Hunting dark Z' and dark Higgs bosons.

Fantastic WIMPs and Where to Find Them

Felix Kahlhoefer
Dark Matter from aeV to ZeV
3rd IBS-MultiDark-IPPP Workshop
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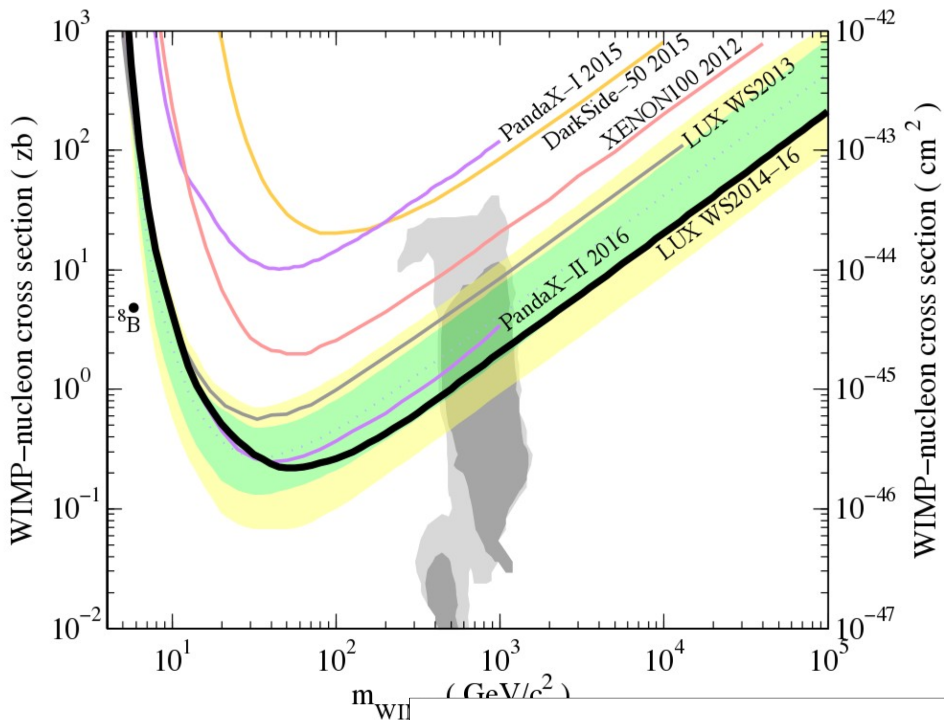
Where are the WIMPs?



The LUX experiment has recently published results from a new search for WIMPs, where no excess over expected backgrounds was observed.

arXiv:1608.07648

Frankfurter Allgemeine

Dunkle Materie

Wo sind die Wimps?

Something is wrong with dark matter

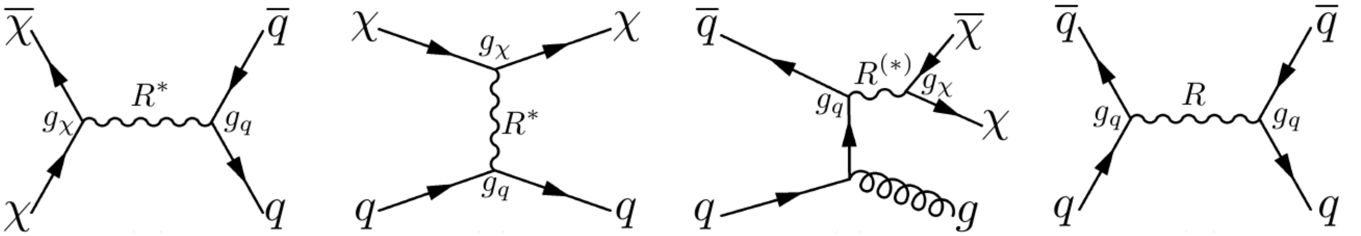
SCIENTIFIC AMERICAN.

In the Dark about Dark Matter

Recent disappointments have physicists looking beyond WIMPs for dark matter particles

