Simplified models of BSM DM mediation

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TRIUMF
with input from many people

Introduction

- **Simplified model benchmarks** used by LHC experiments provide **framework** for contextualising results from different analyses and between ATLAS and CMS
  - Benchmarks introduce two particles: one DM, one mediator
  - Mediator can be vector, axial vector, scalar, or pseudoscalar particle; dark matter is Dirac fermion (no significant difference observed when changing DM particle nature)
  - **Couplings and masses are free parameters** set/scanned by users, where different choices can result in very different sensitivities from a given search approach
- Goals for Snowmass were:
  - Break out of restrictions posed by individual coupling choices to show a **more model-independent picture** of collider sensitivity
  - **Bridge gaps** between LHC/future collider interpretations and other frontiers to highlight regions of complementarity

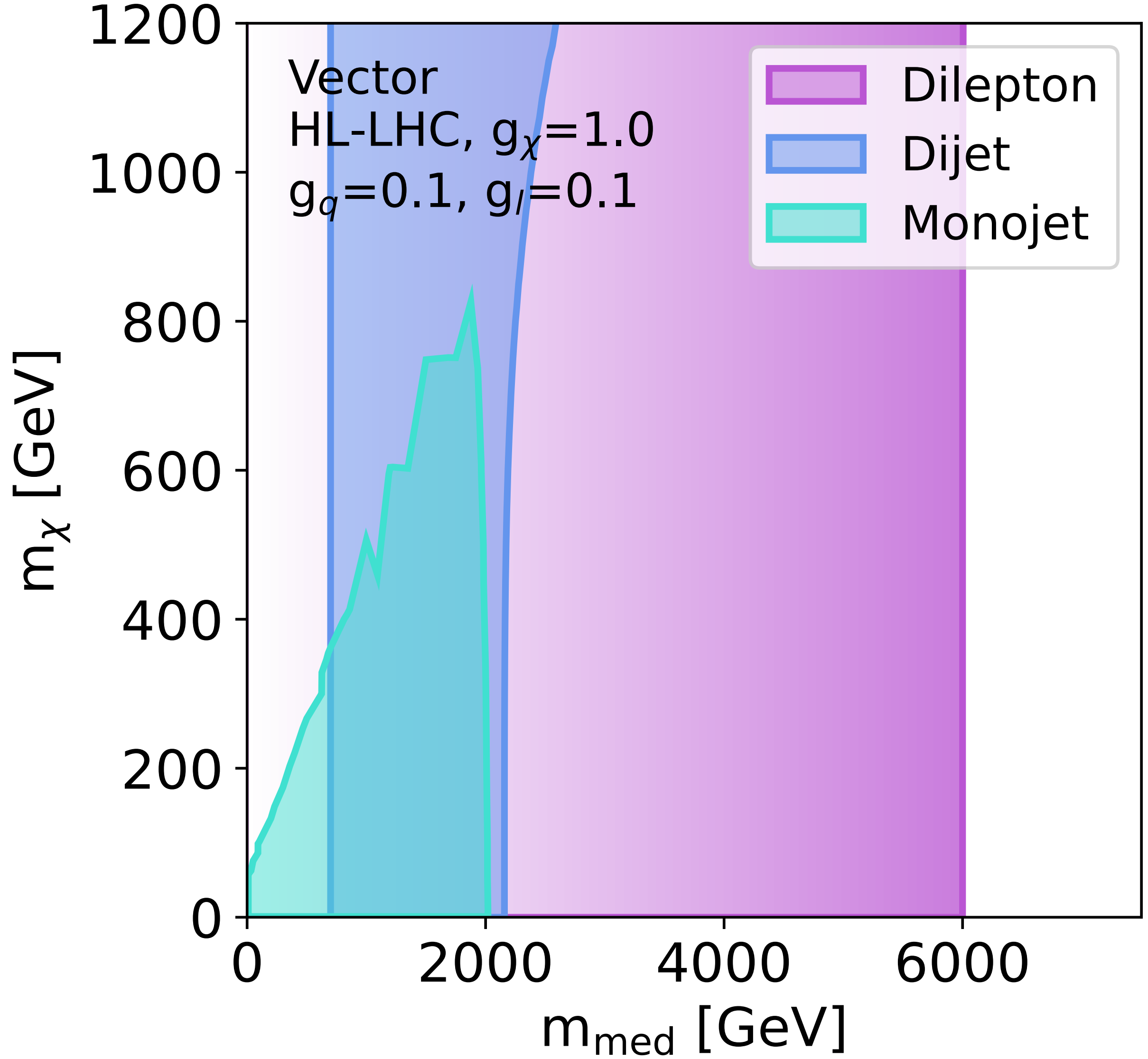
Summary of inputs and what's shown

arxiv:2206.03456

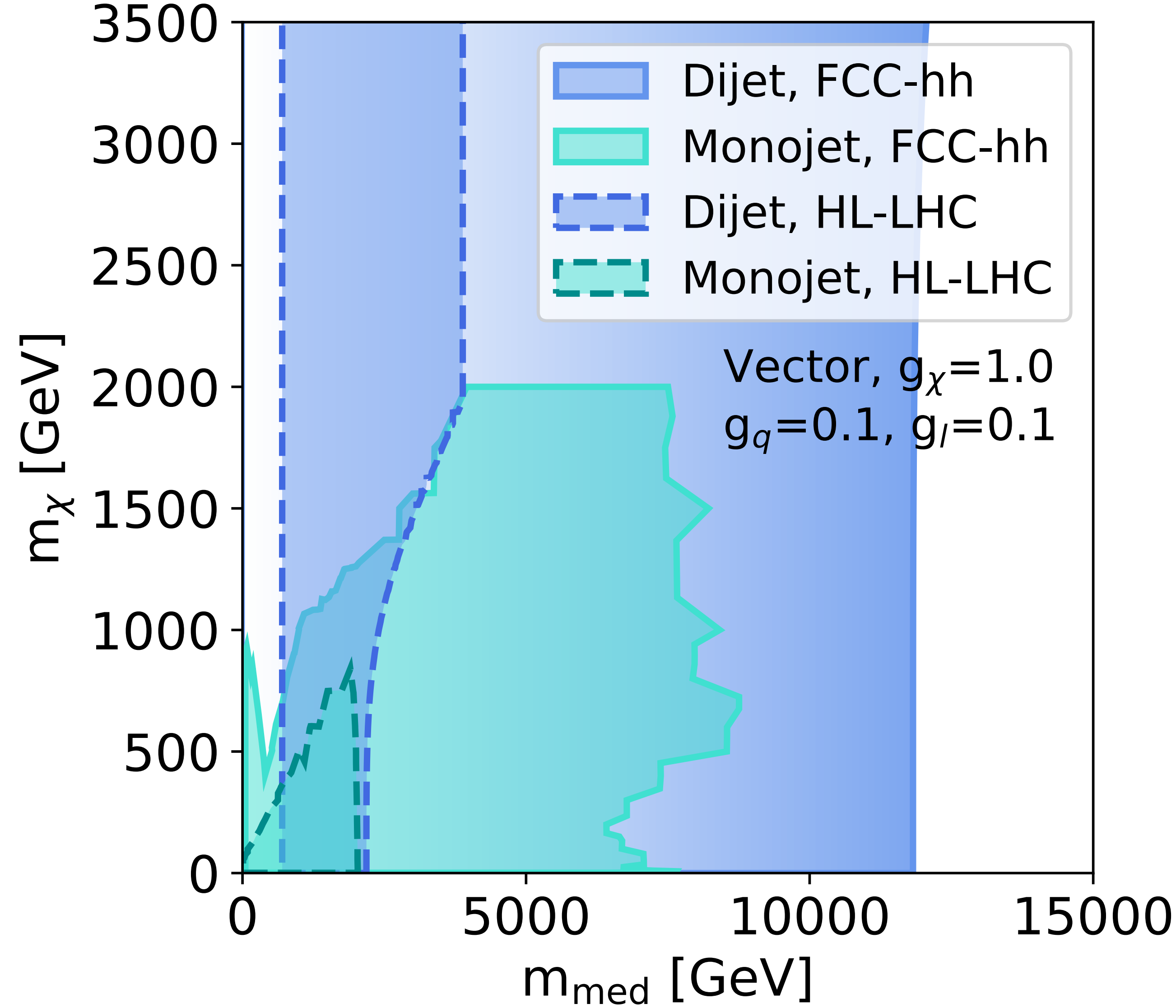
- Four inputs from community incorporated thus far:
  - **MET+jet** (monojet) limit projections for the **HL-LHC**, ATLAS (ATL-PHYS-PUB-2018-043)
  - **MET+jet** (monojet) limit projections the **FCC-hh**, experiment-independent (arxiv:1509.02904)
  - **Dijet resonance** limit projections for **HL-LHC and FCC-hh** (arxiv:2202.03389)
  - **Dilepton** resonance limit projections for **HL-LHC** (ATL-PHYS-PUB-2018-044)
- Dilepton results only available for HL-LHC and thus most coupling sets displayed here/in report have gl = 0.0
- Certain **ILC limits also available**, though require conversion to these simplified models. Intend to include in **future updates**.
- Plots shown here focus on **vector mediators**: axial-vector look sufficiently similar as to not be worth duplicating plots over, while scalar/pseudoscalar are so different as to require entirely different limit projections, largely unavailable for Snowmass.

All included in EF BSM report

Relationships and range within colliders



HL-LHC only. Moderate to large SM couplings. Relative strength of dilepton for g_q=g_l clear.

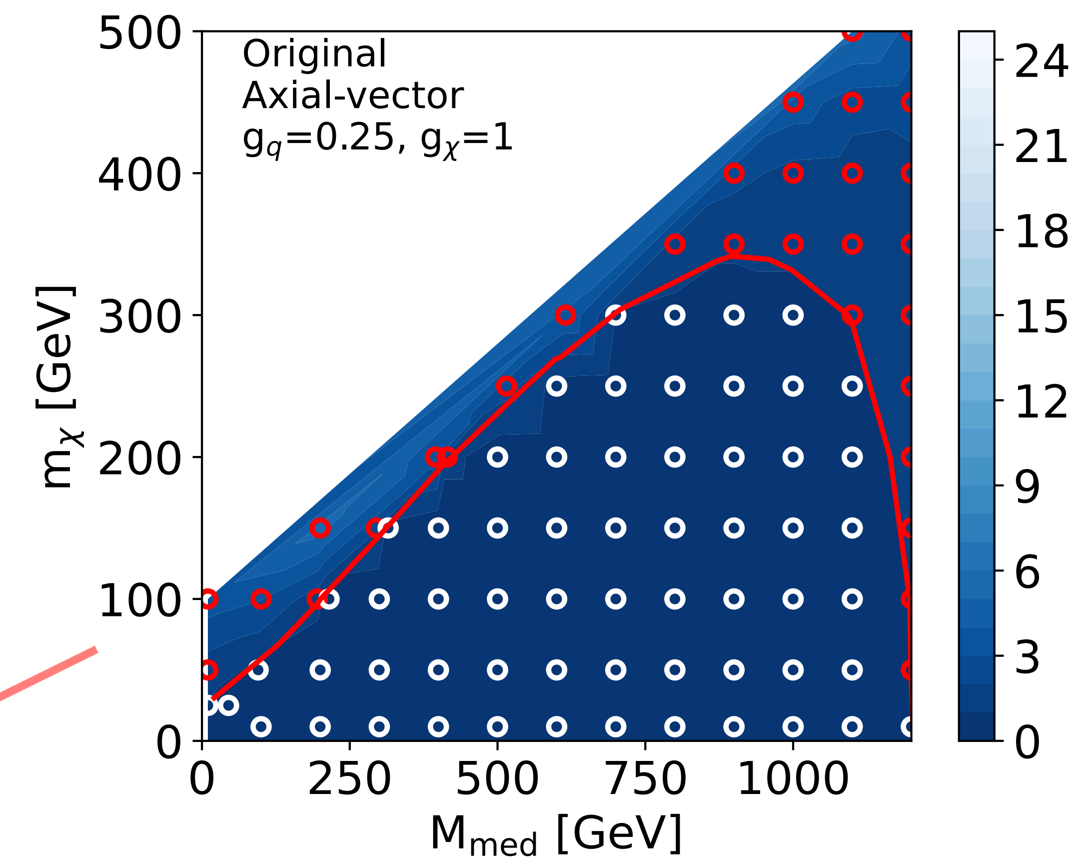


Shows increase in range from HL-LHC, including reach for off-shell monojet, at same couplings

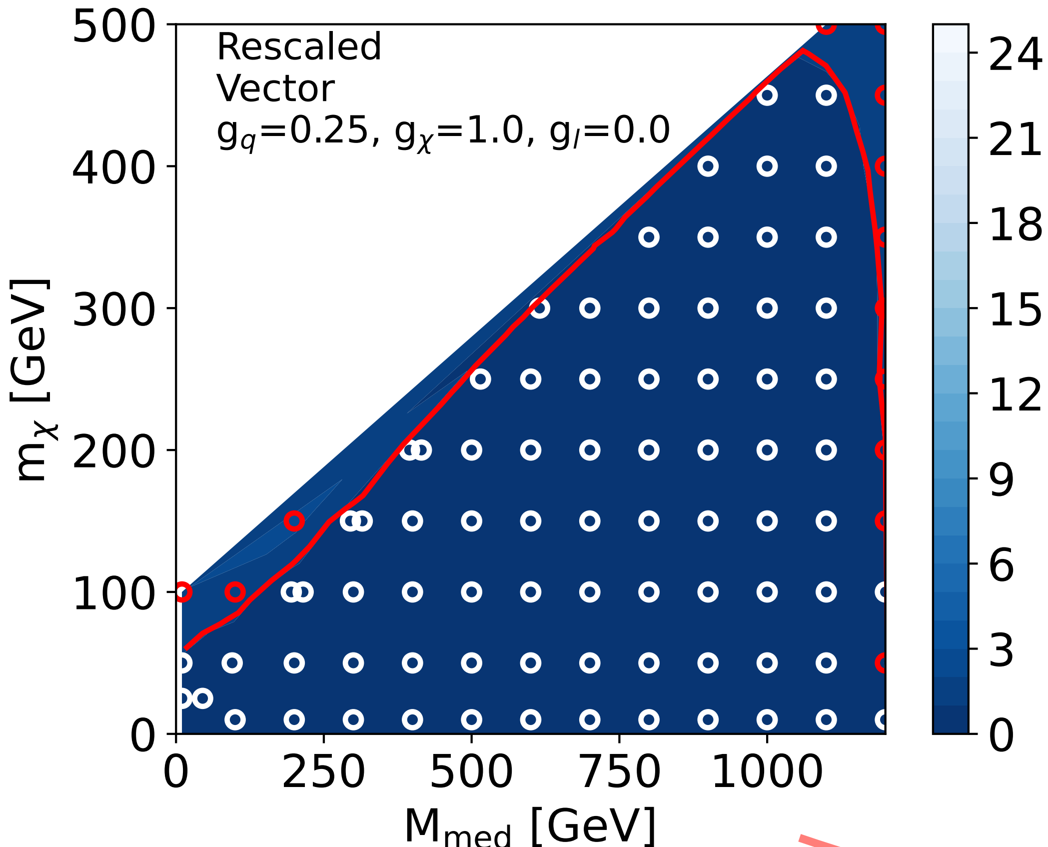
Evading restrictions of coupling choices: Limit rescaling

- LHC limits are evaluated only in the context of a small handful of coupling values
- With the right formulas, can **rescale limits from any set of couplings to any other set of couplings**, with a few restrictions:
    - Cannot rescale across masses unless the signal looks identical. E.g. it is possible to rescale across m_{DM} for visible final state signatures, but not for mono-X signatures
    - Acceptance cannot change significantly as couplings change
    - For resonance searches, significant change in signal intrinsic width should be properly modelled with changing experimental limits
- Visible signature rescaling formulas have been available for some time; mono-X rescaling developed for Snowmass
- Allows insights into how LHC **search sensitivity depends on simplified model parameters**

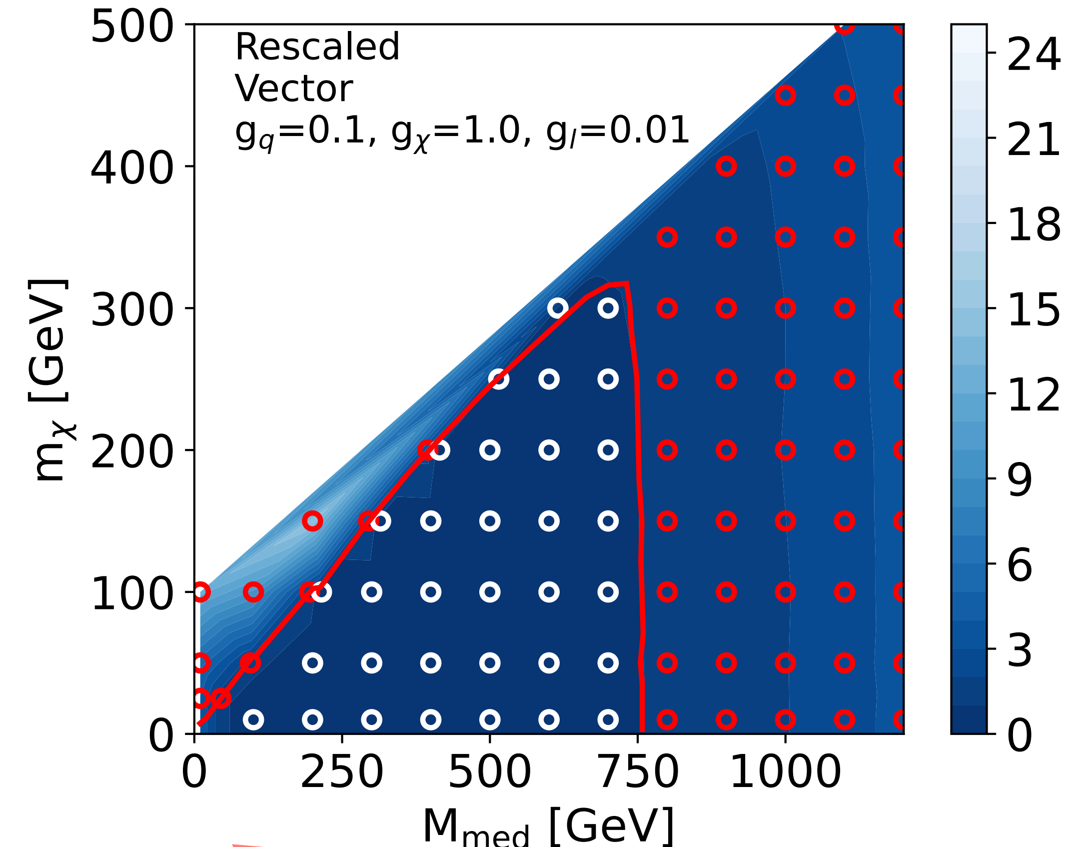
Monojet rescaling example



First translate from axial-vector to vector mediator (slower step involving full cross section integral)

