Mono-W and Gauge Invariance

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Dark Matter and Gauge Invariance

Many DM EFTs do not respect the EW symmetries of the Standard Model
(Need to be careful with simplified models too.)

These descriptions of DM interactions break down at the EW scale (rather than the new physics scale) and are invalid at LHC energies.
→ Problems with longitudinal W & unphysical behaviour of cross sections

Effective operators for DM interactions

Violate $SU(2)_L$ (D1–D4)

Don't necessarily violate $SU(2)_L$ (but can be chosen to do so) (D5–D8)

Violate $SU(2)_L$ (D9–D10)

Name	Operator	Coefficient	DD
D1	$[\bar{\chi}\chi][\bar{f}f]$	$m_f\Lambda^{-3}$	SI
D2	$[\bar{\chi}\gamma^5\chi][\bar{f}f]$	$im_f\Lambda^{-3}$	–
D3	$[\bar{\chi}\chi][\bar{f}\gamma^5 f]$	$im_f\Lambda^{-3}$	–
D4	$[\bar{\chi}\gamma^5\chi][\bar{f}\gamma^5 f]$	$m_f\Lambda^{-3}$	–
D5	$[\bar{\chi}\gamma^\mu\chi][\bar{f}\gamma_\mu f]$	Λ^{-2}	SI
D6	$[\bar{\chi}\gamma^\mu\gamma^5\chi][\bar{f}\gamma_\mu f]$	Λ^{-2}	–
D7	$[\bar{\chi}\gamma^\mu\chi][\bar{f}\gamma_\mu\gamma^5 f]$	Λ^{-2}	–
D8	$[\bar{\chi}\gamma^\mu\gamma^5\chi][\bar{f}\gamma_\mu\gamma^5 f]$	Λ^{-2}	SD
D9	$[\bar{\chi}\sigma^{\mu\nu}\chi][\bar{f}\sigma_{\mu\nu} f]$	Λ^{-2}	SD
D10	$[\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi][\bar{f}\sigma_{\mu\nu} f]$	$i\Lambda^{-2}$	–
D11	$[\bar{\chi}\chi][G_{\mu\nu}G^{\mu\nu}]$	$\alpha_S\Lambda^{-3}$	SI
D12	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}G^{\mu\nu}]$	$i\alpha_S\Lambda^{-3}$	–
D13	$[\bar{\chi}\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$i\alpha_S\Lambda^{-3}$	–
D14	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$\alpha_S\Lambda^{-3}$	–

$SU(2)_L$ invariance and v_{EW}

- Consider fermionic DM interacting with SM fermions.
  → The lowest order effective operators are dimension 6:

$$L_{\text{eff}} = \frac{1}{\Lambda_{\text{eff}}^2} \left(\bar{\chi}\, \Gamma_\chi \chi\right)(\bar{\text{f}}\, \Gamma_f\, \text{f})$$

- If the operators is not invariant under $SU(2)_L$:
  → must be obtained with Higgs vev insertions, or integrating out SU(2)-charged mediators

  → Implicit powers of $\left(\frac{v_{EW}}{\Lambda}\right)^n$ in the operator (Wilson) coefficient

  → Higher order in $\frac{1}{\Lambda}$ than they would naively appear.
  Compete only with subdominant higher order operators.

Gauge invariance & mono-X searches

$SU(2)_L$ invariance is of particular importance for processes involving an $SU(2)_L$ gauge boson → i.e. mono-W or mono-Z

Mono-W signal for SU(2) violating EFT (arXiv:1208.4361):

$$\frac{1}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)(\bar{u}\gamma_\mu u + \boldsymbol{\xi}\bar{d}\gamma_\mu d)$$