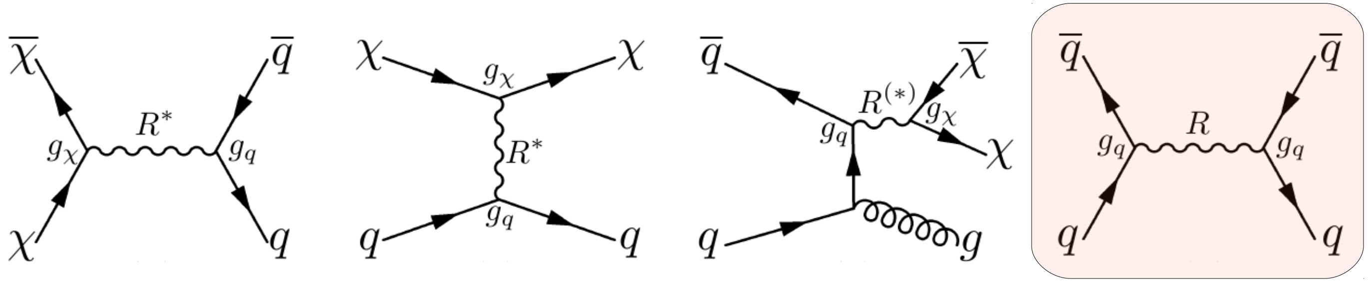
New mediators

- Experiments are closing in on the simplest WIMP models, in which the DM particle interacts via Standard Model bosons.
- A possible conclusion could be to abandon the WIMP idea and focus on different DM candidates, such as axions or sterile neutrinos.
  - Many great proposals discussed at this workshop!
- Nevertheless, the paradigm of thermal freeze-out is very general and does not require the DM particle to directly couple to any of the SM bosons.
- Instead, there may be a new mediator responsible for communicating the interactions of DM.

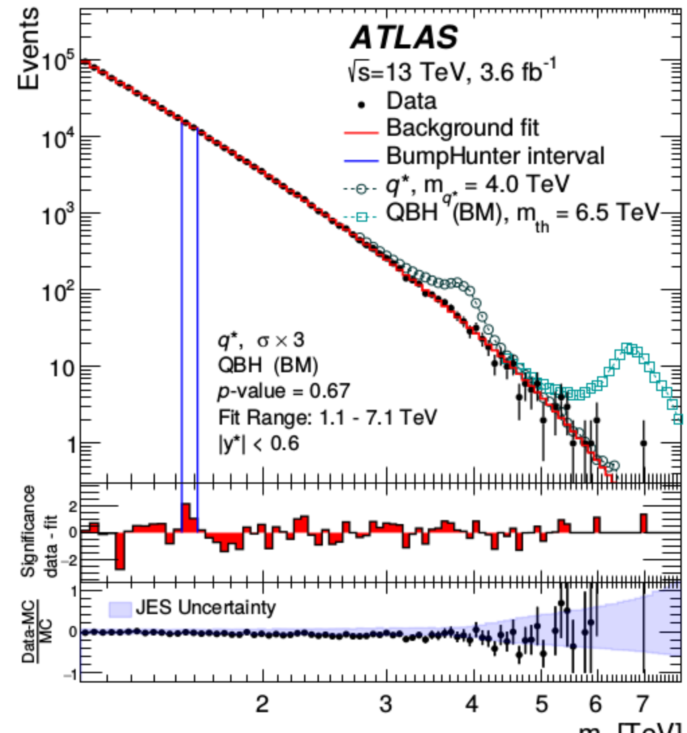


- This opens up new parameter space – but also leads to new constraints.

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.

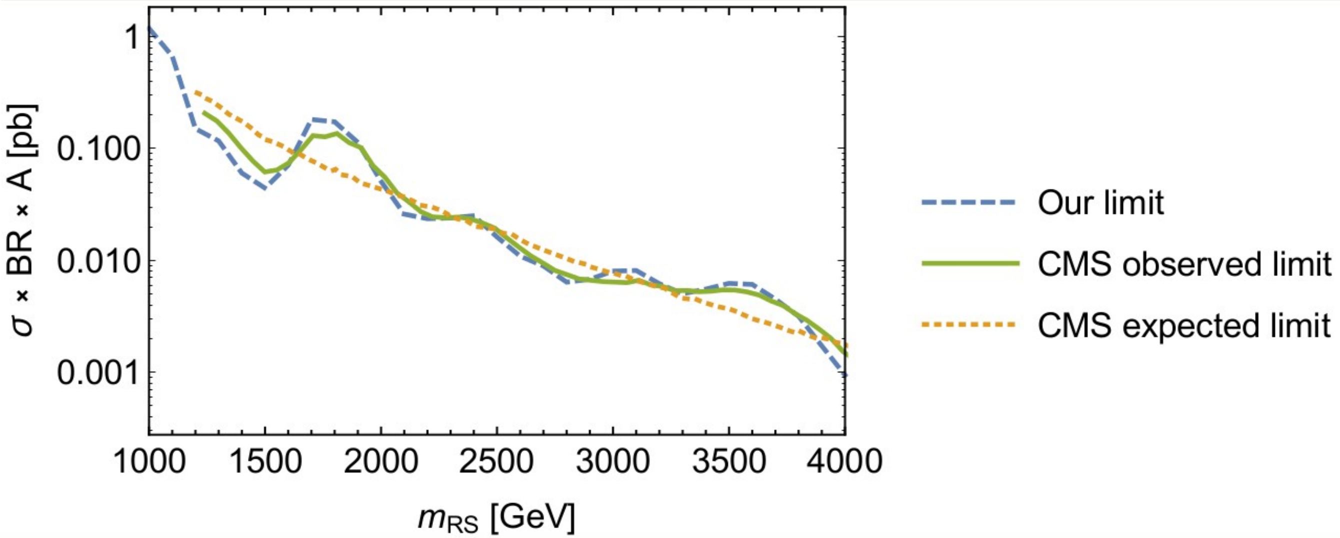


ATLAS, arXiv:1512.01530

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}	$\|\Delta\eta_{jj}\|$	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: Focus either 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

- Possible to analyse LHC dijet searches in a largely model-independent way

- Results can be applied to many different Z' models, including models with invisible or unobserved decay modes.

