Analytical rescaling for s-channel Z’: white paper & code “pre-approval”

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White paper context and goals

- Goal: make sure visible and invisible final states can be analytically rescaled between coupling assumptions for DMWG simplified models
    - Saves time making plots and creates new options for ways of presenting limit information
- CMS developed first such method, very fast and covers visible final states. Some of us in ATLAS later developed approach for invisible final states
- CMS and ATLAS developers worked together to write white paper and code package: goal for both collaborations to 1) can share a single set of code and 2) have something clear and explicit to cite for what they are doing
- DMWG approved this as an effort under their umbrella in 2019. Since then, work has been coordinated through DMWG, then Snowmass. First draft released on arxiv for Snowmass: https://arxiv.org/abs/2203.12035
    - Draft covers: rescaling methods for V and A-V s-channel simplified models, examples of use, and a statement on relationship between couplings probed in DMWG simplified models and relic density
    - Does not cover: S/PS mediators, and (so far) any documentation of code
- We are interested in publishing this paper alongside other DMWG papers. Our question today: is the wider group happy with this? How would we go about “approving” it? How does this tie in to supporting the software package?

Analytical rescaling in resonance analyses

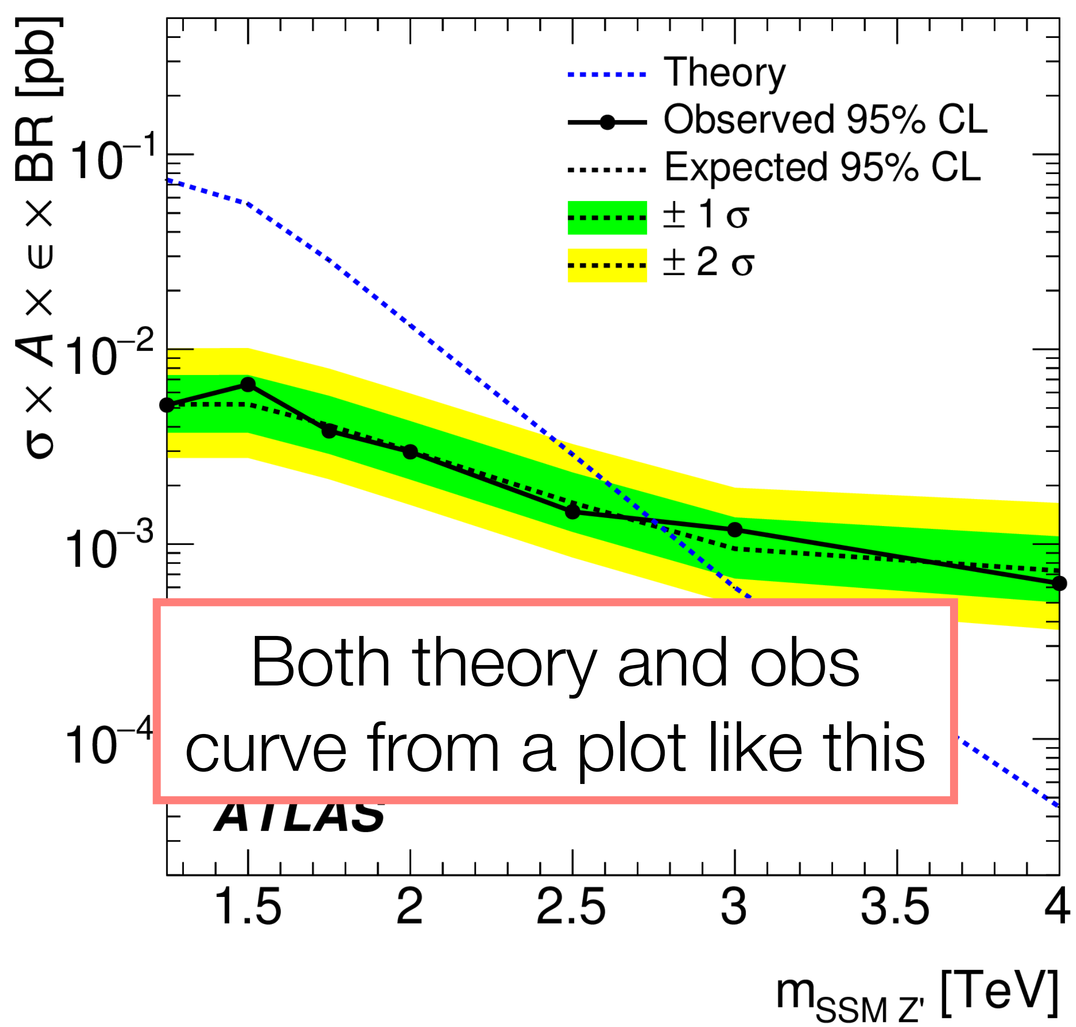
- ATLAS and CMS are already using this method for dijet (and in some cases dilepton) analyses
- The idea: rescale exclusion depth in plane from one set of couplings and masses to another using known proportionality between cross sections:

$$\sigma_{\text{on-shell}} \propto \frac{\Gamma_i \Gamma_f}{\Gamma_{\text{tot}}}$$

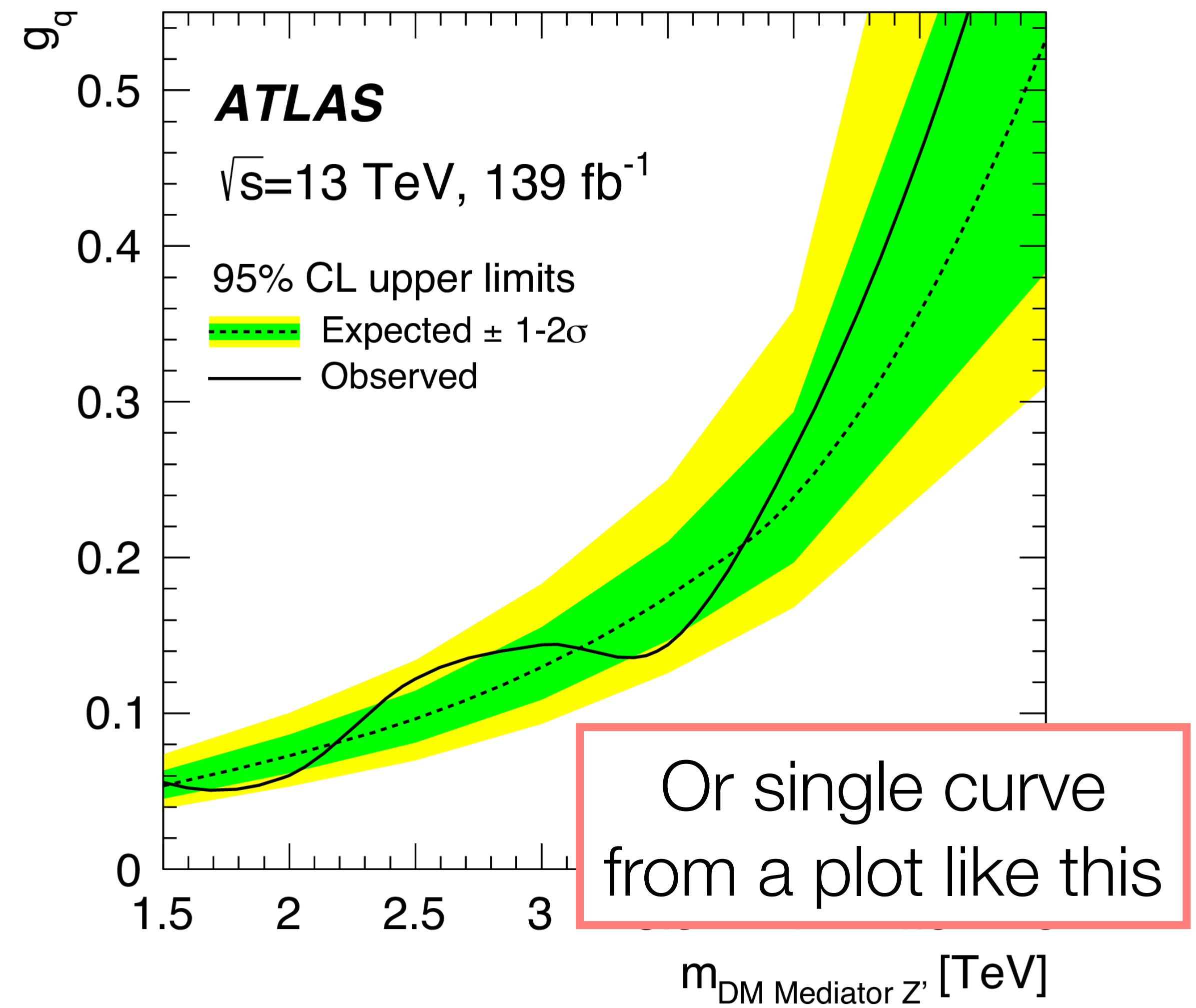
- Take ratio of cross sections in scenario where your limits are and scenario you want to be in, and scale your limits.
- In dijet production, the mediator is always firmly on-shell because Γ_f is always large due to the decay to quarks, so this is a reliable approximation

