Mass-mass plots for s-channel mediators.

Felix Kahlhoefer
LHC Dark Matter WG public meeting
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based on **arXiv:1503.05916** and **arXiv:1510.02110**
in collaboration with
Mikael Chala, Matthew McCullough, Germano Nardini, Kai Schmidt-Hoberg, Thomas Schwetz and Stefan Vogl

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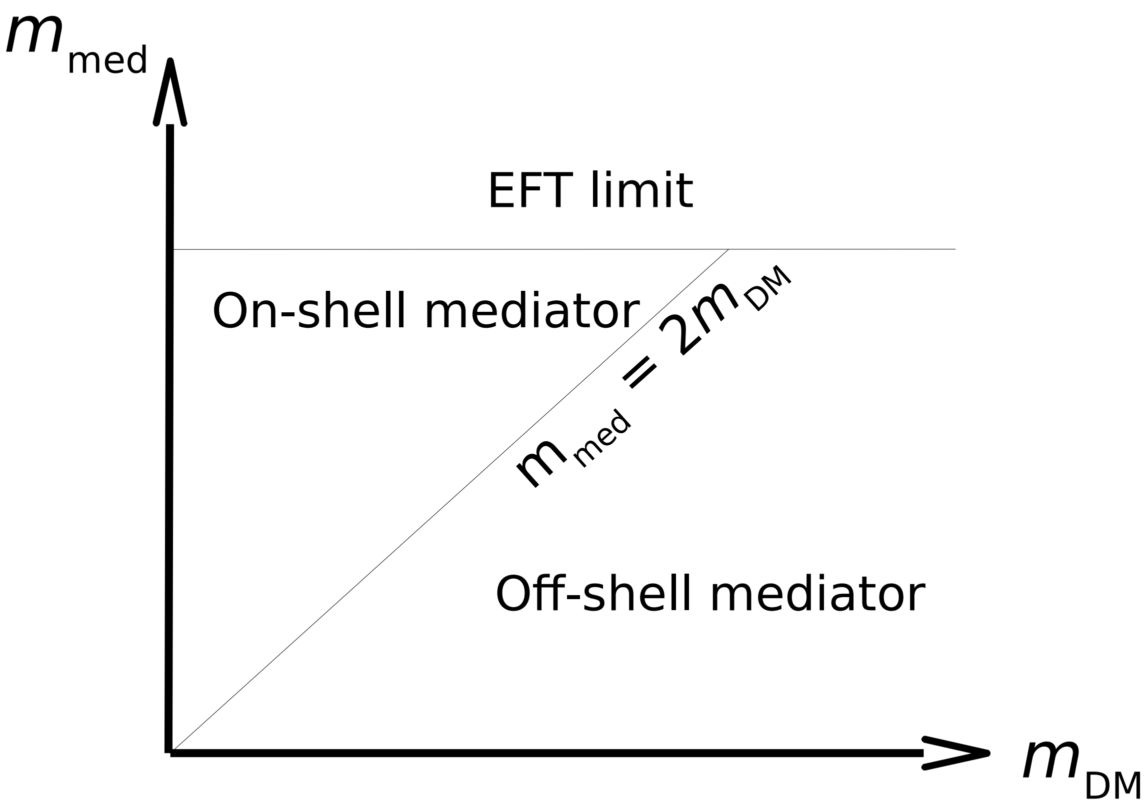
DESY

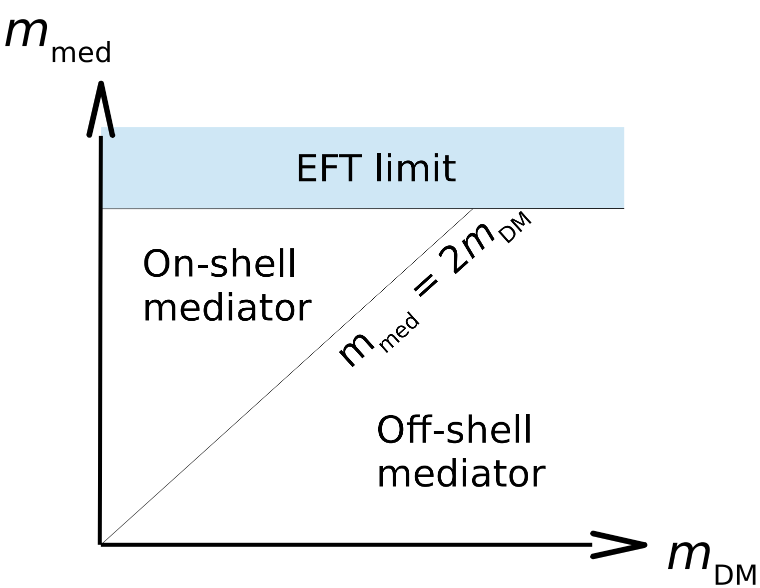
Mass-mass plots



For concreteness, I will focus on a spin-1 mediator and Dirac fermion DM:

$$\mathcal{L} = - \sum_{f=q,l,\nu} Z'^{\mu} \, \bar{f} \left[g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5 \right] f - Z'^{\mu} \, \bar{\psi} \left[g_{\text{DM}}^V \gamma_\mu + g_{\text{DM}}^A \gamma_\mu \gamma^5 \right] \psi$$

