Realistic simplified dark matter models

Stefan Vogl

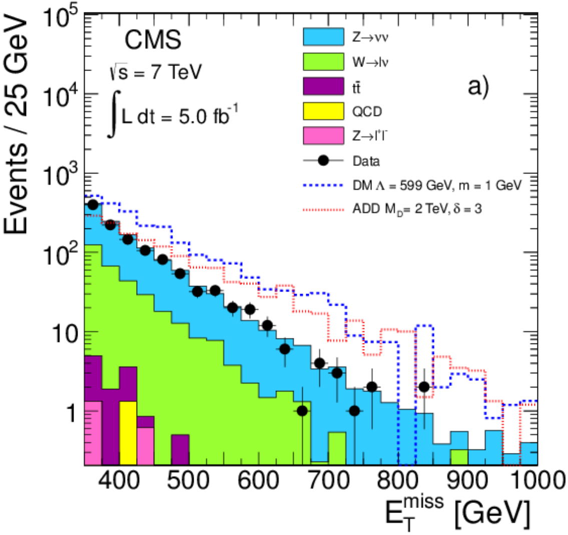
based on
JHEP 1602 (2016) 016 [arxiv:1510.02110]

in collaboration with
F. Kahlhoefer, K. Schmidt-Hoberg and T. Schwetz

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

How do we search for dark matter at the LHC?

Excess of events in high energy tail



What does an excess (the absence of an excess) of events tell us?

average physicist: not much

We need:

- framework for interpretation of LHC searches
- framework for interpretation of different experiments
- provide guide to relevant regions of the parameter space
- ...

$\hookrightarrow$ models for dark matter

Models

UV motivated:

- well motivated DM candidates (neutralino, gravitino, Kaluza-Klein dark matter ...)
- everything calculable
- most signatures/ constraints not related to DM

model independent: EFT

- just keep DM, integrate everything else out
- few parameter, easy comparison with other observables
- suppression scale $\approx$ momentum transfer $\Rightarrow$ unreliable at LHC

Simplified models

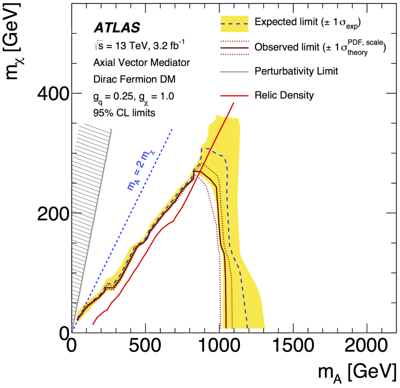
- keep dark matter particle **and** the mediator(s) between dark matter and the Standard Model
- possible ways to think about this:
  - simplification of more complex UV model
  - could be a viable model in itself (dark matter connected to SM by $U(1)_{\text{B-L}}$ etc)
- many possibilities
  scalar dark matter, fermionic dark matter, vector dark matter, scalar mediators, fermionic mediators ...

see "Report of the ATLAS/CMS Dark Matter Forum", 1507.00966 [160 pp.]

S-channel vector mediator

- fermionic dark matter interacts with SM fermions via a Z' boson

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



LHC benchmark model: ATLAS and CMS report limits on this model

Z' mediators: questions

fermionic dark matter interactions with SM fermions are mediated by a Z' boson

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

- Where does this model come from?
- Are results obtained in simplified model reliable?
- Which region of the parameter space are interesting?
- Are there relations between different couplings/parameters?
- ...

Let's get out the toolbox

Perturbative Unitarity

- we know from SM that massive vector boson lead to issues with unitarity
- partial wave analysis of the amplitude

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

with β_{if} : kinematical factor and $d^J_{\mu\mu'}(\theta)$: Wigner d-function

- perturbative unitarity requires

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

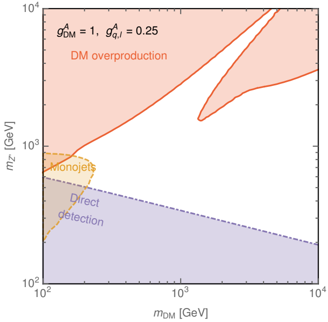
- check validity of model

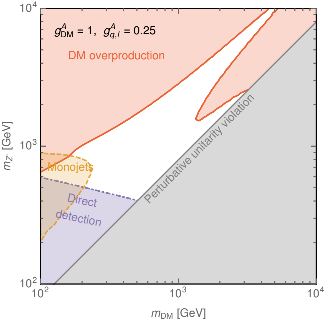
DM side: DM DM $\rightarrow$ DM DM

- longitudinal component of vector couples proportional to $g_A^f m_f / m_{Z'}$
- perturbative unitarity is violated unless

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

- DM can not be arbitrary heavy compared to mediator (or is arbitrarily weakly coupled)



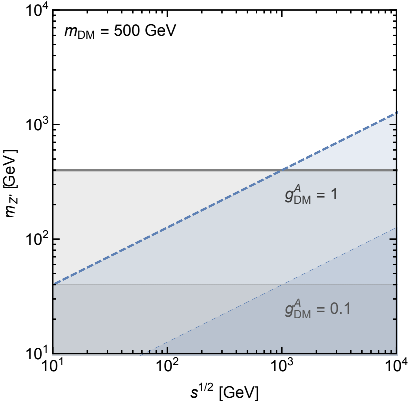


DM side: DM DM $\to Z'Z'$

- matrix element for DM DM $\to Z'Z'$ diverges in high energy limit

$$\mathcal{M} \propto \frac{(g^A_{\mathrm{DM}})^2 \sqrt{s}\, m_{\mathrm{DM}}}{m^2_{Z'}}$$

