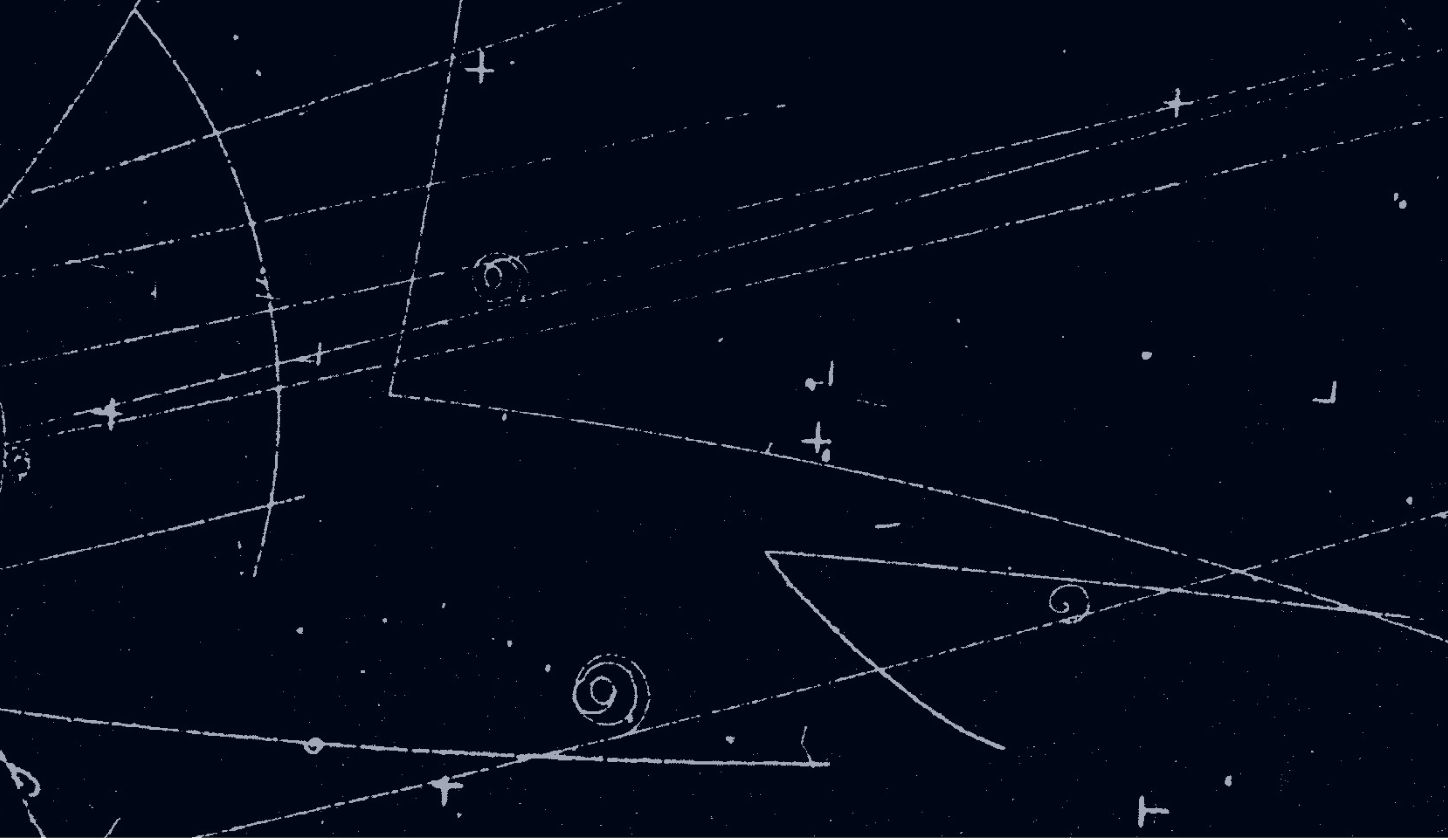


Experimental searches for dark sectors (at accelerators)

Kate Pachal
TRIUMF

Introduction

Dark matter is one of the driving open questions in physics

Experimental searches at accelerators and colliders play a vital role in the search for dark matter

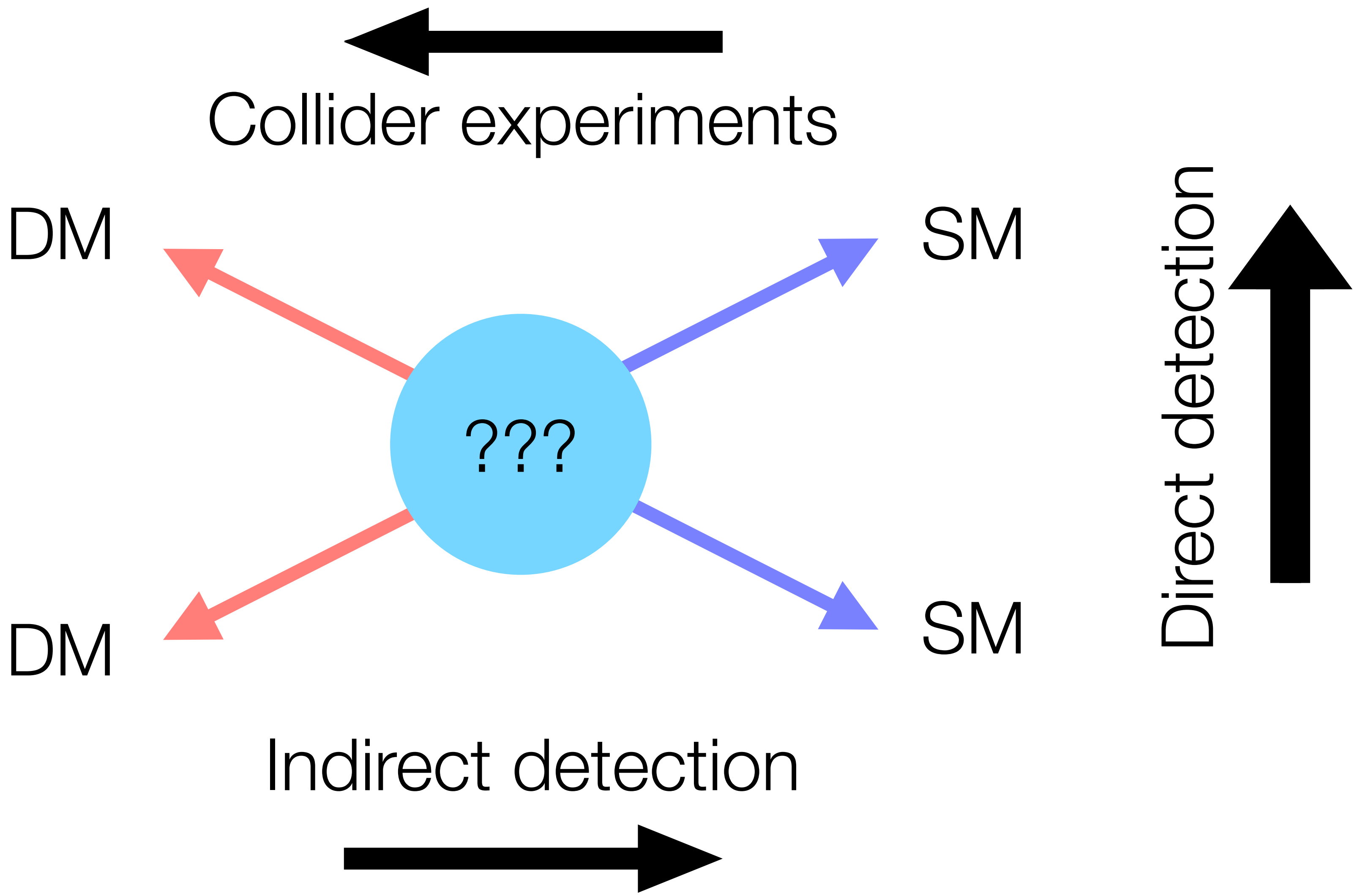
Today's agenda:

- What DM/dark sectors look like at accelerator experiments
- Some cool example experiments and what they can do
- What we could say about DM with future machines

I'll try to set the groundwork for what other speakers will cover in more detail in next three days!

DISCLAIMER: very little shown here is mine - click links and see backup for references!

Complementarity between DM experiments



Tired: all three approaches are probing the same thing (interchangeable)

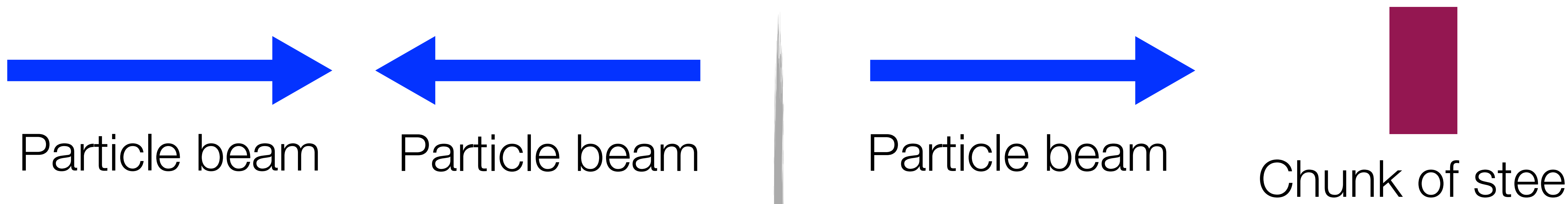
Wired: different DM scenarios may be accessible to only one or two of the three approaches

Inspired: the future of the field needs all three to ensure success

Experiment types and relevant benchmarks

Collider versus fixed target systems

$$E_{lab} = \sqrt{p_1^2c^2 + m_1^2c^2} + \sqrt{p_2^2c^2 + m_2^2c^2}\,, \quad E_{CM} = \sqrt{E_{lab}^2 - p_{lab}^2c^2}$$



CME is **high**: $\sim 2E_{beam}$

Instantaneous luminosity is **low**

Hard to trigger on/record very light signatures relative to CME

Very sensitive to high mass particles

CME is **low**: $\sim \sqrt{2E_{beam}m_t}$

Instantaneous luminosity is **high**

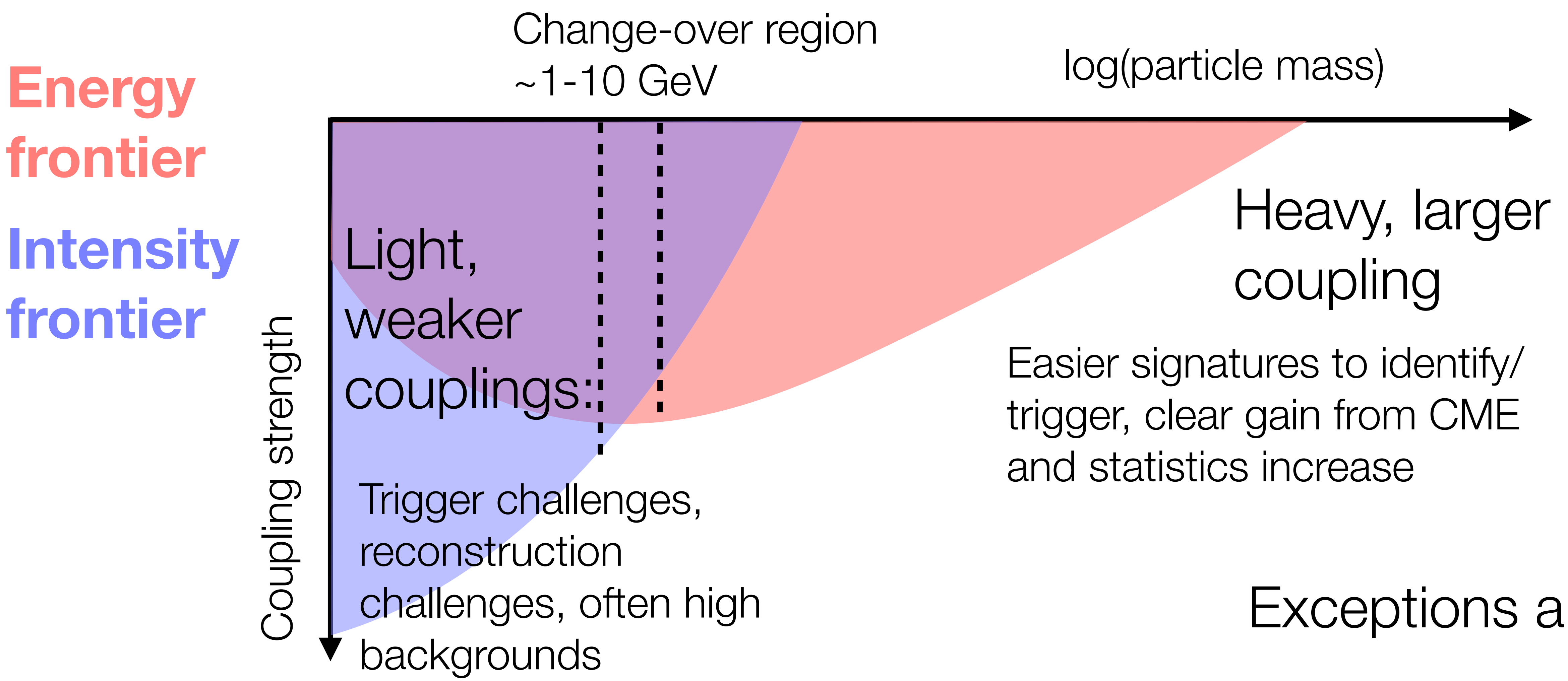
Easier to trigger on/record low mass signatures

Can’t produce high mass particles

“Intensity frontier” vs “energy frontier”

Difference is focus on high data collection rate versus focus on high center of mass energy

Rough correlation to mass of particle being searched for



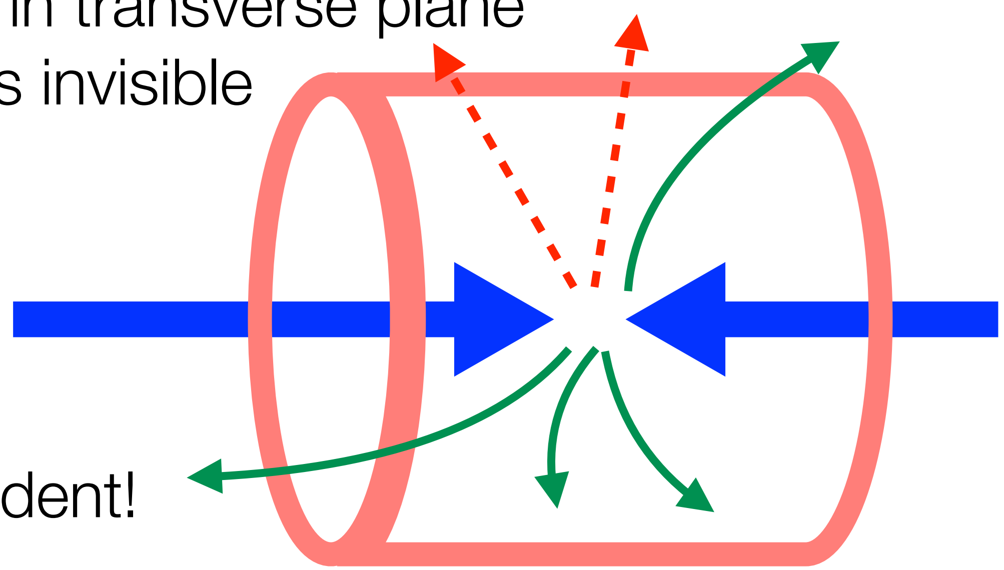
Exceptions apply!

Dark sector particle detection in different experiment types

Missing momentum @ collider

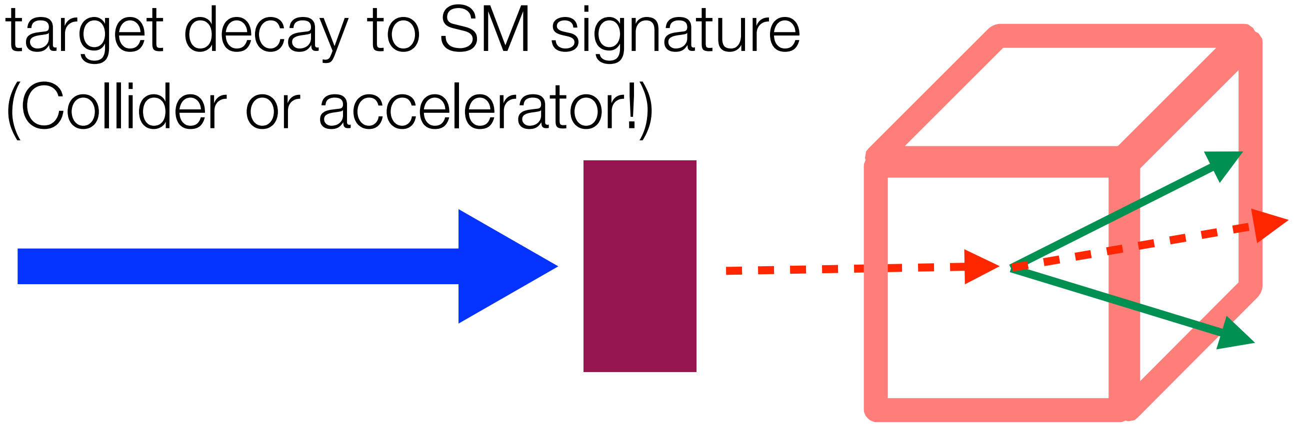
$\Sigma p! = 0$ in transverse plane indicates invisible particle

Model independent!



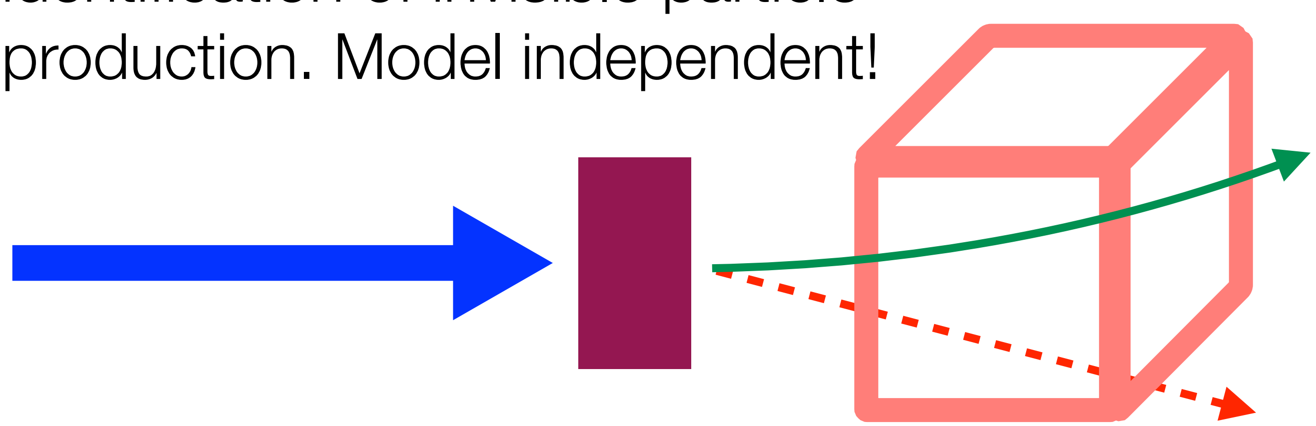
Visible decay products

Dark sector particles produced on target decay to SM signature (Collider or accelerator!)



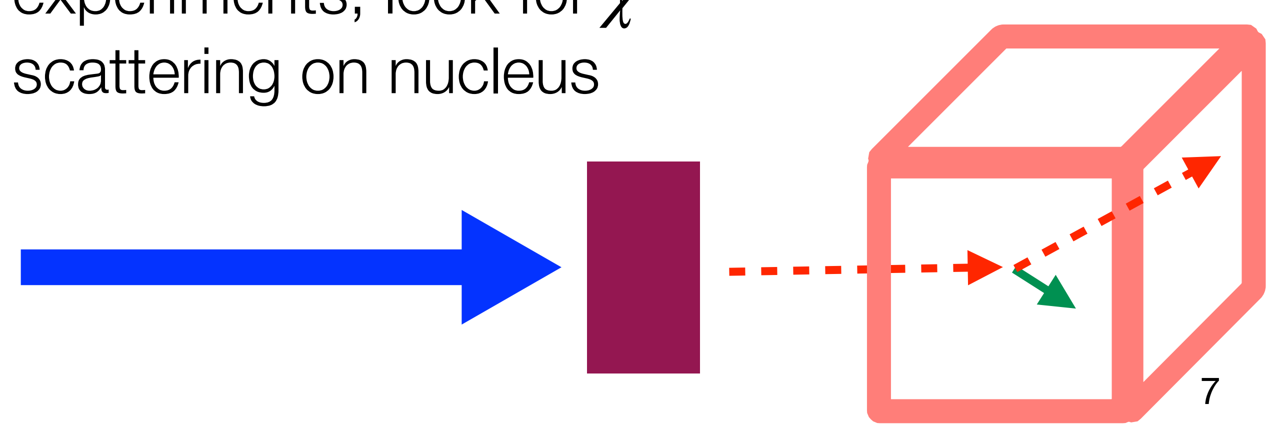
Missing momentum @ fixed target

Precisely known initial state allows identification of invisible particle production. Model independent!



DM Scattering

Like in direct detection experiments, look for χ scattering on nucleus



Choices of benchmark models for framing experimental results

Simplified models

e.g. simple mediator + DM

Ease of comparison between analyses and experiments

Tractable parameter space to understand extent of coverage

Can lead to over-simplified view of what is “excluded” or uncovered

Complete/ complex models

e.g. SUSY

Theoretically robust

Illuminate wide range of final states that are needed for thorough coverage of cases

Hard to form complete picture; hard to compare across contexts

Every sensitivity plot we show for collider/accelerator experiments is relying on some benchmark model

Relevance of relic densities

How much should we care about ensuring benchmarks are **compatible with relic density**?

Anything **up to $\Omega h^2 = 0.12$** is permitted; above that, get overproduction of dark matter relative to cosmological observation

Soft consensus in LHC experiments: know where the constraints are, but do not take them too seriously for simplified models

> Reasoning: goal of simplified models is to understand complementarity between channels and experiments, and identify gaps; theory is often too simple to be taken at face value anyway

However, relic density useful for setting **goal sensitivities**.

