Dark Matter at the LHC

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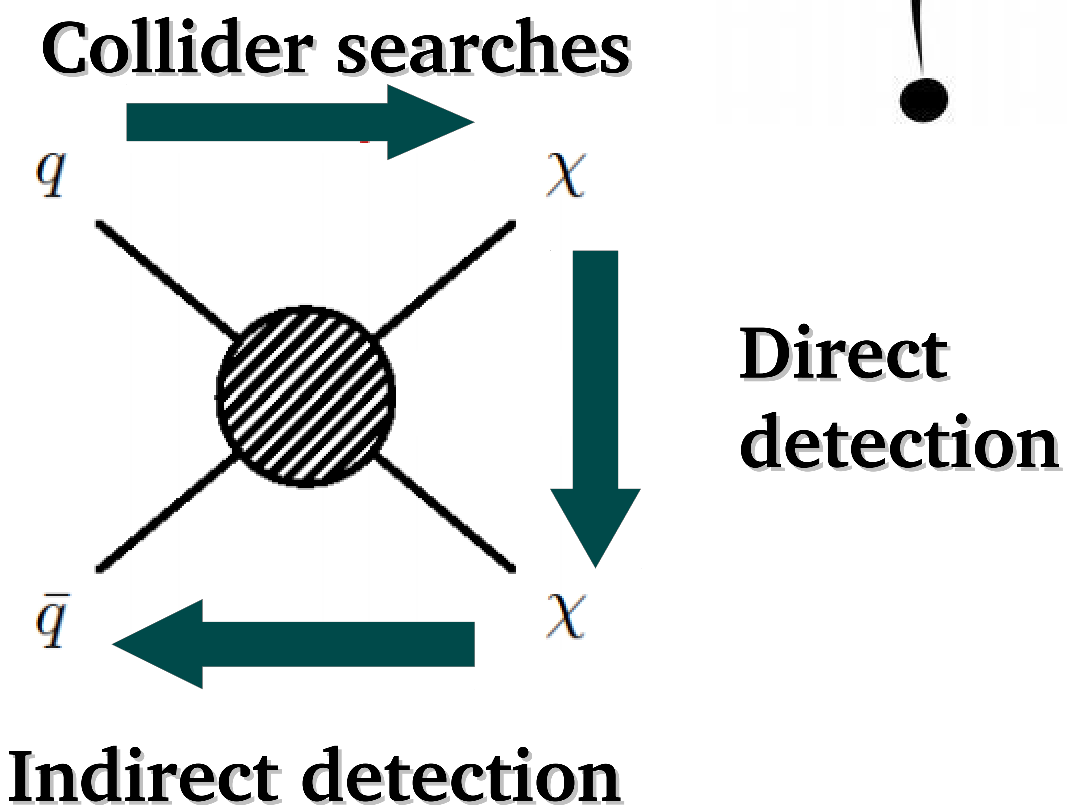
What is dark matter?

- Still no idea about fundamental nature
- WIMP dark matter well motivated
- Realistic detection prospects



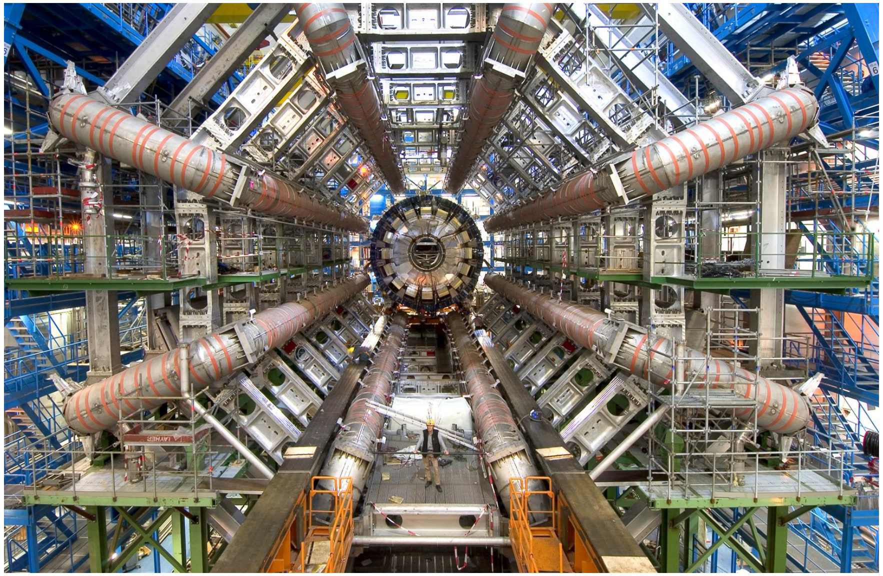
Searches provide complementary information

LHC searches, Mono-X

- Dark matter → missing energy in detector
- Visible matter recoils against this missing energy
- Examples include mono-Z, mono-W, mono-photon, mono-jet…

$$\bar{q}q \rightarrow \chi\bar{\chi} + \text{SM particle}$$

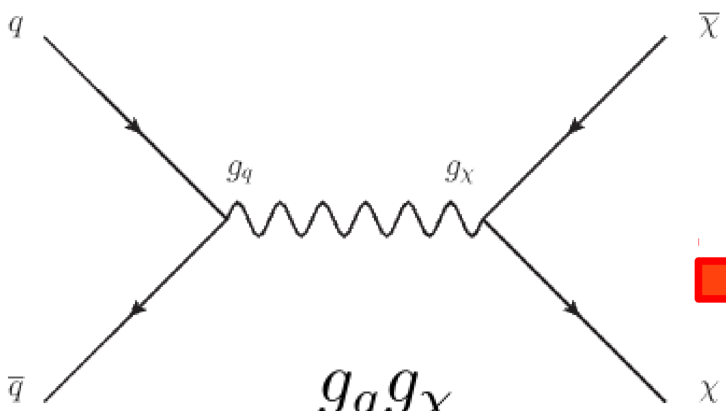
$$pp \rightarrow \text{MET} + \text{SM particle}$$



