How (not) to use simplified models to search for dark matter at the LHC

Felix Kahlhoefer
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based on **arXiv:1510.02110**, **arXiv:1603.01267** and **work in preparation** in collaboration with Michael Duerr, Ulrich Haisch, Kai Schmidt-Hoberg, Thomas Schwetz, Tim Tait and Stefan Vogl

HELMHOLTZ ASSOCIATION

DESY

What do we know?

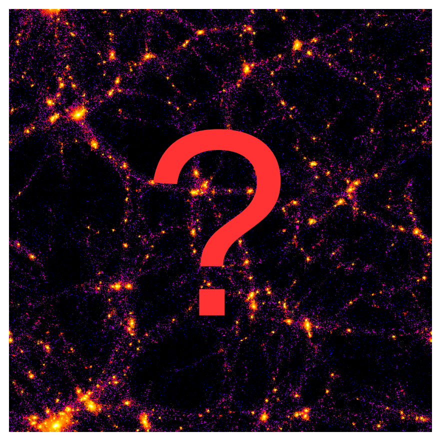
Cold white matter

Known

Hot dark matter

Known

Cold dark matter



Unknown

Dark matter particles

- Astrophysical observations give almost no indications concerning the particle nature of dark matter.
- In particular, the mass of the dark matter particles and their couplings to Standard Model 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.
- Such models should not only be consistent with the known properties of dark matter, but they should be able to predict the amount of dark matter produced in the early Universe, so that we can compare with the observed dark matter abundance.

See talk by Tomer Volansky

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.

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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).

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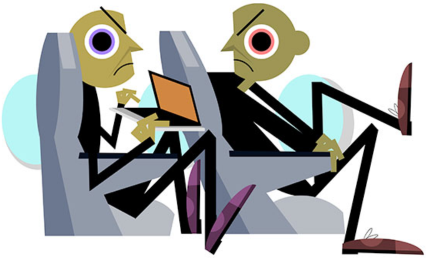
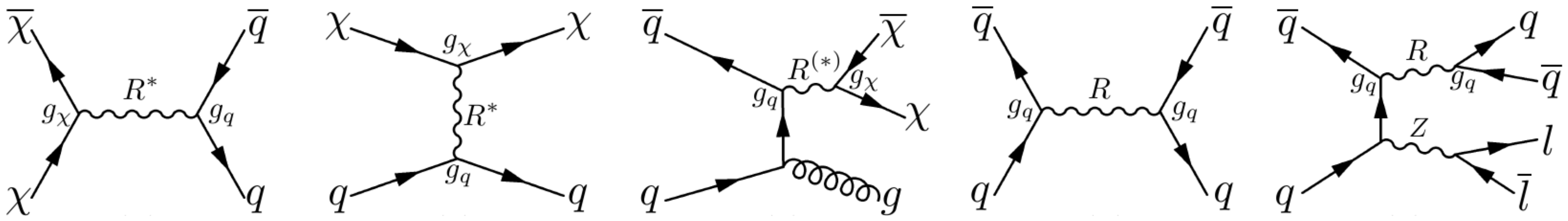
Too little legroom!



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.



- 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.

Outline

- In this talk, I will focus on one specific example for a simplified model, namely the model with an *s*-channel spin-1 mediator (e.g. a *Z'*) and fermionic DM:

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

- We would like to use such a simplified model to answer the following questions:
  - How large is the allowed parameter space? What sensitivity should we aim for? How do we know when to stop?
  - Out of the various searches, which ones are the most promising? Where do we expect to see DM first?

- However, we also need to worry about the following questions:
  - How good an approximation is it to write down just this simplified model and nothing else?
  - Are there theoretical constraints on certain couplings or hidden relations between different couplings not apparent from the simplified model?

How large is the allowed parameter space?

- Guiding principle: Combination of relic density calculations and the requirement of perturbative unitarity.

