Reinterpreting LHC searches for DM models

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(Re)interpreting the results of new physics searches at the LHC
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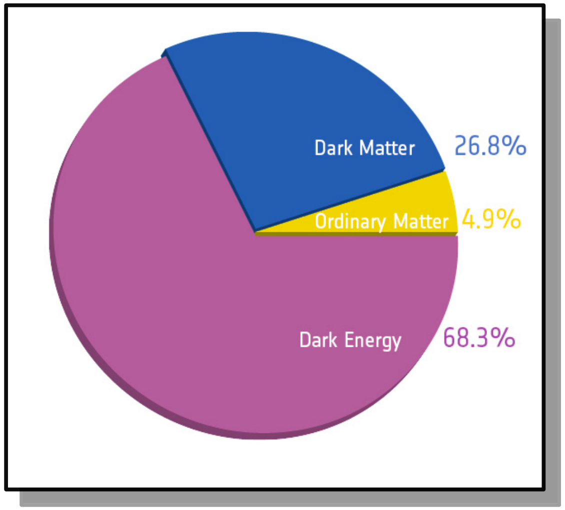
Dark matter particles

- Although astrophysical observations clearly confirm the existence of dark matter (DM) in the Universe, they give almost no indications concerning its particle nature.

- In particular, the mass of the DM particles and their couplings to Standard Model (SM) states are completely unknown and can vary over many orders of magnitude.



- In order to devise experimental search strategies it is necessary to construct specific models for dark matter as a guidance.

- The top-down approach to this problem aims to obtain a well-motivated candidate for DM from theoretical considerations (concerning for example the hierarchy problem or the strong CP problem).

- In the bottom-up approach, on the other hand, the foremost aim is to explain the observed DM relic abundance by adding the minimal necessary amount of additional structure to the SM.

What makes LHC DM searches special?

Three main characteristics:

1. Minimality

- Dedicated DM searches (in contrast to e.g. SUSY searches) typically make no assumptions on the presence of additional particles in the dark sector.
- DM particles can therefore only be produced *directly* from SM states, not from the decays of heavier particles.
- The resulting experimental signatures are events with large amounts of missing transverse momentum in association with a small number of SM final states.
- There have been some recent attempts to extend this framework, for example to include coannihilation.

Baker et al., arXiv:1510.03434

What makes LHC DM searches special?

Three main characteristics:

1. Minimality

2. Complementarity
   - The LHC cannot establish the stability of invisible particles.
   - To infer the DM nature of such a particle necessarily involves the connection to non-collider experiments, such as direct or indirect detection, and to cosmological observations, for example of the DM relic density.
   - These complementary probes of DM typically have very different systematic uncertainties and depend on completely different nuisance parameters (such as astrophysical uncertainties).
   - This makes it necessary to provide information from LHC searches in a way that they can be compared to other kinds of DM searches in a statistically meaningful way.

What makes LHC DM searches special?

Three main characteristics:

1. Minimality
2. Complementarity
3. "Exotic" signatures
   - In most models, DM does not couple directly to the SM (some notable exceptions are Higgs Portal DM and Minimal DM).
   - The common assumption is that a new mediator is responsible for communicating the interactions between the DM and the SM.
   - This may lead to additional experimental signatures, such as (broad) dijet or dilepton resonances, heavy Higgs bosons etc.

Searches for missing energy

- The EFT approach
  - DM interacts with quarks via higher-dimensional operators, so the resulting kinematic distributions are independent of the suppression scale Λ (although they may depend on the DM mass).
  - The predicted MET spectrum is typically very hard (and MET cuts are very tight). As a result, effects from hadronisation and detector simulation are typically small and cut flows are straight-forward to calculate.
  - Most EFT studies are simple cut-and-count analyses, with the results quoted as an upper bound on the new-physics cross section in the search window.
  - As kinematic distributions are independent of Λ, bounds on Λ are therefore essentially equivalent to bounds on the signal strength μ.
- All this is essentially ideal for recasting

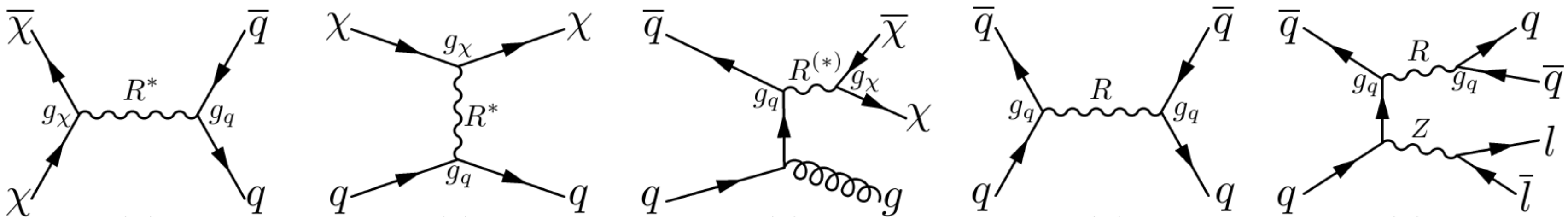
Why should we move beyond EFTs?

