Constraining Dark Sectors at the LHC.

Monojets versus Dijets

Felix Kahlhoefer

ATLAS Astroparticle Forum
13 August 2015

based on **arXiv:1503.05916** in collaboration with Mikael Chala, Matthew McCullough, Germano Nardini and Kai Schmidt-Hoberg

HELMHOLTZ ASSOCIATION

DESY

Outline

- Dark matter (DM) models and dark mediators
- Relic density and DM subcomponents
- Constraints from monojets and dijets
- Combined results
- Discussion and conclusions

Dark matter candidates: The top-down approach

- Many theories of physics beyond the Standard Model, which have been developed for completely different reasons, predict new particles that have the required properties to be dark matter. Two famous examples:
  - WIMPs: Most solutions to the hierarchy problem postulate the existence of new states at the electroweak scale. The lightest new state is typically stable and can naturally be produced in the early Universe with the required relic abundance.
  - Axions: The Peccei-Quinn solution to the strong CP problem naturally predicts a new light particle, which – in spite of its very small mass – could act as cold dark matter.
- While these models provide well-motivated dark matter candidates, most of the experimental and theoretical constraints (and potential search strategies) are actually unrelated to the properties of the dark matter particle.

Too much extra baggage!

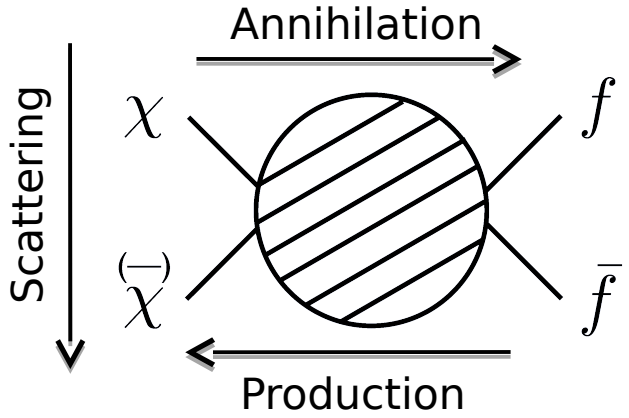
Dark matter candidates: The bottom-up approach

- The opposite strategy is to focus entirely on explaining the observed dark matter abundance. The simplest possibility are so-called portal models, which include just a single new particle with tiny couplings to Standard Model states, such as
  - Sterile neutrinos
  - Hidden photons
  - Scalar singlets
- These models have very few free parameters and are therefore highly predictive – but also strongly constrained.
- These models typically do not provide a useful guideline for devising experimental strategies to search for dark matter (e.g. all the candidates above would be unobservable at the LHC).

Too little legroom!

Dark matter phenomenology: The middle ground

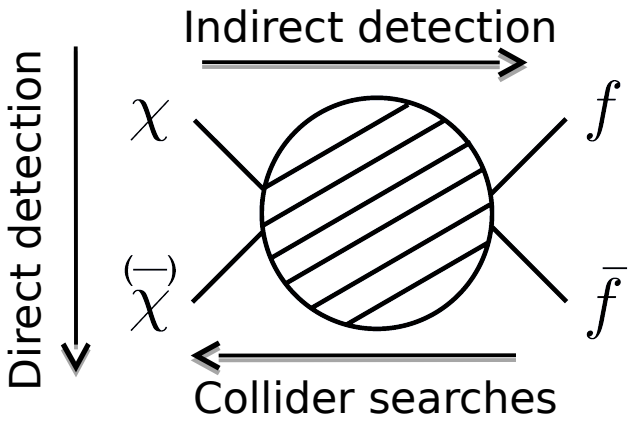
- We want a framework that allows us to focus on the DM particle, while at the same time being flexible enough to offer a rich phenomenology.
- We therefore relax the assumption that DM couples directly to Standard Model states and instead consider the case that interactions between DM and the Standard Model are mediated by additional new particles.
- If these particles are sufficiently heavy, we can describe the interactions between DM and the Standard Model using effective interactions involving higher-dimensional operators.



$\Delta\mathscr{L}$		Int.	Suppression
$\mathcal{O}_s^\phi$:	$\frac{1}{\Lambda}\phi^\dagger\phi\bar{f}f$	SI	1
$\mathcal{O}_v^\phi$:	$\frac{1}{\Lambda^2}\phi^\dagger\partial^\mu\phi\bar{f}\gamma_\mu f$	SI	1
$\mathcal{O}_{va}^\phi$:	$\frac{1}{\Lambda^2}\phi^\dagger\partial^\mu\phi\bar{f}\gamma_\mu\gamma^5 f$	SD	v^2
$\mathcal{O}_p^\phi$:	$\frac{1}{\Lambda}\phi^\dagger\phi\bar{f}i\gamma^5 f$	SD	q^2
$\mathcal{O}_s^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\psi\bar{f}f$	SI	1
$\mathcal{O}_v^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\psi\bar{f}\gamma_\mu f$	SI	1
$\mathcal{O}_a^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\gamma^5\psi\bar{f}\gamma_\mu\gamma^5 f$	SD	1
$\mathcal{O}_t^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\sigma^{\mu\nu}\psi\bar{f}\sigma_{\mu\nu}f$	SD	1
$\mathcal{O}_p^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^5\psi\bar{f}\gamma^5 f$	SD	q^4
$\mathcal{O}_{va}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\psi\bar{f}\gamma_\mu\gamma^5 f$	SD	v^2, q^2
$\mathcal{O}_{pt}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}i\sigma^{\mu\nu}\gamma^5\psi\bar{f}\sigma_{\mu\nu}f$	SI	q^2
$\mathcal{O}_{ps}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}i\gamma^5\psi\bar{f}f$	SI	q^2
$\mathcal{O}_{sp}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\psi\bar{f}i\gamma^5 f$	SD	q^2
$\mathcal{O}_{av}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\gamma^5\psi\bar{f}\gamma_\mu f$	SI SD	v^2 q^2
$\hat{\mathcal{O}}_s^\phi$:	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{f}f$	SI	1
$\hat{\mathcal{O}}_s^\psi$:	$\frac{m_q}{\Lambda^3}\bar{\psi}\psi\bar{f}f$	SI	1
$\hat{\mathcal{O}}_p^\psi$:	$\frac{m_q}{\Lambda^3}\bar{\psi}\gamma^5\psi\bar{f}\gamma^5 f$	SD	q^4

DESY

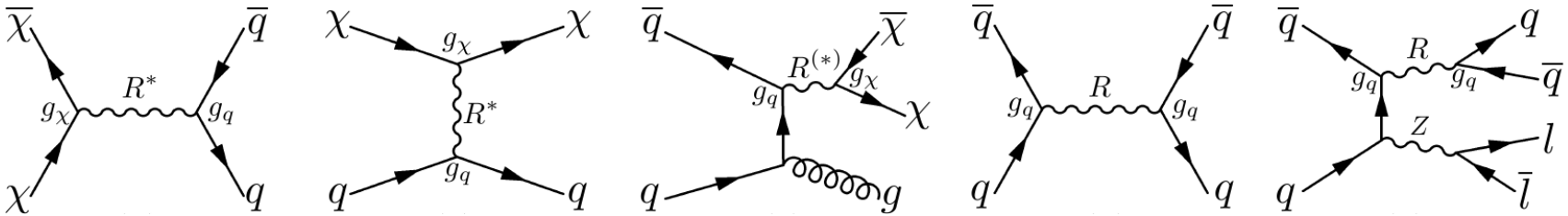
Detecting dark matter particles



- In the effective operator approach, all DM searches constrain the same new-physics scale Λ, so we can directly compare bounds from different search strategies.
- However, the resulting bounds are often rather weak compared to LHC energies (Λ ~ 1 TeV still allowed), so it may be inconsistent to use this approach to interpret DM searches at the LHC.
- Moreover, if the mediator is very heavy compared to the DM particle, it is typically very difficult to achieve a sufficiently large annihilation rate in the early Universe to avoid overproduction of DM.