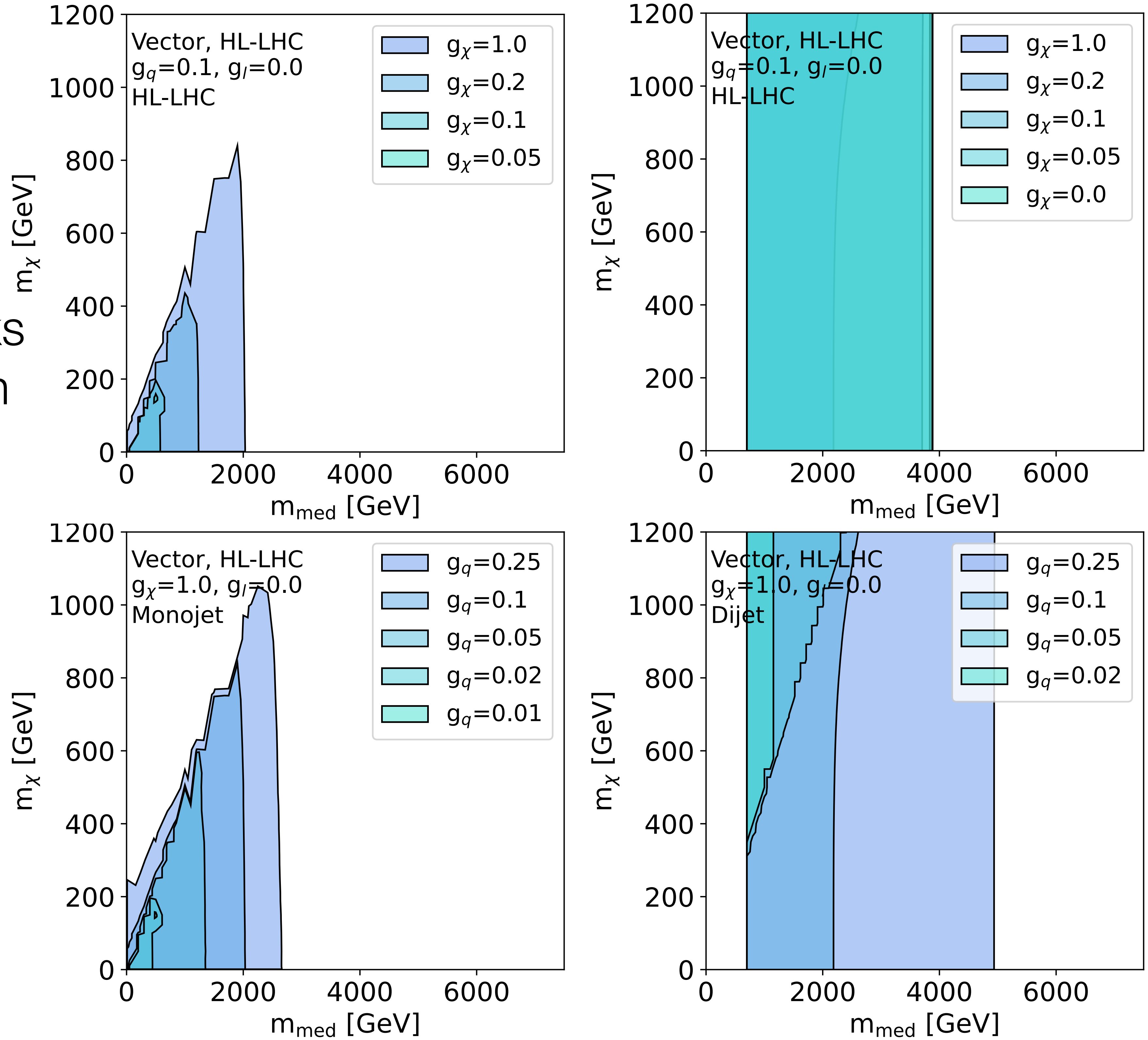


Use fast rescaling approach to arrive at any other combination of couplings



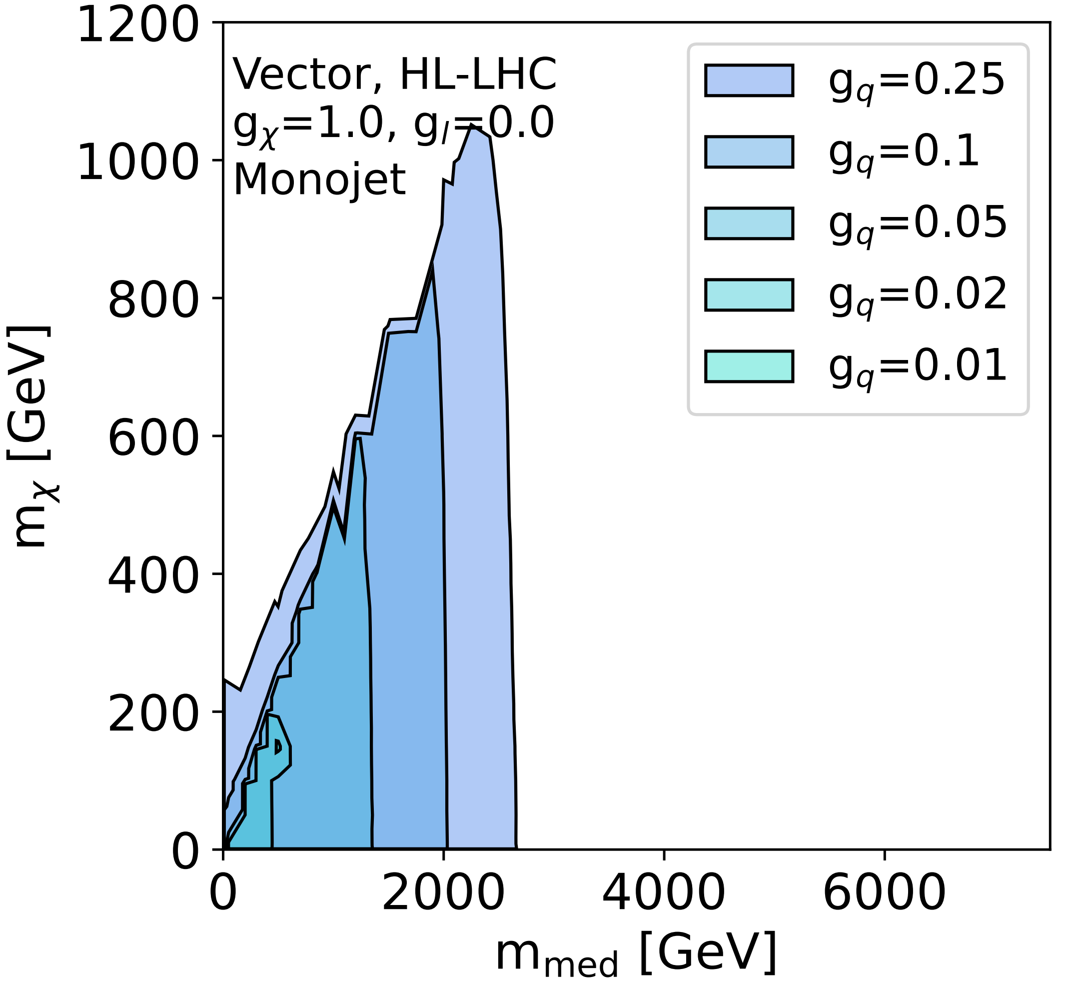
Impact of coupling on exclusions in mass-mass plane

Monojet power shrinks similarly with g_q or g_χ decreasing



Dijet exclusion stronger with small g_χ but much weaker with small g_q

Limits on excluded coupling strengths: what they mean



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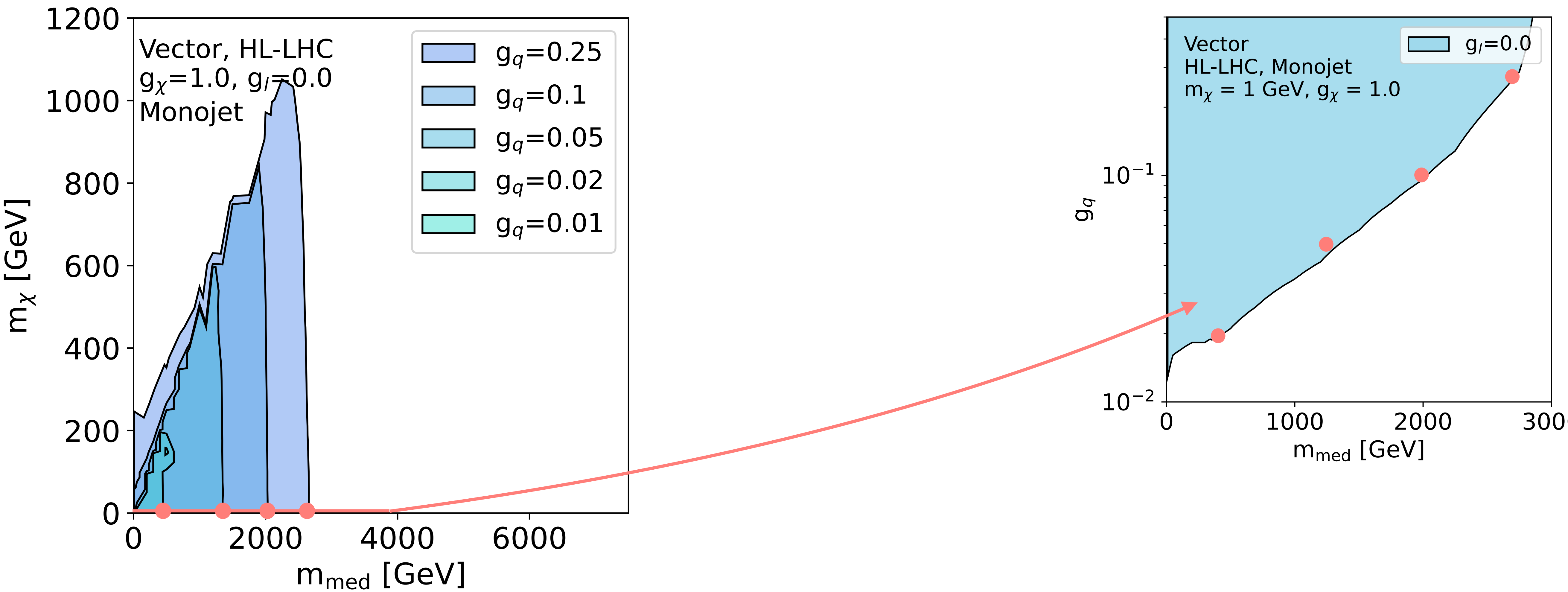

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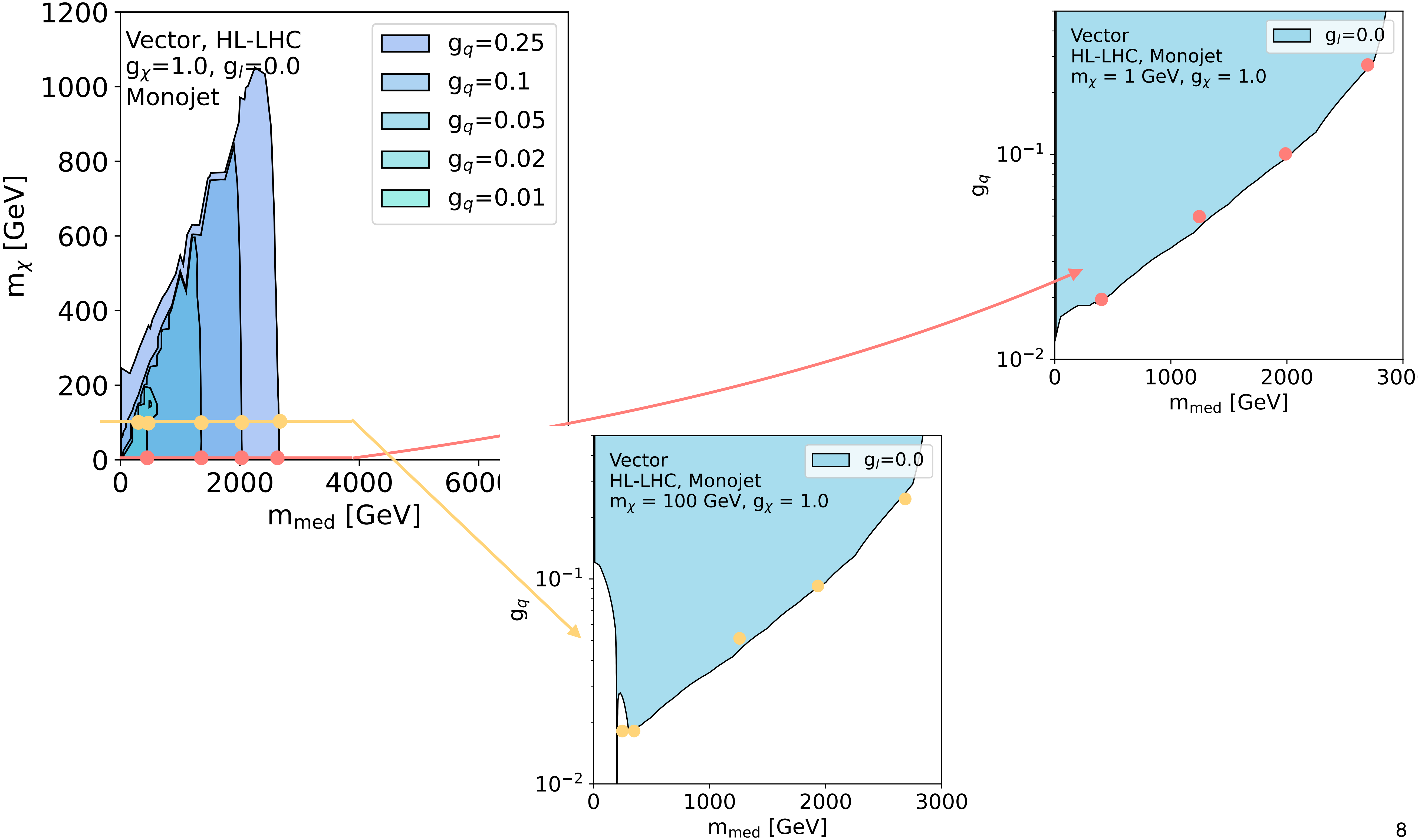

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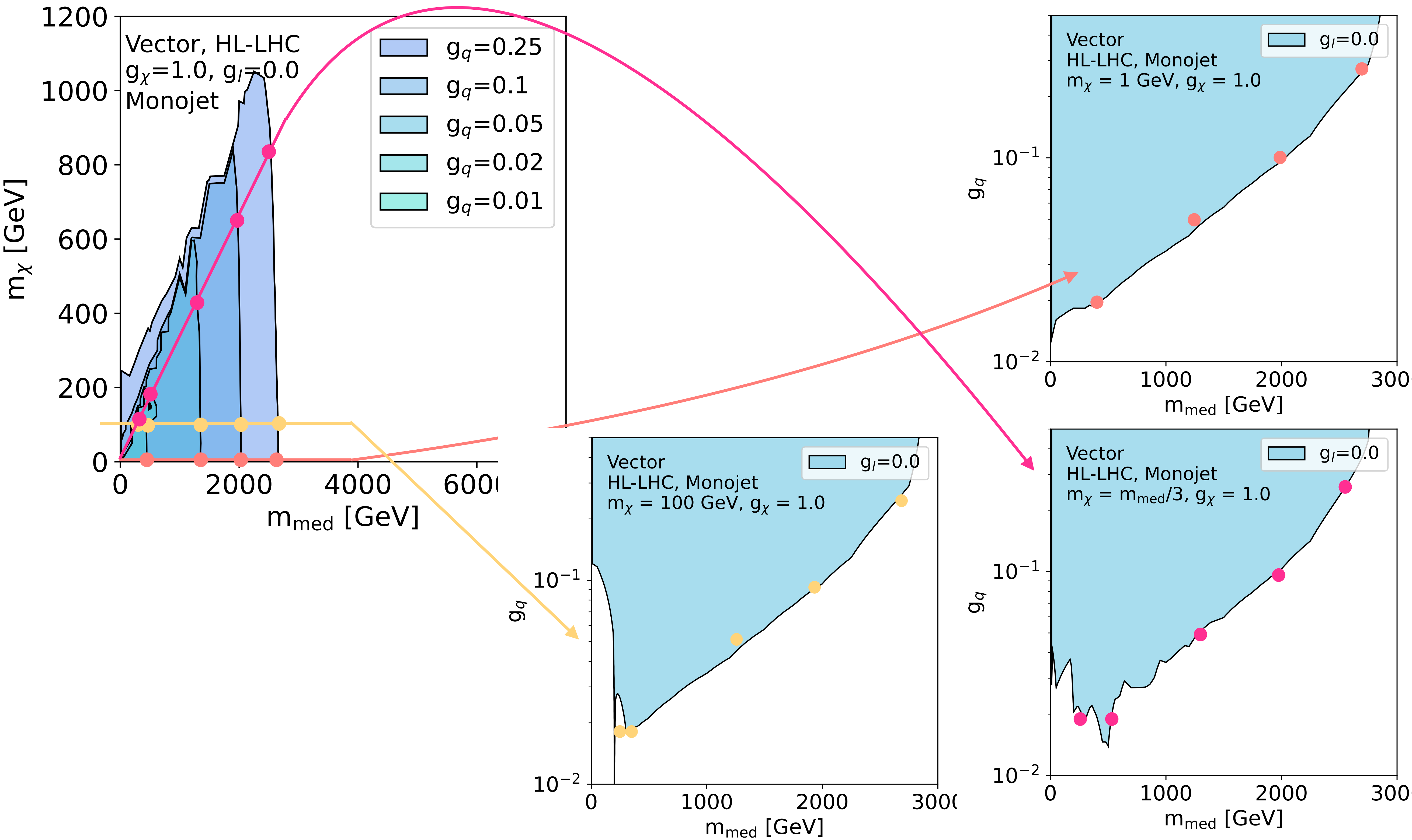

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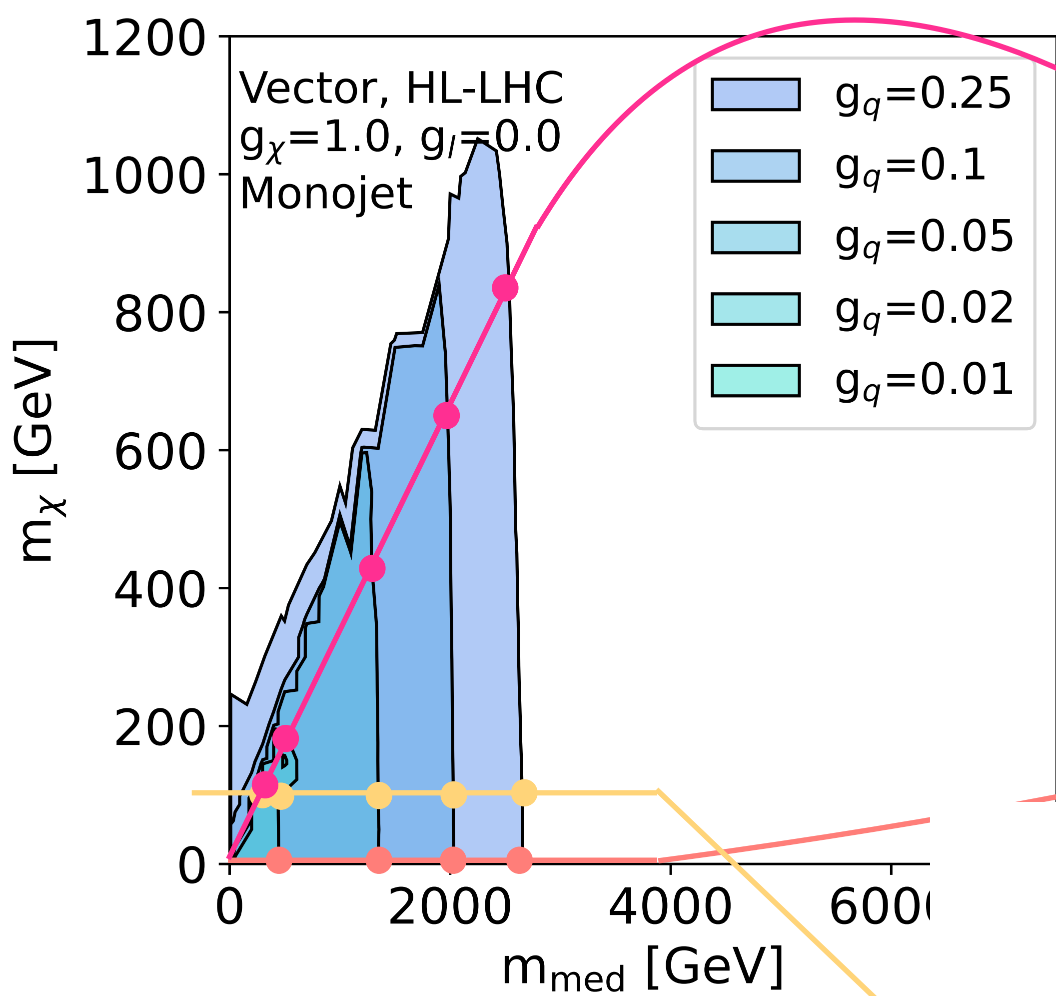
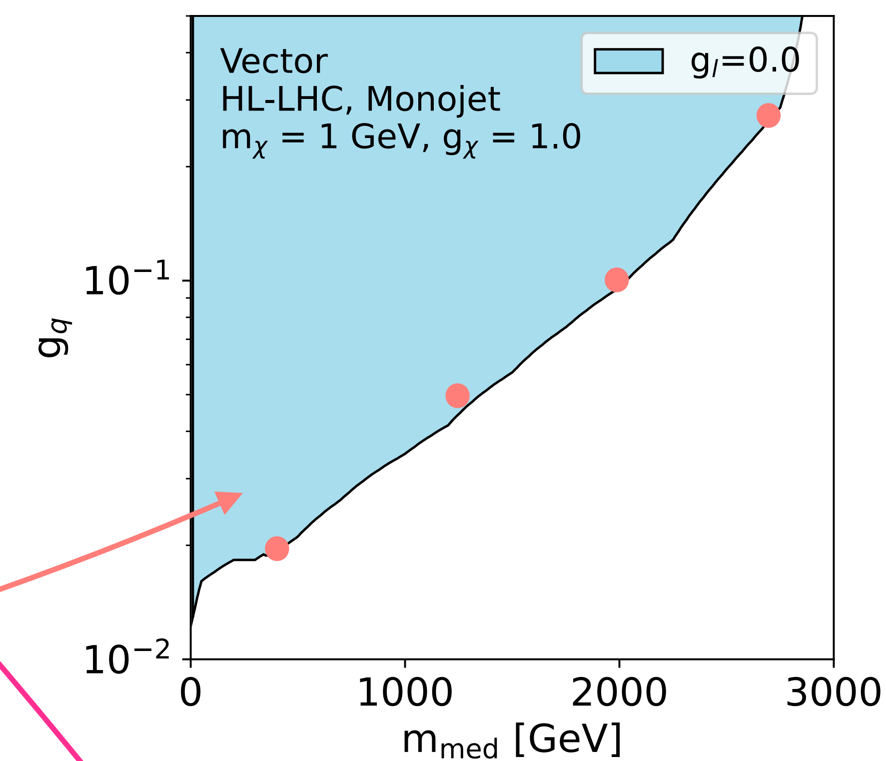
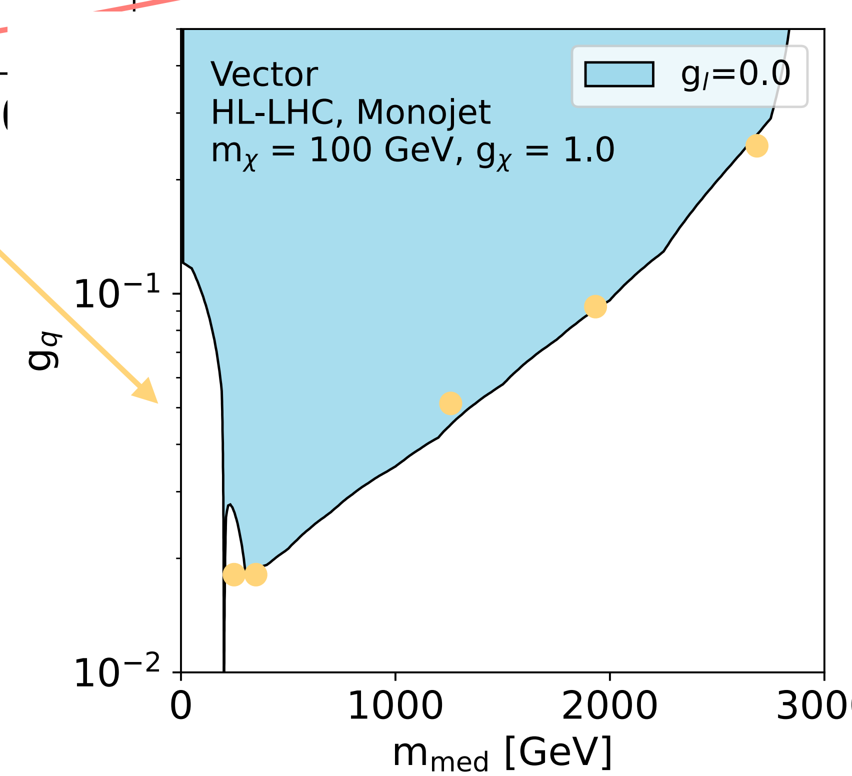
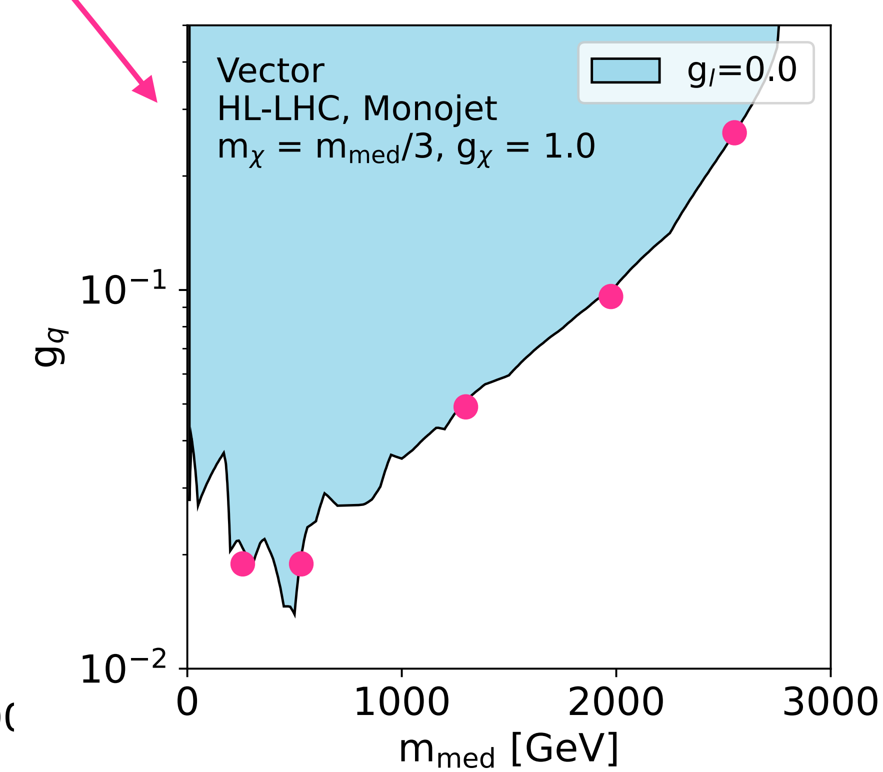