Could say a model is excluded once relic prediction reached

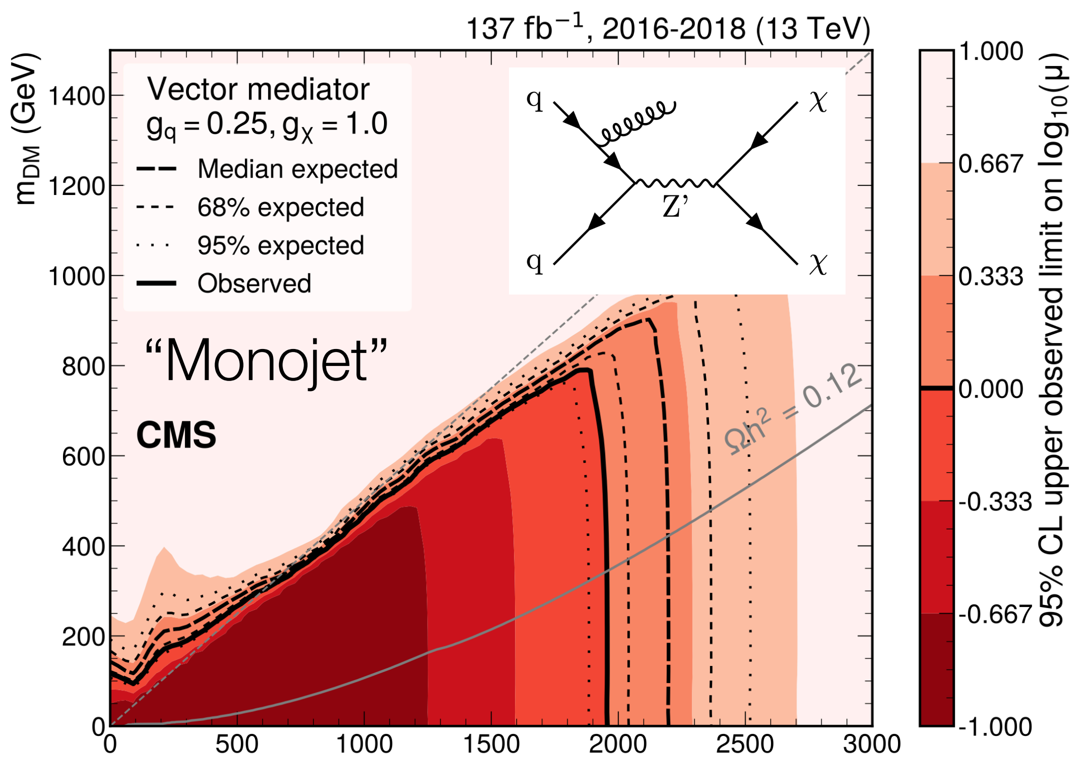
Some illustrative experiments

ATLAS & CMS

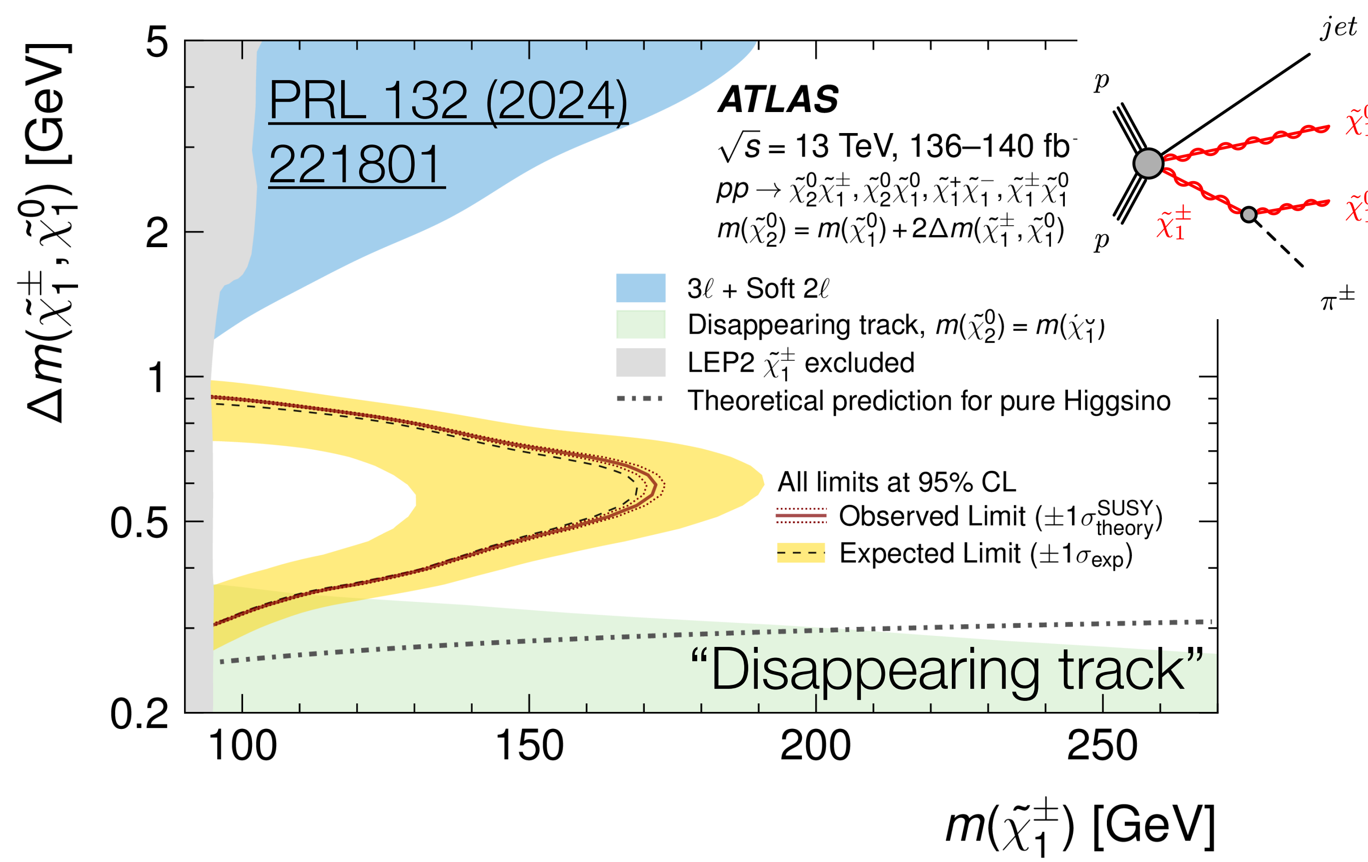
Collider @ LHC (13.5 TeV)

Multi-purpose, full-solid-angle experiments sensitive to missing momentum, visible decay products, & complex final states

SM particle detection limited at low momentum from trigger and reconstruction thresholds



JHEP 11 (2021) 153



Talks with more details!

Diallo, Jackson, Juliette

Also, see backup slides!

LHCb

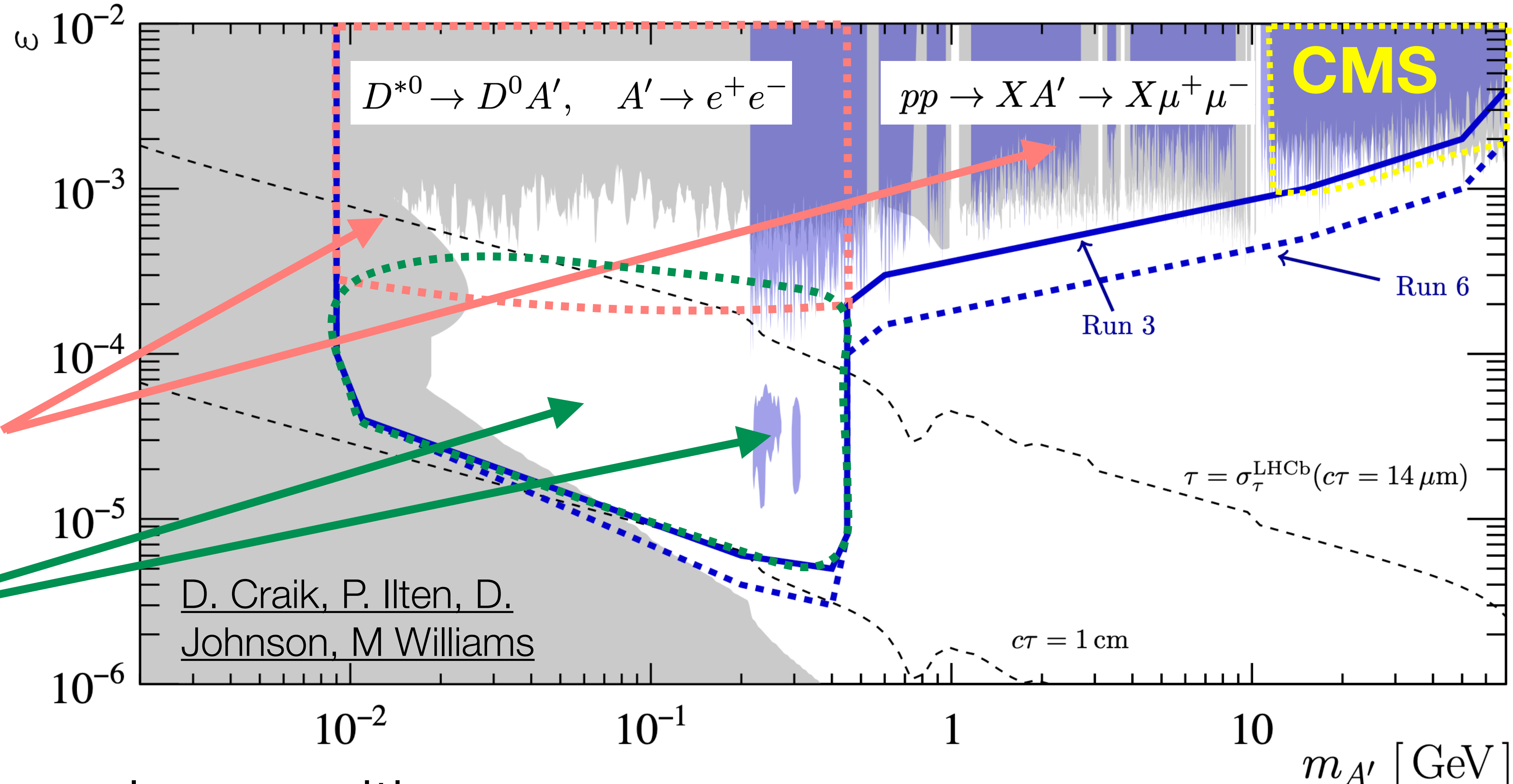
Collider @ LHC (13.5 TeV)

Asymmetric detector not suited to high mass and missing energy searches, but perfect for boosted decays and visible final states

Leading LHC in dark photon sensitivity

Prompt decay

Displaced vertex



LHCb is a powerhouse with Run 3 triggerless readout, able to reach very low masses

Talk with more details!

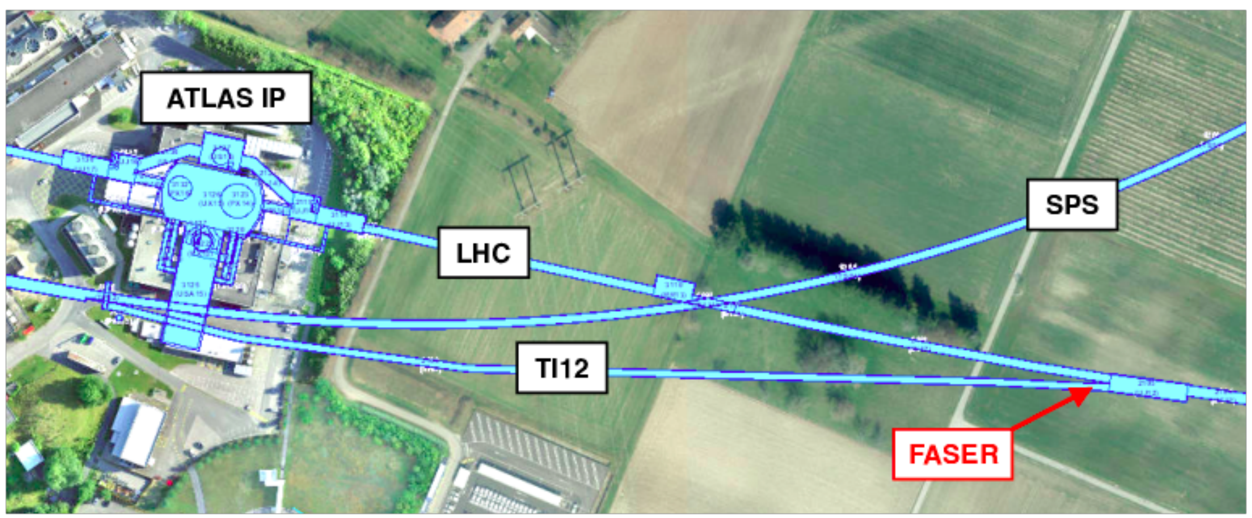
Phil: dark sector searches at LHCb

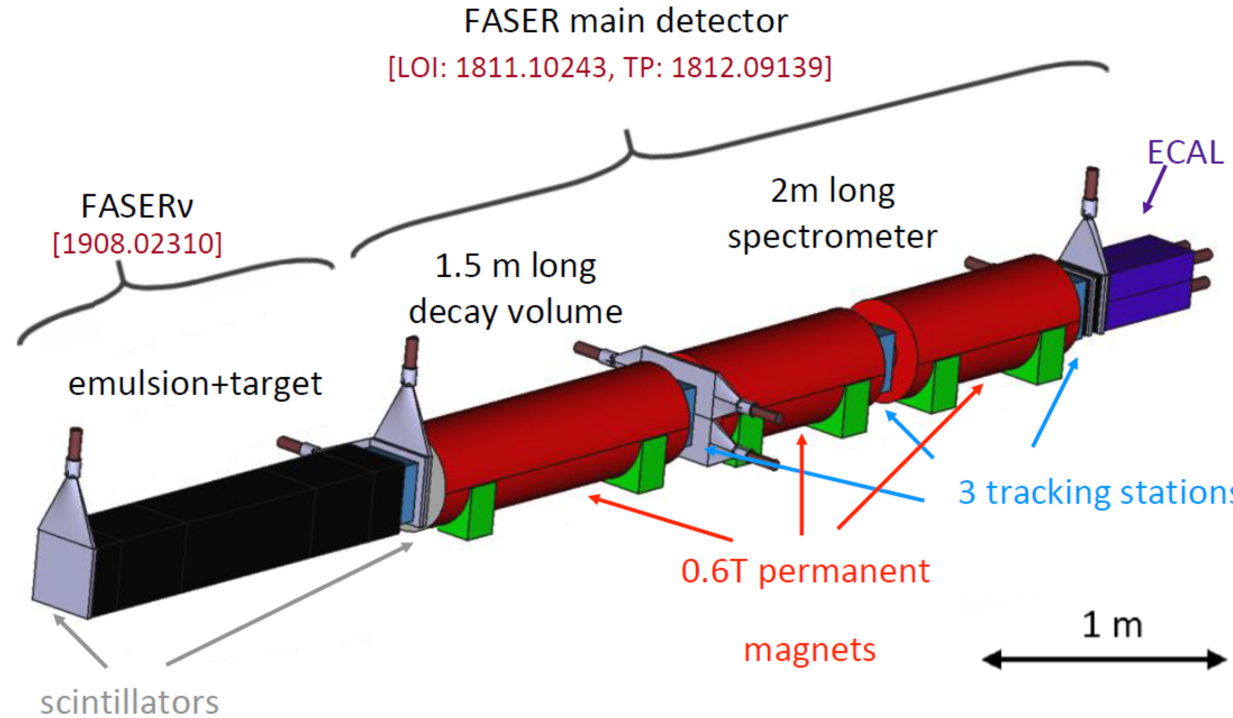
FASER

“Collider” @ LHC (13.5 TeV)

Very forward detector for long-lived particle interactions/decays

faser.web.cern.ch



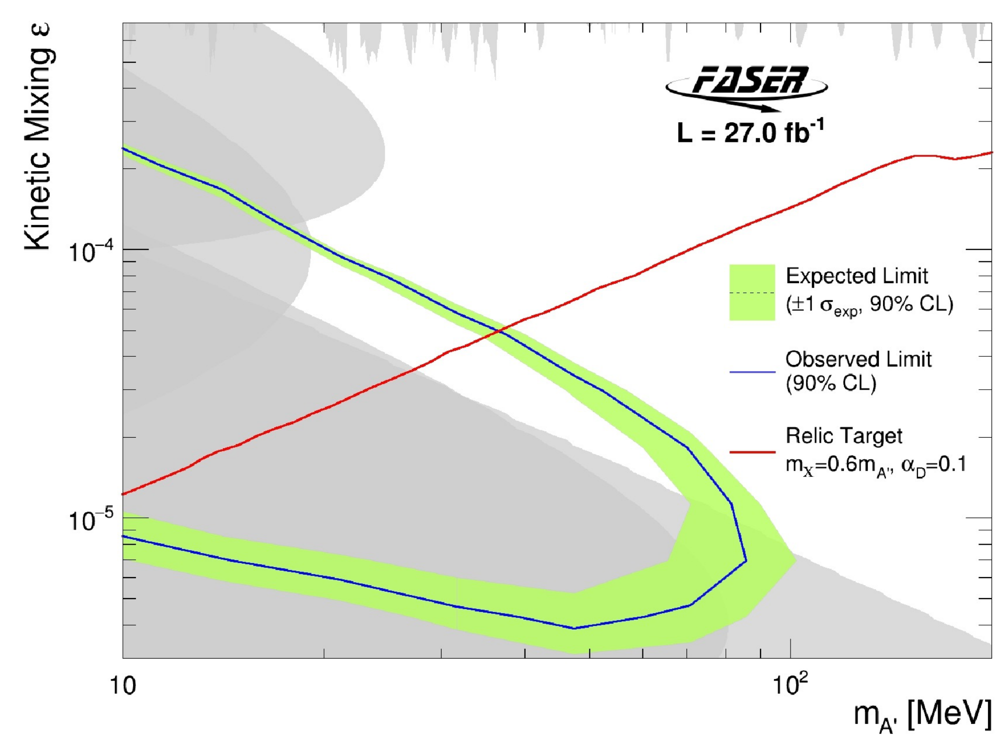


Visible decay experiment: signature is vertex in decay volume

Broad sensitivity to very light LLPs boosted along beam axis

Talk with more details!

Roshan: far forward detectors @ LHC



Phys. Lett. B 848 (2024)

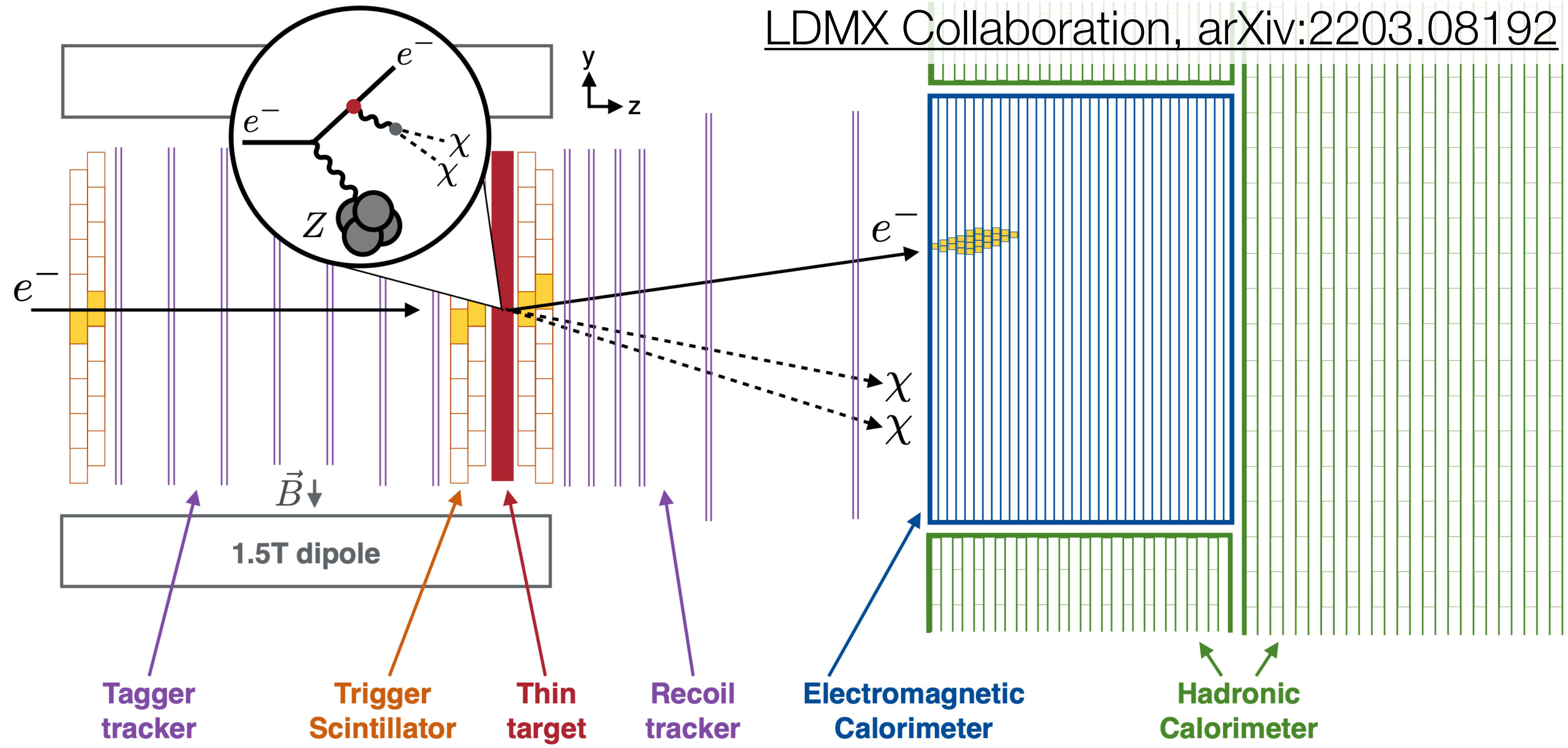
LDMX

Fixed target @ SLAC (4 GeV)

LDMX Collaboration, arXiv:2203.08192

Missing momentum experiment type

Very low-current beam: single electrons



Extremely high projected sensitivity despite low luminosity: great background suppression

Generalizable signature: sensitive to production through any light new mediator, millicharged particles, axions/ALPs, … (see Berlin et al 2019)