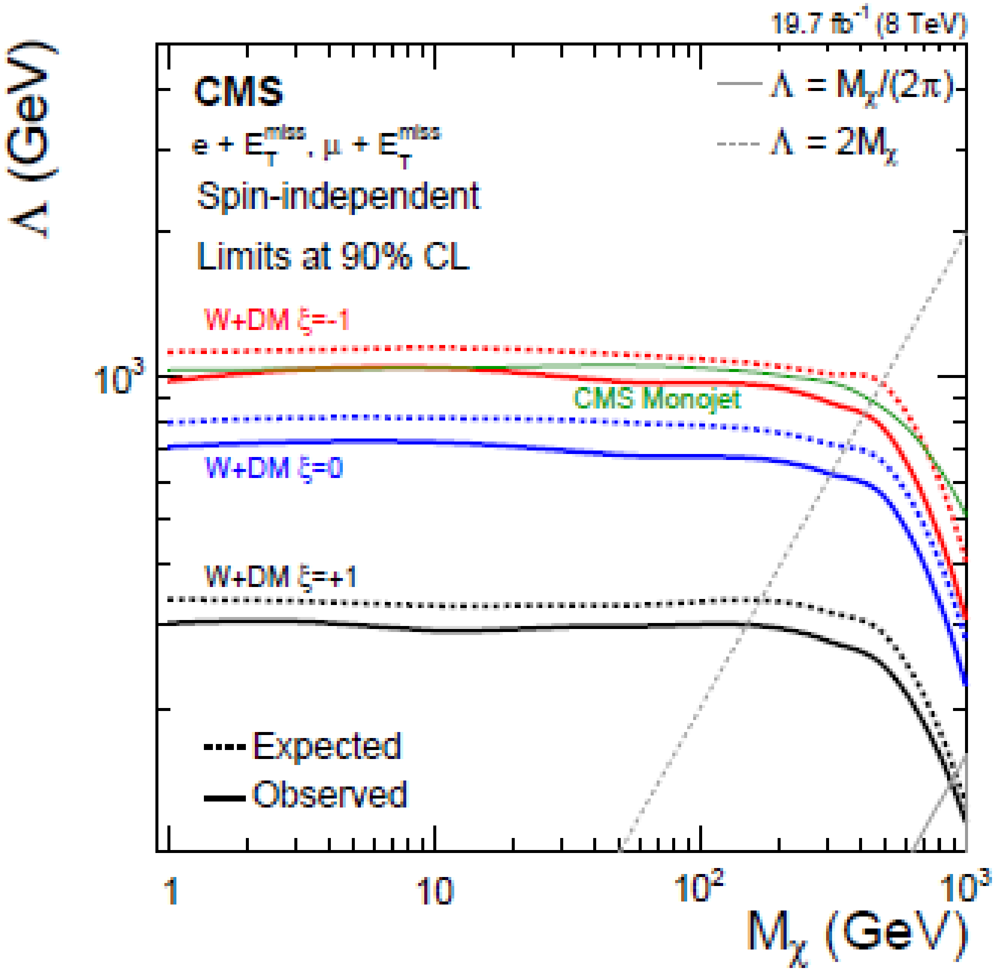
$\boldsymbol{\xi}$ parameterizes relative strength of DM coupling to $\boldsymbol{u}$ and $\boldsymbol{d}$.

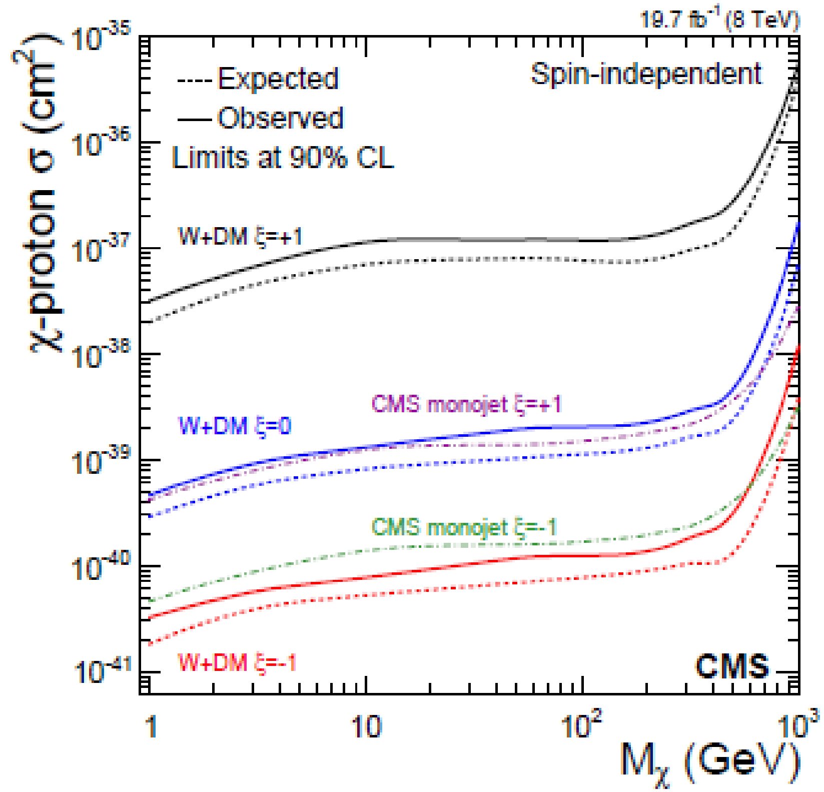
For some parameters, the mono-W results are apparently stronger than those from mono-jets!

This effect has been analysed by both ATLAS and CMS:

- G. Aad et al. (ATLAS Collaboration), Phys.Rev.Lett. 112, 041802 (2014), arXiv:1309.4017 [hep-ex]
- G. Aad et al. (ATLAS Collaboration), JHEP 1409, 037 (2014), arXiv:1407.7494 [hep-ex]
- CMS-Collaboration (2013), CMS-PAS-EXO-13-004
- V. Khachatryan et al. (CMS Collaboration)(2014), arXiv:1408.2745 [hep-ex]
- …