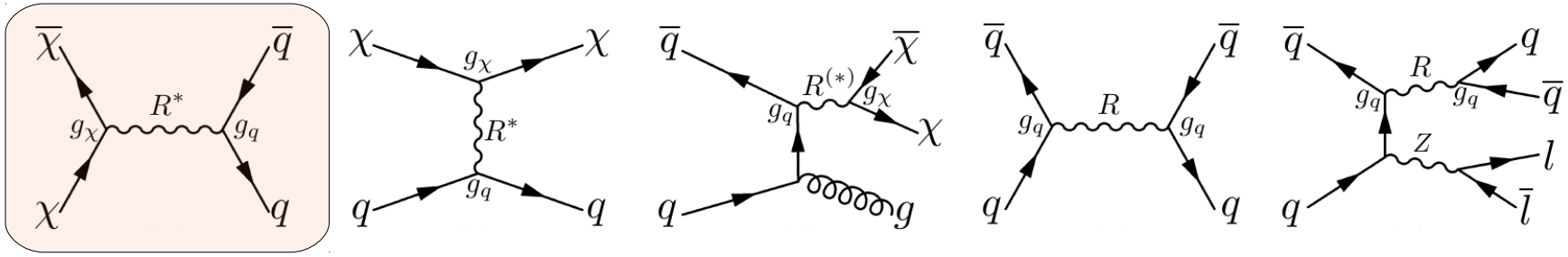
Motivation: New mediators

- If the DM particle and the mediator of the DM interactions are comparable in mass, the phenomenology can become much more interesting:



Motivation: New mediators

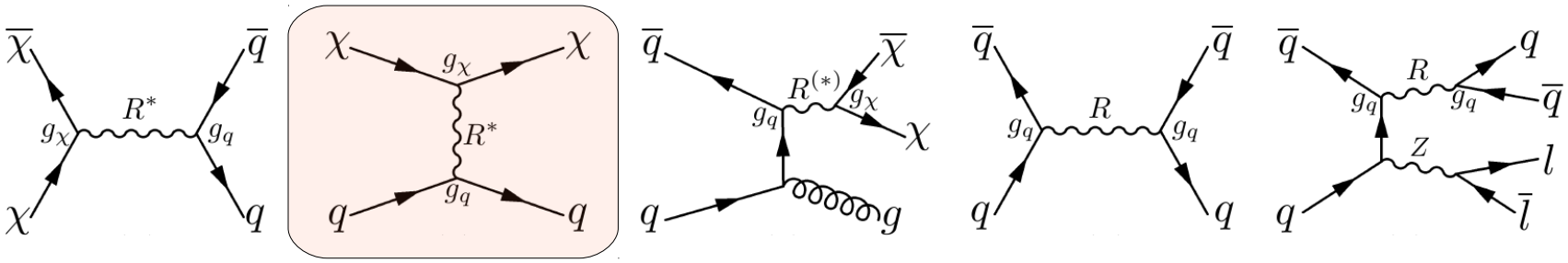
- If the DM particle and the mediator of the DM interactions are comparable in mass, the phenomenology can become much more interesting:



- The rate for DM annihilation into SM fermions in the early Universe determines the DM relic abundance.
- It is easy in these models to avoid the overproduction of DM. In particular, for $m_\chi \sim M_R/2$ annihilation receives a resonant enhancement.
- The same process can be probed by indirect detection experiments.

Motivation: New mediators

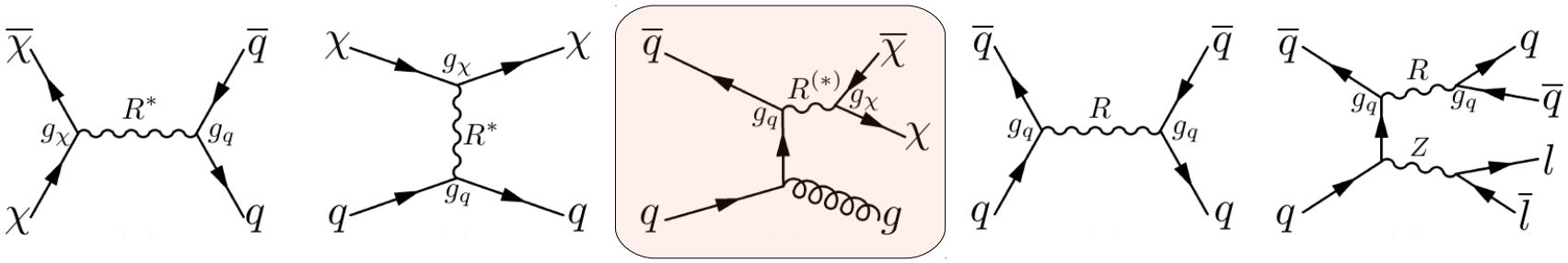
- If the DM particle and the mediator of the DM interactions are comparable in mass, the phenomenology can become much more interesting:



- Depending on the coupling structure of the mediator, there will be spin-independent or spin-dependent interactions between DM and nuclei, which can be constrained by direct detection experiments.

Motivation: New mediators

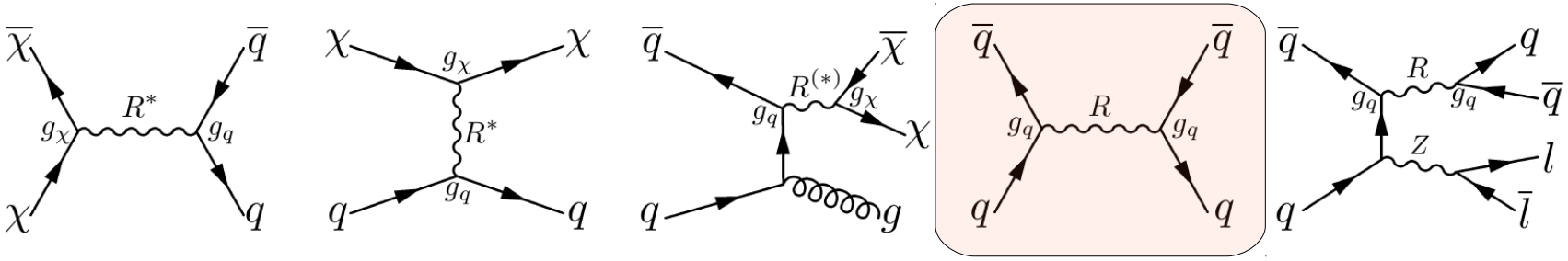
- If the DM particle and the mediator of the DM interactions are comparable in mass, the phenomenology can become much more interesting:



- One of the most constraining searches for DM production at the LHC are monojet searches, where an additional jet (e.g. from initial state radiation) is produced in association with a pair of DM particles.