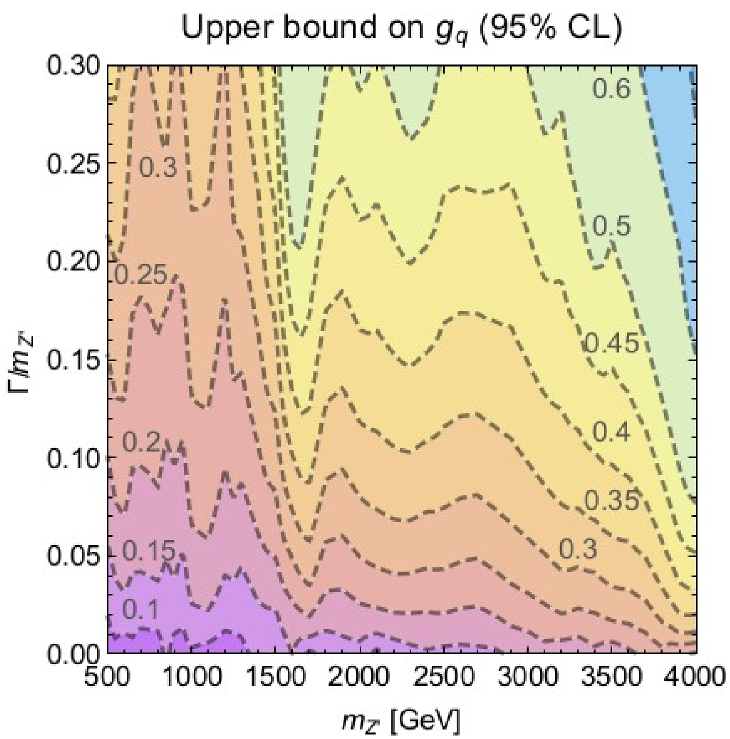
- Key idea: take the width of the Z' as a free parameter (rather than to calculate it from the assumed couplings).

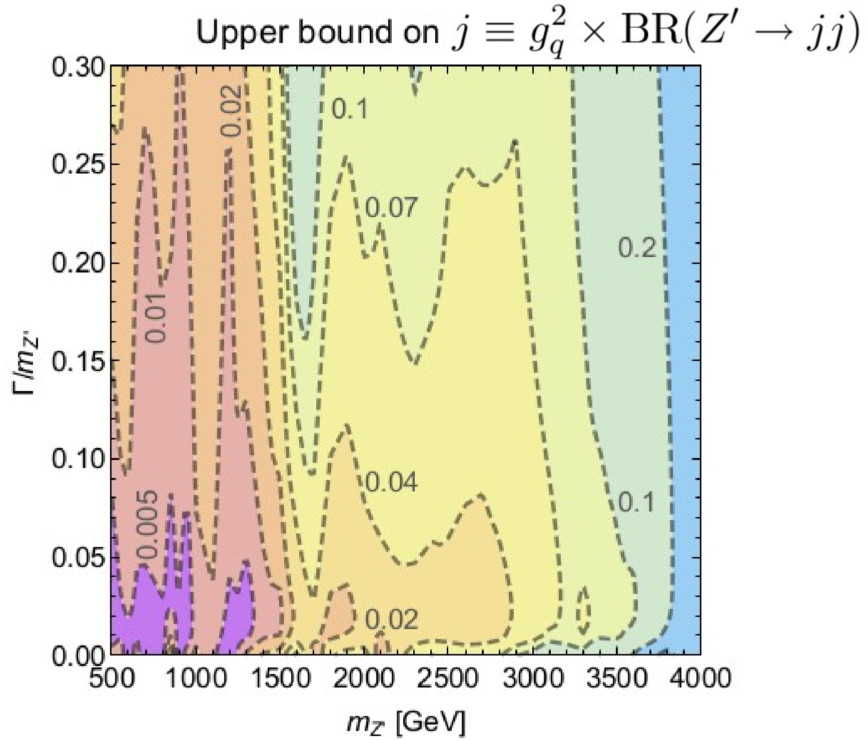
- Since the shape of the dijet invariant mass distribution depends only on $m_{Z'}$ and $\Gamma_{Z'}$, changing g_q then only changes the normalisation of the signal.

- 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: $g_q \sim 0.3$

- Sensitive to the typical weak interaction strength relevant for thermal freeze-out!

Models of new mediators

- Aim: combine all these LHC results with the information from other DM searches in order to understand whether thermal freeze-out can still be viable in this set-up.
- This will typically only be possible within the context of a specific DM model.
- At first sight, there is a huge number of DM models interacting via a new mediator.
- However, experimental constraints and theoretical considerations eliminate a large number of possibilities:
  - Direct detection experiments strongly disfavour a spin-1 mediator coupling to the DM vector current. Focusing on Majorana DM evades this constraint.
  - LHC dilepton resonance searches strongly constrain the coupling of the mediator to leptons. Consider models where the mediator couples dominantly to quarks.
  - The couplings of the mediator to SM fermions should respect the full symmetry of the SM gauge group before electroweak symmetry breaking.

