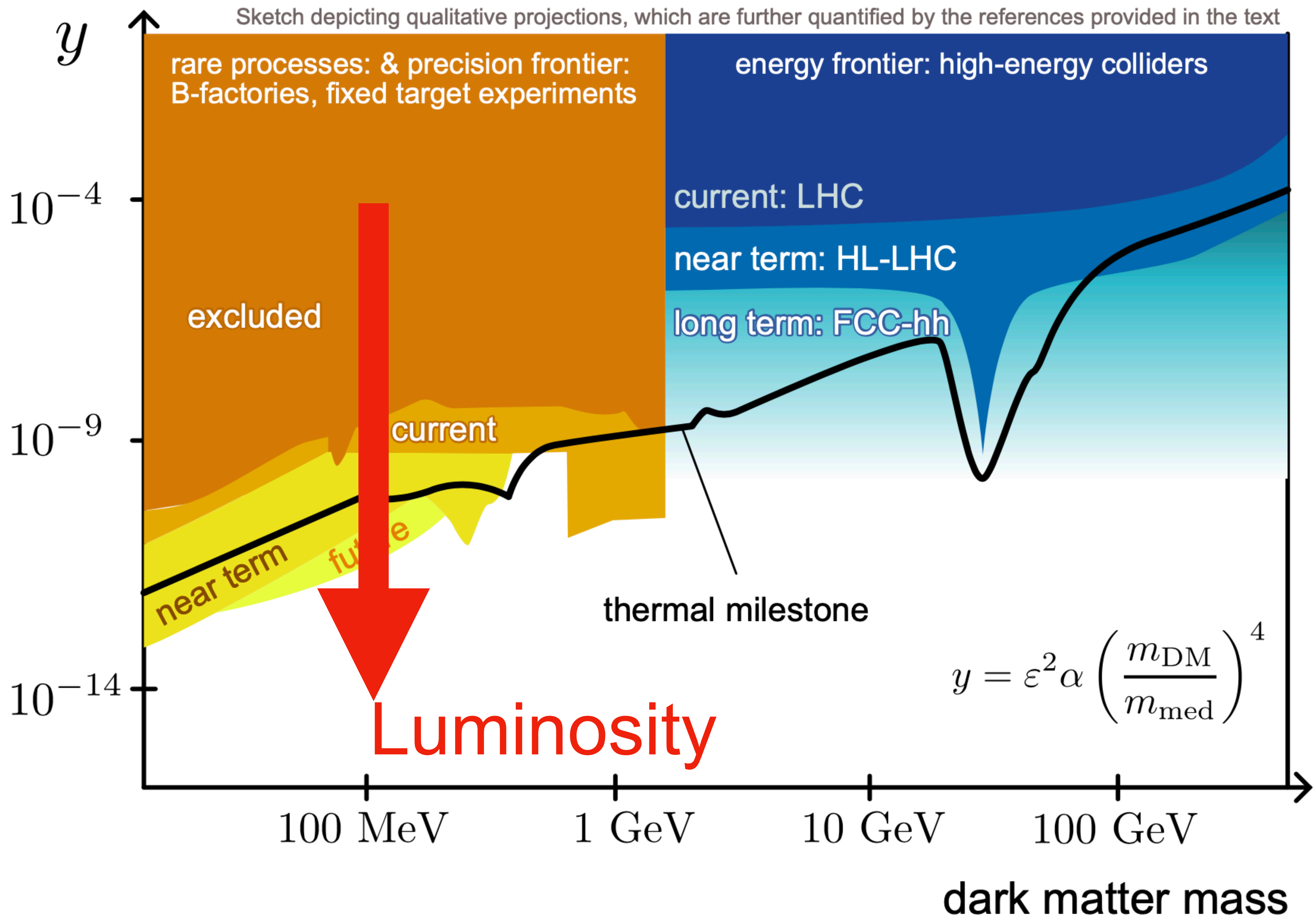


Complicating Models Complicates Relic

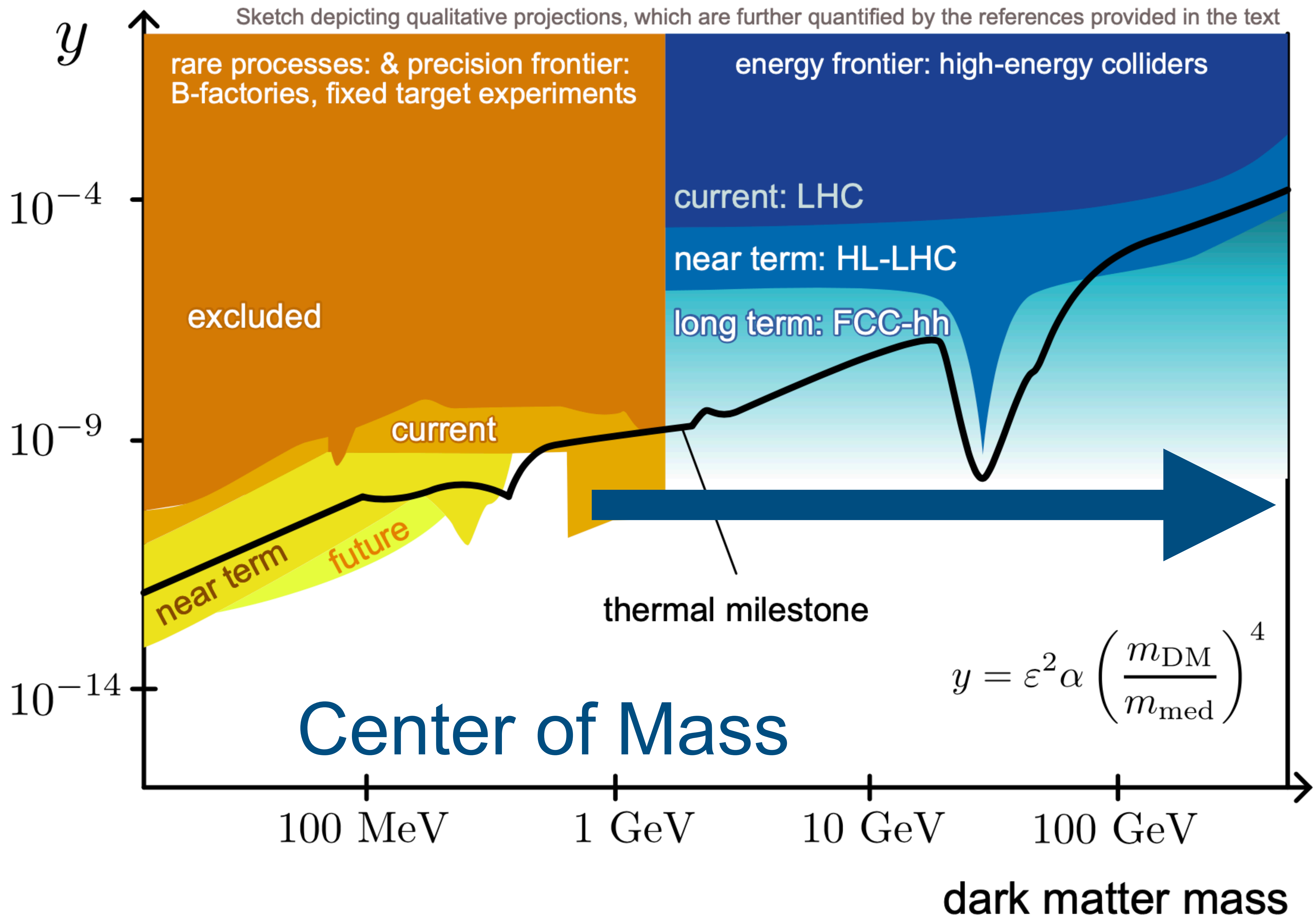


m_{DM} [GeV]

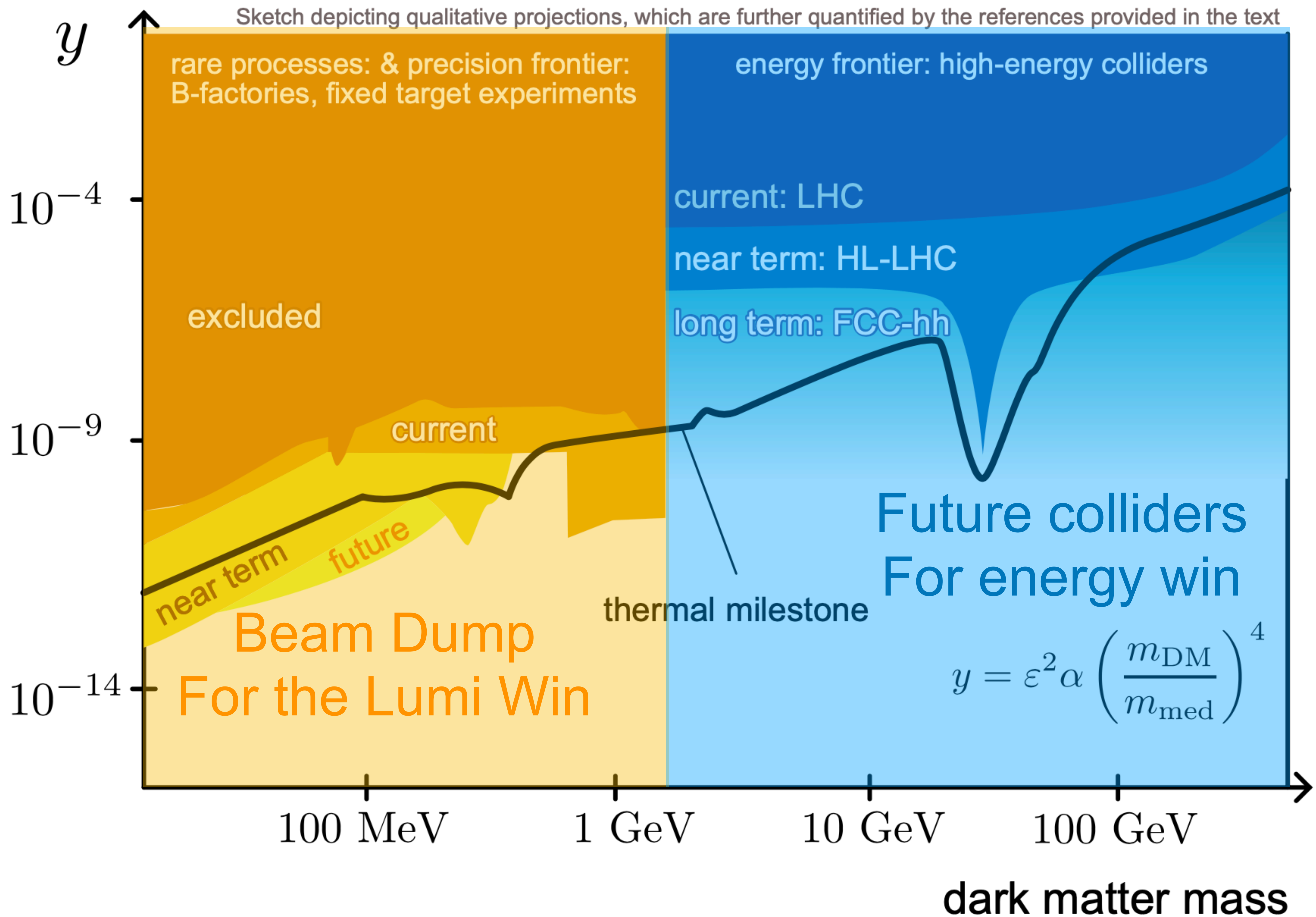
Driving Factors



Driving Factors



Driving Factors



Whats on the Market

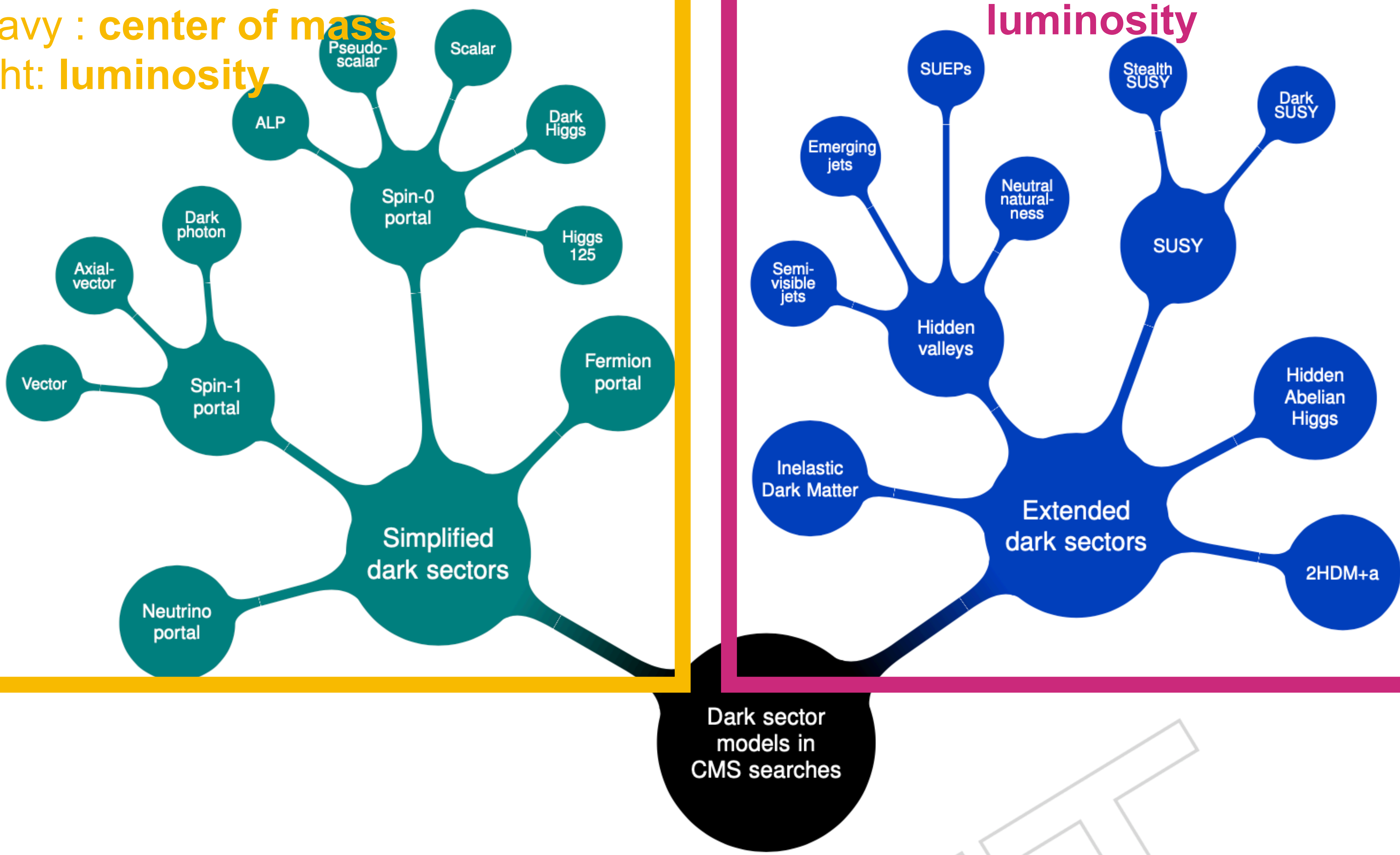
BeamDump+

LHC	0.2×10^{12} Z bosons 2×10^{12} W bosons 0.2×10^{9} H bosons Up to COM of 8 TeV	<10 years
e^{+}/e^{-}	3×10^{12} Z bosons 2×10^{8} W bosons 1×10^{6} H bosons Up to COM of 500 GeV	2055-2060
μ^{+}/μ^{-}	Muons are cool Up to COM of 10 TeV	By 2060?
PbPb	50x Current bounds? 0.45×10^{8} γ-enhancment	<10 years
100 TeV-pp	1×10^{13} Z bosons 1×10^{14} W bosons 1×10^{10} H bosons Up to COM of 8 TeV	The Future

Scope of DM at Colliders

Portal searches
Heavy : **center of mass**
Light: **luminosity**

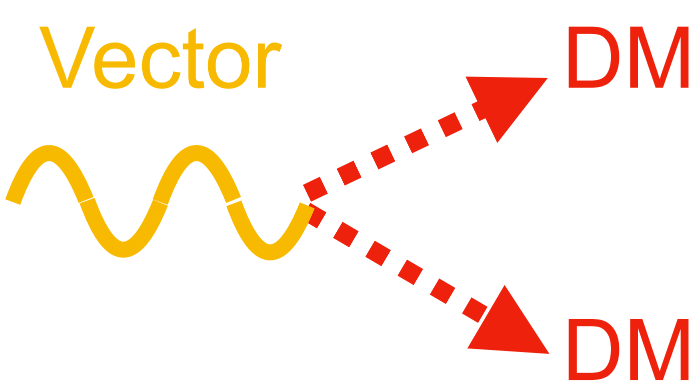
Complex signatures tend to win from **luminosity**



Searches @ colliders

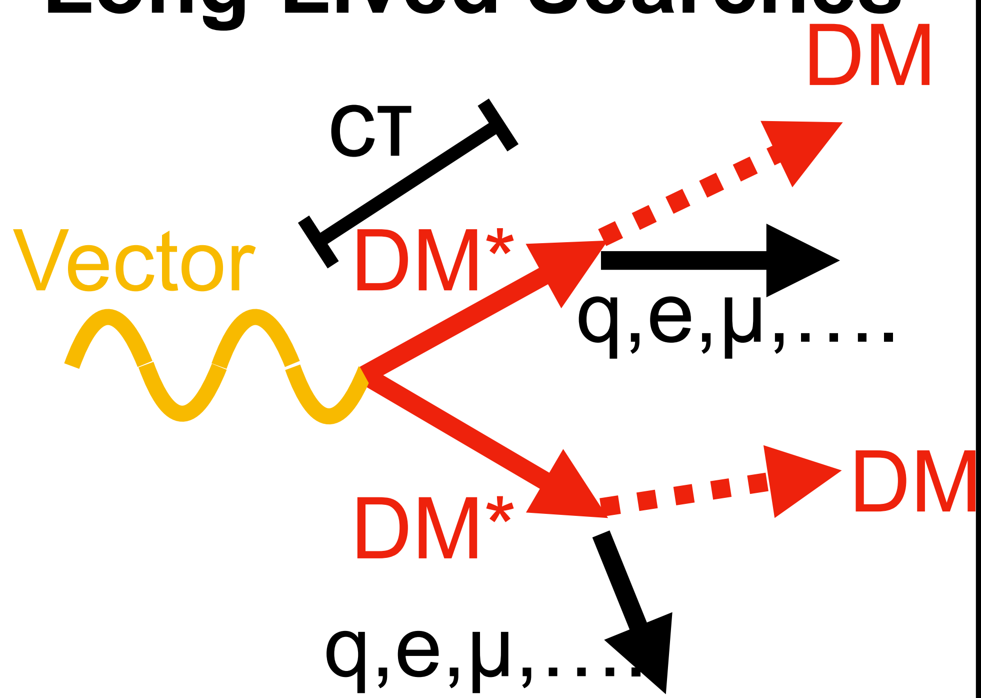
- Light light dark matter there are 3 styles of searches

Invisible Searches



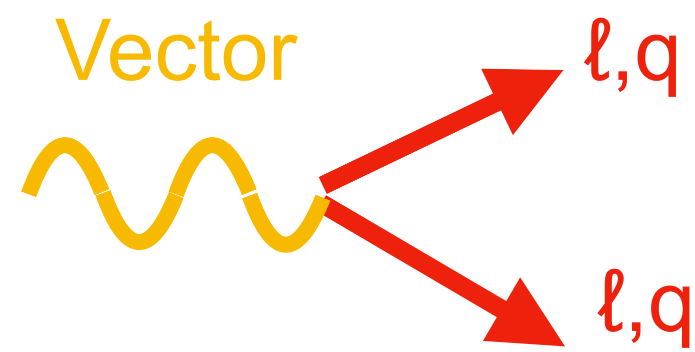
4π detectors @ LHC (ATLAS/CMS) use conservation of transverse energy for signatures

Long-Lived Searches



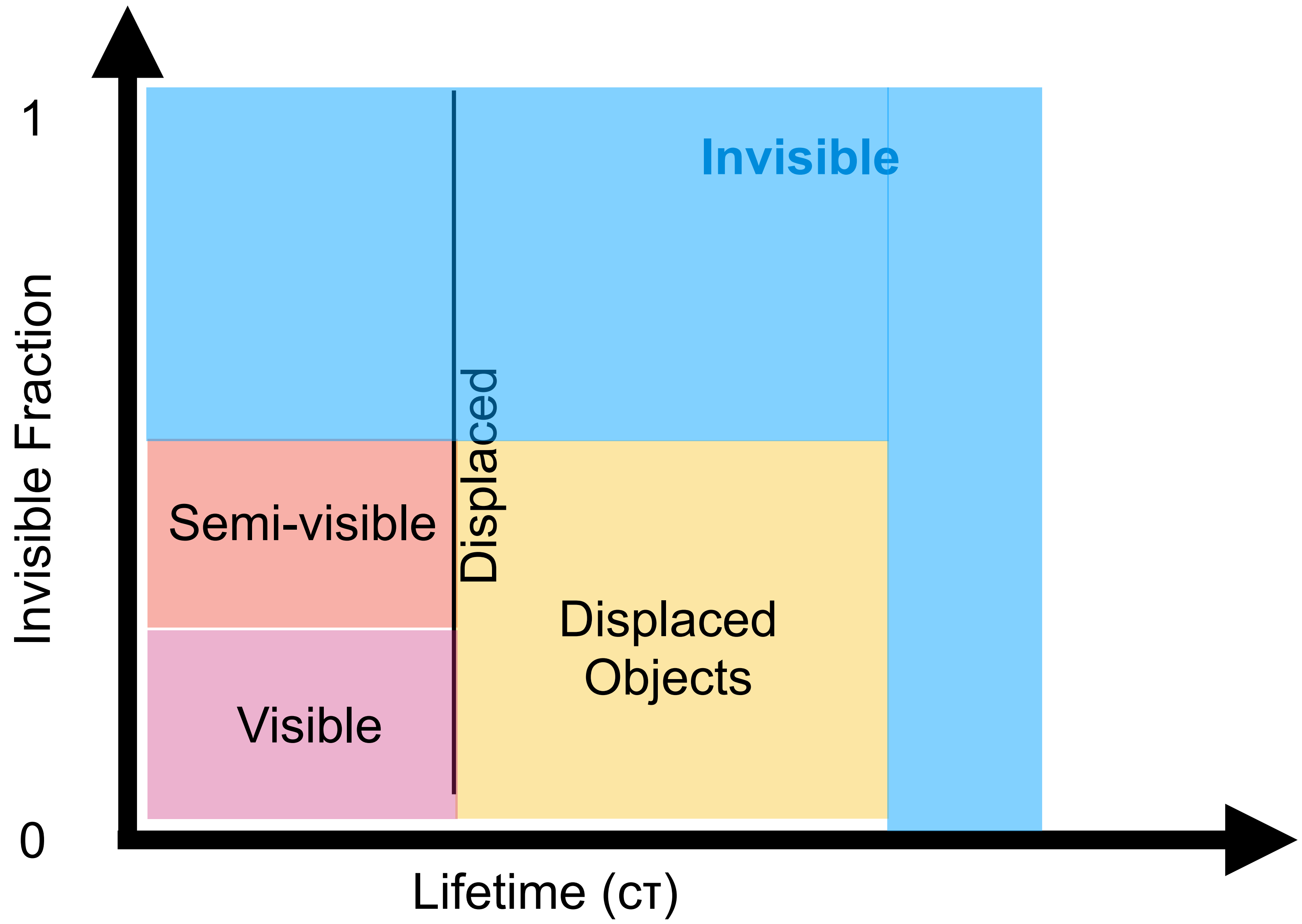
Extensive detector capabilities make displaced signatures up to 5m possible

Visible Searches

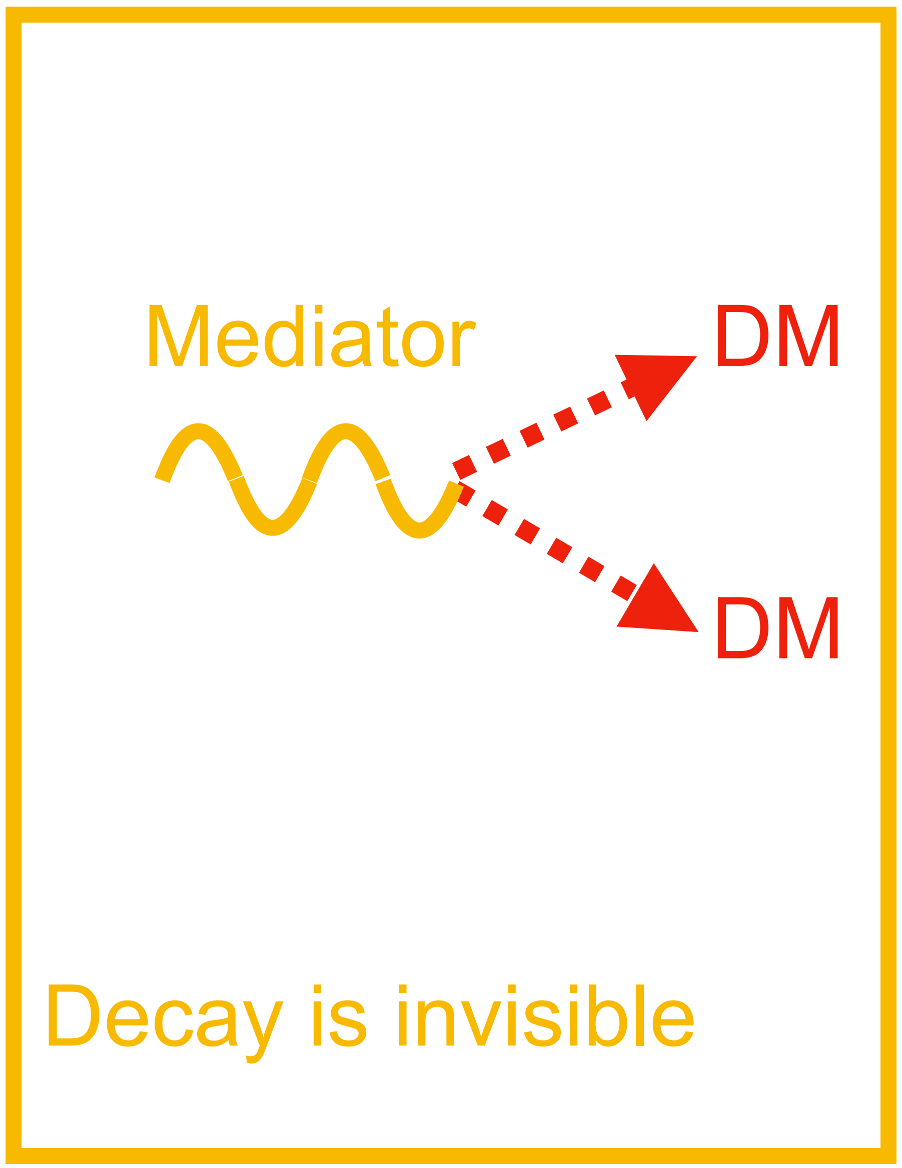


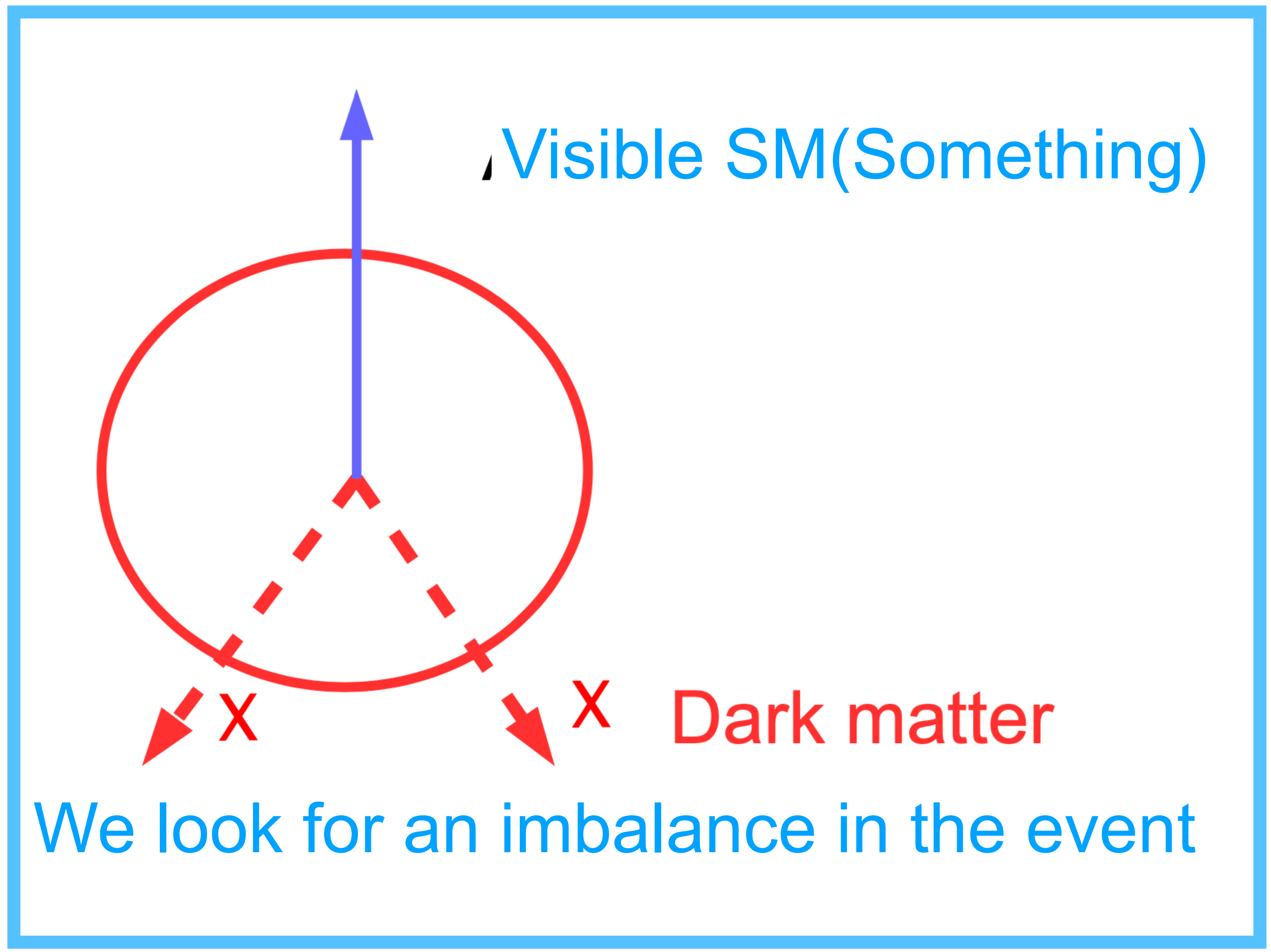
LHC can tag every type of object

Visualizing the landscape

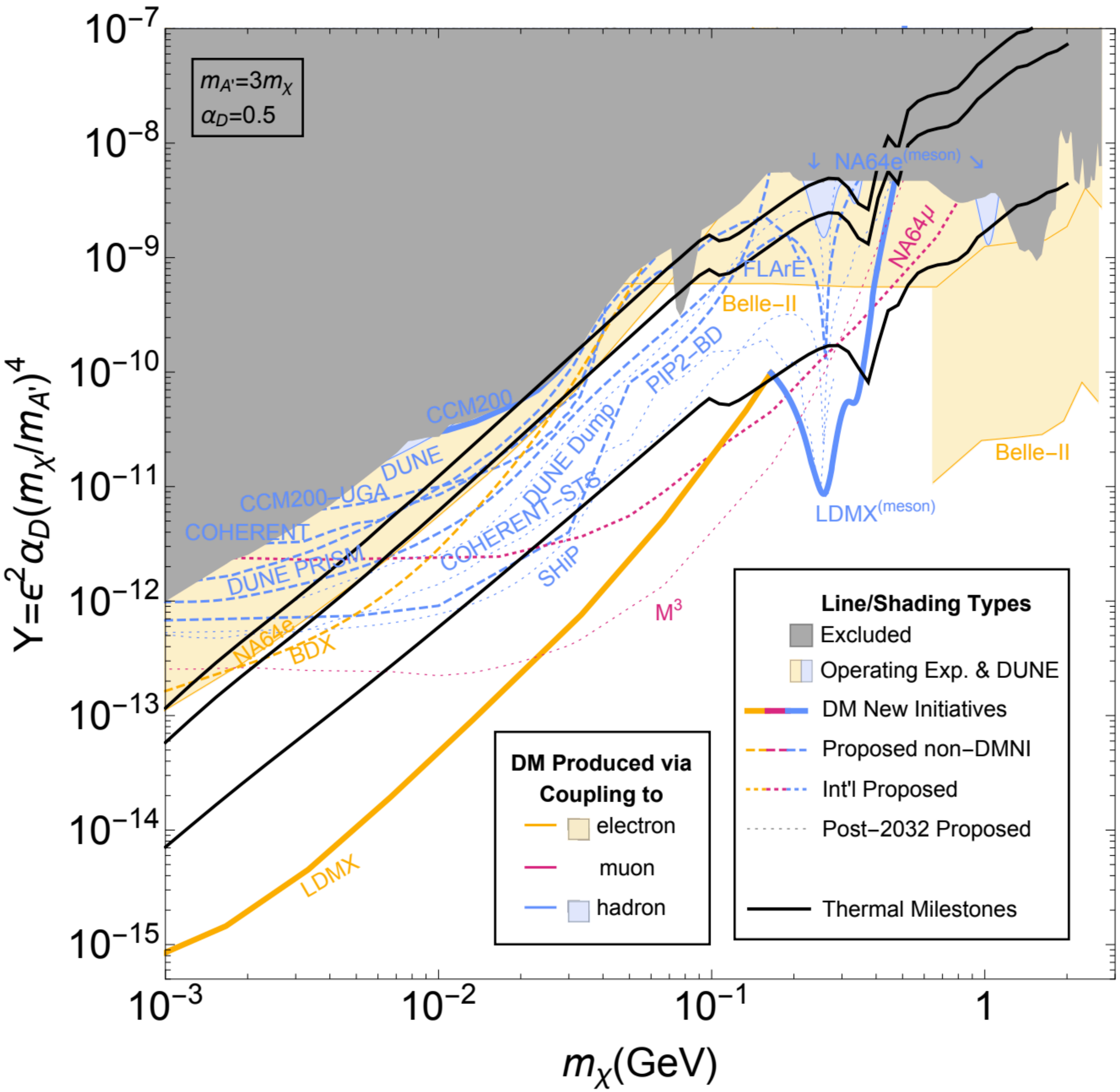


Invisible Searches





Invisible Searches

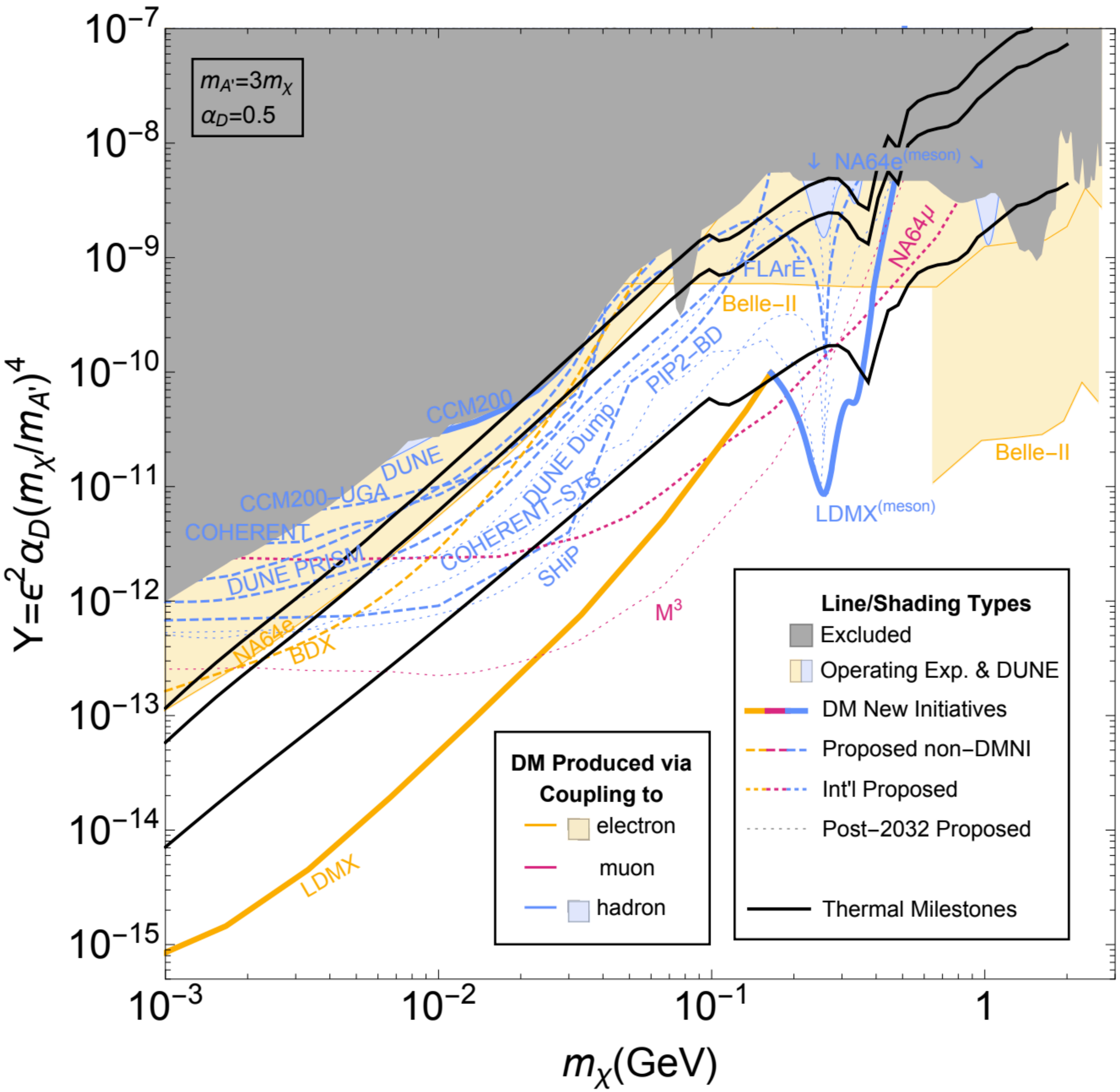


For Light Invisible DM

Next decade bodes well

Experiments like LDMX
Can probe many
convential invisible
decays

Invisible Searches



What can you do over here?

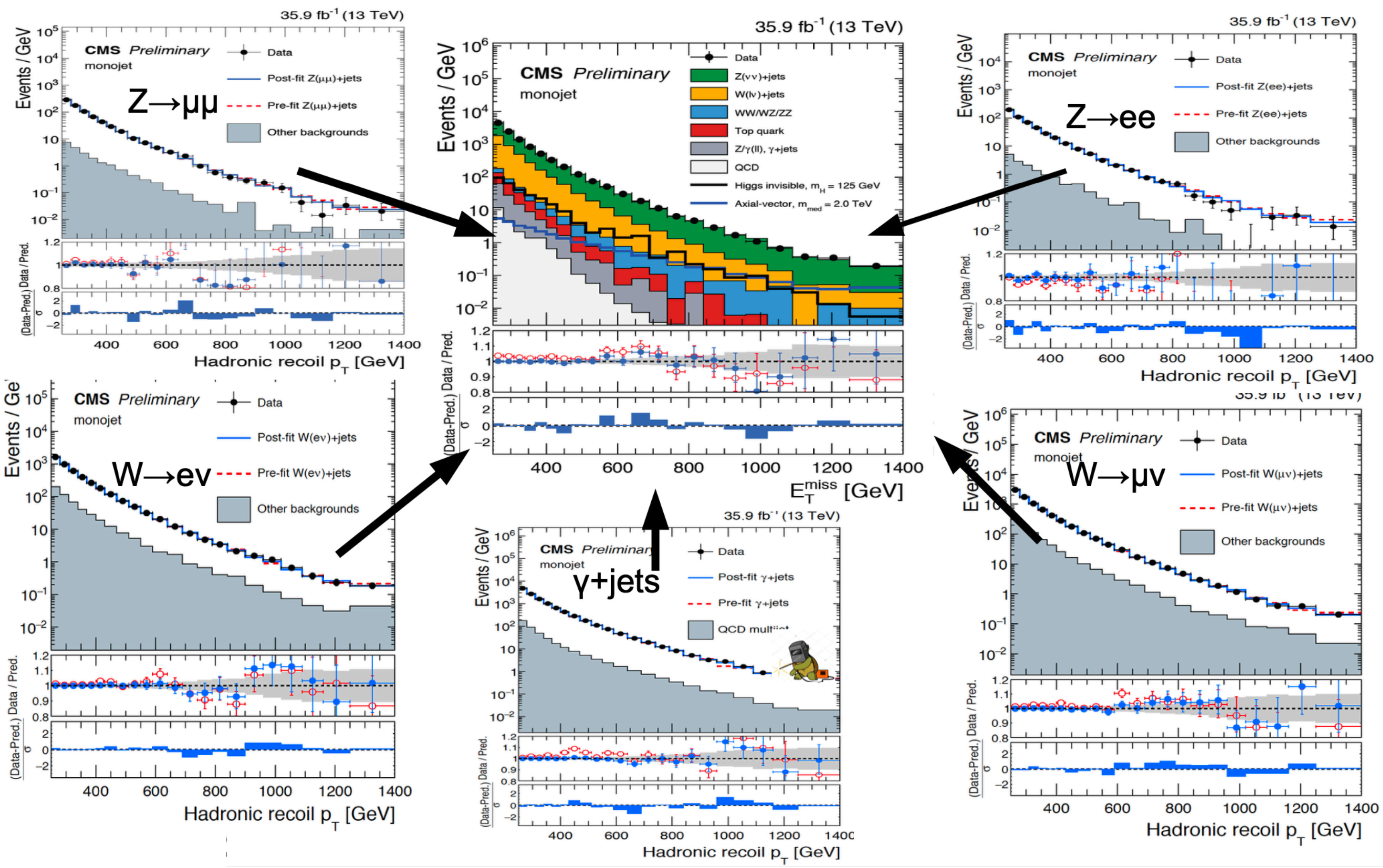
$M_\chi > 3.5$ GeV

$M_{med} > 10$ GeV

The LHC is the only game in town

LHC Invisible Search

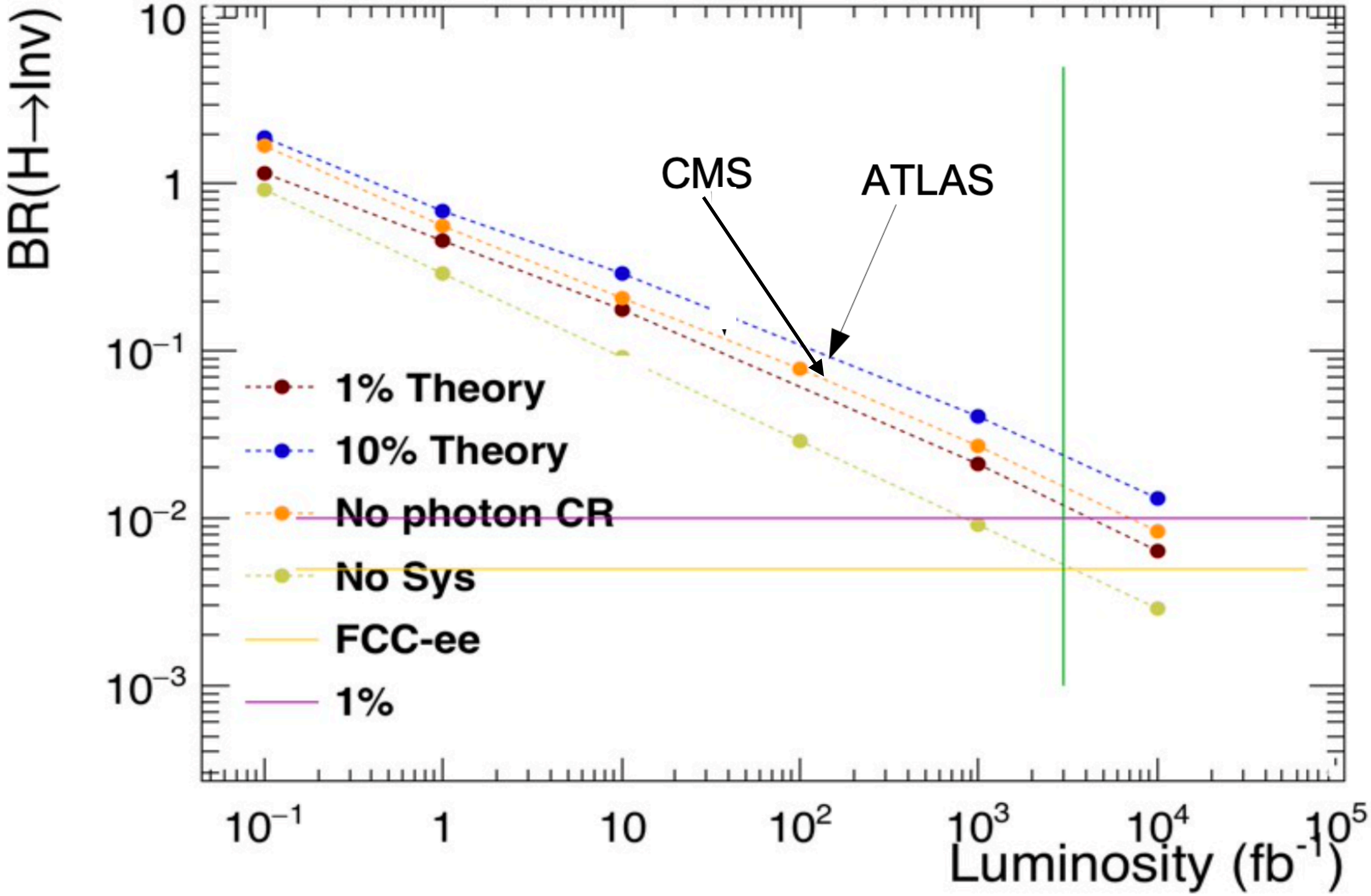
- This analysis tends to be dominated by the monojet search
  - MET+X searches, such as tt+X are also powerful
  - We focus on the monojet to start with



Monojet analysis (MET+X) are built out of multi control regions exptrapoaltiosn

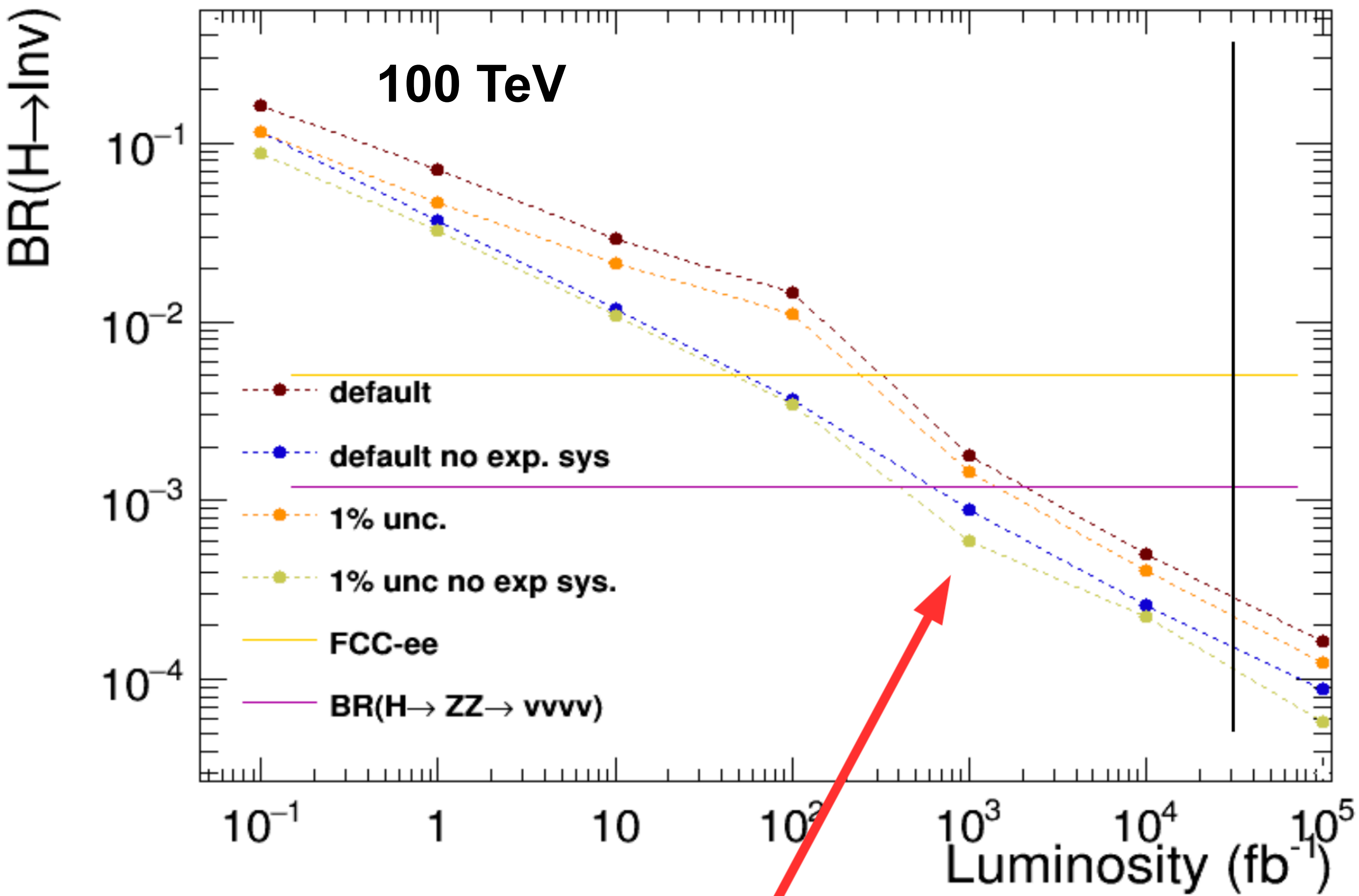
LHC Invisible Search

- Analysis scale with sqrt(luminosity) forever
  - Provided we keep experimental uncertainties under control



FCC-hh Invisible Search

- Analysis scale with sqrt(luminosity) forever
  - Provided we keep experimental uncertainties under control



Cross the SM neutrino wall at FCC with < 1 ab^{-1}

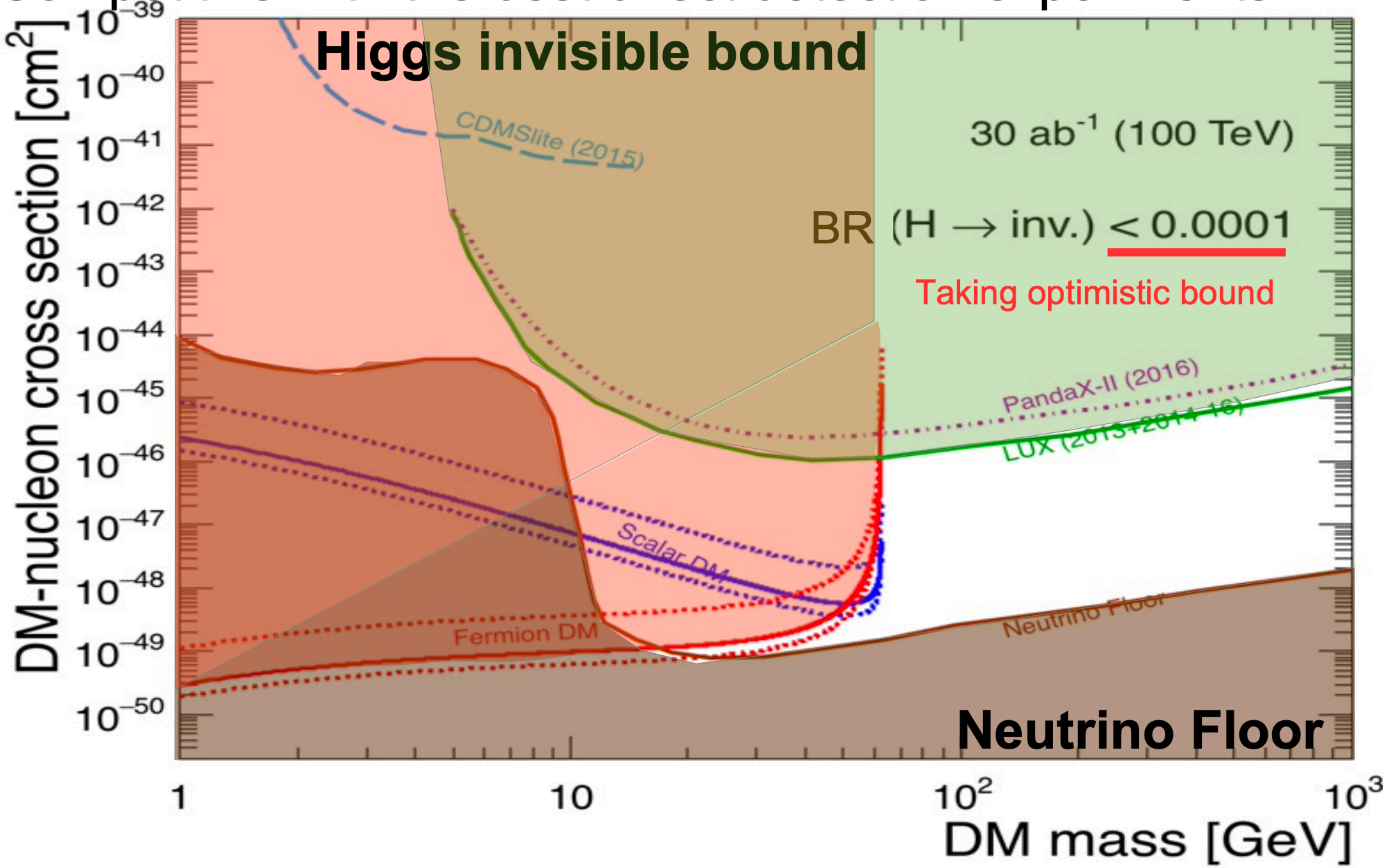
There is no systematics wall

Sensitivity

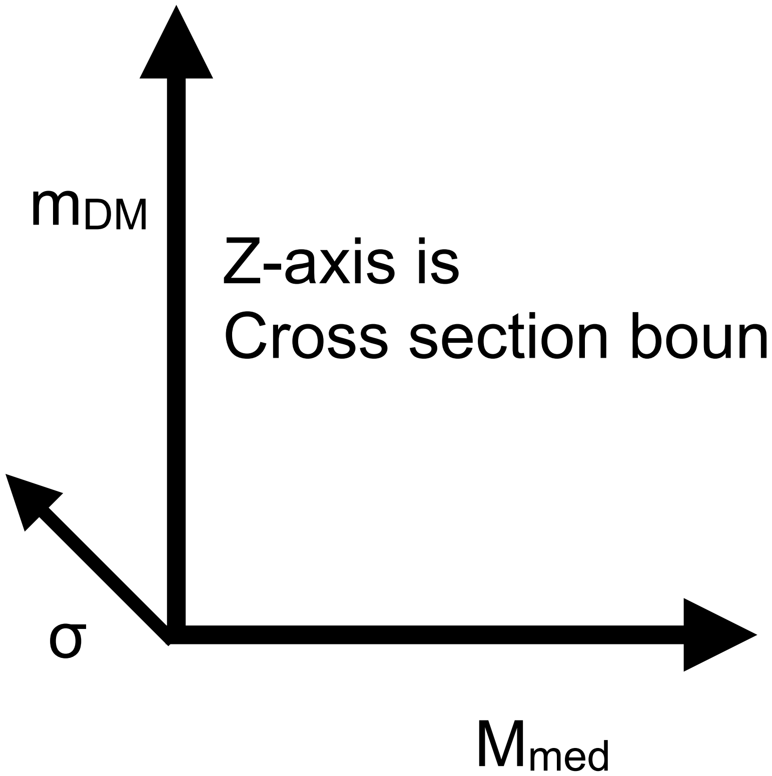
- Benchmarking on Higgs to invisible we find
  - Current LHC H(inv) > 0.08
  - Future LHC H(inv) > 0.02 (Lumi projected is 0.018)
  - FCC-ee H(inv) > 0.005 (Less Higgs and Less Bkg)
  - FCC-hh H(inv) > 0.0002 (Lumi+σ projected is 0.0002)
    - Note : $\dfrac{\sigma(100\ \mathrm{TeV})}{\sigma(14\ \mathrm{TeV})} \approx 20$
- Analytic lumi and cross section scaling works quite well
  - Event with systematics embedded in fit
  - This is because of the all the control regions

