Probing thermal freeze-out with searches for dijet resonances at LHC and 100 TeV.

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Based on
arXiv:1605.07940 with Malcolm Fairbairn, John Heal and Patrick Tunney
arXiv:1606.00947 with Mikael Chala, Germano Nardini and Kai Schmidt-Hoberg

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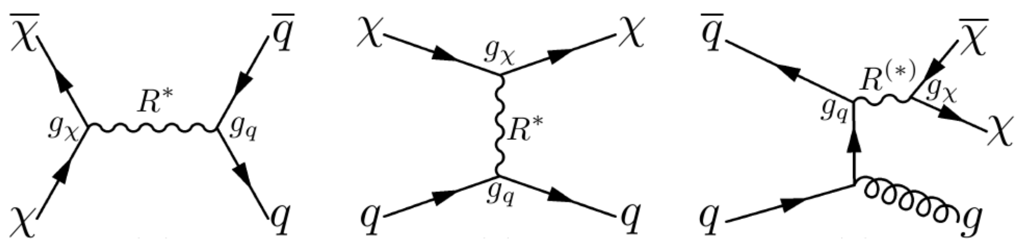
DESY

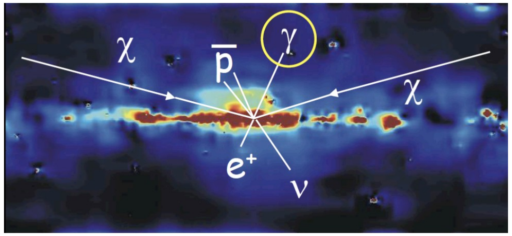
A new mediator

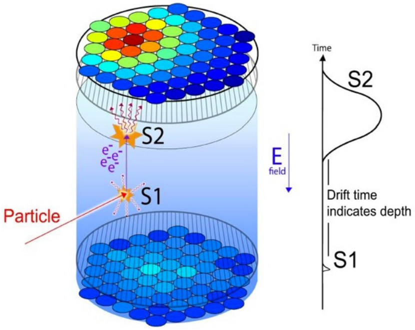
- The paradigm of thermal freeze-out requires sizeable interactions between Dark Matter (DM) particles and Standard Model (SM) states, which keep DM in thermal equilibrium in the Early Universe.
- An interesting and well-motivated class of models considers the case that a new mediator is responsible for these interactions.

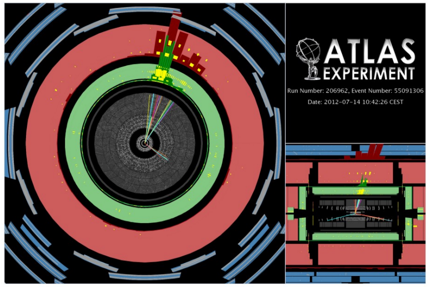
See talk by Thomas Jacques

- This mediator can then potentially induce DM signals in a number of search channels, such as indirect detection, direct detection and LHC monojet searches:









A new mediator

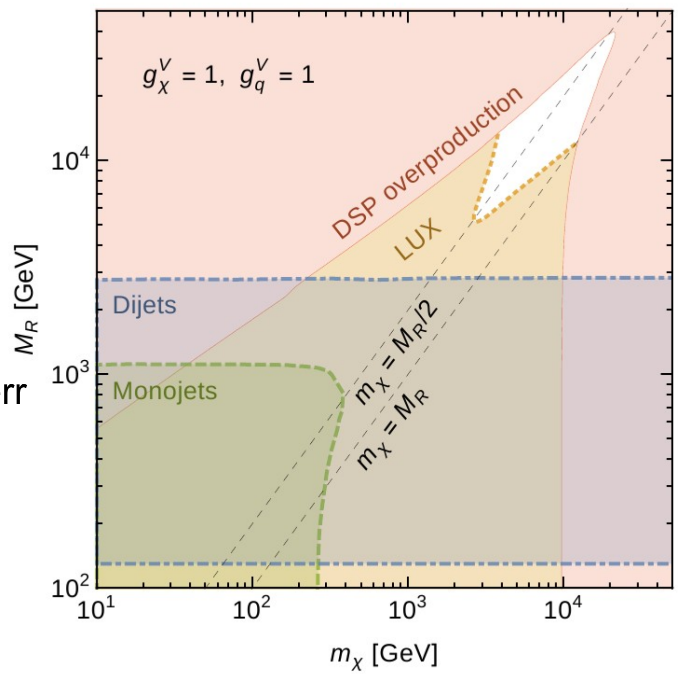
- For Dirac DM particles, interactions with quarks are strongly constrained by direct detection experiments.

  See talk by Stefan Vogl

- For Majorana DM, on the other hand, direct detection bounds are much weaker (either spin-dependent or momentum-suppressed).

  See talk by Michael Duerr

- As a result, it is still a perfectly viable possibility that the DM-quark interactions are sufficiently large that the observed DM relic abundance can be reproduced via annihilation exclusively into quarks.