ATLAS Experiment, CERN

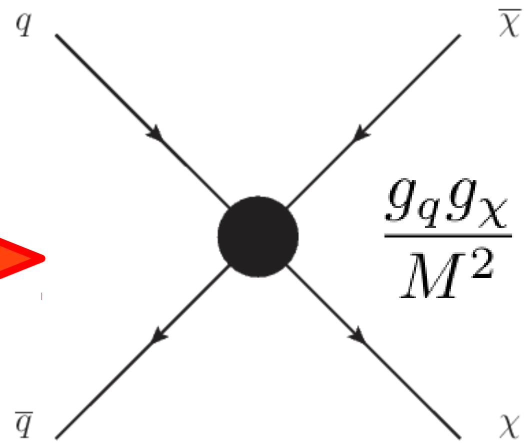
EFTs in a nutshell

$$\frac{1}{\Lambda^2}\left(\overline{\chi}\Gamma_\chi \chi\right)\left(\overline{f}\Gamma_f f\right)$$



$$\frac{g_q g_\chi}{p^2 - M^2}$$

$$M^2 \gg p^2$$



$$\frac{g_q g_\chi}{M^2} = -\frac{1}{\Lambda^2}$$

- Model independent
- Useful at low energies, i.e. direct detection
- Colliders? Need to be careful, and this is well appreciated now. Break down at scale of new physics.

Other times EFTs are invalid?

If an EFT does not respect the electroweak gauge symmetries of the SM, it may be invalid around the electroweak scale, rather than the scale of new physics.

This means using such EFTs at LHC energies will lead to serious problems.

I.e. violation of unitarity in SU(2) non-invariant WW scattering, due to longitudinal modes induced by electroweak symmetry breaking.

Internal Higgs removes violations.

In EFTs, internal fields are integrated out!

Need to enforce gauge invariance!

DM-SM effective operators which violate the SM weak gauge symmetries necessarily carry an extra prefactor of the Higgs vev to some power. Origin is the SU(2) scalar doublet

$$\Phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 = \frac{1}{\sqrt{2}}(H + v_{\mathrm{EW}} + i\Im\phi^0) \end{pmatrix}$$

Suppression of operators by extra factors, to powers of n:

$$(v_{\mathrm{EW}}/\Lambda)^n$$

Examples of SU(2) breaking operators

Scalar operator:

$$\frac{m_q}{\Lambda^3}\left(\overline{\chi}\chi\right)\left(\overline{q}q\right) = \frac{m_q}{\Lambda^3}\left(\overline{\chi}\chi\right)\left(\overline{q}_L q_R + h.c.\right)$$

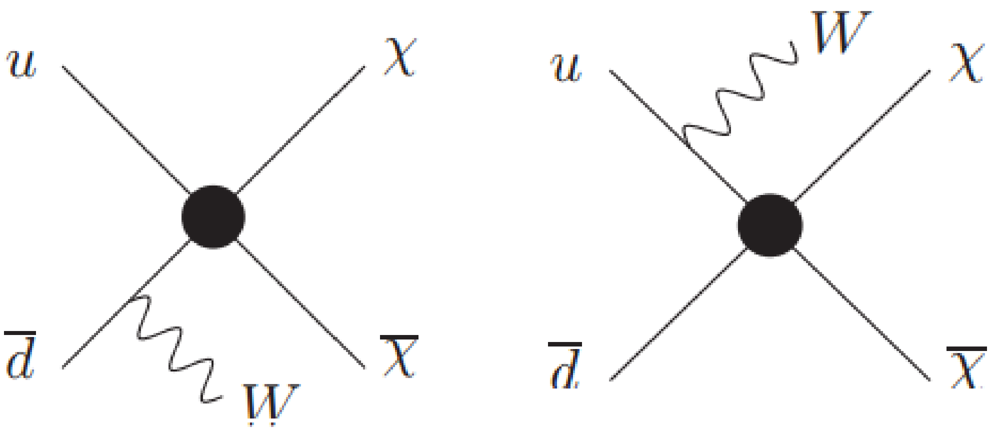
LH quark SU(2) doublet, DM and RH quark singlets.

Vector operator:

$$\frac{1}{\Lambda^2}\left(\overline{\chi}\gamma^\mu\chi\right)\left(\overline{q}\gamma_\mu q\right) = \frac{1}{\Lambda^2}\left(\overline{\chi}\gamma^\mu\chi\right)\left(\overline{q}_L\gamma_\mu q_L + \overline{q}_R\gamma_\mu q_R\right)$$

OK provided same coefficients for each LH up and down quark.

Application to Mono-W EFT



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

Literature sets $\xi \neq +1$, claims to find "interference effect". Analysis is repeated by ATLAS and CMS and it is used to set strong bounds on DM from mono-W searches.