Significant Impact

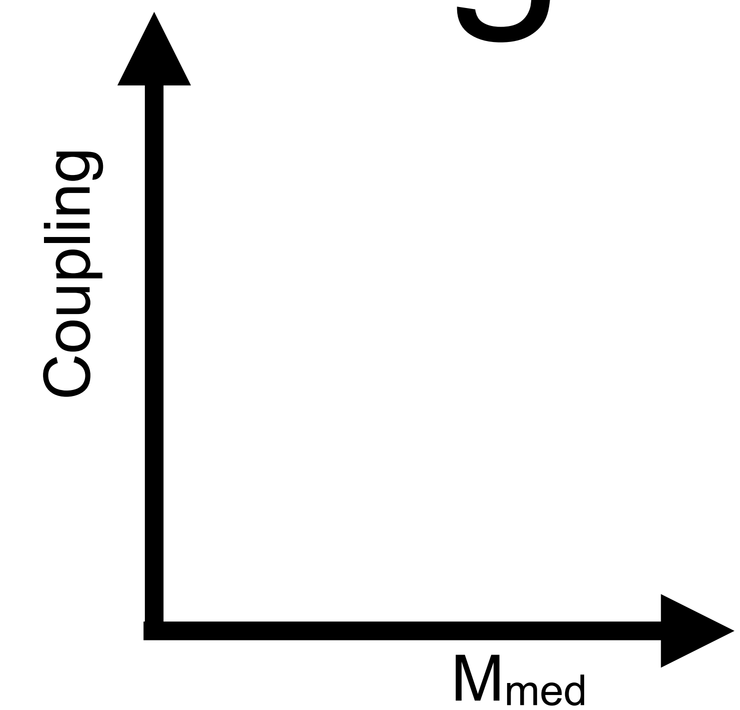
Competitive with the best direct detection experiments

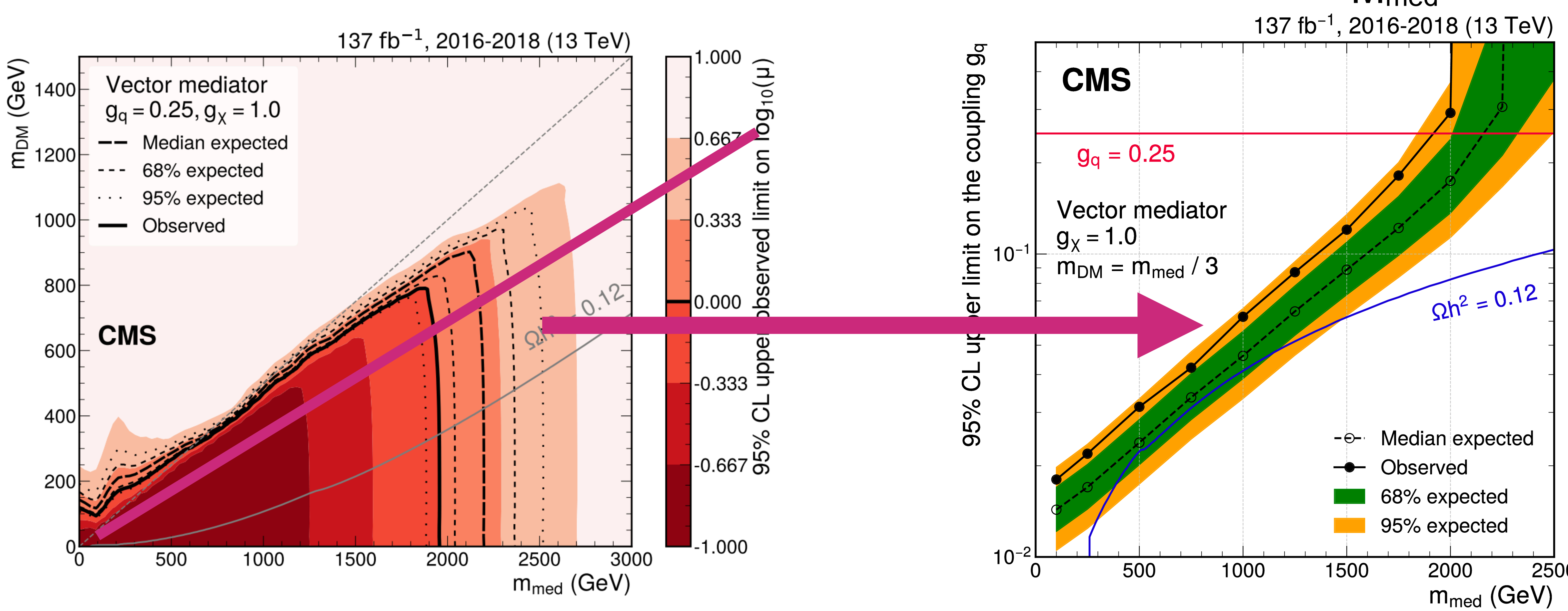


Translating to y



Fix a specific axis
$m_{DM} = M_{med}/3$





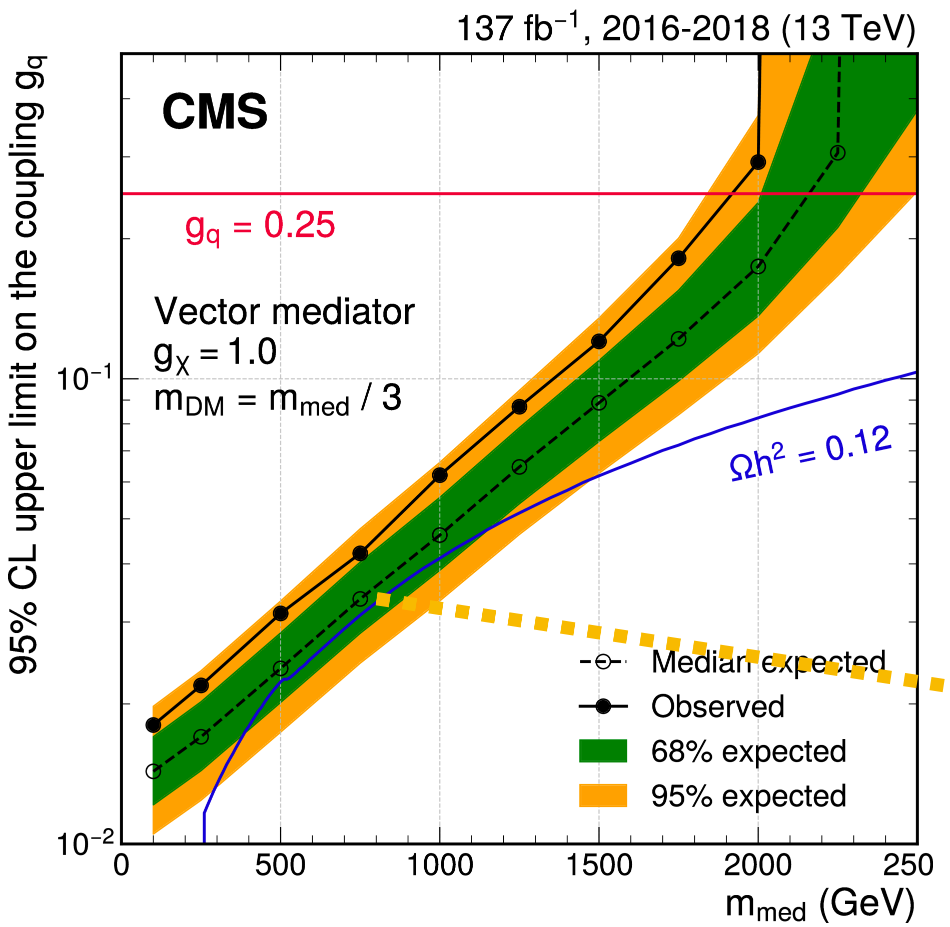
https://arxiv.org/abs/2107.13021

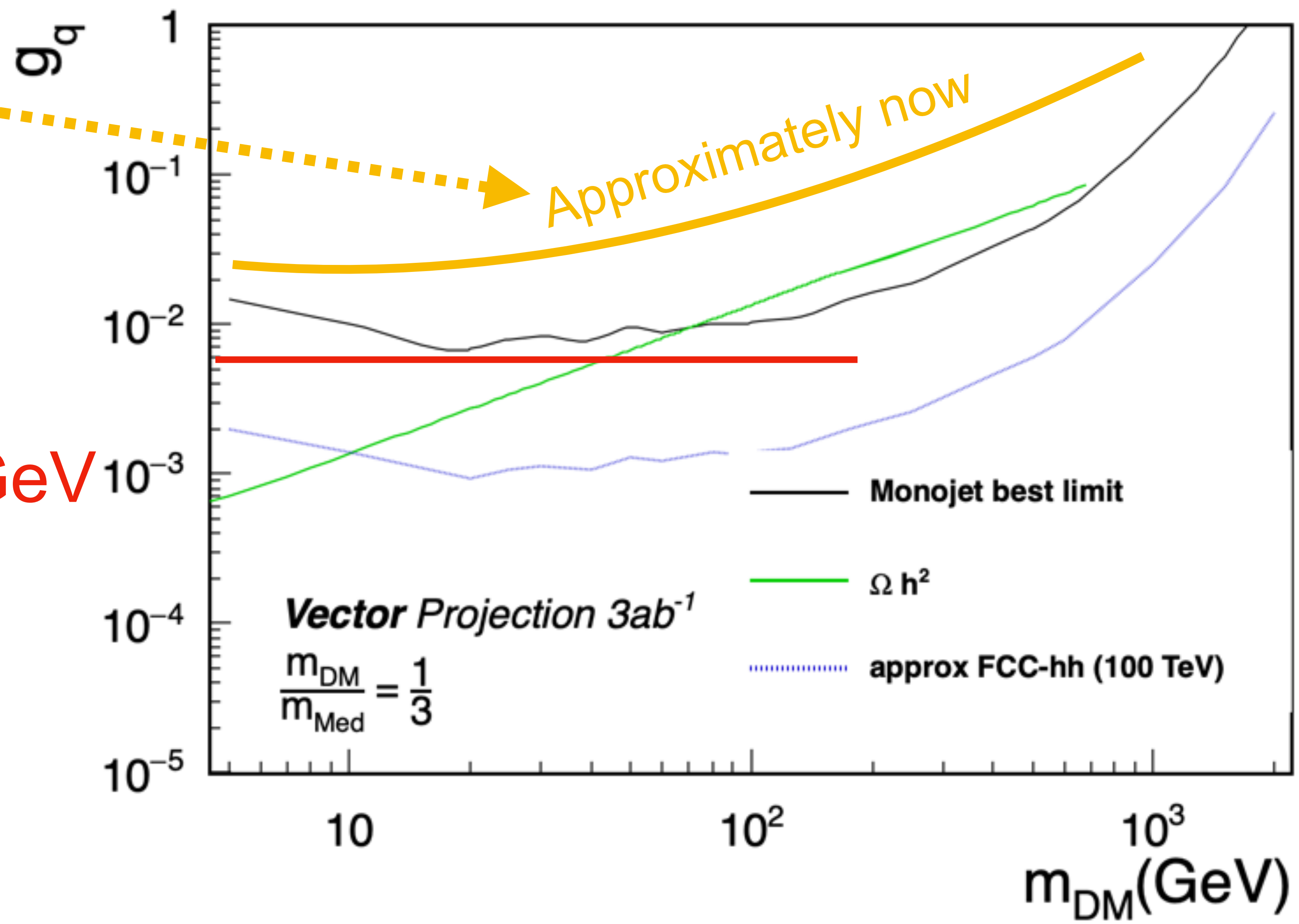
Coupling on y-axis shows overall sensitivity

Projecting To the Future

For Heavy Vector and Axial vector DM we exclude with the LHC

With 100 TeV, we exclude everything



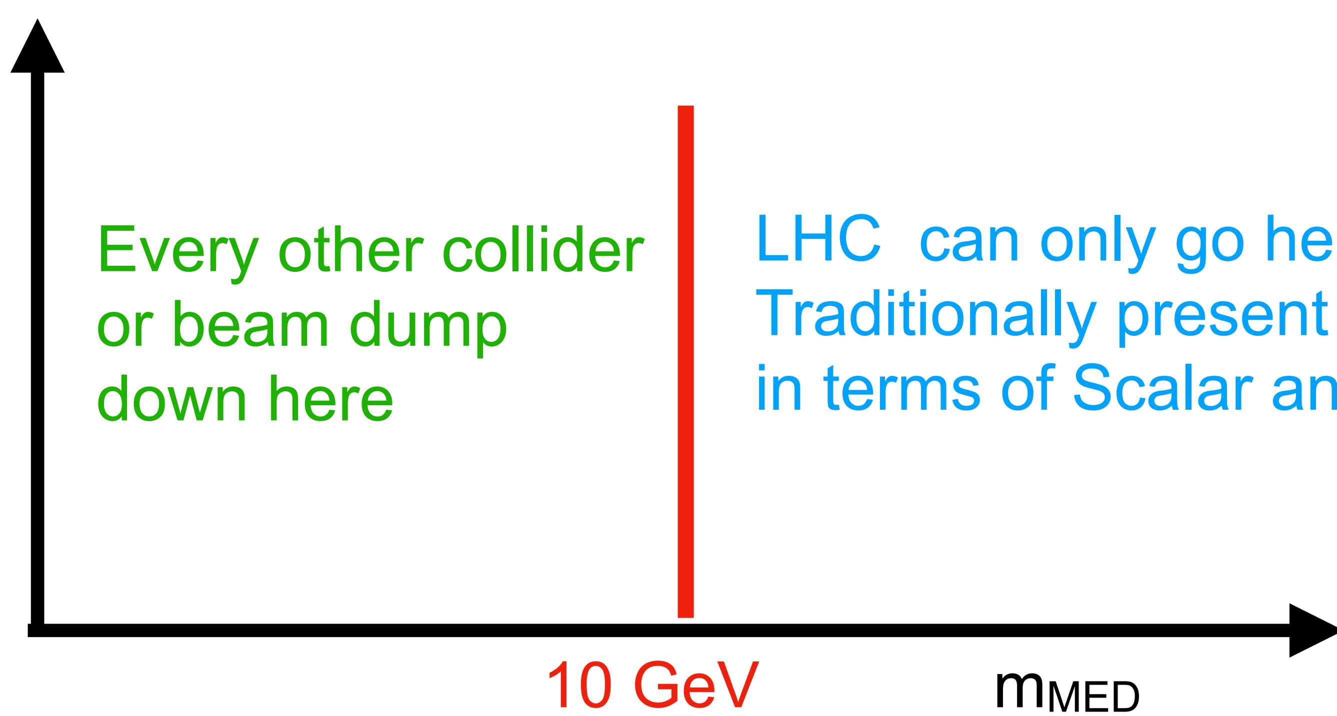


With e+/e- polarized 500 GeV Linear collider Beam

FCC is not competitive

Lost in Translation

- LHC has used a different model/notation to present results
  - These models basically the same to FIP/PBC benchmarks
- In the past year we have made an attempt to consolidate
  - General we can recast many analysis towards dark sectors
  - This talk will cover FIP based results at the LHC
  - The full range of LHC goes beyond FIP based models



Mapping Analogies

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

To get to the FIP Models

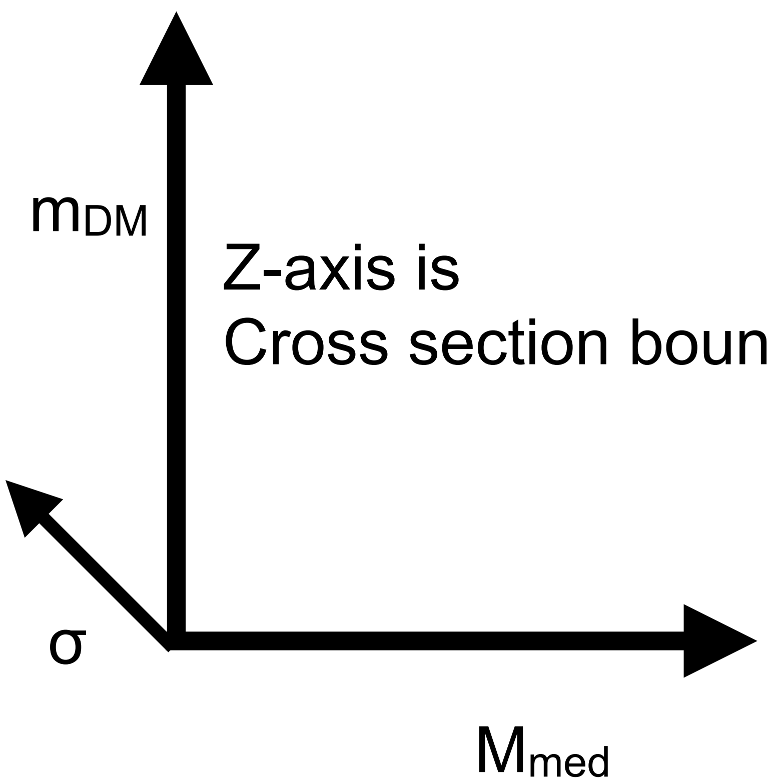
Vector Model : Translate the Couplings and add Z interference

Scalar Model : Add the mixing with the Higgs boson

Pseudoscalar : Translate the Couplings

HNL : Nothing

Translating to y



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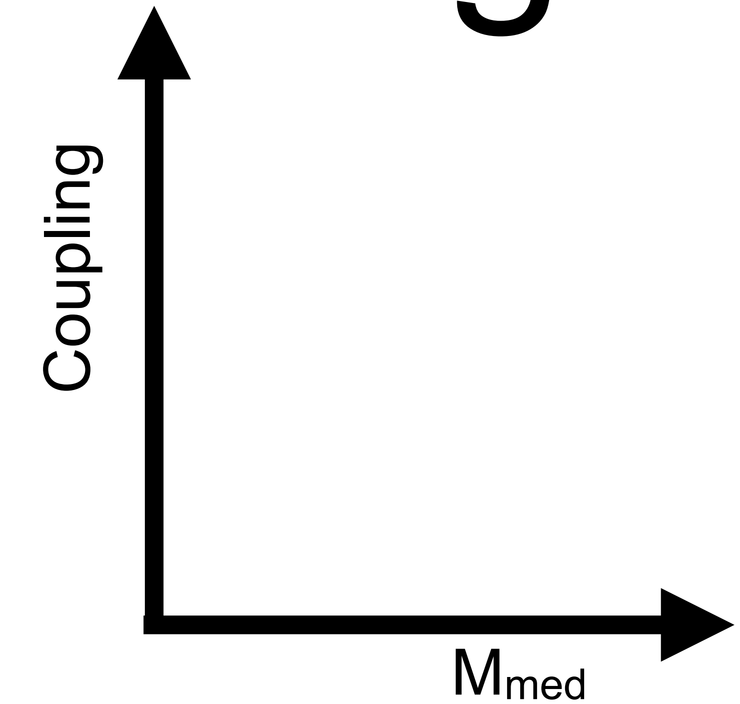
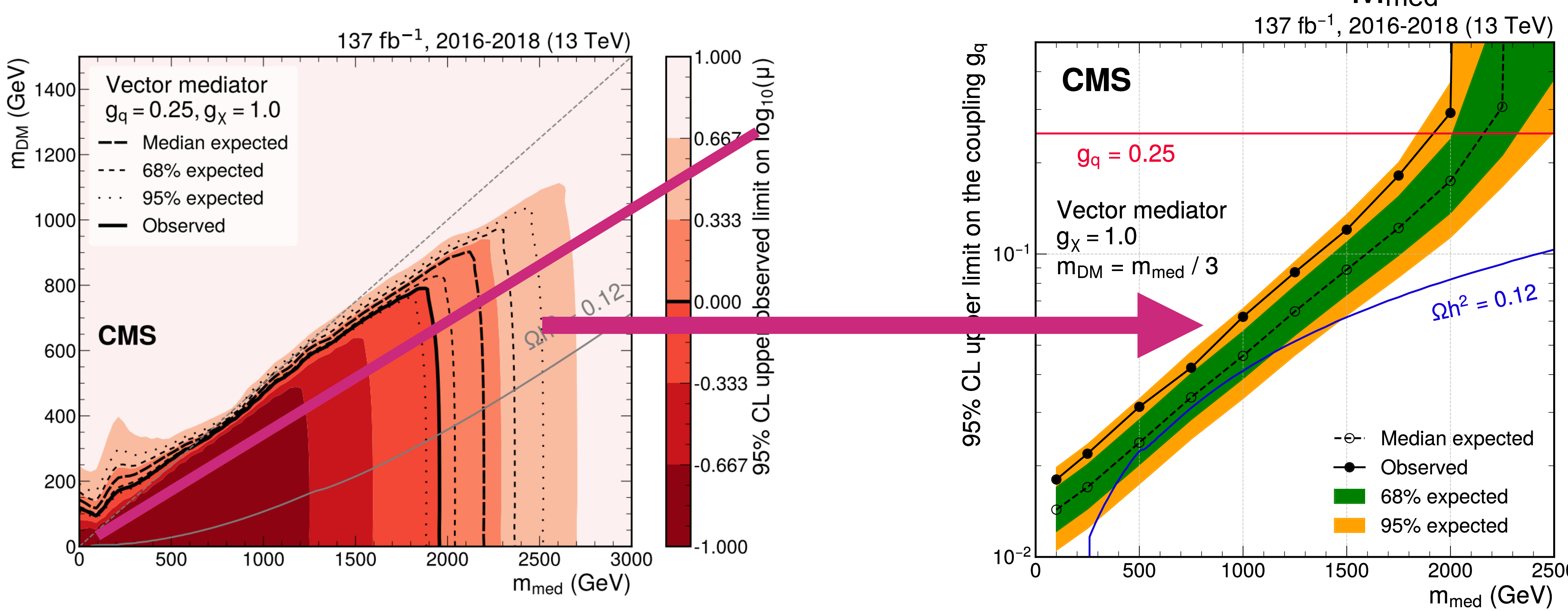




https://arxiv.org/abs/2107.13021

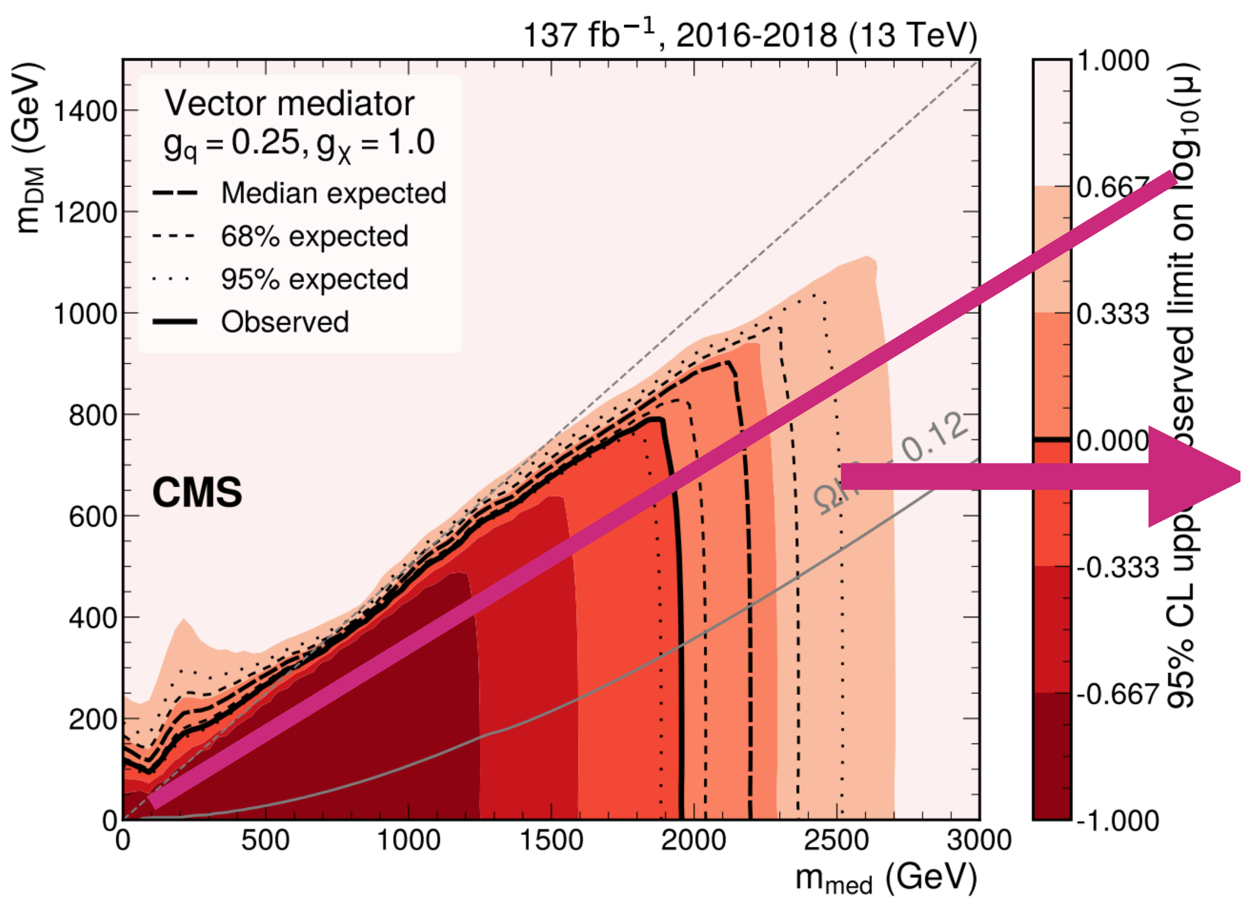
Coupling on y-axis shows overall sensitivity

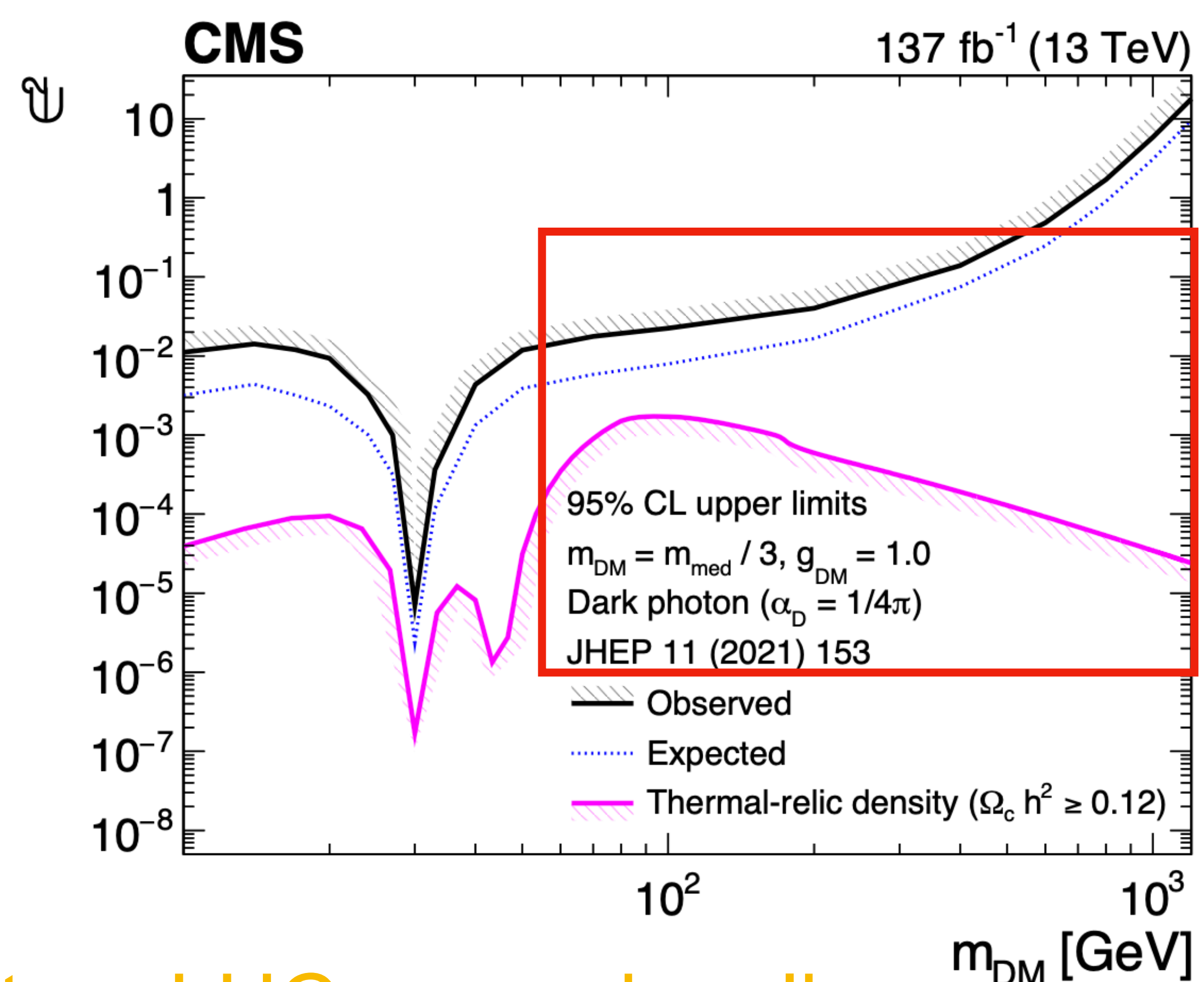
Translating to Dark Photon

$$g_q \simeq \epsilon e \frac{1}{\cos^2\theta_W} \frac{1}{1-\Delta_Z}\left(\sqrt{\langle Q^2\rangle}\cos^2\theta_W + \Delta_z\sqrt{\langle Y^2\rangle}\right)$$

$$\langle Q^2\rangle = 0.3 \text{ and } \langle Y^2\rangle \approx 0.7 \qquad \Delta_Z = (m_{Z'}/m_Z)^2$$

Heavy Dark Photons

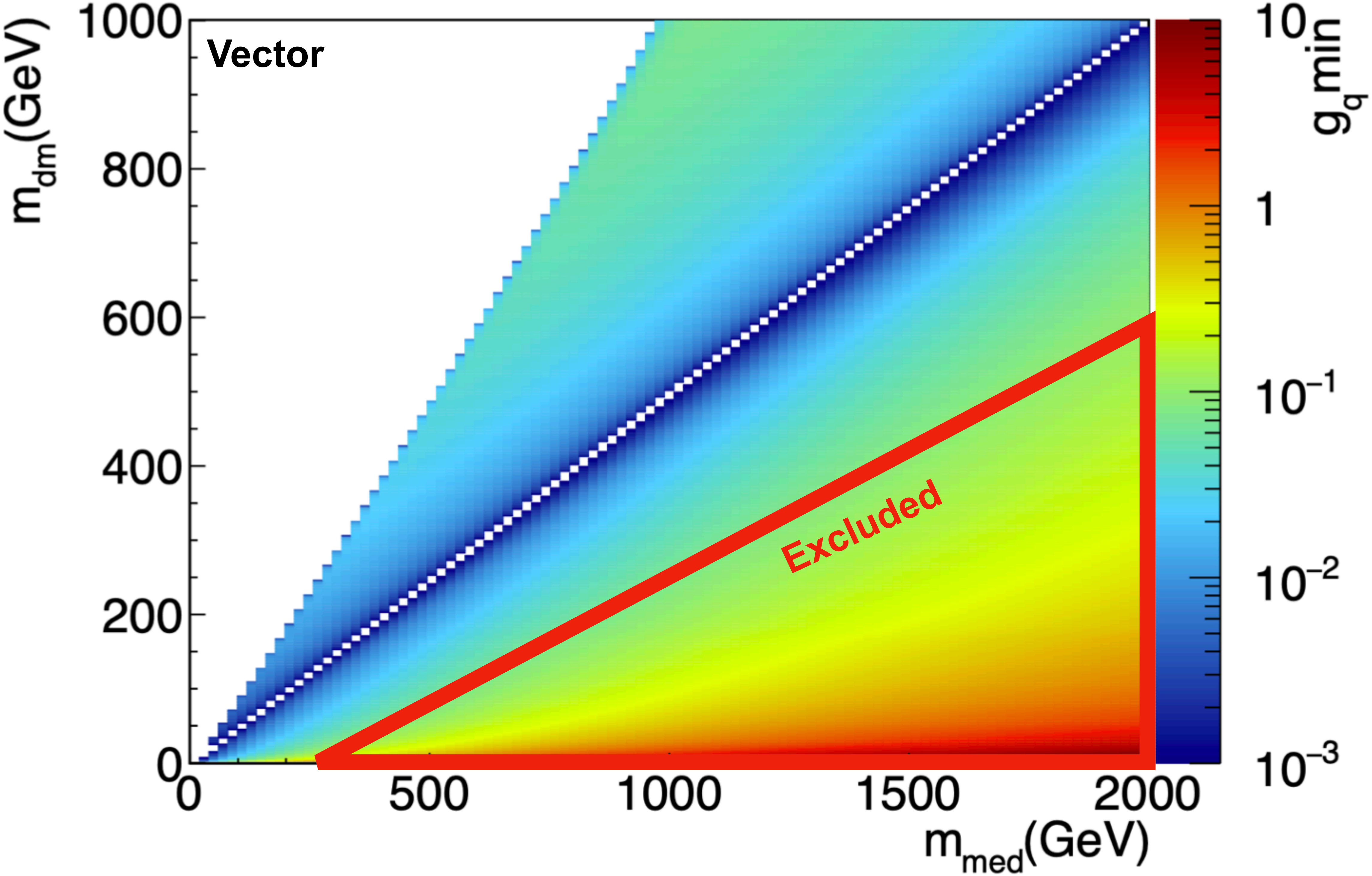




https://arxiv.org/abs/2107.13021

Future LHC exceeds relic

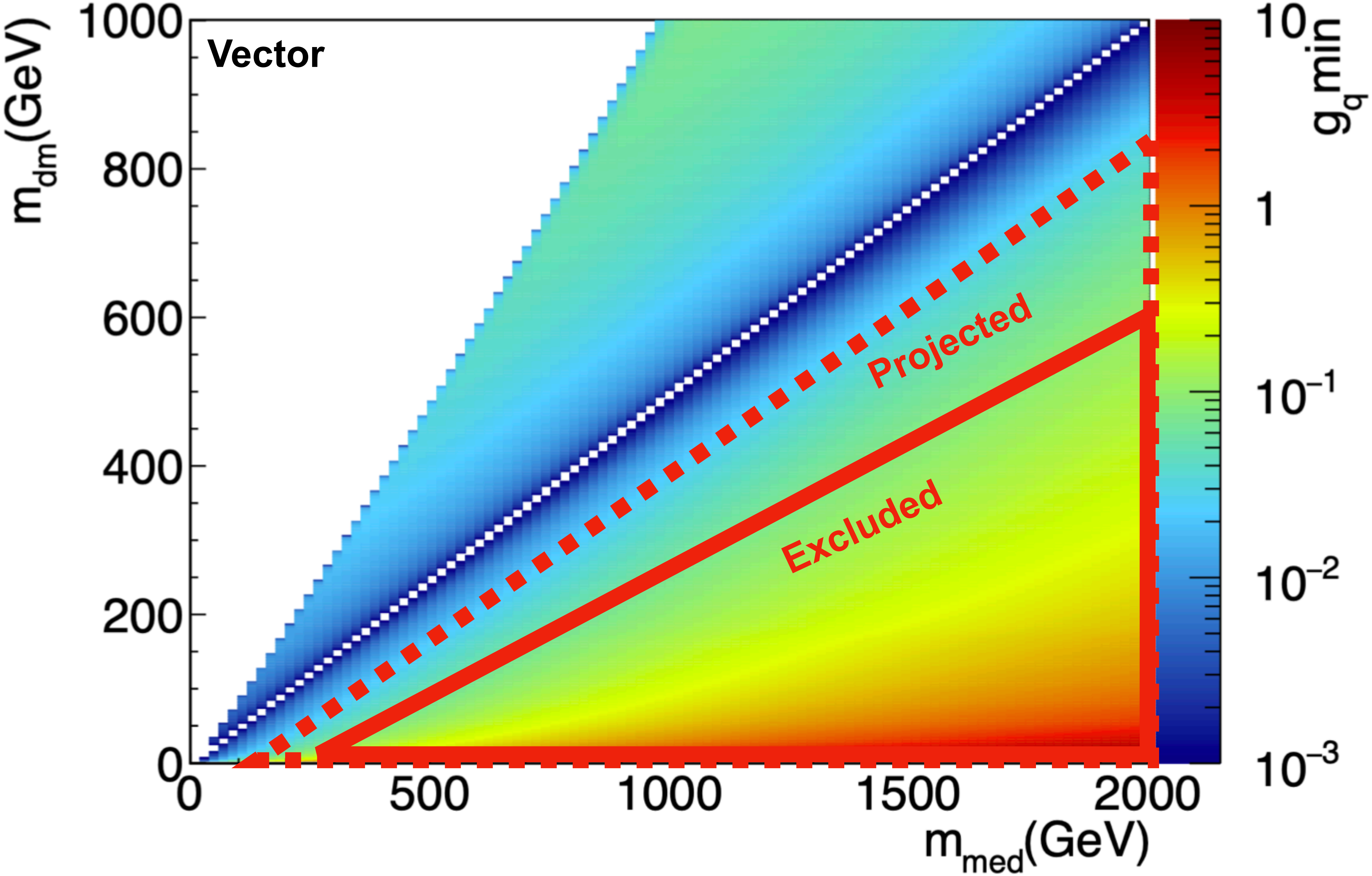
Min Coupling For Relic



arxiv:2203.12035

LHC already excludes $g_q > 0.1$

Min Coupling For Relic



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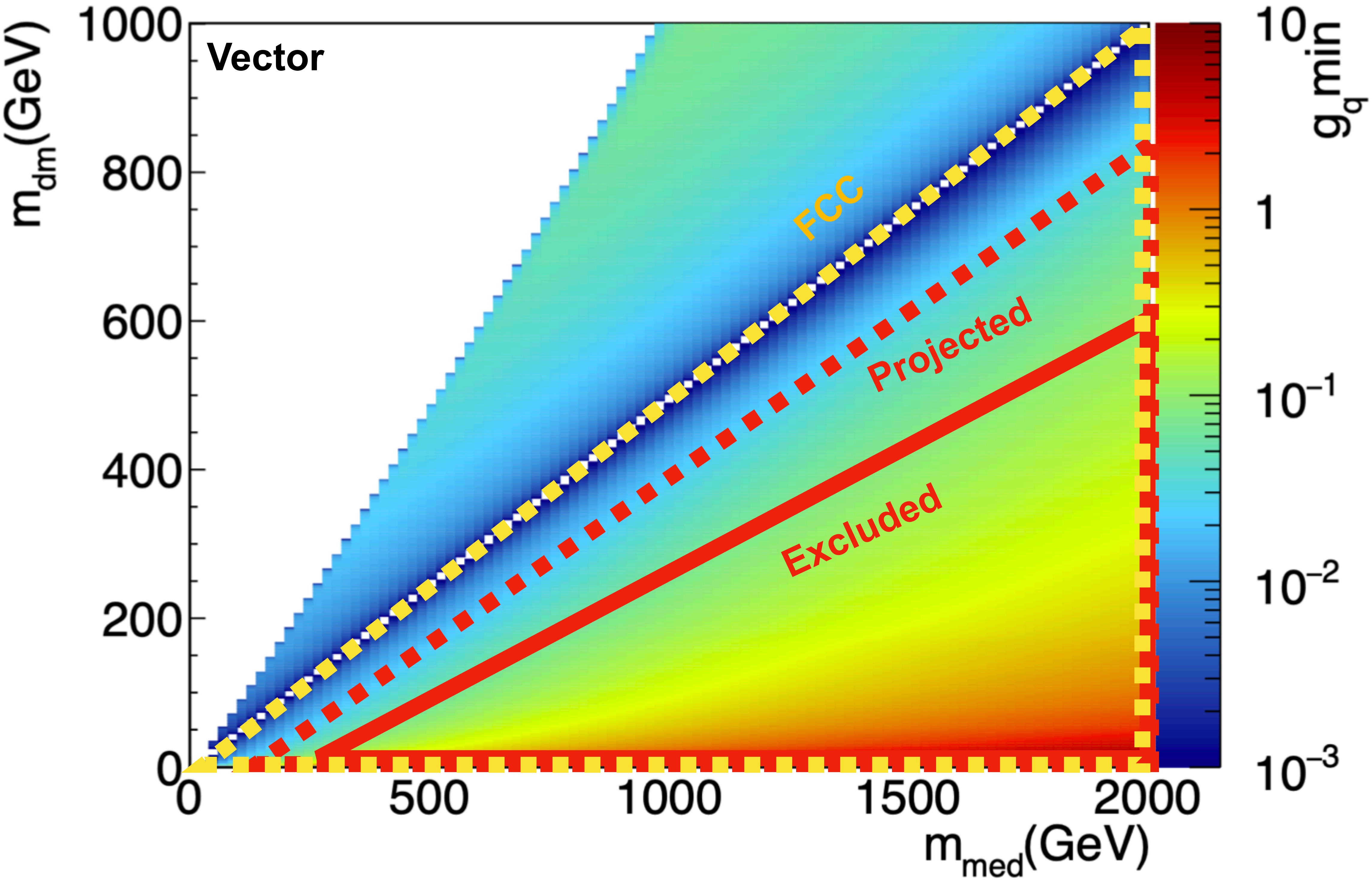

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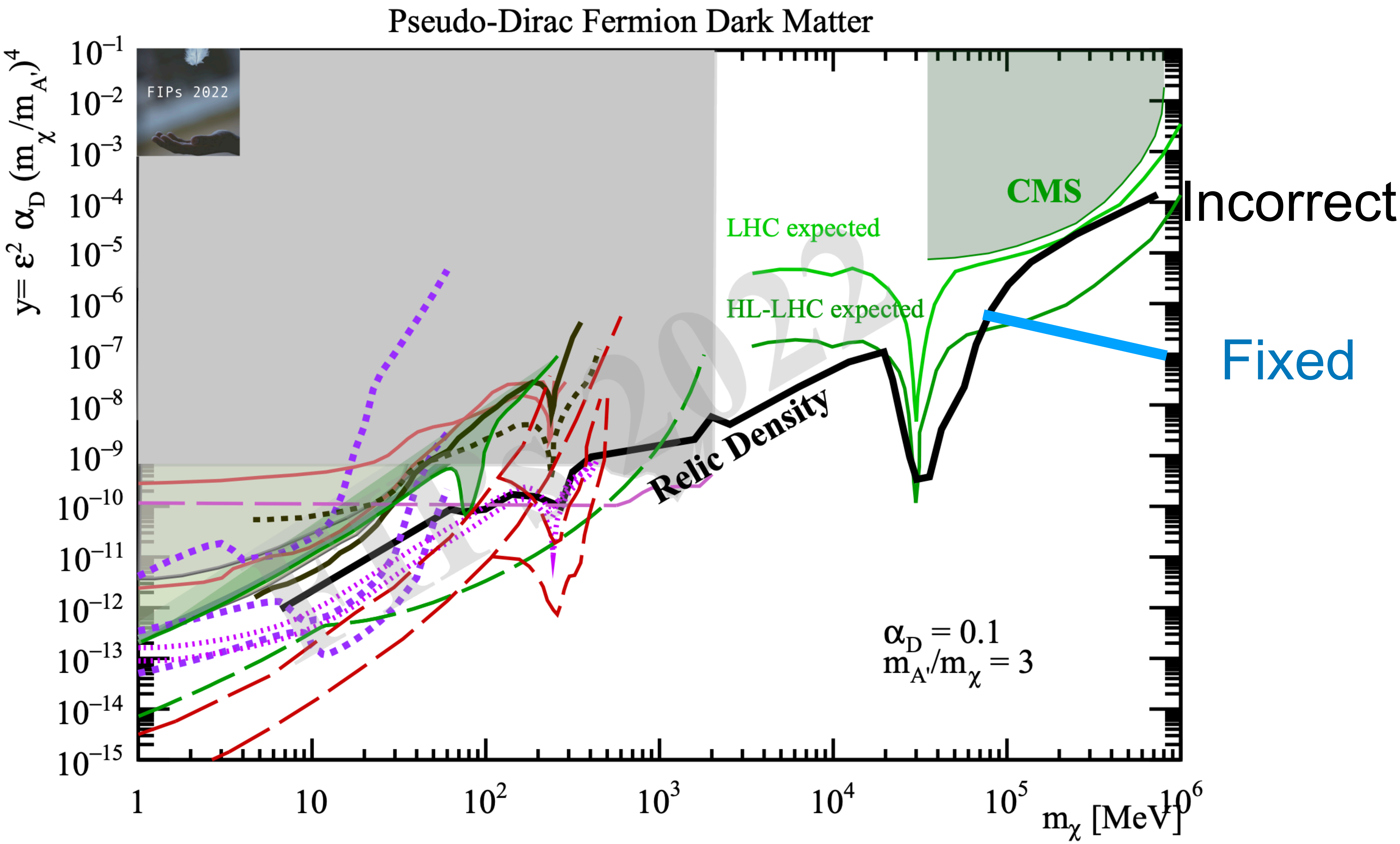
LHC already excludes $g_q > 0.1$

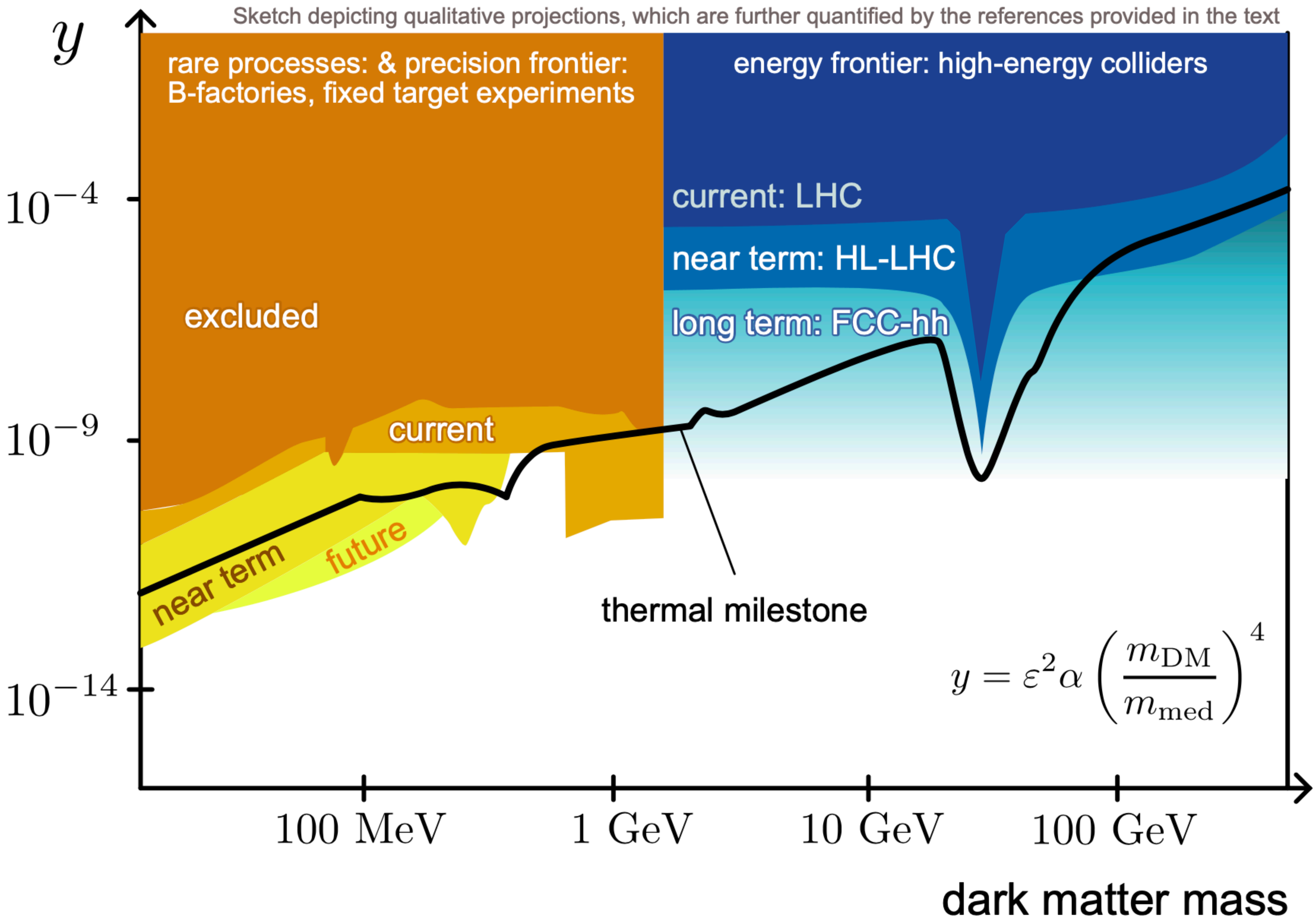
Connecting with low mass



LHC goes left when mediator mass gets larrger

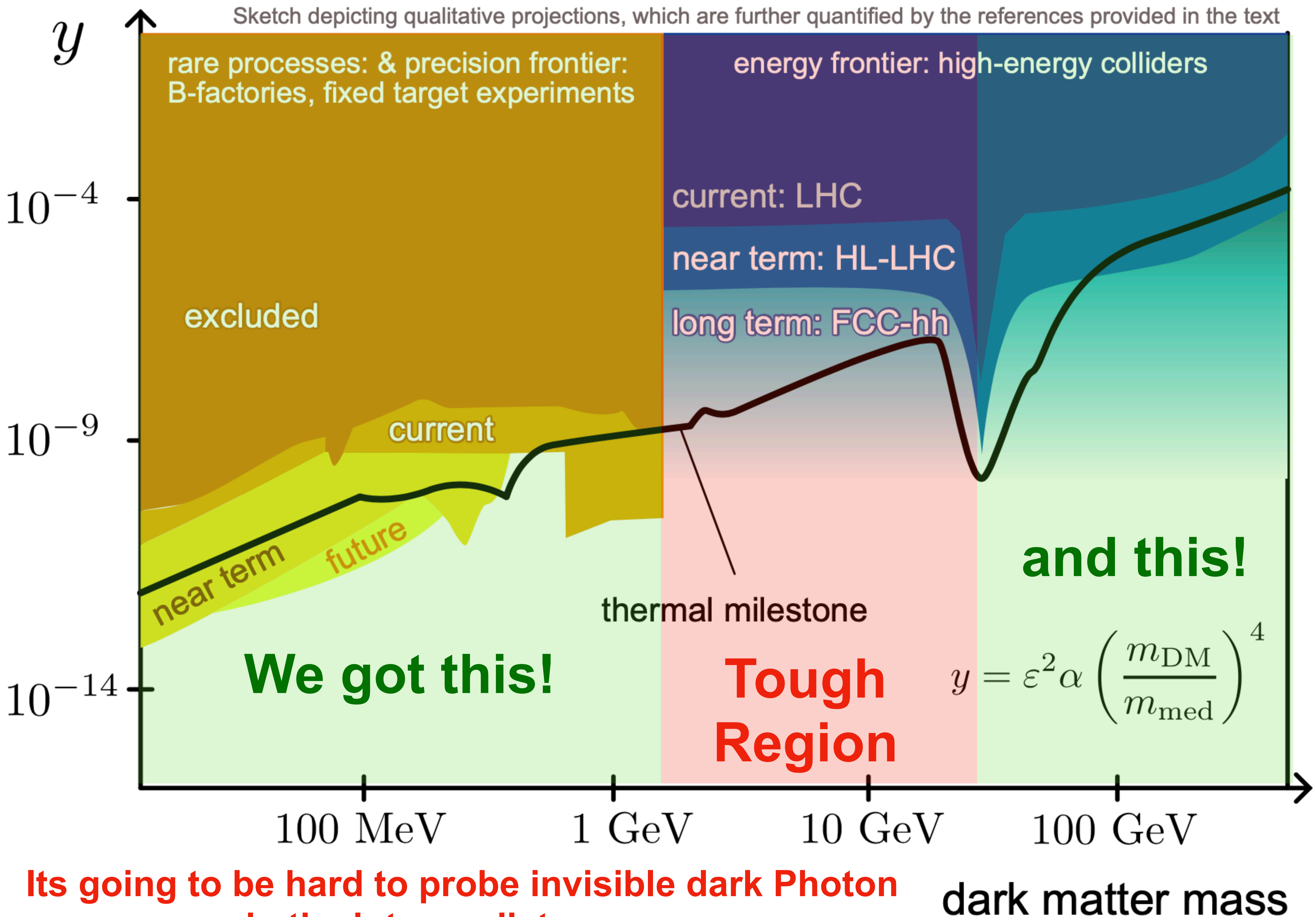
Note Also that as $\frac{m_{DM}}{m_{med}}$ gets larger LHC DM searches are the only game in town

A Nicer Plot



arxiv:2210.01770

A Better Connection



Its going to be hard to probe invisible dark Photon in the intermediate range

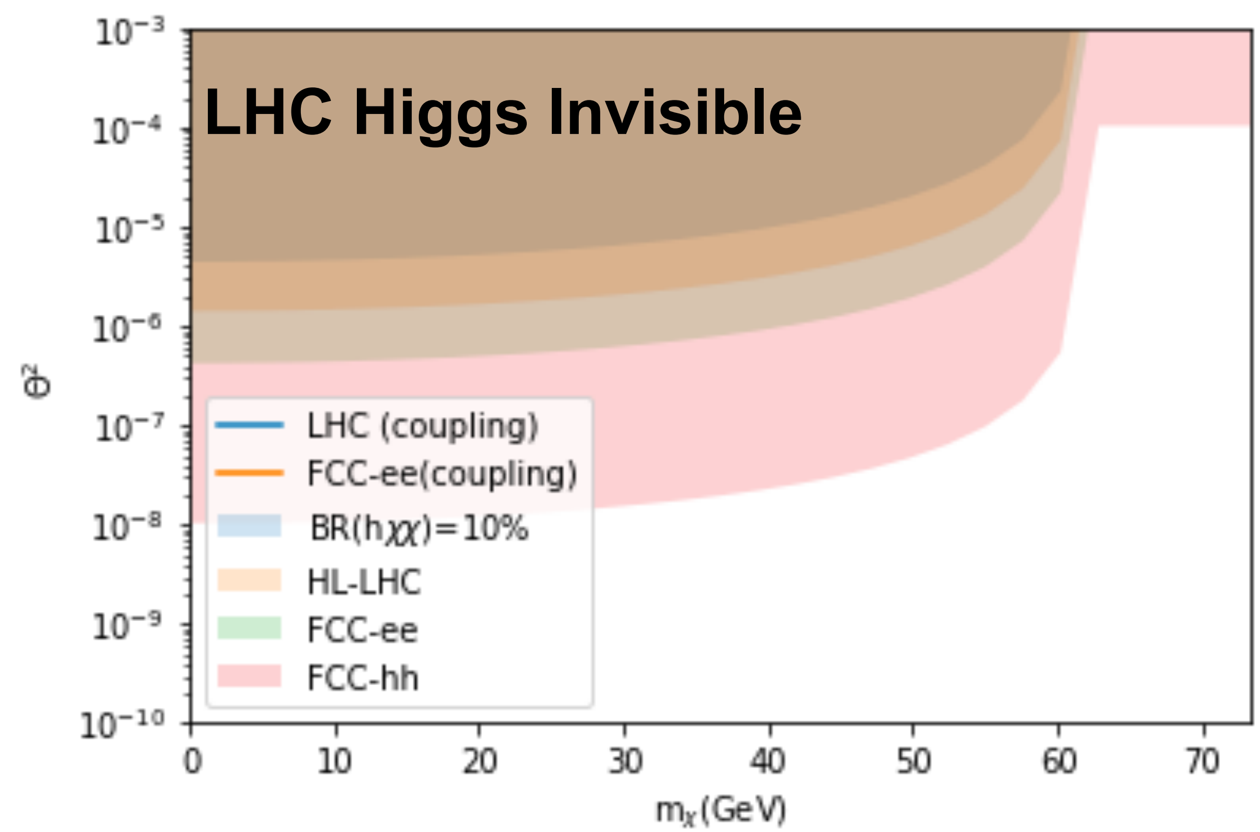
arxiv:2210.01770

Scalar Portal(Dark Higgs)

- In a similar vein we can recast Dark Higgs model to LHC

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

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



- It is hard to have the Dark Higgs model explain DM (Natalia's talk)
  - Requires a very large coupling to satisfy relic

Scalar Portal(Dark Higgs)

