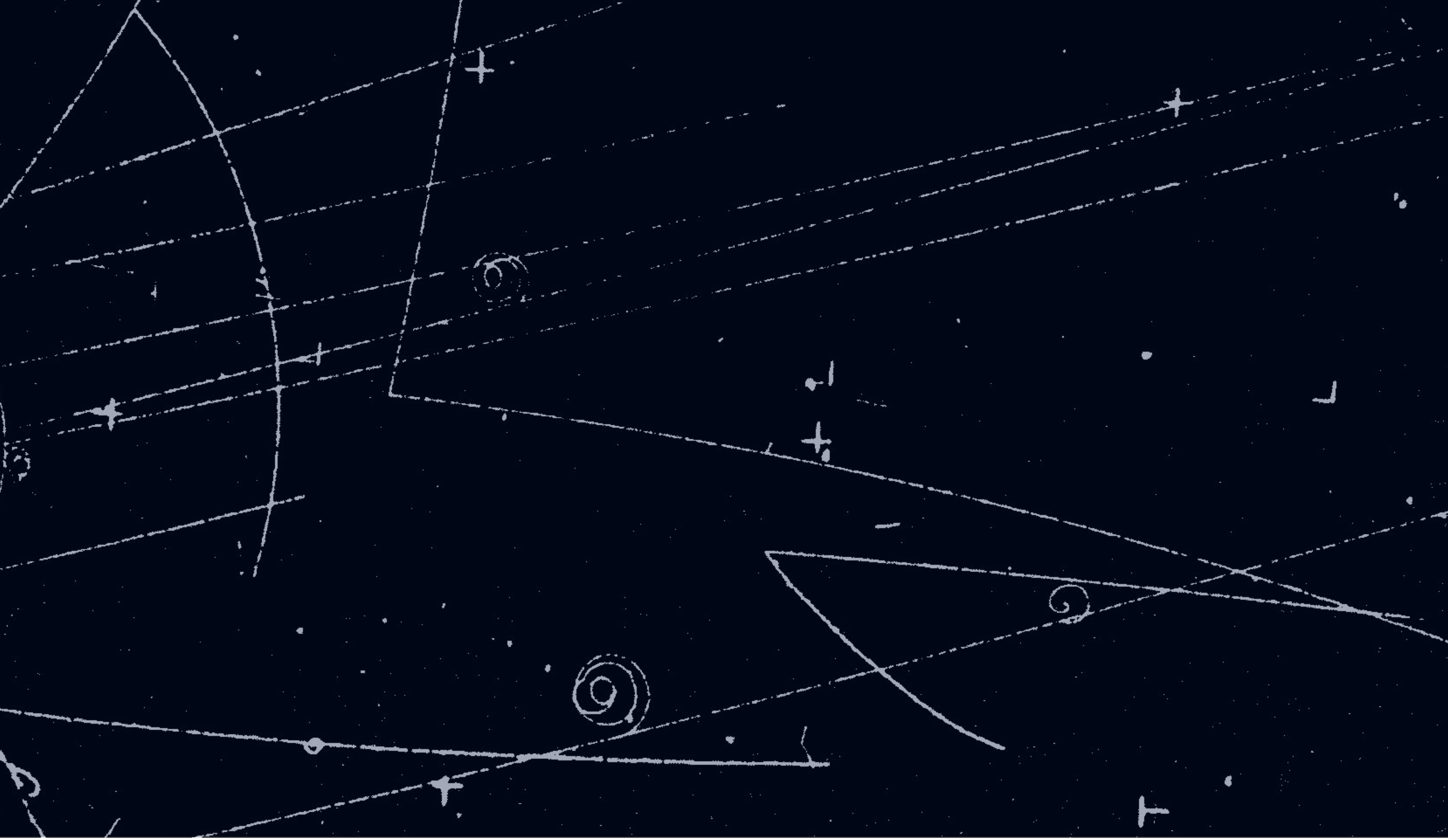

Accelerator based dark matter probes

Kate Pachal
TRIUMF

Introduction

We are here this week to talk about the future of high energy physics

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That future has to center dark matter

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- What we are currently able to say about it
- What we could say about it with future colliders
- How we might think about framing this to the community

Medium-mass dark matter

Today, largely talking about cases with dark matter and/or associated new particles over ~ 1 GeV in mass

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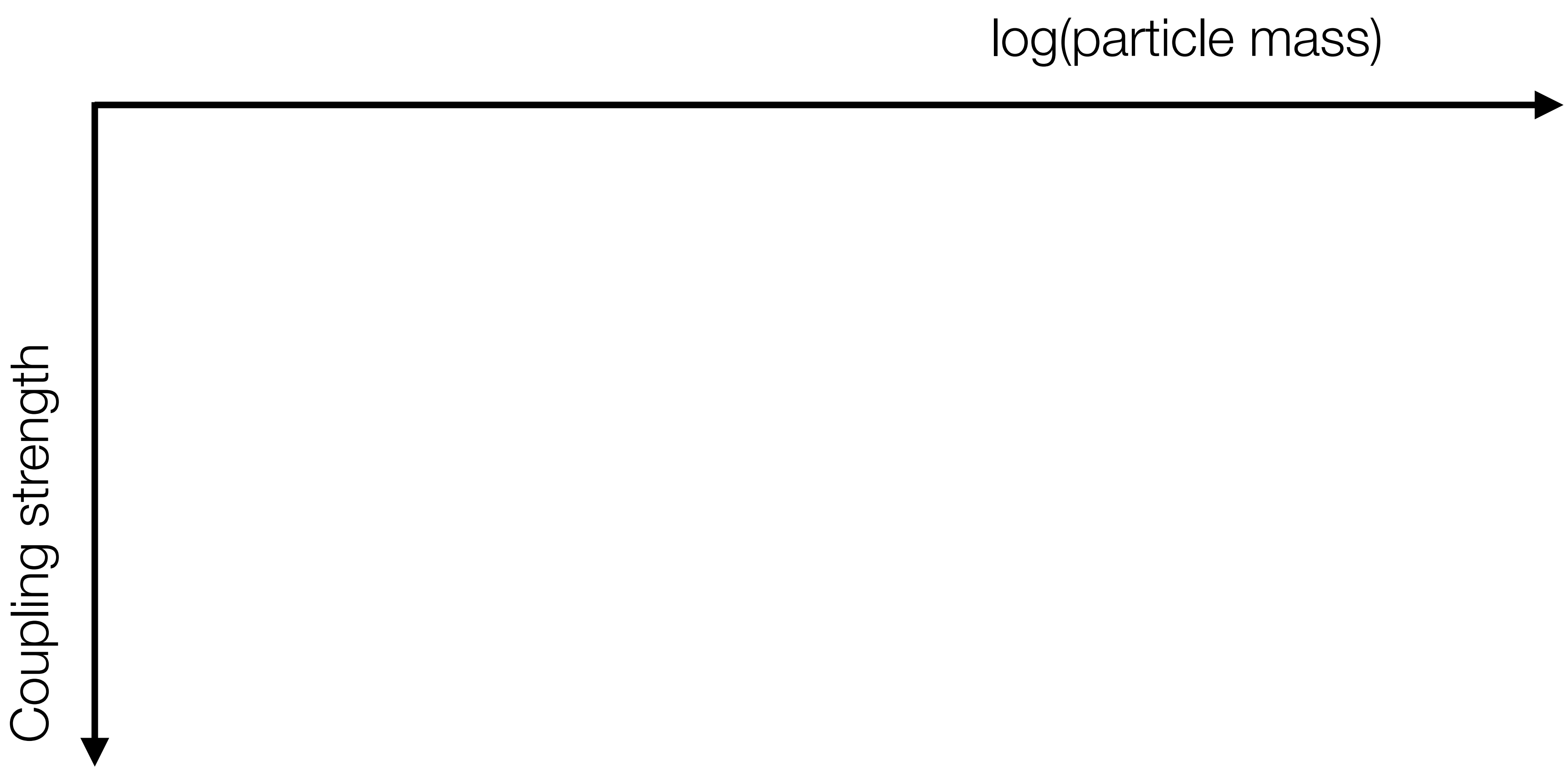

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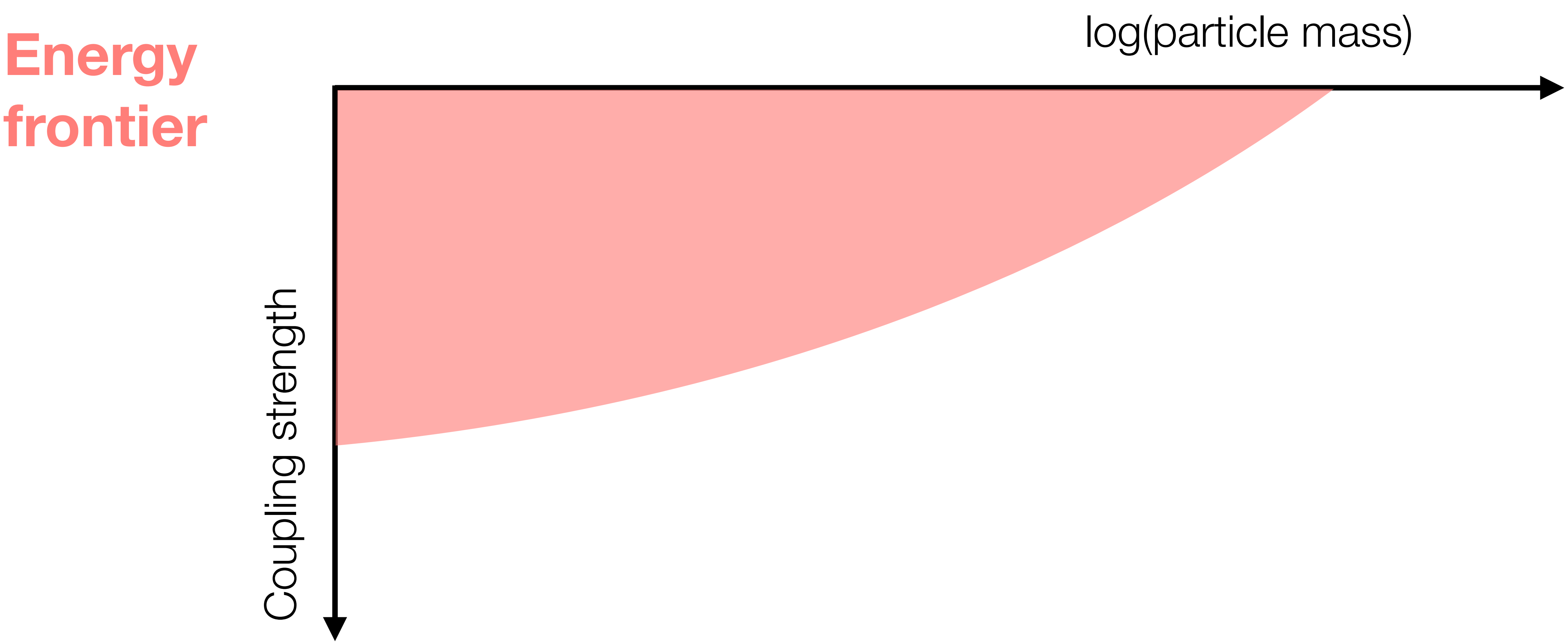

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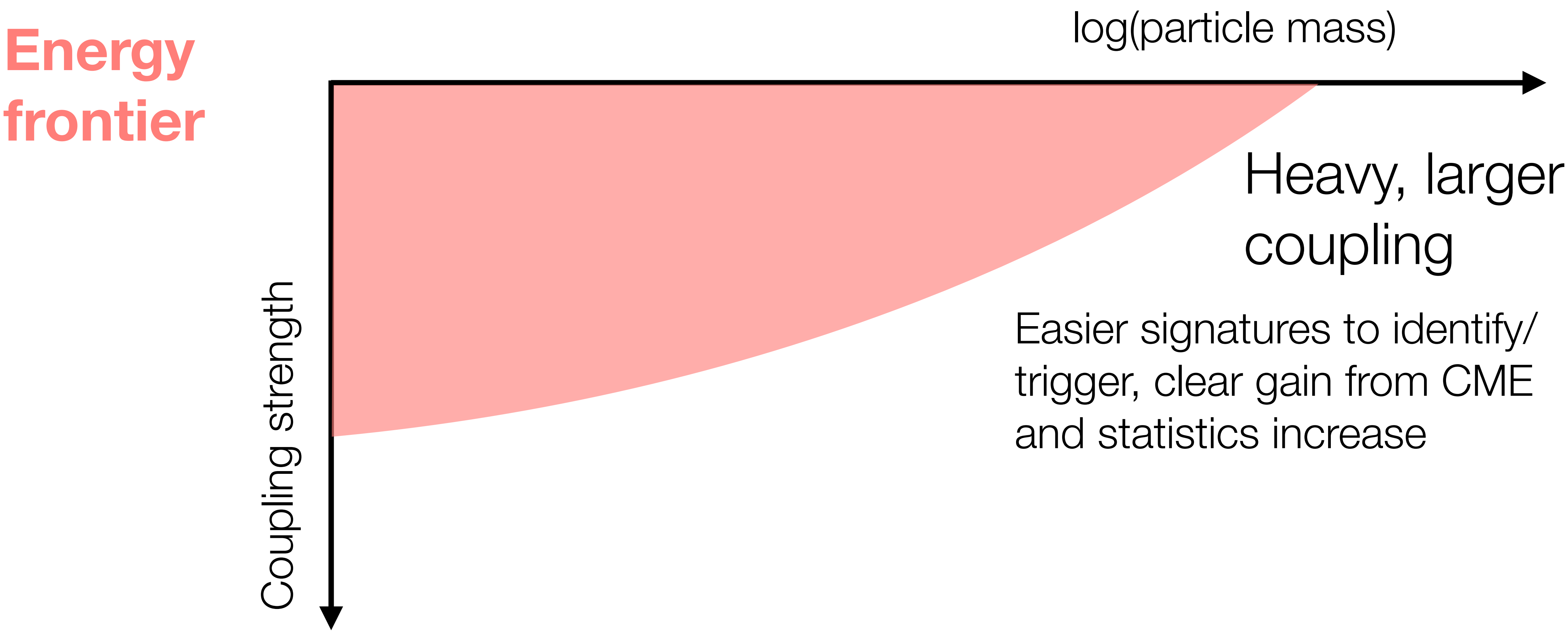

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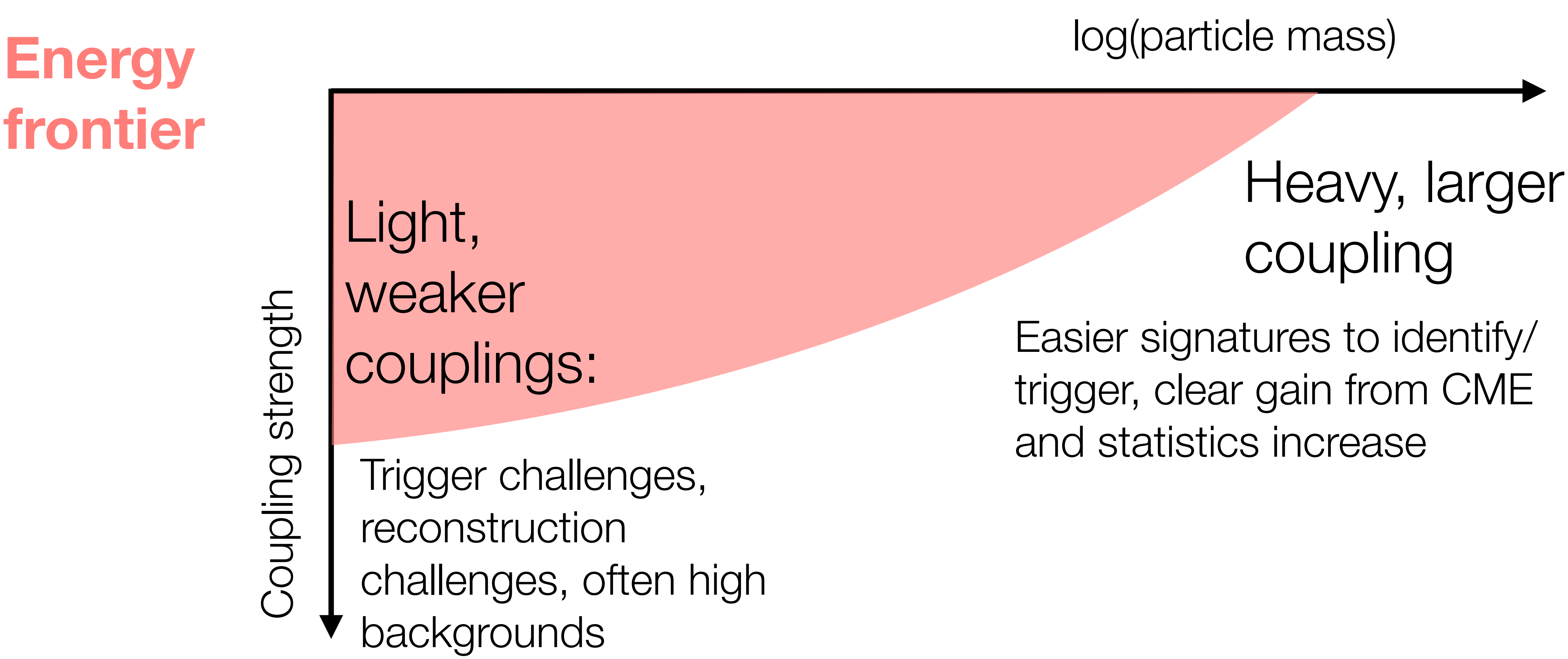

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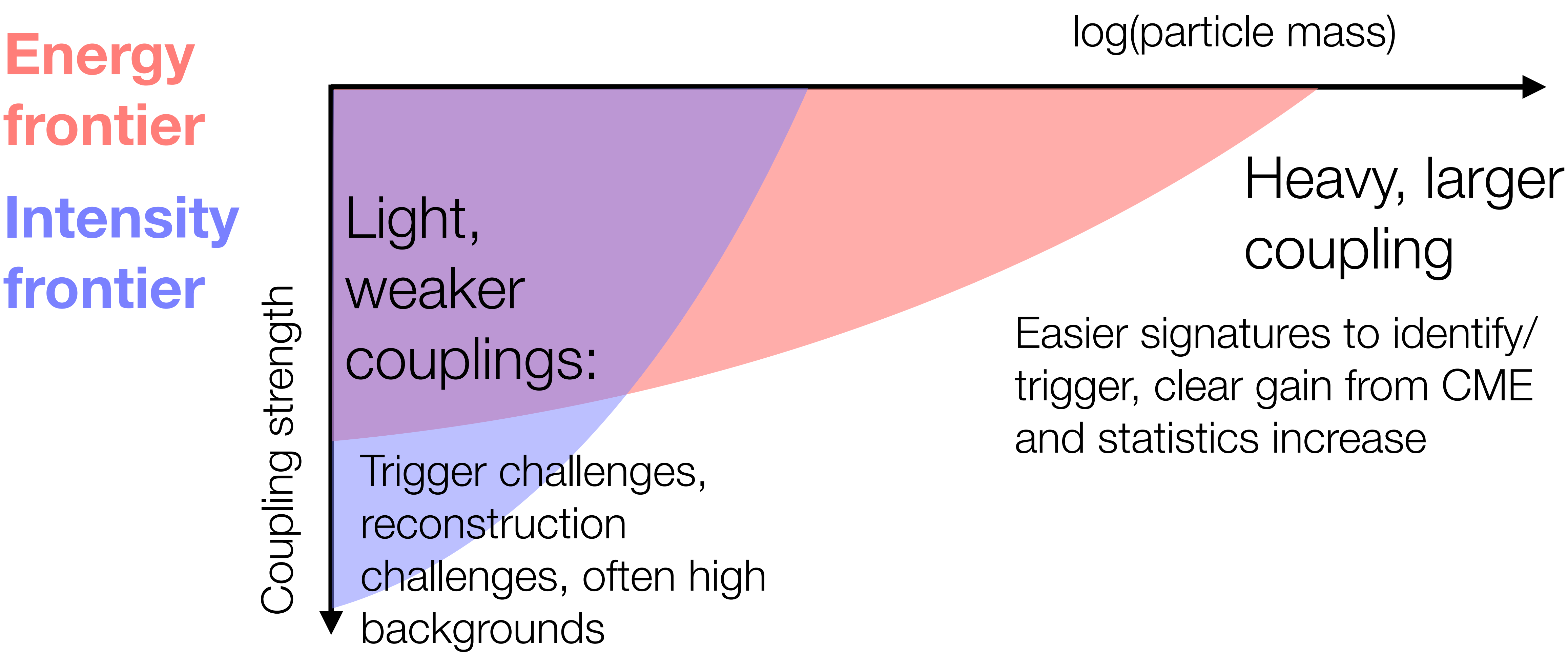

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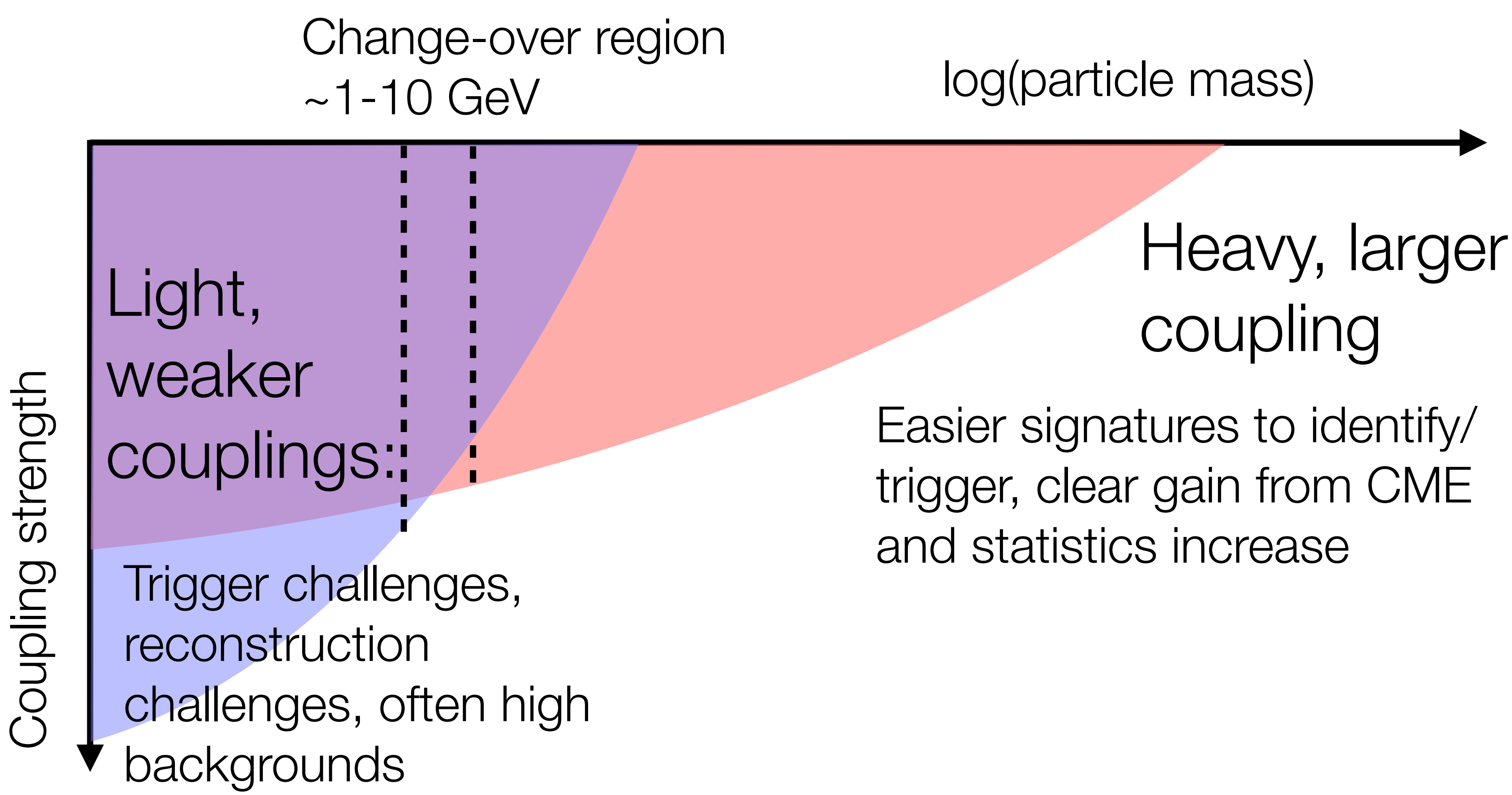
Energy frontier

Intensity frontier



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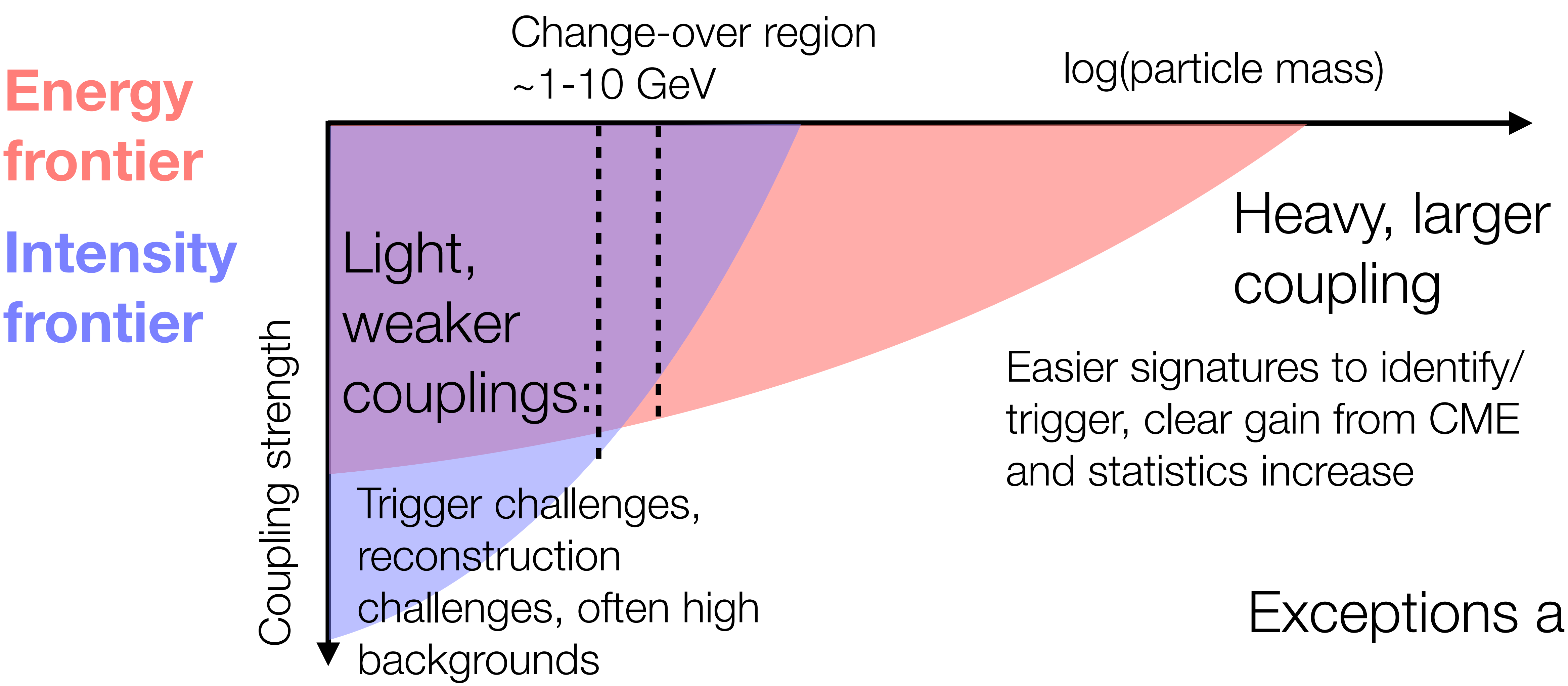
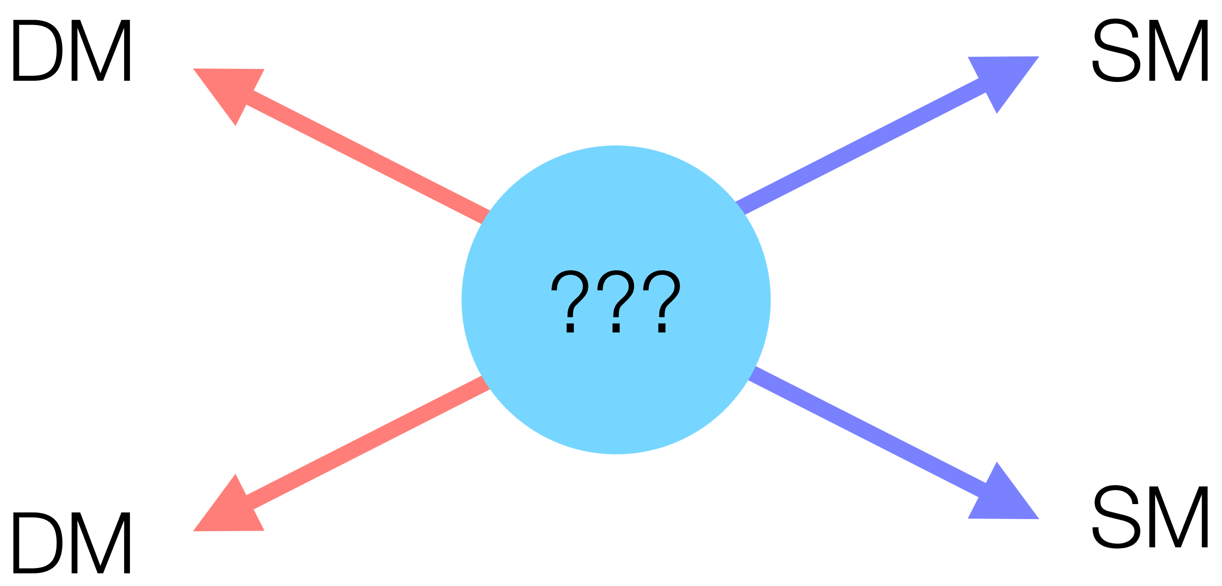


Exceptions apply!

Complementarity between DM experiments



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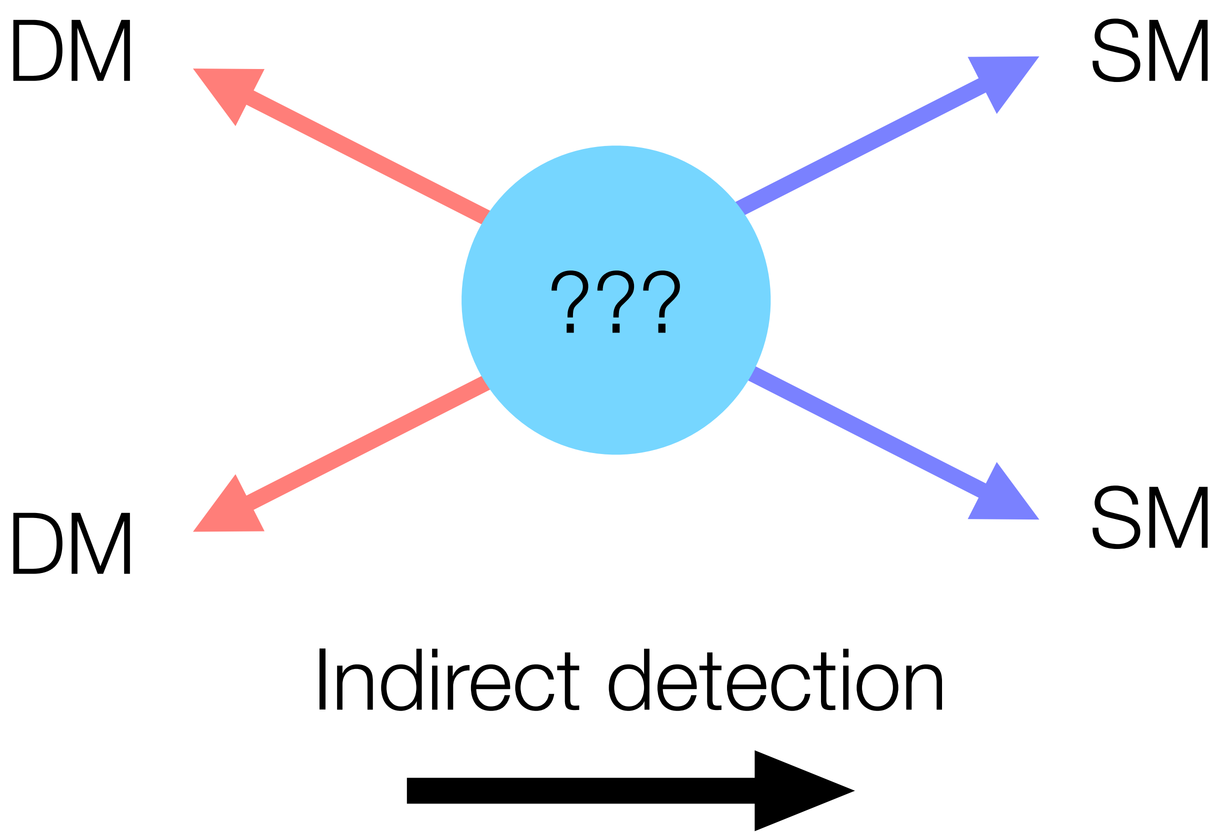

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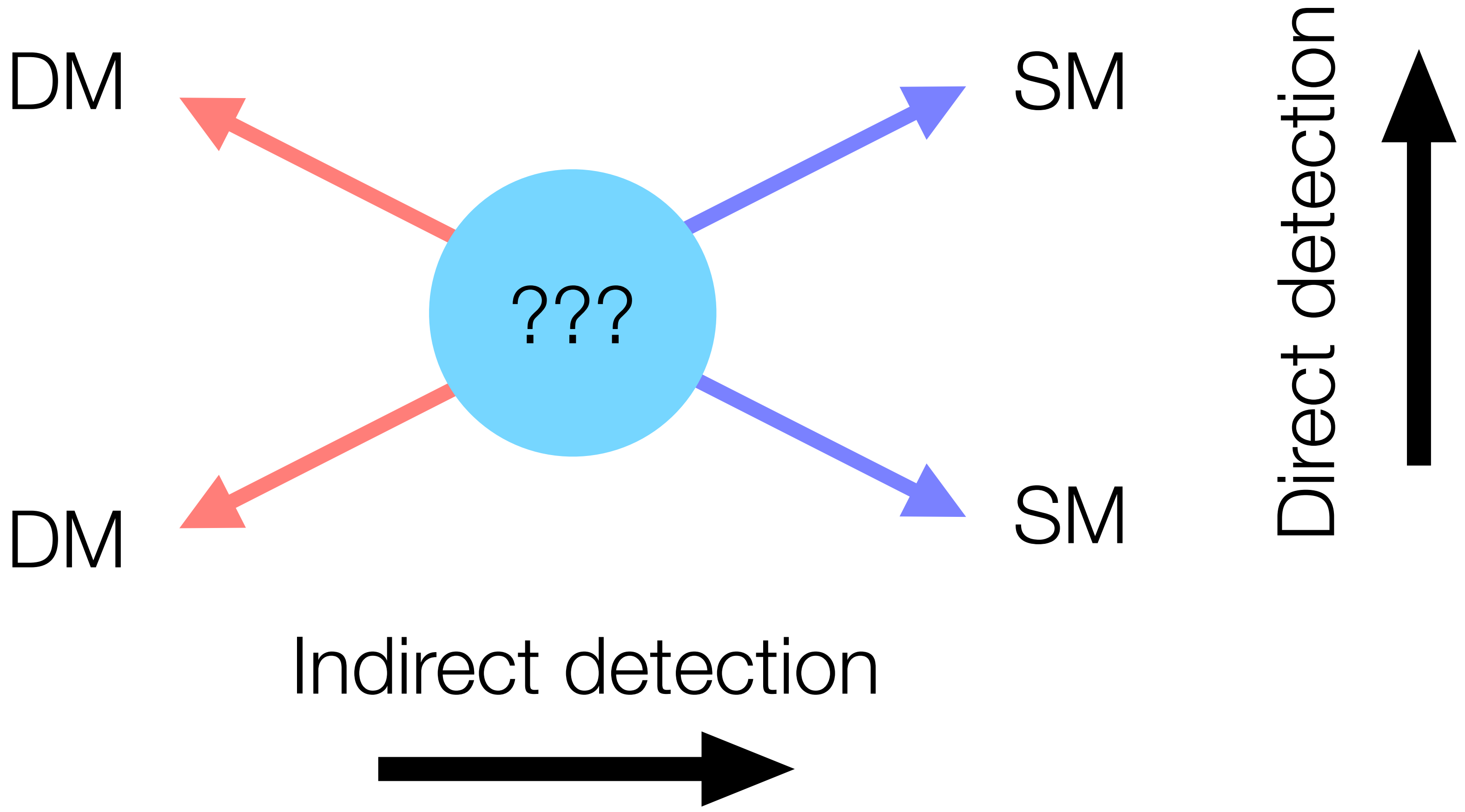

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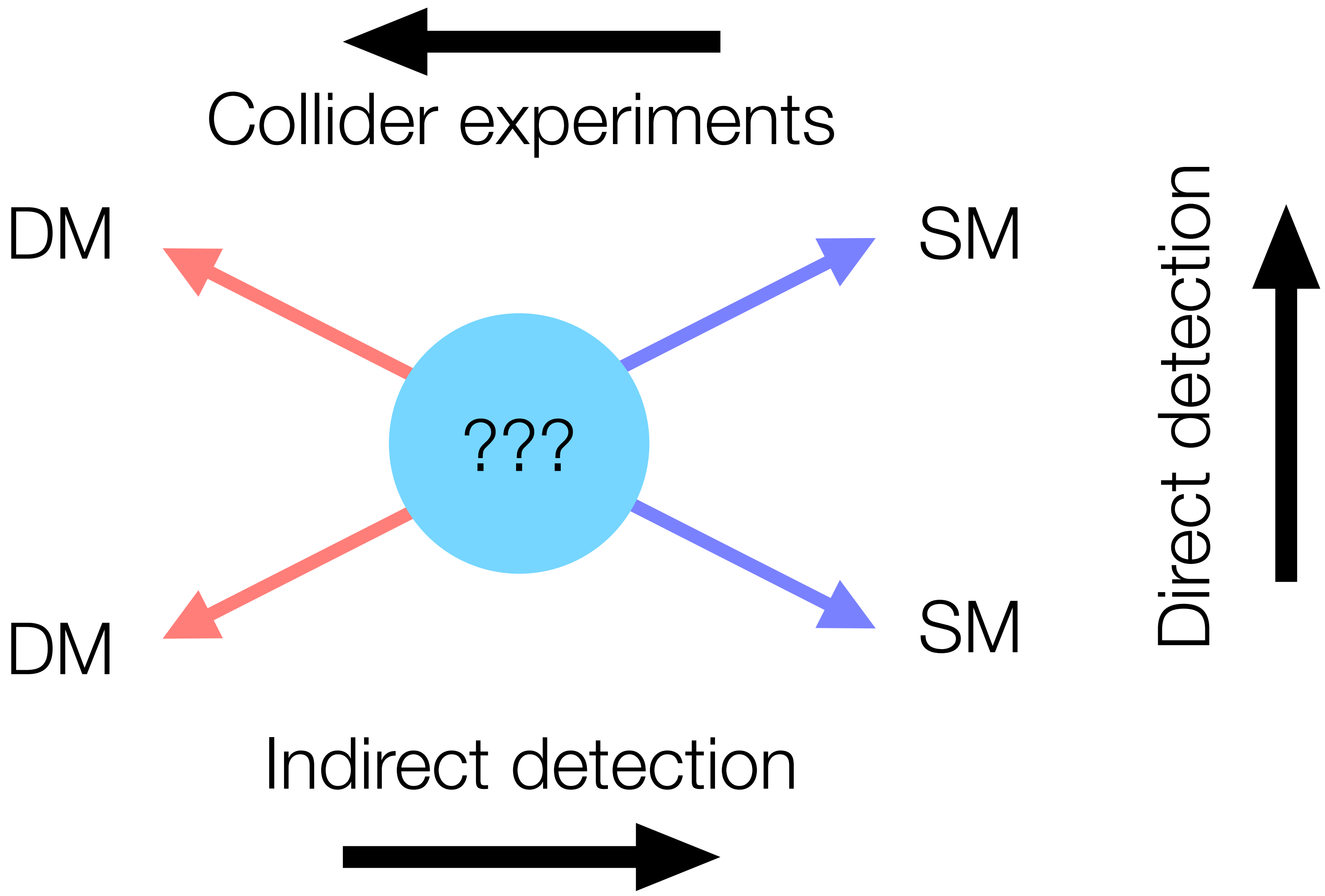

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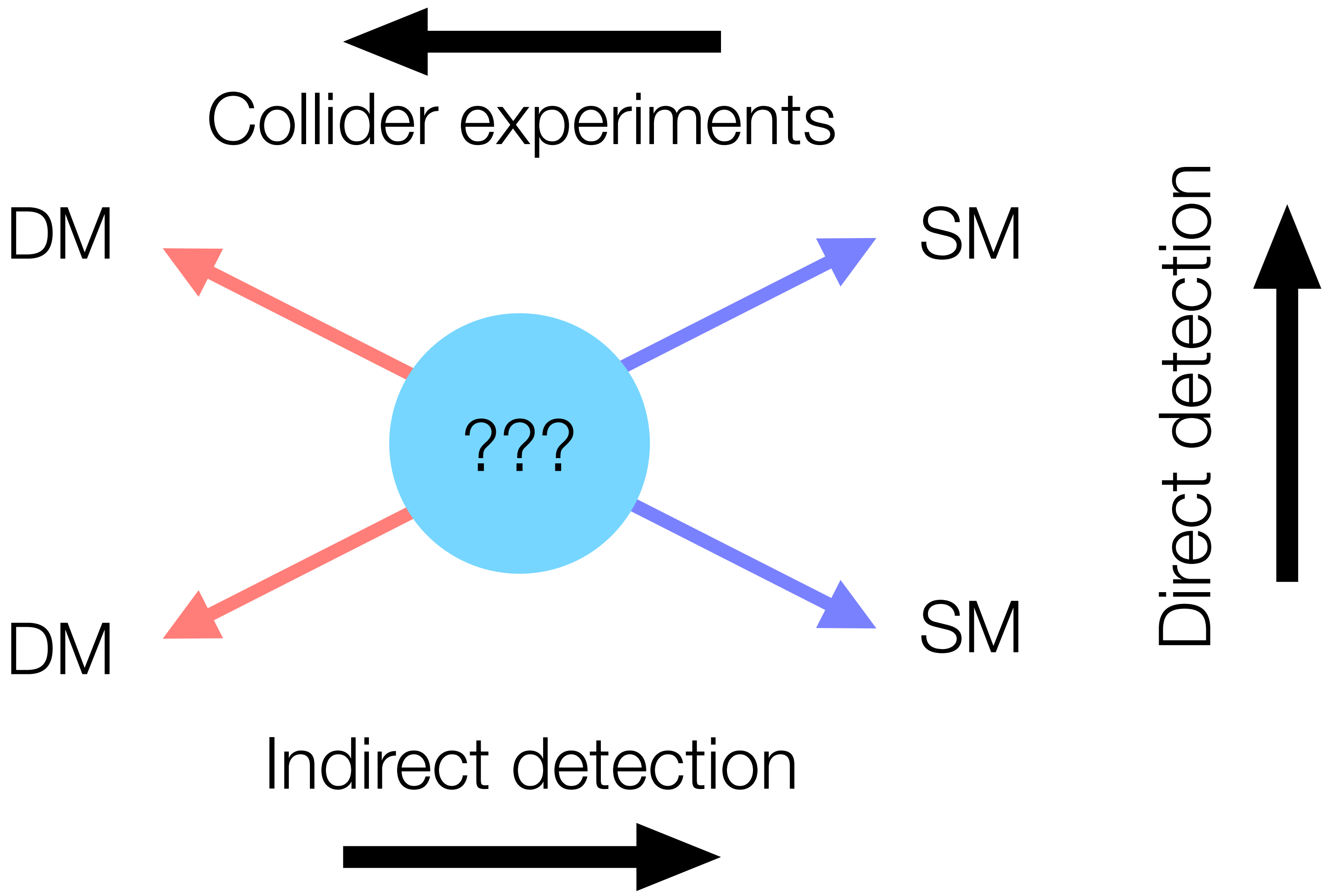

Tired: all three approaches are probing the same thing (interchangeable)

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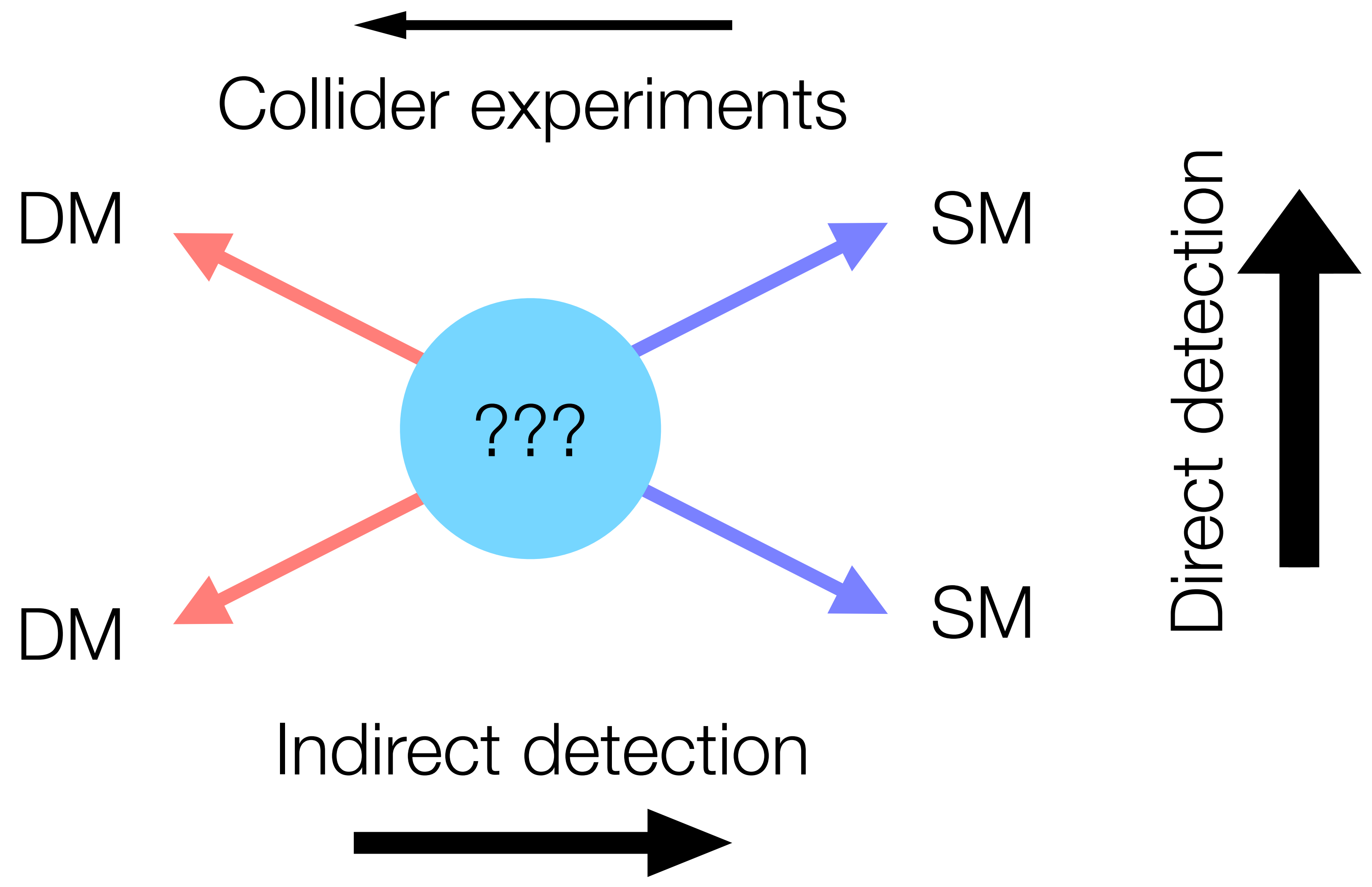

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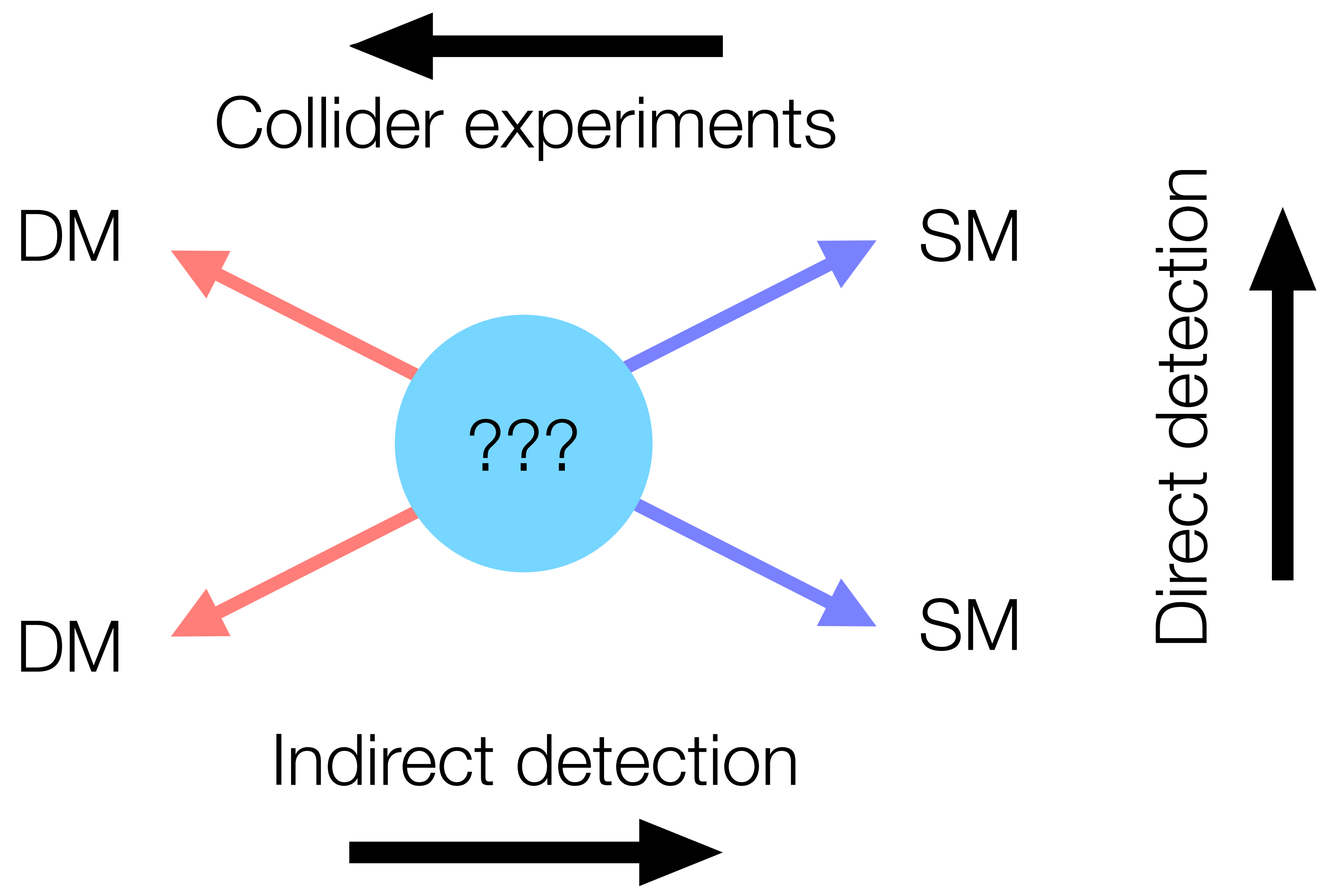

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Wired: different DM scenarios may be accessible to only one or two of the three approaches

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

Benchmarks

Dark matter models at the LHC

No EFTs

Mediator masses around energy scale of collider

Dark matter models at the LHC

Standard Model: black
BSM: blue

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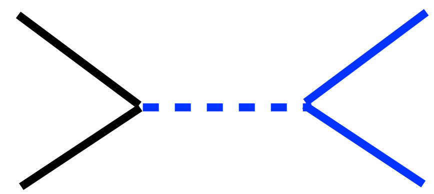
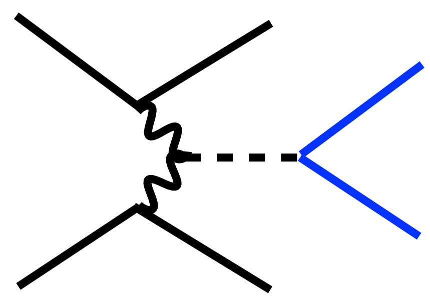
Simplified models

Spin-1 mediator, one DM particle





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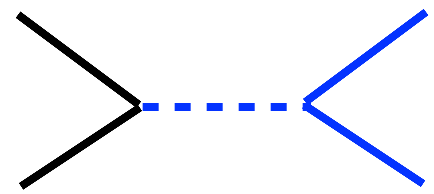

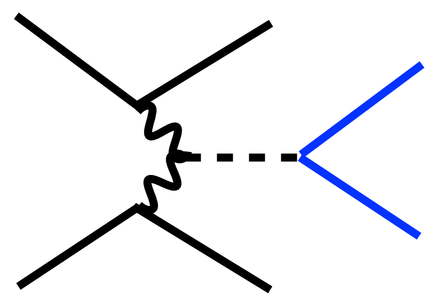

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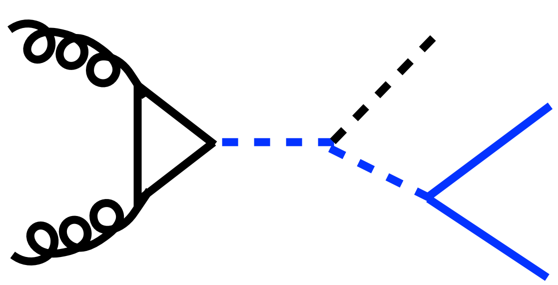
2HDM + pseudoscalar



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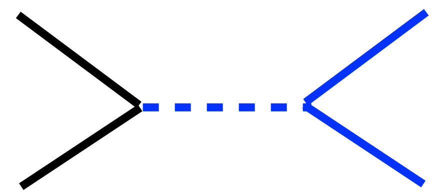
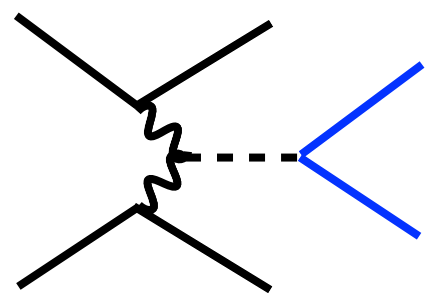
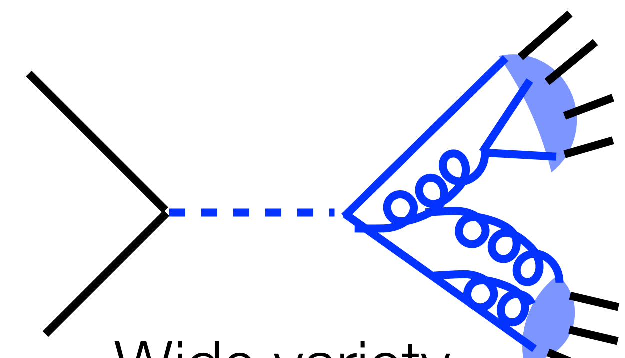




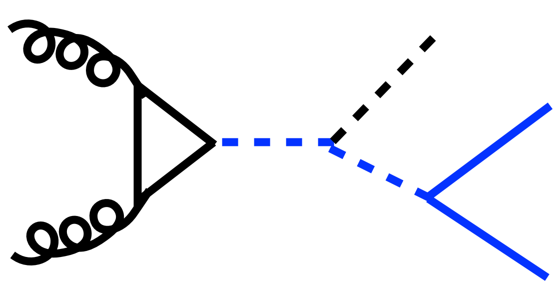
Simplified Higgs portal

Extended dark sectors



Wide variety

2HDM + pseudoscalar



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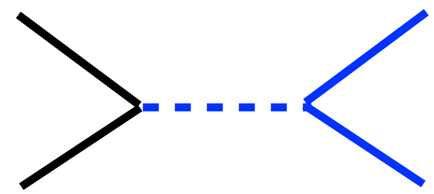