Analytical rescaling in resonance analyses

- Code base is set up to allow an analyser to start from either of two inputs:



Both theory and obs curve from a plot like this



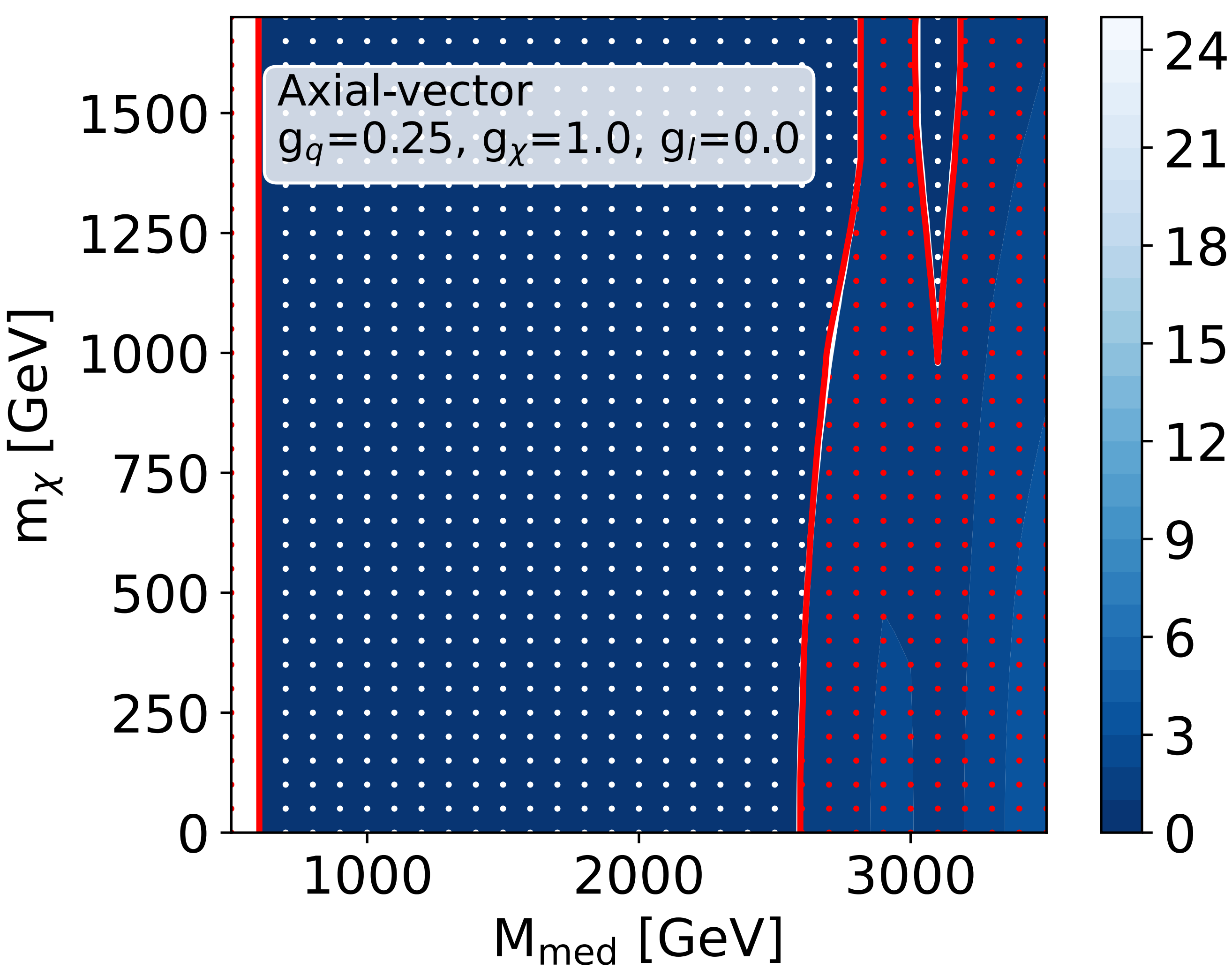
Or single curve from a plot like this

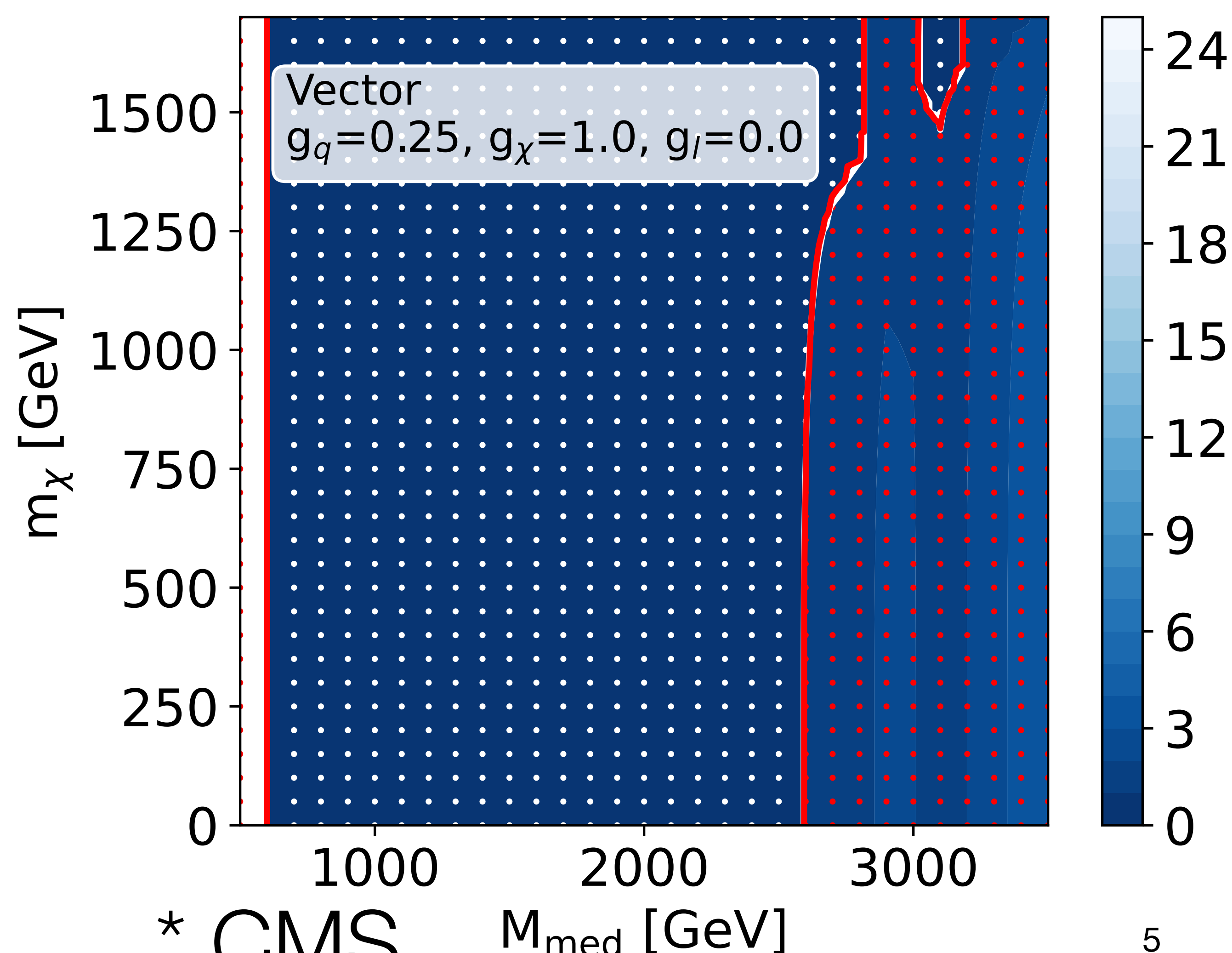
- Valid so long as limit is in DMWG Z’ simplified model specifically. No special couplings needed
- First input (cross section limit) is better because it allows user to supply multiple observed limits for different resonance widths (see a few slides from now …)

Resonant rescaling: figures in paper

- Goal is to demonstrate some validation of the resonant rescaling method, but struggled to find a public result to use to compare this to another method. Wanted a CMS result since only found an ATLAS one for MET+X rescaling, and one from an older result to not conflict with any upcoming summary plots.

- Eventually, demonstrating compatibility between two rescaling methods (g_q limit input versus cross section limit input) using CMS dijet with 36 ifb. Only tiny novelty is demonstrating liberation from “decoupled DM” input scenario.

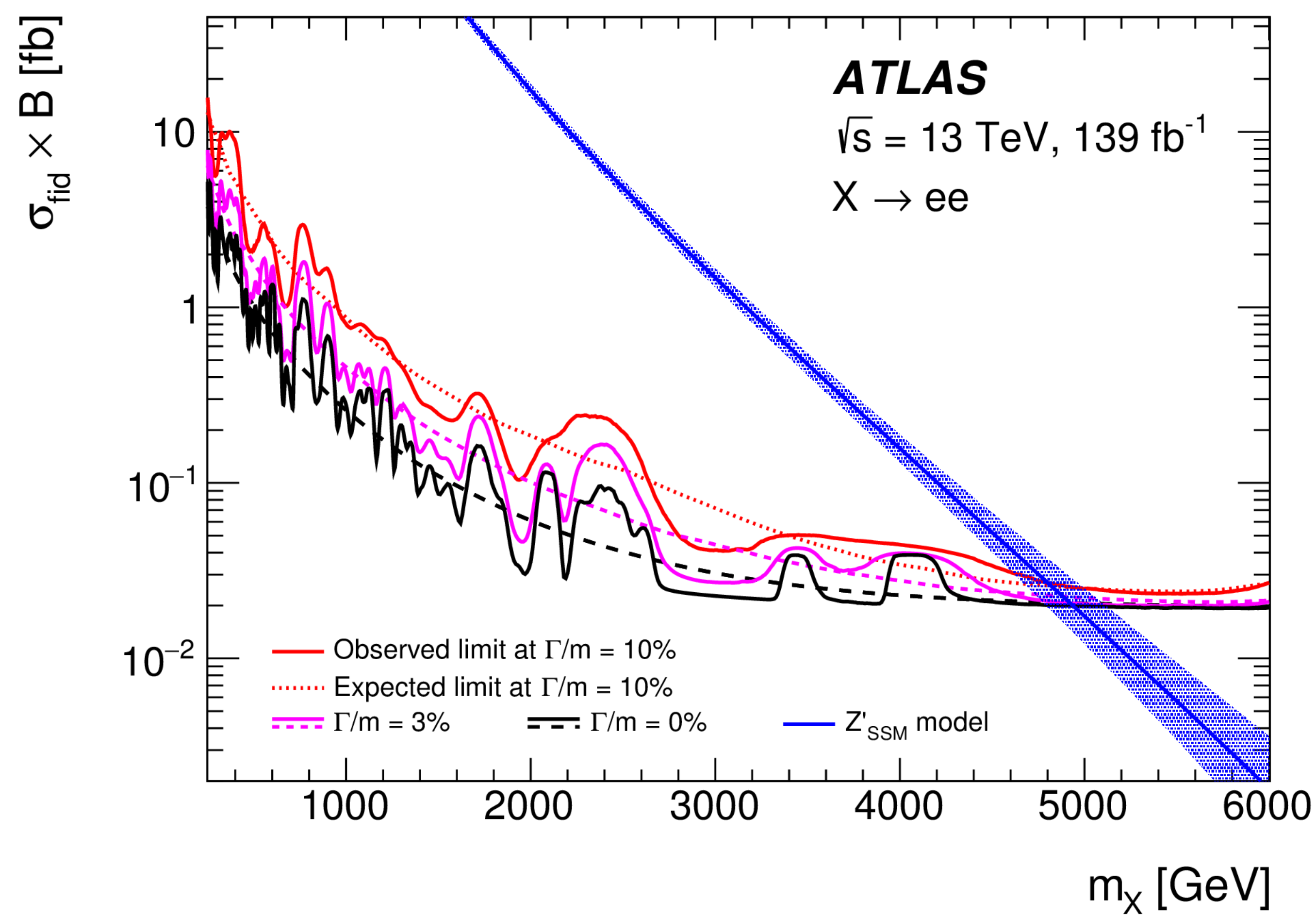