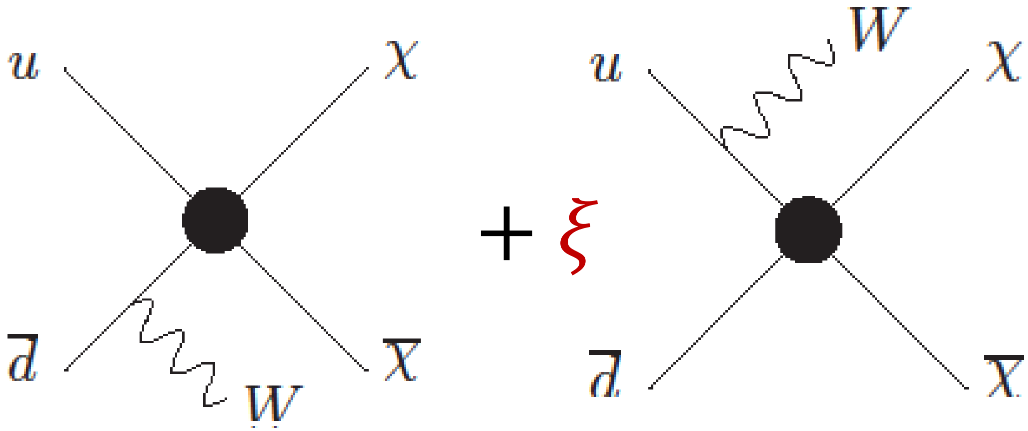
Mono-W more constraining than mono-jet?!





CMS collaboration
arXiv:1408.2745

Mono-W process

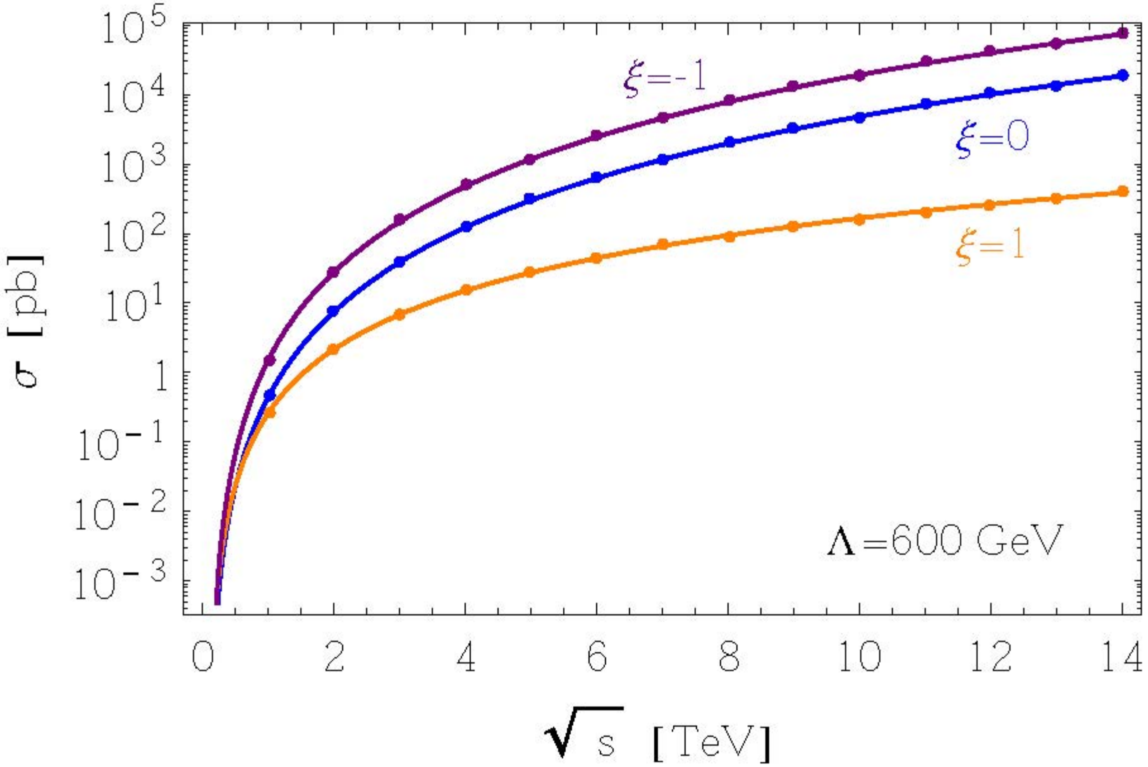


Contributions to the (parton-level) mono-W process $u\bar{d} \rightarrow \chi\chi W^+$ in the effective field theory framework

$$\frac{1}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)\left(\bar{u}\gamma_\mu u + \xi\bar{d}\gamma_\mu d\right)$$

- For $\xi = 1$ ($\xi = -1$) a very strong destructive (constructive) interference effect was observed.
- However, this effect is in fact due to unphysical W_L contributions, which arise due to the lack of gauge invariance.