Calorimeter structure allows displaced decay reconstruction too

DarkLight

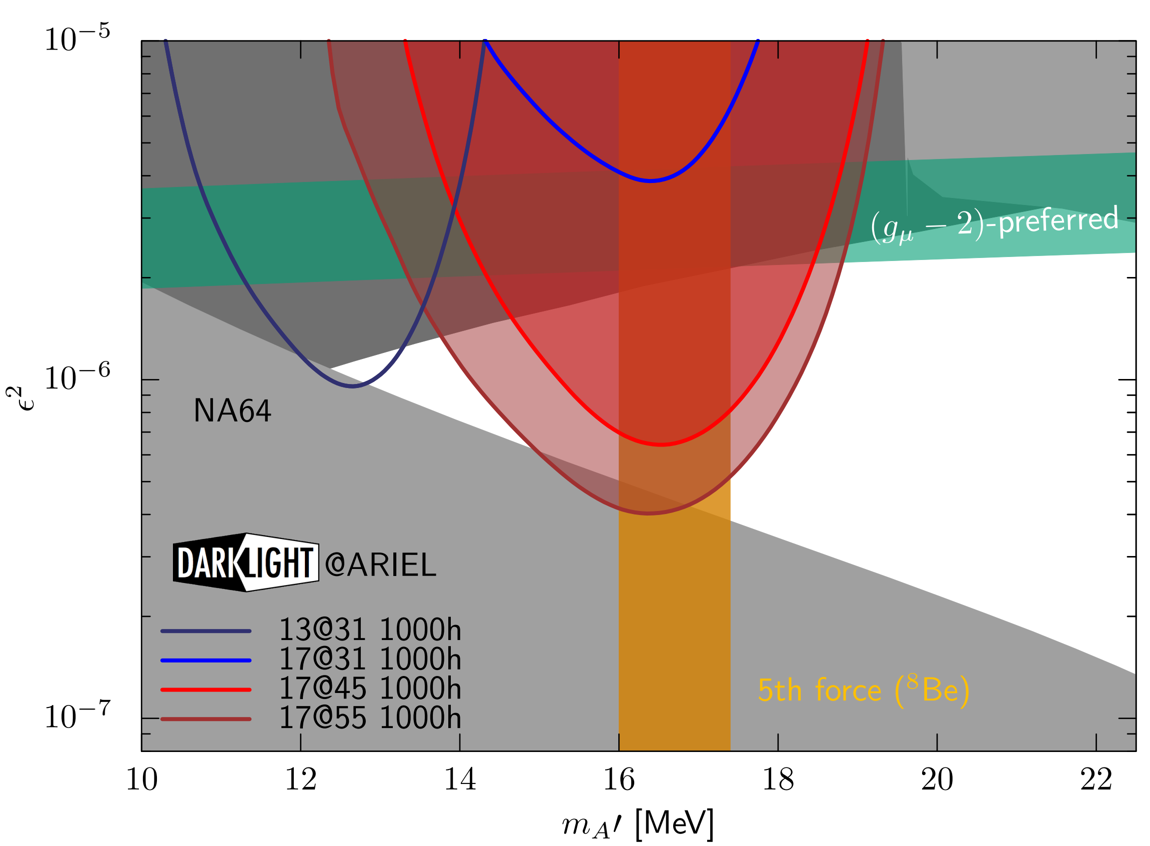
Fixed target @ TRIUMF (30/50 MeV)

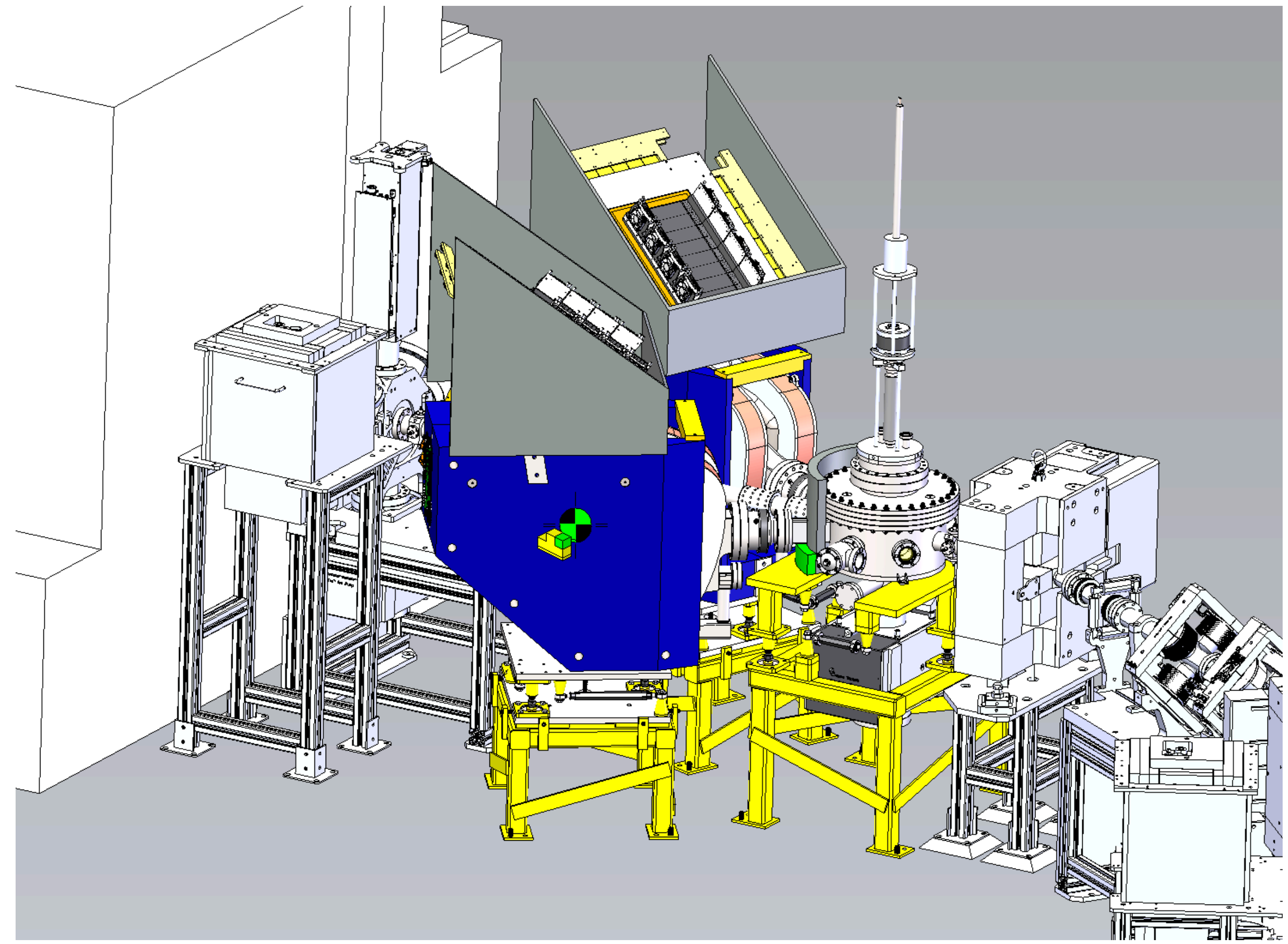
Visible decay experiment: high current e- beam on Ta target

Low energy beam → low boost for dark sector mediator

Wide opening angle suits dual spectrometer experiment

arXiv:2208.04120





Exclusions for vector mediator with suppressed proton couplings

Goal relies on 50 MeV e- beam: upgrade planned for 2026

Future possibilities

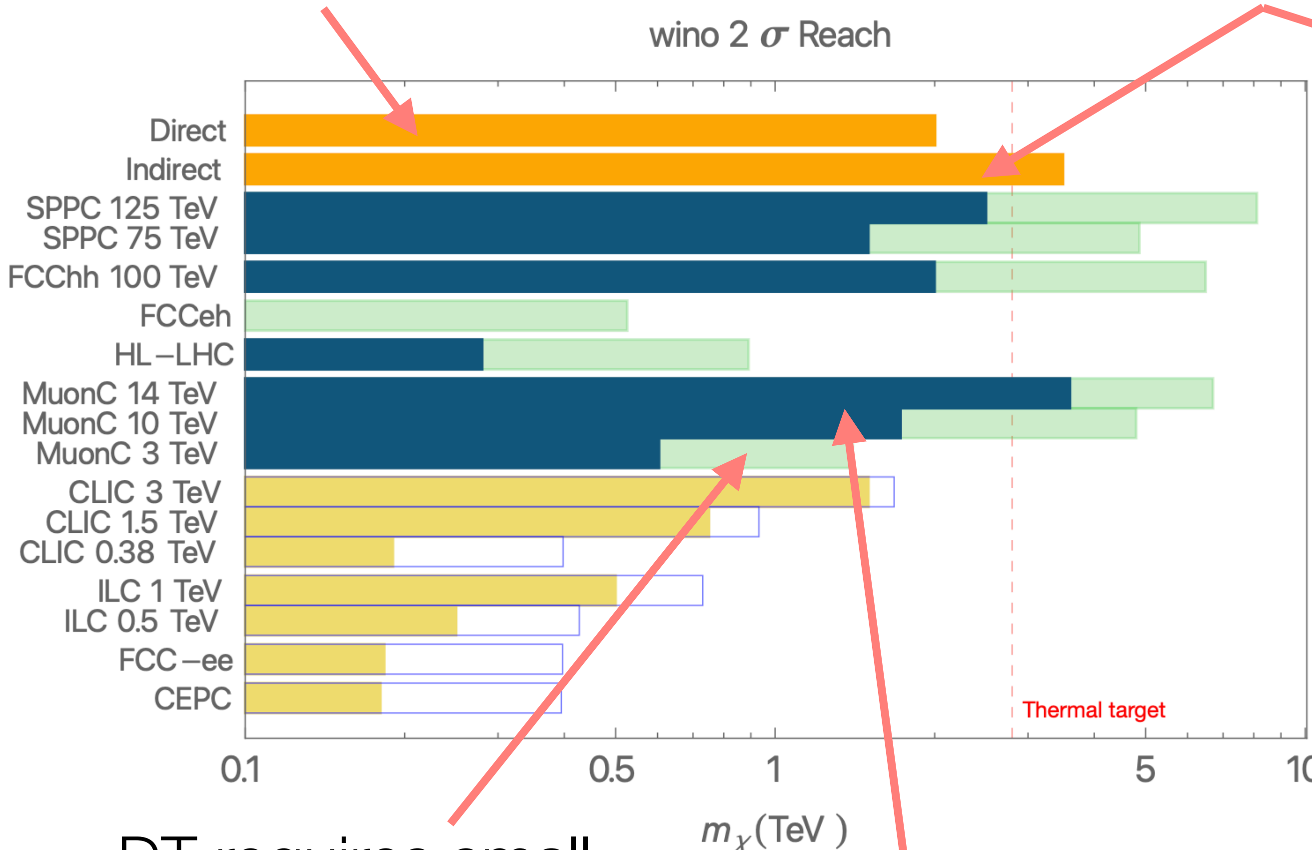
Opportunities at future colliders: SUSY DM

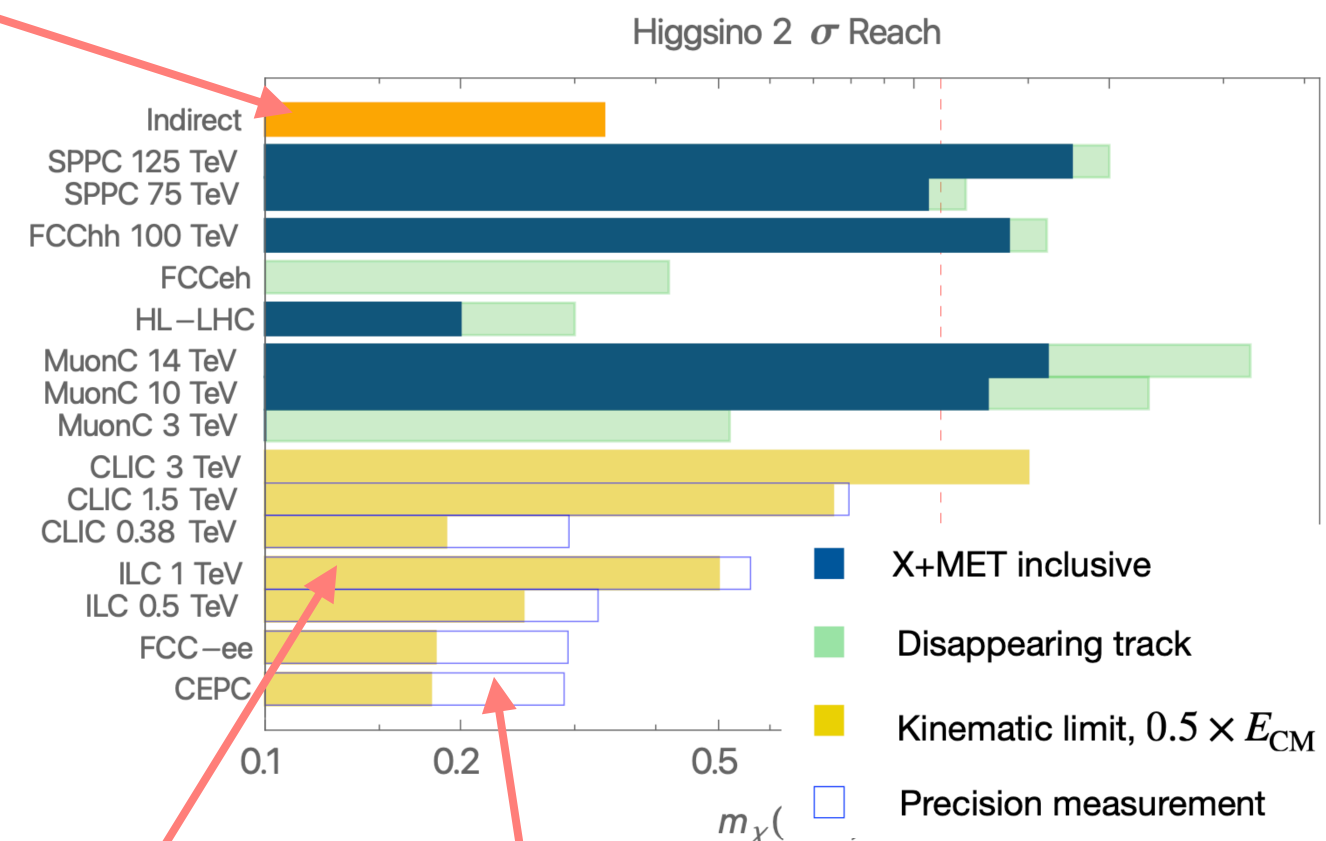
Minimal EW multiplet scenario: SM gauge couplings fix interactions so mass is only free parameter and thermal DM predictions simple.

DARWIN (50T) projection

FERMI & H.E.S.S.

DD below neutrino fog





DT requires small mass splittings

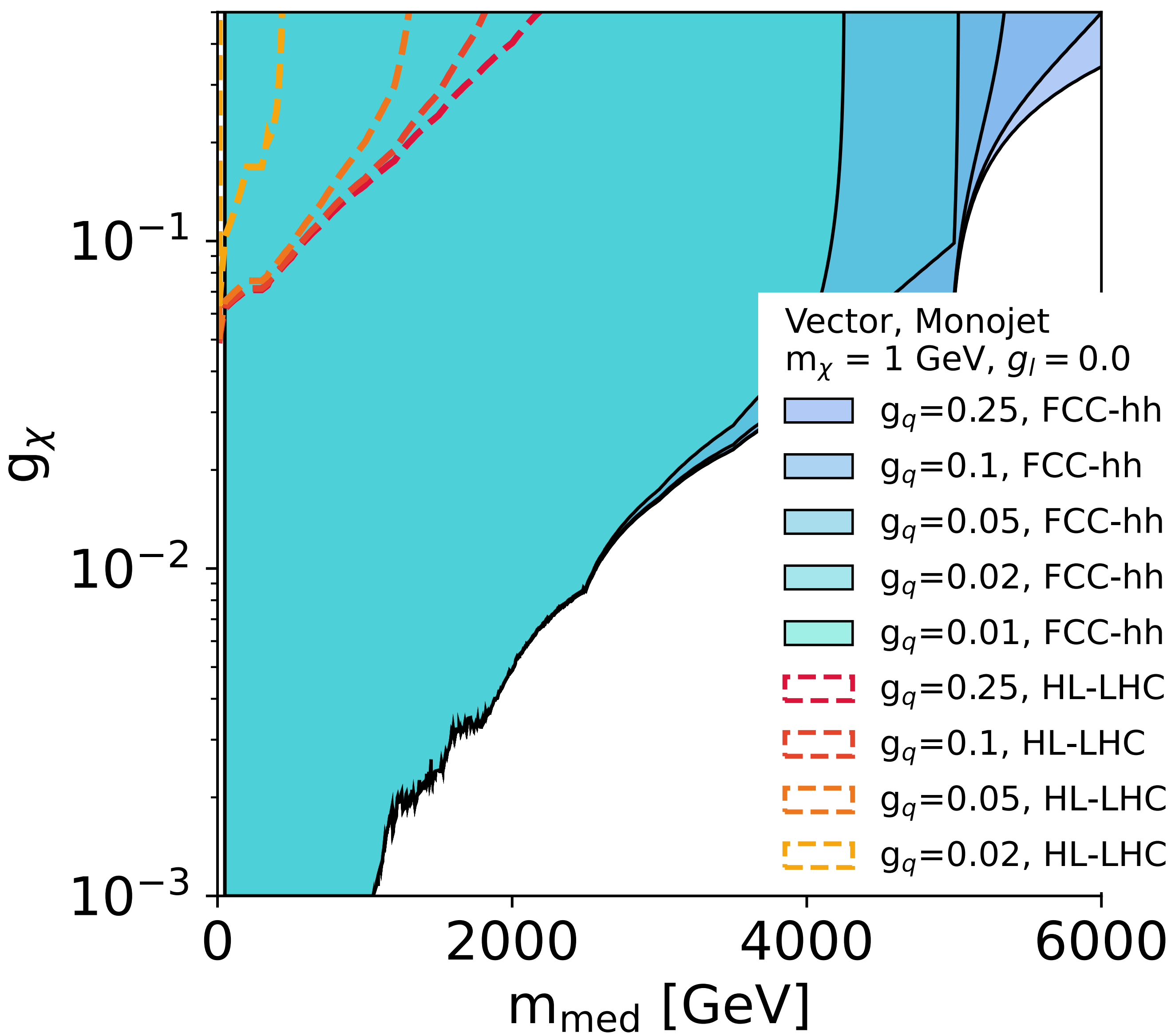
More general for other scenarios

Optimistic?

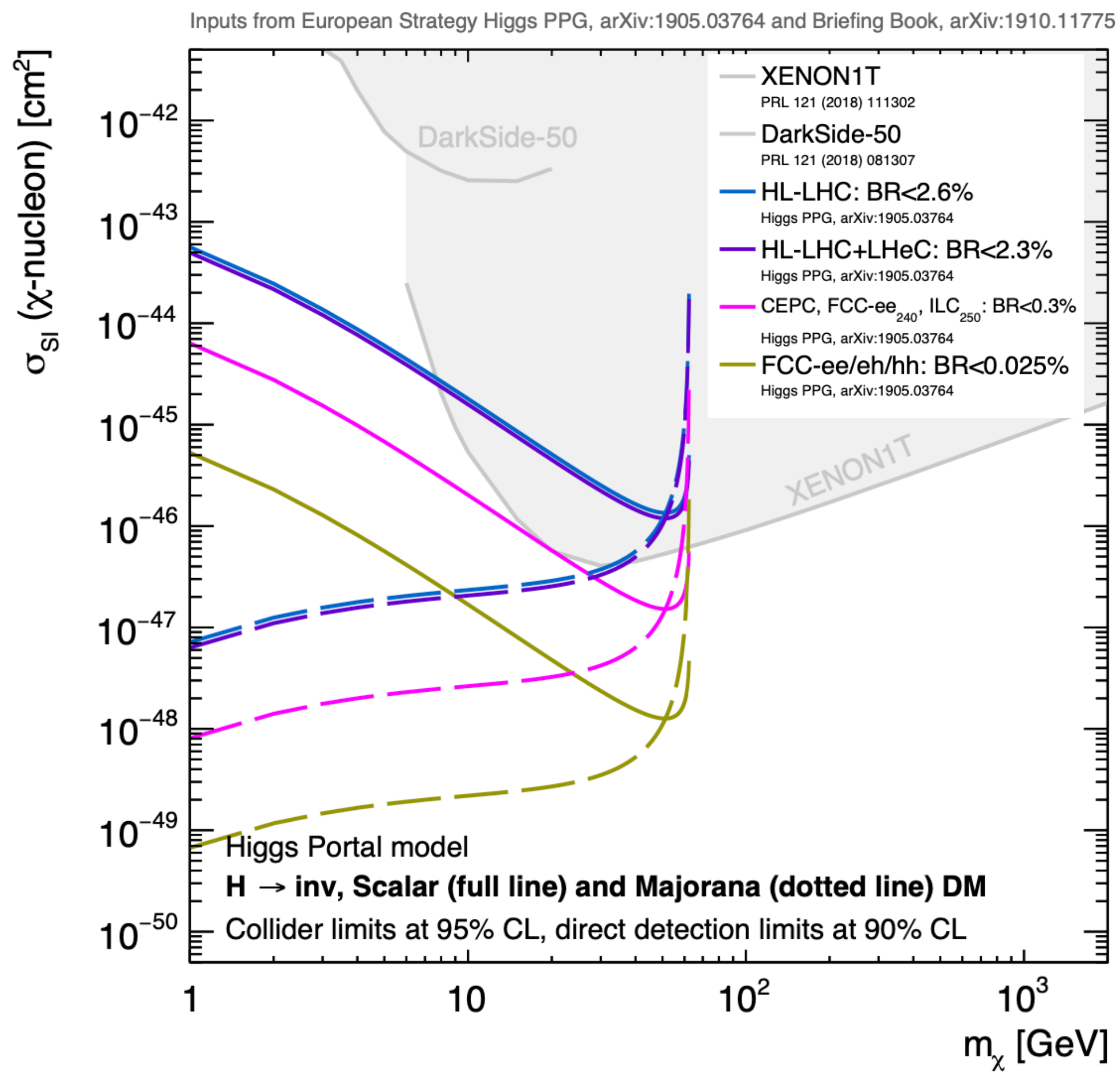
EW measurements set indirect but strong constraints