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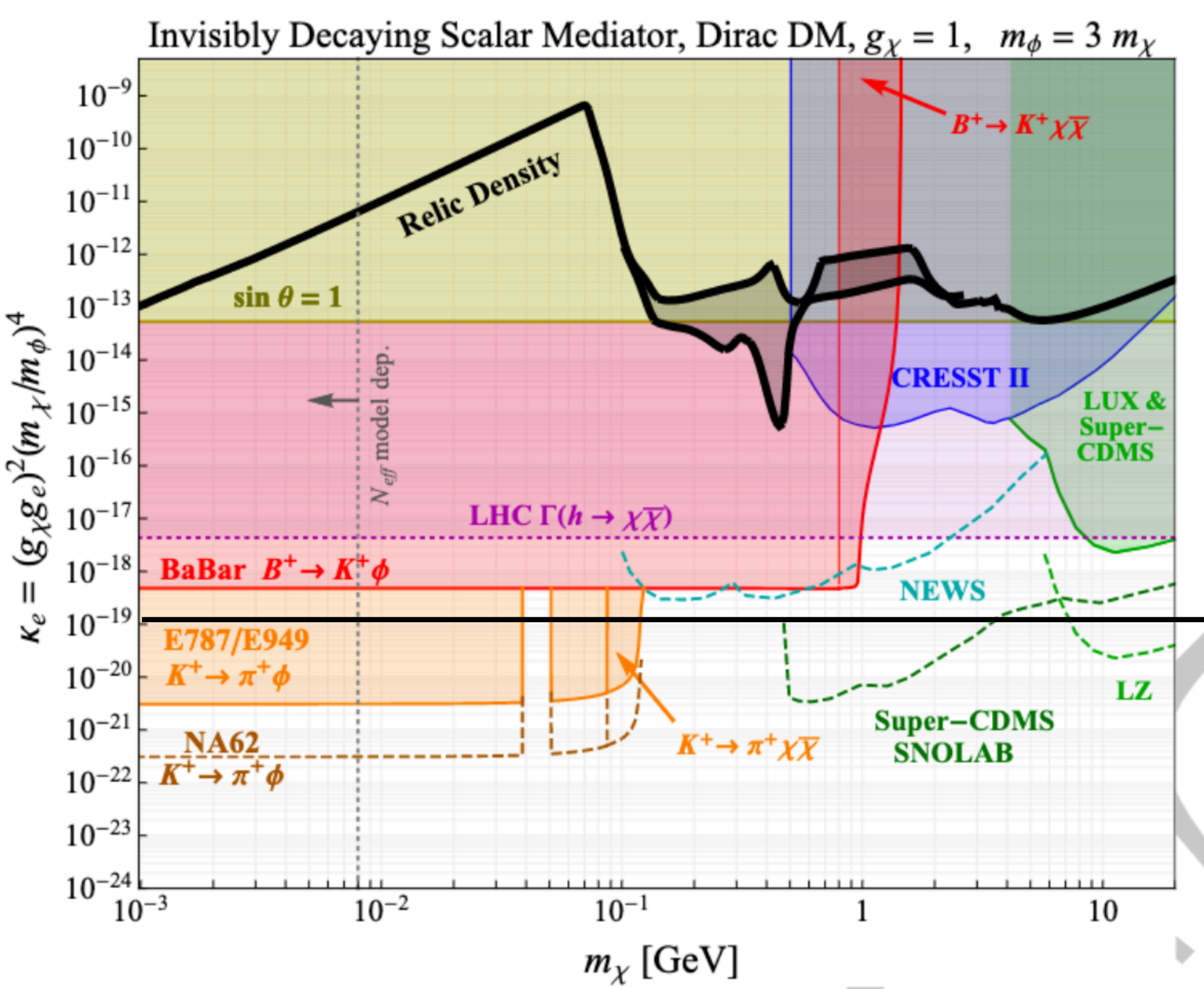
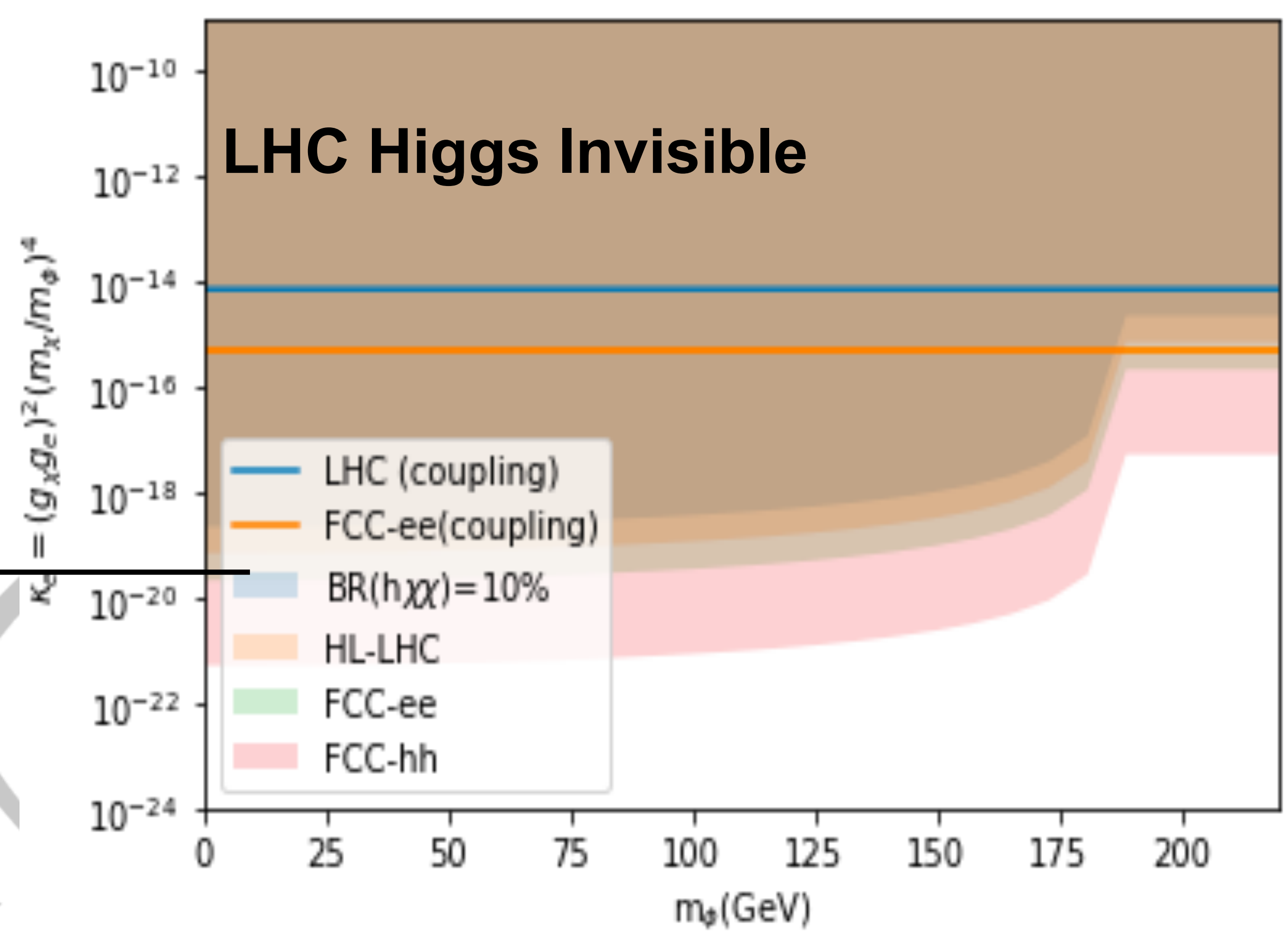


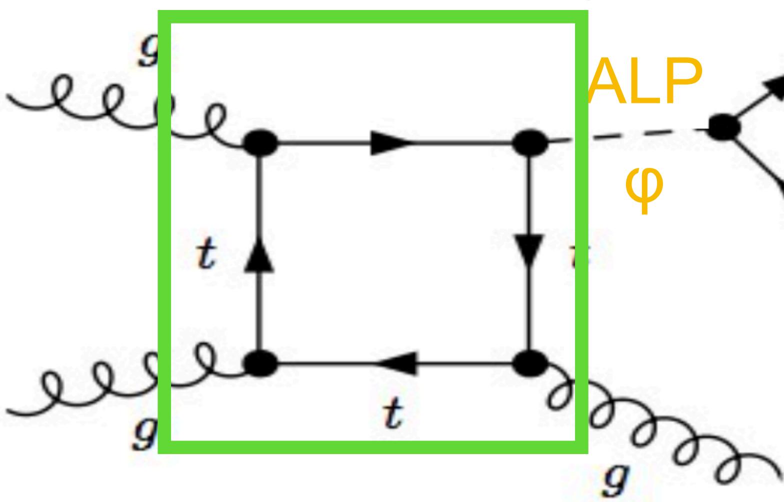


arxiv:2206.03456

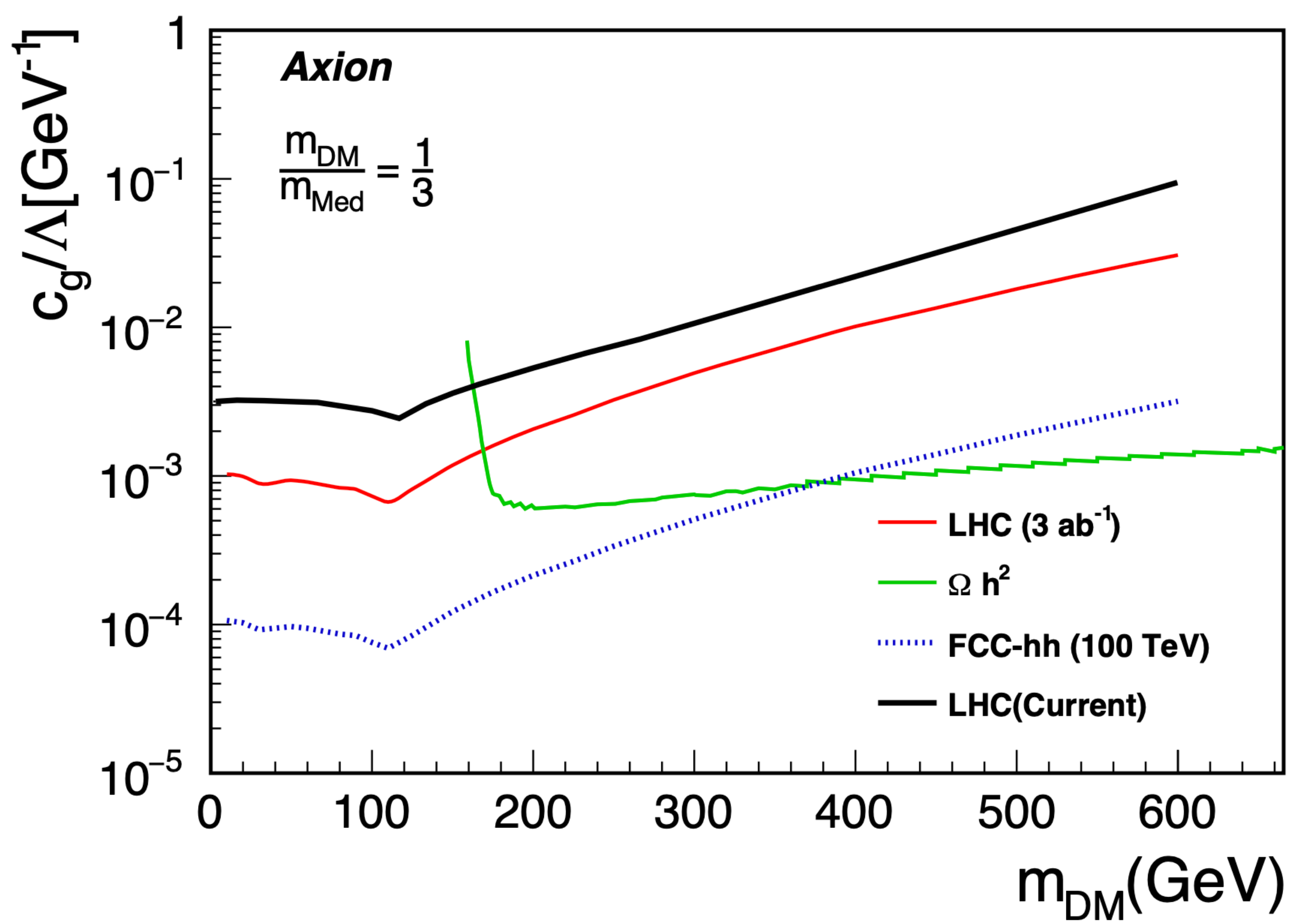
Axion Portal

- The Axion portal decaying to invisible particles
  - Generally less explored
  - We can again recast existing LHC bounds to this
- The simplest model requires a heavy mediator to reconcile relic

Just Gluon Coupling

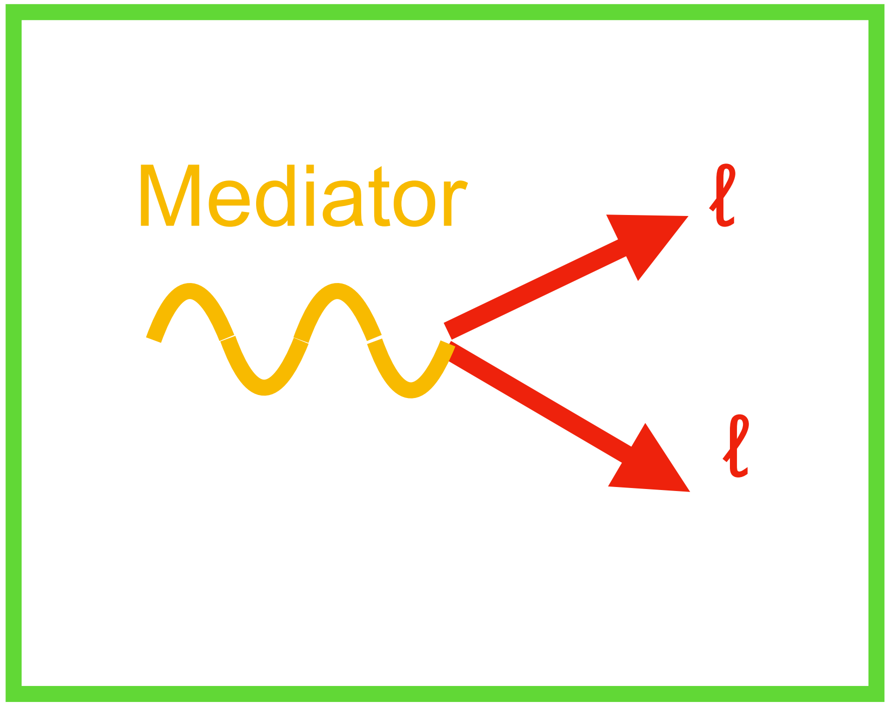


Axion, a $\quad \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$ $\quad \frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$

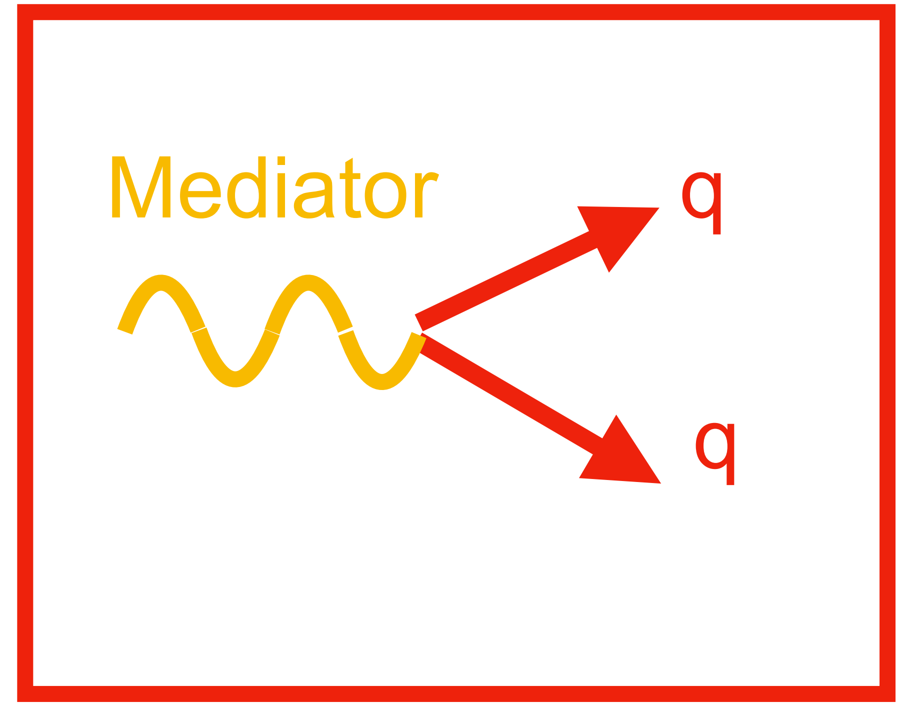


arxiv:2206.03456

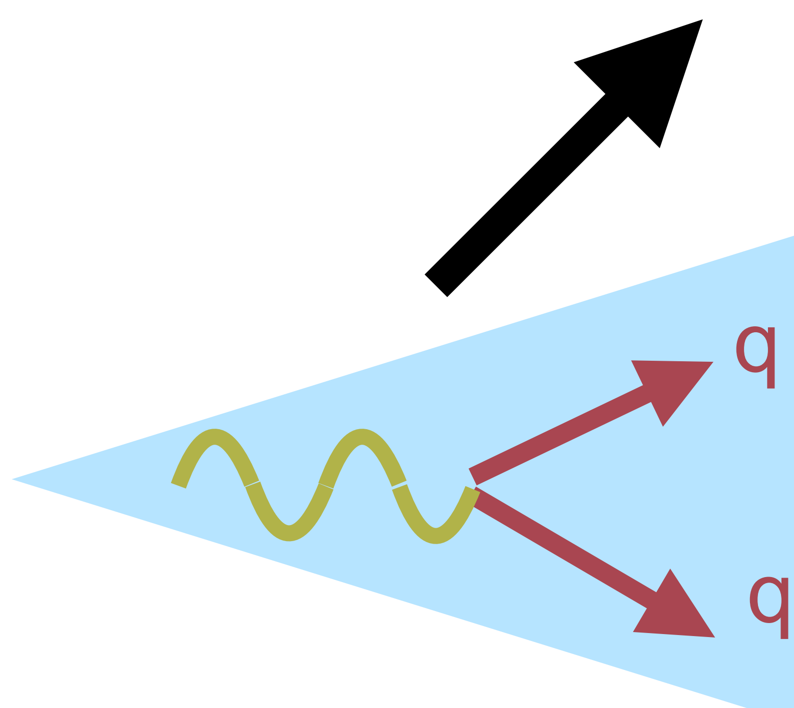
Visible Searches



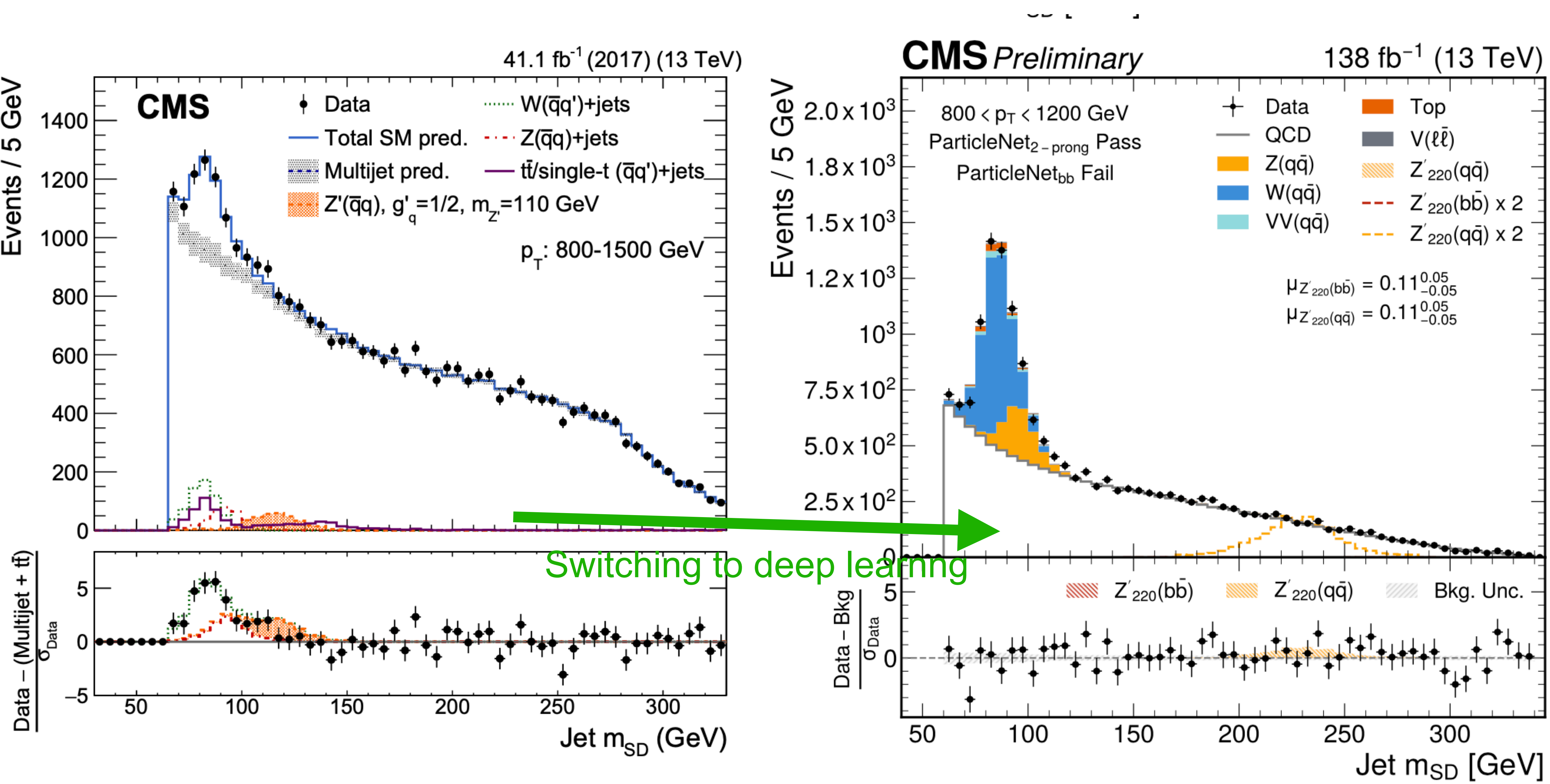
LHC Produces a huge number of leptons



This is very hard but we still do it

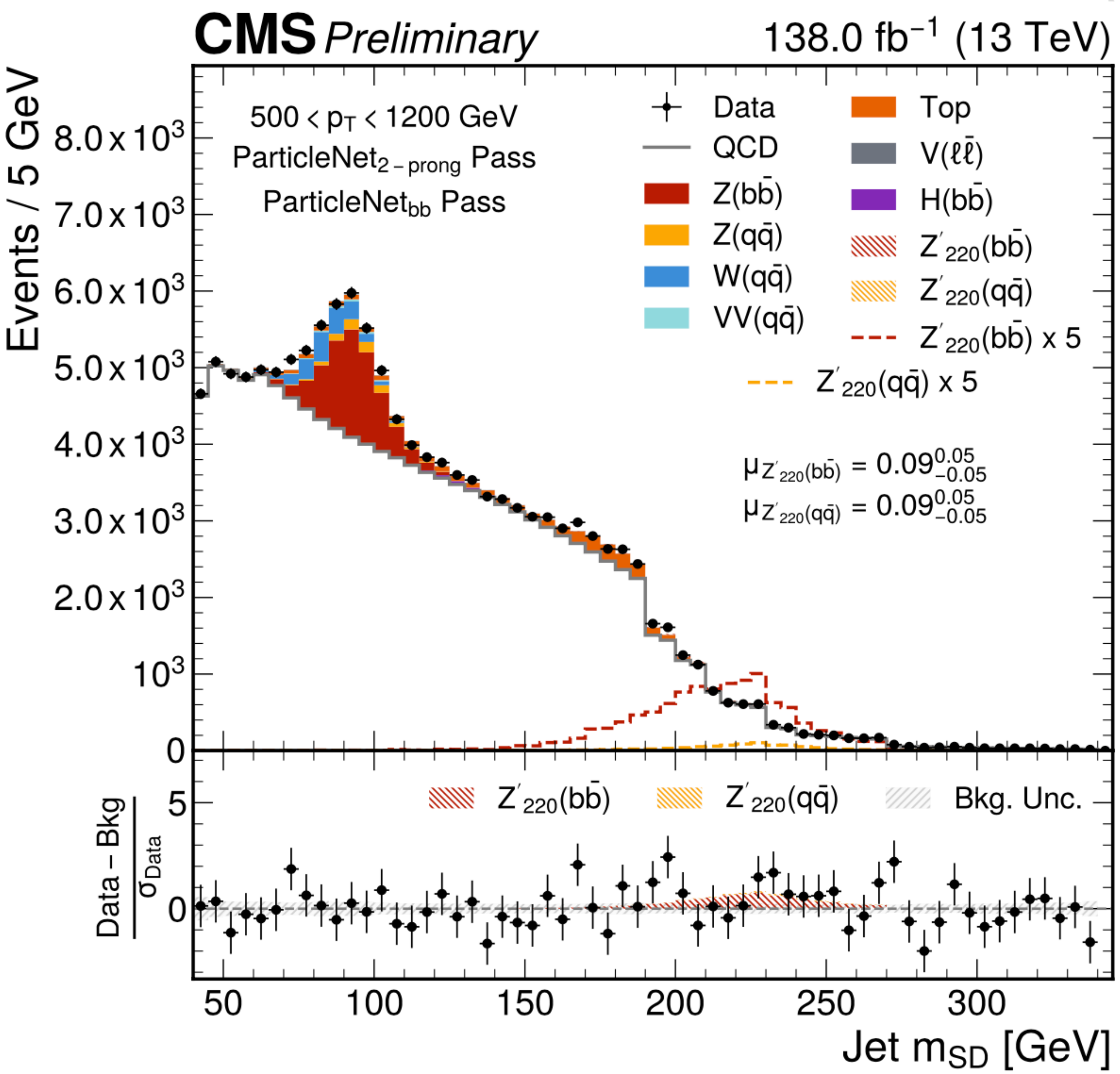


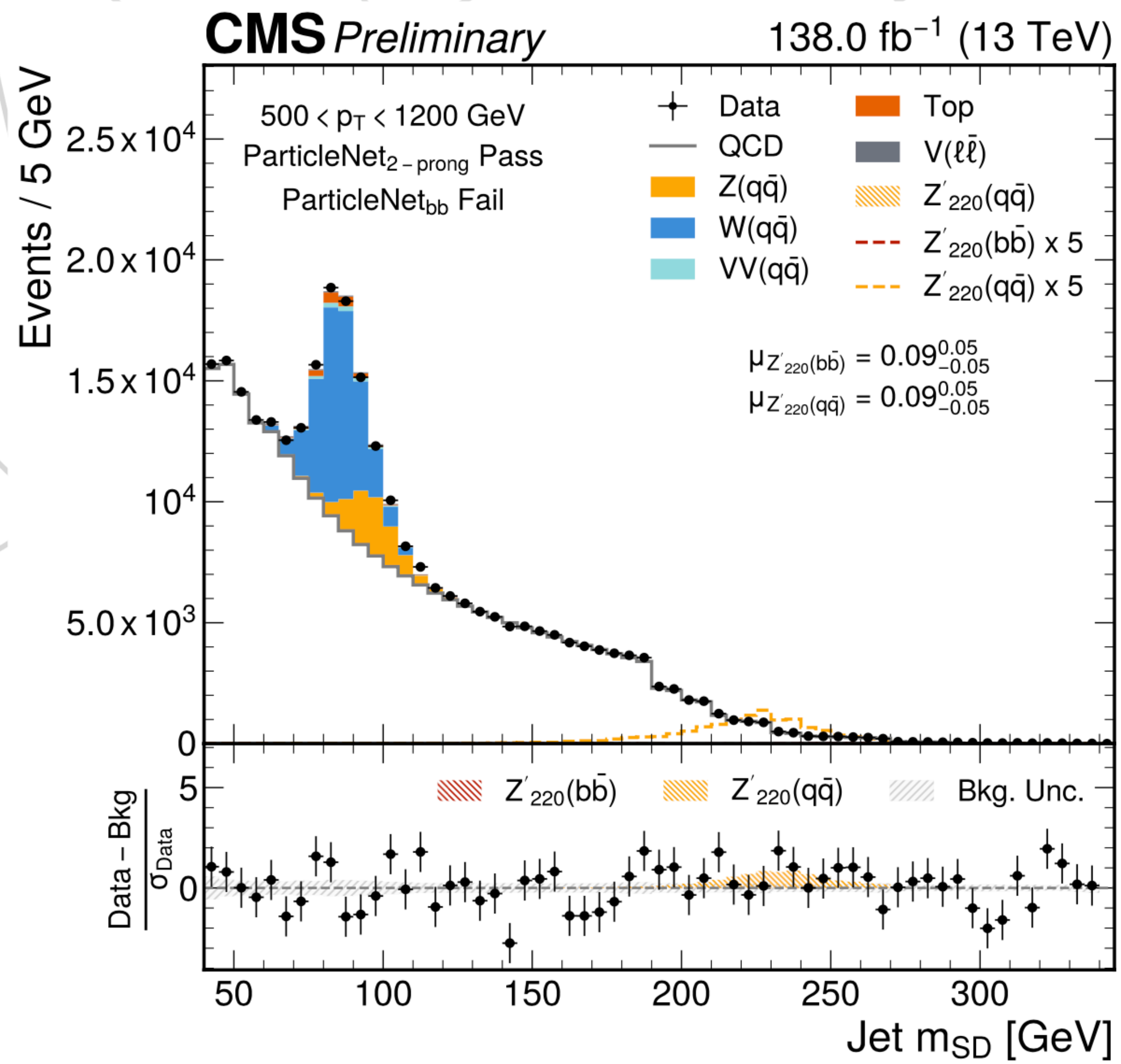
Resonant Serches



This work highlights the power of deep learning

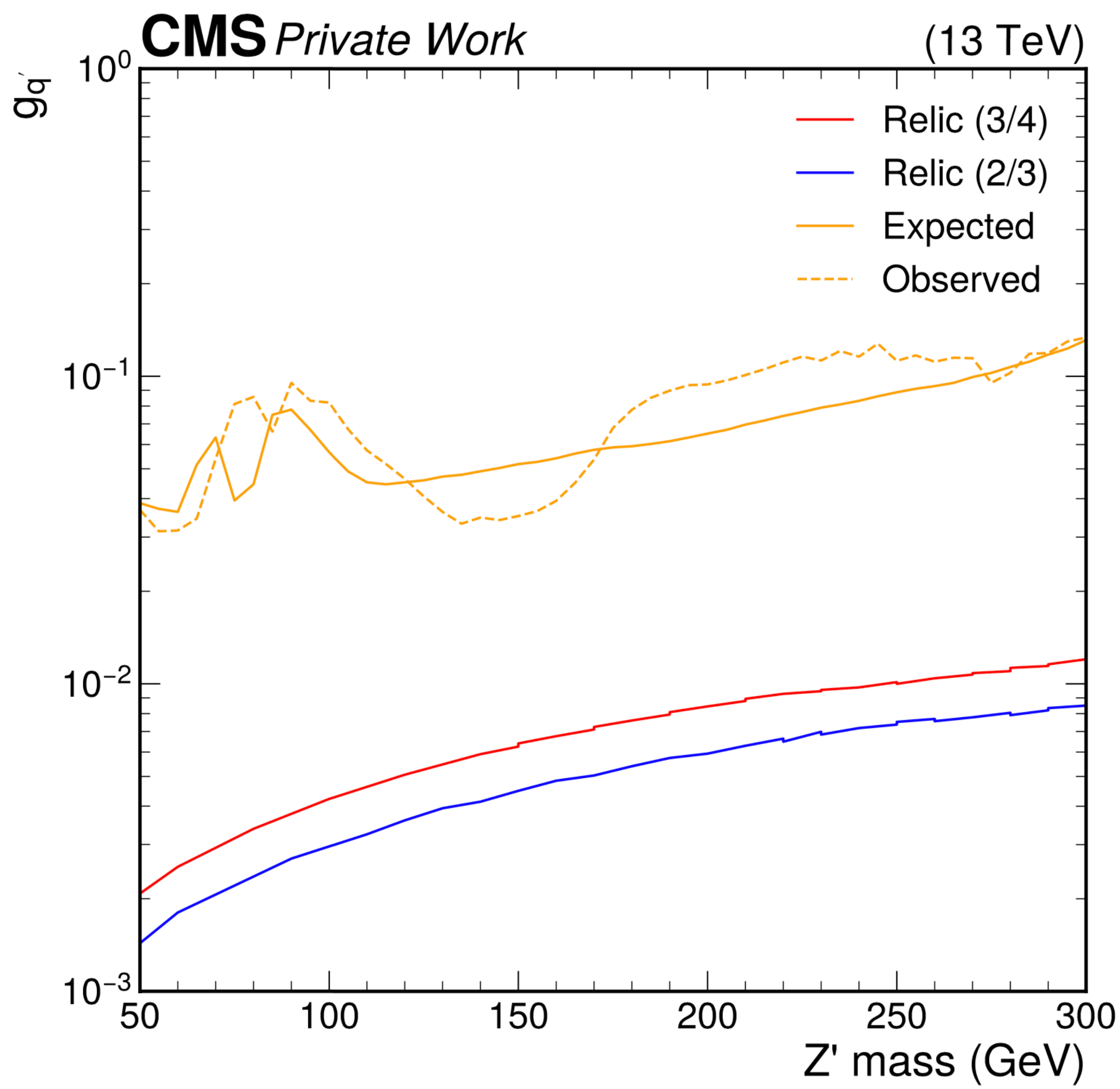
The Search

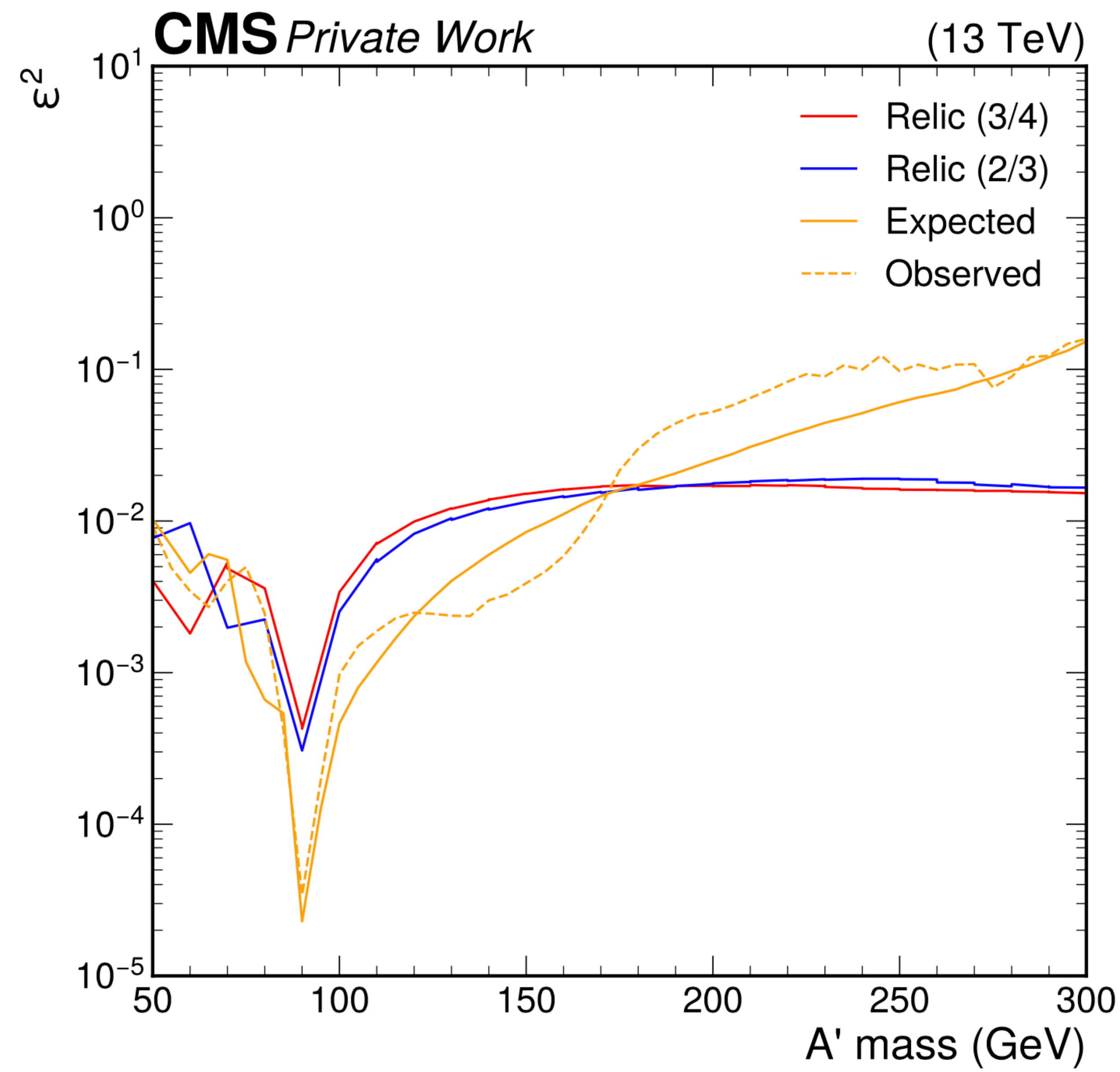




- More Hadronic W bosons here than at LEP
  - These are very highly boosted

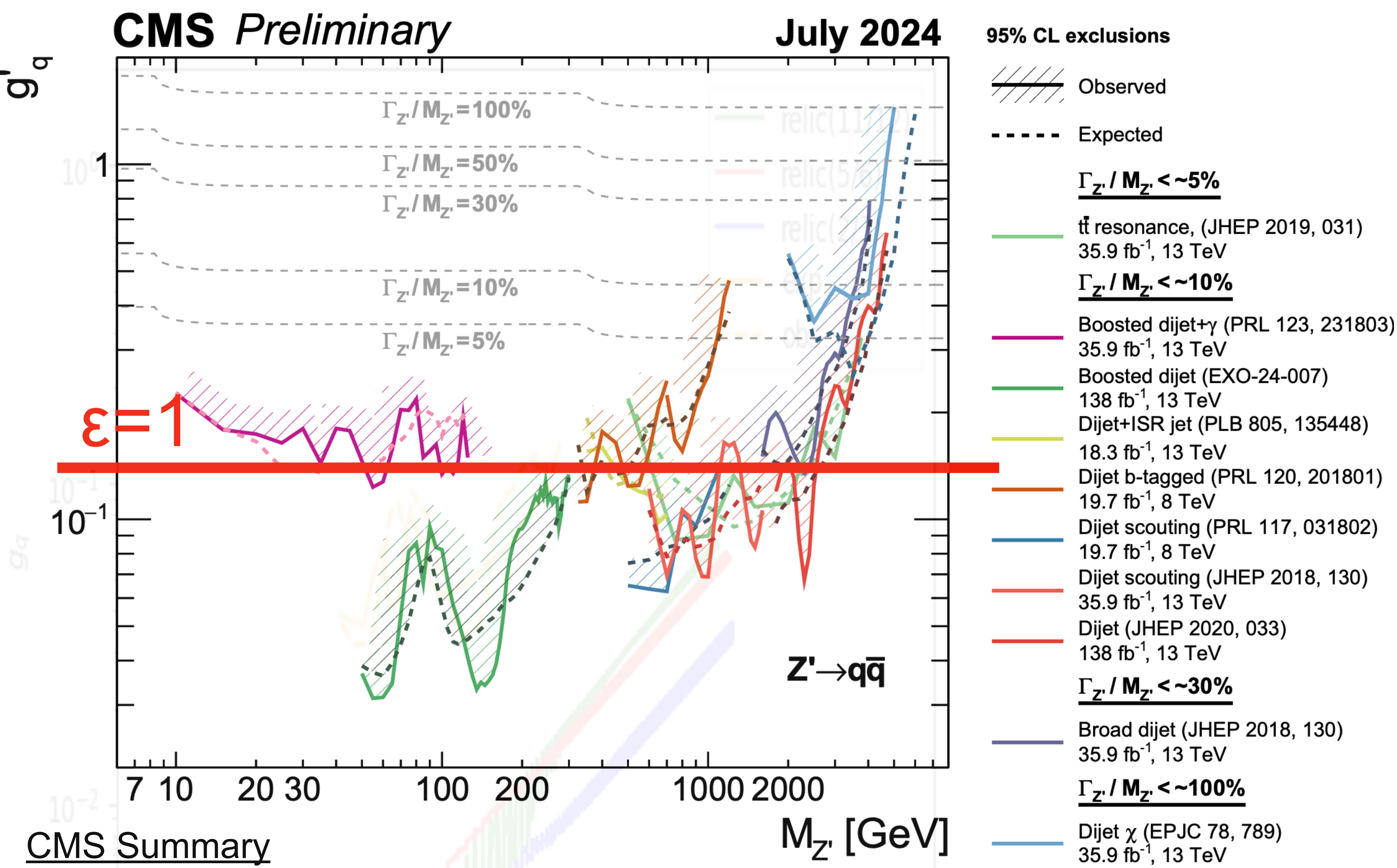
Comparison w/dark sector





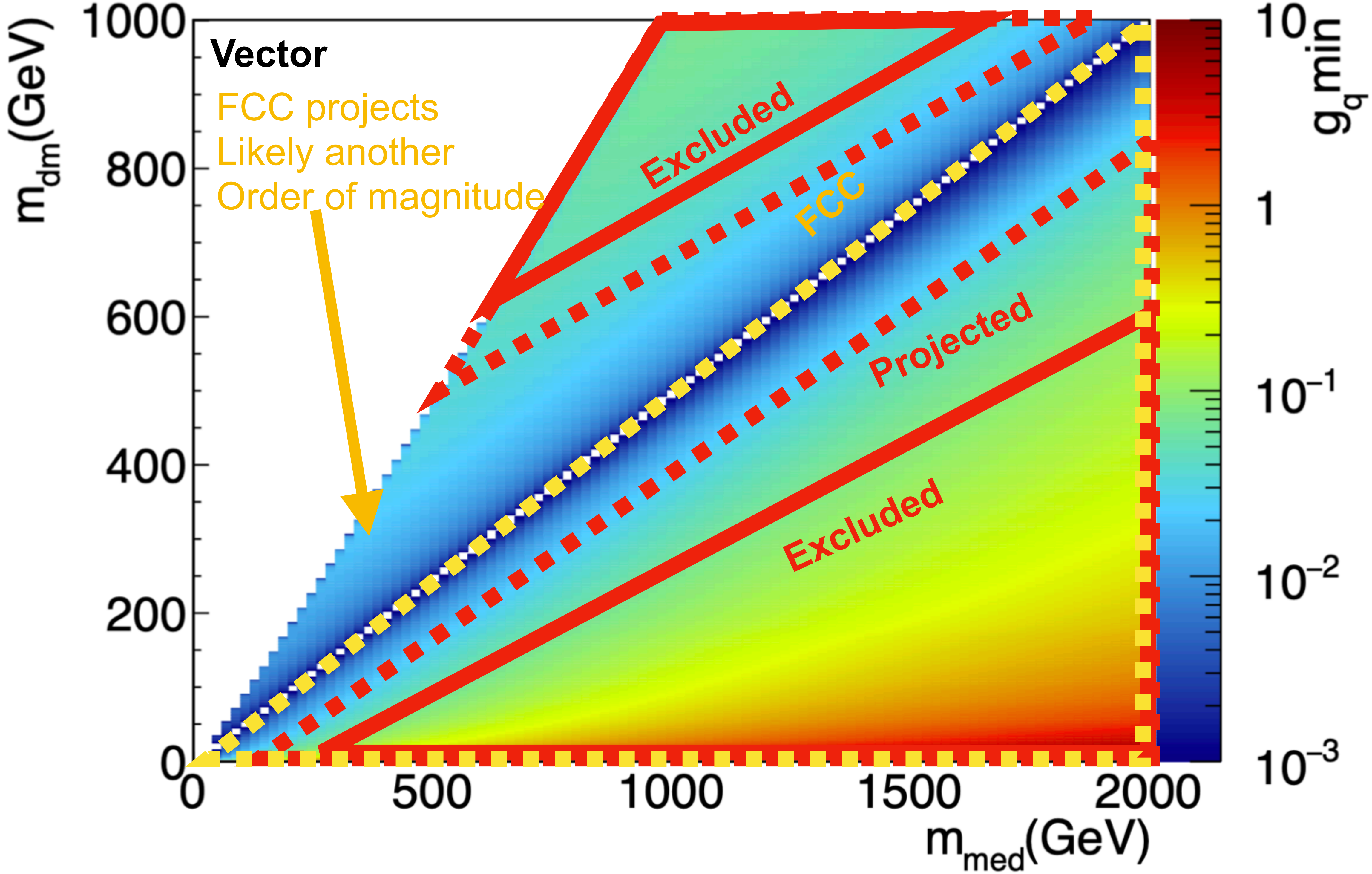
- Significant constraints that start to approach interesting regions
  - Relic density is just a motivator here, its not a true benchmark

