# DARK MATTER AND DARK SECTORS

Theory Frontier Session, Snowmass 2022

*23 July 2022*

Jonathan Feng, UC Irvine

# INTRODUCTION

- Dark Matter and Dark Sectors is currently a topic of great interest.

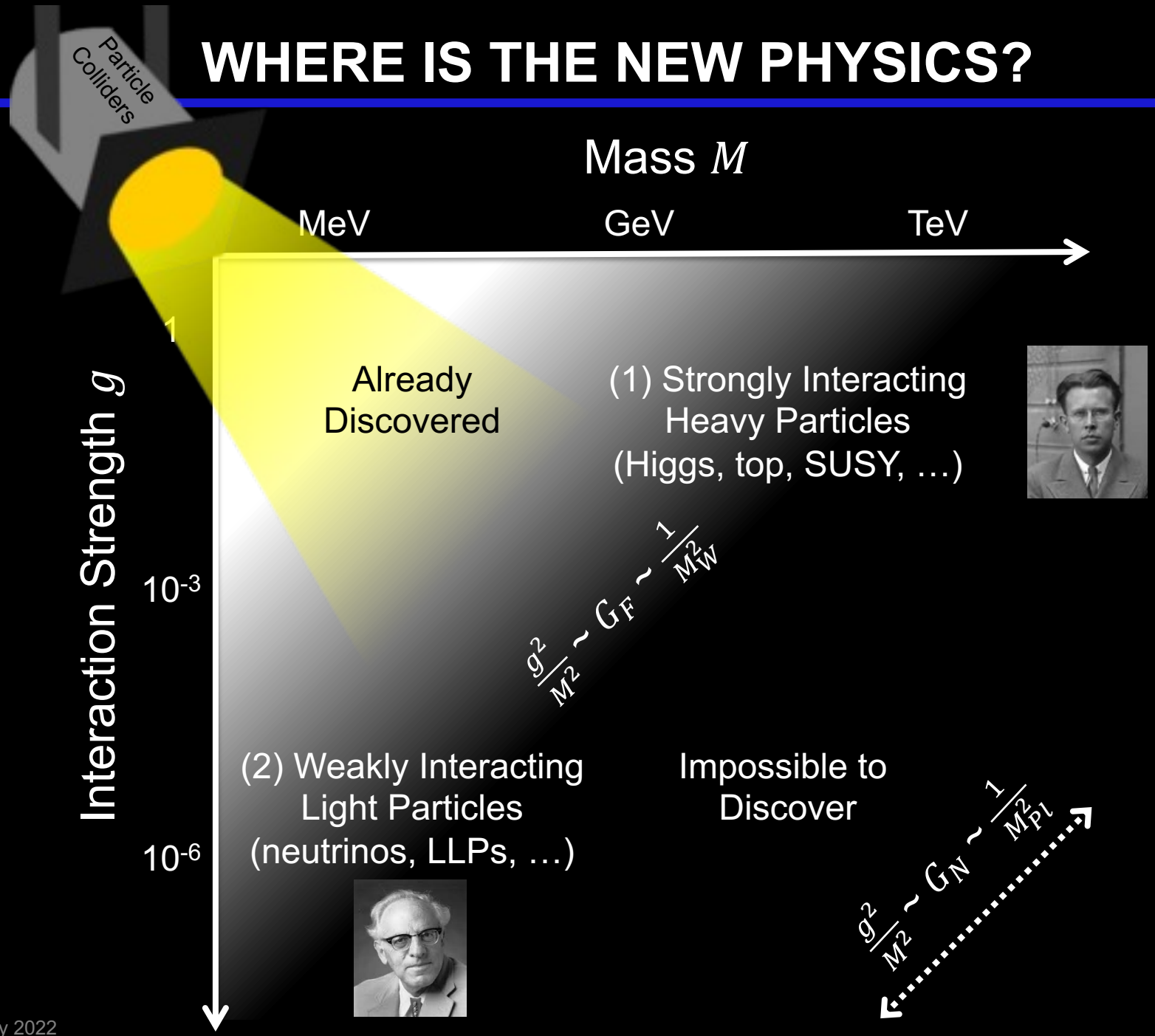
- Many talks at Snowmass, including several talks with almost the identical title:
  - Dark Matter and Dark Sectors: from Theory to Discovery in the Lab, Wednesday, Masha Baryakhtar
  - Dark Matter and Dark Sectors: from Theory to Discovery in the Sky, Wednesday, Joshua Foster
  - Understanding Dark Matter and Dark Sectors at RP Frontier, Wednesday, Stefania Gori
  - Dark Matter and Dark Sectors, Saturday, Jonathan Feng

- Some of the interest follows null results from LHC and ton-scale WIMP searches. But, as I will discuss, there are strong independent reasons to consider dark sectors, and much of the initial interest preceded these null results.

- Connections to almost every frontier, and also to adjacent fields (nuclear physics, condensed matter physics, AMO, and, of course, astrophysics).

- A beautiful example of what can result from the serious and persistent interaction of theorists and experimentalists.

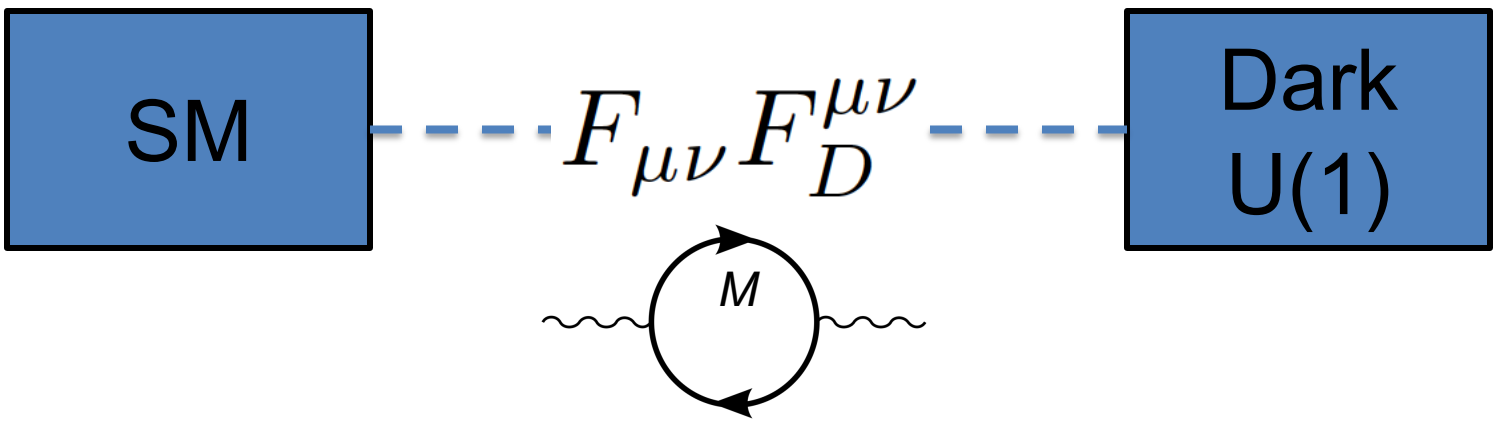
# WHERE IS THE NEW PHYSICS?



# DARK SECTORS

- DM is one of the strongest BSM motivations. In general, it is part of a dark sector. What are its most likely non-gravitational interactions?

- Suppose the dark sector has U(1) electromagnetism. There are infinitely many possible SM-dark sector interactions, but one is induced by arbitrarily heavy mediators:




- It is "most likely" because it is non-decoupling. Cf. $\frac{F_{\mu\nu}F_D^{\nu\alpha}F_\alpha^\mu}{M^2}$

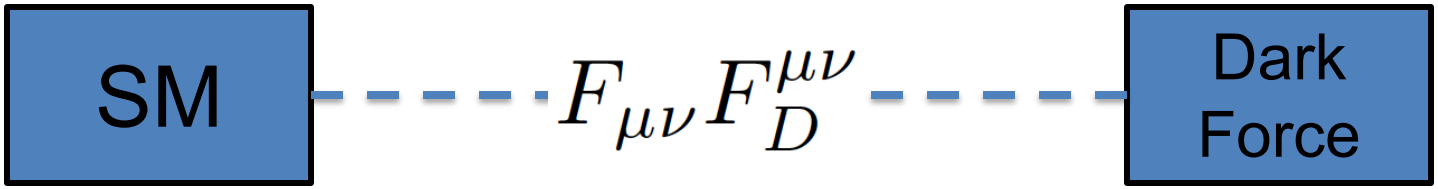
- Note that it is also naturally small, since it is induced by a loop. This whole story is special to U(1).

Okun (1982), Galison, Manohar (1984), Holdom (1986)

# DARK PHOTON, DARK HIGGS, STERILE NUS

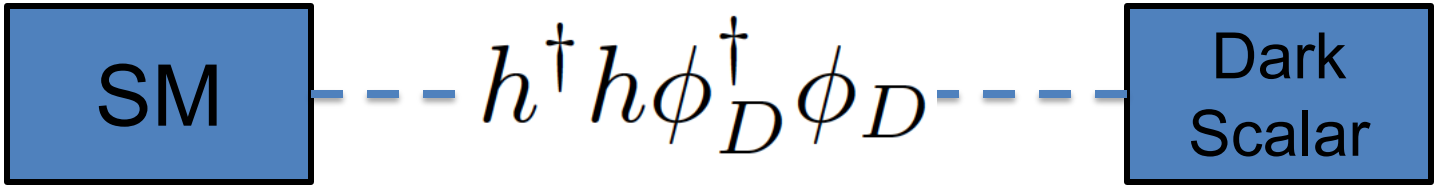
- This provides an organizing principle that motivates specific examples of new, weakly interacting light particles. There are just a few options:

- Spin 1



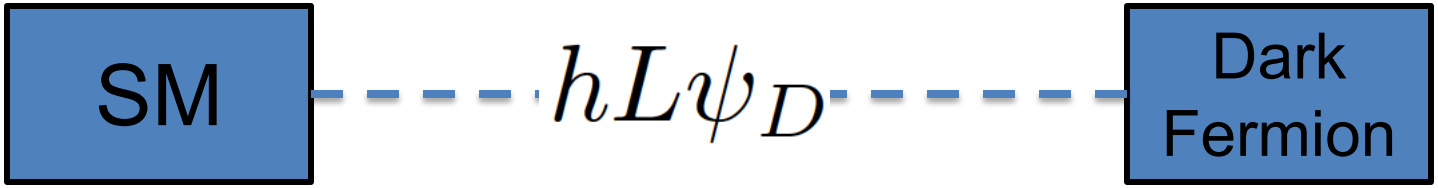

→ dark photon, couples to SM fermions with suppressed couplings proportional to charge: $\varepsilon q_f$. Holdom (1986)