Griest & Kamionkowski, 1990

- Unitarity implies that $0 \leq \mathrm{Im}(\mathcal{M}^J_{ii}) \leq 1\,, \quad \left|\mathrm{Re}(\mathcal{M}^J_{ii})\right| \leq \frac{1}{2}$, where

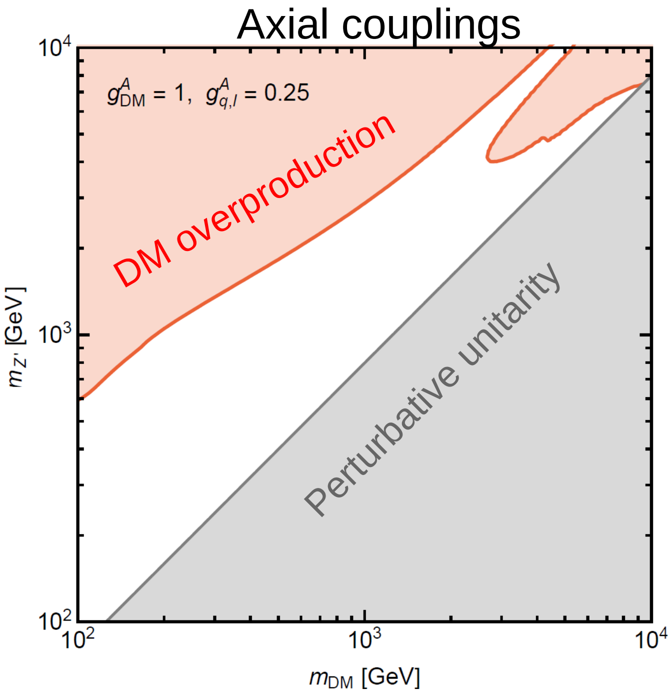
$$\mathcal{M}^J_{if}(s) = \underbrace{\frac{1}{32\pi}\beta_{if}}_{\text{Kinematical factor}} \int_{-1}^{1} \mathrm{d}\cos\theta \, \underbrace{d^J_{\mu\mu'}(\theta)}_{\text{Wigner d-function}} \, \mathcal{M}_{if}(s, \cos\theta)$$

- Unitarity can be violated in two ways:
  - Large couplings: If the theory becomes non-perturbative, tree-level matrix elements will no longer satisfy the unitarity conditions from above (but the all-order matrix element is still unitary).
  - Large energies: If the theory is incomplete (i.e. only an effective low-energy description), matrix elements may grow with the centre-of-mass energy, leading to unphysical predictions at large energies.

How large is the allowed parameter space?

- If we impose the unitarity requirement on the tree-level matrix elements, this will yield upper bounds on the various couplings of the model in order to ensure that the theory remains perturbative.

- If couplings cannot be arbitrarily large, the requirement that DM is not overproduced then implies an upper bound on the particle masses.



Chala, FK et al., arXiv:1503.05916

- In the red parameter region additional interactions are required in order to achieve sufficiently large annihilation rates.

- For axial couplings, there is another non-trivial implication of perturbative unitarity:

$$m_f \lesssim \sqrt{\frac{\pi}{2}} \frac{m_{Z'}}{g_f^A}$$

- Reason: For axial couplings, DM couples to the longitudinal component of the mediator with coupling strength $2\, g_f^A\, m_f / m_{Z'}$.

Another look at perturbative unitarity

- We could also consider the process $\psi\bar{\psi} \to Z'_L Z'_L$.