- Complaint 1:
  - EFTs predict very specific kinematics (hard MET spectra), so experimental searches may be biased.
  - To optimise the sensitivity for a wider range of models, one needs to consider a more flexible parametrization.
- Complaint 2:
  - Bounds on the EFT suppression scale may be unphysical (i.e. low compared to the region of EFT validity).
  - It is then not directly possible to compare LHC bounds to other kinds of DM searchers.
- ATLAS/CMS DM Forum and LHC DM Working Group established as a joint platform of experimentalists and theorists to address these issues.
- Development of simplified DM models as the way forward.

New mediators

- Basic idea: We should not limit ourselves to the assumption that the particles responsible for mediating DM interactions are very heavy.

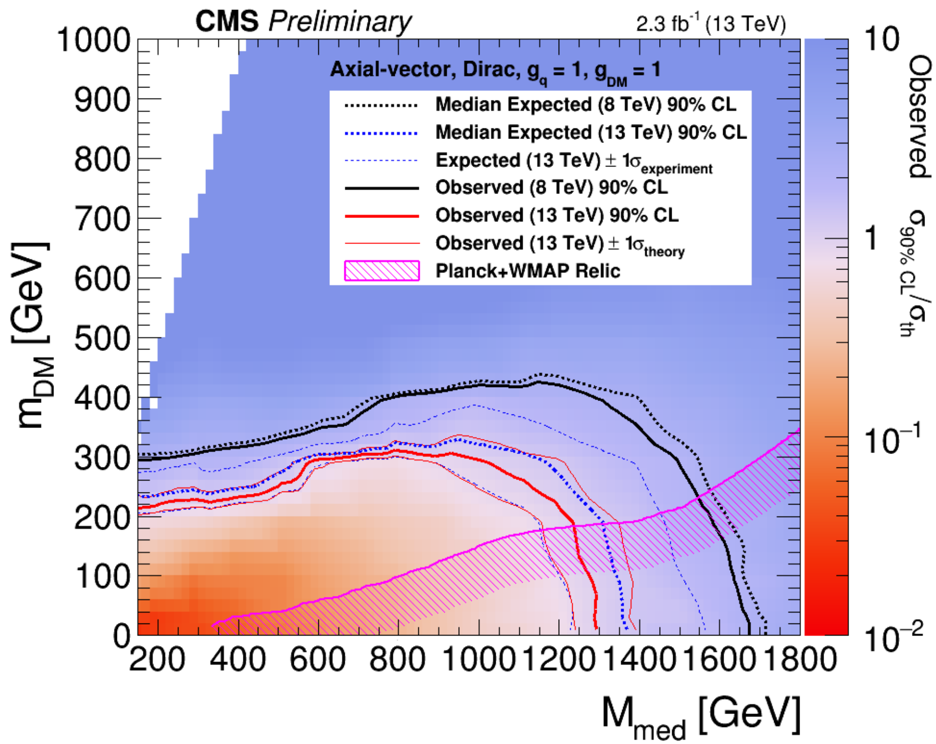
- Indeed, if the DM particle and the mediator of the DM interactions are comparable in mass, the phenomenology can become much more interesting.



- There are two ways to think of such a model:
  - In the top-down approach, this model is a simplification of a UV-complete theory of dark matter, boiled down to capture the most relevant experimental signatures.
  - In the bottom-up approach, this model contains the minimal number of ingredients necessary to calculate predictions for a range of different experiments in a self-consistent way.

Re-interpretation of simplified model results

- Experimental bounds on DM simplified models are now conventionally presented in the parameter plane showing DM mass versus mediator mass.
- While this is useful for comparing the sensitivity of different LHC (and non-LHC) searches, it is difficult to compare such a bound to alternative models (or even the same model with different coupling choices).



- Experimental collaborations often provide their results in terms of an upper bound on the signal strength, i.e. the required rescaling of the predicted signal necessary for an exclusion.
- This information is extremely valuable for a rough re-interpretation of experimental results.