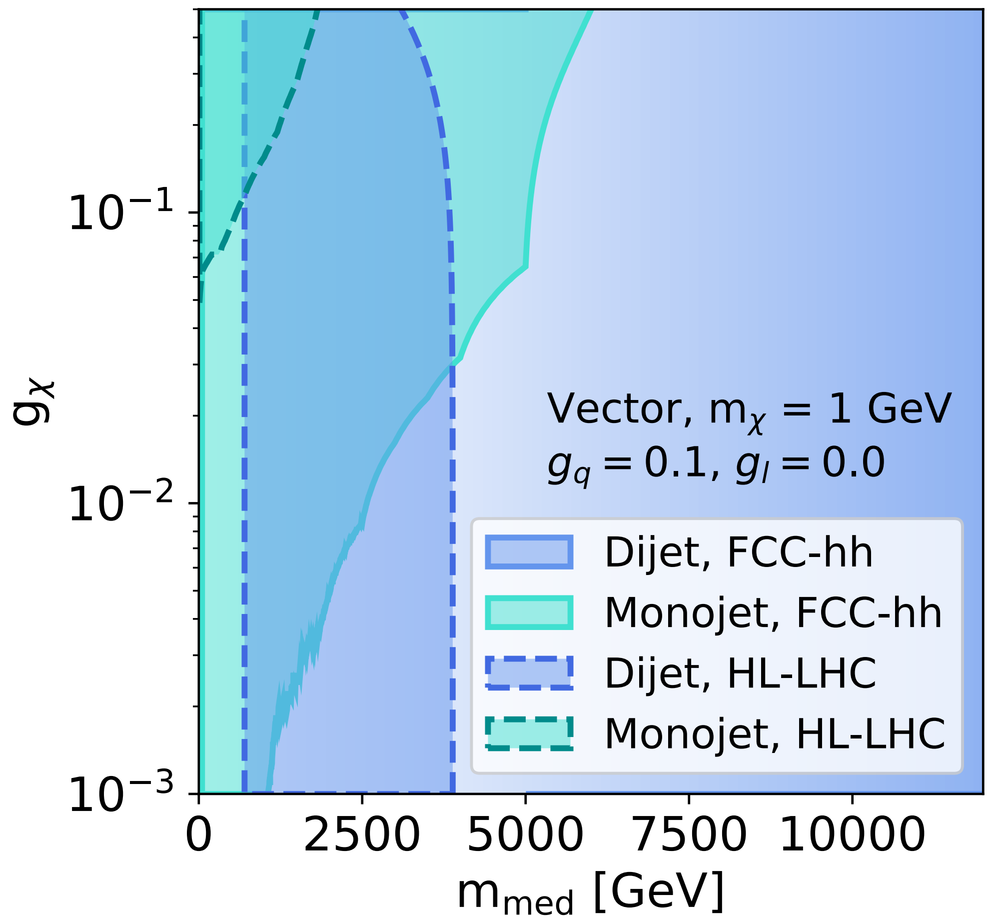




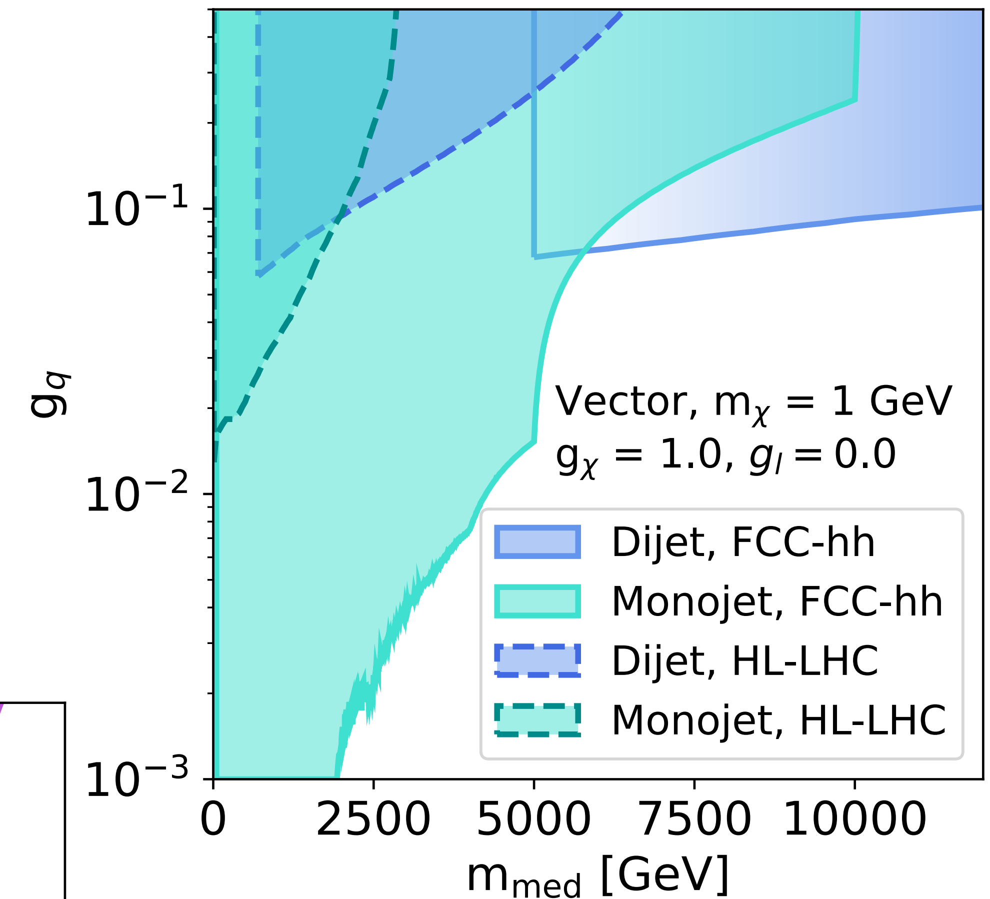


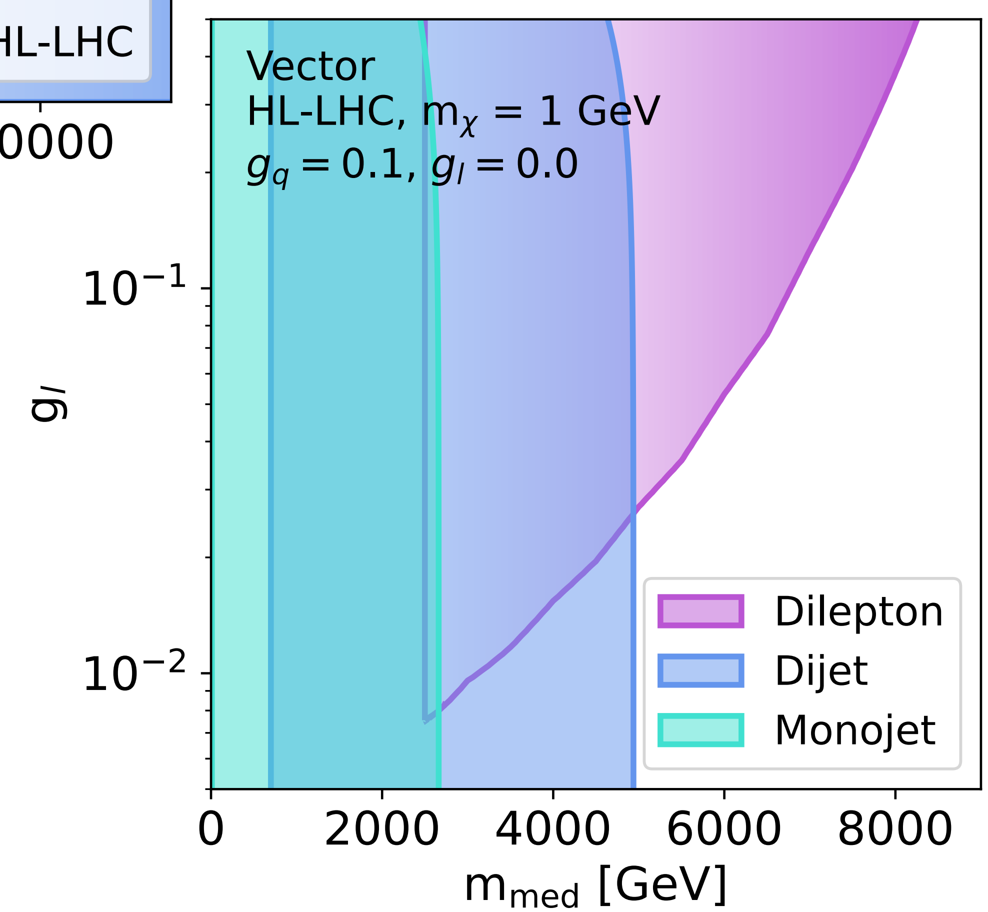
Each corresponds to a vertical slice through a mass-mass exclusion plot, but samples more couplings to get a smoother curve

Limits on excluded coupling strengths: analysis and collider relationships



All LHC/FCC signatures require g_q and so all limits get weaker at smaller g_q

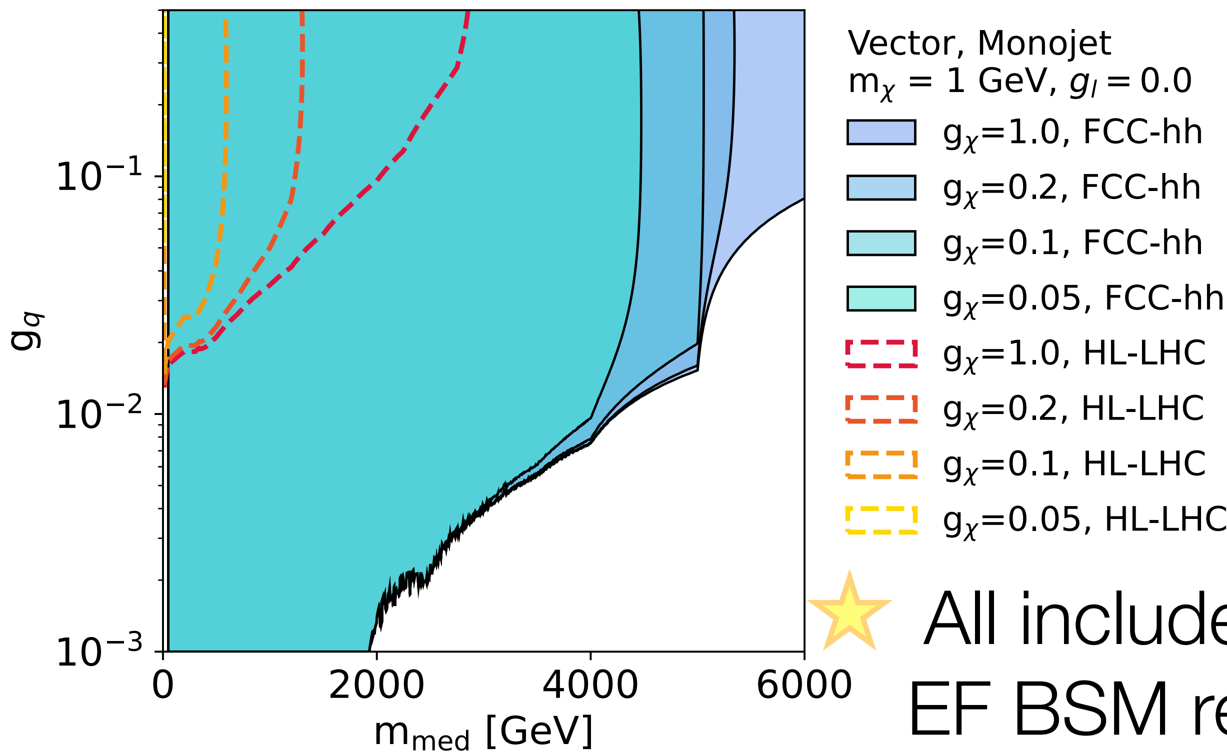




For g_χ and g_l, limits in final states with no dependence on y axis coupling get stronger with smaller values

All included in EF BSM report

Limits on excluded coupling strengths: collider reach and dependence on 2nd coupling



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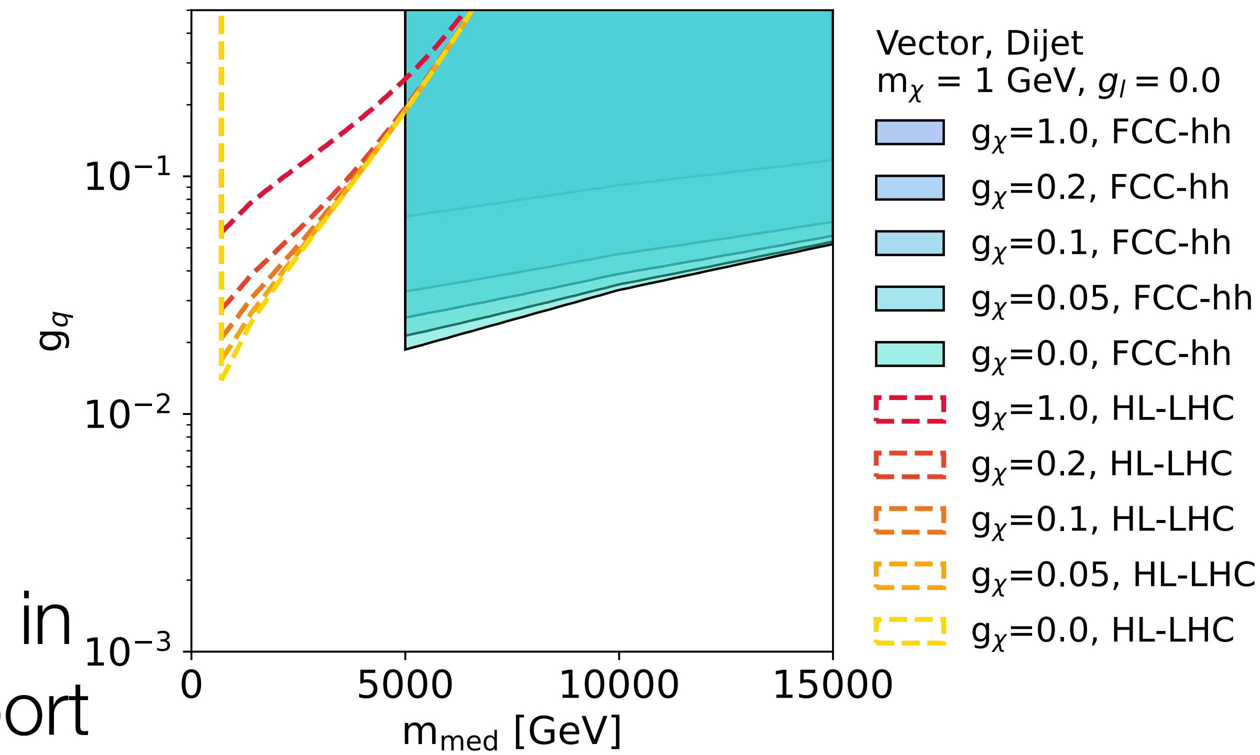
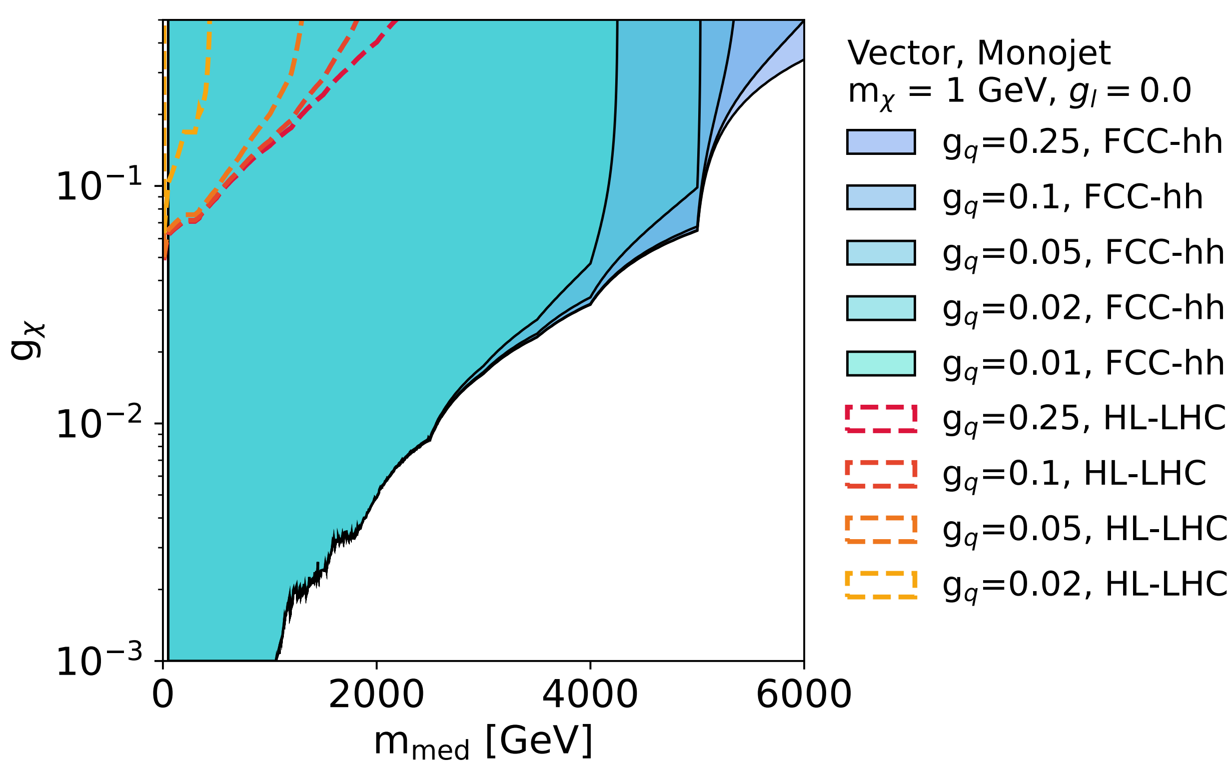
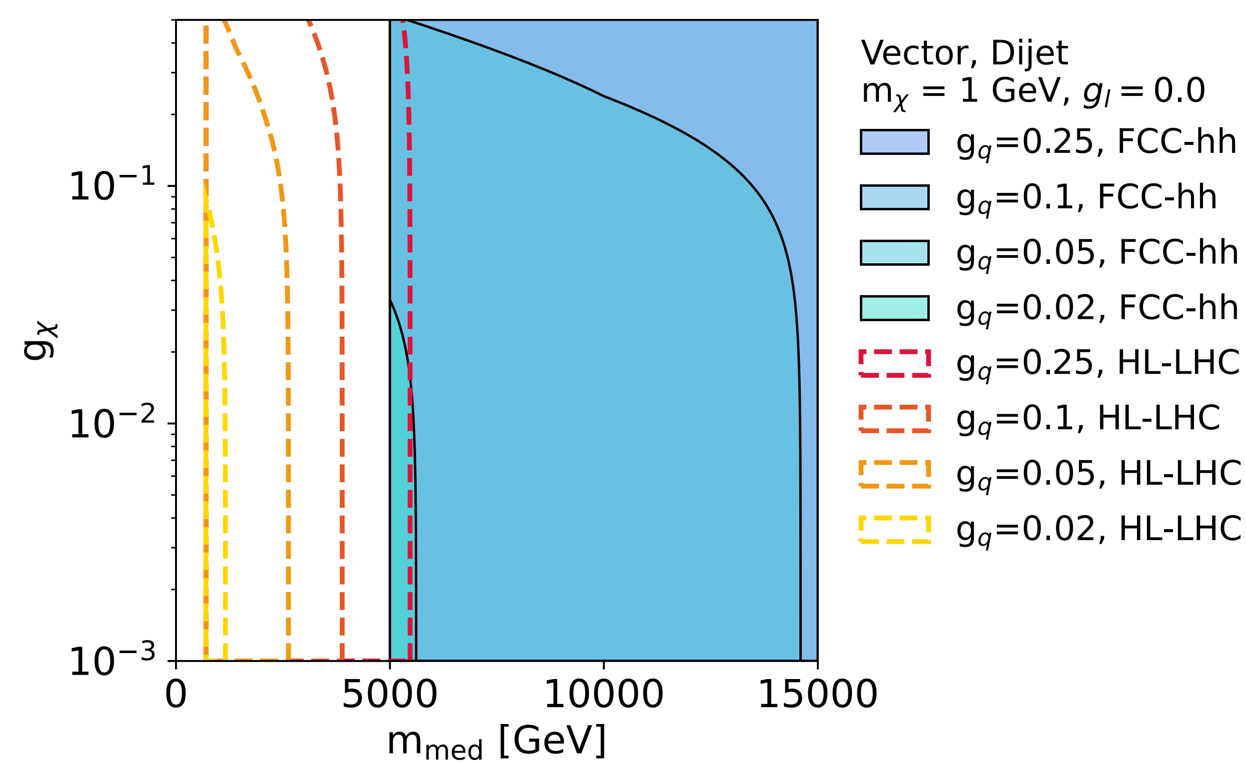