FK et al., arXiv:1510.02110

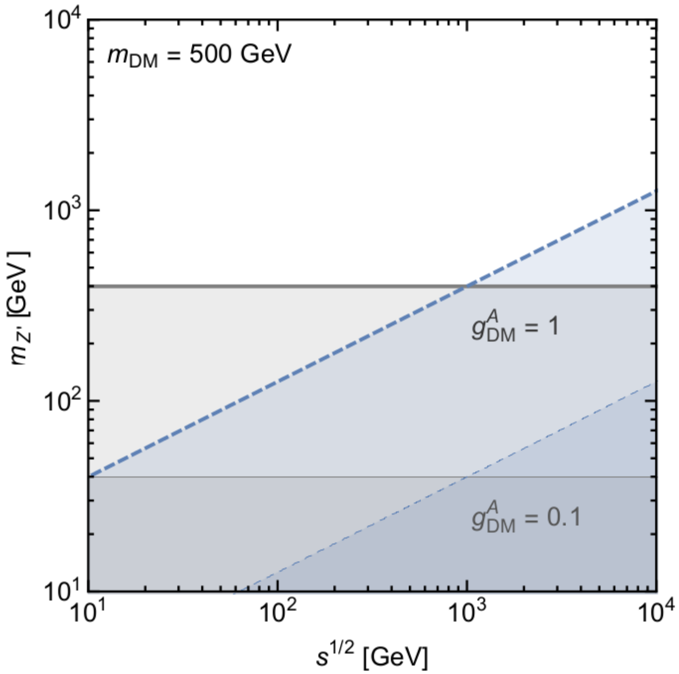
- For axial coupligs, the matrix element for this process grows with energy proportional to

$$(g_{\mathrm{DM}}^A)^2 \sqrt{s}\, m_{\mathrm{DM}} / m_{Z'}^2$$

- Perturbative unitarity then implies

$$\sqrt{s} < \frac{\pi\, m_{Z'}^2}{(g_{\mathrm{DM}}^A)^2\, m_{\mathrm{DM}}}$$

- New physics must appear below this scale to restore unitarity.



Take-home message:

The problem of unitarity violation present in effective theories is not simply solved by reducing the mass of the mediator. The issue remains relevant even for simplified models.

Including a dark Higgs

- The simplest way to restore perturbative unitarity is to generate the mass of the mediator from an additional Higgs mechanism.
- The mediator is then assumed to be the gauge boson of a new *U(1)′* gauge group, which is broken by the vev of a SM singlet *S*.
- We furthermore assume that the DM particle is a Majorana fermion, such that the DM vector current vanishes and tension with direct detection is reduced.
- The Lagrangian of the dark sector is then given by

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

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

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

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

Implications for the visible sector

- Including a dark Higgs to restore perturbative unitarity only works if the coupling structure of all interactions respects gauge invariance of the full gauge group before EWSB (which is not normally imposed on simplified models).

- Writing the interactions between the Z' and the visible sector as

$$\mathcal{L}'_{\mathrm{SM}} = \frac{1}{2}\left[(D^\mu H)^\dagger(-i\, g'\, q_H\, Z'_\mu\, H) + \mathrm{h.c.}\right] + \frac{g'^2\, q_H^2}{2} Z'^\mu Z'_\mu H^\dagger H - \sum_{f=q,\ell,\nu} g'\, Z'^\mu \left[q_{f_L}\, \bar{f}_L \gamma_\mu f_L + q_{f_R}\, \bar{f}_R \gamma_\mu f_R\right] \, ,$$

we immediately obtain the requirements

$$q_H = q_{q_L} - q_{u_R} = q_{d_R} - q_{q_L} = q_{e_R} - q_{\ell_L}$$

which furthermore ensures that no new coloured states are needed to cancel anomalies.