Just Quark Couplings



CMS Summary

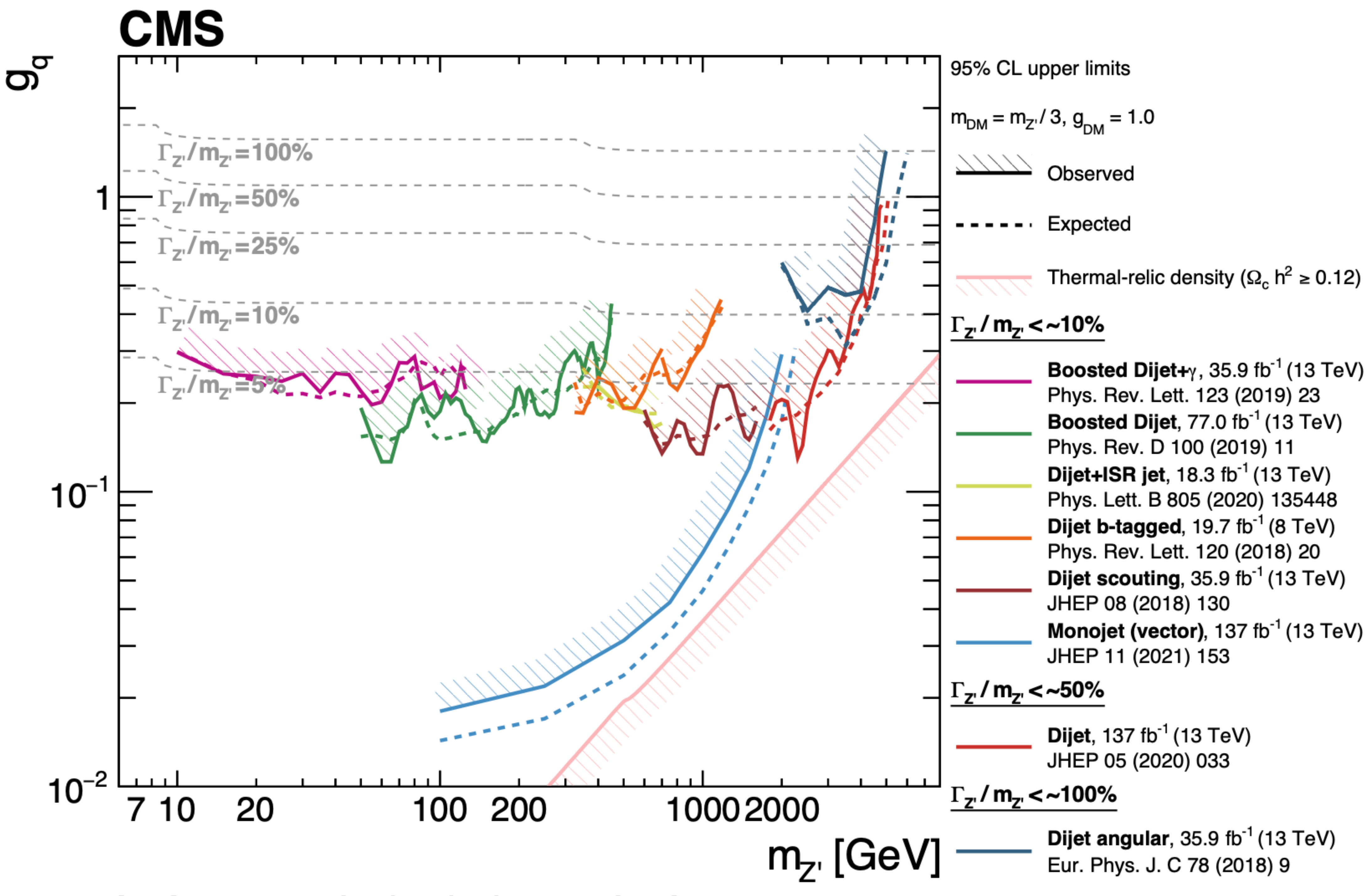
Min Coupling For Relic



arxiv:2203.12035

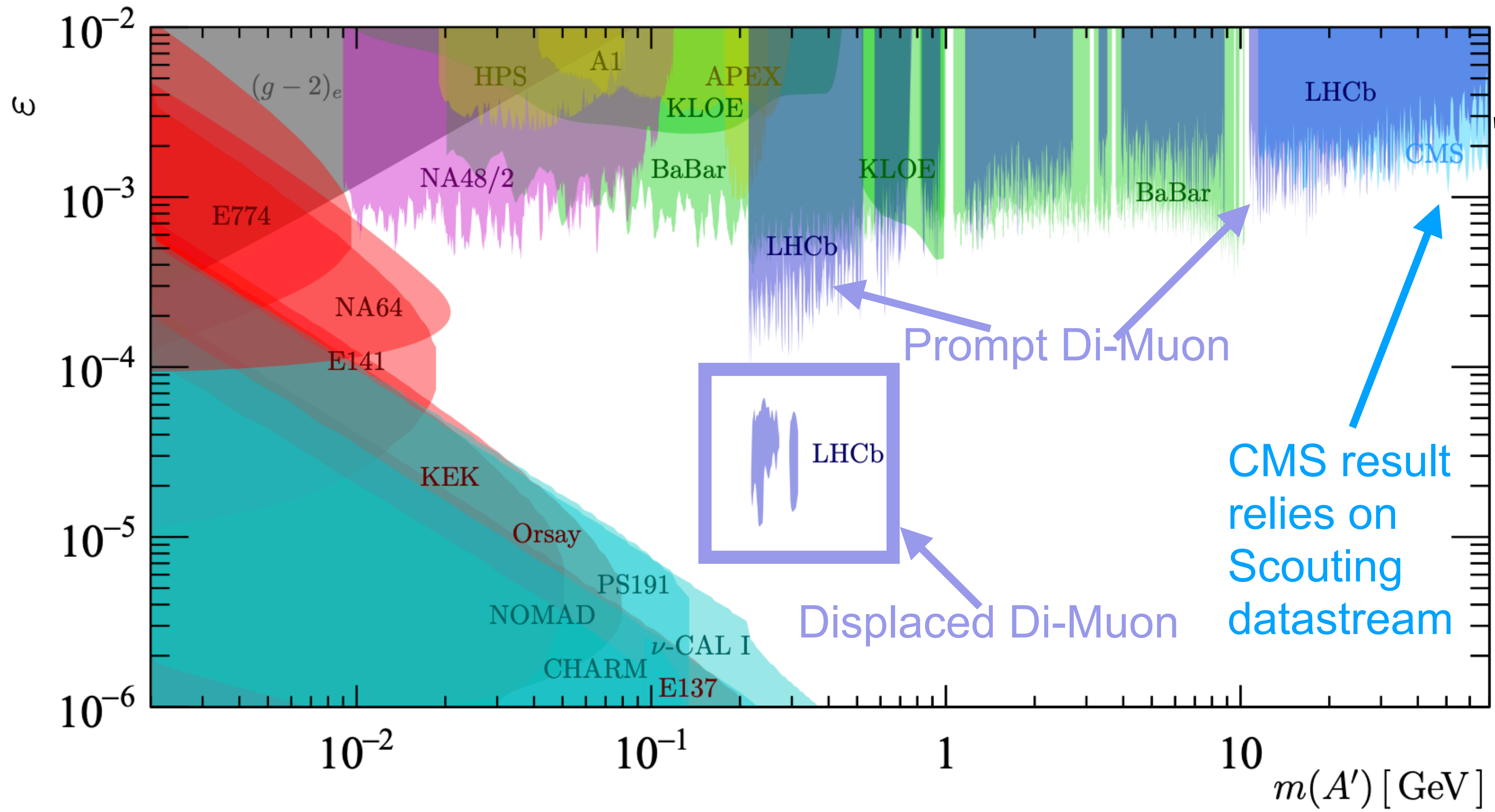
LHC already excludes $g_q > 0.1$

Now considering Invisible



Dark Photons

Visible Dark Photons at High Mass dominated by LHCb+CMS



ATLAS/CMS Traditional Dilepton Results

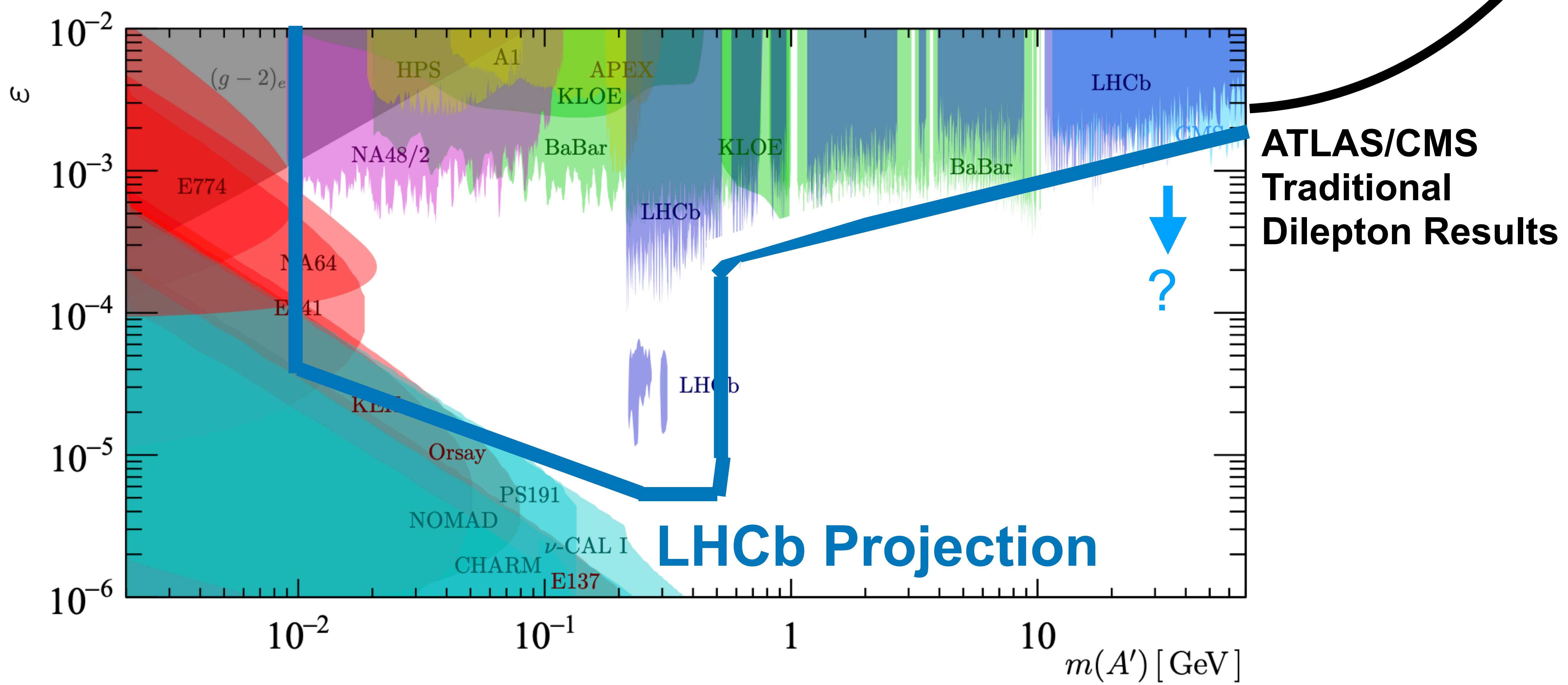
LHCb capable of triggering all di-muons

CMS result relies on innovative Scouting Stream

LHCb ICHEP

Future Dark Photons

Addition of di-electron channel makes LHCb very sensitive



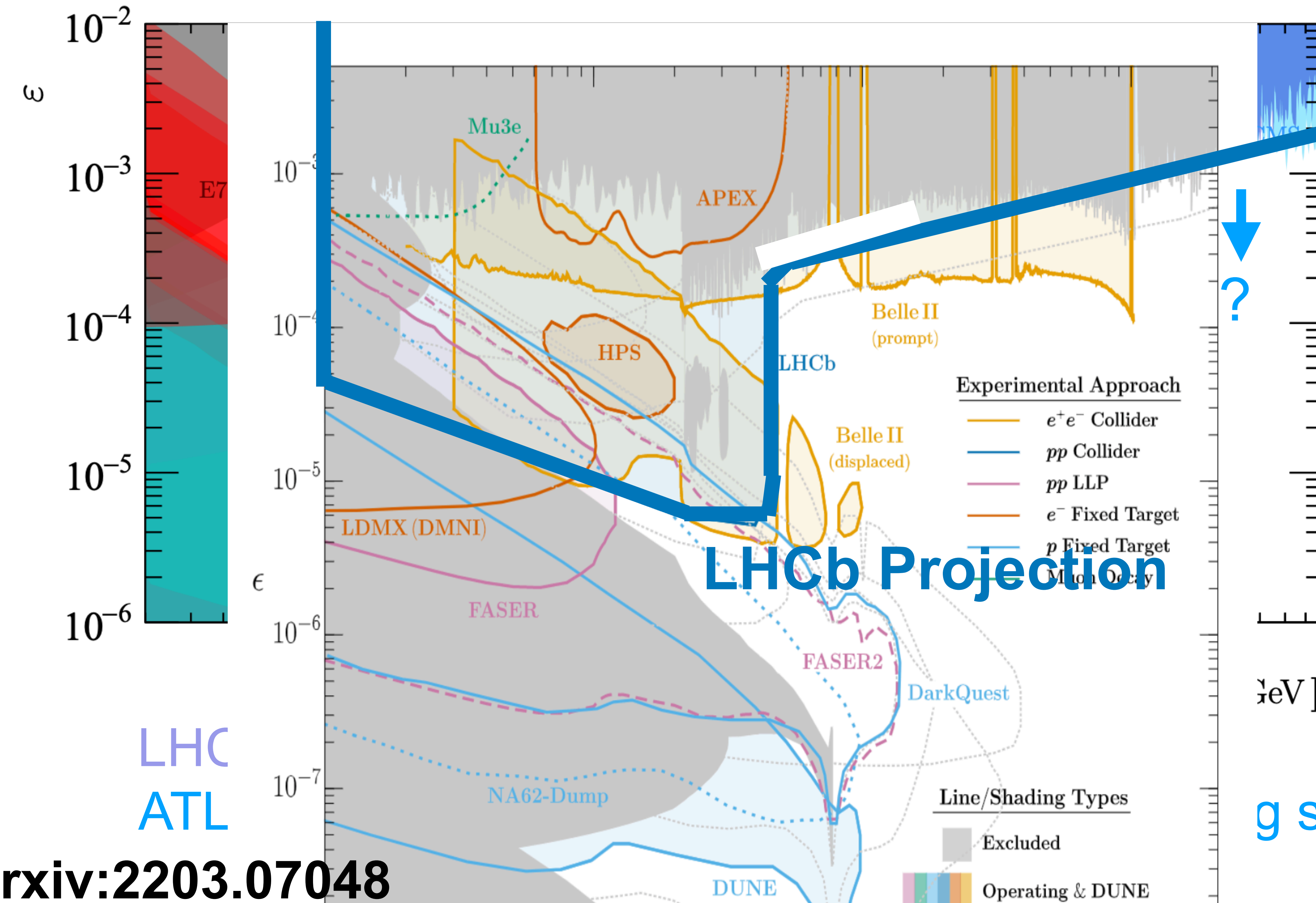
LHCb will add D*⟶A+SM Decys

ATLAS and CMS will have better trigger/scouting systems

arxiv:2203.07048

Future Dark Photons

Addition of di-electron channel makes LHCb very sensitive



ATLAS/CMS Traditional Dilepton Results

LHC

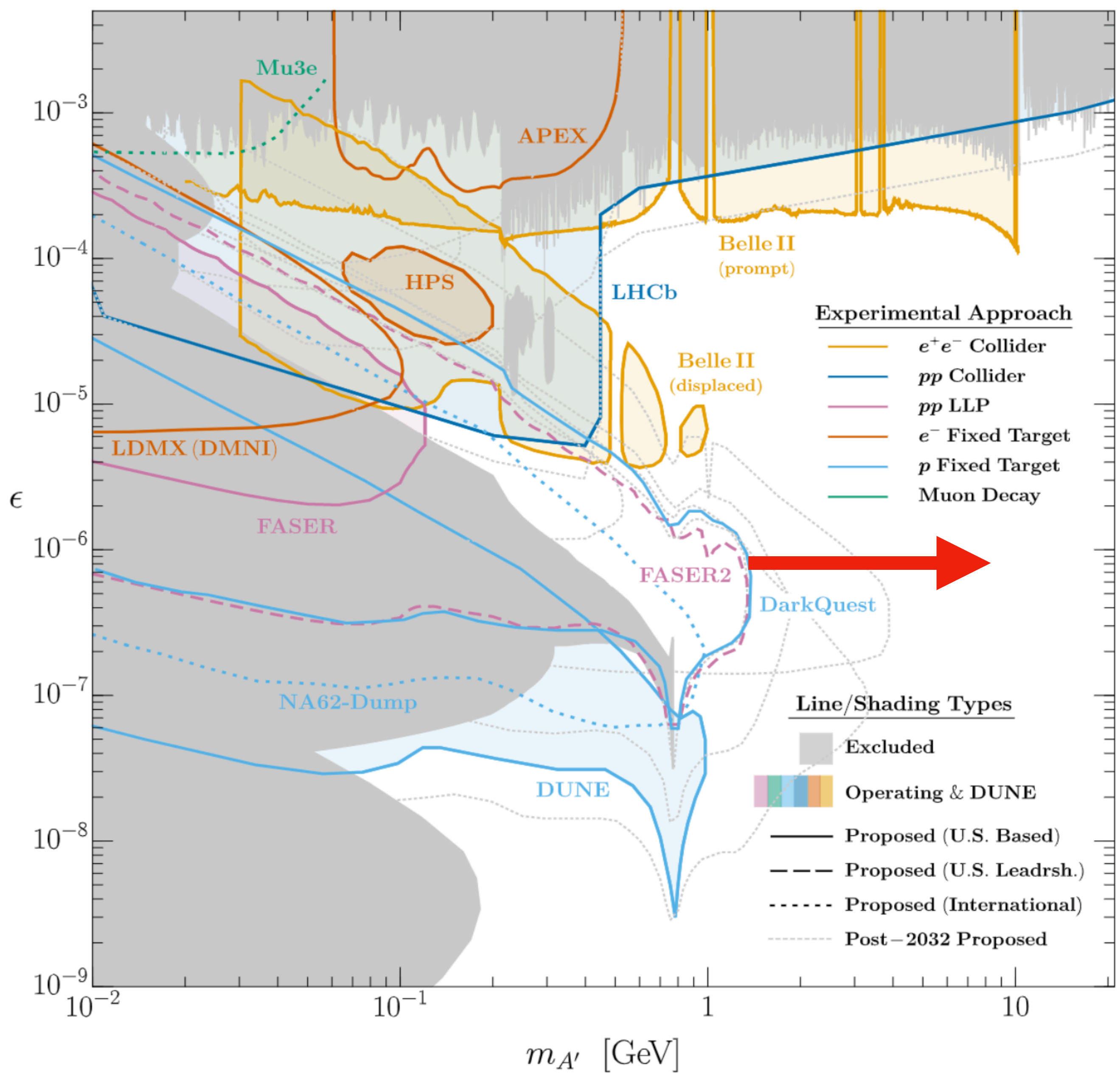
ATL

g systems

arxiv:2203.07048

Future Dark Photons

Addition of di-electron channel makes LHCb very sensitive



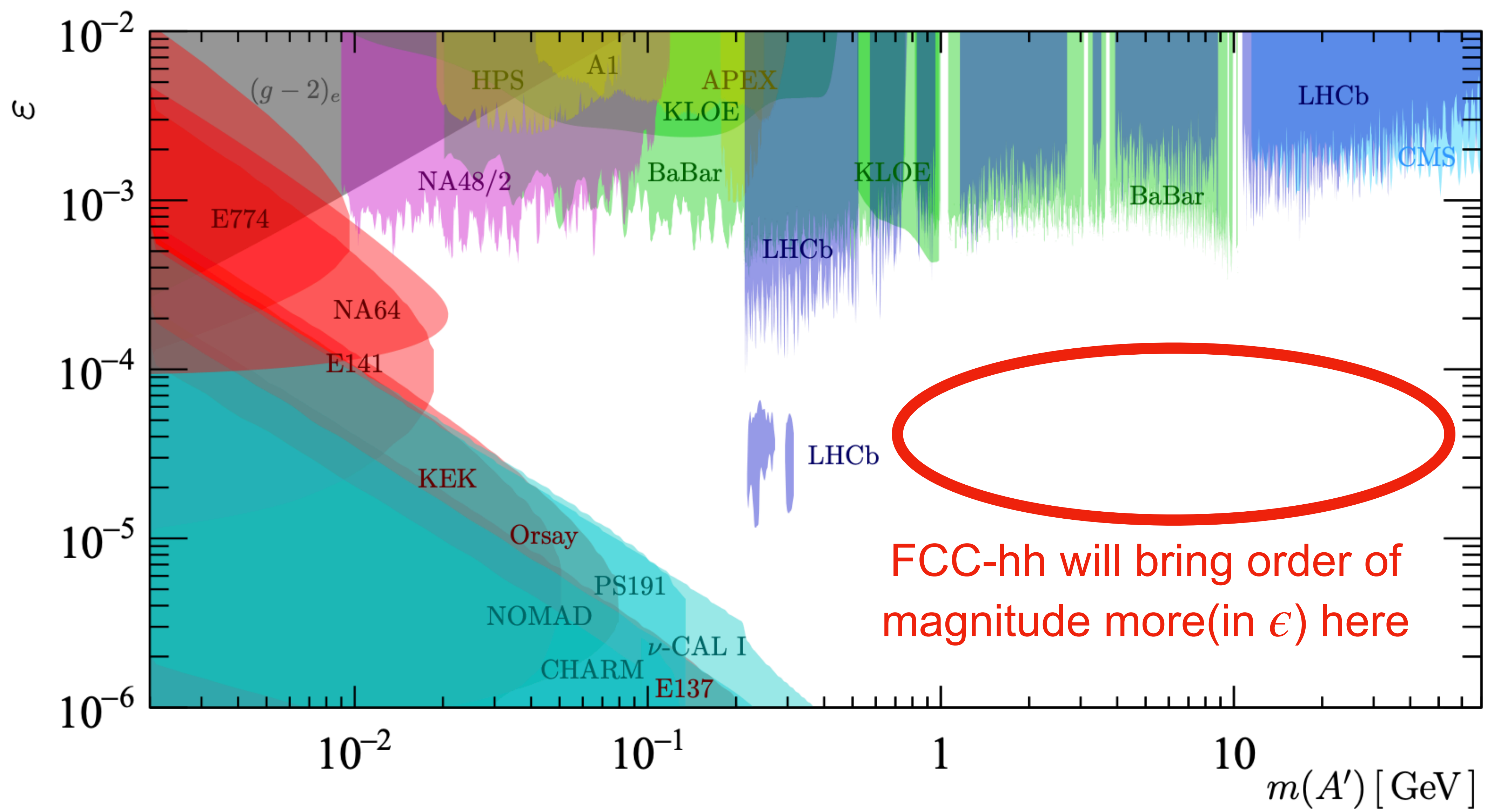
A small coupling is still motivated for heavy Dark Matter and a light mediator

Higher COM beam dumps help here?

arxiv:2203.07048

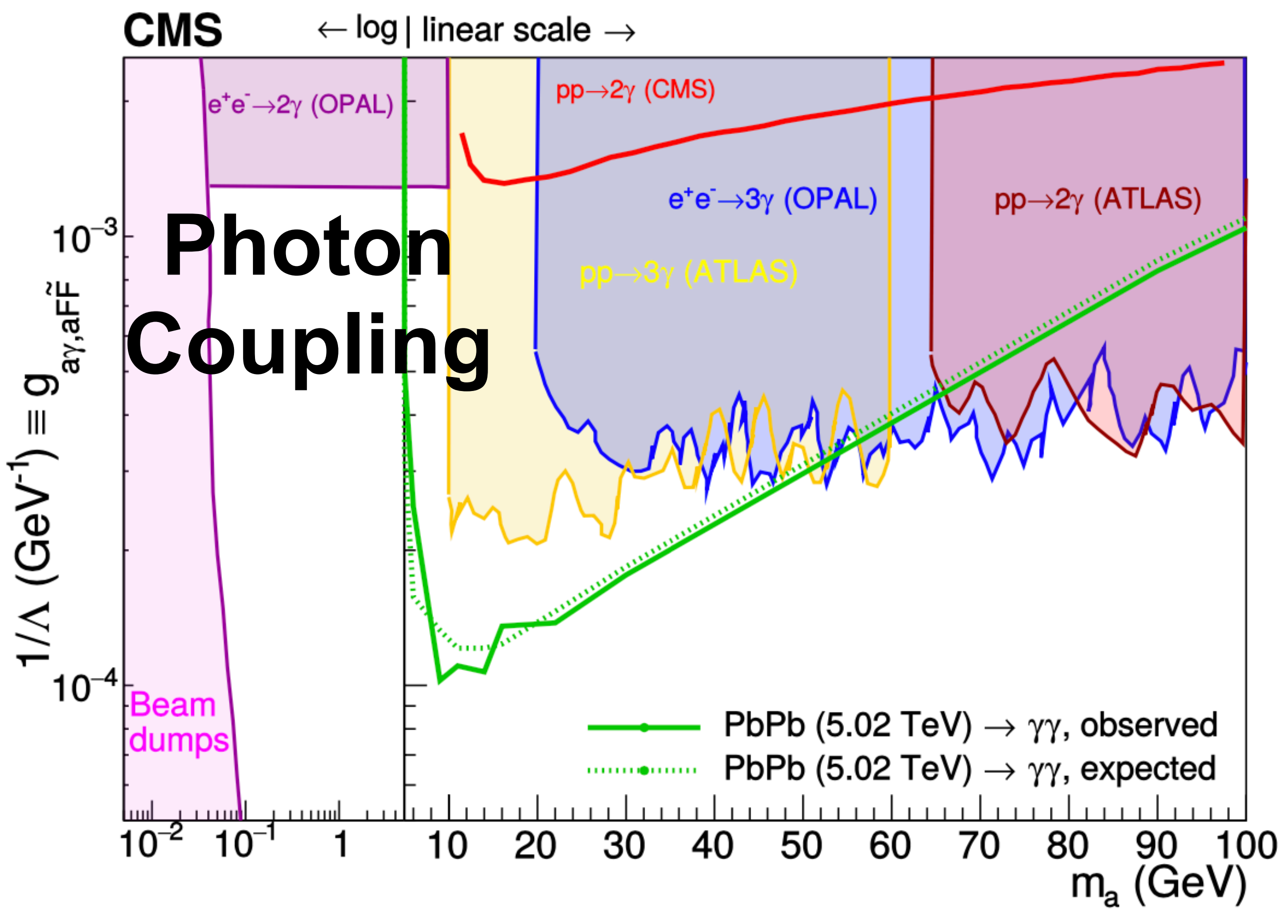
Beyond LHC?

FCC-hh or a higher energy beam dump would help
Not clear that others would



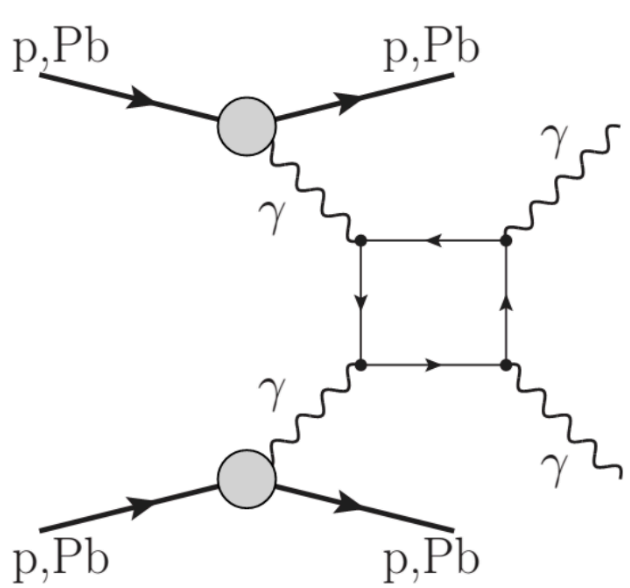
Axion Portal

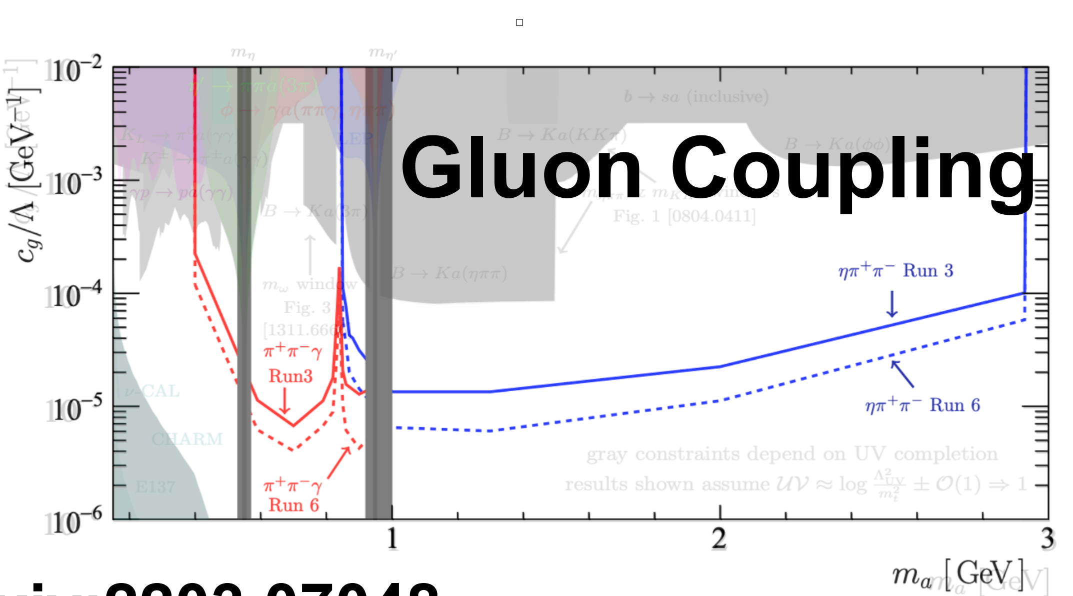
- Visible bounds dominated by light-light scatter



Heavy Ions very sensitive

Z^4 enhancement





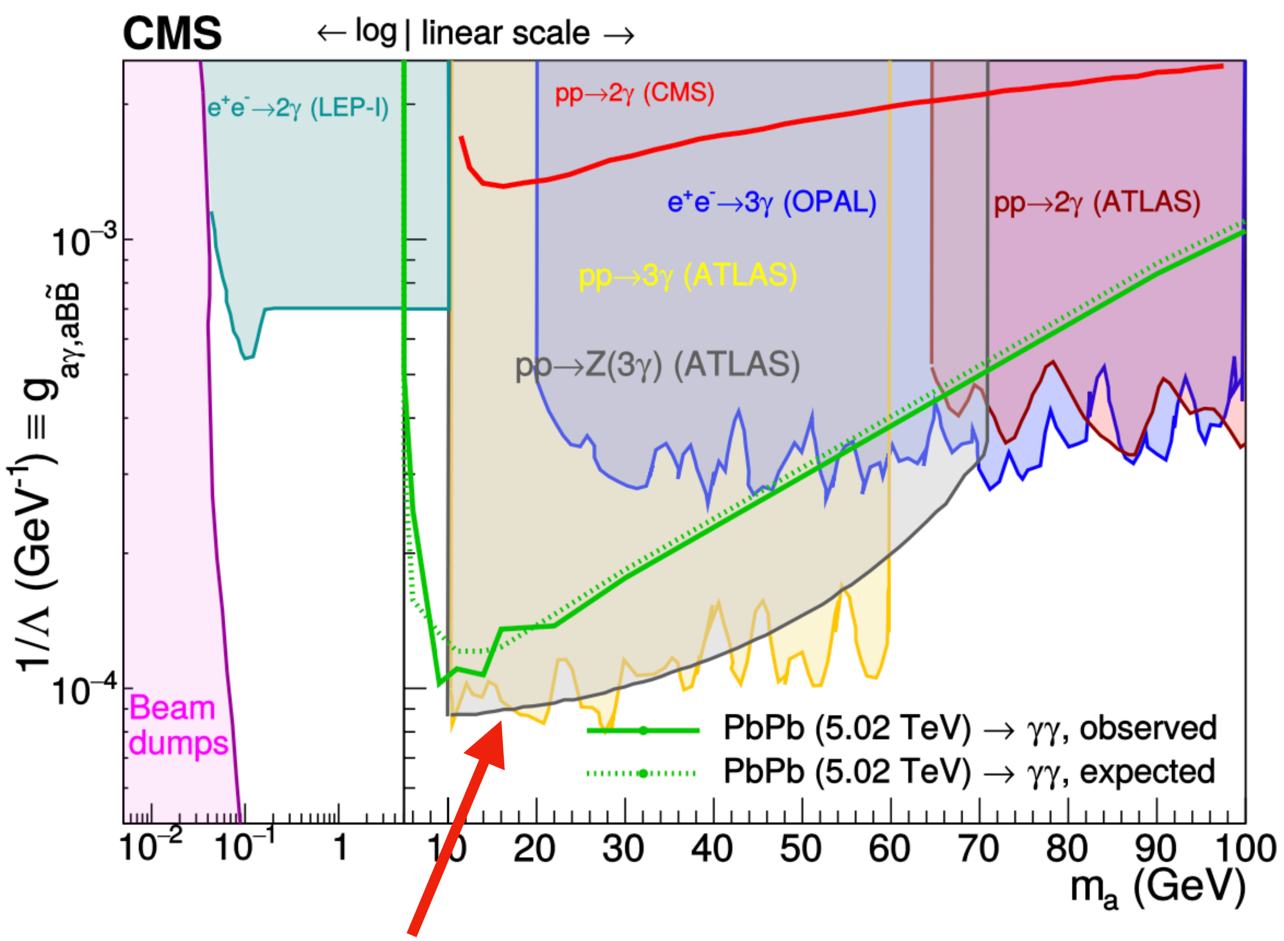
Gluon Coupling is much harder

LHCb has proposed searches in ηππ

arxiv:2203.07048

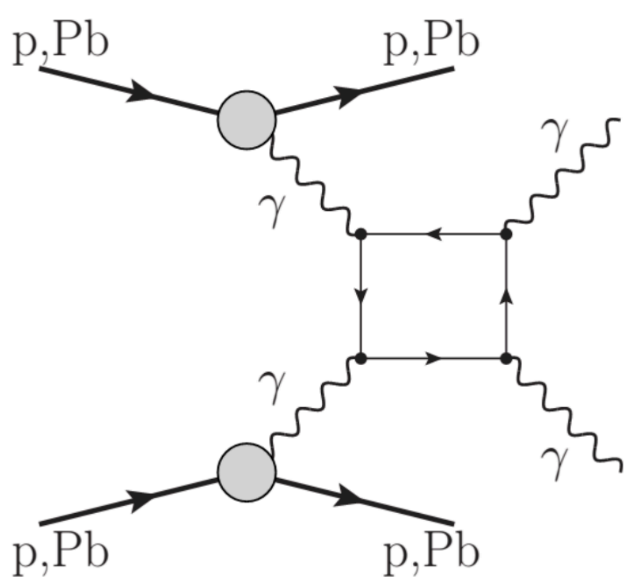
Axion Portal

- Visible bounds dominated by light-light scatter



Heavy Ions very sensitive

Z^4 enhancement



Adding Z decays (Fcc-ee) may be competitive

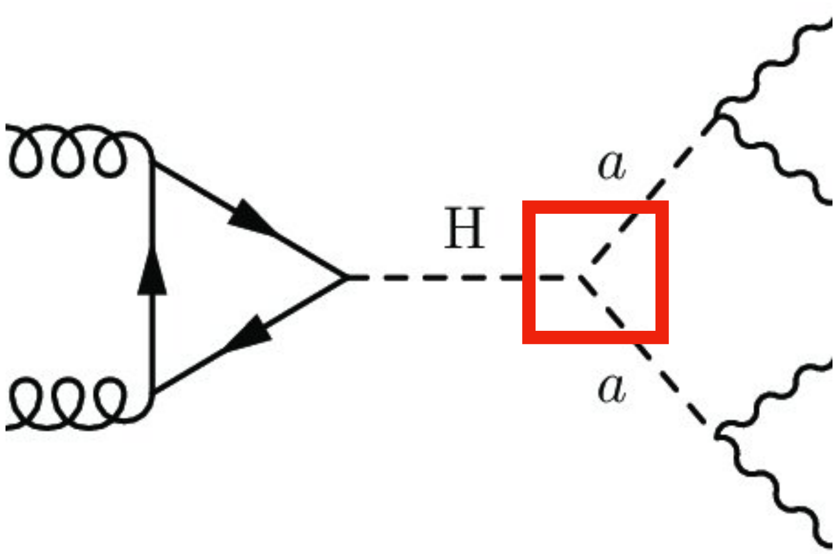
However a big heavy ion run may help much more

arxiv:2203.07048

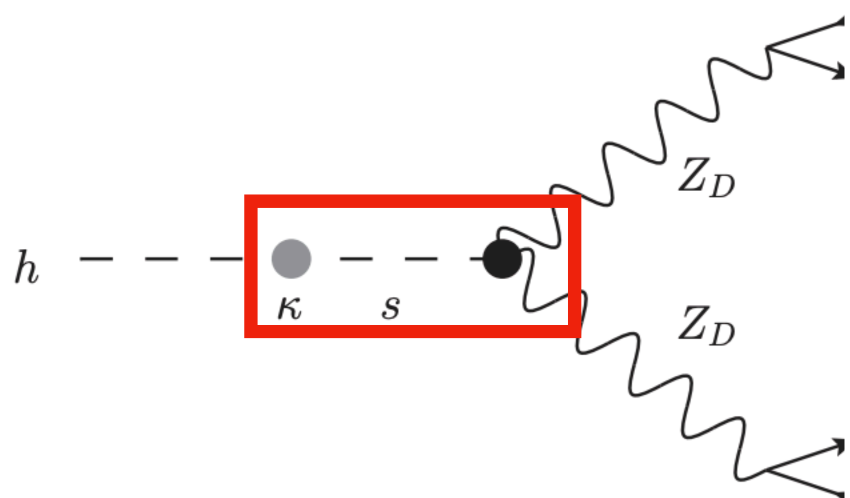
Unique Models

- Unlike other experiments, LHC has access to the Higgs
  - The Higgs enables the possibility of new final states
- The LHC also has more Z bosons than anywhere on earth
  - Z boson decays gives rise to additional final states

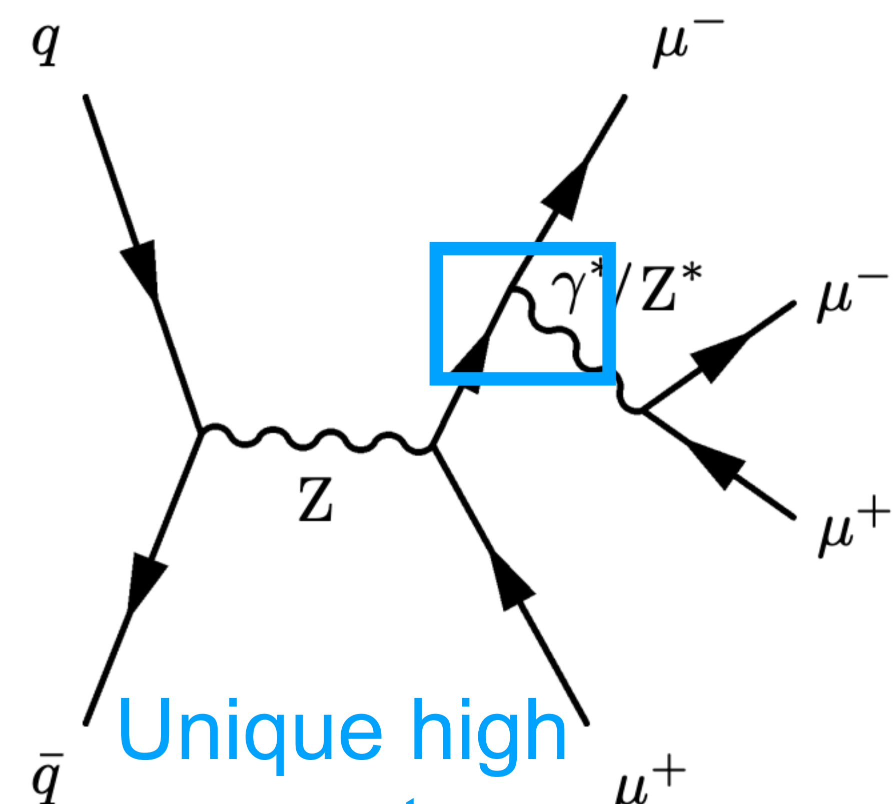
ALPs



Dark Photons



mu-Philic Photons



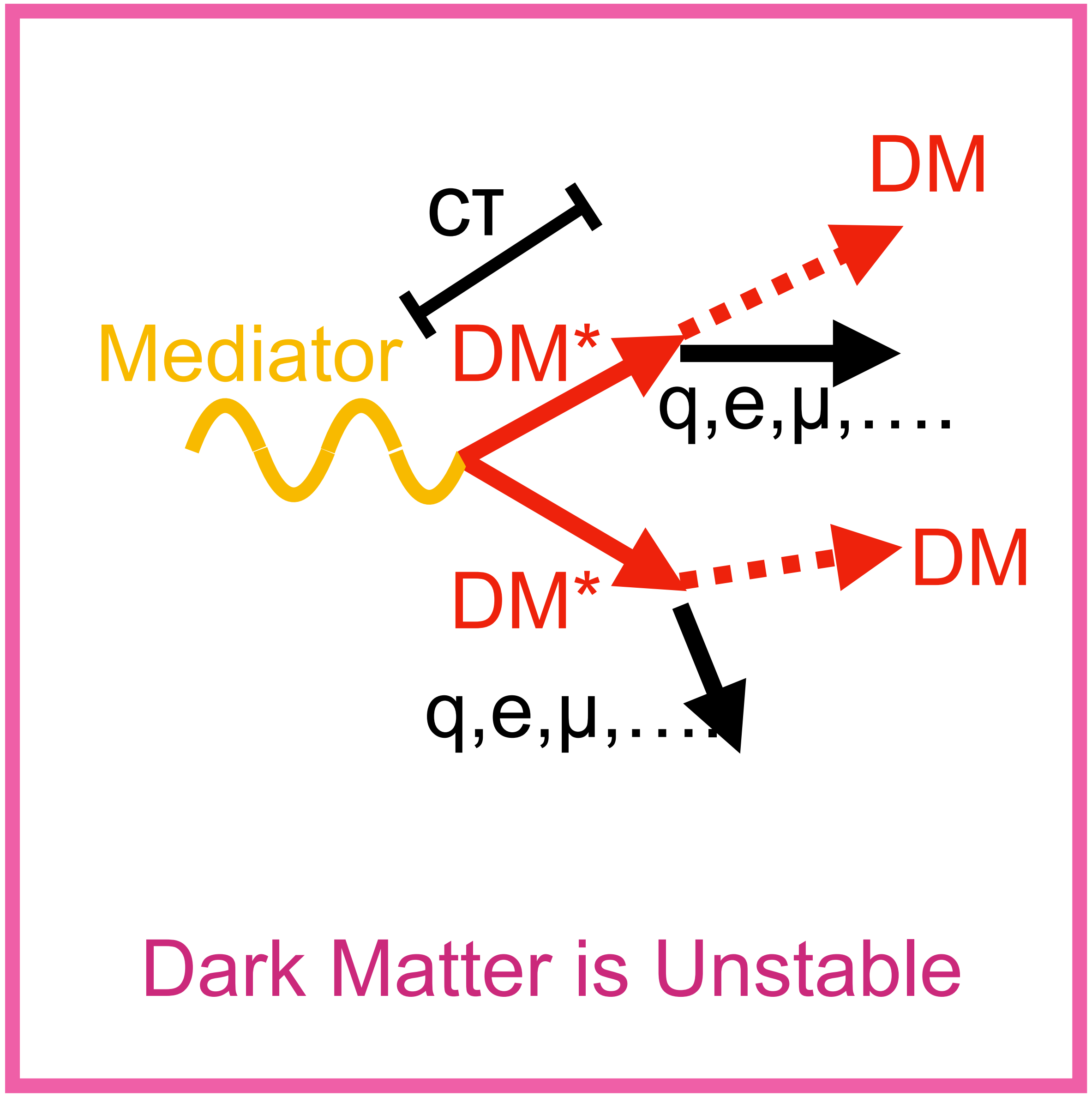
Unique high momentum Muon Beam

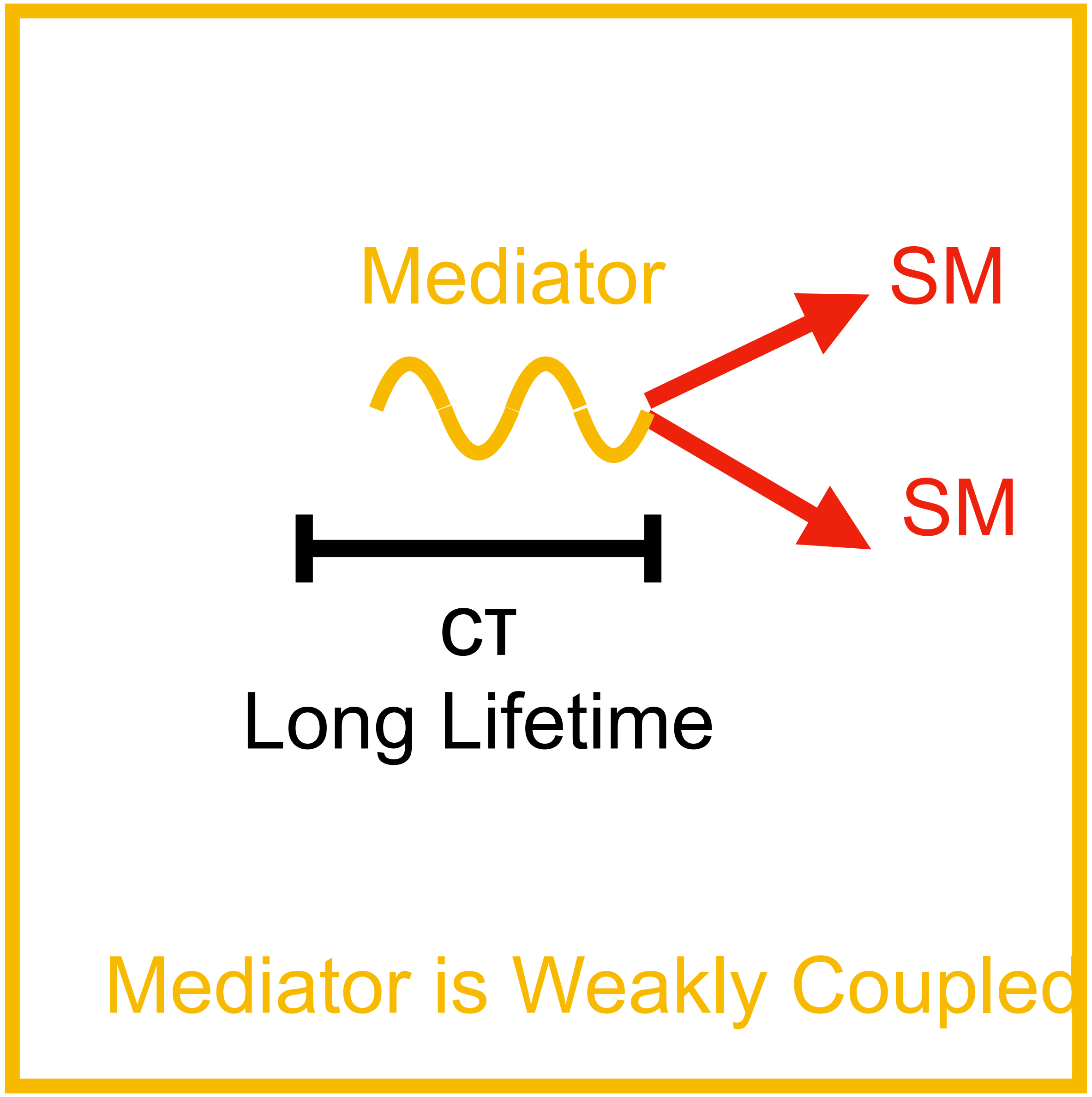
Requires a Higgs Coupling to the Dark Sector
Large additional coupling can make LHC sensitive

Luminosity @ LHC

- There will be an enormous amount of data at the LHC
  - Strong bounds provided we can tap this dataset
- Higgs or Z boson couplings to Dark Sector yield enhancments
  - Provided we have the right model
    - Higgs and Z boson couplings are needed for this

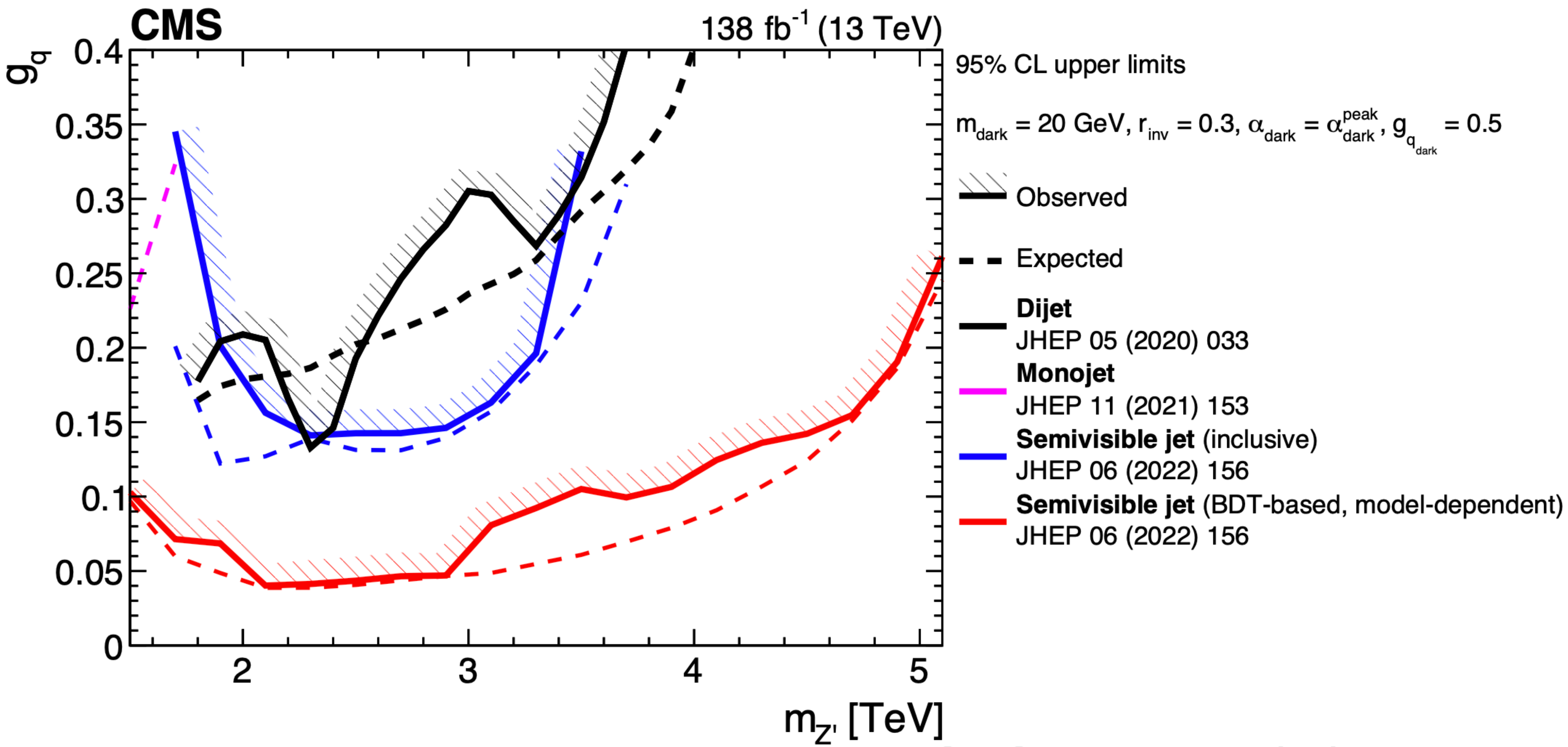
Long-Lived Searches





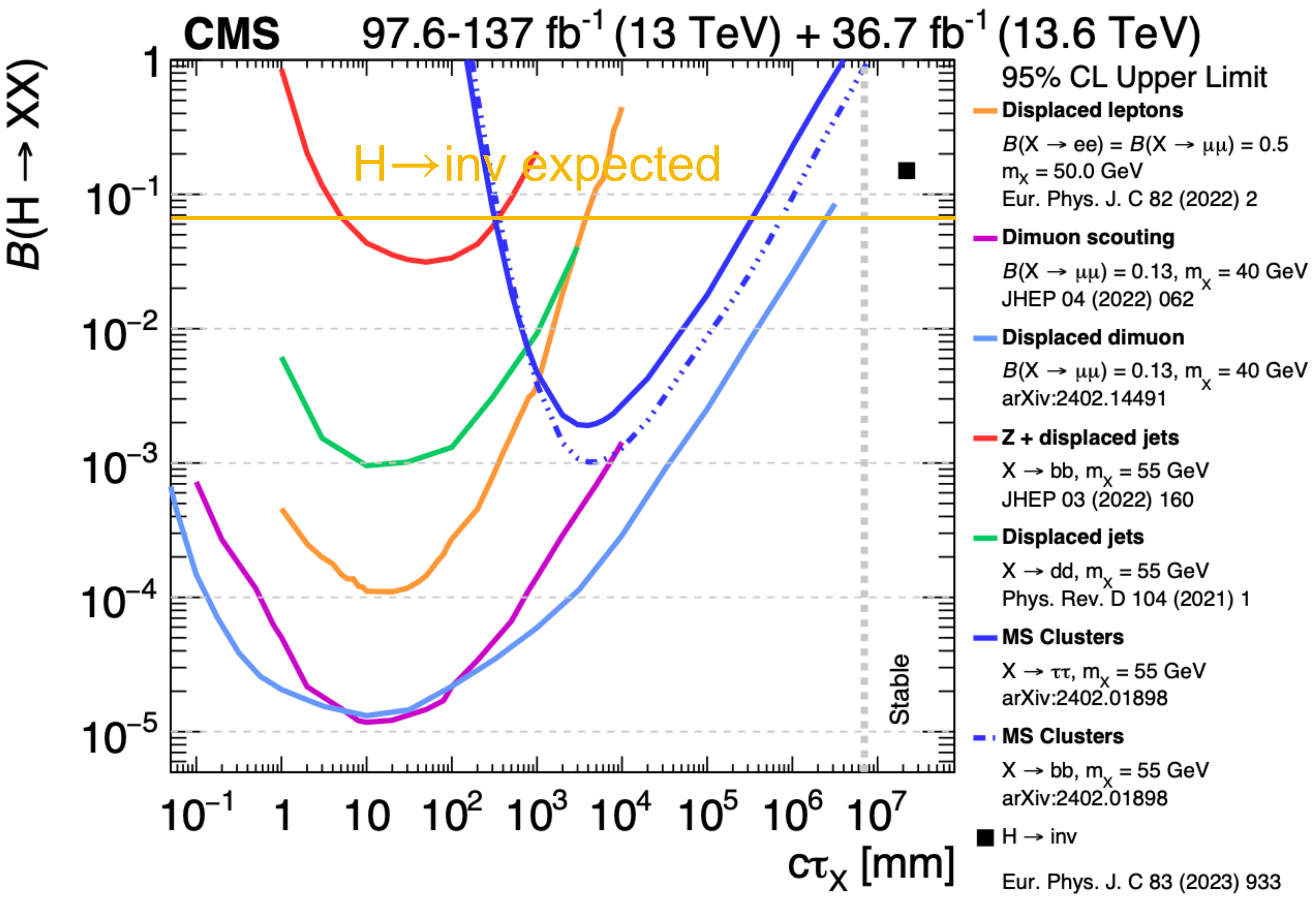
Semi-visible decays help

- Adding complexity to the model enahnces overall sensitivity



Long-lived decays help

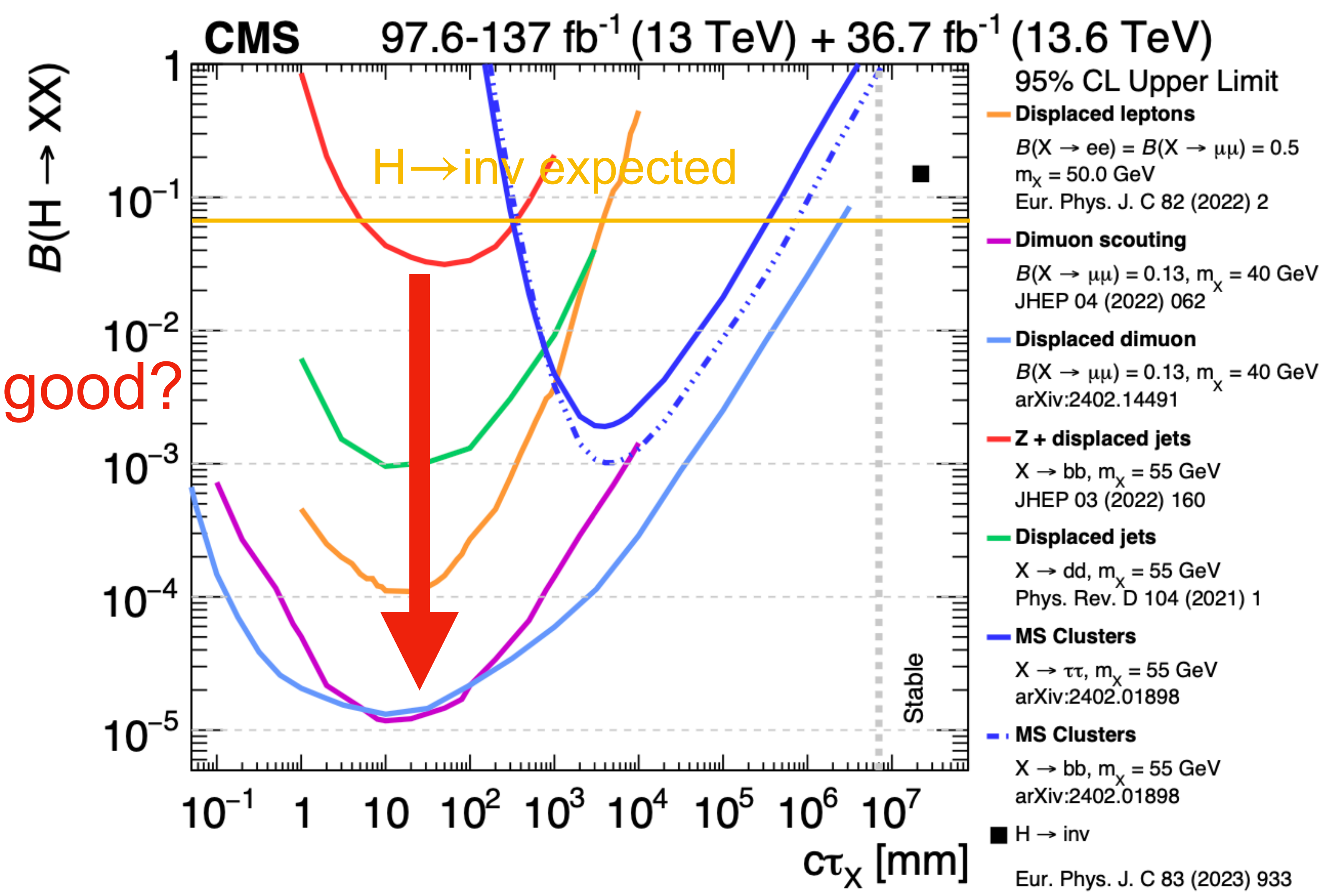
- Adding complexity to the model enahnces overall sensitivity



Long-lived decays help

- Adding complexity to the model enahnces overall sensitivity

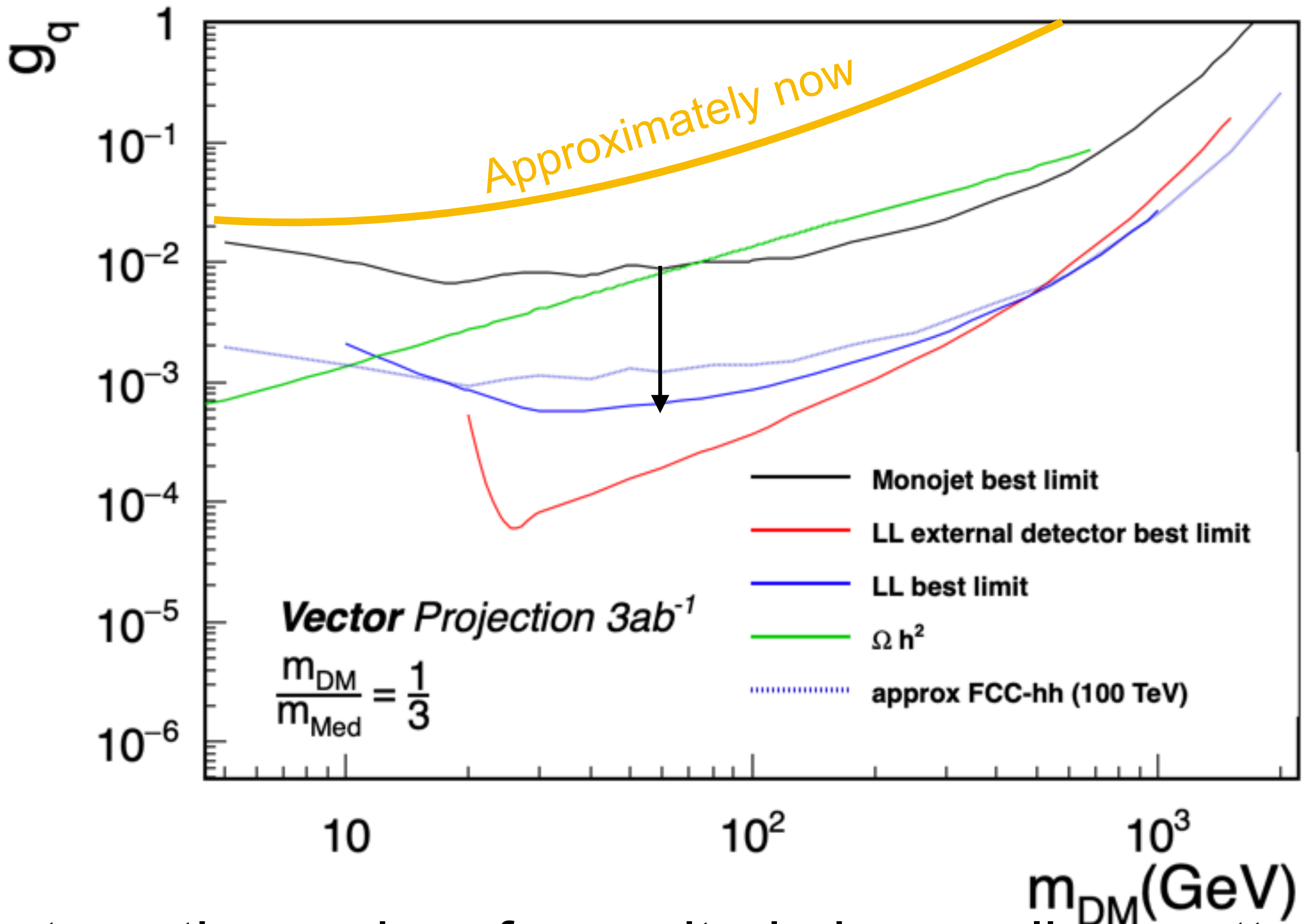
Why so good?