- Spin 0




→ dark Higgs boson, couples to SM fermions with suppressed coupling proportional to mass: $\sin\theta\, m_f$. Patt, Wilczek (2006)

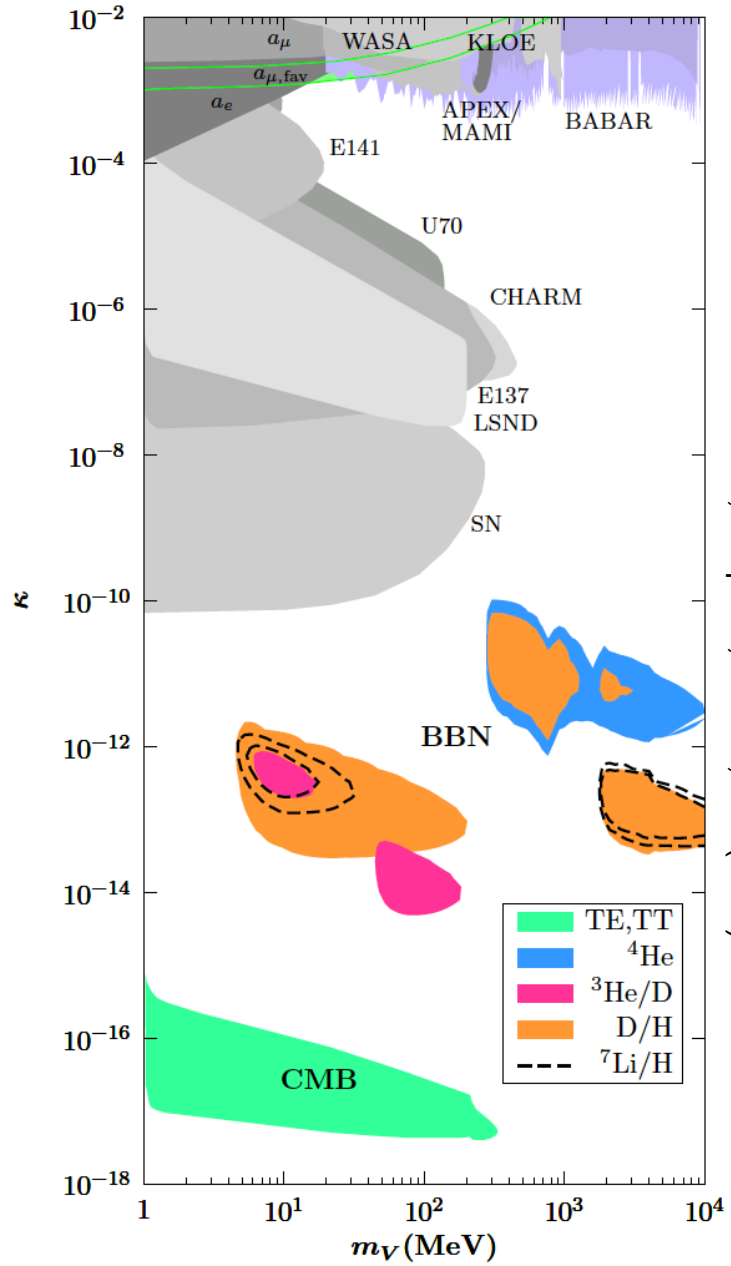
- Spin 1/2




→ sterile neutrino, mixes with SM neutrinos with suppressed mixing $\sin\theta$.

# EXISTING CONSTRAINTS

- We now have a few portal models, characterized by just a few parameters, and we can start exploring the parameter space.
- Consider dark photons. There is a vast parameter space.
  - "Bump hunts" exclude $\epsilon > 10^{-3}$.
  - Fixed target experiments exclude most of the gray region.
  - Astrophysics (supernova, BBN, CMB) excludes patches at very low coupling.
- But overall, light, weakly-interacting particles are much less constrained than ~TeV, strongly-interacting particles.



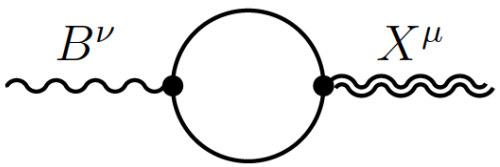

Fradette, Pospelov, Pradler, Ritz (2014)

# DARK PHOTON MODELS

- If the dark photon is a portal particle, coupling arises from kinetic mixing:

| Visible Sector<br>SM, $U(1)_{EM}$, $B^\nu$ | $\frac{1}{2}\epsilon\, F^{\mu\nu}F_{D\mu\nu}$ | Dark Sector<br>DM, Dark Forces, $X^\mu$ |
|---|---|---|

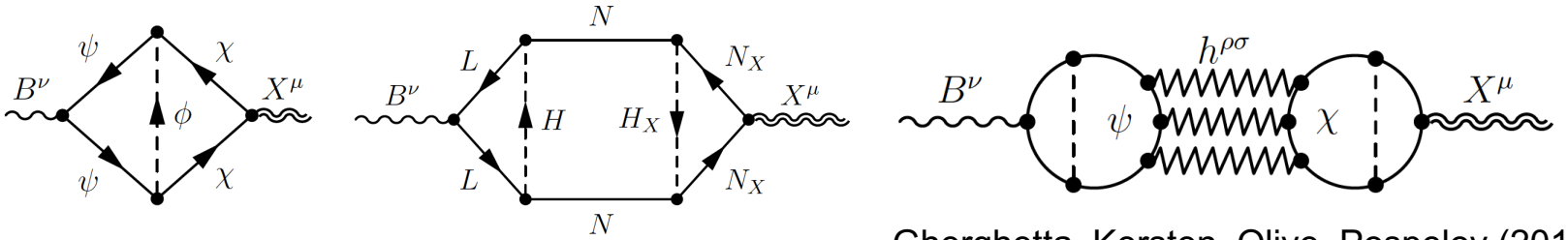
- Mixing can be generated at 1-loop. If 0 at high scale, expect $\epsilon \sim 10^{-3}$.




$$\epsilon = -\frac{g' g_X}{16\pi^2}\sum_i Y_i q_i \ln\frac{M_i^2}{\mu^2}$$

Holdom (1986)

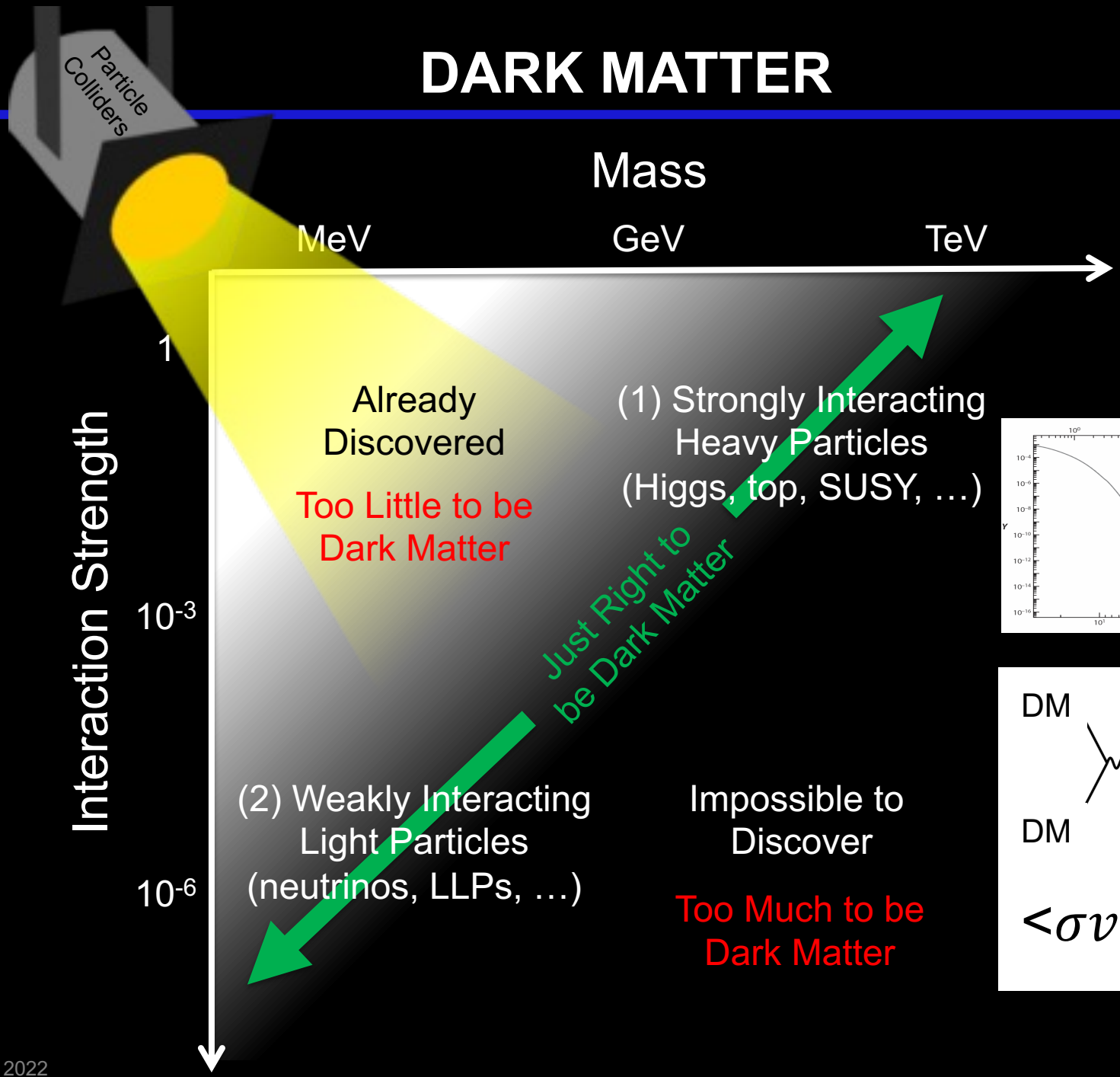
- But there are also theories with mixing generated only at higher loop level.