The EFT limit



In the EFT limit, cross sections just depend on the effective suppression scale

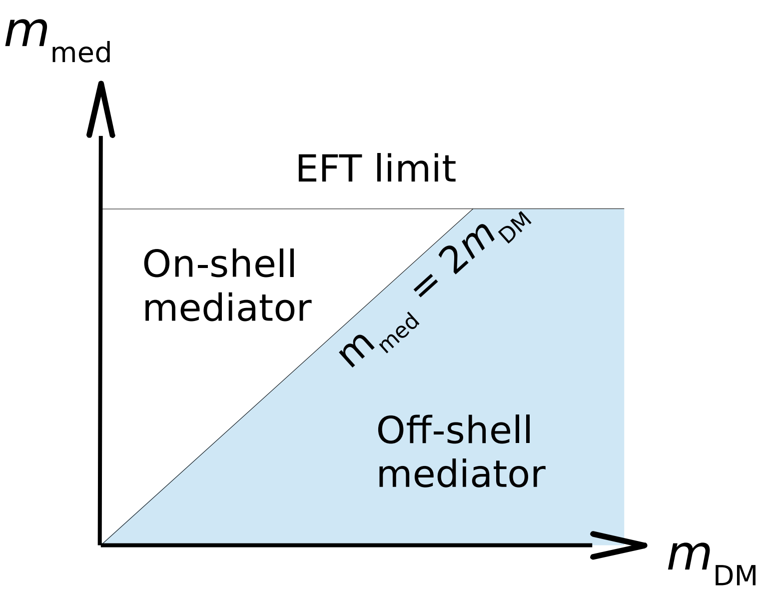
$$M^* = m_{\rm med} / (g_{\rm DM}\, g_q)^{1/2}$$

and on the DM mass $m_{\rm DM}$.

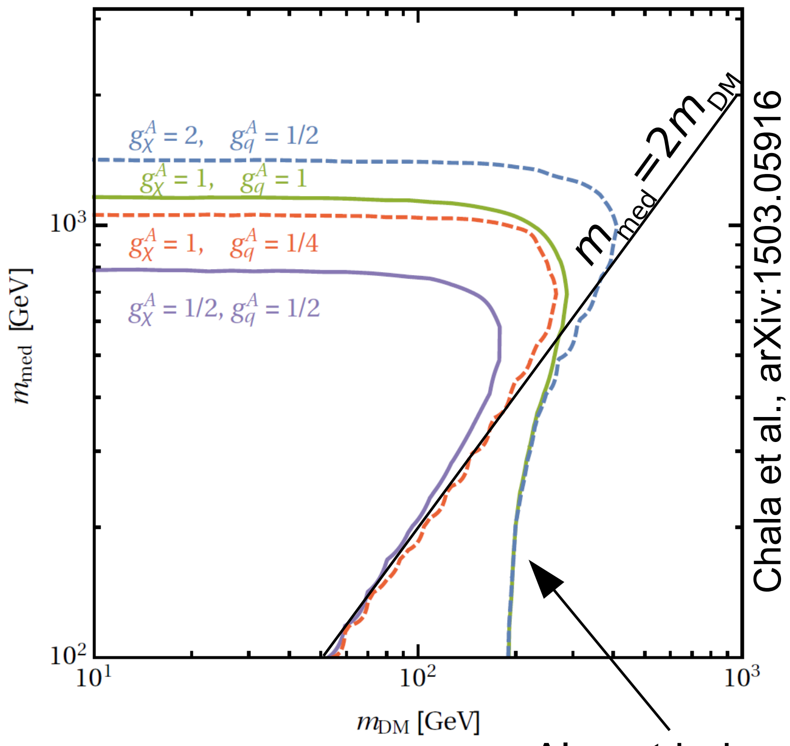
However, for perturbative couplings such large mediator masses are very difficult to reach with monojet searches.

Moreover, it is typically very difficult to reproduce the observed DM relic abundance from thermal freeze-out for very heavy mediators.

The off-shell region

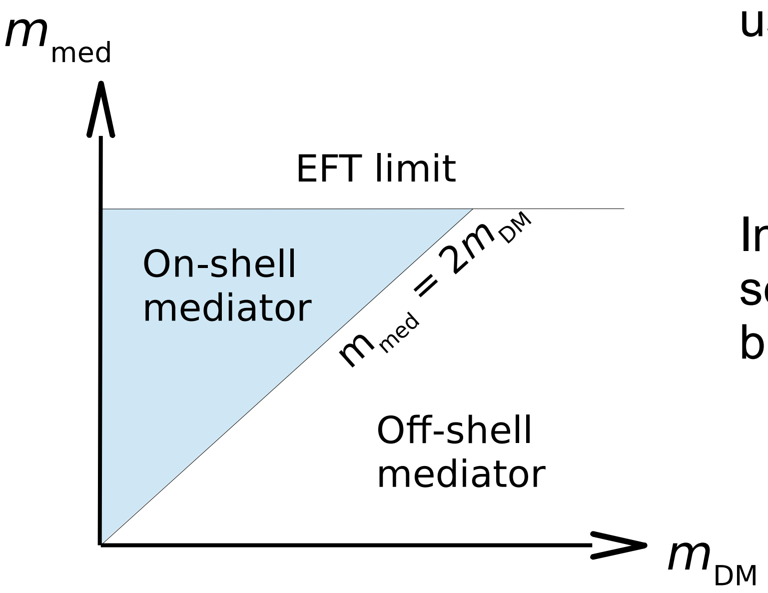


In the off-shell region, cross sections depend only on $(g_{DM}\, g_q)^{1/2}$ and on the DM mass m_{DM}.