Mono-W cross section

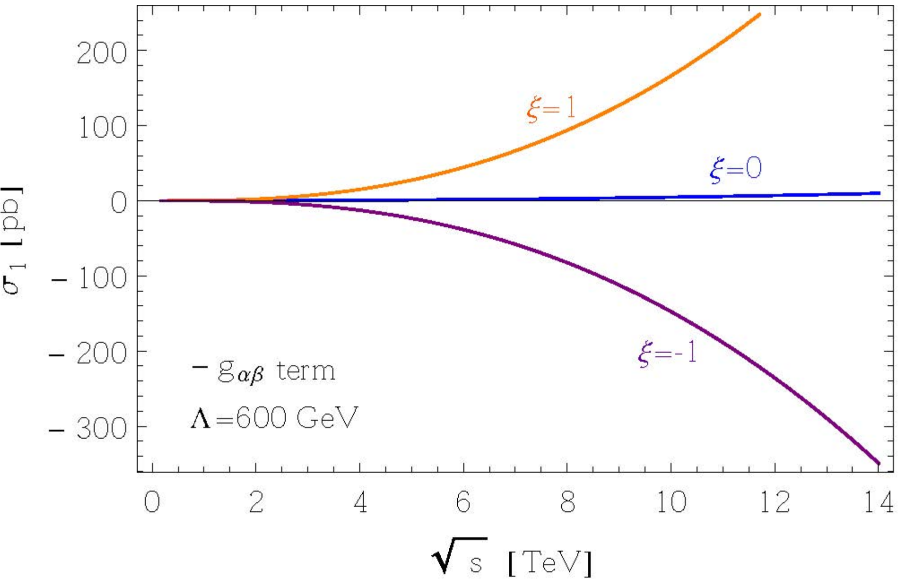


Bell, Cai, Dent, Leane & Weiler, arXiv:1503.07874

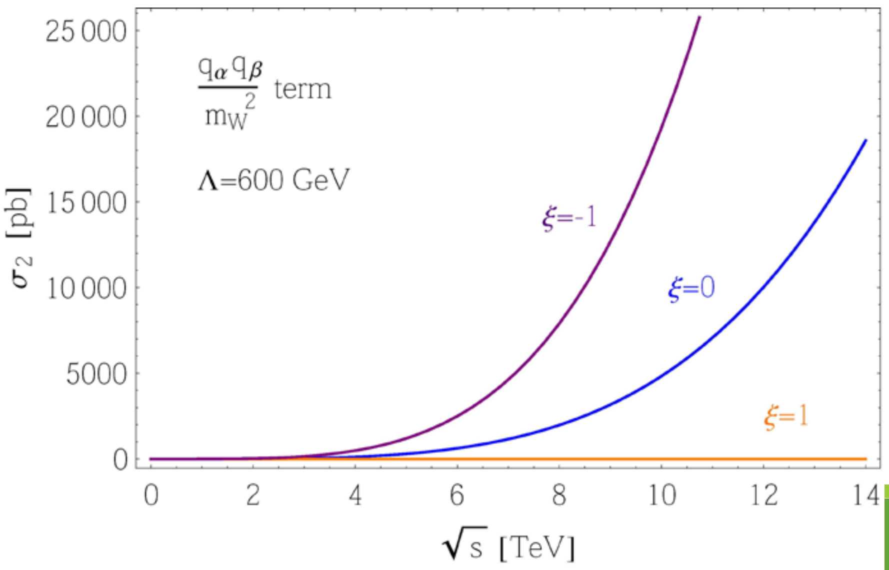
Total parton-level cross sections for Λ = 600 GeV.

(Solid lines are the analytic calculation and dots are the MadGraph calculation.)

Total parton-level cross sections versus energy, for Λ= 600 GeV. (Notice the differing vertical scales between the two panels.)



Contribution from the $-g_{\alpha\beta}$ term in the W polarization sum ($\approx W_T$ contribution).



Contribution from the $\frac{q_\alpha q_\beta}{m_w^2}$ term ($\approx W_L$ contribution).

This term dominates at LHC energies (unless $\xi \simeq 1$).

Bell, Cai, Dent, Leane & Weiler, arXiv:1503.07874

Goldstone boson equivalence theorem & Ward identity

At high energy, Goldstone boson equivalence theorem says:

- We can replace W_L with the corresponding Goldstone boson.
  - Since the Goldstone boson couples to quarks with strength proportional to their mass, these terms are close to zero.
    - We should not get W_L production.

For $\xi \neq 1$, the relevant Ward identity is broken.
→ Missing diagrams?
→Diagrams where W radiated from the mediator!

Mono-W signals in simplified models

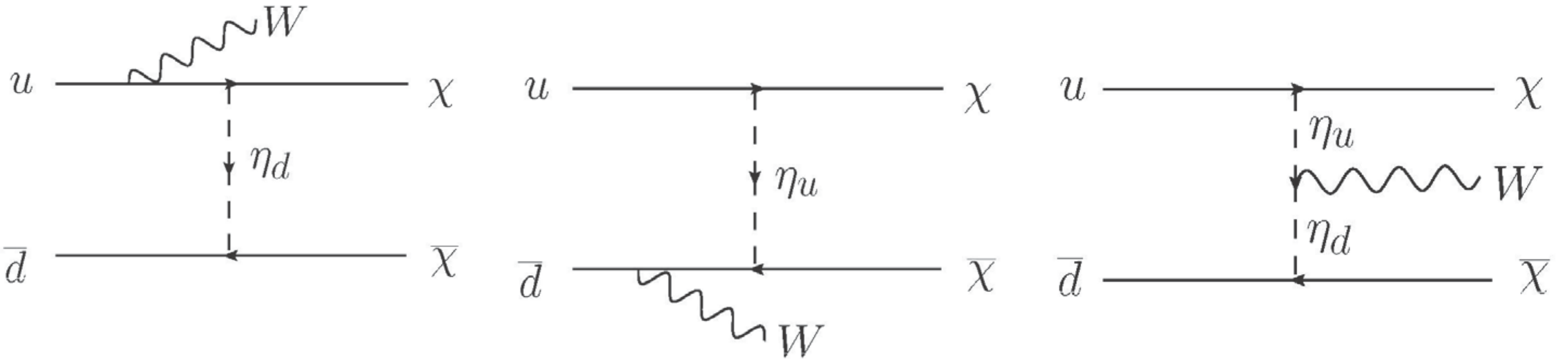
Aim: Study mono-W signals in renormalizable models in which gauge invariance is enforced from the outset.