Motivation: New mediators

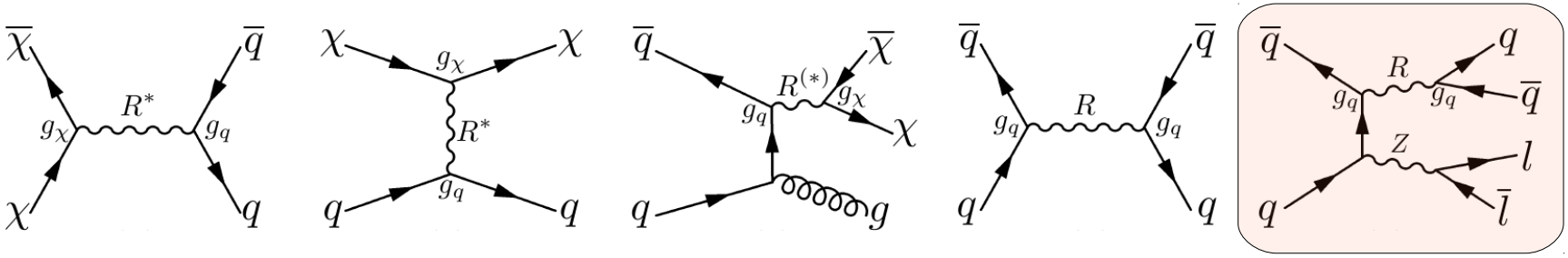
- If the DM particle and the mediator of the DM interactions are comparable in mass, the phenomenology can become much more interesting:



- If the mediator can be produced at LHC energies, it can also decay back into quarks. One therefore also needs to consider dedicated searches for the mediator particles themselves, such as searches for dijet resonance.

Motivation: New mediators

- If the DM particle and the mediator of the DM interactions are comparable in mass, the phenomenology can become much more interesting:



- It is very difficult for the LHC to constrain dijet resonances below 1 TeV due to large QCD background. A particularly promising way to suppress this background are searches for dijet resonances produced in association with leptonically decaying gauge bosons.

Motivation: Axial-vector mediators

- A model for a dark mediator has at least 4 free parameters: The quark coupling g_q, the DM coupling g_χ, the DM mass m_χ and the mediator mass M_R.

  Frandsen, FK et al., arXiv:1204.3839; Buchmueller et al., arXiv:1308.6799; Buchmueller et al., arXiv:1407.8257; Harris et al., arXiv:1411.0535

- In particular, the ratio m_χ/M_r determines whether certain processes are kinematically allowed and whether there are resonant enhancements.

- We will illustrate these features by considering the case of an axial-vector mediator, which could for example be a massive *Z'* arising from a new broken *U(1)'* gauge symmetry:

$$\mathcal{L} \supset g_\chi^A \, \bar{\chi}\gamma^\mu\gamma^5\chi \, R_\mu + \sum_q g_q^A \, \bar{q}\gamma^\mu\gamma^5 q \, R_\mu$$

Dudas et al., arXiv:0904.1745; Arcadi et al., arXiv:1401.0221; Lebedev & Mambrini, arXiv:1403.4837; Frandsen, FK et al., arXiv:1107.2118; An et al., arXiv:1202.2894, arXiv:1212.2221; Alves et al., arXiv:1312.5281, arXiv:1501.03490

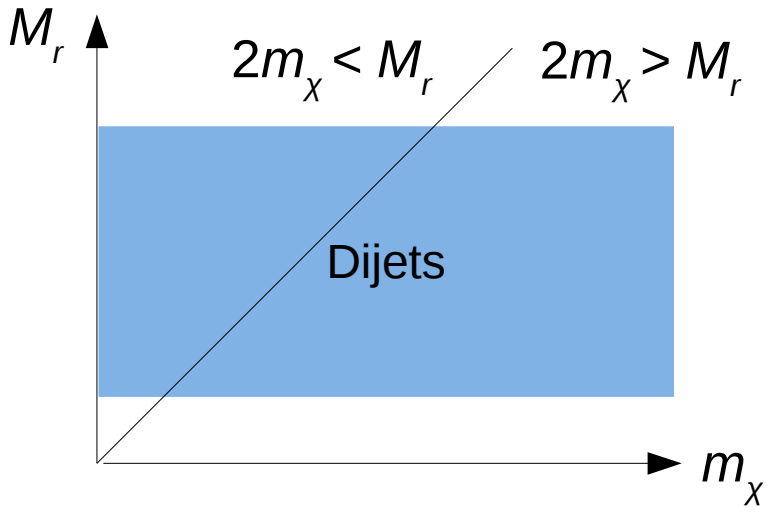
- As we will see, this set-up is particularly well suited for demonstrating the complementarity between different experimental probes.

- Many of the dominant features apply to other DM models as well.

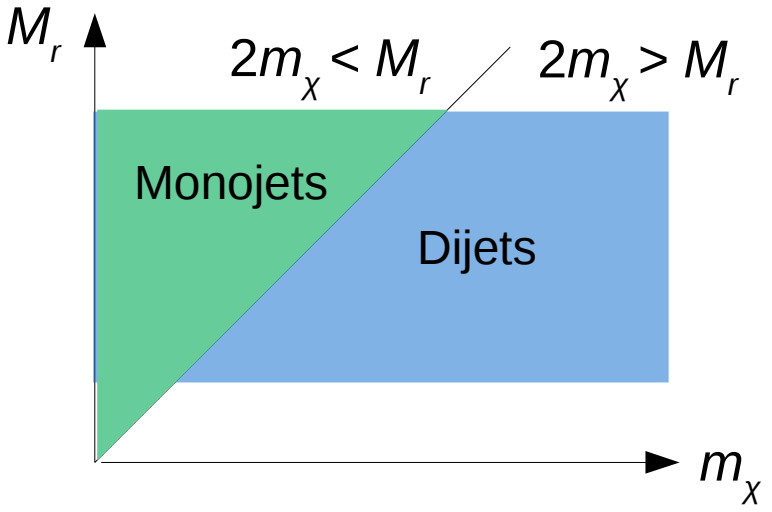
DESY

Motivation: Axial-vector mediators

- For $g_\chi^A / g_q^A \lesssim 4$ the mediator decays dominantly into quarks (even if $M_R >> m_\chi$).
- We expect dijet searches to give the strongest constraints on the entire parameter space.