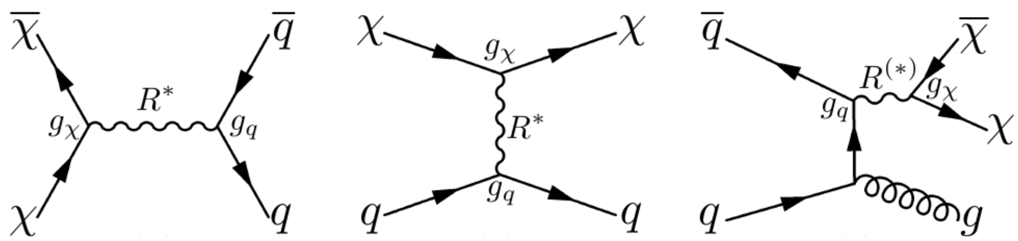


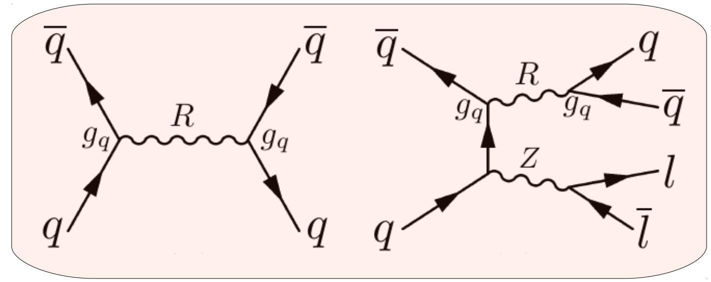
Chala, FK et al., arXiv:1503.05916

- One of the simplest ways to realise such a scenario is via a leptophobic Z' that also couples to DM (as in models of Baryonic DM).

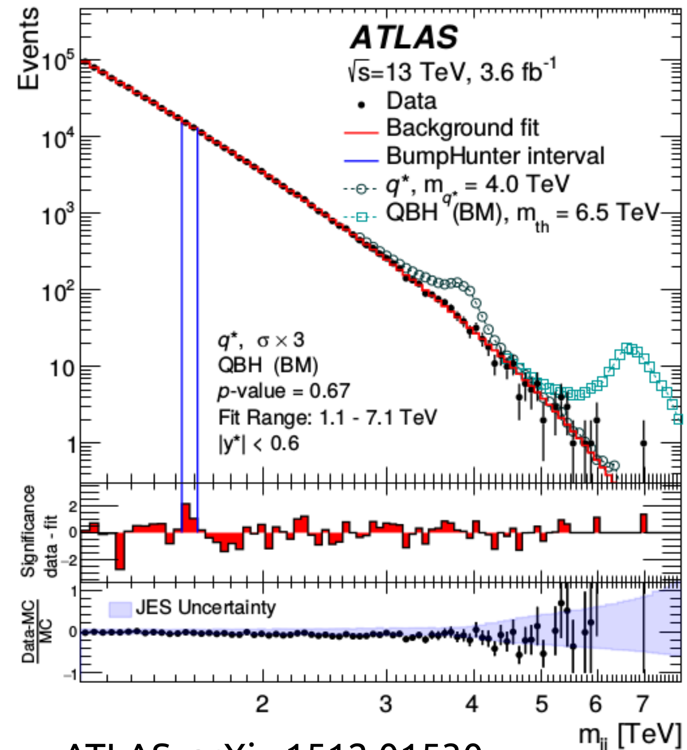
Fileviez & Wise, arXiv:1002.1754, Duerr et al., arXiv:1304.0576

Searches for new resonances





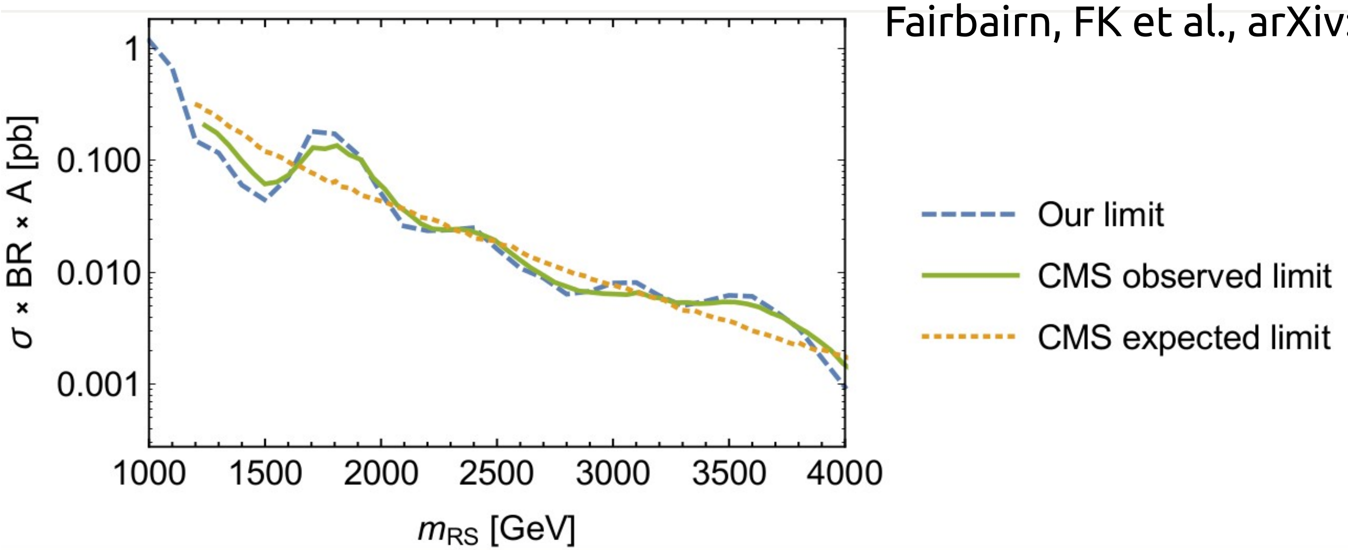
- Crucially, the mediator of the DM interactions will also lead to new interactions between Standard Model states,
- There may be observable signals from processes involving no DM particles at all.
- For example, if the mediator can be produced at the LHC, it can also decay back into quarks.
- One should therefore consider dedicated searches for the mediator particles themselves, such as searches for dijet resonances.