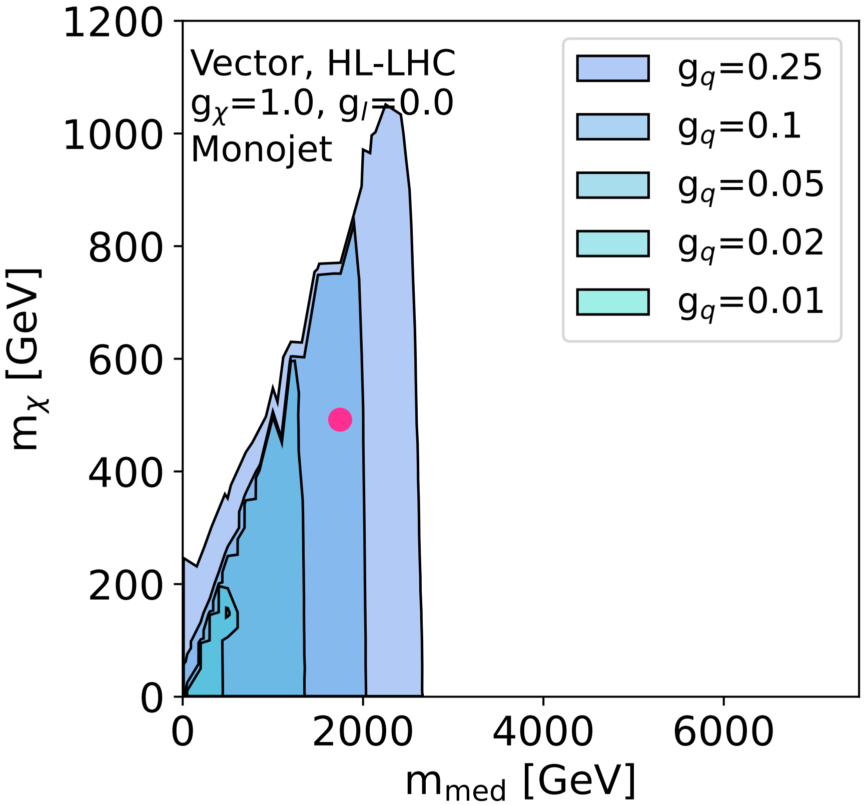




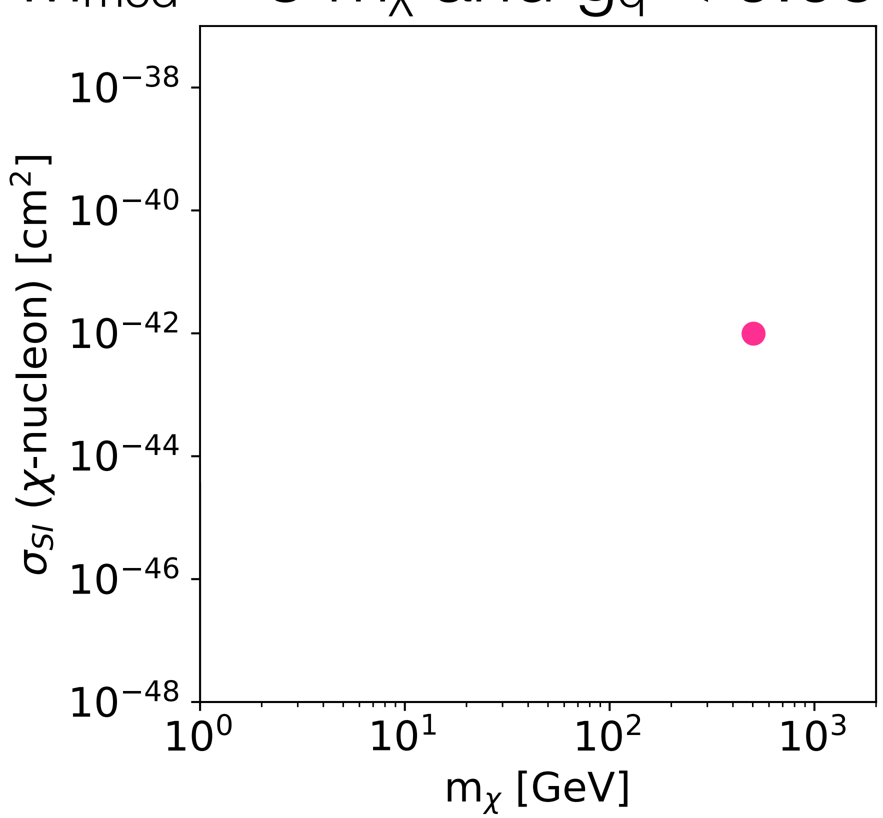
Framing colliders in the same context as direct detection

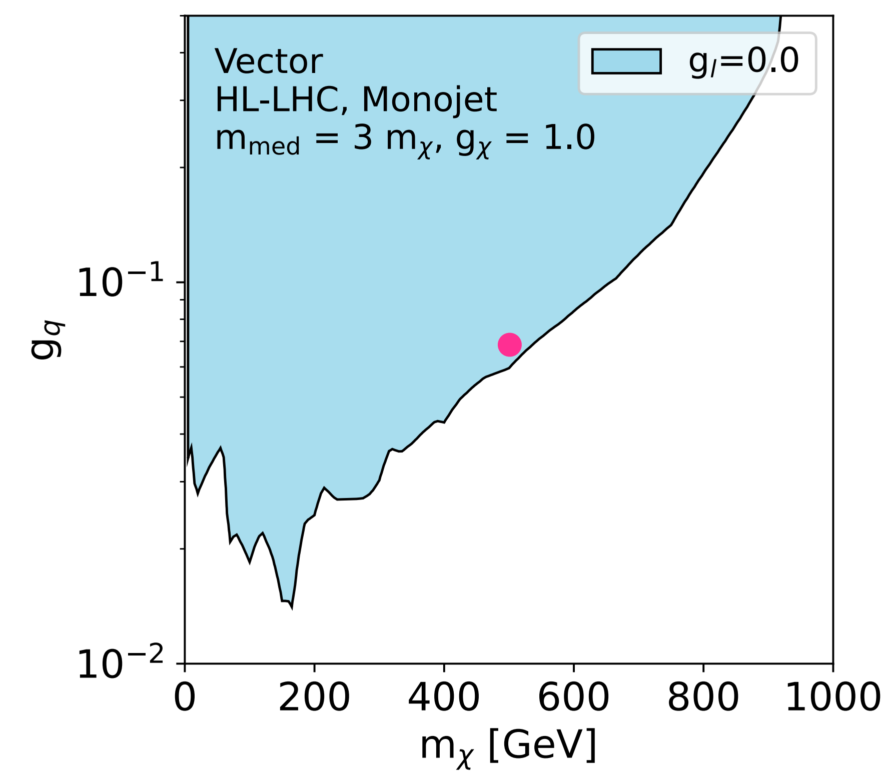
$$\sigma_{\mathrm{SI}} \simeq 6.9 \times 10^{-41}\ \mathrm{cm}^2 \cdot \left(\frac{g_q g_{\mathrm{DM}}}{0.25}\right)^2 \left(\frac{1\,\mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\mathrm{GeV}}\right)^2$$

3 variables on right: fix 2 and convert 3rd to σ_{SI}



(500, 10^{-42}) excluded with g_χ = 1.0 at HL-LHC if we can exclude…
g_q = 0.1 & M_{med} > 1822 GeV
or
M_{med} = 3 m_χ and g_q < 0.06





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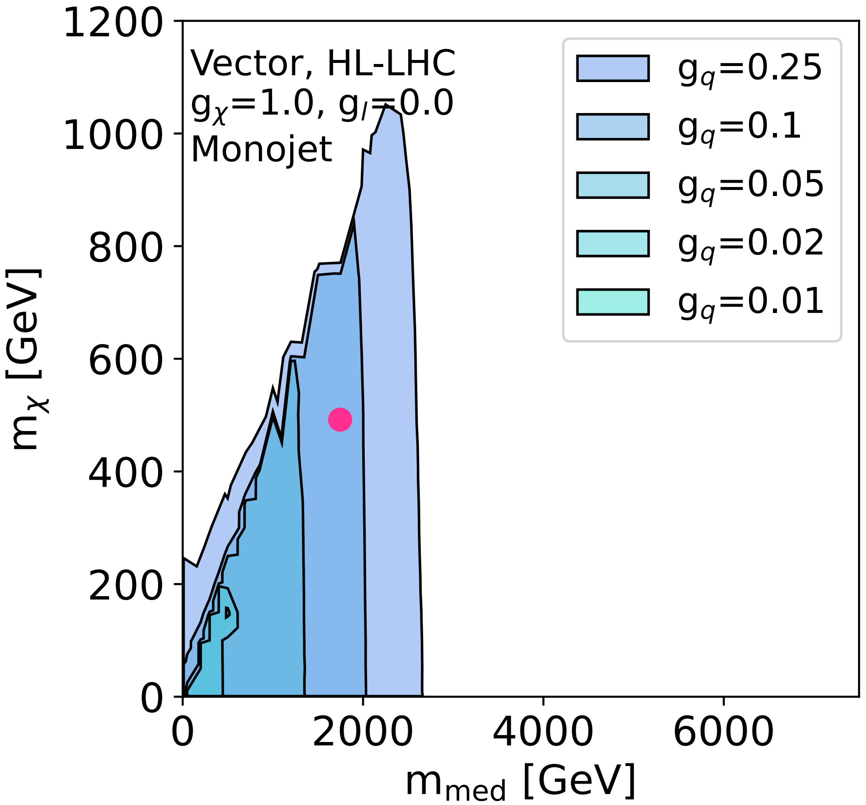

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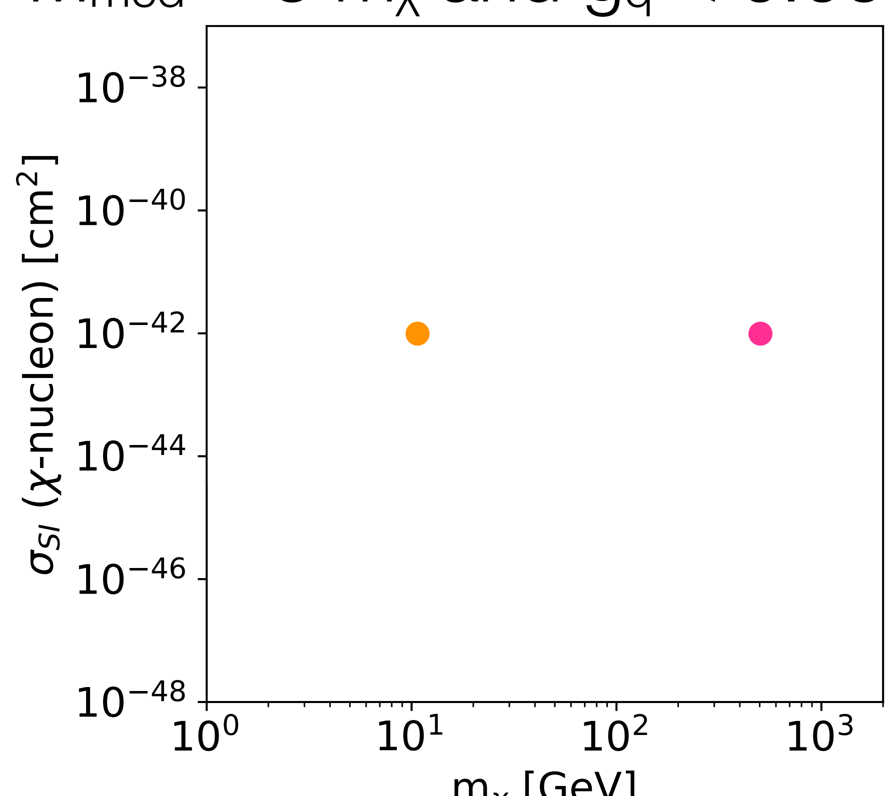

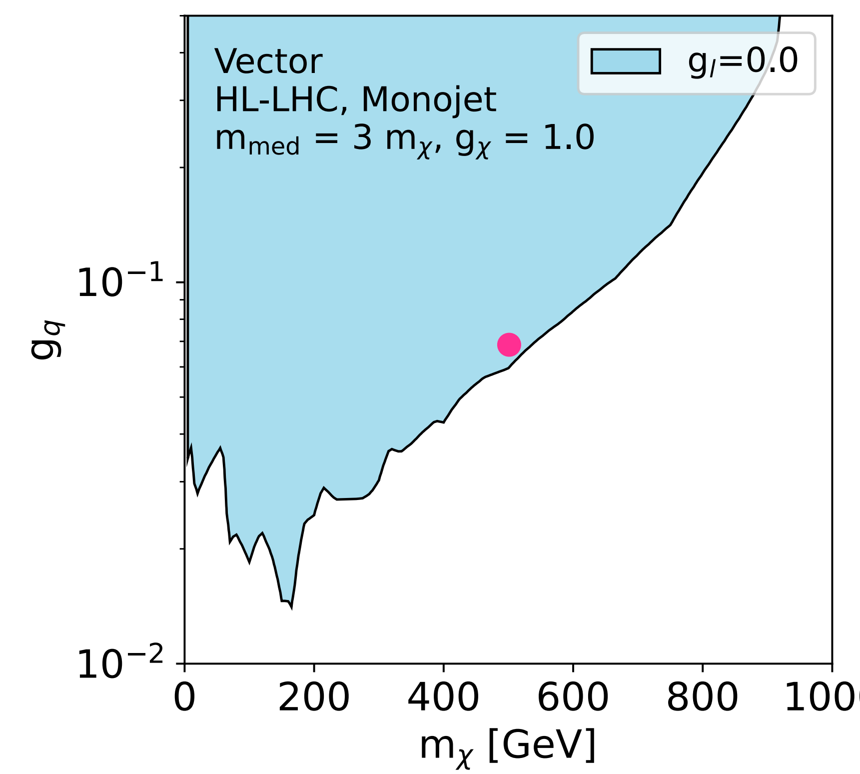

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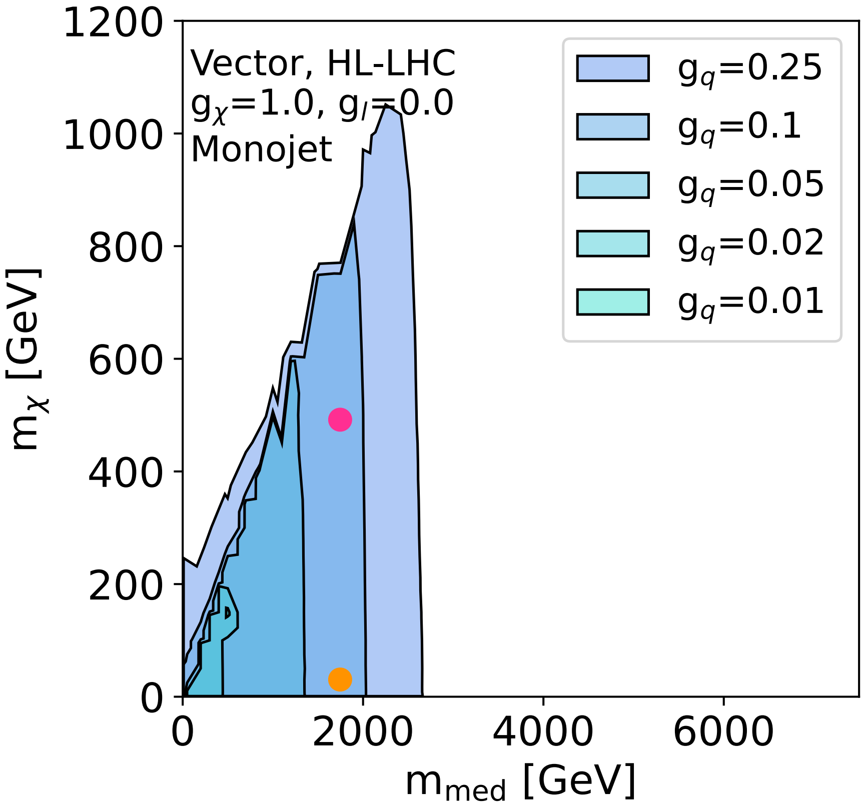

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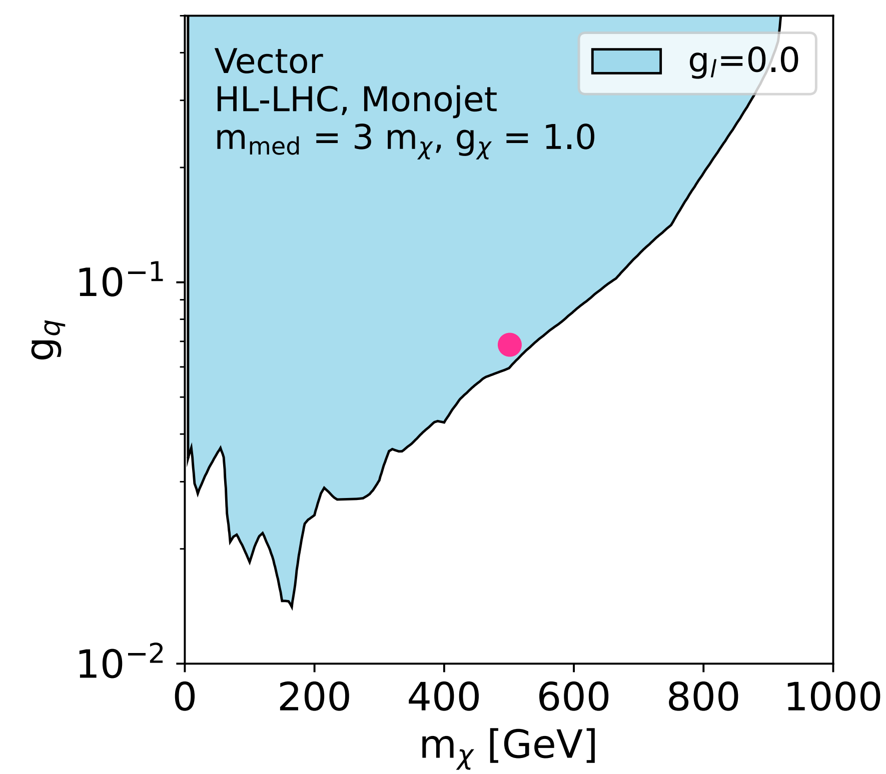