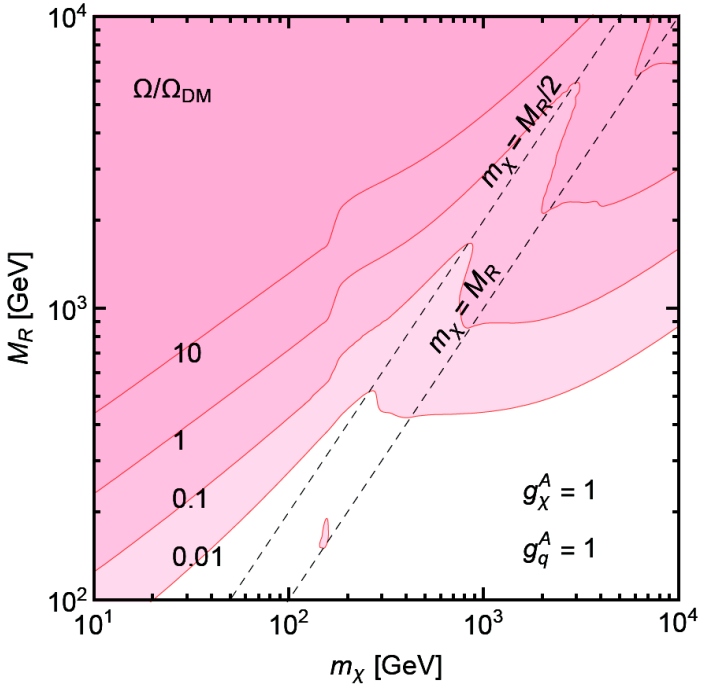


- For $g_\chi^A / g_q^A \gtrsim 4$ the mediator decays dominantly into DM as soon as the phase space for this decay channel opens up.
- For light DM, the strongest constraints are expected to result from monojet searches.



Relic density constraints

- A small diversion: What about the relic density?



- In significant parts of the parameter space, the interactions between DM, axialvector mediator and quarks lead to an underproduction of DM.*
- Additional interactions with other particles are expected to suppress the DM relic abundance even further.
- Should this parameter region be excluded?

*Note: The *s*-wave contribution to the annihilation cross section is helicity suppressed, so higher-order terms in the velocity expansion must be considered. Close to the resonance, the velocity expansion breaks down entirely, so we use micrOMEGAs to take into account the full expression.

Motivation: Phenomenology

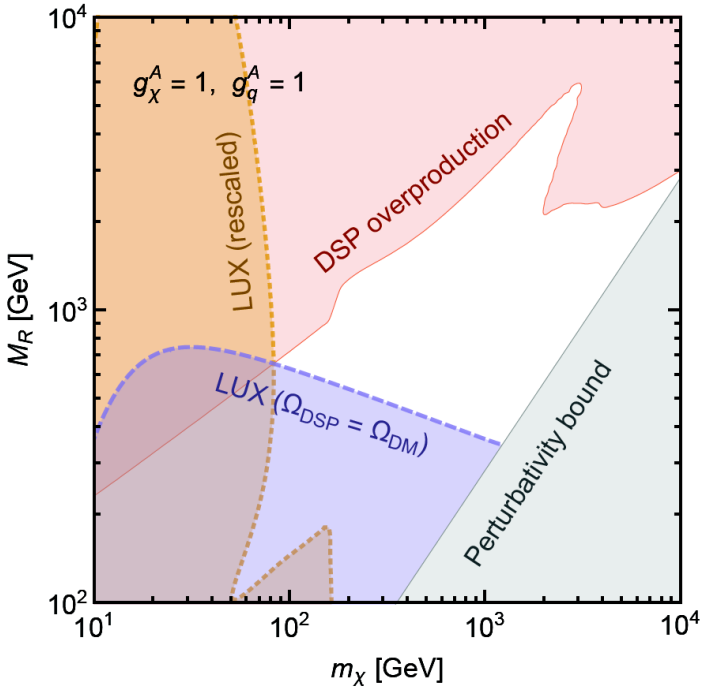
- Rather than excluding the parameter region where the DM particle is underproduced, we allow for the possibility that it constitutes only a fraction of the dark matter.
- This is perfectly consistent: We never expected our simple model to be the full story!
- To make this change of perspective explicit, we call such a DM subcomponent a dark sector particle (DSP).
- The crucial observation is that the local DSP density ρ_{DSP} is proportional to the relic abundance Ω_{DSP}, which scales according to

$$\Omega_{\mathrm{DSP}} \propto \frac{1}{\langle \sigma v \rangle} \propto g^{-4}$$

  where $g = \sqrt{g_q \, g_\chi}$.
- As a result, there is a strong suppression of the expected event rates in indirect ($\sim \rho_{\mathrm{DSP}}^2$) and direct ($\sim \rho_{\mathrm{DSP}}$) detection experiments.
- The LHC offers a unique opportunity to search for DM subcomponents!

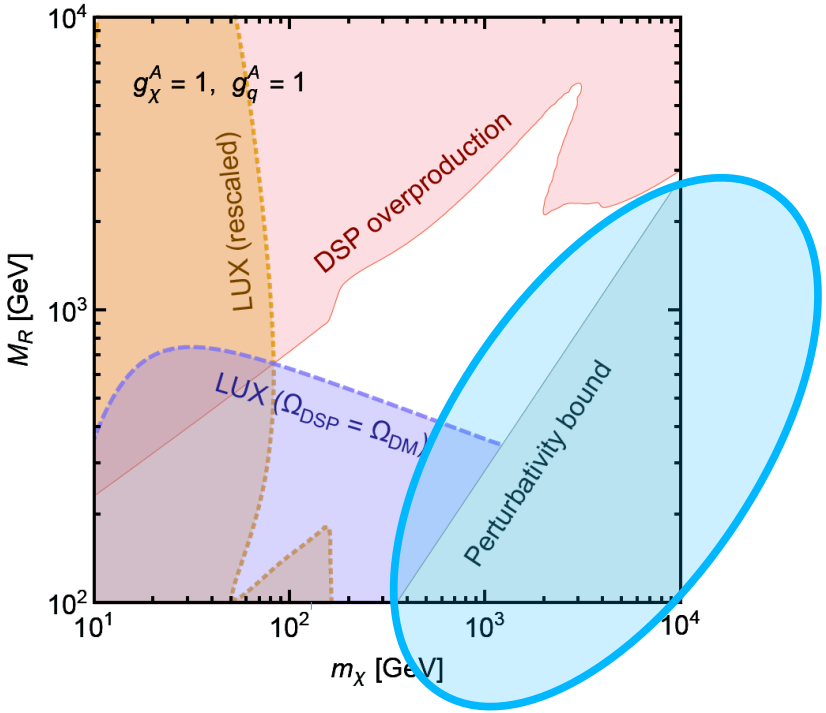
Relic density constraints

- The DSP-nucleus interactions are spin-dependent, so we re-analyse the published LUX results to derive a bound.
- We then rescale the conventional bound (assuming $\Omega_{DSP} = \Omega_{DM}$) using the results from the relic density calculation. This rescaling weakens the bound from direct detection in the parameter region where the DSP is underproduced.



Relic density constraints

- The DSP-nucleus interactions are spin-dependent, so we re-analyse the published LUX results to derive a bound.
- We then rescale the conventional bound (assuming $\Omega_{DSP} = \Omega_{DM}$) using the results from the relic density calculation. This rescaling weakens the bound from direct detection in the parameter region where the DSP is underproduced.