Re-interpretation of simplified model results

1. Analytical re-interpretation

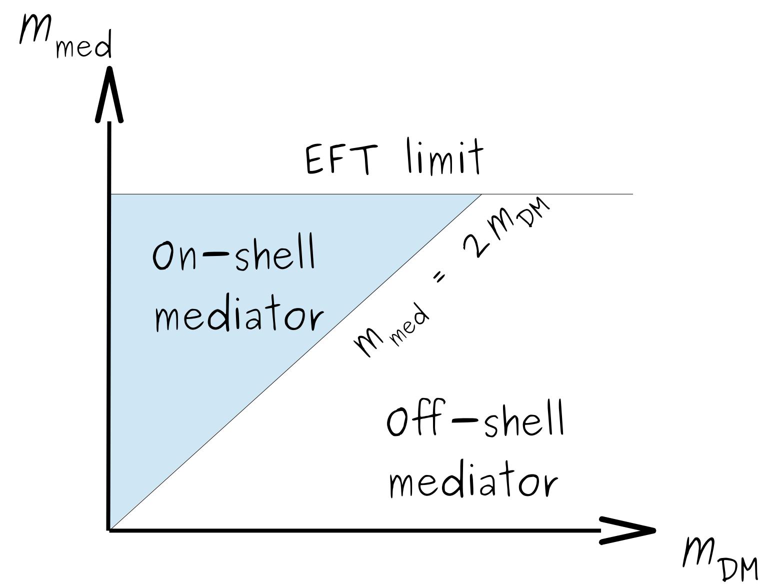
   - In the on-shell region it is often possible to use the narrow-width approximation (NWA):

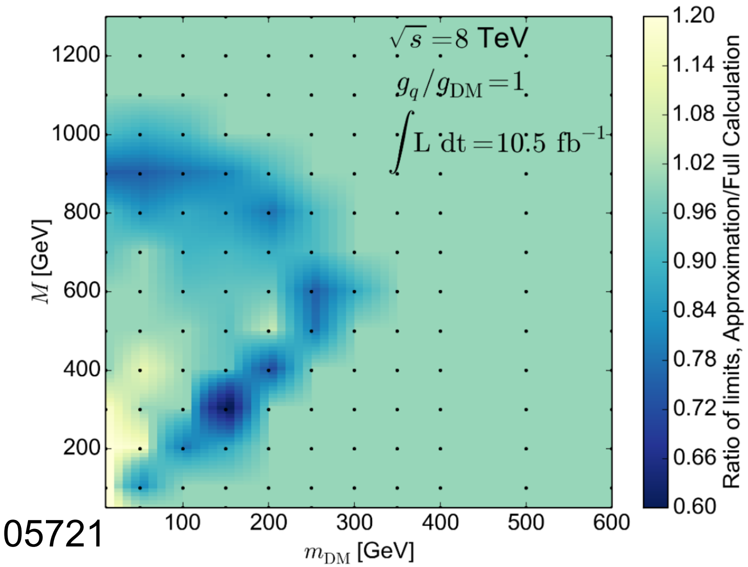
$$\sigma(q\bar{q} \to Z' + Y \to xy + Y) = \sigma(q\bar{q} \to Z' + Y) \cdot \mathrm{BR}(Z' \to xy)$$

   - A bound on μ can then be used to infer a limit on the invisible branching ratio of the mediator.
   - Similar scaling relations can also be derived in the off-shell region:

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

   - This approach fails, however, close to the boundary and for broad widths.





Jacques & Nordstrom, arXiv:1502.05721

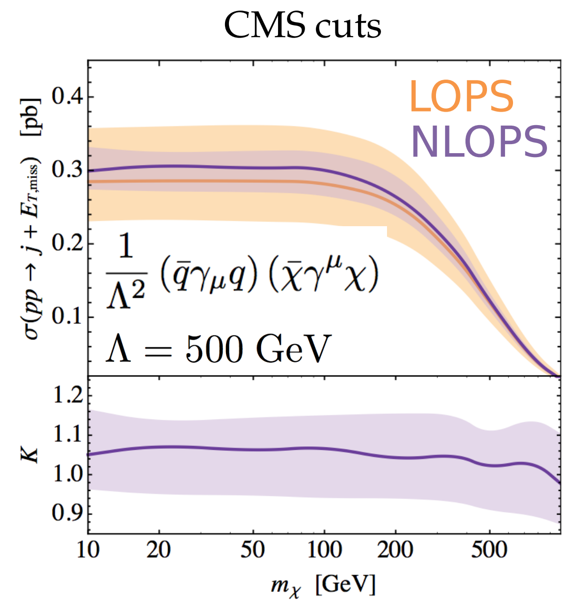
Re-interpretation of simplified model results

1. Analytical re-interpretation

2. Empirical re-interpretation
   - But even when no analytical rescaling can be performed, bounds on the signal strength may be useful.
   - Given an arbitrary new-physics model, one can simulate the MET spectrum and identify the simplified-model parameter point that matches this spectrum most closely (using the same coupling choices as the experimental collaboration).
   - (Ideally, one should also compare other spectra, such as the leading jet p_T, and move to a different simplified model if necessary.)
   - One can then compare the cross section predicted by the new-physics model to the largest cross section that can be excluded for the corresponding simplified-model parameter point.

