Simplified models in collider searches for dark matter

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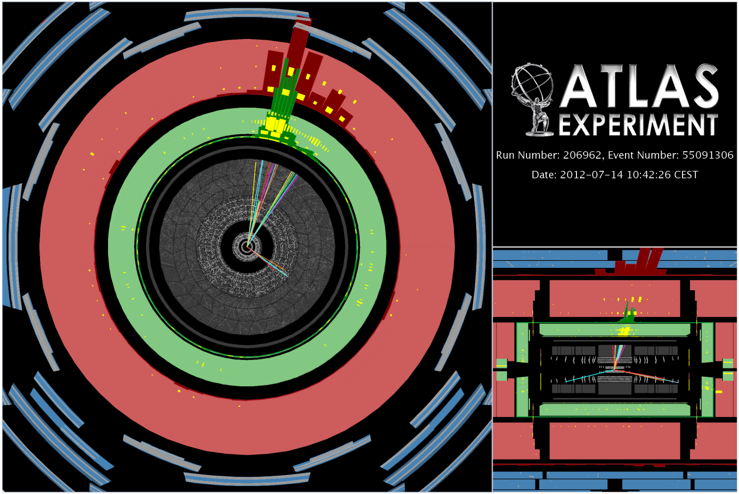
Outline

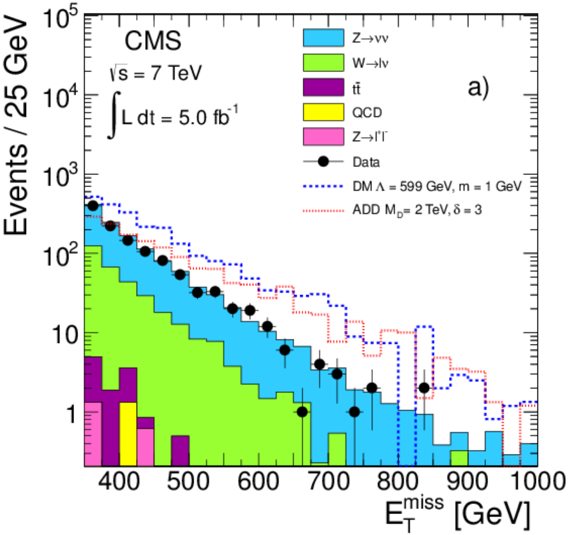
How to look for dark matter at the LHC?

- experimentally very challenging environment with huge backgrounds
- need to know something about the expected signal to devise a search strategy
- dark matter does not interact with detector
- only one observable directly connected to dark matter: missing transverse energy E^T_{miss}
- two options:
  - dark matter part of new sector, look for signs of mediators
  - more model independent look for E^T_{miss} and something (jet, photon, Z, ...)
    $\hookrightarrow$ let's try to follow this line of thought for now

Monojet searches



Monojet searches



What does an excess (the absence of an excess) in high E^T_{miss} events tell us?

average physicist: not much

We need:

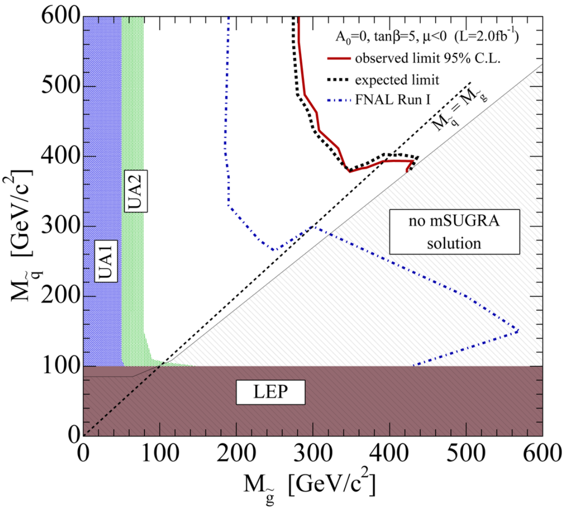
- framework for interpretation of LHC searches
- framework for interpretation of different experiments
- provide guide to relevant regions of the parameter space
- ...