See talk by Michael Duerr

Axial couplings to Standard Model fermions

- The consistency conditions

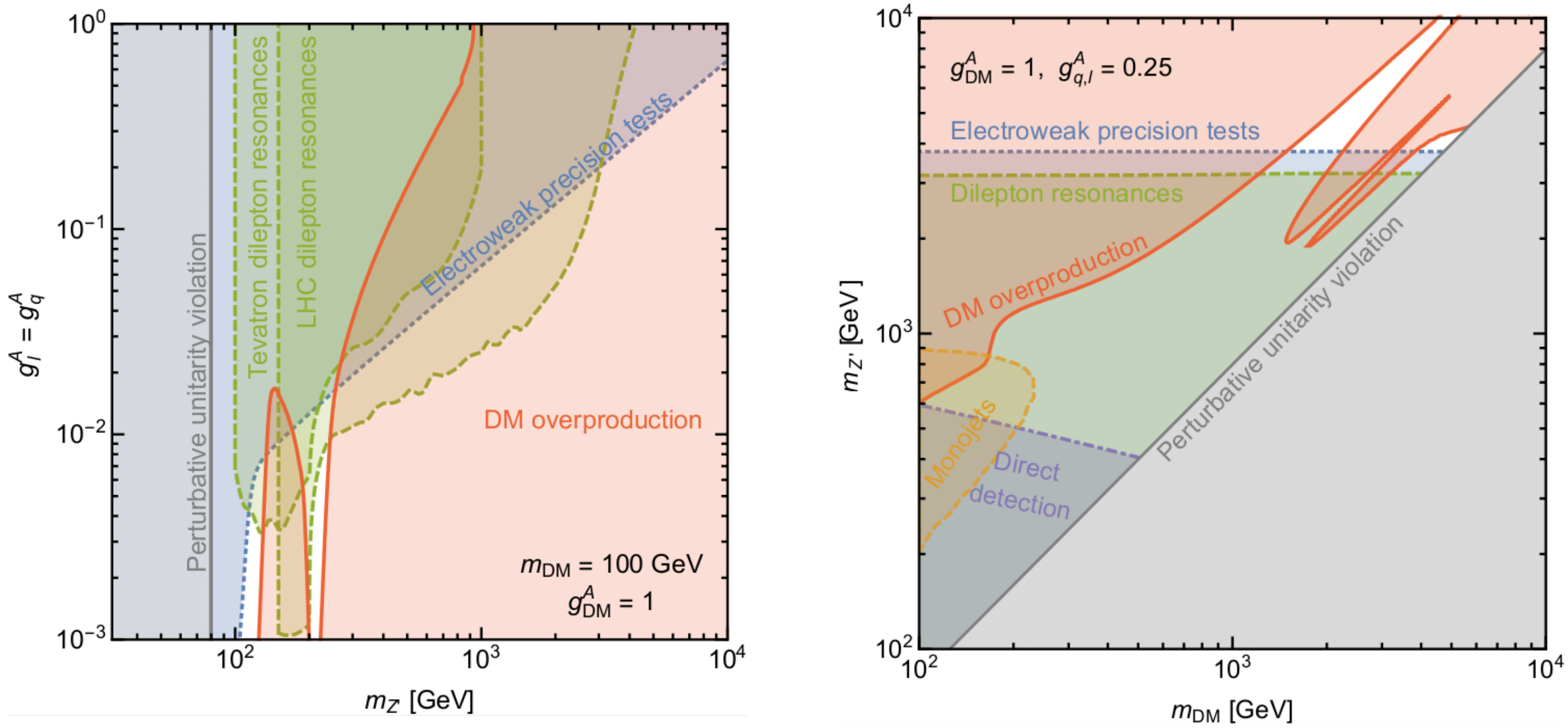
$$q_H = q_{q_L} - q_{u_R} = q_{d_R} - q_{q_L} = q_{e_R} - q_{\ell_L}$$

imply that for non-zero axial couplings to SM fermions, the SM Higgs must be charged under the new *U(1)'*. This has two important consequences:

1. The *Z'* must couple with the same strength to all generations of quarks and to leptons (assuming a single Higgs doublet), such that we can expect strong constraints from searches for dilepton resonances.

2. The vev of the SM Higgs induces a non-diagonal mass term of the form $\delta m^2 \, Z^\mu Z'_\mu$, which leads to mixing between the *Z'* and the SM *Z* boson and hence strong constraints from electroweak precision tests (EWPT).

Axial couplings to Standard Model fermions: Constraints



- The case with non-vanishing axial couplings on the SM side is strongly constrained by dilepton searches as well as EWPT, implying that in a UV complete model this is where a signal should first be seen.
- Monojet and dijet searches as well as direct detection experiments are typically not competitive in this case.