* CMS

Handling variation in resonance widths

- When experimental resolution such that limit changes with intrinsic width of resonance, need to accommodate that



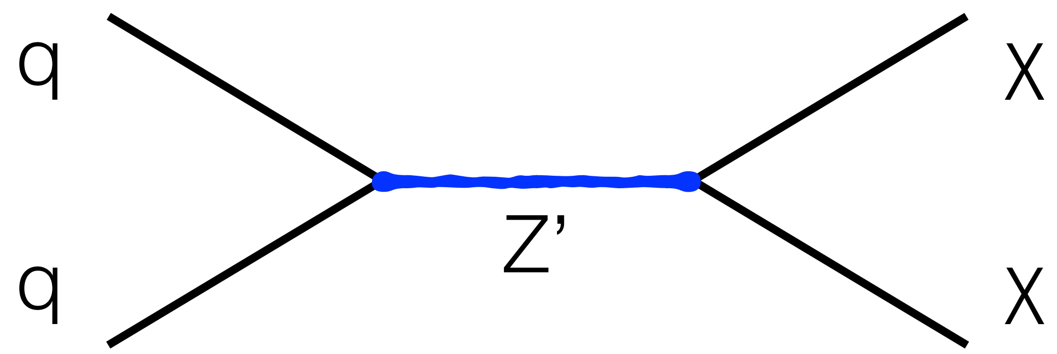
- Use same method as on previous slide, but need to compare theory prediction to appropriate observed limit at each point

- As mentioned, equivalence between gq/gl limit and cross section limit is broken here: width variations which are easily represented by separate cross section limits are hidden in a gq or gl plot

- So only cross section limits accepted as input in code when this feature is required

Mono-X signatures

- Because "X" (jet, photon, etc) is just ISR, only thing required to rescale limits at leading order is approximation of cross section for one basic tree-level diagram:



- Cannot use the same approximation as dijets: does not handle the off-shell region nor the transition towards it well at all
- Instead, use more complete expressions for the cross section
- Two methods available: one for rescaling by changing only couplings and the other for scaling from axial-vector to vector mediators and vice versa.