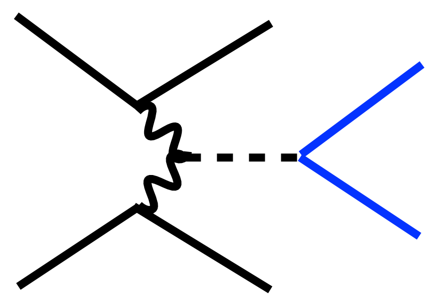

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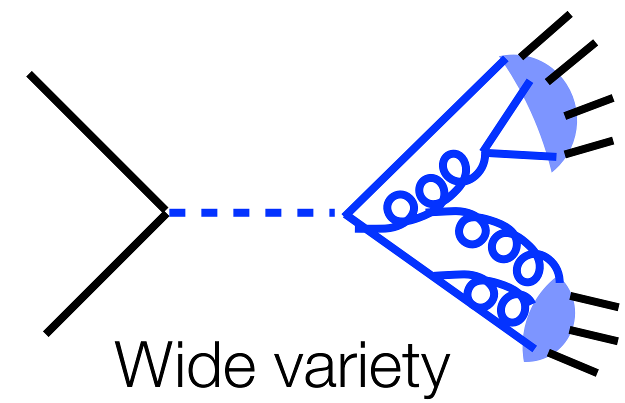

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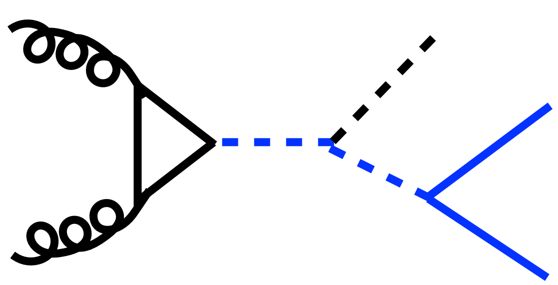

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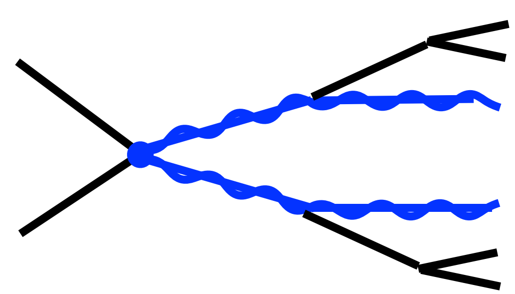
SUSY scenarios

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



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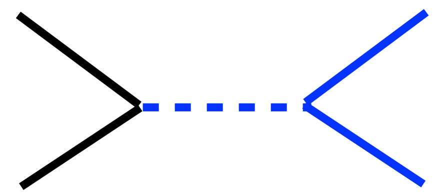

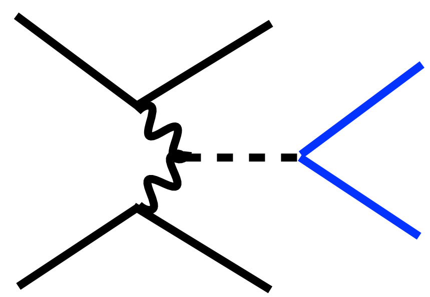

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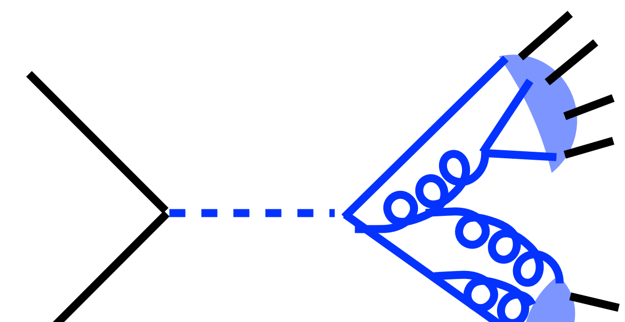

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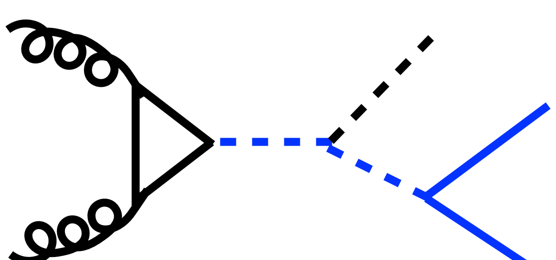

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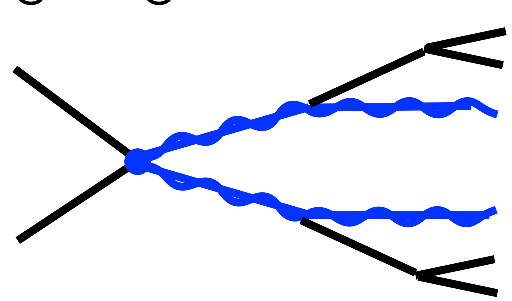

Often simplified for practicality

Long-lived particles

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

Pros and cons of different benchmarks*

* speaking as an experimentalist

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Simplified models

Ease of comparison between analyses and experiments

Complete/ complex models

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Hard to form complete picture; hard to compare across contexts

No single answer. ATLAS & CMS lean on simplified models for comparisons; use complex models on analysis-by-analysis basis and for smaller comparison use cases

Relevance of relic densities

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

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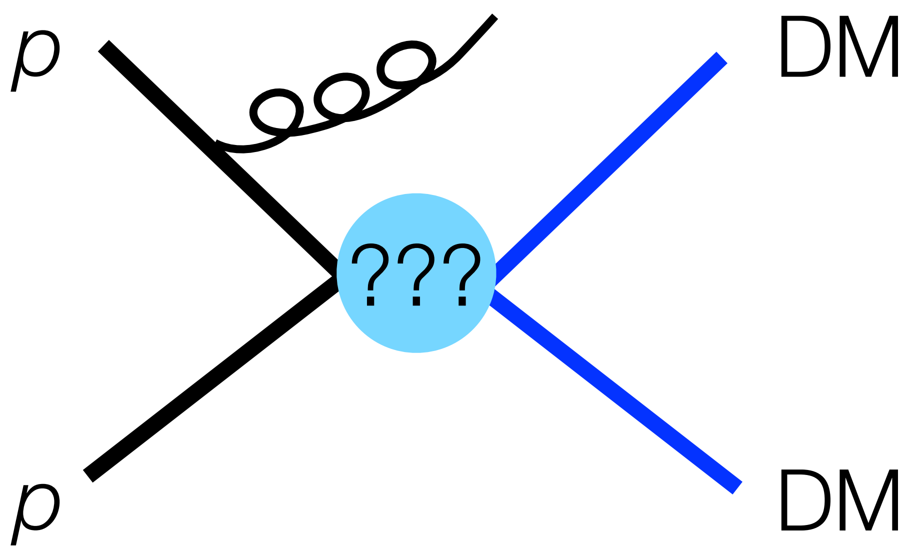
Could say a model is excluded once relic prediction reached

DM at the LHC

LHC signatures for DM searches

Most general: mono-X



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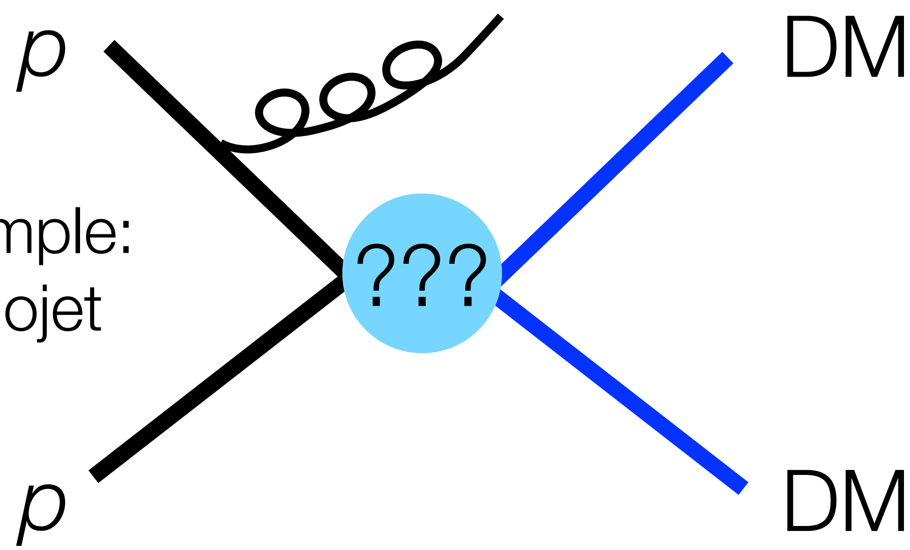

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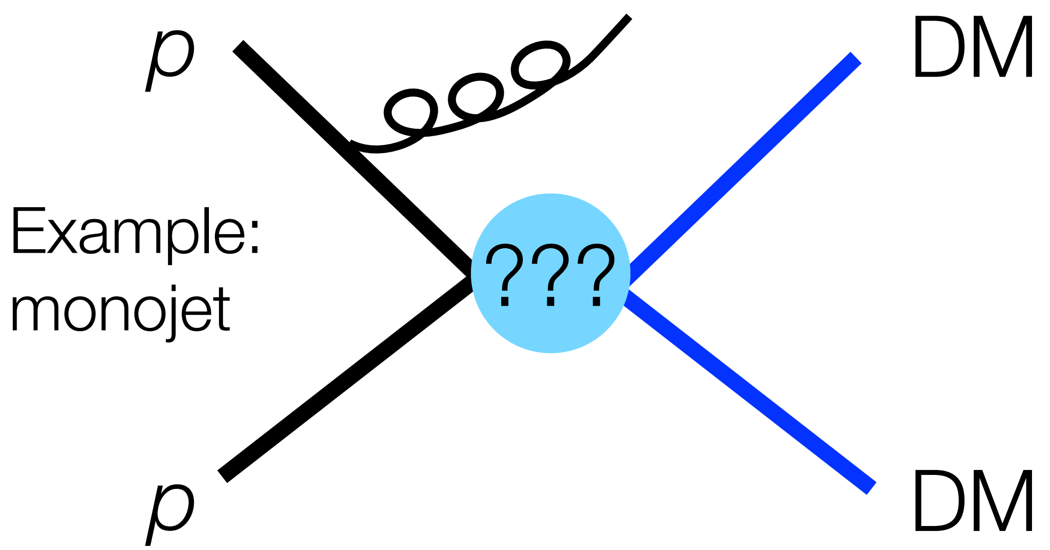

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ISR provides momentum, enabling
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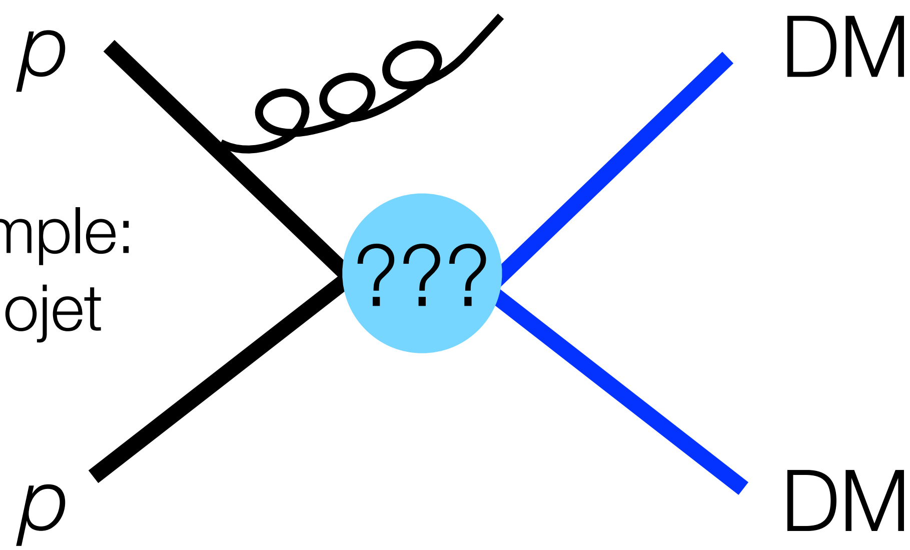

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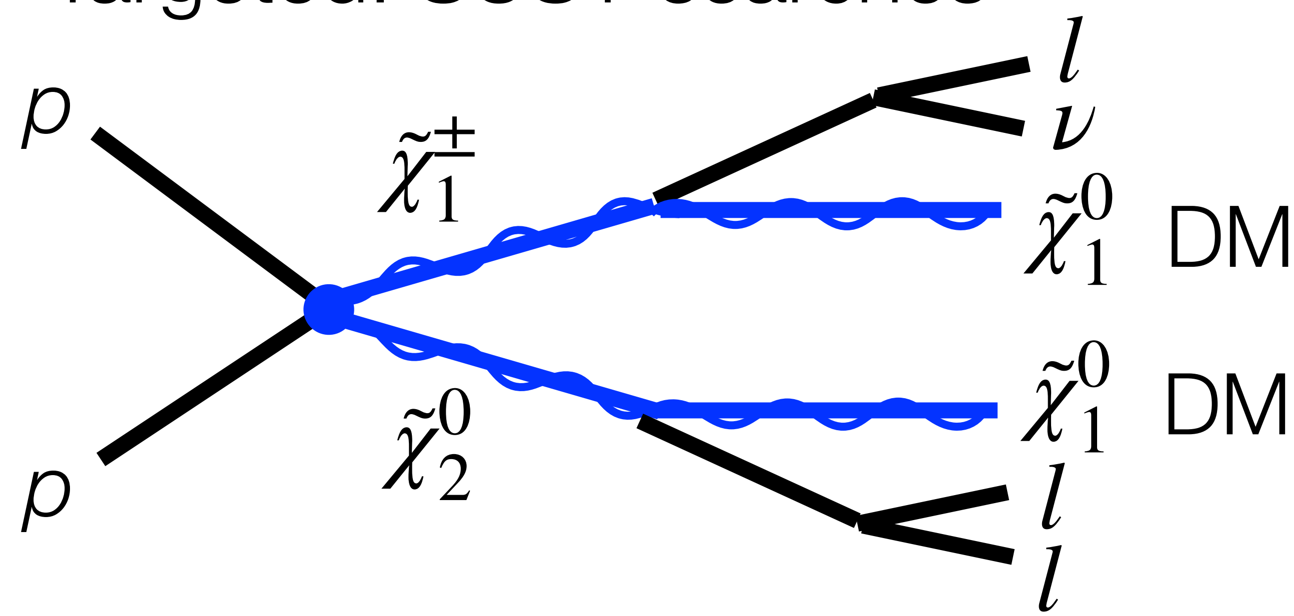

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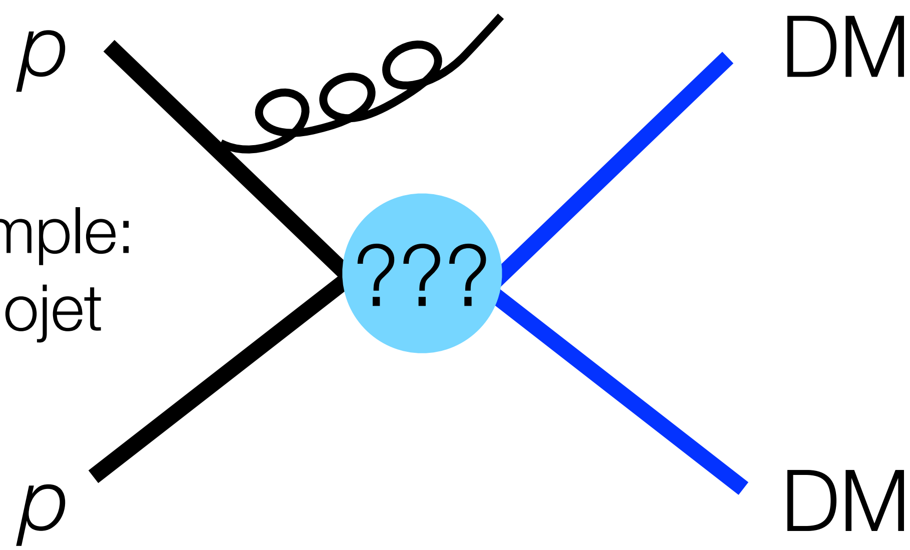

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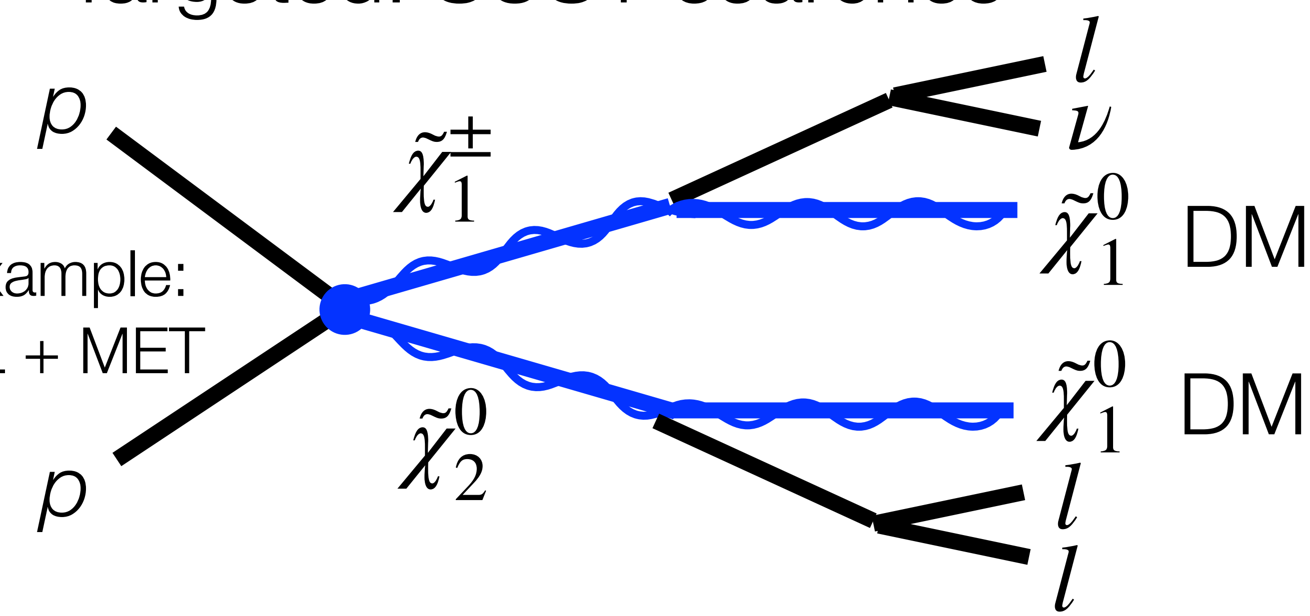

Example: 3L + MET

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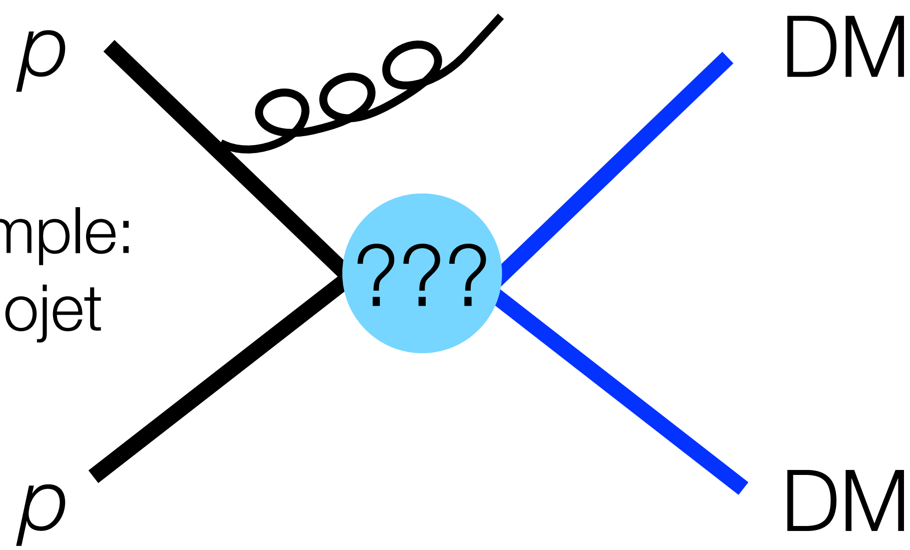

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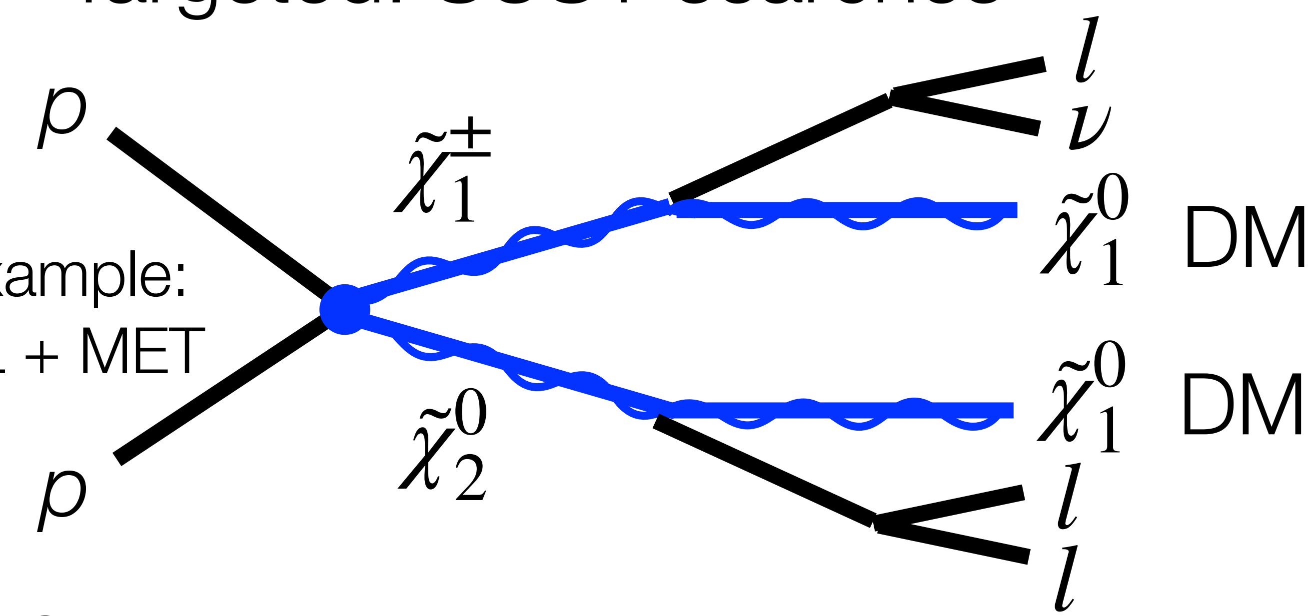

Example:
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Generally complex final state allowing significant background suppression. MET remains key feature of selection

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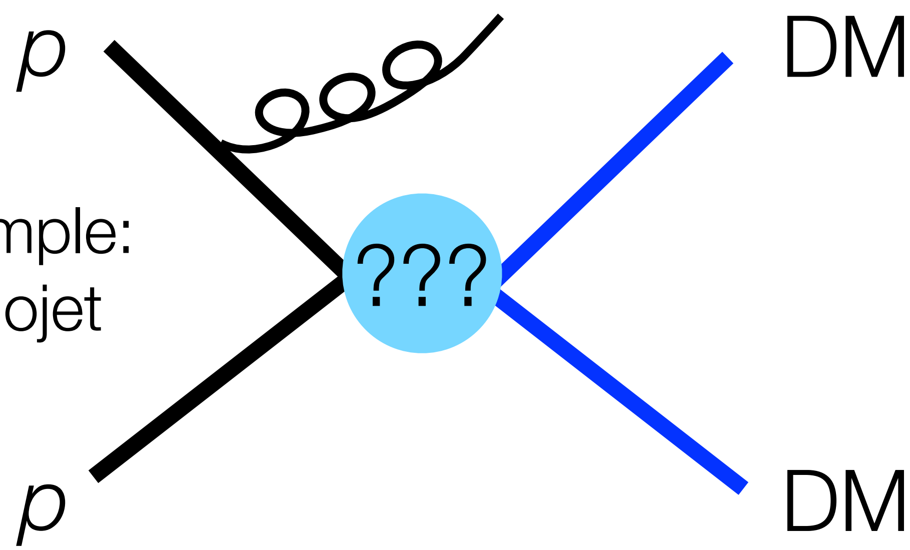

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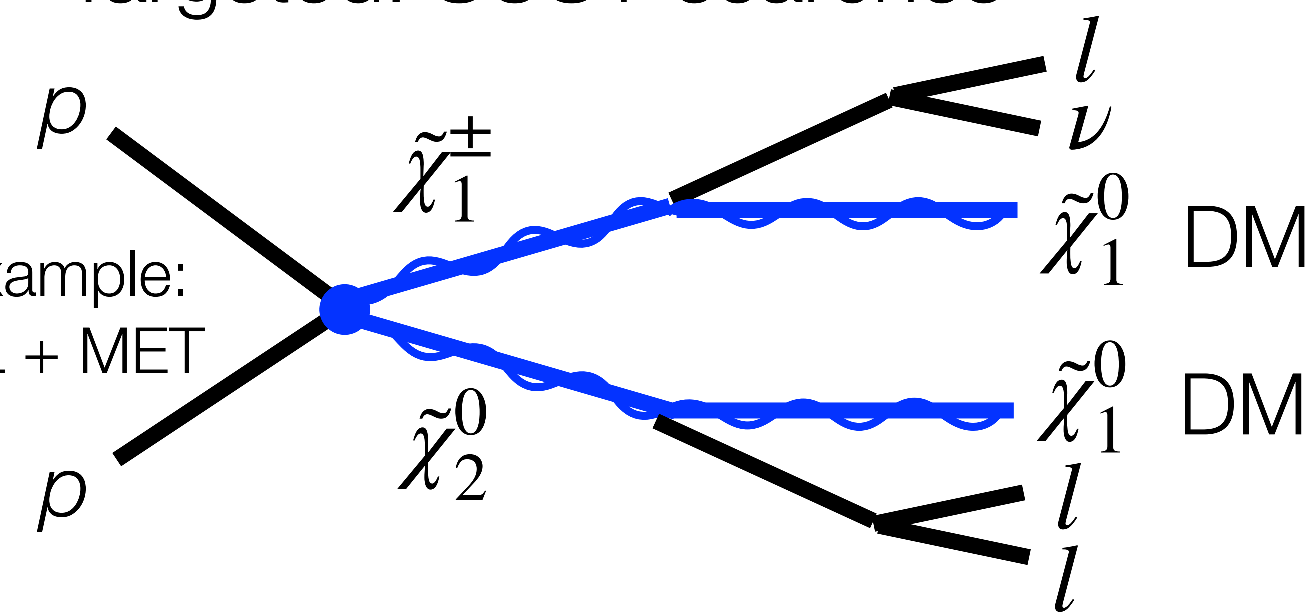

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Non-MET-focused

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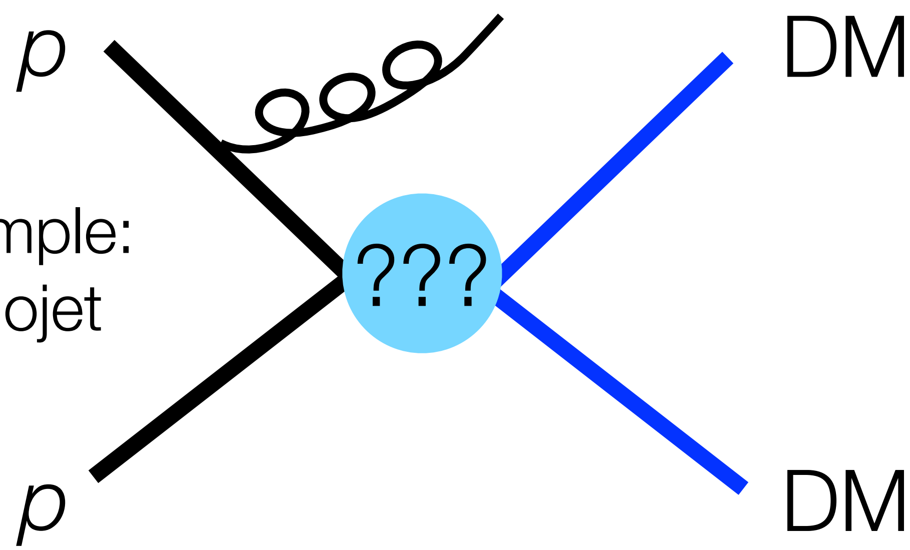
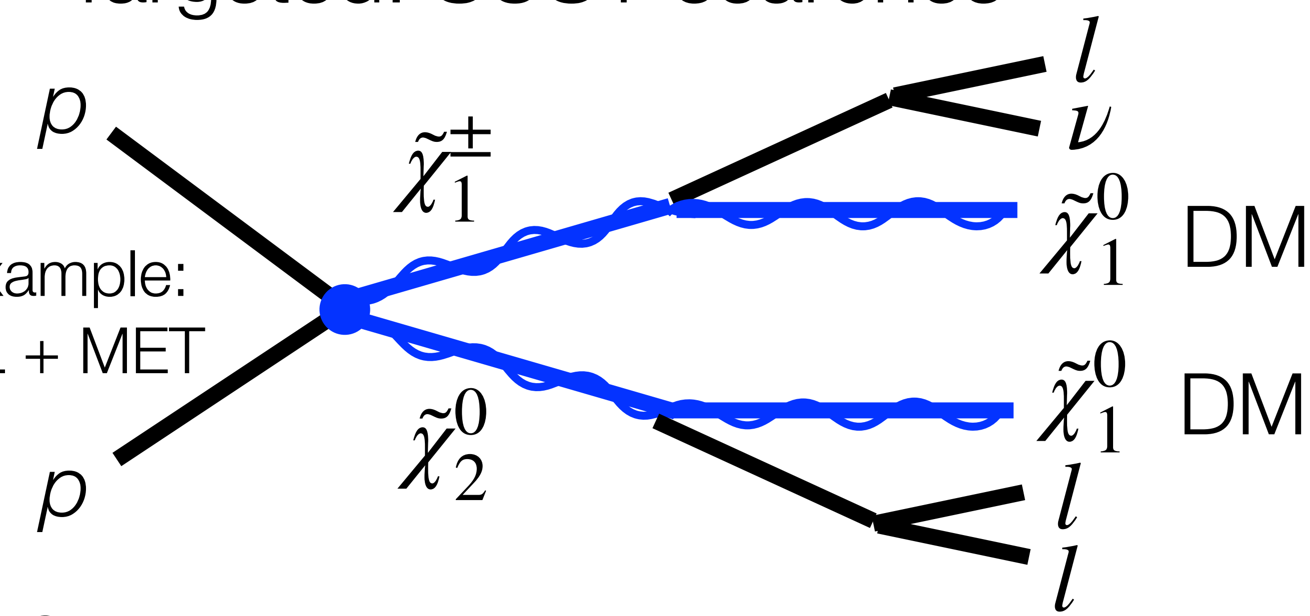


Model-independent; high backgrounds. ISR provides momentum, enabling missing energy reconstruction

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

LHC signatures for DM searches

Most general: mono-X

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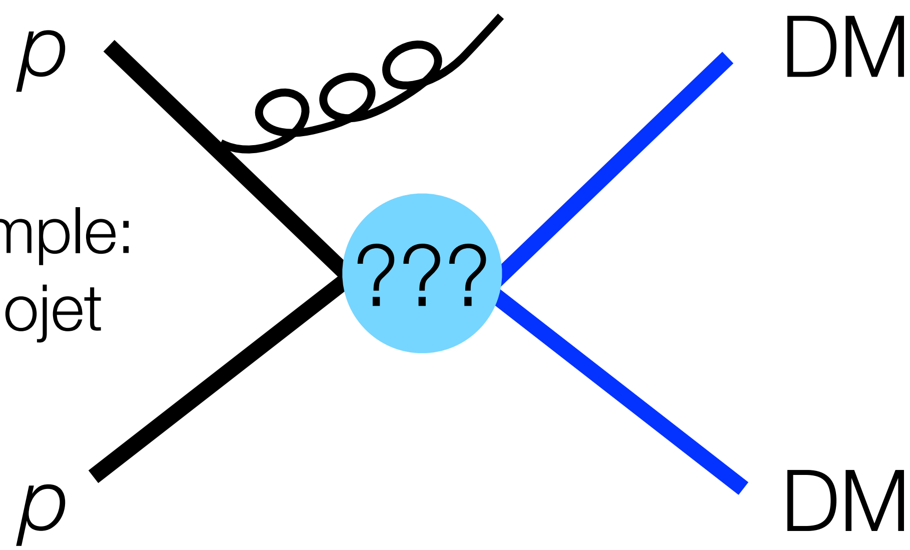

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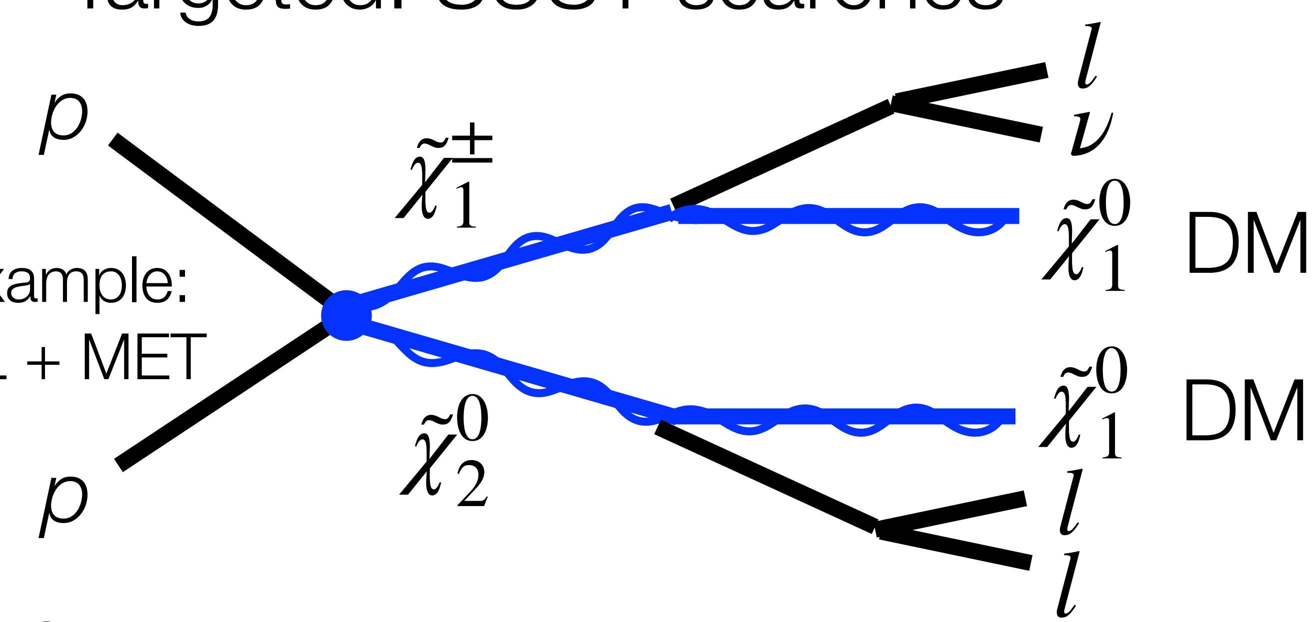

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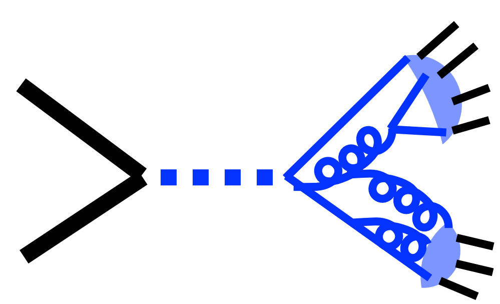

QCD final states with distinctive features

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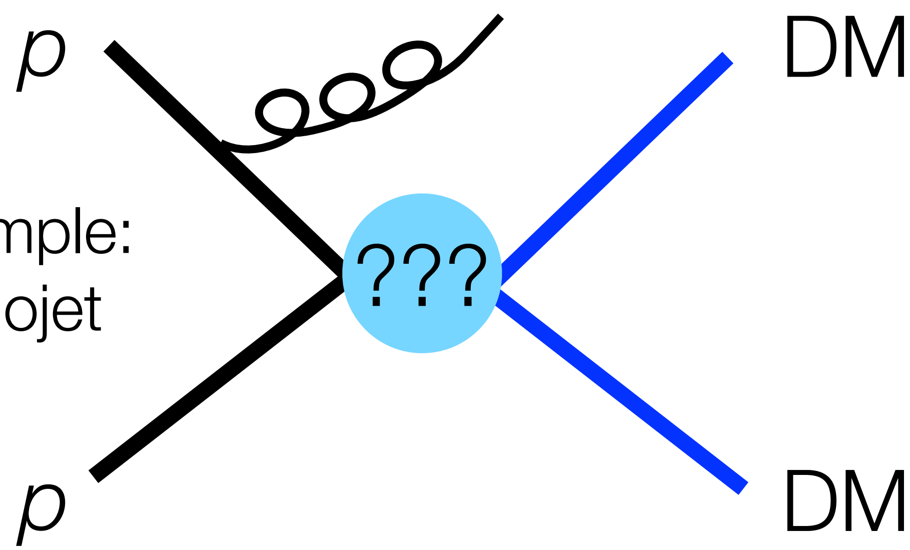

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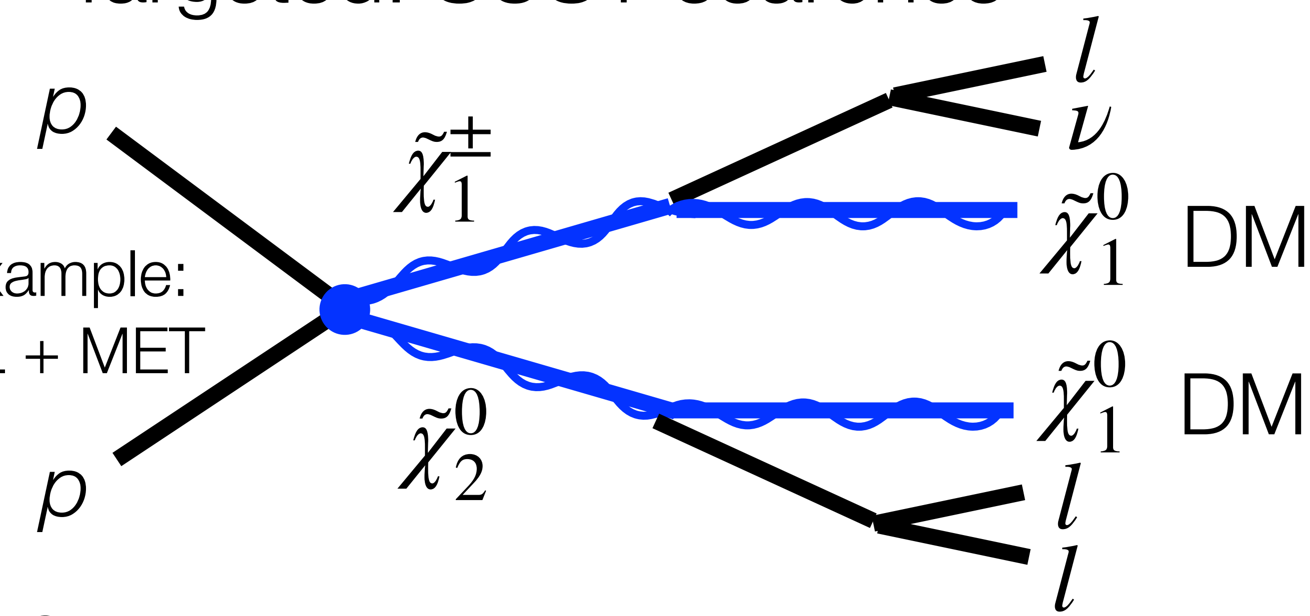

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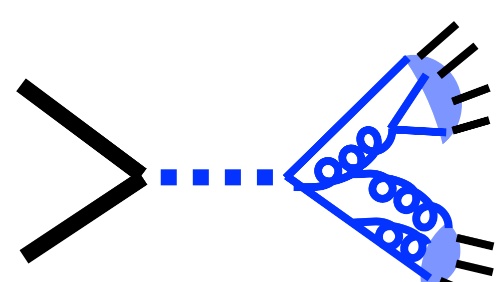

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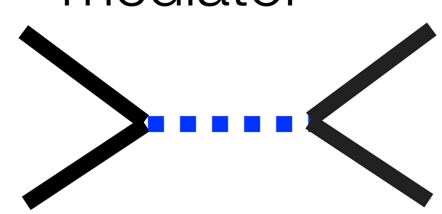
SM decay of mediator



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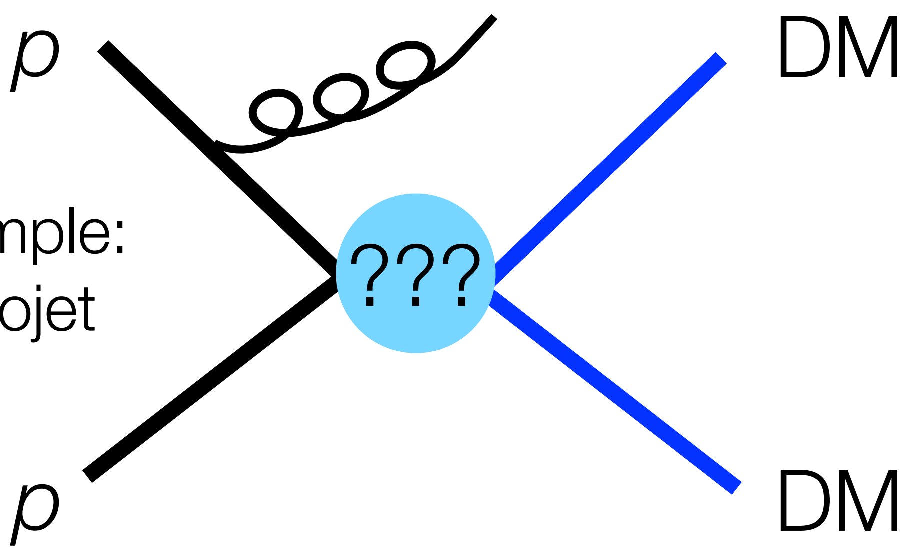

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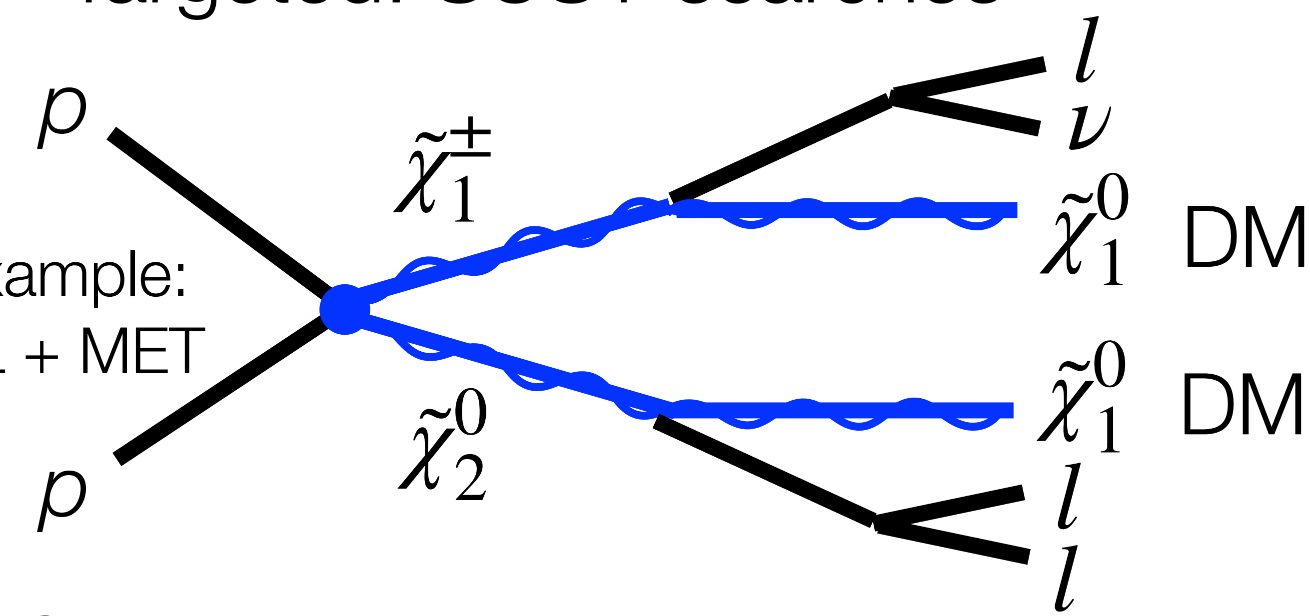

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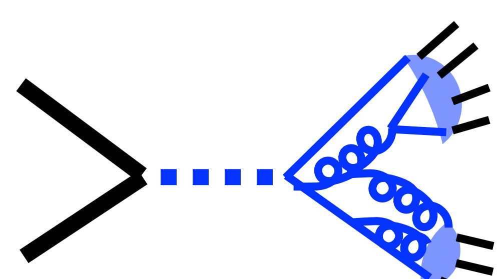

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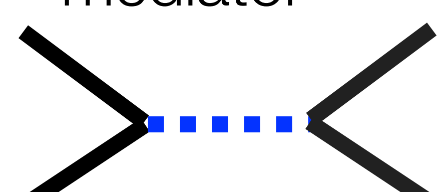

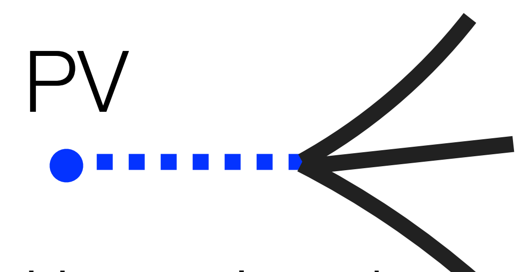

Unusual tracks or displaced energy deposits

Current status of LHC spin-1 simplified models

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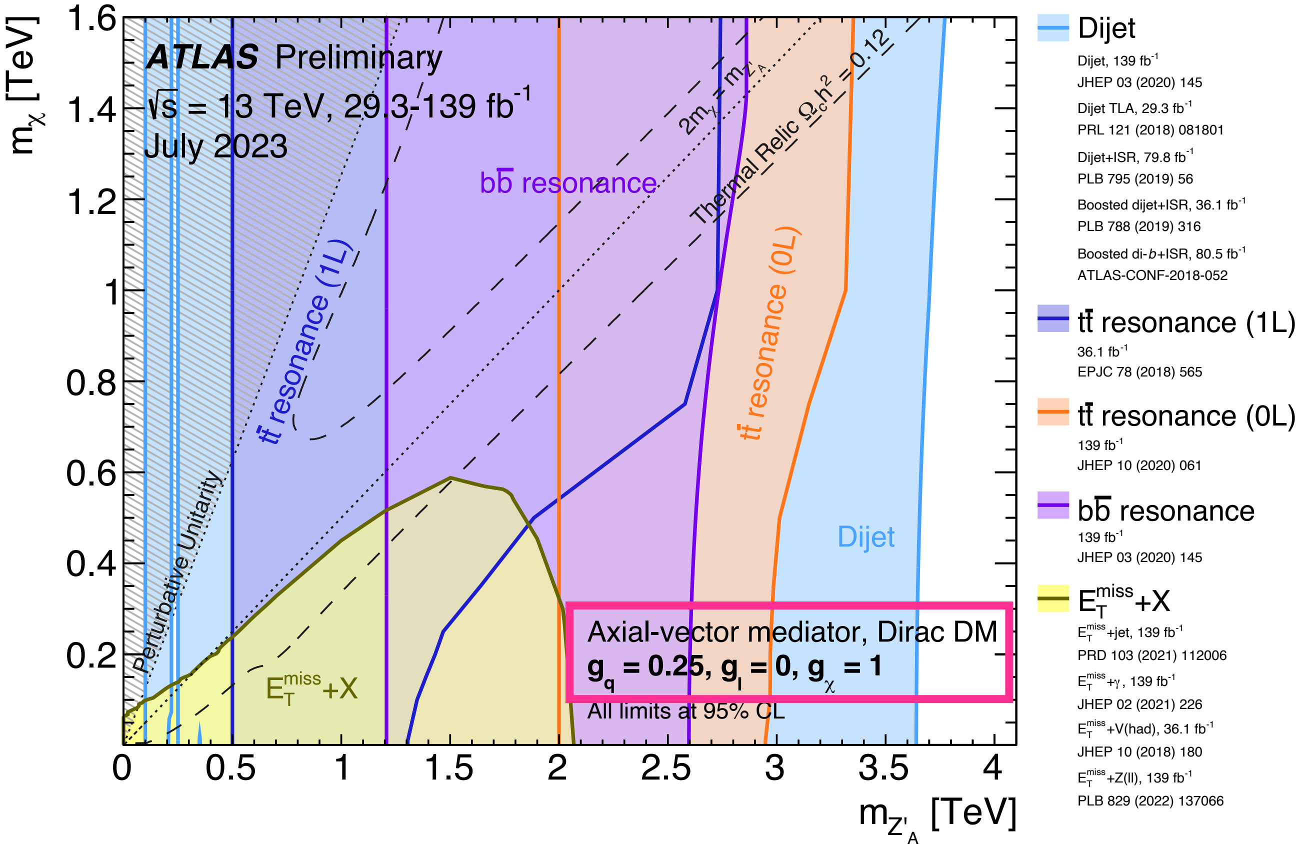

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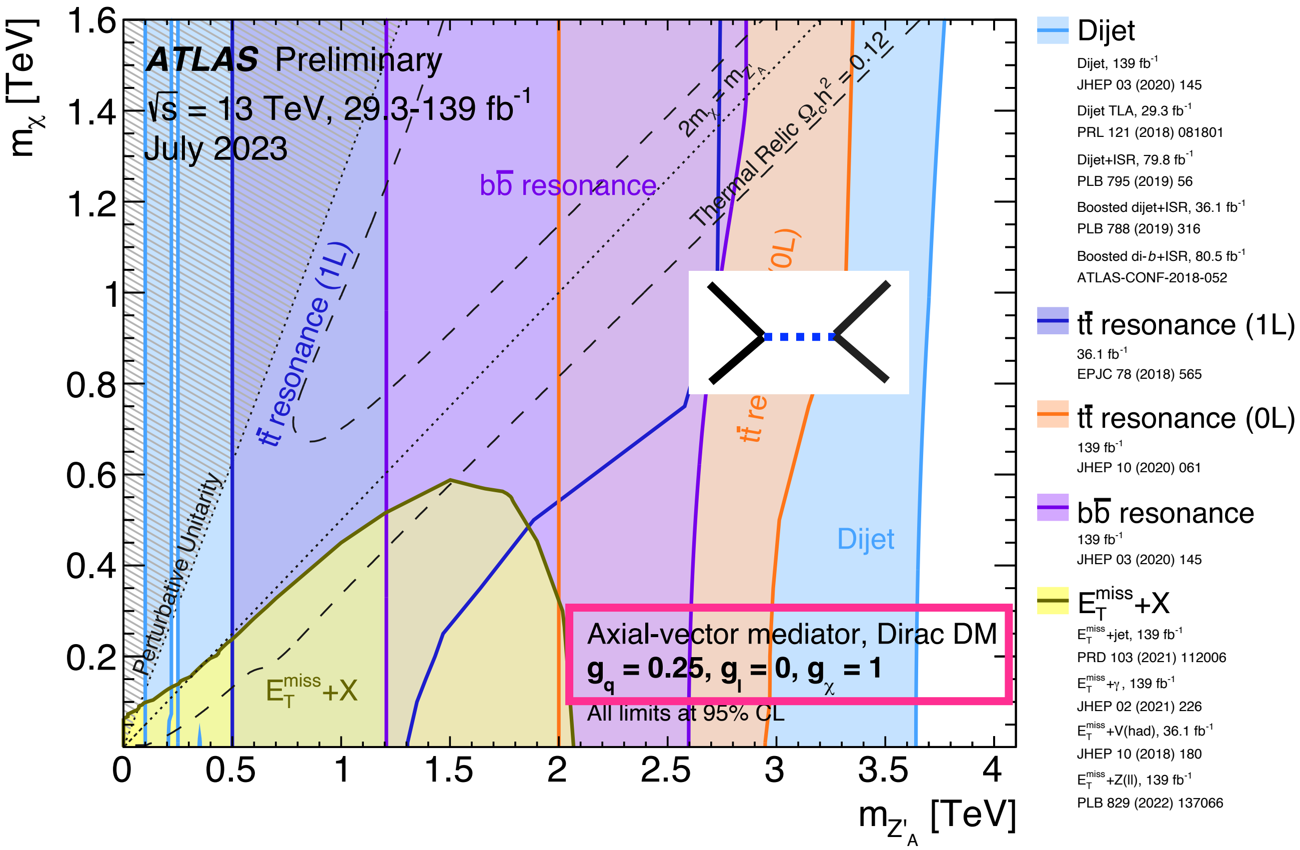

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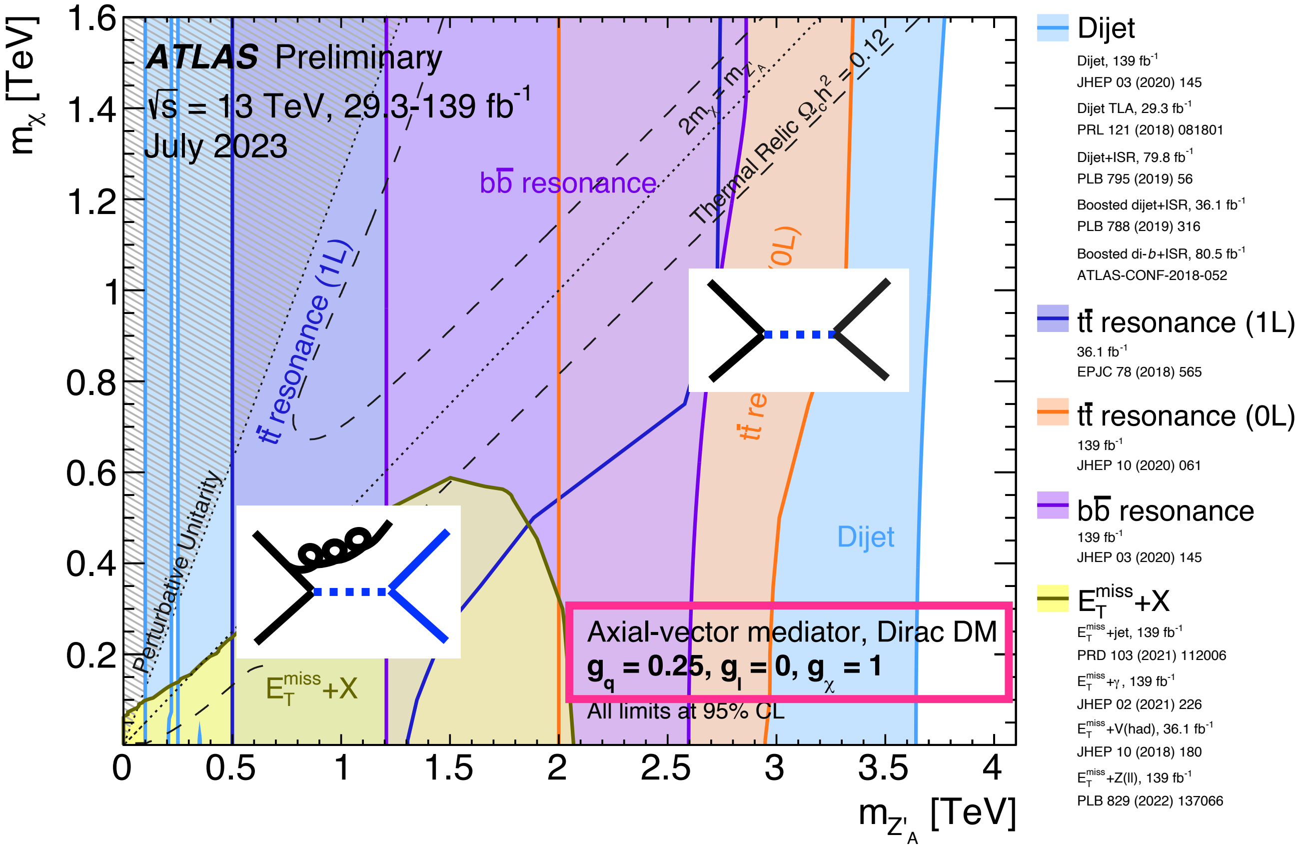