Many new ideas
For triggering
Are helping a lot

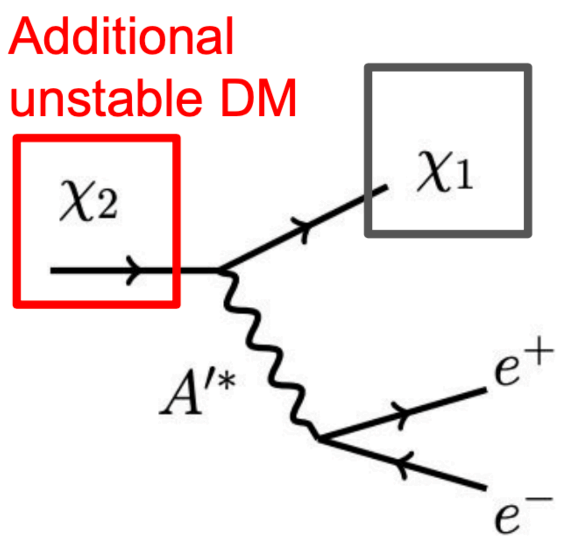
Projecting To the Future

With a naive recast of the monojet analysis for displaced vertices

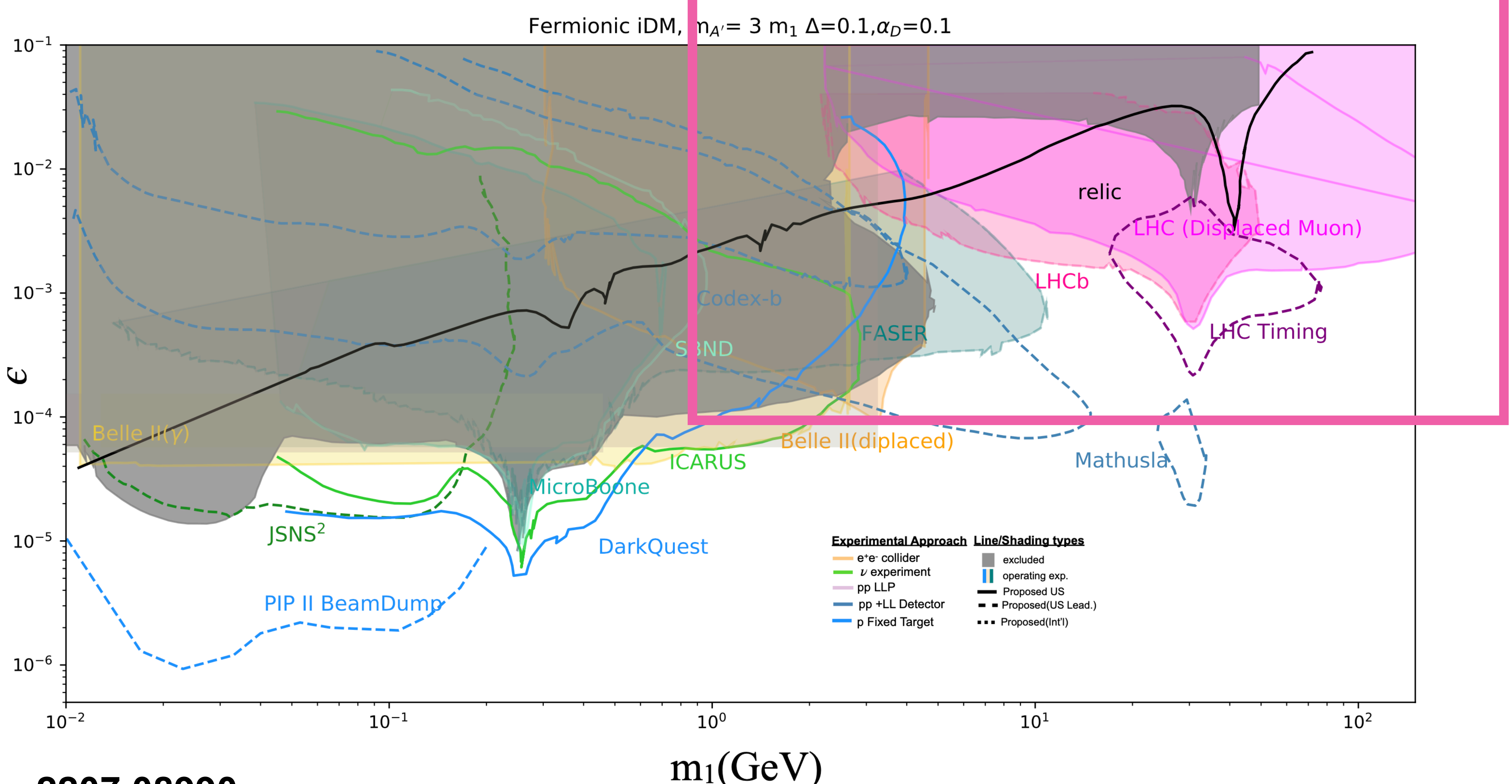


Can get another order of magnitude in coupling pretty generically

Many Others



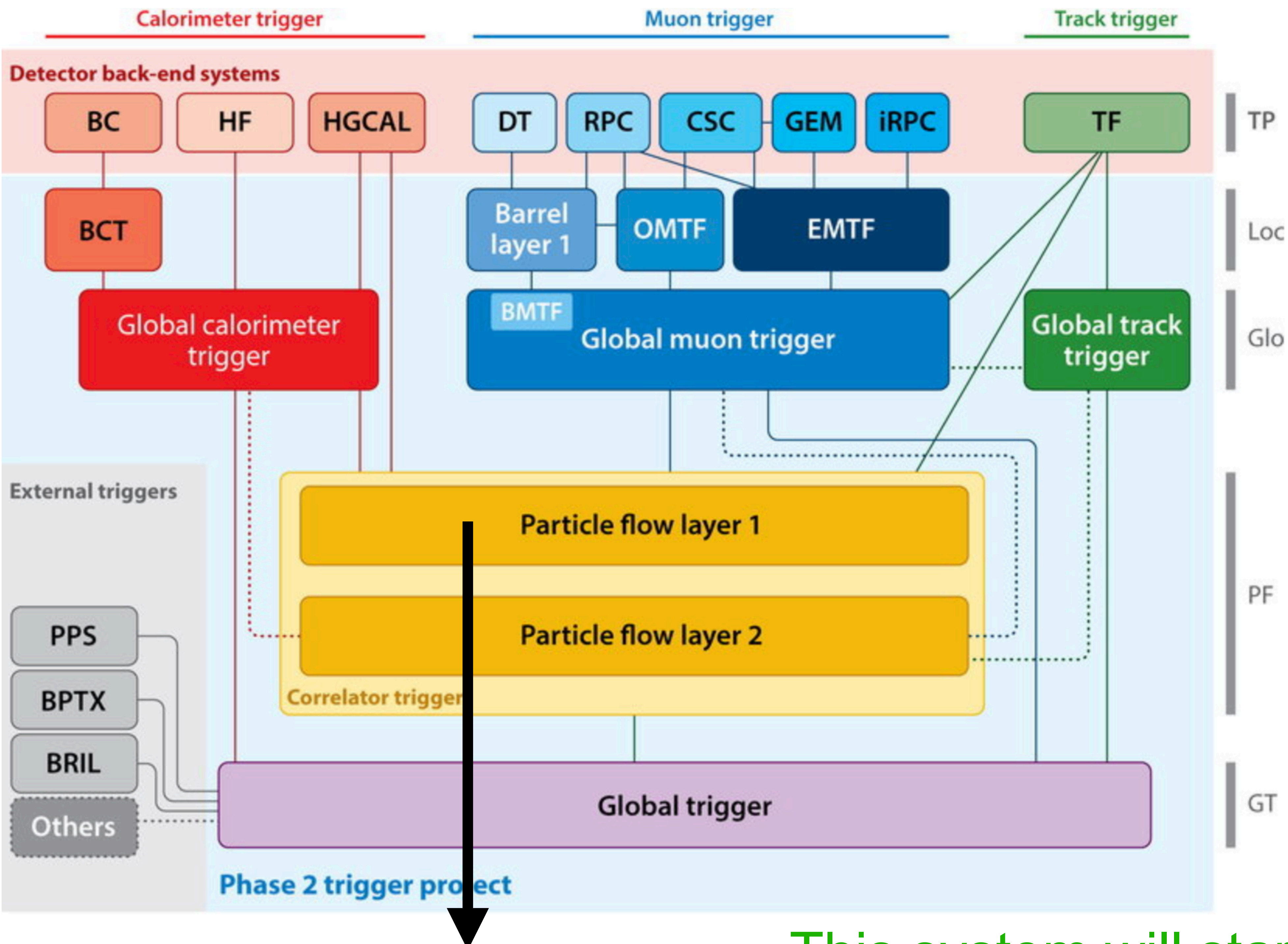
By Making the Dark Matter Unstable
Invisible searches become Long lived LHC



arxiv:2207.08990

We are developing a system that hopefully can
Do **any** analysis on all events
It can't do **every** analysis on all events

HL-LHC



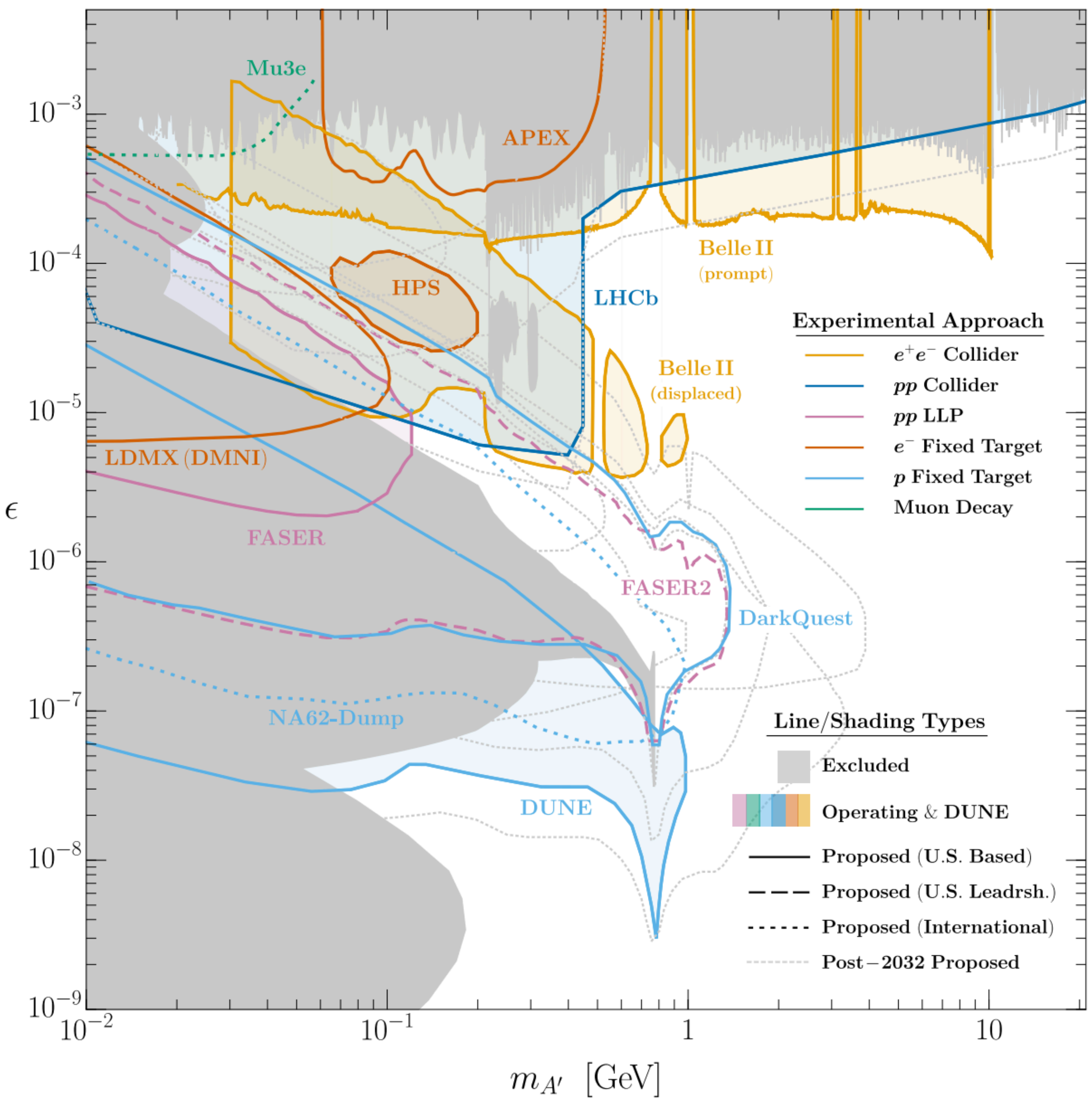
40 MHz Scouting system

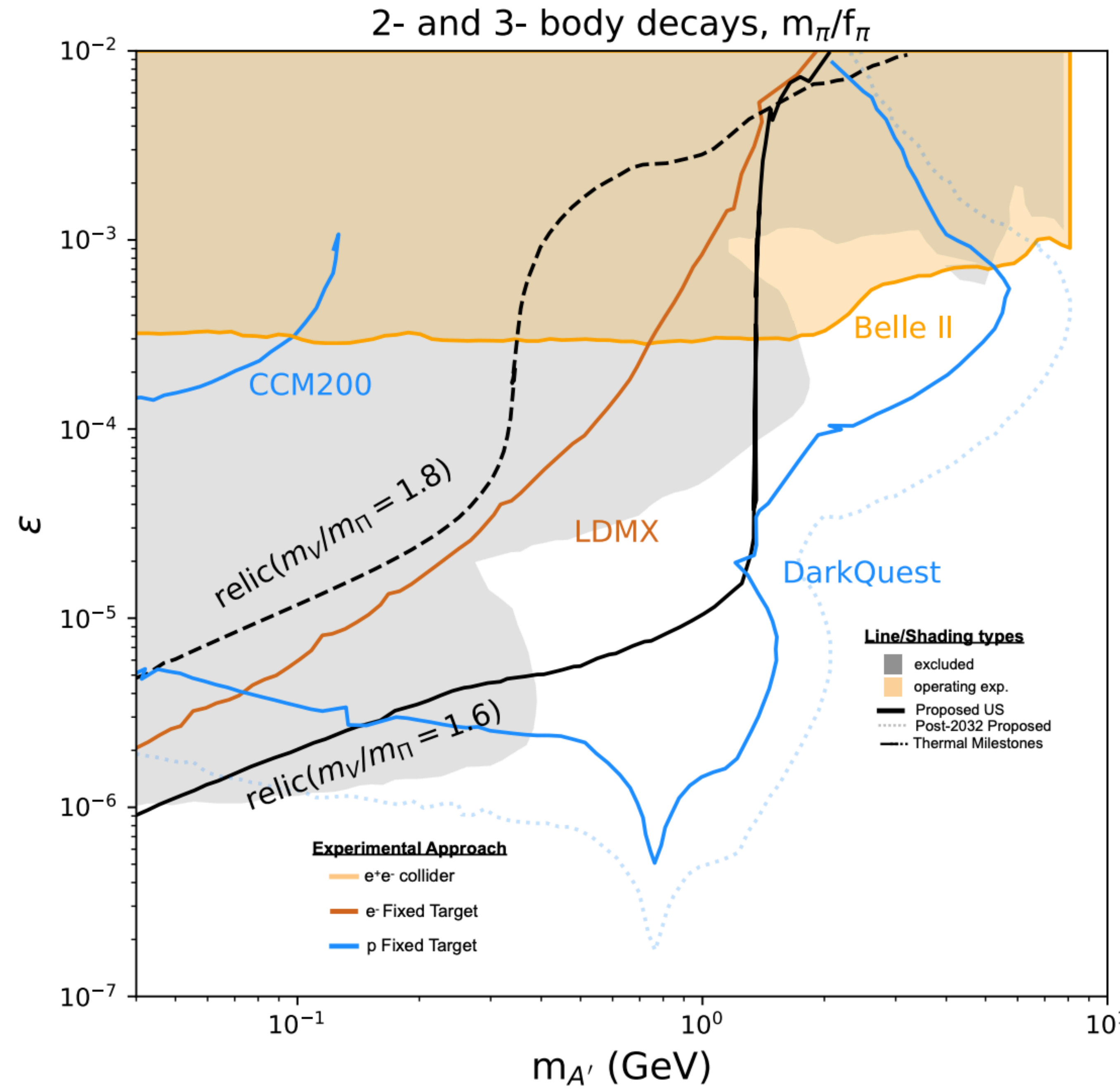
This system will start form L1 Puppi candidates but will possibly add more

Conclusions

- Invisible searches
  - γ_D benchmark : will cover m < 3 GeV and m > 45 GeV
  - It is not clear that we can cover the middle region
- Visible searches
  - LHC will cover broad range of prompt di-lepton signatures
    - Will be the leading constraint for γ_D benchmark at large ε
  - Higgs and Z decays can enhance things
- Long-lived searches : further enhancments
- Future colliders:
  - My view: high mass is not the most exciting region
  - FCC-hh will helpl with lumi, not clear others will help
  - A high COM beam-dump would be something to think about

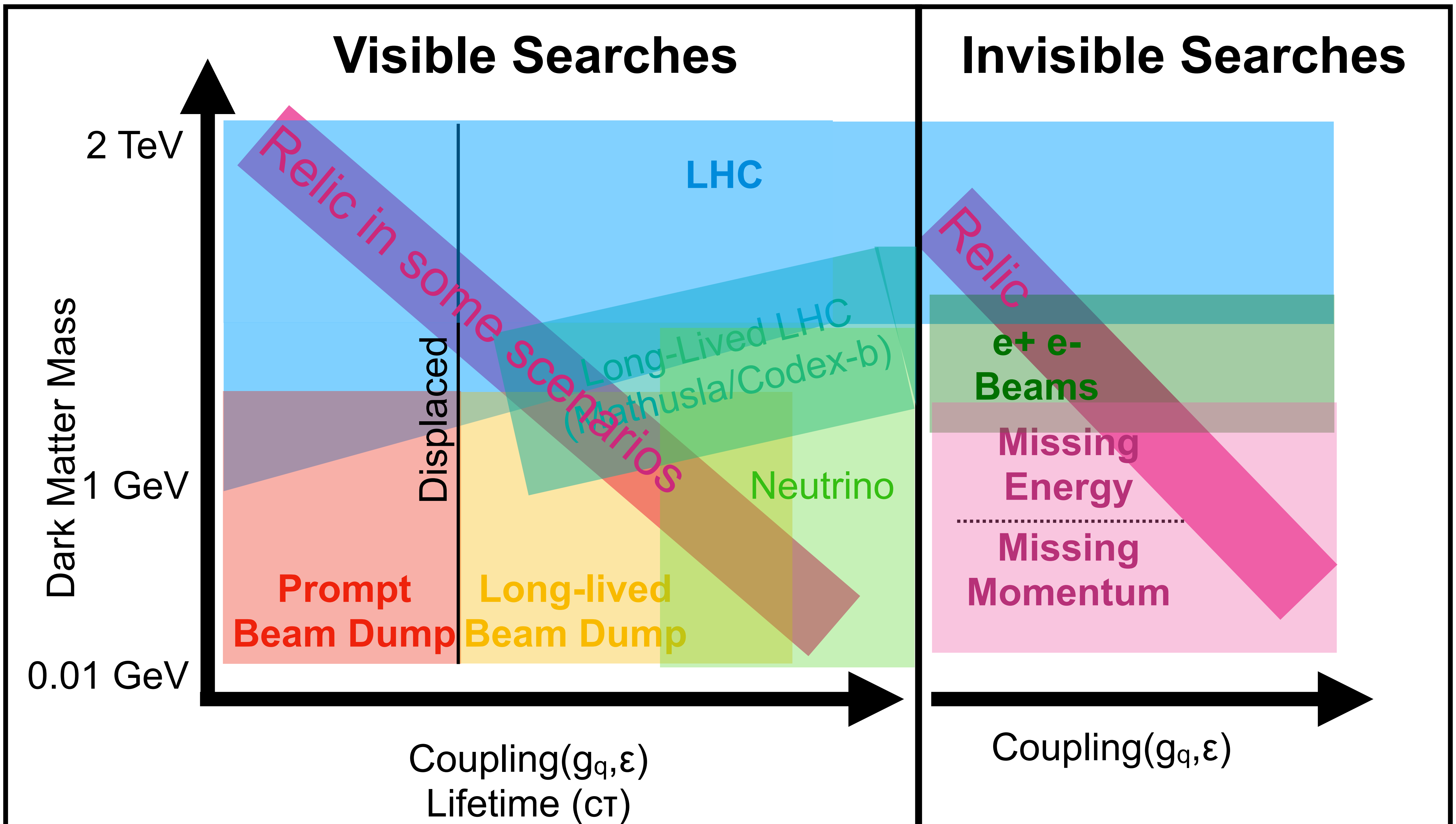
DarkQuest



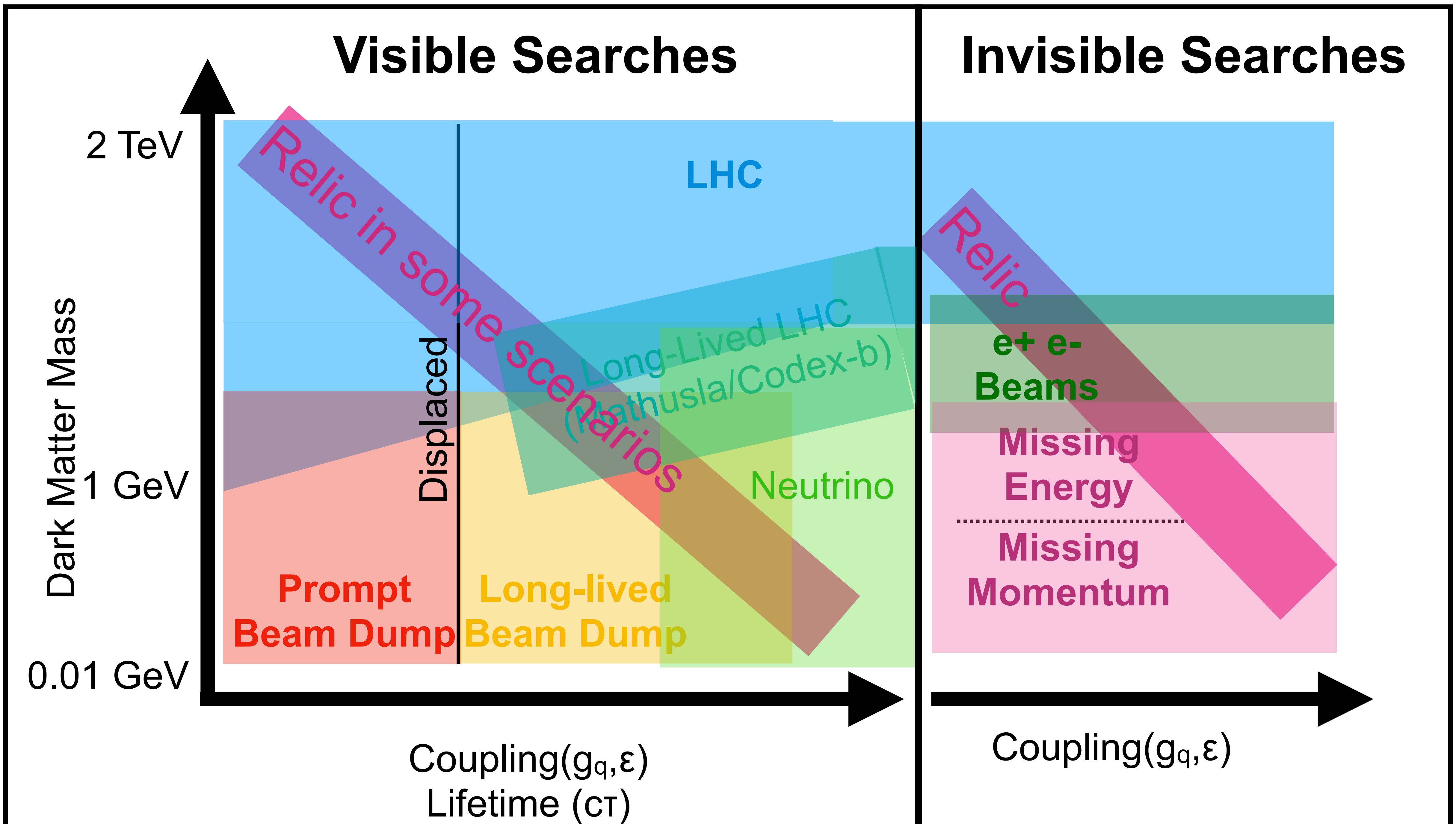


DarkQuest is a funded experiment
Come and join if you are interested!

Thanks!

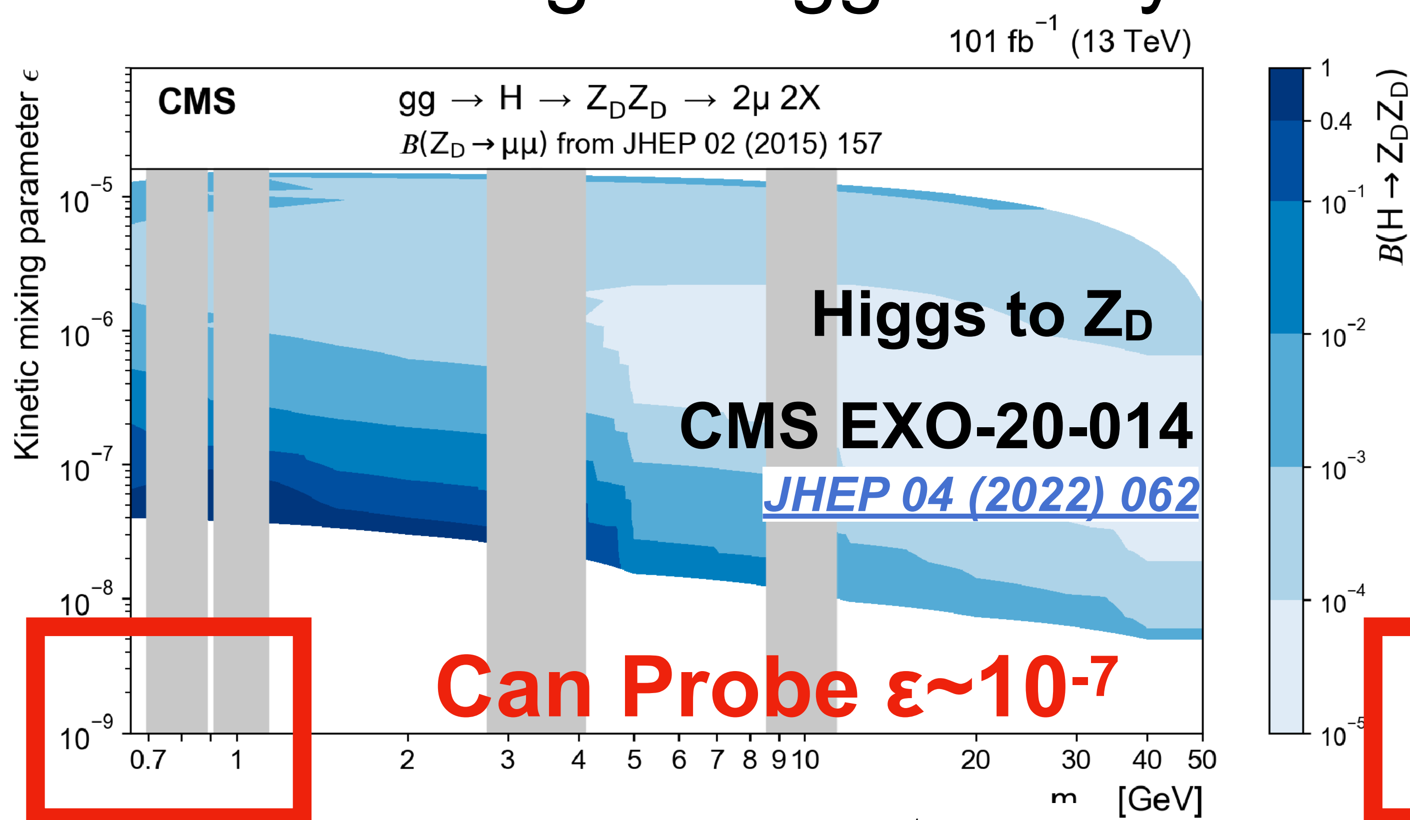

Visible Searches
Invisible Searches
2 TeV
1 GeV
0.01 GeV
Dark Matter Mass
LHC
Relic in some scenarios
Relic
Displaced
Long-Lived LHC
(Mathusla/Codex-b)
Neutrino
e+ e-
Beams
Missing
Energy
Missing
Momentum
Prompt
Beam Dump
Long-lived
Beam Dump
Coupling(gq,ε)
Lifetime (cτ)
Coupling(gq,ε)

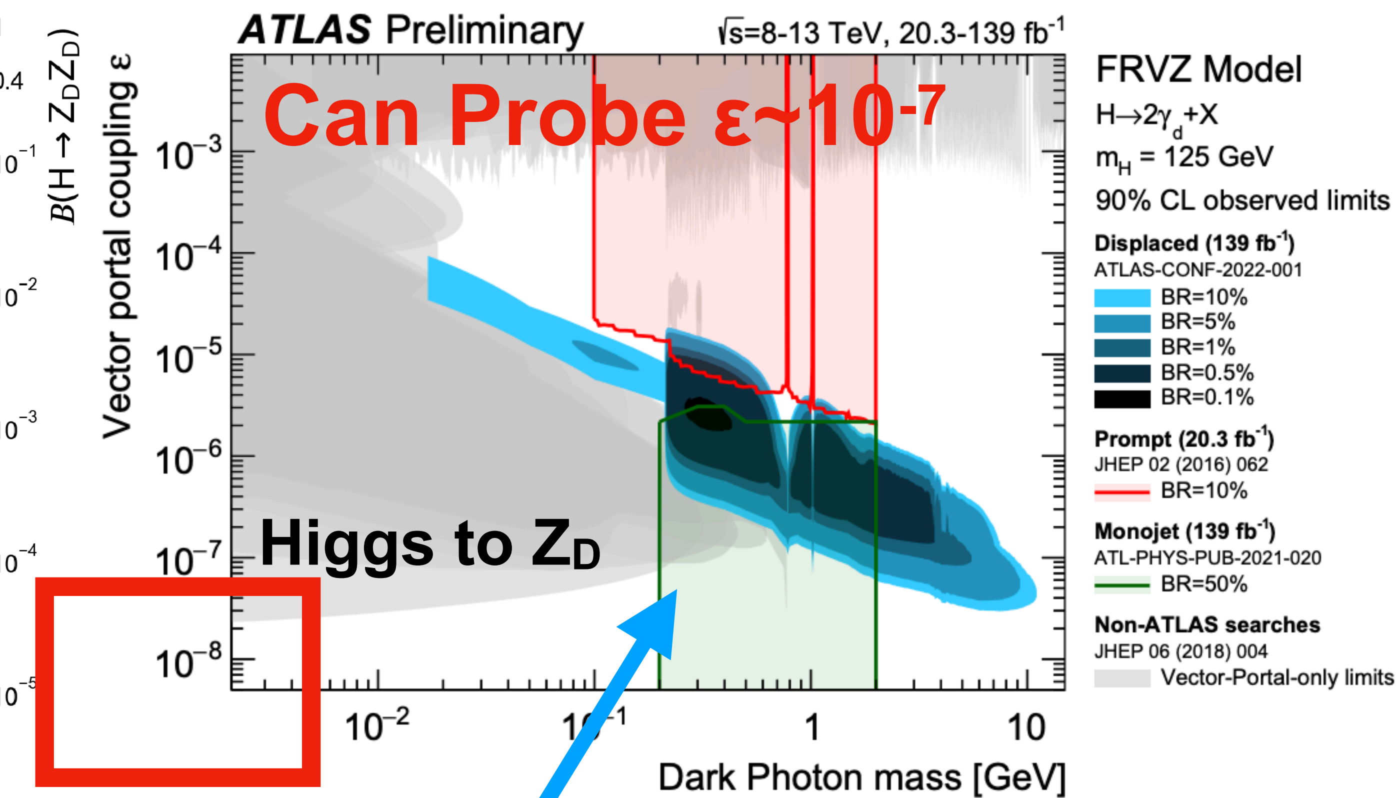
Visualizing the landscape

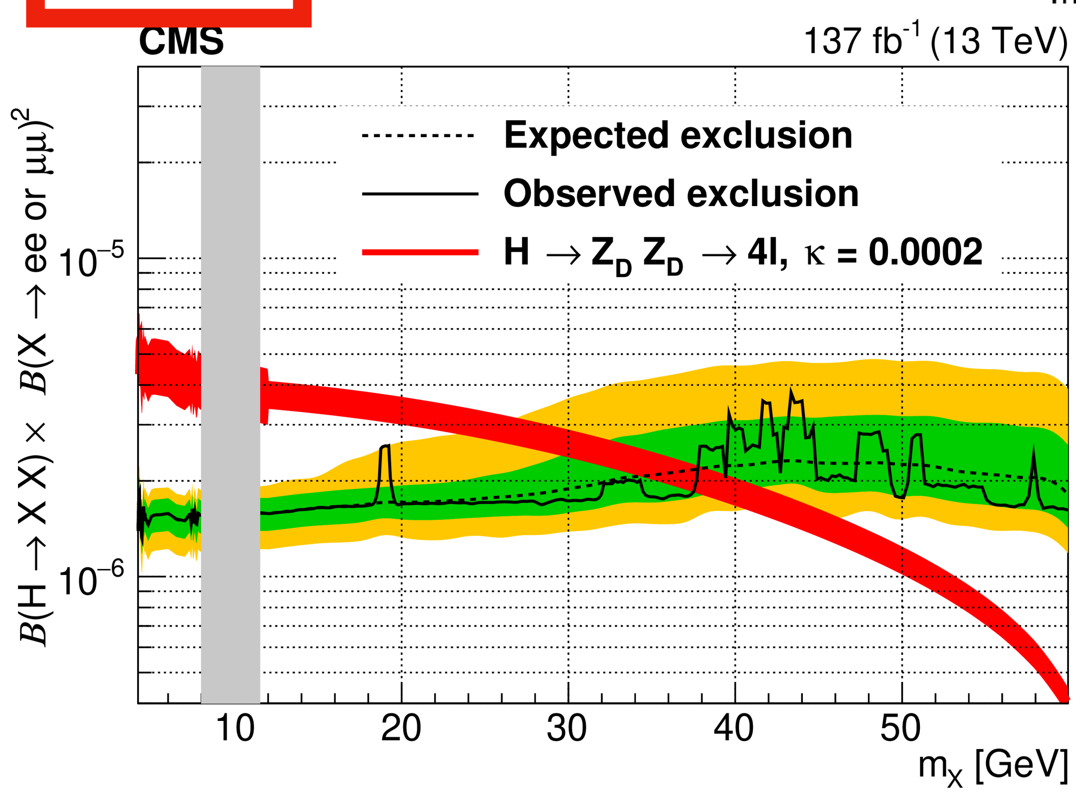


What Results are there?

- Looking at Higgs decays to dark photons



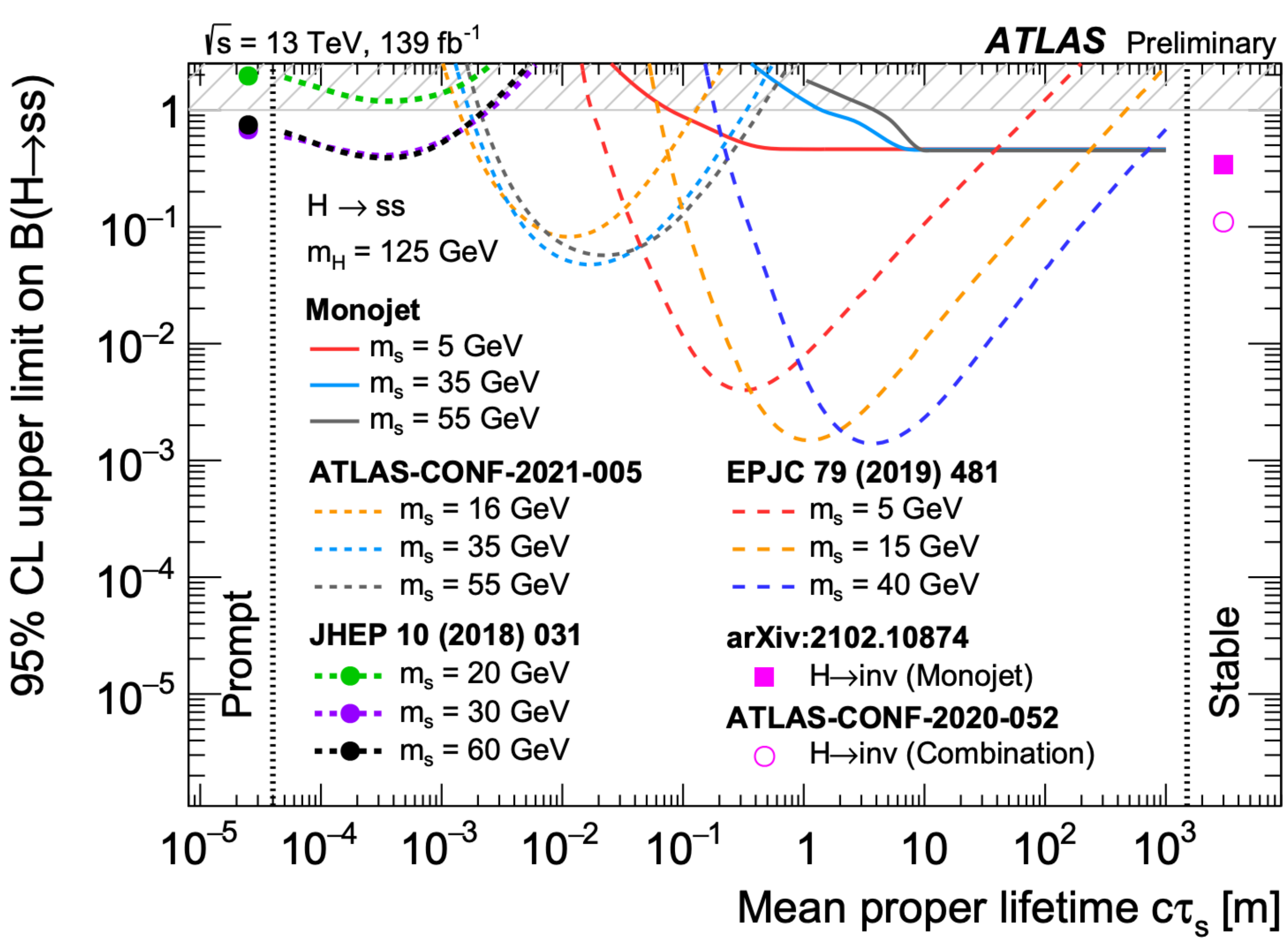


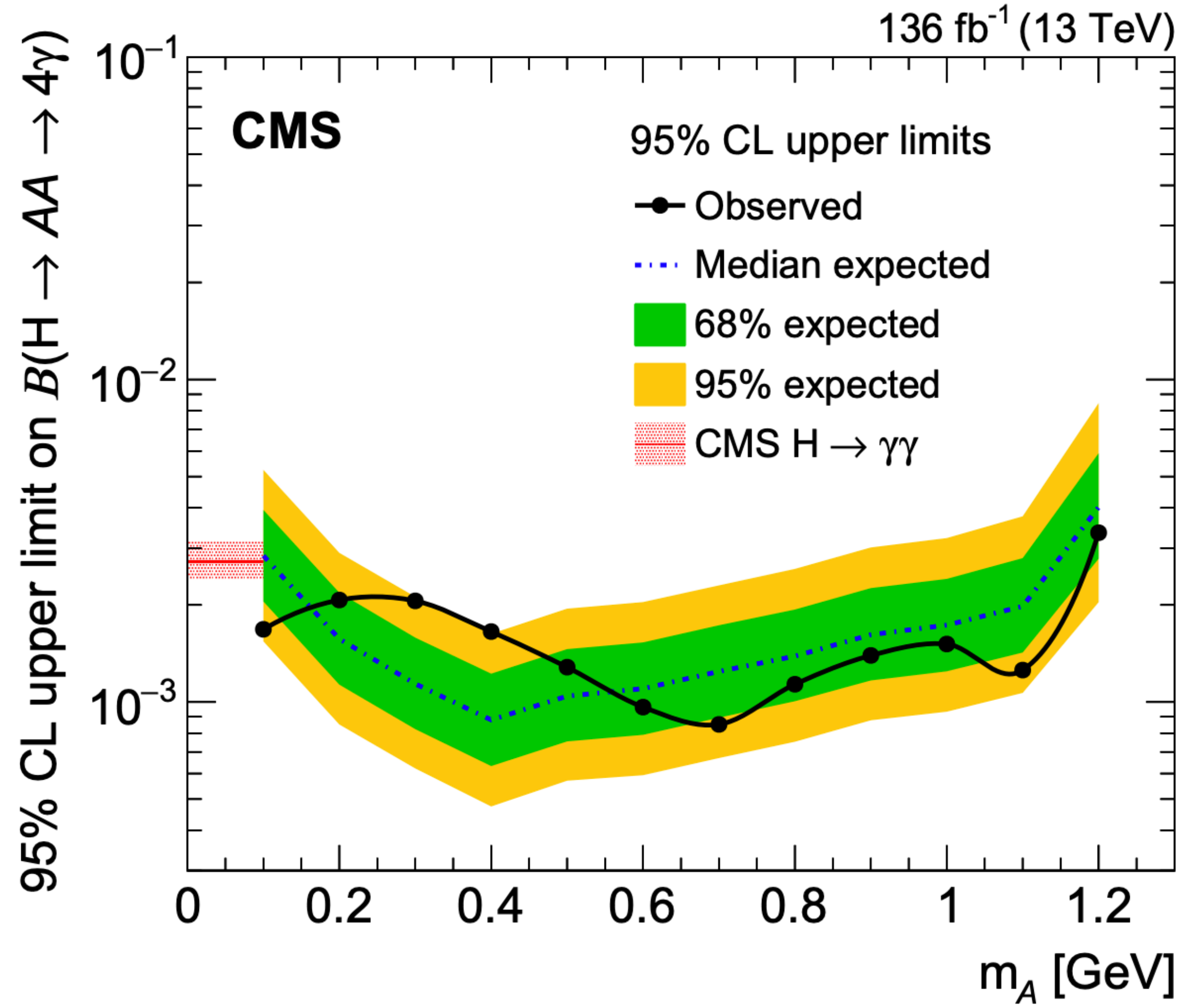


Given right choice of Higgs Dark Coupling
Can probe allowed range of sensitivity
Long Lived particle signatures emerge
Invisible and visible also contribtue

Higgs to spin-0

- Looking at Higgs decays to ALPs and Scalars



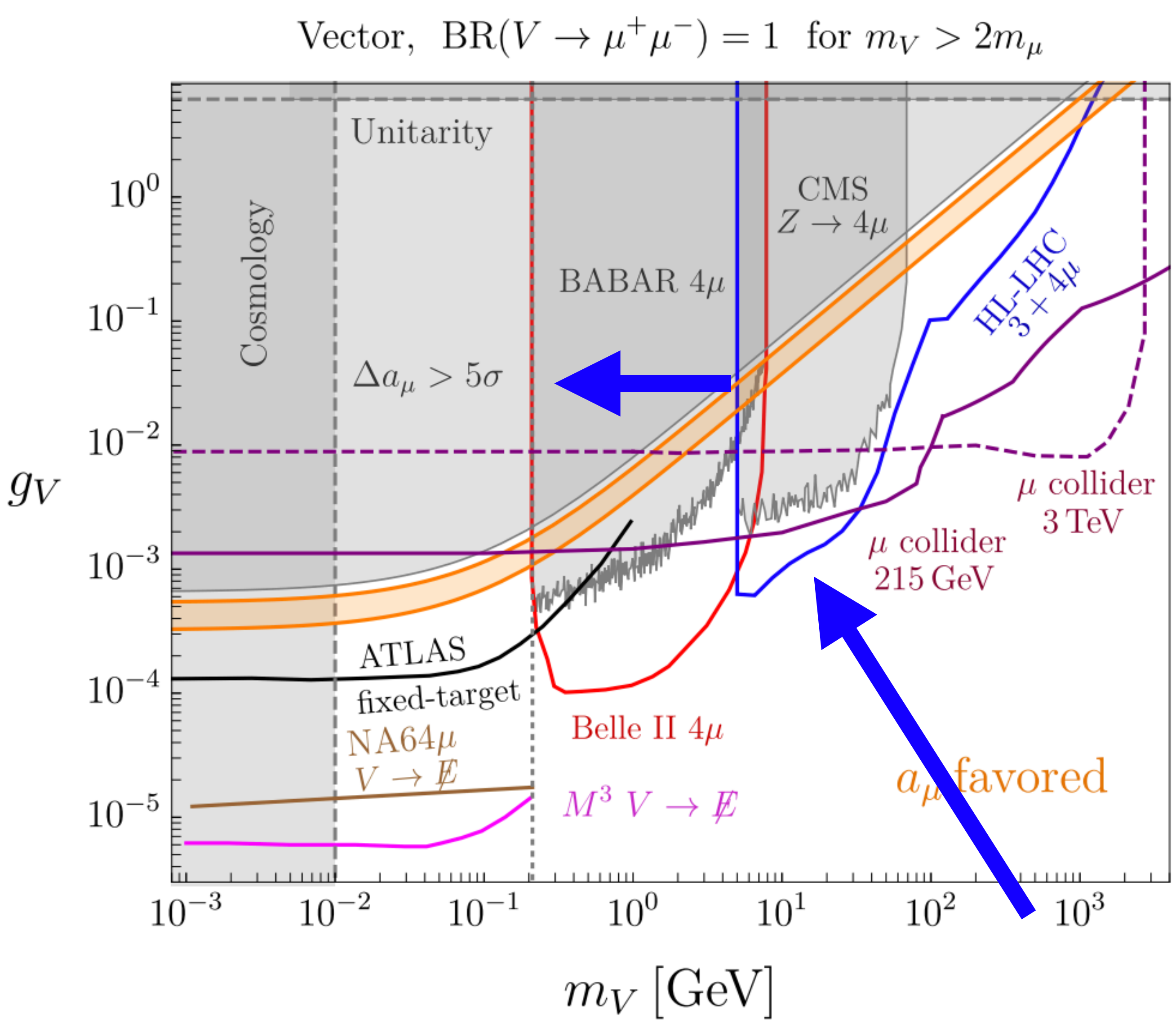


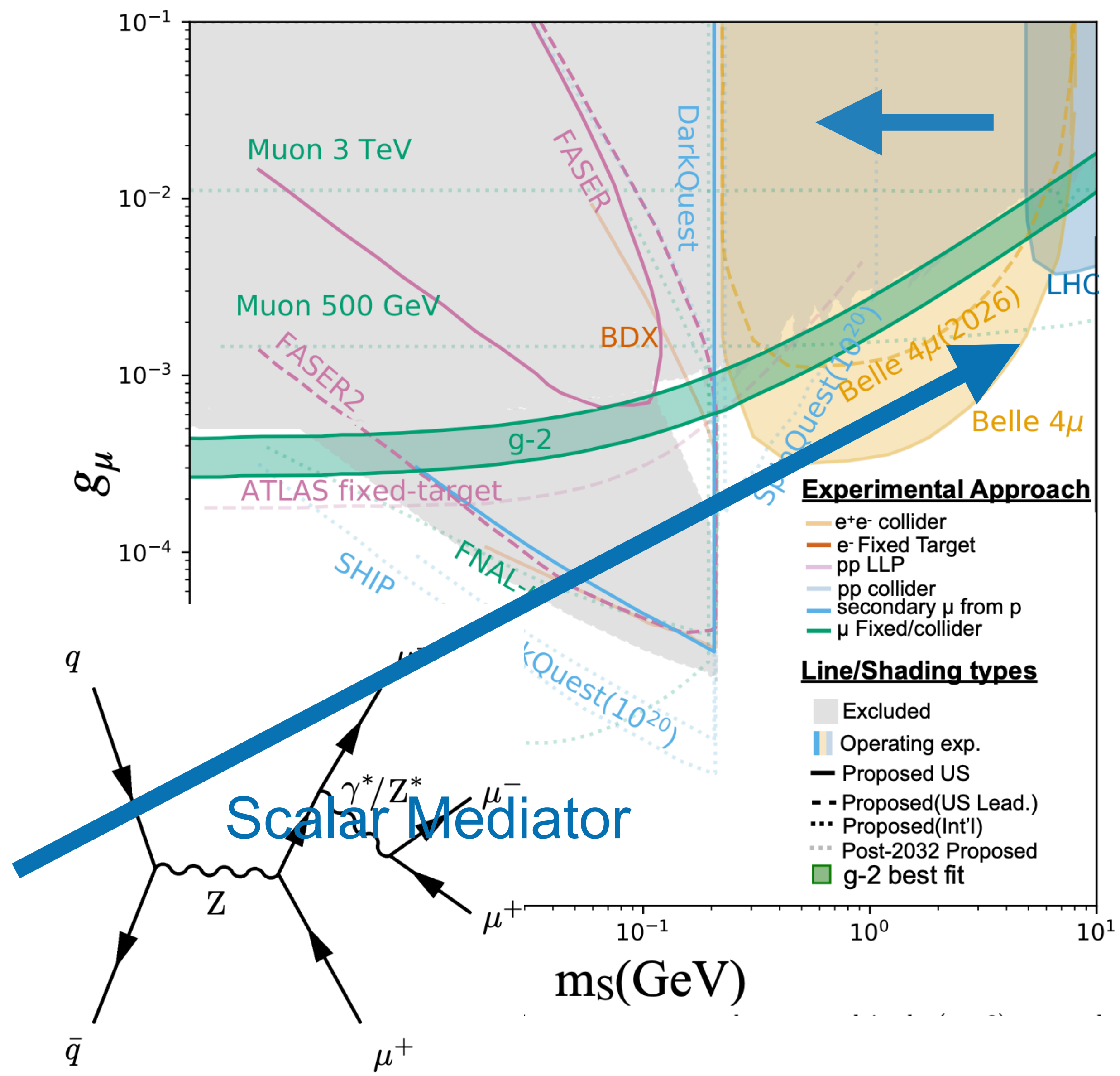
Long lifetimes often lead to very small couplings

Longer Lifetime: Higgs to invisible bounds dominate

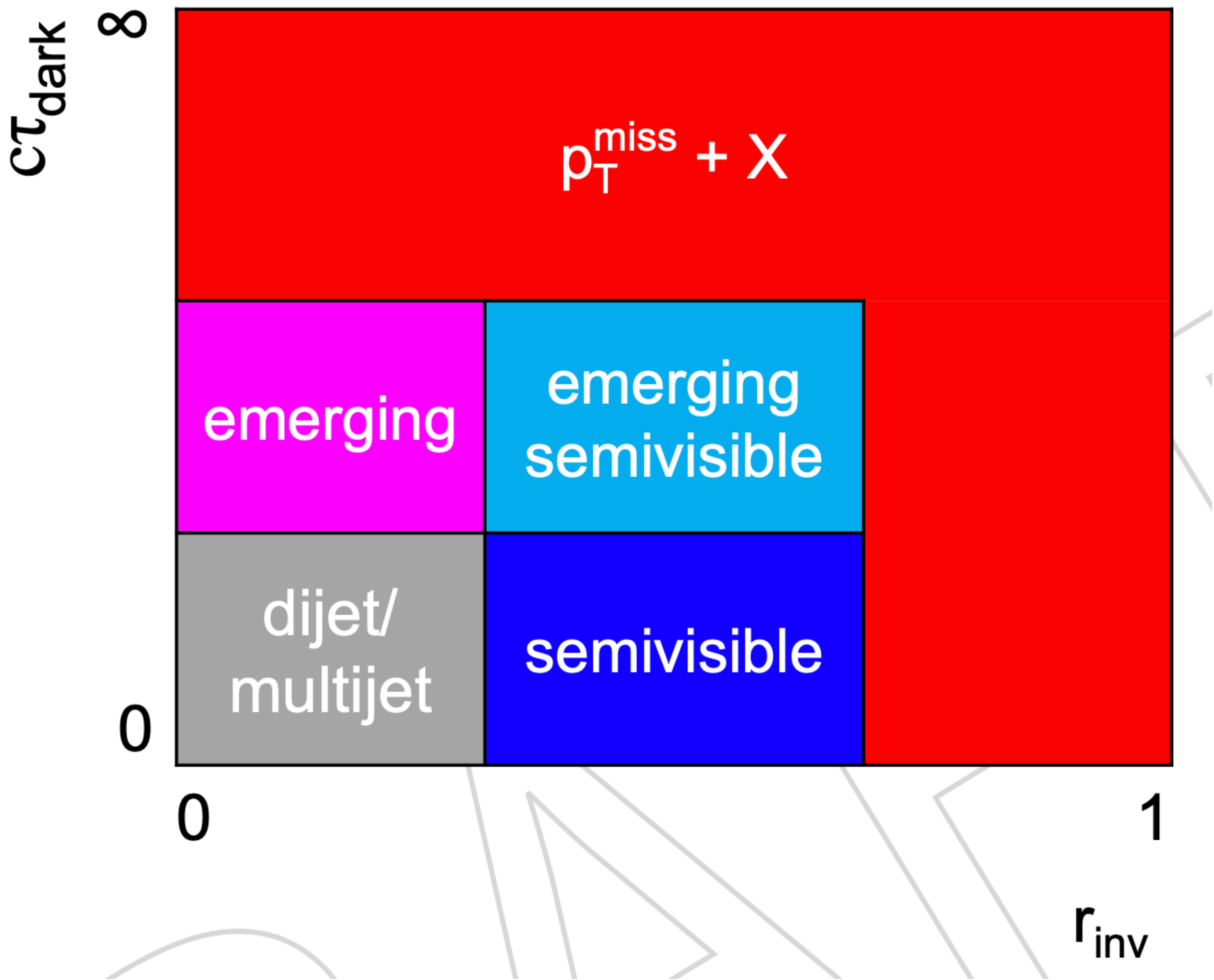
g-2 mediator (Just muons)

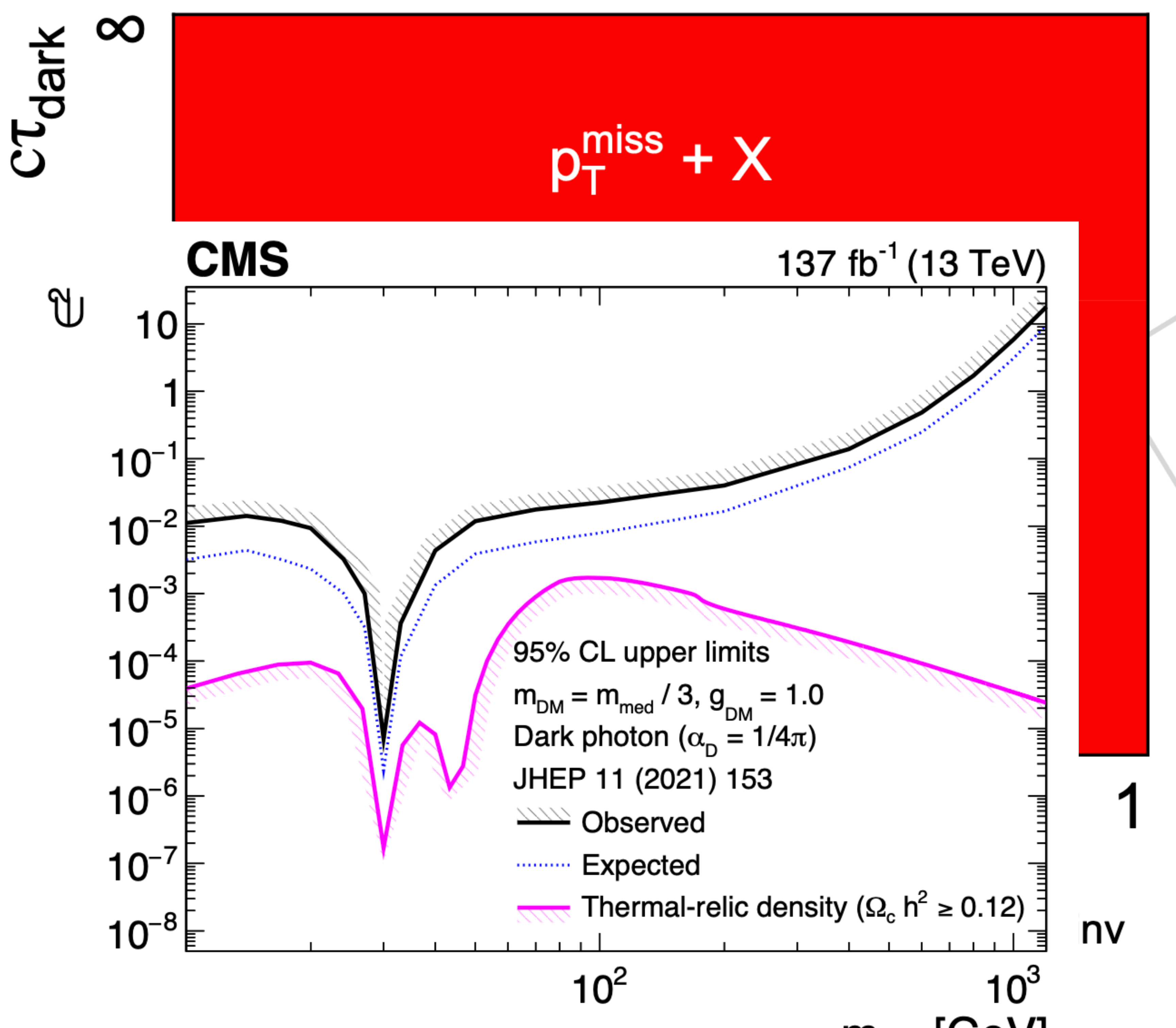
- Z to 4 muon channel provides unique high mass constraints

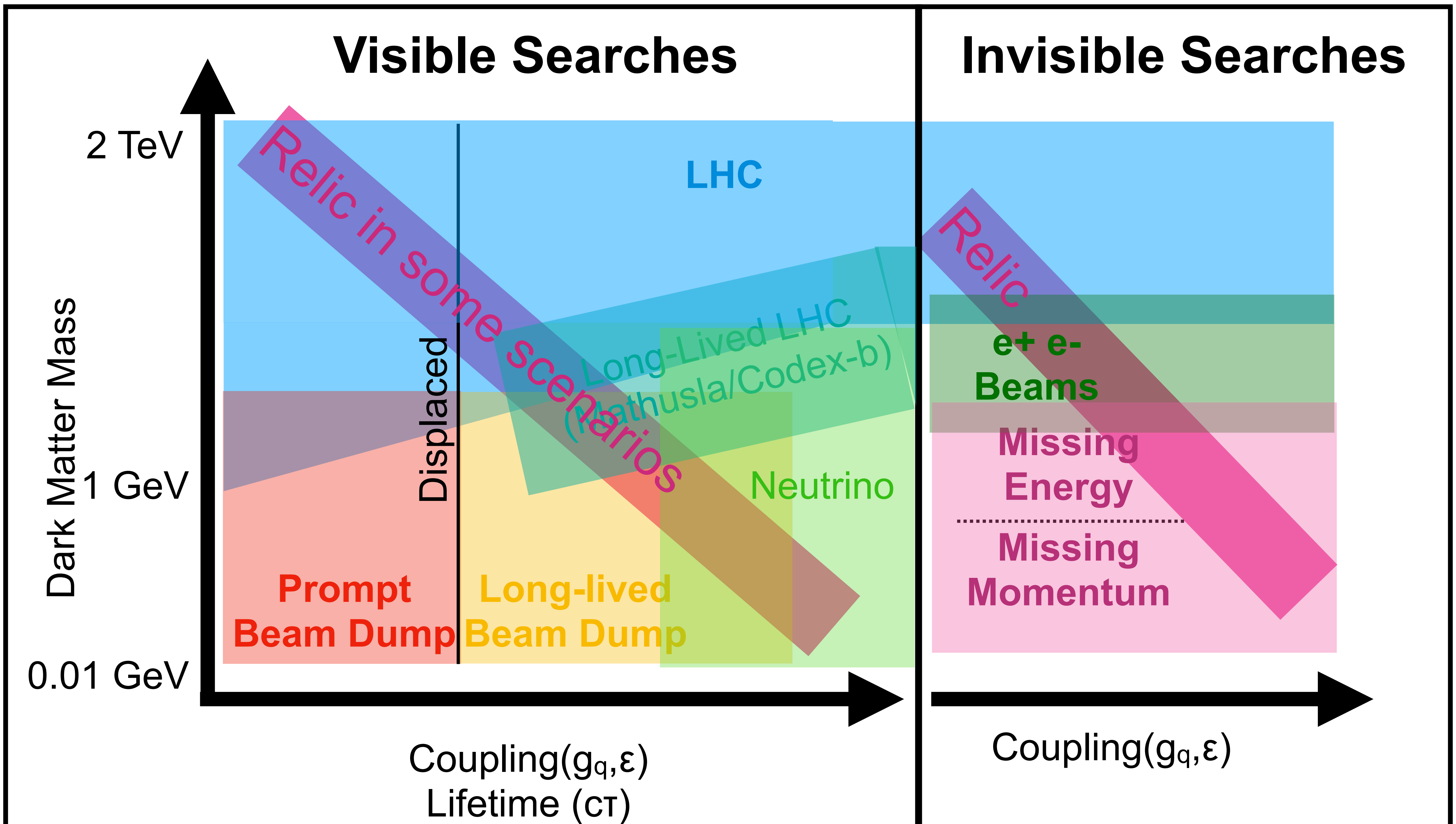




Visualizing the landscape




$c\tau_{dark}$
∞
p_T^{miss} + X
CMS
137 fb^{-1} (13 TeV)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^2
10^3
95% CL upper limits
$m_{DM} = m_{med} / 3$, $g_{DM} = 1.0$
Dark photon ($\alpha_D = 1/4\pi$)
JHEP 11 (2021) 153
Observed
Expected
Thermal-relic density ($\Omega_c h^2 \geq 0.12$)
1
nv