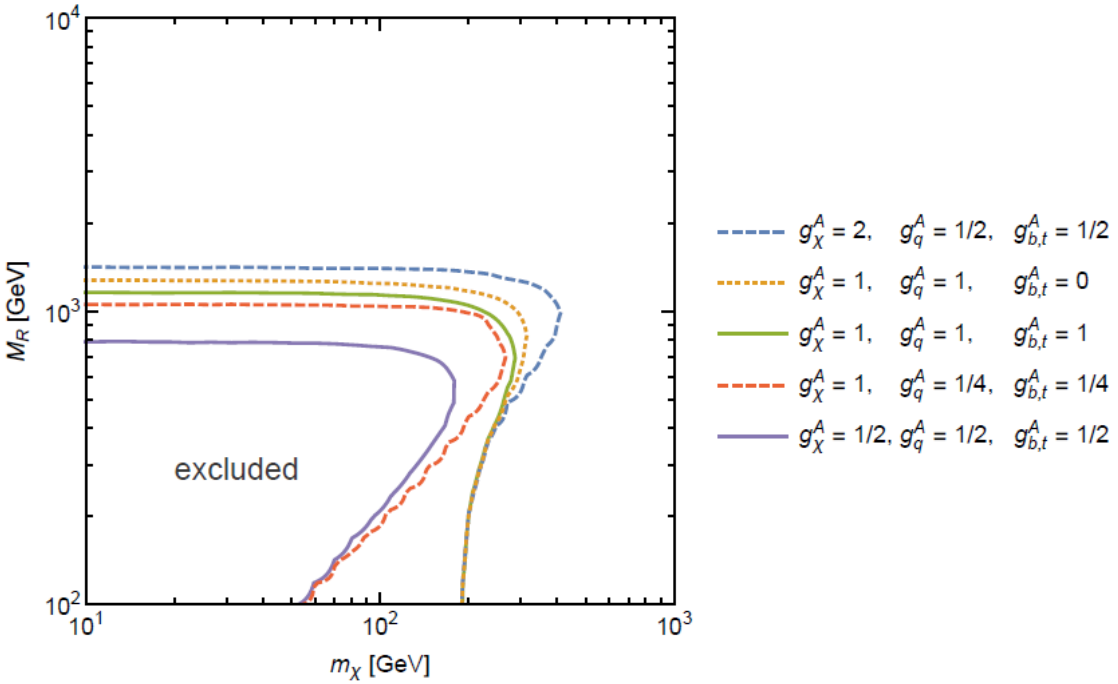
- Another important constraint comes from the fact that the DSP mass cannot be raised arbitrarily above the mediator mass, if both masses are generated by the same mechanism in a perturbative UV-completion.
- Indeed, we must impose $M_R > g_\chi^A\, m_\chi / \sqrt{4\pi}$ to ensure that DSP scattering and annihilation via the longitudinal component of *R* do not violate perturbative unitarity.

Collider constraints: Monojets

- MET > 450 GeV
- $p_T(j_1)$ > 110 GeV
- No tertiary jets
- Event simulation in the Powheg-Box

Haisch, FK, Re, arXiv:1310.4491

- Showering with Pythia 6.



- Monojet searches are most sensitive for $m_\chi < M_R/2$, such that the mediator can be on-shell and there is a resonant enhancement.
- For small DSP masses, current searches (here from CMS arXiv:1408.3583) probe mediator masses up to 1–1.5 TeV.
- Even for rather large couplings there is yet insufficient energy to produce DSPs with masses above 300–400 GeV.

Collider constraints: Dijets

- Searches for dijet resonances give the strongest constraints when the invisible branching ratio of the mediator is small, either because g_χ^A / g_q^A is small or because the invisible decay channel is kinematically closed.
- There are, however, two important complications limiting the sensitivity of dijet searches in the context of our model:

Dobrescu & Yu, arXiv:1306.2629

1. For small mediator masses (MR < 1 TeV) the QCD background (from two gluons in the initial state) becomes so large, that the LHC cannot record and process all of these events.

2. For large couplings the width of the mediator becomes so large that the usual searches for narrow resonances no longer apply.

Collider constraints: Dijets

- Searches for dijet resonances give the strongest constraints when the invisible branching ratio of the mediator is small, either because g_χ^A / g_q^A is small or because the invisible decay channel is kinematically closed.
- There are, however, two important complications limiting the sensitivity of dijet searches in the context of our model:

Dobrescu & Yu, arXiv:1306.2629

1. For small mediator masses (MR < 1 TeV) the QCD background (from two gluons in the initial state) becomes so large, that the LHC cannot record and process all of these events.

   Solution: Consider dijet searches from UA2 and Tevatron, as well as LHC searches with smaller backgrounds, such as searches for dijet resonances produced in association with Z and W bosons.

ATLAS-CONF-2013-074

2. For large couplings the width of the mediator becomes so large that the usual searches for narrow resonances no longer apply.

DESY

Collider constraints: Dijets

- Searches for dijet resonances give the strongest constraints when the invisible branching ratio of the mediator is small, either because g_χ^A / g_q^A is small or because the invisible decay channel is kinematically closed.
- There are, however, two important complications limiting the sensitivity of dijet searches in the context of our model:

Dobrescu & Yu, arXiv:1306.2629

1. For small mediator masses (MR < 1 TeV) the QCD background (from two gluons in the initial state) becomes so large, that the LHC cannot record and process all of these events.

   Solution: Consider dijet searches from UA2 and Tevatron, as well as LHC searches with smaller backgrounds, such as searches for dijet resonances produced in association with Z and W bosons.

ATLAS-CONF-2013-074

2. For large couplings the width of the mediator becomes so large that the usual searches for narrow resonances no longer apply.

   Solution: Reinterpret existing searches in terms of broad resonances using MadGraph+Pythia6+Delphes for the signal generation and FastJet+MadAnalysis+MCLimit for the analysis.

DESY

Example: Lepton-associated dijets

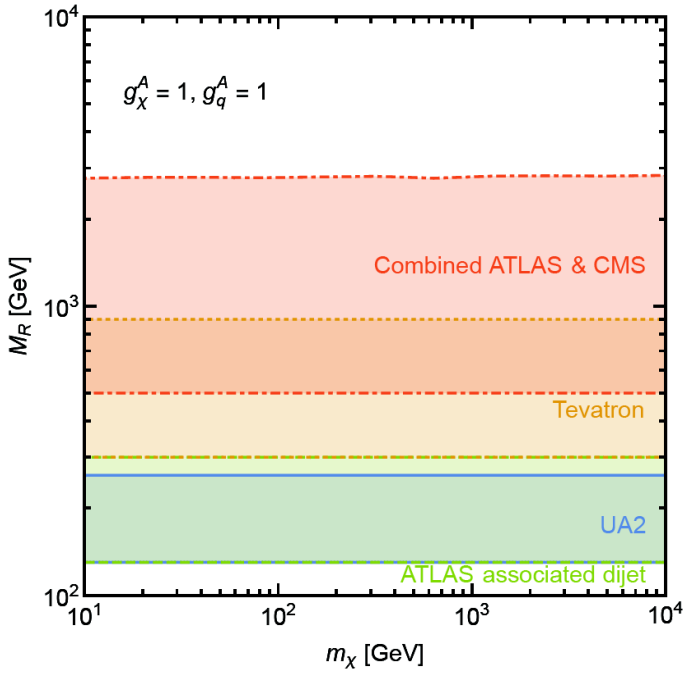
- ATLAS search for $pp \to R\,Z \to jj\ell^+\ell^-$ and $pp \to R\,W^\pm \to jj\ell^\pm\nu$ at 8 TeV with 20.3 fb^{-1}.