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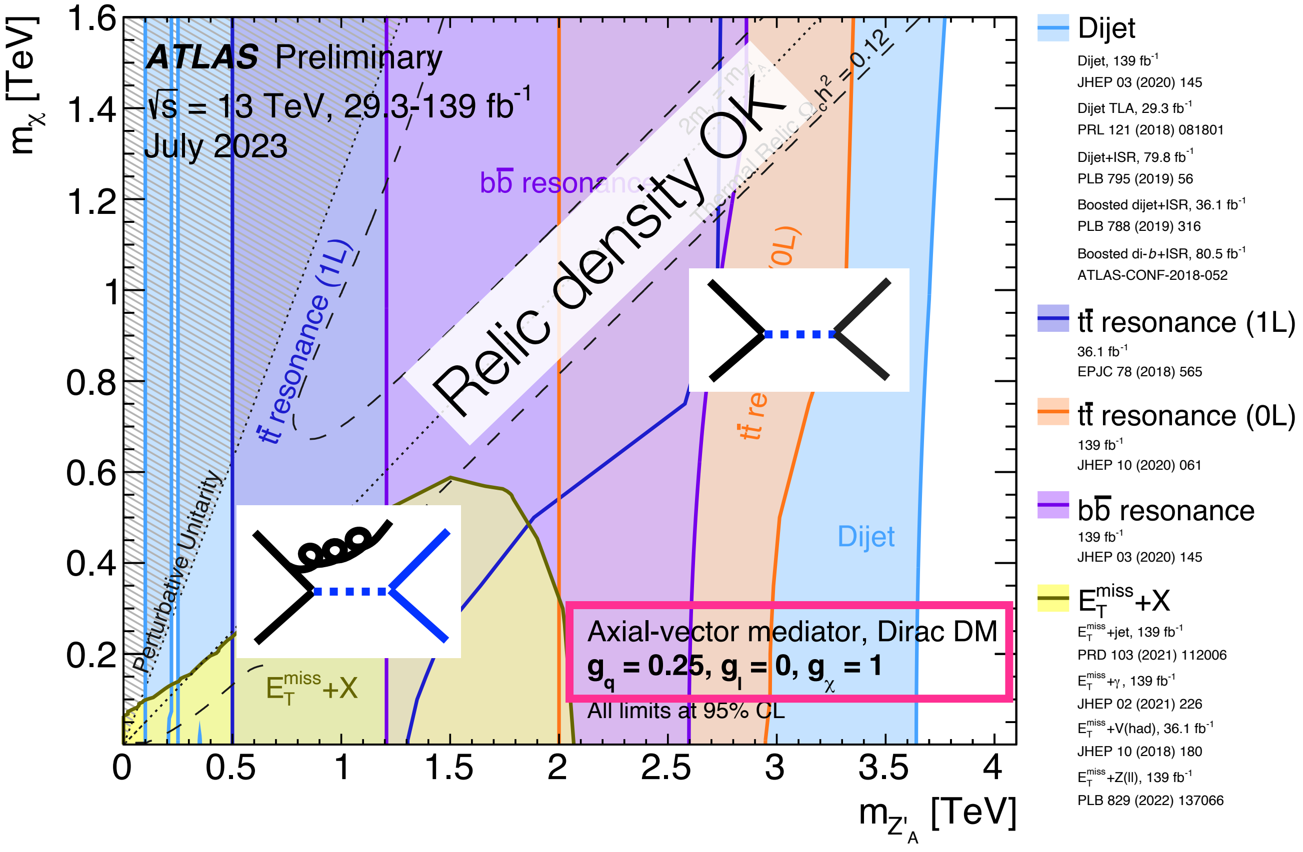

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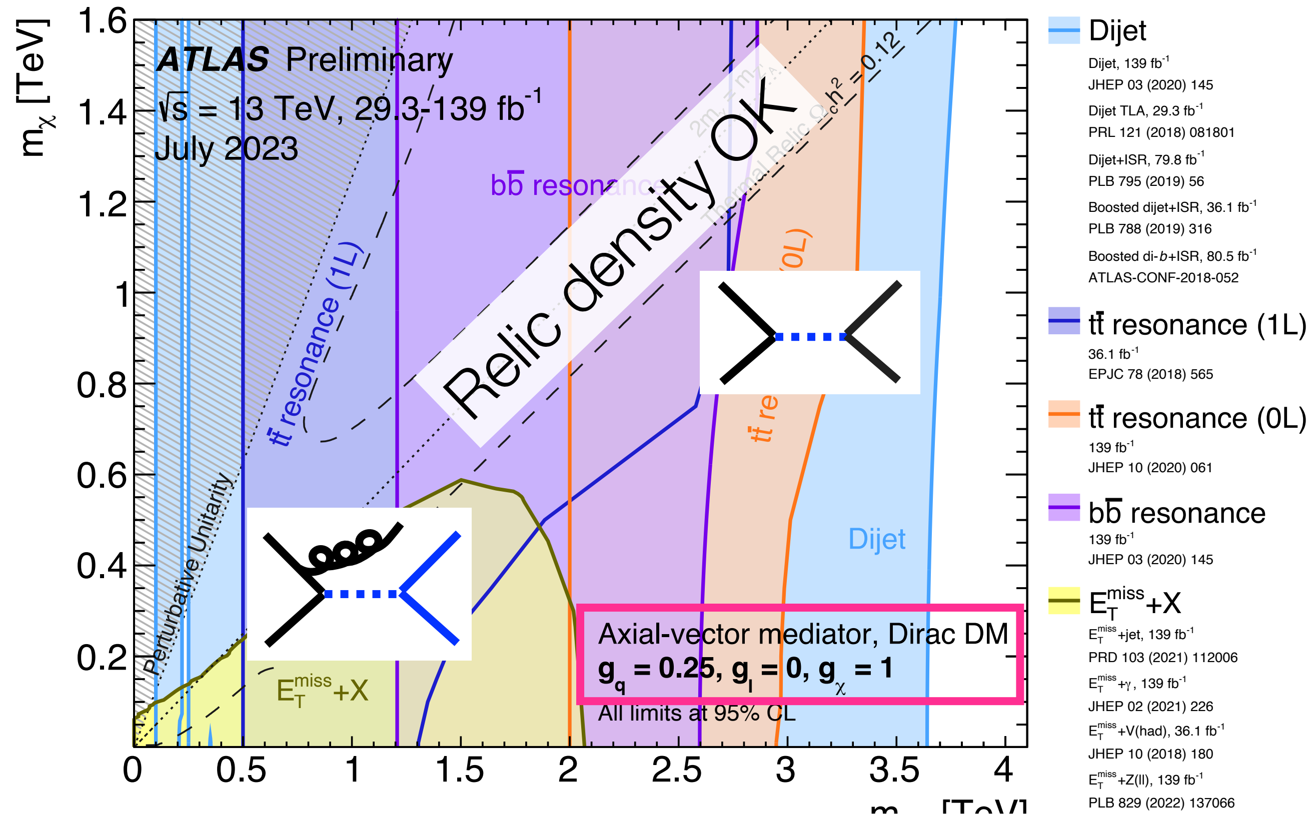

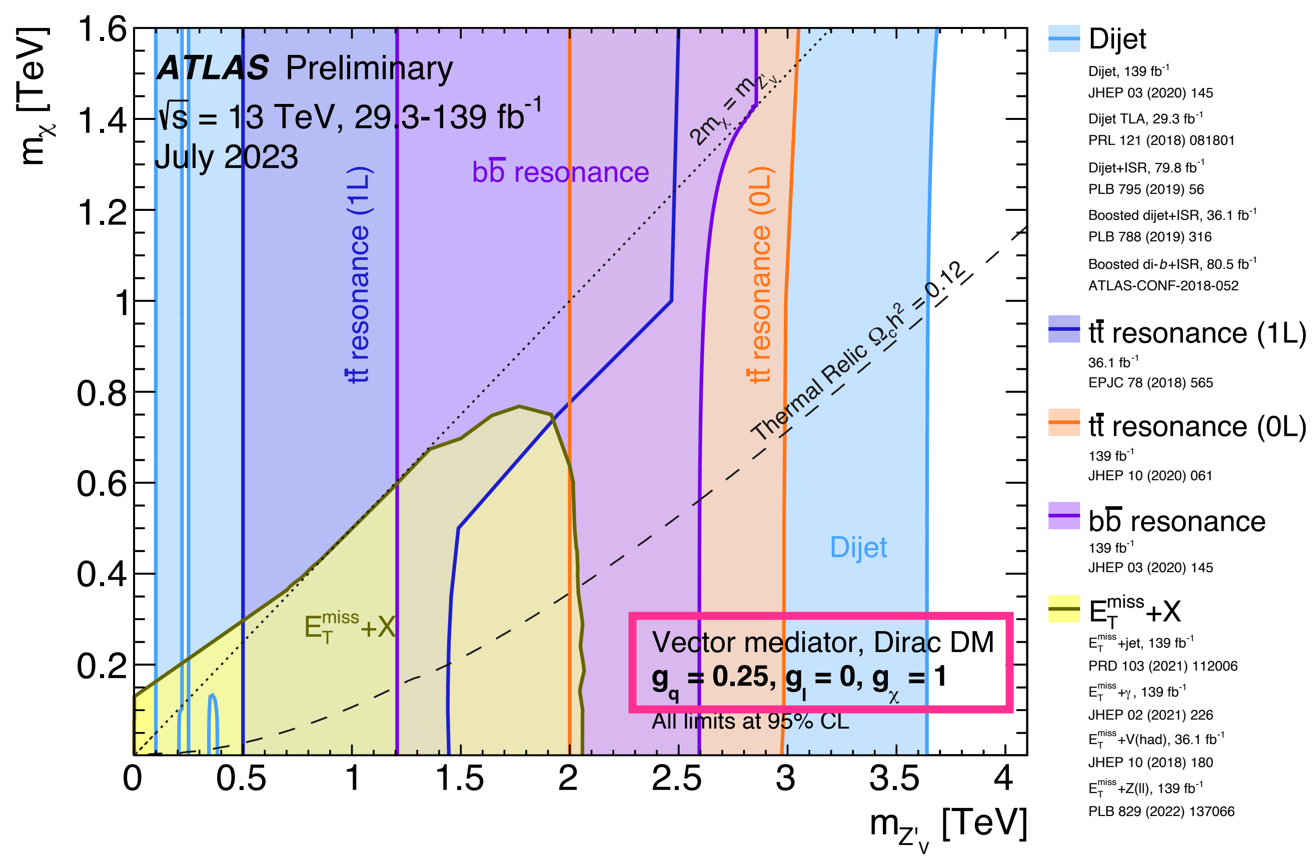

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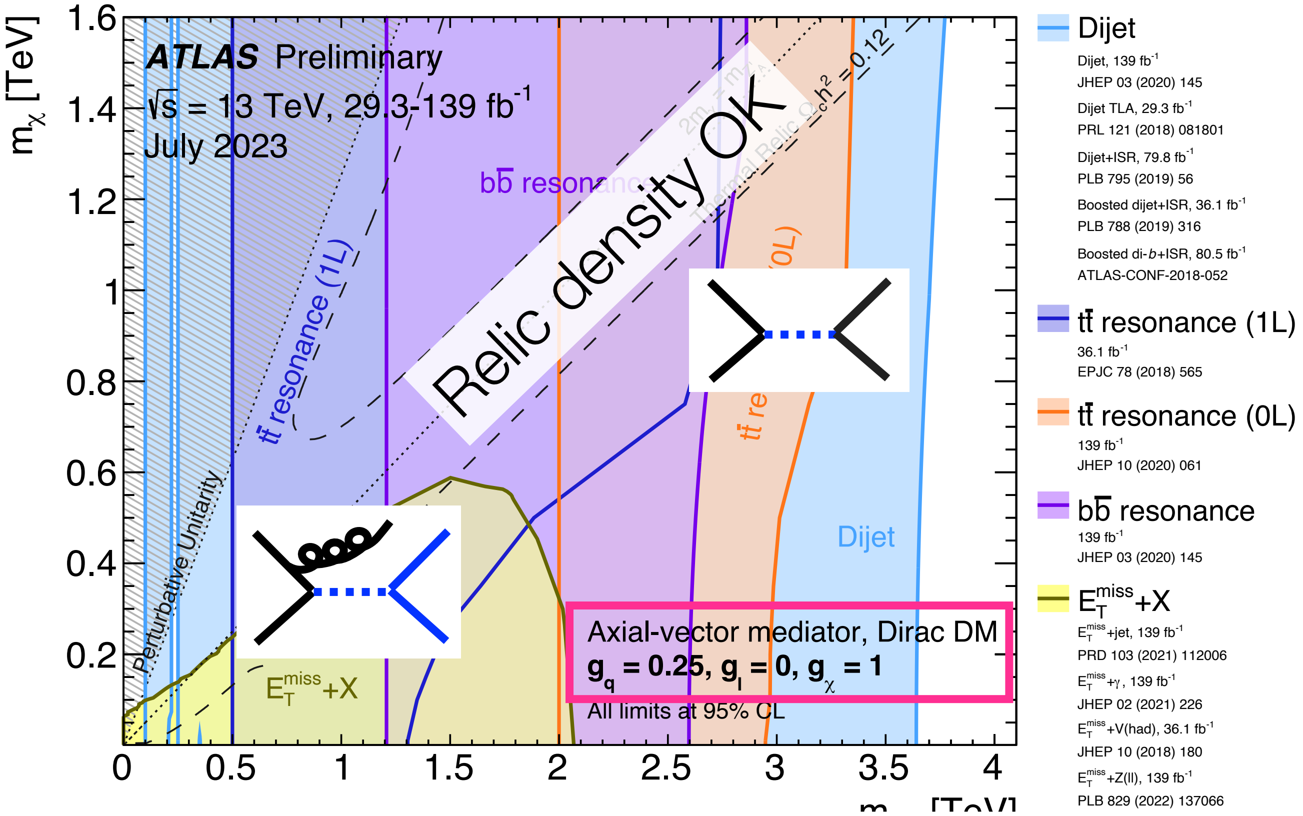

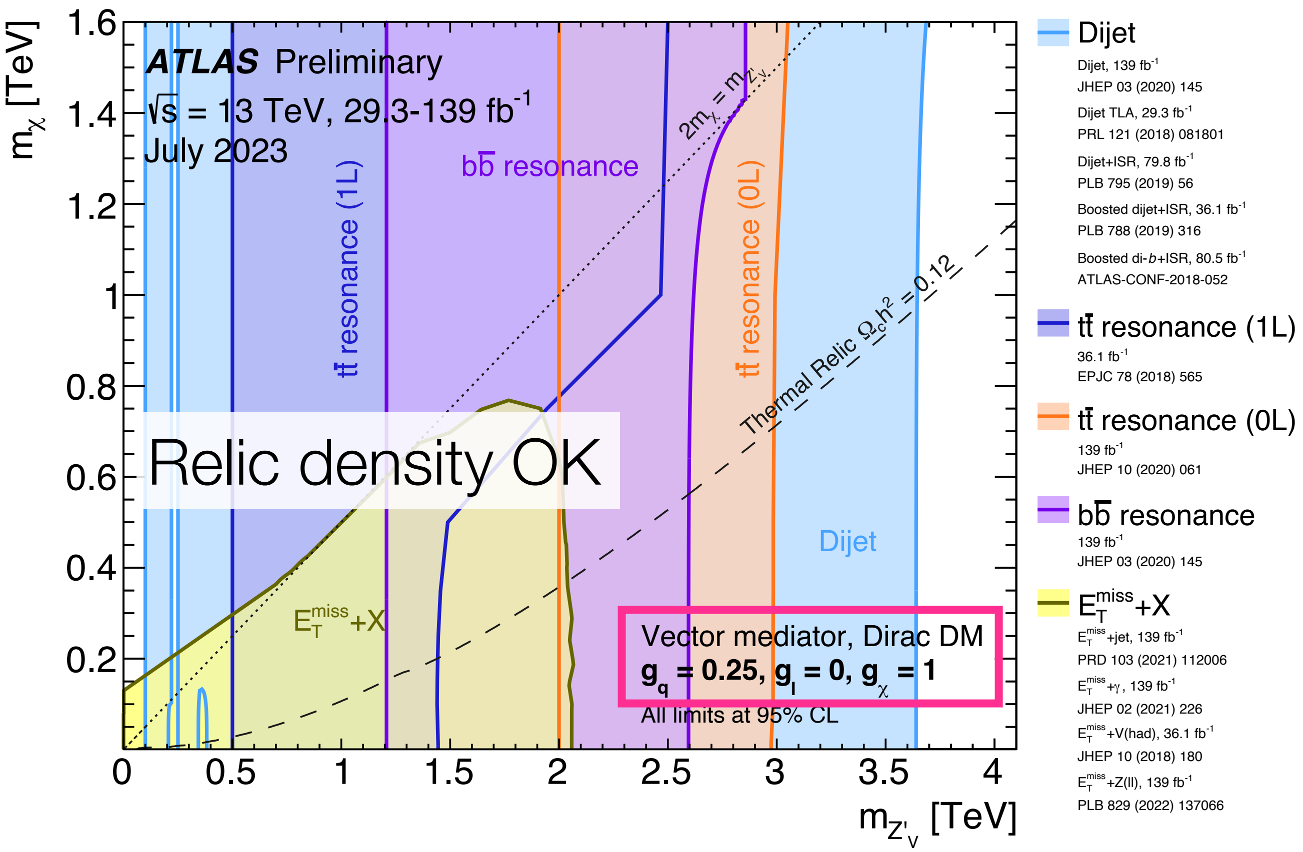

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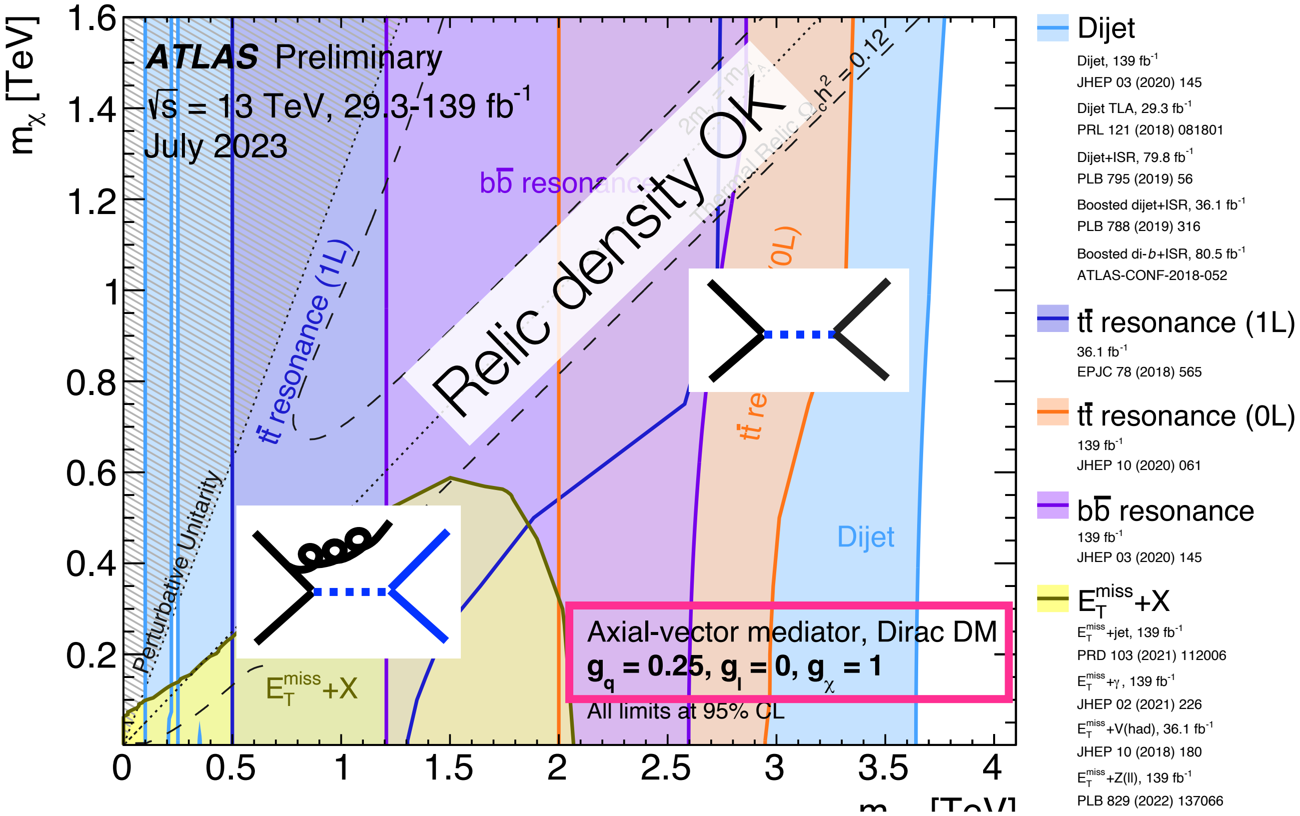

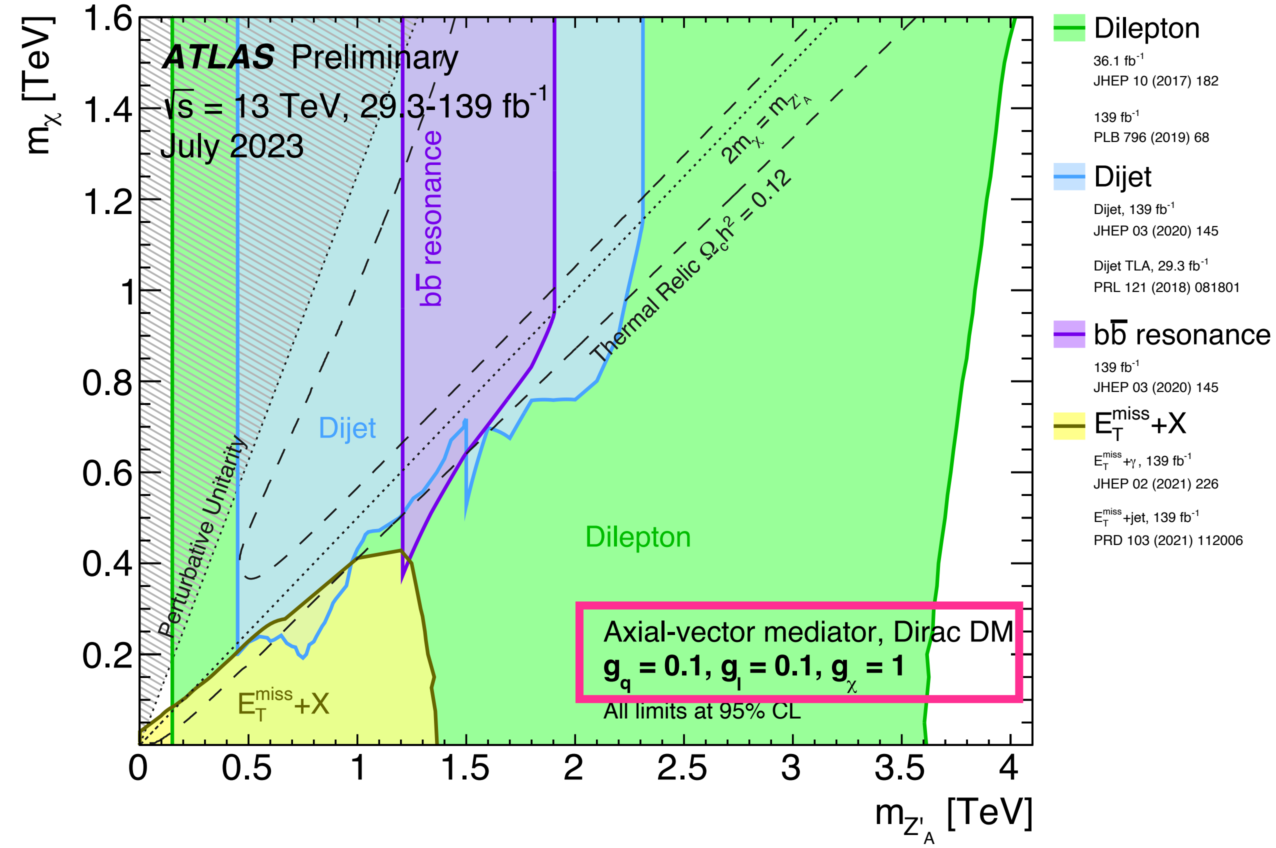

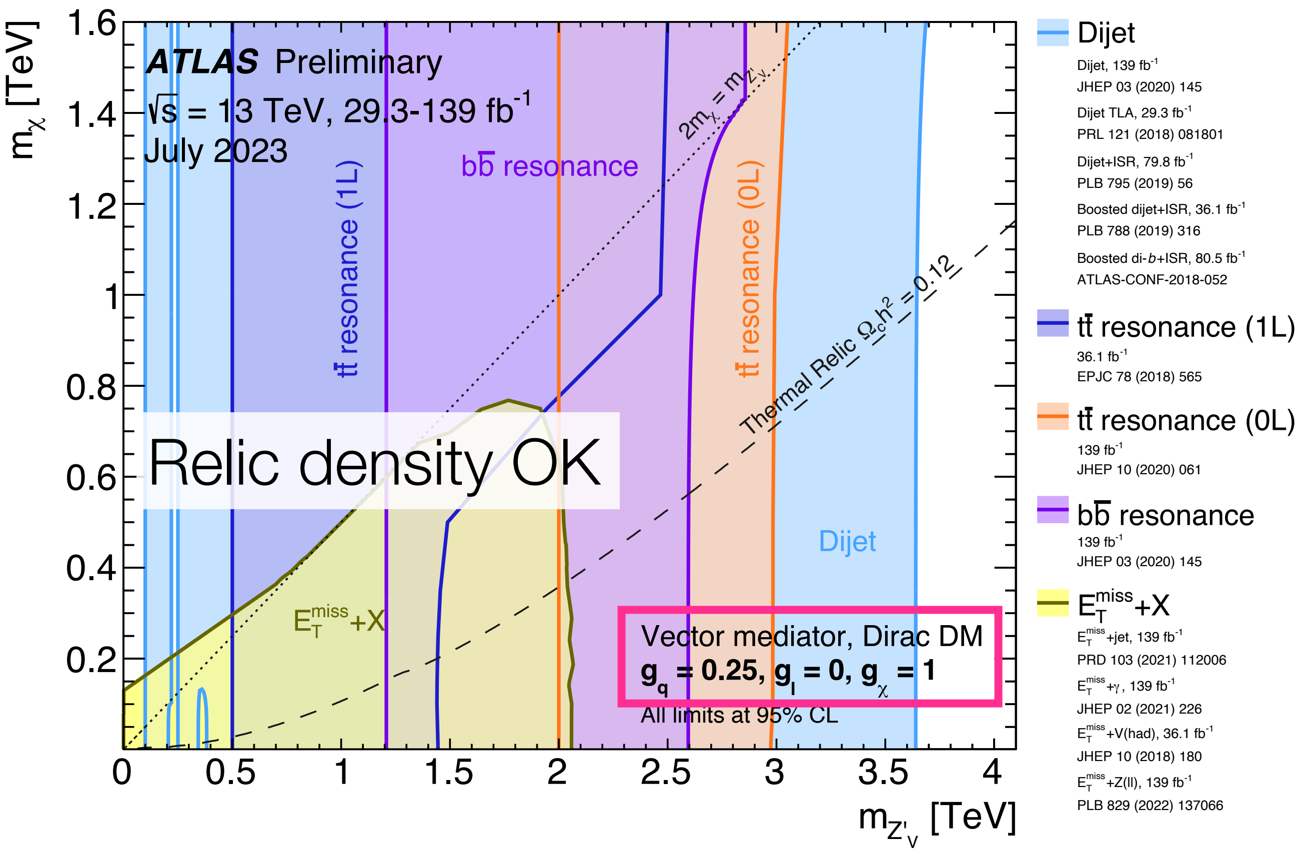

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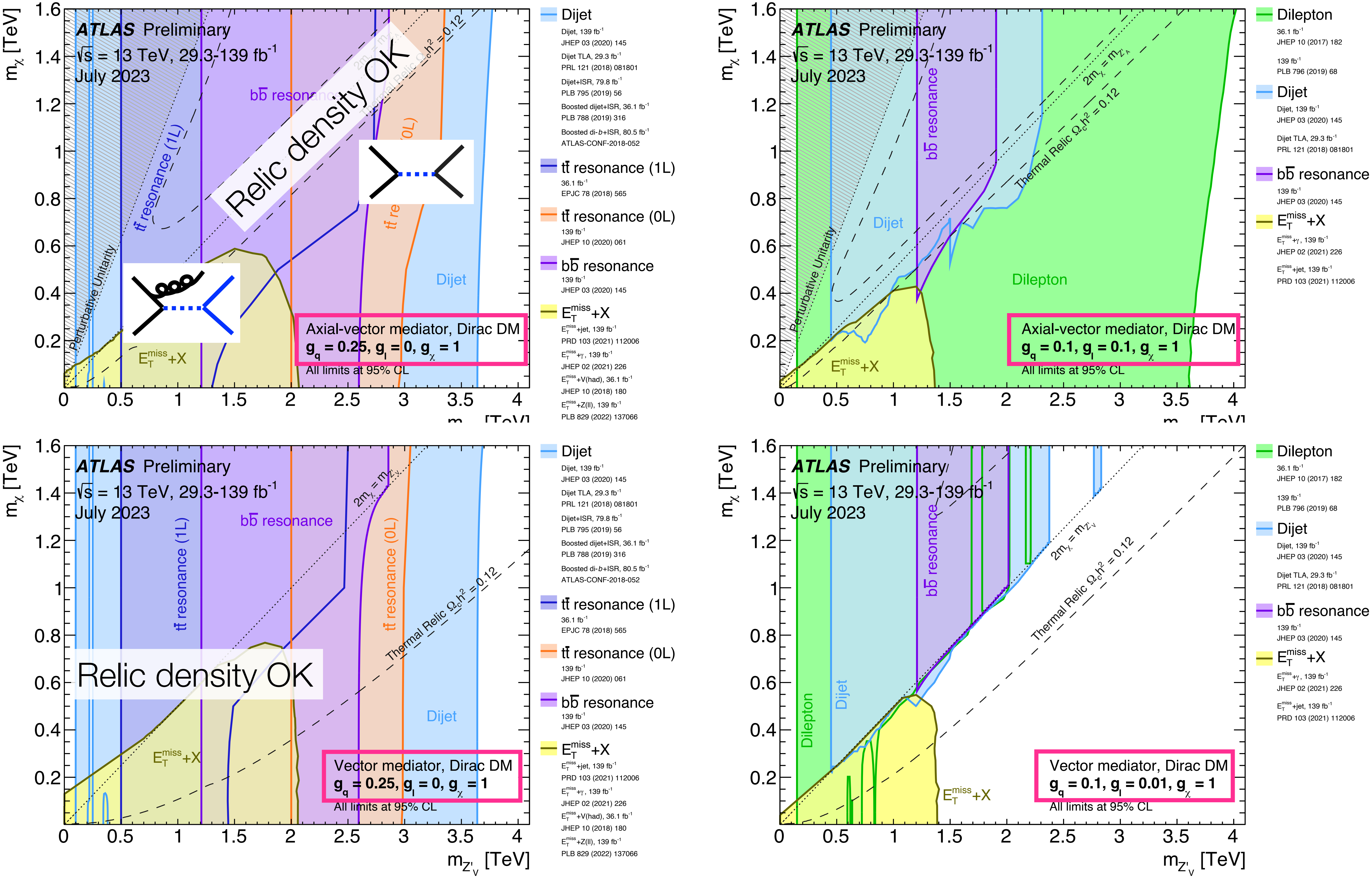
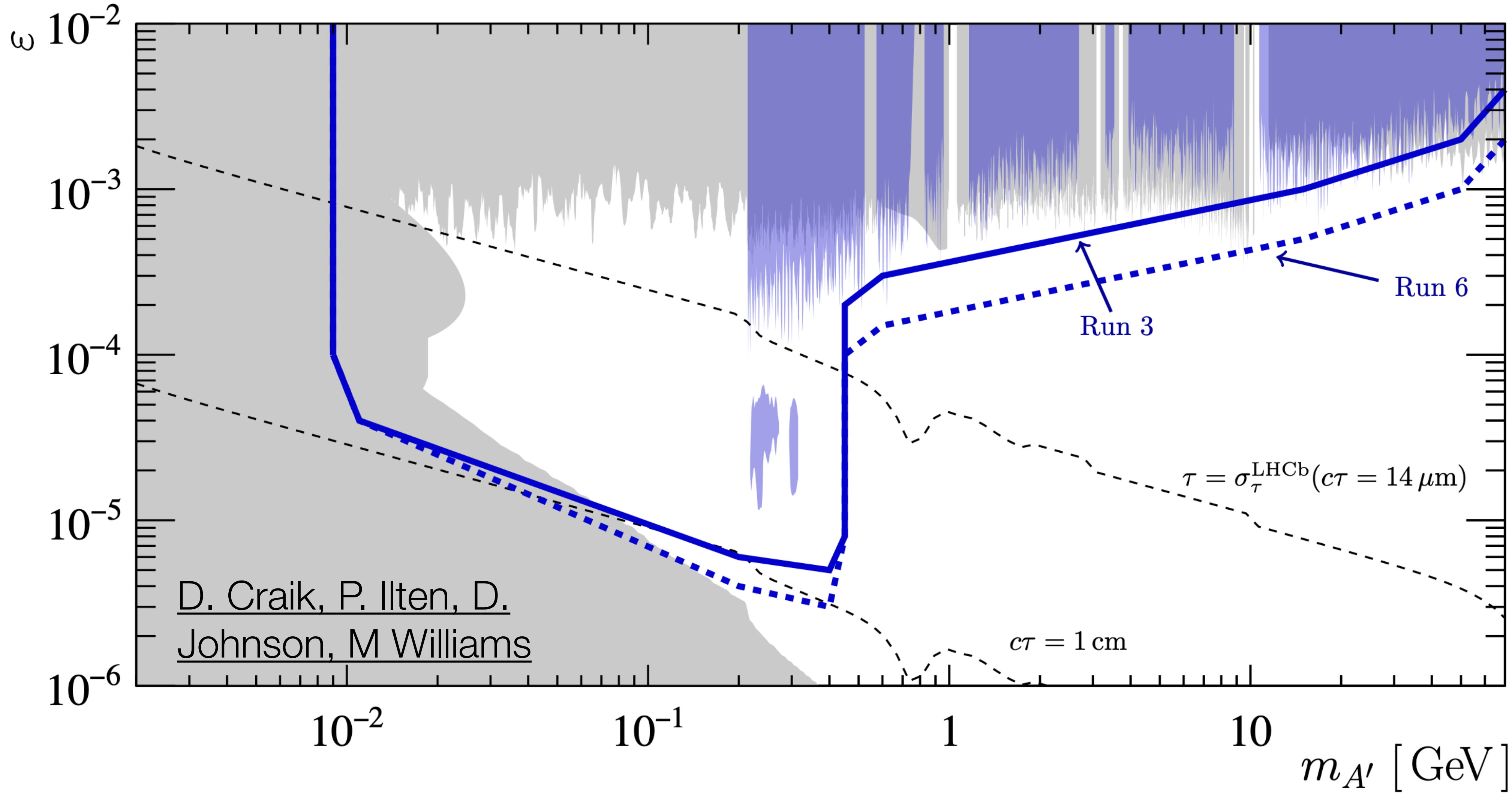


Dark photons at the LHC

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

LHCb is a powerhouse with Run 3 triggerless readout



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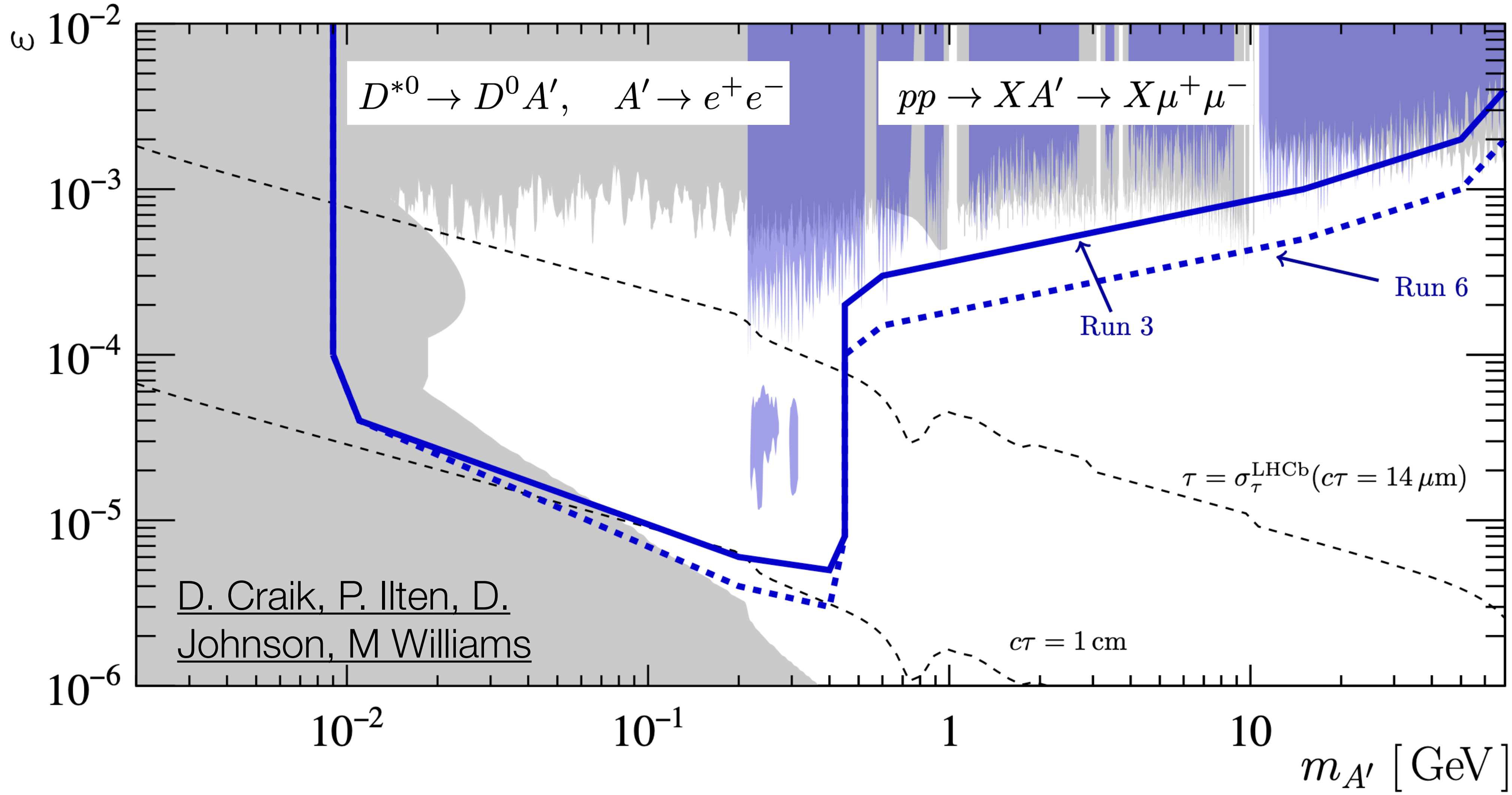

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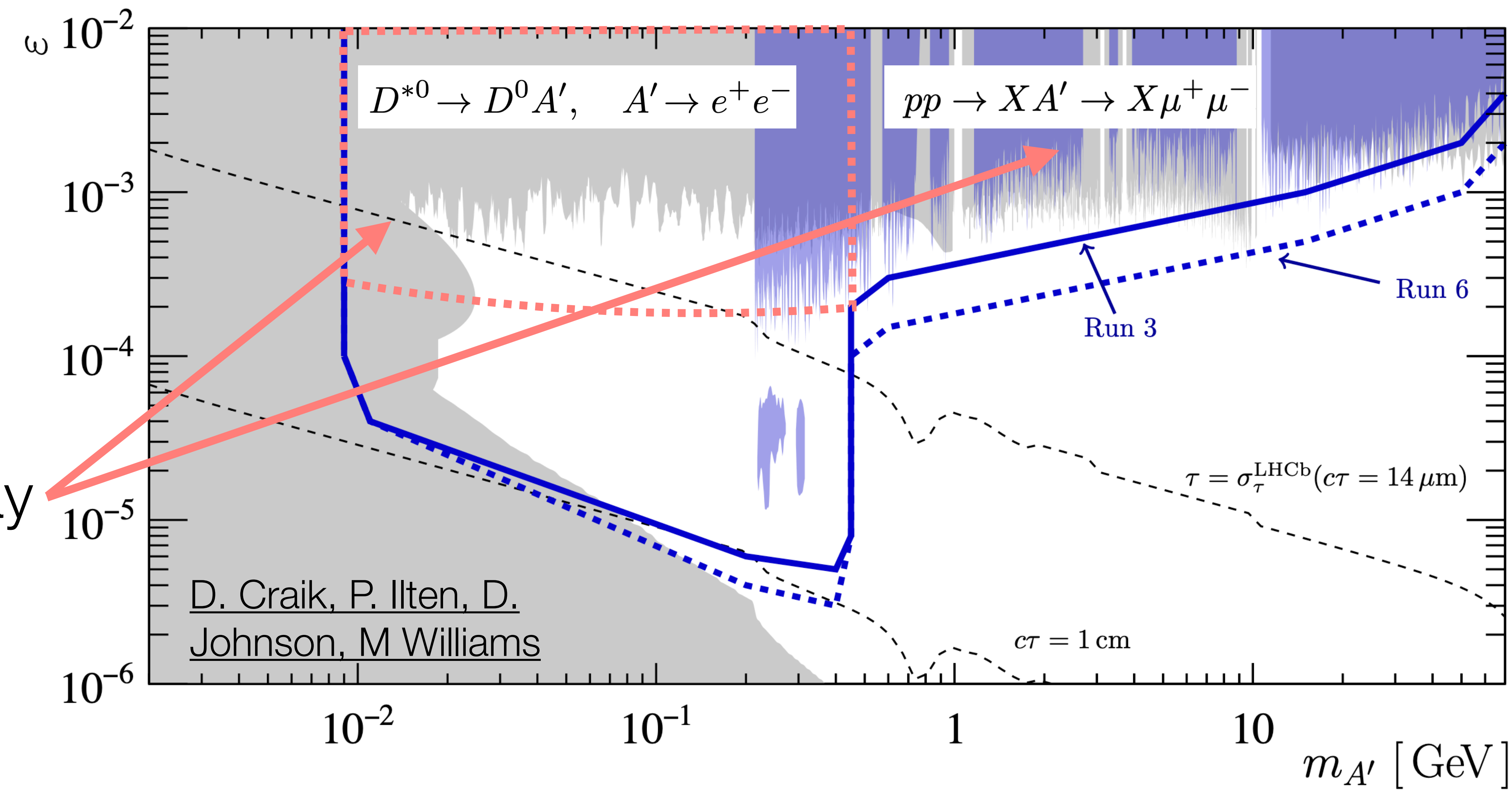

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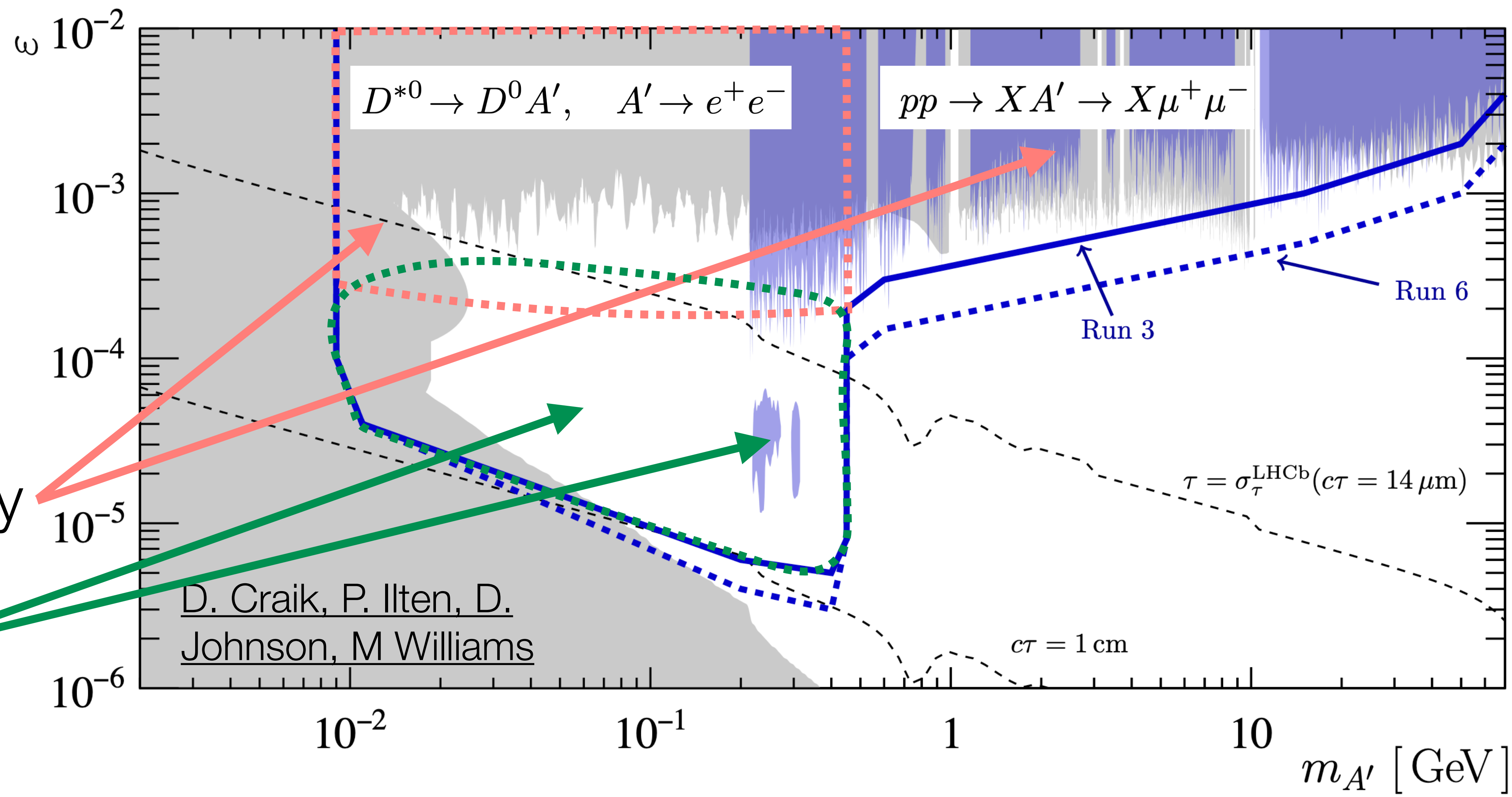

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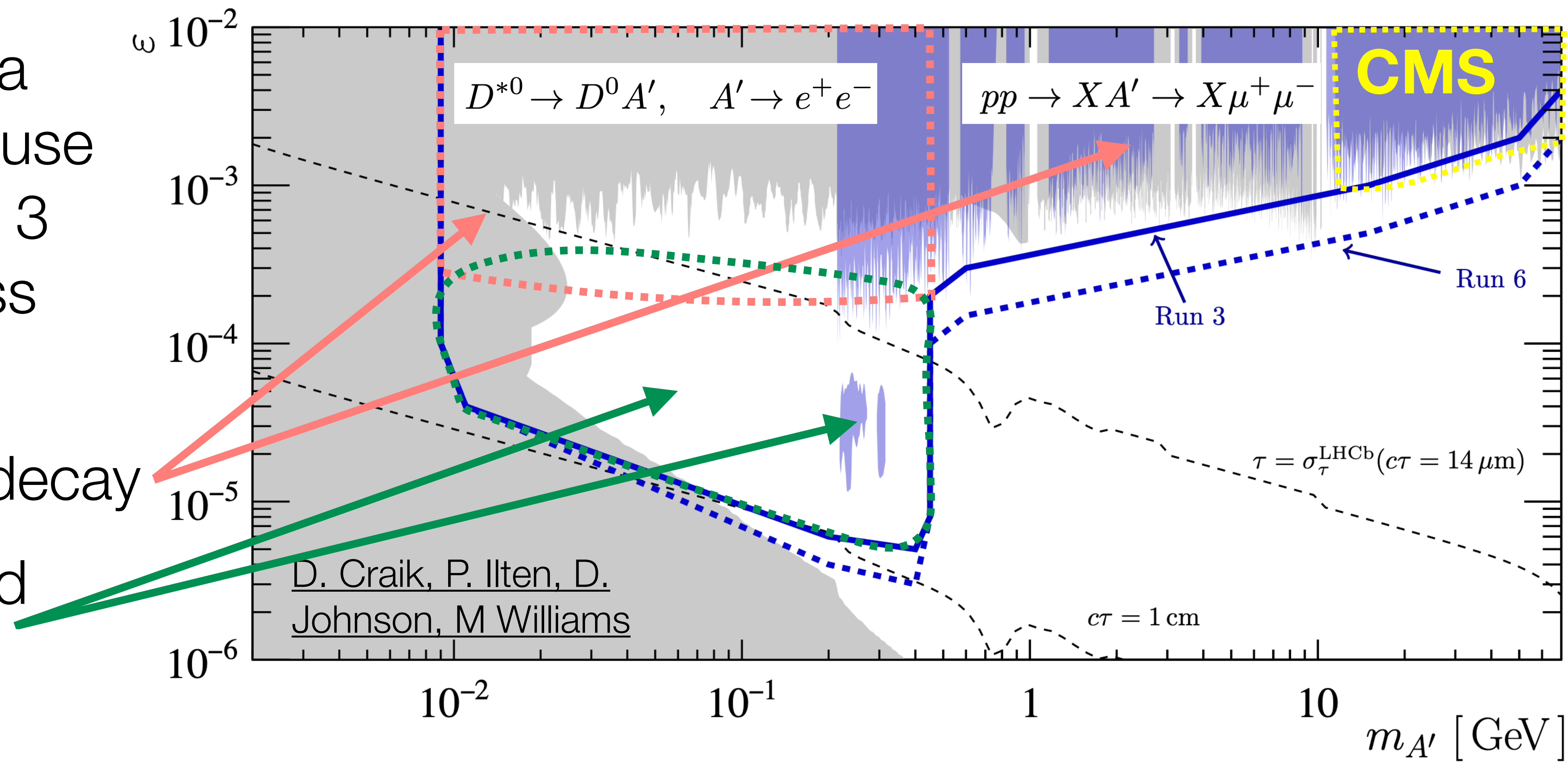
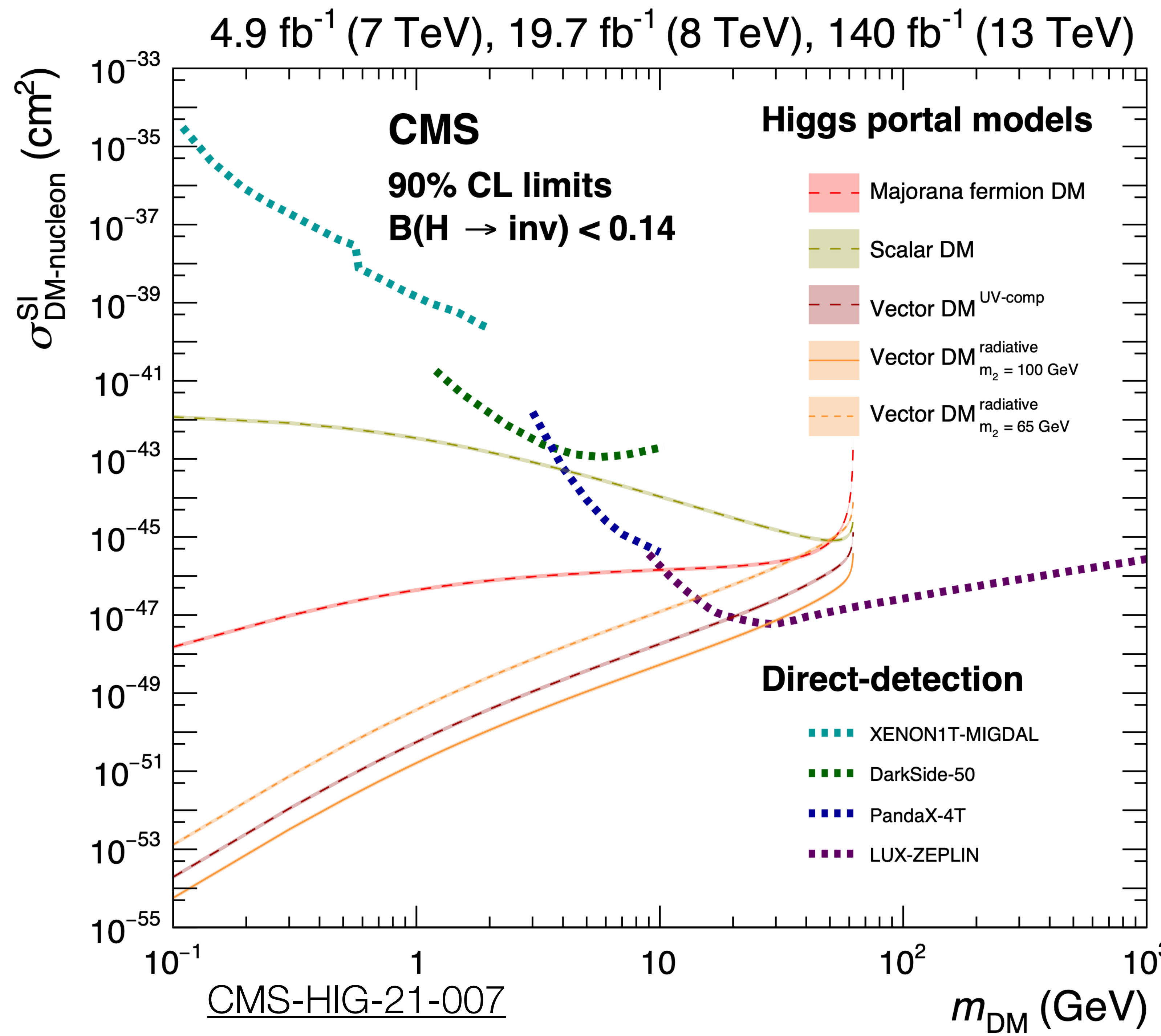


ATLAS & CMS can contribute at higher masses. Trigger poses a challenge. Simplified spin-1 limits translate fairly directly, but this is not currently a standard interpretation.