- Strength of mono-W limits in gauge invariant models?
- EW symmetry breaking can introduce isospin violating effects. How large can these effects be?

t-channel simplified model

DM interaction with quarks mediated by exchange of a (squark-like) $SU(2)_L$ doublet scalar, $(\eta_u, \eta_d) \sim (3, 2, 1/3)$:

$$L = f\overline{Q_L}\eta\chi_R + h.c. = f(\eta_u\overline{u_L} + \eta_d\overline{d_L})\chi_R + h.c.$$

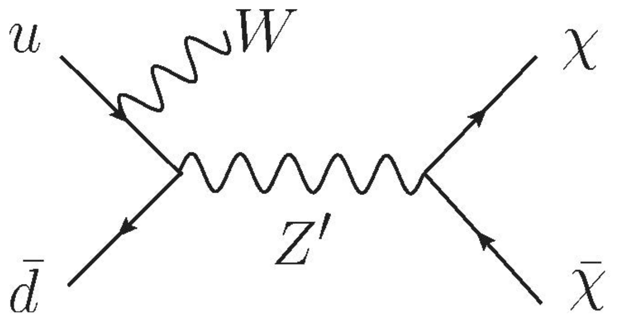


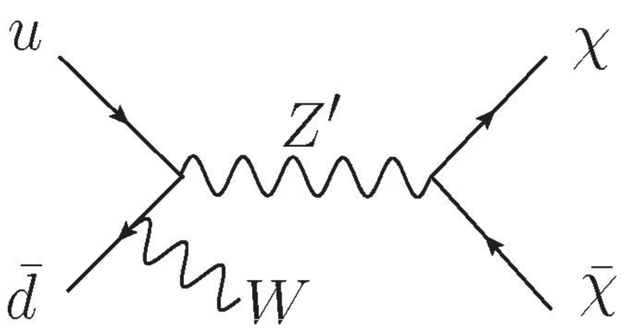
Note that the 3[rd] diagram, with radiation from the propagator, is necessary for gauge invariance but would be lost in the lowest-order EFT description.

s-channel simplified model

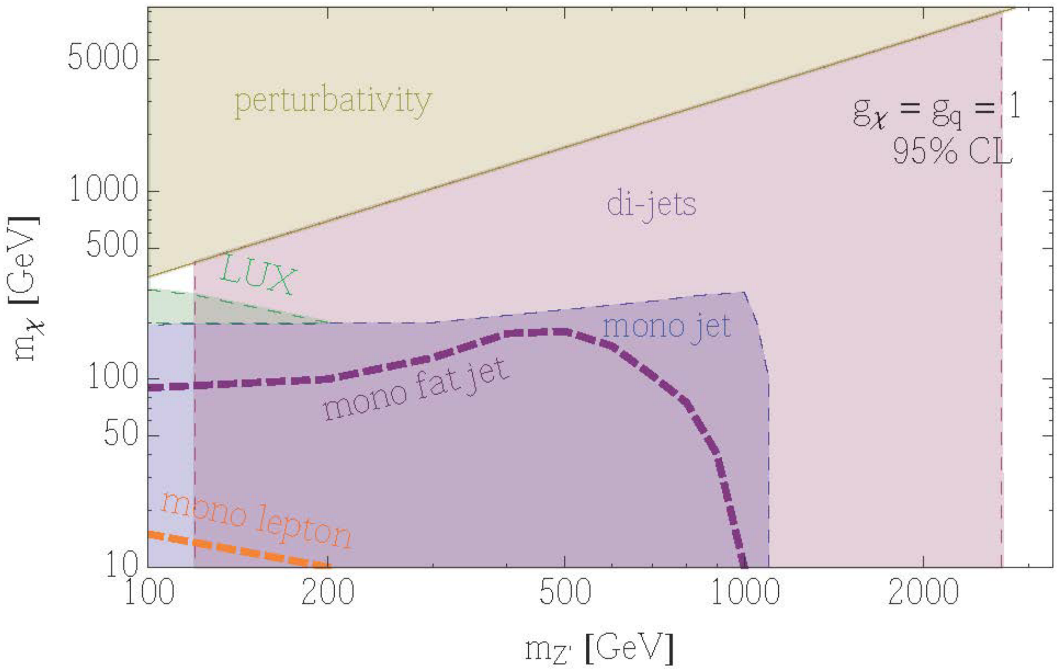
Interactions mediated by exchange of a Z' with axial-vector couplings. (Vector is strongly constrained by direct detection.)