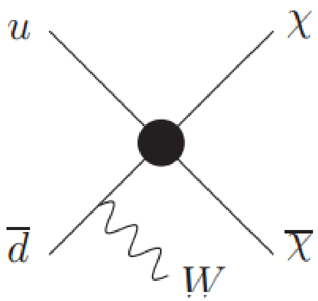
$$\frac{v_{\rm EW}^2}{\Lambda^4}(\overline{\chi}\gamma^\mu\chi)(\overline{u_L}\gamma_\mu u_L)$$

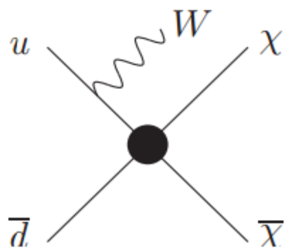
$$\begin{pmatrix} u \\ d \end{pmatrix}_L$$

Ward identity violated:

$$q_\alpha \mathcal{M}^\alpha = \frac{g_W}{\Lambda^2}\left[\bar{v}(p_2)\,(1-\xi)\,\gamma^\mu \frac{P_L}{\sqrt{2}}u(p_1)\right]\left[\bar{u}(k_1)\gamma_\mu v(k_2)\right]$$

Polarization vectors





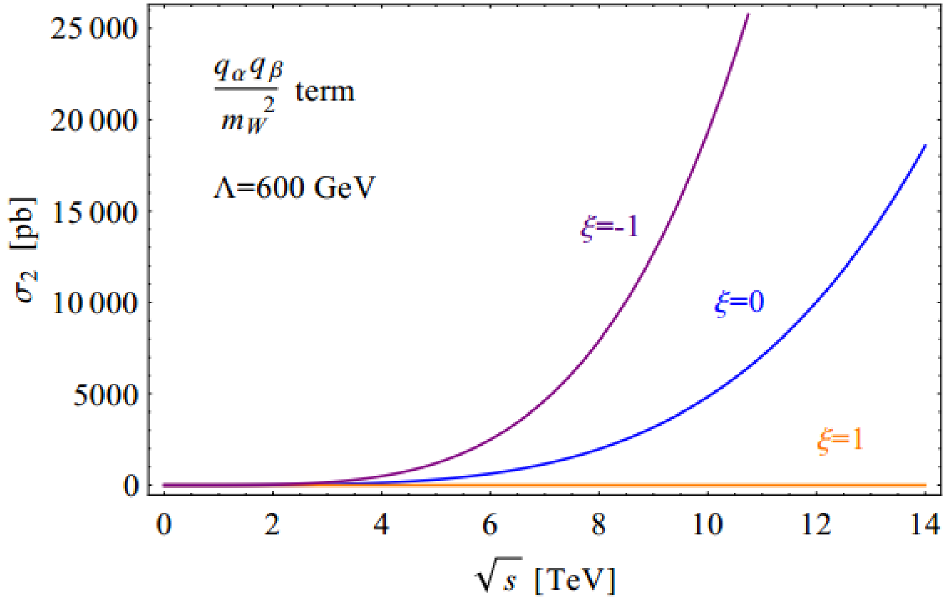
$$\sum_\lambda \epsilon_\alpha^\lambda \epsilon_\beta^{\lambda\,*} = -g_{\alpha\beta} + \frac{q_\alpha q_\beta}{m_W^2}$$

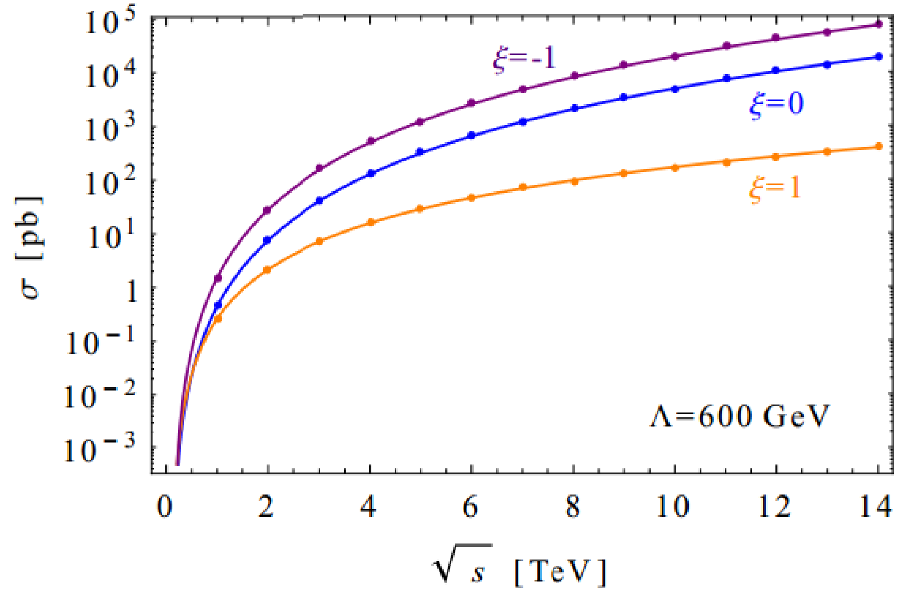
$$\epsilon_\alpha^L = \frac{q_\alpha}{m_W} + \mathcal{O}\left(\frac{m_W}{E}\right) \sim \frac{\sqrt{s}}{m_W}$$