Higgs decays to dark matter

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



CMS-HIG-21-007

Model motivation from Arcadi, Djouadi, and Kado

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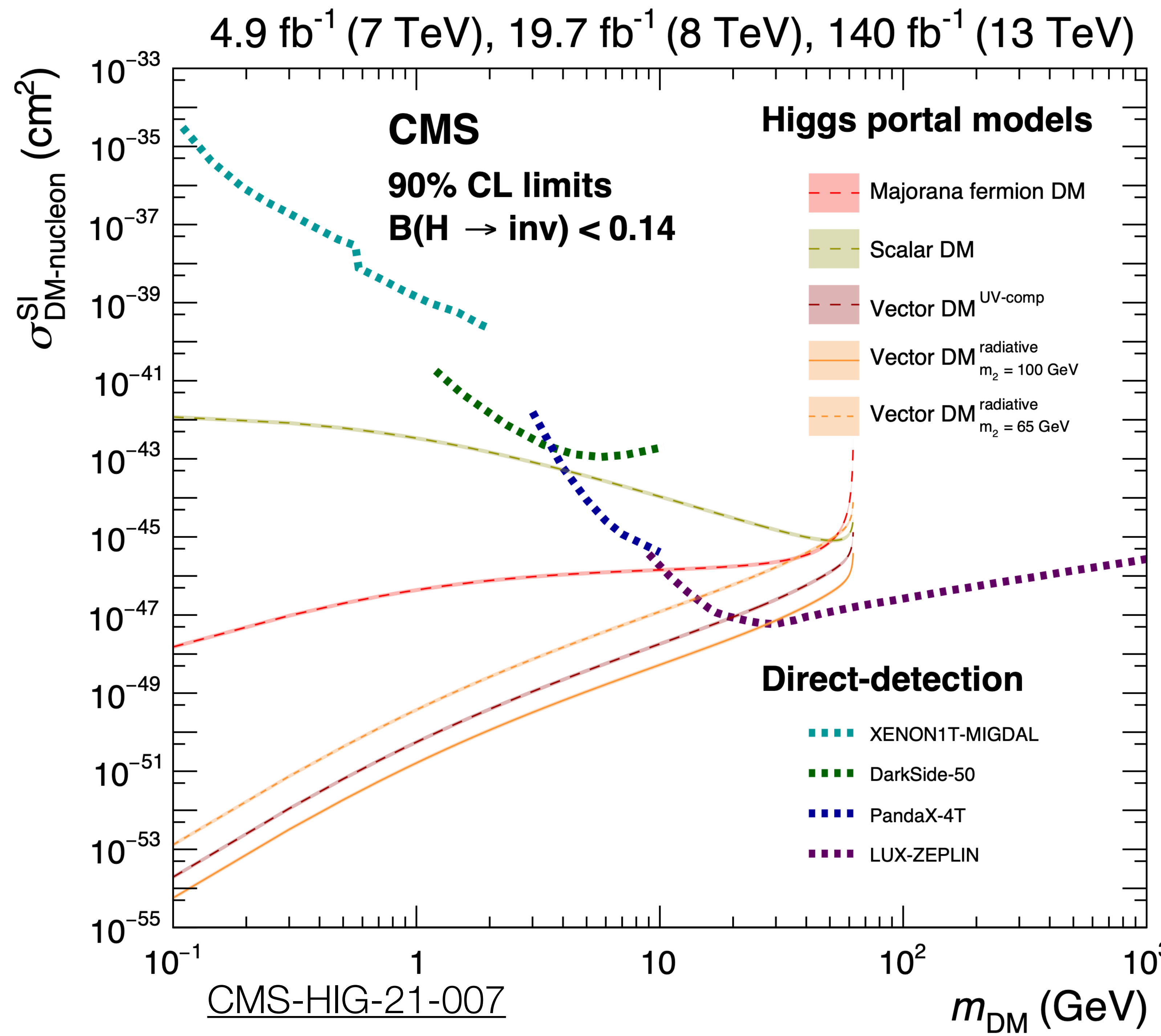

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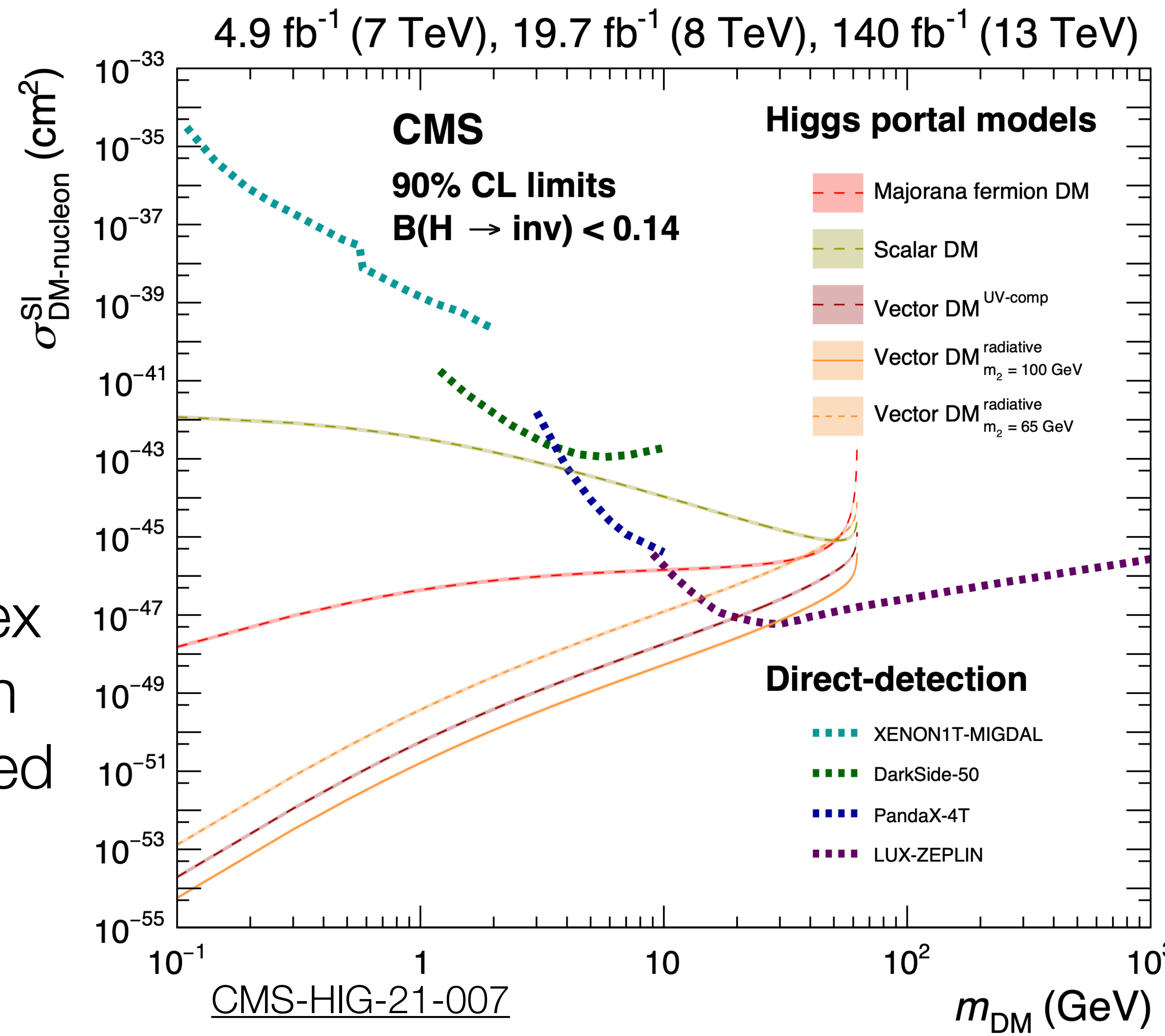

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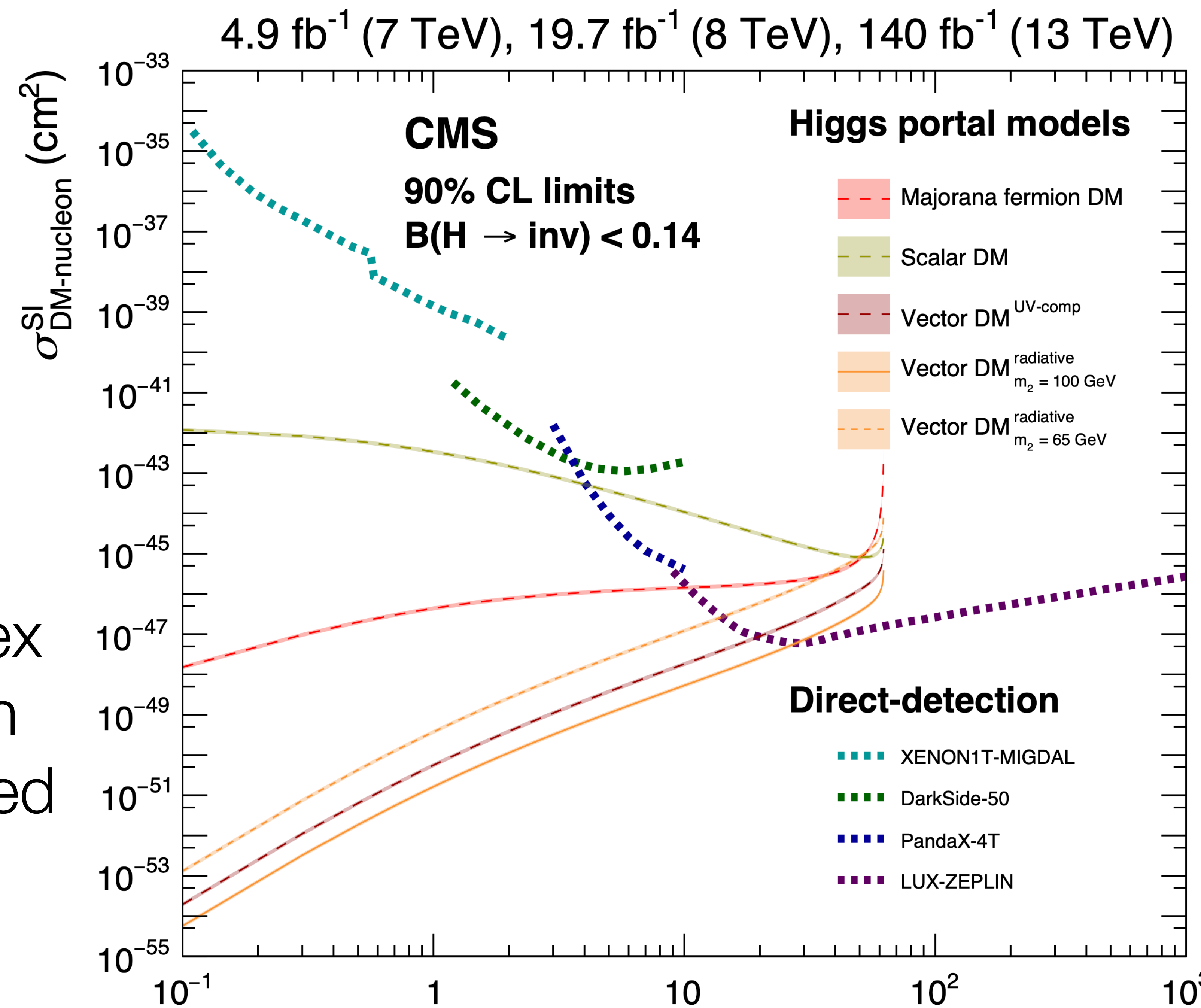
Current upper limits on $BR(h \to \text{inv}) \sim 0.11$ (ATLAS)



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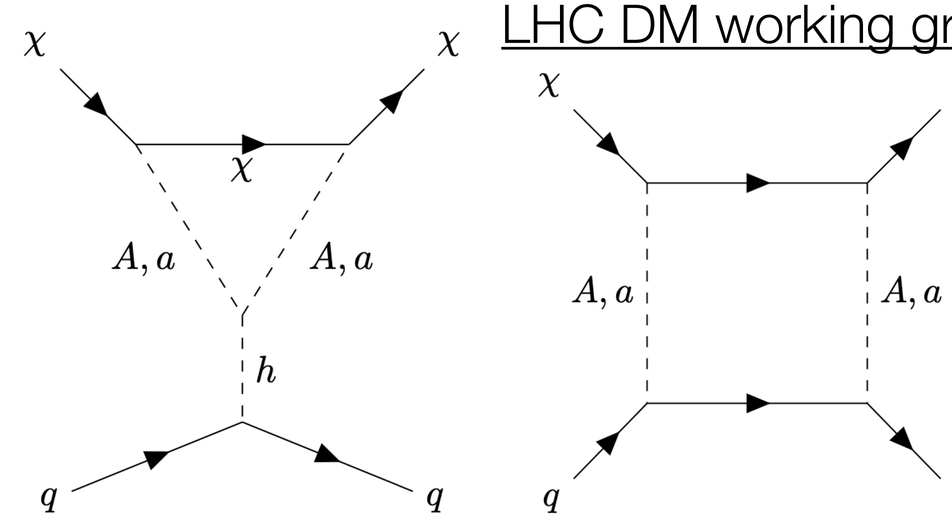
2HDM+a motivation and limits

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

LHC DM working group



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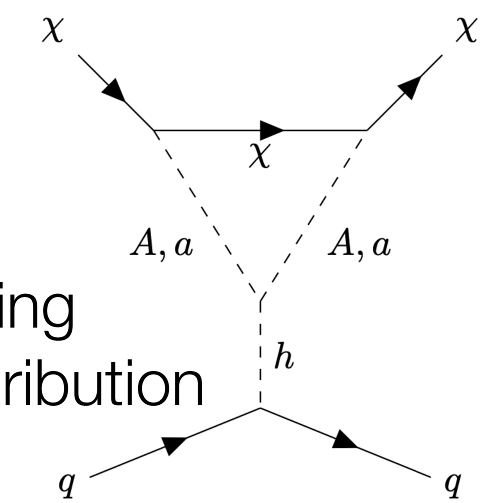

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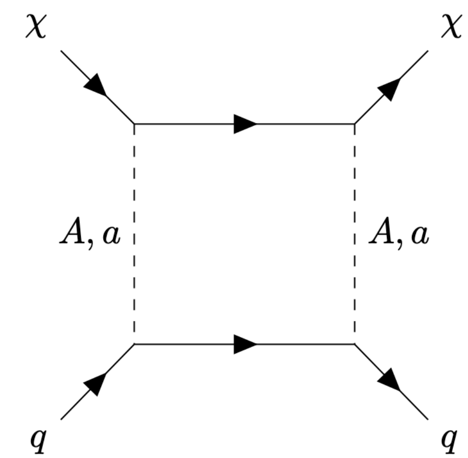

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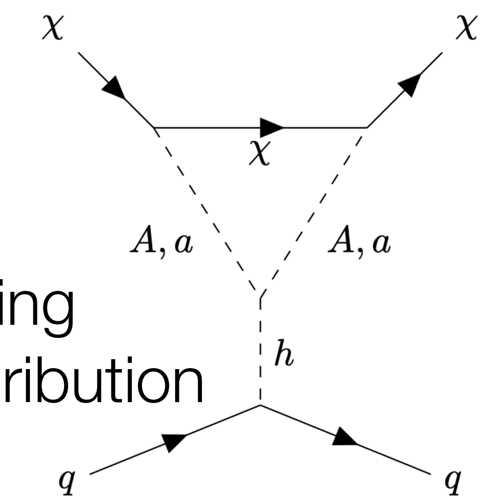

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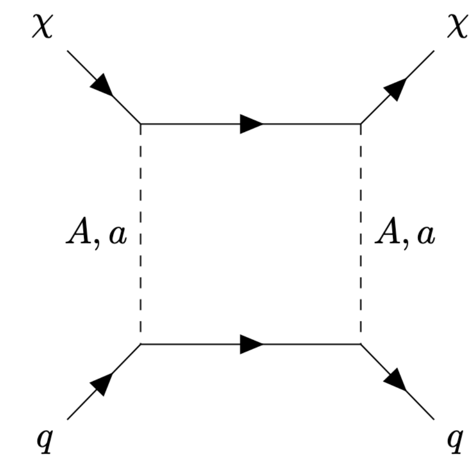

Additional DD box diagrams

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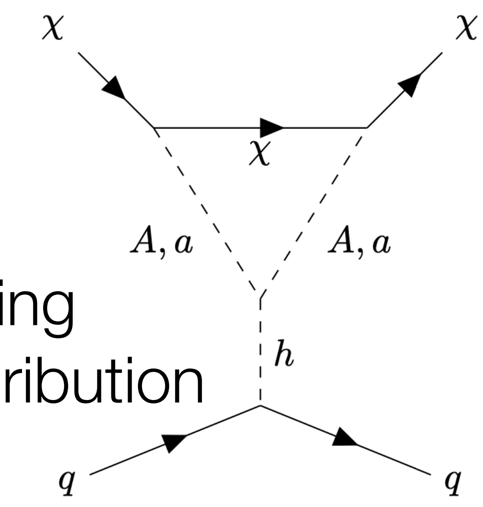

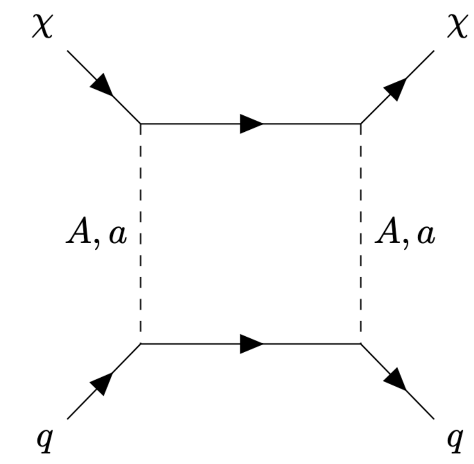

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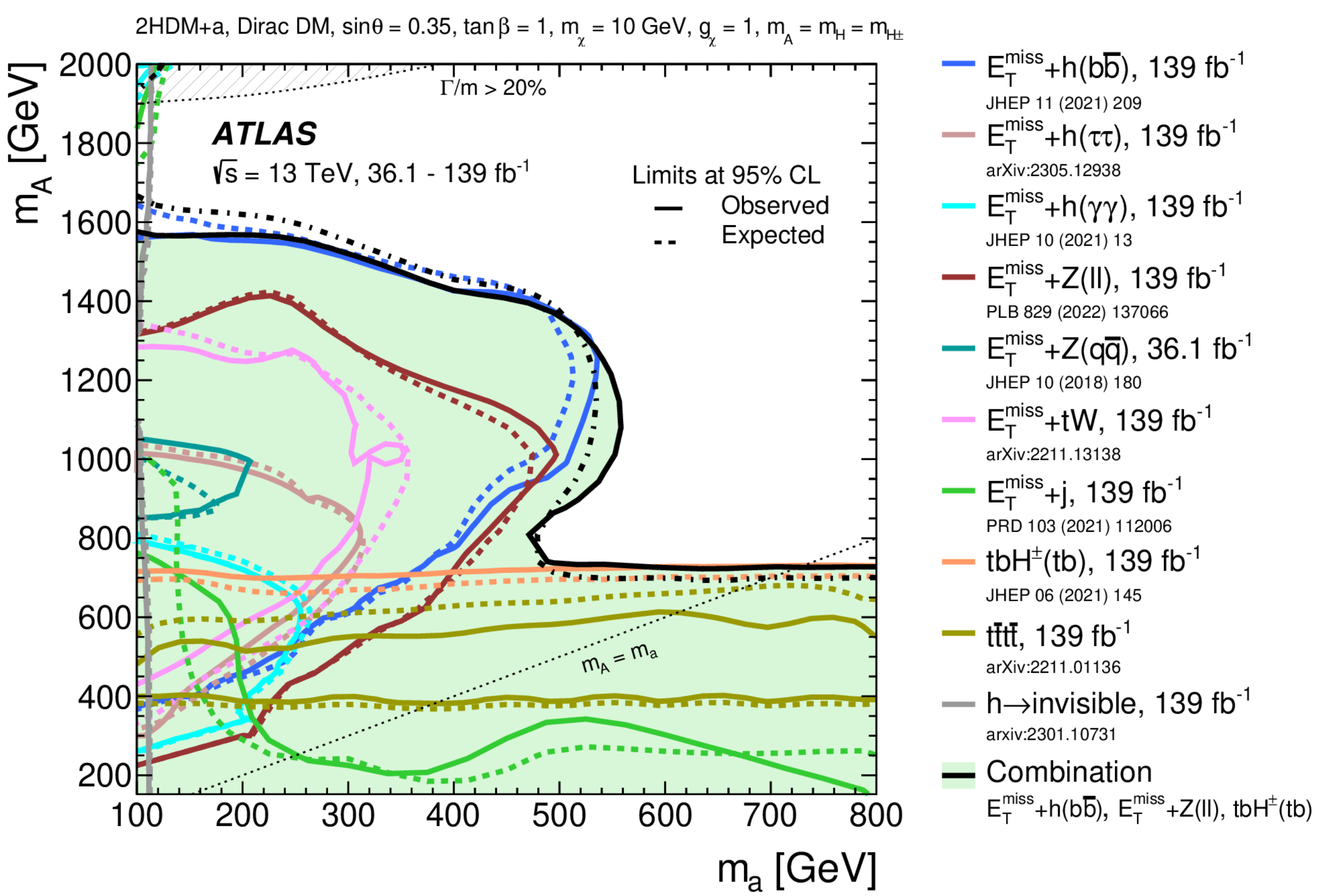

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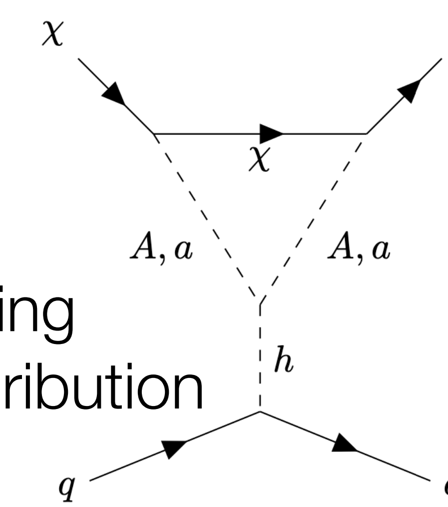

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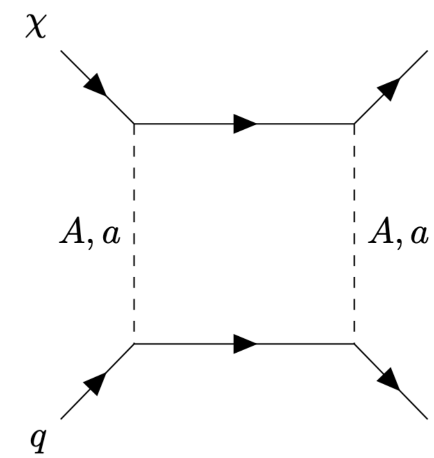

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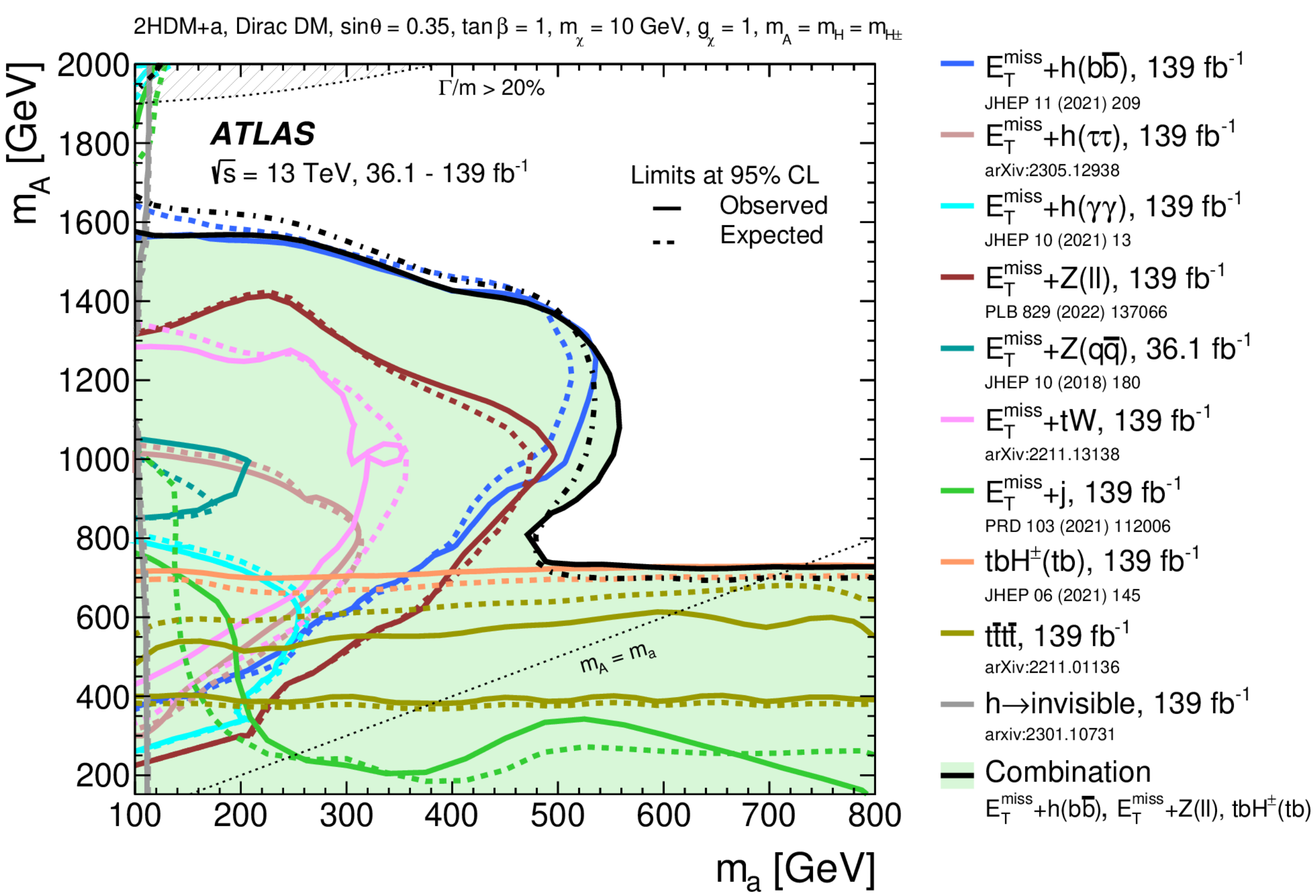

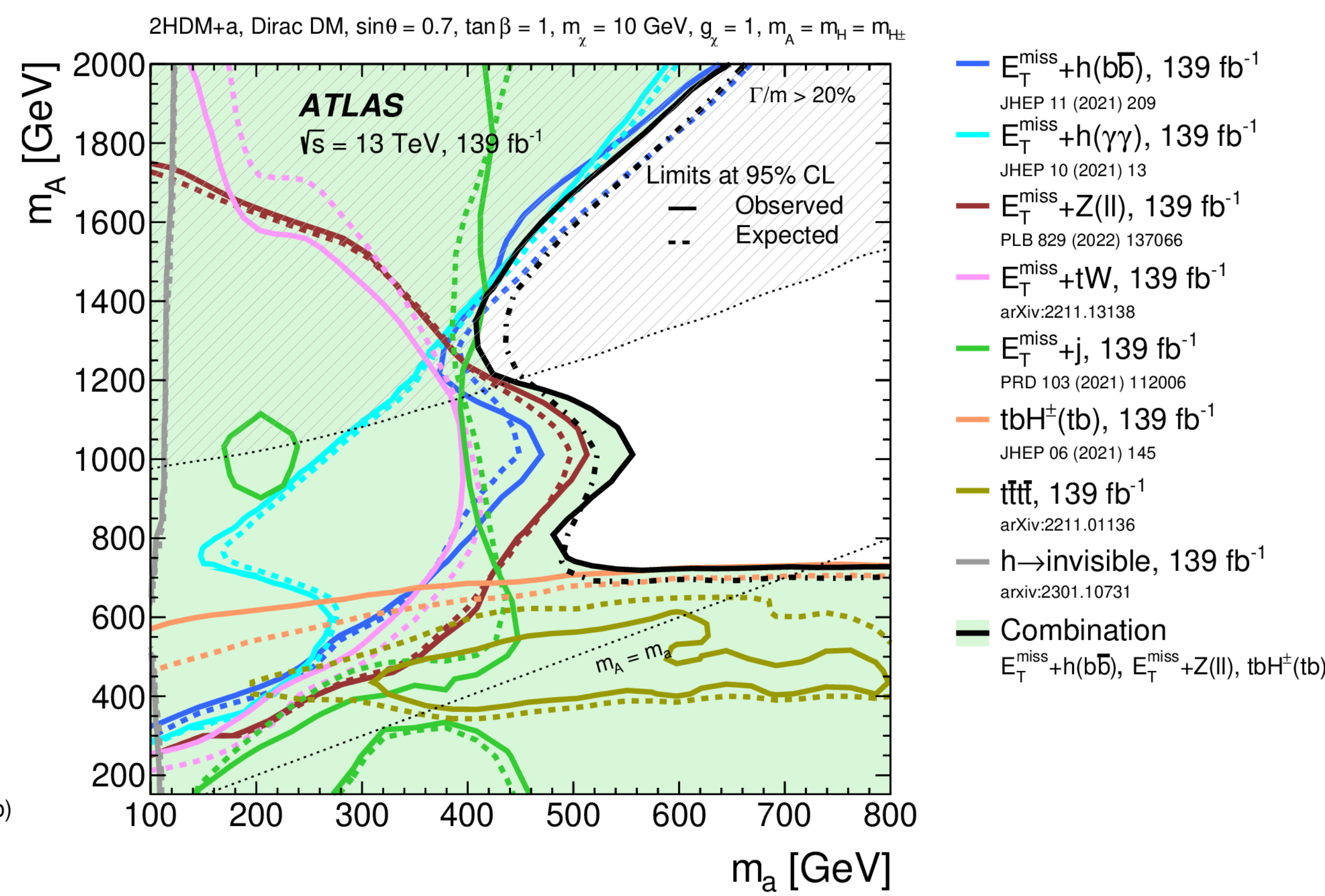

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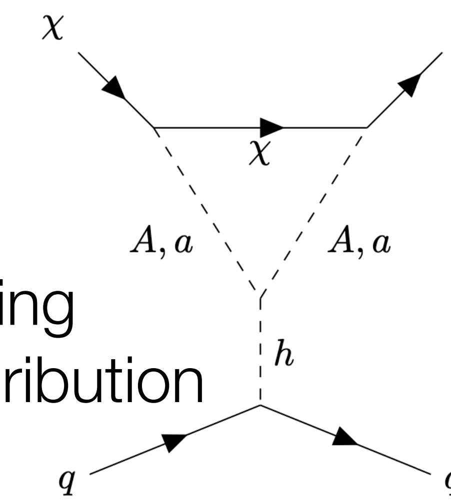

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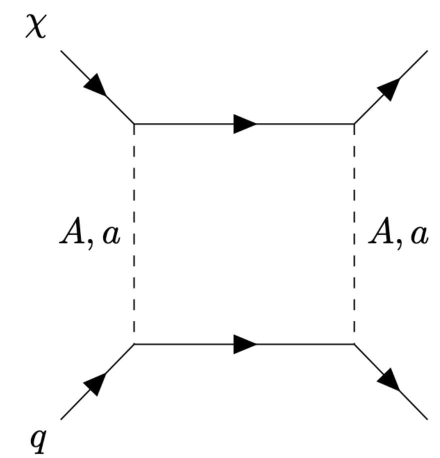

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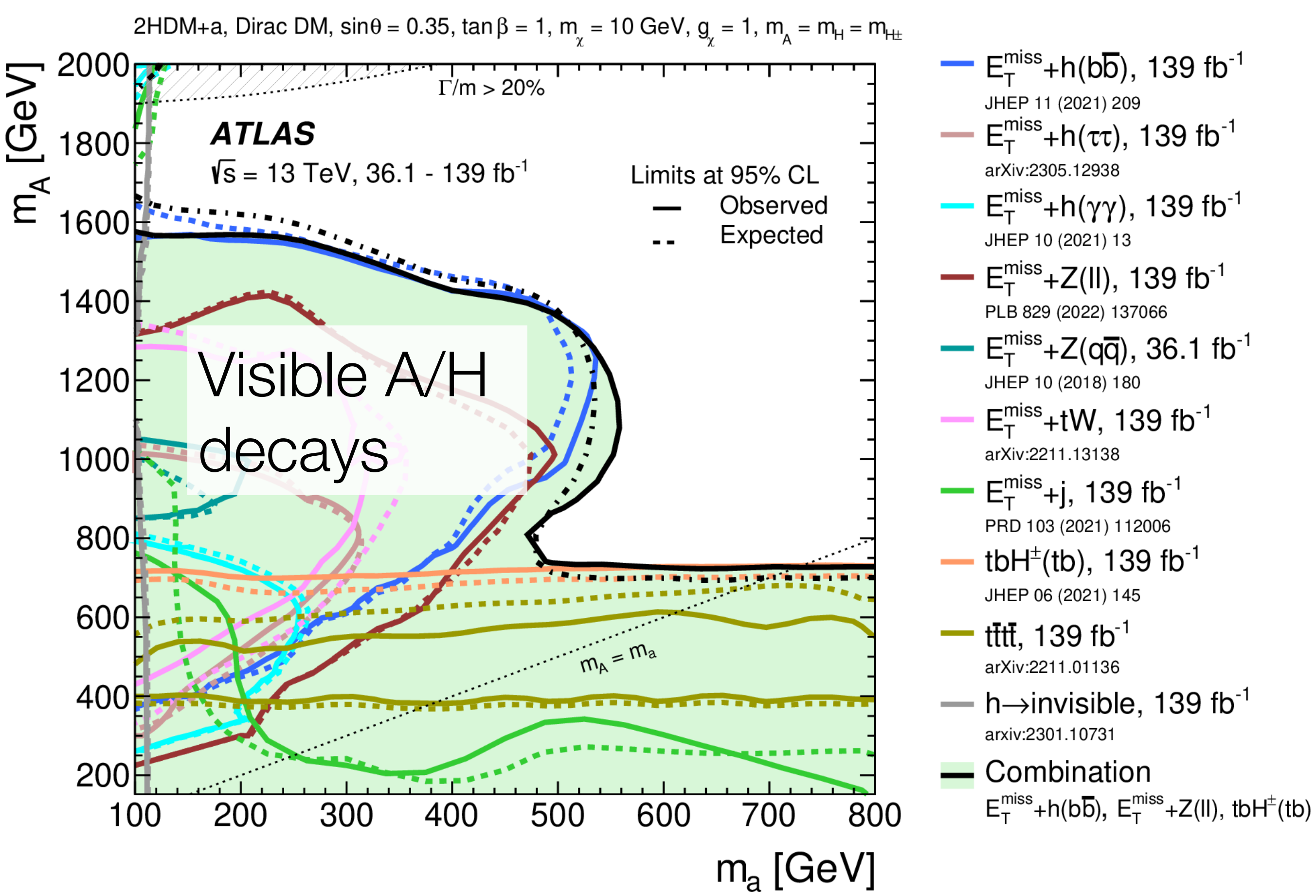

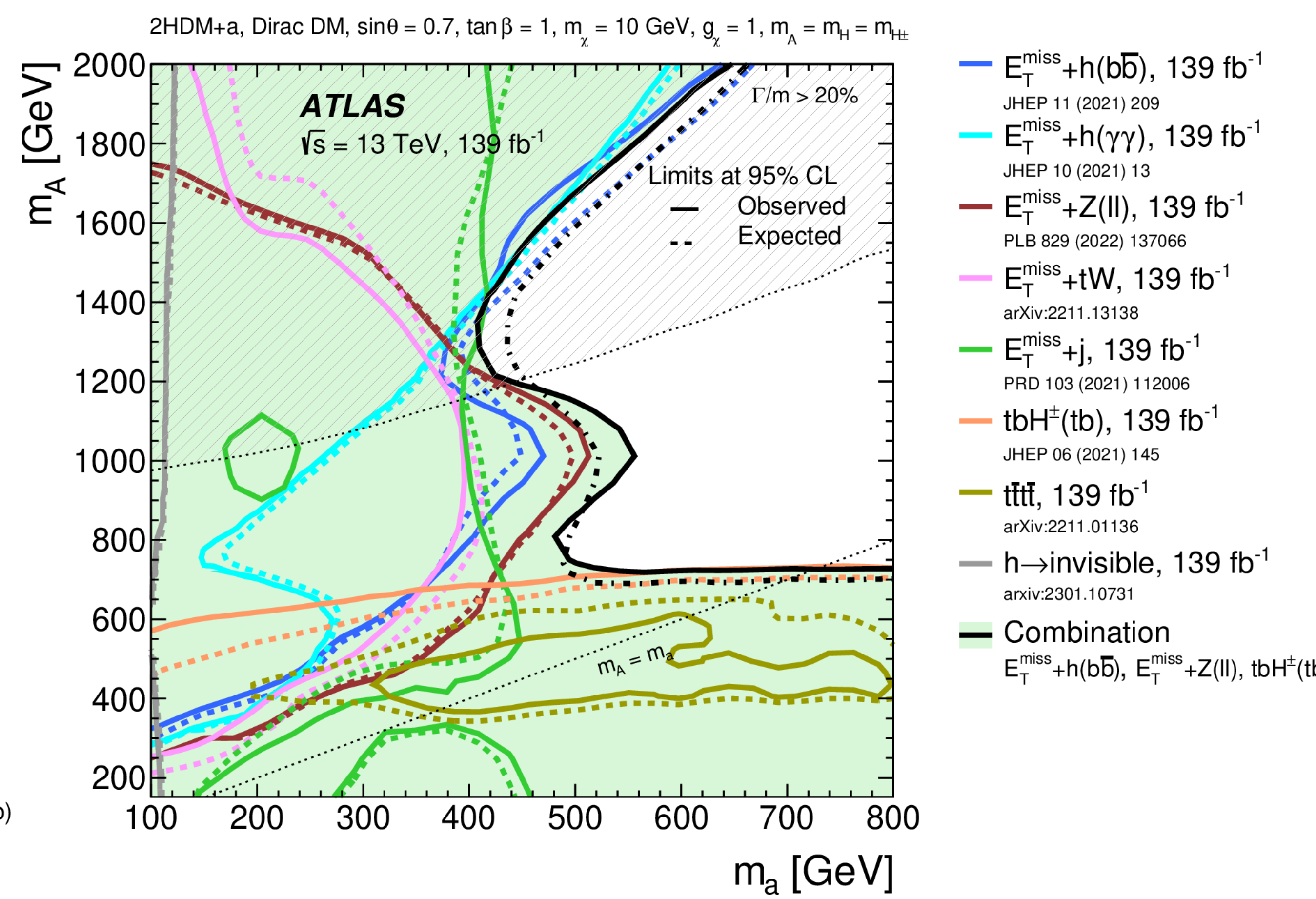

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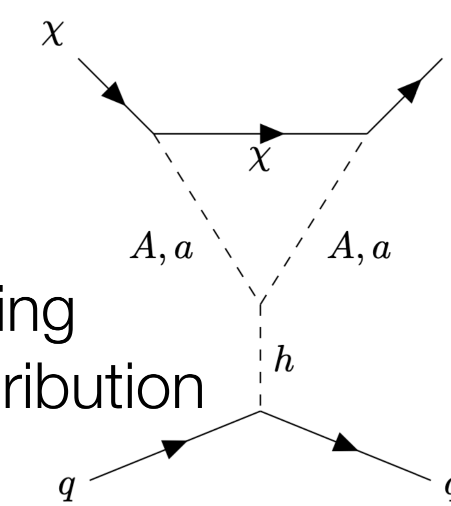
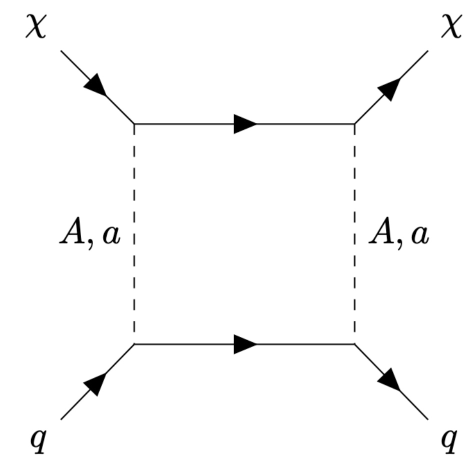


[LHC DM working group](#)



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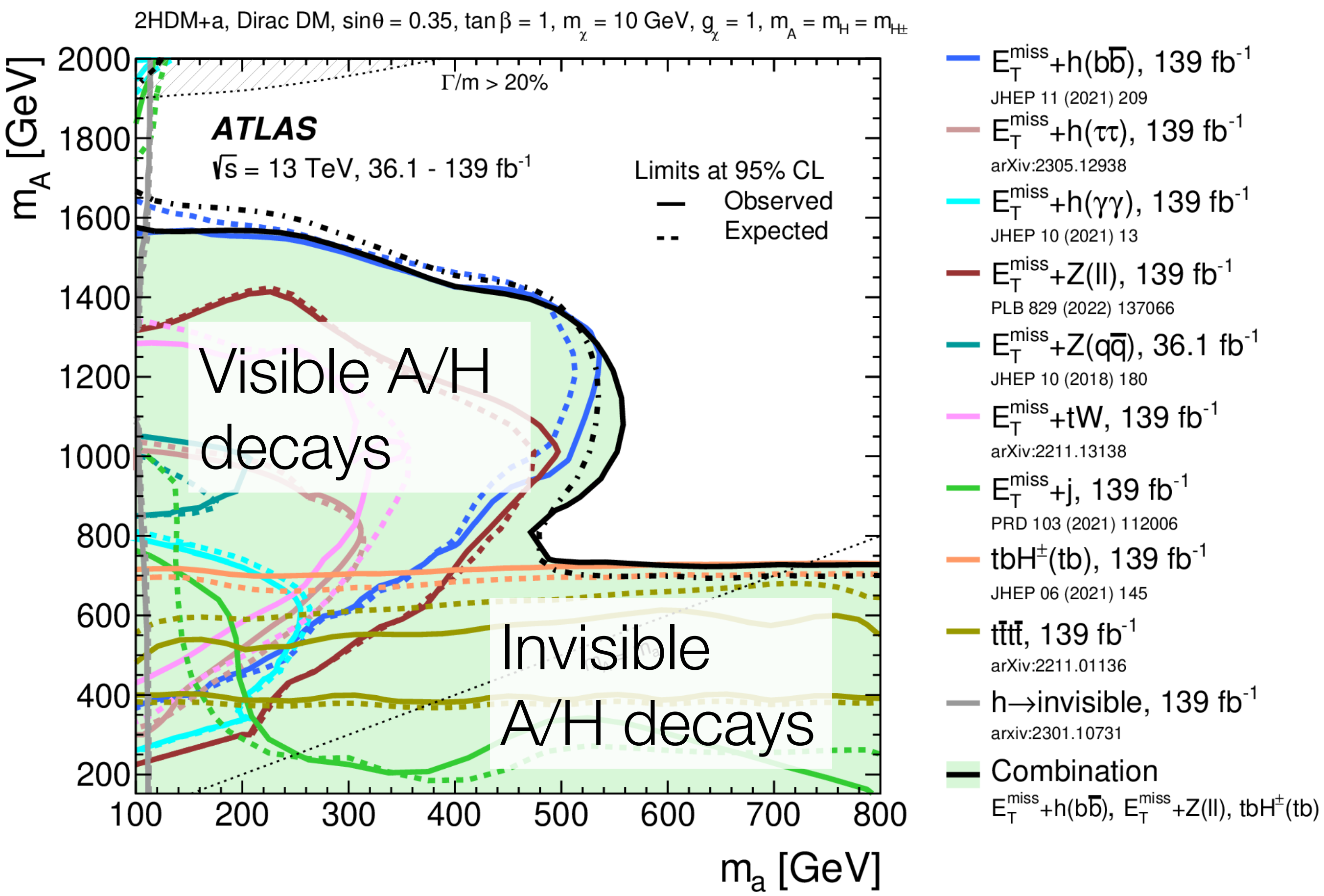

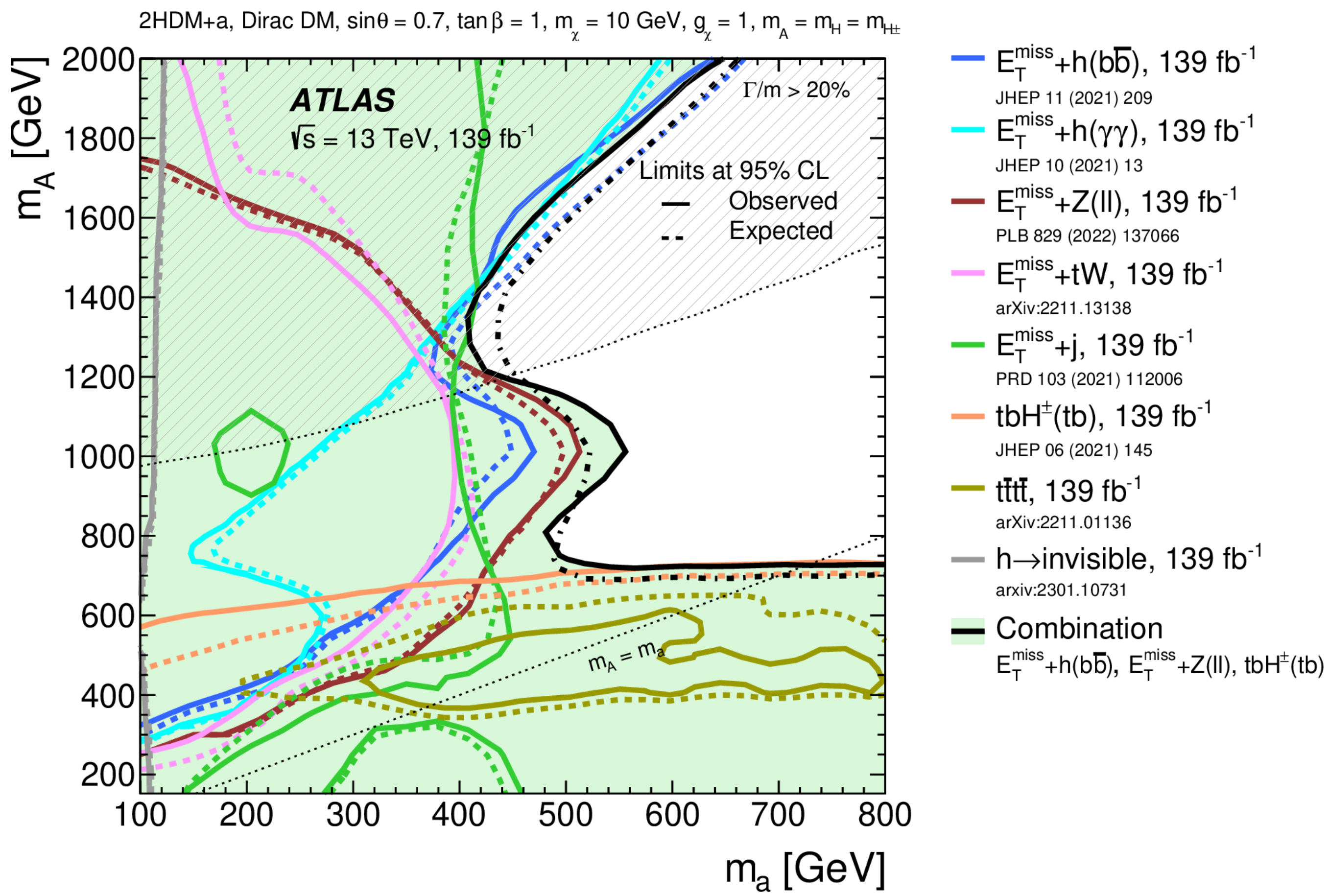

ATL-PHYS-PUB-2023-018

The state of SUSY dark matter

Let's look at pMSSM scan of DM candidates

ATLAS CERN-EP-2024-021

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

The state of SUSY dark matter

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ATLAS CERN-EP-2024-021

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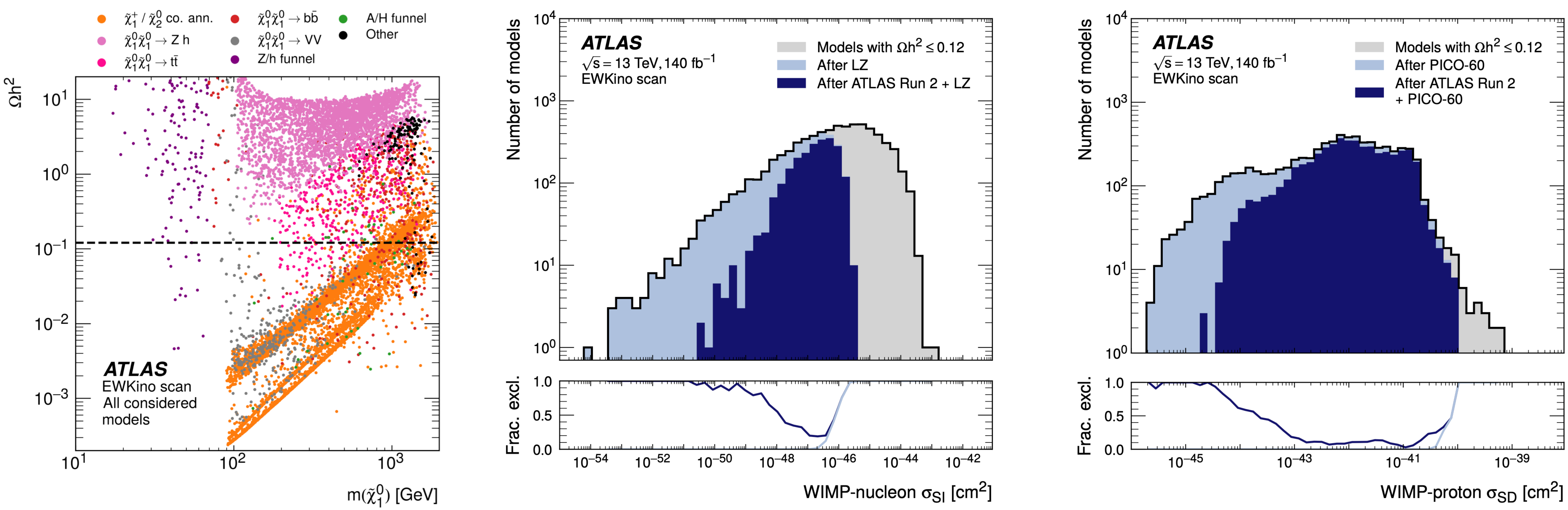

The state of SUSY dark matter

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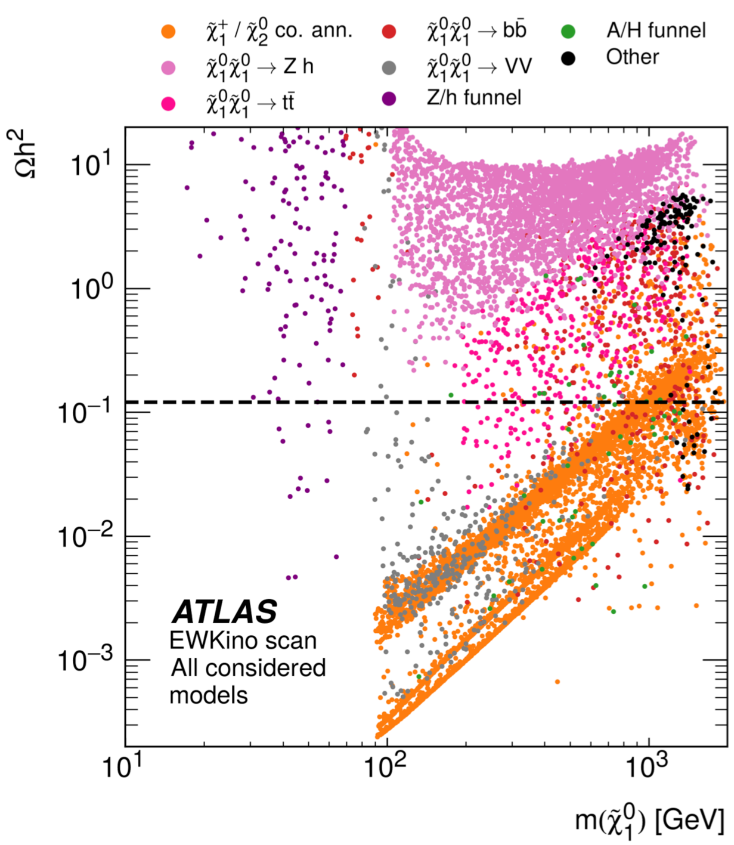

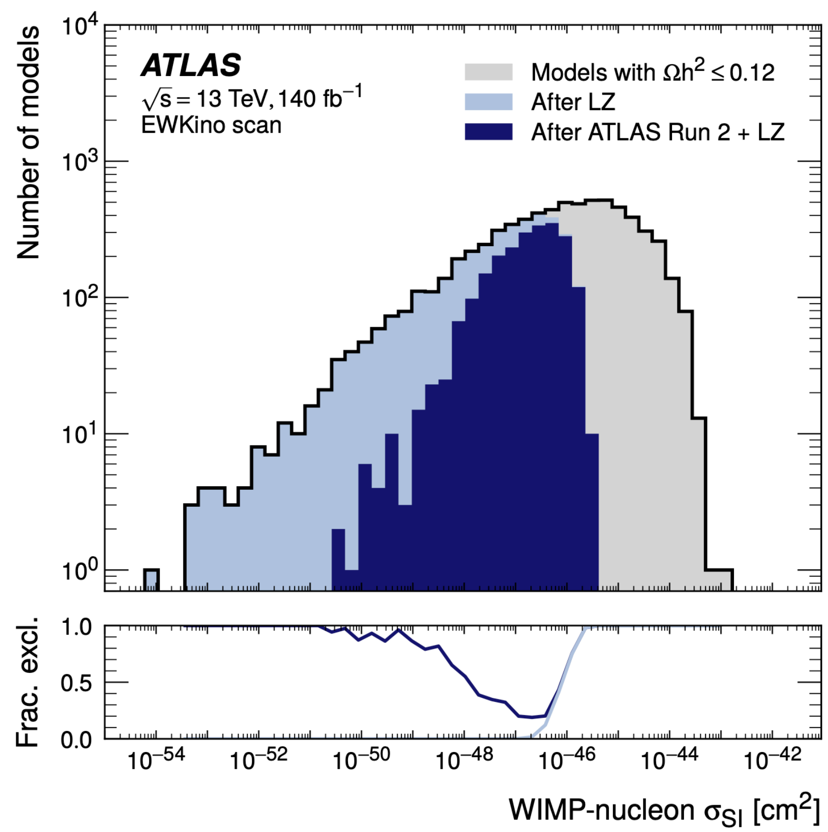

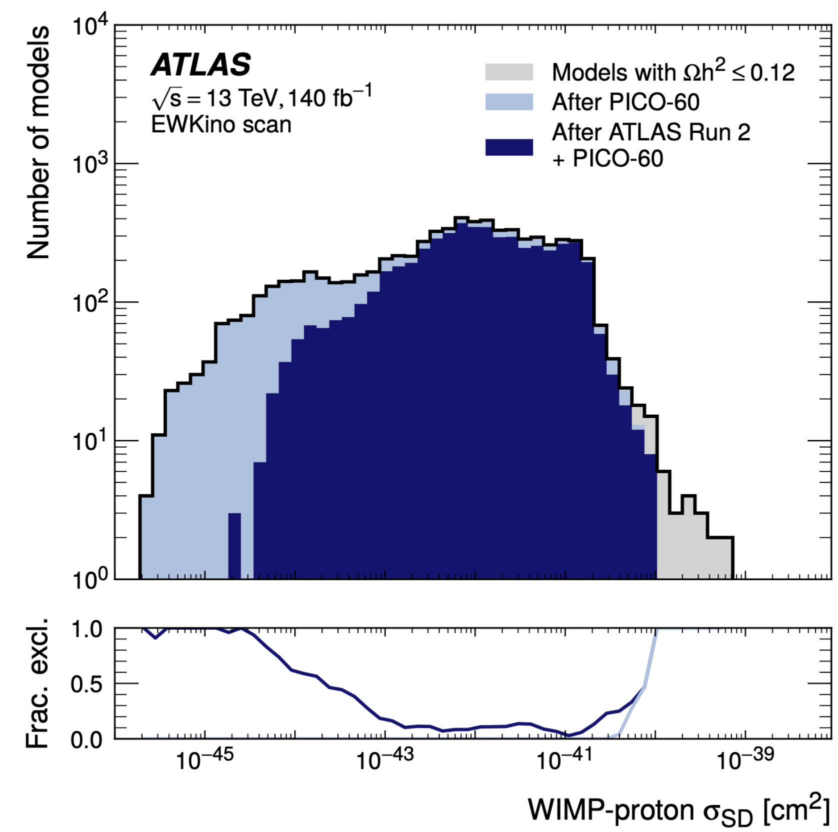

Can see 1) there is considerable space left for SUSY DM candidates in hard-to-reach electroweak signatures, and 2) there is good complementarity between LHC and direct detection reach