Within a single model

- As long as we are scaling e.g. a vector mediator with one set of couplings to a vector mediator with another, all we need is the integral of the propagator and all other factors in the cross section cancel out.

$$\int_{4m_\chi^2}^{\infty} \frac{ds}{(s - M_{\mathrm{med}^2})^2 + M_{\mathrm{med}}^2 \Gamma^2} = \frac{1}{\Gamma M_{\mathrm{med}}} \left(\frac{\pi}{2} + \arctan\left(\frac{M_{\mathrm{med}}^2 - 4m_\chi^2}{\Gamma M_{\mathrm{med}}} \right) \right)$$

Note this reduces to familiar expressions in the on-shell and off-shell regions

Very off-shell:

$$s >> M_{\mathrm{med}}^2$$

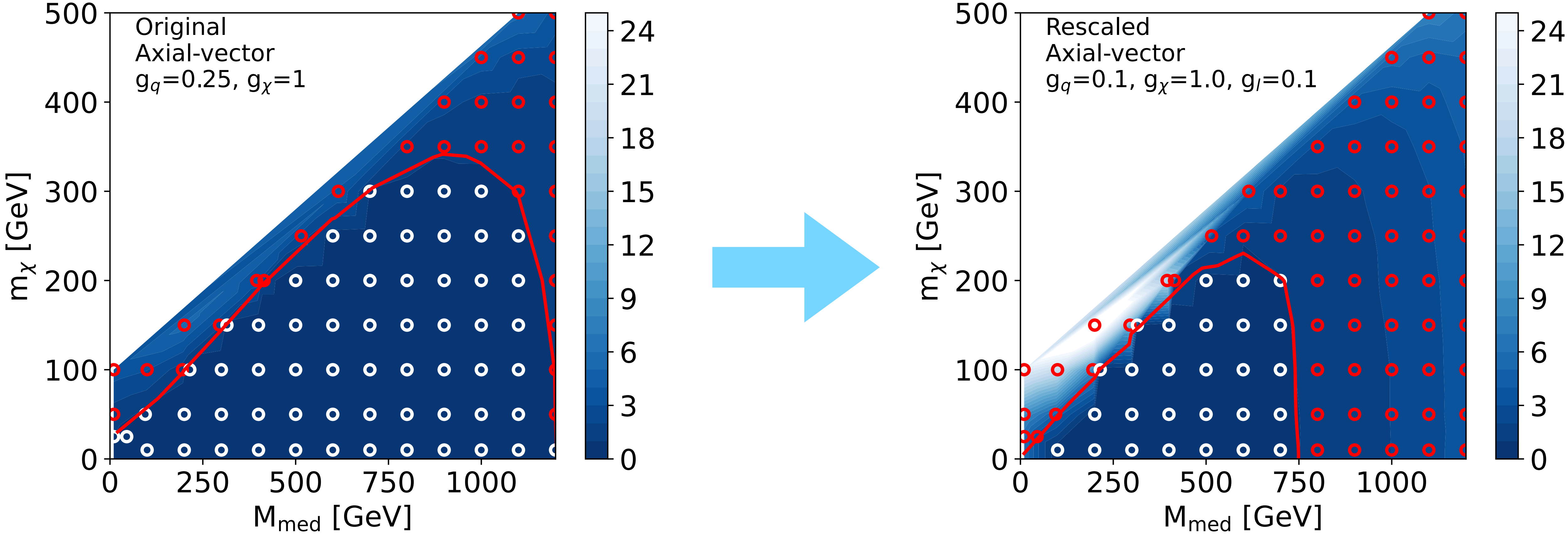
$$\sigma \propto g_q^2 g_\chi^2$$

Very on-shell:

$$S \sim M_{\mathrm{med}}^2 >> \Gamma$$

$$\sigma \propto \frac{g_q^2 g_\chi^2}{M_{\mathrm{med}} \Gamma}$$

Example in practice



- Left: original from monojet 36 ifb ATLAS analysis: no rescaling. “A1” scenario
- Right: rescaled to A2 at each individual grid point by the new software
- White point = rescaled result excluded, red point = rescaled result not excluded. Red contour = ATLAS published contour for this scenario. Agreement not perfect in bottom left corner (not sure how contour is made though) but sufficient

V ←→ AV scenarios

- To properly convert between V and AV scenarios in mono-X, must use the full LO cross section for the relevant diagram, less whatever factors cancel. This way we recover the terms which differ between V and AV.

- Parton level cross sections are:

$$\sigma_{\rm V}(S) \propto \frac{g_q^2 g_\chi^2 (S + 2m_\chi^2)\sqrt{S - 4m_\chi^2}}{(\Gamma_{\rm tot}^2 M_{\rm med}^2 + (M_{\rm med}^2 - S)^2)\sqrt{S}} \quad ; \quad \sigma_{\rm AV}(S) \propto \frac{g_q^2 g_\chi^2 (S - 4m_\chi^2)^{3/2}}{(\Gamma_{\rm tot}^2 M_{\rm med}^2 + (M_{\rm med}^2 - S)^2)\sqrt{S}}$$