ATLAS, arXiv:1512.01530

Searches for dijet resonances

- Results from dijet resonance searches at the LHC are presented in a way that they can be applied to a wide range of different models.
  - In particular, it is possible to directly compare simulated distributions of the dijet invariant mass to the observed spectra.
  - The SM expectation for these spectra are obtained by fitting a smooth function to the observed distribution: $f(z) = p_1(1-z)^{p_2} z^{p_3}$
  - It is possible with this approach to reproduce experimental bounds (e.g. for the case of an RS graviton) to very good accuracy.



Fairbairn, FK et al., arXiv:1605.07940

Combination of dijet resonance searches

- The great advantage of using actual dijet invariant mass spectra rather than published bounds is that one can not only reproduce the 95% CL bound, but in fact reconstruct the full likelihood (using e.g. a χ^2 test statistic).

- This makes it possible to combine dijet resonance searches from both ATLAS and CMS, as well as searches at both 8 TeV and 13 TeV.

	m_{jj}	$\lvert\Delta\eta_{jj}\rvert$	additional
ATLAS 13 TeV	> 1.1 TeV	< 1.2	$p_{T,j_1} > 440$ GeV and $p_{T,j_2} > 50$ GeV
CMS 13 TeV	> 1.2 TeV	< 1.3	$p_{T,j_1} > 500$ GeV or $H_T > 800$ GeV
ATLAS 8 TeV	> 250 GeV	< 1.2	-
CMS 8 TeV	> 890 GeV	< 1.3	-
CMS 8 TeV (low)	> 390 GeV	< 1.3	-

Deriving model-independent bounds

- Previous analyses of LHC dijet searches have either focused on resonances that decay exclusively into quarks or on certain DM models with specific choices of couplings.

  An, Ji & Wang, arXiv:1202.2894
  Dobrescu & Yu, arXiv:1306.2629
  Chala, FK et al., arXiv:1503.05916

- It is, however, possible to analyse LHC dijet searches in a largely model-independent way, so that the results can be applied to many different Z' models, including models with invisible or unobserved decay modes.

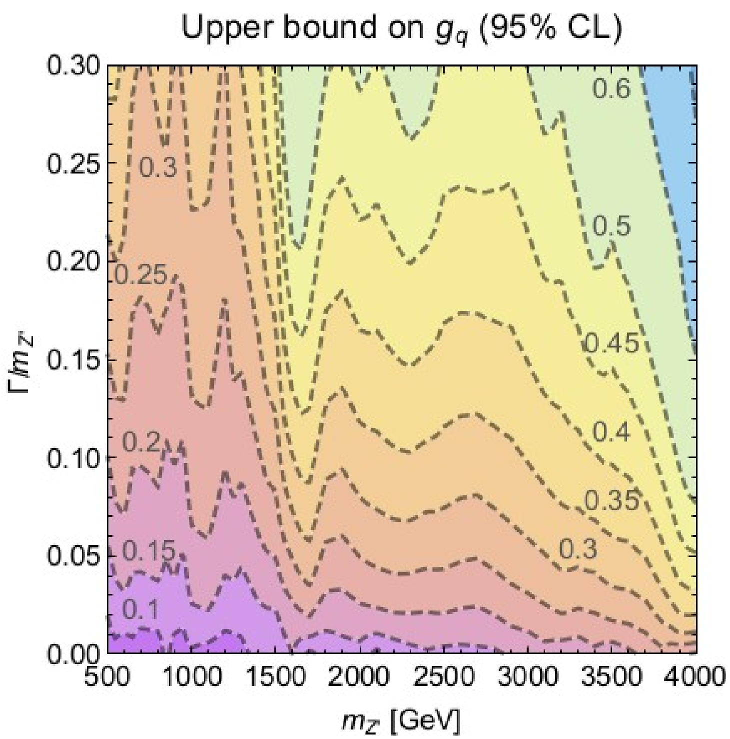
- The key idea is to take the width of the Z' as a free parameter (rather than to calculate it from the assumed couplings).