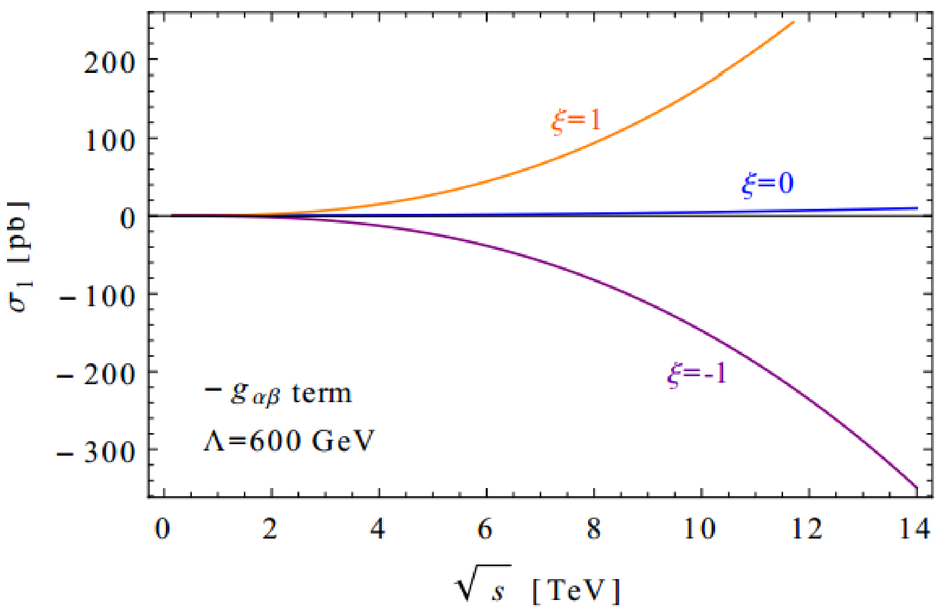
$$\epsilon_\alpha^L \epsilon_\beta^{L\,*} \approx q_\alpha q_\beta / m_W^2 \sim s/m_W^2$$

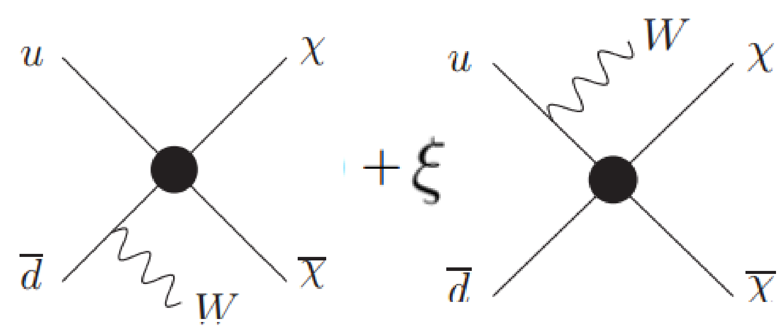
- Goldstone boson equivalence theorem states that, in the high energy limit, the amplitude for emission of a longitudinally polarized W is equivalent to the amplitude for emission of the corresponding Goldstone boson
- Goldstone couples proportionally to mass of quarks, so for longitudinal W emission, expect

$$i\mathcal{M}(\phi^+(q)) \simeq 0$$









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Can be seen in the cross section

$$\left.\frac{d^2\sigma}{dx\,d\cos\theta}\right|_{\xi=1} = \frac{A}{3^2 2^8 \pi^3 \Lambda^4 \left(s^2x^2\sin^2\theta + 2sm_W^2\left(\cos\left(2\theta\right) - 2x + 1\right) + 4m_W^4\right)^2},$$

where

$$A = s^2 g_W^2 \sqrt{x^2 - \frac{4m_W^2}{s}} \left(1 - x + \frac{m_W^2}{s}\right) \Big[s^3x^2\sin^2\theta\left(\cos\left(2\theta\right)x^2 + 3x^2 - 8x + 8\right)$$
$$+ 2s^2m_W^2\left(\cos\left(4\theta\right)x^2 + 2\cos\left(2\theta\right)\left(x^3 - x^2 - 4x + 4\right) - 2x^3 + 17x^2 - 24x + 8\right)$$
$$- 4sm_W^4\left(\cos\left(4\theta\right) + \cos\left(2\theta\right)\left(x^2 + 4x - 8\right) - x^2 + 20x - 17\right) + 16m_W^6\left(\cos\left(2\theta\right) + 3\right)\Big]$$

$$\left.\frac{d^2\sigma}{dx\,d\cos\theta}\right|_{q_\alpha q_\beta/m_W^2} = \frac{(\xi-1)^2 s^2 g_W^2 \sqrt{x^2 - \frac{4m_W^2}{s}}\left(2x^2\sin^2\theta - 16x + 16 + \frac{4m_W^2}{s}\left(\cos\left(2\theta\right) + 3\right)\right)}{3^2 2^{13}\pi^3\Lambda^4 m_W^2}$$

Interference effect?

- No, just a manifestation of the fact that the breaking of electroweak gauge-invariance has given rise to a longitudinal W component.