- theory only valid up to scale $\sqrt{s} < \frac{\pi\, m^2_{Z'}}{(g^A_{\mathrm{DM}})^2\, m_{\mathrm{DM}}}$
- thermal dark matter typically requires g^A_{DM} of $\mathcal{O}(1) \Rightarrow$ dangerous $\sqrt{s}$ typically low
- need new physics to unitarize vector boson



A dark Higgs

- need to restore perturbative unitarity ⇒ Higgs mechanism
- break $U(1)'$ with scalar singlet S
- Lagrangian is given by (Majorana dark matter)

$$\mathcal{L}_{\rm DM} = \frac{i}{2}\bar{\psi}\partial\!\!\!/\psi - \frac{1}{2}g^A_{\rm DM}Z'^{\mu}\bar{\psi}\gamma^5\gamma_\mu\psi - \frac{1}{2}y_{\rm DM}\bar{\psi}(P_L S + P_R S^*)\psi\,,$$
$$\mathcal{L}_S = [(\partial^\mu + i\,g_S\,Z'^\mu)S]^\dagger\left[(\partial_\mu + i\,g_S\,Z'_\mu)S\right] + \mu_s^2\,S^\dagger S - \lambda_s\left(S^\dagger S\right)^2$$

side remark: vector interaction don't generate these problems ($m_{Z'}$ from Stueckelberg mechanism)

A look at the SM side: gauge invariance

- fermionic dark matter interactions with SM fermions mediated by Z' boson

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

- a closer look at the SM gauge structure:

$$g_f^V = \frac{1}{2} g' (q_{f_R} + q_{f_L}) \,, \quad g_f^A = \frac{1}{2} g' (q_{f_R} - q_{f_L})$$

- general Z' couplings break SM gauge invariance (SM Yukawa terms)

SM side: gauge invariance

- need a consistent picture for $SU(2) \times U(1) \times U(1)'$ breaking

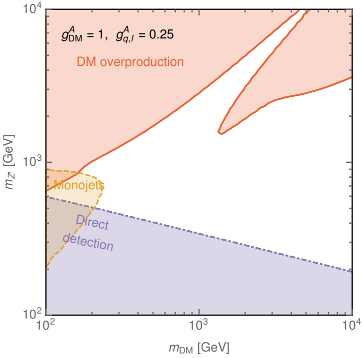
$$g_f^A = \frac{1}{2} g' (q_{f_R} - q_{f_L}) \text{ breaks gauge invariance}$$
$$q_H = q_{q_L} - q_{u_R} = q_{d_R} - q_{q_L} = q_{e_R} - q_{\ell_L} \text{restores it}$$

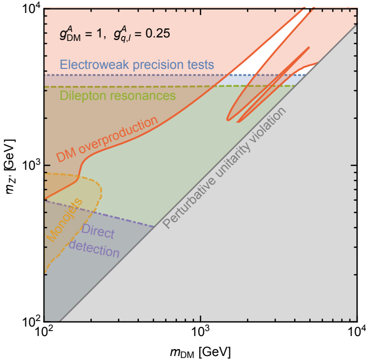
- leads to following Lagrangian:

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

- Z' interacts with all generations of quarks and with **leptons**
  $\Rightarrow$ stringent constraints from searches for dilepton resonances
- off-diagonal mass term $\delta m^2 Z^\mu Z'_\mu \Rightarrow$ electroweak precision tests

Spot the difference: axial(DM)-axial(SM)

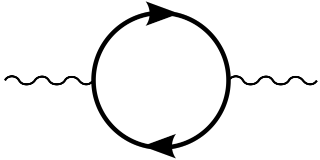




- stringent constraints from EWPTs and dilepton resonance
- naive calculations inconsistent in substantial parts of parameter space
- modified thermal expectation

Vector interactions: loop induced effects

- for $g_f^A = 0$ SM Higgs remains uncharged and $g_l \ll g_q$ possible
- kinetic mixing $-\frac{1}{2} \sin \epsilon F'^{\mu\nu} B_{\mu\nu}$ allowed at tree level
- quarks charged under $U(1)_Y$ and $U(1)'$ generate kinetic mixing at 1-loop

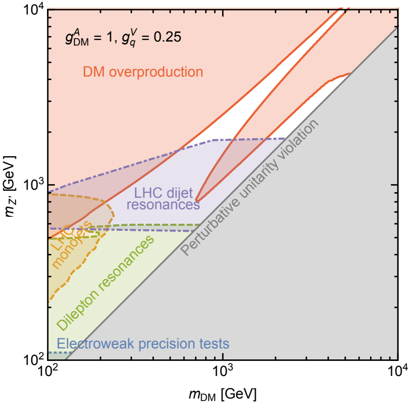


- expect:

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

Limit on loop induced kinetic mixing

- relevant limits from loop induced coupling to leptons
- di-jet resonance
- different searches complementary



Conclusion

- simplified models are a useful tool for DM/collider phenomenology
- "naive" simplified models can violate gauge invariance and perturbative unitarity
- interpretation needs care
- interesting and powerful new signatures in realistic models