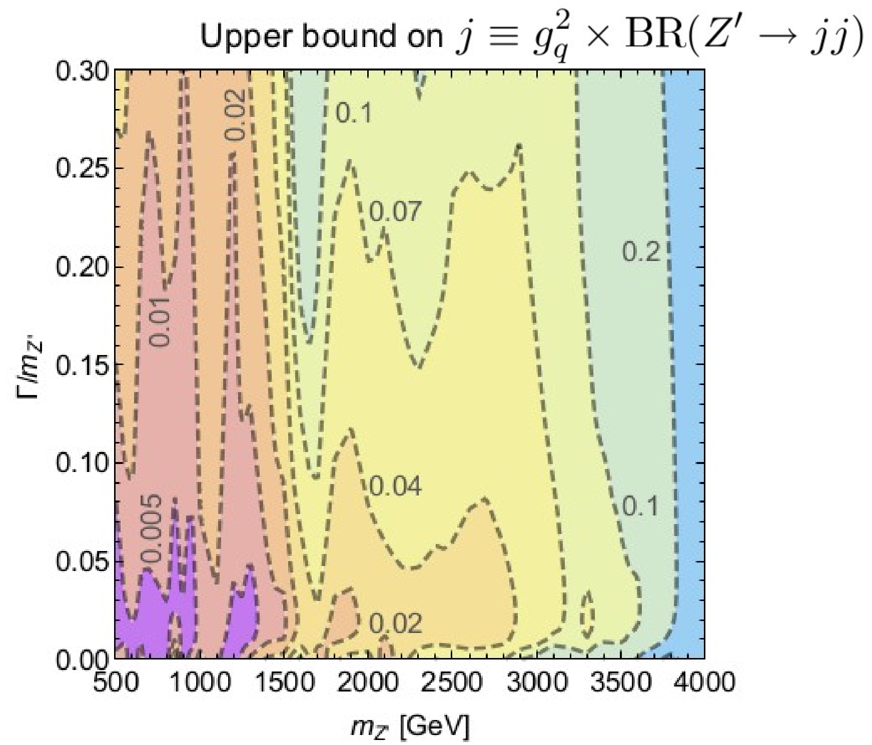
- Since the shape of the dijet invariant mass distribution depends only on $m_{Z'}$ and $\Gamma_{Z'}$, changing g_q then only changes the normalisation of the signal.

- For given $m_{Z'}$ and $\Gamma_{Z'}$, we can thus easily construct an upper bound on the magnitude of the signal, leading to a bound on g_q.

Results

Fairbairn, FK et al., arXiv:1605.07940





- Typical sensitivity for $m_{Z'} < 1.5$ TeV:
  - Narrow width: $g_q \sim 0.1$
  - Broad width: $g_q \sim 0.3$
- Weaker bounds for larger Z' masses.

A specific example: Z' coupling to quarks and DM

- To illustrate our method, we consider a 4-parameter model of a leptophobic Z' coupling to quarks and DM:

$$\mathcal{L}_{\text{kin}} = \frac{i}{2}\bar{\psi}\gamma^\mu\partial_\mu\psi - \frac{1}{2}m_{DM}\bar{\psi}\psi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{Z'}^2 Z'_\mu Z'^\mu$$
$$\mathcal{L}_{\text{int}} = -\frac{1}{2}g_{DM}^A Z'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi - g_q Z'_\mu \sum_q \bar{q}\gamma^\mu q \; .$$

- We would like to understand in which regions of parameter space this model alone (without the presence of any other annihilation channels or modifications to standard cosmology) can reproduce the observed DM relic abundance via thermal freeze-out.

- The conventional way to answer this question would be to eliminate one parameter (e.g. g_q) using the relic density requirement and then scan over the remaining three parameters.

Combining relic density and dijet constraints

- The problem with this approach is that the Z' width (and hence the strength of the dijet constraints) depends on all the other parameters in a non-trivial way.

- For example, when reducing g_{DM} the relic density constraint implies that g_q must grow, which changes the width of the Z'.
  - Unclear whether such a change leads to stronger or weaker dijet constraints.

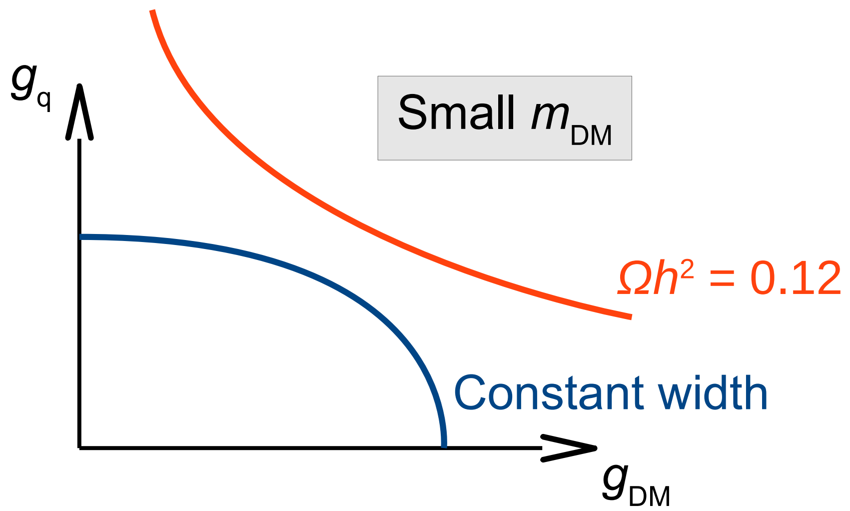
- Solution: We rephrase our model in terms of those parameters directly probed by LHC dijet searches, i.e. $m_{Z'}$ and $\Gamma_{Z'}$. Imposing a fixed Z' width allows us to eliminate another parameter (for example g_{DM}).