$\hookrightarrow$ models for dark matter

General BSM models

- many models for BSM physics at the weak scale can easily accommodate dark matter (supersymmetry, extra dimensions ...)
- these models offer well motivated candidates, everything is calculable, many experimental signatures
- **BUT**: most of the experimental signatures and/or theoretical constraints are not related to DM properties
- **BUT**: reinterpretation of experimental results in terms of other model nontrivial

Worst case scenario



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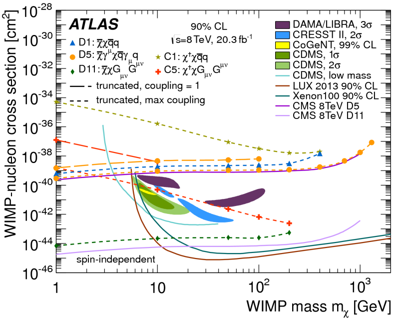
- theoretical prejudice should always be treated as a prejudice

Effective field theory

new physics is heavy $\rightarrow$ Fermi-like theory for DM?

$$\mathcal{L} = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

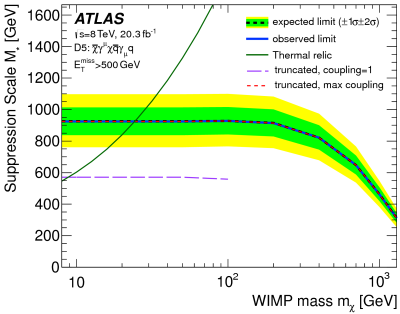
- $\mathcal{O}(10)$ possible operators
- some operators only generated by loops
- very few parameters (m_{DM} , Λ)
- easy comparison with other observables



Effective field theory

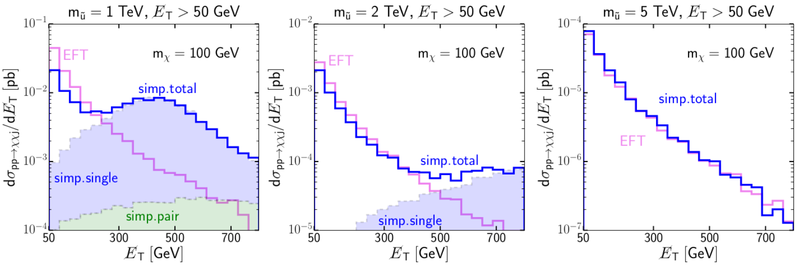
$$\frac{g_{DM} g_q}{q^2 - M^2} \to \frac{g_{DM} g_q}{M^2} + \mathcal{O}(q^2/M^2) + \dots$$

- expansion relies on $q < M$
- typical momentum transfer: $q = \mathcal{O}(100 \text{ GeV})$
- typical excluded scale: $M = \mathcal{O}(100 \text{ GeV})$



$\Rightarrow$ **unreliable**

EFT vs model



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- EFT typically does not reproduce distributions correctly
- **BUT:** EFT not necessarily inapplicable

Not quite as model independent interpretation: Simplified models

- if new physics is not very heavy we have to keep these degrees of freedom in order to capture the phenomenology
- dark matter particle and the mediator(s) between dark matter and the Standard Model
  - parameter count: 2 masses, a few couplings ...
- possible ways to think about this:
  - simplification of more complex UV model
  - way to parametrize a differential cross sections/distributions in an experiment
  - could be a viable model in itself (dark matter connected to SM by $U(1)_{\text{B-L}}$ etc)