Mediators from a *U(1)'*

- We consider a new *U(1)'* gauge group under which only quarks and the Majorana DM particle are charged. This gauge group is spontaneously broken by the vev of a SM singlet S.

$$\mathcal{L}_{\rm DM} = \frac{i}{2}\bar{\psi}\partial\!\!\!/\psi - \frac{1}{2}g_{\rm DM}^A Z'^\mu \bar{\psi}\gamma^5\gamma_\mu\psi - \frac{1}{2}y_{\rm DM}\bar{\psi}(P_L S + P_R S^*)\psi\,,$$

$$\mathcal{L}_S = \left[(\partial^\mu + i\, g_S\, Z'^\mu)S\right]^\dagger \left[(\partial_\mu + i\, g_S\, Z'_\mu)S\right] + \mu_s^2\, S^\dagger S - \lambda_s \left(S^\dagger S\right)^2$$

- The Higgs singlet vev therefore generates both the Z' mass and the DM mass.

$$m_{\rm DM} = \frac{1}{\sqrt{2}}\, y_{\rm DM}\, w\,, \quad m_{Z'} \approx 2 g_{\rm DM}^A\, w$$

- This set-up is similar to DM models with gauged baryon number. For the purpose of this talk, I will not discuss the issue of anomaly cancellation.

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

The two-mediator dark matter (2MDM) model

- The Z' is in fact not the only particle in this model that can mediate the interactions of DM.

- The dark Higgs will in general mix with the SM Higgs and thereby obtain couplings also to SM fermions.

- We then obtain two dark mediators with the following interactions:

$$\mathcal{L}_\chi \supset -\frac{g_\chi}{2}\bar{\chi}\gamma^\mu\gamma^5\chi Z'_\mu - \frac{y_\chi}{2\sqrt{2}}\bar{\chi}\chi s \,, \qquad \frac{y_\chi}{m_\chi} = 2\sqrt{2}\,\frac{g_\chi}{m_{Z'}}$$

$$\mathcal{L}_q \supset -\sum_q \left(g_q \bar{q}\gamma^\mu q Z'_\mu + \sin\theta \frac{m_q}{v}\bar{q}qs \right)$$

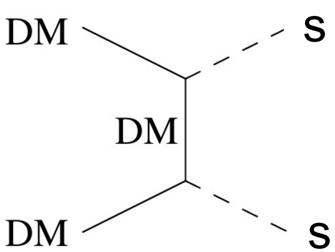
- The model is described by 6 independent parameters (three masses and three couplings).

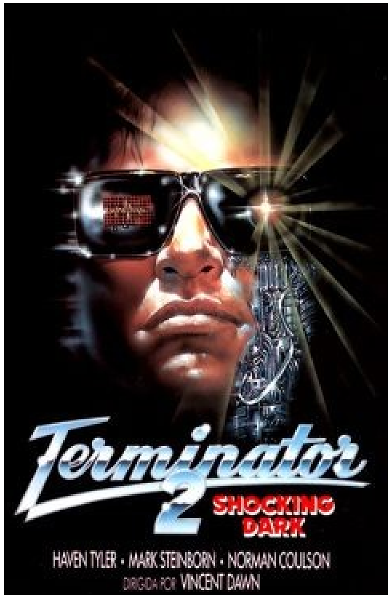
Duerr, FK et al., arXiv:1606.07609

Dark mediators and dark terminators

- If one of the mediators is heavy and weakly-coupled, it will play no role in the phenomenology and one recovers a simpler model with only one mediator.

- If one of the two mediators is *light* and weakly coupled, it can provide a new final state for DM annihilation.

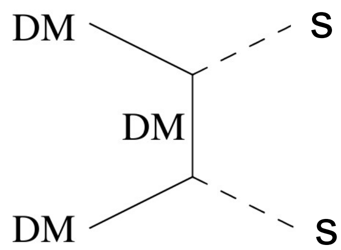




- We call such a light state a dark terminator, because it *terminates* rather than *mediates* the interactions of DM.

- Such a dark terminator can relax the relic density constraints on the interactions of the second mediator and thus extend the viable parameter space.