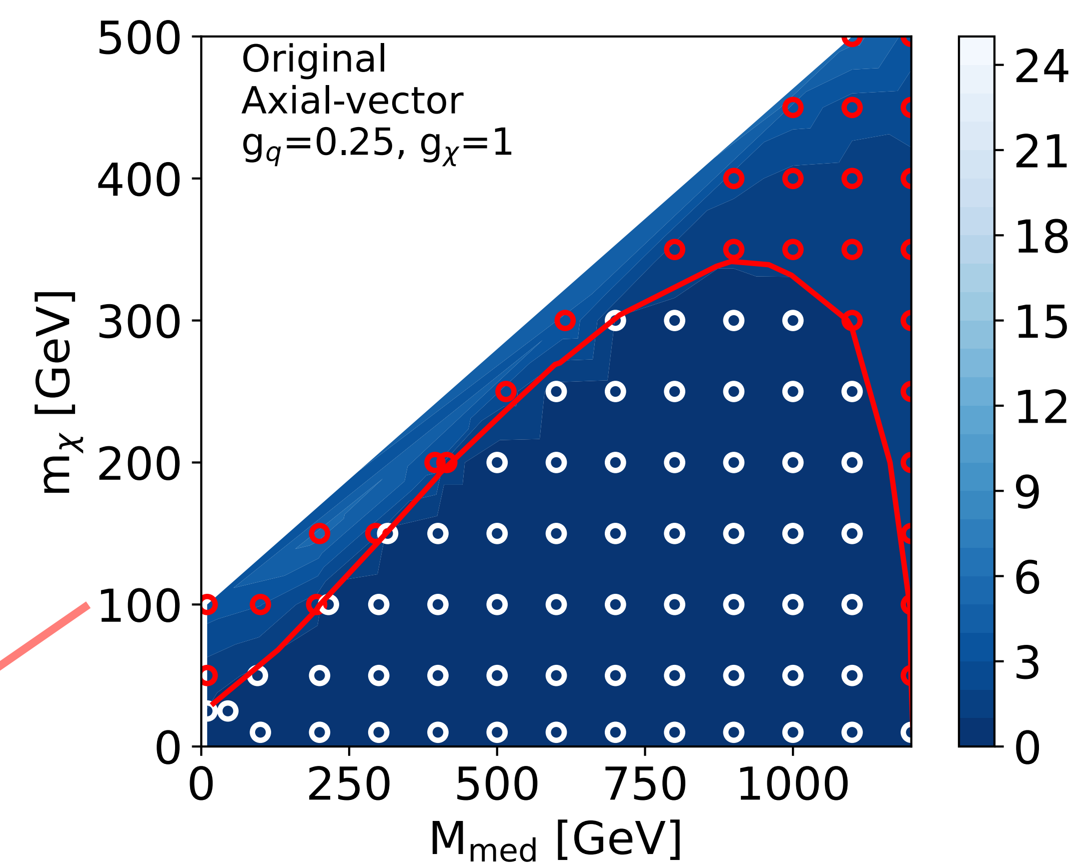
- Not sufficient along on-shell to off-shell transition: PDF effects are noticeable here

- Software for V ←→ AV conversion thus multiplies σ above by the PDFs (via LHAPDF) and does a 2d numerical integral over x_1 and x_2 to find cross section

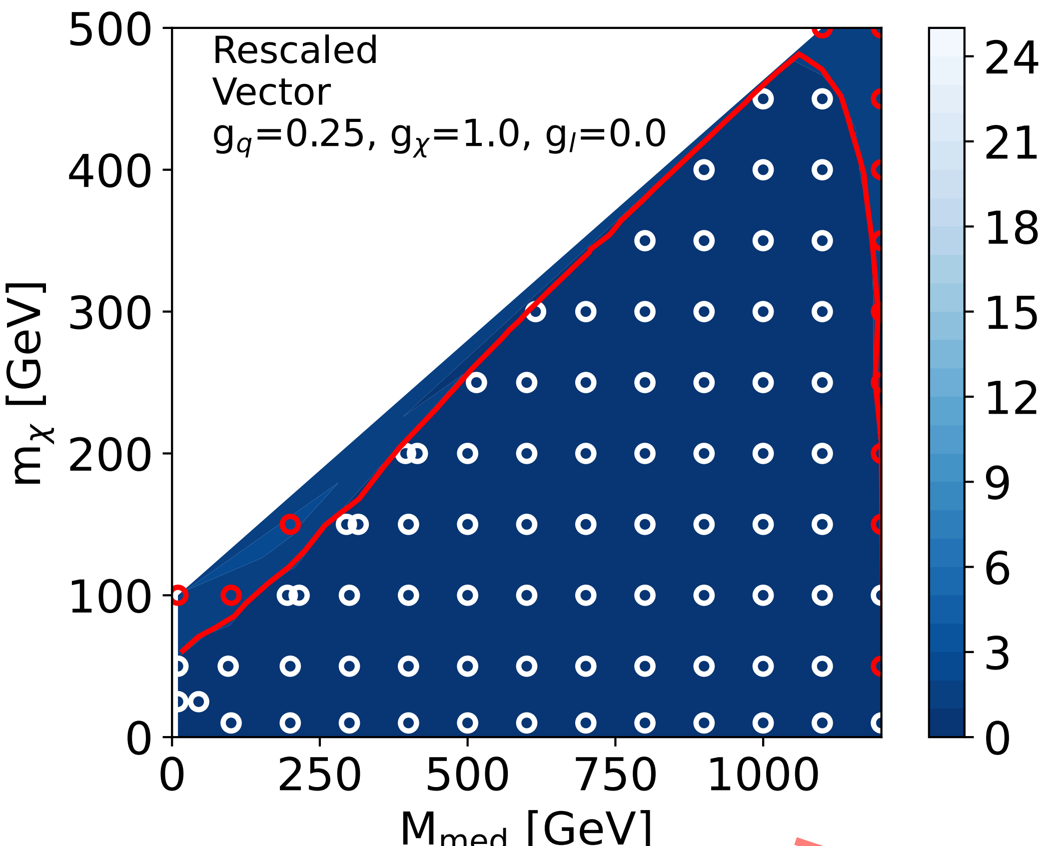
- No longer totally analytical - must specify a PDF - but in practice PDF choice seems to have no noticeable effect

Figures in paper draft

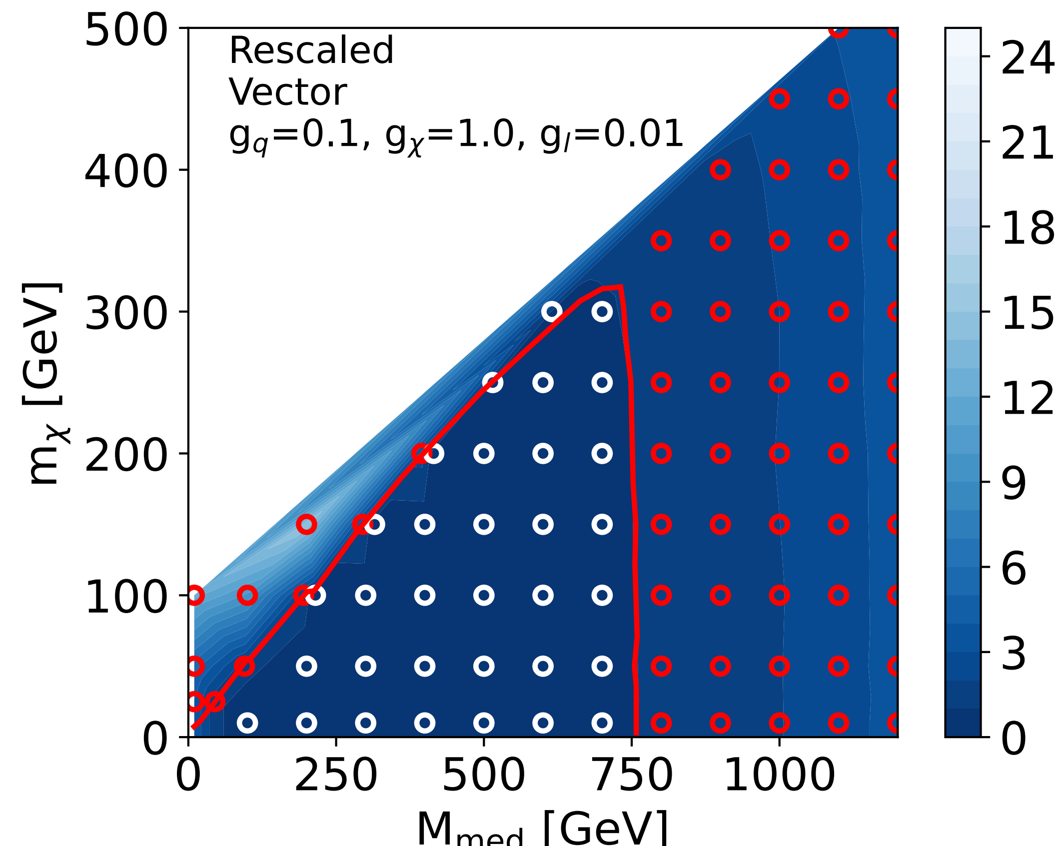
Validated in ATLAS 36 ifb monojet



Original rescaled to V1 (same couplings, vector mediator) using full cross section with PDFs