Re-interpretation of simplified model results

1. Analytical re-interpretation
2. Empirical re-interpretation
3. Rigorous re-interpretation
   - Run a full simulation of the model under consideration (preferably at NLO)
   - Identify signal region with largest expected sensitivity
   - Compare the observed bound on the cross section to the predicted cross section.



Haisch, FK, Re; arXiv:1310.4491

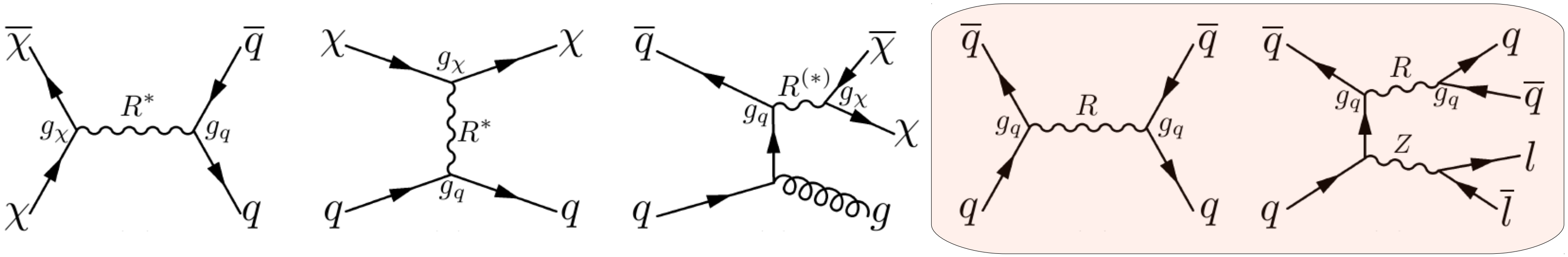
Signal channel		$\langle\sigma\rangle^{95}_{\mathrm{obs}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}
IM1	(MET > 250 GeV)	553	1773	1864^{+829}_{-548}
IM2	(MET > 300 GeV)	308	988	1178^{+541}_{-348}
IM3	(MET > 350 GeV)	196	630	694^{+308}_{-204}
IM4	(MET > 400 GeV)	153	491	401^{+168}_{-113}
IM5	(MET > 500 GeV)	61	196	164^{+63}_{-45}
IM6	(MET > 600 GeV)	23	75	84^{+32}_{-23}
IM7	(MET > 700 GeV)	19	61	48^{+18}_{-13}

ATLAS, arXiv:1604.07773

Re-interpretation of simplified model results: Wish list

- In their most recent analysis (arXiv:1604.07773), ATLAS also considers exclusive signal regions with different MET windows (250-300 GeV, 300-350 GeV, etc.).
- In principle, all these bins could be used simultaneously to exploit the full information on the shape of the MET spectrum.
- Big problem: Due to systematic uncertainties in the background estimation, the errors in the different MET bins are correlated.
- The information on these correlations is presently not available to the community, making the exclusive bins less useful in constraining new-physics models.
- It would be highly desirable to develop a standard/framework for communicating this kind of information.

Searches for new resonances



- The mediator of the DM interactions will also lead to new interactions between Standard Model states, so there may be observable signals from processes involving no dark matter 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.

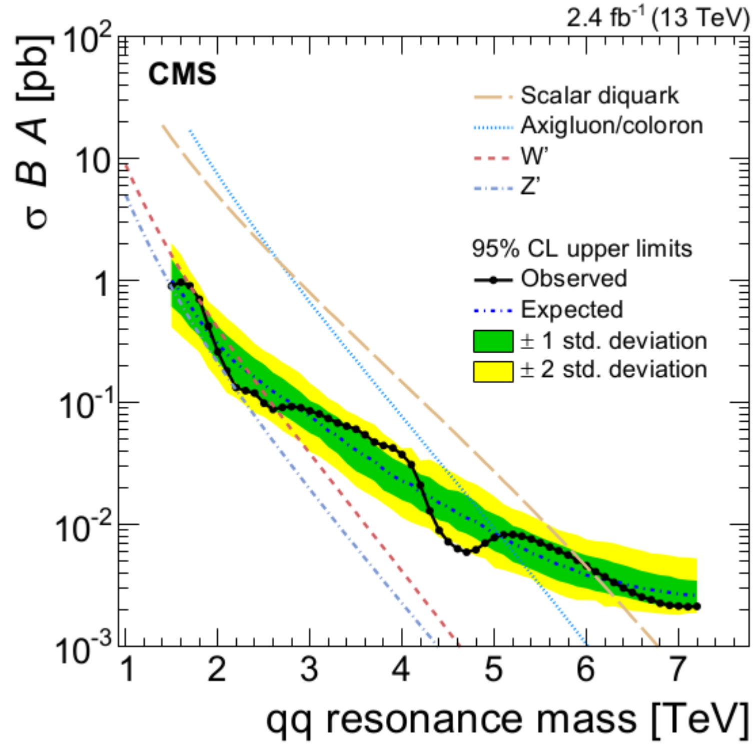
- While it is difficult for the LHC to constrain dijet resonances below 500 GeV due to large QCD background, this background can be suppressed by searching for dijet resonances produced in association with leptonically decaying gauge bosons.