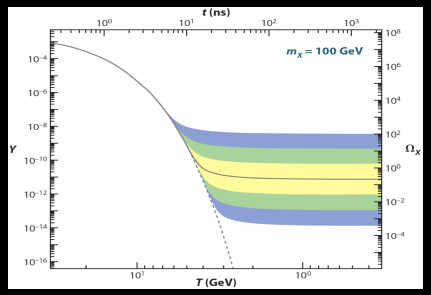


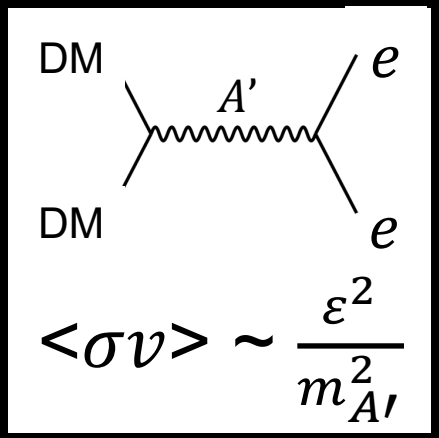

Gherghetta, Kersten, Olive, Pospelov (2019)

- Other than making us feel ok that $\epsilon > 10^{-3}$ is excluded, models don't provide much guidance about the coupling, and none at all about the mass.

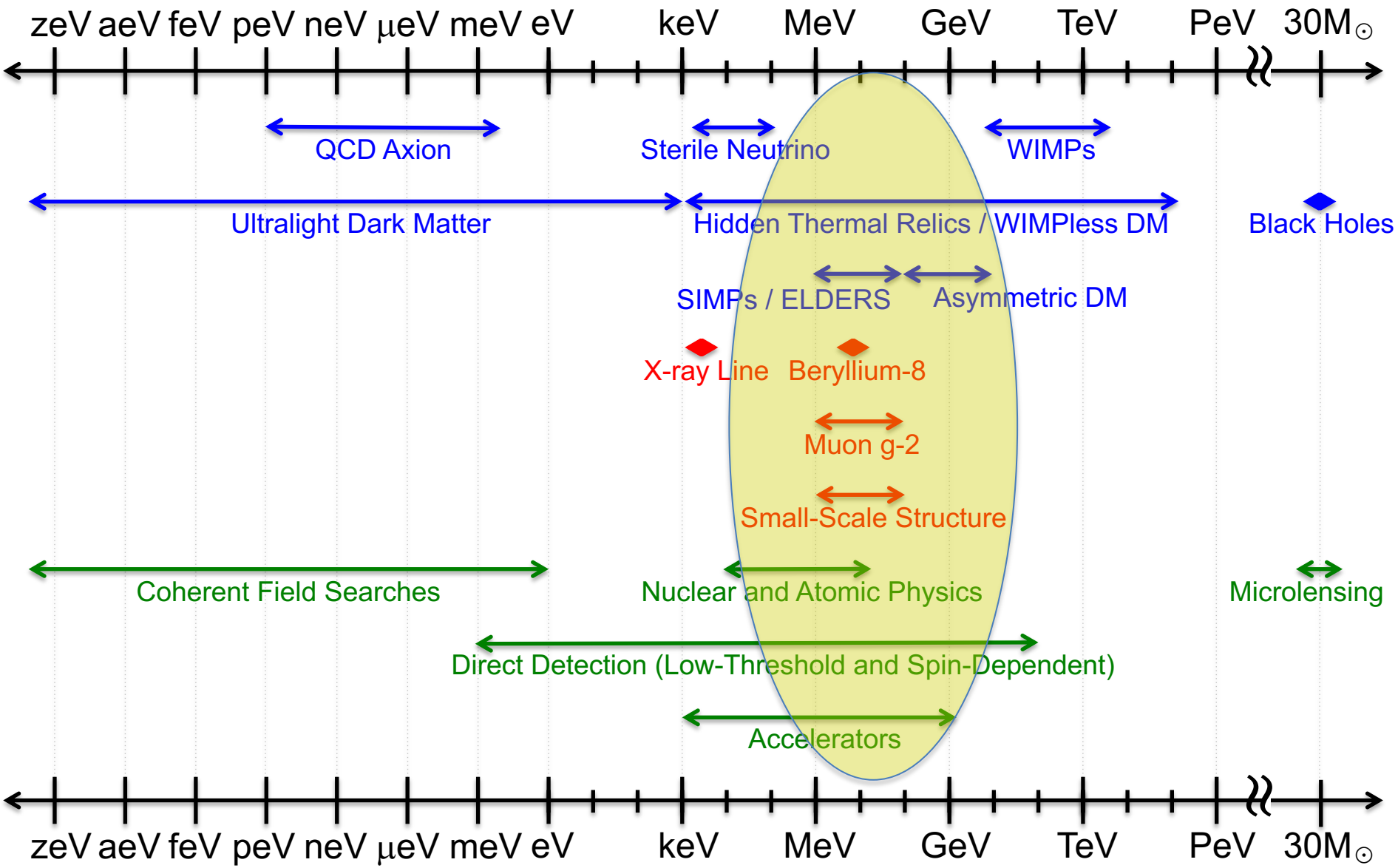
# DARK MATTER


Particle Colliders
Mass
MeV
GeV
TeV
Interaction Strength
1
$10^{-3}$
$10^{-6}$
Already Discovered
Too Little to be Dark Matter
(1) Strongly Interacting Heavy Particles (Higgs, top, SUSY, …)
Just Right to be Dark Matter
(2) Weakly Interacting Light Particles (neutrinos, LLPs, …)
Impossible to Discover
Too Much to be Dark Matter


t (ns)
$m_\chi$ = 100 GeV
Y
$\Omega_\chi$
T (GeV)


DM
DM
A'
e
e
$<\sigma v> \sim \frac{\varepsilon^2}{m_{A'}^2}$

# Dark Sector Candidates, Anomalies, and Search Techniques




Cosmic Visions Report (2017)

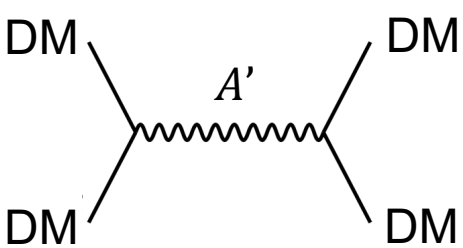
# SELF-INTERACTING DARK MATTER

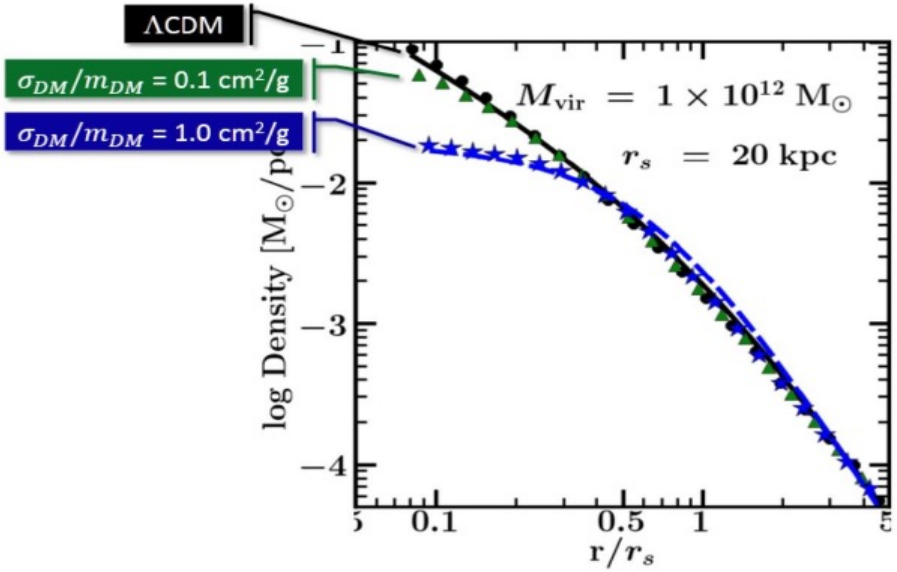
- WIMP DM is in the "strongly interacting heavy particles" category. But there are indications that DM may not be WIMPs. No discovery so far, and also evidence from small-scale structure that dark matter may be strongly self-interacting.

- For example, there appear to be halo profiles that are not as cuspy (high central density) as predicted for standard collisionless cold dark matter (WIMPs, axions, sterile neutrinos, …).

- To smooth out the cusps, need a self-interaction cross section

$$\frac{\sigma}{m} \sim \frac{\mathrm{cm}^2}{\mathrm{g}} \sim \frac{\mathrm{barn}}{\mathrm{GeV}} \sim (100\ \mathrm{MeV})^{-3}$$




Tulin, Yu (2017)
Rocha et al. (2012); Peter et al. (2012)
Vogelsberger et al. (2012); Zavala et al. (2012)

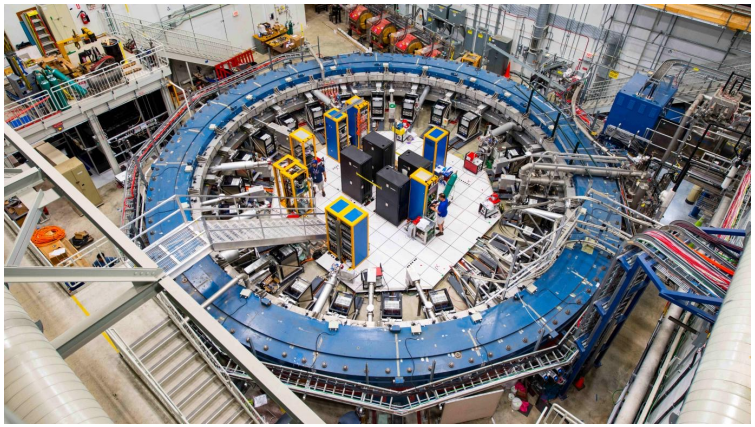
- This can be explained by a dark sector mass scale of ~ 10-100 MeV ("dark neutrons interacting through dark pions").

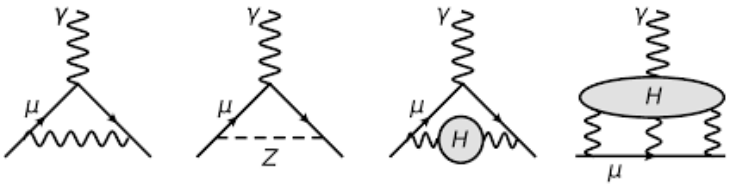
# THE MUON'S ANOMALOUS MAGNETIC MOMENT

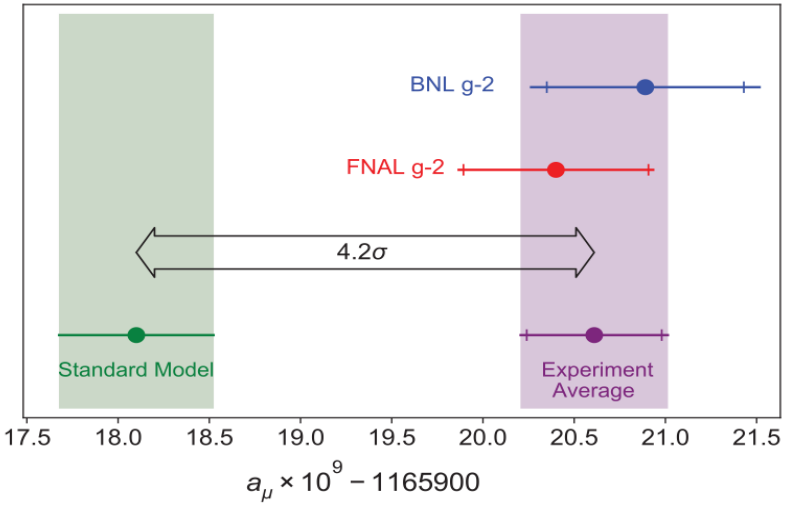
- In 2021, the Muon g-2 Collaboration announced a high precision measurement that deviates from the SM prediction by 3.3σ.