FK et al., arXiv:1510.02110

Vector couplings to Standard Model fermions

- The picture changes significantly if the couplings on the SM side are purely vectorial, such that the SM Higgs is uncharged under the *U(1)'*, and if we furthermore assume that $g_q^V \gg g_\ell^V$.

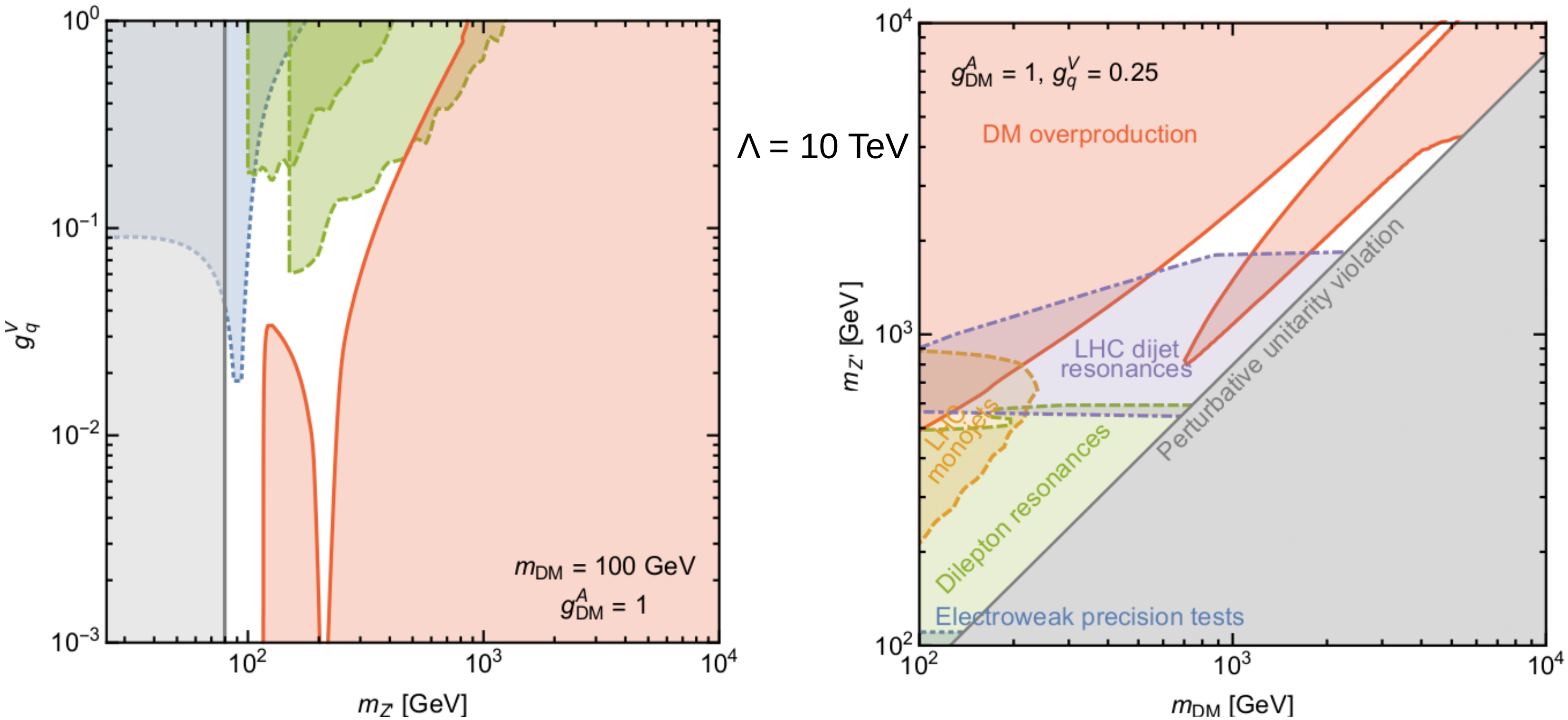
- Nevertheless, there will still be constraints from searches for dilepton resonances and EWPT due to kinetic mixing between the *Z'* and the *Z*:

$$\mathcal{L} \supset -\frac{1}{2} \sin \epsilon \, F'^{\mu\nu} B_{\mu\nu}$$

- While it is reasonable to assume that the kinetic mixing vanishes at high scales, quark loops will always induce kinetic mixing at lower scales, since quarks are assumed to be charged under both *U(1)*s:

$$\epsilon(\mu) = \frac{e \, g_q^V}{2\pi^2 \, \cos\theta_\mathrm{W}} \log \frac{\Lambda}{\mu} \simeq 0.02 \, g_q^V \, \log \frac{\Lambda}{\mu}$$

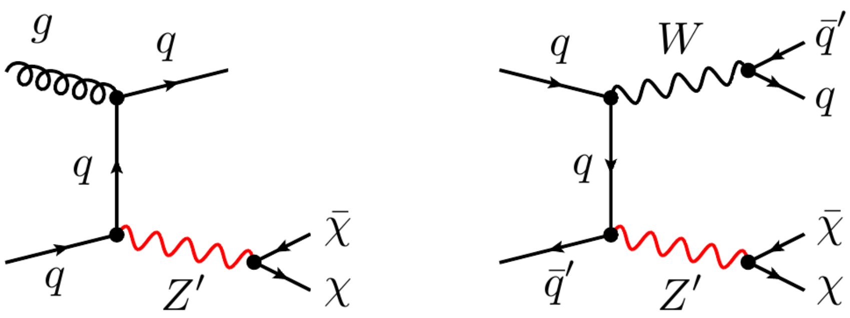
Vector couplings to Standard Model fermions: Constraints

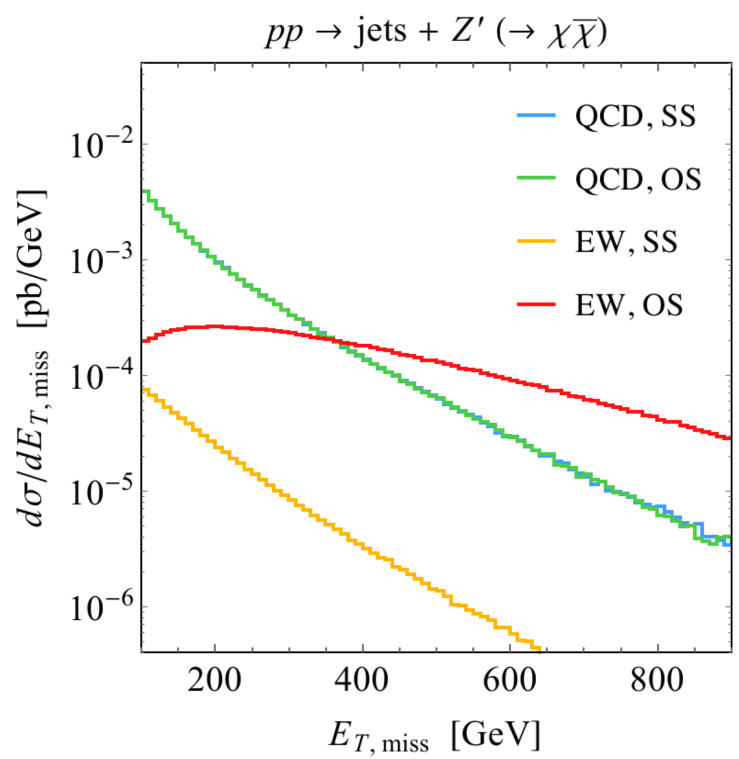


- There is a compelling interplay of the constraints due to loop-induced kinetic mixing and bounds from conventional LHC DM searches.
- The combined constraints leave only a small region in parameter space (close to the Z resonance), where DM overabundance is avoided.

How dangerous is unitarity violation really?

- How do these theoretical consistency requirements impact LHC DM searches?
- Consider the hadronic mono-W process, which contributes to LHC “mono”jet searches:





- For same-sign (SS) couplings to up-type quarks and down-type quarks, the mono-W process gives a subleading contribution.
- For opposite-sign (OS) couplings, the mono-W process seems to dominate over QCD processes at large energies.