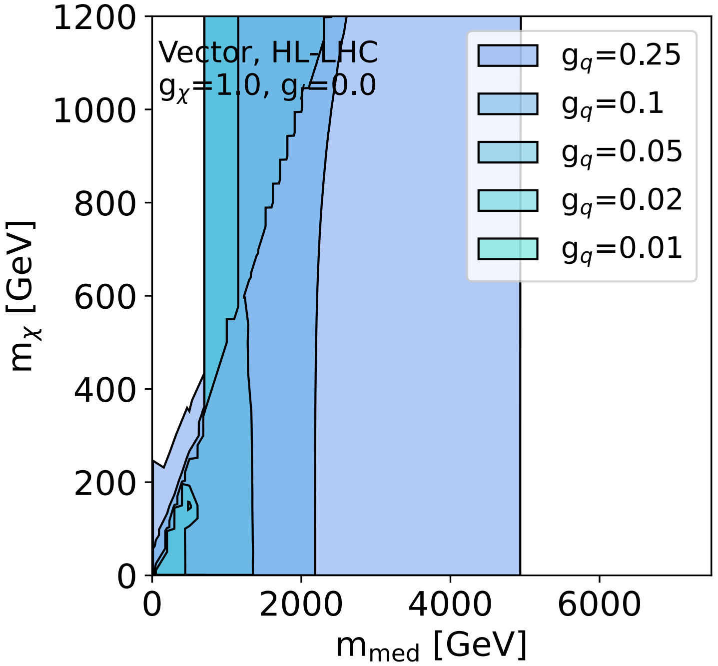


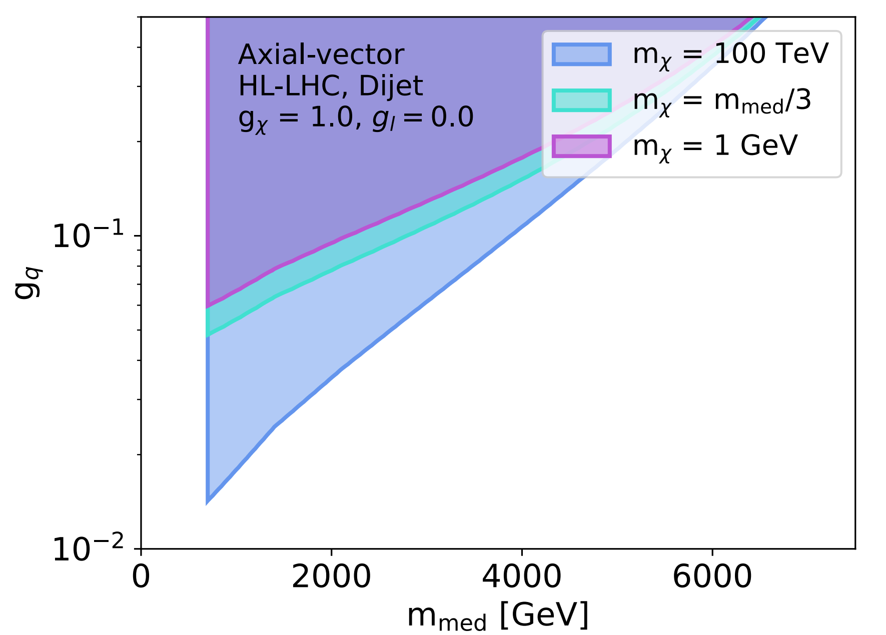
Then use propagator integral to rescale to other couplings in vector model (here, V2)

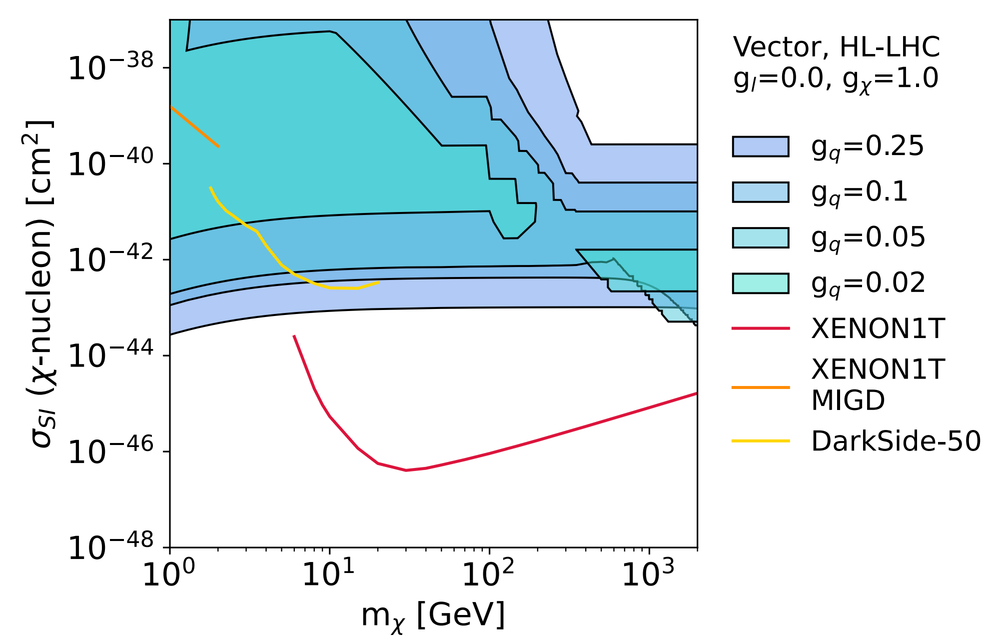


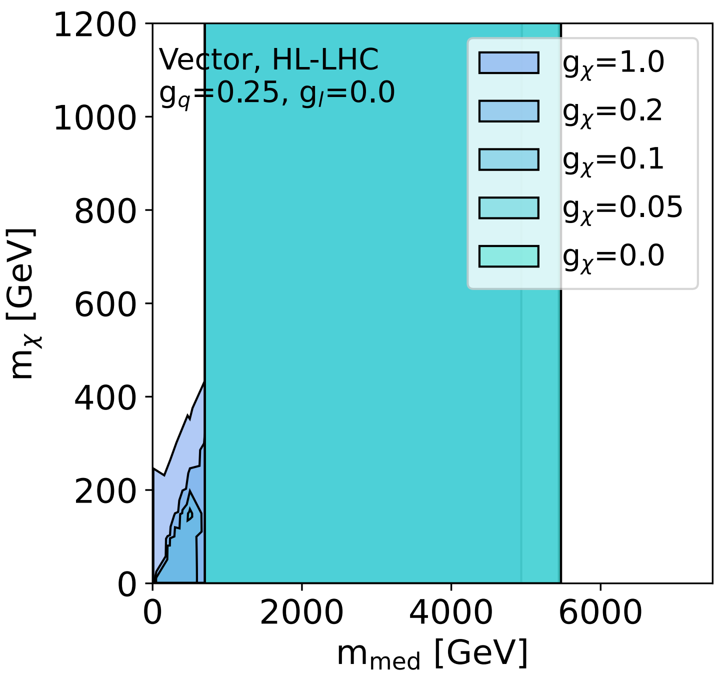
What can we do with the code?