Extended dark sectors: growing area of interest

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

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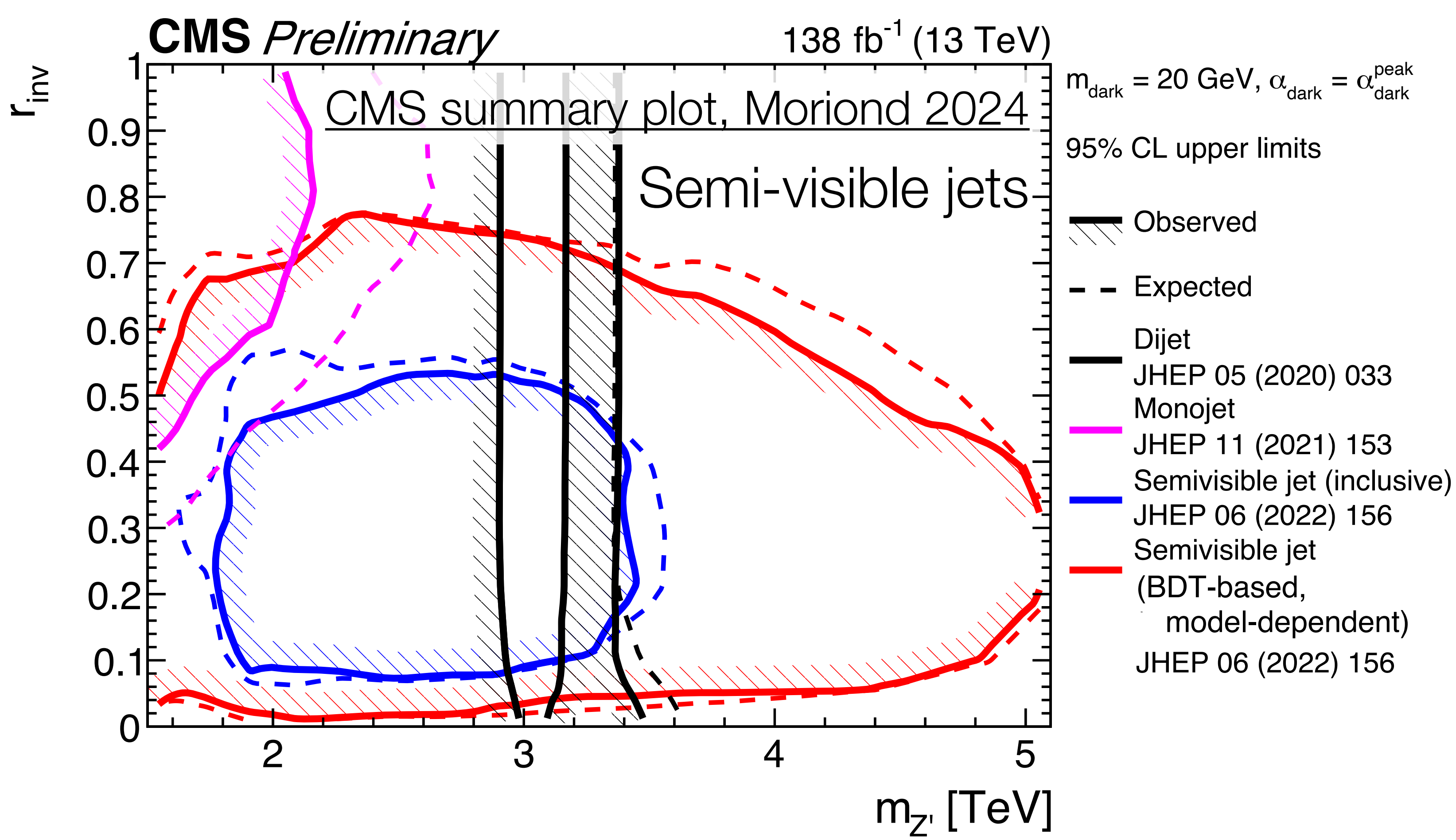

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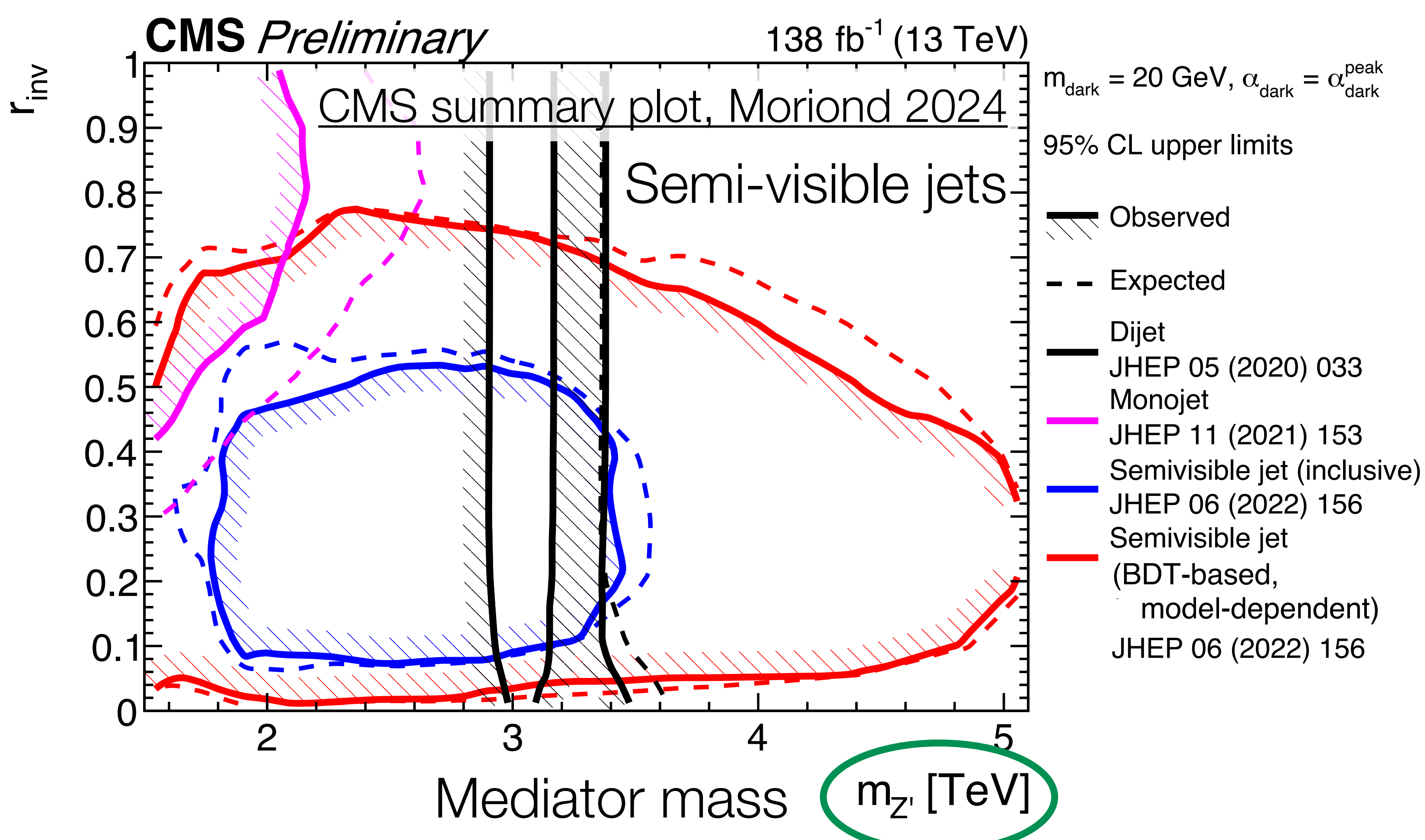

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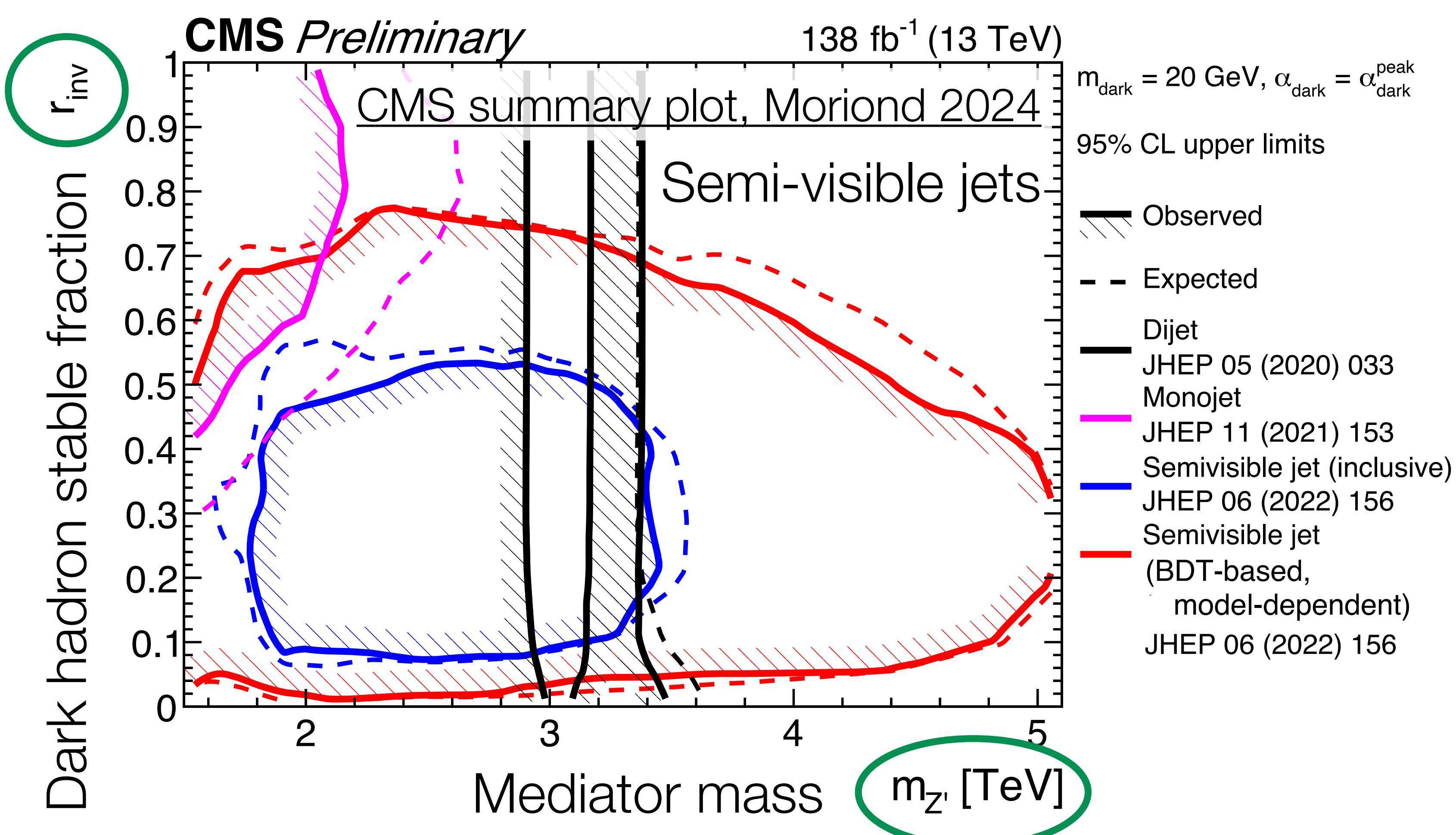

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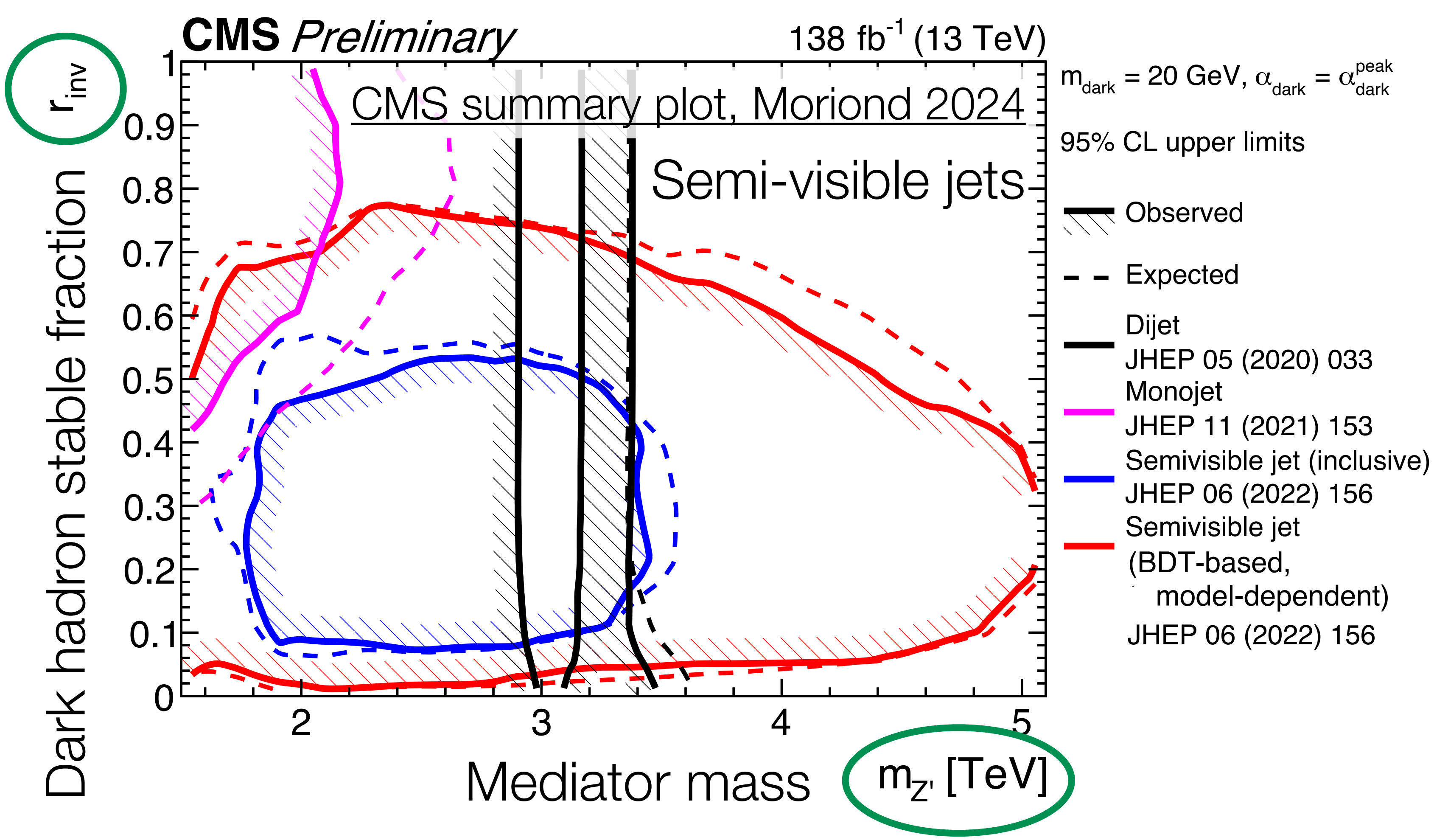

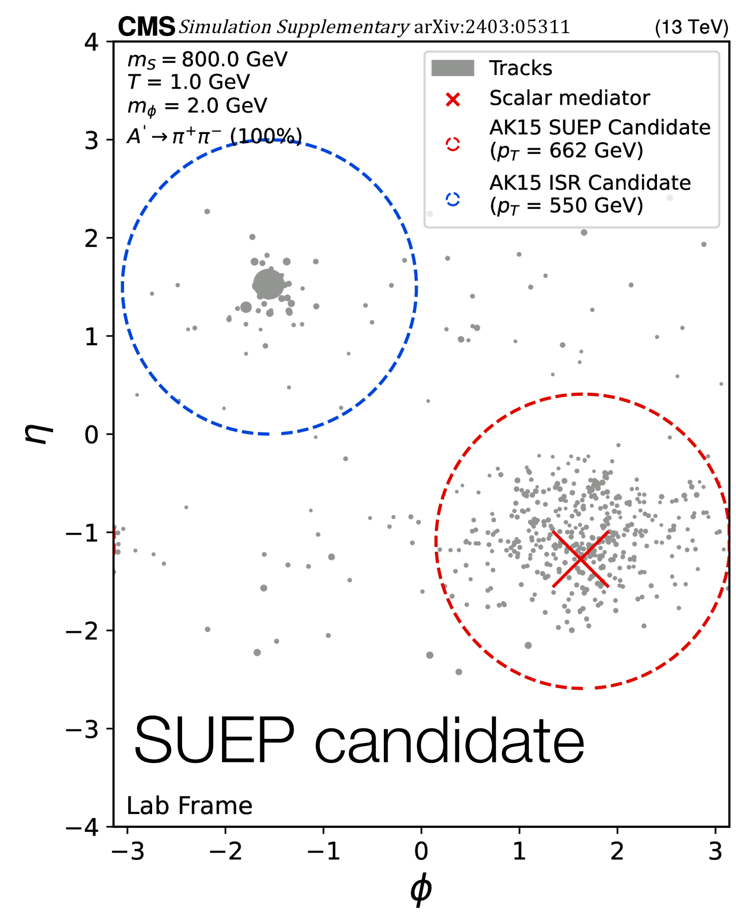

CMS EXO-23-002

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

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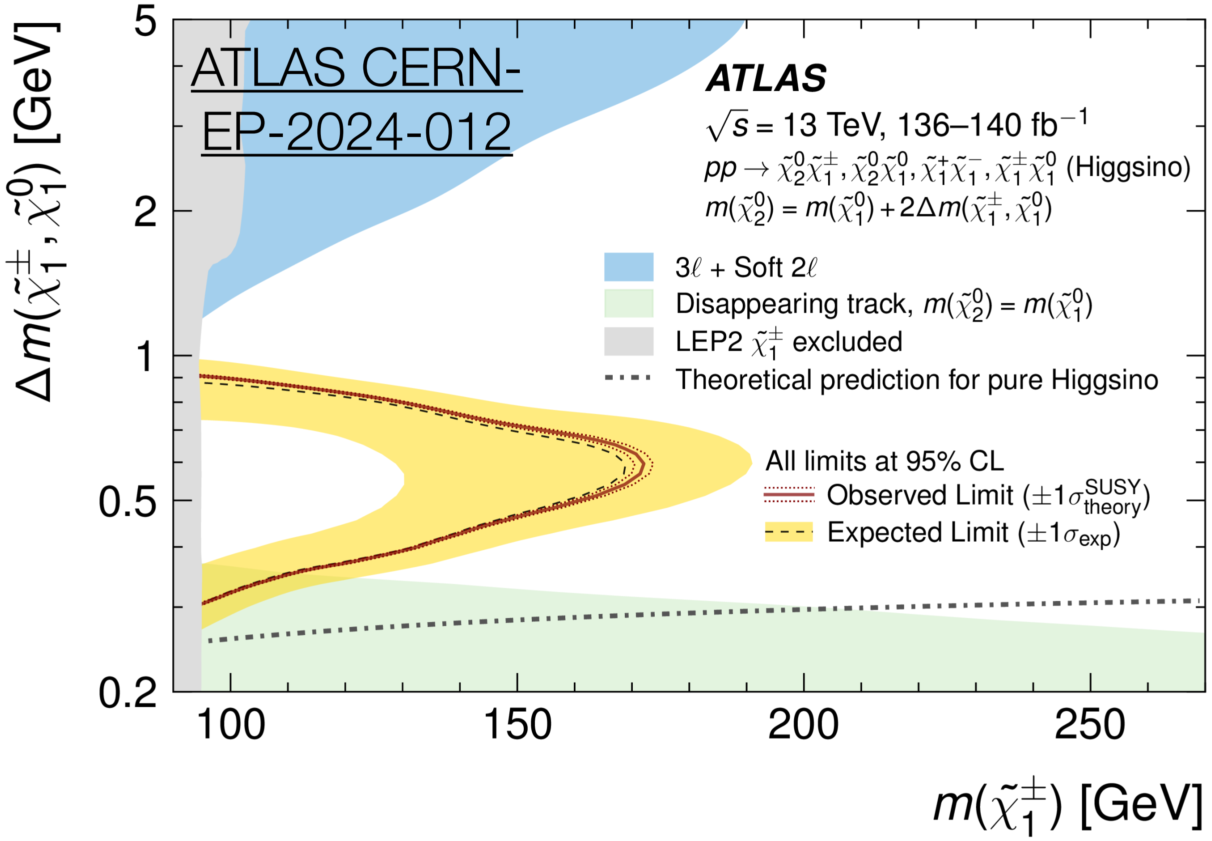

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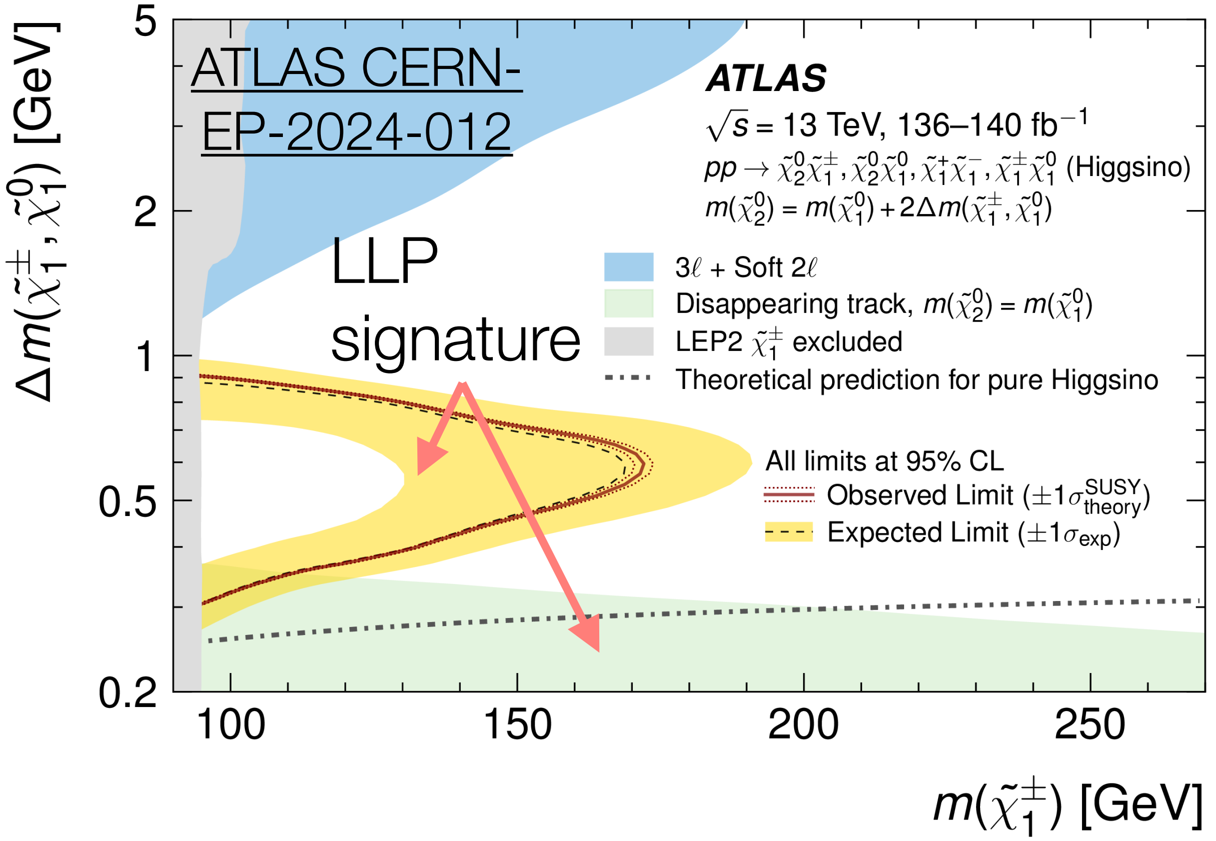

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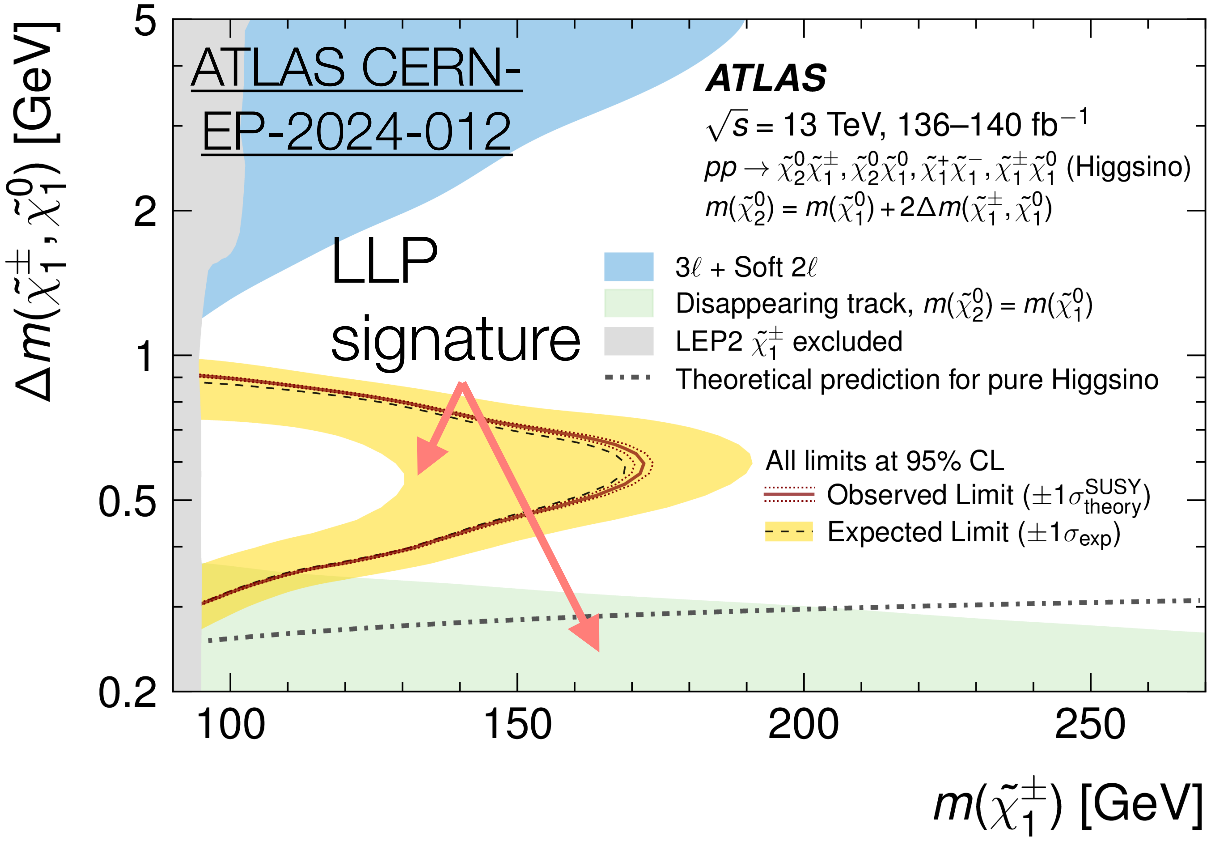
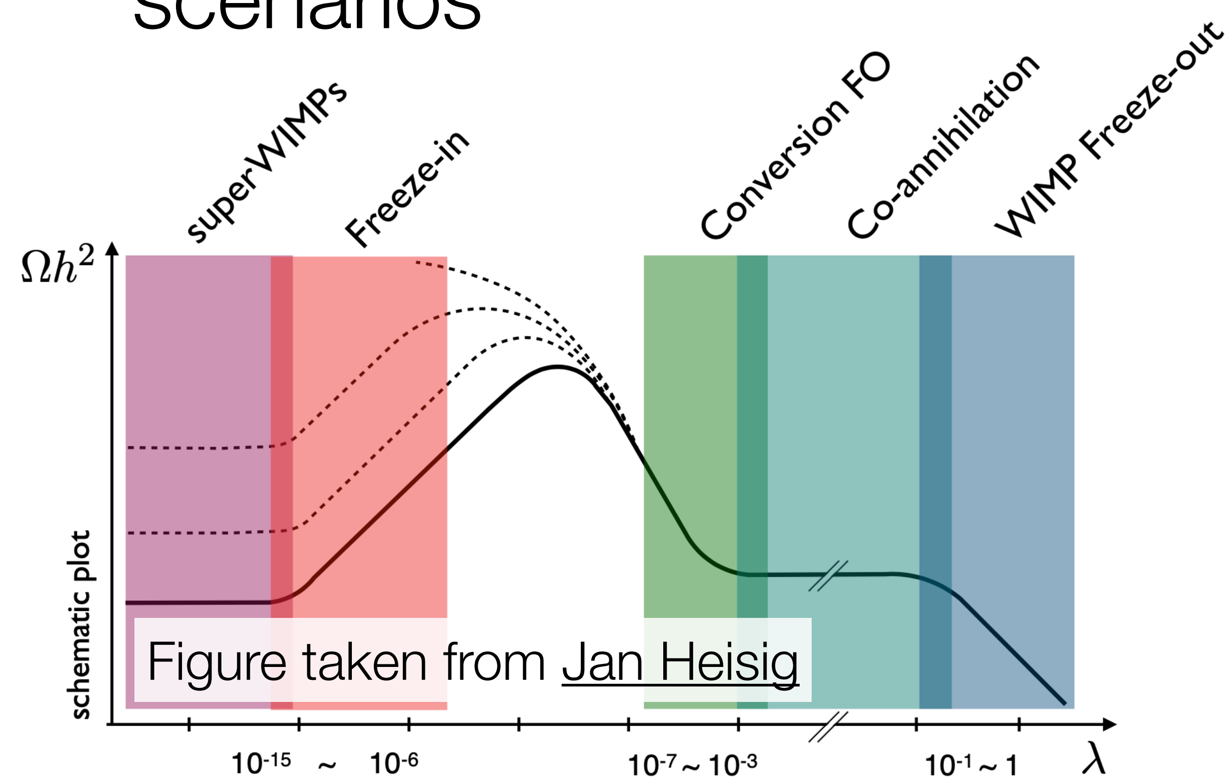


Freeze-in dark matter scenarios



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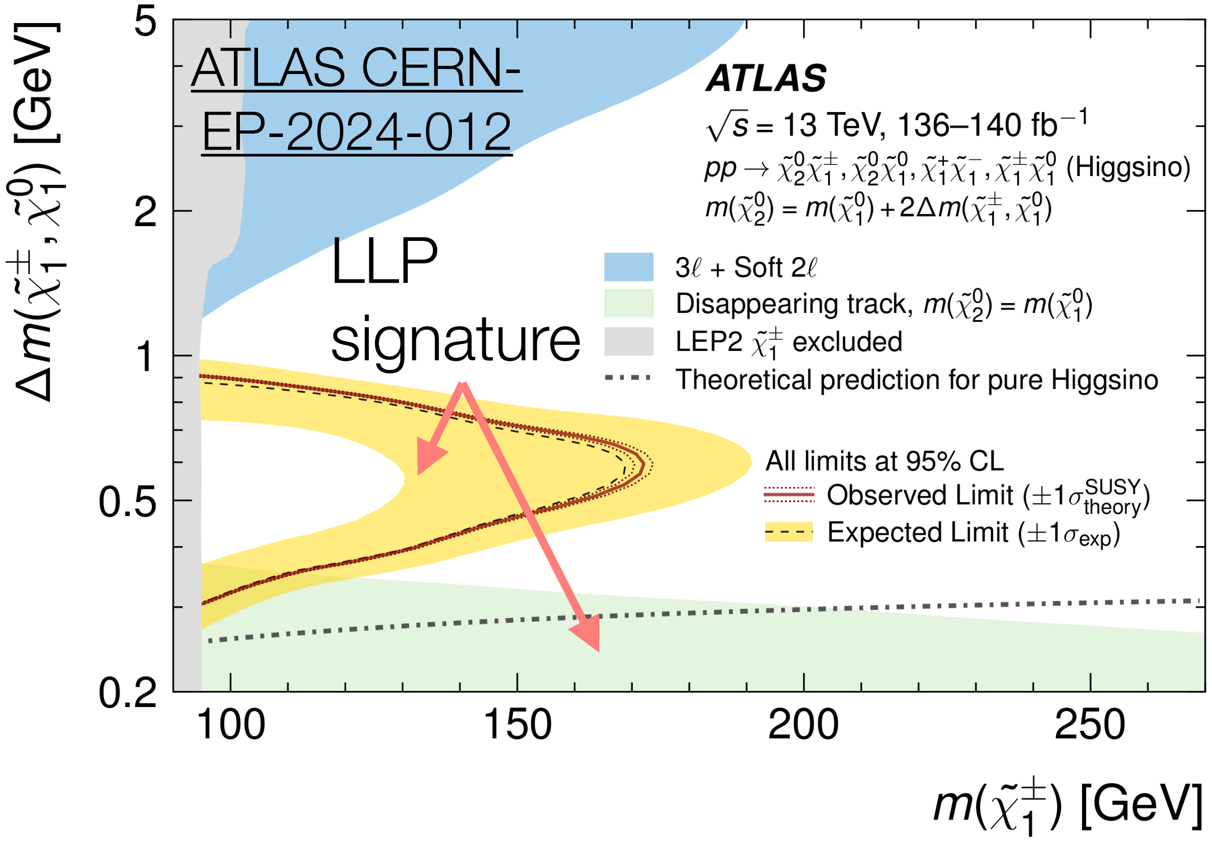

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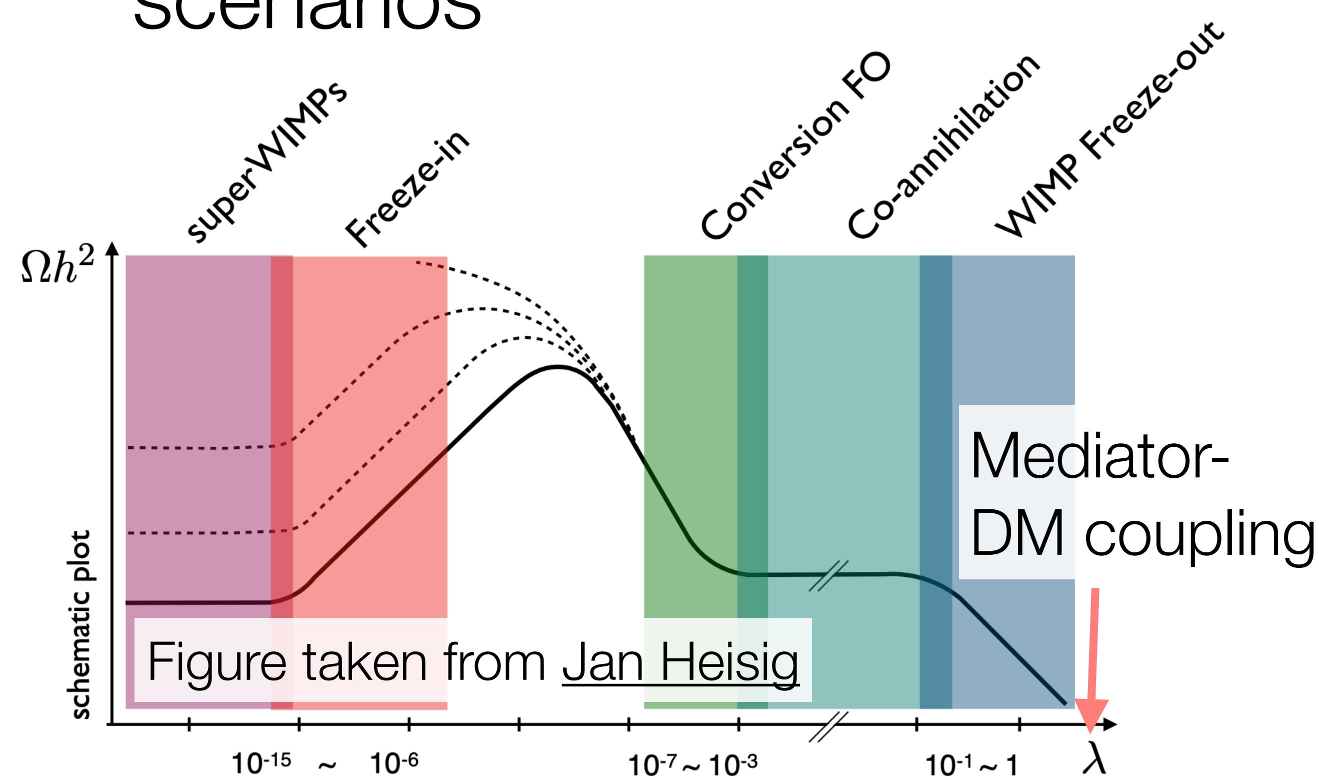

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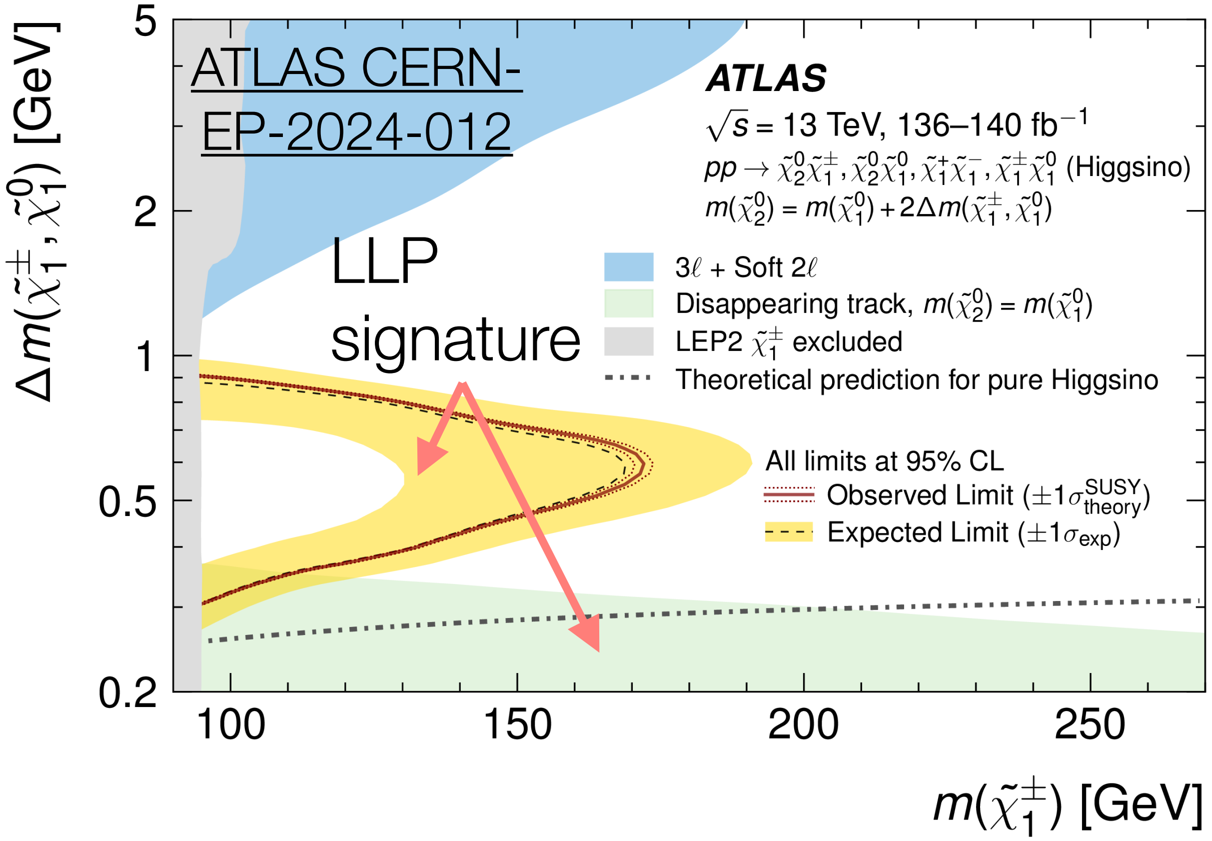

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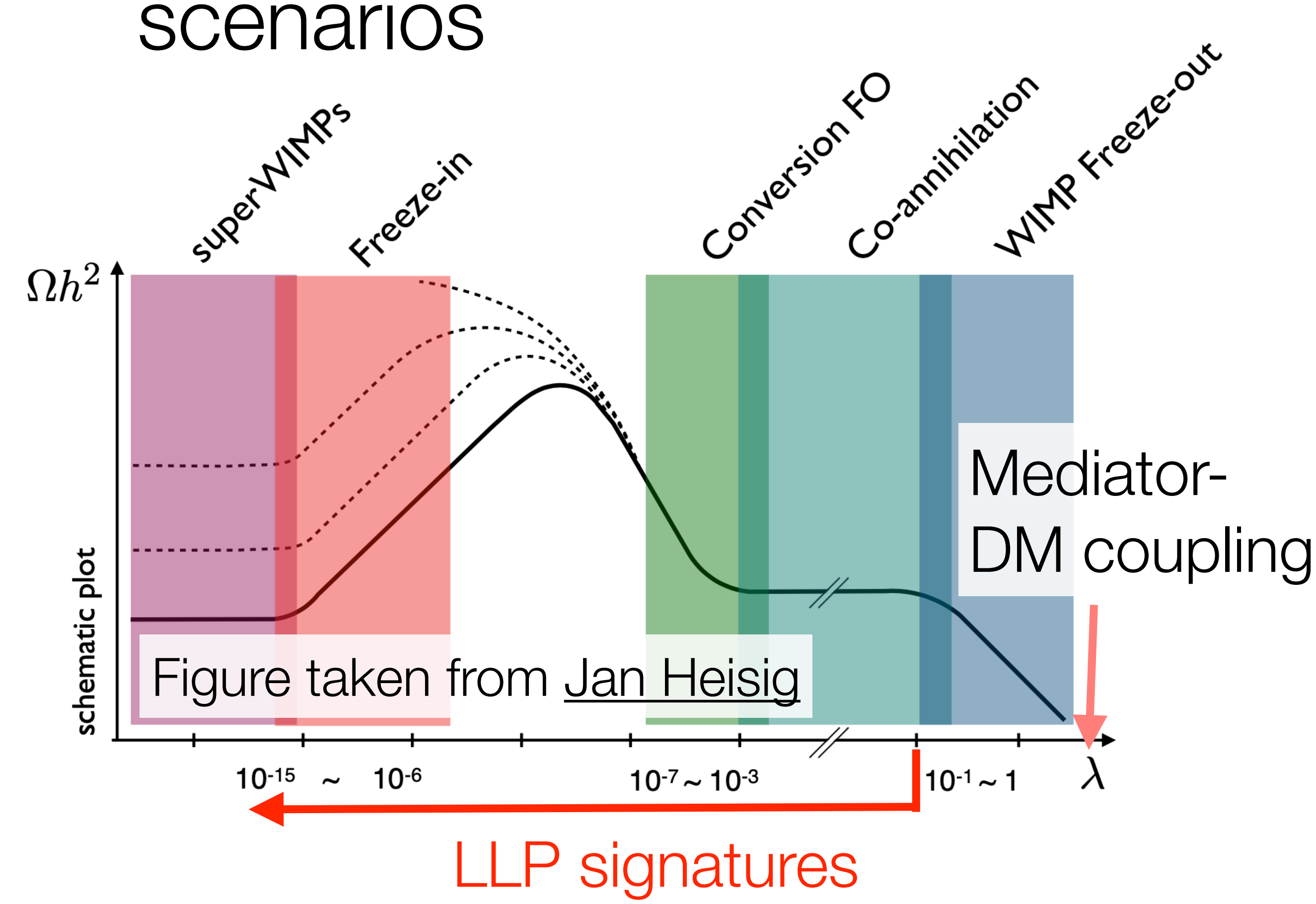

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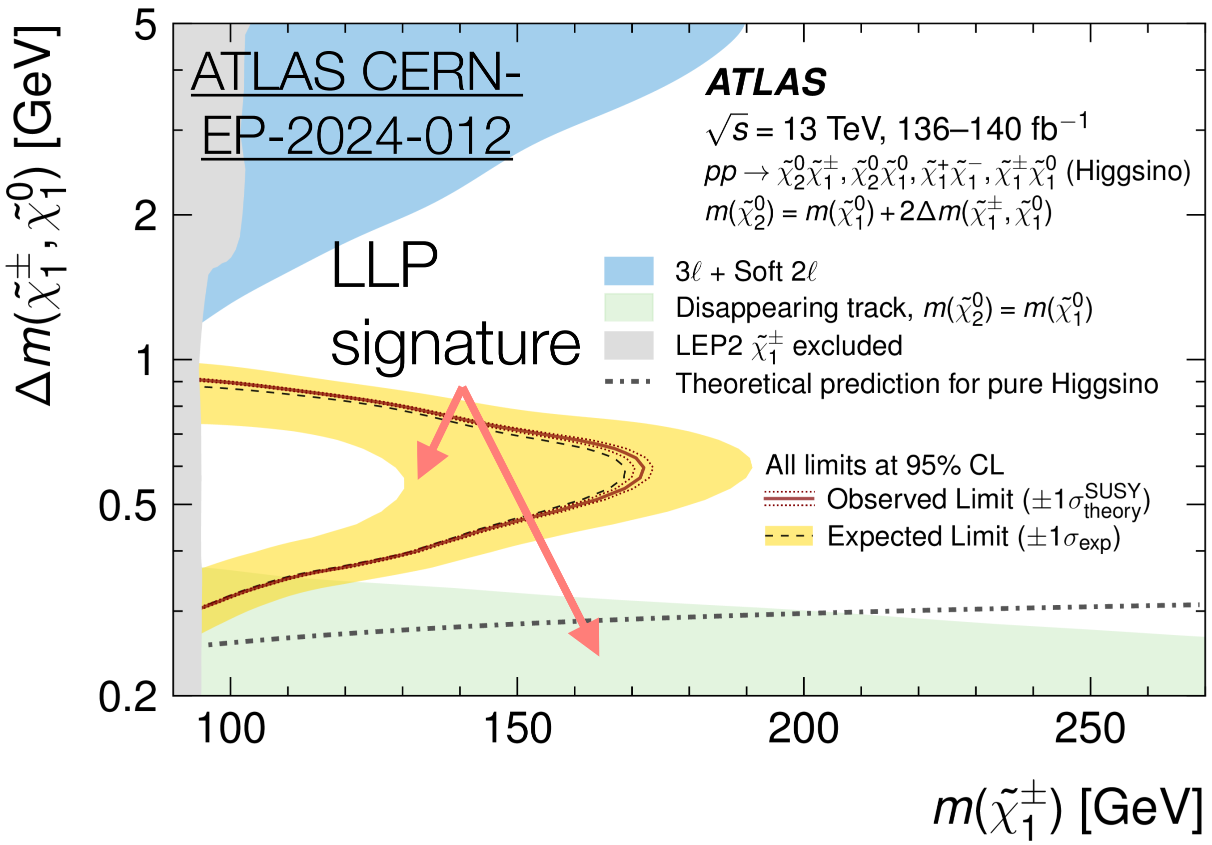

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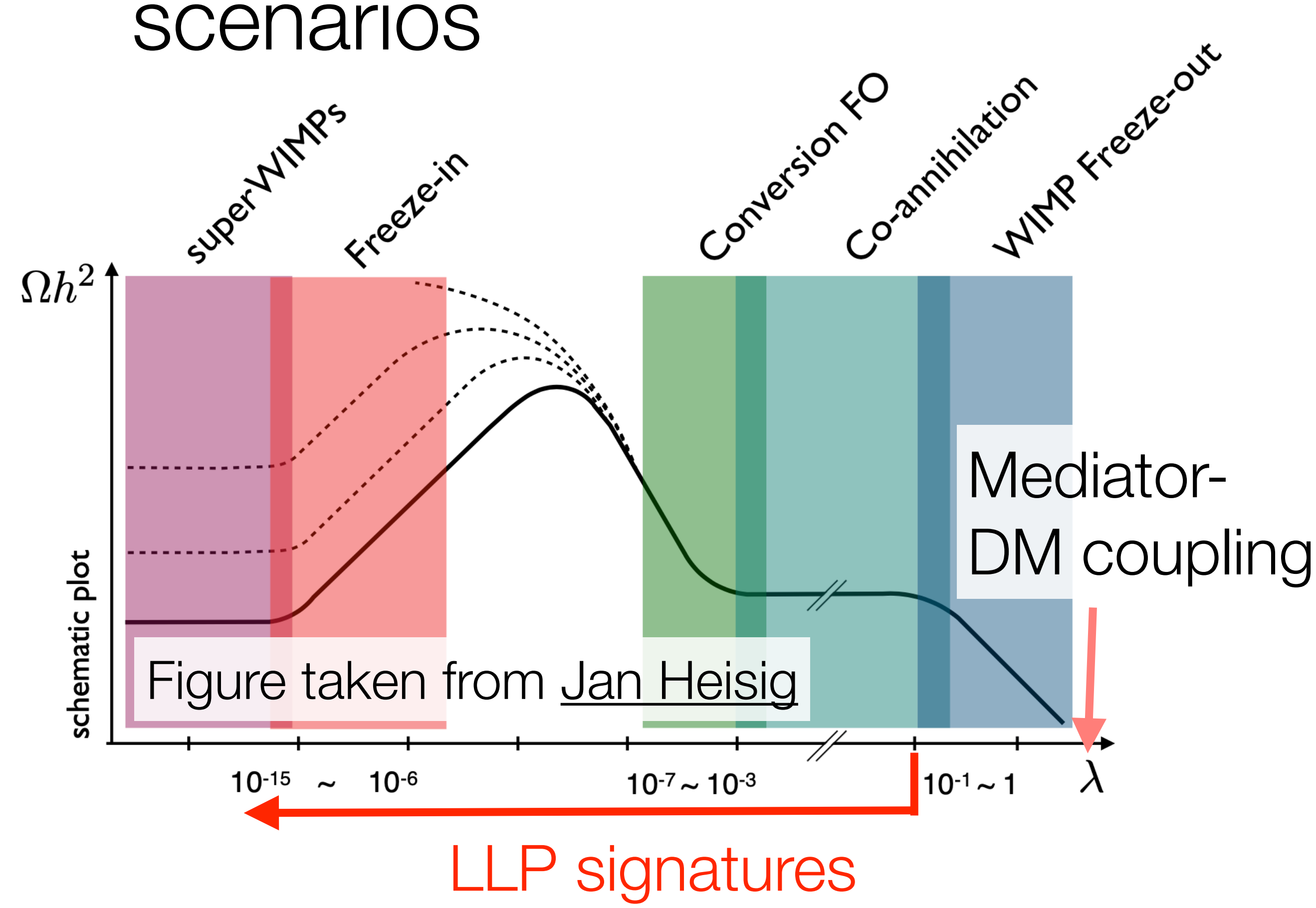
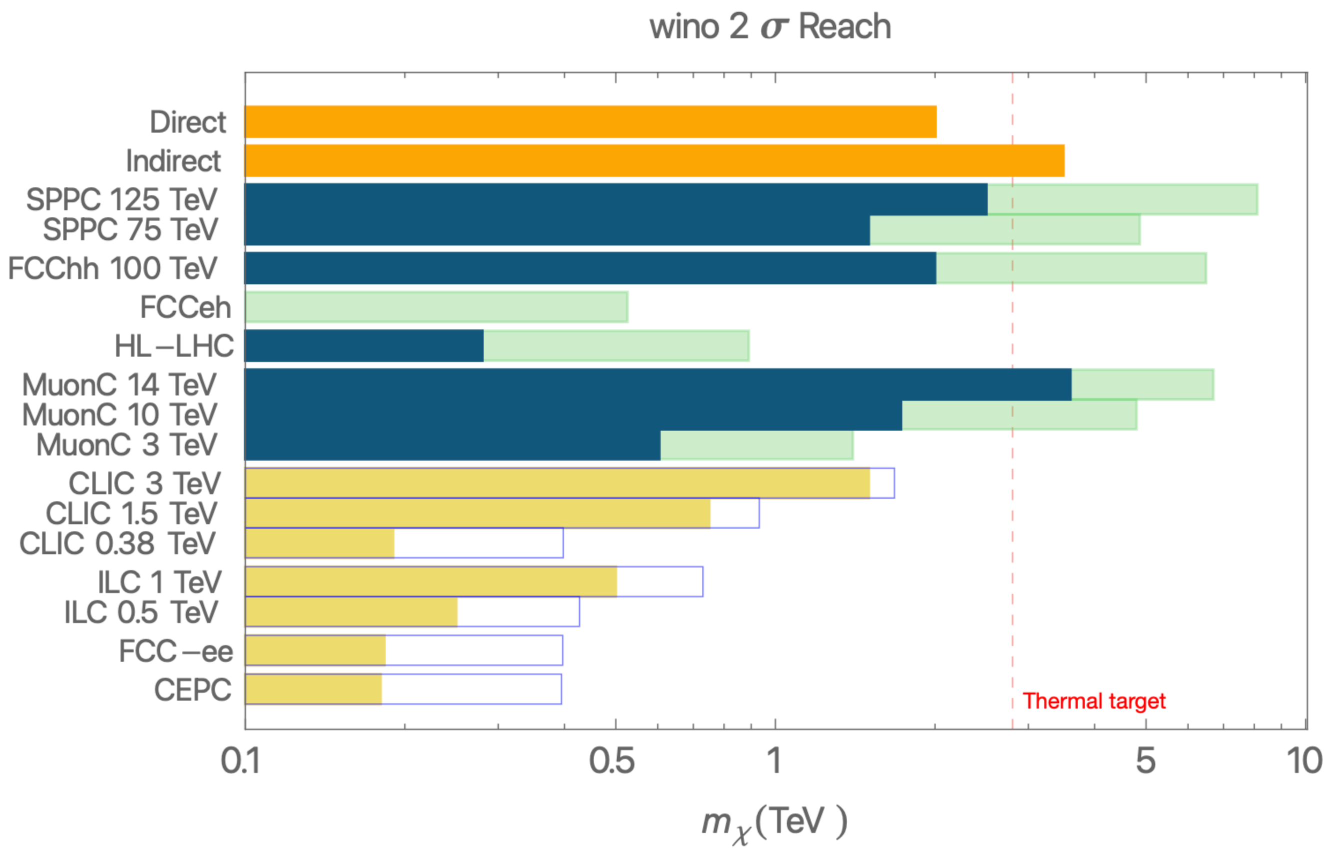


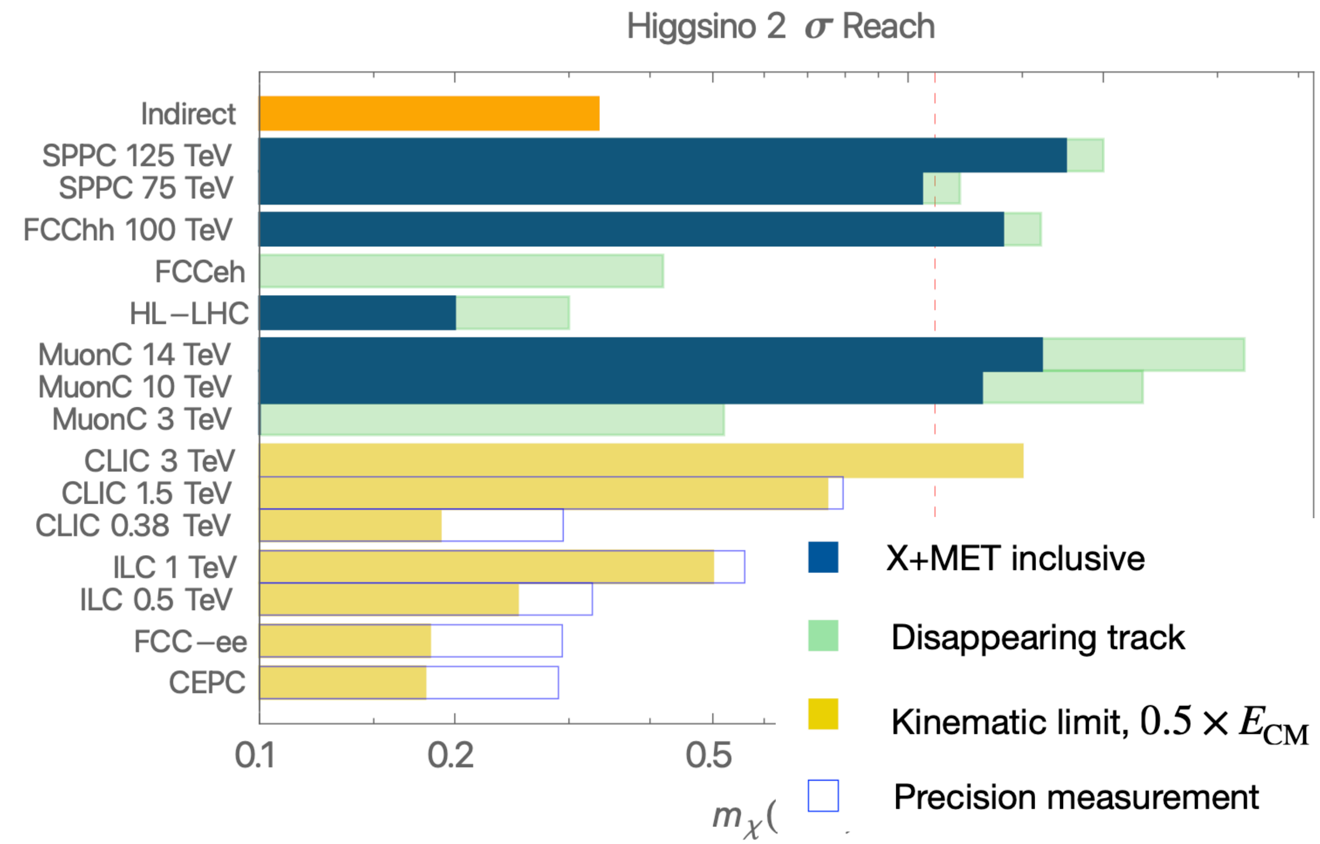
Can get LLPs from small mass splittings or small couplings, and turn up frequently in asymmetric, freeze-in, & SUSY DM

DM at HL-LHC and future colliders

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.