- The increased cross section for ξ = - 1 is in fact due to unphysical terms that grow like s/mw^2 , which originate from the term in the polarization sum below:

$$\epsilon^L_\alpha = \frac{q_\alpha}{m_W} + \mathcal{O}\left(\frac{m_W}{E}\right) \sim \frac{\sqrt{s}}{m_W}$$

$$\epsilon^L_\alpha \epsilon^L_\beta{}^* \approx \quad q_\alpha q_\beta / m_W^2 \sim s/m_W^2$$

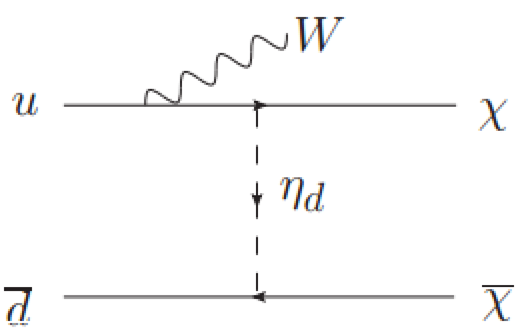
Renormalizable model

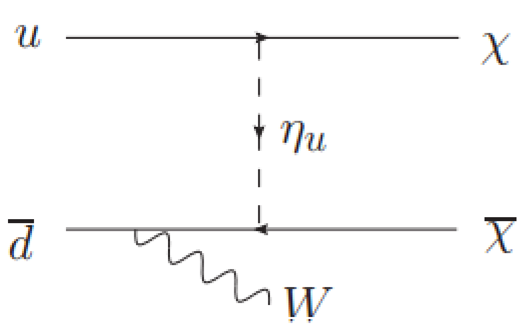
$$\mathcal{L}_{\rm int} = f\overline{Q_L}\eta\chi_R + h.c$$
$$= f_{ud}\left(\eta_u\overline{u}_L + \eta_d\overline{d}_L\right)\chi_R + h.c.$$

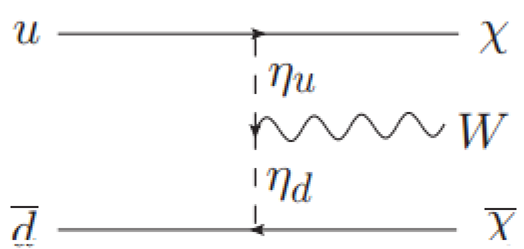
$$V = m_1^2(\Phi^\dagger\Phi) + \frac{1}{2}\lambda_1(\Phi^\dagger\Phi)^2 + m_2^2(\eta^\dagger\eta) + \frac{1}{2}\lambda_2(\eta^\dagger\eta)^2$$
$$+ \lambda_3(\Phi^\dagger\Phi)(\eta^\dagger\eta) + \lambda_4(\Phi^\dagger\eta)(\eta^\dagger\Phi)$$

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

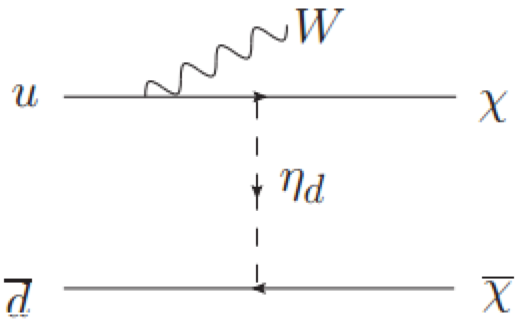
$$m_{\eta_u}^2 = m_2^2 + \lambda_3 v_{\rm EW}^2$$

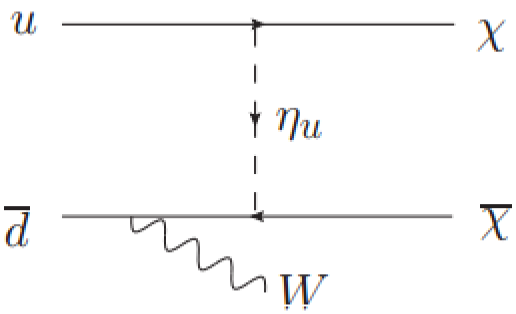


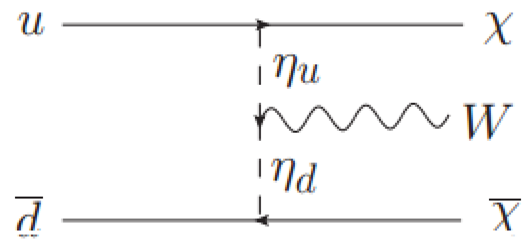


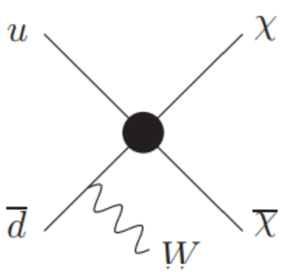


Parallels to EFT effect

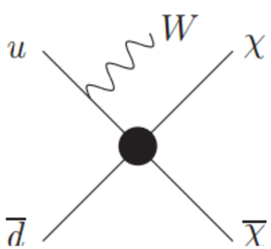








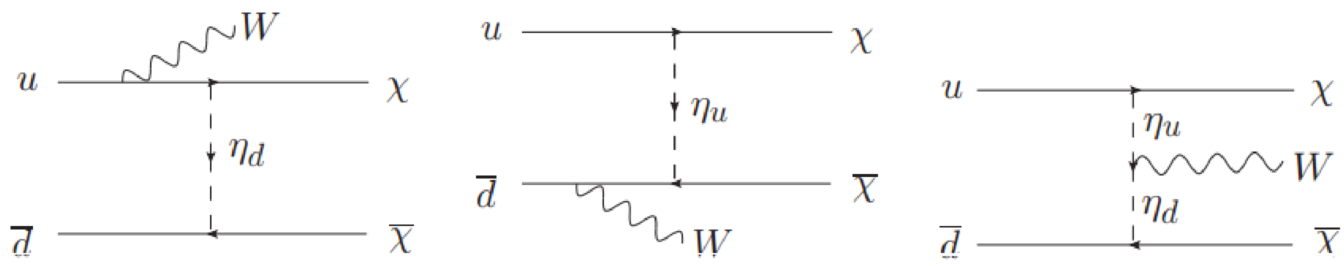
$$\frac{1}{\Lambda_u^2}(\overline{u}\Gamma u)(\overline{\chi}\Gamma\chi)$$