Almost independent of the mediator mass

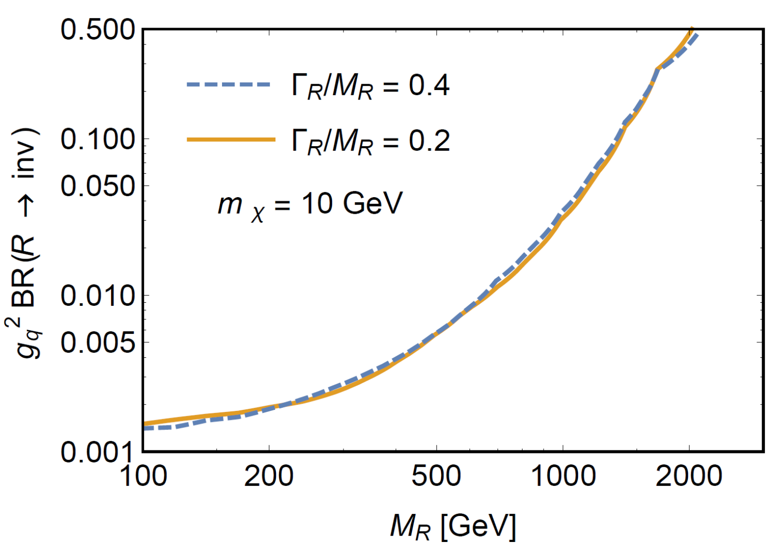
The on-shell region



In the on-shell region things become more complicated. However, in many cases we can use the narrow-width approximation (NWA):

$$\sigma(q\bar{q} \to Z' + Y \to xy + Y)$$
$$= \sigma(q\bar{q} \to Z' + Y) \cdot \mathrm{BR}(Z' \to xy)$$

In this approximation the monojet cross section is proportional to the invisible branching ratio of the mediator.



Chala et al., arXiv:1503.05916

Advanced rescaling attempts

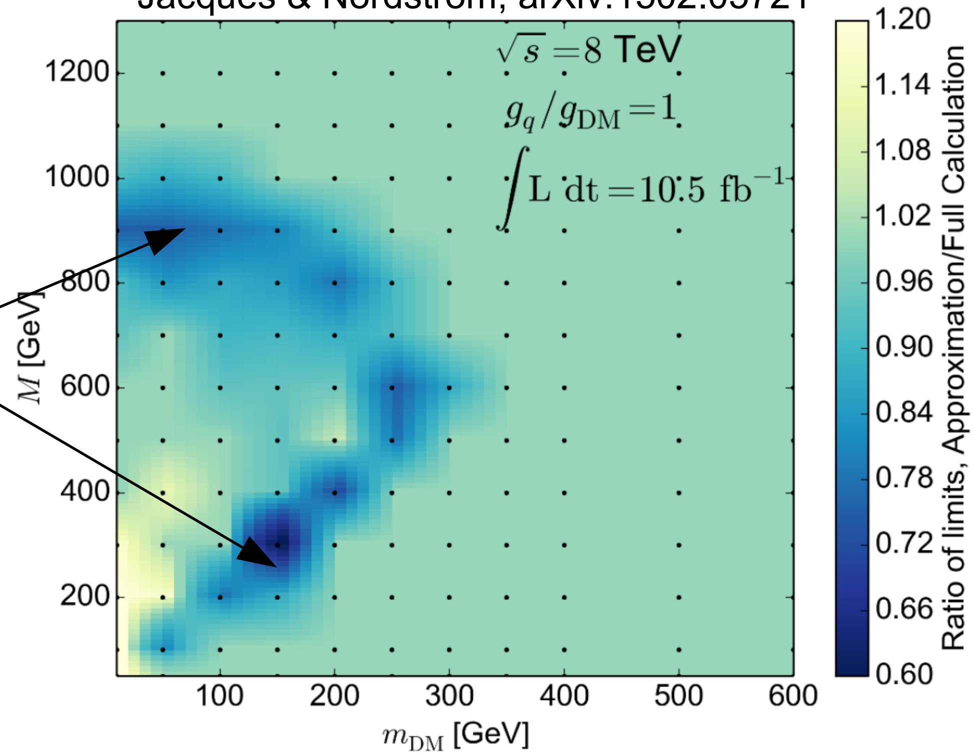
One could try to use different rescaling rules in the on-shell region and in the off-shell region.

$$\sigma \propto \begin{cases} g_q^2 g_{\rm DM}^2/\Gamma_{\rm OS} & \text{if } M > 2m_{\rm DM} \\ g_q^2 g_{\rm DM}^2 & \text{if } M < 2m_{\rm DM} \end{cases}$$

But even advanced rescaling rules do not capture all the relevant physics.