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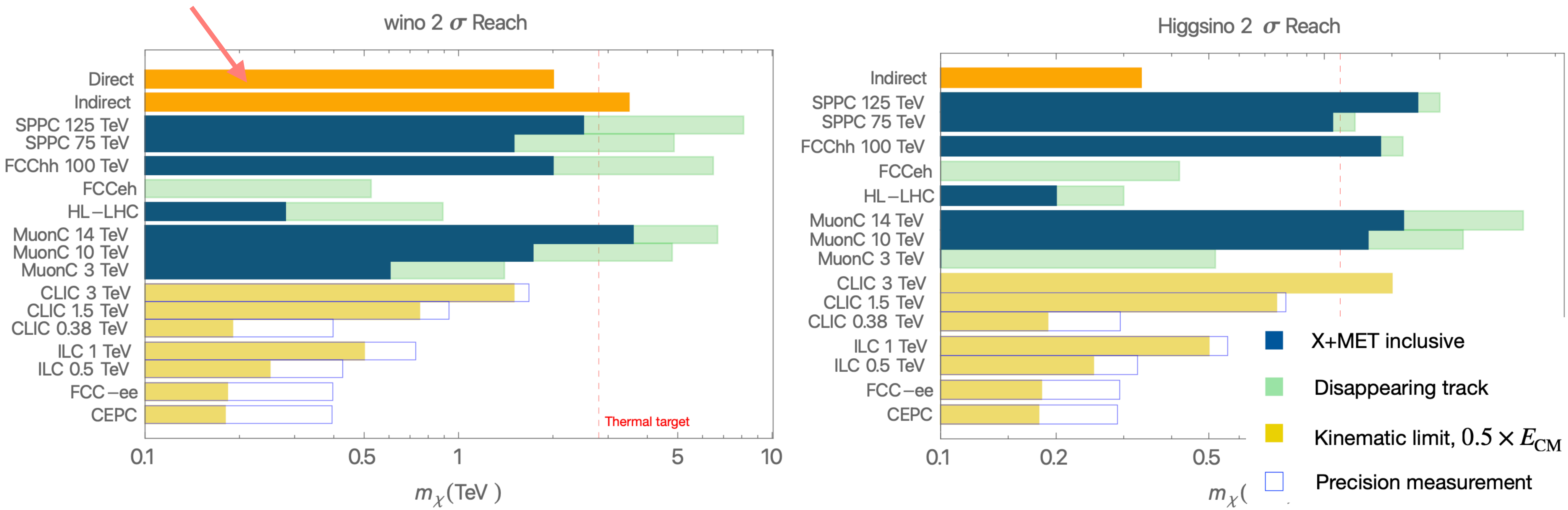

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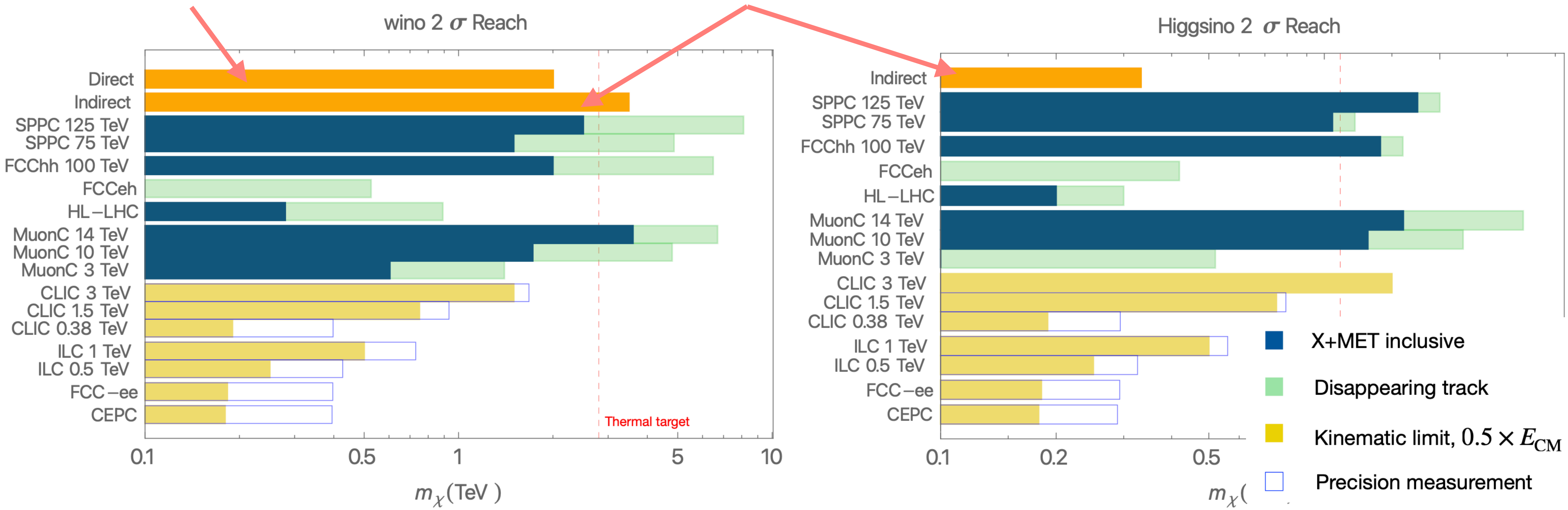

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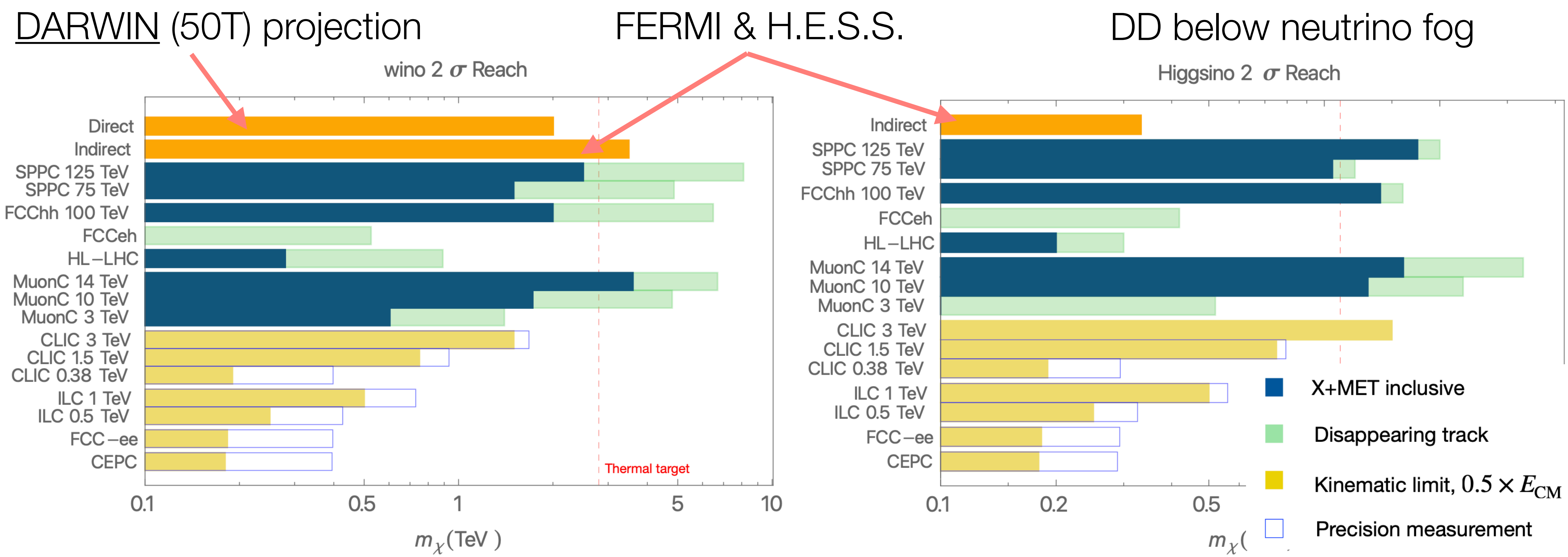

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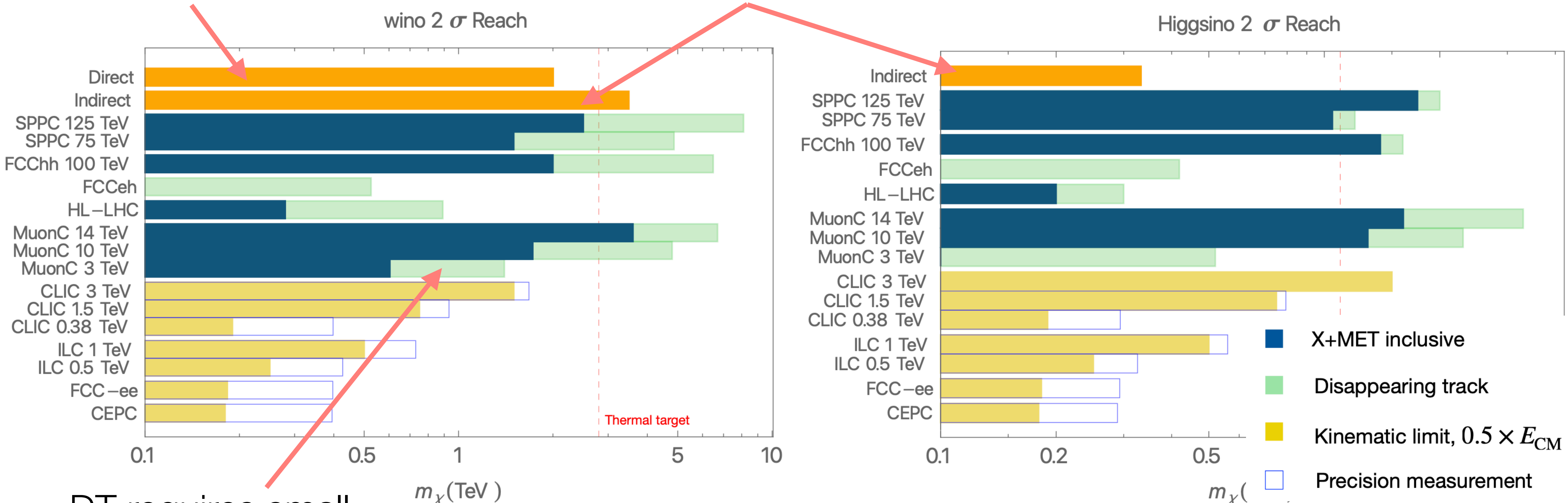

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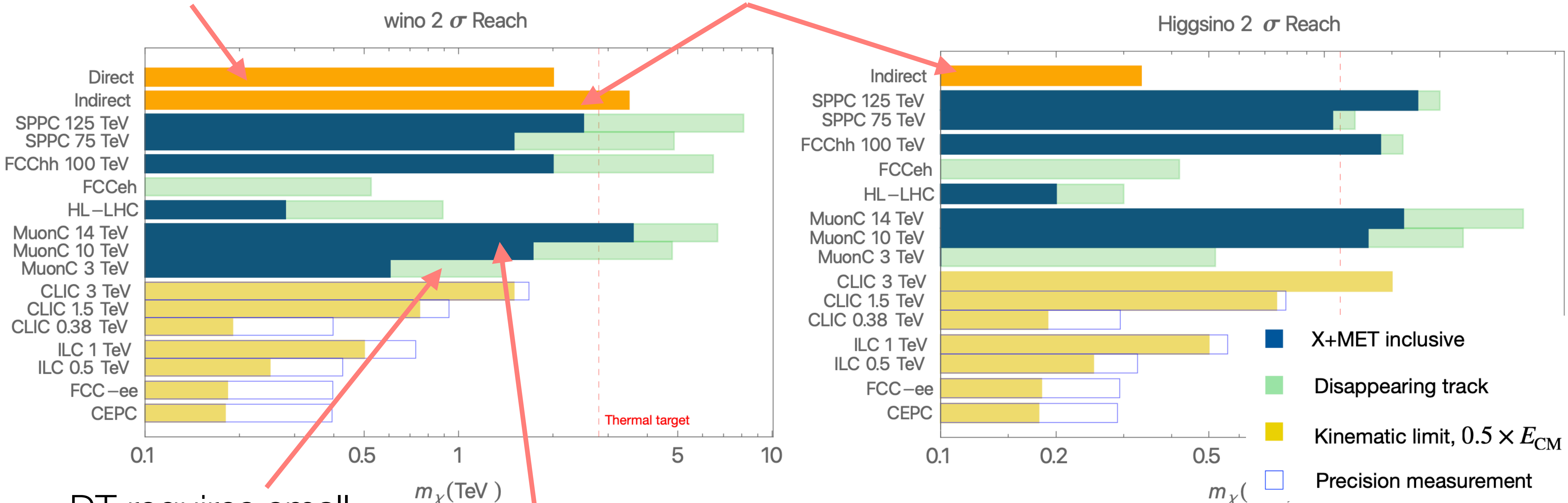

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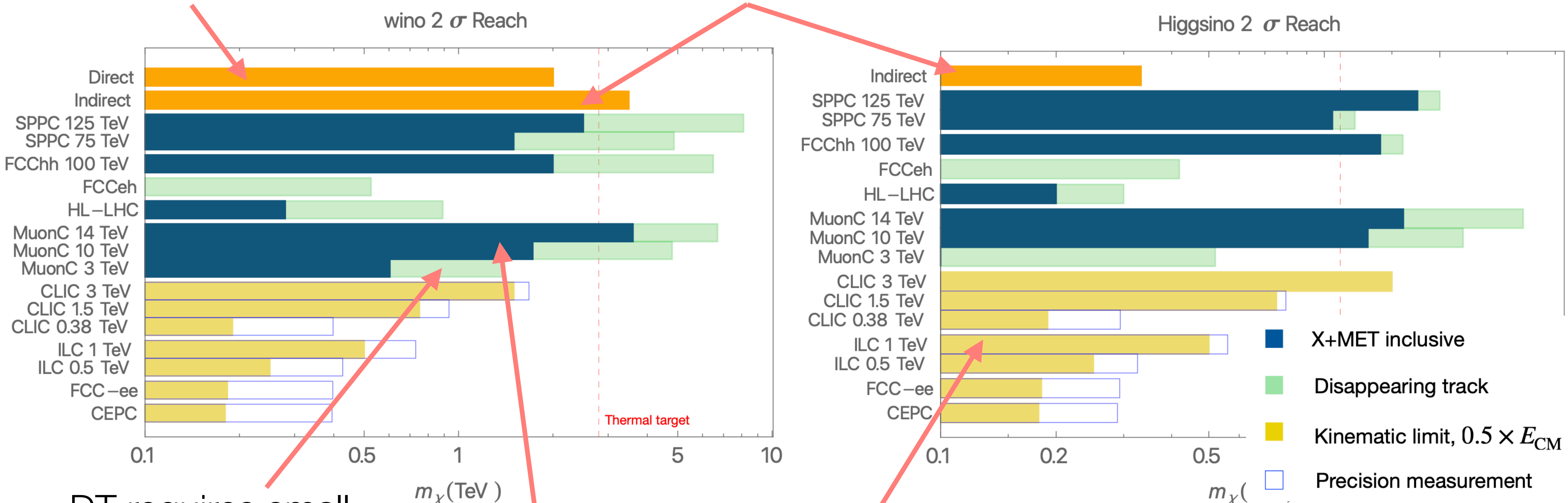

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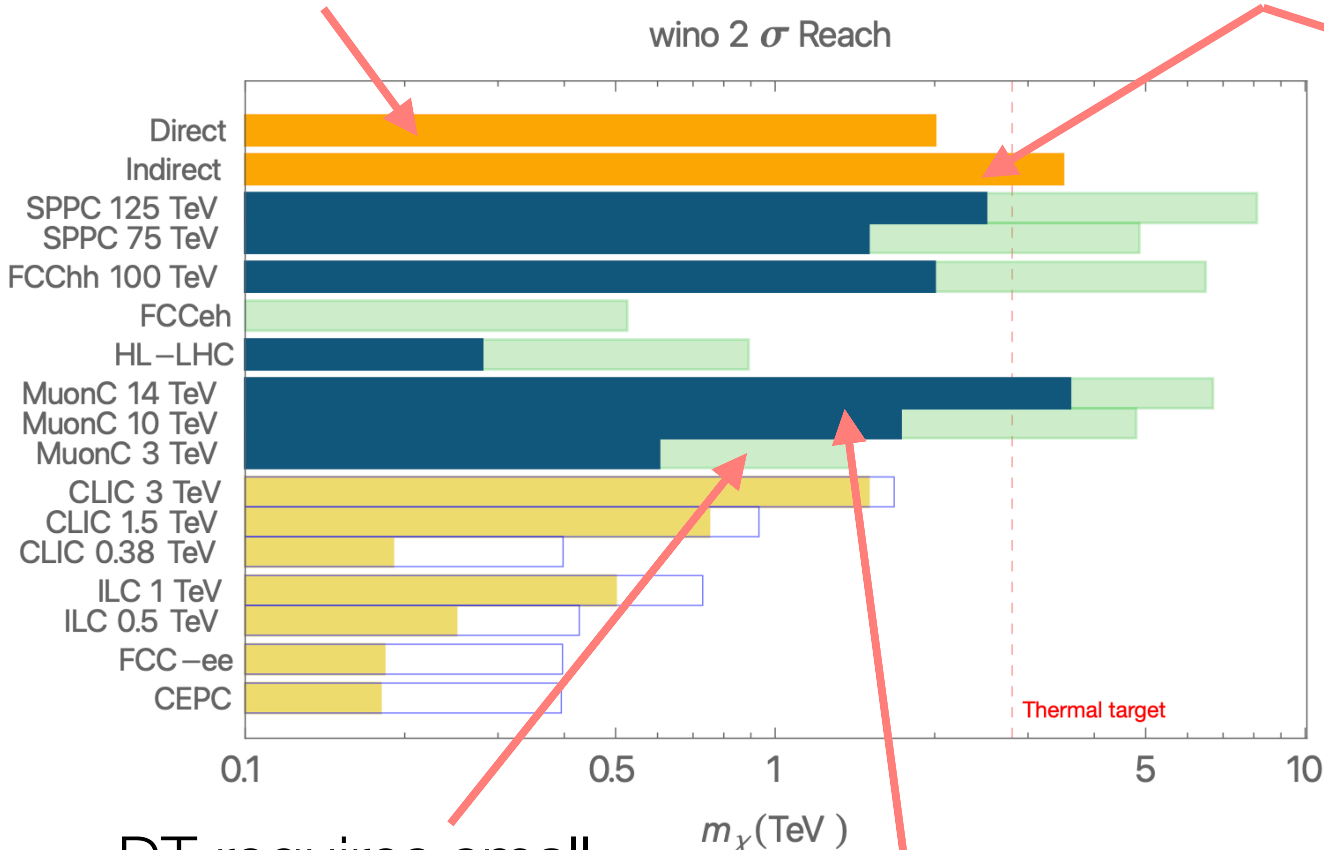

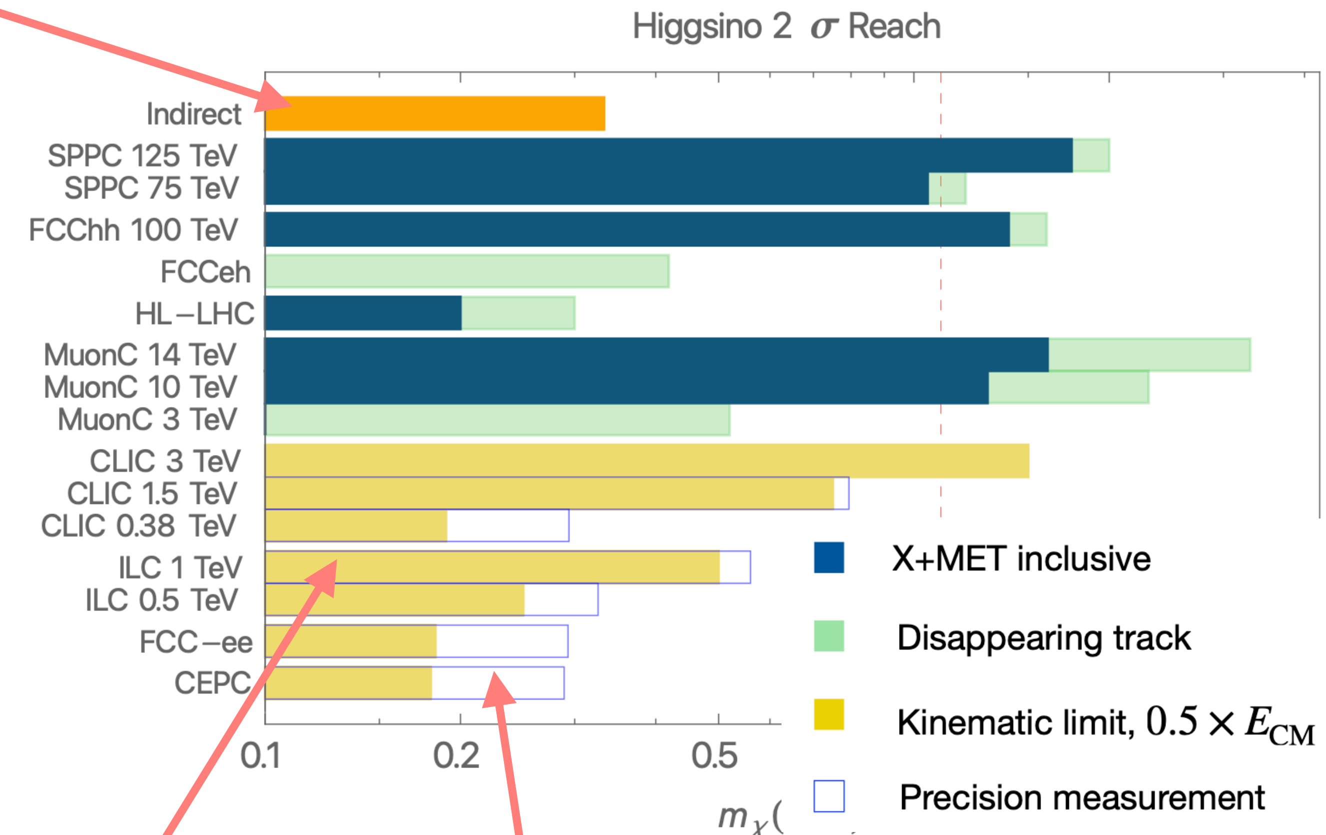

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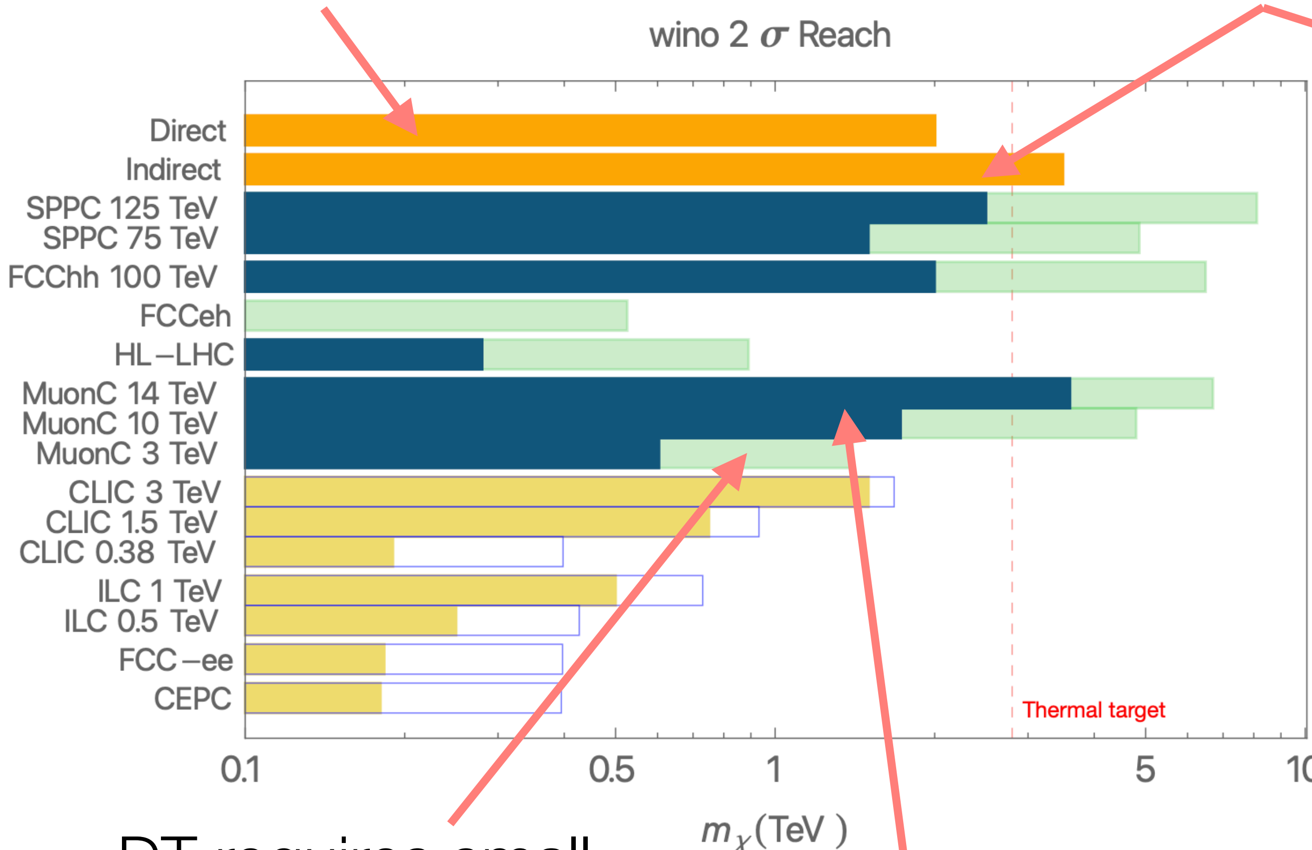

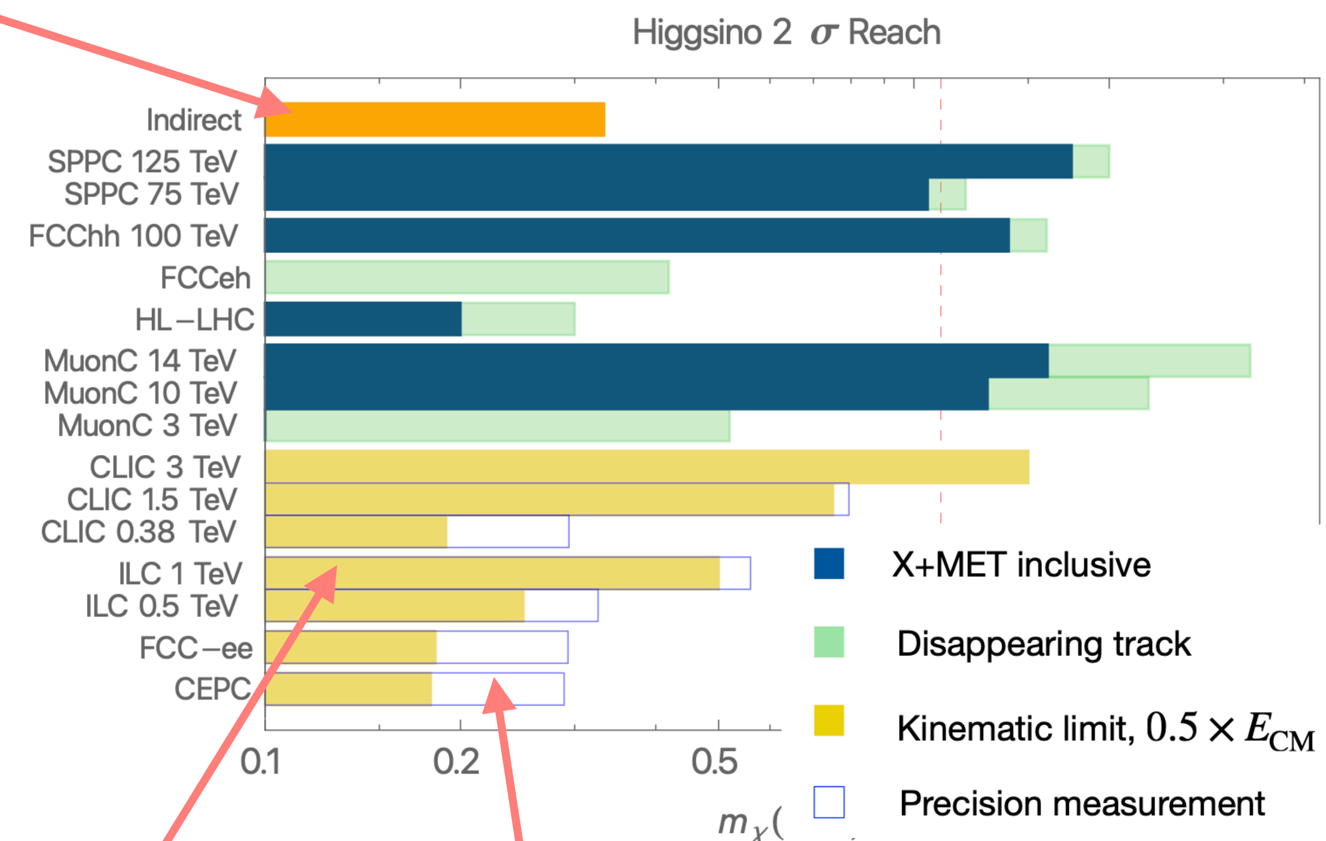

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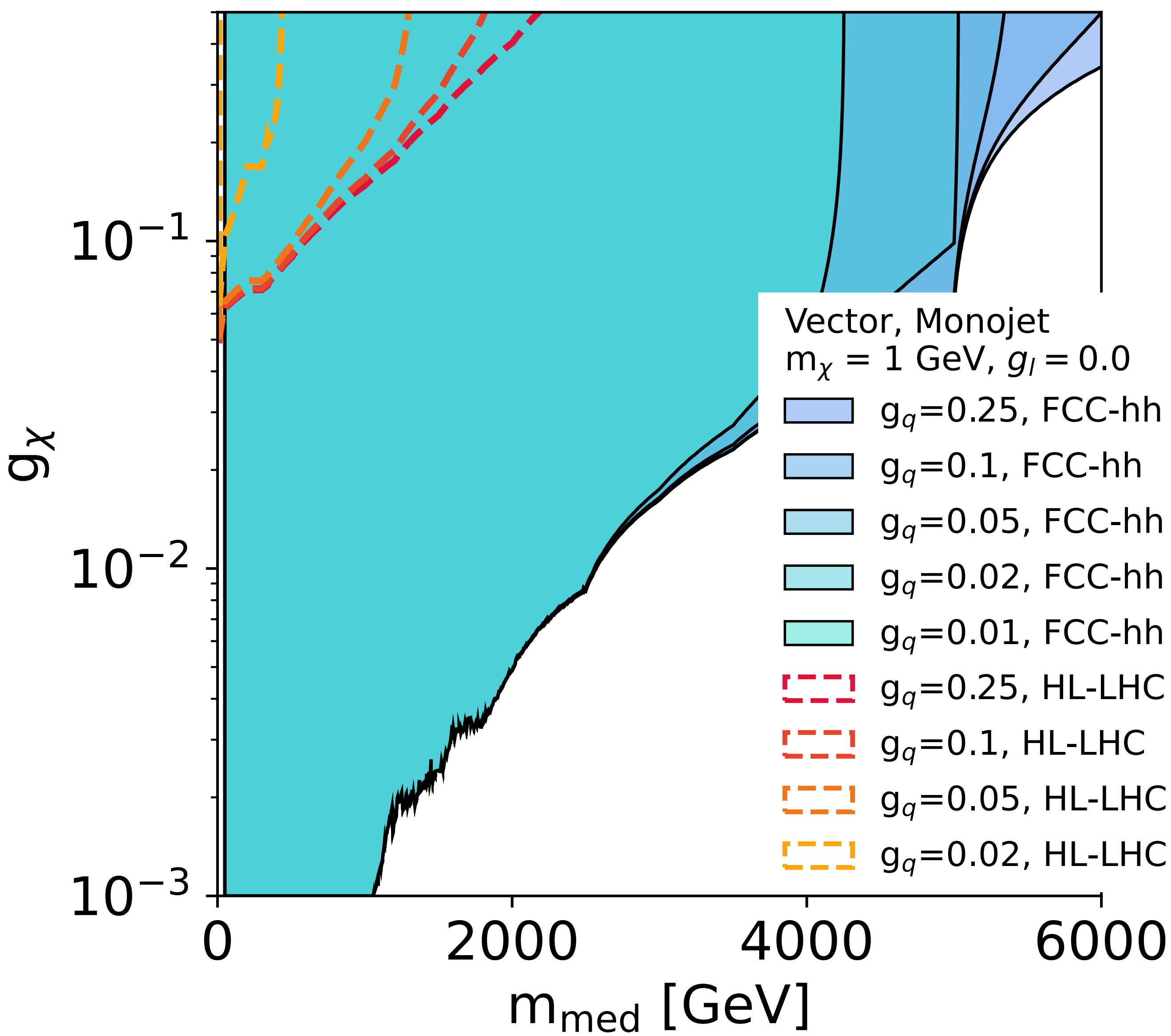
Reaching thermal target is not easy, but possible at some colliders

Opportunities at future colliders: non-SUSY DM



Spin-1 vector mediator: monojet sensitivity to DM coupling

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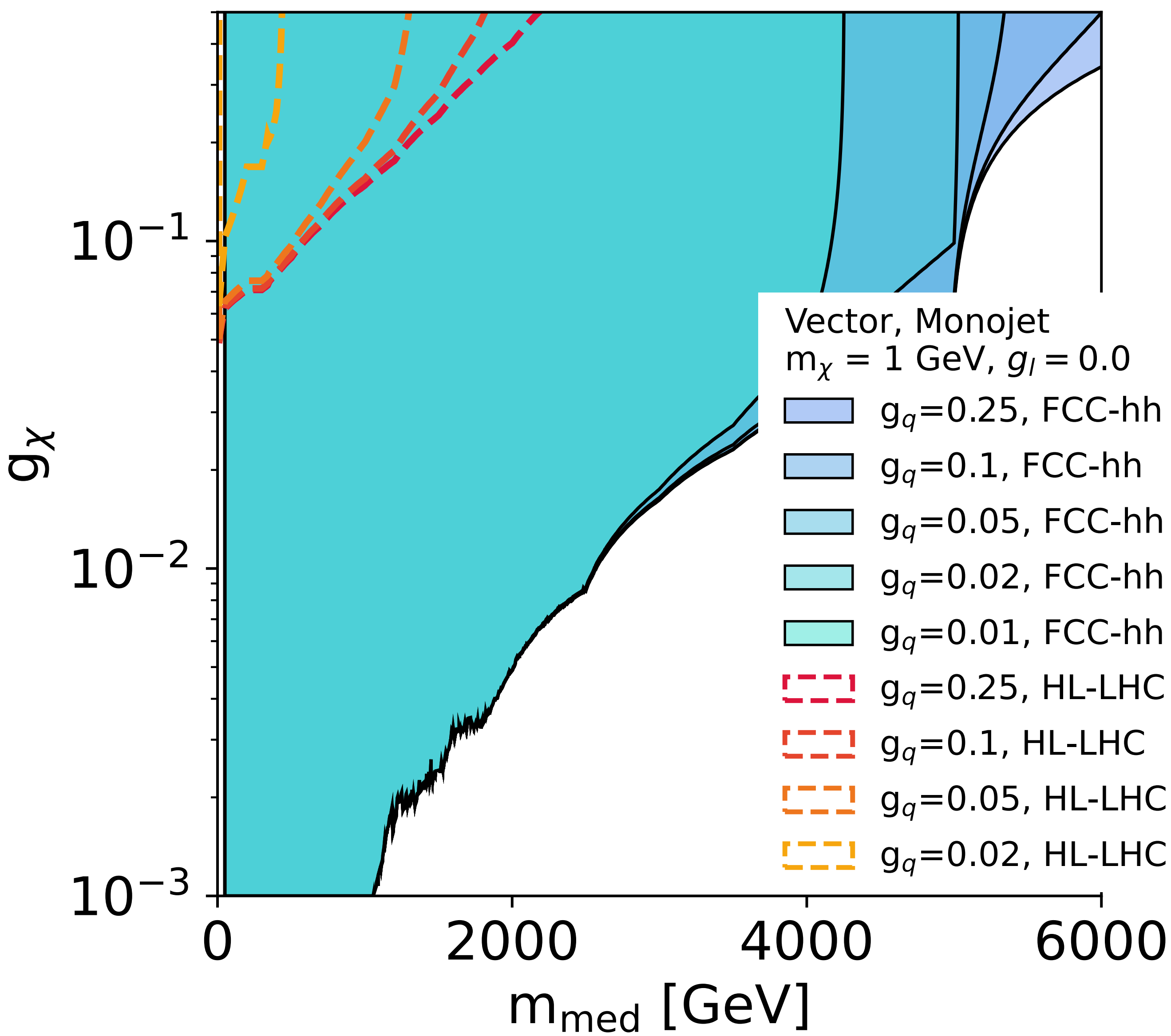

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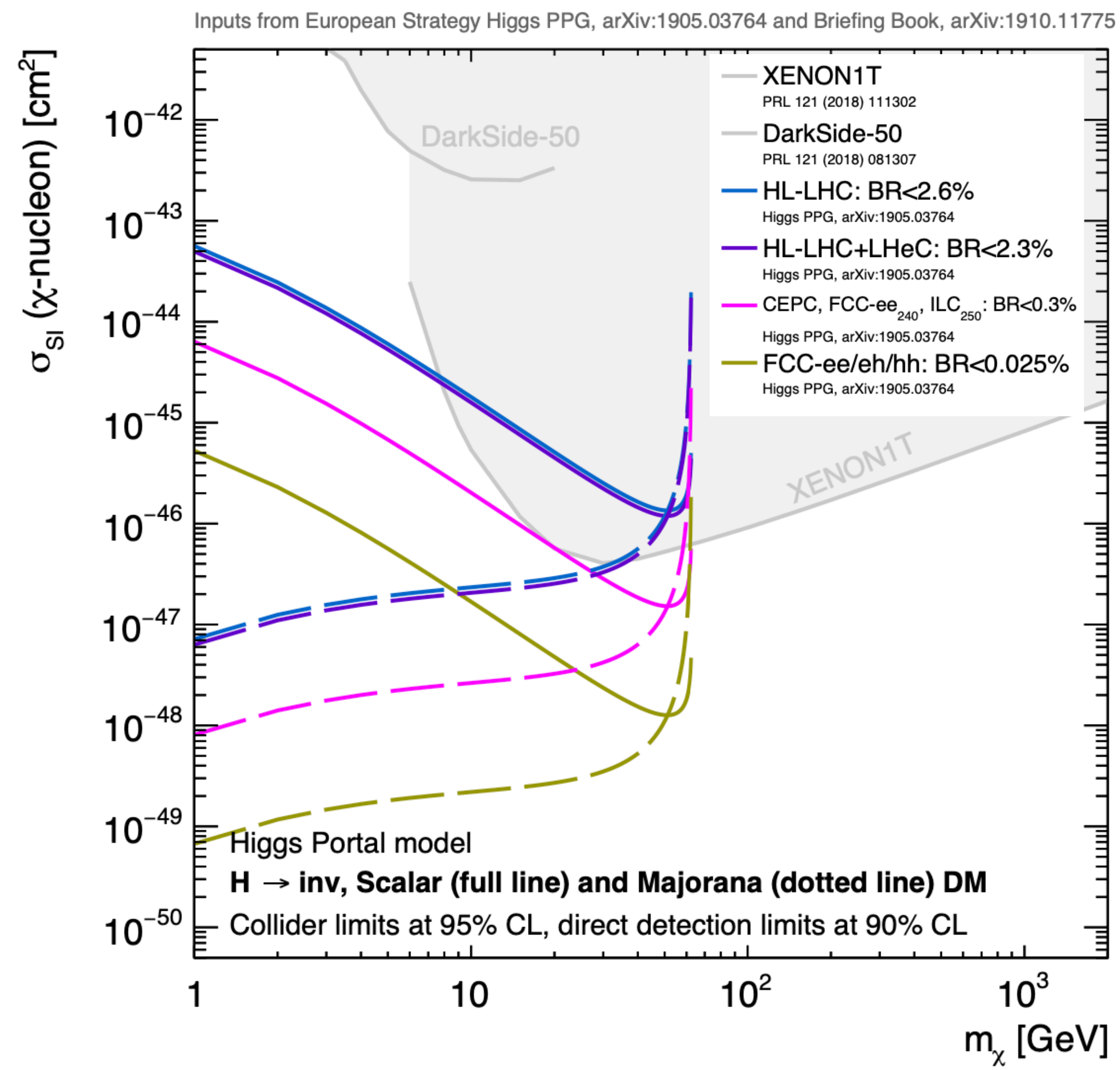

Higgs portal: $H \to \mathrm{inv}$ sensitivity compared to current DD

Parasitic experiments at future colliders

Future colliders have possibilities beyond collision point detectors

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Beam dump experiments

Missing energy/mass experiments not possible at EF machines

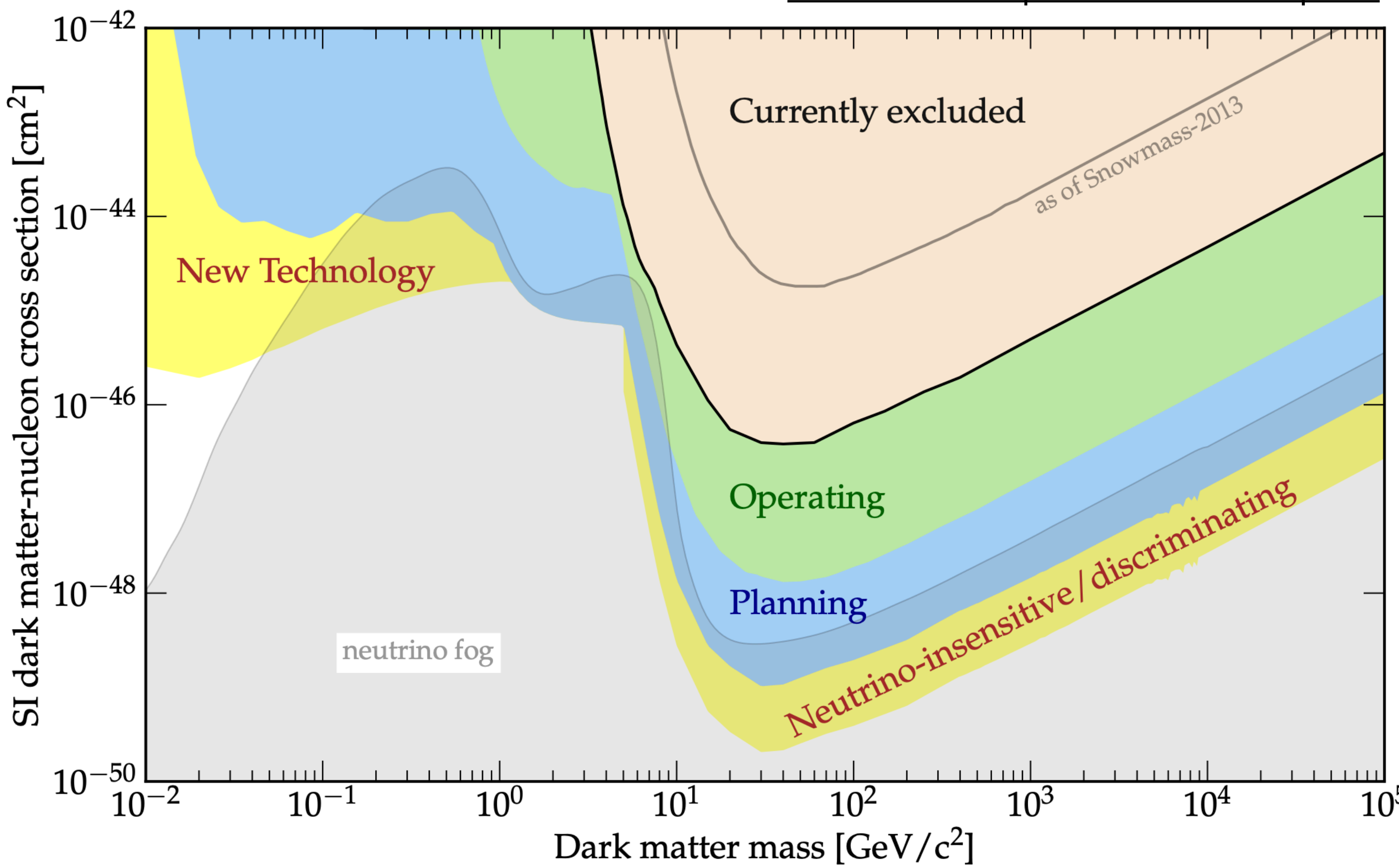
Could probably do a re-scattering experiment here but I've not seen it talked about

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

Discussing complementarity

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

Snowmass particle DM report



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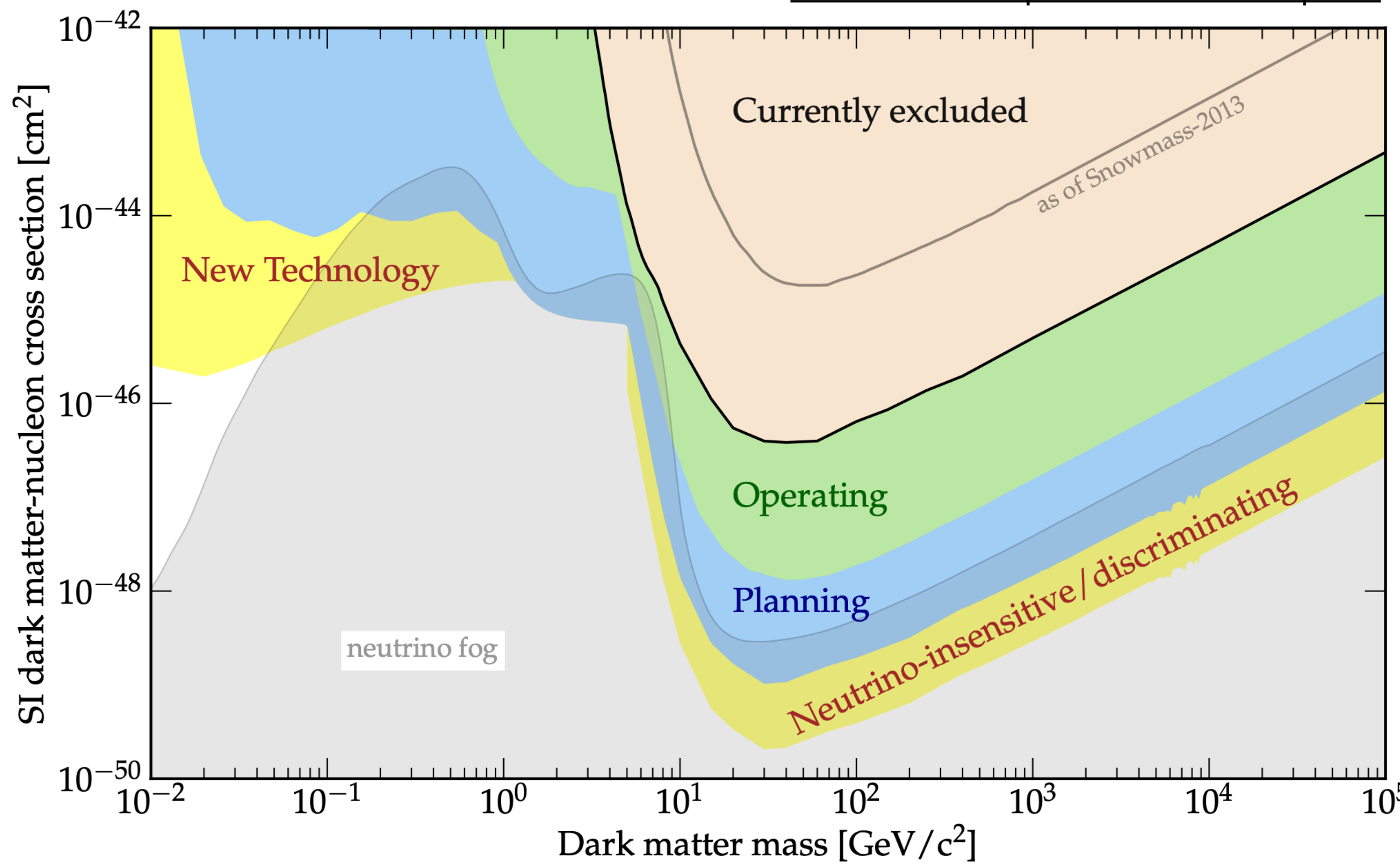

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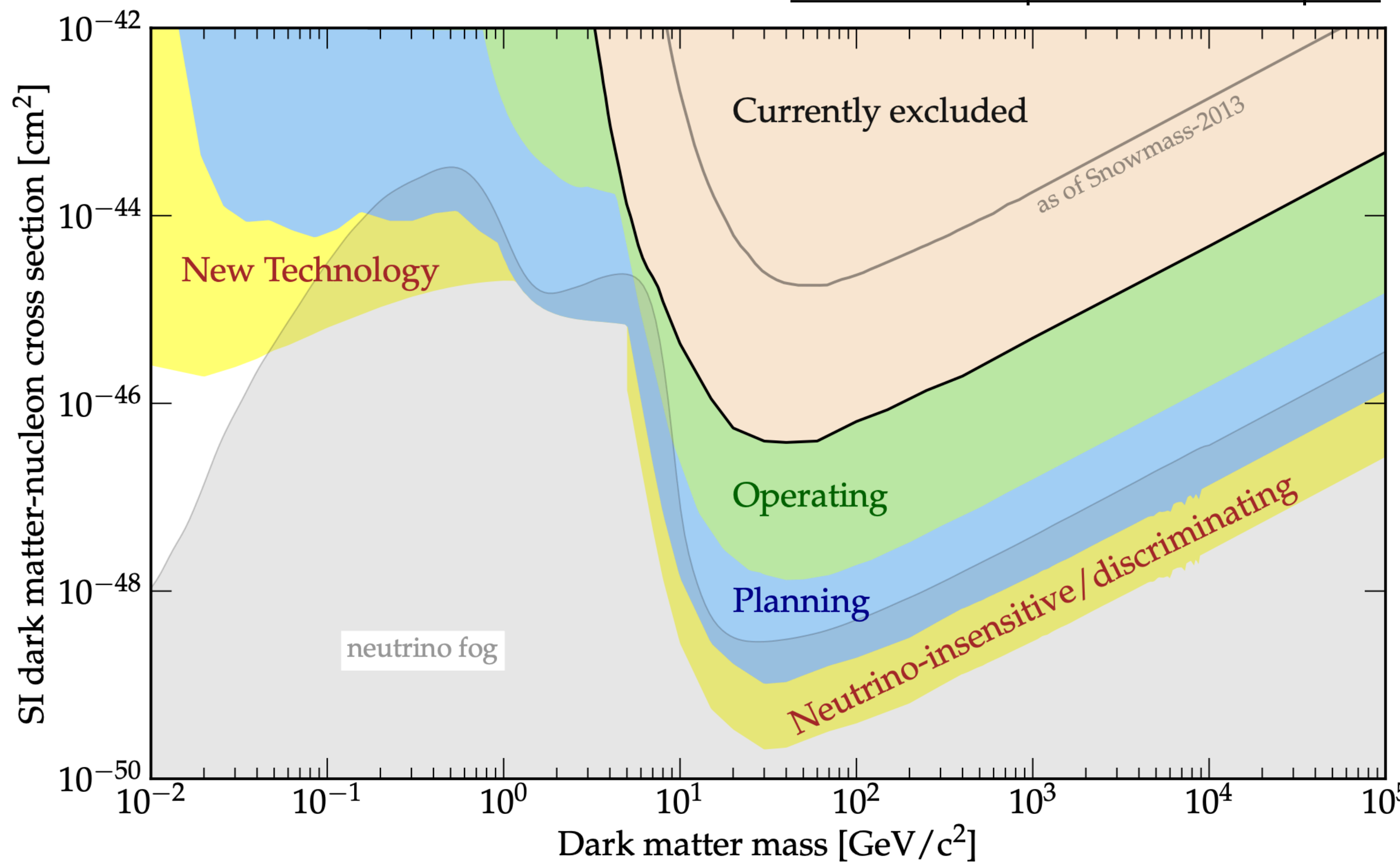

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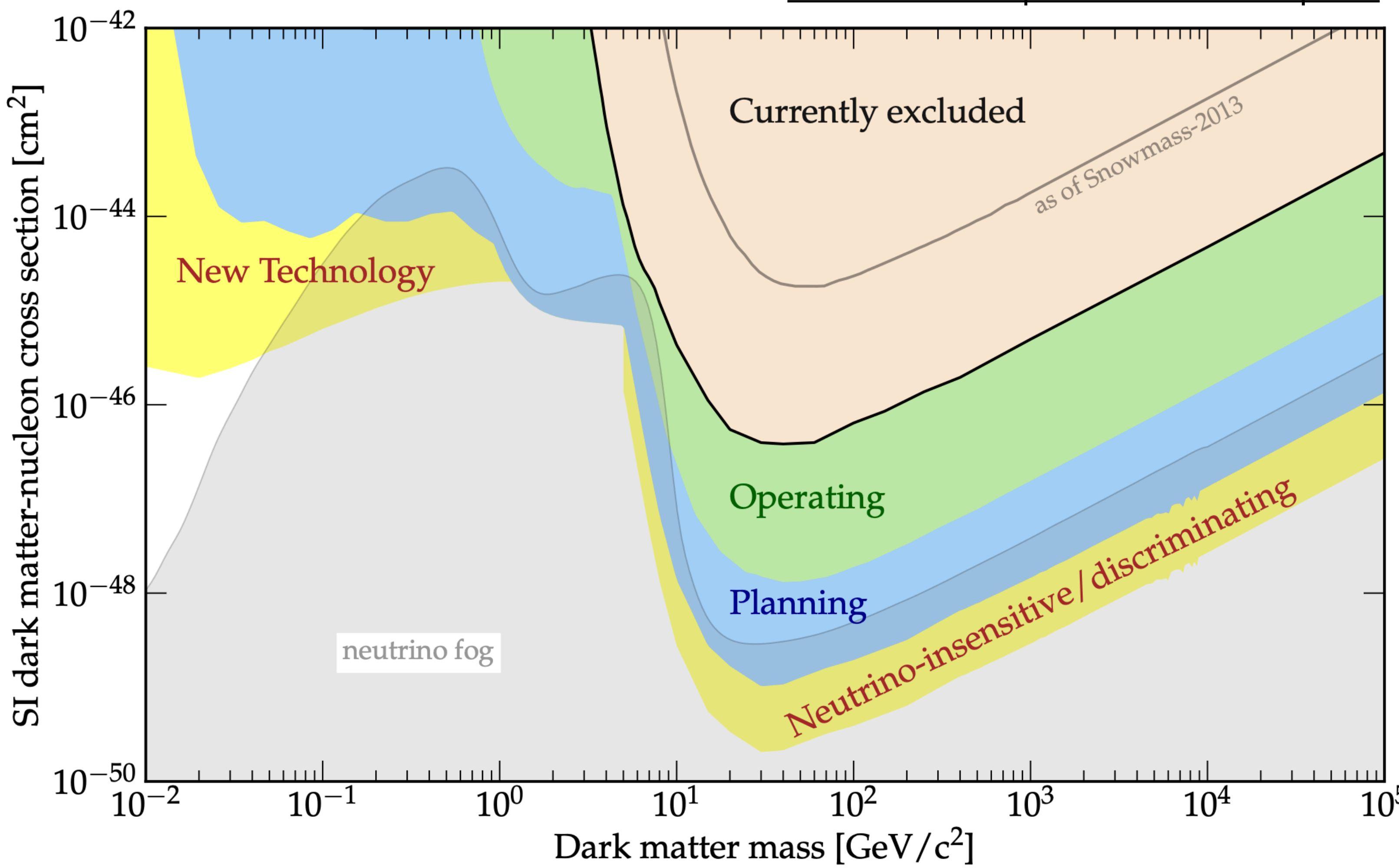