Reaching thermal target is not easy, but possible at some colliders

Opportunities at future colliders: non-SUSY DM



Spin-1 vector mediator: monojet sensitivity to DM coupling



Higgs portal: $H \to \mathrm{inv}$ sensitivity compared to current DD

Intensity frontier experiments at future colliders

Future colliders have possibilities beyond collision point detectors

Dedicated LLP experiments

Valuable when LLP signature is trigger limited

Limited use at e+e- machines but useful at hadron & probably muon machines

Different signatures can favour forward (FASER-esque) vs off-axis far detectors

Beam dump experiments

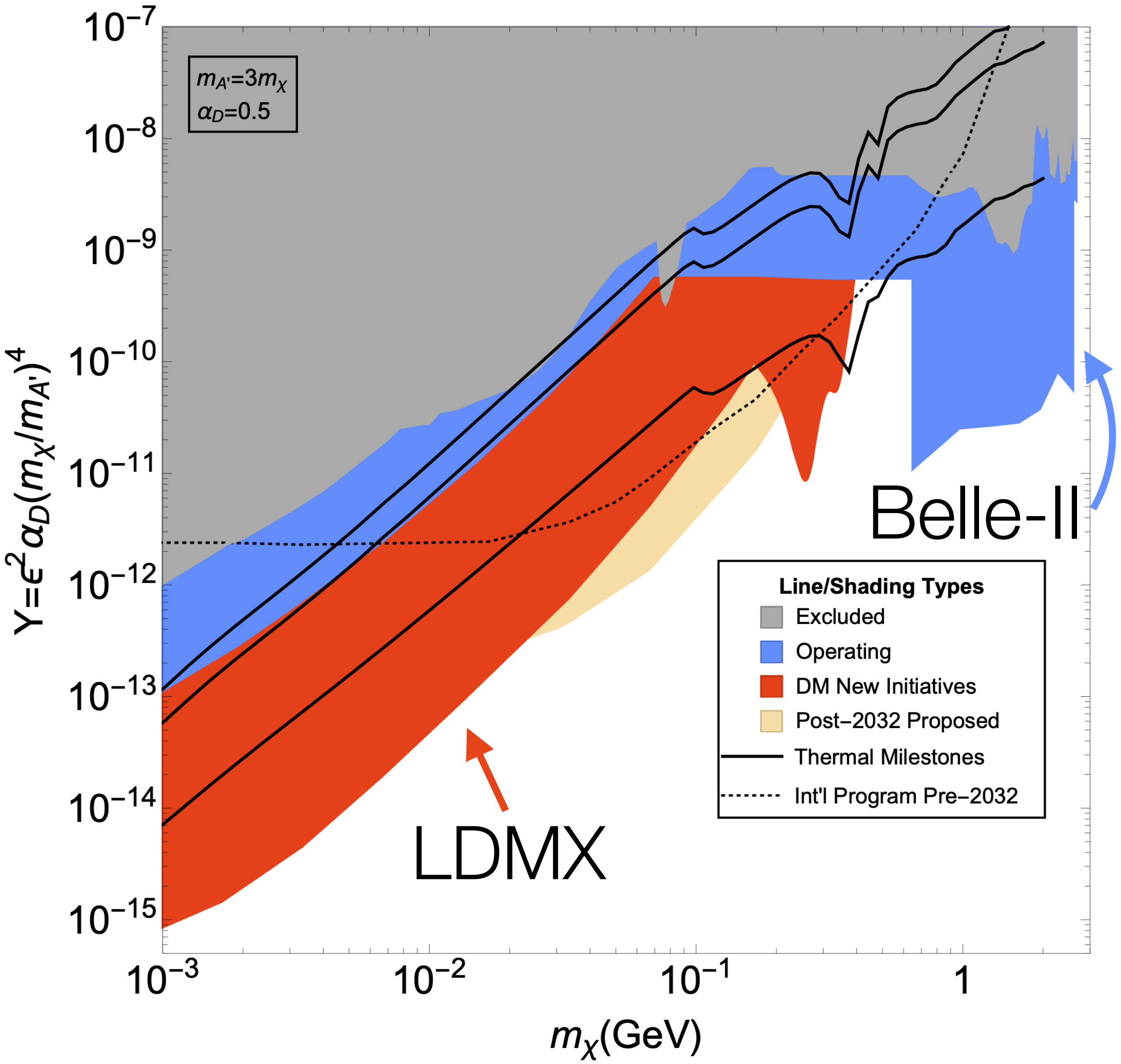
Missing energy/mass experiments not possible at EF machines

Could probably do a re-scattering experiment here but I've not seen it talked about

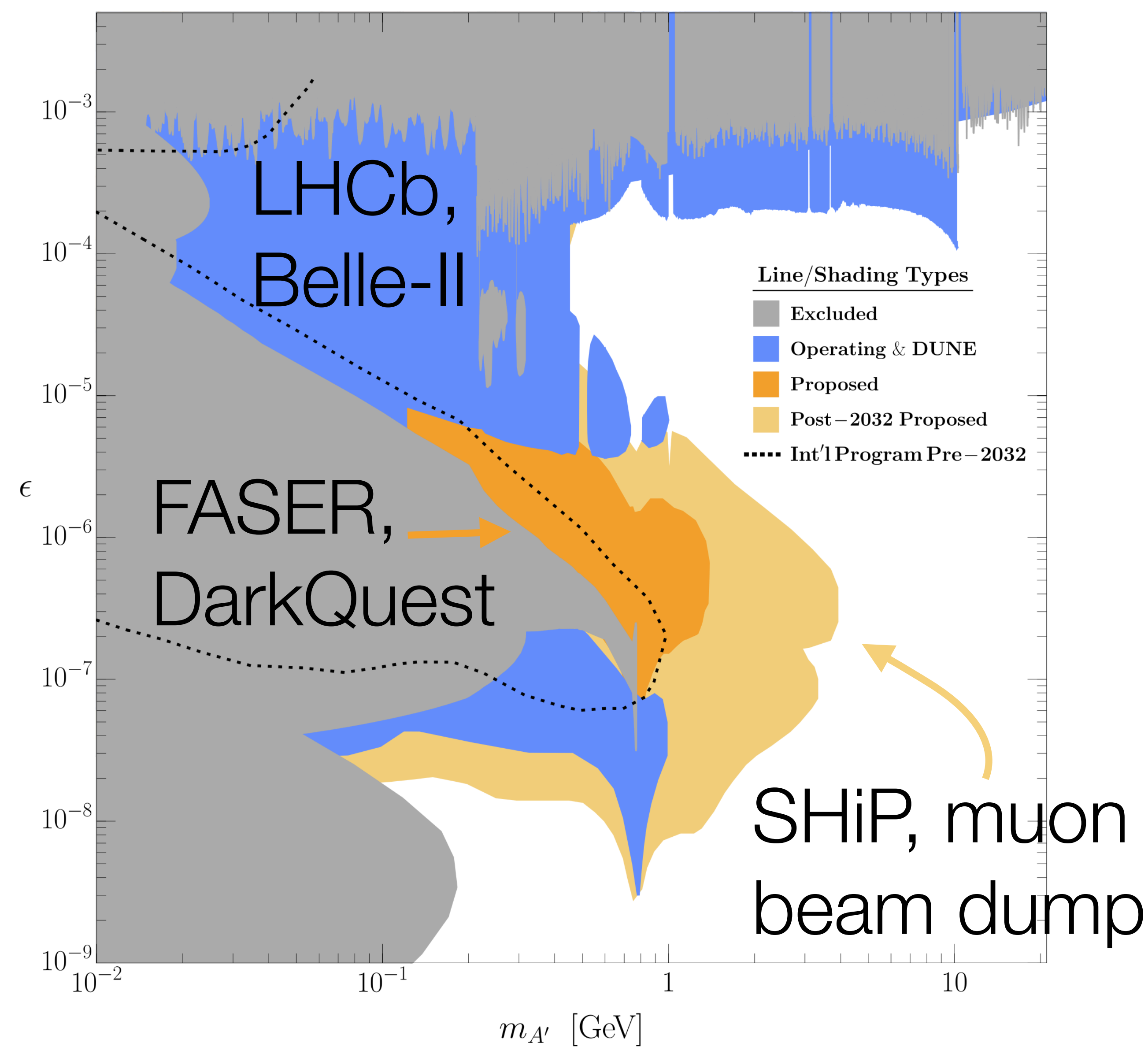
Visible decay searches are well suited and could be added to future colliders (examples 1, 2)

Intensity frontier projections for next years

Invisible dark photon decays



Visible dark photon decays



Where thermal targets well defined, accessible in the next ~decade with proposed experiments

Discussing complementarity

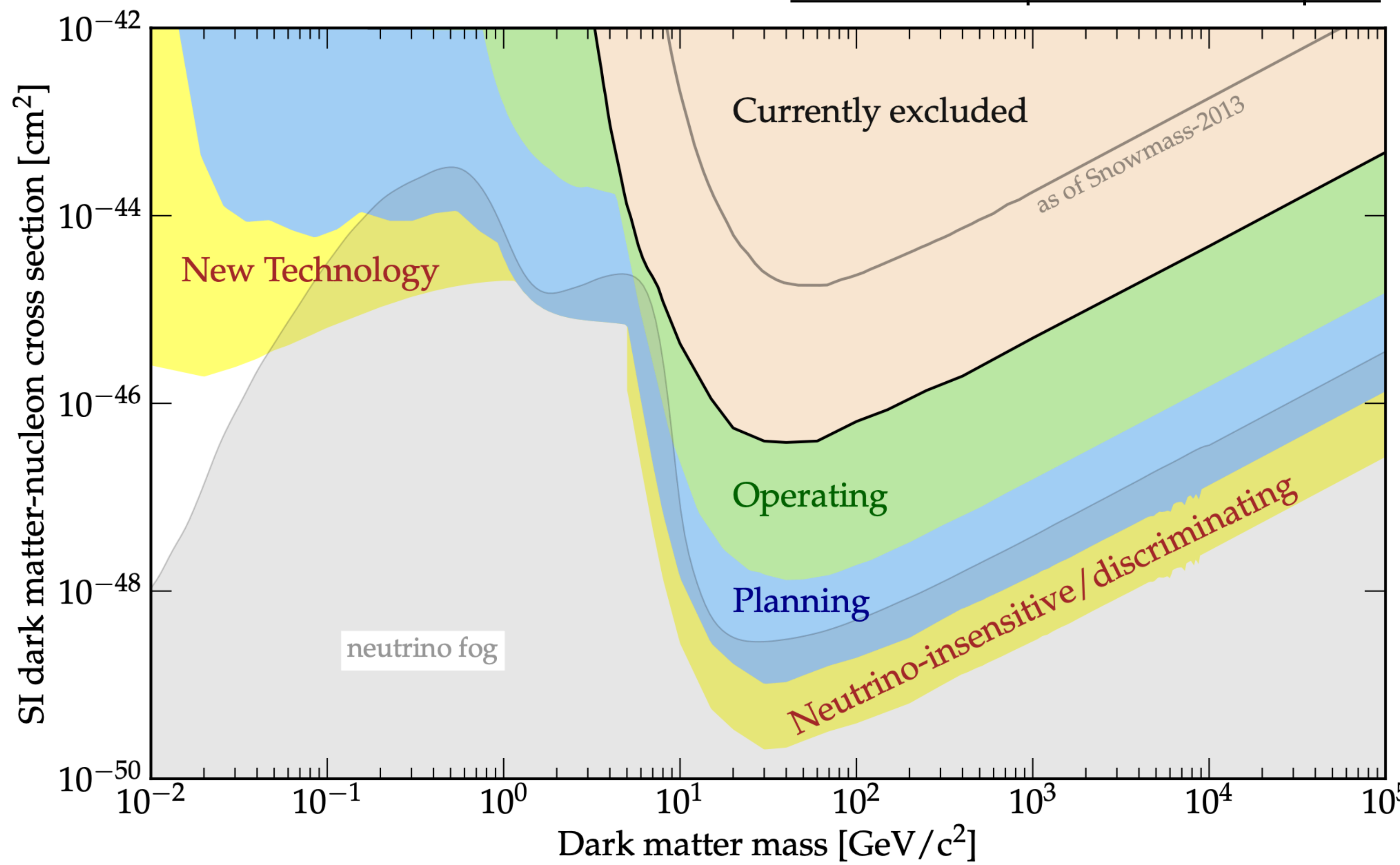
Mentioned earlier that we need to highlight complementary areas of strength between DD, ID, and future colliders

This will be key to building the field we want to see

Snowmass particle DM report

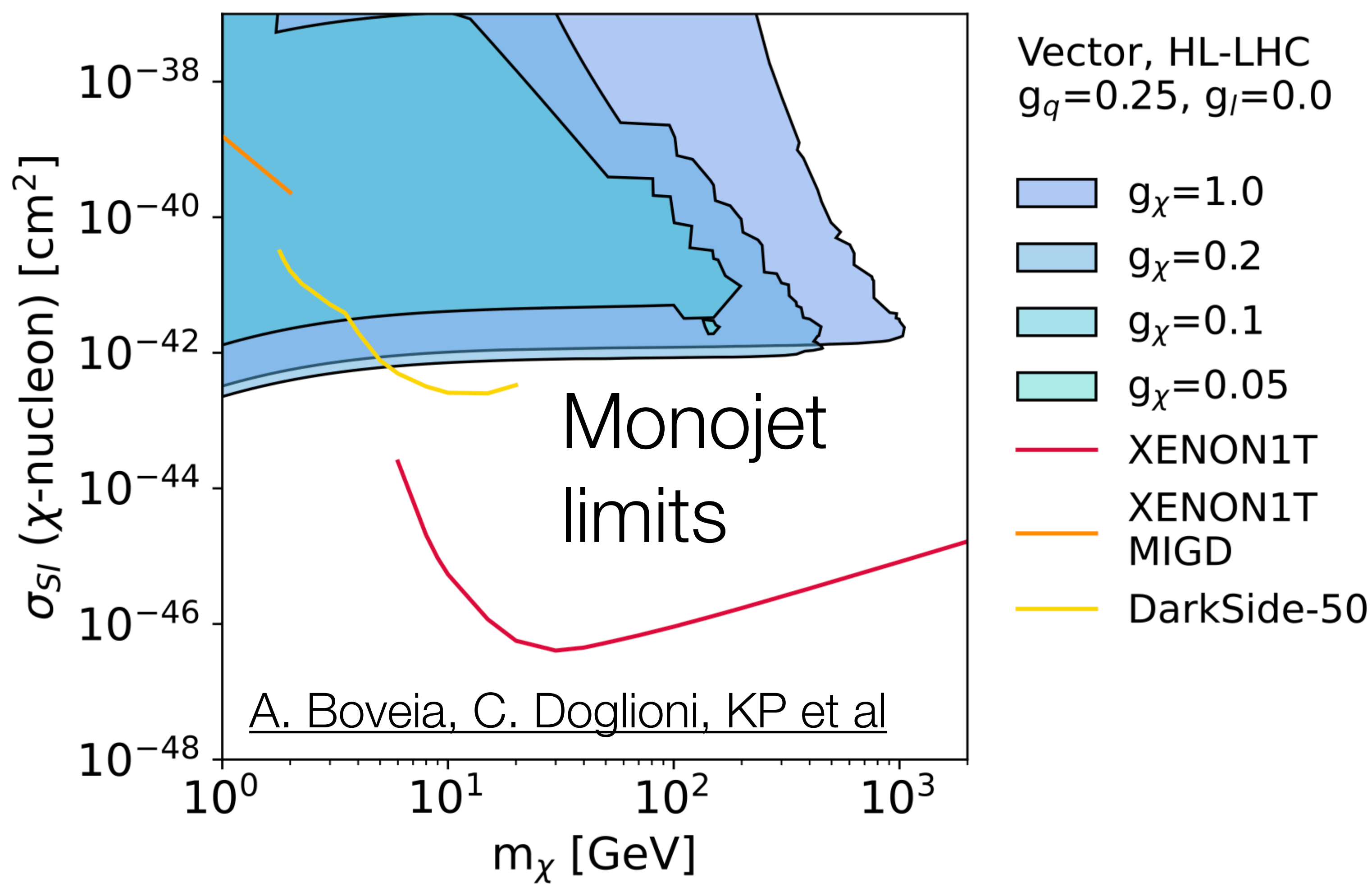
Often easier said than done.

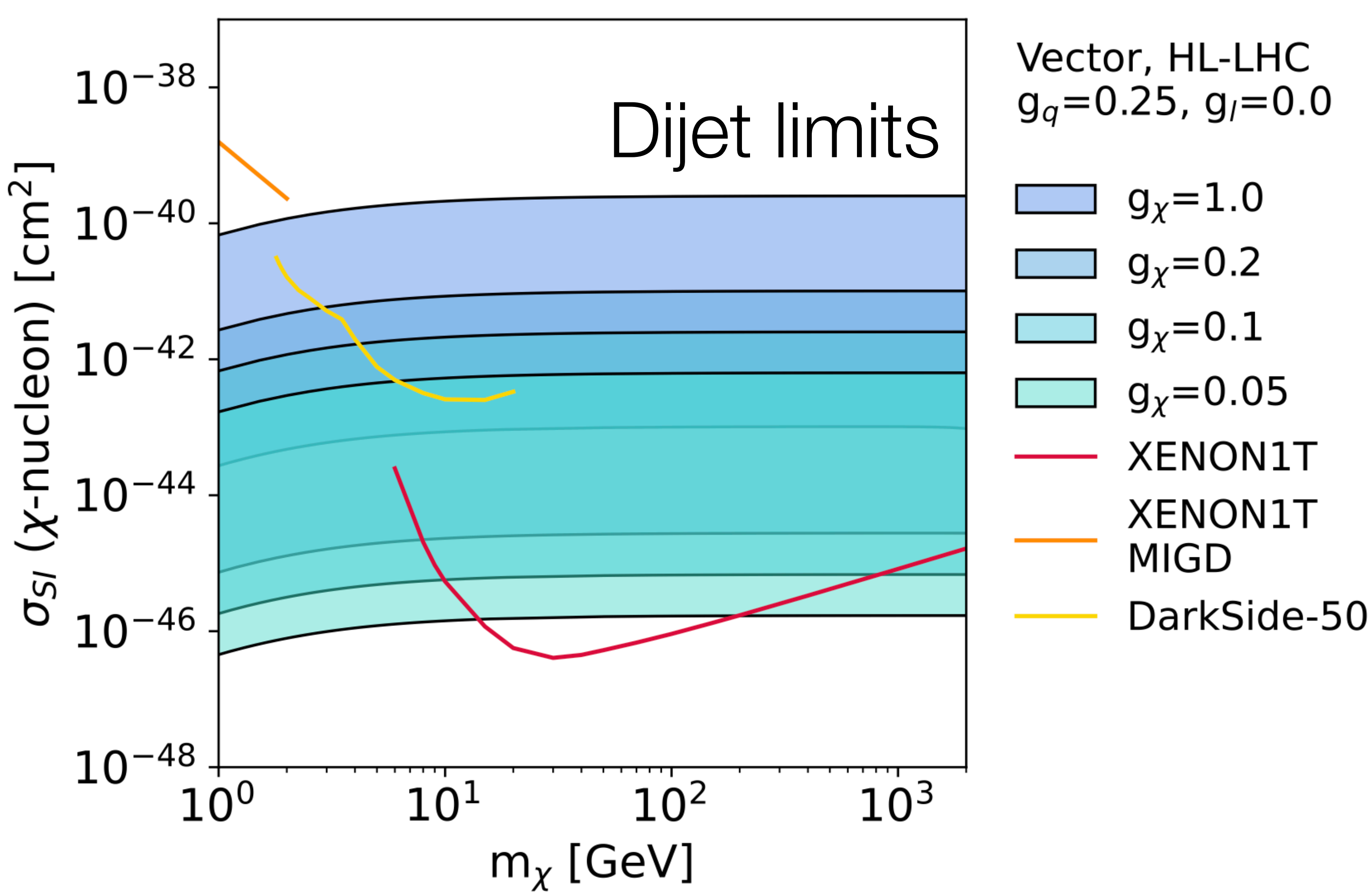
DD limits can use EFT; collider searches require model assumptions. Reducing problem dimensions to 2D plane usually needs extra assumptions



Show example I know best: LHC DMWG spin-1 simplified model

Must reduce 4-5 free parameters ($m_{\rm med}$, m_χ, g_{SM}, g_χ) to 2





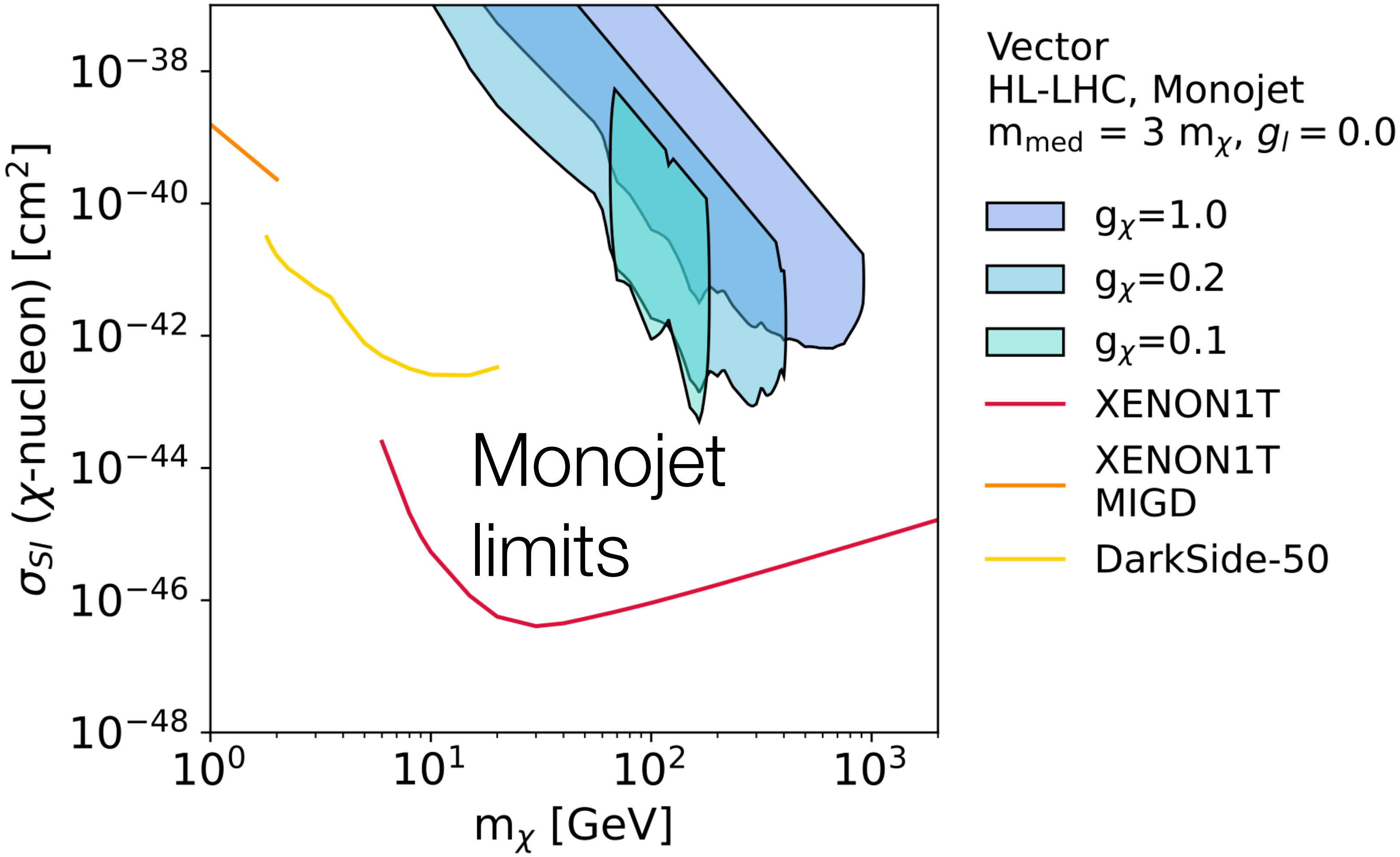
These are the type of projections we usually show from ATLAS and CMS