- We can then consistently apply dijet constraints in this new parameter space.

- Note that this parameter space is not only convenient for setting bounds, but also for interpreting potential excesses, as the mass and the width of a resonance are the first two quantities that can be inferred from data.

Applying the relic density constraint

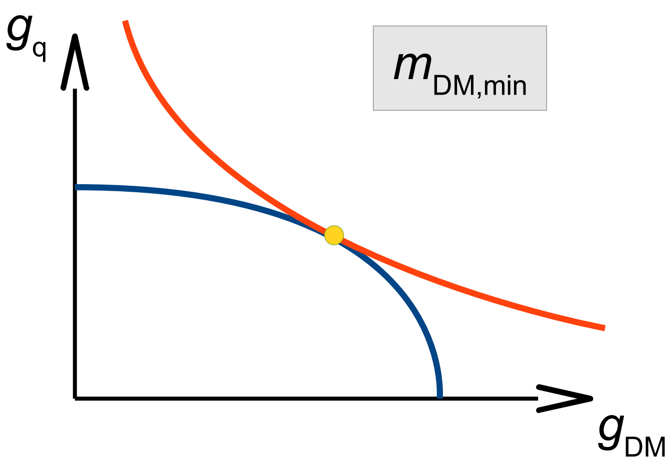
- For fixed $m_{Z'}$, m_{DM} and $\Gamma_{Z'}$ we want to identify those couplings that are consistent with the assumed width and reproduce the observed DM relic abundance via thermal freeze-out into quarks.



- For small DM masses, these two requirements are typically not compatible, i.e. all couplings consistent with the assumed width lead to DM overproduction.

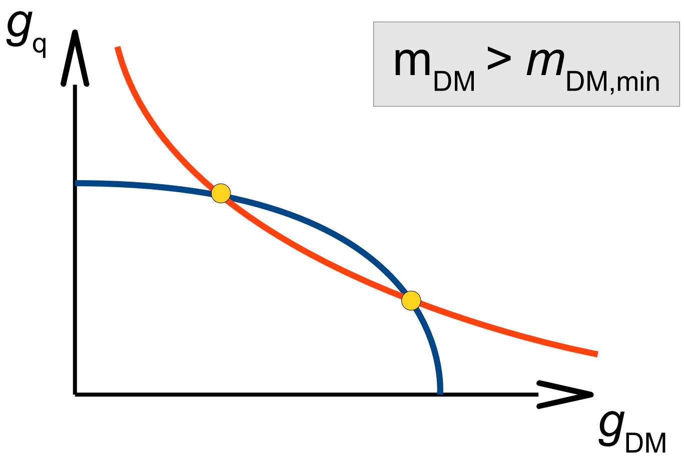
Applying the relic density constraint

- For larger DM masses, the relic density line moves down, so at some point the two curves will intersect.



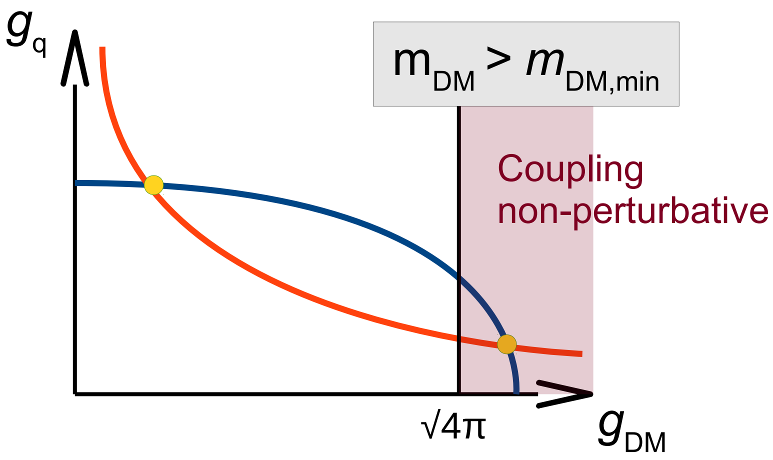
Applying the relic density constraint

- For DM masses above $m_{\mathrm{DM,min}}$ there are typically two solutions consistent with the assumed width and compatible with the observed relic abundance.



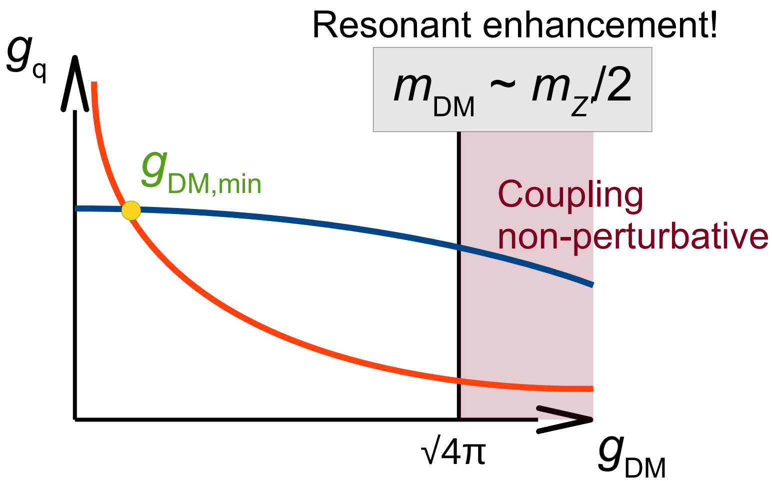
Applying the relic density constraint

- At some point, however, the solution corresponding to larger g_{DM} will become non-perturbative ($g_{DM} > \sqrt{4\pi}$), so only one viable solution remains.