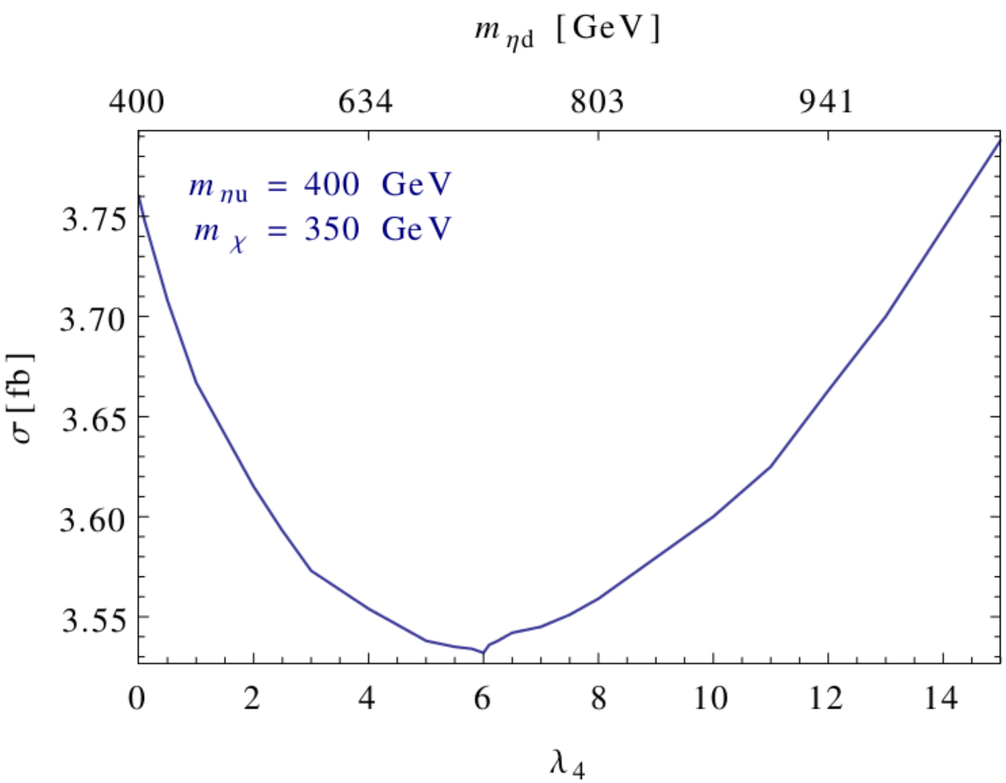


$$\frac{1}{\Lambda_d^2}(\overline{d}\Gamma d)(\overline{\chi}\Gamma\chi)$$

$$\delta m_\eta^2 \equiv m_{\eta_d}^2 - m_{\eta_u}^2 = \lambda_4\, v_{\rm EW}^2$$

Longitudinal effects



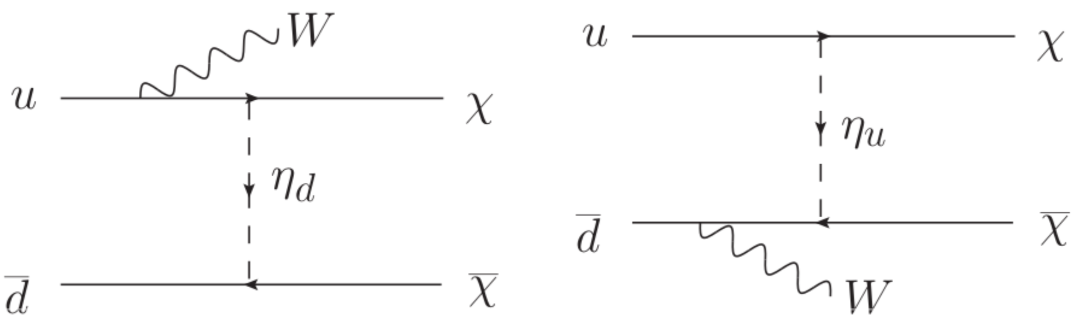


Cross section first suppressed due to increase in propagator mass, then increases when third diagram begins to dominate

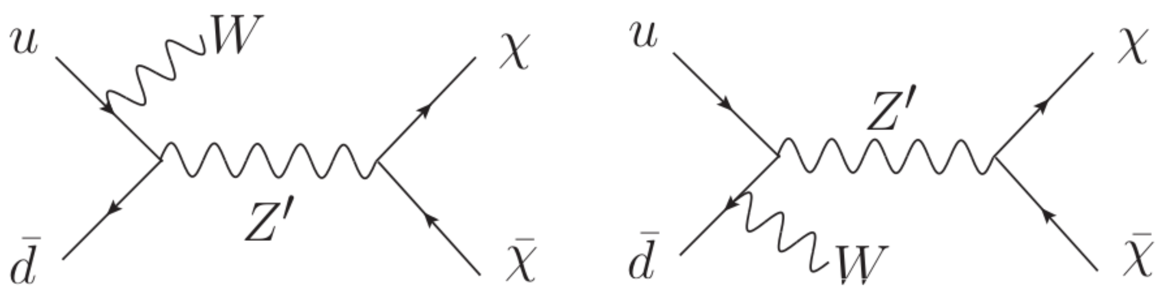
However, enforcing gauge invariance and perturbativity, this effect can't be large