Visible Searches
Invisible Searches
2 TeV
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Dark Matter Mass
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Relic in some scenarios
Displaced
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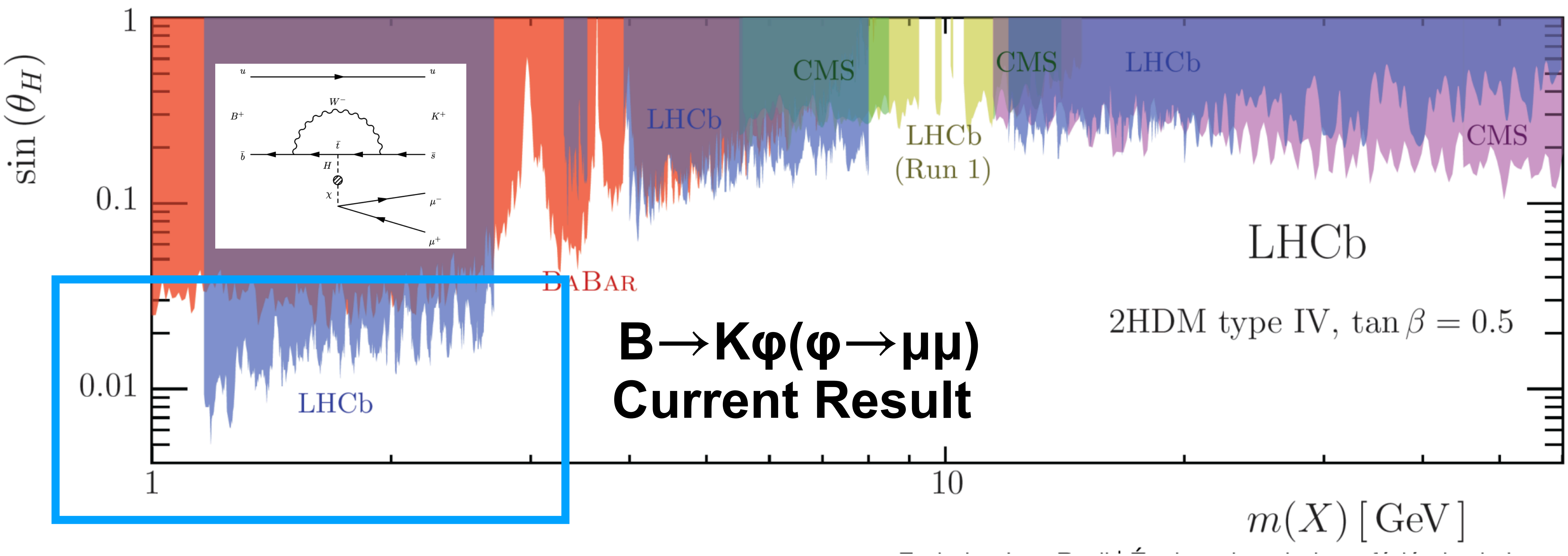
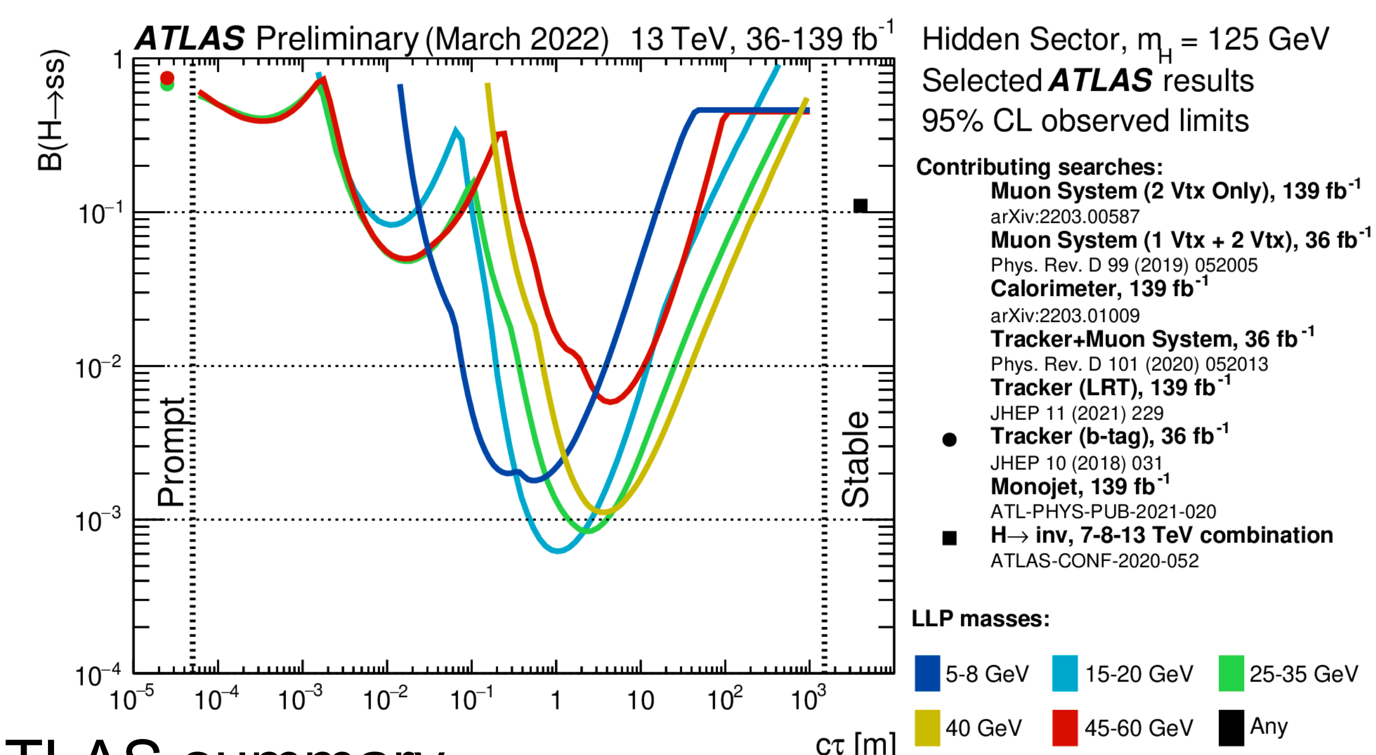
Beam Dump
Coupling(gq,ε)
Lifetime (cτ)
Relic
e+ e-
Beams
Missing
Energy
Missing
Momentum
Coupling(gq,ε)

Scalar Portal



B→Kφ(φ→μμ)
Current Result

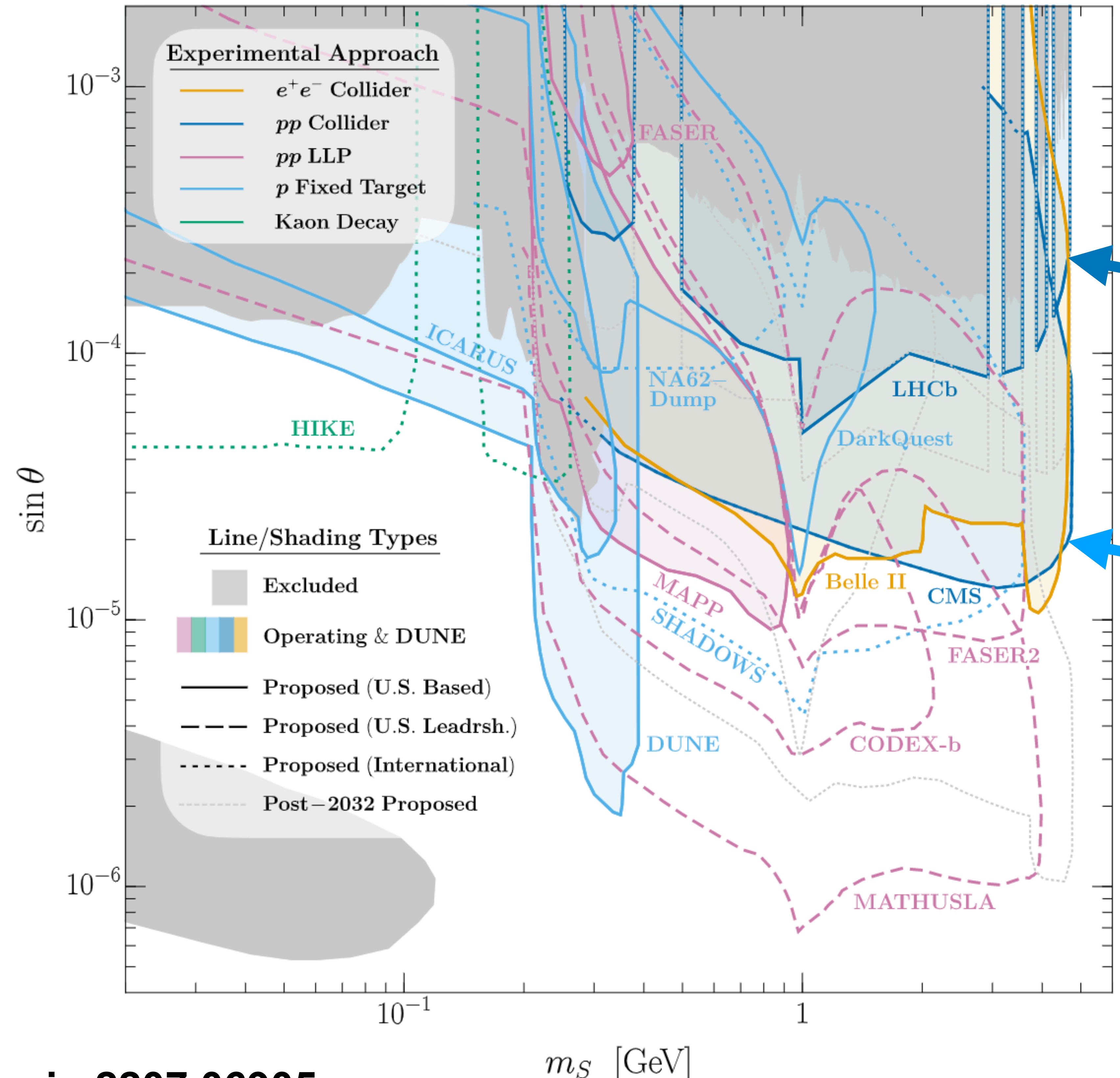


ATLAS summary

Once we get into the small coupling regime

Long-Lived searches start to domiante

Scalar Portal



B→Xφ(φ→μμ)
LHCb Future Projections

B→Xφ(φ→μμ)
Future CMS Long Lived Track Trigger

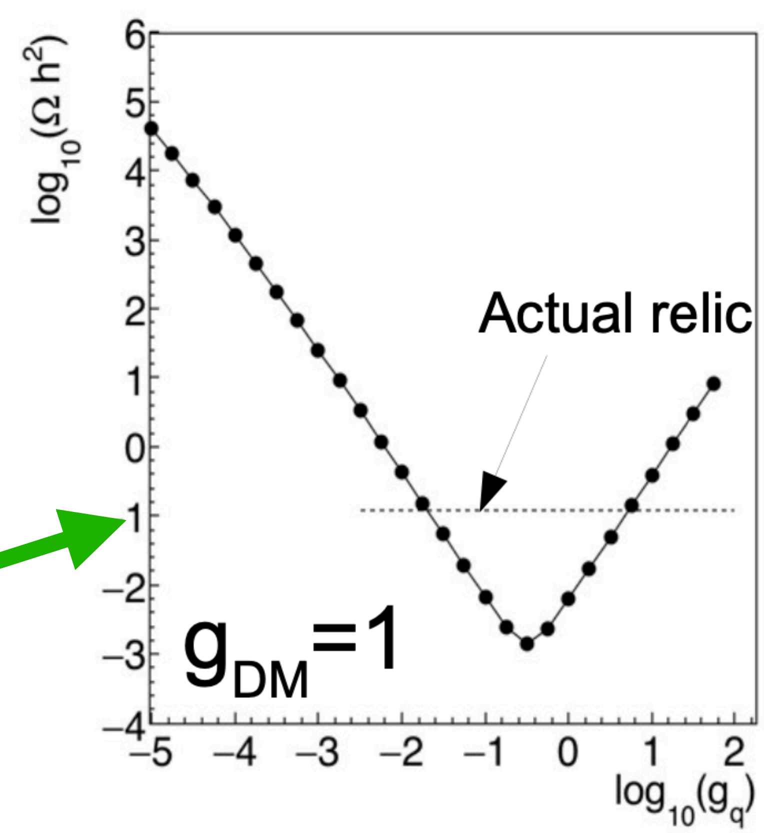
Era of Long Lived Exploration is just starting
Many more like CMS on their way

arxiv:2207.06905

Minimum Coupling Scan

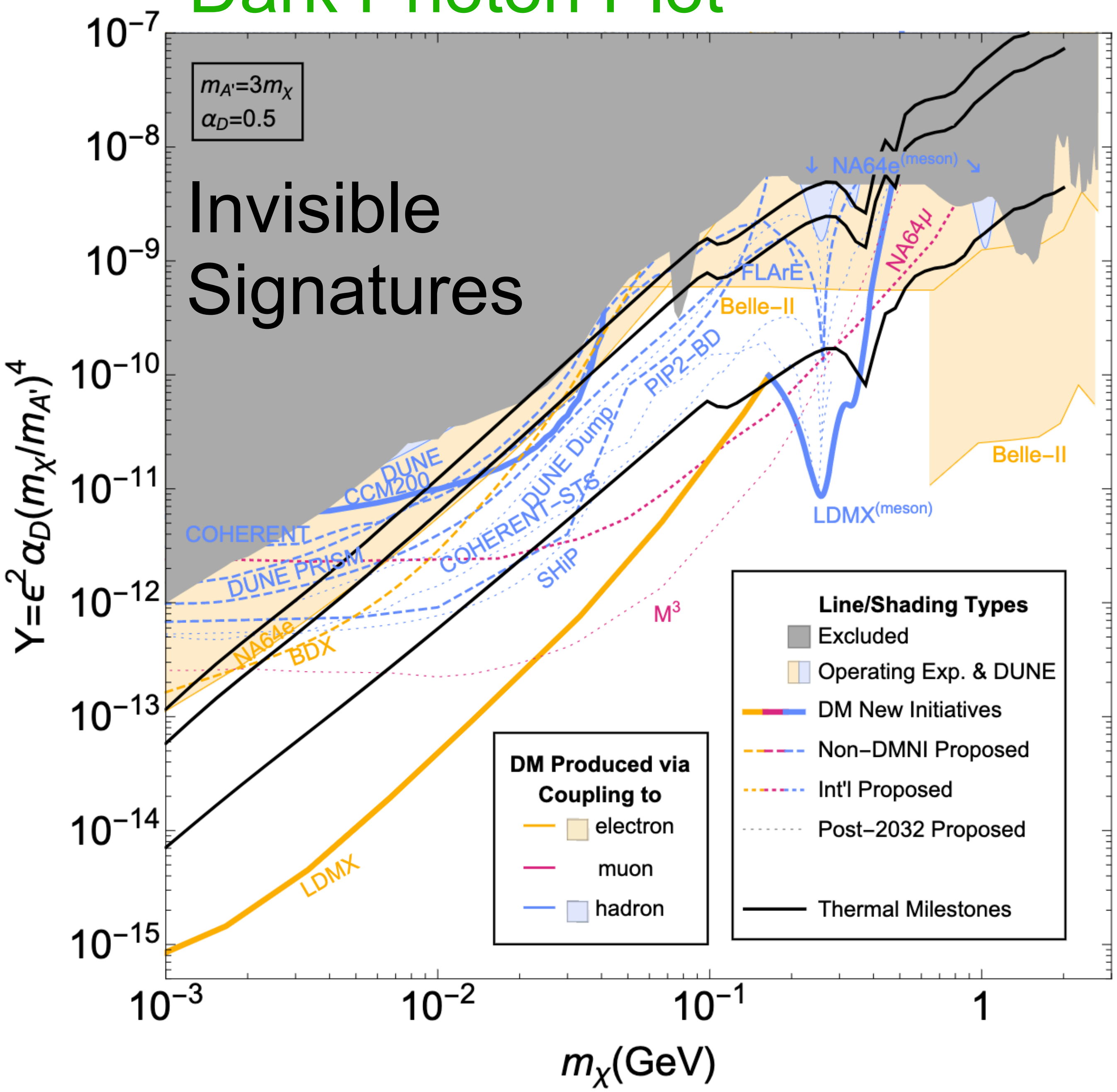
- As w/all simpified DM models there is a minimum coupling
- For the LHC models we can compute the relic density
  - Simplified models, so relic calculation is simplified
  - Compute relic density with MadDM
- We scan the full dark matter mass vs mediator mass
  - Useful to see

The Mininmum



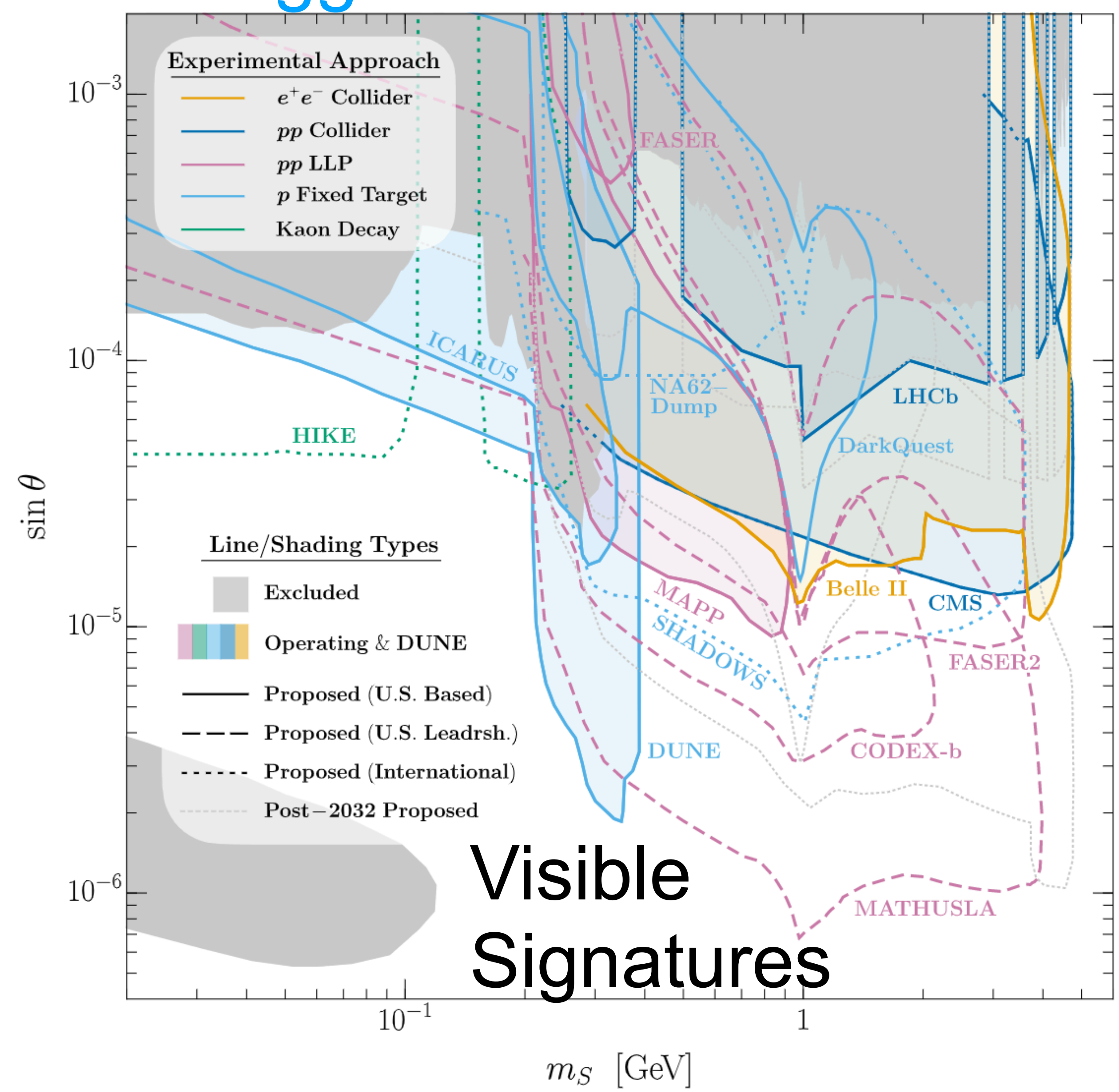
Light DM at Snowmass

Dark Photon Plot



We will focus on invisible signatures for LHC to compare with

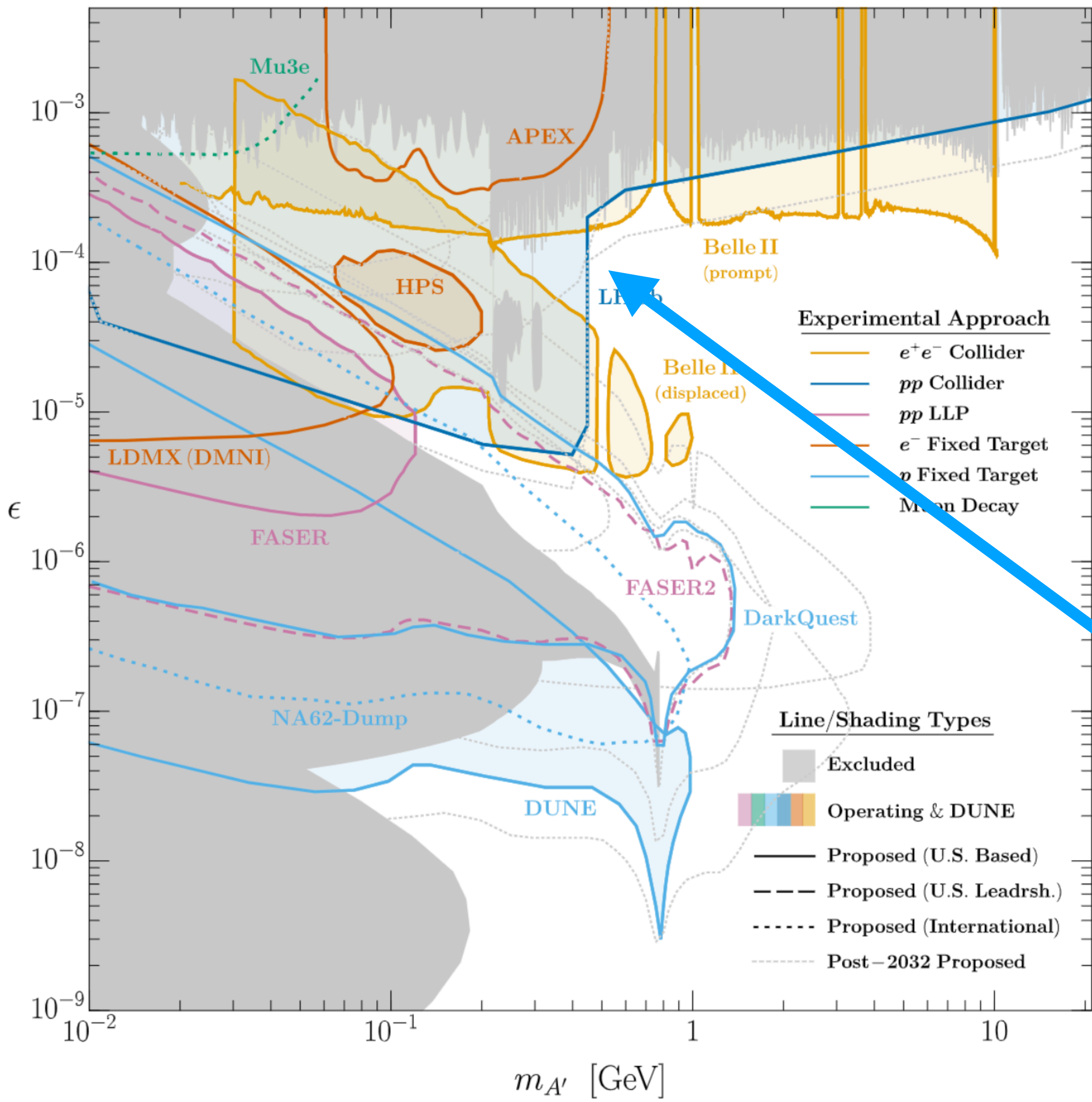
Dark Higgs Plot



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

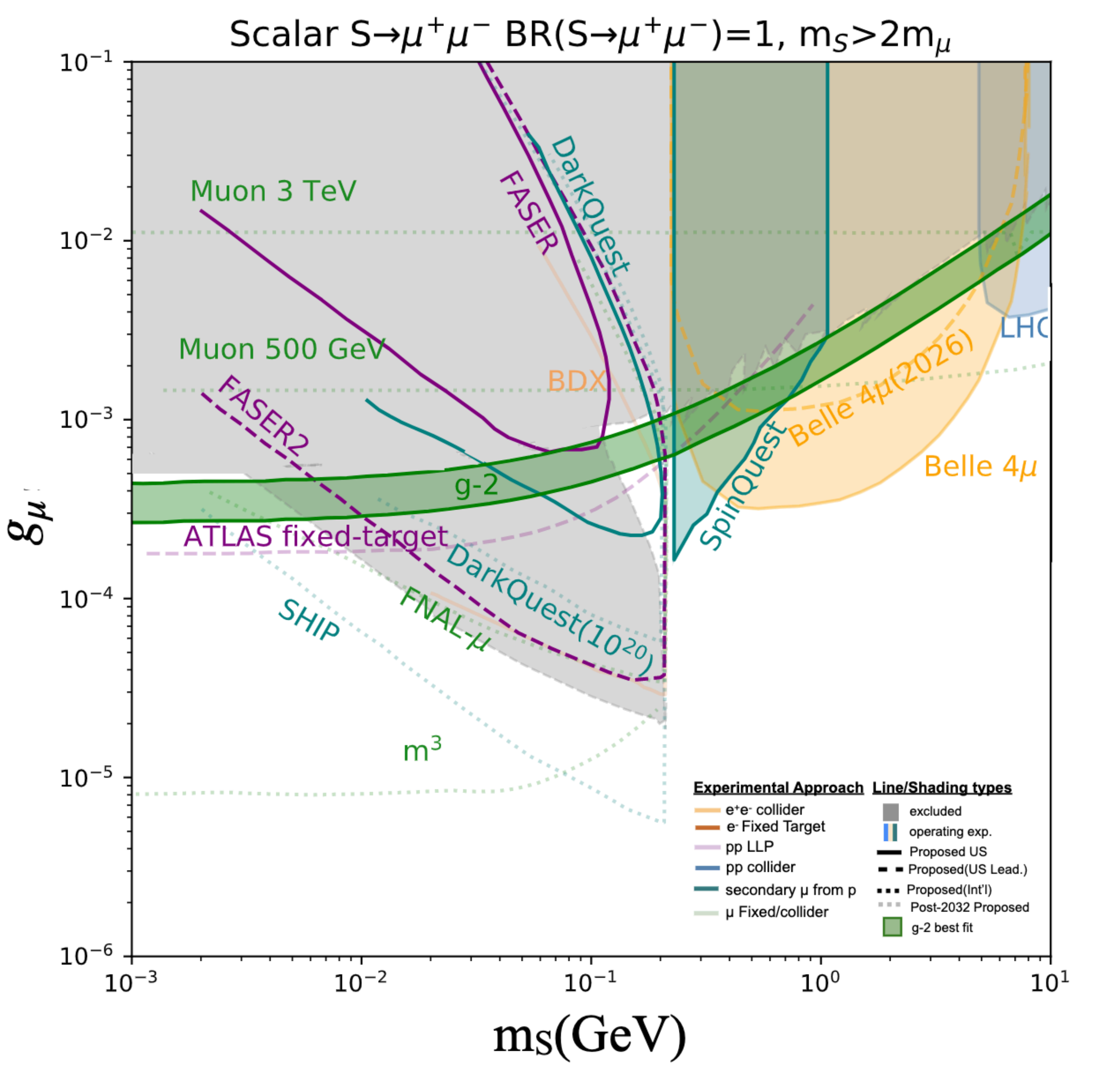
Effort to highlight weak coupled Dark Photon

Coupling weak enough to be long-lived

Potential to connect w/LL group

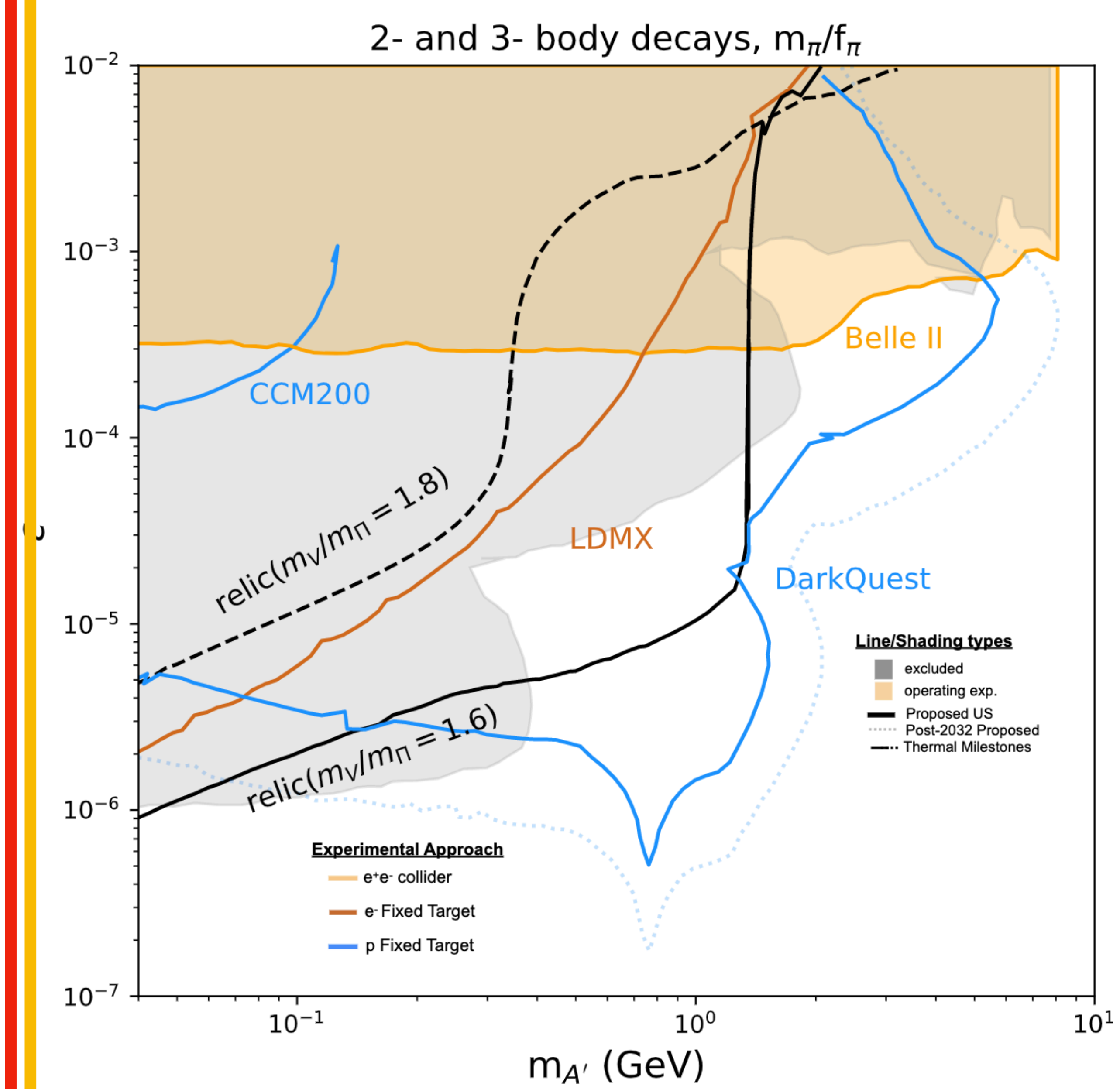
Other Highlights

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

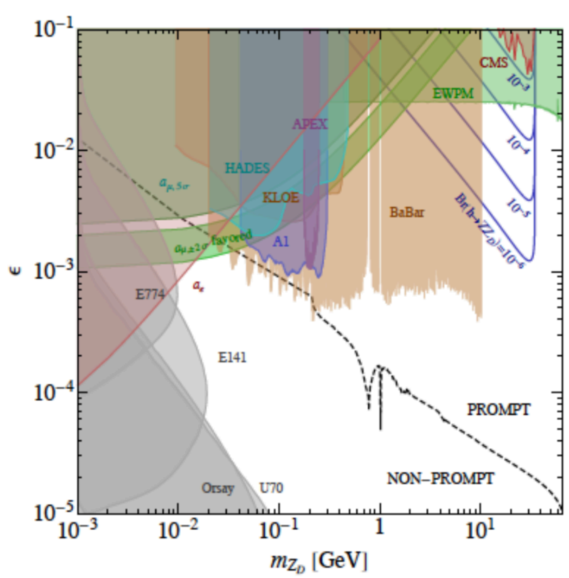
Actually Reconciling

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

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

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

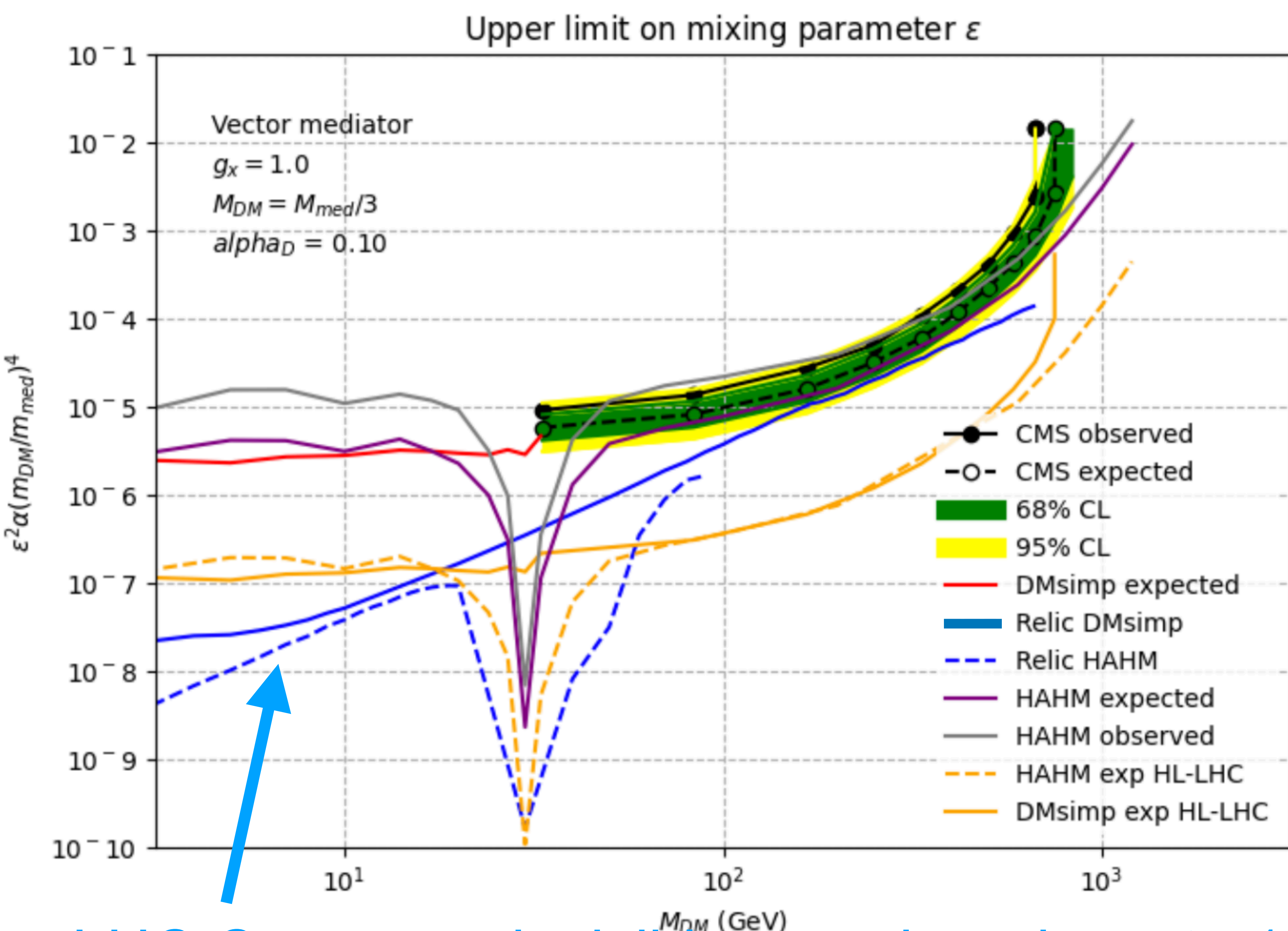
$$g_q = \frac{e\sin\theta_a}{2\tan\theta_w} \approx e\epsilon \frac{1}{\Delta_z - 1} \frac{\cos\theta_w}{2}$$

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

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

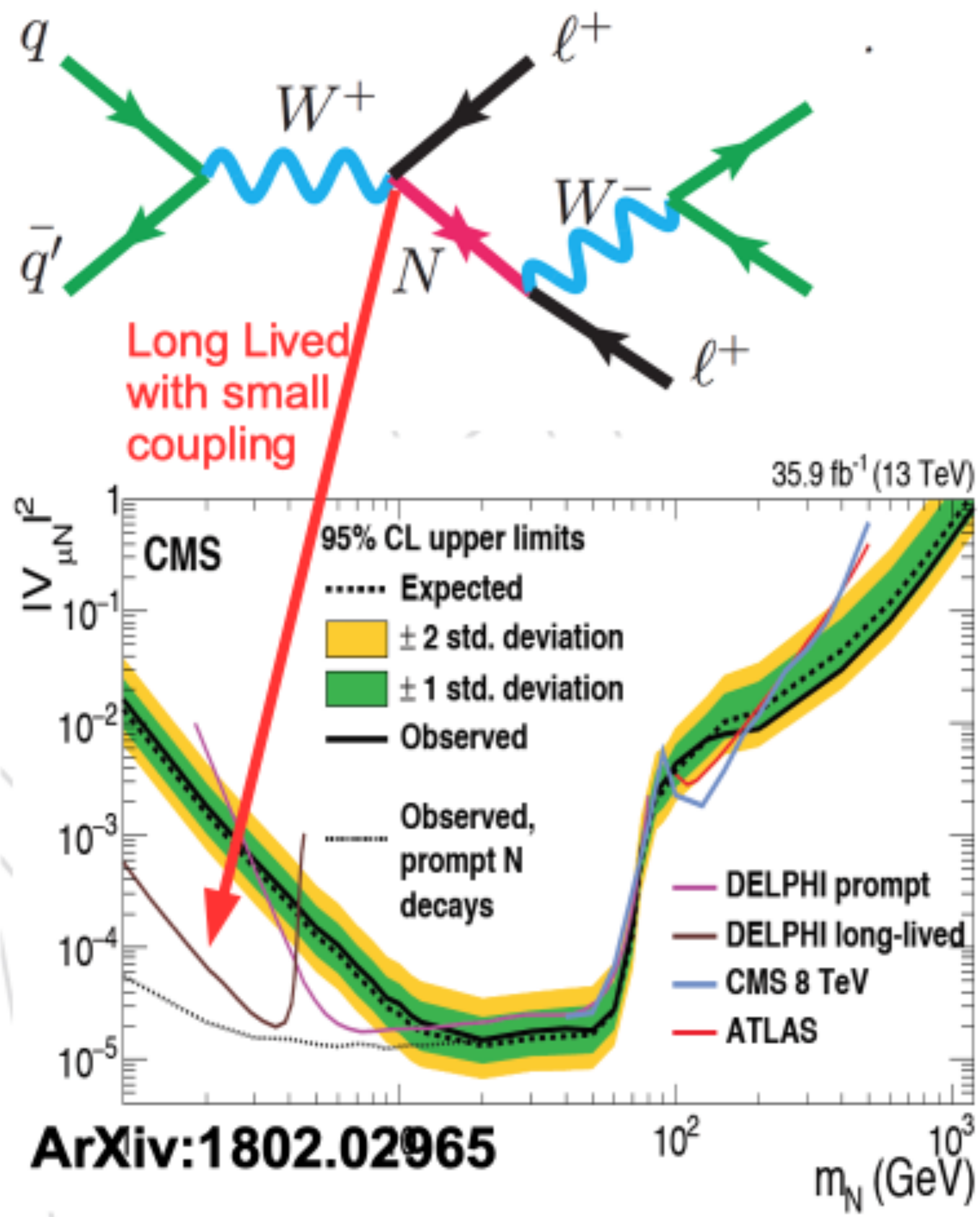
LHCDMWG Projected

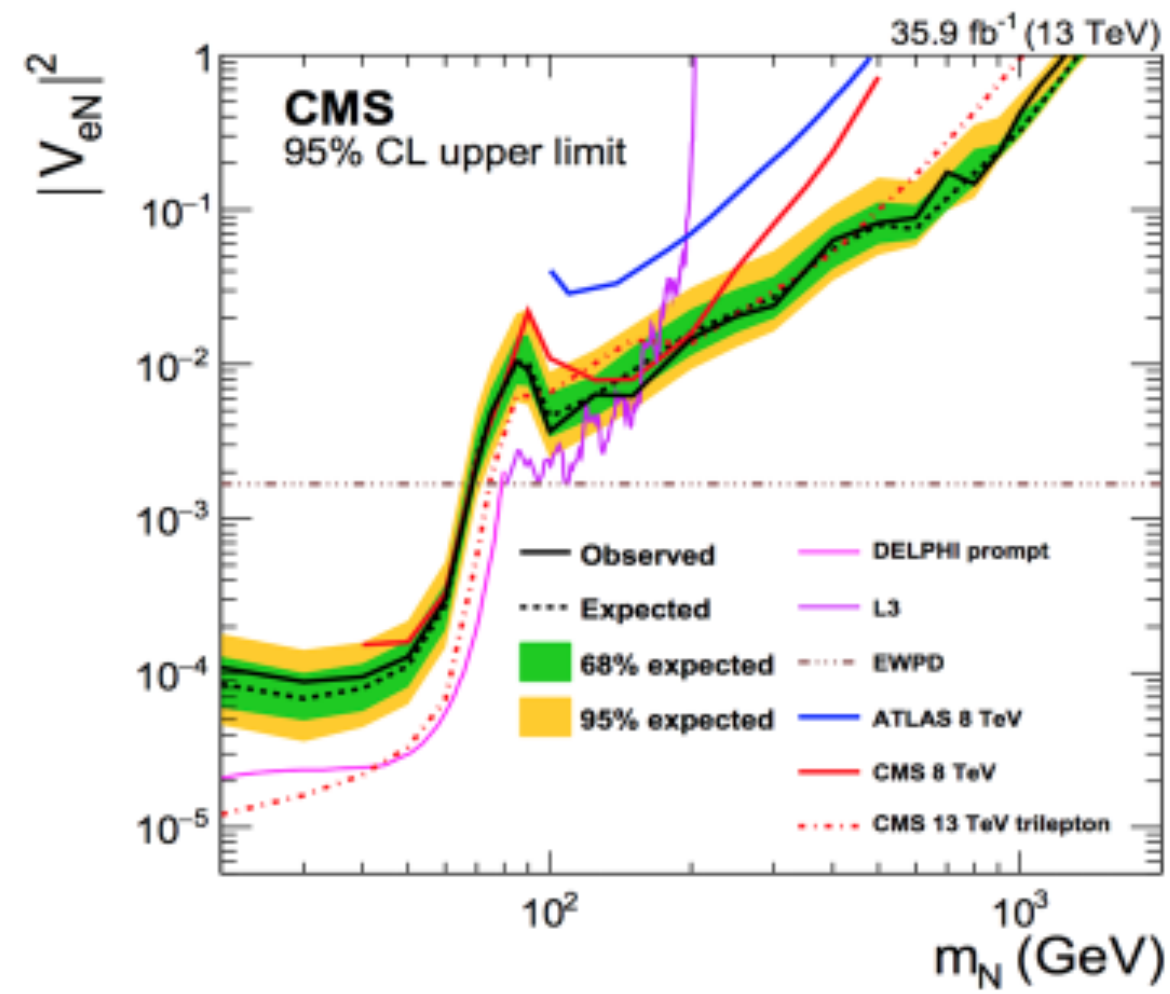
LHC Can cover invisible searches down to 10 GeV in DM mass

HNLs

Expect Bounds at low mass to improve

Once long lived analysis is performed

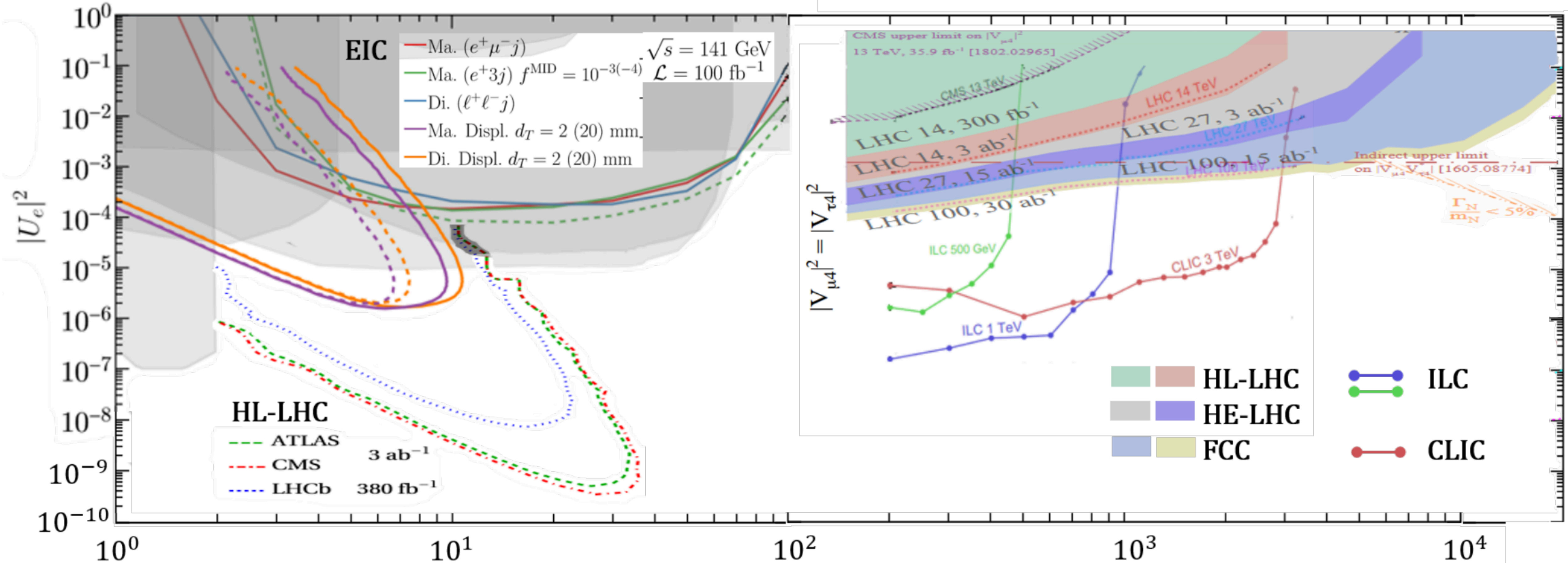


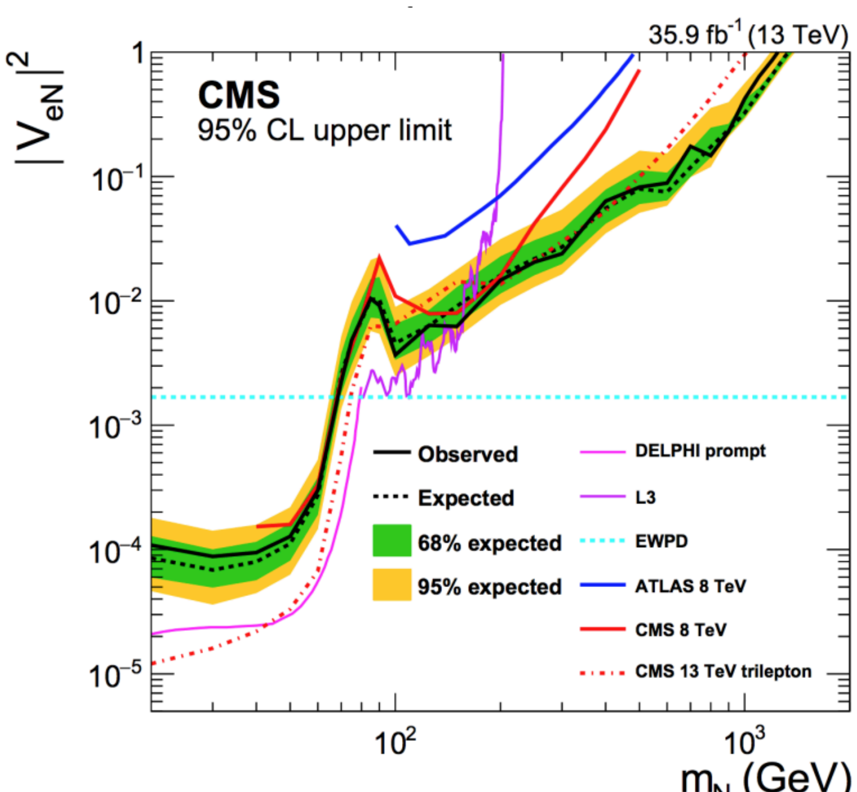


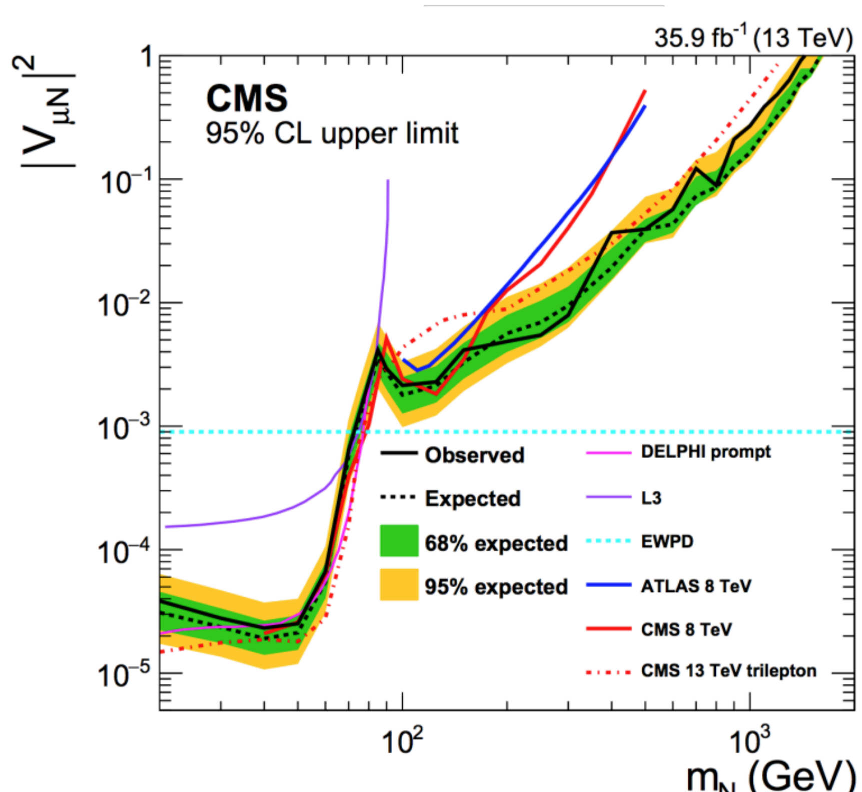
ArXiv:1802.02965

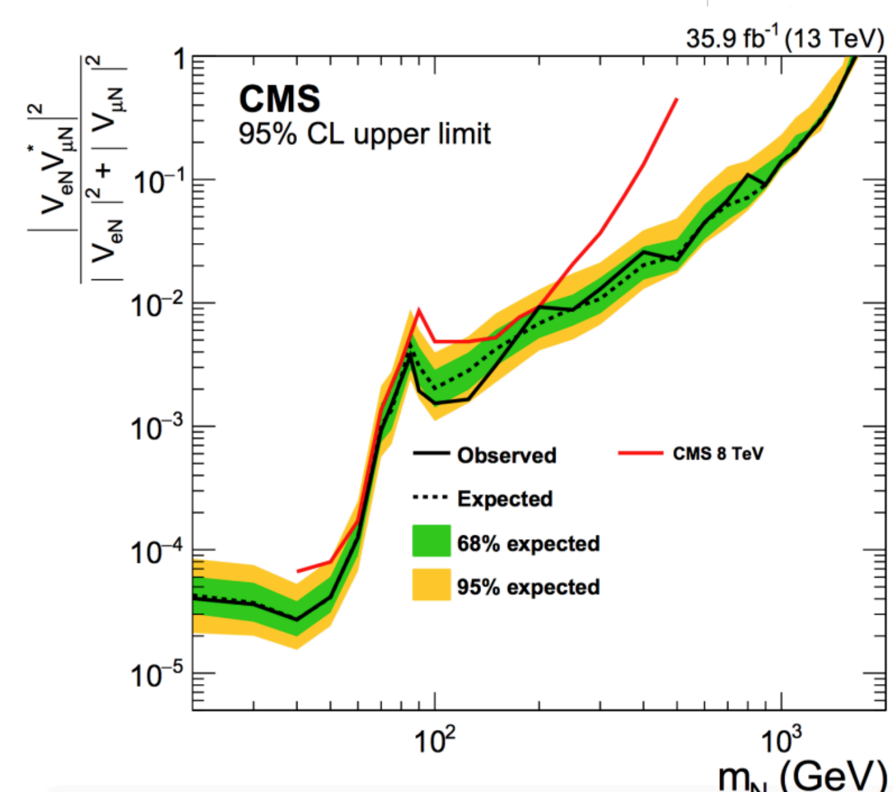
CMS-EXO-17-028

HNLs

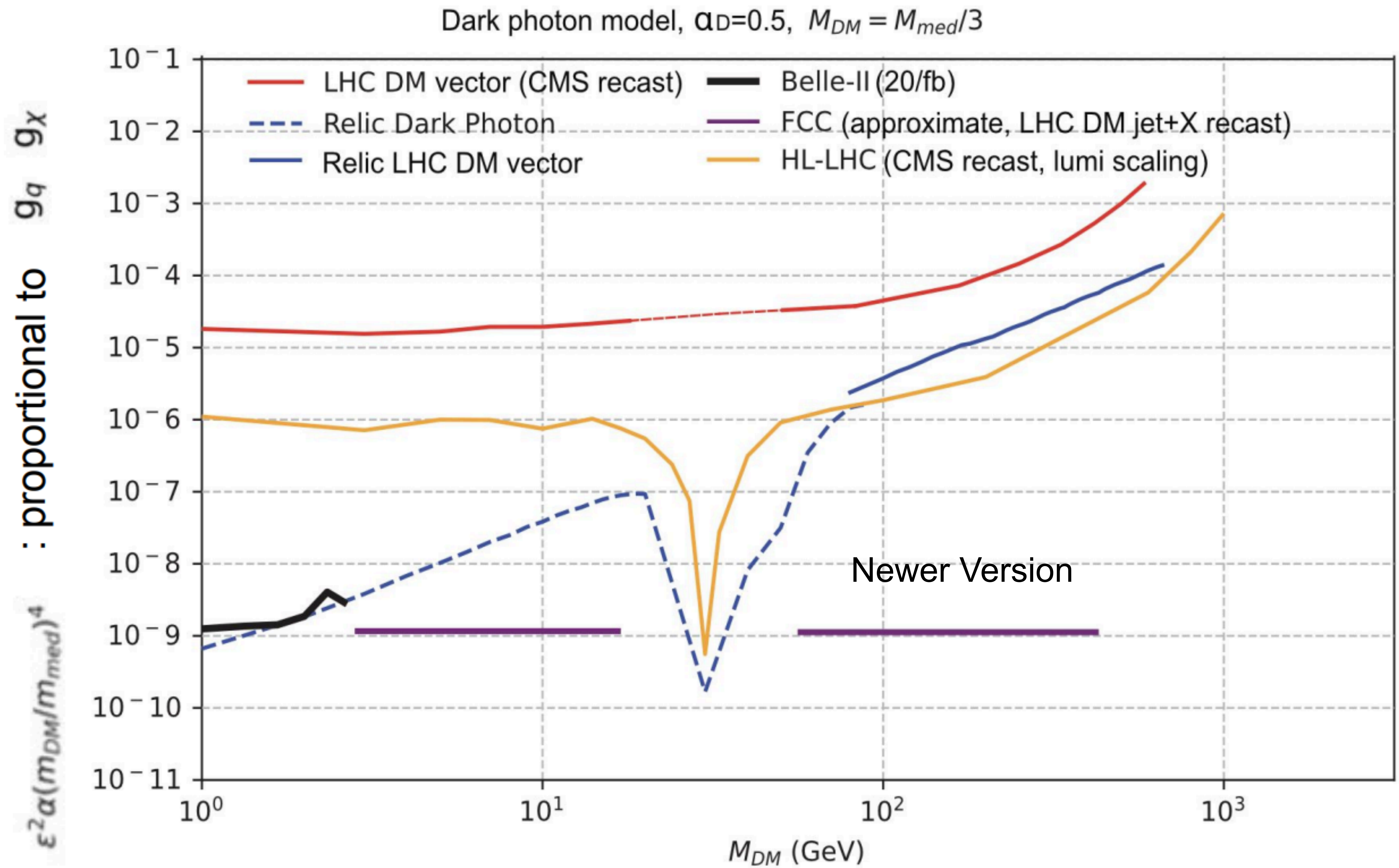

EIC
Ma. $(e^+\mu^- j)$
Ma. (e^+3j) $f^{\text{MID}} = 10^{-3(-4)}$
Di. $(\ell^+\ell^- j)$
Ma. Displ. $d_T = 2$ (20) mm
Di. Displ. $d_T = 2$ (20) mm
$\sqrt{s} = 141$ GeV
$\mathcal{L} = 100$ fb^{-1}
$|U_e|^2$
HL-LHC
ATLAS
CMS
LHCb
3 ab^{-1}
380 fb^{-1}
$|V_{\mu 4}|^2 = |V_{\tau 4}|^2$
LHC 14, 300 fb^{-1}
LHC 14, 3 ab^{-1}
LHC 27, 15 ab^{-1}
LHC 100, 30 ab^{-1}
LHC 27, 3 ab^{-1}
LHC 100, 15 ab^{-1}
LHC 14 TeV
LHC 27 TeV
ILC 500 GeV
ILC 1 TeV
CLIC 3 TeV
HL-LHC
HE-LHC
FCC
ILC
CLIC
10^0
10^1
10^2
10^3
10^4


35.9 fb^{-1} (13 TeV)
CMS
95% CL upper limit
$|V_{eN}|^2$
Observed
Expected
68% expected
95% expected
DELPHI prompt
L3
EWPD
ATLAS 8 TeV
CMS 8 TeV
CMS 13 TeV trilepton
m_N (GeV)


35.9 fb^{-1} (13 TeV)
CMS
95% CL upper limit
$|V_{\mu N}|^2$
Observed
Expected
68% expected
95% expected
DELPHI prompt
L3
EWPD
ATLAS 8 TeV
CMS 8 TeV
CMS 13 TeV trilepton
m_N (GeV)