Searches for di-jet resonances

- Results from di-jet resonance searches are routinely presented in a way that they can be applied to a wide range of different models.

  1. Analytical re-interpretation

     - For a narrow resonance, one can directly read off the bound on σ × BR × A depending on the final state (qq, qg or gg).

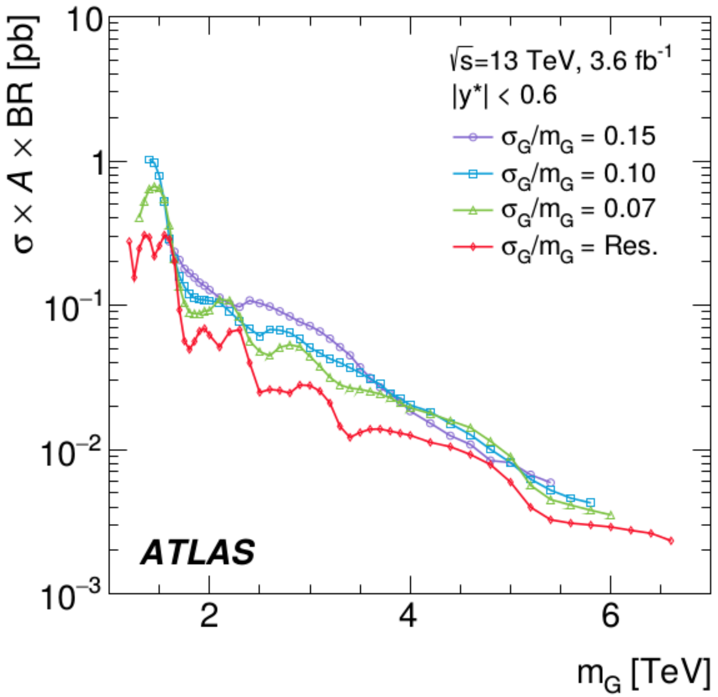


CMS, arXiv:1512.01224

Searches for di-jet resonances

- Results from di-jet resonance searches are routinely presented in a way that they can be applied to a wide range of different models.

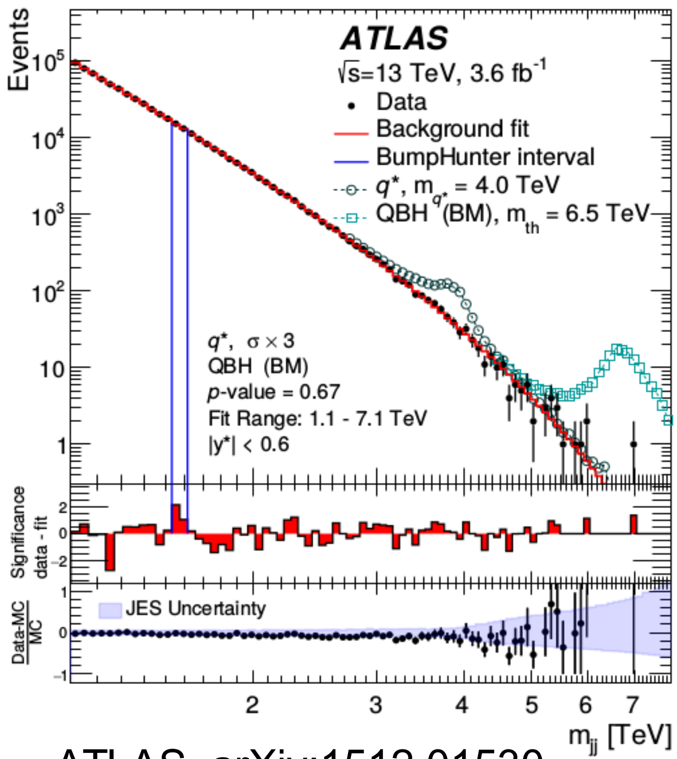
  1. Analytical re-interpretation
  2. Empirical re-interpretation
     - For broad resonances, one should first simulate the signal (including detector effects) and then fit the di-jet invariant mass distribution with a peak (Breit-Wigner or Gaussian, depending on the shape of the tails).
     - For the best-fit width one can then read of the appropriate bound on $\sigma \times BR \times A$.