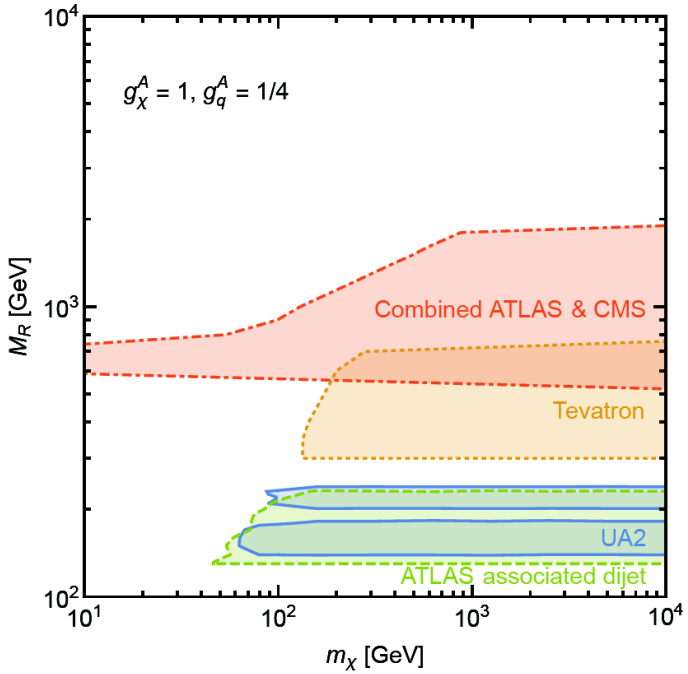
- Leptons: $p_T^{\ell\ell(\ell\nu)} > 50\ \mathrm{GeV}$
- Jets: $p_T > 30\ \mathrm{GeV}\ ,\ |\Delta\eta_{jj}| < 1.75$
  $130\ \mathrm{GeV} < m_{jj} < 300\ \mathrm{GeV}$

- Should be easy in principle to extend to larger values of m_{jj}.

- We simulate the SM backgrounds and compare the resulting mjj distribution to the experimental measurements.
- We then include an additional dijet signal from the dark mediator (neglecting interference effects) and use the CLs method to set bounds.

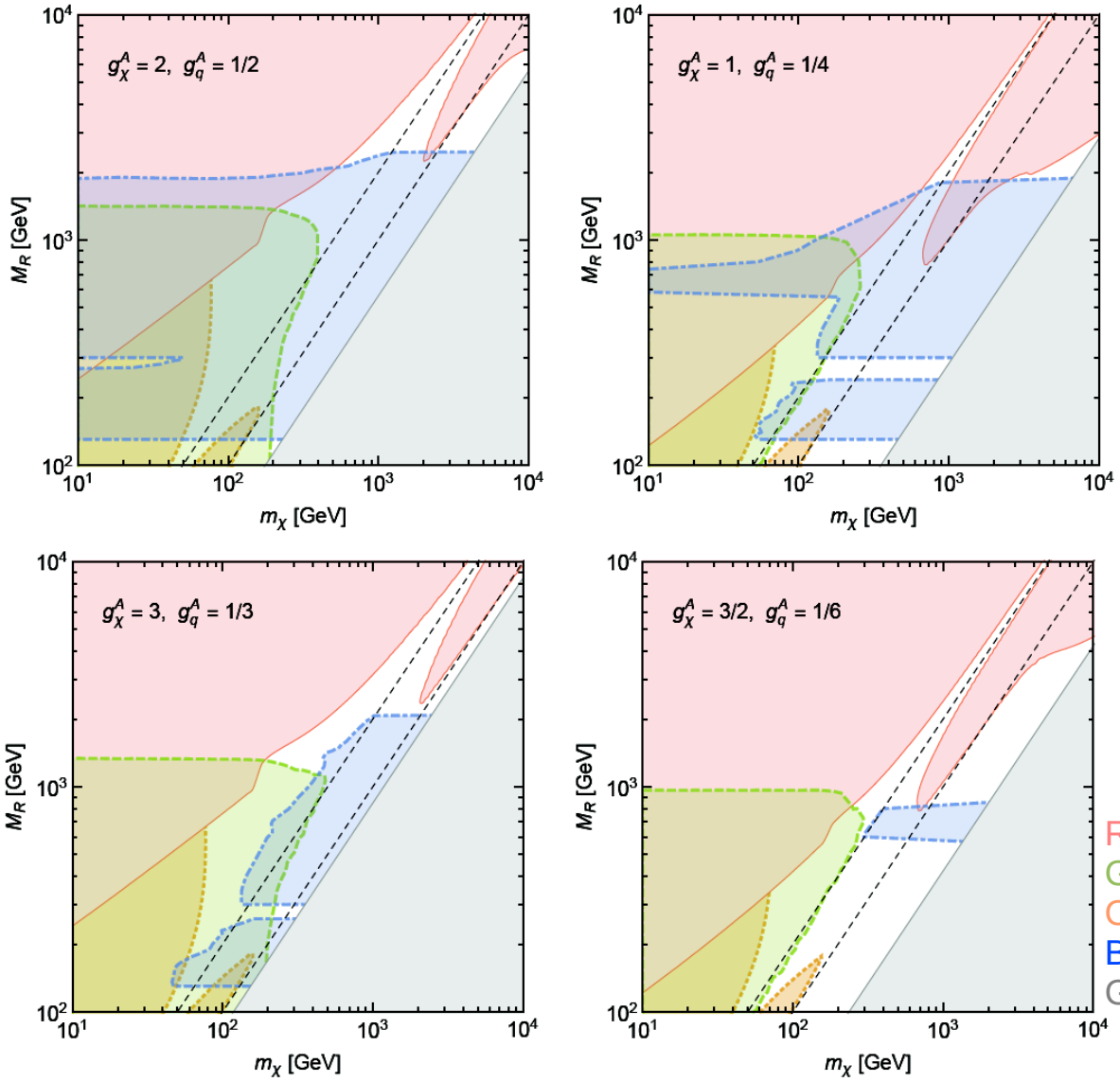
Dijets: Results





- We find that (at least as long as $g_q < 1$), we obtain stronger bounds for larger couplings, i.e. the enhancement of the production cross section overcompensates the reduction of the efficiency due to the broadening of the resonance.
- For $g_q = g_x = 1$, we exclude all mediator masses with 130 GeV < M_R < 2.8 TeV.
- For smaller quark couplings, dijet searches are most sensitive to $M_R > 2\, m_\chi$.