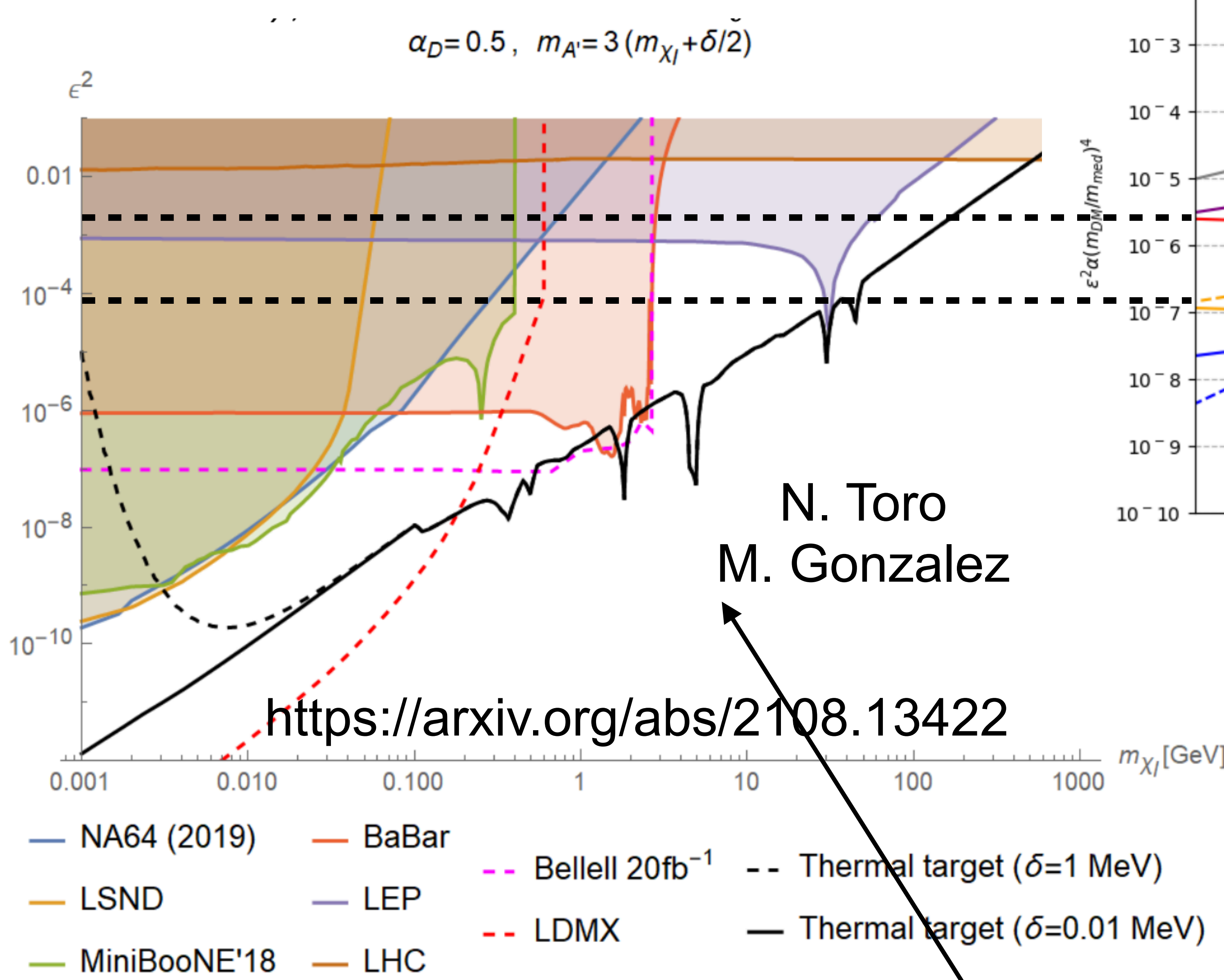

35.9 fb^{-1} (13 TeV)
CMS
95% CL upper limit
$\frac{|V_{eN}V^*_{\mu N}|^2}{|V_{eN}|^2 + |V_{\mu N}|^2}$
Observed
Expected
68% expected
95% expected
CMS 8 TeV
m_N (GeV)

Dark Photon w/α_D=0.5



Check of Some Params

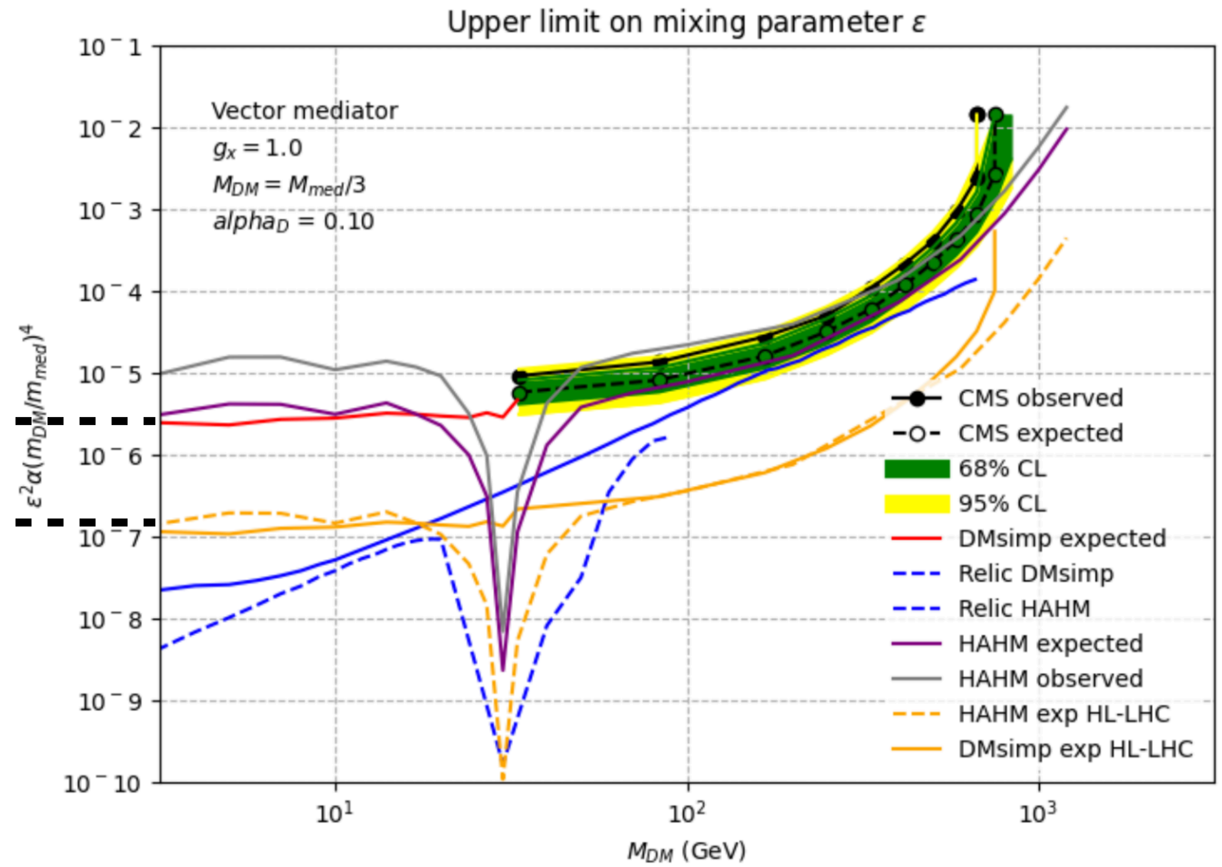
Relic calculations match pretty closely with other calculations



N. Toro
M. Gonzalez

https://arxiv.org/abs/2108.13422

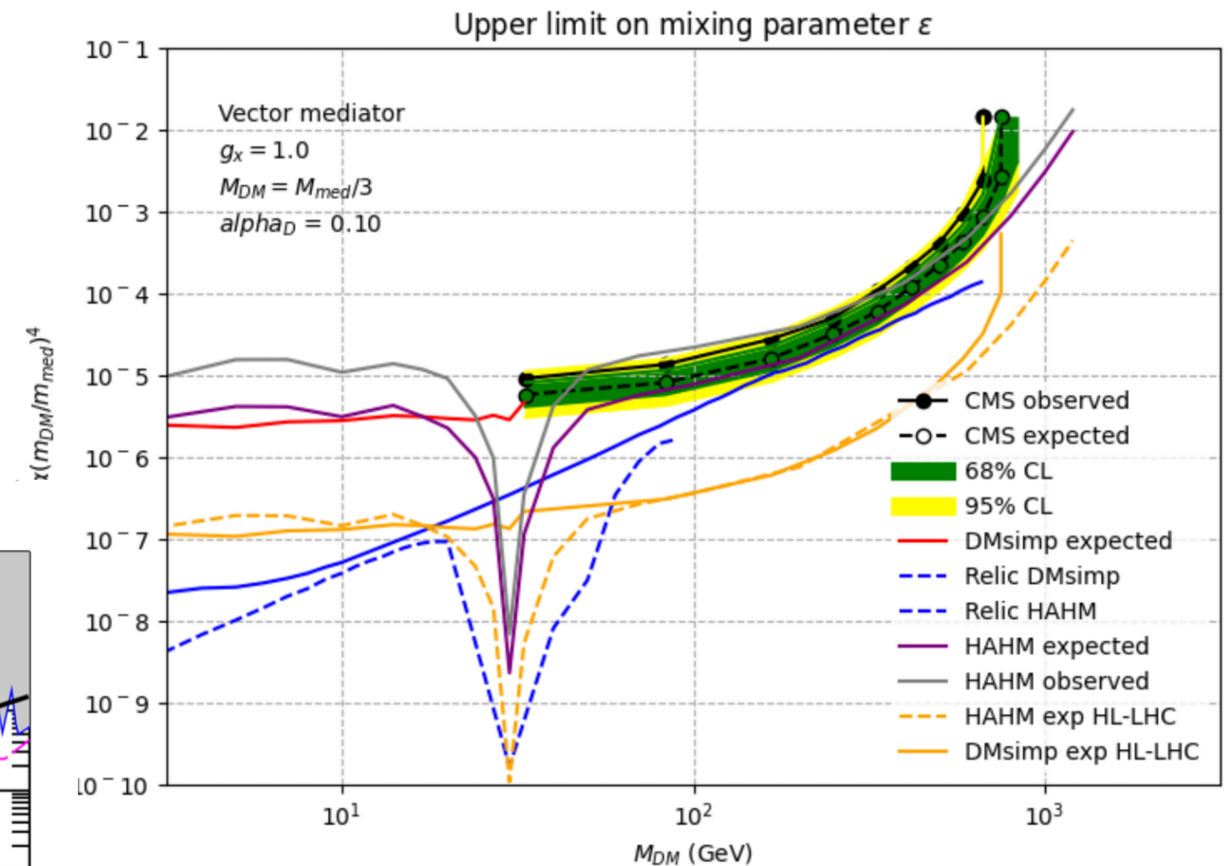
Cross Check

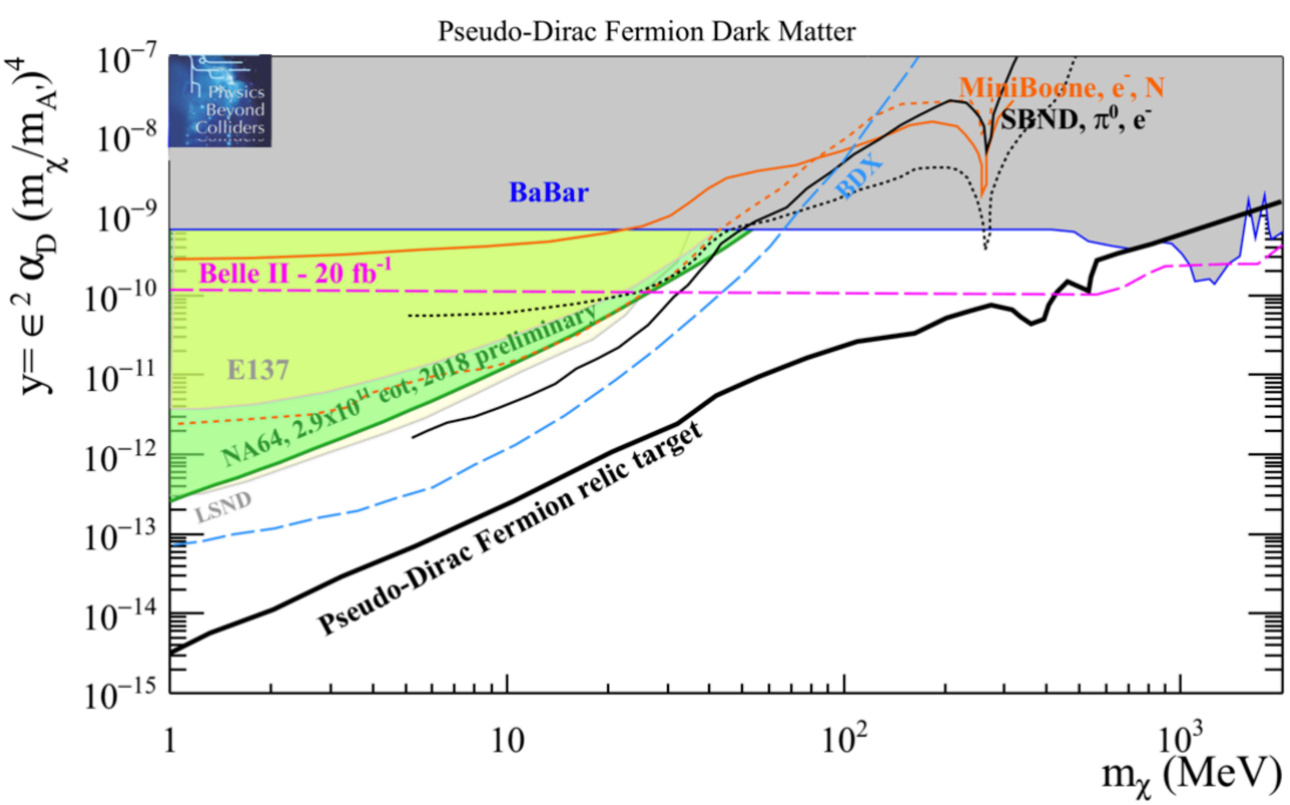


Bounds from LHC appear stronger than on left plot

Now Connecting them

Appears that w can now connect plots into one





LHC is complemntary

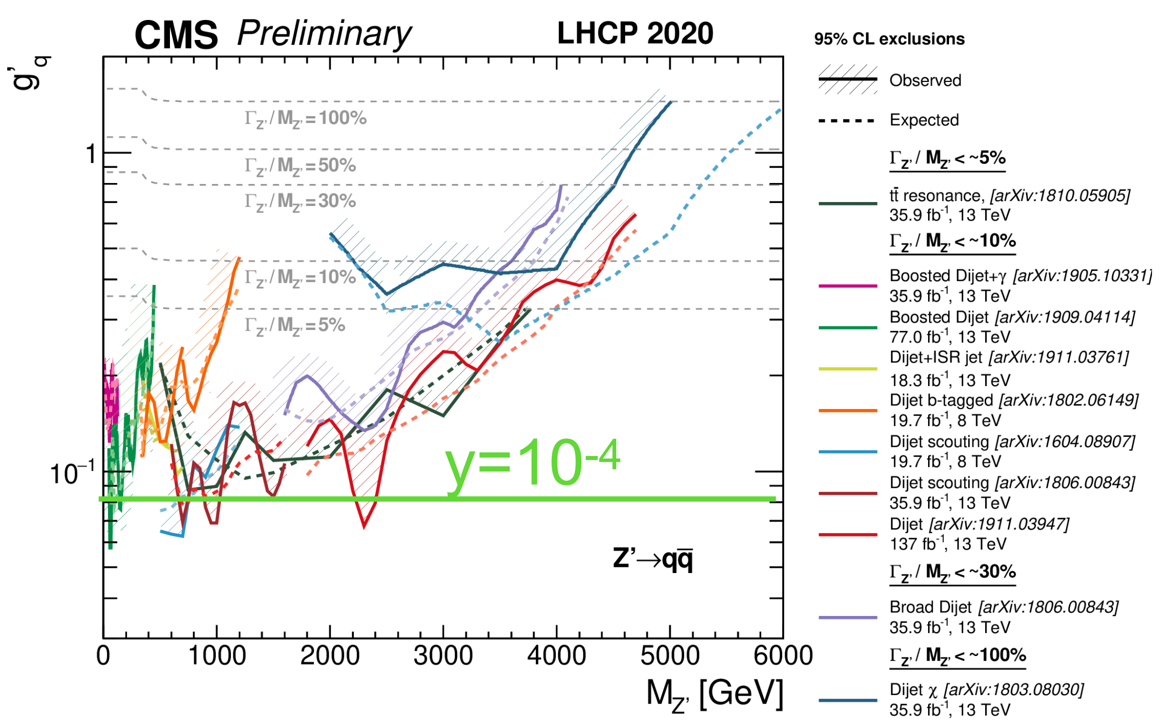
Similar goals on similar timesales

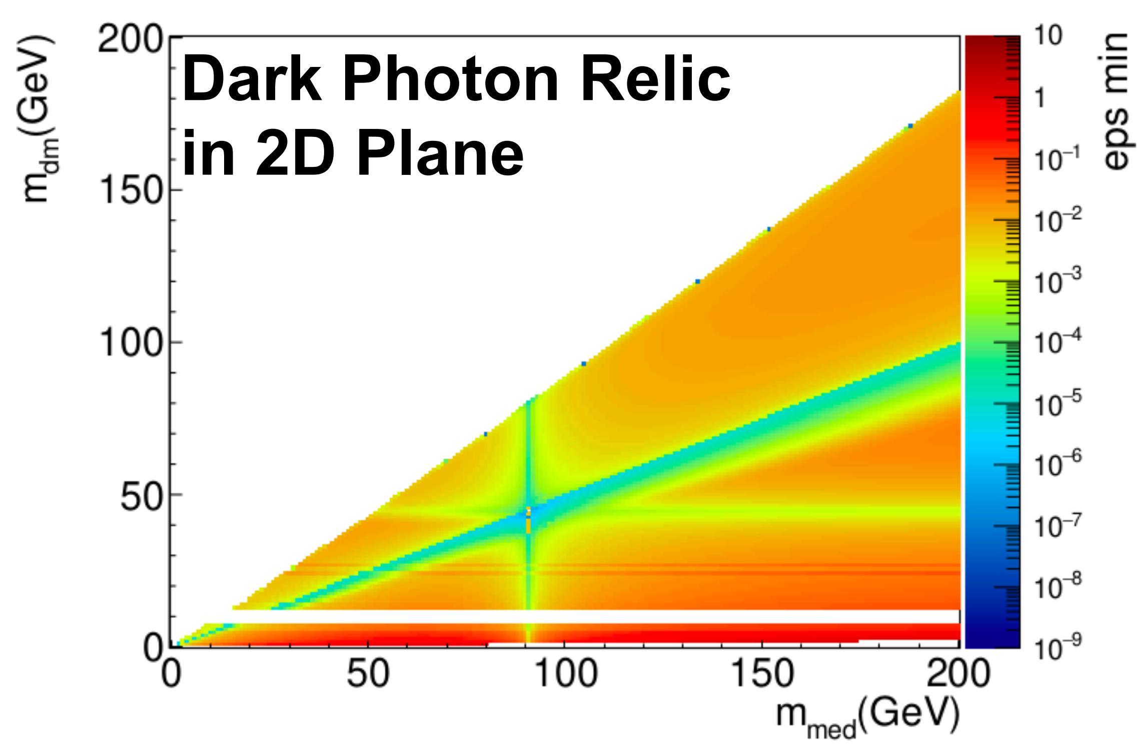
LHC goes left when mediator mass gets larrger

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

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

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	$y_N L H N$

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

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

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

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

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

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

What if we make a complete singlet scalar model?

Observed mass eigenstates

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

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

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

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

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

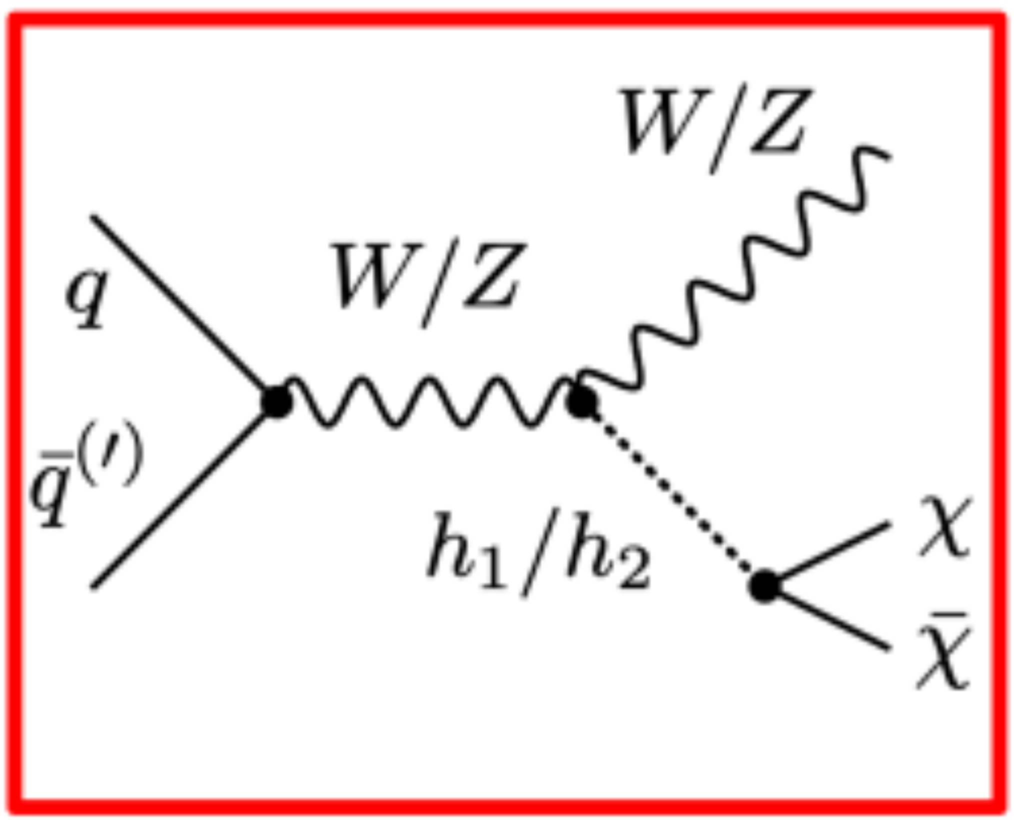
$$\mathcal{L} \supset -g_{\rm DM}\left(\sin\theta\, h_1 + \cos\theta\, h_2\right)\bar{\chi}\chi$$

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

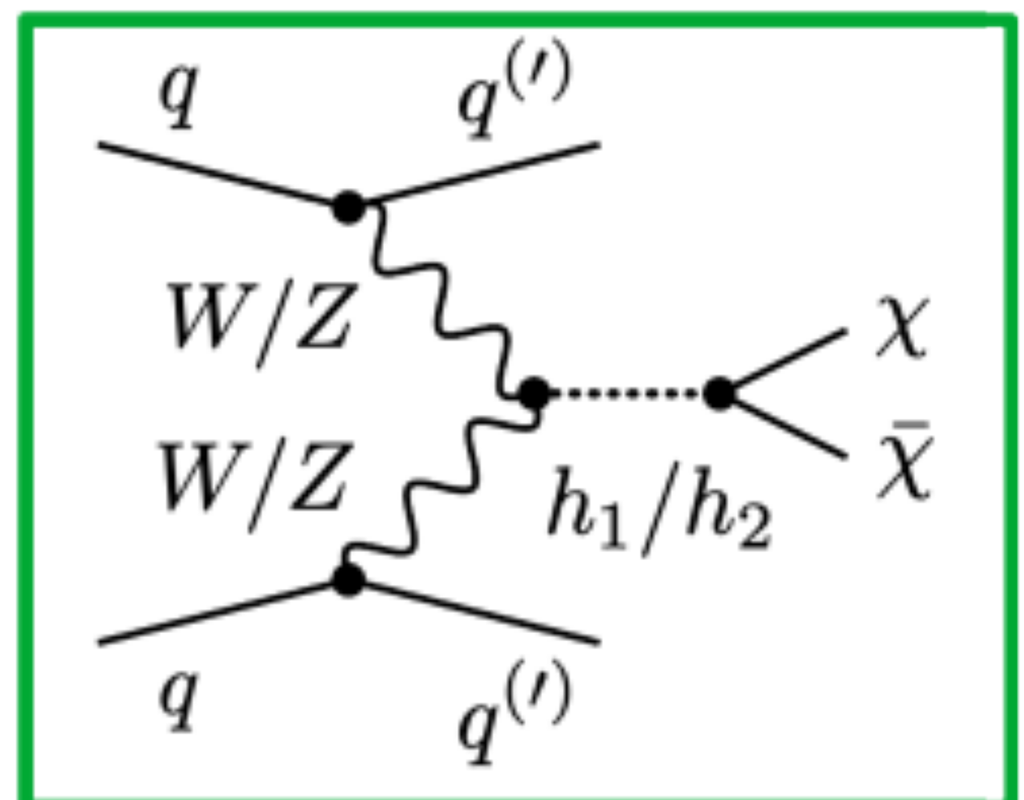
Details of Model Here

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

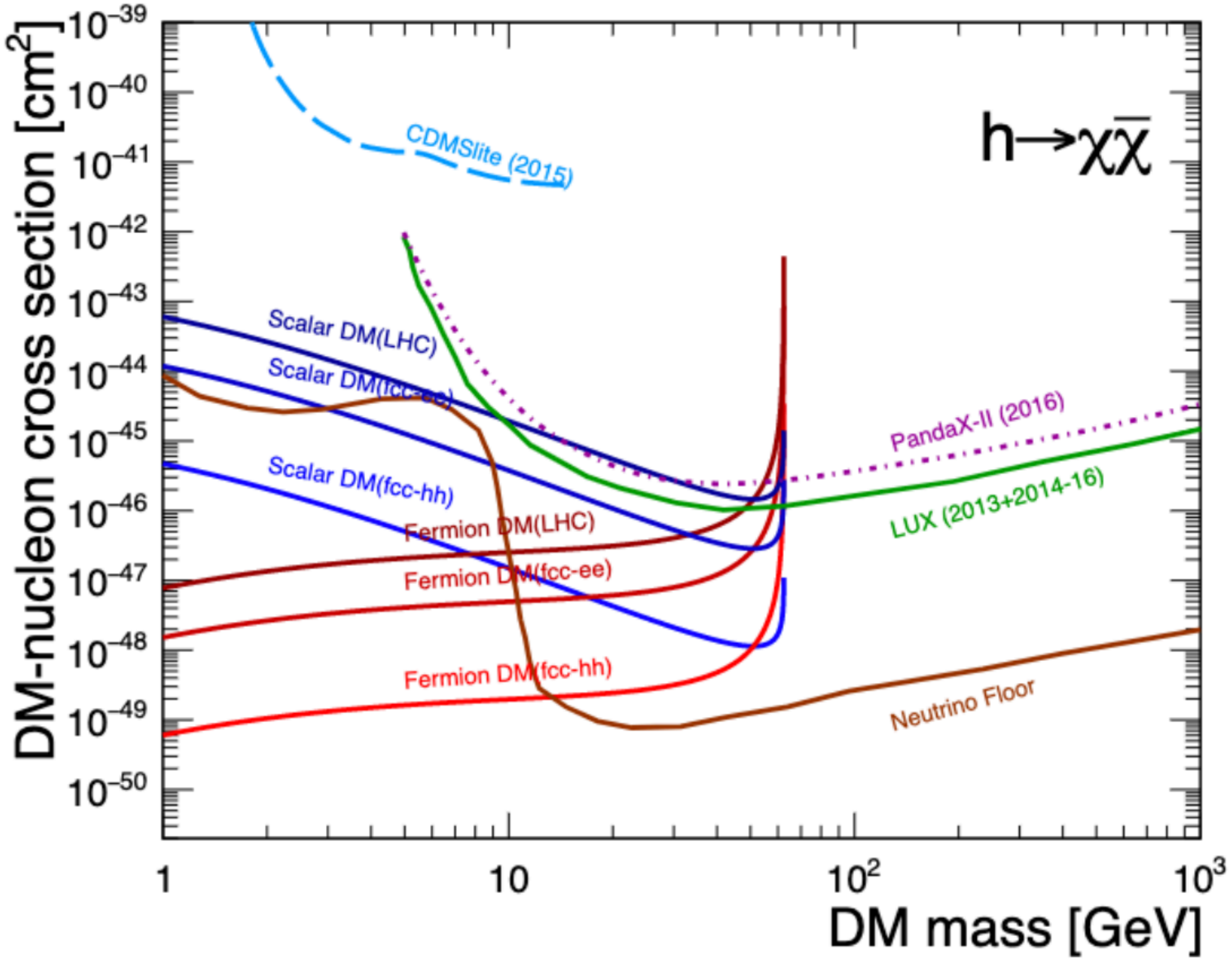
Both invisible decay and Couplings play a critical role

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

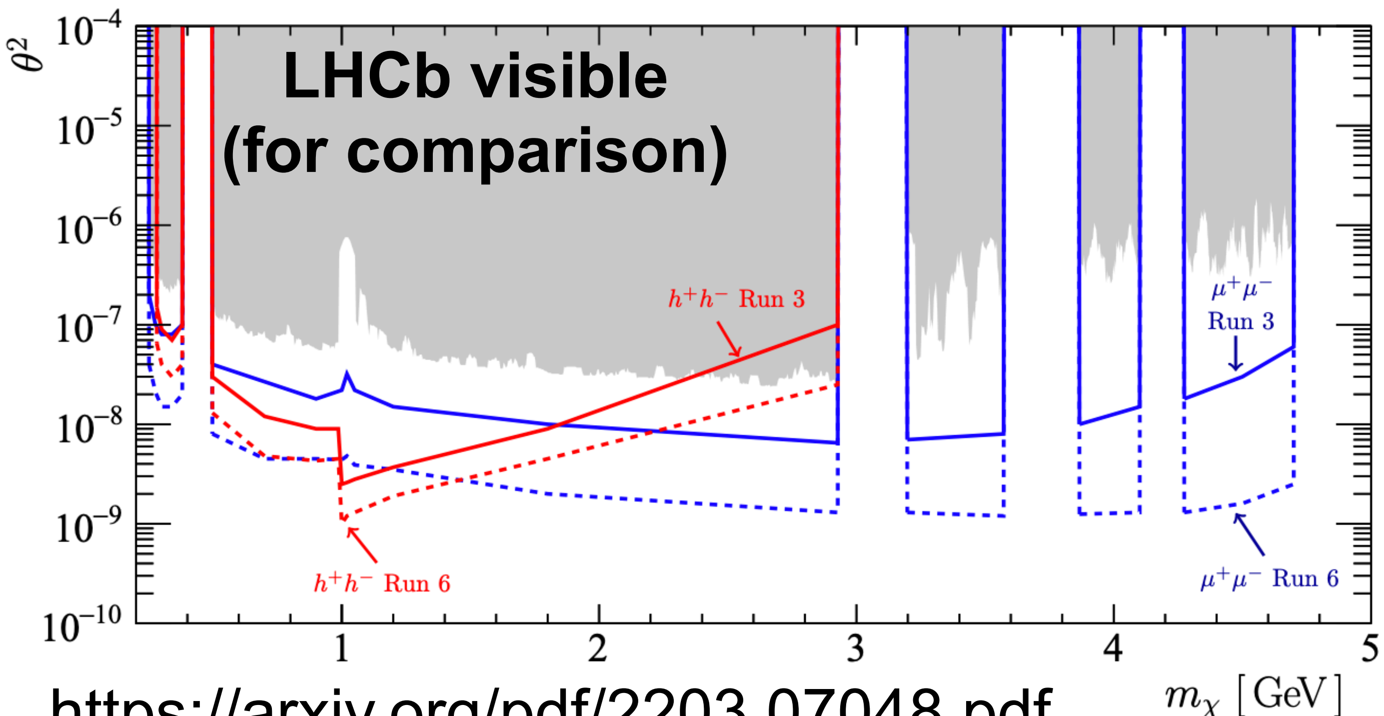
- Higgs to invisible Bounds
  - Current LHC H(inv) > 0.1
  - Future LHC H(inv) >0.02
  - FCC-ee H(inv) > 0.005
  - FCC-hh H(inv) > 0.0001



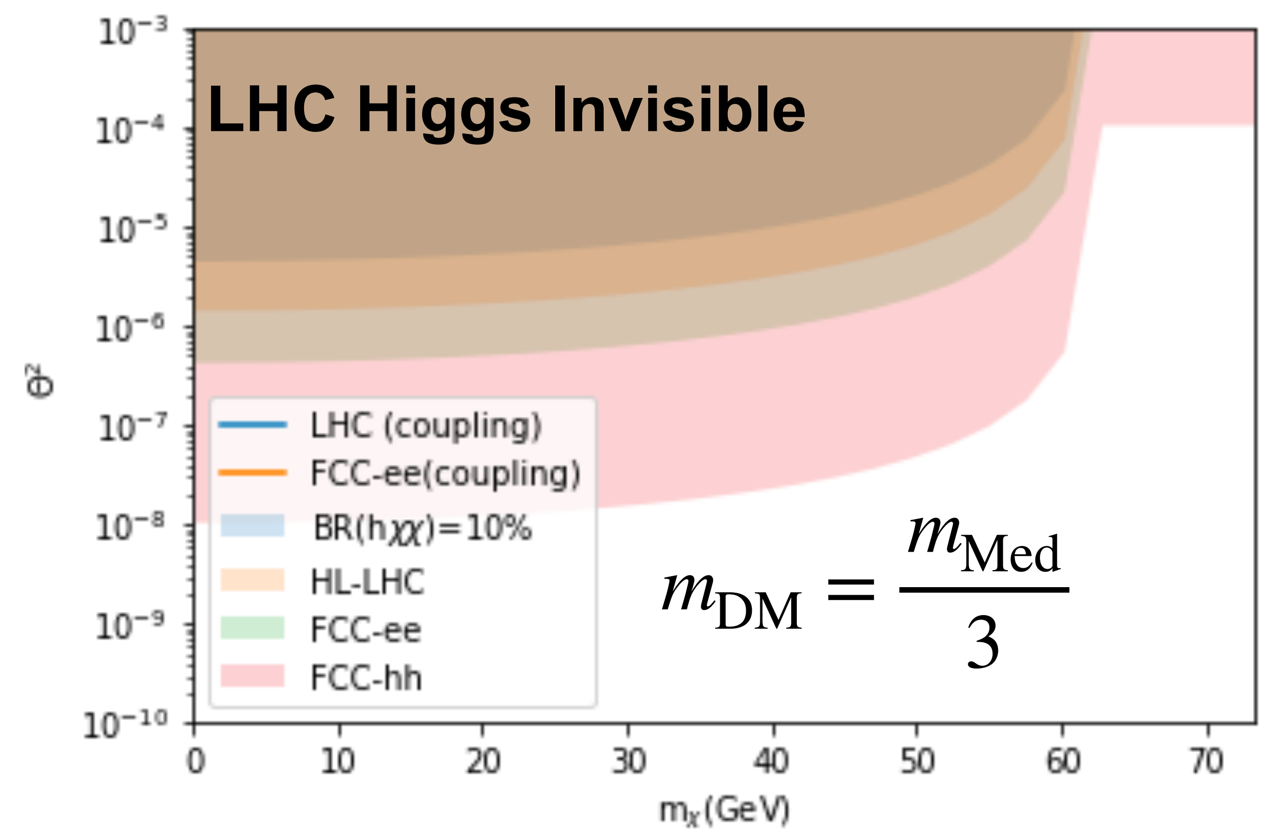
- Current projections of Higgs to invisible similar to Direct Detection
  - Sensitivities comaprable in the low DM mass region
  - LHC exceed neutrino floor for light DM

Comparing Standard Plot

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

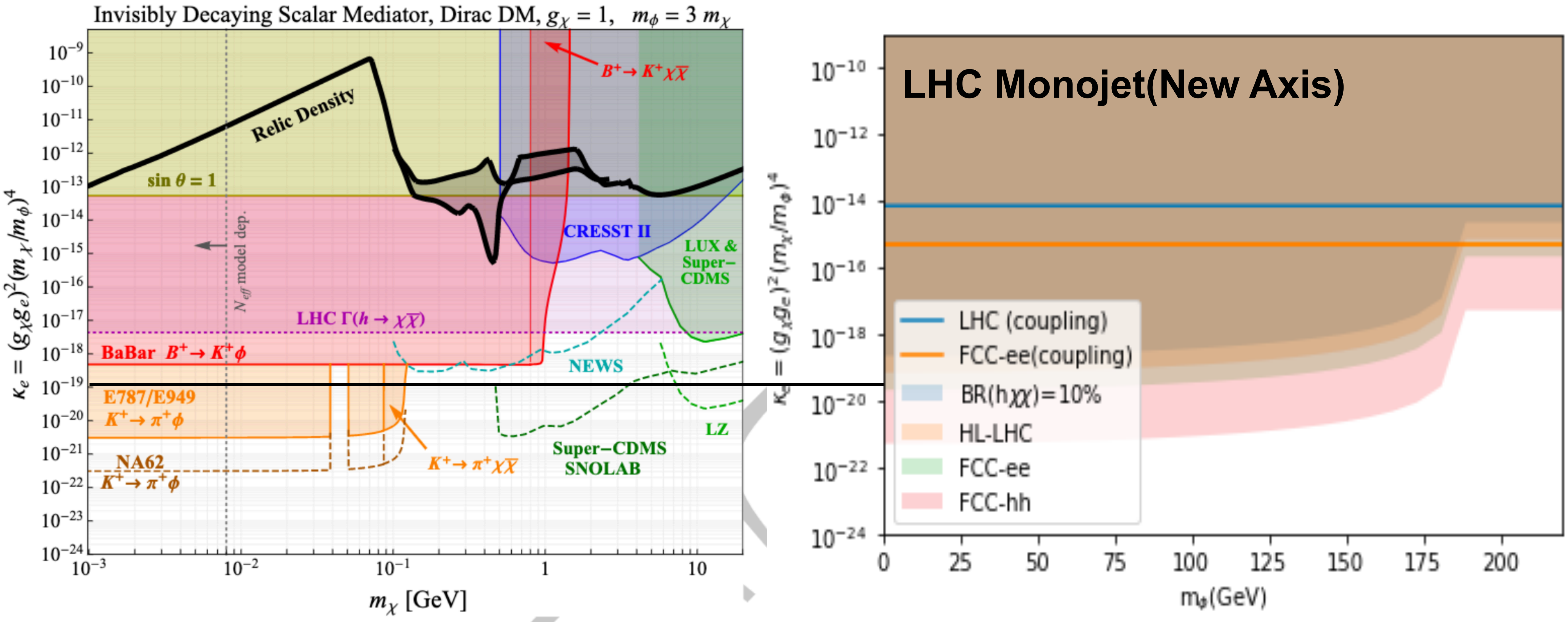


https://arxiv.org/pdf/2203.07048.pdf



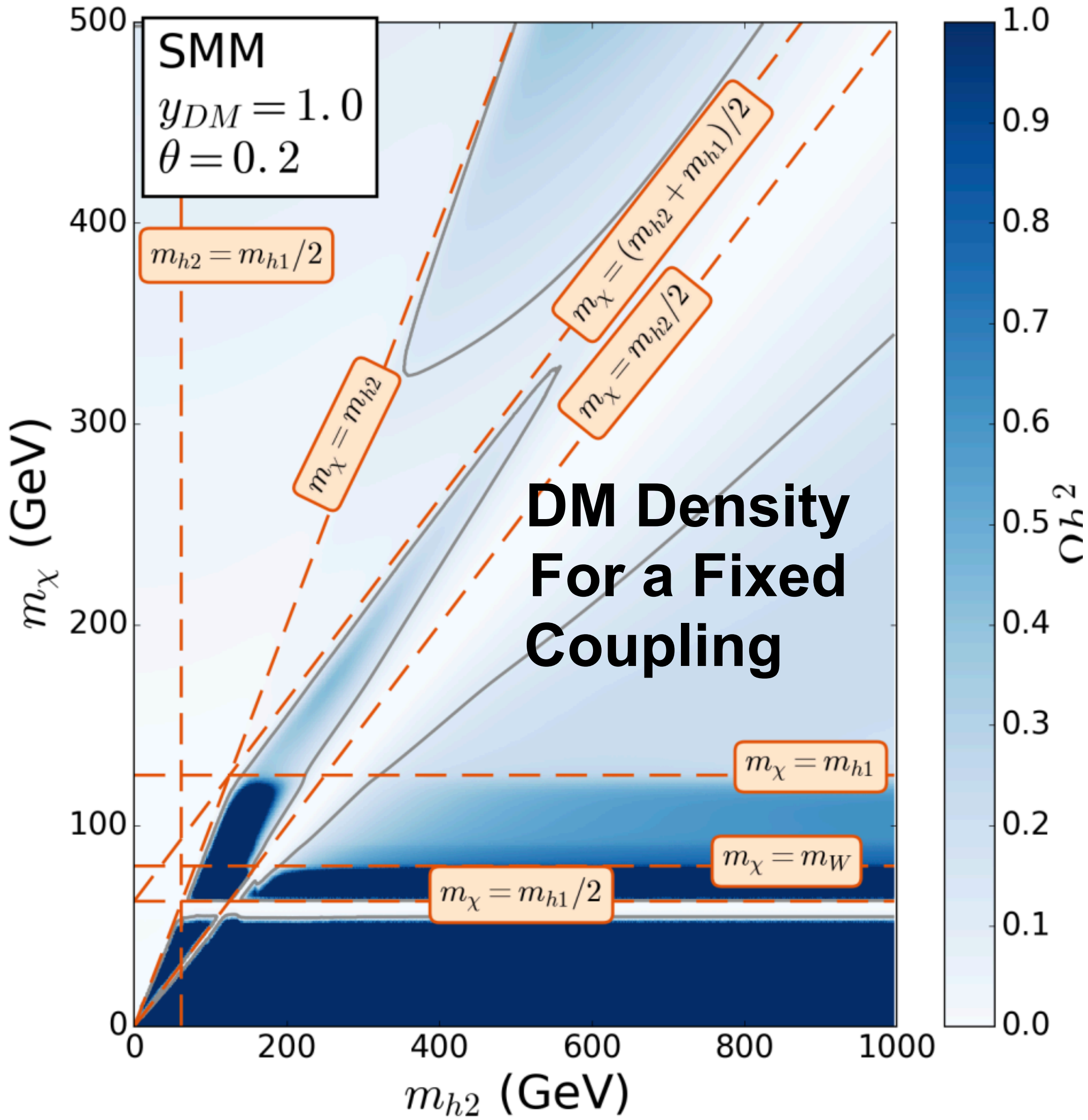
- Bounds for Monojet(invisible) comparable to visible bounds
  - Covers a variety of important final states

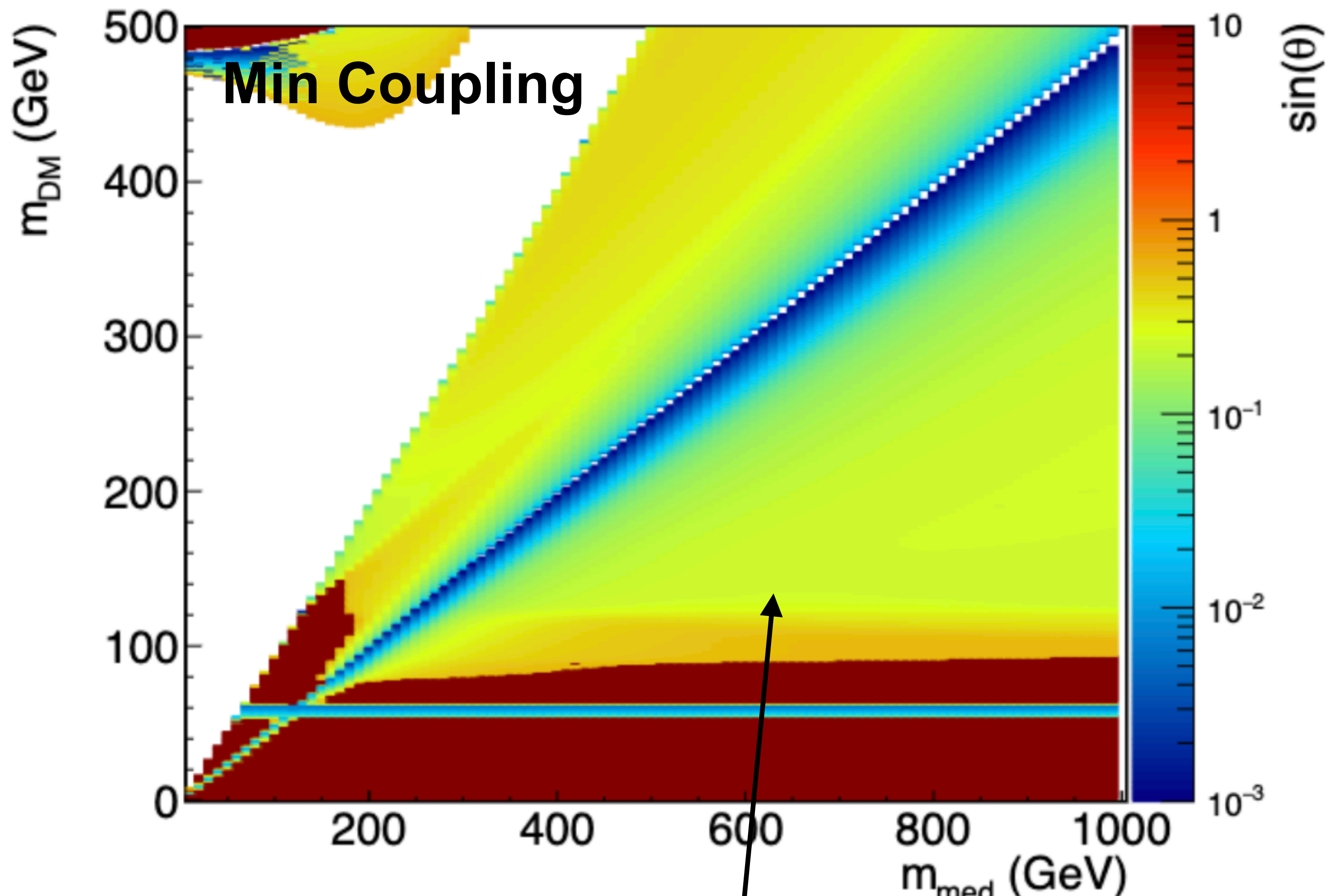
Scalar DM Bounds



- 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

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

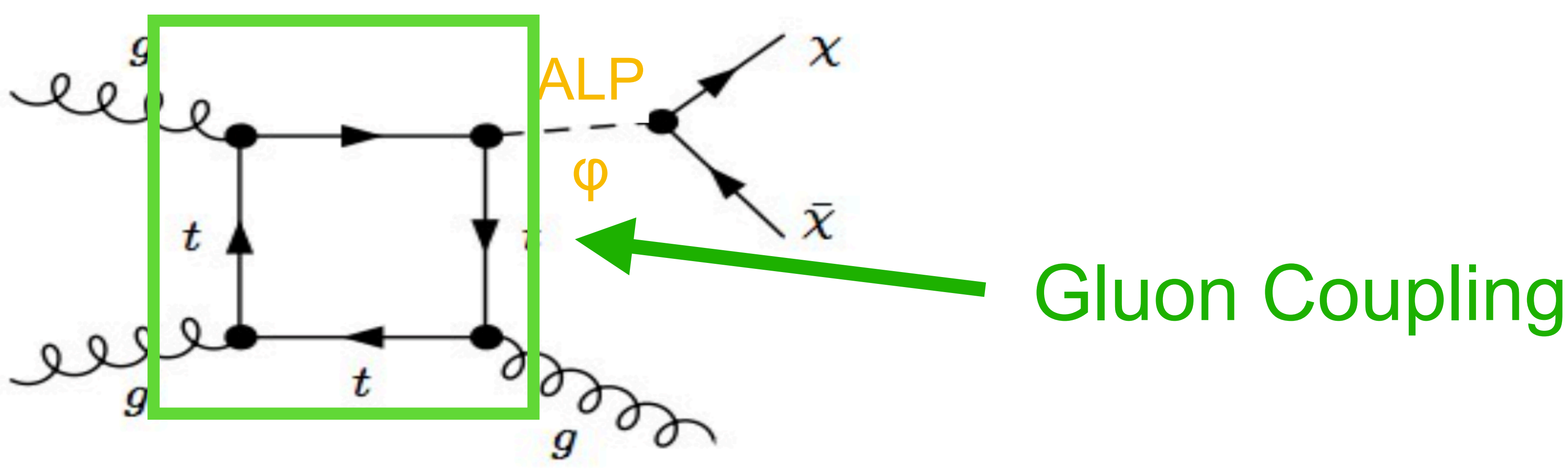
Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2)H^\dagger H$
Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$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

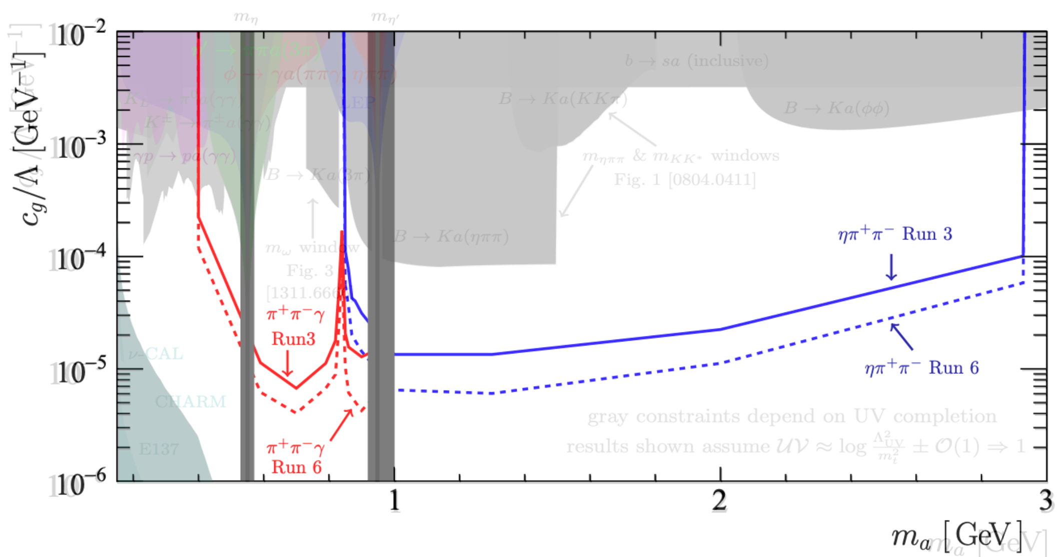
Axion Portal is a recast

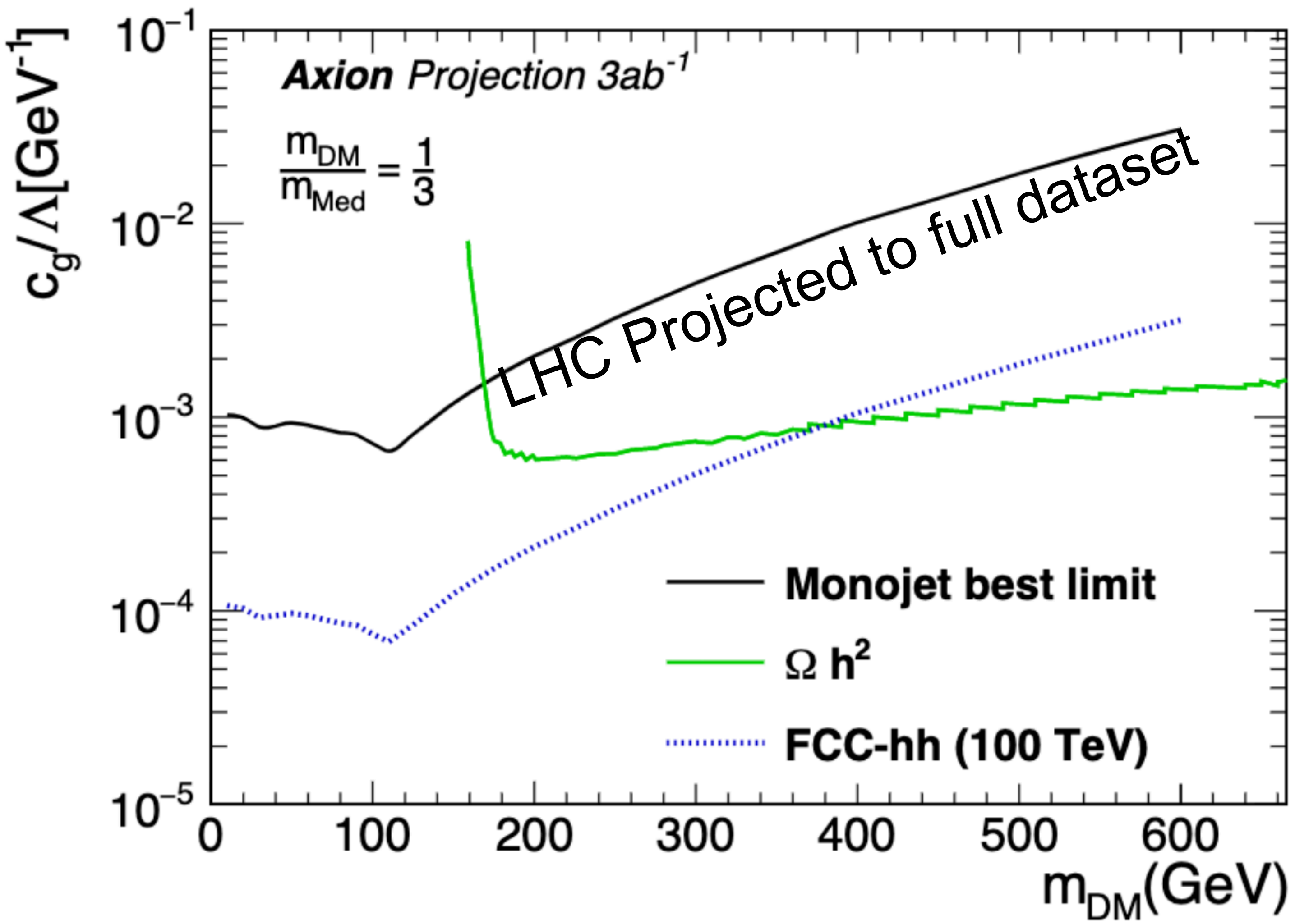
- We can translate directly into the axion like portal
  - Governed by one formula $\frac{c_g}{\Lambda} = \frac{g_q}{v}$
  - Assumes Gluon coupling comes from a yukawa loop
  - Also LHC model assumes yukawa coupling(not need)
    - Photon coupling not considered in this setup
- With the model used by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