- It is sensitive to the weak interactions, but unlike other precision probes, it requires neither flavor nor CP violation, and so is a "natural" place for new particles to appear, provided they couple to muons.

$$\vec{\mu} = g\frac{q}{2m}\vec{S} \qquad a_l = (g_l - 2)/2$$

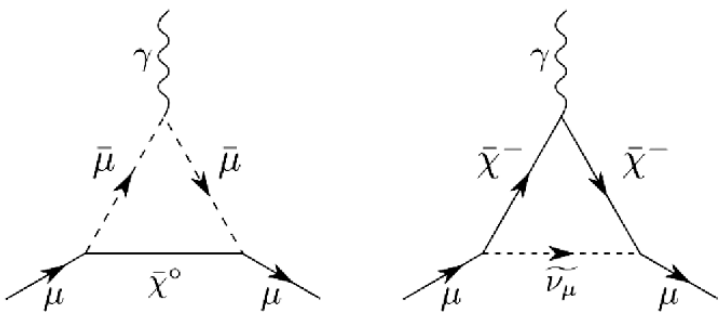


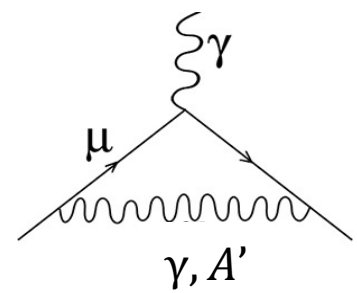


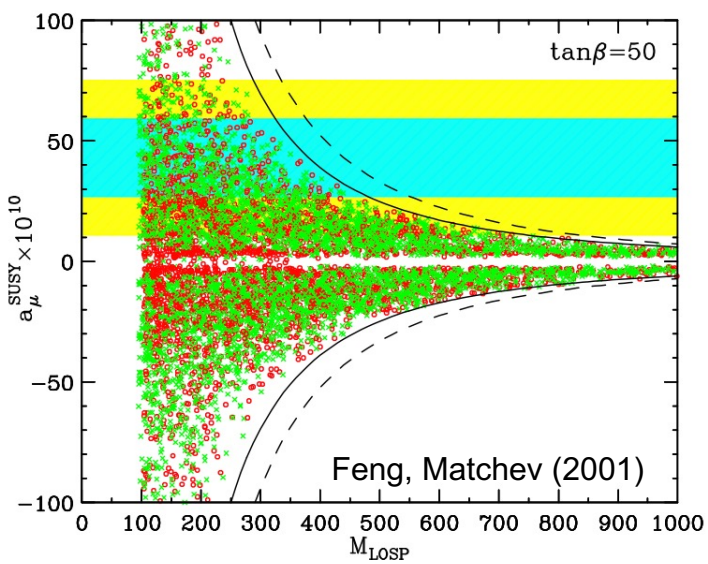



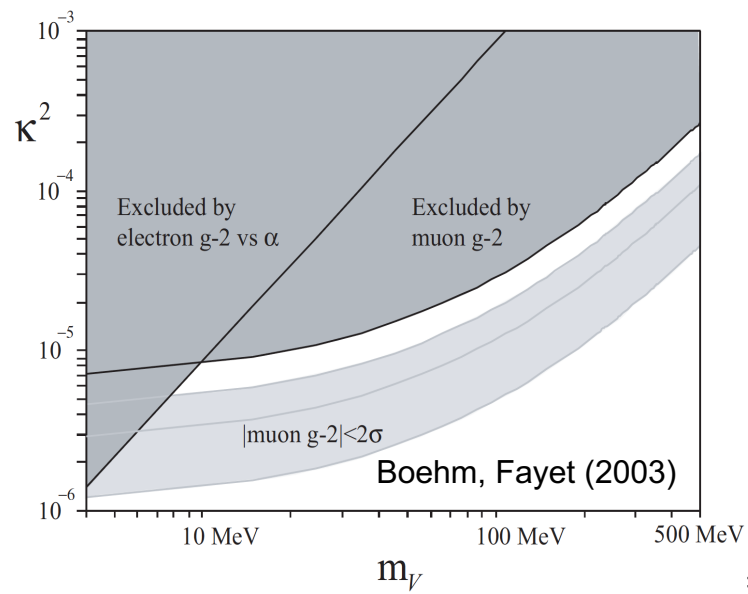
# THE MUON'S ANOMALOUS MAGNETIC MOMENT

- The discrepancy can be resolved by heavy particles, e.g., SUSY with superpartners at the 100s of GeV to TeV scale.
- But it can also be resolved with MeV-GeV masses and couplings ~ $10^{-3}$. (Dark photon now excluded, but other similar particles remain viable.)



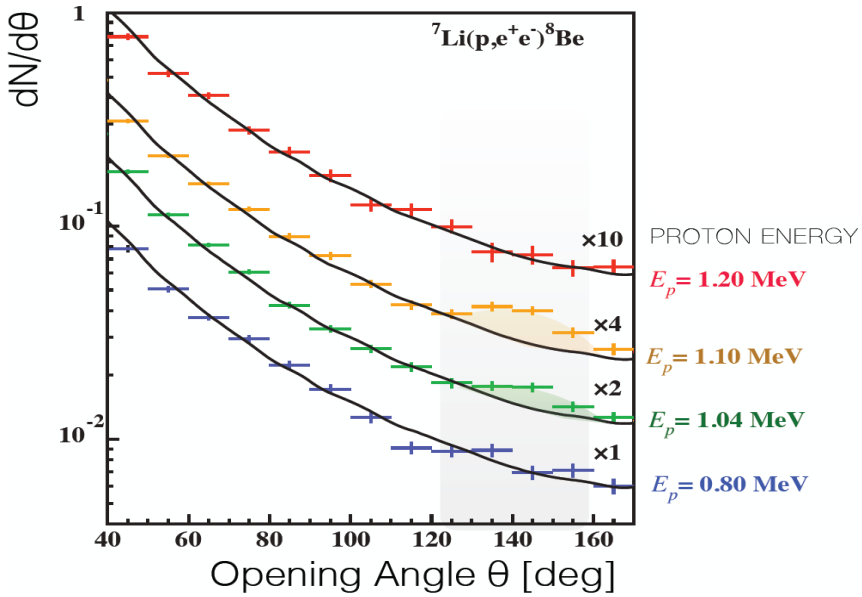
# THE $^8$BE AND $^4$HE ATOMKI ANOMALIES

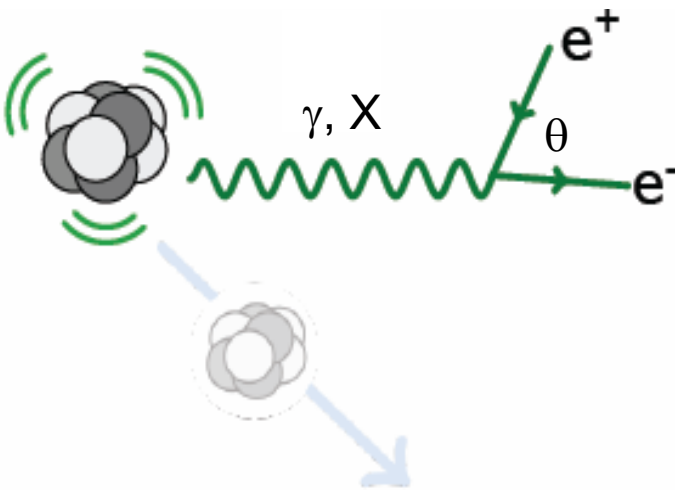
- New particles at the ~ 10 MeV scale and below can be produced in the decays of excited nuclei.

  Treiman, Wilczek (1978); Donnelly, Freedman, Lytel, Peccei, Schwartz (1978); Savage, McKeown, Filippone, Mitchell (1986)

- In 2015, an ATOMKI group reported a 7σ excess in $^8$Be (18.15) → $^8$Be $e^+e^-$ decays at $\theta_{e^+e^-} \approx 140°$.

  Krasznahorkay et al., PRL, 1504.01527 [nucl-ex]



# THE $^8$BE AND $^4$HE ATOMKI ANOMALIES

- The anomaly in the decays of excited $^8$Be nuclei can be explained by a new protophobic gauge boson X with mass 17 MeV and couplings ~ $10^{-4}$ to $10^{-3}$: $^8$Be (18.15) → $^8$Be X, followed by X → $e^+ e^-$.

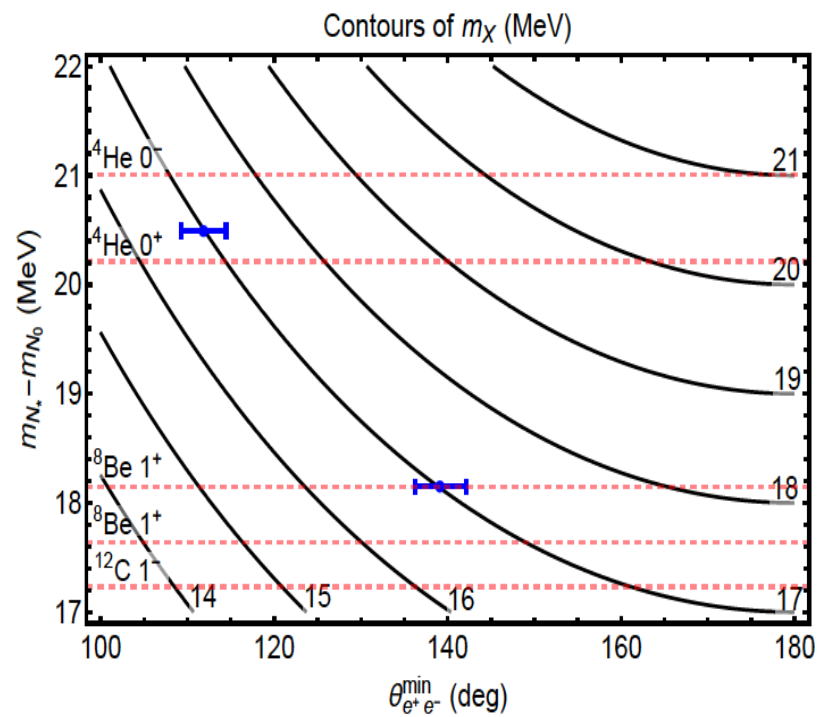
Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, Tait (2016)

- In 2019 the ATOMKI group reported a new 7σ excess in the decays of excited $^4$He (20.49) nuclei at $\theta_{e^+e^-} \approx 115°$.