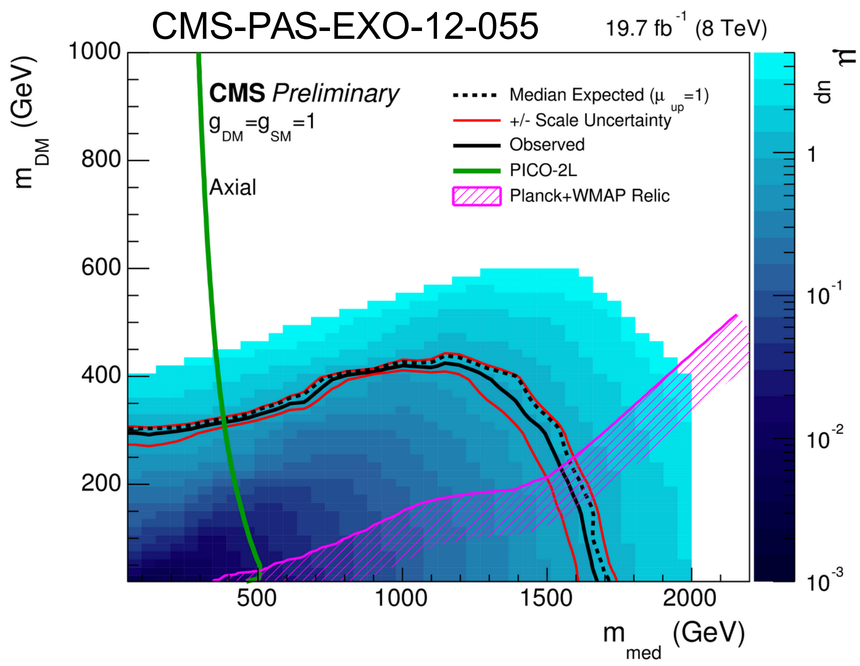
Breakdown of the NWA

Jacques & Nordstrom, arXiv:1502.05721

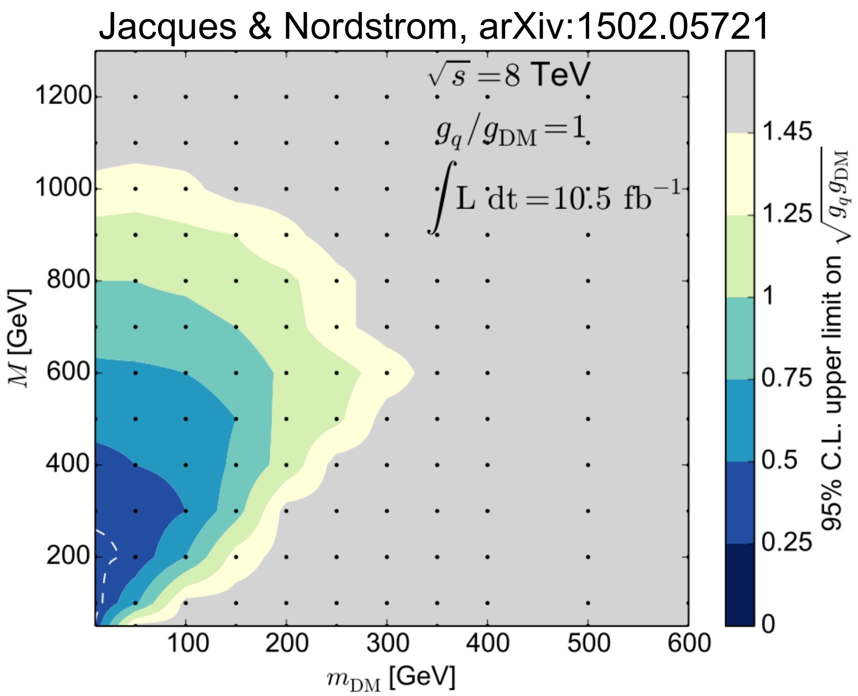


How to present results without assumed rescaling

Option 1: Fix both couplings and quote an upper bound on the signal strength.



Option 2: Fix one coupling (or the ratio of the couplings) and quote an upper bound on the other coupling (or the product of the couplings).



How to present results without assumed rescaling

Option 1: Fix both couplings and quote an upper bound on the signal strength.

+ The mediator width is fixed for each value of $m_{\rm DM}$ and $m_{\rm med}$, so only two parameters need to be scanned for the signal generation.

+ It is immediately clear how to include other constraints (dijets, direct detection...) in these plots.

- Requires a (somewhat arbitrary) choice of couplings. Translation to different couplings is non-trivial.

Option 2: Fix one coupling (or the ratio of the couplings) and quote an upper bound on the other coupling (or the product of the couplings).

+ Results can be understood intuitively.

- The width (and therefore kinematic distributions) depend on the coupling, so signal generation becomes more complicated.

- Need to make sure to avoid non-perturbative couplings and large mediator width.

- Difficult to show other constraints in the same parameter plot.

How to present results without assumed rescaling

Option 1: Fix both couplings and quote an upper bound on the signal strength.

+ The mediator width is fixed for each value of m_{DM} and m_{med}, so only two parameters need to be scanned for the signal generation.

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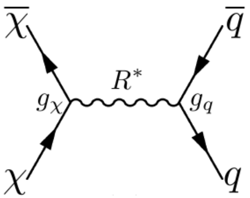
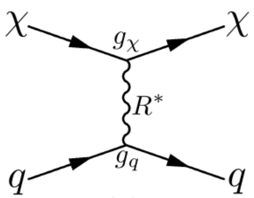
What are good choices for g_{DM} and g_q?

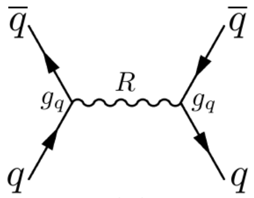
DM Forum recommendation (for spin-1 mediators): $g_{DM} = 1$, $g_q = 0.25$

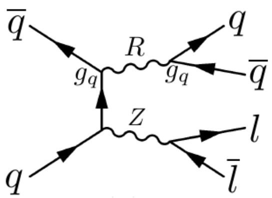
- Reasonable mediator width: $\Gamma_{med} / m_{med} \sim 0.2$
- BR(Z' → qq) ~ BR(Z' → invisible) ~ 50%
- No overwhelming constraints (but potential sensitivity) from dijet searches

What other constraints should be shown?