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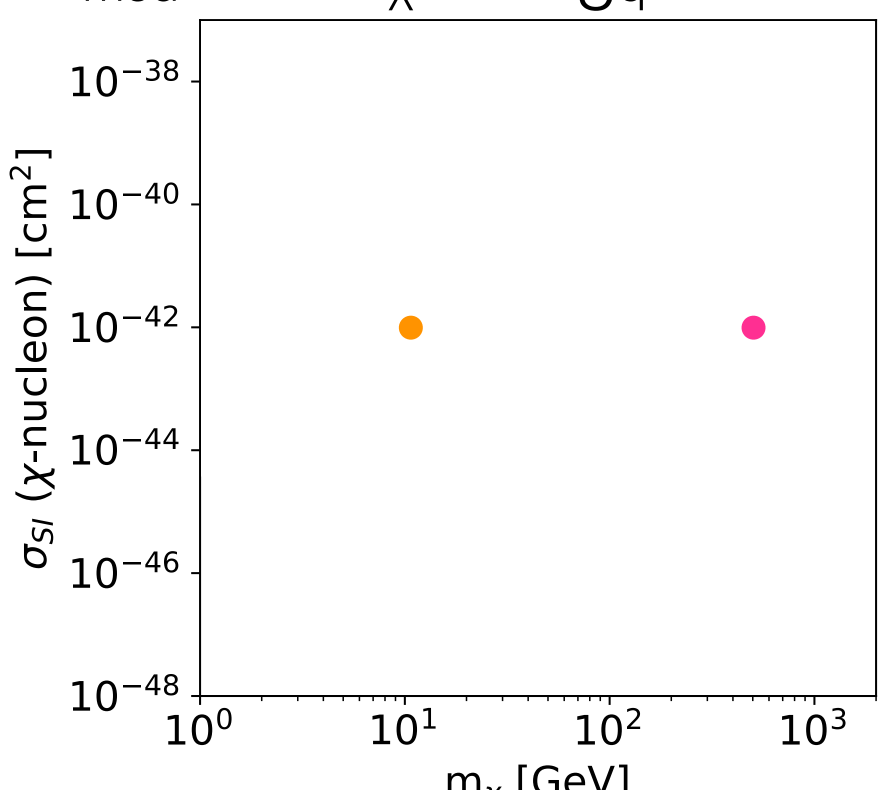

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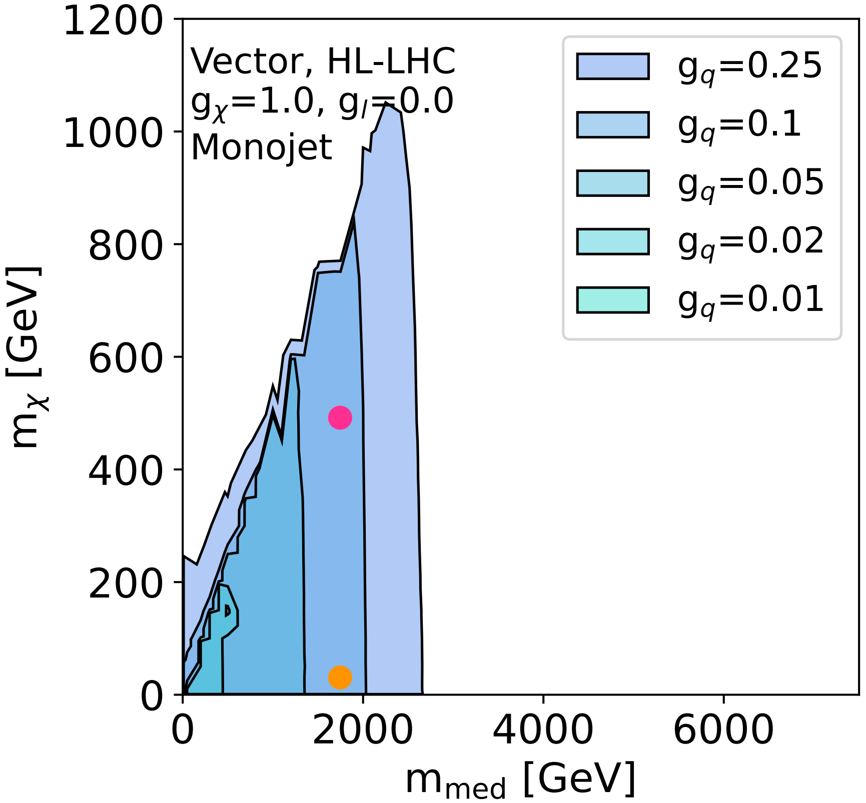

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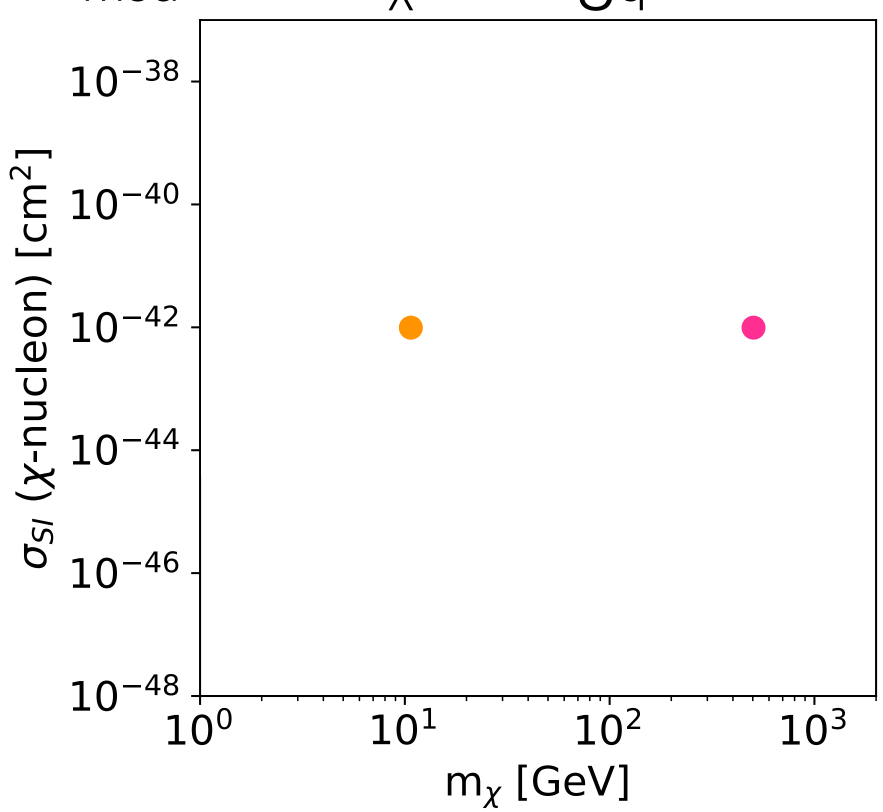

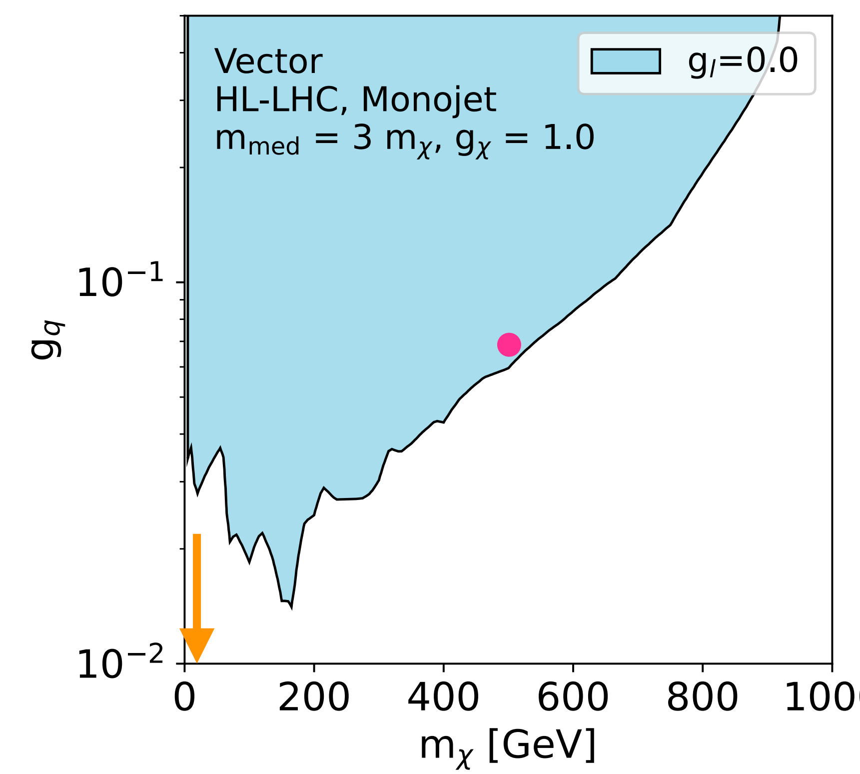

But if instead we fix M_{med} = 3 m_χ, point (10, 10^{-42}) requires exclusion of g_q to 1e-5

Framing colliders in the same context as direct detection

$\sigma_{SI} \simeq 6.9 \times 10^{-}$ ...

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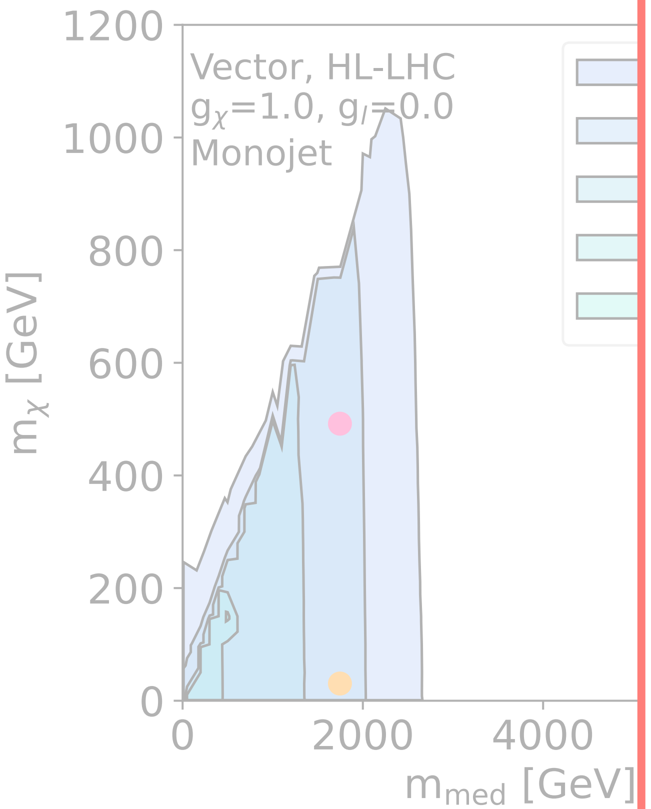
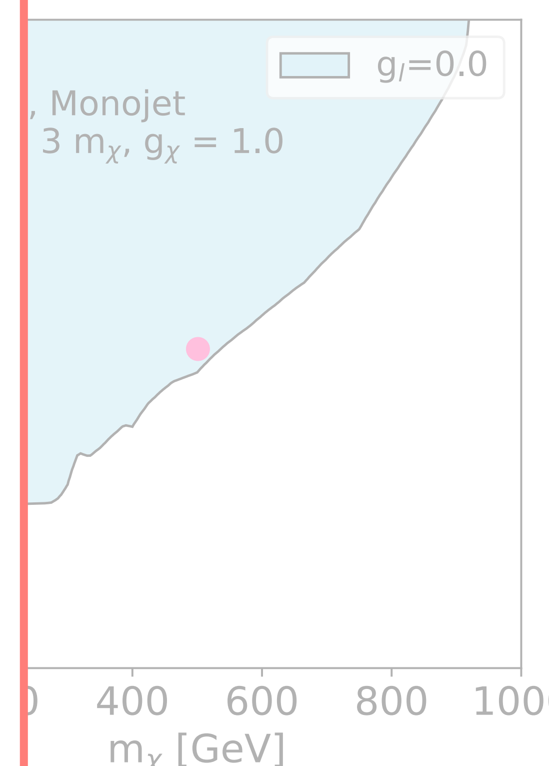


It is well defined if a point in the simplified model is excluded or not by a given limit



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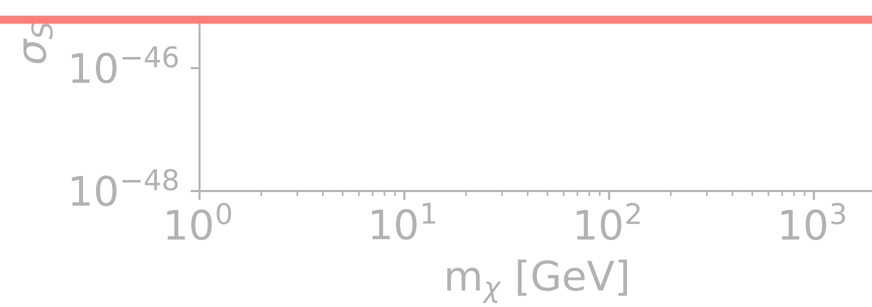

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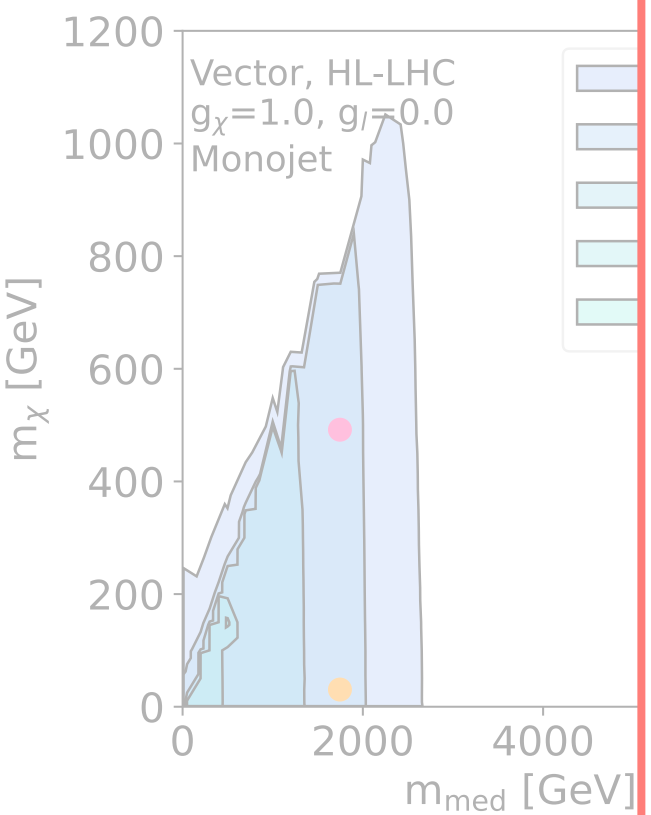

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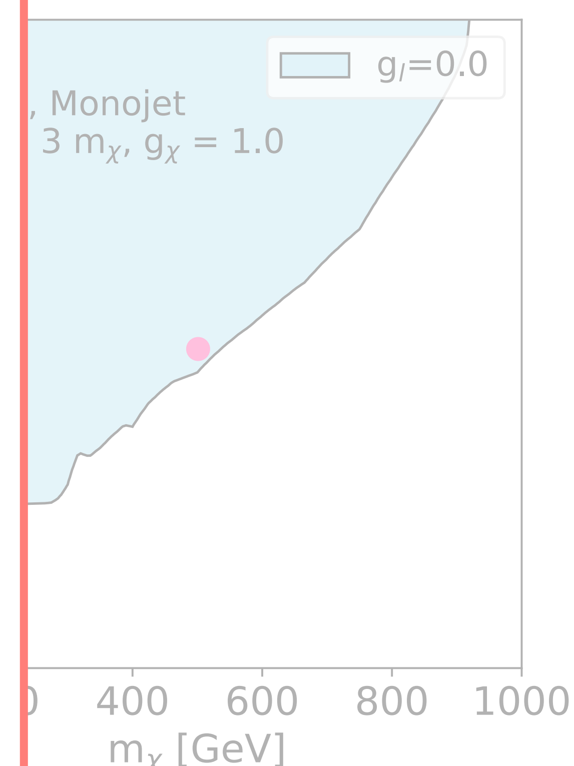
But not well defined if the same point in direct detection plane is excluded



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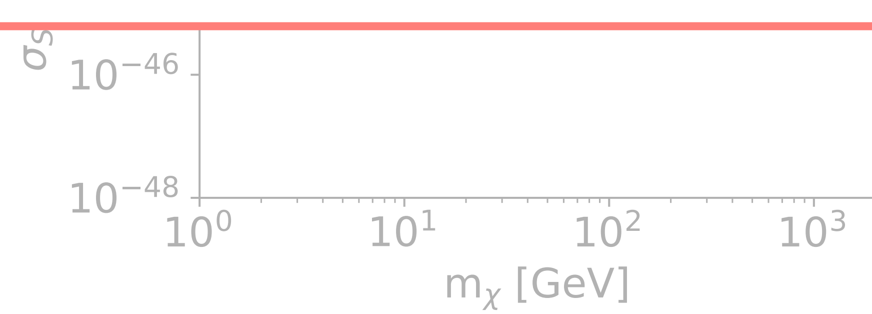

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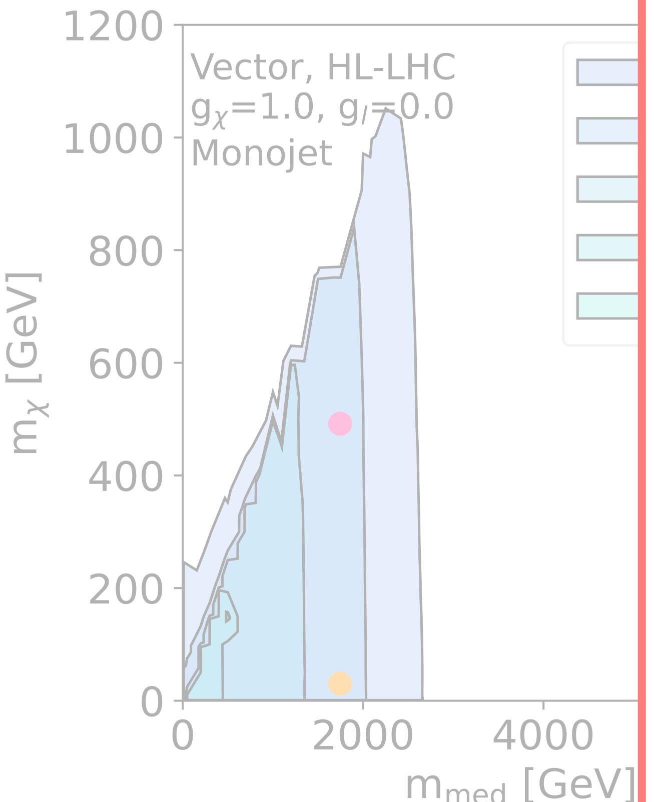

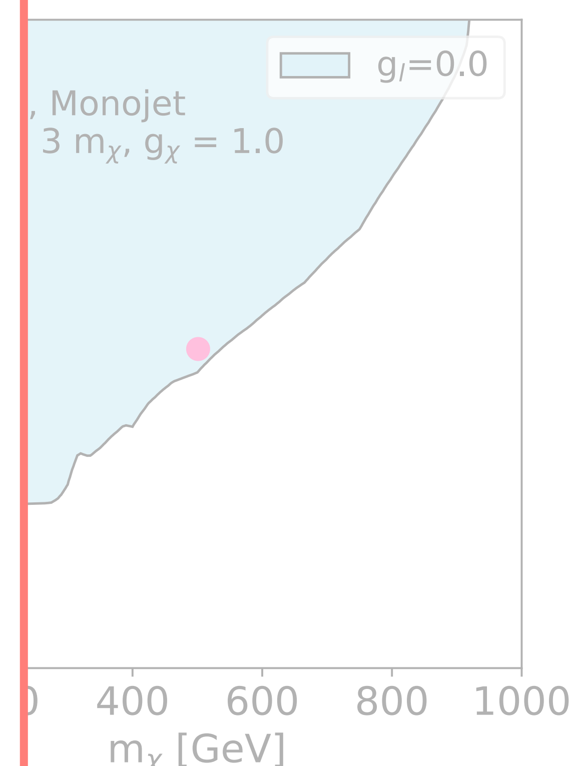

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Colliders better at high masses than small couplings

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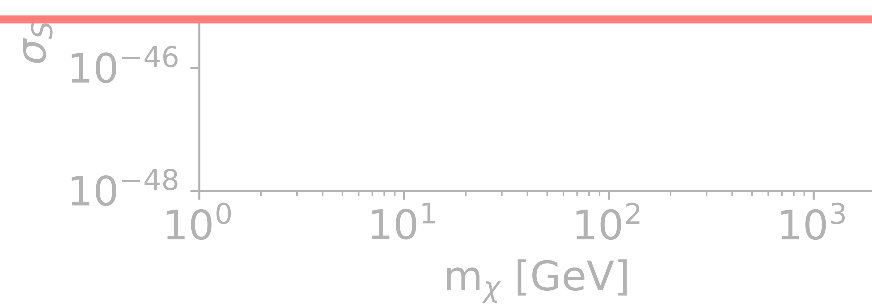