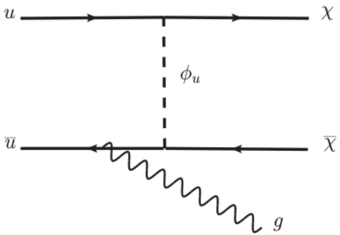
Simplified models

- substantial number of possibilities
  scalar dark matter, fermionic dark matter, vector dark matter, scalar mediators, fermionic mediators ...
- Warning: Simplicity is in the eye of the beholder
- the three most widely used simplified models for fermionic dark matter
  - scalar t-channel
  - scalar s-channel
  - vector s-channel

Scalar t-channel mediator

- dark matter couples to a quark and a colored scalar mediator ϕ

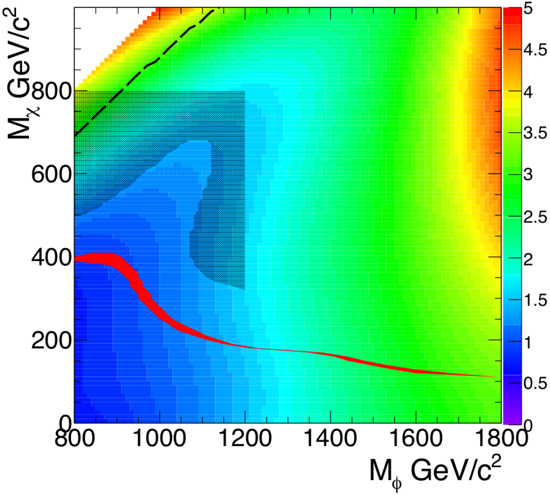
$$\mathcal{L}_{int} = y\bar{q}\chi\phi_q + h.c.$$



- 3D parameter space: m_χ, m_{ϕ_q}, y
- similar to SUSY (neutralino and squarks)

Limits

- run search $\rightarrow$ derive limit map



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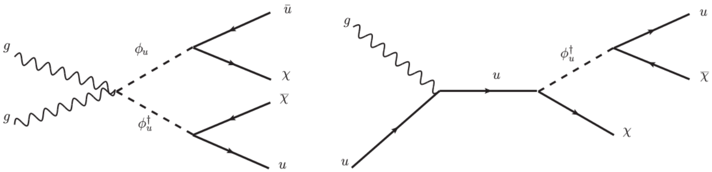
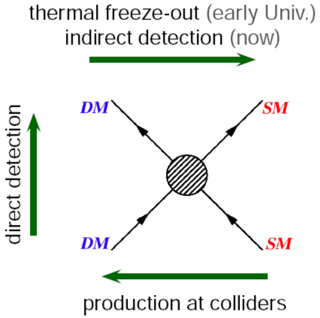
Add more LHC signatures

- simplified models can predict multiple LHC signatures and different production channels
  - $\phi\phi^\dagger$ production from pure QCD $\Rightarrow$ multi-jet + E^T_{miss} final states
  - mixed $\chi\phi$ production $\Rightarrow$ mono-jet

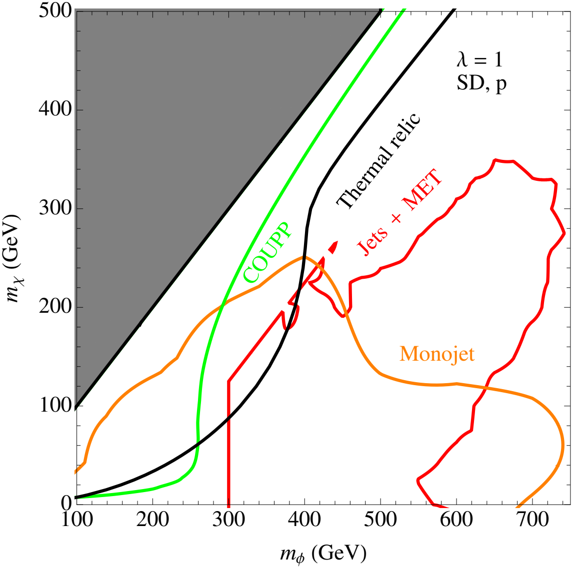


Add more experiments



- simplified models are not limit to LHC searches
- thermal freeze-out, indirect detection and direct search add valuable information
- combine available data