The mono-W problem

- Indeed, one finds that the J=1 partial wave of the amplitude grows proportional to

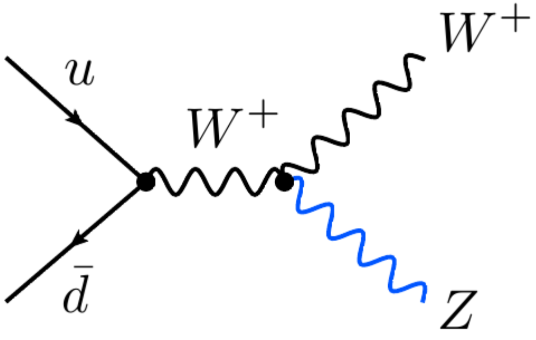
$$\mathcal{M}^1 = \frac{g\,s}{96\pi\,M_W\,M_{Z'}}\left(g_u^A - g_d^A - g_u^V + g_d^V\right)$$

- This leads to violation of unitarity at large energies unless the couplings satisfy the conditions derived above (to conform to the $SU(2)_L$ symmetry of the SM).

- Note: The SM *Z* does not actually satisfy the coupling structure discussed above due to the effects of electroweak symmetry breaking.

- A mono-W problem in the SM is however absent, due to the presence of an additional diagram, which cancels the unitarity-violating behaviour.

- It may be an interesting possibility to copy this structure into the simplified model.



Bell et al., arXiv:1503.07874; Bell et al., arXiv:1512.00476; Haisch, FK, Tait, arXiv:1603.01267

Unitarity bounds on the dark Higgs

- In order to restore perturbative unitarity in the process $\psi\bar{\psi} \to Z'_L Z'_L$, the mass of the dark Higgs must satisfy the inequality

$$m_s < \frac{4\sqrt{2}\pi w}{y_{\mathrm{DM}}}$$

- In fact, an even stronger bound is obtained from considering processes like $ss \to Z'_L Z'_L$. Considering all such processes, we recover the famous Lee-Quigg-Thacker bound

$$m_s \leq \frac{\sqrt{\pi}\, m_{Z'}}{g^A_{\mathrm{DM}}} = \sqrt{4\pi}w$$

- Given this bound we can expect the dark Higgs to play a relevant role in the phenomenology of our model.

Take-home message:

Consistent simplified models may require additional degrees of freedom that cannot be made arbitrarily heavy.

Dark Higgs mixing

> Indeed, the presence of the dark Higgs can significantly change the phenomenology of the model if it mixes with the SM Higgs:

$$V(S, H) \supset \lambda_{hs}(S^* S)(H^\dagger H)$$

$$H_1 = s \sin\theta + h \cos\theta$$
$$H_2 = s \cos\theta - h \sin\theta$$

$$\mathcal{L} \supset -\frac{m_\text{DM} \sin\theta}{2\,w} h\,\bar{\psi}\psi \simeq -\frac{m_\text{DM}\,\lambda_{hs}\,v}{2(m_s^2 - m_h^2)} h\,\bar{\psi}\psi$$