Generic simplified models for mono-W

T-channel colored scalar



S-channel Z'



Consider both:

Mono lepton channel

Mono fat jet channel

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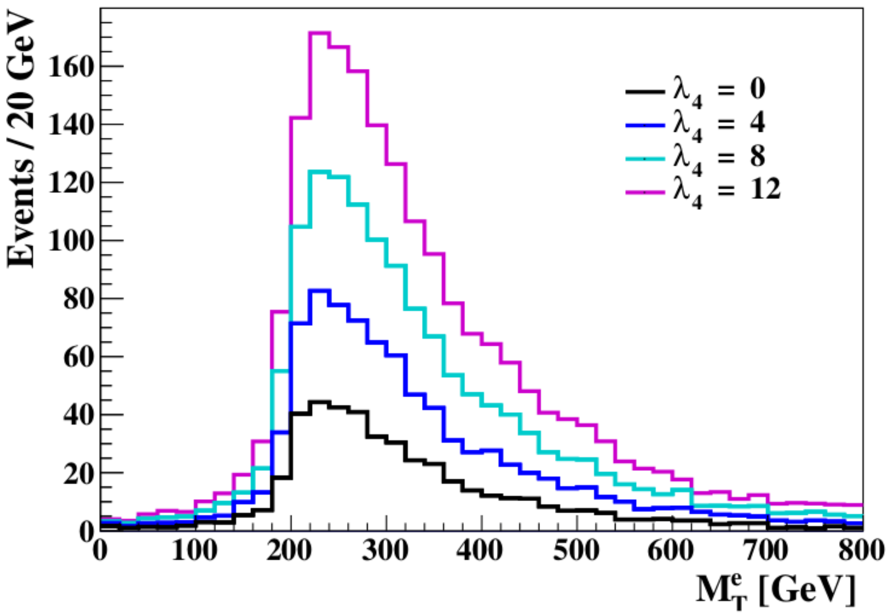
Mono lepton channel

Follow CMS mono-lepton search (arXiv: 1408.2745).
Main background W > lv. Important kinematic variable:

$$M_T = \sqrt{2 p_T^\ell \not{E}_T (1 - \cos\Delta\phi_{\ell,\nu})}$$

MC with MadGraph, Showering with Pythia, Detector effects with Delphes / Fastjet. Run two regions, with low pt and high pt cuts



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Mono fat jet channel

Follow ATLAS Hadronic W/Z + MET (arXiv:1309.4017).