Krasznahorkay et al. (2019)

- Remarkably, this anomaly can be explained by the same new particle, which can also reduce the muon g-2 discrepancy to 2σ.

Feng, Tait, Verhaaren (2020)
See also Zhang, Miller (2020)

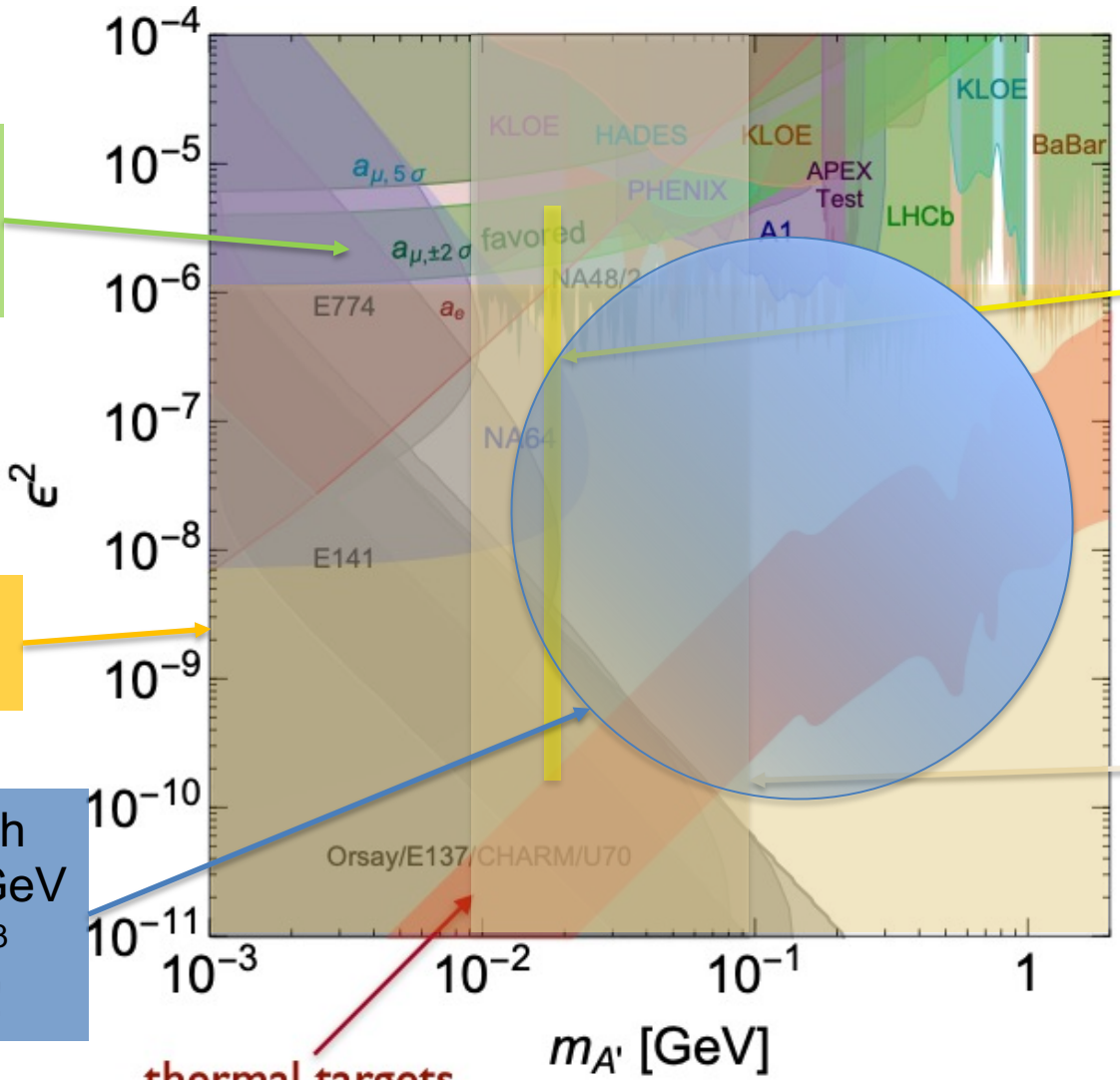


# TARGETS IN DARK PHOTON PARAMETER SPACE

Muon g-2 Anomaly

Loop-induced Coupling

The region with m ~ 10 MeV – GeV $\varepsilon \sim 10^{-6} - 10^{-3}$ is *interesting*!




thermal targets

$\alpha_D = 0.5, M_{A'}/M_\chi = 1.5$

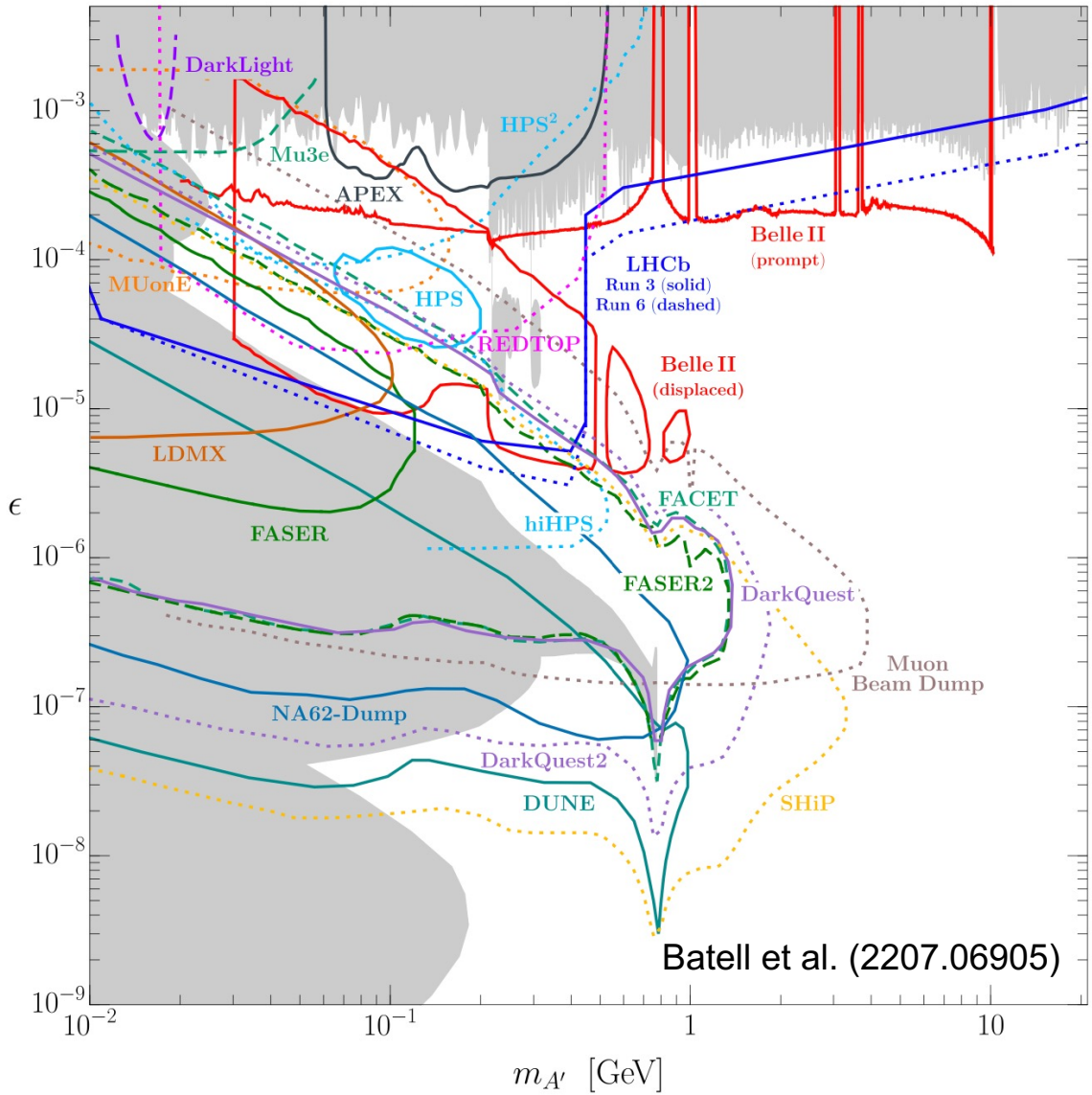
Tim Nelson, Snowmass RP6 (2020)

$^8$Be and $^4$He ATOMKI Anomalies

Self-interacting Dark Matter

# CURRENT EXPERIMENTAL SEARCHES

- In the next few years, this region will be probed by currently running experiments (LHCb, Belle2, NA64, FASER, …) and also proposed experiments. This is the low-hanging fruit of dark sectors – similar to Z-mediated WIMP cross sections. Soon this parameter space will look completely different.