Applying the relic density constraint

- The smallest possible solution, $g_{\mathrm{DM,min}}$, is found for $m_{\mathrm{DM}} \sim m_{Z'}/2$, such that DM annihilation receives a resonant enhancement in the early Universe.

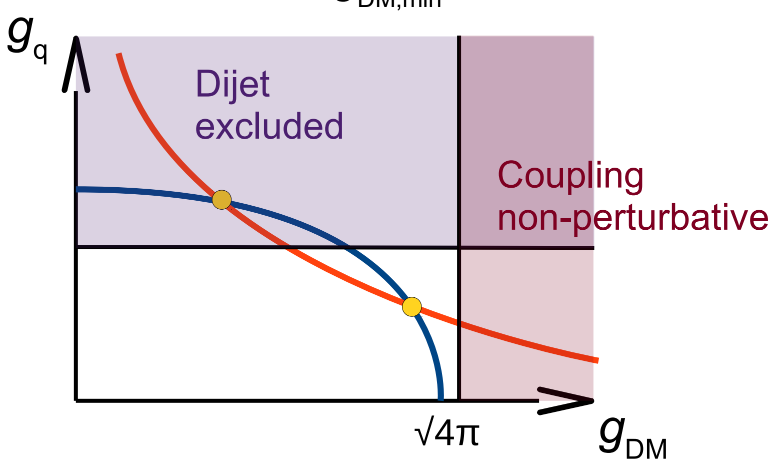


- We do not consider $m_{\mathrm{DM}} > m_{Z'}/2$, as in this case the mediator width becomes independent of g_{DM} and dijet constraints become trivial.

Applying dijet constraints

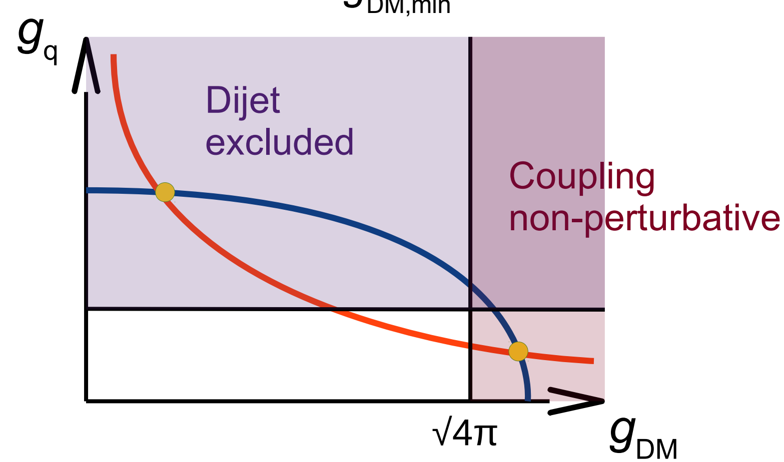
- Since we consider fixed $m_{Z'}$ and $\Gamma_{Z'}$, LHC dijet searches simply place an upper bound on g_q, which can be translated into a lower bound on g_{DM}.
- We can thus determine the smallest coupling $g_{\mathrm{DM,min}}$, for which the assumed width is compatible with dijet constraints and the model reproduces the observed relic abundance via thermal freeze-out into quarks.

Scenario 1: $g_{\mathrm{DM,min}} < \sqrt{4\pi}$



Allowed perturbative solutions remain for some values of m_{DM}.

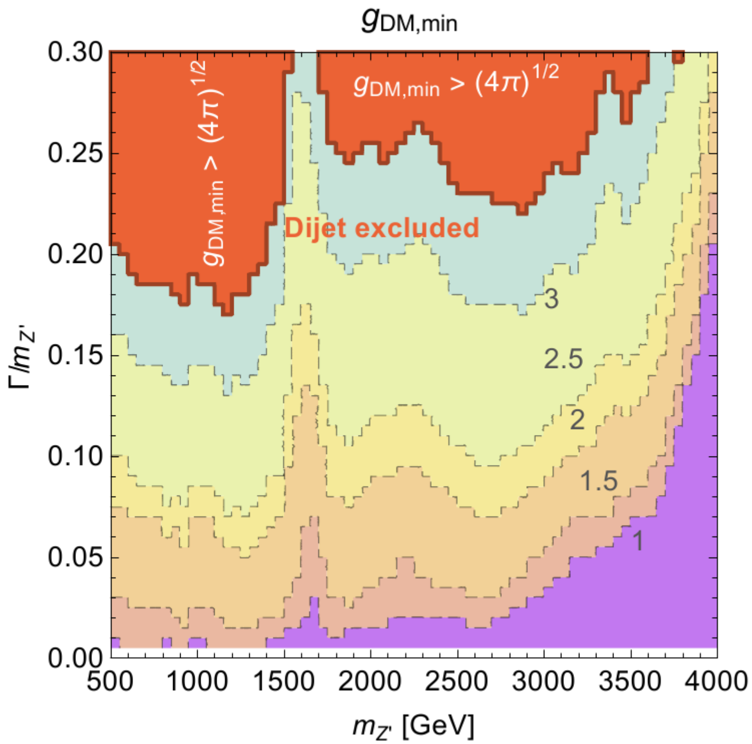
Scenario 2: $g_{\mathrm{DM,min}} > \sqrt{4\pi}$



All perturbative solutions excluded

Results

- We can repeat this procedure for all mediator masses and widths and identify those combinations that are already excluded (for perturbative couplings) by dijet searches.