ATLAS, arXiv:1512.01530

Searches for di-jet resonances

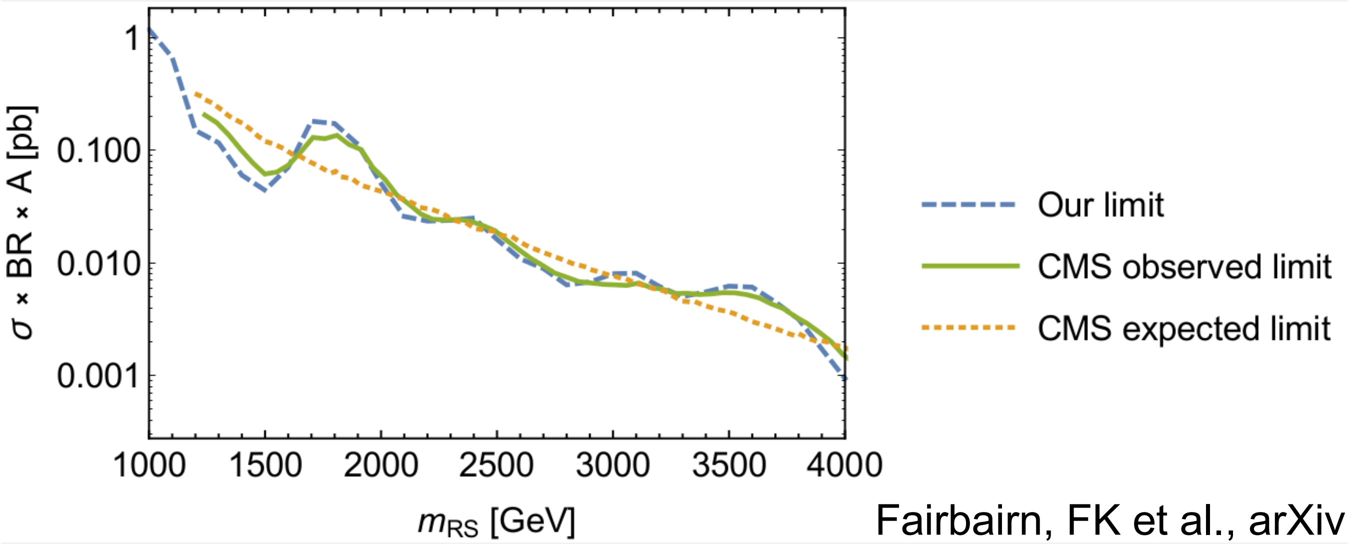
- Results from di-jet resonance searches are routinely presented in a way that they can be applied to a wide range of different models.
  1. Analytical re-interpretation
  2. Empirical re-interpretation
  3. Rigorous re-interpretation
     - For more complicated models (e.g. resonances with a VERY broad width), it is also possible to directly compare simulated distributions of the di-jet invariant mass to the observed spectrum.
     - The SM expectation for this spectrum is obtained by fitting a smooth function to the observed distribution: $f(z) = p_1(1-z)^{p_2} z^{p_3}$
     - Experimental errors are completely dominated by statistics (and uncorrelated between different bins), so it is straight-forward to repeat this procedure for any given new-physics model.



ATLAS, arXiv:1512.01530

Searches for di-jet resonances

- Results from di-jet resonance searches are routinely presented in a way that they can be applied to a wide range of different models.
  1. Analytical re-interpretation
  2. Empirical re-interpretation
  3. Rigorous re-interpretation
     - Experimental papers (and HEP data) provide all the information necessary.
     - It is possible with this approach to reproduce experimental bounds (e.g. for the case of an RS graviton) to very good accuracy.