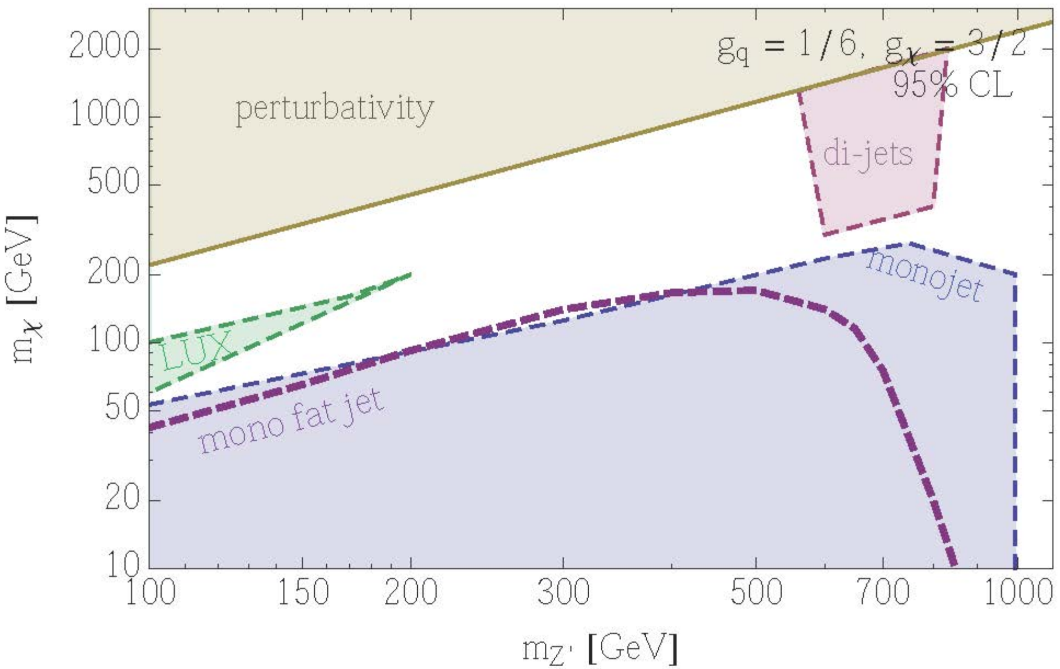
$$L = g_\chi \bar{\chi}\gamma^\mu\gamma^5\chi Z'_\mu + g_q \bar{q}\gamma^\mu\gamma^5 q Z'_\mu$$





If no Z-Z' mixing → no radiation from the mediator





s-channel model

"Mono fat jet" = hadronic mono-W/Z estimate, at 14 TeV, 3000fb^{-1}.

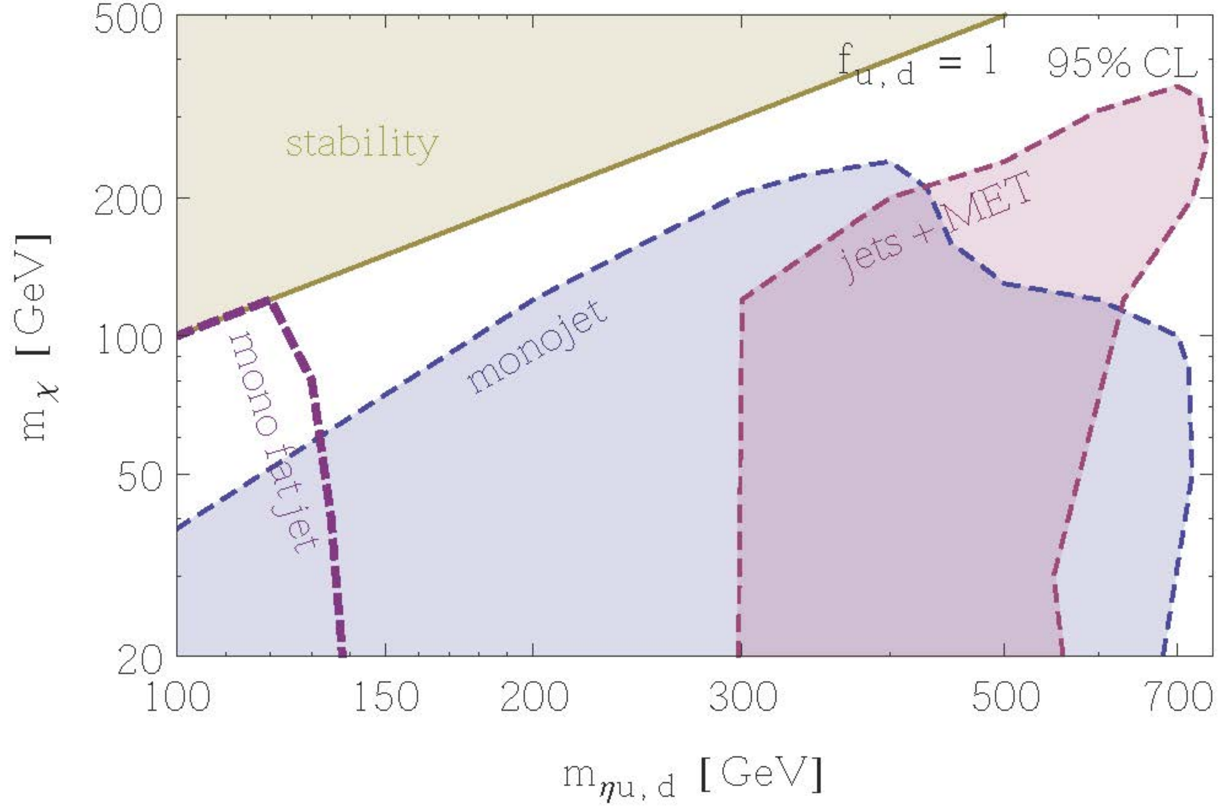
Compared with 8 TeV mono-jet and di-jet limits from arXiv:1503.05916 (M.Chala et al.)