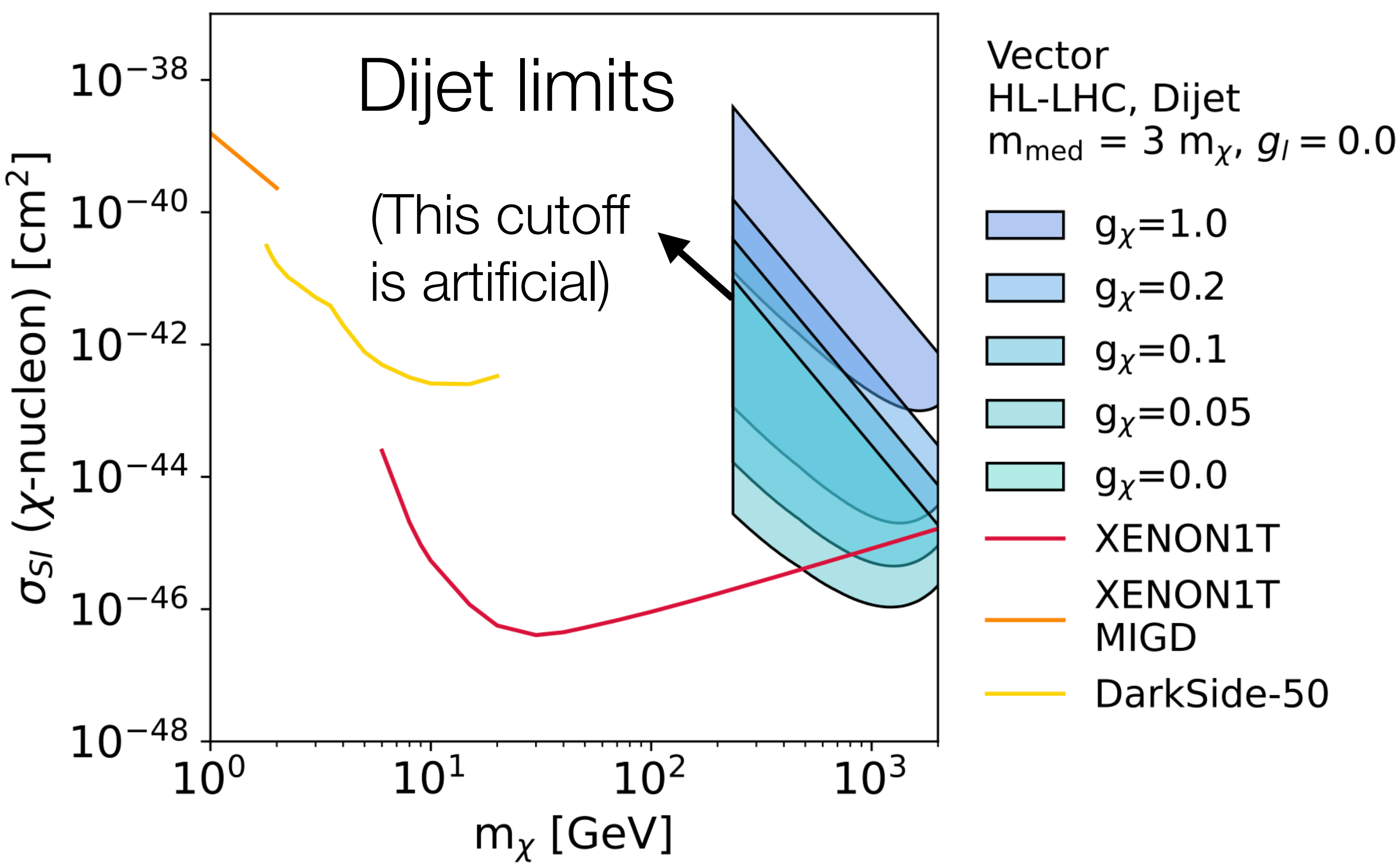
Couplings take explicit values

Mediator mass absorbed into y axis variable

Implication: no constraint on mediator mass

Points with strong collider limits have high mediator mass to DM mass ratio





Same concept, different projection into two dimensions

Now ratio between mediators is fixed and g_q is absorbed into y axis

Colliders have unique strengths in accessing heavy mediators

Direct detection has unique strengths in accessing small couplings

Must present both for complete picture

Conclusion

Conclusion

Dark sector searches at accelerators and colliders are complicated, take many forms, and are still not fully explored

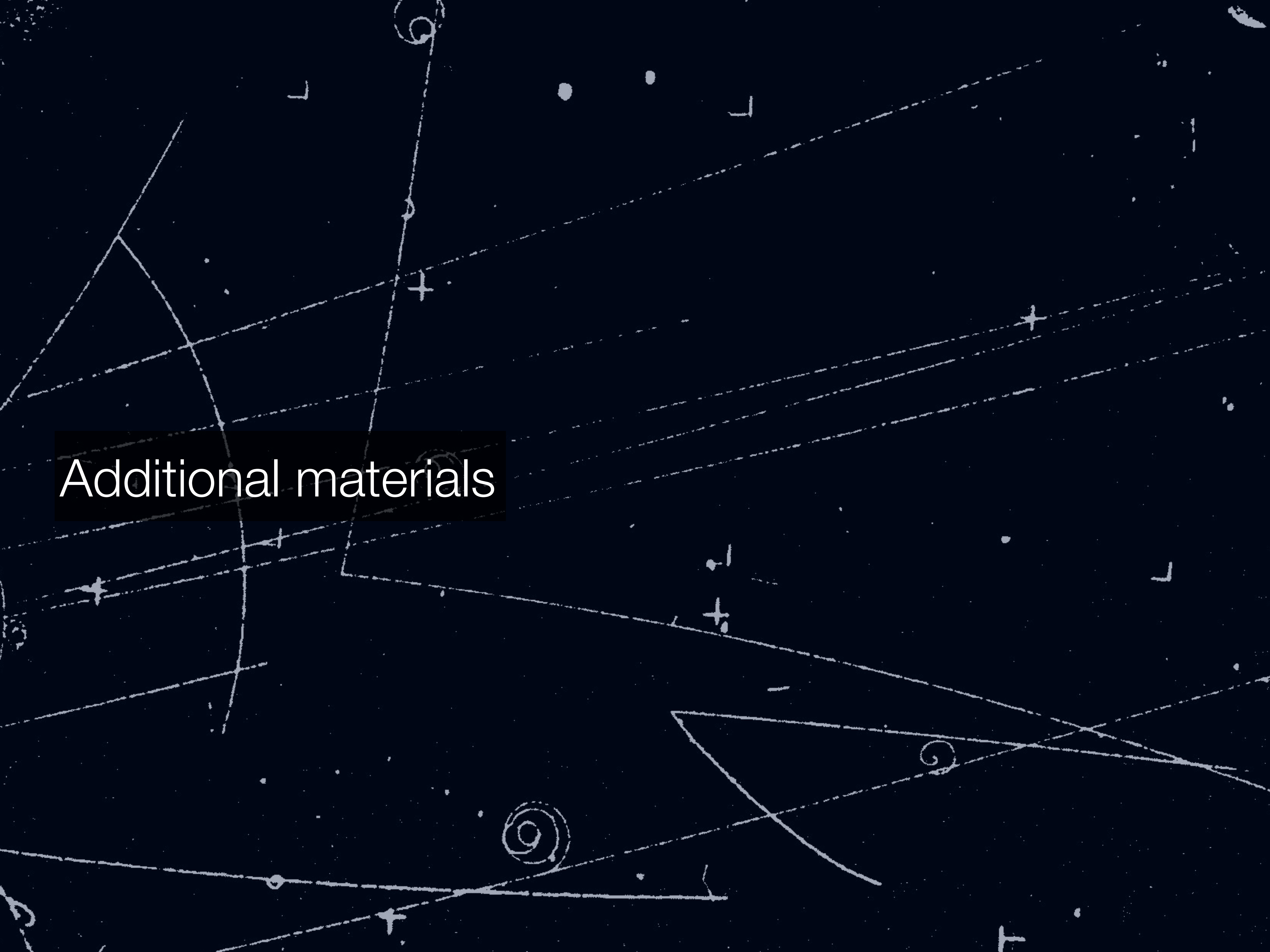
We rely on theory community to help us guide this work

There remains plenty of non-excluded space for cosmologically motivated particle dark matter accessible at accelerators

There are also areas of DM phase space that only accelerator-based experiments can probe, just as there are areas that only direct or indirect detection experiments can probe

Complementarity, DM discovery potential, and the potential to exclude values aligning with cosmological observations should be included in future experiment/accelerator proposals

Additional materials



References

- LHC simplified models (s-channel mediators) arXiv:1507.00966
- LHC 2HDM+a model: arXiv:1810.09420
- Notes on Higgs portal: arXiv:2001.10750, arXiv:1903.03616
- Snowmass BSM topical group report arXiv:2209.13128
- Snowmass particle dark matter topical group report arXiv:2209.07426
- Snowmass DM complementarity report: arXiv:2210.01770
- Spin-1 projection comparisons for HL-LHC and FCC arXiv:2206.03456
- European Strategy briefing document: cds link

References

- Dark sector portals at high intensity experiments: arXiv:2207.06905
- RF6 topical group report: arXiv:2209.04671
- Dark sector LLPs at Belle-II: arXiv:1911.03490
- Flavour in dark sectors: arXiv:2207.08990

Dark sector benchmarks at the energy frontier

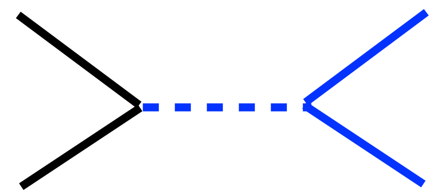
Standard Model: black
BSM: blue

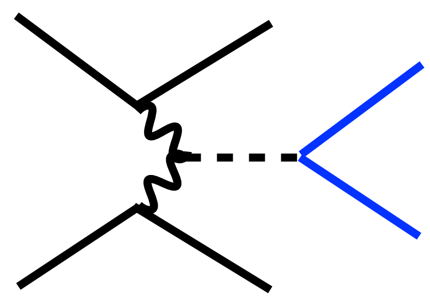
No EFTs

Mediator masses around energy scale of collider

Simplified models

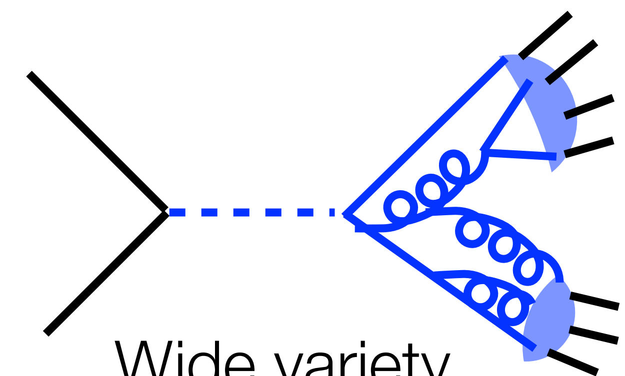
Spin-1 mediator, one DM particle





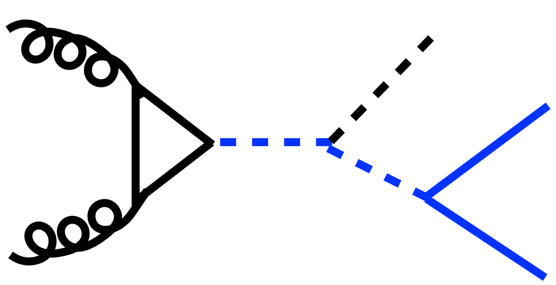
Simplified Higgs portal; spin-0 mediators

Extended dark sectors



Wide variety

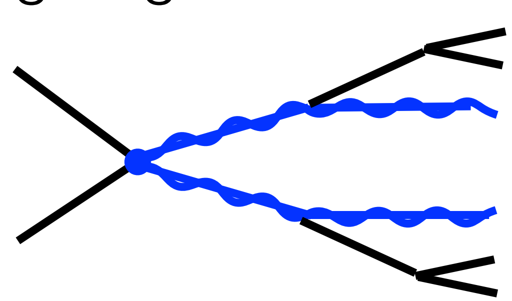
2HDM + pseudoscalar



Still simple, UV-complete pseudoscalar mediator model

SUSY scenarios

Cases with wino or higgsino-like LSP can give good DM candidates



Often simplified for practicality

Long-lived particles

Not a model; rather, a class of signatures emerging from many of the others

Dark sector benchmarks at the intensity frontier

arXiv:2209.04671

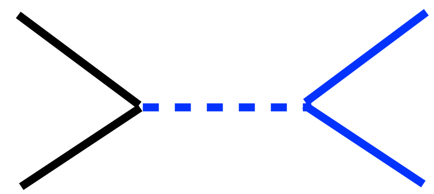
Standard Model: black
BSM: blue

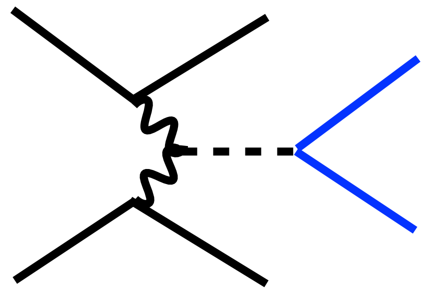
Off-shell processes strongly suppressed

Focus on light dark matter

Simplified models

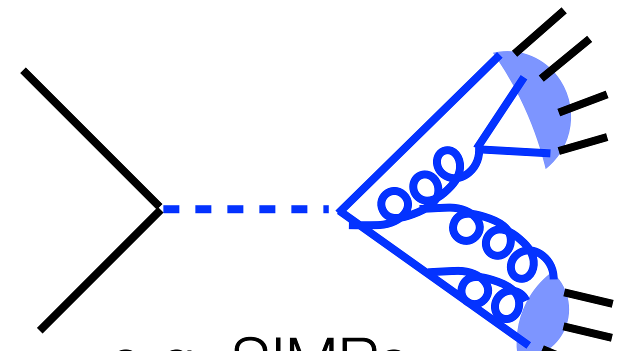
Spin-1 mediator, one DM particle





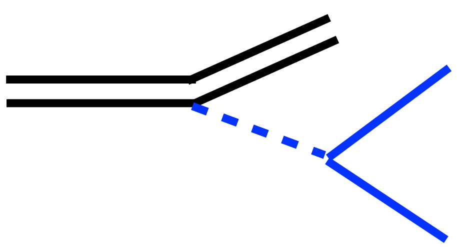
Scalar and pseudo scalar mediators

Extended dark sectors



e.g. SIMPs

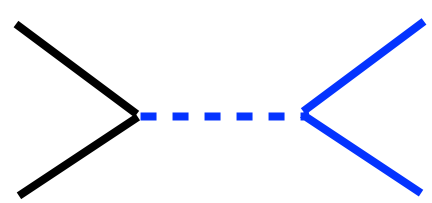
Flavour-dependent



Search via meson decays, at muon beams, in flavour asymmetry signatures

Minimal portals

Dark photon, scalars from Higgs portal, neutrino portal, ALPs



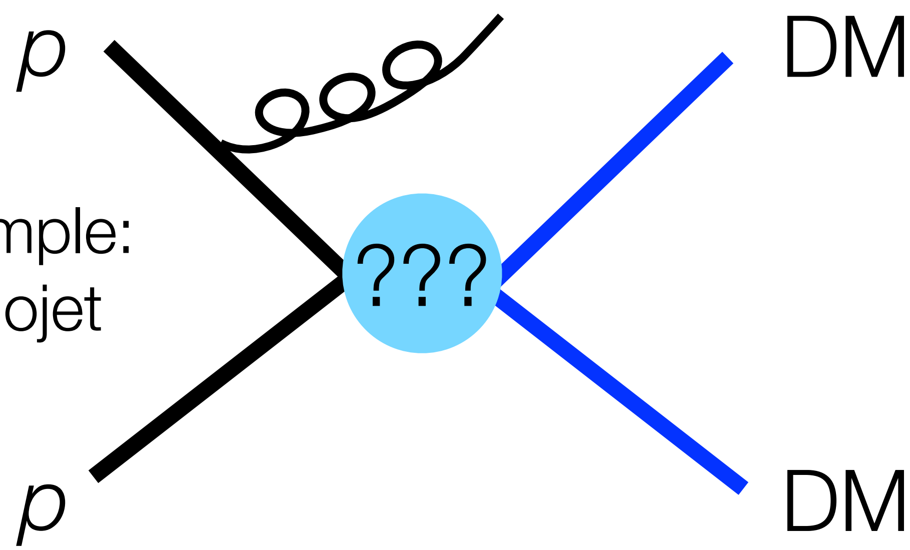
Well-defined relatives of simplified models

Long-lived particles

Not a model; rather, a class of signatures emerging from many of the others

ATLAS/CMS signatures for DM searches

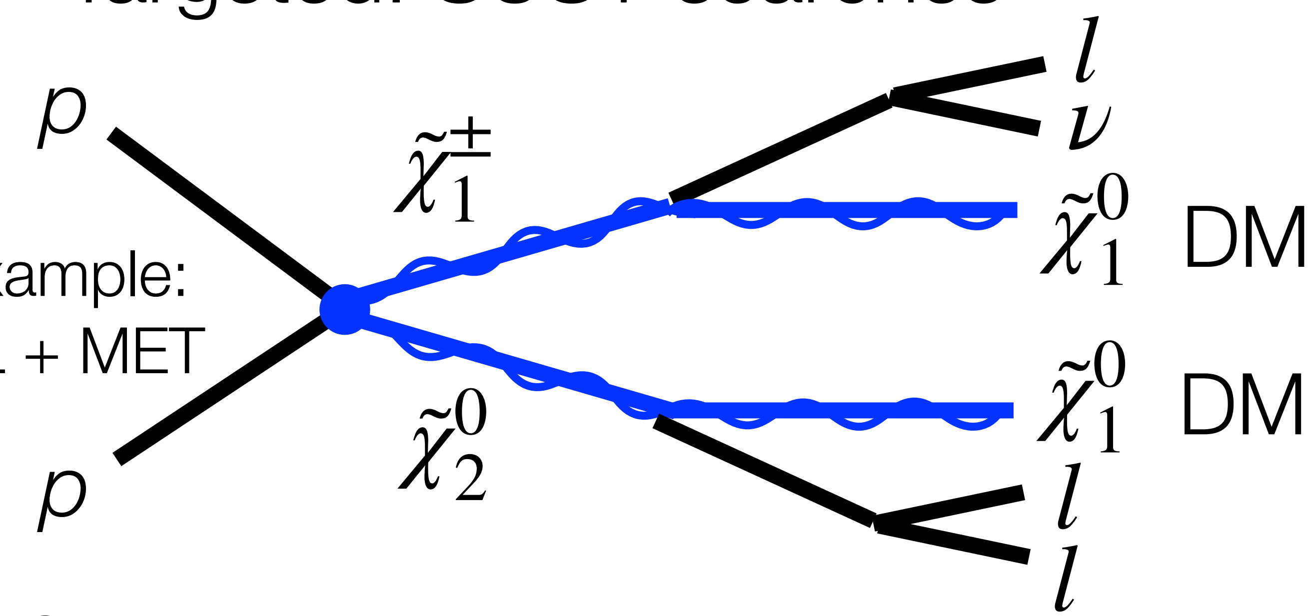
Most general: mono-X



Example:
monojet

Model-independent; high backgrounds. ISR provides momentum, enabling missing energy reconstruction

Targeted: SUSY searches

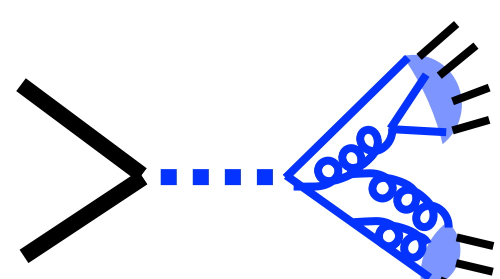


Example:
3L + MET

Generally complex final state allowing significant background suppression. MET remains key feature of selection

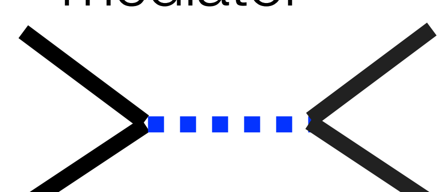
Non-MET-focused

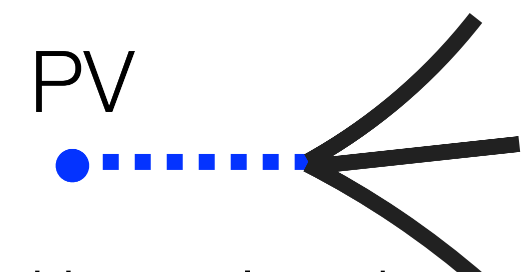
Various searches target models with dark matter implications, but that do not rely on MET in final state. Extended dark sectors, direct mediator searches, LLPs