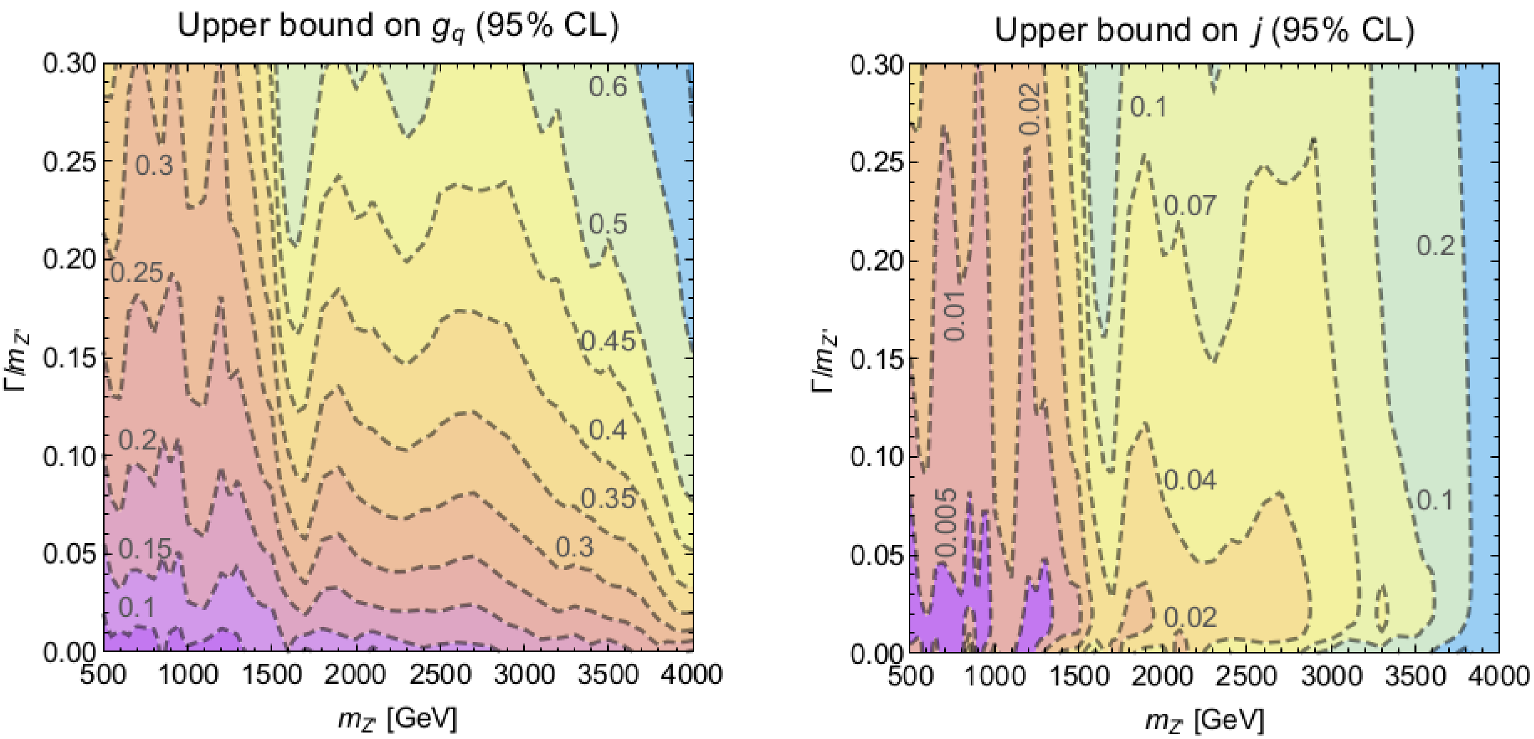
Fairbairn, FK et al., arXiv:1605.07940

Rigorous re-interpretation of di-jet resonance searches

- The great advantage of using actual di-jet 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 di-jet resonance searches from both ATLAS and CMS, as well as searches at both 8 TeV and 13 TeV.

Fairbairn, FK et al., arXiv:1605.07940



DESY

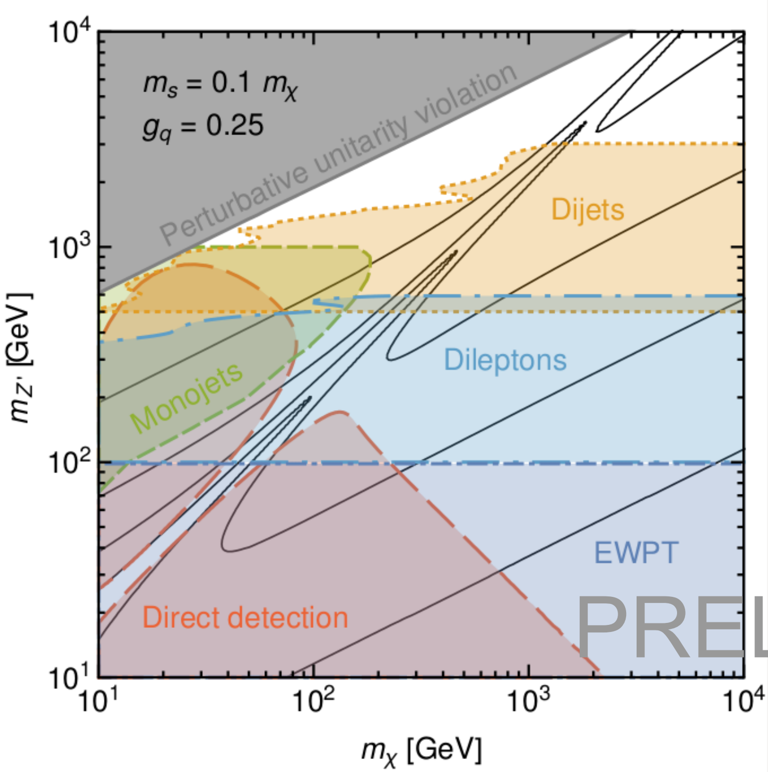
Complementarity of different DM searches