→ It will be challenging to see a mono-W signal in this model.

Bell, Cai & Leane,
arXiv:1512.00476

t-channel model

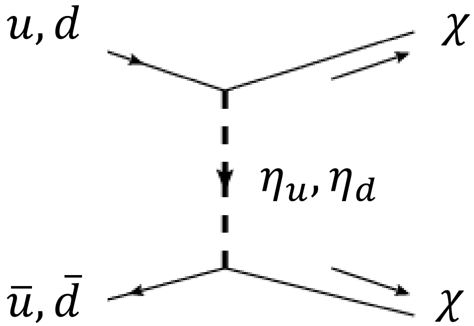
Mono fat jet = 14 TeV hadronic mono-W/Z estimate, at 3000fb^{-1}.
Compared with 8 TeV mono-jet and jets+MET limits.



Bell, Cai & Leane,
arXiv:1512.00476

Isospin violating effects arising from EW symmetry breaking

t-channel model



$$L = f\overline{Q_L}\eta\chi_R + h.c.$$
$$= f(\eta_u\overline{u_L} + \eta_d\overline{d_L})\chi_R + h.c.$$

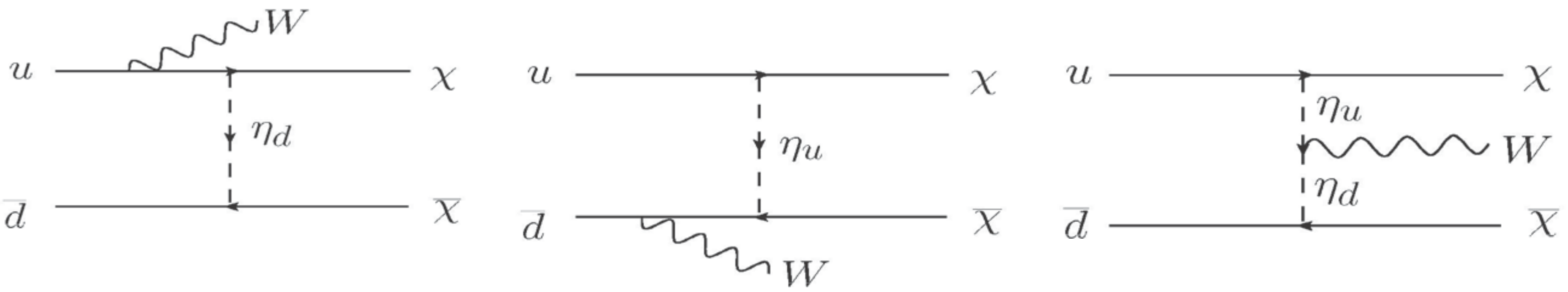
If the (η_u, η_d) have non-degenerate mass, the u and d quarks will interact with DM with different strength.

$$V = m_1^2(\Phi^\dagger\Phi) + m_2^2(\eta^\dagger\eta) + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2(\eta^\dagger\eta)^2 + \lambda_3(\Phi^\dagger\Phi)(\eta^\dagger\eta) + \lambda_4(\Phi^\dagger\eta)(\eta^\dagger\Phi)$$