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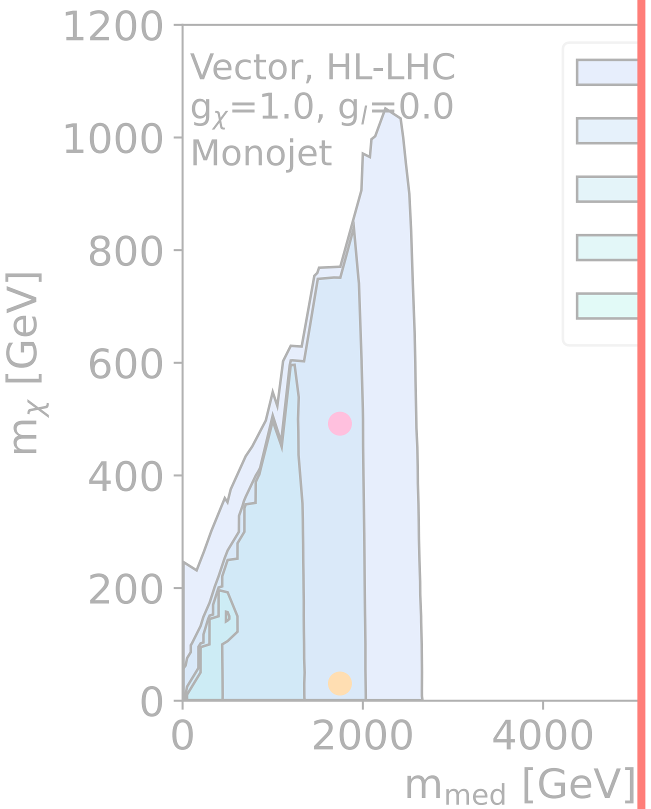

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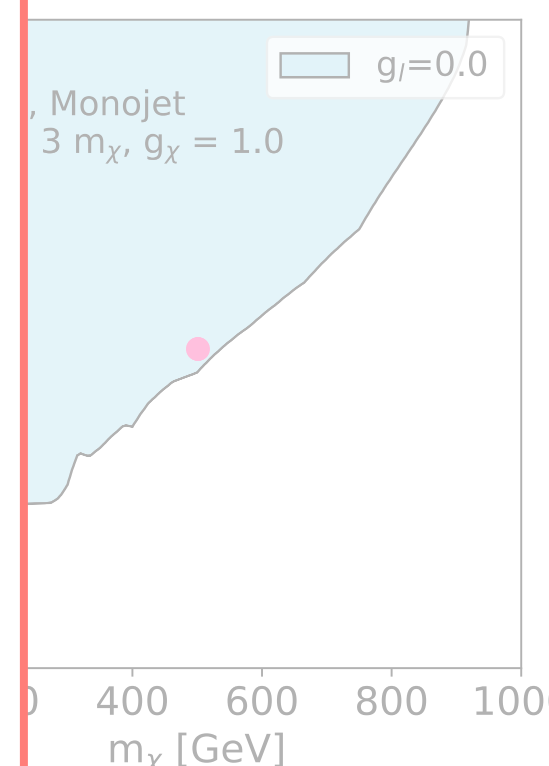
Exclusion of a DD point depends on fixed quantities in conversion



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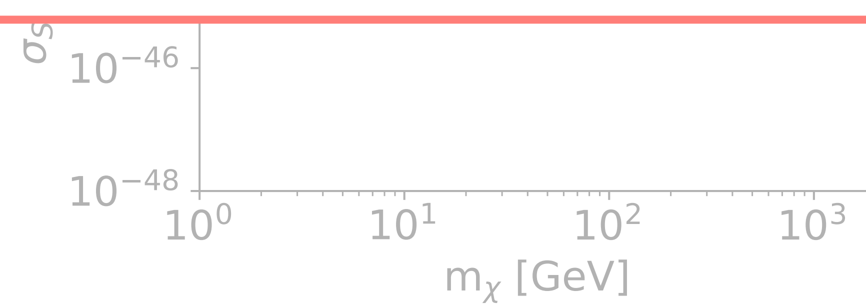

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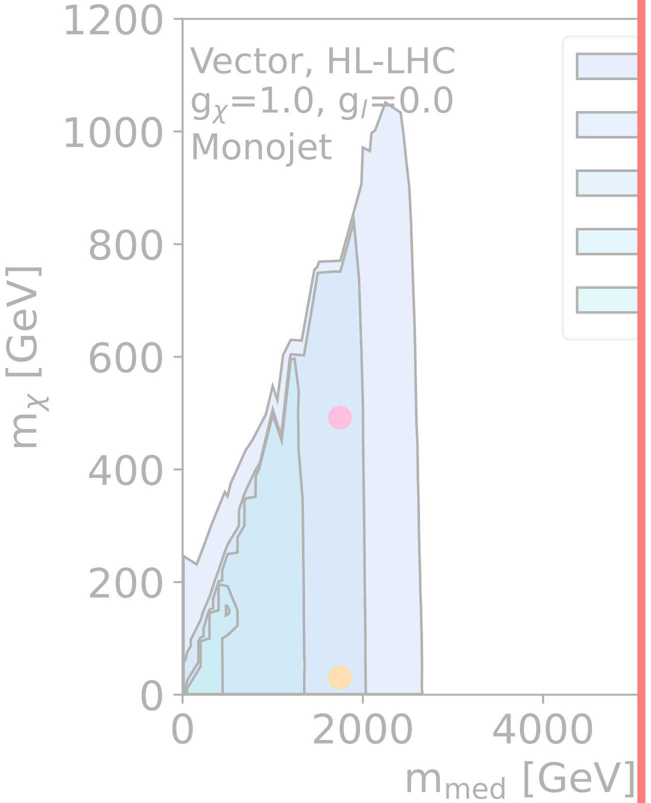

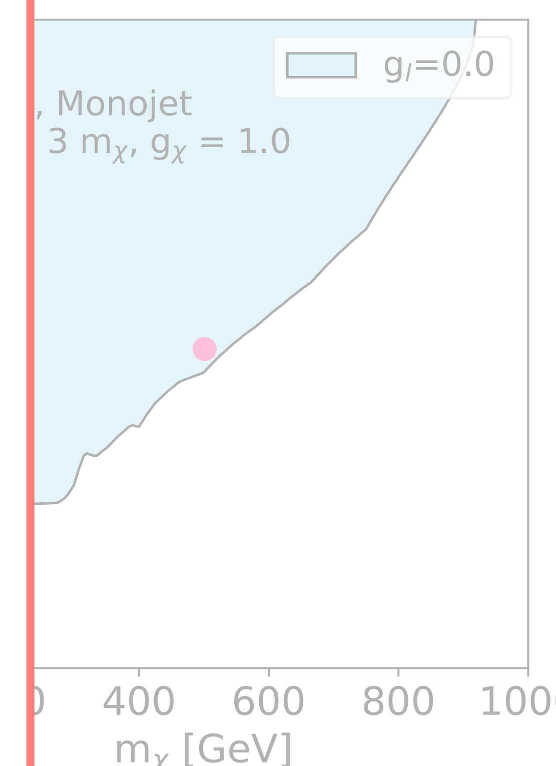

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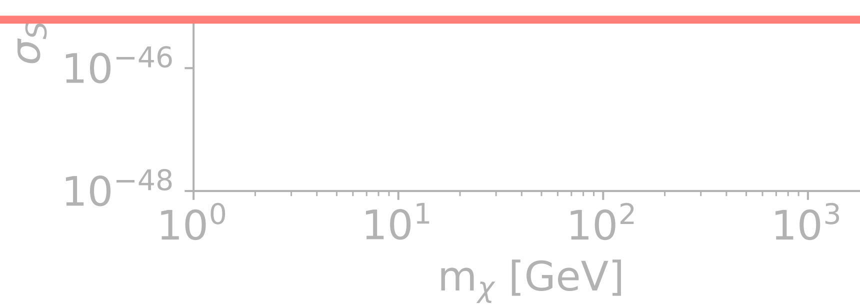
Accurate message requires showing two complementary projections



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Relationship between coupling and exclusion limit in χ-nucleon cross section plane

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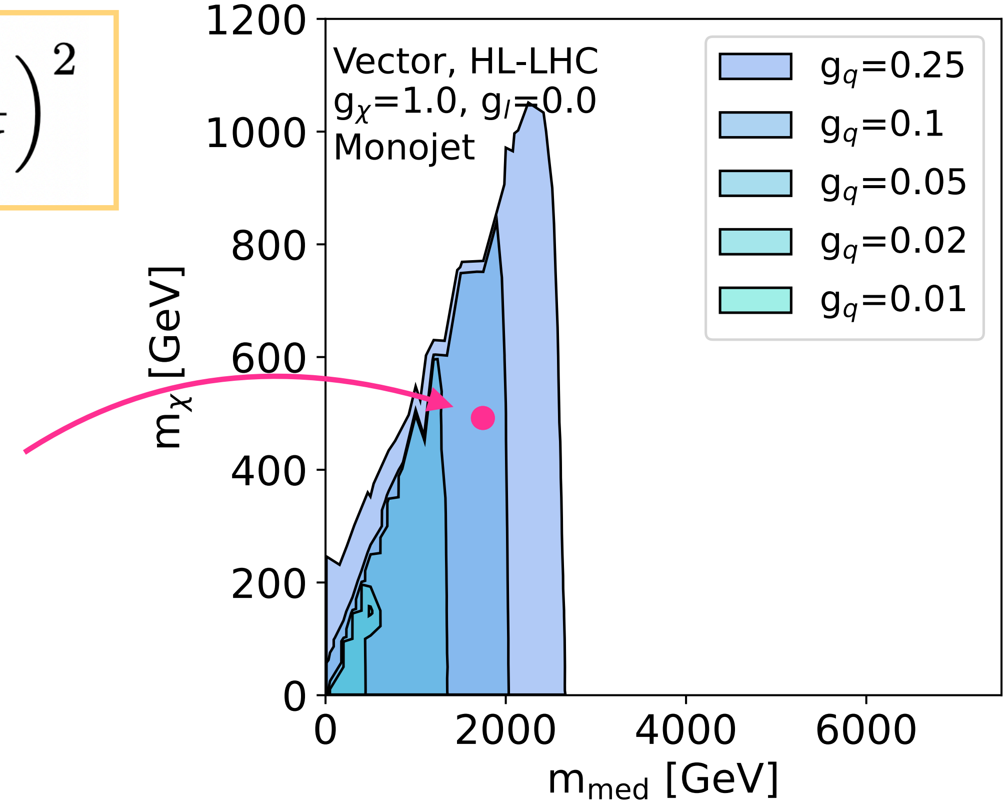
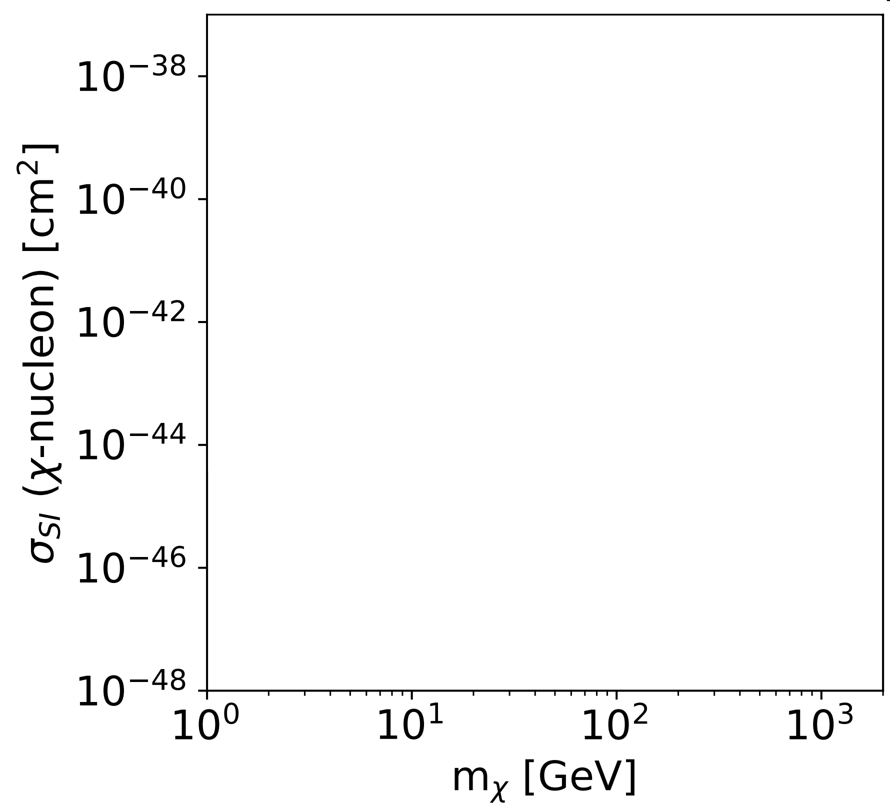
- If a fixed point in mass-mass plane is excluded for multiple values of g_q (g_{DM}), strength of exclusion in DD plane improves as smaller values of g_q (g_{DM}) are assumed in interpretation



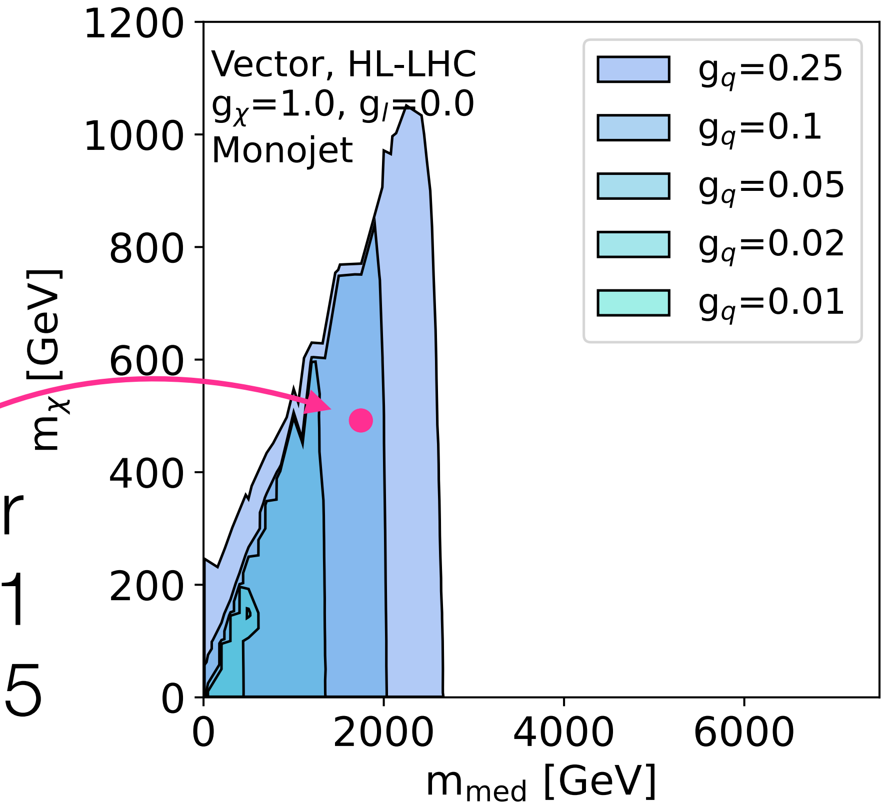


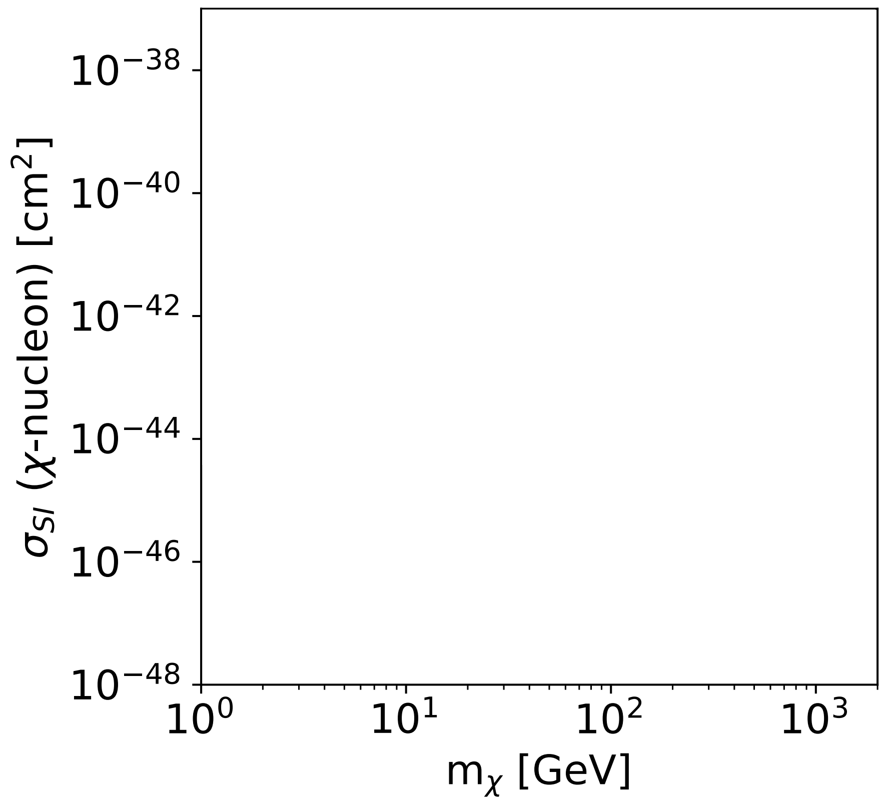
Relationship between coupling and exclusion limit in χ-nucleon cross section plane

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

- If a fixed point in mass-mass plane is excluded for multiple values of g_q (g_{DM}), strength of exclusion in DD plane improves as smaller values of g_q (g_{DM}) are assumed in interpretation

Excluded for both $g_q = 0.1$ and $g_q = 0.25$





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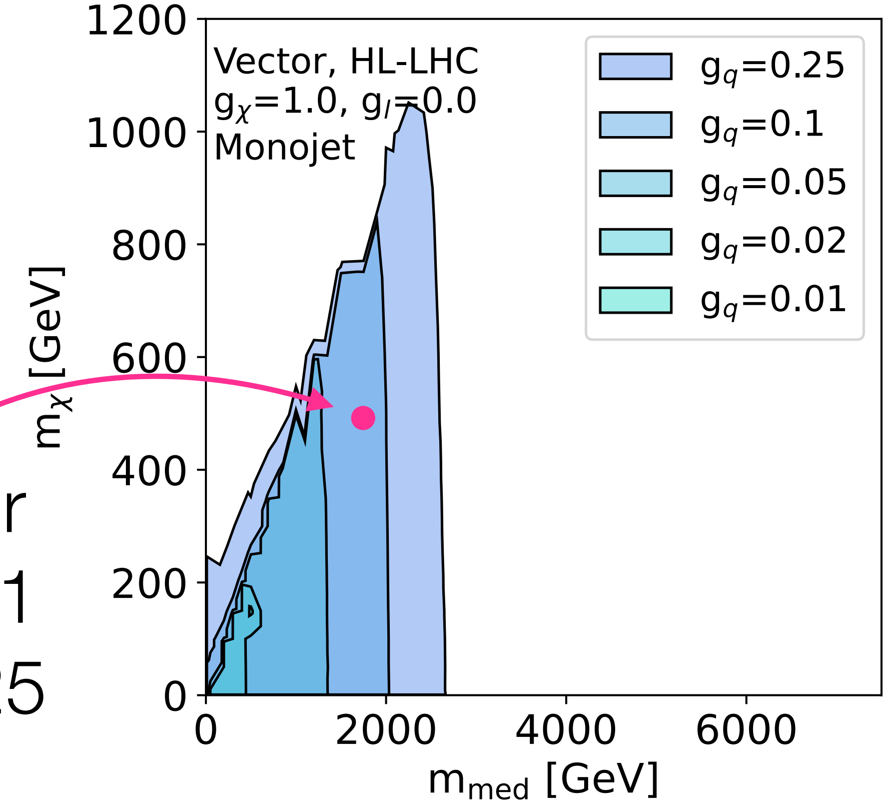