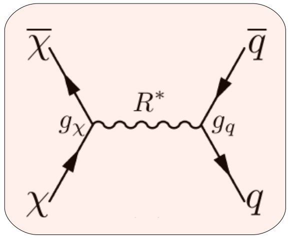


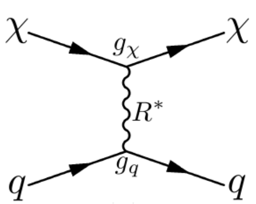


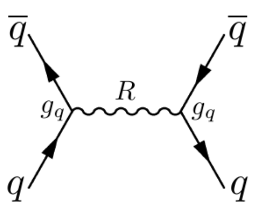


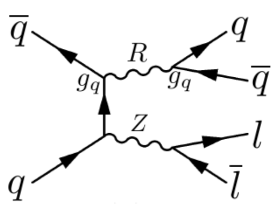


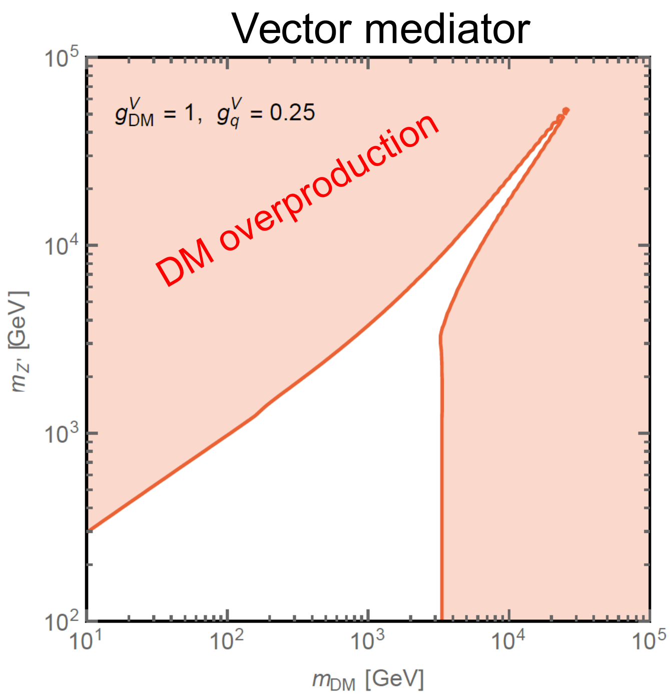
Relic density

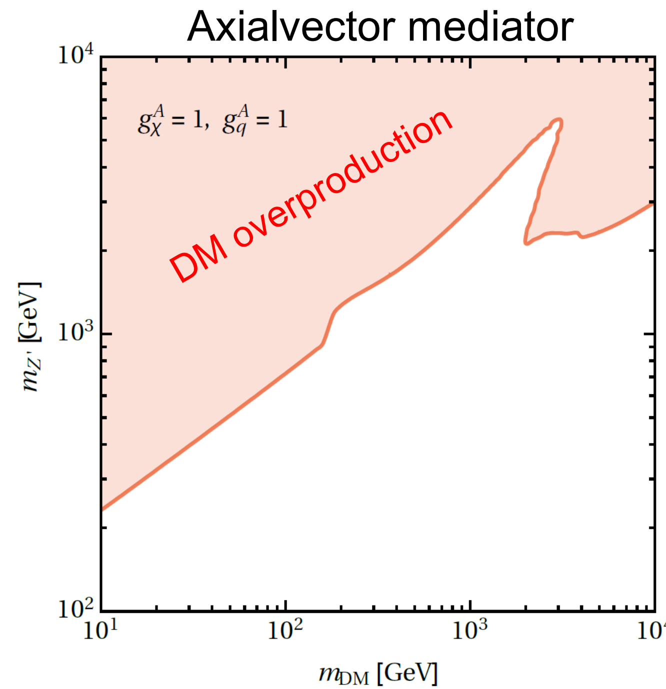






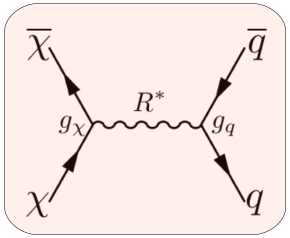


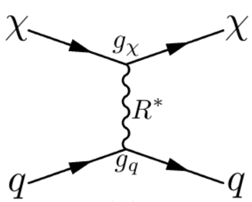


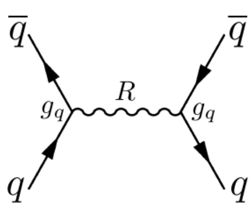


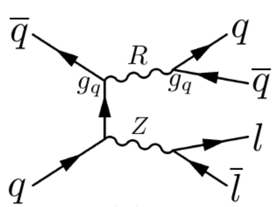
- It is a useful guideline to indicate the parameters where interactions between DM and quarks alone are sufficient to explain the observed DM abundance.
- Should be thought of more as a model prediction (for one specific model) rather than a model-independent bound.