QCD final states with distinctive features

SM decay of mediator

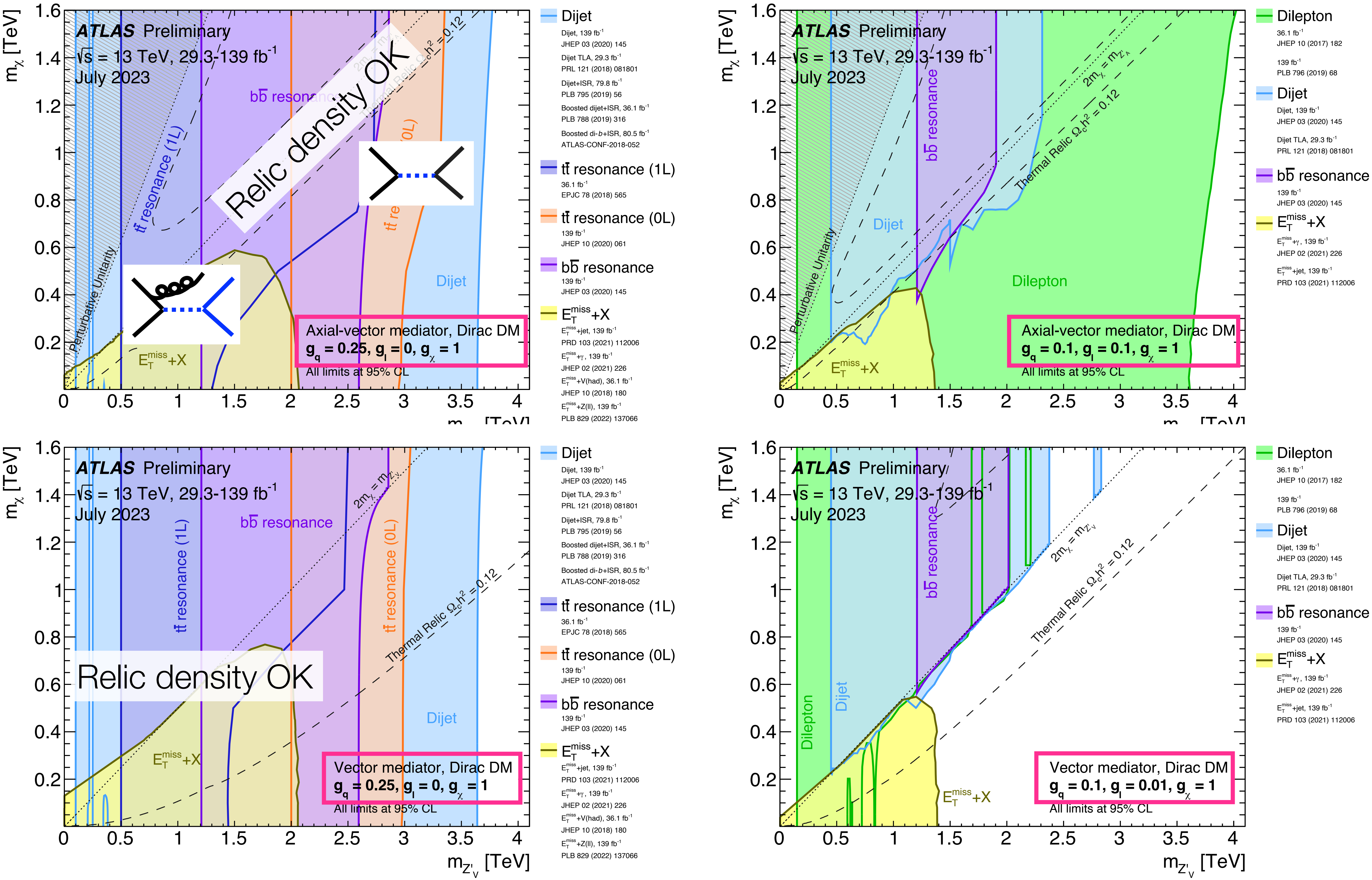




Unusual tracks or displaced energy deposits

Current status of LHC spin-1 simplified models

ATL-PHYS-PUB-2023-018



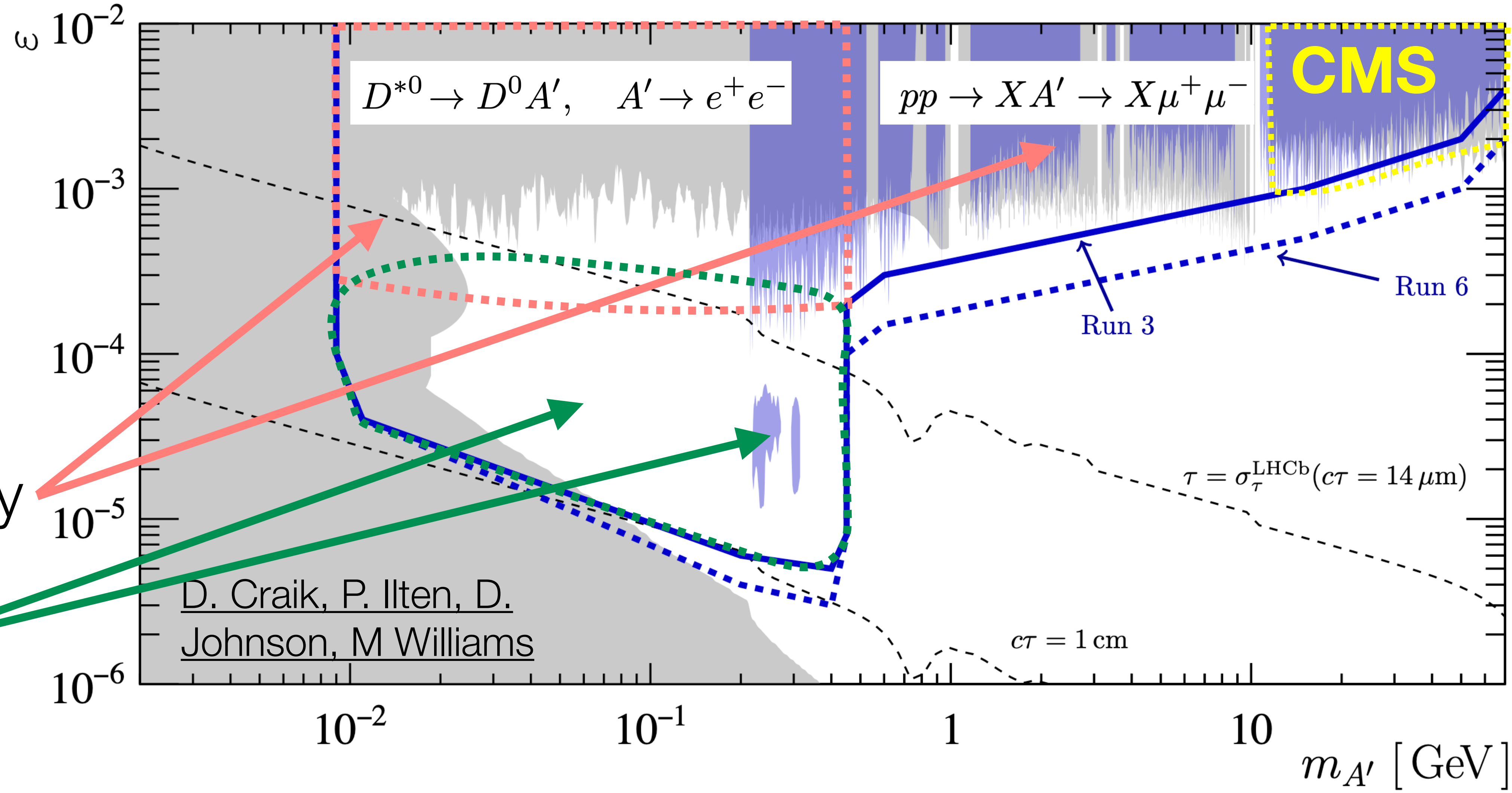
Dark photons at the LHC

Very popular spin-1 vector benchmark, especially with intensity frontier and physics beyond colliders community

LHCb is a powerhouse with Run 3 triggerless readout

Prompt decay

Displaced vertex



ATLAS & CMS can contribute at higher masses. Trigger poses a challenge. Simplified spin-1 limits translate fairly directly, but this is not currently a standard interpretation.

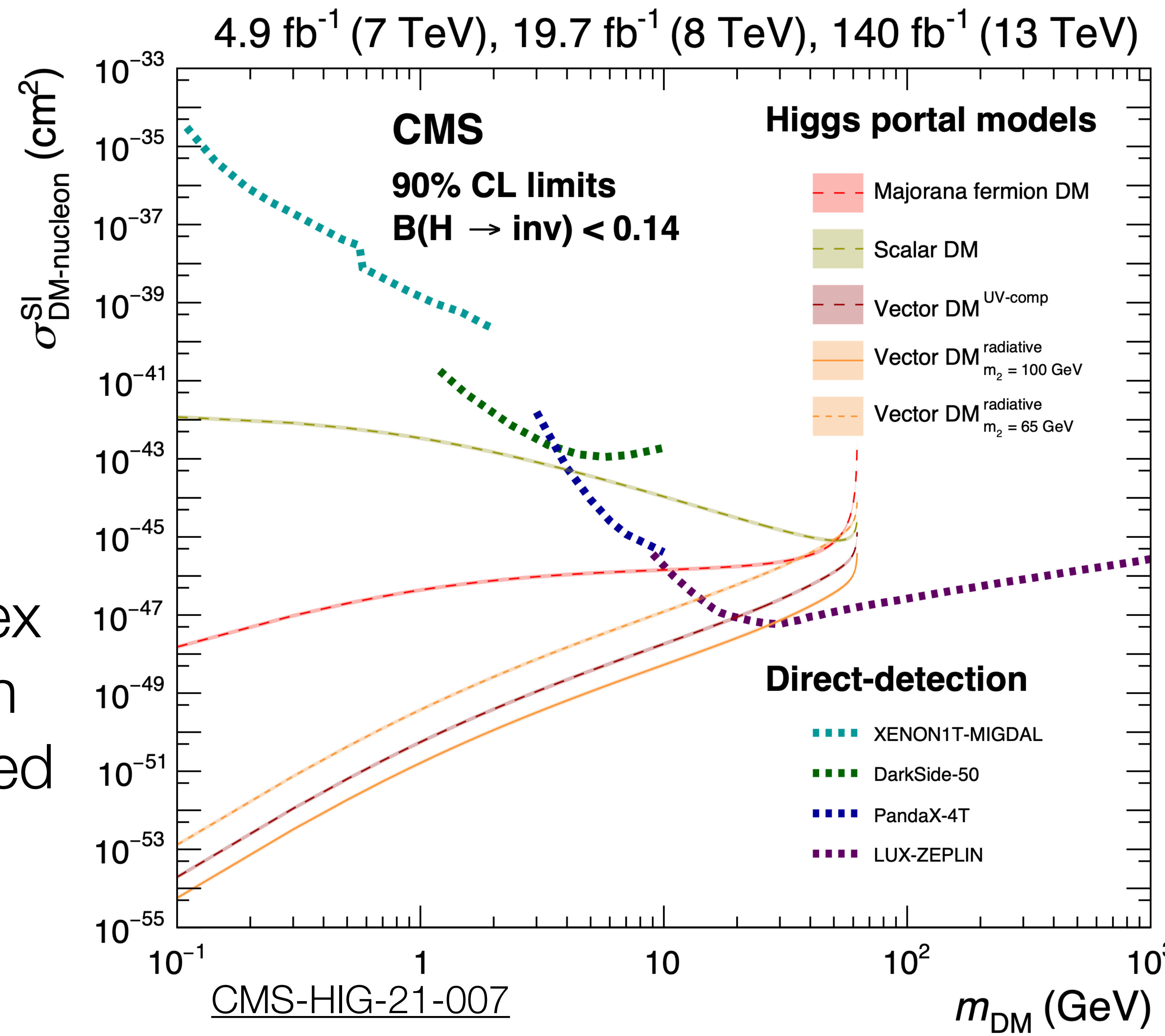
Higgs decays to dark matter

In Higgs portal models, the Higgs decays to DM, creating a MET signature

Possible UV-complete SM extension with just one DM particle if DM is a scalar

For vector DM, more complex scenario with dark Higgs can still be appropriately estimated via this EFT approach (ref.)

Current upper limits on $BR(h \to \text{inv}) \sim 0.11$ (ATLAS)



CMS-HIG-21-007

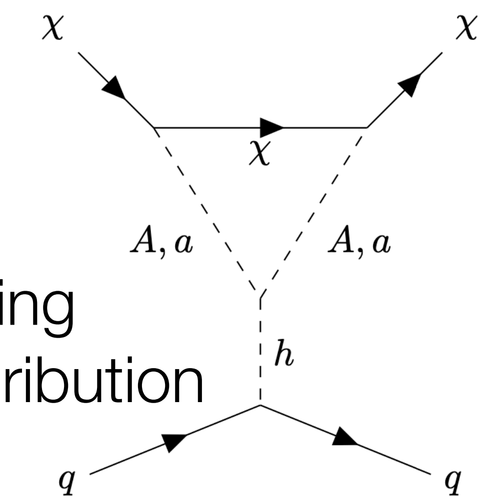
Model motivation from Arcadi, Djouadi, and Kado

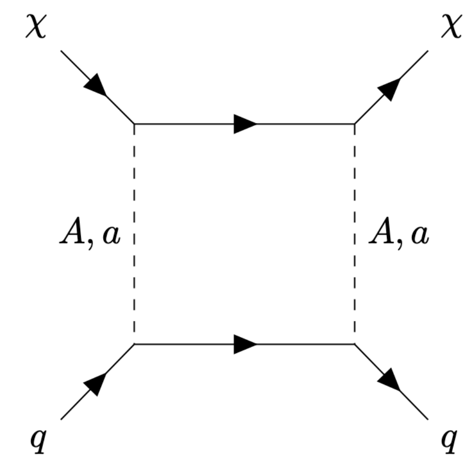
2HDM+a motivation and limits

DM with pseudoscalar mediator is a key LHC target because direct detection interactions are suppressed at tree level

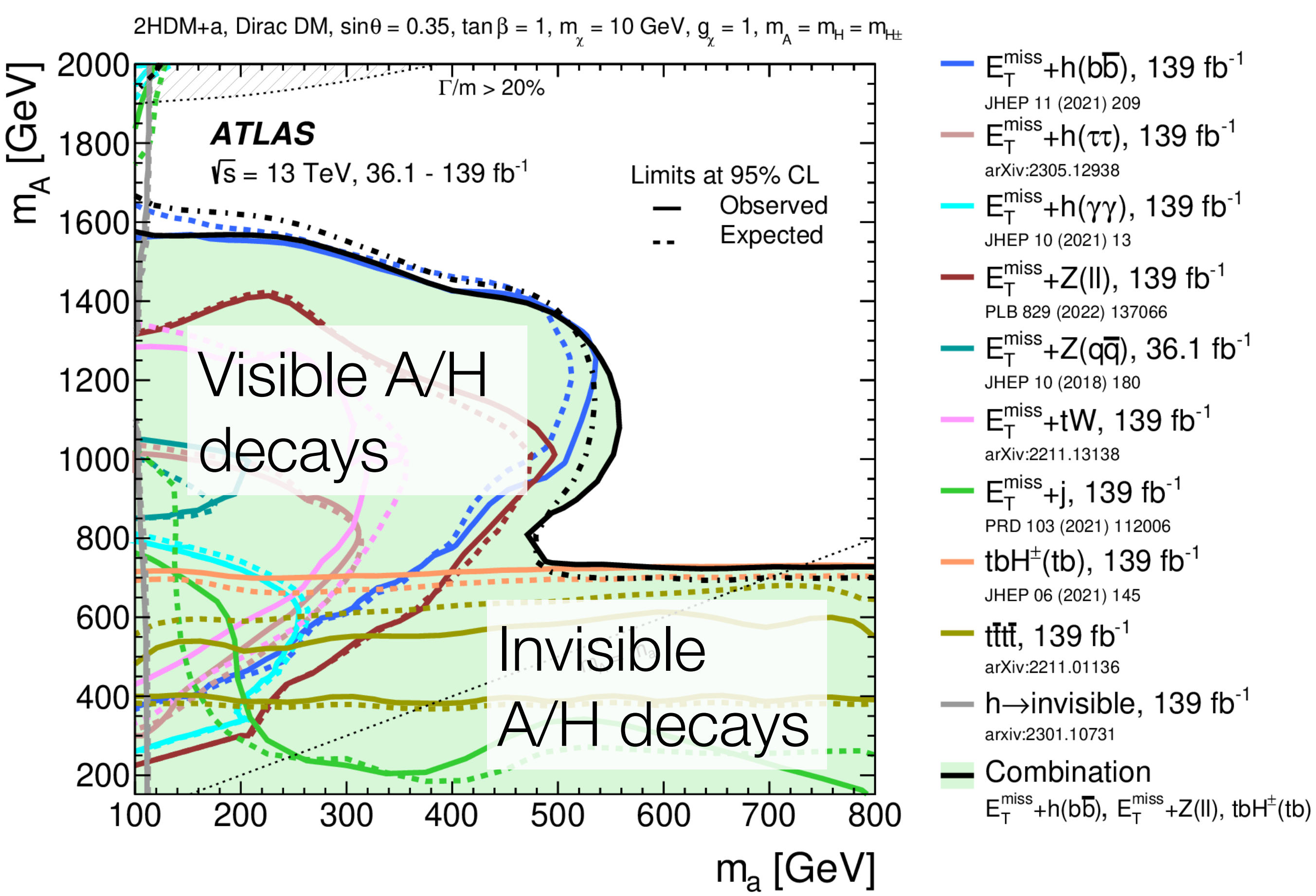
LHC DM working group

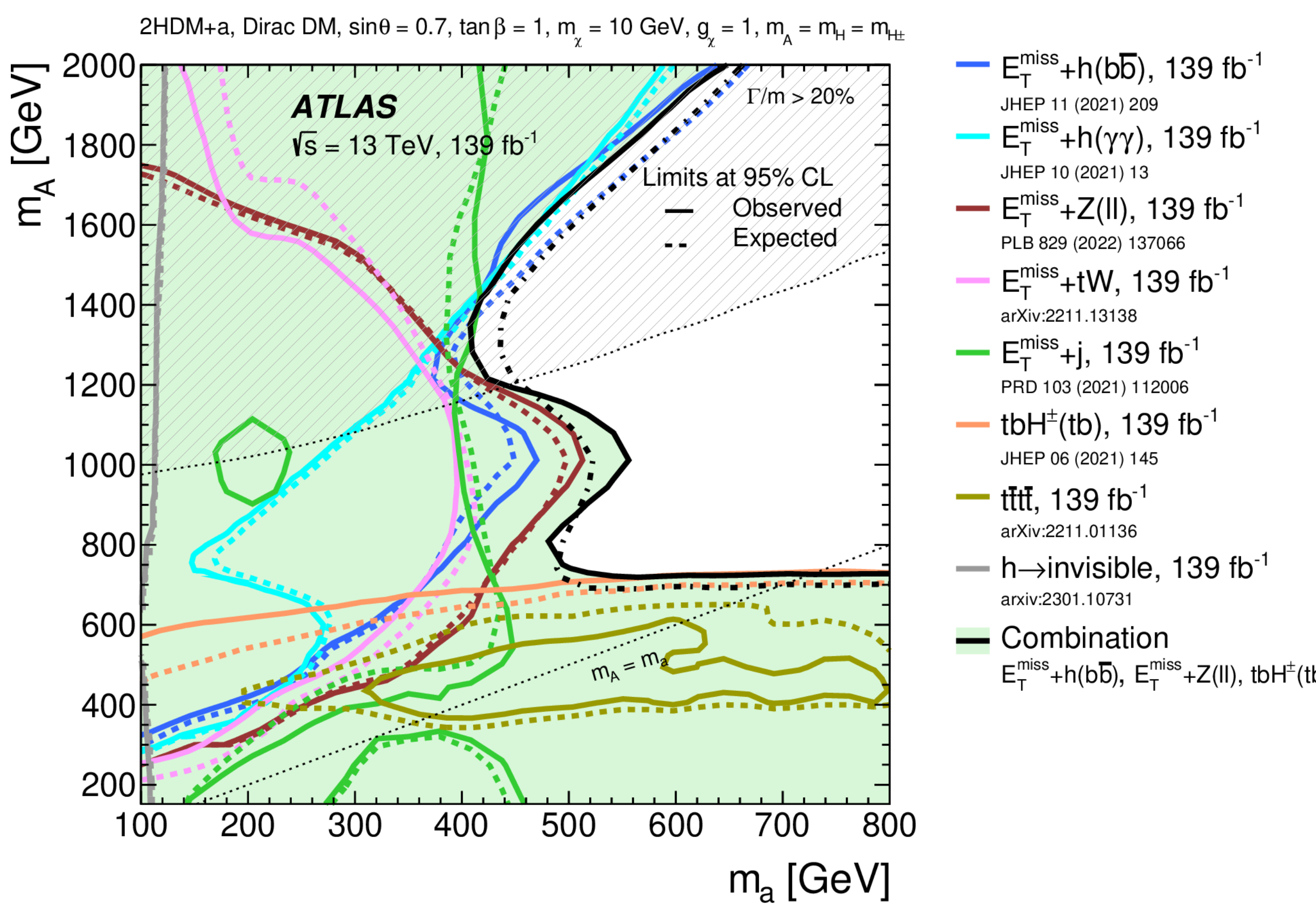
DD leading contribution





Additional DD box diagrams



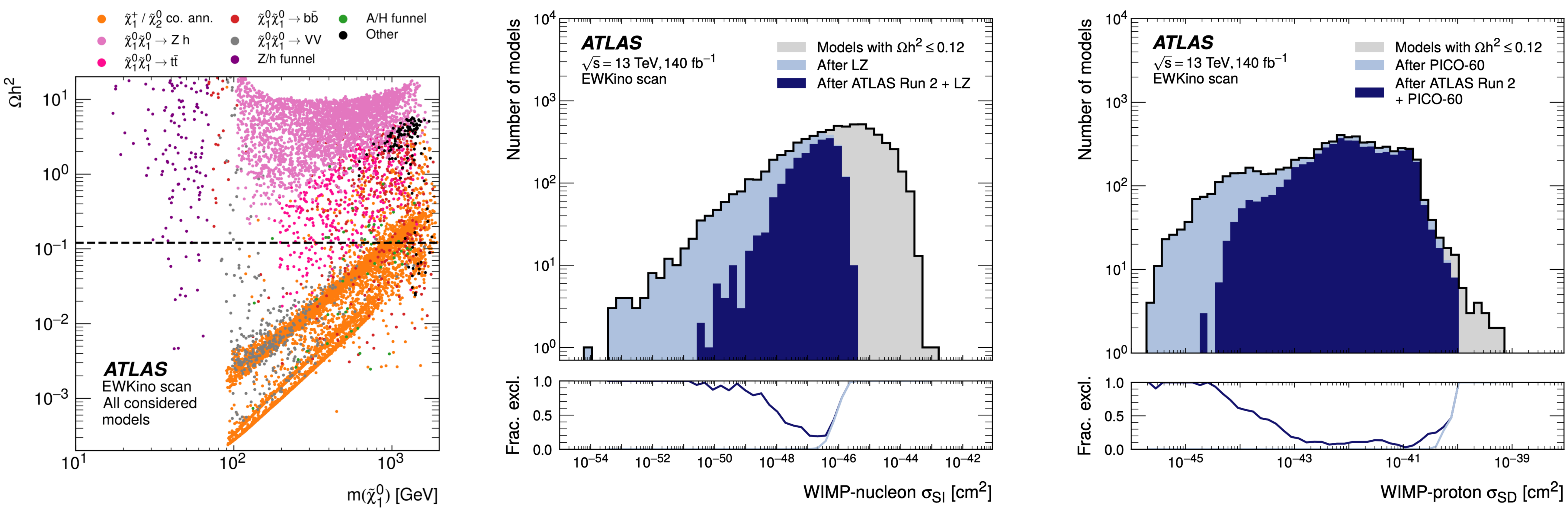


ATL-PHYS-PUB-2023-018

The state of SUSY dark matter

Let's look at pMSSM scan of DM candidates ATLAS CERN-EP-2024-021

Co-annihilation with small mass splitting from wino/higgsino-like $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ to LSP gives most of the viable candidates explored here