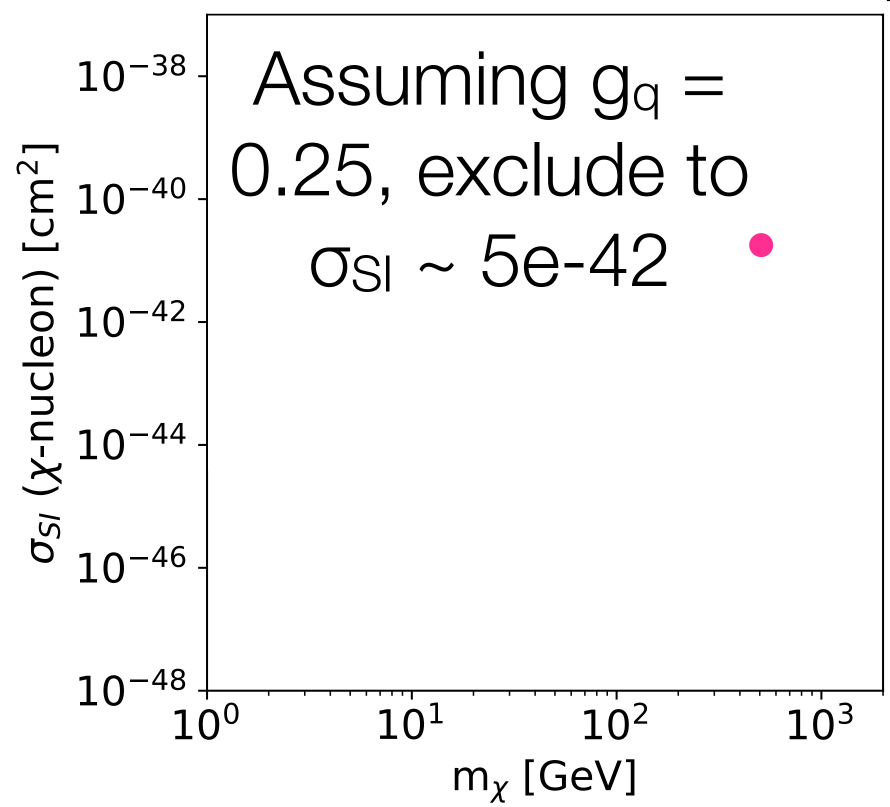

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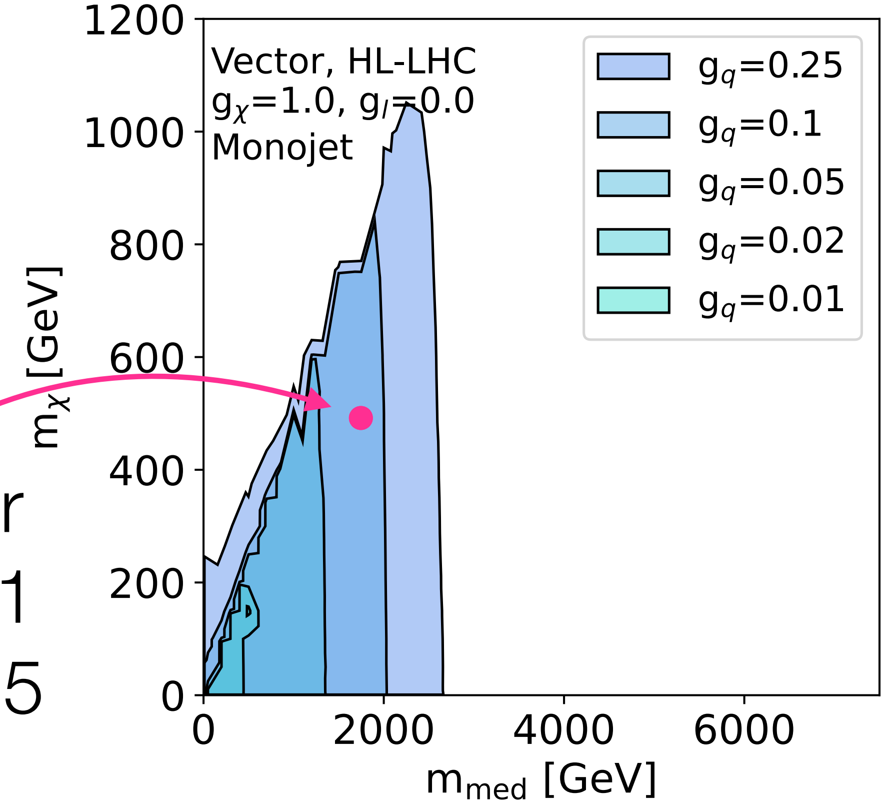

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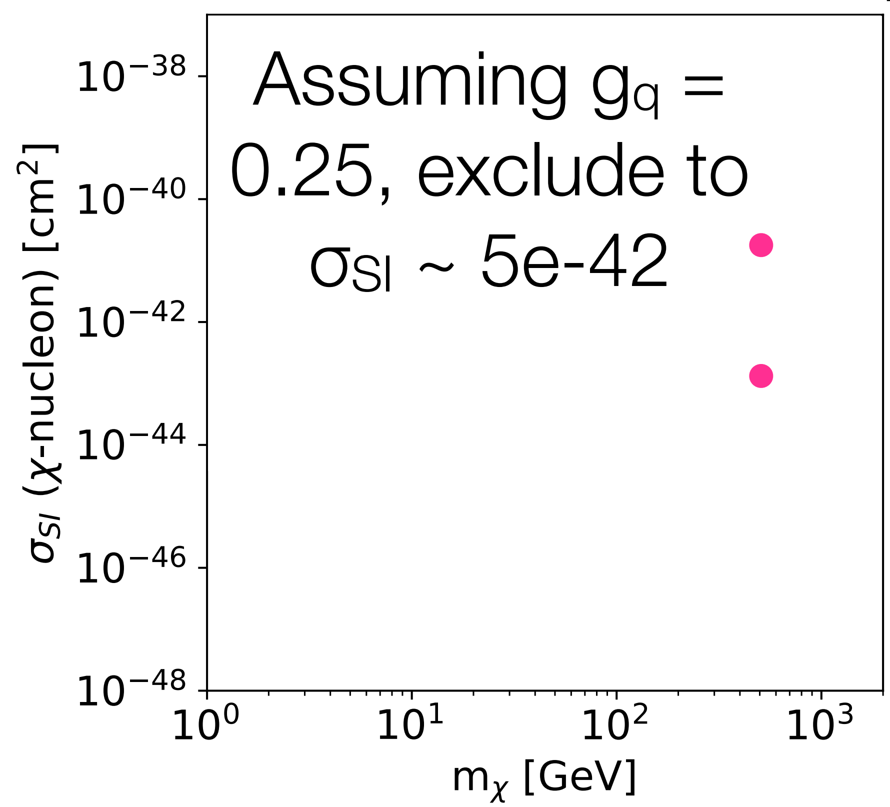

With g_q = 0.1, reach σ_{SI} ~ 5e-44

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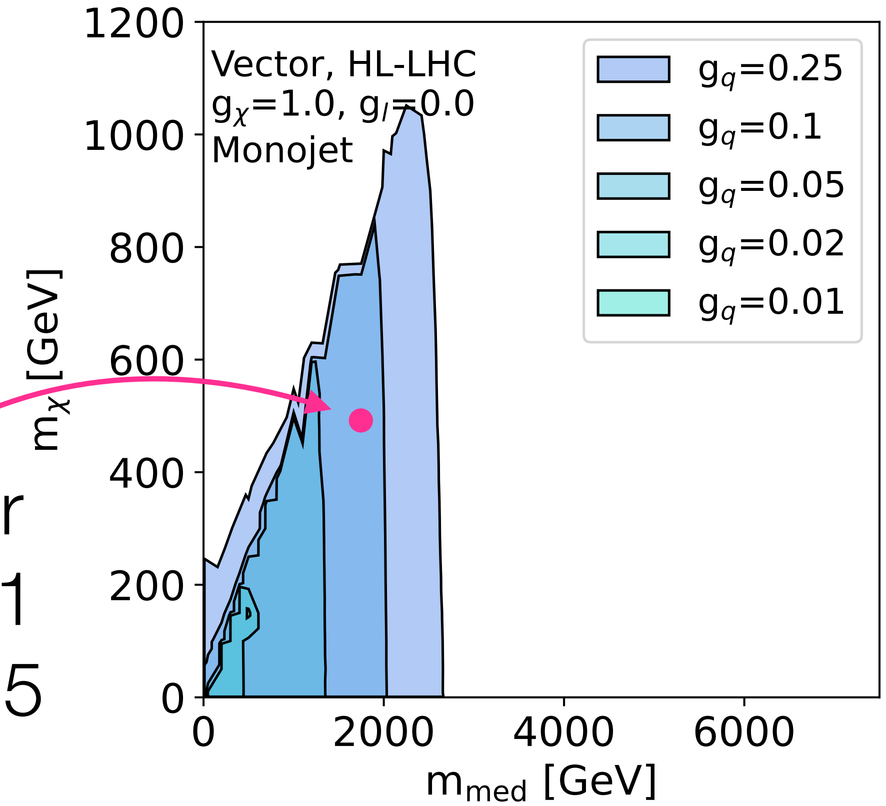
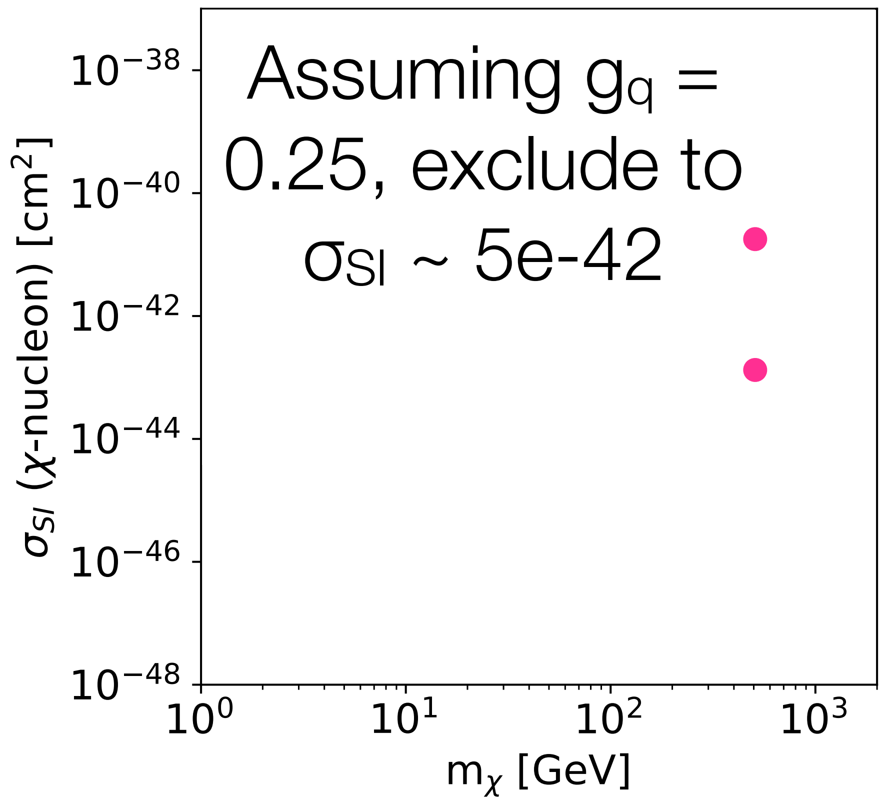
- Excluded region smaller (in mass-mass) at smaller coupling, but also moves lower on y axis. Effects essentially cancel out for monojet.

Excluded for both g_q = 0.1 and g_q = 0.25





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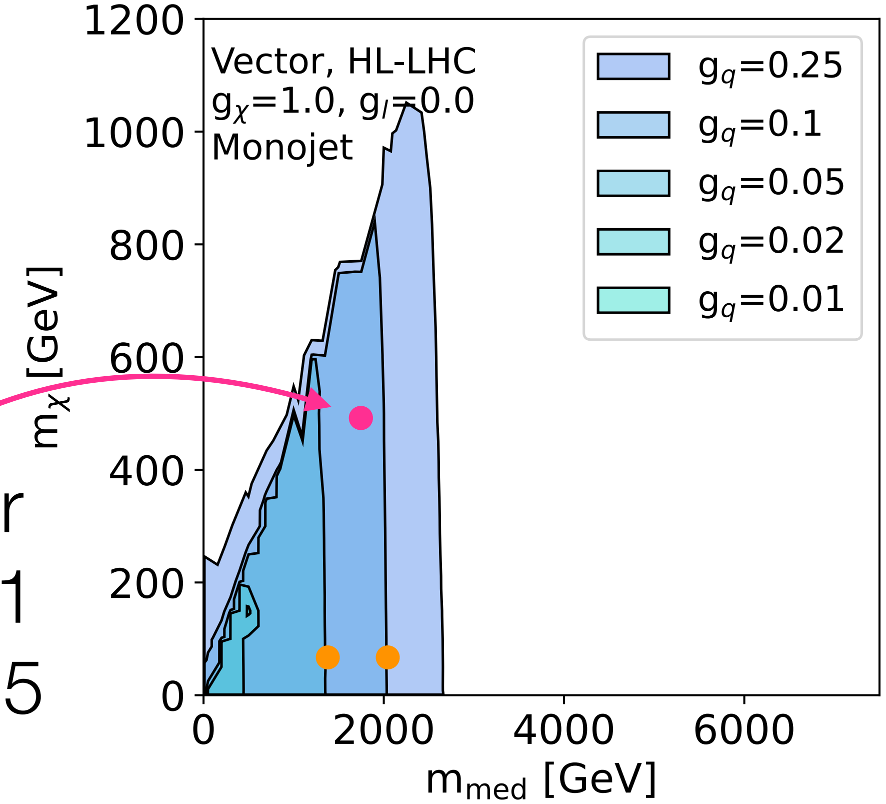

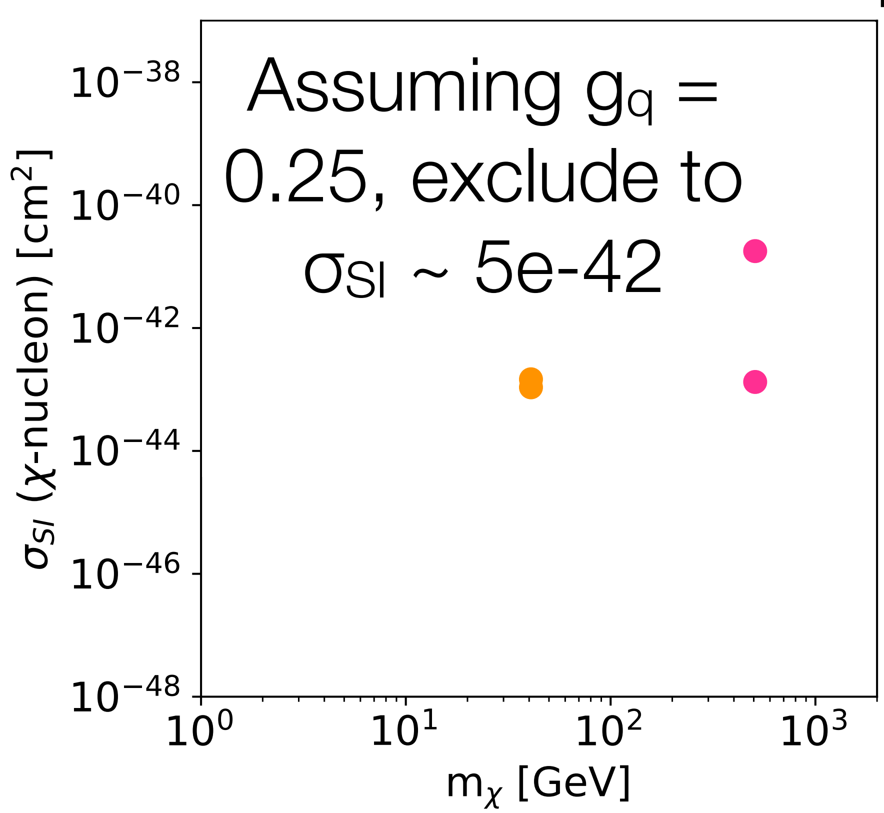

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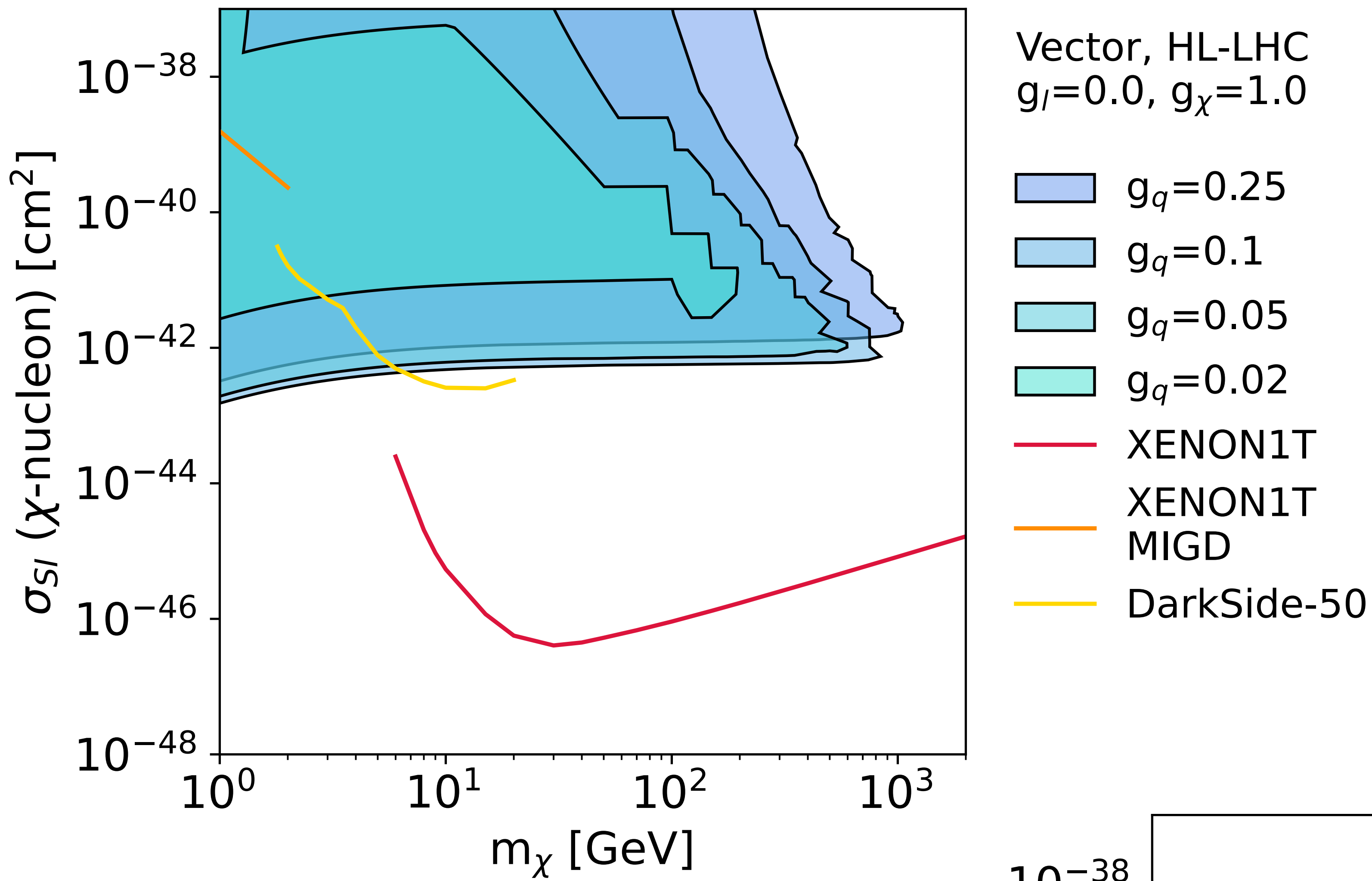
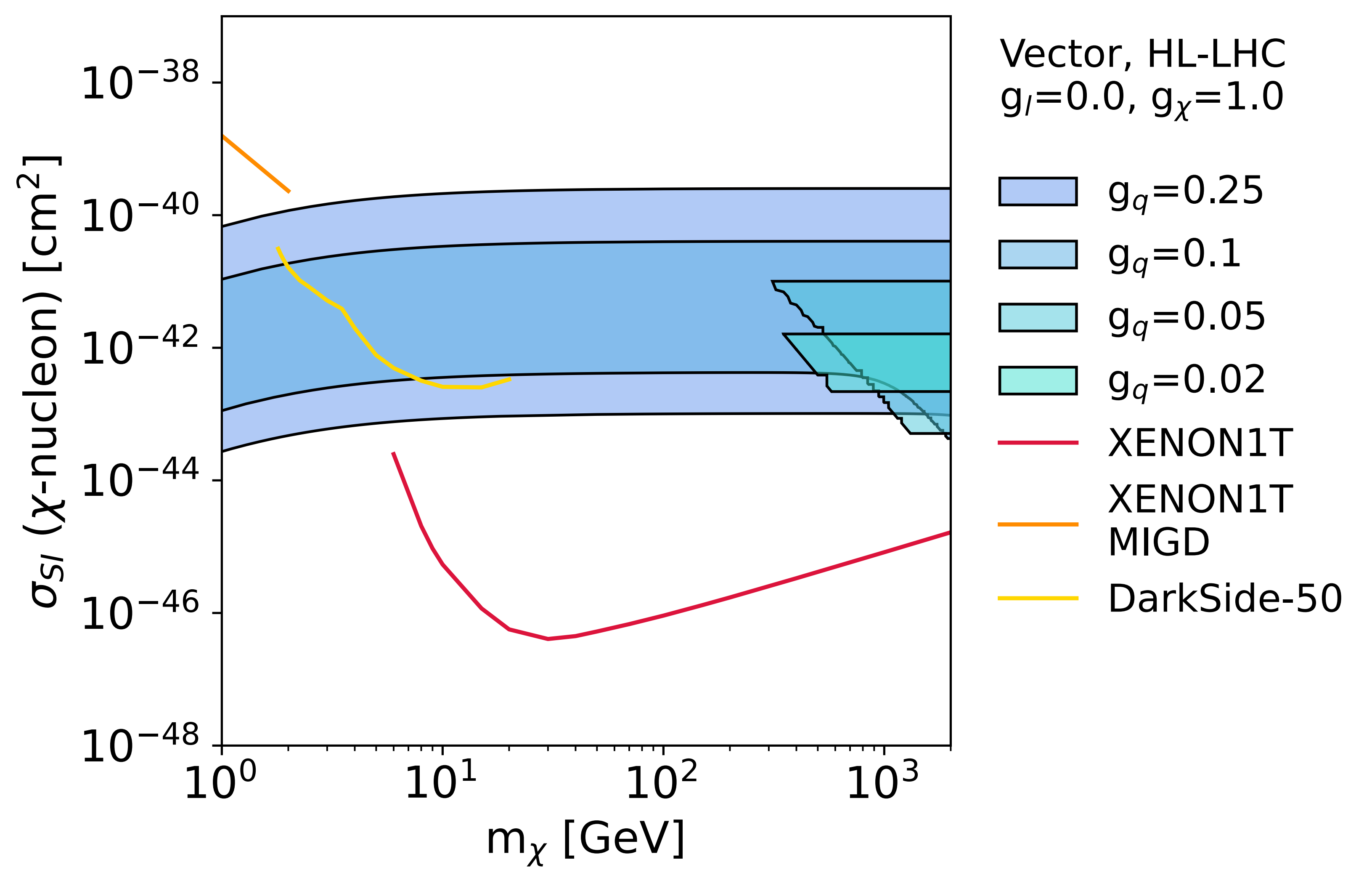
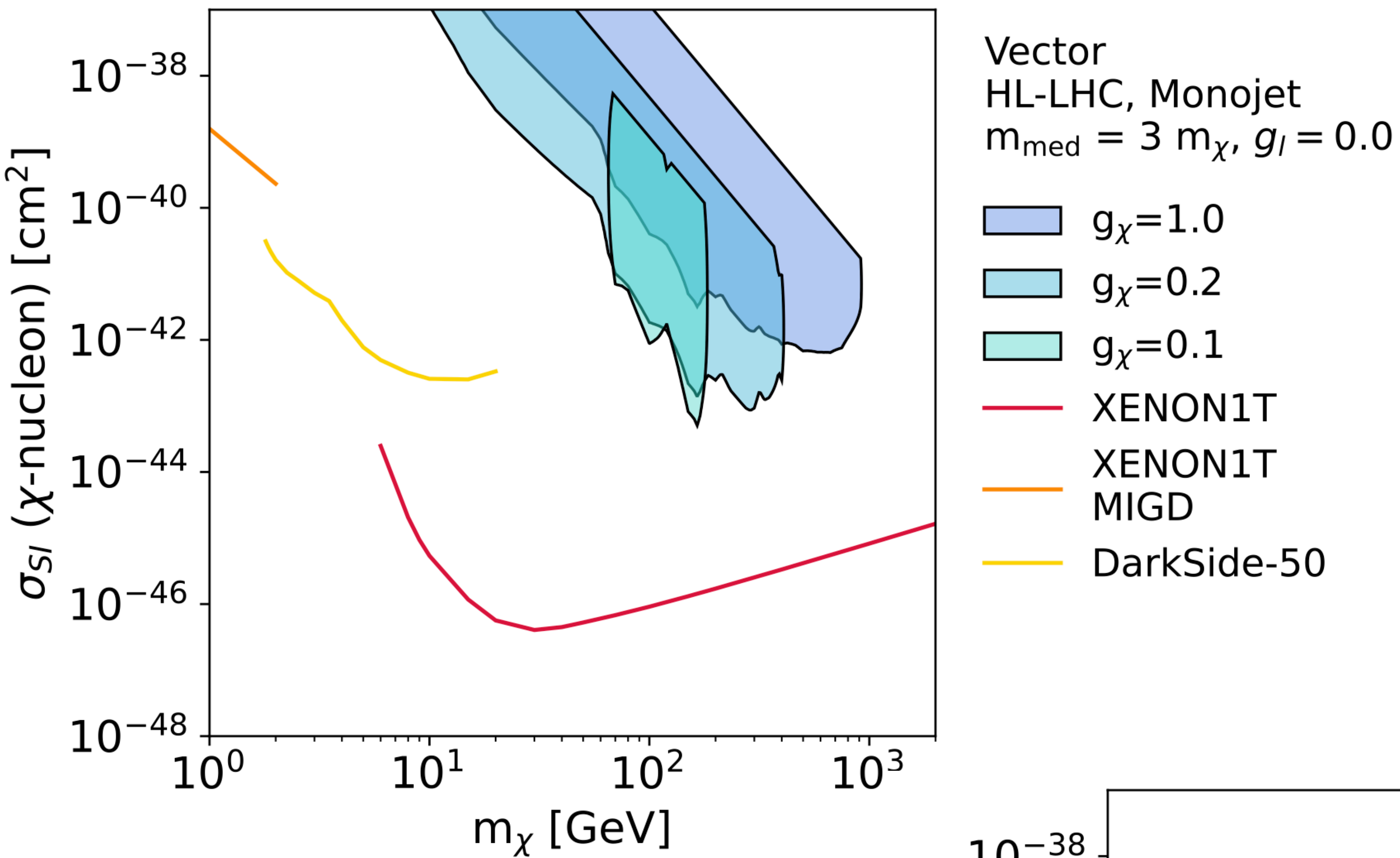
χ-nucleon cross sections with fixed couplings, allowing any mediator masses