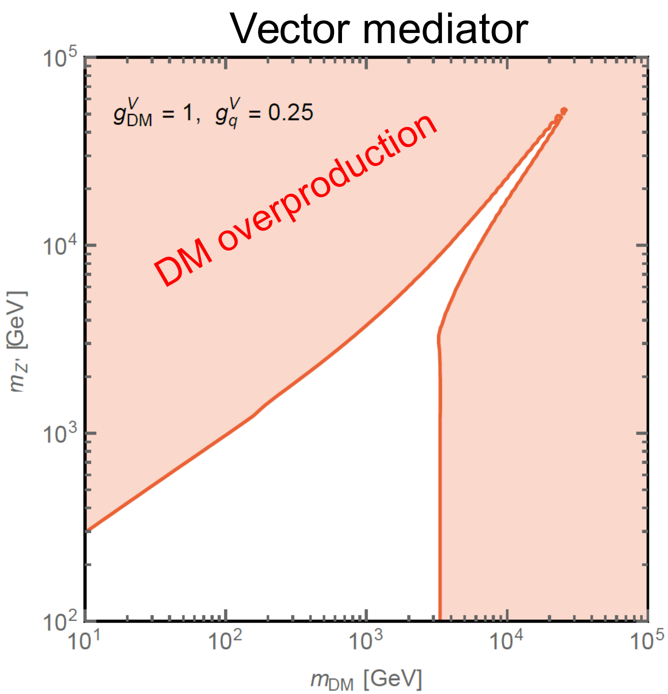
Unitarity

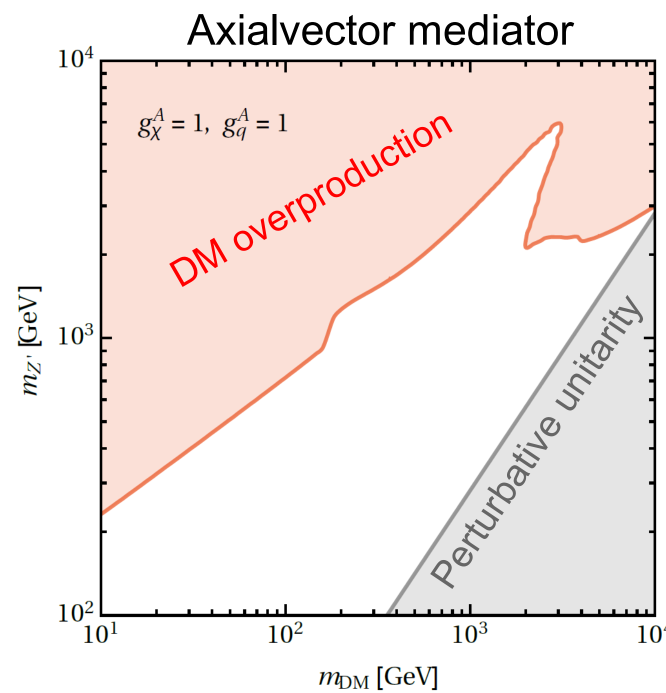








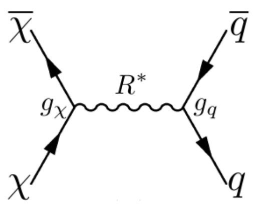


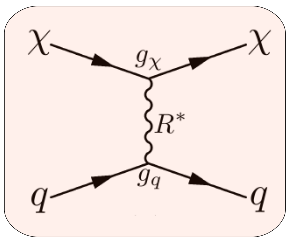


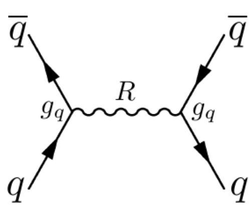
- Moreover, for axial couplings the longitudinal component of the mediator couples to fermions with a coupling strength that is given by $2\,g_f^A\,m_f/m_{Z'}$.
- Perturbative unitarity thus bounds the DM mass: $m_f \lesssim \sqrt{\frac{\pi}{2}}\frac{m_{Z'}}{g_f^A}$