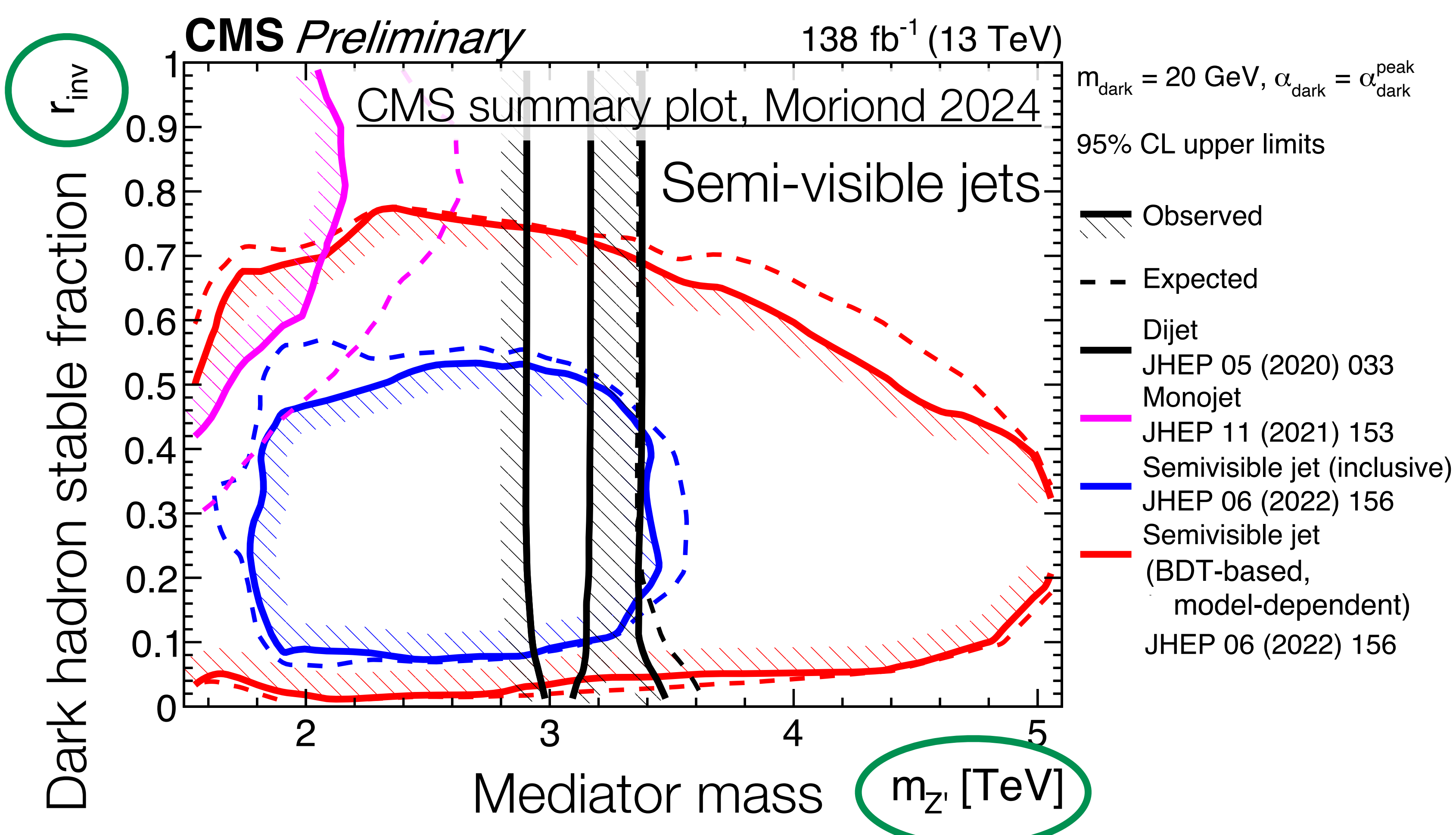


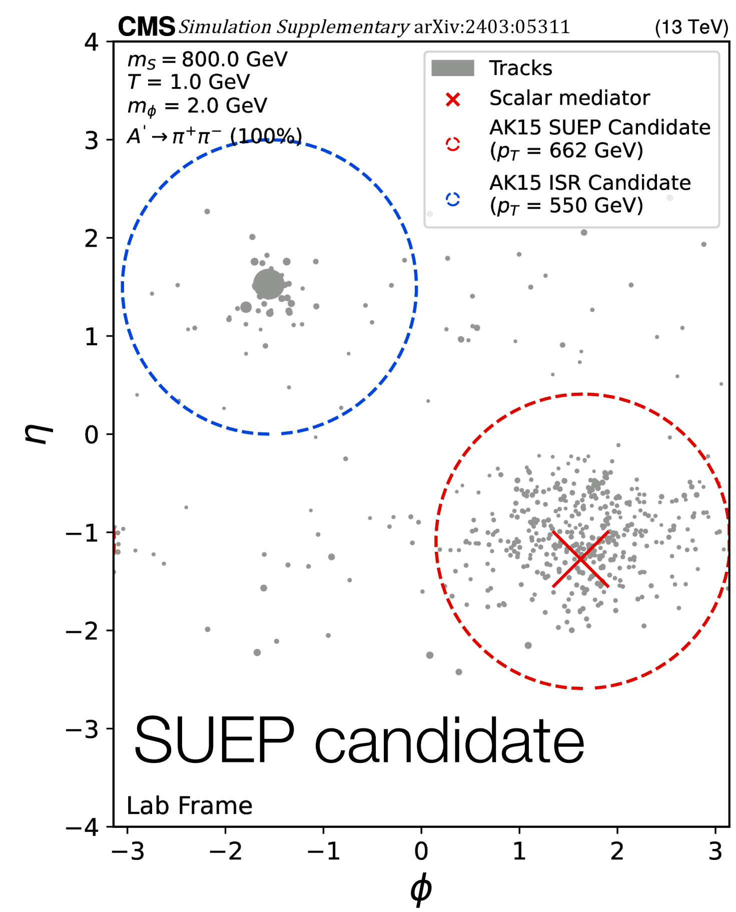
Can see 1) there is considerable space left for SUSY DM candidates in hard-to-reach electroweak signatures, and 2) there is good complementarity between LHC and direct detection reach

Extended dark sectors: growing area of interest

Assume numerous additional particles, one of which could provide stable DM candidate

Dark QCD & related give signatures with “weird jets”: containing displaced vertices, high fraction of invisible particles, etc depending on model details. Other cases give no jets at all (e.g. SUEPs)



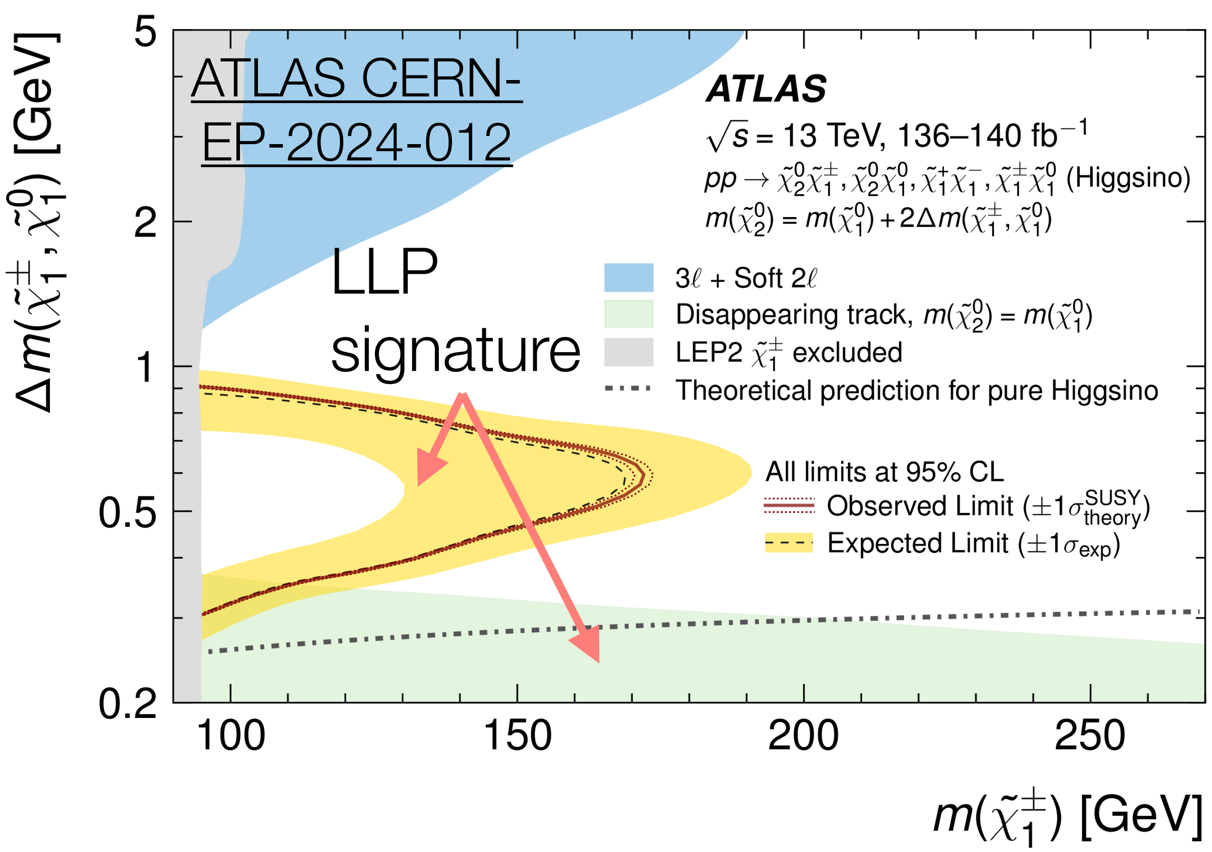


CMS EXO-23-002

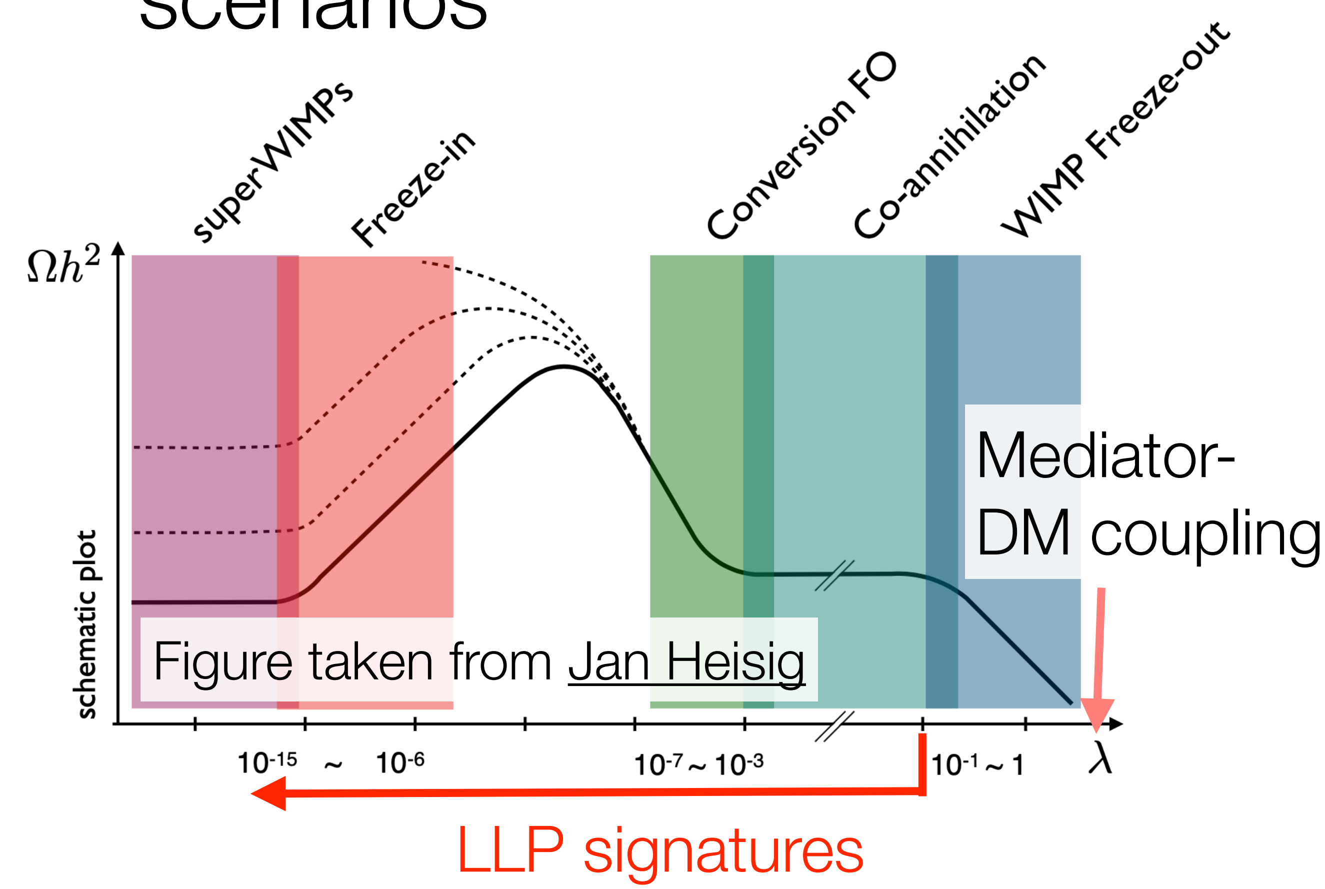
Long-lived particle searches

Saw one case already: displaced decays in dark photons with small ε. Other important examples:

Models with very small mass splittings, e.g. Higgsino DM

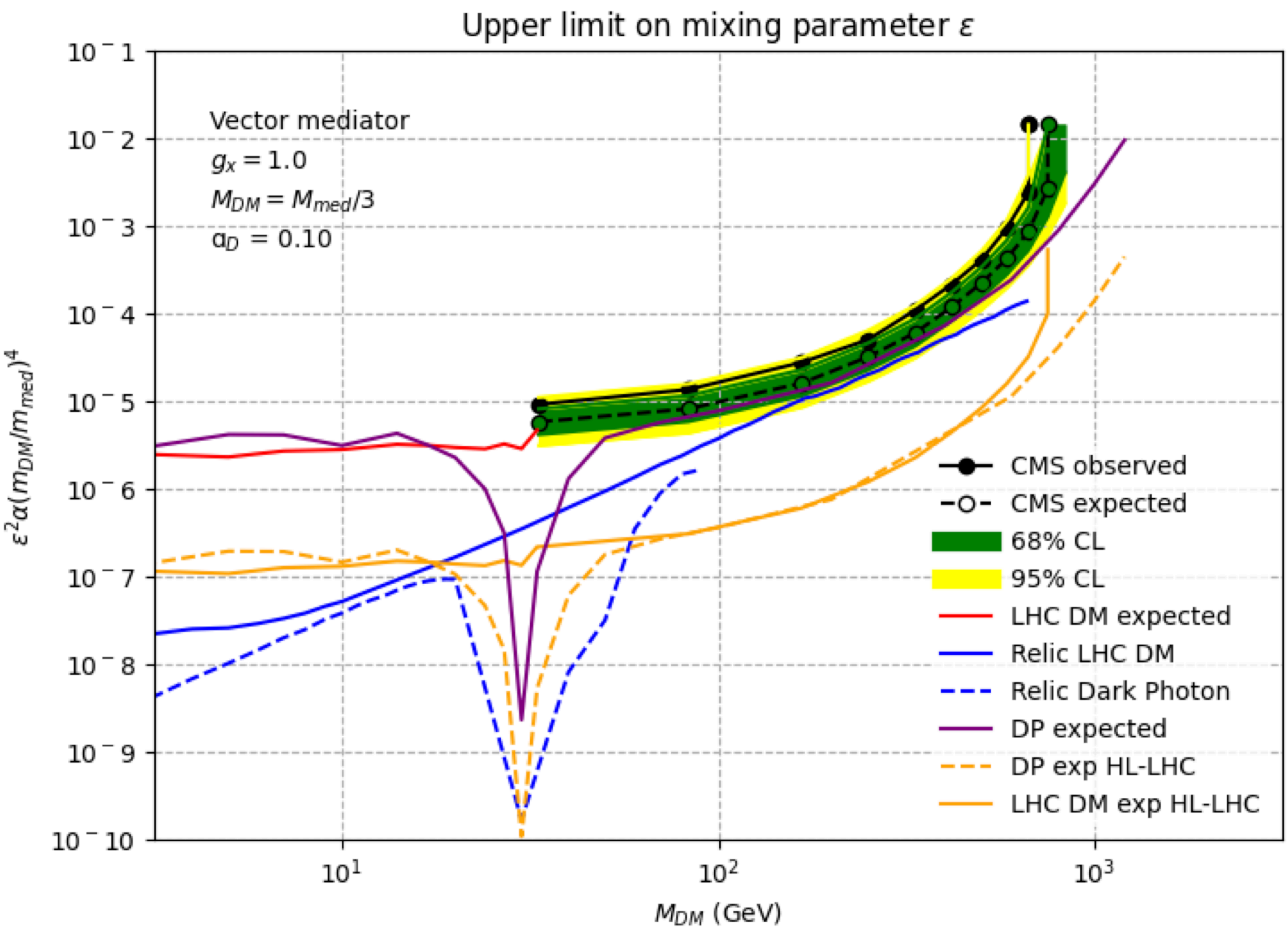


Freeze-in dark matter scenarios



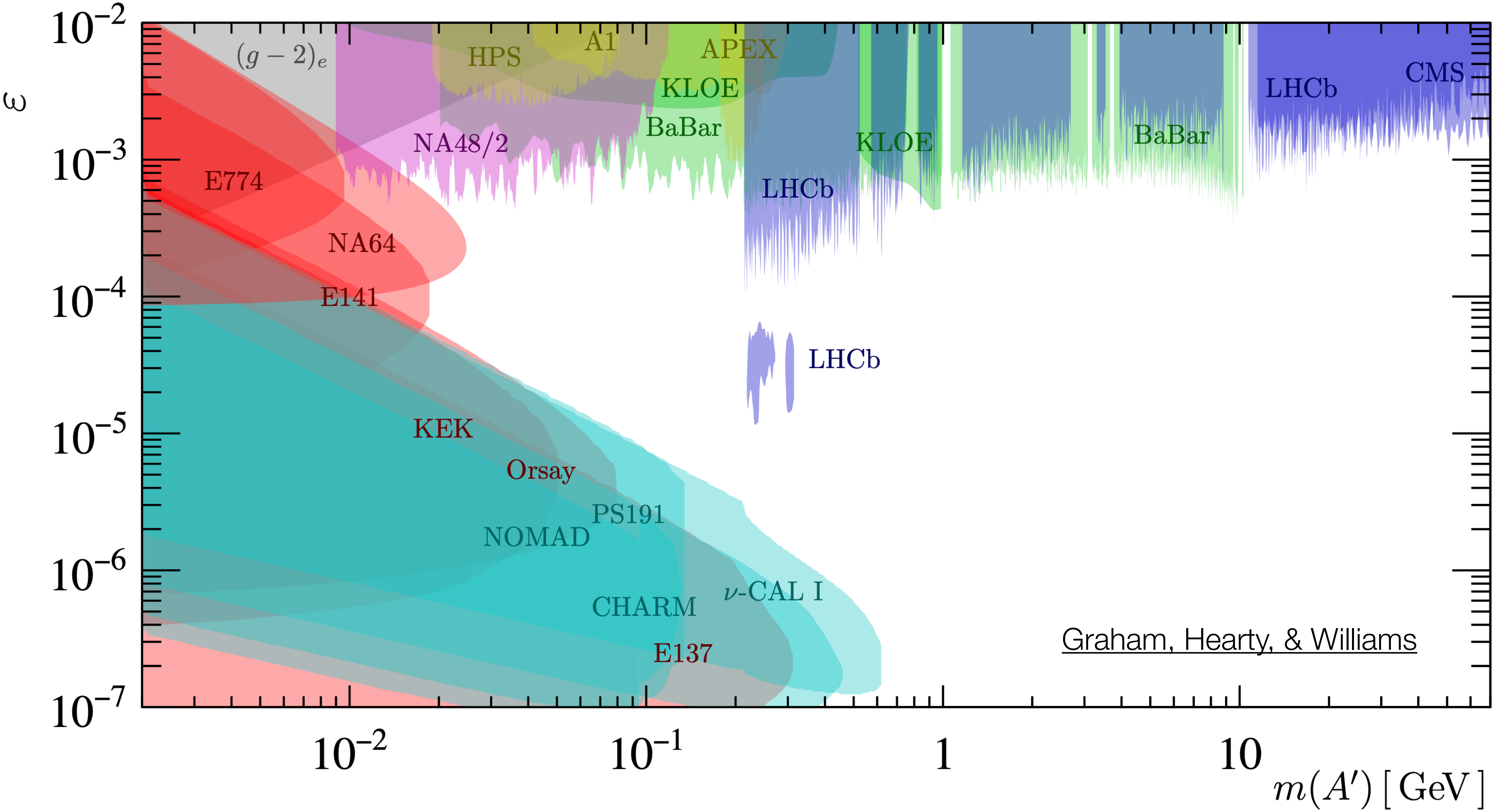
Can get LLPs from small mass splittings or small couplings, and turn up frequently in asymmetric, freeze-in, & SUSY DM

Comparison between true dark photon model and LHC simplified Z' mediator model, demonstrating good agreement above Z peak



A. Boveia, C. Doglioni, P. Harris, KP, et al

Current limits on visible dark photon decays, by experiment



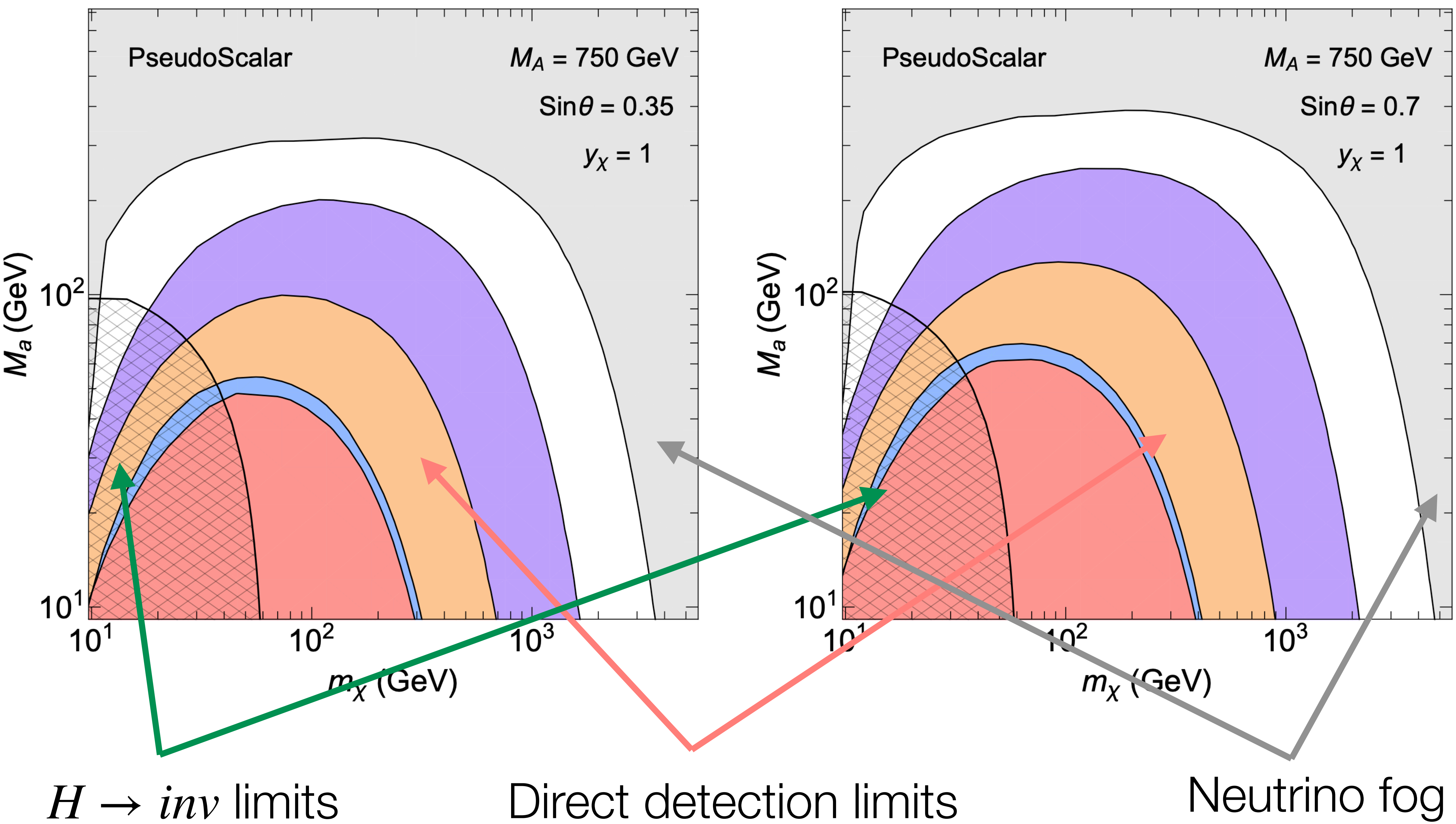
2HDM+a model and parameter choice description

The model considered here is the 2HDM+a model suggested by the LHC DM Working Group, which is the simplest gauge-invariant and renormalizable ultraviolet completion of the simplified pseudoscalar model initially recommended by the LHC DM Forum, which only contained the DM candidate and the mediator. This model is a type-II two-Higgs-doublet (2HDM) model to which an additional pseudoscalar *a* and a fermionic DM candidate χ are added. After electroweak symmetry breaking, the 2HDM contains five Higgs bosons: a lighter CP-even boson, h, a heavier CP-even boson, H, a CP-odd boson, A, and two charged bosons, $H\pm$. While the phenomenology of the model would be determined by 14 free parameters, some benchmark choices are made in order to match *h* with the observed SM Higgs boson, to ensure the stability of the Higgs potential, or to evade electroweak precision measurement constraints. In the end, the benchmarks are defined by five parameters: the mass of the heavy Higgs bosons, which are taken to be degenerate, $m_A = m_H = m_{H\pm}$; the mass of the pseudoscalar mediator, m_A; the mass of the DM particle, m_χ; the mixing angle θ between the two CP-odd states a and A; and the ratio of the vacuum expectation values of the two Higgs doublets, tan β.