After EW symmetry breaking

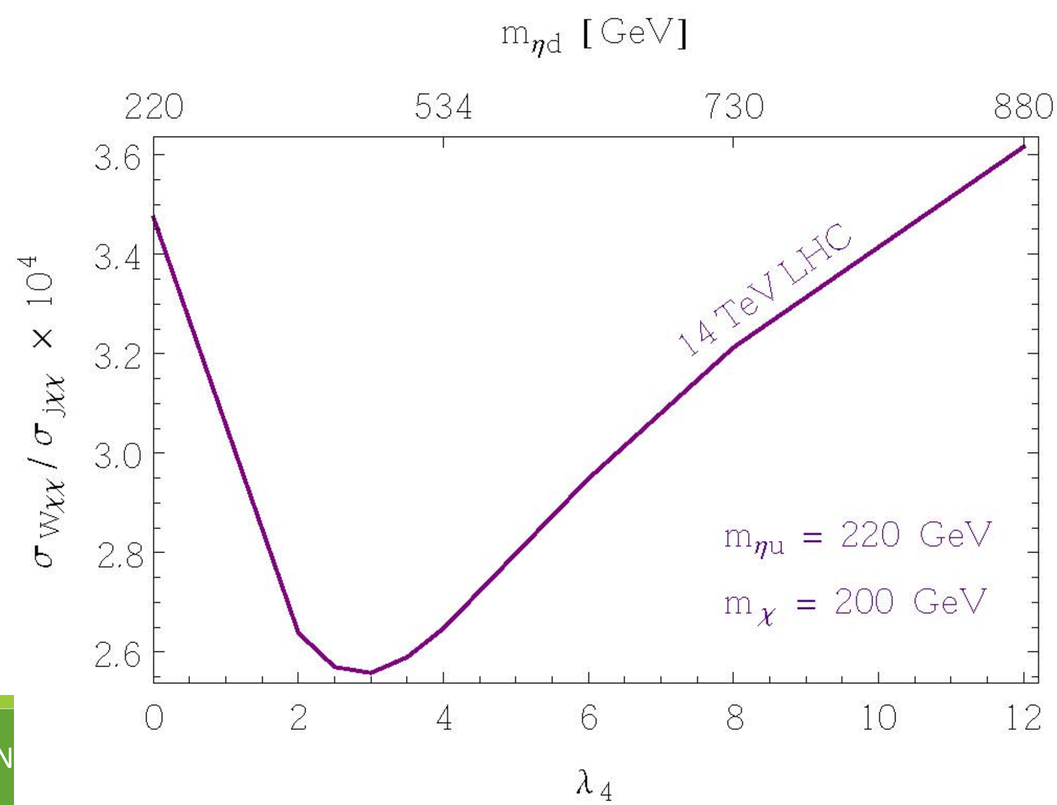
$$m_{\eta_u}^2 = m_2^2 + (\lambda_3 + \lambda_4)v_{EW}^2$$

$$m_{\eta_d}^2 = m_2^2 + \lambda_3 v_{EW}^2 \qquad \Longrightarrow \delta m^2 = \lambda_4 v_{EW}^2$$



- Increasing λ_4 increases the isospin violation of the DM couplings, and allows radiation of W_L from the η propagator.
- However, no large cross section enhancement is obtained.

Ratio of mono-jet to mono-W cross sections

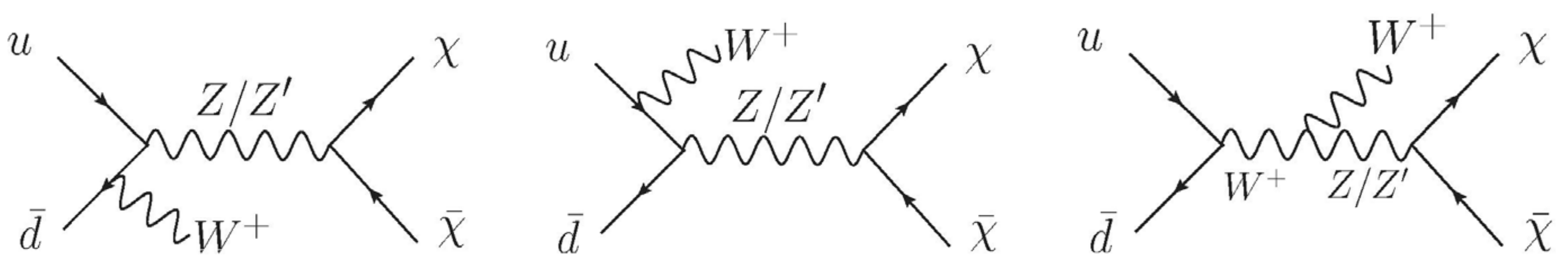


Bell, Cai & Leane, arXiv:1512.00476

s-channel model

Suppose the Z'-quark couplings arise only due to mixing with the SM Z.
→ Z'-quark couplings proportional to Z-quark couplings
→ opposite sign for (u,d) quarks due to weak isospin assignments $T_3 = \pm\frac{1}{2}$.

- EFT limit is $\frac{1}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)\left(\bar{u}\gamma_\mu u + \xi\bar{d}\gamma_\mu d\right)$ with a negative value of ξ
- But the 3rd diagram is needed to enforce gauge invariance



- High energy W_L production arises only from the 3rd diagram
- Suppressed by the Z-Z' mixing angle, $\sim v_{EW}^2/{M_Z'}^2$

Summary

- Some dark matter EFTs violate EW gauge symmetries
  - These operators break down at the EW (rather than scale of new physics) and should not be used at LHC energies.

- We should use a gauge invariant framework, to avoid unphysical enhancements from longitudinal vector polarizations.

- $SU(2)_L$ violating effects can be introduced by EW symmetry breaking. These effects should be suppressed by $\left(\frac{v_{EW}}{\Lambda}\right)^n$ and are generally small.