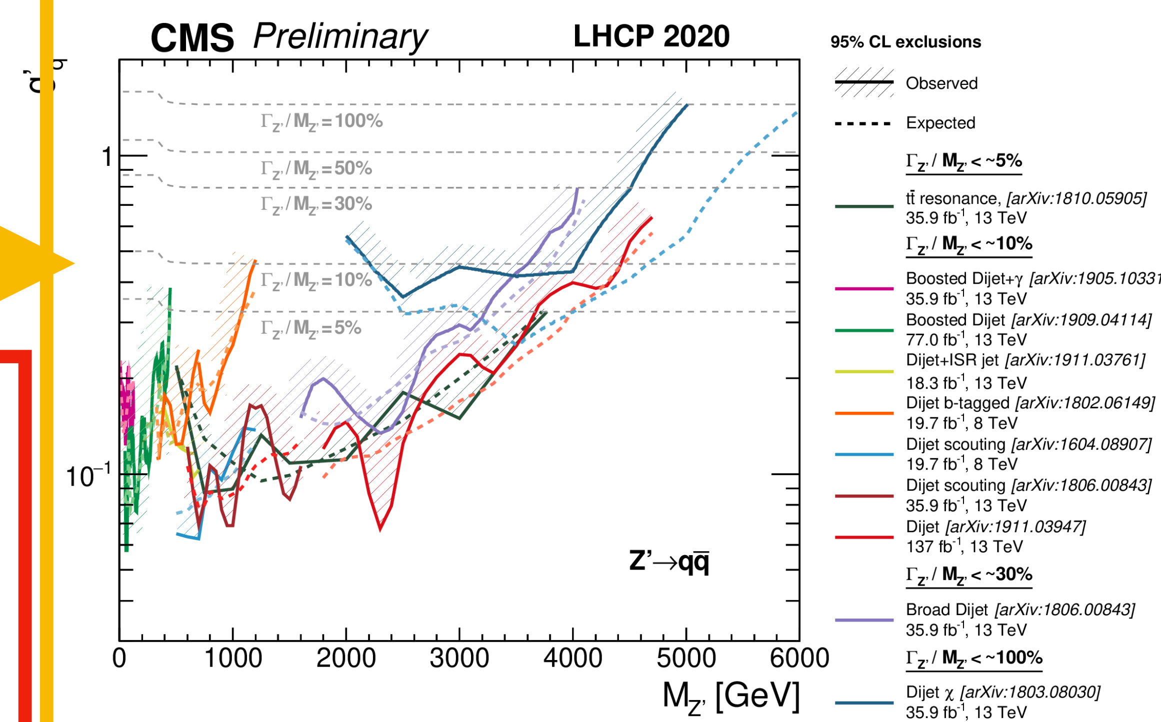


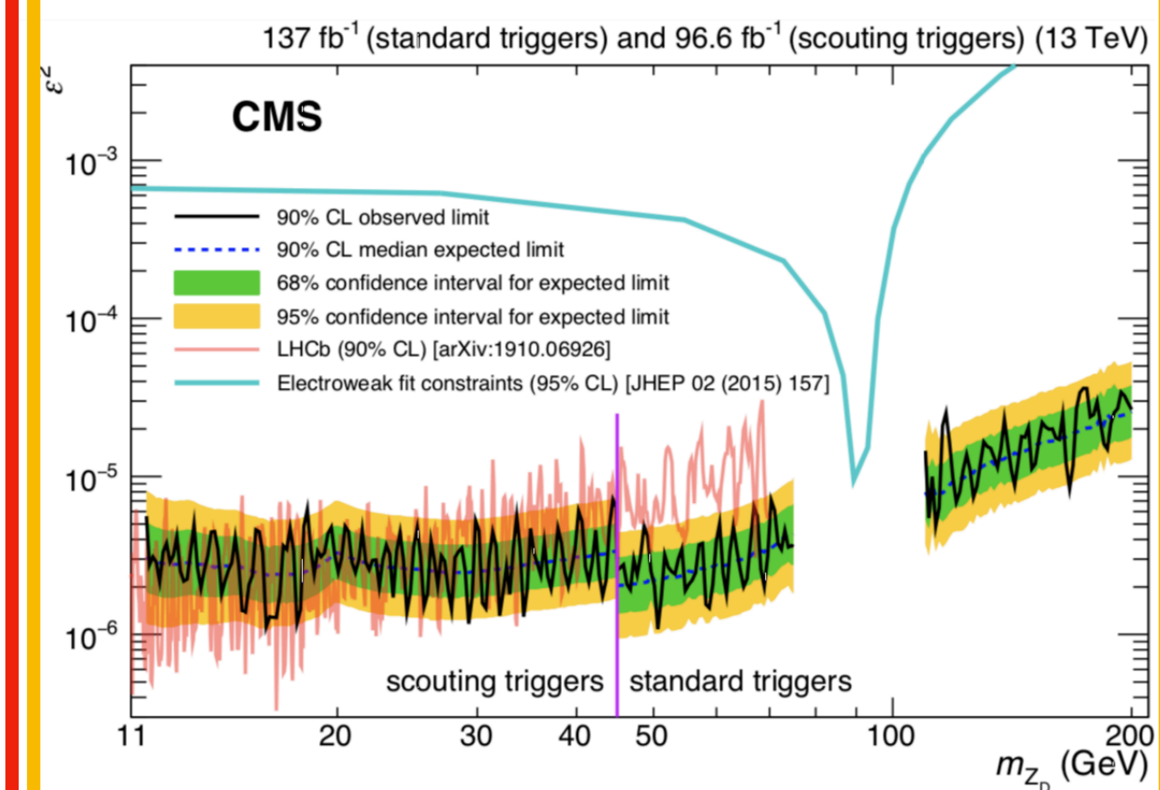
LHCDMWG & FIP

- 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

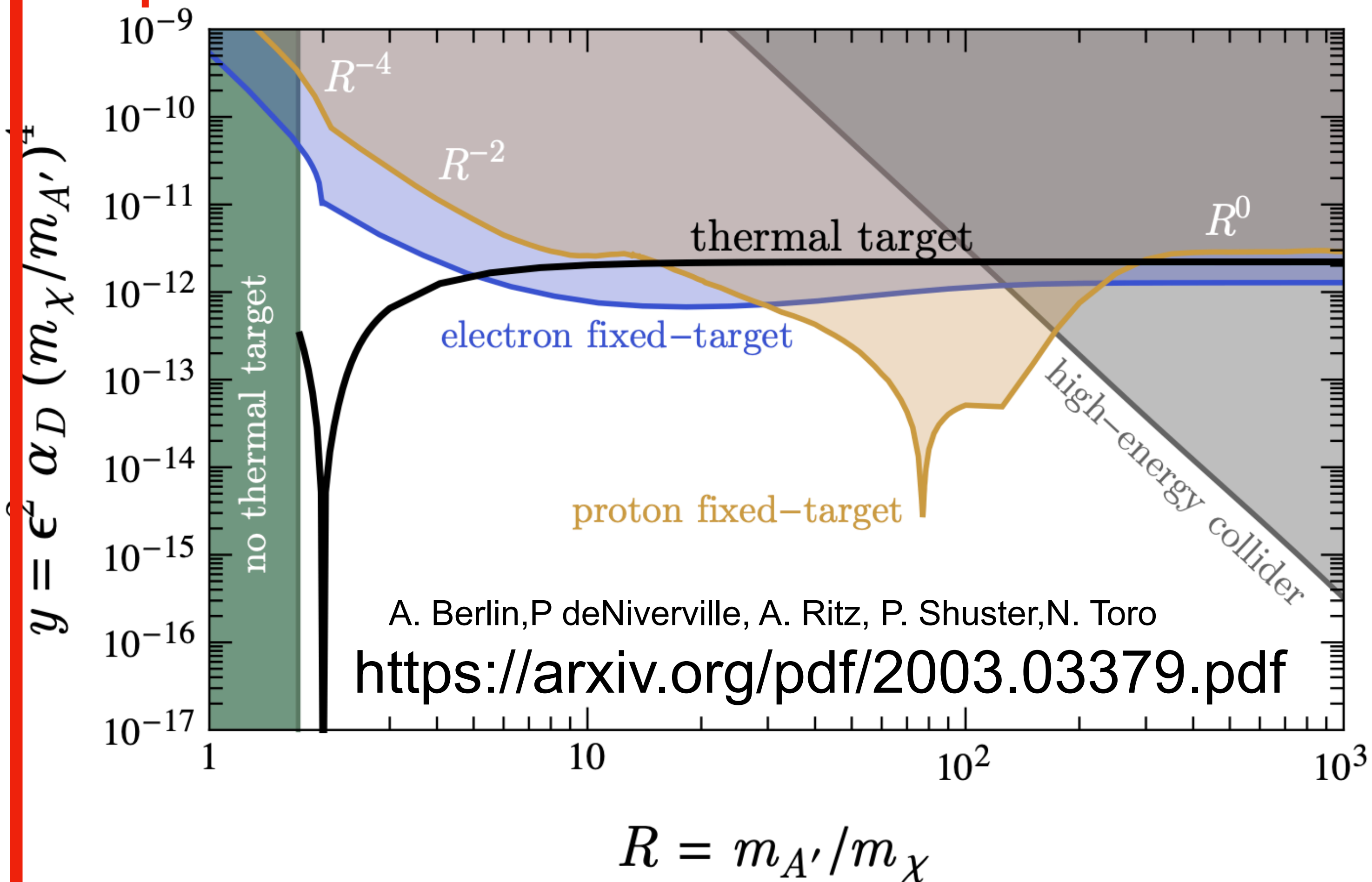
Other Points to keep in mind

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





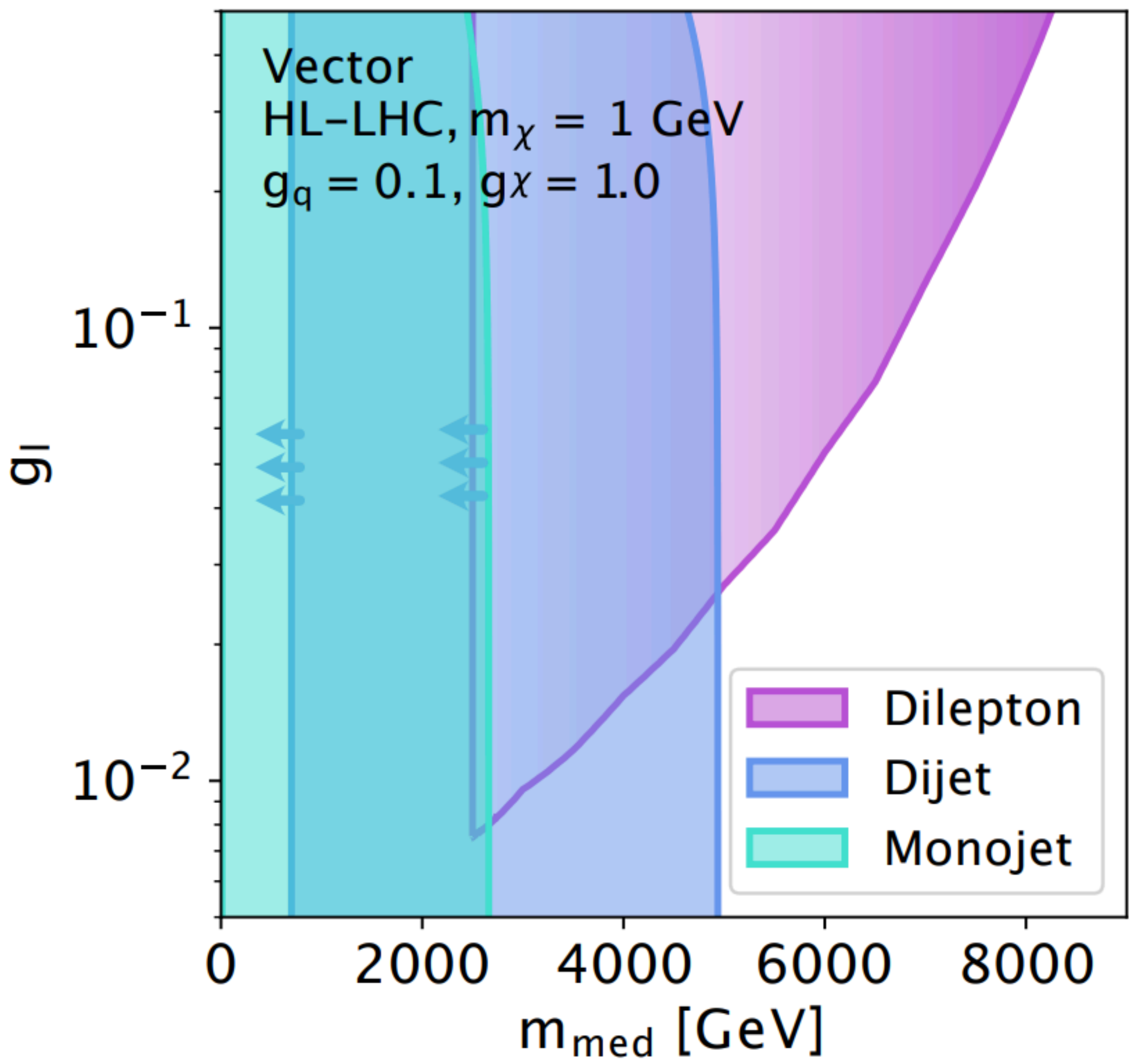
There are other ways to present LHC results on the same plot w/light DM experiments



A. Berlin, P deNiverville, A. Ritz, P. Shuster, N. Toro

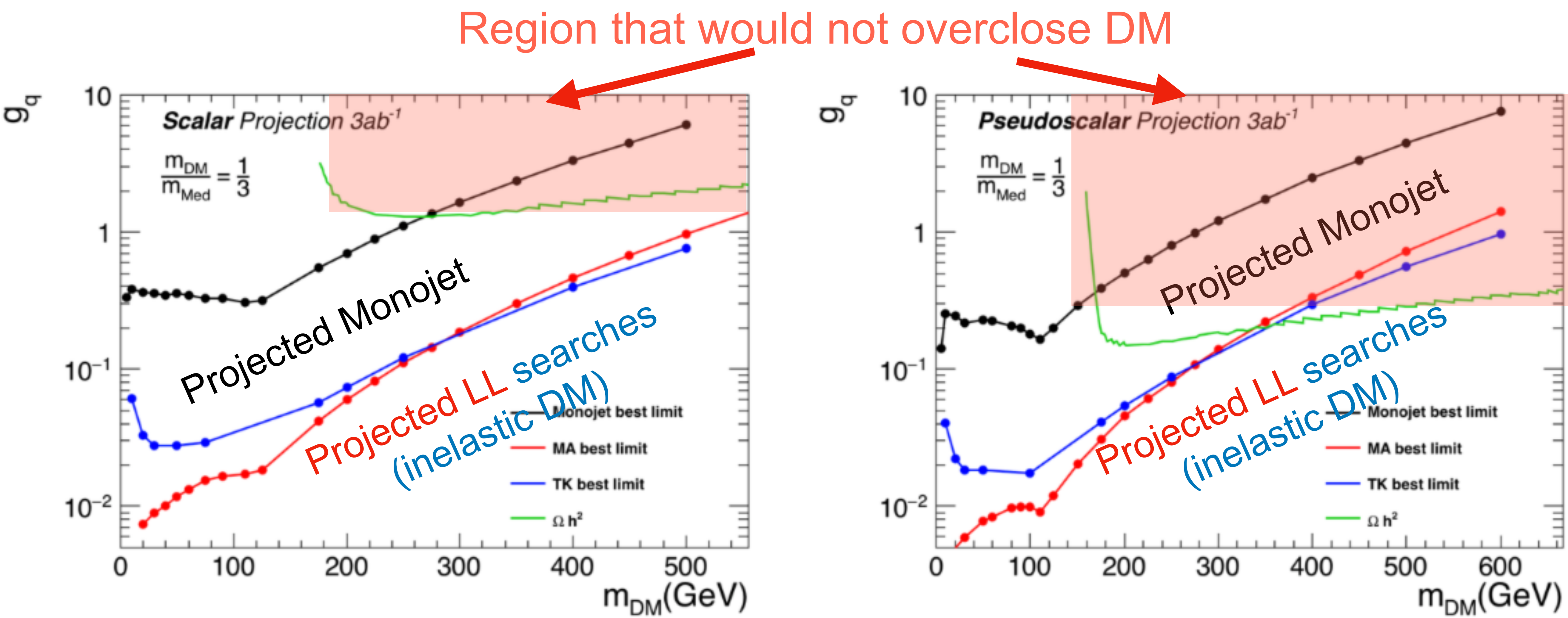
https://arxiv.org/pdf/2003.03379.pdf

LHC Lepton Projections



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



Floating the couplings

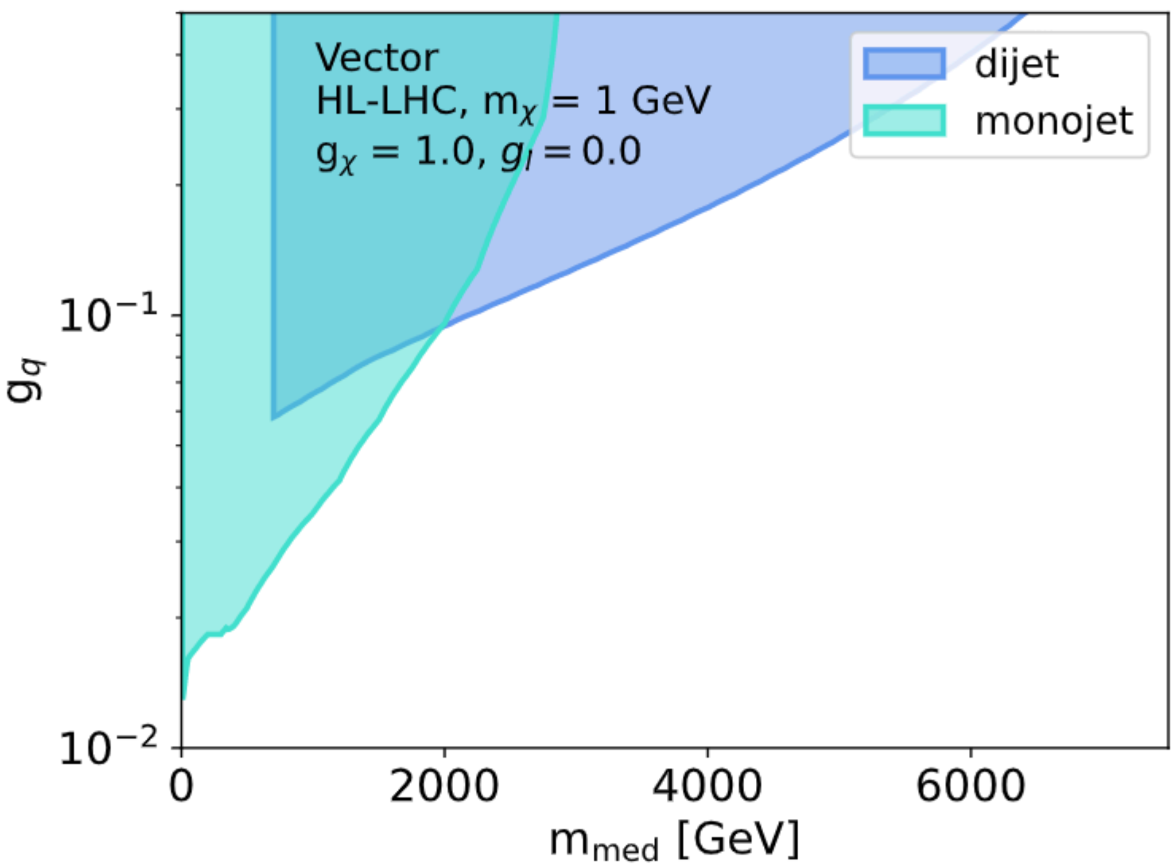
- Floating the couplings gives us a new set of bounds
  - In practice varying couplings doesn't change bounds
  - However to make direct detection bounds coupling fixed
  - Monojet and dijet can probe couplings below g_q = 0.1

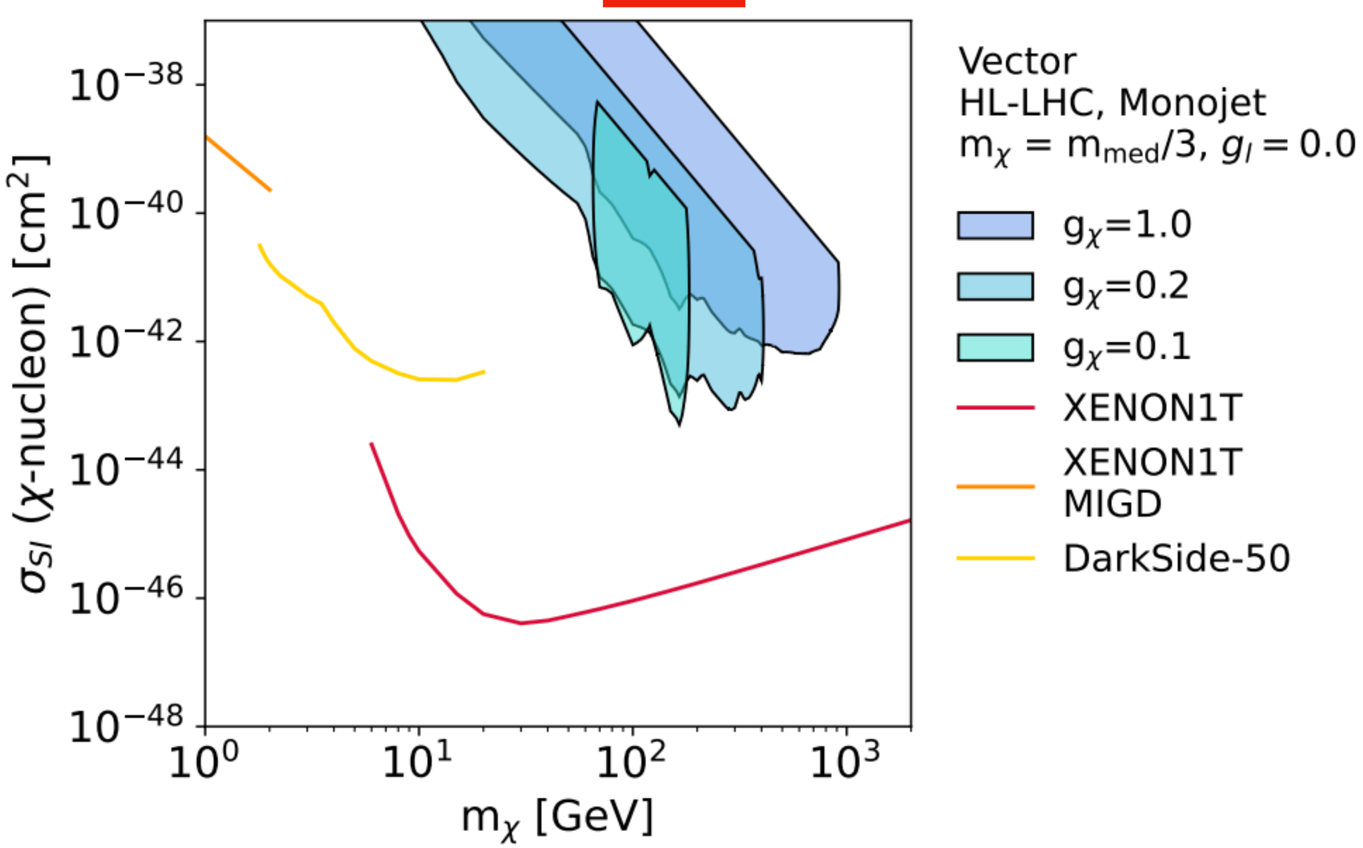
Float

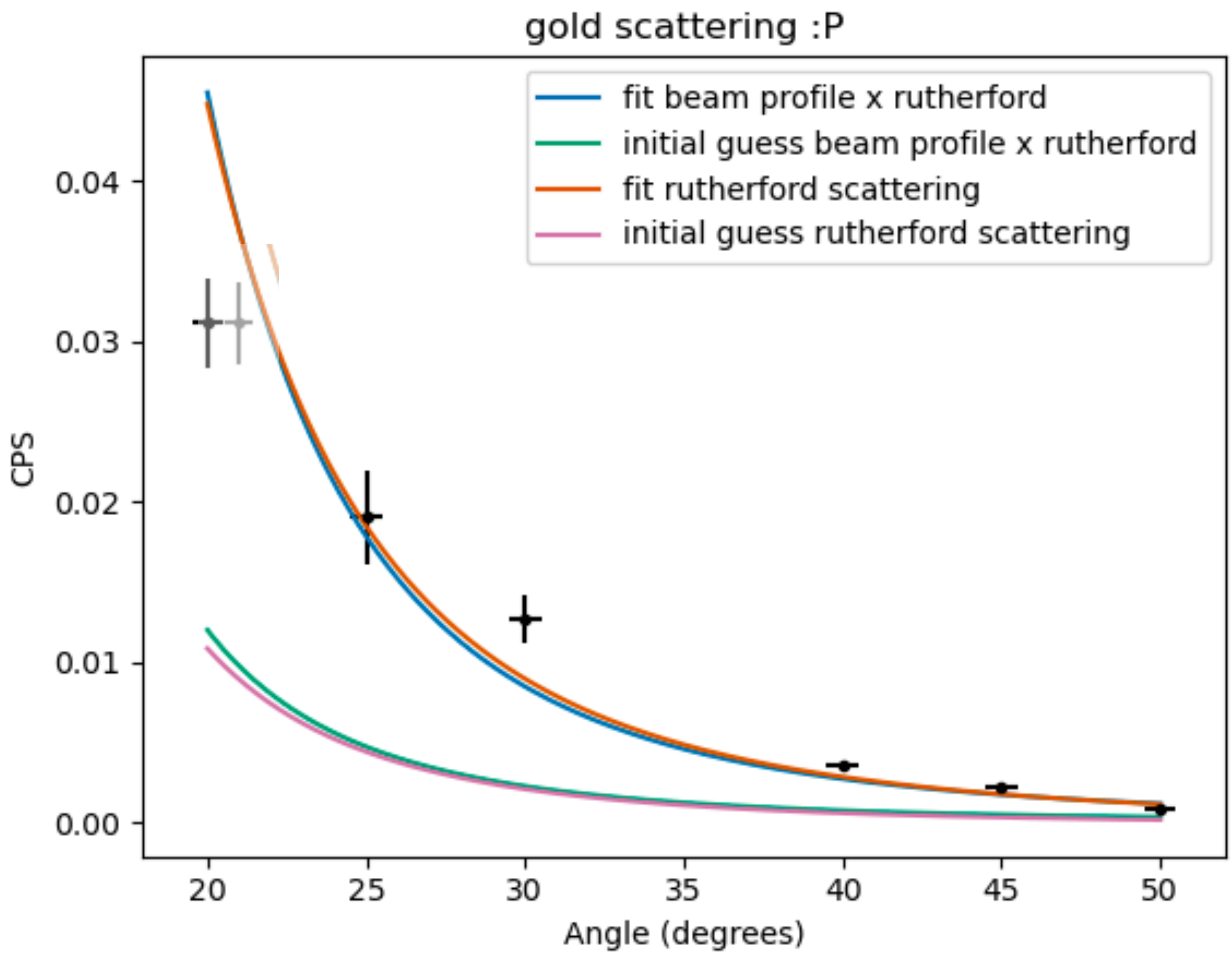
$$\sigma_{\rm SI} = \frac{f^2(g_q)\, g_{\rm DM}^2\, \mu_{n\chi}^2}{\pi M_{\rm med}^4}$$

Fix

Fixing the Dark Matter Mass






gold scattering :P
fit beam profile x rutherford
initial guess beam profile x rutherford
fit rutherford scattering
initial guess rutherford scattering
CPS
0.00
0.01
0.02
0.03
0.04
20
25
30
35
40
45
50
Angle (degrees)

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

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

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

No Interference with the Z boson

Spin 0

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

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

No Interference with the higgs boson

Only quark couplings guaranteed in interpretation

These remain the main ways to interpret DM at LHC

LHC Model Presentation

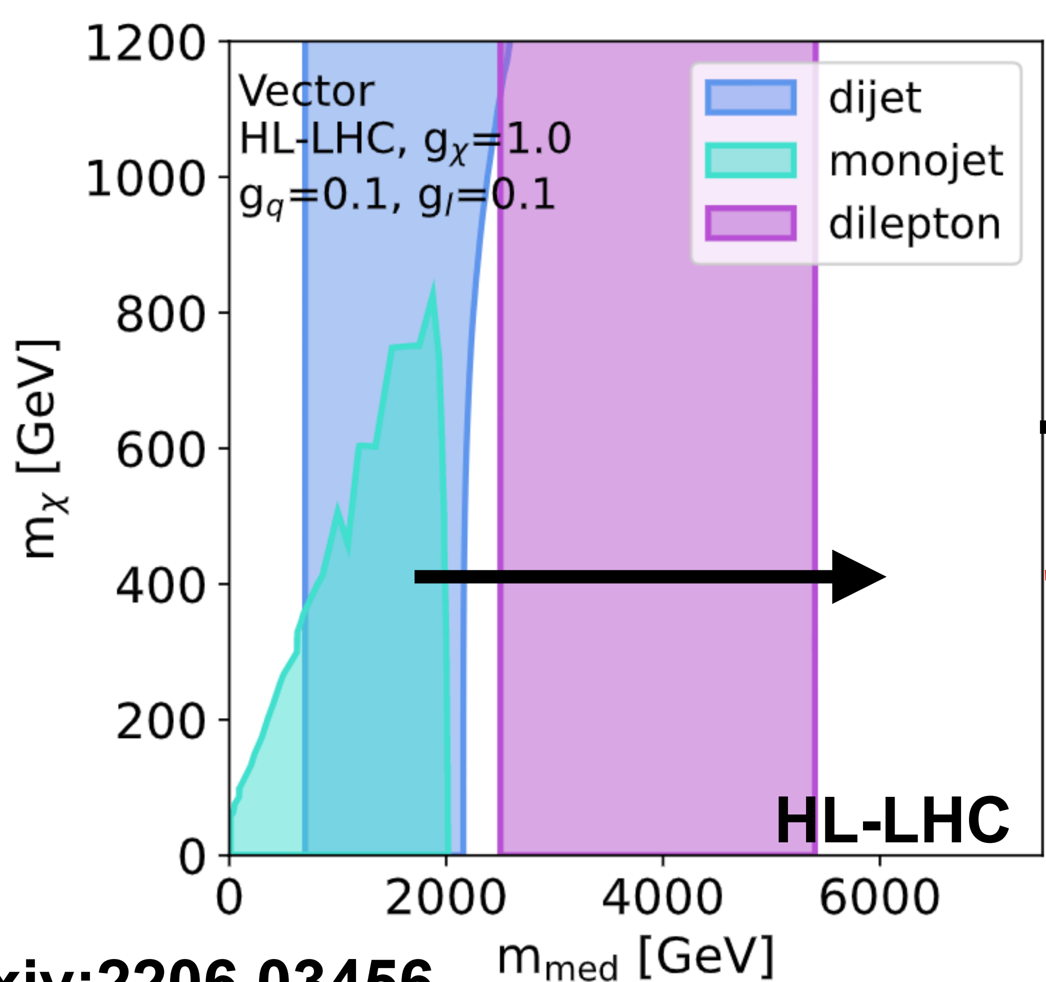
- Traditionally presented models in mass vs mass plane
  - With fixed couplings
  - Idea was to see how high a mass we could achieve

Fixed

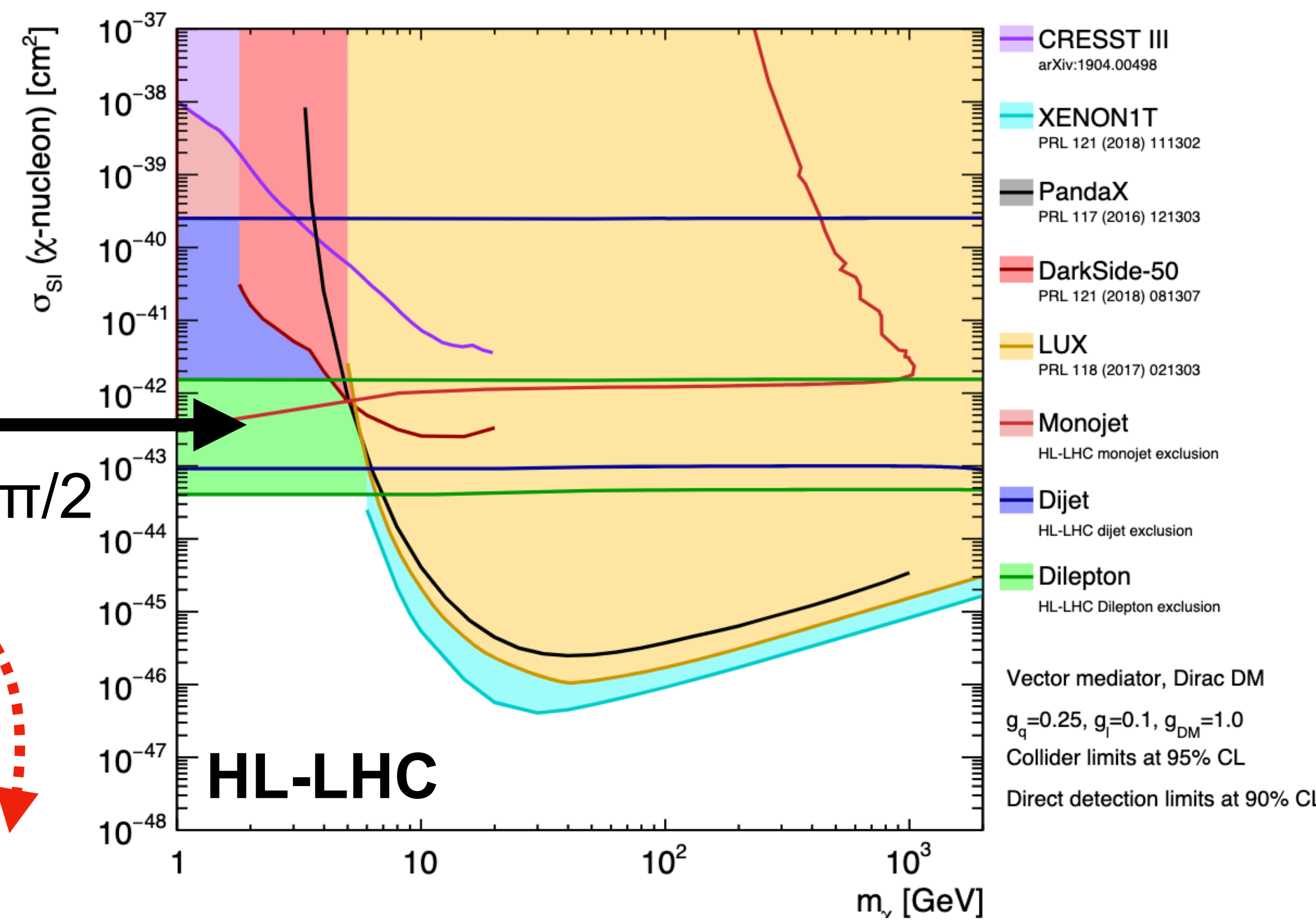
$$\sigma_{\mathrm{SI}} = \frac{f^2(g_q)g_{\mathrm{DM}}^2 \mu_{n\chi}^2}{\pi M_{\mathrm{med}}^4}$$

Floated

Wanted to see how high we could go



Rotate π/2

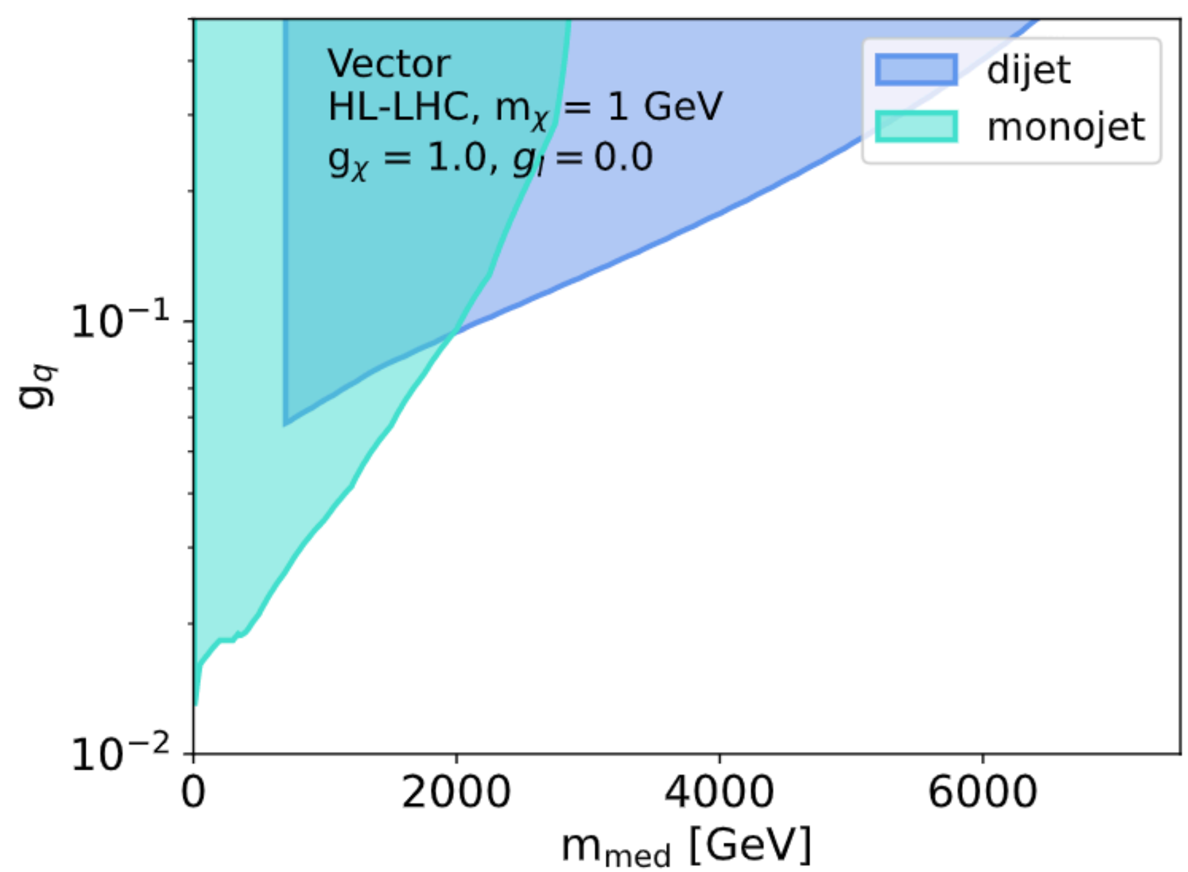


arxiv:2206.03456

Floating the couplings

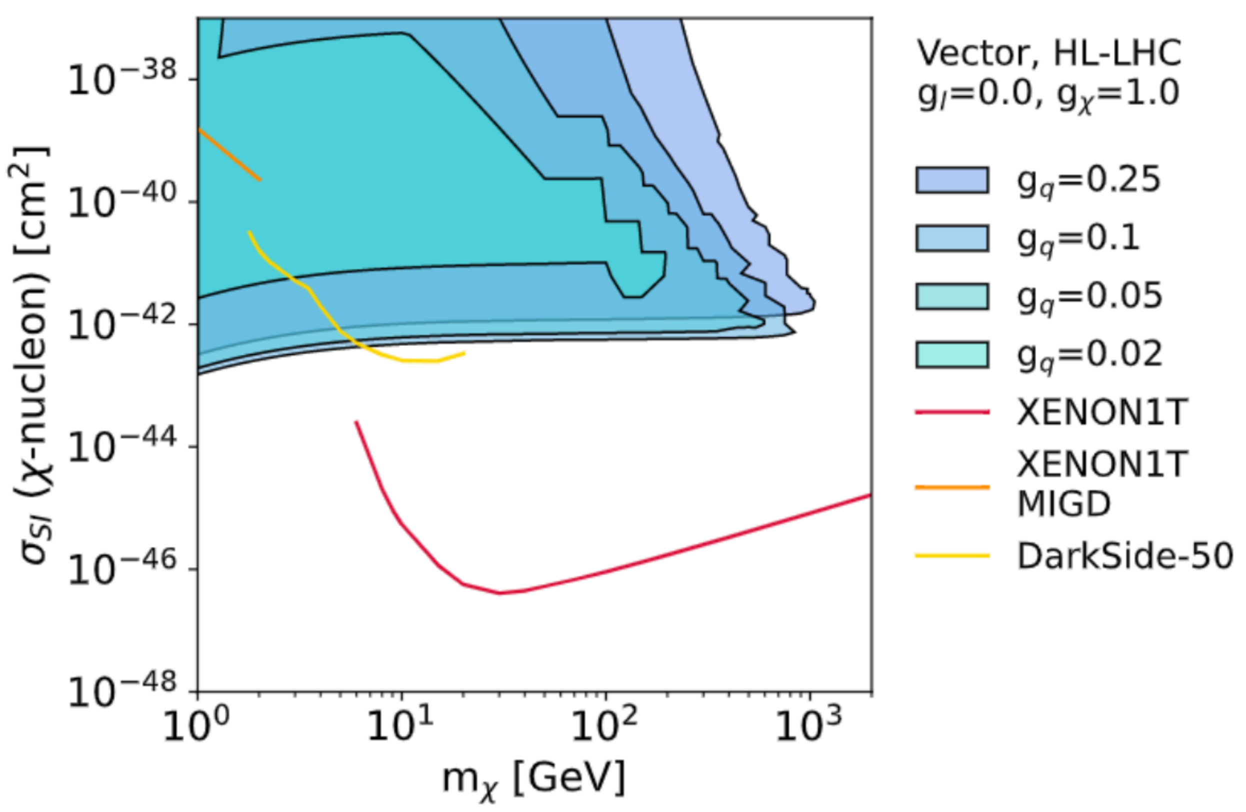
- Floating the couplings gives us a new set of bounds
  - In practice varying couplings doesn't change bounds much
  - However to make direct detection bounds coupling fixed
  - Monojet and dijet can probe couplings below $g_q = 0.1$

Fixing the Dark Matter Mass



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

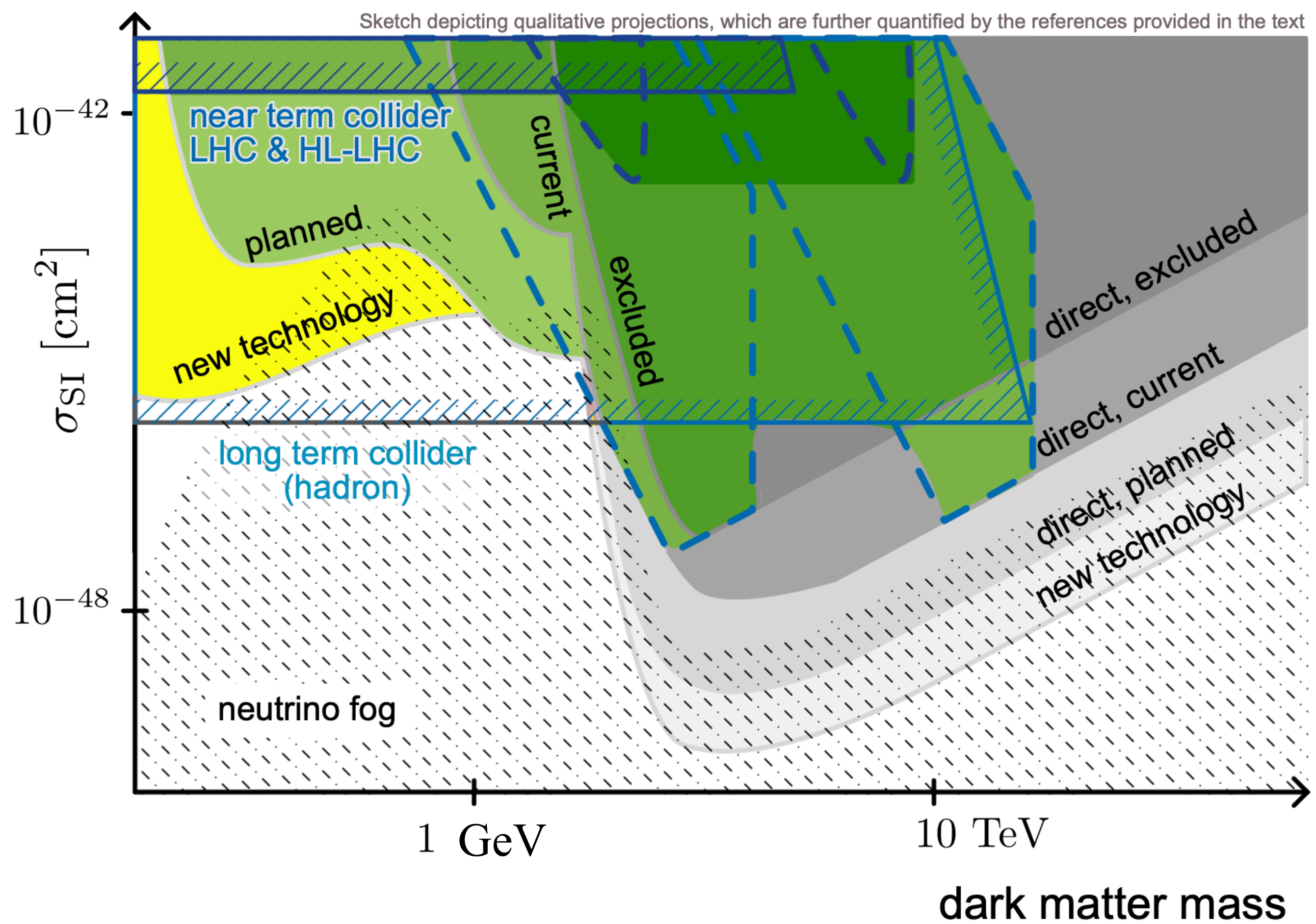
Float

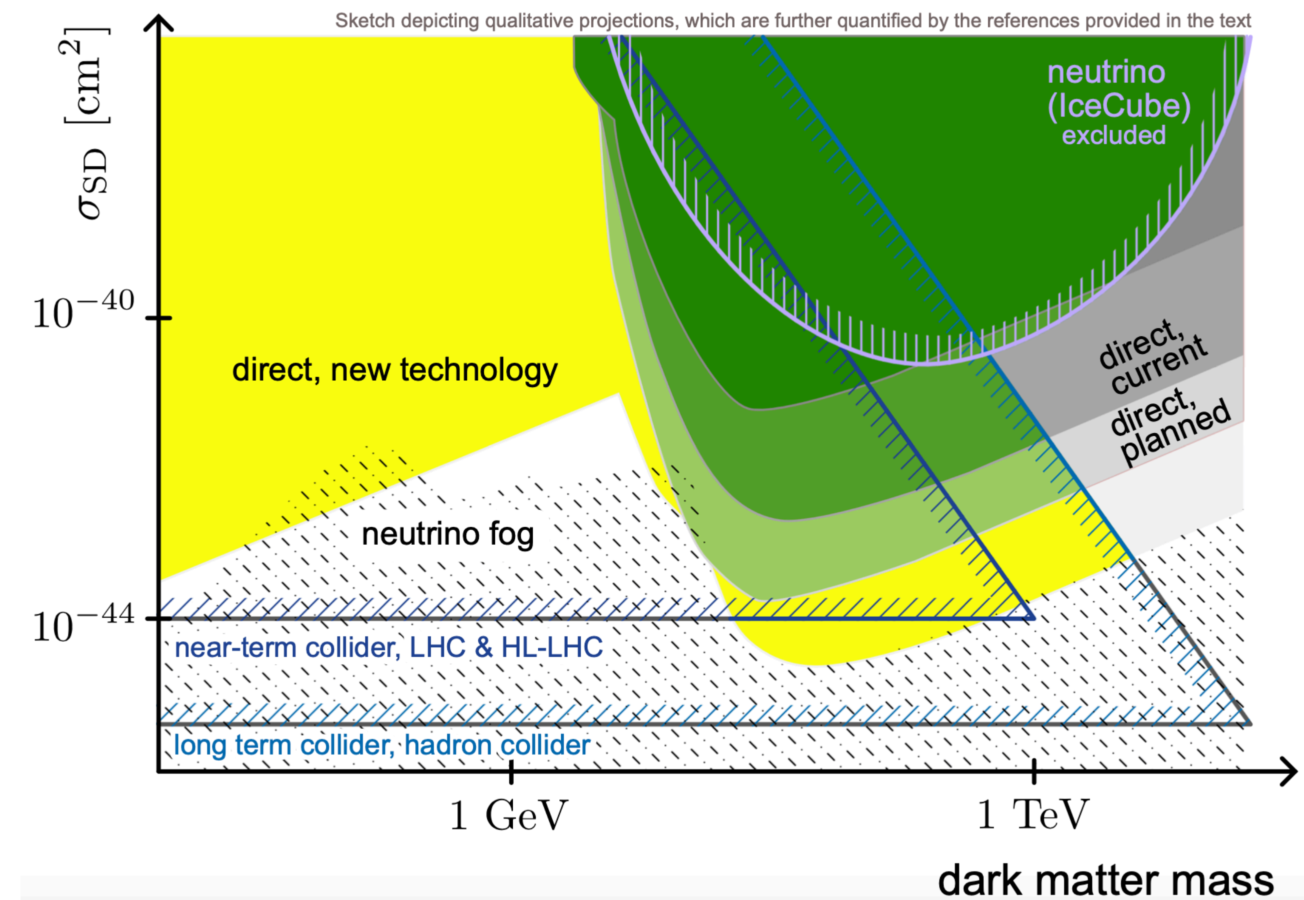


arxiv:2206.03456

Ultimate Bounds

- Given these variations we can standardize these

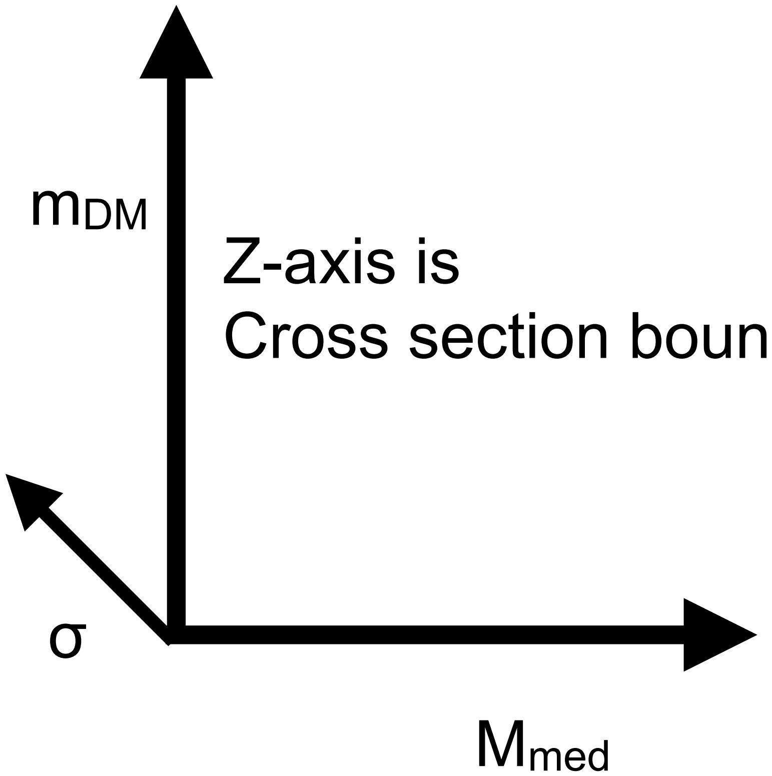




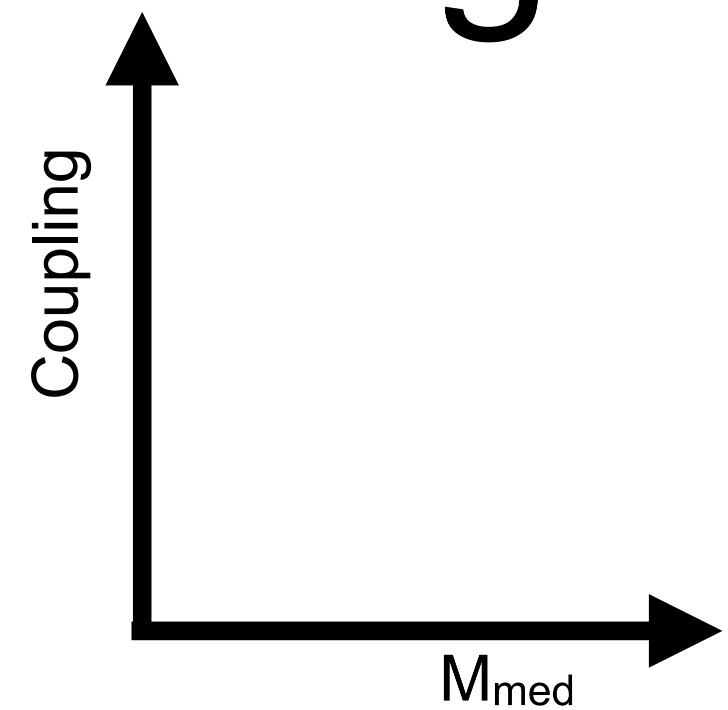
- From high mass invisible studies draw general conclusions
  - Varying coupling bounds doesn't dramatically change LHC
  - The LHC can provide complementarity to Direct Detection

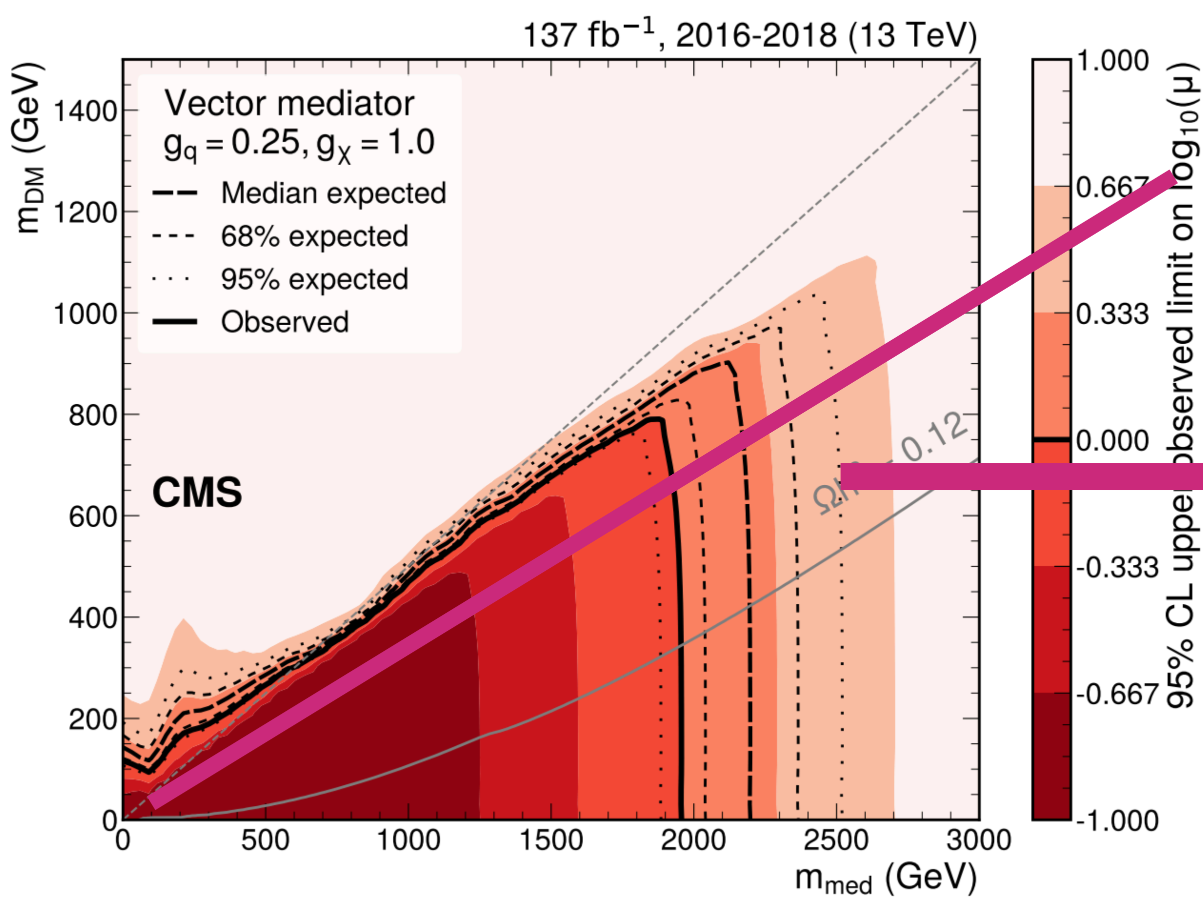
arxiv:2210.01770

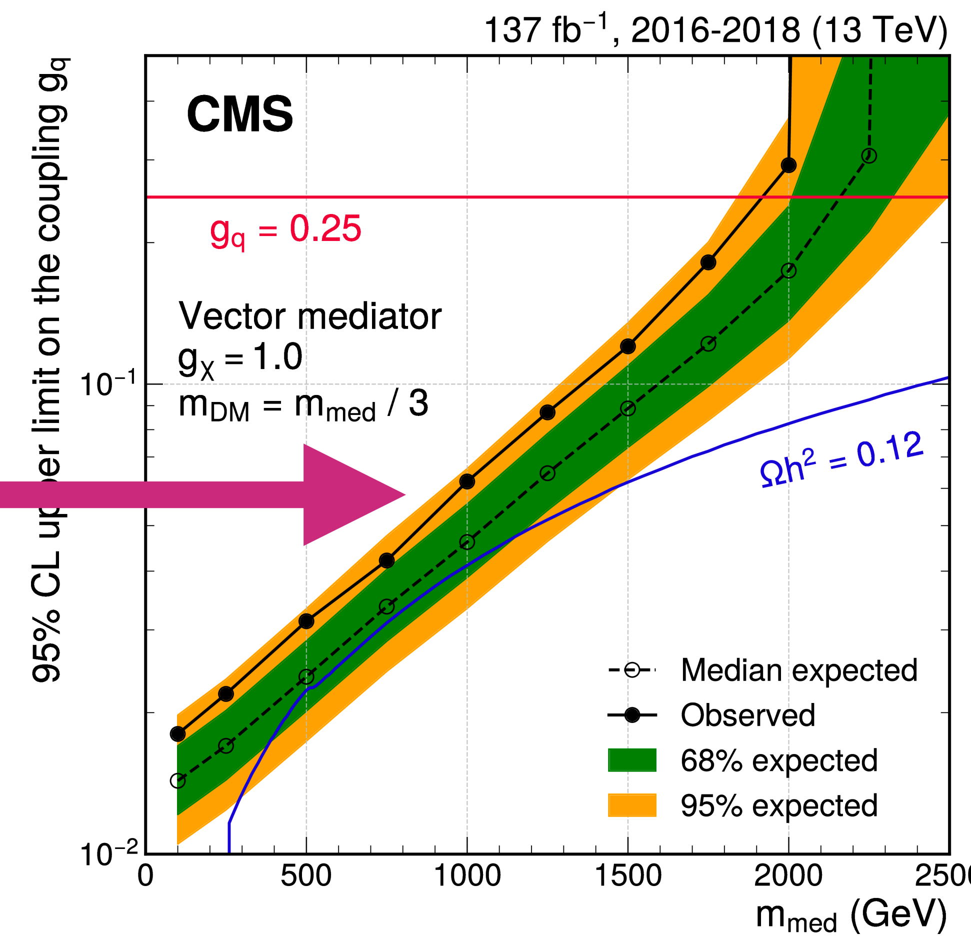
Translating to y



Fix a specific axis
$m_{DM} = M_{med}/3$







https://arxiv.org/abs/2107.13021

Coupling on y-axis shows overall sensitivity