ATLAS EXOT-2023-14

Shape of direct detection exclusions in 2HDM+a model, M_a vs m_χ plane. Requires fixing of other three parameters

LHC Dark Matter Working Group



How spin-1 simplified model to DD plane conversion works

For details, see this talk

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

1 variable

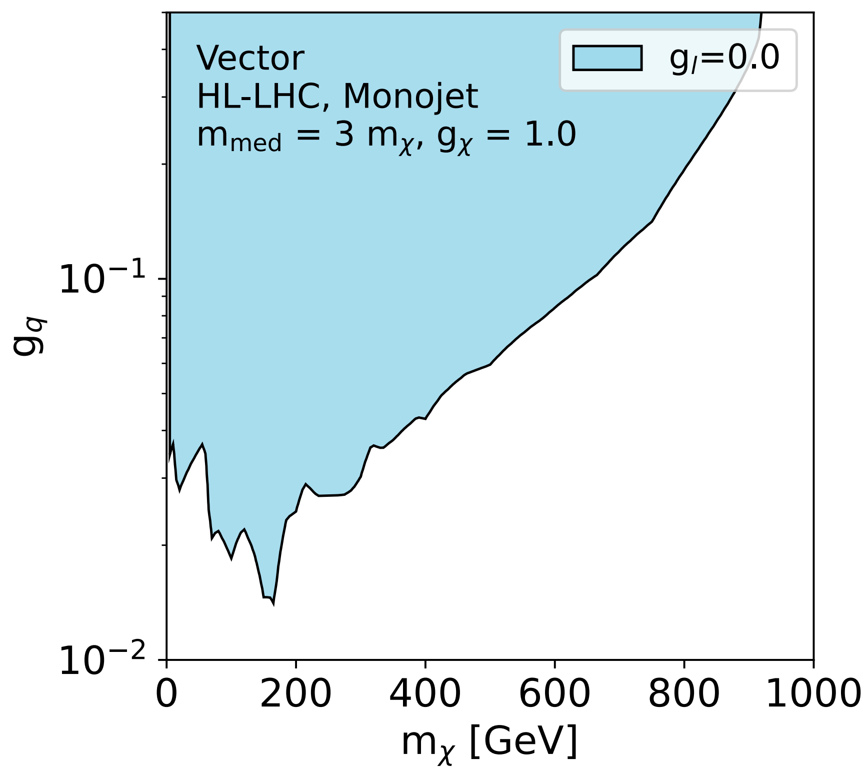
3 variables

Fix two and the other one becomes the thing that changes as σ_{SI} changes.

Implications and consequences can be very different, but can also be somewhat opaque when just looking at final 2D plot.

What actually dictates the angle of this shape?

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



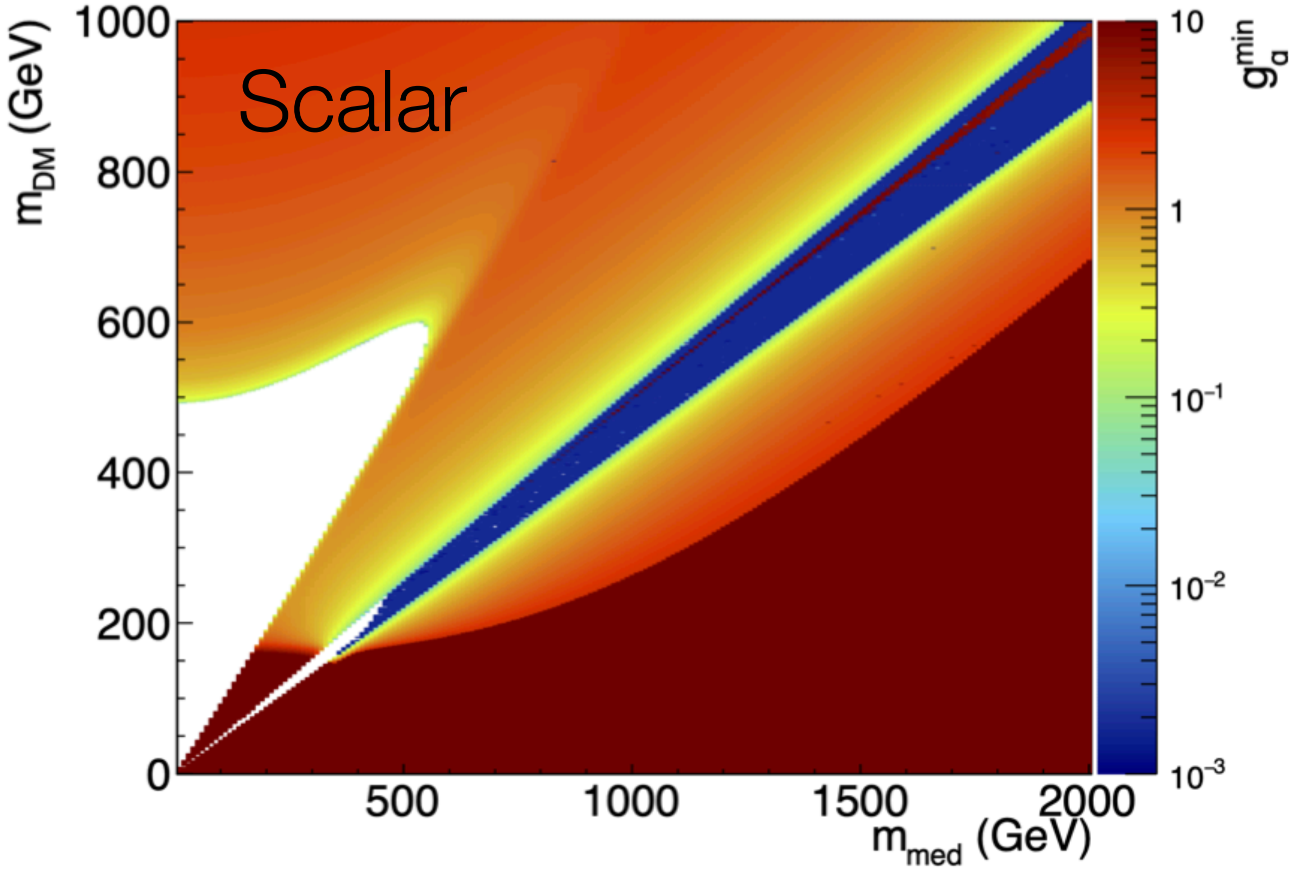
Let's take the top. Top is a flat line at g_q=0.5 (for now, just assuming limits above this are not valid). And note top of this plot is a flat line at 0.5 regardless of $A = m_{med}/m_\chi$. Keep $g_\chi = 1.0$.

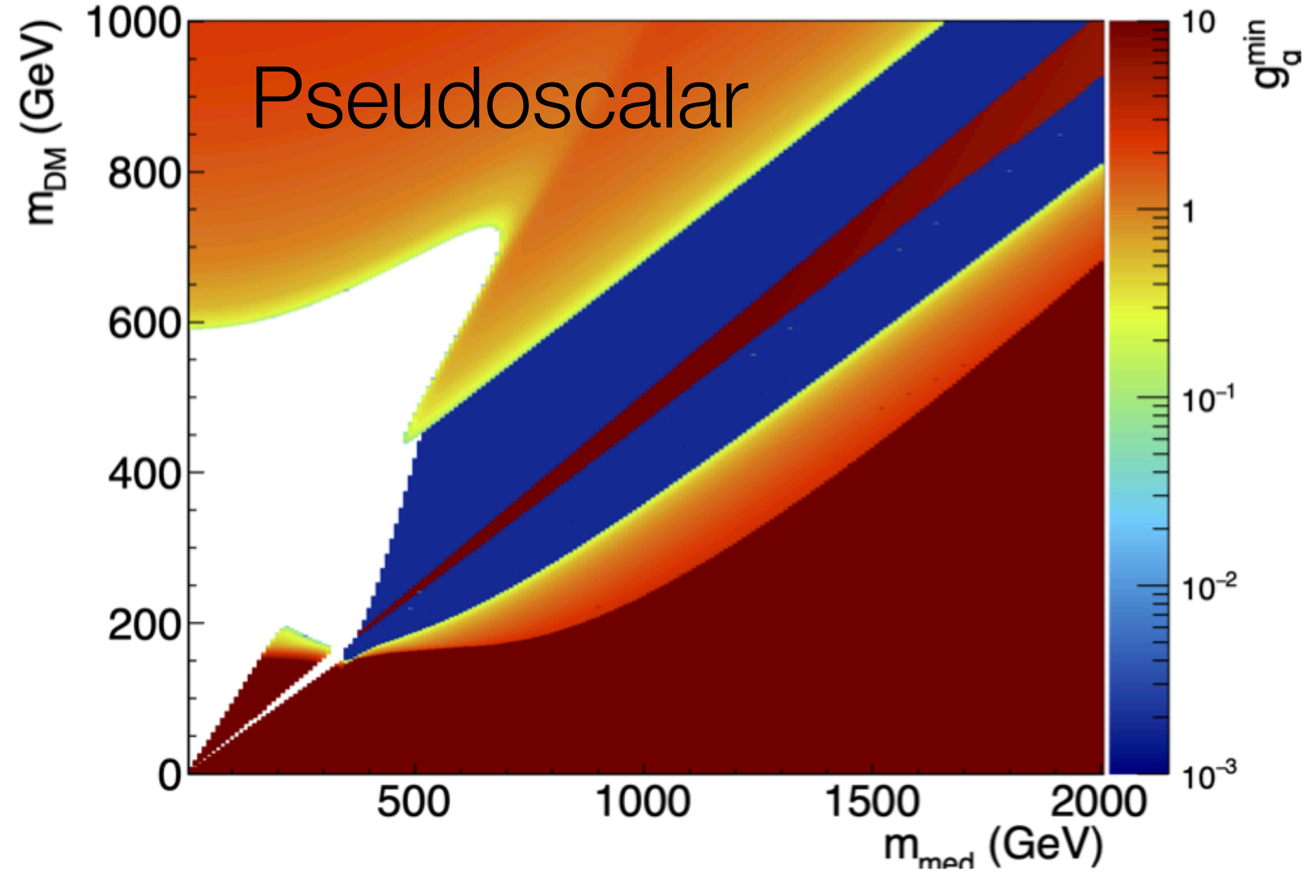
$$\sigma_{SI} \sim 6.9 \times 10^{-41} (\frac{0.5}{0.25})^2 (\frac{1000}{M_{\rm med}})^4 = 2.76 \times 10^{-28} (\frac{1}{A\, m_\chi})^4$$

On a log-log axis, $X = \log(m_\chi)$ and $Y = \log(\sigma_{SI})$.

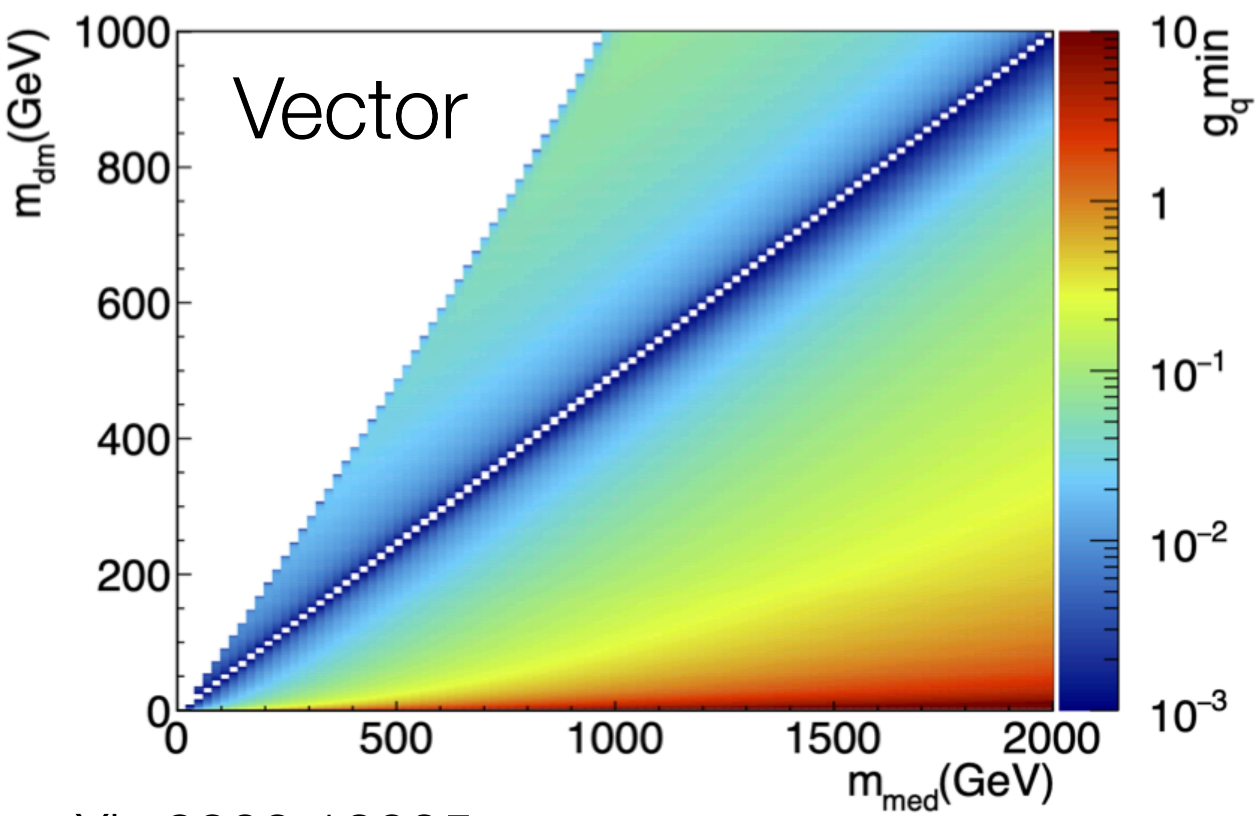
$$Y = \log(2.76 \times 10^{-28}) - 4\log(A) - 4X$$

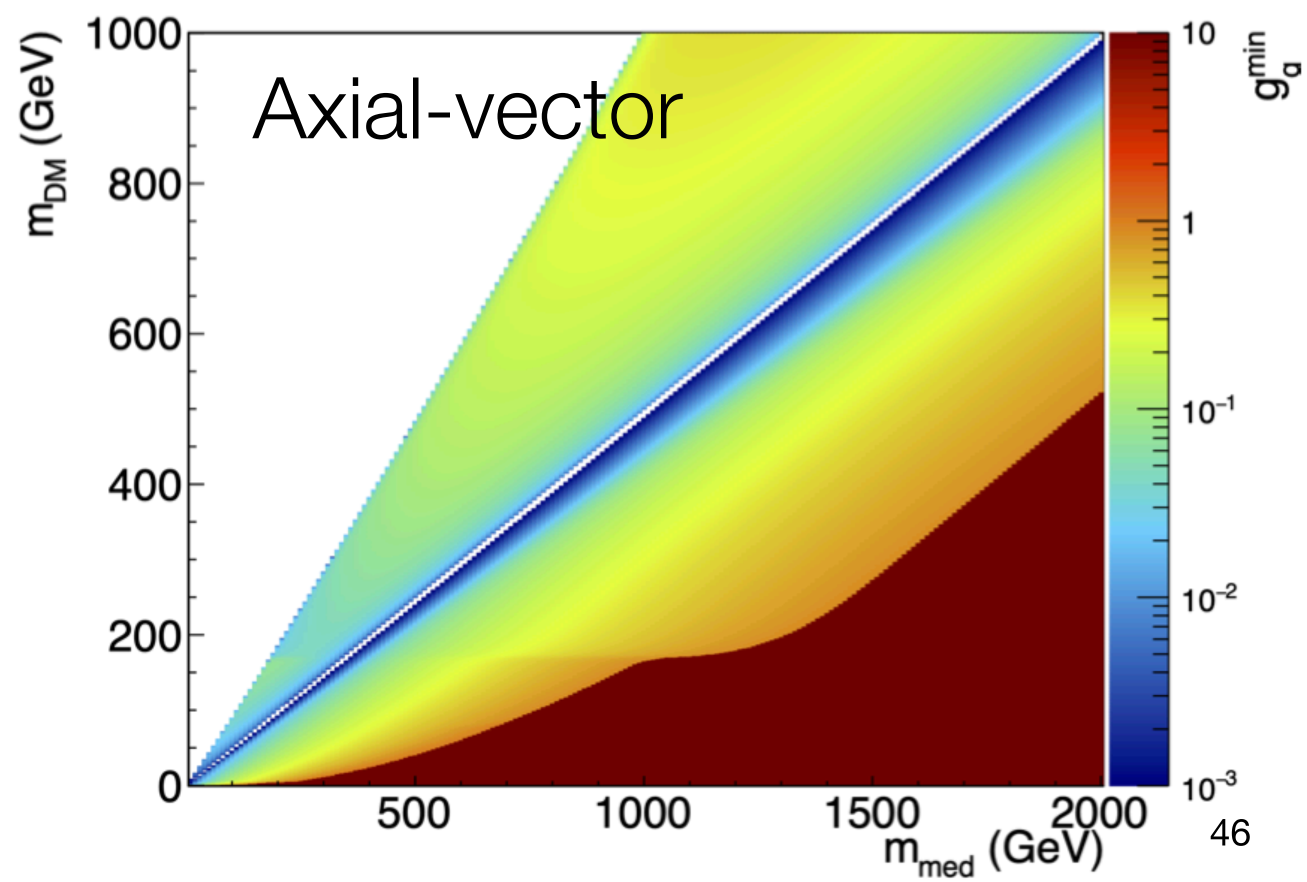
This is a linear relationship with slope -4. Changing $A = m_{med}/m_\chi$ only **shifts the line left or right and does not affect its angle.**



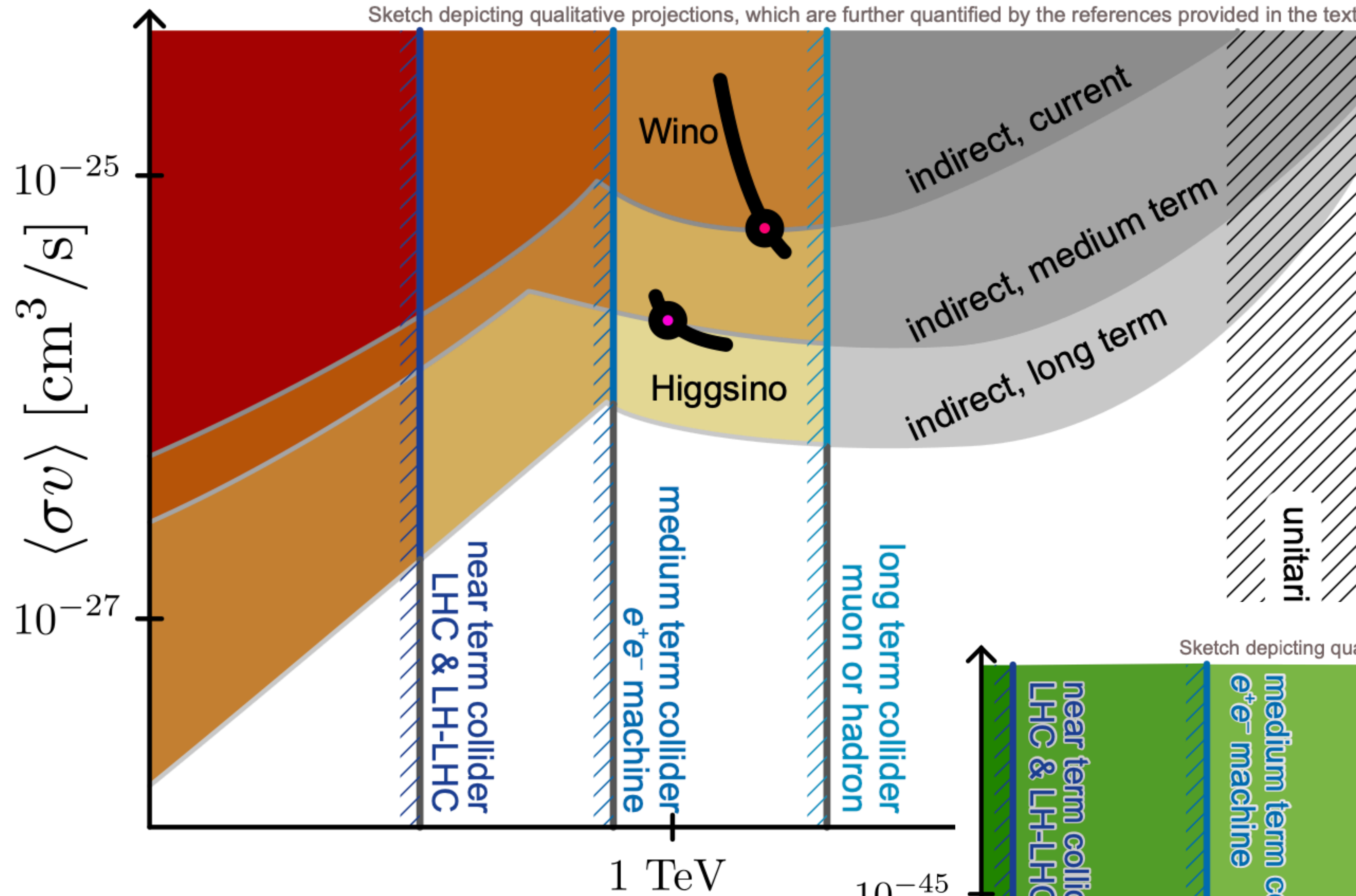


Minimum allowed couplings before overproducing DM





arXiv:2203.12035



A few sketches from Snowmass dark matter complementarity report

arXiv:2210.01770

Wino & Higgsino DM candidate sensitivity vs mass for indirect and direct detection and future colliders