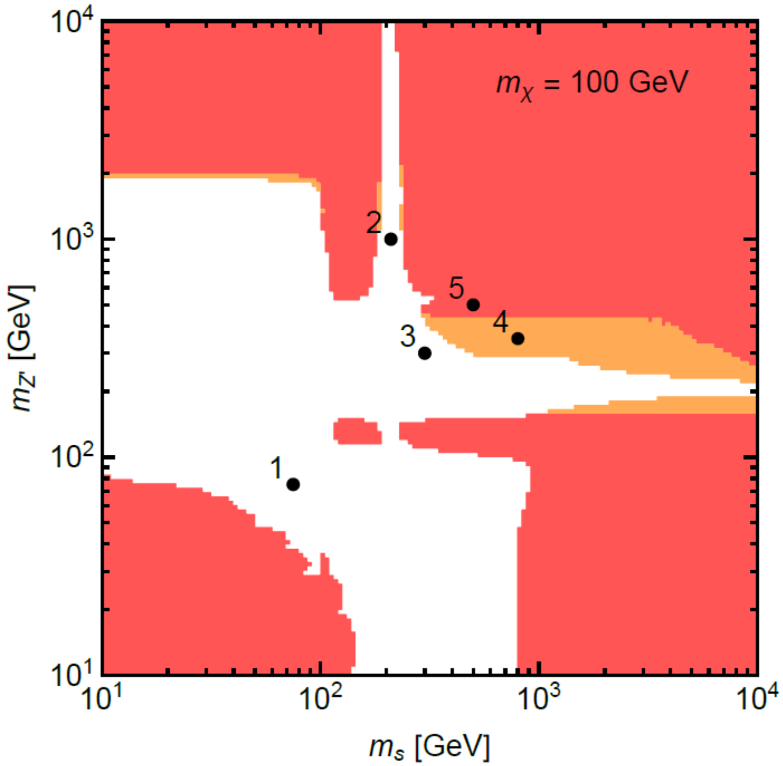
Saving WIMPs with dark terminators?



- Introducing a new weakly-coupled particle in the final state of DM annihilations is a drastic change of the traditional WIMP idea.
- It is certainly controversial whether such a model can still be called WIMP DM or if we need a different name (e.g. secluded DM, hidden sector freeze-out, …).
- Nevertheless, in the context of the 2MDM model, we can continuously move from the traditional WIMP idea (Higgs exchange) to WIMP models with a new mediator (Z' exchange, dark Higgs exchange) to models with a dark terminator.
- This makes it possible to understand in general whether the simple WIMP idea is still viable or whether experiments favour more complex dark sectors.

Global scans

- We can now perform a global analysis: For fixed masses we scan over all coupling combinations consistent with the relic density requirement.