Compare experiments



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Scalar s-channel

- dark matter and quarks interact with a (pseudo-)scalar mediator

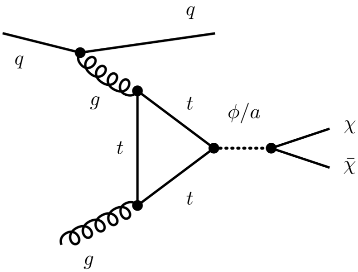
$$\mathcal{L}_{int} = g_\chi \bar{\chi}\chi\phi + g_q \bar{q}q\phi$$

- However: $\bar{q}qS = \bar{q}_R q_L S + \bar{q}_L q_R S$, i.e. not gauge invariant
- typical assumption: coupling proportional to SM Yukawa

$$g_q = y_q g'_q$$

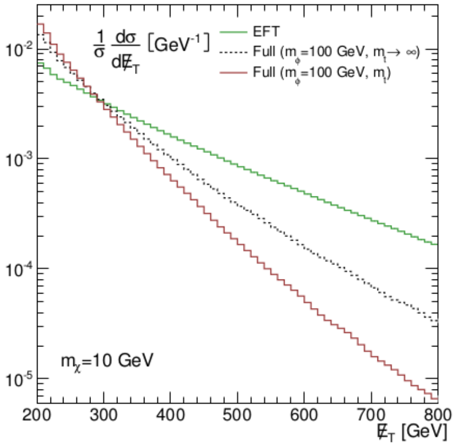
- DM couples mainly to tops

Simplified model for loop induced coupling



- no top in proton
- scalar couples to gluon via top loop (similar to Higgs)

Loop-induced production



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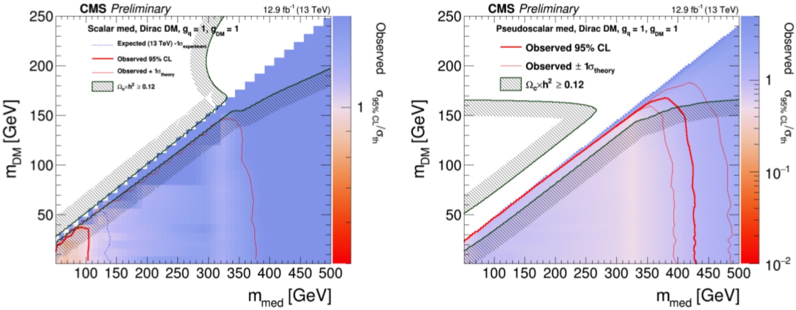
- simplified model allows consistent treatment of loops

LHC limits

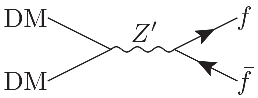


CMS Preliminary
12.9 fb⁻¹ (13 TeV)
Scalar med, Dirac DM, g_q = 1, g_{DM} = 1
Expected (13 TeV) -1σ experiment
Observed 95% CL
Observed + 1σ theory
$\Omega_c \times h^2 \geq 0.12$
Pseudoscalar med, Dirac DM, g_q = 1, g_{DM} = 1
Observed 95% CL
Observed ± 1σ theory
$\Omega_c \times h^2 \geq 0.12$
m_{DM} [GeV]
m_{med} [GeV]
Observed $\sigma_{95\% CL}/\sigma_{th}$