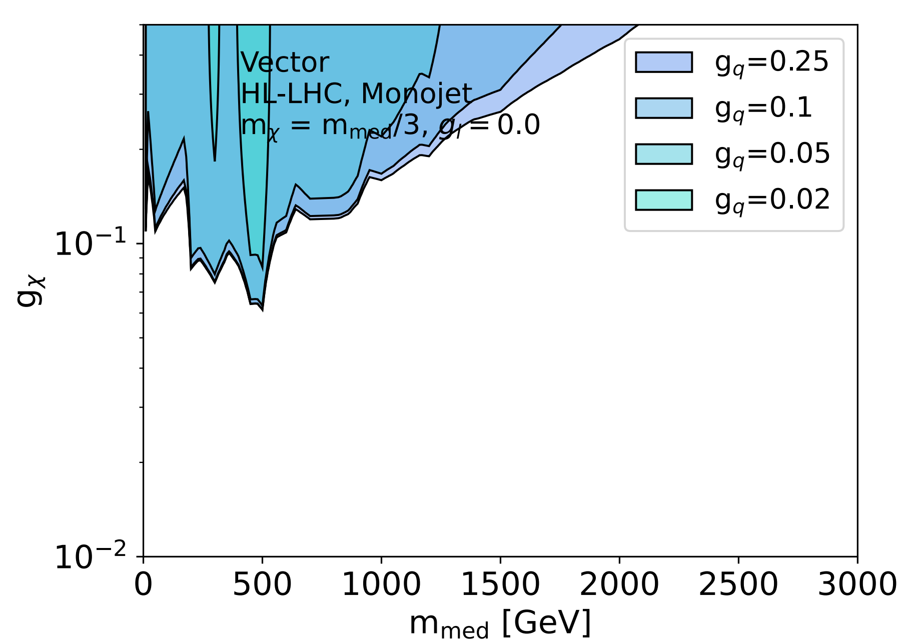
- These examples are from a Snowmass whitepaper including various cross-experiment participants where we explore projections for future colliders using this software. See arXiv:2206.03456