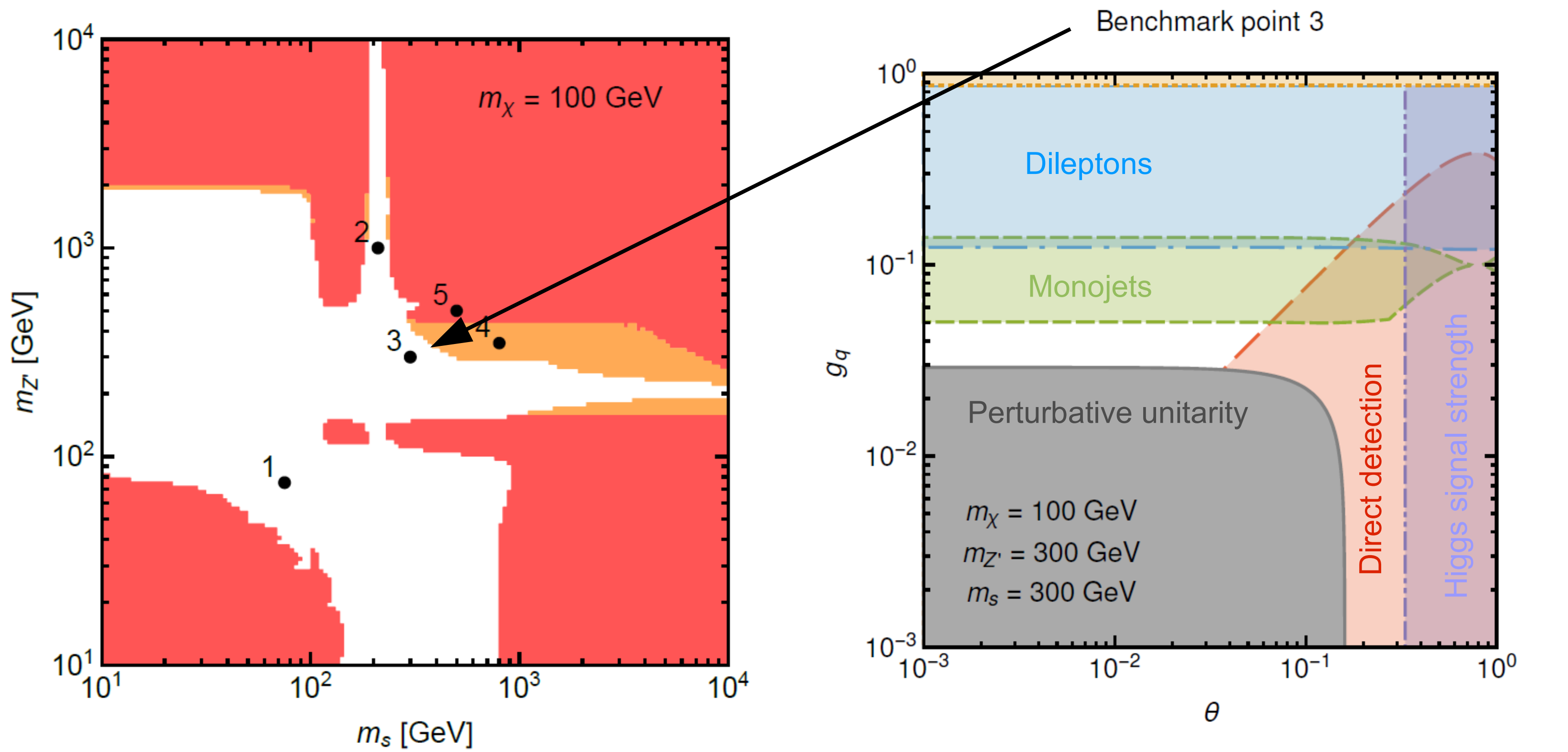


Red: All coupling combinations are excluded by at least one constraint.

White: At least one coupling combination is compatible with all constraints.

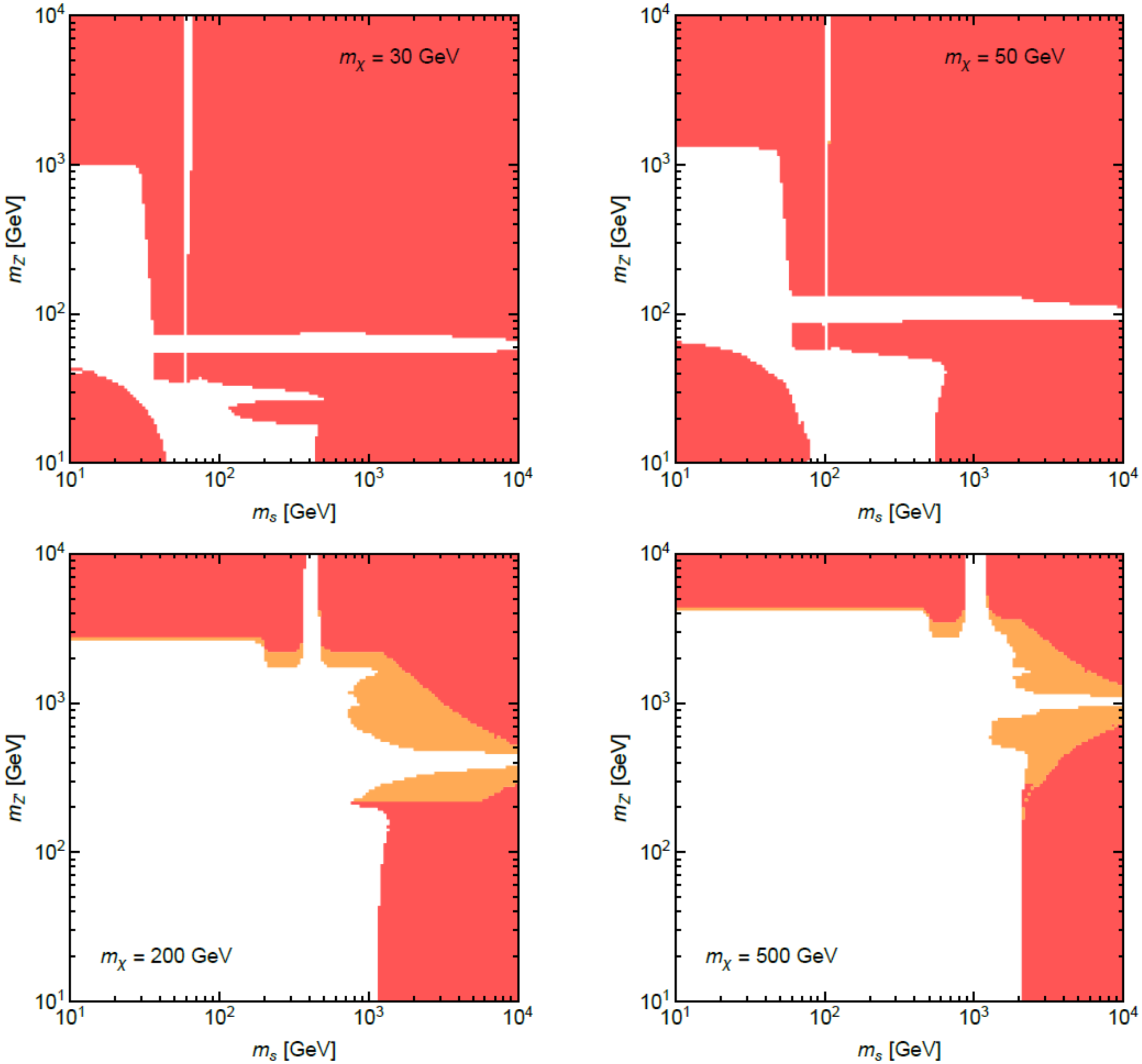
Orange: Large values of g_q cannot reliably be excluded due to the mediator width becoming large ($\Gamma/m_{Z'} > 0.3$).