Combined constraints

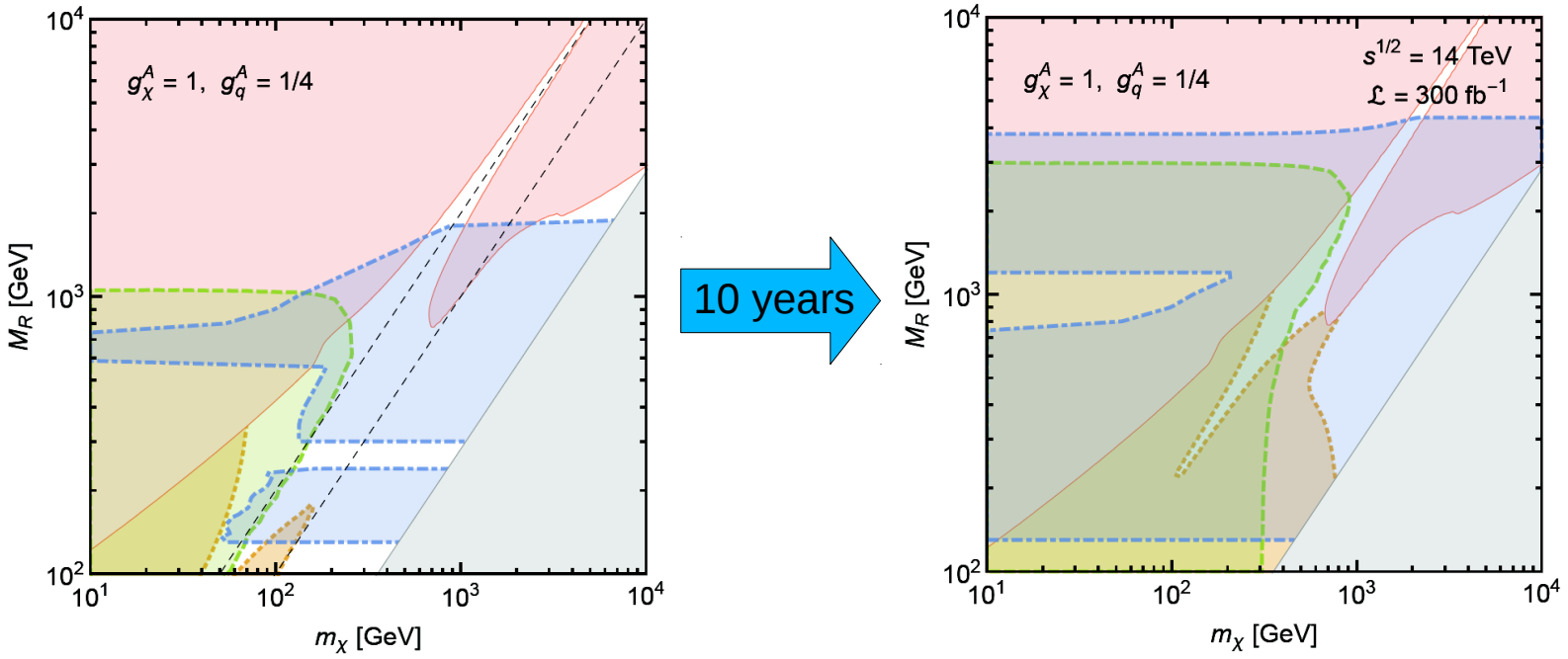


- Almost no constraints from direct detection in the parameter region where the DSP is underproduced.
- Strong complementarity between monojet searches and dijet searches
- For g > 0.5, only small mass ranges remain viable.
- Presently very limited sensitivity for g < 0.2.

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

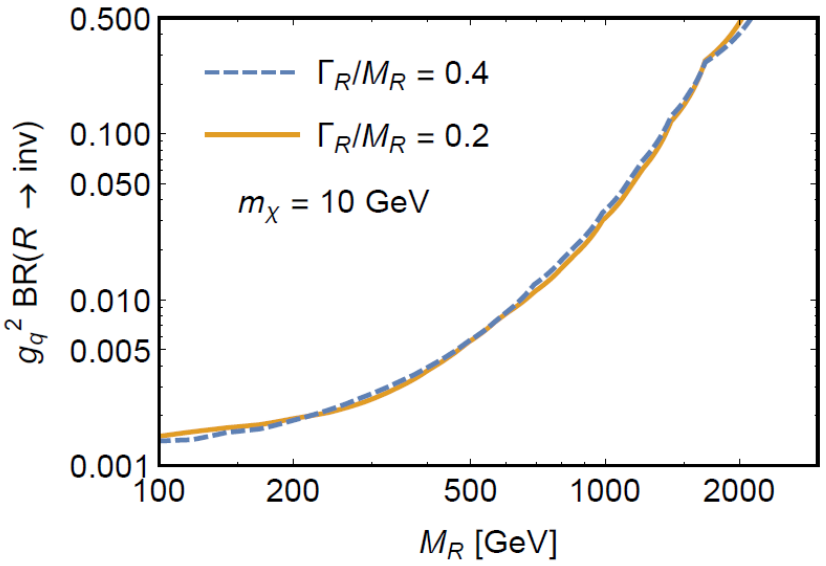
DESY

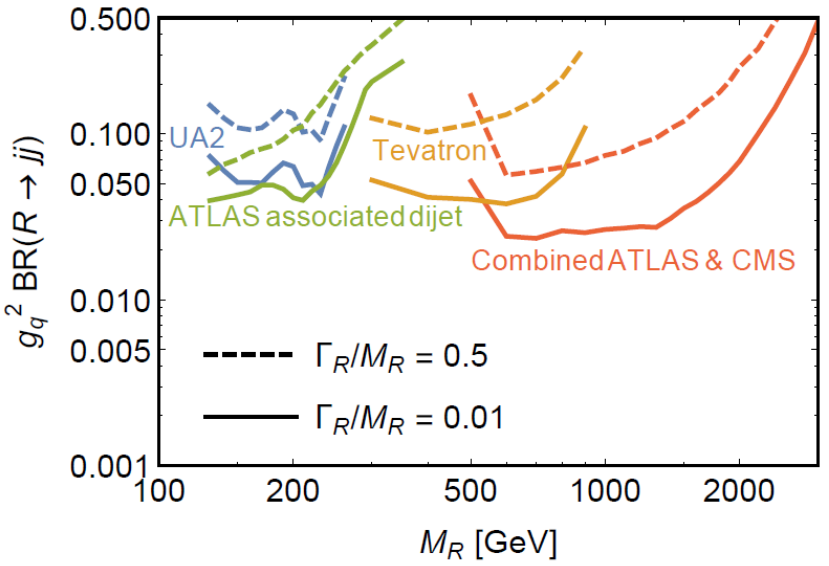
Future prospects



- Large improvements expected in the near future:
  - LHC@14TeV will probe mediator masses up to 4 TeV and DSP masses up to 1 TeV.
  - Searches for dijet resonances in association with SM gauge bosons will significantly gain in sensitivity. Chiang et al., arXiv:1502.00855; Xiang et al, arXiv:1503.02931
  - The upcoming direct detection experiments XENON1T and LZ will be highly competitive with LHC searches.

Discussion





- We can also use our analysis to construct more model-independent bounds on the mediator production cross section times its branching ratios.
- These bounds apply to cases where additional decay channels contribute to the total width of the mediator.
- Additional constraints for such models could come from dijet angular correlations and searches for ttbar resonances.

Plenty of opportunities for future work!