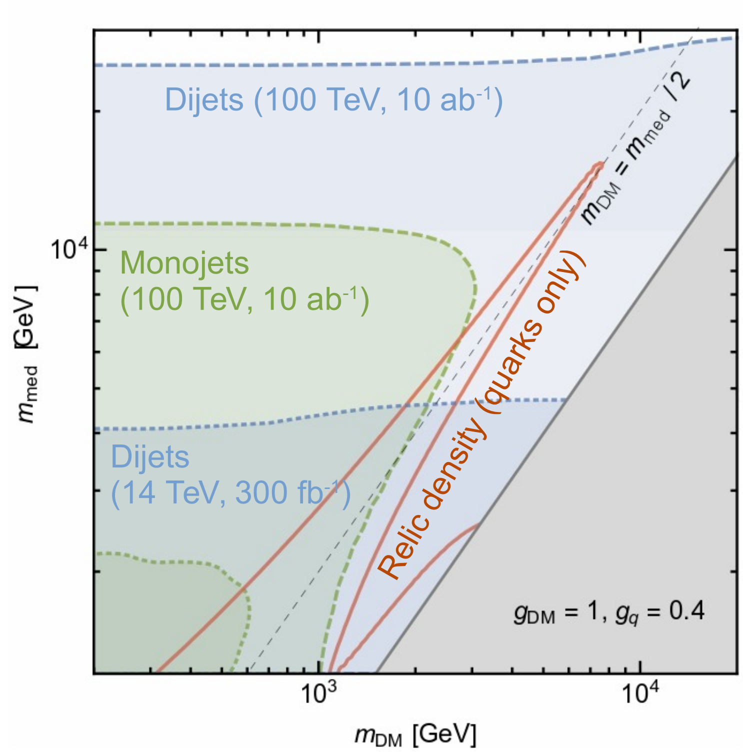


- Dijet searches give the strongest bounds on relatively light Z' and large width (which requires larger quark couplings).
- But even at smaller widths and larger masses, dijet searches imply that g_{DM} must be rather large.

- Note: As some other things, the slight excess at ~1.6 TeV has now disappeared in the 2016 data...

Science fiction at 100 TeV

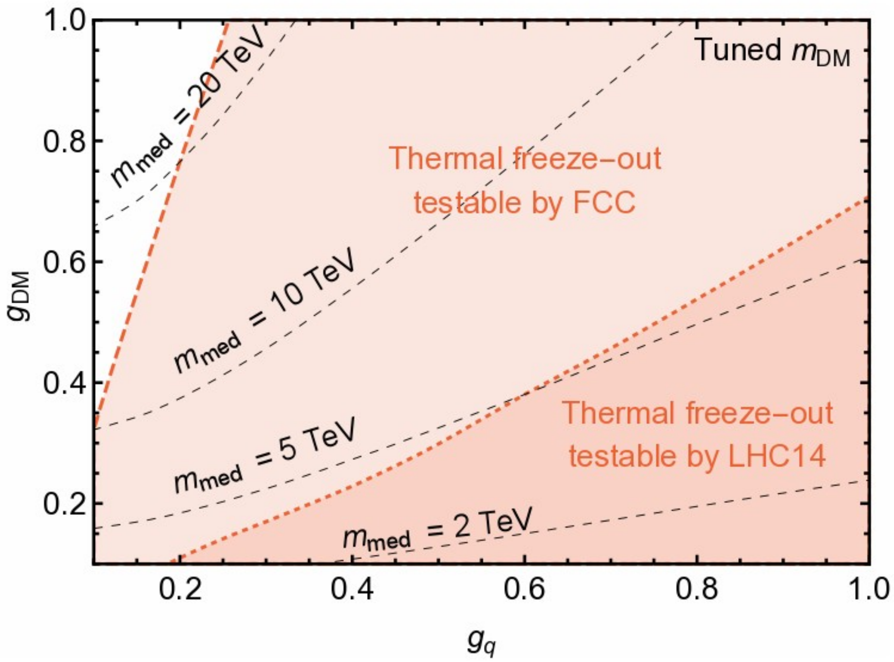
- If the DM mass is close to half the mediator mass, DM annihilations receive a resonant enhancement.
- The observed relic abundance can be reproduced for either very small couplings (10^{-2} and below) or very large masses (10 TeV and above).
- The LHC is not sensitive to this kind of scenario.
- A future circular p-p collider (FCC), however, may have a chance.
- At least for certain choices of couplings, the 100 TeV collider is sensitive to all parameter points where the observed DM relic abundance is achieved via annihilation into quarks.
- What about other coupling combinations?