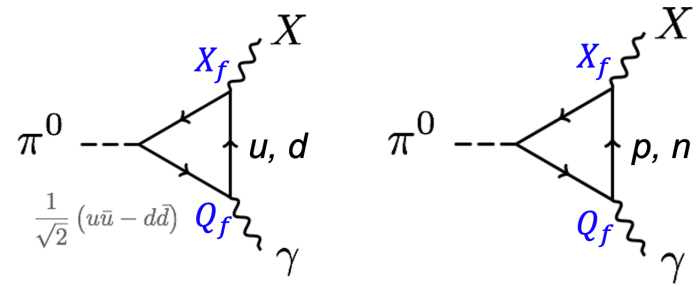



Batell et al. (2207.06905)

# PROTOPHOBIC GAUGE BOSONS

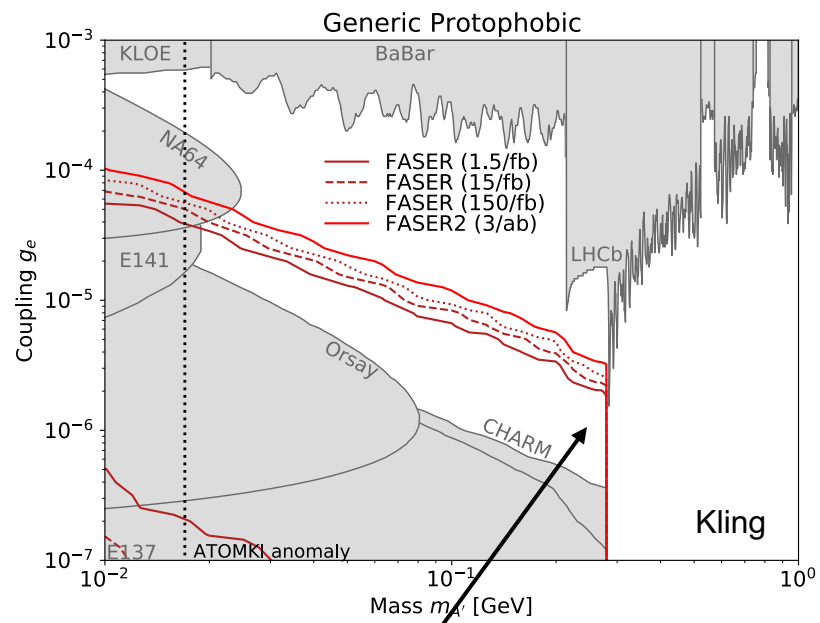
- Photophobic gauge bosons X are quite different from dark photons
  - No production by dark bremsstrahlung off protons
  - No production in pion decays: protophobic → pion-phobic
  - Dominantly produced in η / η' decays.

Feng, Kling (2022)




This is eliminated if $Q_u X_u - Q_d X_d \approx 0$ or $2X_u + X_d \approx 0$ or $X_p \approx 0$.

- Consider a model-independent analysis: fix $g_u$ , $g_d$ ~ $10^{-3}$ (very large!) to explain ATOMKI, scan over $g_e$ .
- With 1 $fb^{-1}$, FASER will probe the low $g_e$ region. NA64 will probe high $g_e$.
- The 7-year-old ATOMKI anomalies will likely be first confirmed or refuted by high-energy experiments.

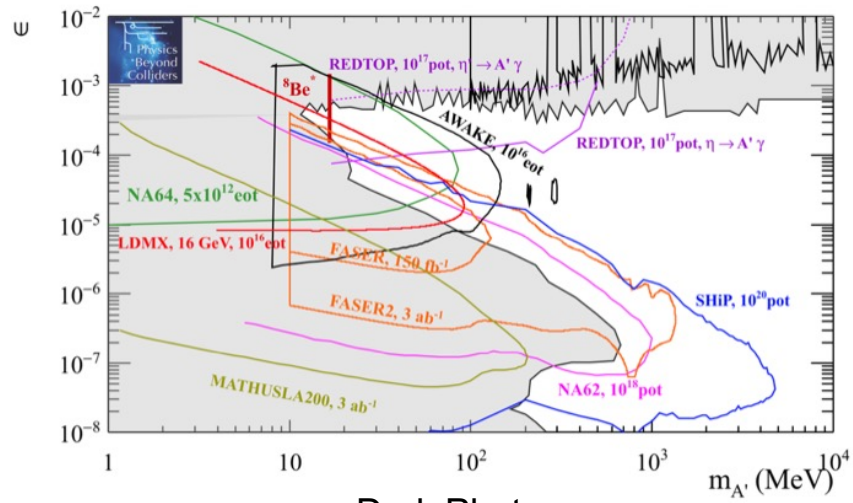



$X \to \mu^+ \mu^-$ for $2m_\mu < m_X < 2m_\pi$

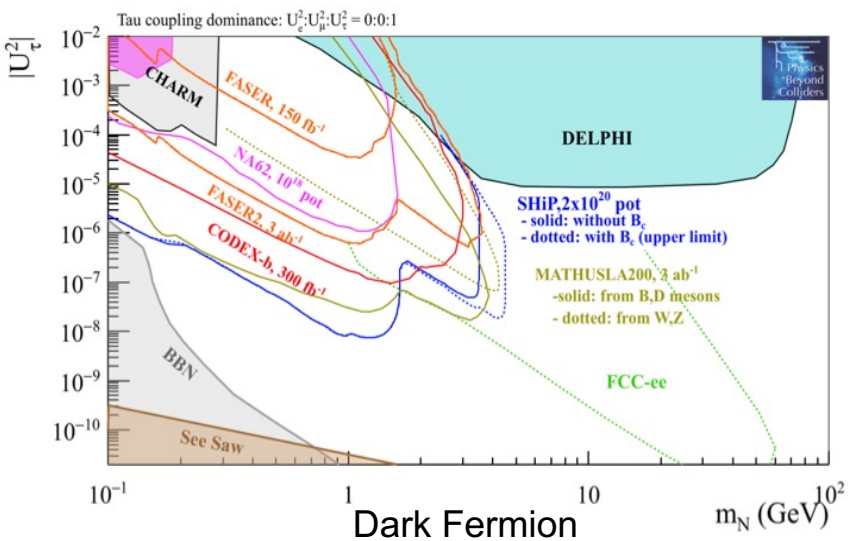
# FUTURE EXPERIMENTAL SEARCHES

- For the future, dedicated detectors have significant discovery potential for a wide variety of dark sector particles: dark photons; B-L and related gauge bosons; dark Higgs bosons; HNLs with couplings to e, mu, tau; ALPs with photon, gluon, fermion couplings; light neutralinos, inflatons, relaxions, and many others.

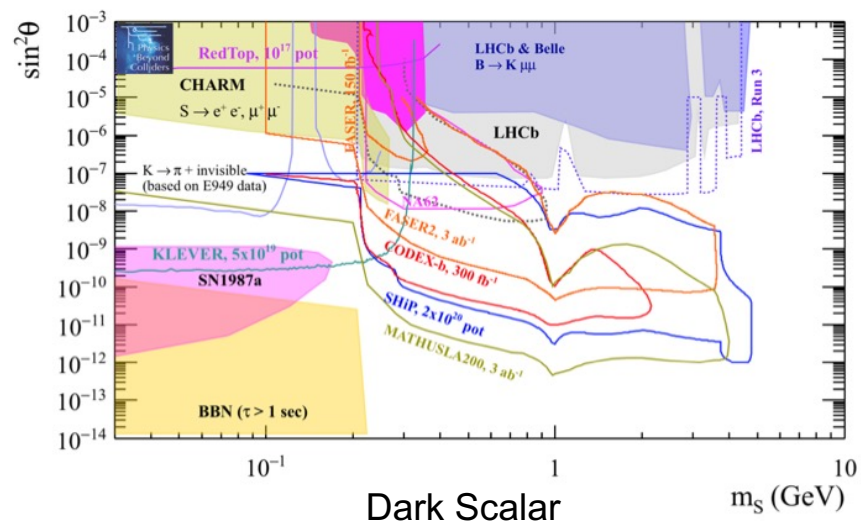
FPF White Paper (2022)




Dark Photon




Dark Fermion

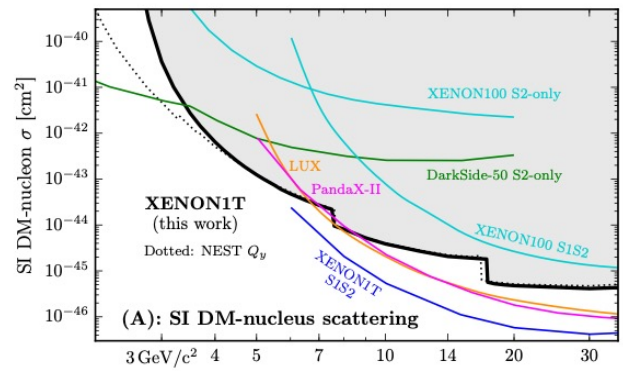



Dark Scalar

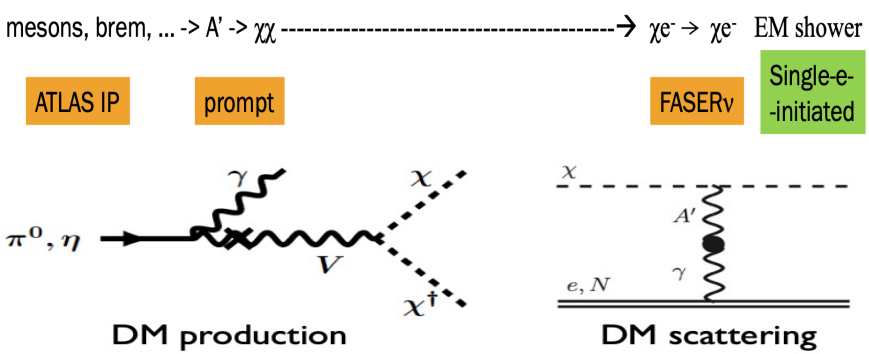
# DARK MATTER DIRECT DETECTION

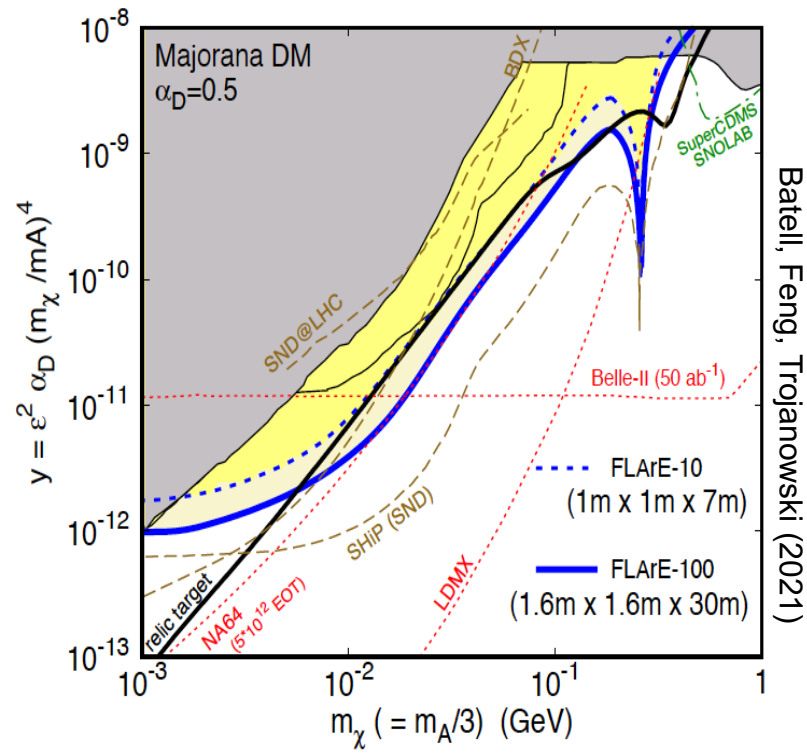
- What if the portal particle decays back to the dark sector? Light DM with masses at the GeV scale and below is famously hard to detect, but there is a great deal of creative work going on in this area.