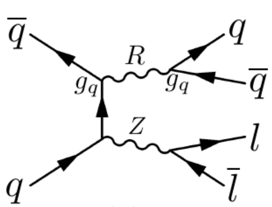
FK et al., arXiv:1510.02110

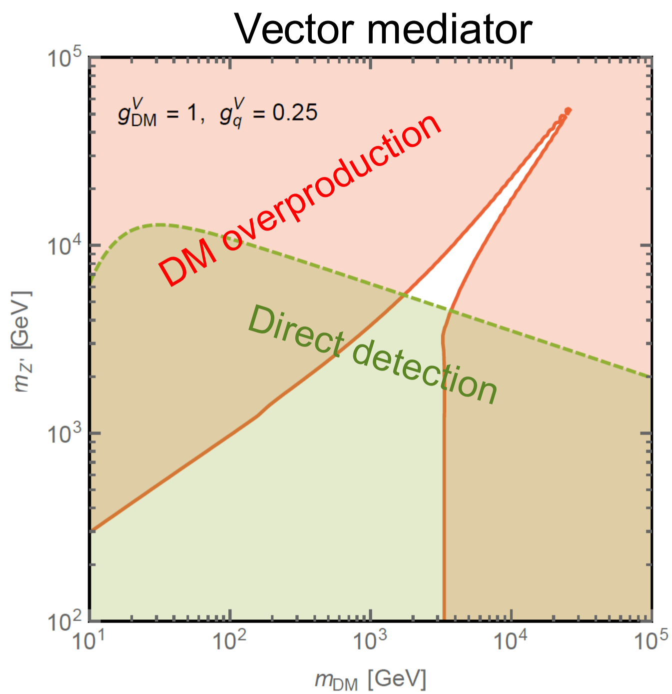
Direct detection

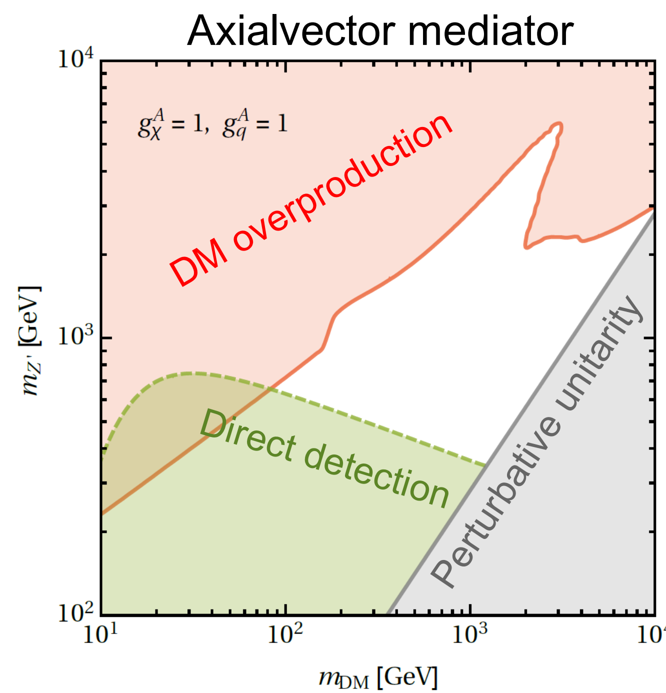






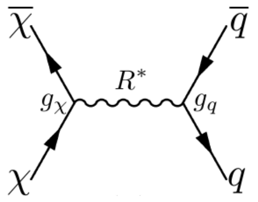


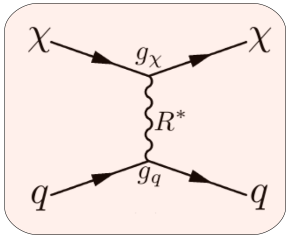


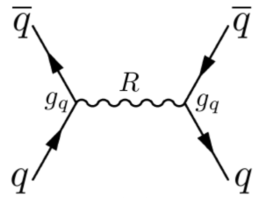


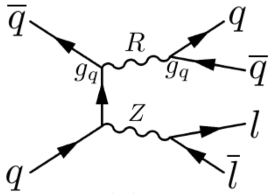
- To show direct detection bounds, two important assumptions are necessary:
  - Relative sign between up-quark coupling and down-quark coupling.
  - Rescaling of direct detection bounds for DM sub-components.

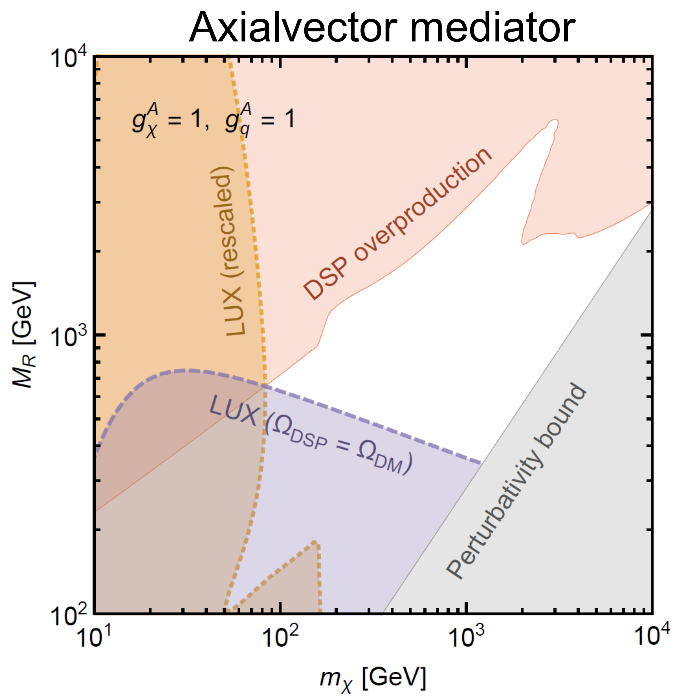
Direct detection





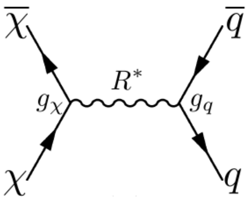


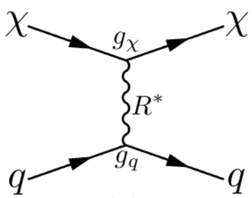


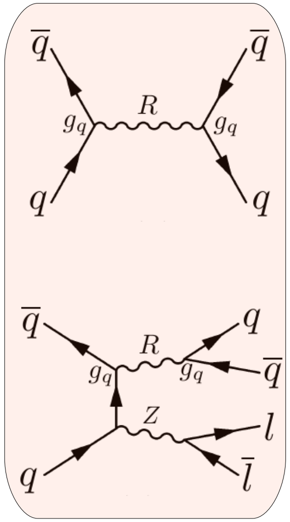


- To show direct detection bounds, two important assumptions are necessary:
  - Relative sign between up-quark coupling and down-quark coupling.
  - Rescaling of direct detection bounds for DM sub-components.