A closer look



- Allowed parameter space for $g_q \sim 0.04$ and $\theta < 0.06$.

Global scans: Final results



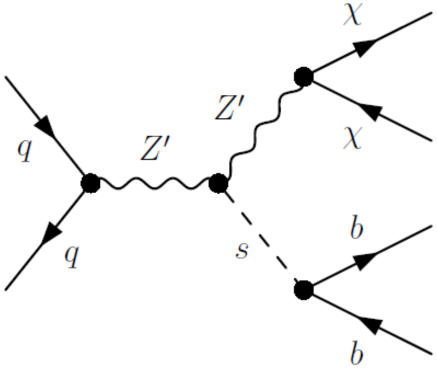
- Small DM masses are tightly constrained by the data.
- The presence of a dark terminator is essential!
- Models with two dark terminators are in fact excluded by indirect detection constraints for $m_\chi < 100$ GeV.
- For larger DM masses, there is larger viable parameter space (we find allowed solutions up to $m_\chi < 50$ TeV).

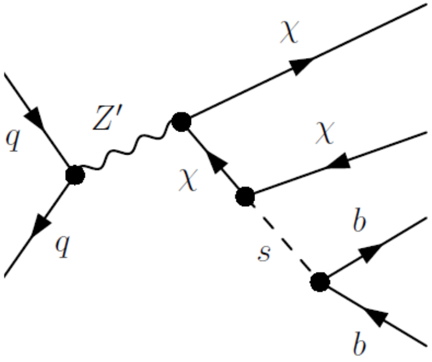
Hunting the dark Higgs

- At first sight, the case of a light dark Higgs terminator with tiny mixing with the SM Higgs seems impossible to probe experimentally.

- Nevertheless, the dark Higgs typically couples quite strongly to the DM particle and the Z'.

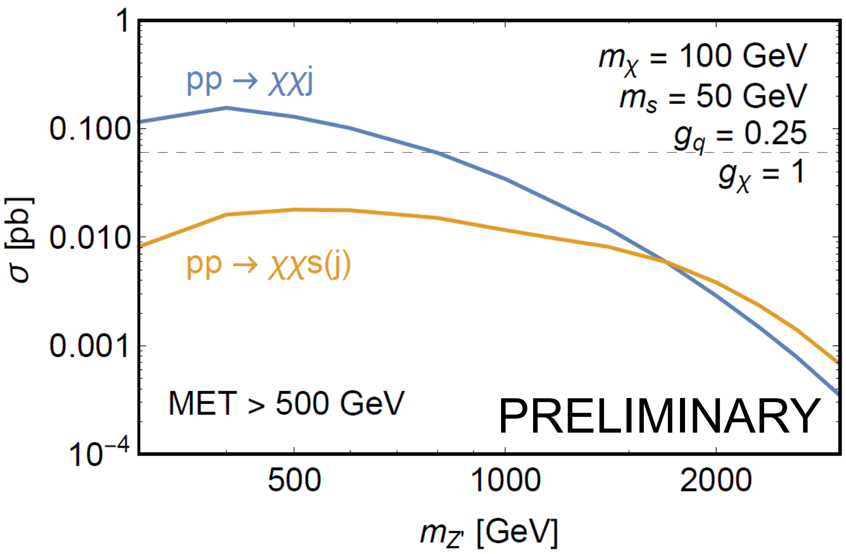
- If it is possible to produce these states at the LHC, they may emit Dark-Higgs-Strahlung.

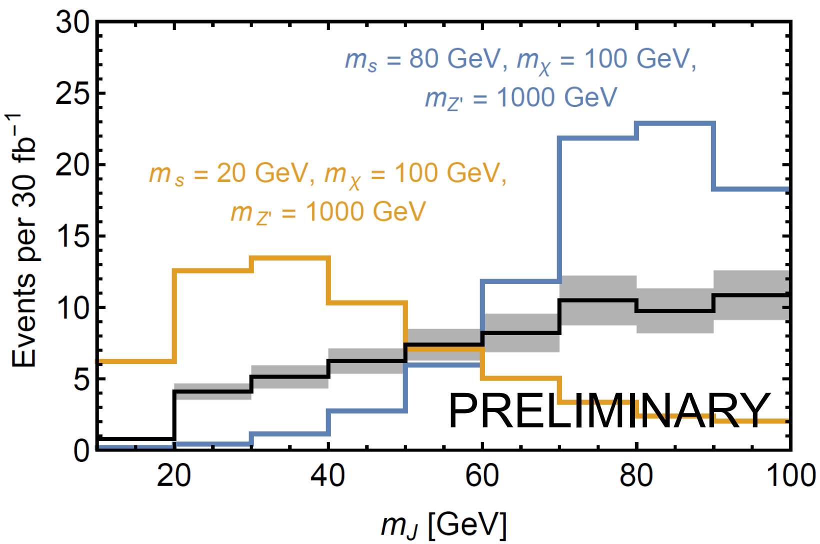




Hunting the dark Higgs - predicted event rates

- For large Z' masses, the rate of Dark-Higgs-Strahlung may actually exceed the rate of QCD radiation from the initial state.