  See Asher Berlin's talk




- At the LHC, we can produce DM at high energies, look for the resulting DM to scatter in FLArE, Forward Liquid Argon Experiment, a proposed 10 to 100 tonne LArTPC.




Batell, Feng, Trojanowski (2021)

- FLArE is powerful in the region favored/allowed by thermal freezeout. Note complementarity: q vs. e coupling, direct detection vs. missing X, etc.

# SUMMARY

- Dark matter and dark sectors are currently among the leading motivations for BSM searches.

- In general, dark sectors predict new particles with an enormous range of masses and interaction strengths and also many qualitatively different possibilities; B, B-3tau gauge bosons, milli-charged particles, quirks, …; see backup slides.

- But there is a relatively small region of parameter space that has motivations comparable to WIMPs: masses ~ MeV to GeV, couplings ~ micro to milli.
  - WIMPs: coincidence of particle experiment (current threshold of what is observable), particle theory (gauge hierarchy problem), cosmology (WIMP miracle), astrophysics (large-scale structure), anomalies
  - Dark sectors: coincidence of particle experiment (current threshold of what is observable), particle theory (portals), cosmology (WIMPless miracle), astrophysics (small-scale structure), anomalies

- Most importantly, this region can be probed by many experiments in the coming 10 years. Just as WIMP DM became the subject of a world-wide research program in the 2000's and 2010's, dark sectors will become the subject of a world-wide research program in the 2020's and 2030's.

# BACKUP

# NEW SIGNALS: QUIRKS

Kang, Luty (2008)

- Quirks are matter particles charged under a hidden strong force with mass m >> $\Lambda_{hidden}$. E.g., m ~ 100 GeV – TeV, $\Lambda_{hidden}$ ~ keV.

- Quirks may also have SM charge and color. They are then pair produced at the LHC, and are connected by a hidden color string.

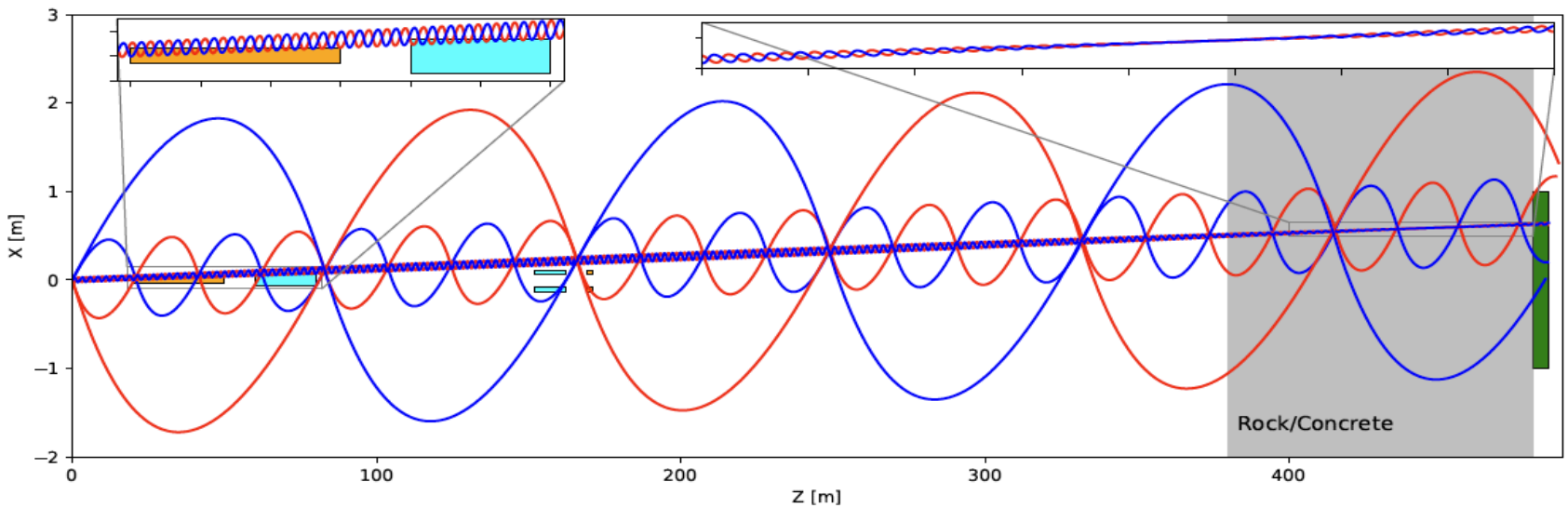
- For quarks and standard QCD, m << $\Lambda_{QCD}$, and so it becomes energetically favorable to pair produce new quarks from the vacuum. Quarks hadronized.

- But for quirks, since m >> $\Lambda_{hidden}$ , it is never energetically favorable to break the string by pair producing quirks from the vacuum: quirks do not hadronize, they oscillate.

# QUIRK SIGNATURE

- Of course, the quirk – anti-quirk system has low $p_T$.
- The pair therefore oscillates, with length scale ~ 1/ $\Lambda_{hidden}$.
- For a range of $\Lambda_{hidden}$ , the quirk system travels down the beamline, escaping most LHC detectors, but ultimately leaving (strange!) tracks in FASER.

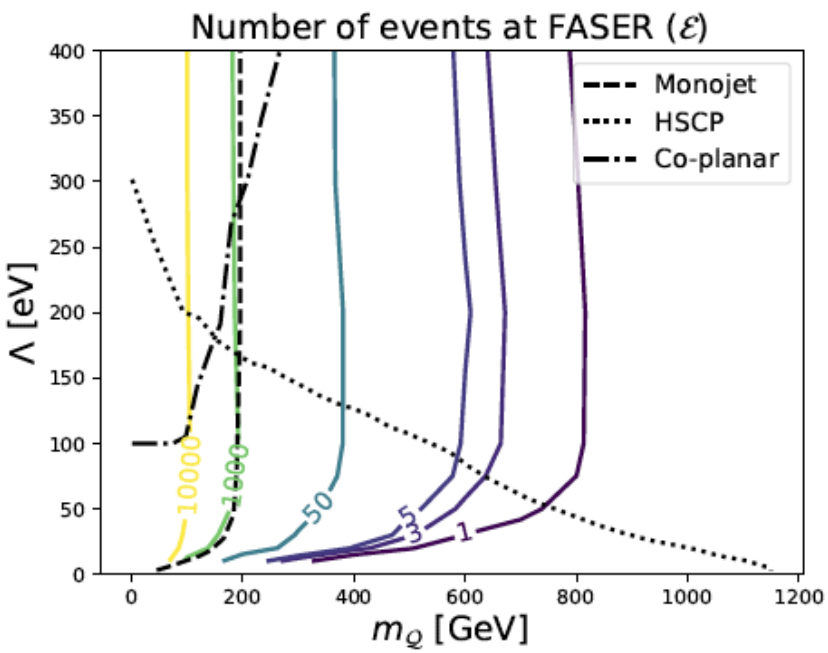
Li, Pei, Ran, Zhang, 2108.06748

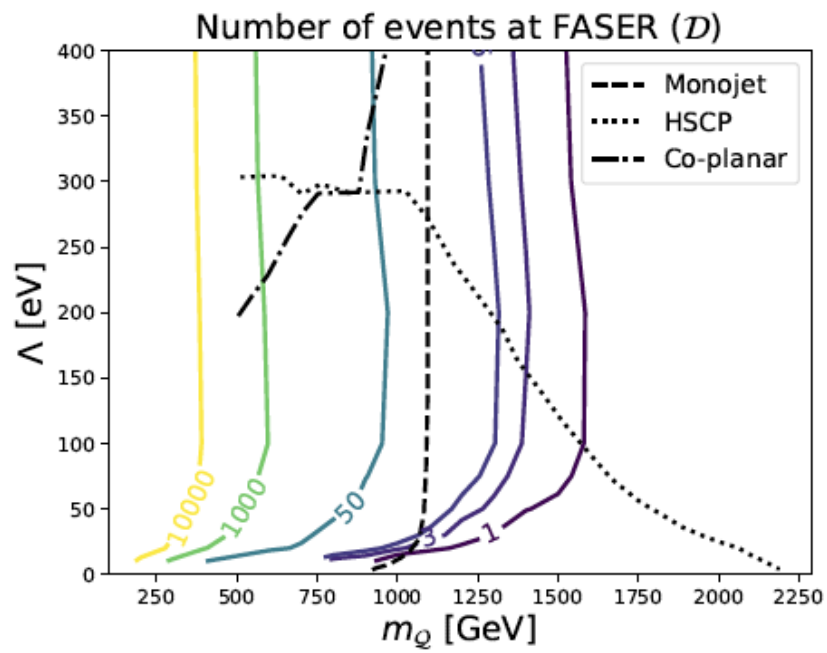


# QUIRK DISCOVERY PROSPECTS

- Far-forward detectors at the LHC are ideally suited to search for quirks.
  - Like heavy particles, they require the LHC to be produced
  - Like light particles, they are dominantly produced along the beamline