Testing the resonance region at future colliders

- For a given combination of couplings g_q and g_{DM}, we can find the largest mediator mass compatible with the requirement $\Omega h^2 < 0.12$.
- For this purpose we "tune" the DM mass to maximise the resonant enhancement (this typically requires $m_{DM} \sim 0.48\ m_{med}$).
- We can then compare the largest mediator mass allowed by thermal freeze-out with the largest mediator mass that can be probed by the FCC.
- To evade the FCC reach requires large g_{DM} and small g_q!
- Only highly-tuned corners of parameter space can potentially evade detection at a 100 TeV collider.

Physics at a 100 TeV pp collider: beyond the Standard Model phenomena, arXiv:1606.00947



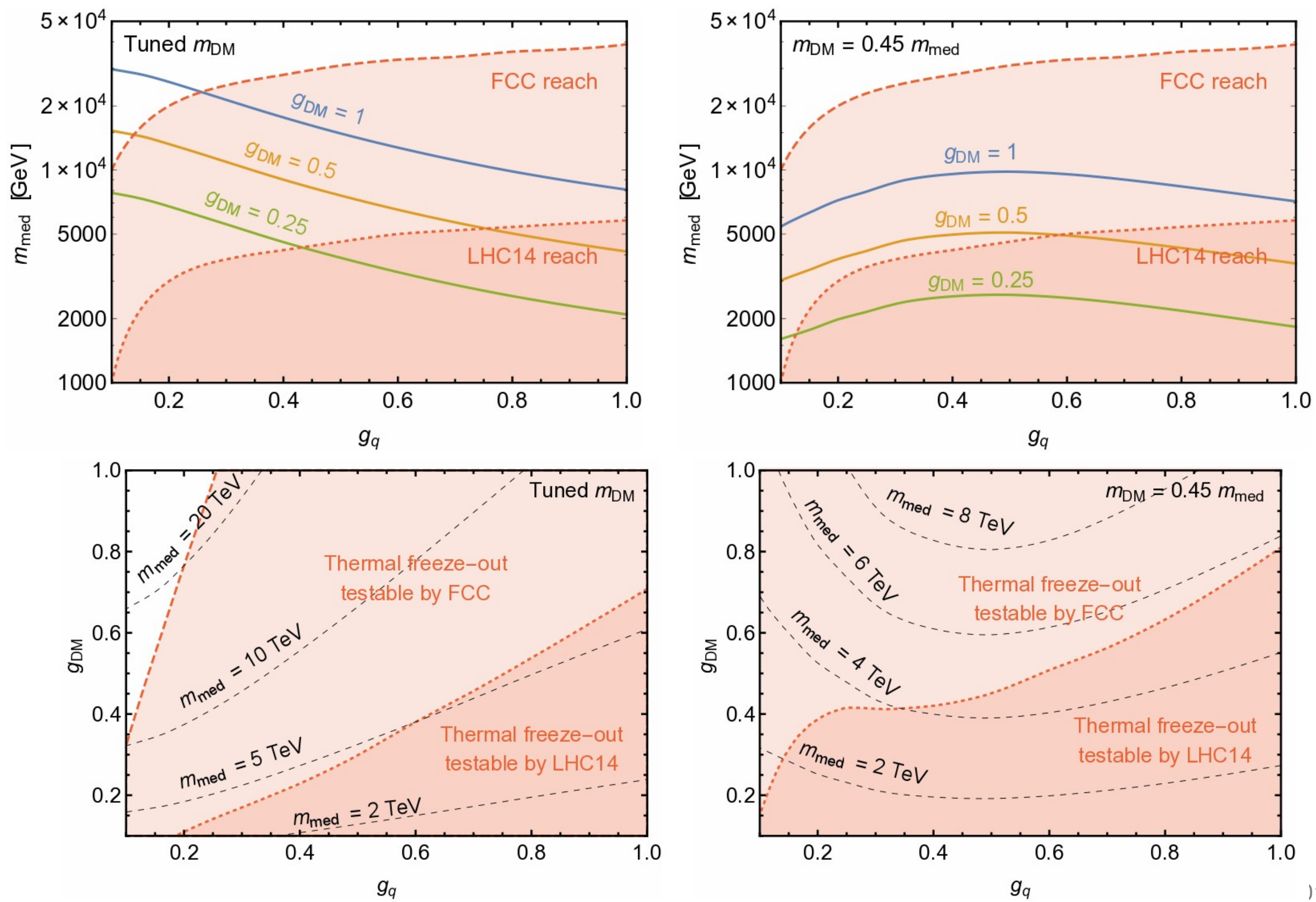
Conclusions

- Searches for dijet resonances provide a sensitive probe of models where DM couples to quarks via a new mediator.
- It is possible to combine different LHC searches for dijet resonances to derive bounds on a wide range of Z' models.
- These bounds can be combined with the information on the DM relic abundance to understand whether thermal freeze-out proceeds via DM annihilation into quarks.
- A 100 TeV collider will be able to even probe the case where DM annihilation receives a resonant enhancement.
- Apart from highly-tuned parameter regions, colliders will be able to probe the freeze-out paradigm for DM-quark interactions.

Backup

How much tuning is required?

- To quantify the amount of tuning necessary to avoid detection at the 100 TeV collider, we also consider the case that m_{DM} = 0.45 m_{med} (~5% away from the peak of the resonance).



The case with less tuning can be probed comprehensively at the 100 TeV collider!