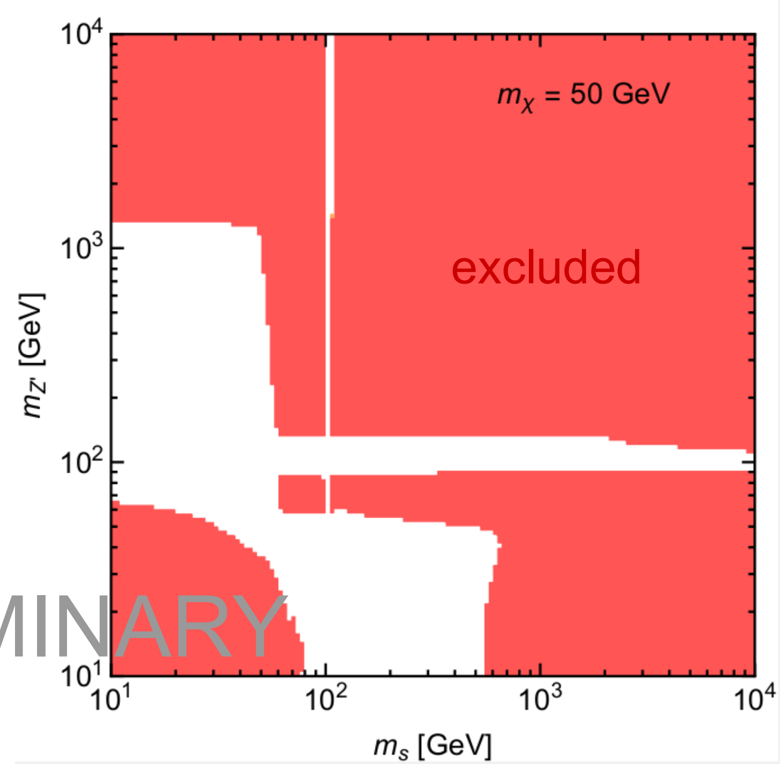
- DM simplified models are often considered mere tools for generating and studying events with missing energy.
- However, in many cases one is interested in comparing results from the LHC with other experimental or observational probes of DM.
- For example, it is interesting to investigate whether the interactions probed at the LHC may be responsible for DM freeze-out in the Early Universe or whether they are constrained to be so weak that additional annihilation channels must be present.
- For this more ambitious approach it becomes essential that the models under consideration fulfil certain basic requirements, such as gauge invariance and perturbative unitarity.

  FK et al., arXiv:1510.02110
- These considerations have led to the construction of more complex DM models, containing for example a dark Higgs that generates the mass of the mediator.
- By construction, LHC DM searches based on simplified DM models can be fully reinterpreted in such a framework.

Some recent results

- One can then combine LHC searches for monojets, dijets and dileptons with EWPT, perturbative unitarity, and direct and indirect detection experiments.
- Scanning over couplings then allows to determine combinations of DM mass and mediator mass for which the relic density is compatible with all constraints.





Duerr, FK, Schmidt-Hoberg, Schwetz, Vogl, arXiv:1606.XXXXX

Going further with DarkBIT

- A statistically rigorous combination of all the different experimental probes of DM is a hugely challenging task.

- Nevertheless, this issue is essential in order to extract the maximal amount of information from data and narrow down the properties of the DM particle.

- These issues will be addressed by DarkBIT, a numerical framework for calculating DM observables and likelihoods, developed for the use in global scans (for example with GAMBIT).
  - High modularity, easy to implement new DM models
  - Rigorous treatment of nuisance parameters (e.g. related to the Galactic DM halo).
  - Interface with existing DM codes, such as DarkSUSY and micrOMEGAs.
  - Powerful tools for the analysis of direct detection (DDCal and indirect detection (nulike, gamlike) experiments.

- To perform a global scan over the DM properties, we now need likelihood functions from LHC DM searches!

Conclusions

We have no idea what the properties of DM particles are.

We cannot identify DM particles using LHC measurements alone.

- We need LHC searches for DM that can be re-interpreted for a wide range of different models and be compared to other kinds of DM searches in a statistically meaningful way.
- The move from EFTs to simplified models offers many new chances for a flexible re-interpretation, but it has also made analyses more involved.
- DM simplified models can also be constrained by searches for di-jet resonances, which can be very successfully re-interpreted in different contexts.
- Simple consistent DM models can be directly used to interpret LHC bounds on simplified DM models and compare the results to other kinds of DM searches.