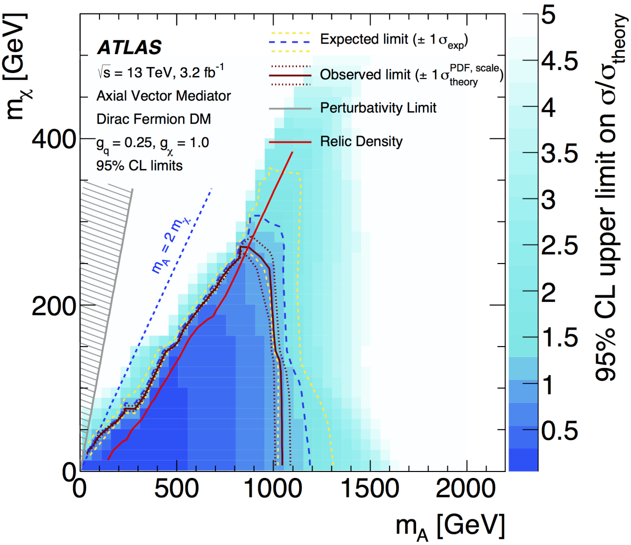
Vector s-channel mediator

- fermionic dark matter interacts with SM fermions via a Z' boson
- 2 masses, 2 vector couplings + 2 axial-vector couplings (+ potentially additional flavor structure)

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

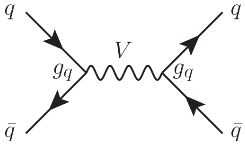


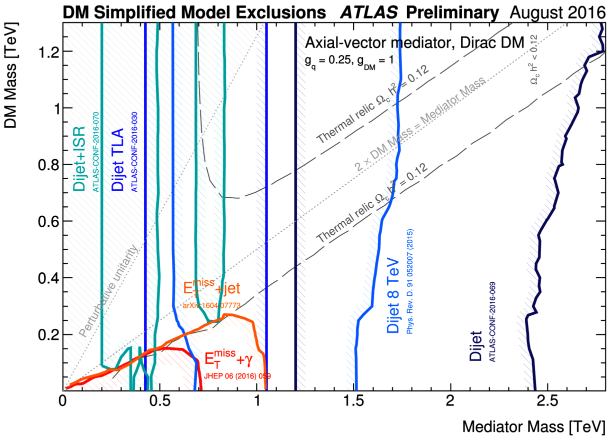
LHC benchmark models



Additional signatures

- Z' also leads to dijet resonance





Questions

- Are results obtained in simplified model reliable?
- Where does this model come from?
- Which parts of their parameter space are theoretically motivates?
- ...

$\rightarrow$ take Z' models as example in the following

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

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

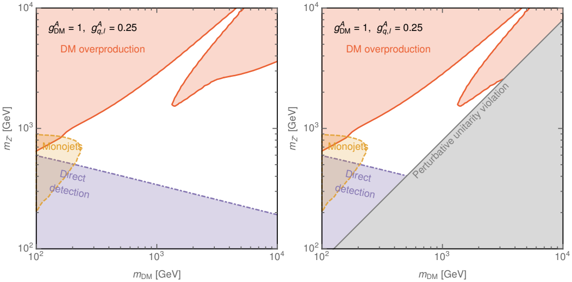
- check validity of model

DM side: self scattering

- 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)



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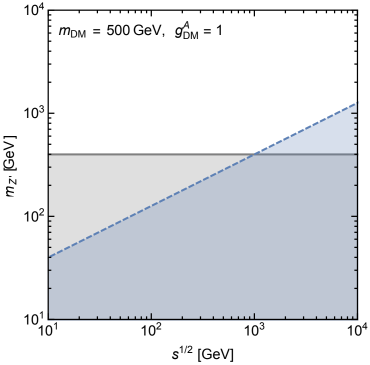
DM side: DM DM $\to Z'Z'$