DESY

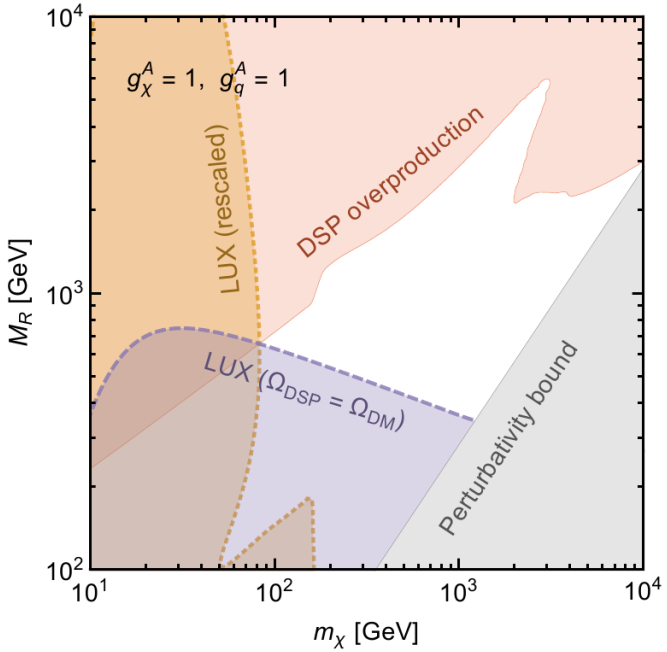
Conclusions

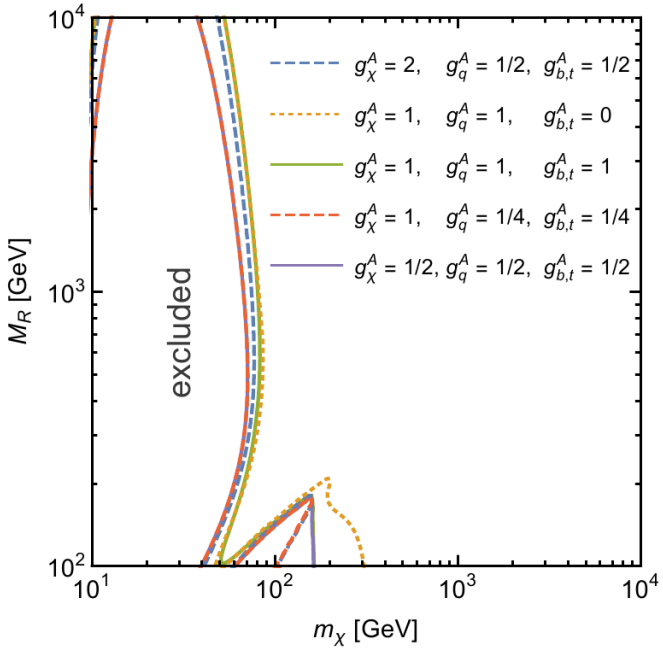
- There are many different candidate theories for the DM particle, but fortunately we have a broad range of experimental strategies to shed light on its nature.
- An interesting possibility both from both model-building and phenomenological perspective are dark mediators coupling the visible and dark sectors. In particular, axial-vector mediators provide a useful example to study the compelling interplay between different DM detection techniques.
- In large parameter regions the DSP is underproduced in the early Universe and bounds from direct detection experiments are therefore suppressed.
- There is an important complementarity between monojet searches and dijet searches in constraining both visible and invisible decays of the mediator.
- Searches for dijet resonances remain sensitive even for very broad resonances. A combination of different searches allows to probe mediator masses in the range 130 GeV < M_R < 3 TeV.
- Viable models require either g_q < 0.2 or special corners of parameter space, which can be probed in the very near future.

DESY

Backup

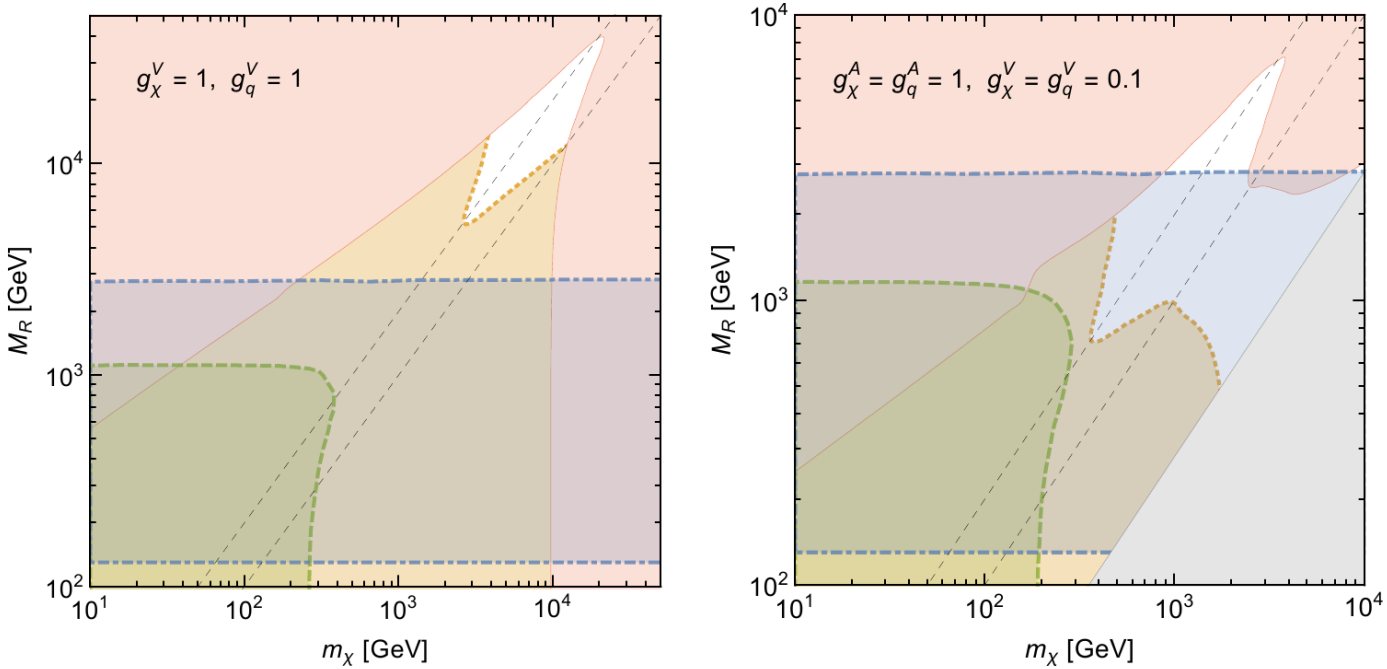
Details on direct detection





- Direct detection bounds are not entirely independent of couplings, due to a combination of three different reasons:
  - Variations in the freeze-out temperature
  - Variations in the mediator width
  - Relevant contributions from direct annihilation of DSPs into mediators.

Vector couplings



- The presence of non-zero vector couplings enhances both the DSP annihilation rate and the DSP-nucleus scattering cross section.
- If vector couplings dominate, bounds from LHC searches are significantly less constraining than direct detection experiments.
- An interesting interplay of different searches is possible if the vector couplings are small compared to the axial couplings.