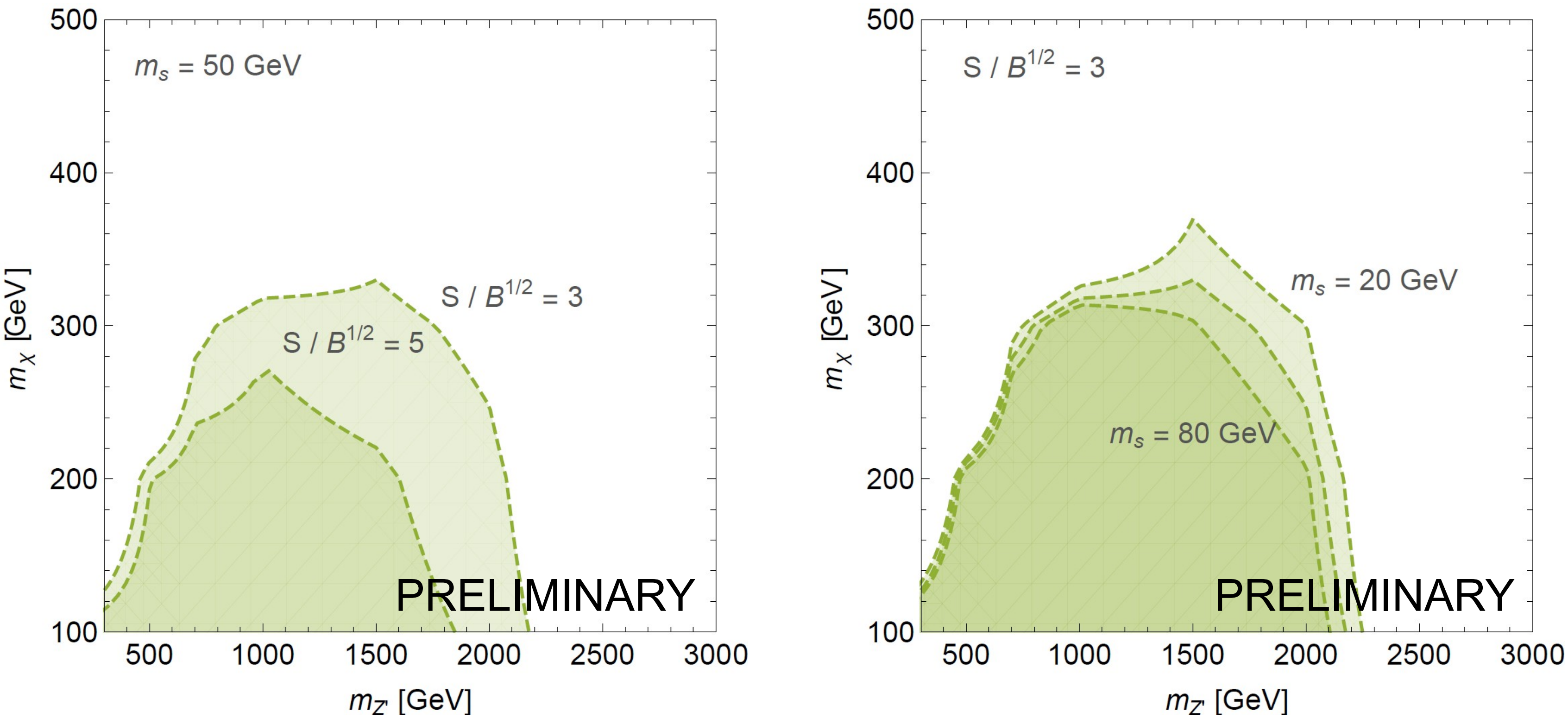


- Moreover, the dark Higgs is typically highly boosted and its decay therefore leads to a very characteristic signal: a fat jet containing two b-jets with an invariant mass close to the dark Higgs mass.

Hunting the dark Higgs - projected sensitivity

- Looking specifically for this signature can suppress experimental backgrounds with high efficiency.
- This makes it possible to probe the 2MDM model up to very large Z' masses.

Duerr, FK, et al., in preparation



Conclusions

- The non-observation of new physics at the LHC and null results in direct DM searches put significant pressure on the WIMP idea.
- A possible way forward: New mediators open up large new parameter space but also predict many new signatures (e.g. dijet resonances).
- The two-mediator DM model offers an attractive framework to study these ideas by allowing for a continuous transition from more conventional WIMPs (e.g. Higgs portal) to more exotic realizations of thermal freeze-out (e.g. dark terminators).
- We find significant experimental constraints on heavy mediators, unless DM is also rather heavy.
- Nevertheless, thermal freeze-out is certainly still viable if the dark sector has additional structure, for example if there is a new light terminator.
- Such models with light terminators can in fact be probed experimentally, for example with dedicated LHC searches for dark Higgs jets.