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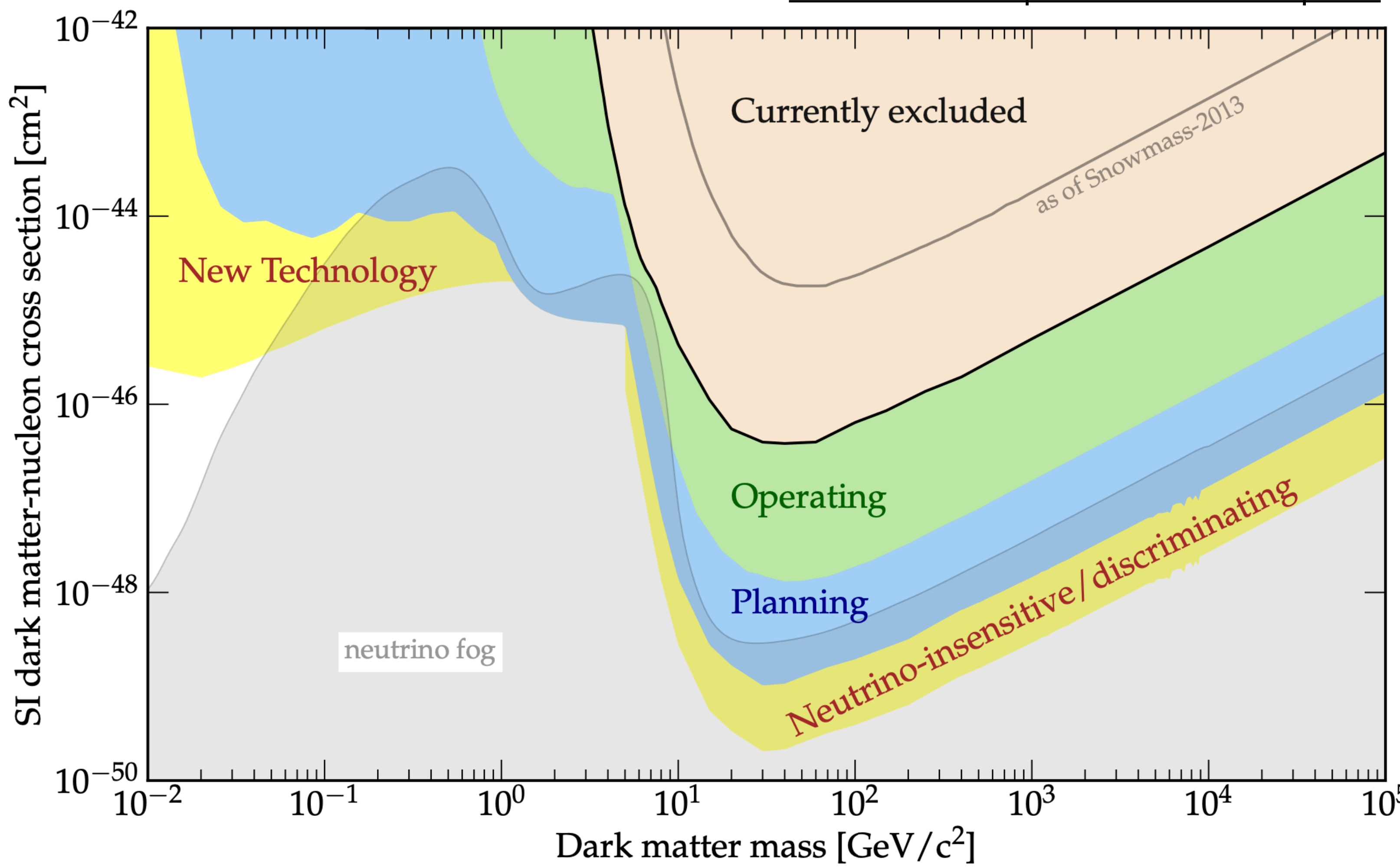

Show example I know best: LHC DMWG spin-1 simplified model

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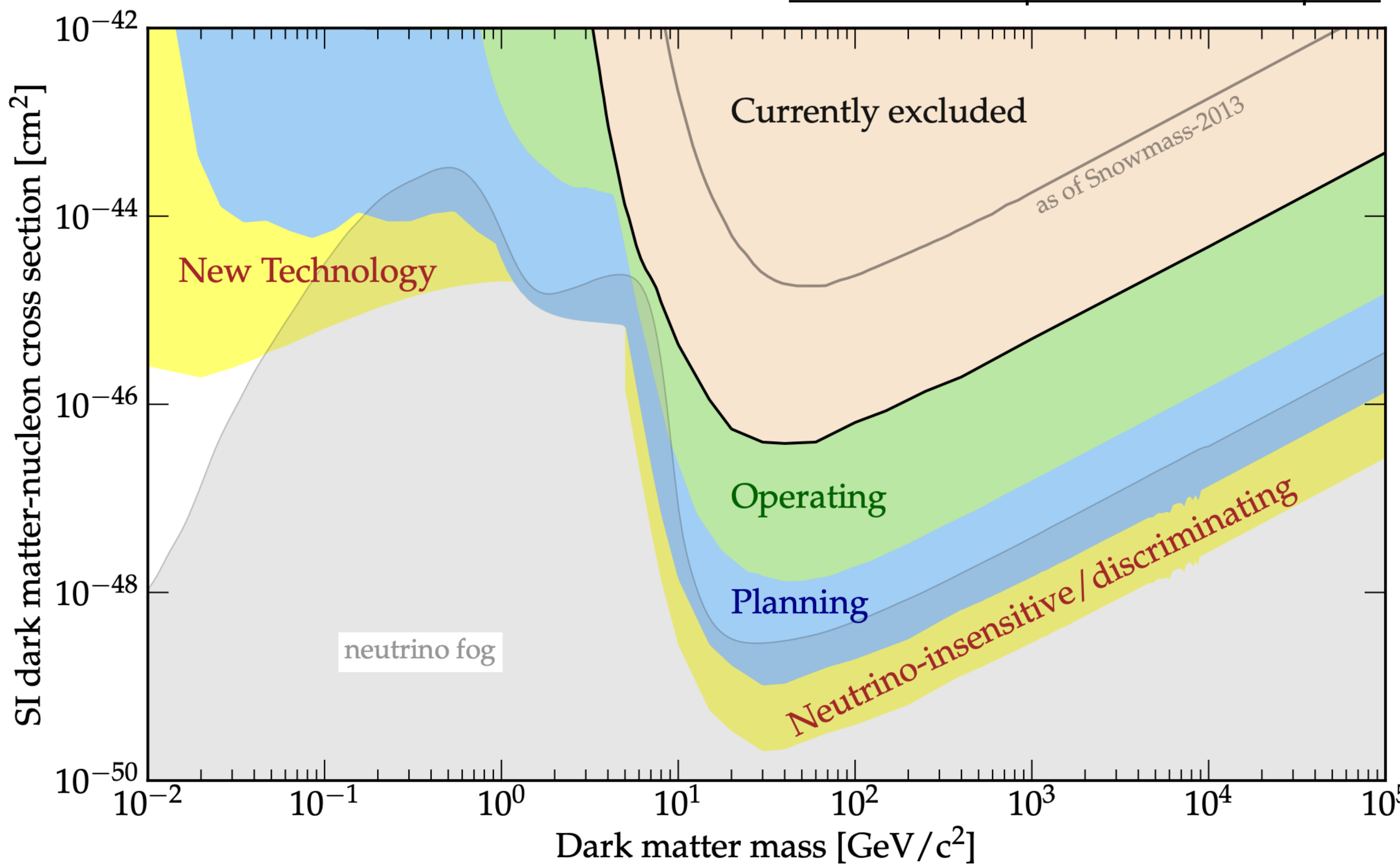

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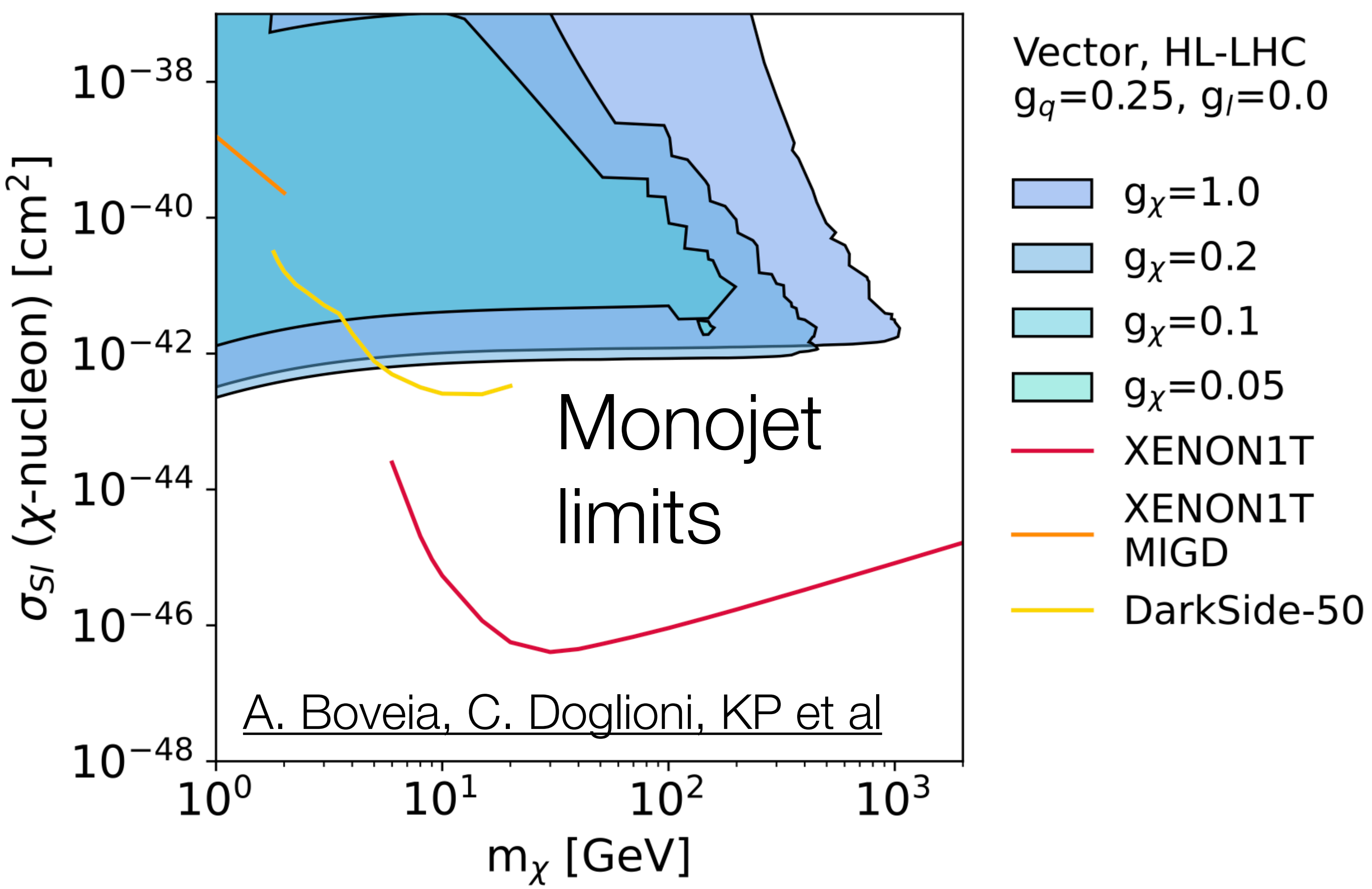
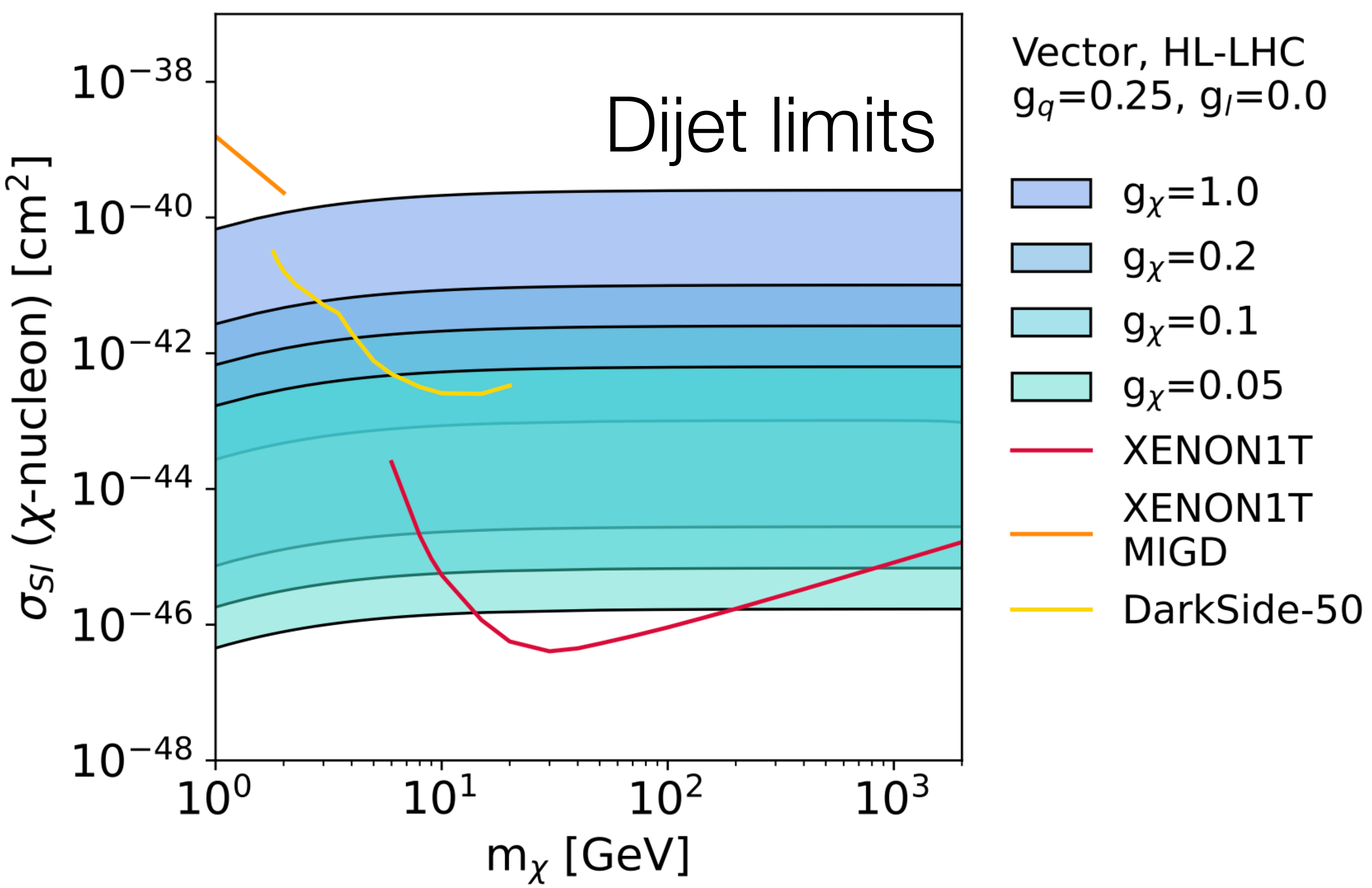
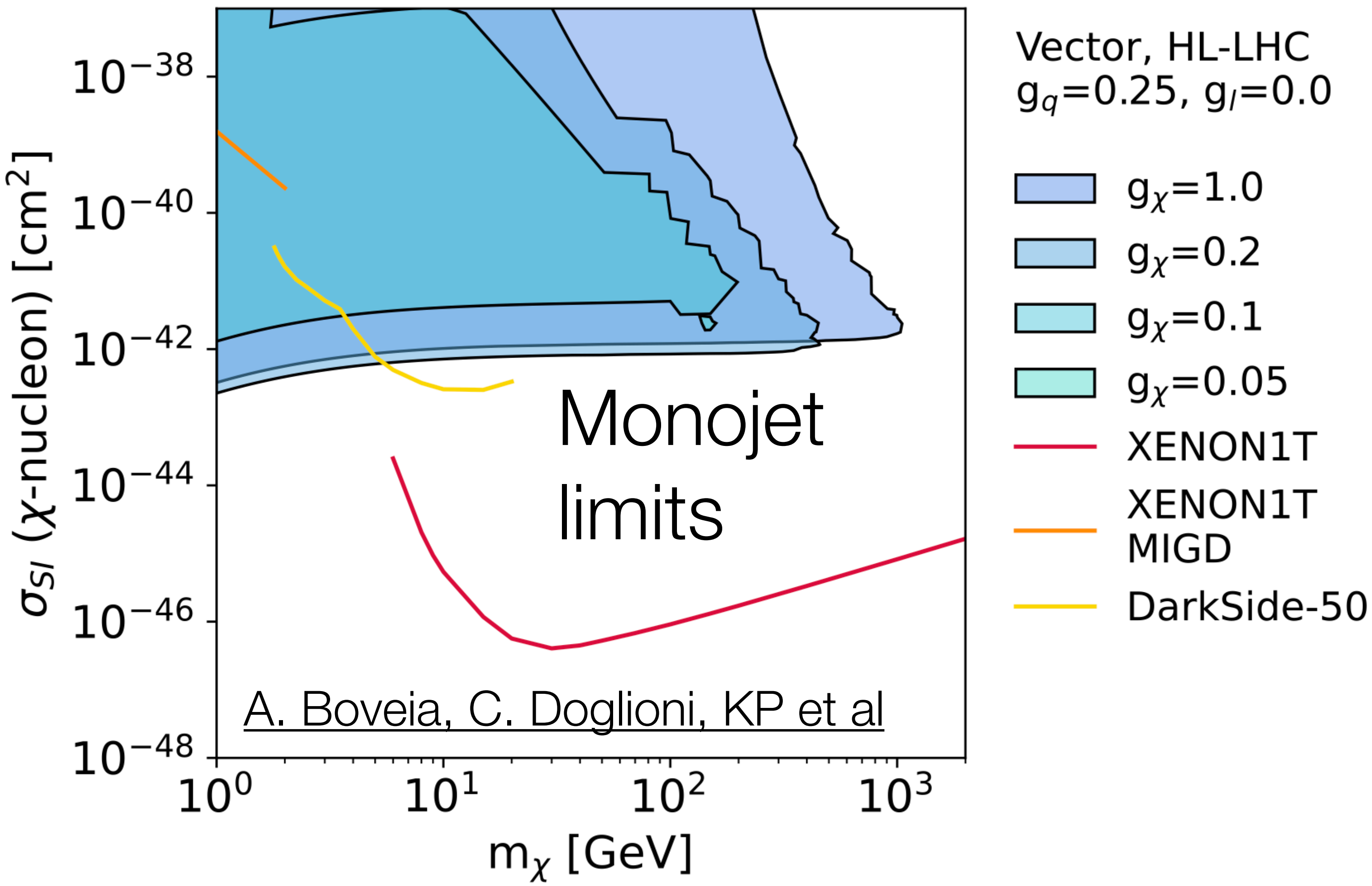
Must reduce 4-5 free parameters (m_{med}, m_χ, g_{SM}, g_χ) to 2





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



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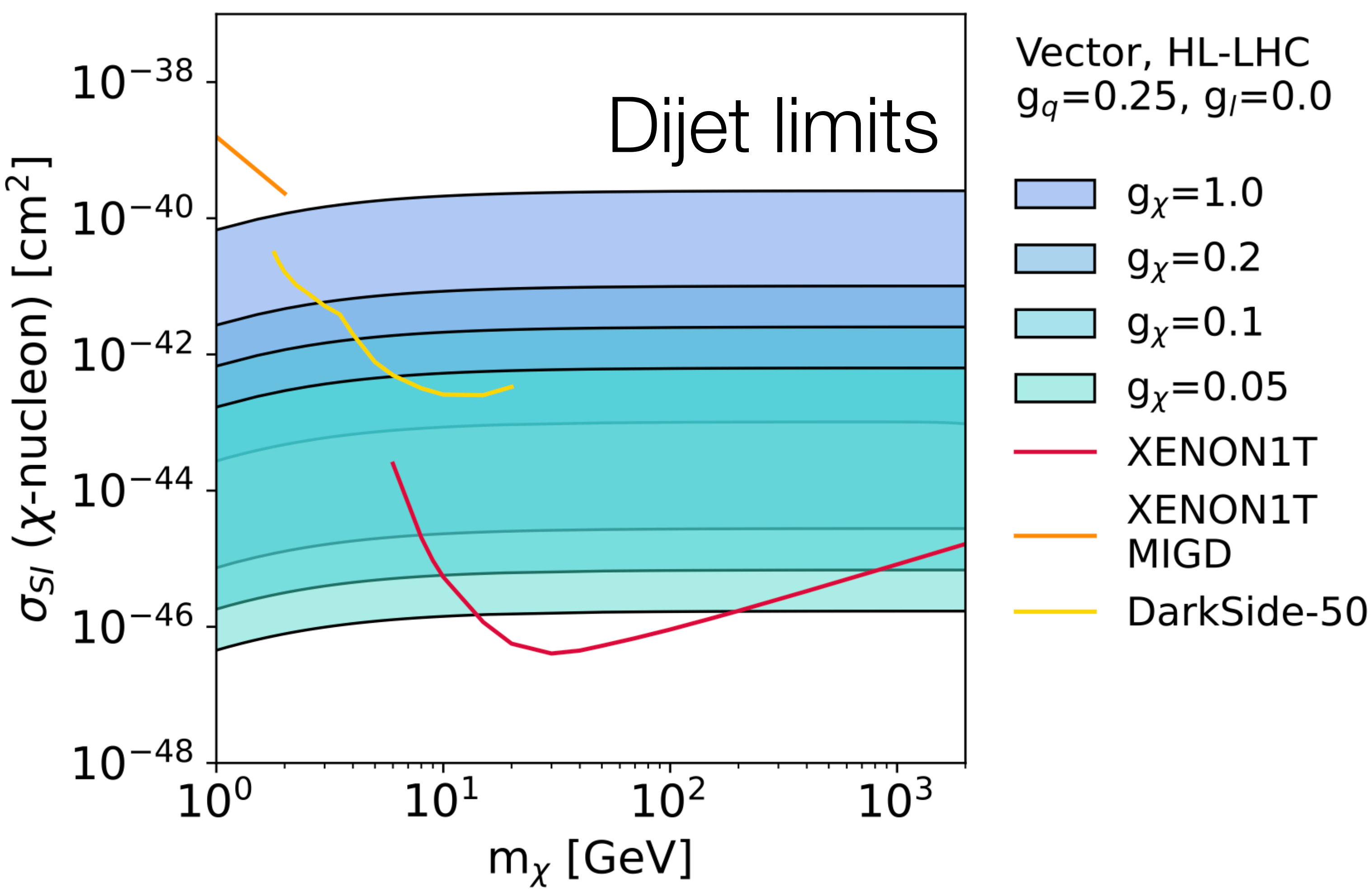

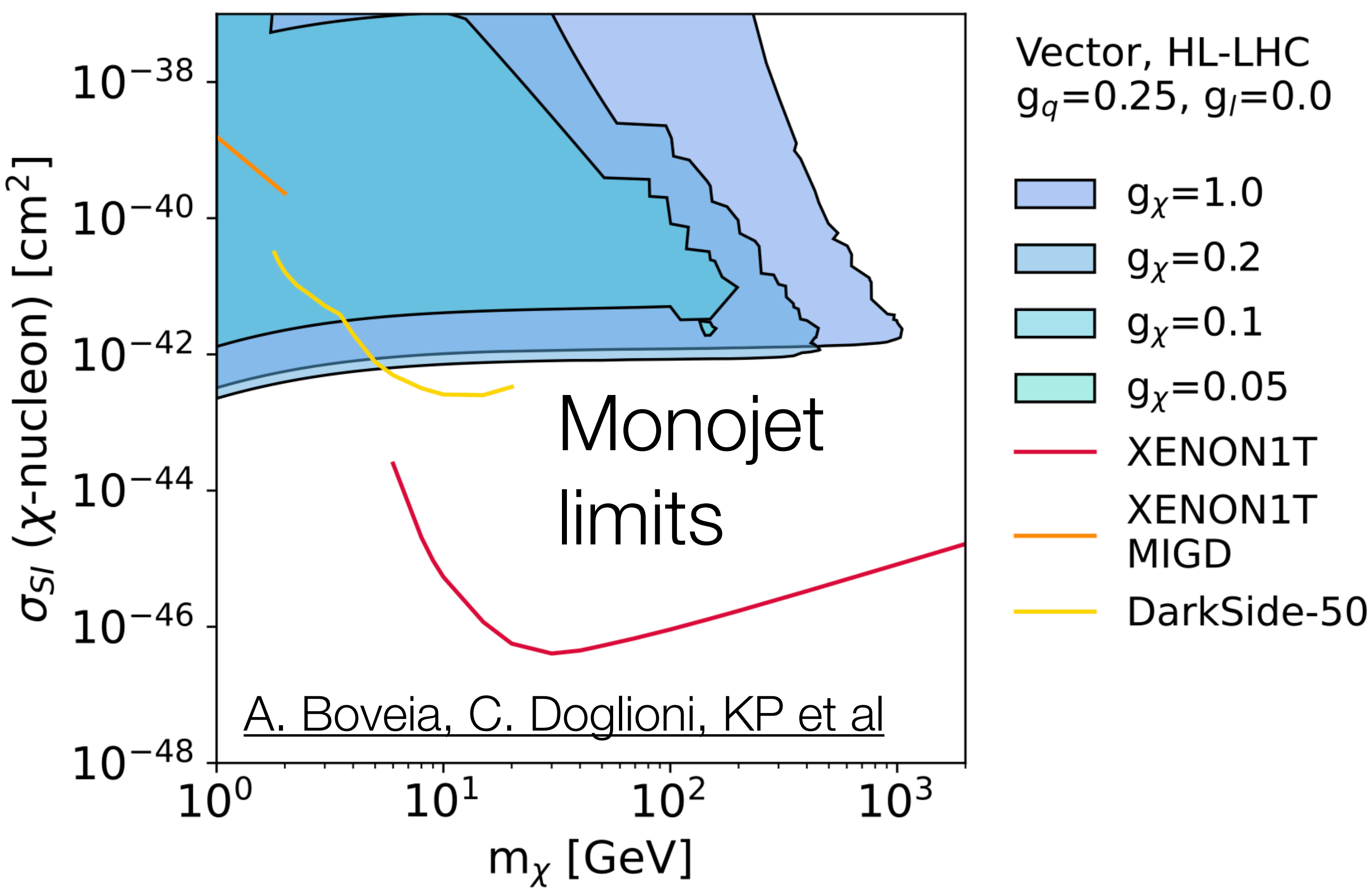

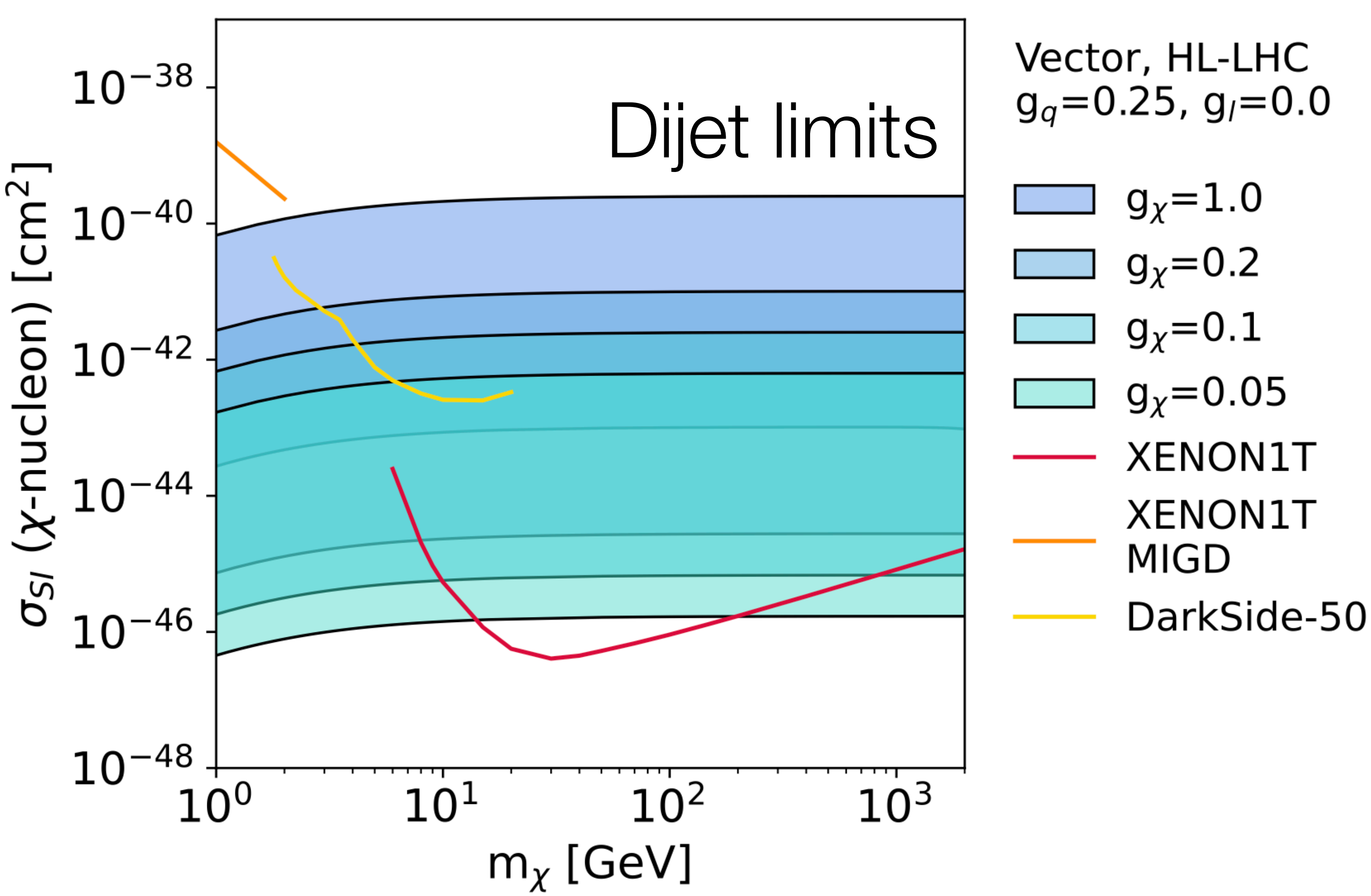

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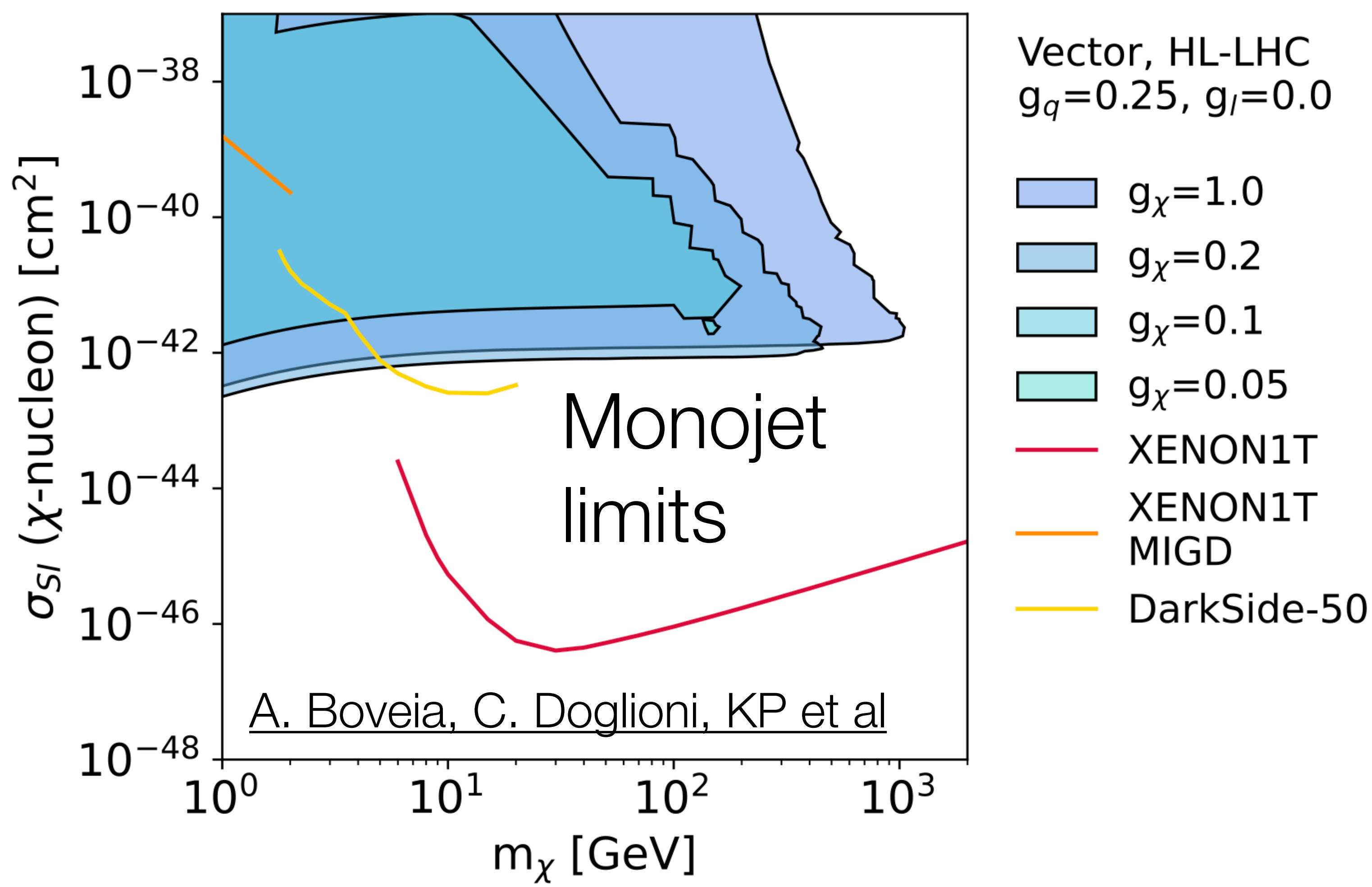
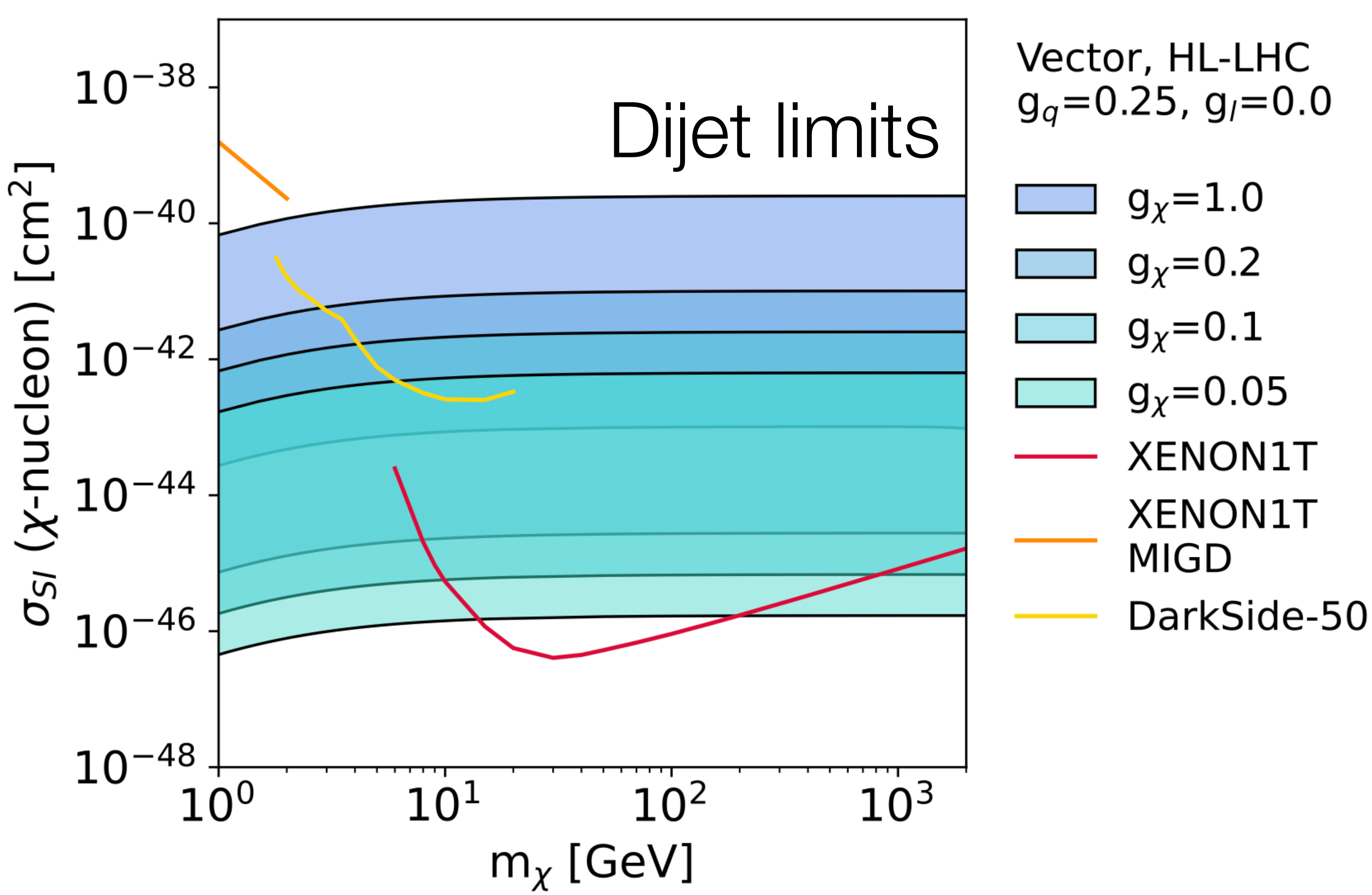
Mediator mass absorbed into y axis variable





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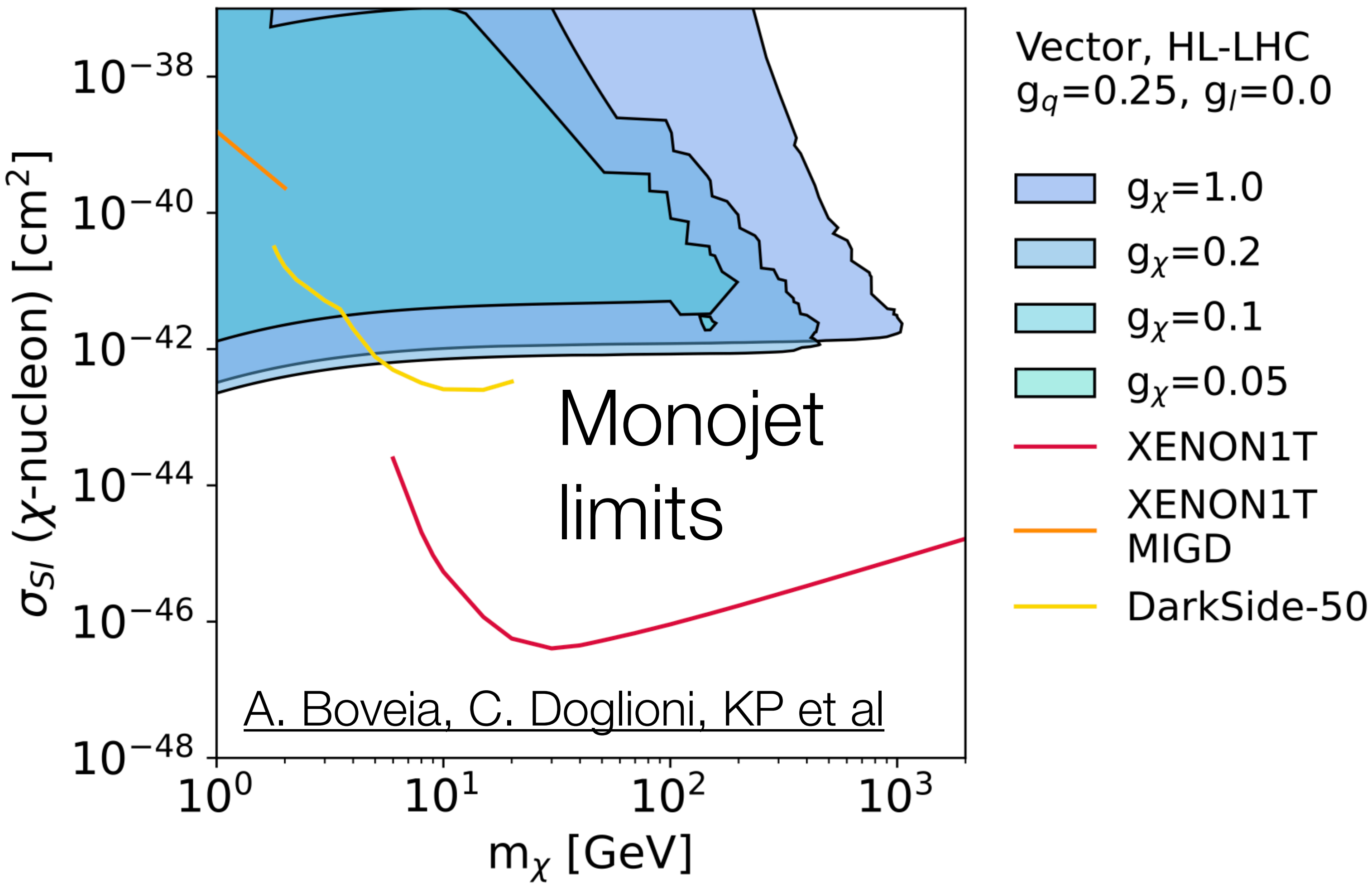

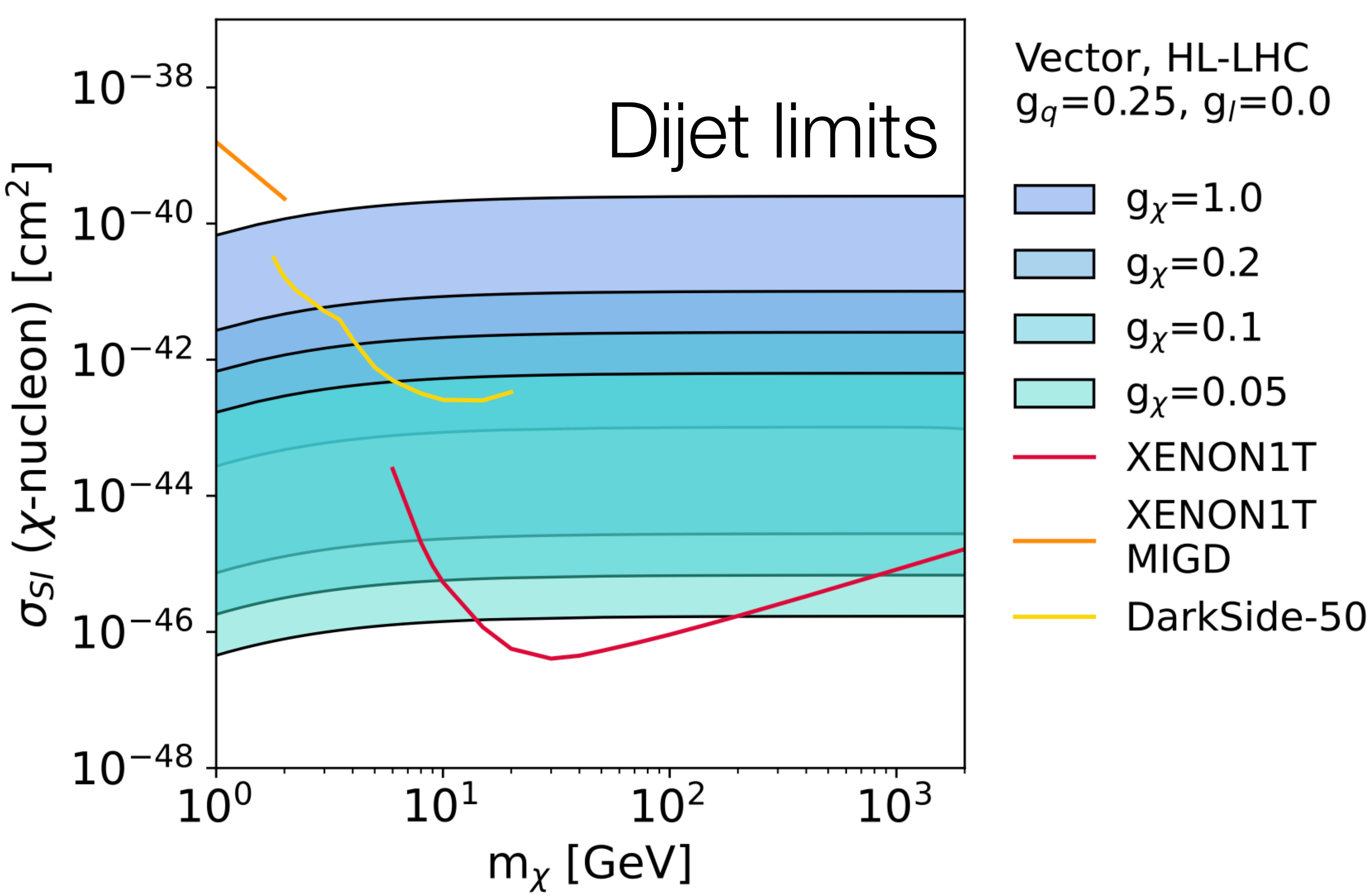

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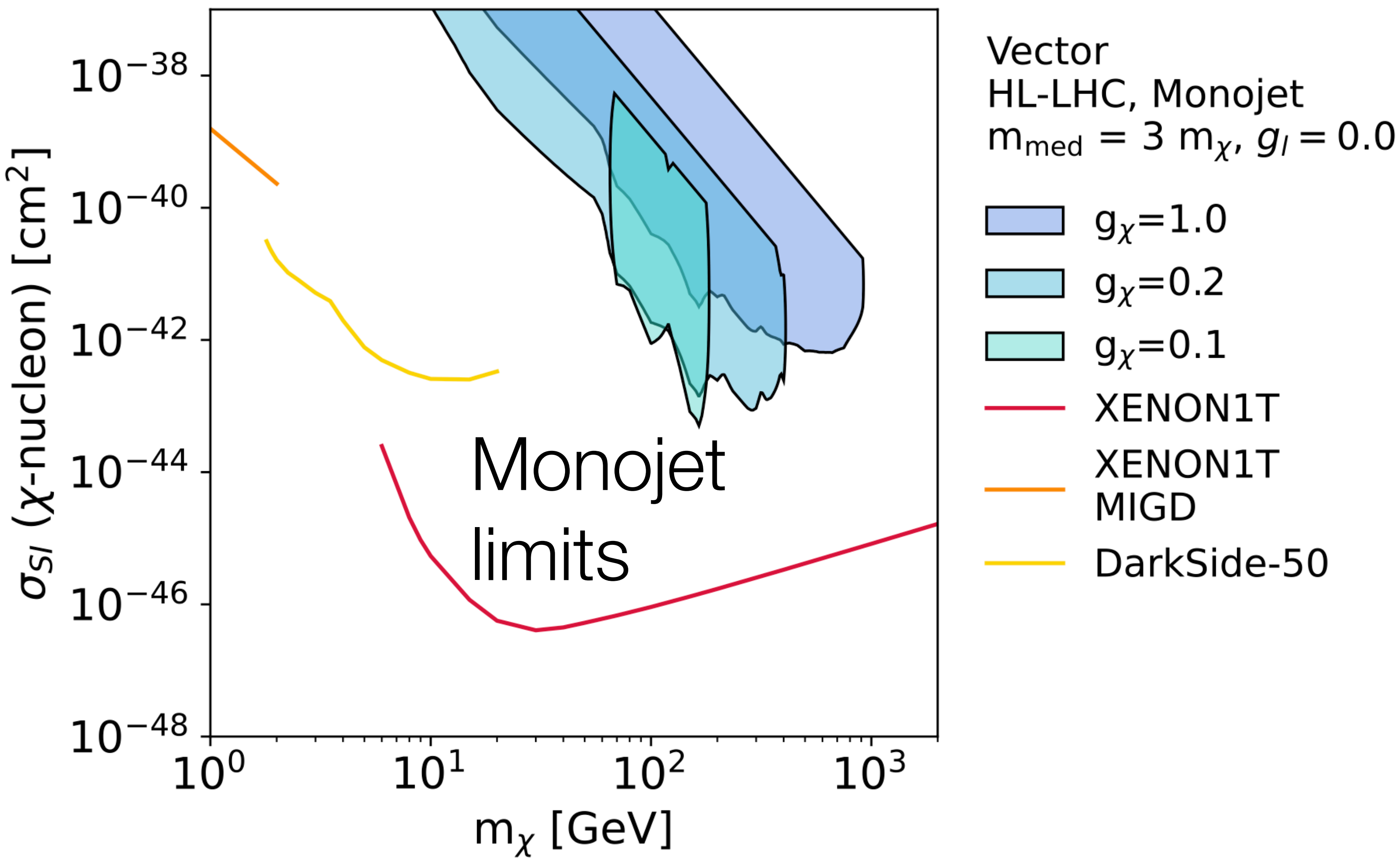
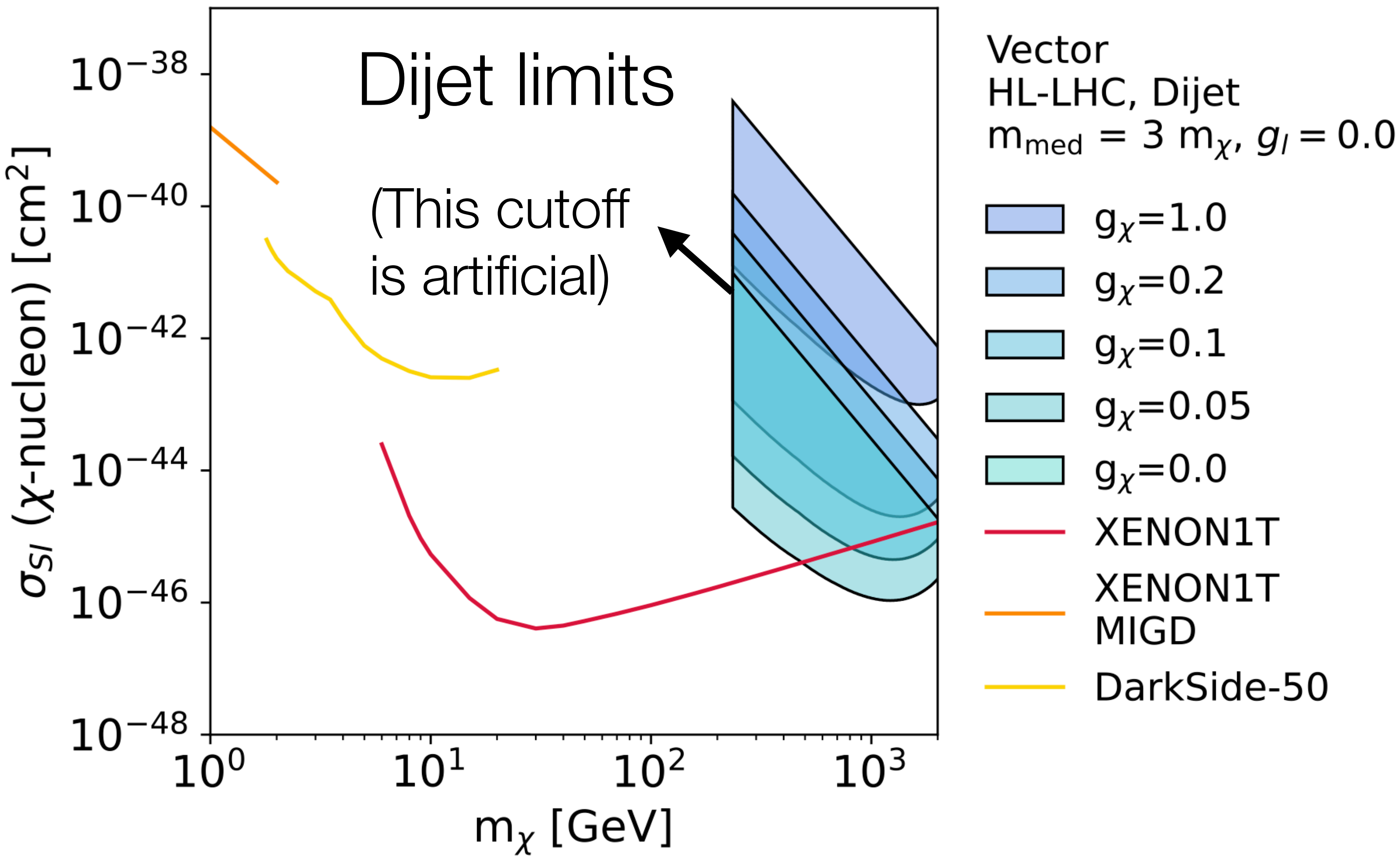
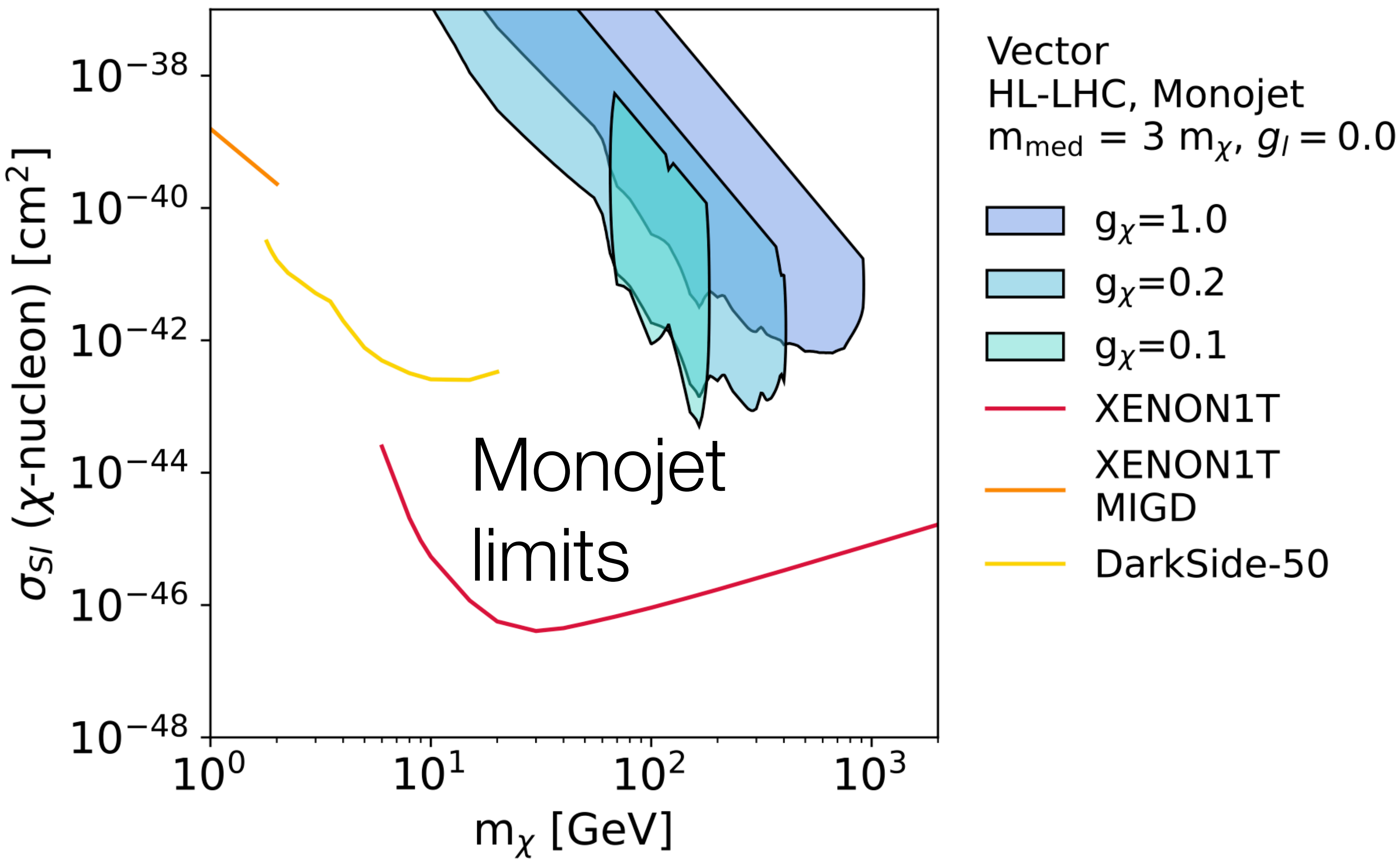
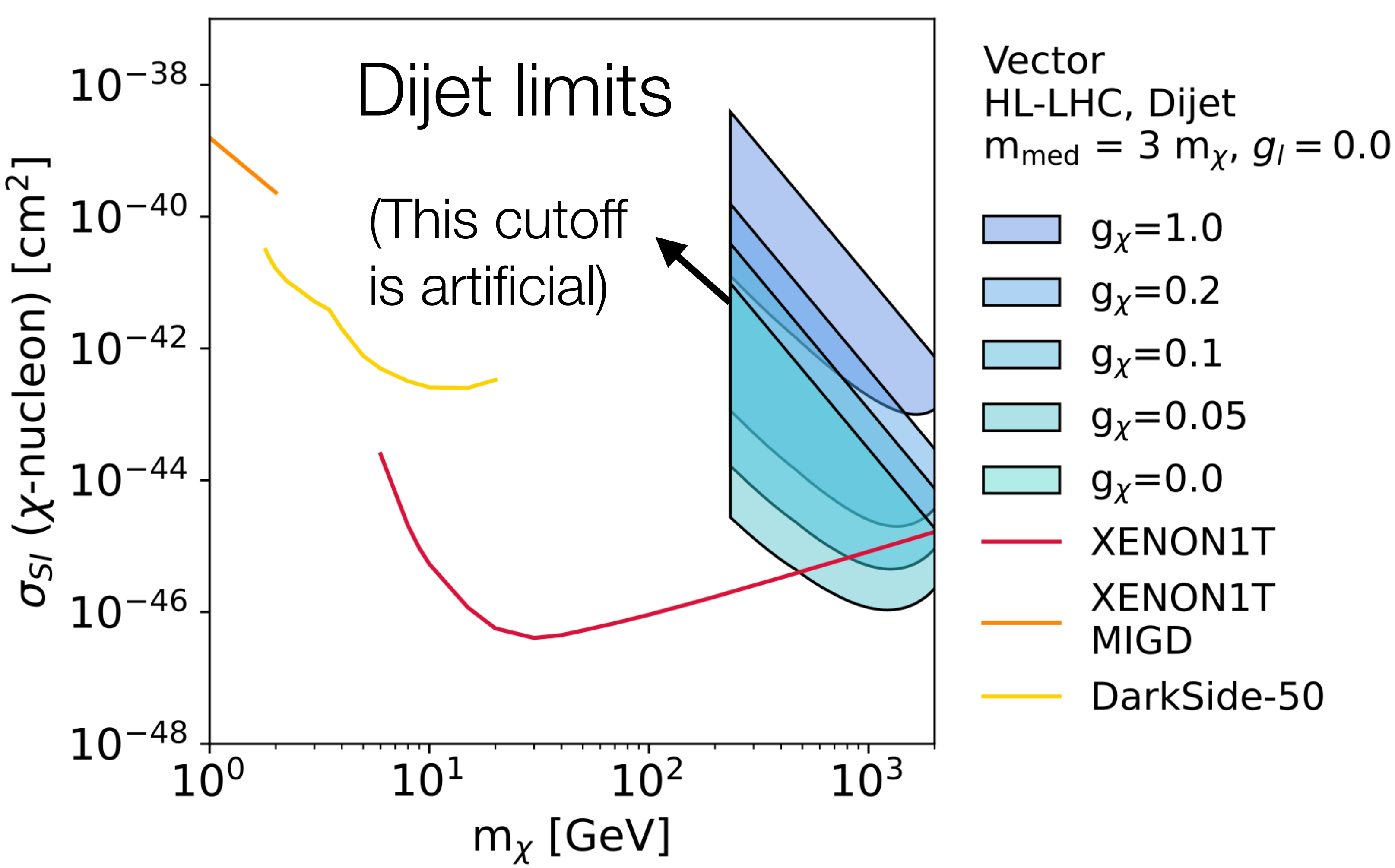
Points with strong collider limits have high mediator mass to DM mass ratio