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

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

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



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A dark Higgs

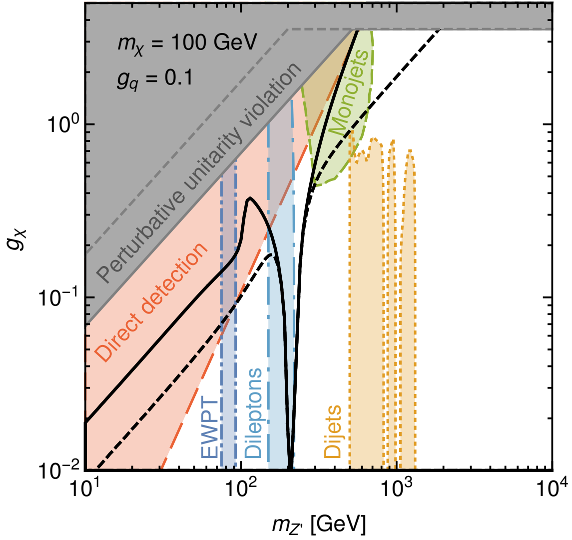
- need to restore perturbative unitarity $\Rightarrow$ Higgs mechanism
- break $U(1)'$ with scalar singlet S
- Lagrangian is given by (Majorana dark matter)

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

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

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

Shifting benchmark



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A look at the SM side: gauge invariance

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

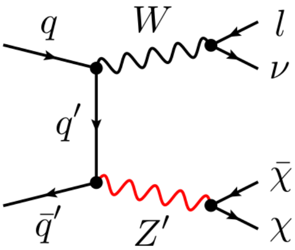
$$\mathcal{L} = -\sum_{f=q,l,\nu} Z'^{\mu}\, \bar{f}\left[g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5\right] f - Z'^{\mu}\, \bar{\psi}\left[g_{\rm DM}^V \gamma_\mu + g_{\rm DM}^A \gamma_\mu \gamma^5\right] \psi\ .$$

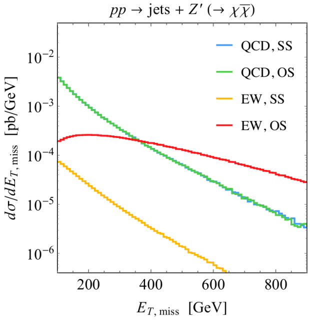
- looks fine but:

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

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

Broken SU(2) invariance





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- broken gauge invariance ⇒ processes including gauge bosons violate unitarity
- mono-W harder than QCD
- QCD cross sections not affected

Required level of UV completeness depends on considered signature!

Fixing gauge invariance

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

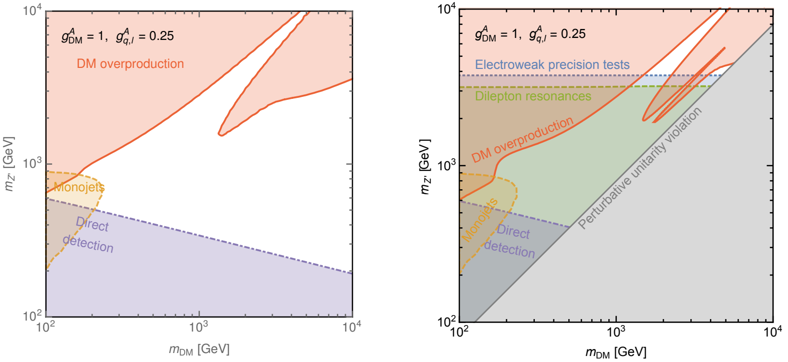
$$g_f^A = \frac{1}{2} g' (q_{f_R} - q_{f_L}) \text{ breaks gauge invariance}$$
$$q_H = q_{q_L} - q_{u_R} = q_{d_R} - q_{q_L} = q_{e_R} - q_{\ell_L} \text{restores it}$$

- 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 $\delta m^2 Z^\mu Z'_\mu$
  $\Rightarrow$ constraints from electroweak precision tests

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



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- stringent constraints from EWPTs and dilepton resonance
- substantial part of parameter space inconsistent

Conclusion

- new tools for efficient interpretations of LHC searches necessary
- simplified models are a useful to map out collider phenomenology of DM
- interpretation needs care ("naive" simplified models can violate gauge invariance and perturbative unitarity)
- required level of "UV-completeness" depends on signature