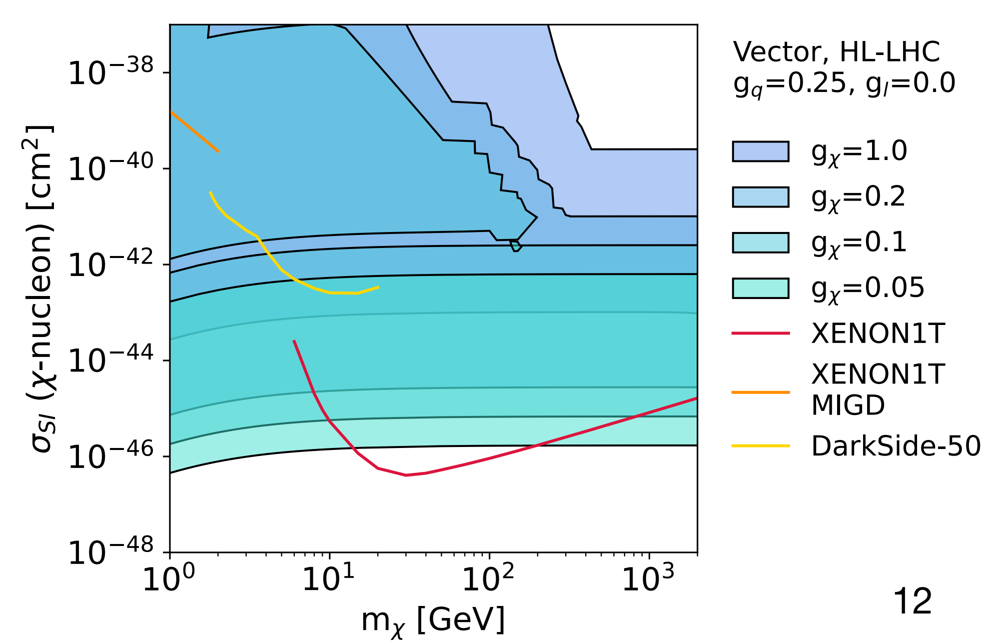






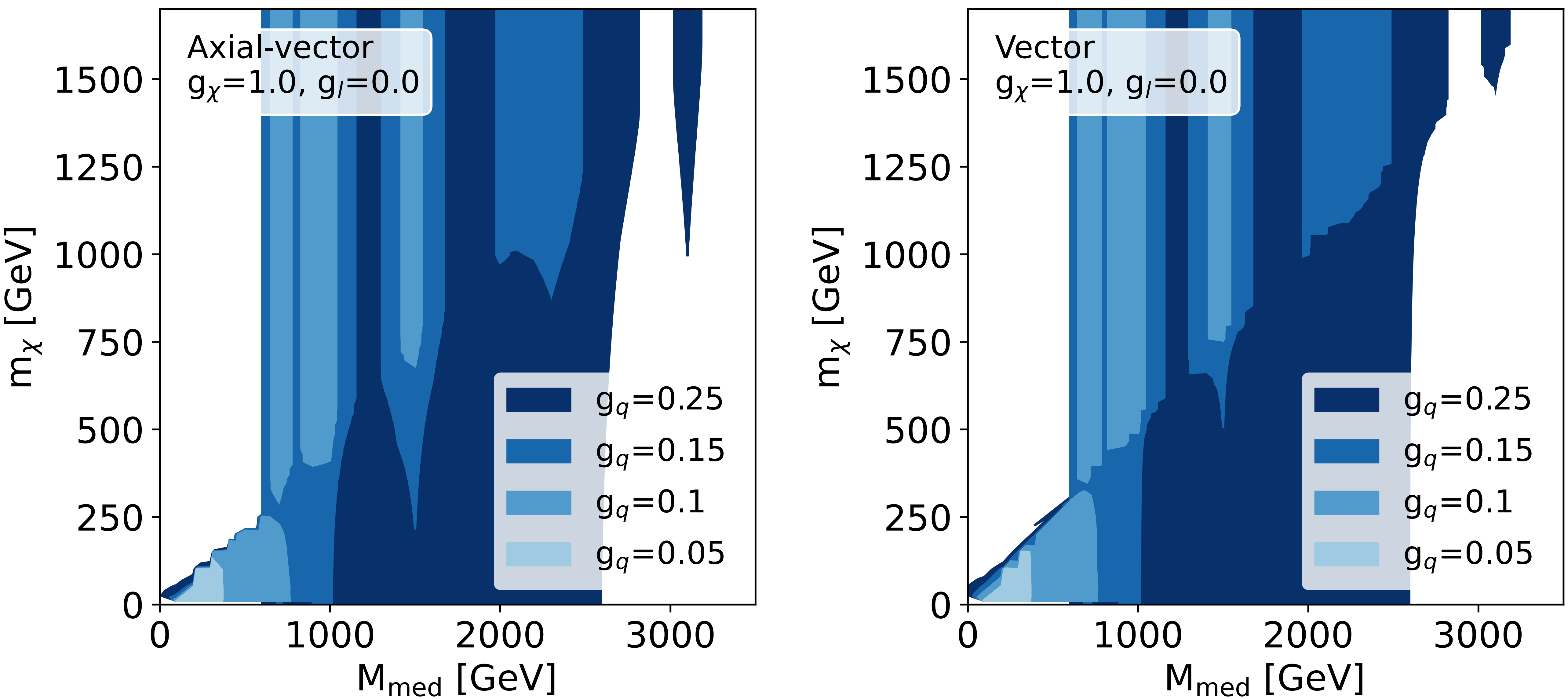






Figures in paper draft

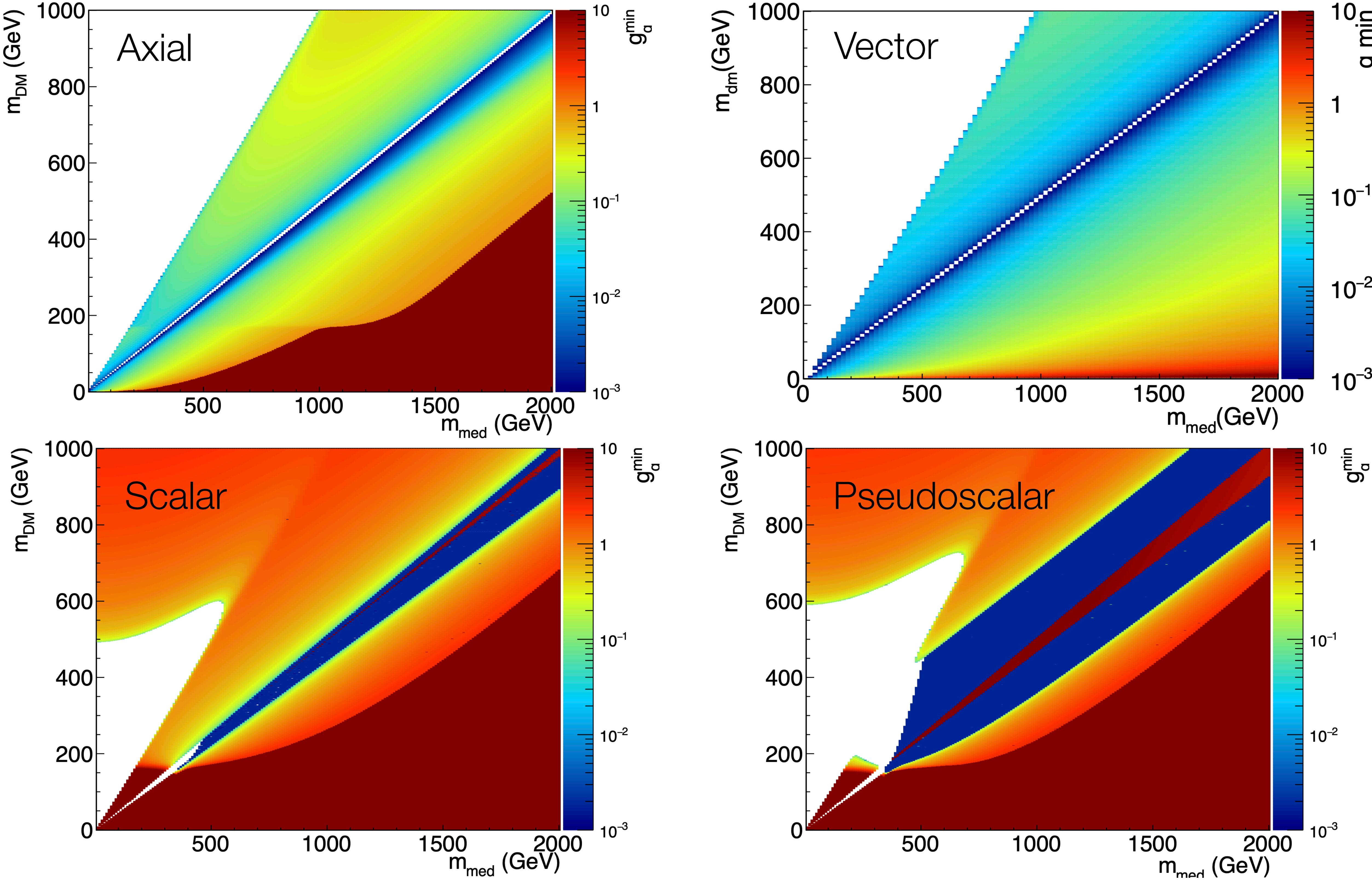
- Wanted to include a simpler demonstration in the paper and leave the complex plots for experiments to explore. Show only two plots exploring consequence of decreasing g_q on monojet and dijet, using same two 36 fb^{-1} analyses as rest of paper.



Relationship between simplified models and relic density

- Regularly occurring question on DMWG simplified models is their relationship to relic density.
- For each model and set of masses, if one of g_χ or g_q is fixed, one can compute the minimum allowed value of the other such that DM is not overproduced in the universe
- When minimum value is very large, or larger than existing exclusions, no viable space for model
- That said: we are providing examples of these calculations simply as a guideline for those interested and not to indicate that there is no value to the simplified models in these “non-permitted” regions. As the LHC DMWG has always stated, these simplified models are stand-ins for more complex ones that simply provide a clear comparison and benchmark.
  - We try to state this clearly in the paper draft - feedback on tone/message is welcome and in fact desired!

Figures in paper draft



The code

- Lives in GitHub here: https://github.com/LHC-DMWG/DMWG-couplingScan-code
- Combination of README and paper hopefully sufficient for anyone currently wanting to test, but not up to snuff for a real “supported package”
- Package is pip installable. Two options for installation: with or without LHAPDF, documented (briefly) in README. If installed without LHAPDF it does not support V ←→ AV conversion for mono-x analyses but should be able to do everything else, including monojet rescaling within a mediator type.
- Very limited testing so far! We need more people to use the code and provide feedback.
    - Also, KP no longer has lxplus access so can’t test the instructions there. I vaguely recall LHAPDF access is a bit tricky. README updates very welcome
- Example scripts are provided in the test/ directory which make plots like the ones in the paper. Some cleanup needed here for sure. They draw on .jsons from HEPData which probably shouldn’t be distributed with the code
- Note that the full cross section rescaling for V ←→ AV is the only fairly slow thing in here (takes ~20 to 25 minutes to do one monojet grid). Need a good way to make clear that we recommend doing this only once, then rescaling the result to other couplings with the propagator rescaling method

How do we proceed now?

- We would like to publish this as a paper via the DMWG, if the group approves our doing so
  - No formal approval process that we are aware of? So let's come up with one today.
  - Ideally approval/submission would happen fairly soon so this can be a useful citation for upcoming experiment results that may want to use this rescaling method. Would like to find a way to make progress in between DMWG meetings, since next meeting is forecasted for ~October
- Paper draft: could we create a google doc and collect comments, circulate a second draft to LHC DMWG, give people an objection period, then submit? How do we collect authors/endorsers? Is there a group policy?
- Software: currently hosted in DMWG gitlab repo. Do we need to approve the software to approve the paper? Can someone volunteer to test as part of approval, if so?

Future steps/extensions for the software

- Intend to add support for lepton initial states shortly in response to Snowmass request for ILC comparisons
- Interested in possibility of adding support for spin-0 models. Very unlikely to ever be able to convert spin-1 limits to spin-0 and vice versa, but converting e.g. scalar to pseudo-scalar for monojet should be quite easy
  - Lots more signatures relevant here - unclear which ones can be supported, will require careful thinking
- Others have suggested a model decoupling gl, gq into additional flavour dependent couplings. Community interest?
- Current code can be annoying by giving NaNs for out of range results. Some errors/warnings too.
- But for any of these steps, key question:

Does the DMWG hold responsibility for the tool, alongside the paper?
Can/should we commit to maintenance and development?
(Note KP is here, but is no longer on an LHC experiment …)

Let’s discuss!