Exclusions arise directly from mass-mass limit plots, with change of variable from M_{Med} to y axis (fixed coupling values)

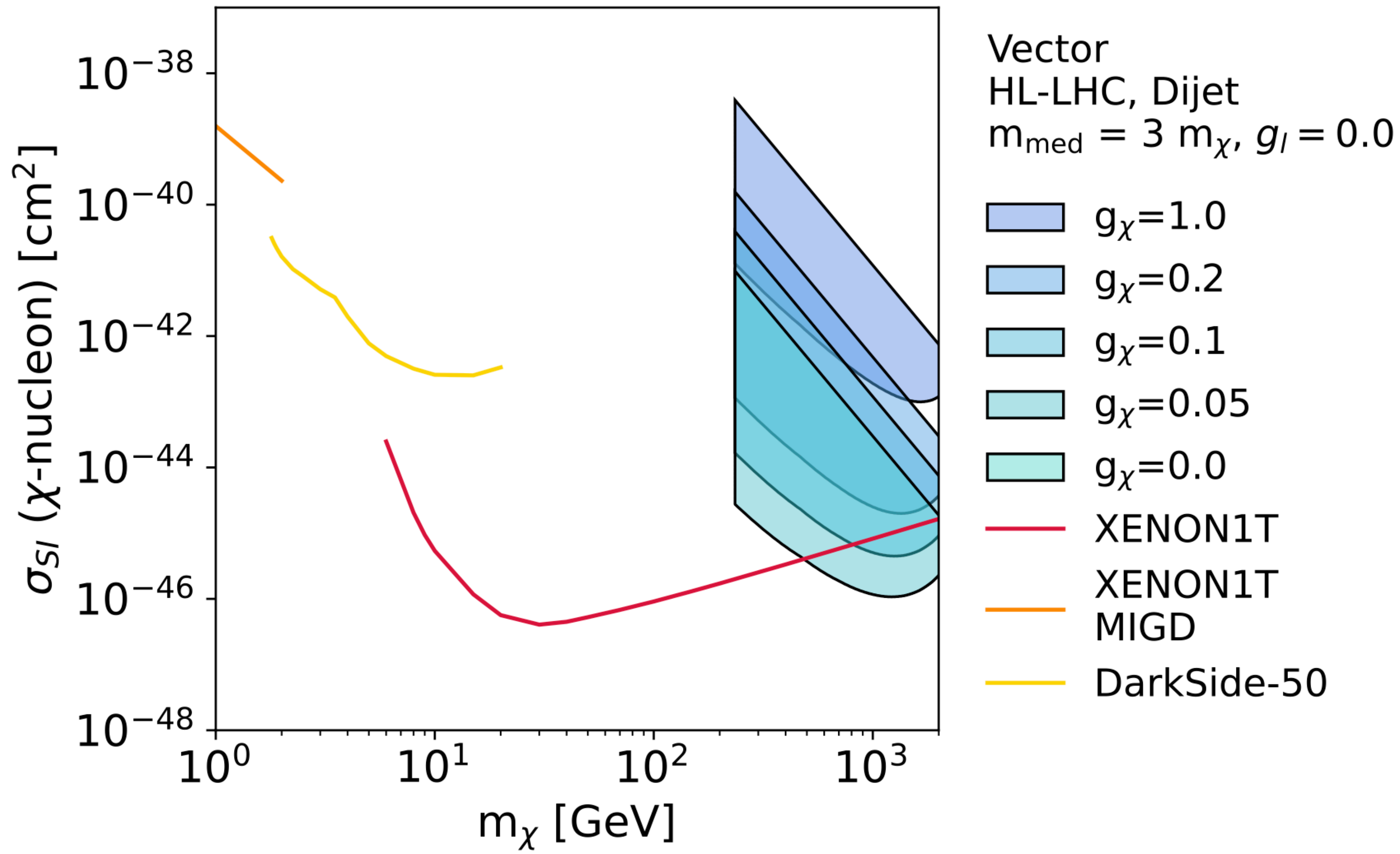


☆ Both included in EF BSM report



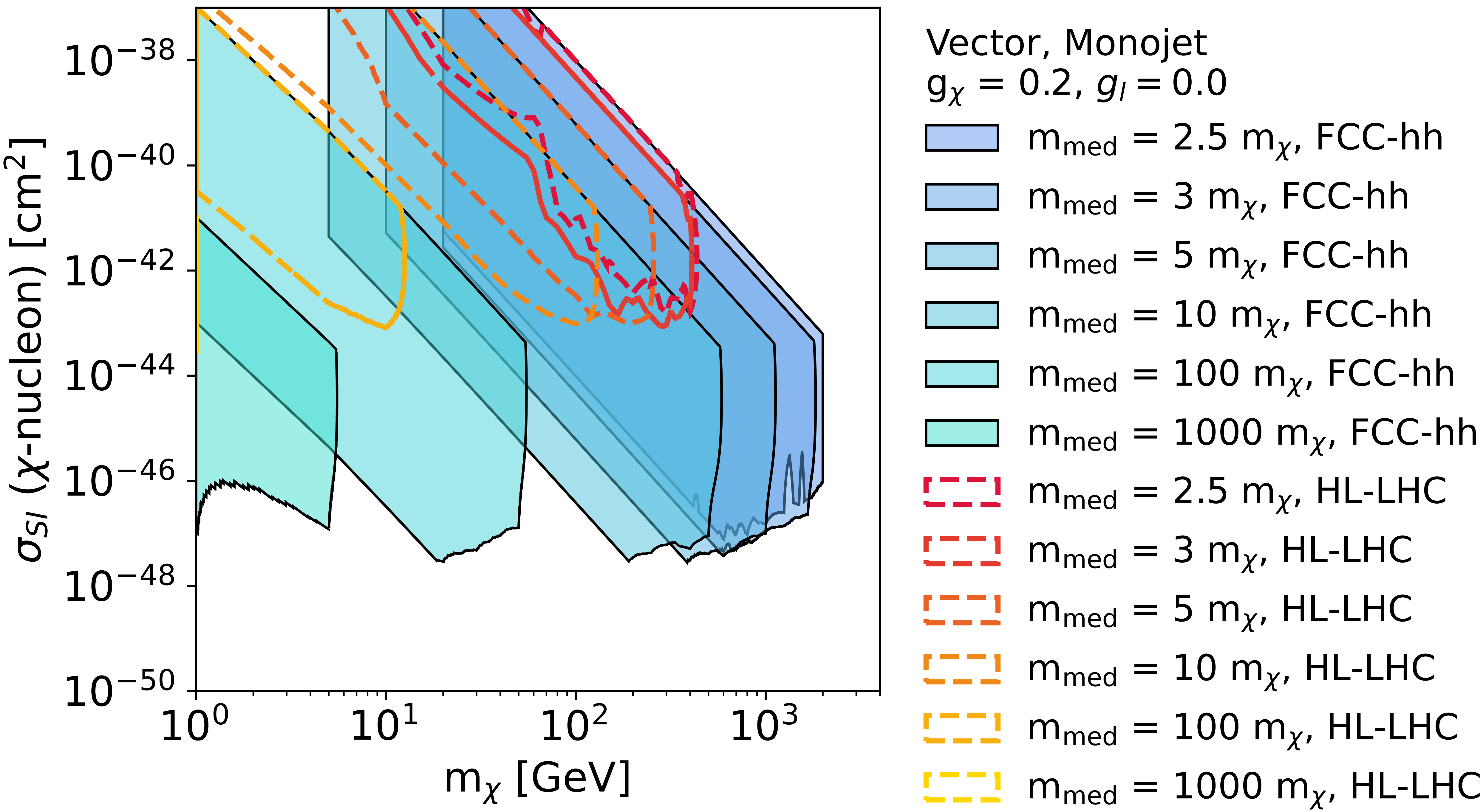
χ-nucleon cross sections with fixed mediator mass, allowing any coupling to quarks

Exclusions arise directly from mass-coupling limit plots, with change of variable from gq to y axis (mediator mass values fixed to a specific factor of DM mass)



Impact of varying the mass ratio

☆ Included in EF BSM report



Take-home messages

- These simplified models have limitations/caveats, but are useful benchmarks which can be interpreted to directly correspond to dark photon (see Suchita's talk) and direct detection scenarios
- This lets us bring RF, EF, & CF onto the same plot
- When we do this, we see regions accessible mostly/only to direct detection and others accessible mostly/only to colliders, depending on which point in this space nature gives us
- We don't know in advance what nature holds, so we should emphasise the need for both approaches to cover all the possibilities
- There are many more complex models for which these simplified models are just stand-ins: BUT these simplified models can already give us a multi-dimensional phase space that provides a clear case for complementarity of DD and colliders
- Fair to assume similar outcomes would arise from more complex models as well, but this lets us provide a concrete example to support the need for all approaches

Discussion points

Comment received: impact of relic abundance

- Some areas in simplified model space are already excluded by observed relic density.
- We are aware of this - it is indeed part of why we are focusing on vector and axial-vector mediators, since the space for scalar/pseudoscalar mediators is so much more strongly constrained by relic abundance
- But in general, we feel this point should not be taken overly seriously given nature of simplified models. Purpose of these models is to provide concrete examples of interplay between experiments/frontiers in a way that illustrates complementarity while keeping interpretations simple enough to display on a few plots
    - (And even then, as shown here, it’s still not that simple!)

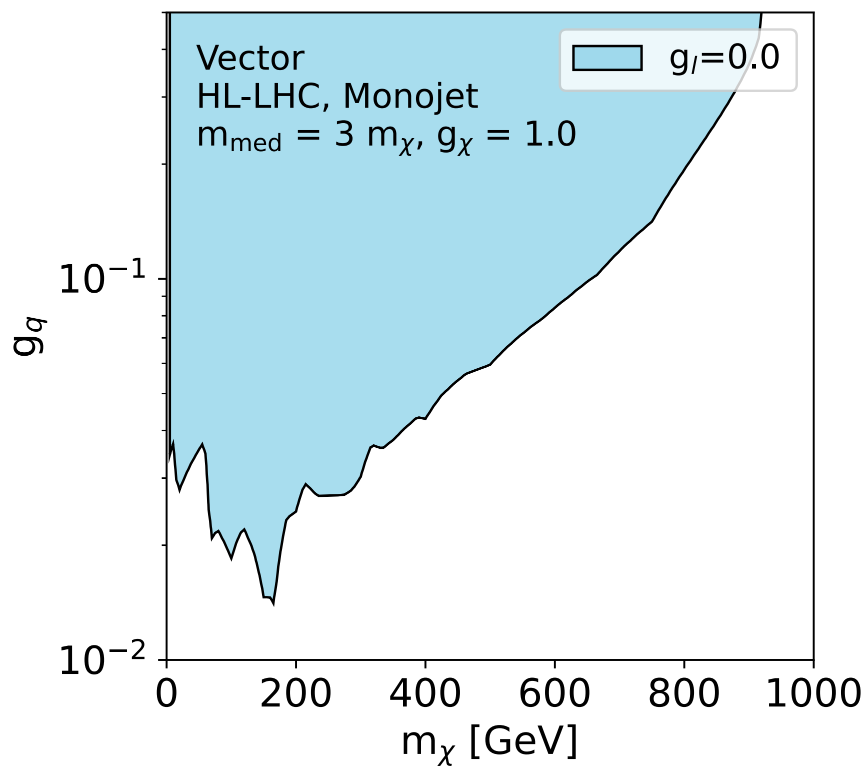
Discussion points

- How can we most strongly use these simplified models to make the case for complementarity?
- How do we most clearly present this information in the smallest number of plots?
- How should we phrase statements to make it clear that we understand how simplified these models are, but that we want to give clear examples?
- Are the current plots successfully conveying our message?
- If we want to simplify farther to a few “doodles” for inclusion with cross-frontier summary plots, which doodles do we want? How do we frame them?

Backup slides

What actually dictates the angle of this shape?

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



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_χ. Keep g_χ = 1.0.

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

On a log-log axis, X = log(m_χ) and Y = log(σ_{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_χ only **shifts the line left or right and does not affect its angle.**

And what about the other side of the shape?

For medium to high M_{Med}/m_{χ}, projection of a slice across g_q contours onto the mmed axis basically doesn't change.
$g_q = f(M_{Med})$ is the same for all $A = m_{med}/m_{\chi} >$ ~5.

All essentially match m_{χ} = 1 GeV. And here we can see that $g_q \sim ae^{bM_{med}}$ for some a ~ 0.012 and b ~ 0.0011.
So now, wrapping all numbers into a constant C,

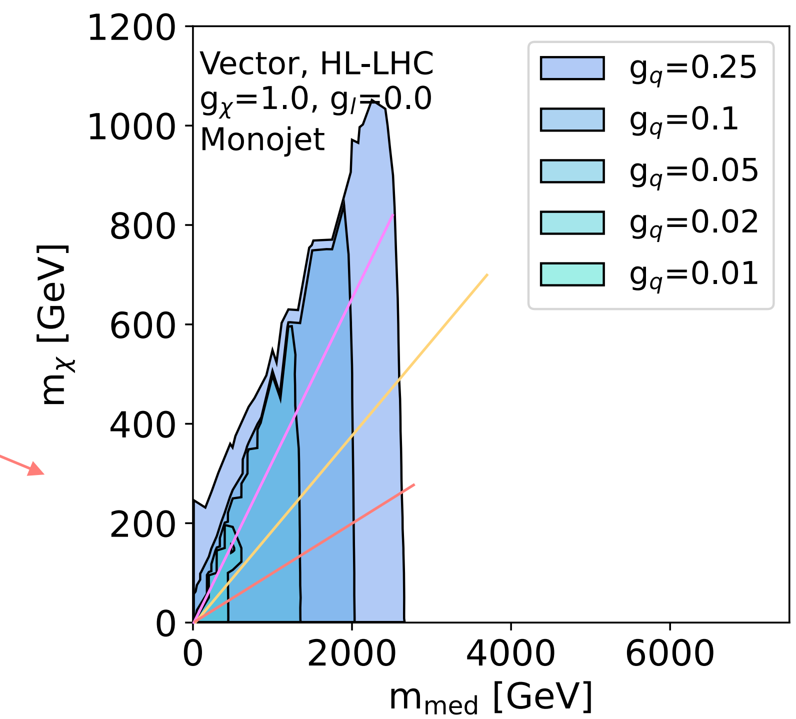
$$\sigma_{SI} \sim Ce^{2bM_{med}}M_{\mathrm{med}}^{-4}$$

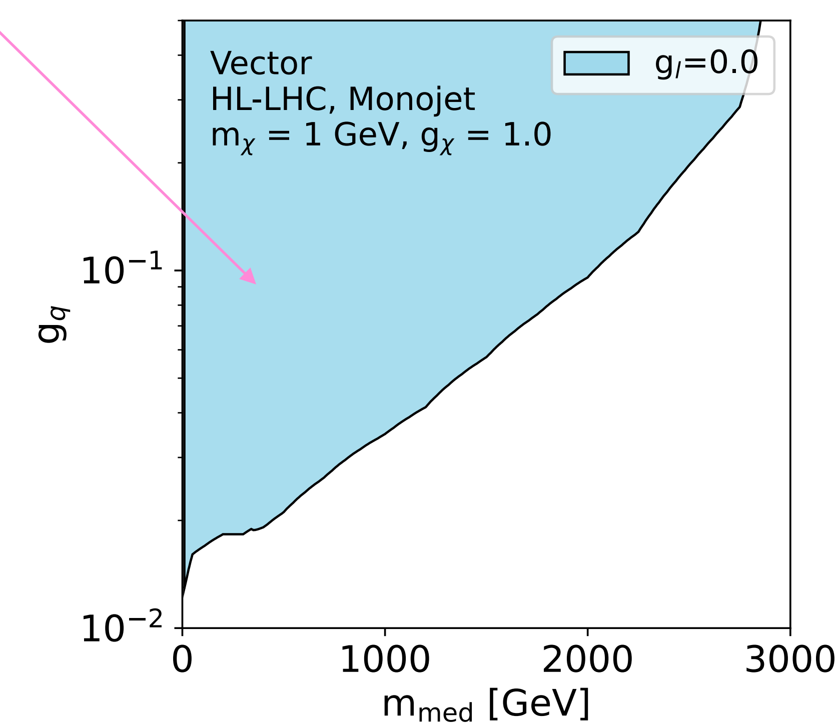
$$Y = \log(C) + 2bM_{\mathrm{med}}\log(e) - 4\log(M_{\mathrm{med}})$$

$$Y = \log(C) + 2Ab\log(e)10^{X} - 4X$$

So here there is some dependence on A, but the smaller X (i.e. where we are interested in covering), the less this is true. At x = 10 GeV/ X = 1, this term is only 0.001A.

—> Practically speaking, the whole DD exclusion shape doesn't change much with angle. It mostly moves left or right. To exclude smaller mDM we **do** need a larger m_{med}/m_{χ}, but it will just move our lozenge shape more to the left.





Minimum allowed couplings to not overproduce dark matter