- ~1000 of events possible at FASER in Run 3



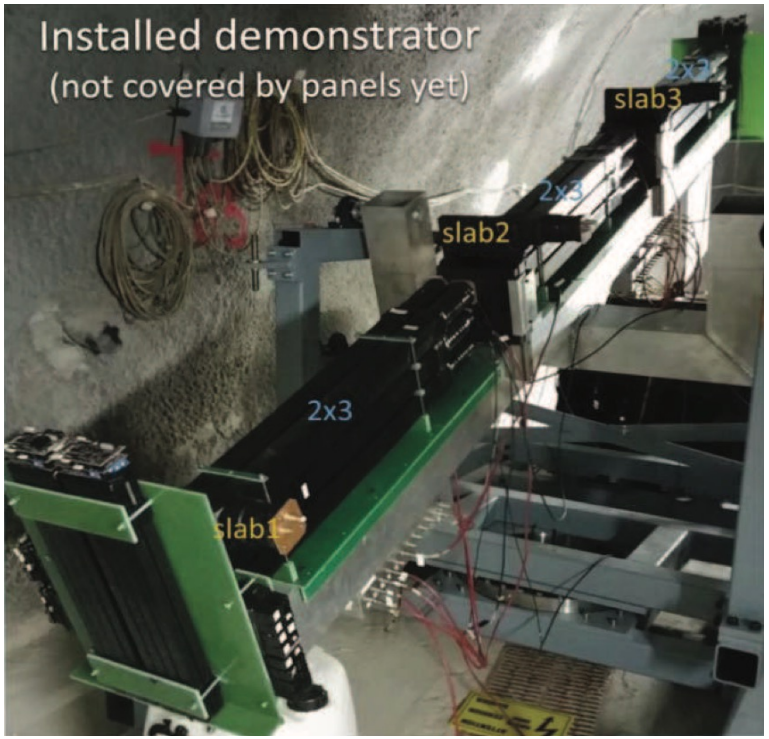



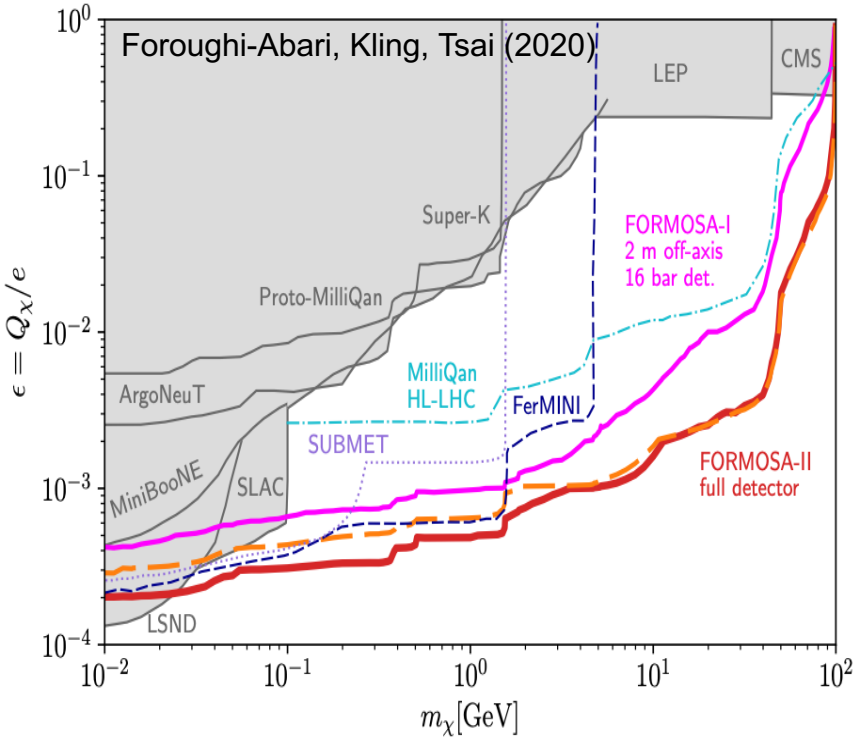

Li, Pei, Ran, Zhang, 2108.06748

# MILLI-CHARGED PARTICLES

- A completely generic possibility motivated by dark matter, dark sectors. Currently the target of the MilliQan experiment, located at the LHC near the CMS experiment in a “non-forward” tunnel.

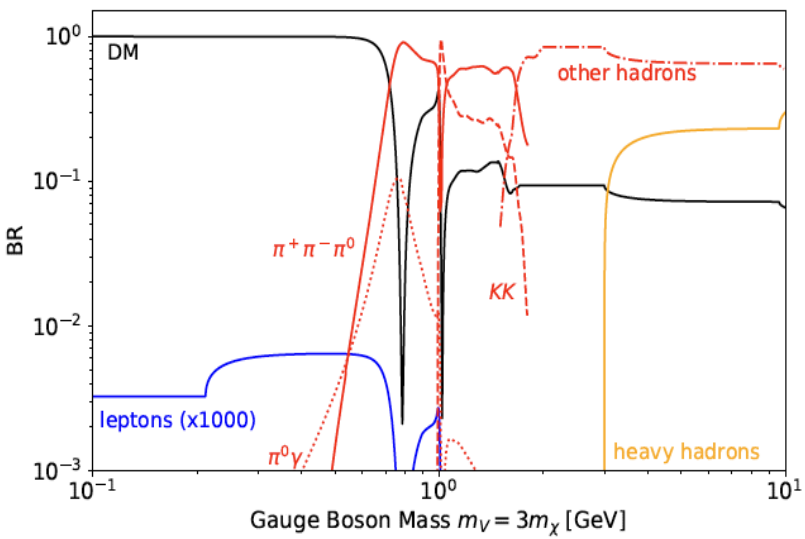
- The MilliQan Demonstrator (Proto-MilliQan) already probes new region. Full MilliQan can also run in this location in the HL-LHC era, but the sensitivity may be improved significantly by moving it to the FPF (FORMOSA).

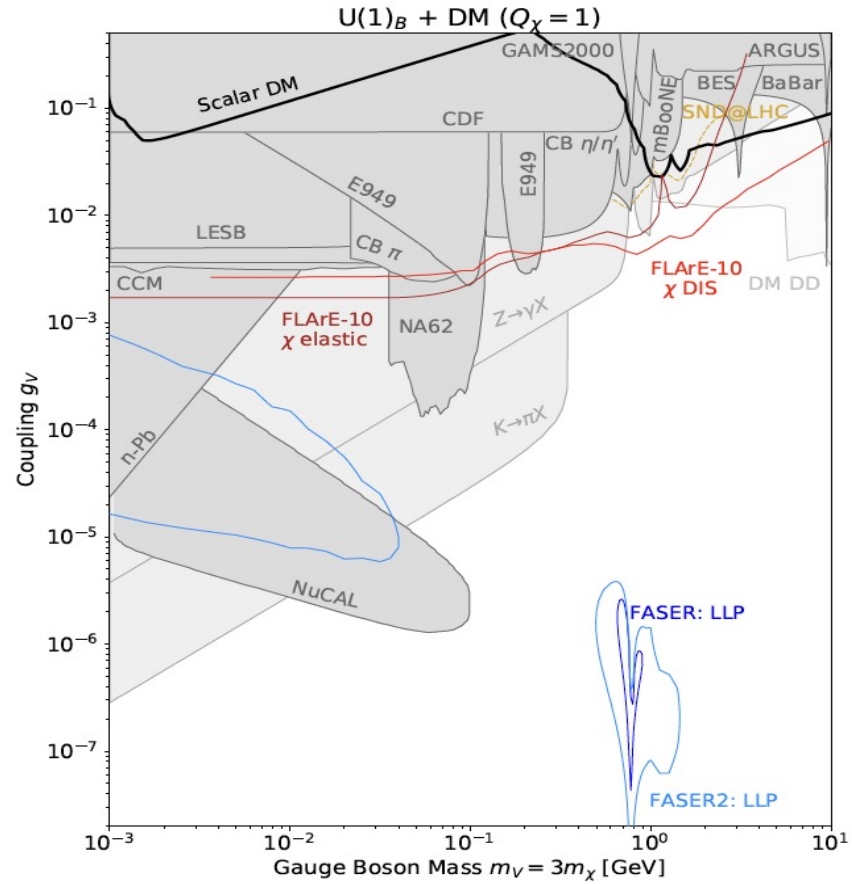


# NEW SIGNALS: B AND B-3τ GAUGE BOSONS

- Consider a light gauge boson coupled to baryon number
- Produced through $q\bar{q} \to V$
- Many interesting hadronic decays
  $V \to \pi^0\gamma,\ \pi^+\pi^-\pi^0,\ K^+K^-,\ K_S K_L$
- Greatly expands the standard $e^+e^-$, $\gamma\gamma$ signatures; similar signatures for "anomaly-free" gauge bosons

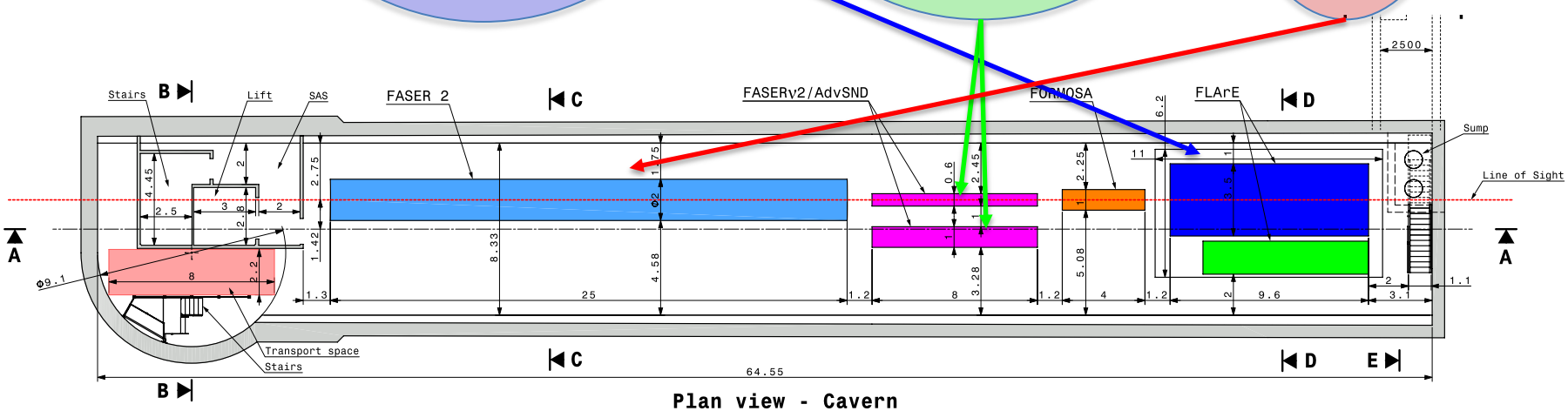



Batell, Feng, Fieg, Ismail, Kling, Abraham, Trojanowski, 2111.10343; see also Boyarsky, Mikulenko, Ovchynnikov, Shchutska, 2104.09688

# SIGNATURES FOR OTHER FPF EXPERIMENTS

| Signature | DM DIS | DM Elastic | $\nu$ NC DIS | $\nu_\tau$ CC DIS | LLP decays |
|---|---|---|---|---|---|
| Models | $U(1)_B$, $U(1)_{B-3\tau}$ | $U(1)_B$, $U(1)_{B-3\tau}$ | $U(1)_{B-3\tau}$ | $U(1)_{B-3\tau}$ | $U(1)_B$, $U(1)_{B-3\tau}$ |
| Production | $pp \to V \to \chi\chi$ | $pp \to V \to \chi\chi$ | $pp \to D_s \to \nu_\tau$ | $pp \to V \to \nu_\tau\bar{\nu}_\tau$ | $pp \to V$ |
| Detection | $\chi N \to \chi X$ | $\chi p \to \chi p$ | $\nu_\tau N \to \nu_\tau X$ | $\nu_\tau N \to \tau X$ | $V \to$ hadrons |




Plan view - Cavern
1:100

Batell, Feng, Fieg, Ismail, Kling, Abraham, Trojanowski, 2111.10343