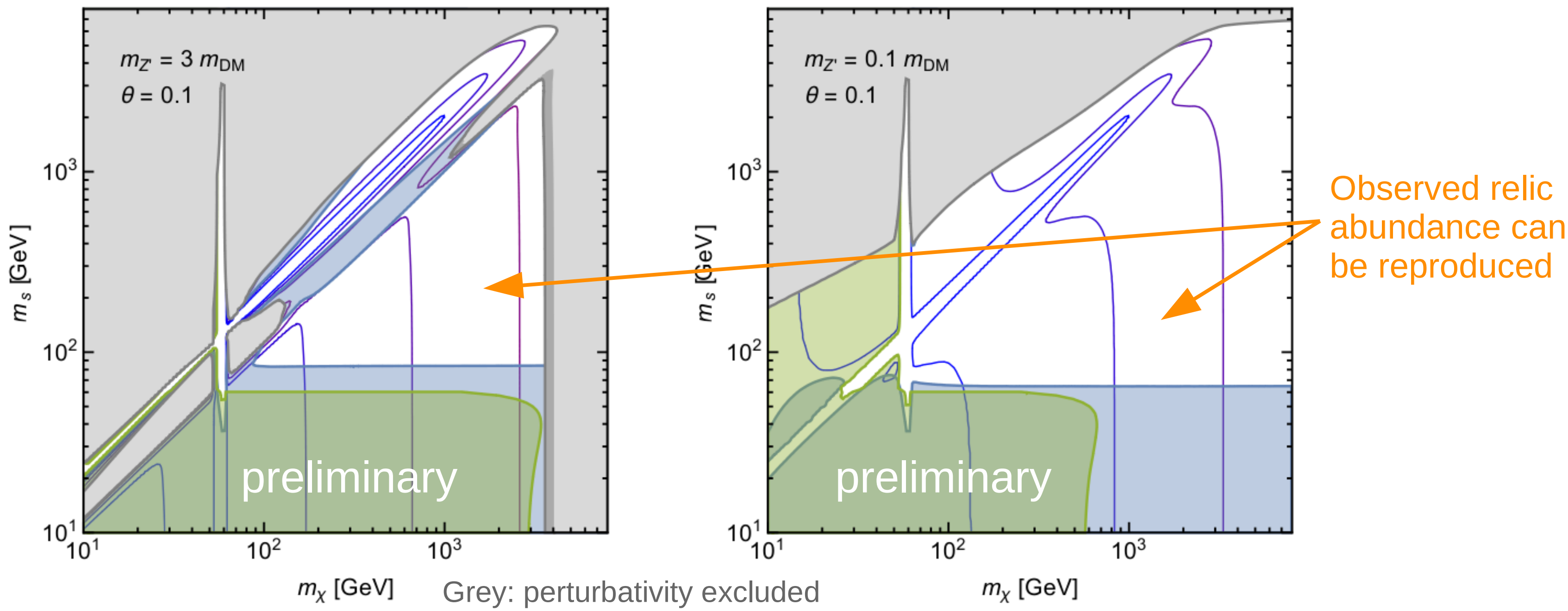
> Such a mixing can lead to a number of observable effects:

- Modification of the SM Higgs signal strengh μ and electroweak observables
- New decay modes of the SM Higgs (such as $h \rightarrow$ inv)
- New resonances at heavy masses (such as $S \rightarrow ZZ \rightarrow 4l$)
- Spin-independent scattering in DM direct detection experiments

The return of the dark Higgs

- But mixing between the dark Higgs and the SM Higgs does not only lead to additional constraints. The presence of an additional mediator between the dark sector and the visible sector may help avoid DM overproduction.

Duerr, FK, Schmidt-Hoberg, Schwetz, Vogl, in preparation



Grey: perturbativity excluded
Green: Higgs signal strengh excluded
Blue: DM direct detection excluded

- Interesting interplay between the two mediators

Conclusions

- Simplified models are a useful tool for describing the phenomenology of DM at the LHC and compare the sensitivity with other kinds of DM searches.
- The requirement of perturbative unitarity provides a guideline to determine the most interesting parameter regions in such models and at the same time allows to determine where the validity of the simplified description breaks down.
- In many situations, consistent simplified models require additional degrees of freedom that cannot be arbitrarily heavy (such as an additional dark Higgs) or additional interactions (such as couplings to leptons and gauge bosons).
- Moreover, it is important that even simplified models are constructed in a way that is consistent with the gauge structure of the SM. This requirement often implies certain non-trivial relations between the different couplings not normally imposed on a simplified model.
- It is often insufficient to only consider the interactions of the mediator with DM and quarks in order to correctly address these issues. Relevant constraints may arise from other signatures like EWPT or searches for dilepton resonances.