Dijets

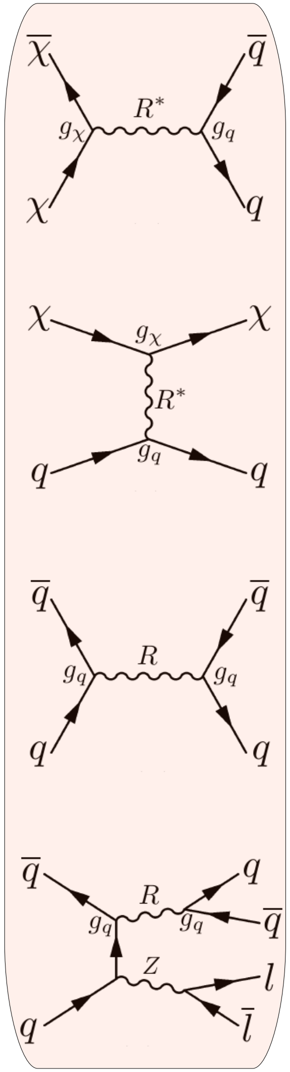


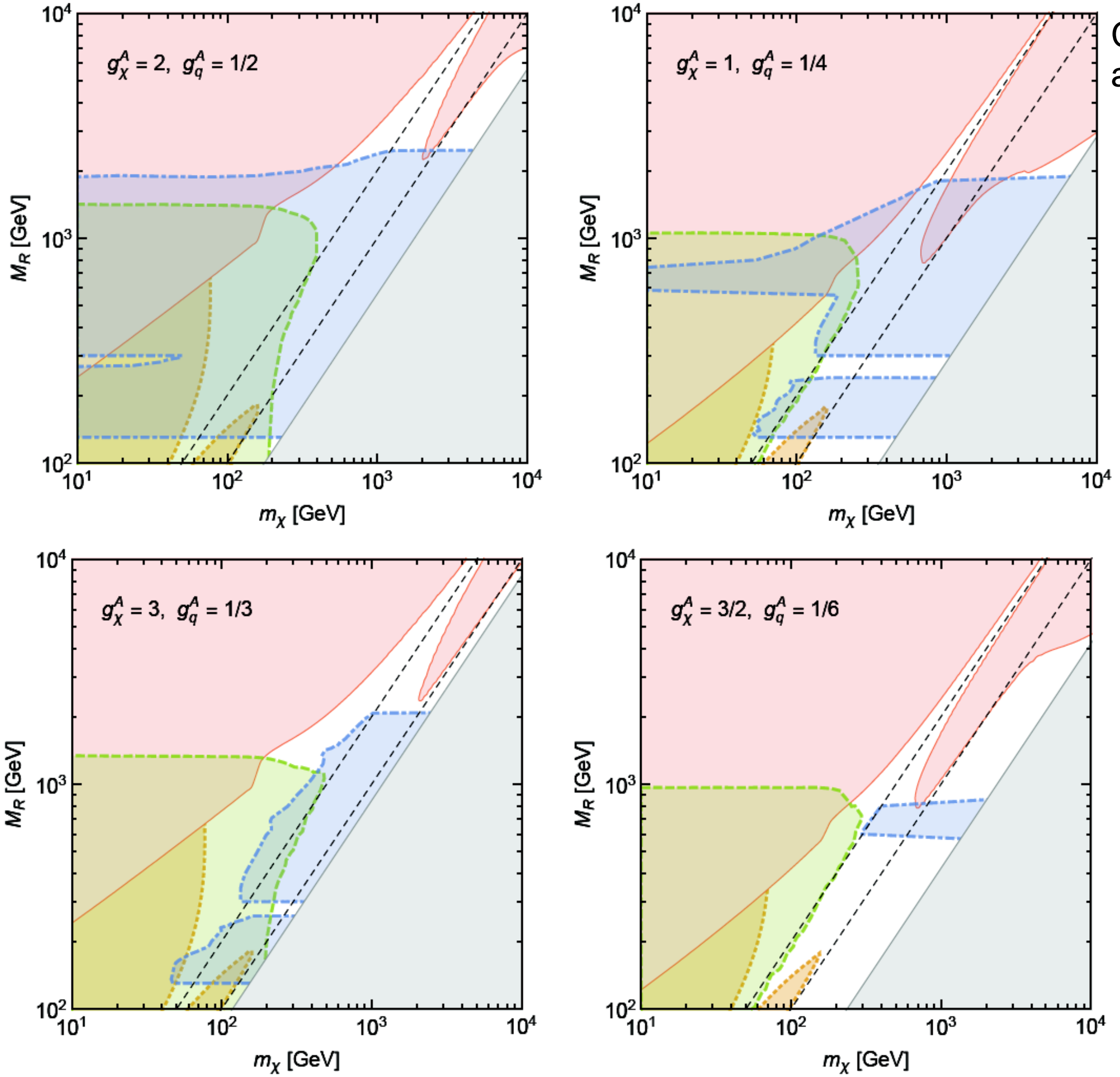




- See talk by Matthew McCullough (tomorrow)

Combined constraints





Chala et al., arXiv:1503.05916

Red (solid line): Relic density
Green (dashed line): Monojets
Orange (dotted line): Direct detection
Blue (dot-dashed line): Dijets
Grey (solid line): Perturbativity

Conclusions

- Mass-mass plots are a useful way to present results from mono-X searches at the LHC and provide an interpretation in terms of simplified models.
- Since there is no simple scaling rule relating different couplings, it will be necessary to fix one (or both) coupling(s) in order to produce such a plot.
- Fixing both couplings has the advantage that one can compare the results to other bounds (relic density, direct detection, …).
- Such a comparison always requires additional assumptions, so one should either specify the assumptions clearly or produce several bounds for different assumptions.
- In the end it may be necessary to produce plots for different coupling combinations in order to capture the full phenomenology of the simplified model (and the complementarity of different search stategies).