Same concept, different projection into two dimensions







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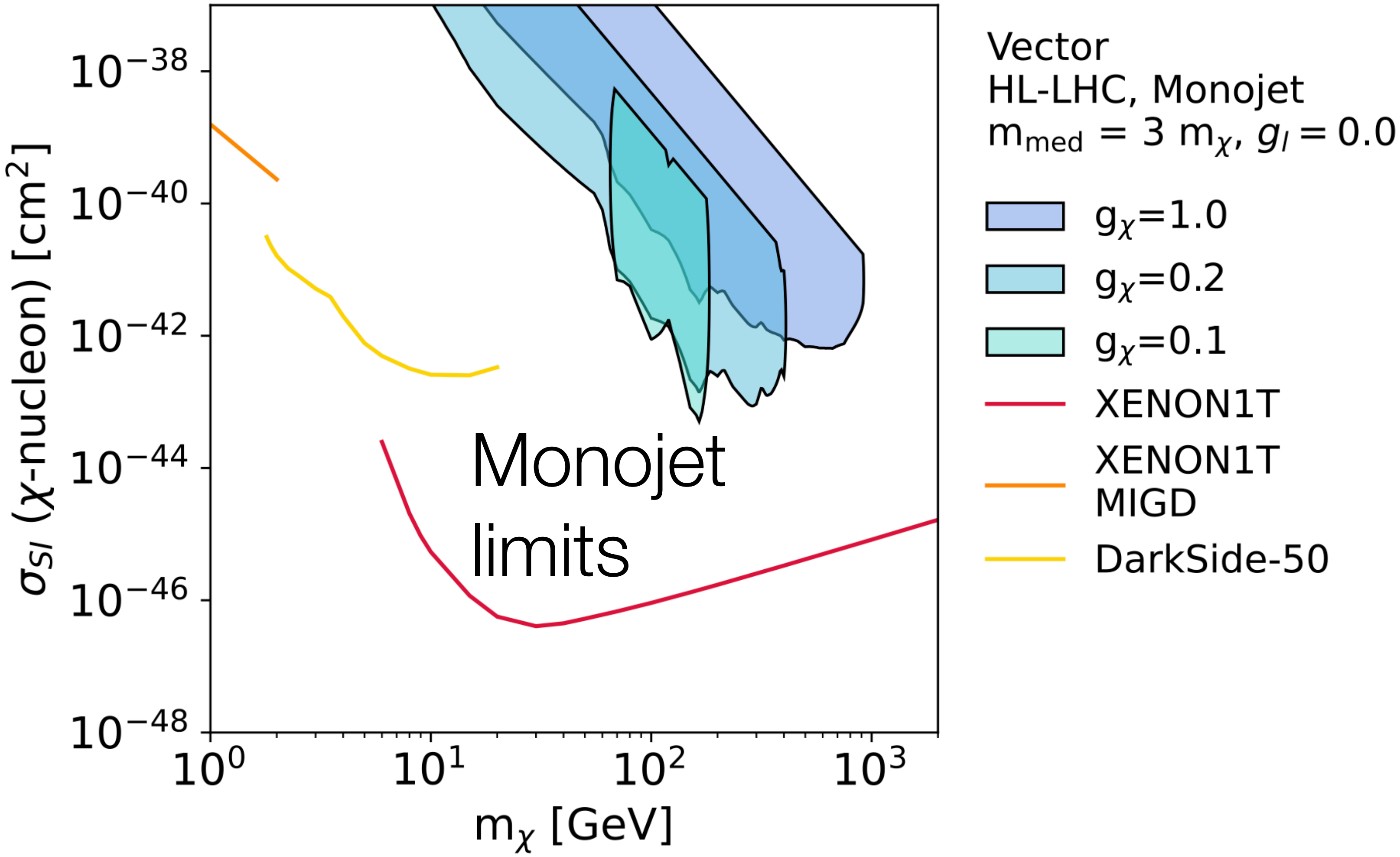
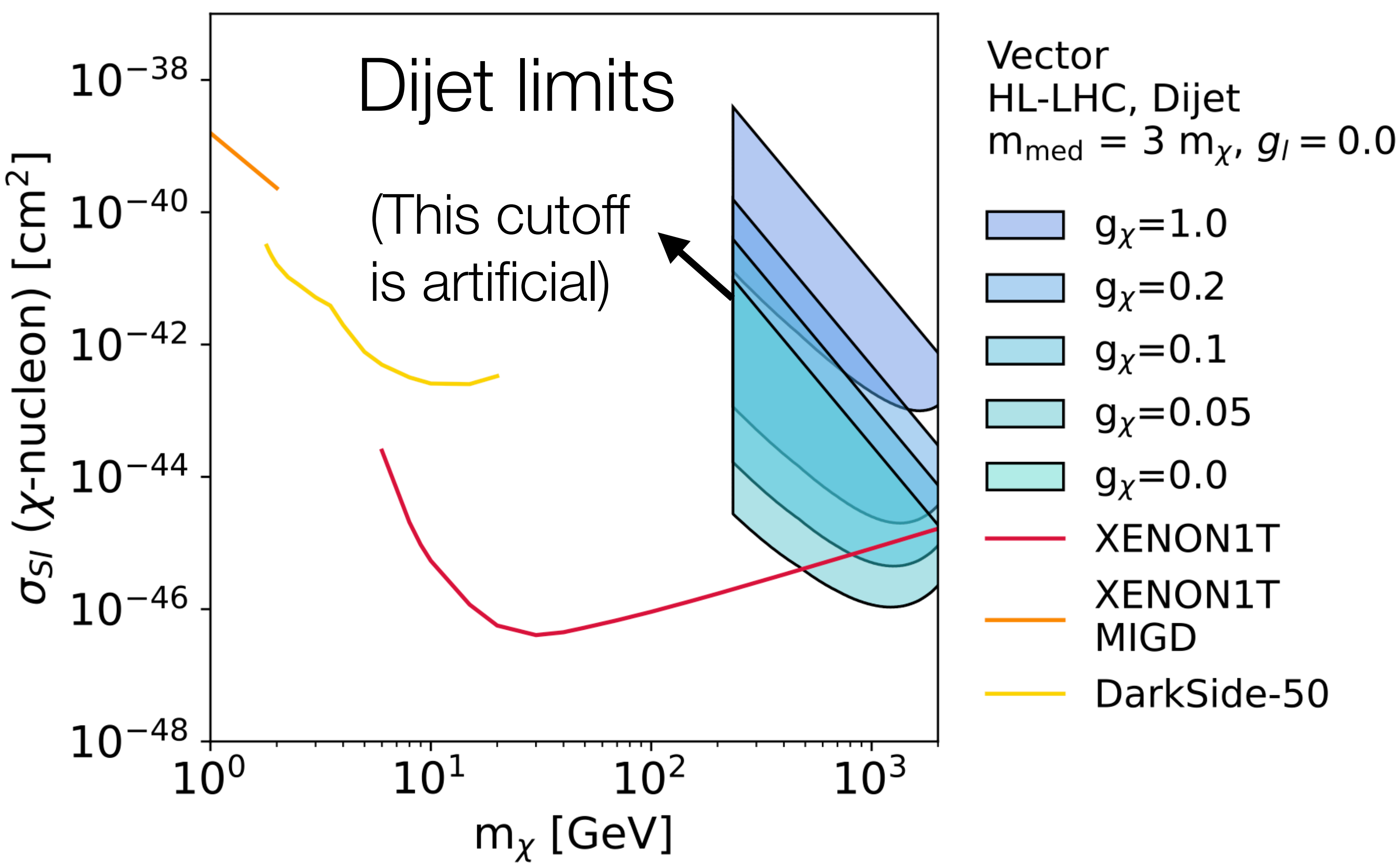
Now ratio between mediators is fixed and g_q is absorbed into y axis





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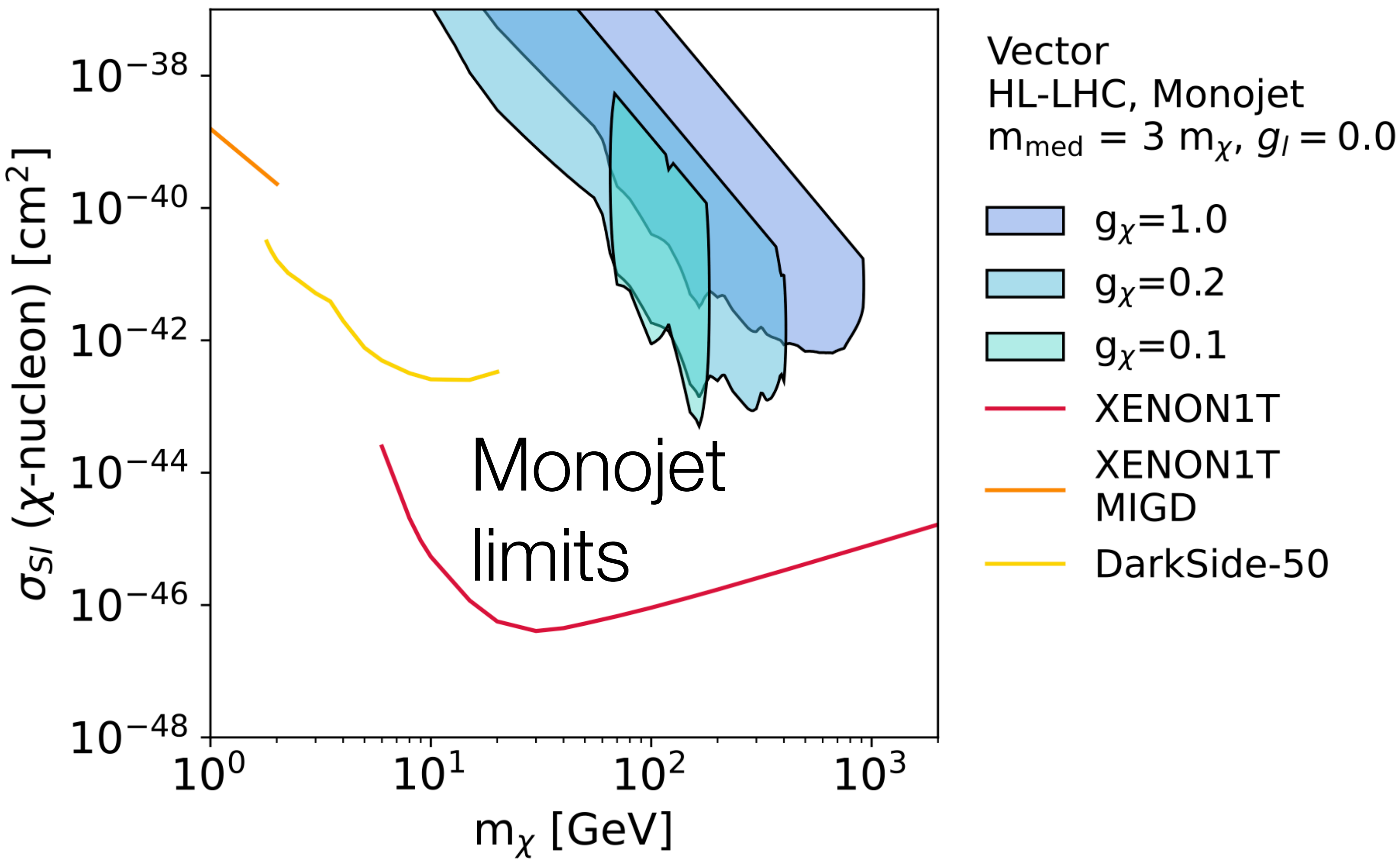
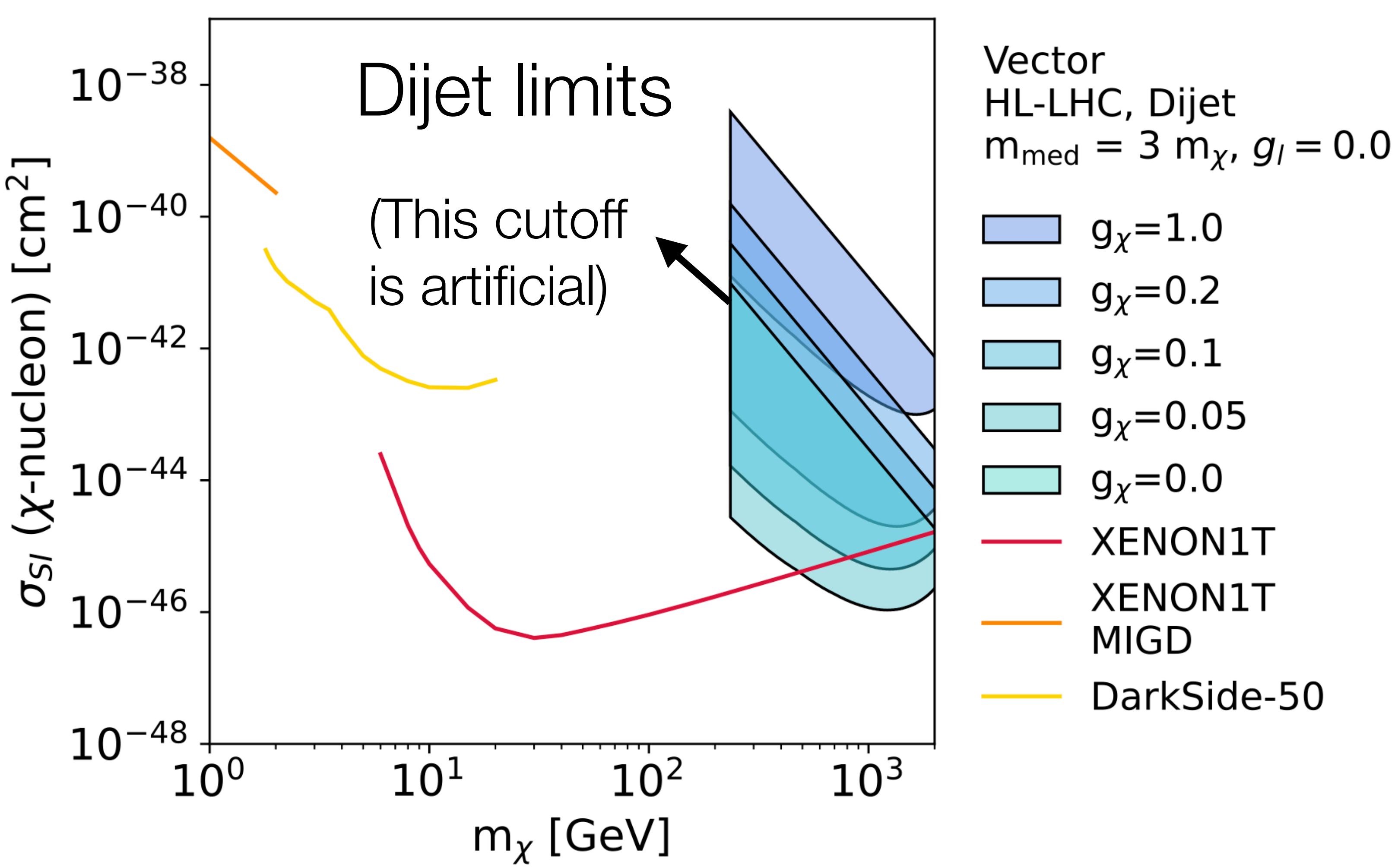
Colliders have unique strengths in accessing heavy mediators





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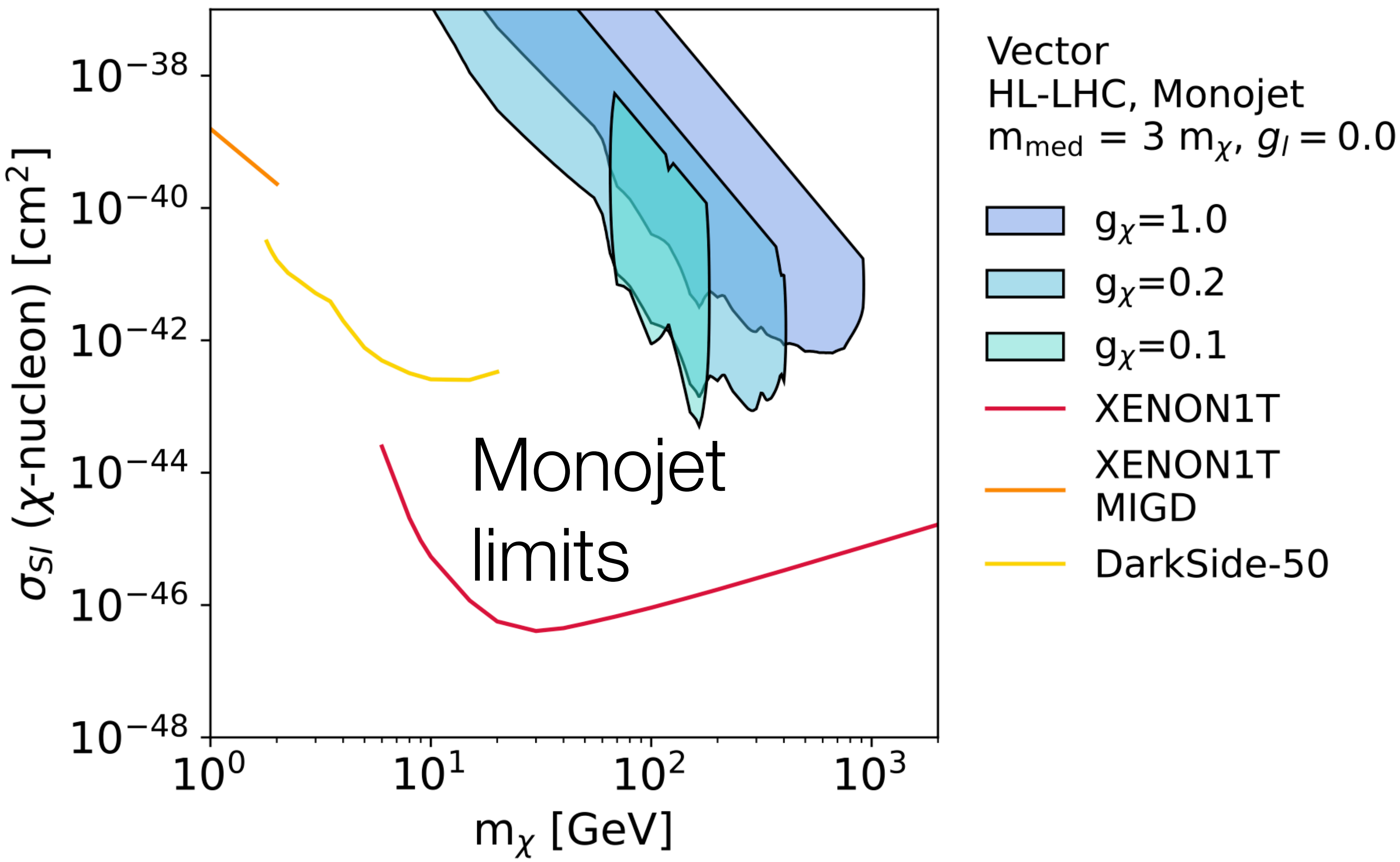
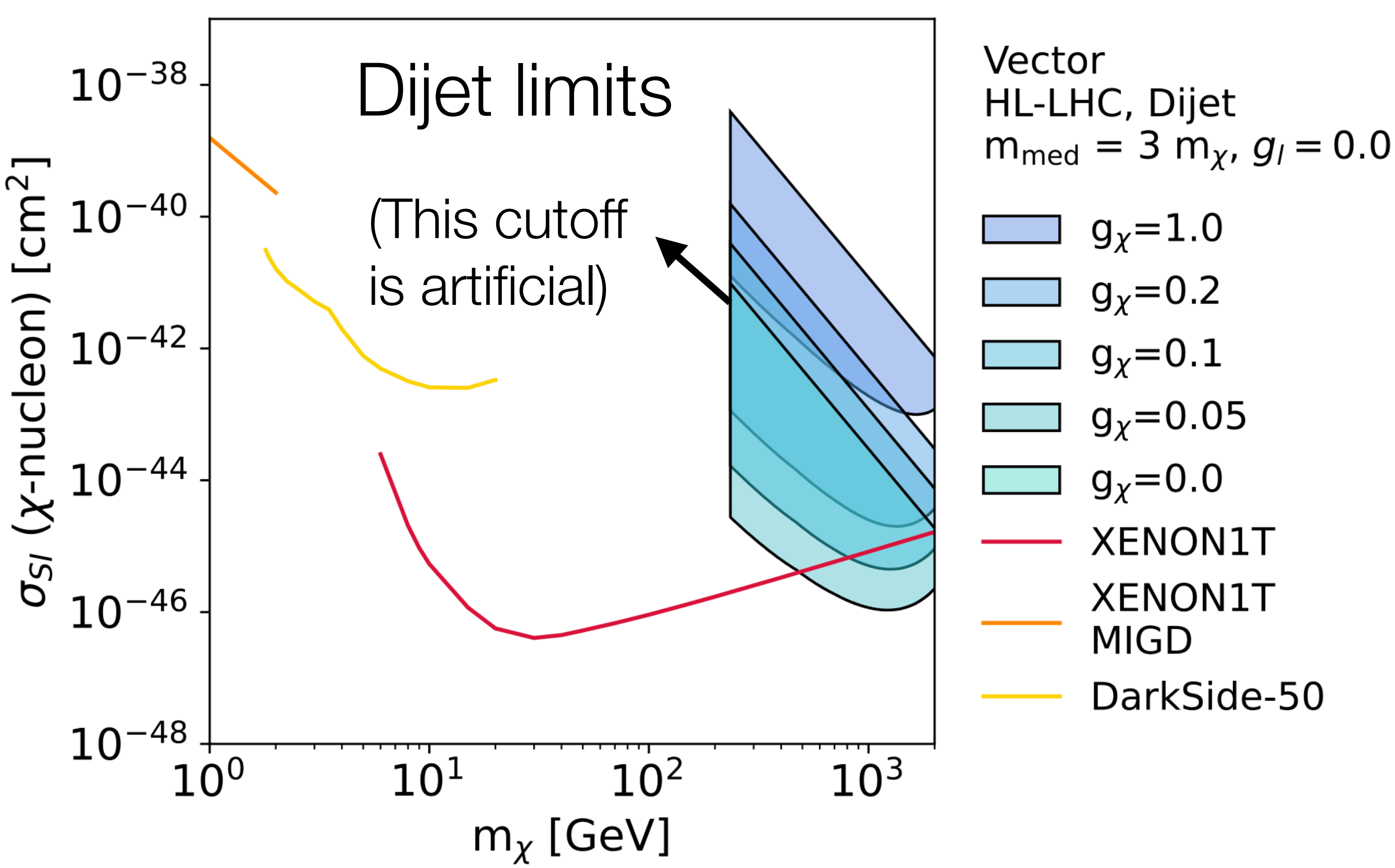
Direct detection has unique strengths in accessing small couplings





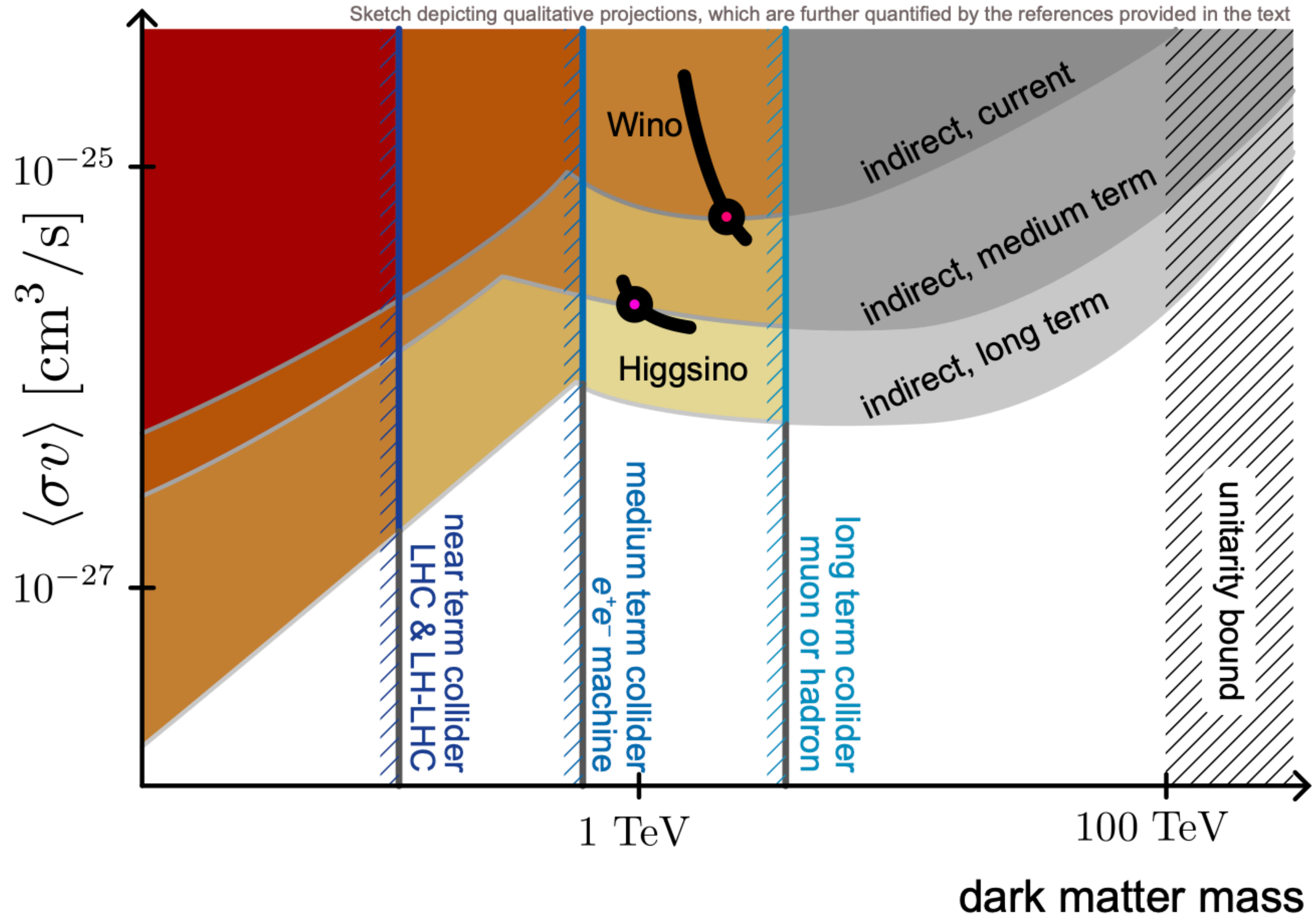
Same concept, different projection into two dimensions

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



A few sketches from Snowmass dark matter complementarity report

arXiv:2210.01770

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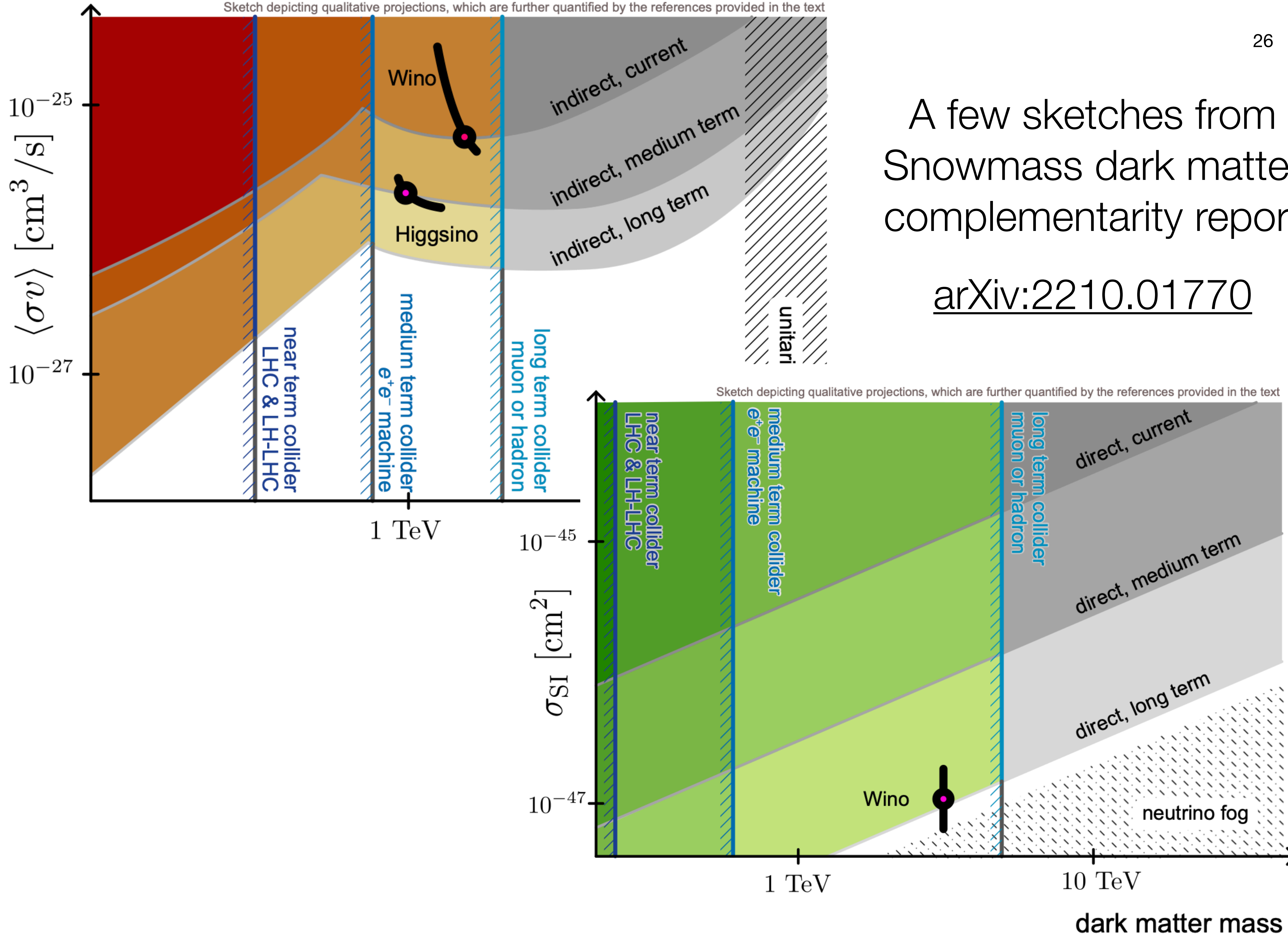

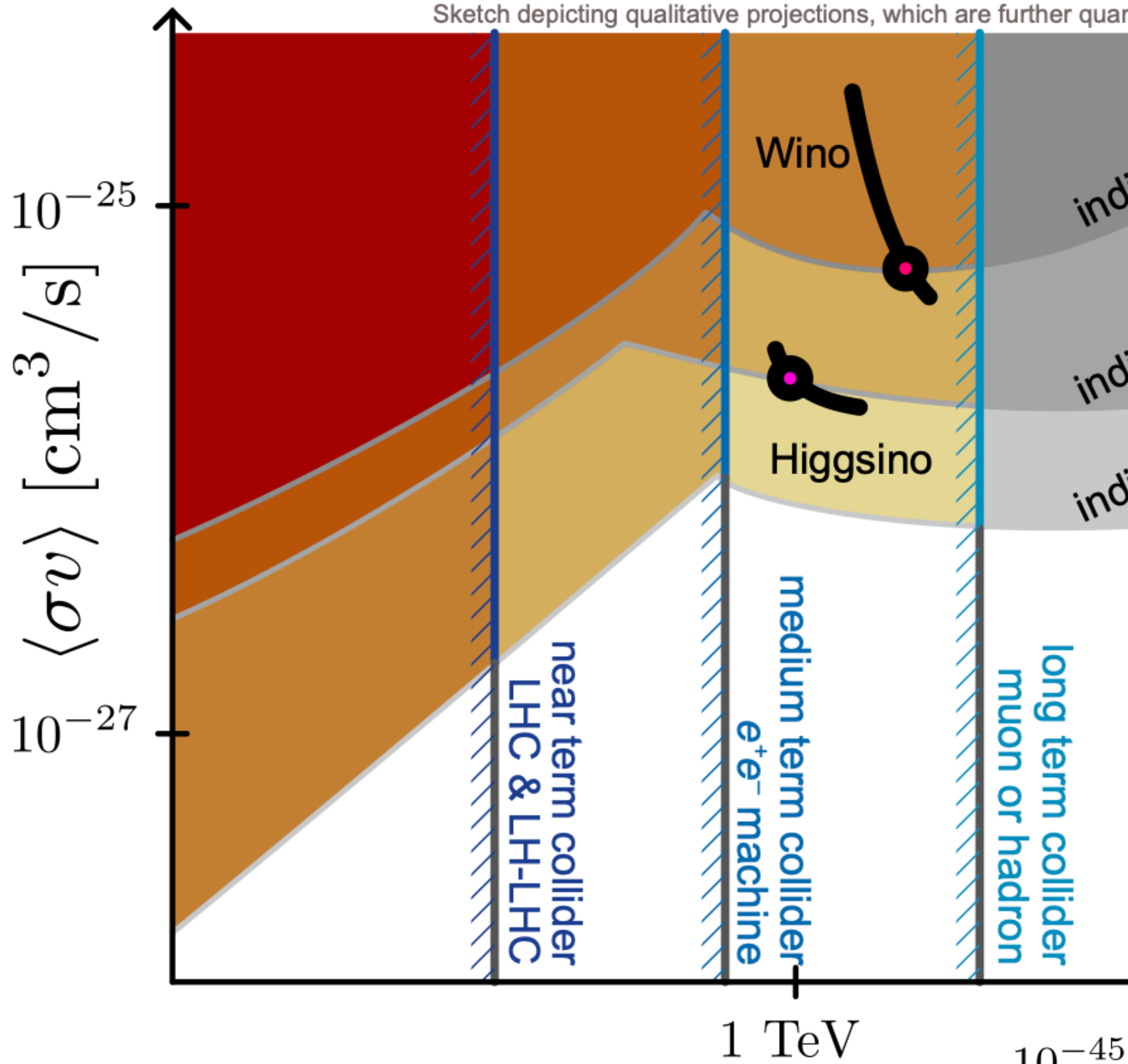

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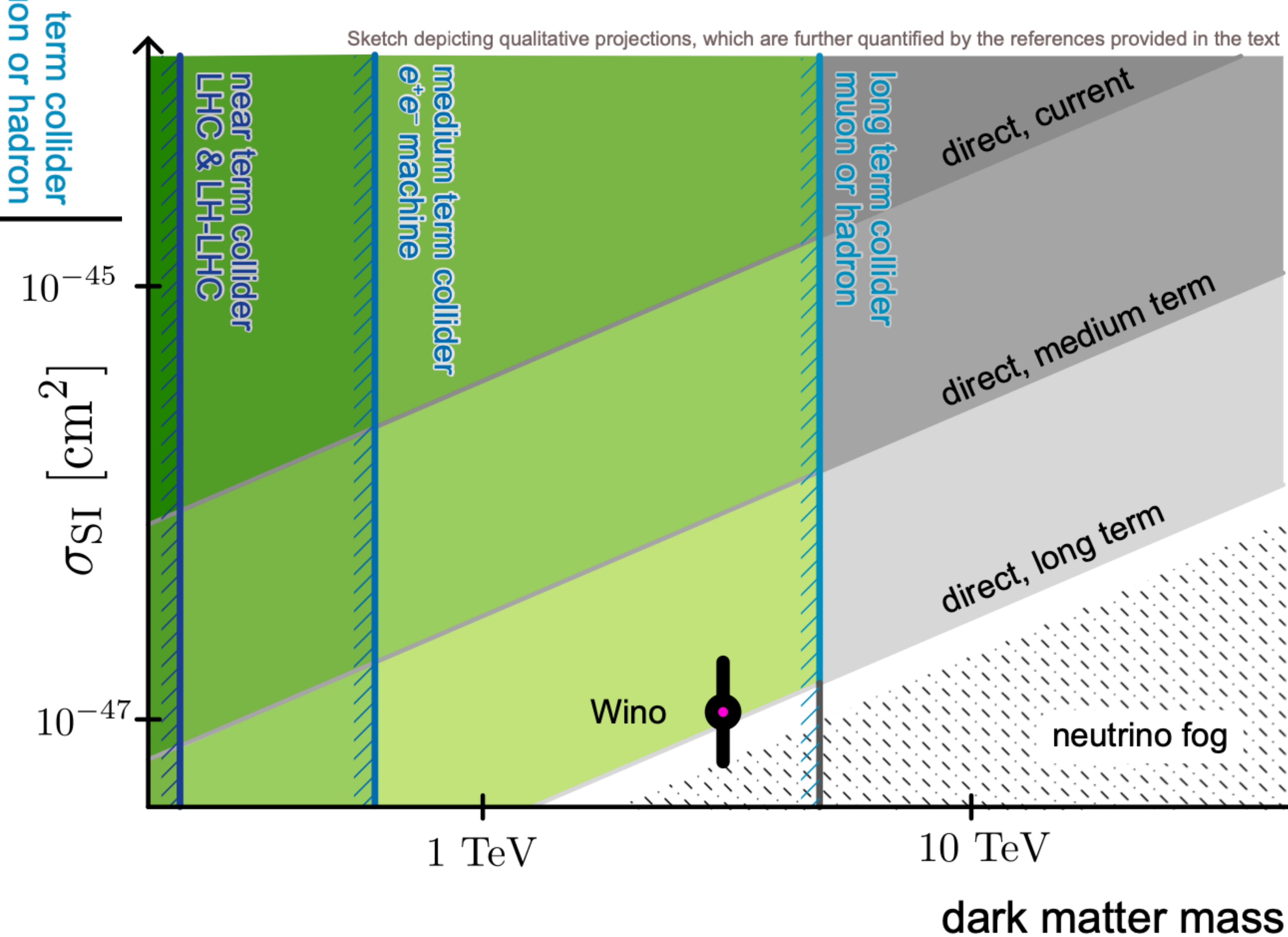

Wino & Higgsino DM candidate sensitivity vs mass for indirect and direct detection and future colliders

Conclusion

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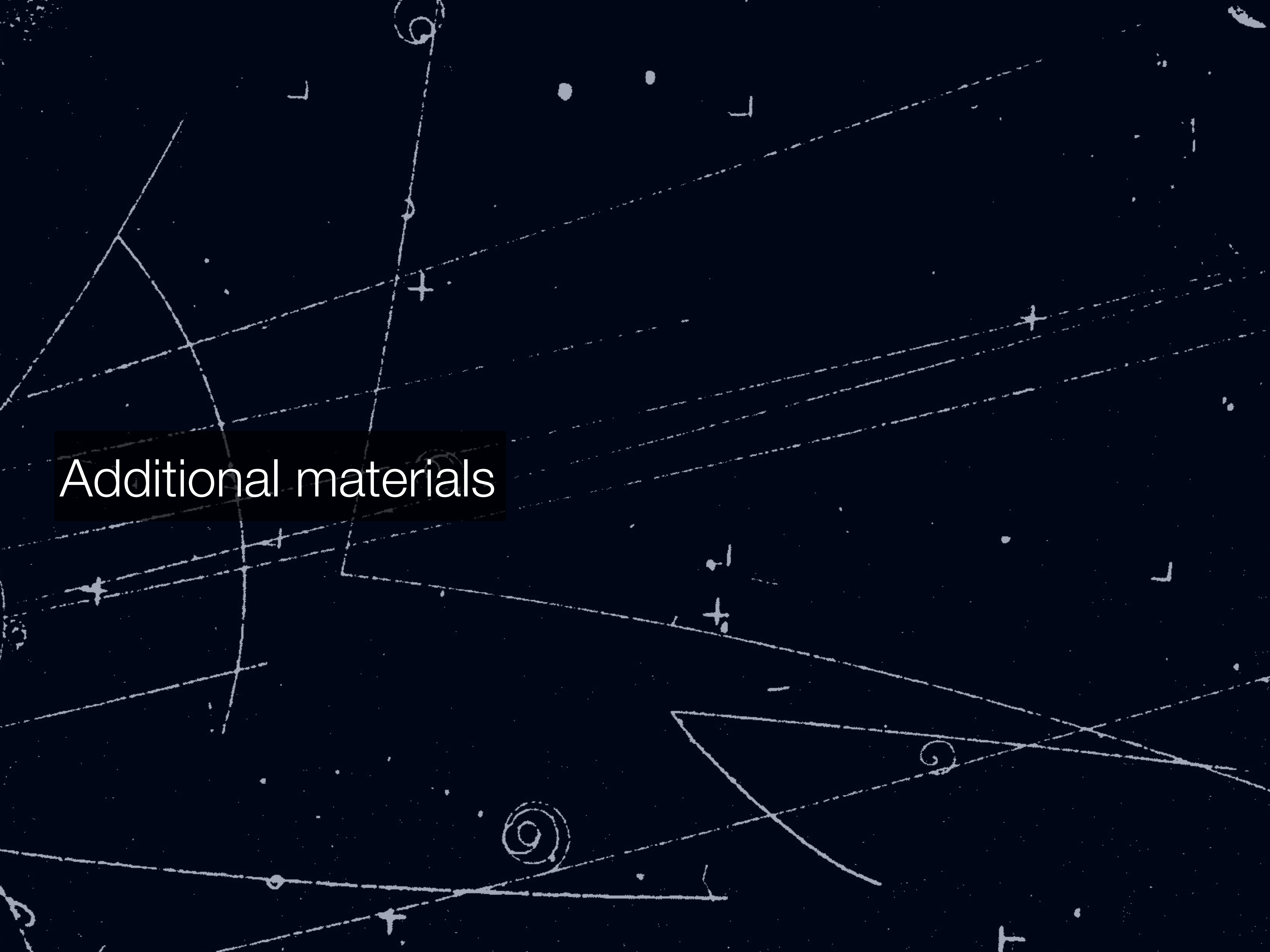
Complementarity, DM discovery potential, and the potential to exclude values aligning with cosmological observations should be thoroughly understood and included in future collider proposals

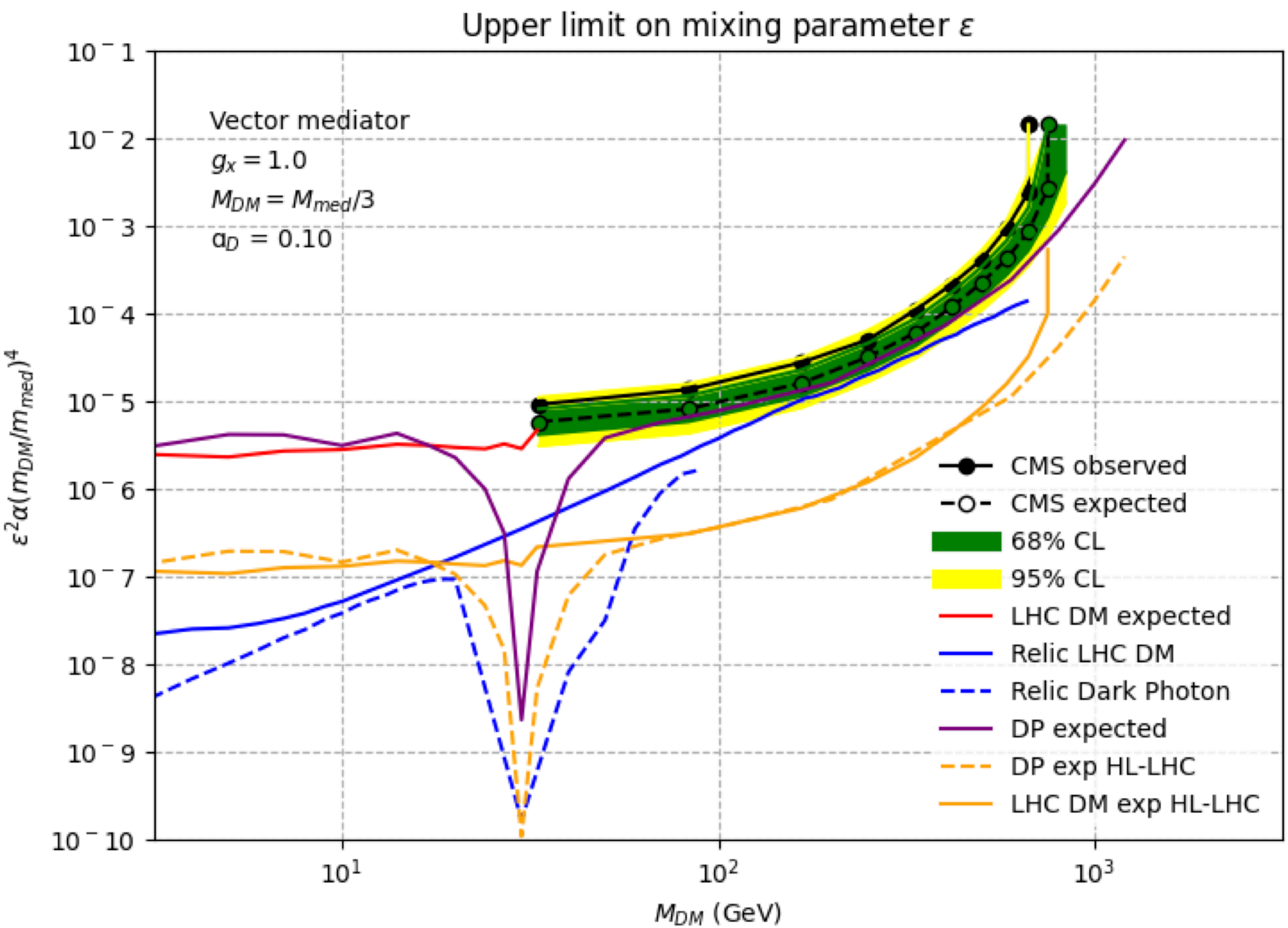


Additional materials

References

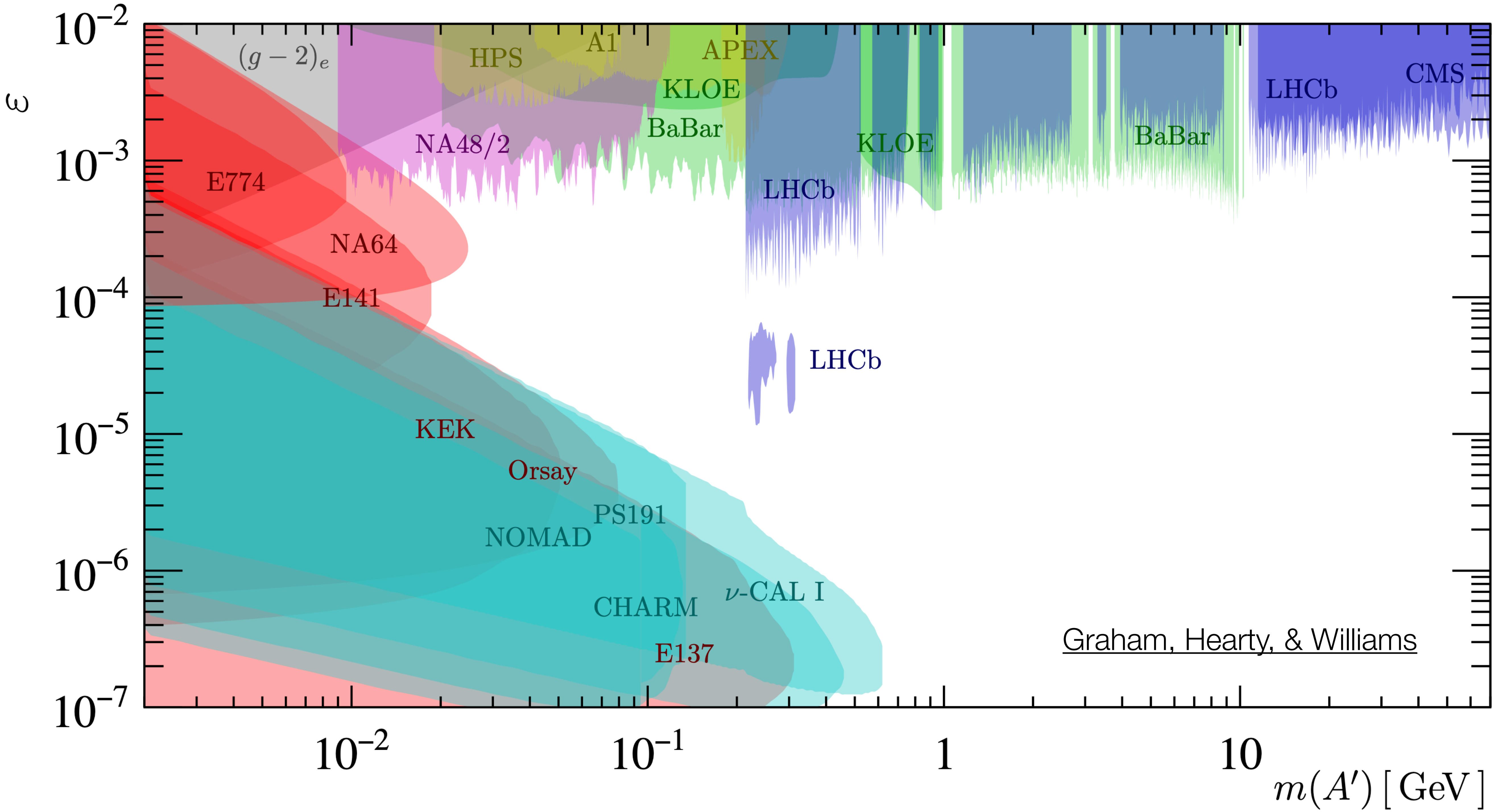
- LHC simplified models (s-channel mediators) arXiv:1507.00966
- LHC 2HDM+a model: arXiv:1810.09420
- Notes on Higgs portal: arXiv:2001.10750, arXiv:1903.03616
- Snowmass BSM topical group report arXiv:2209.13128
- Snowmass particle dark matter topical group report arXiv:2209.07426
- Snowmass DM complementarity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

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.

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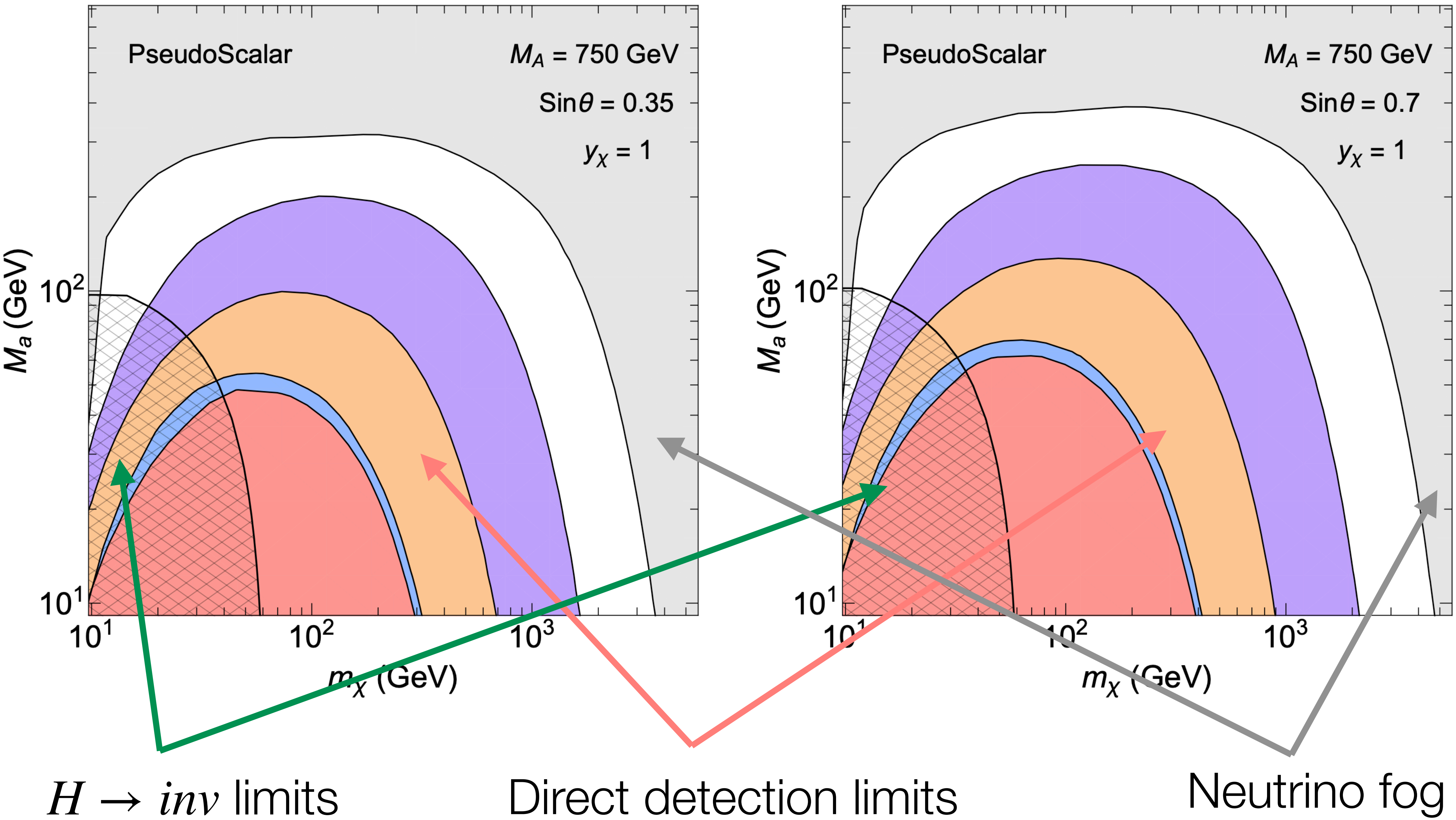
Shape of direct detection exclusions in 2HDM+a model, M_a vs m_χ plane. Requires fixing of other three parameters

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.