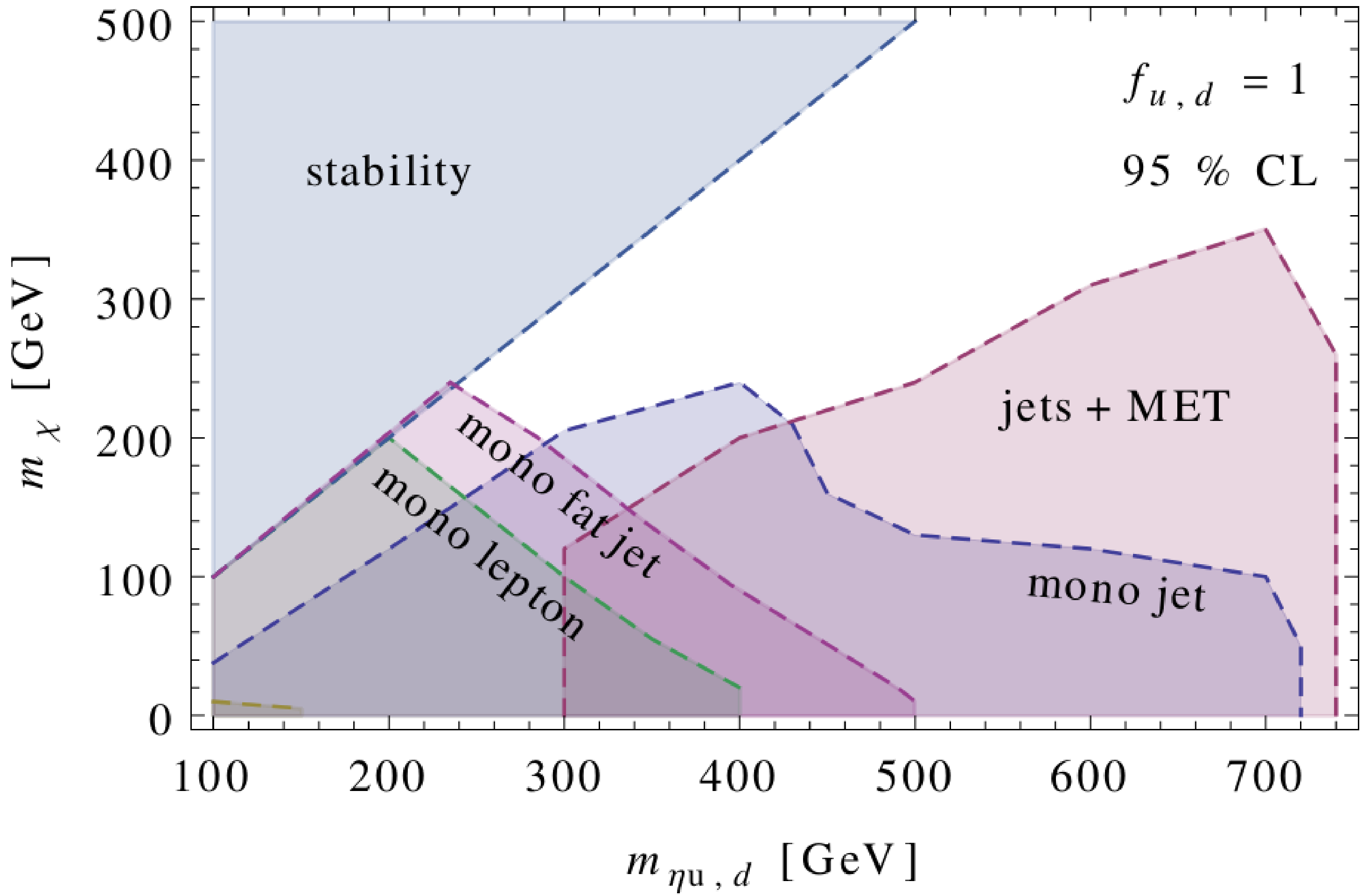
Main backgrounds are Z > vv and W > lv

- Large radius jet, “fat jet” comes from boosted W or Z bosons, Cambridge Aachen jet algorithm
- Mass drop/filter used to examine substructure of fat jet, anti-kt jet algorithm

- Allows to differentiate from large QCD backgrounds.

- MadGraph → Pythia → Fastjet /Delphes / Root

T-channel LHC limits and reach summary



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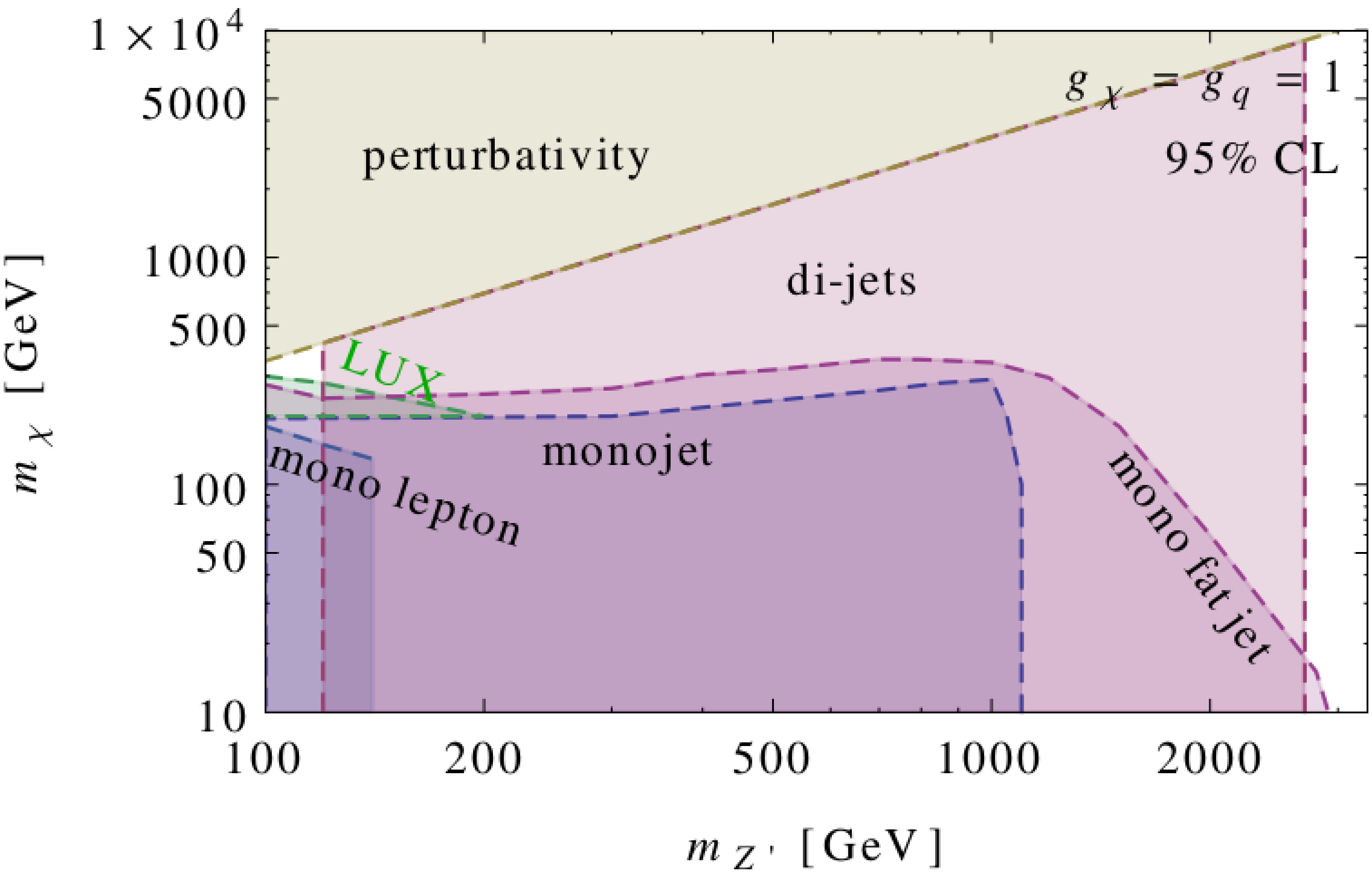
S-channel LHC limits and reach summary



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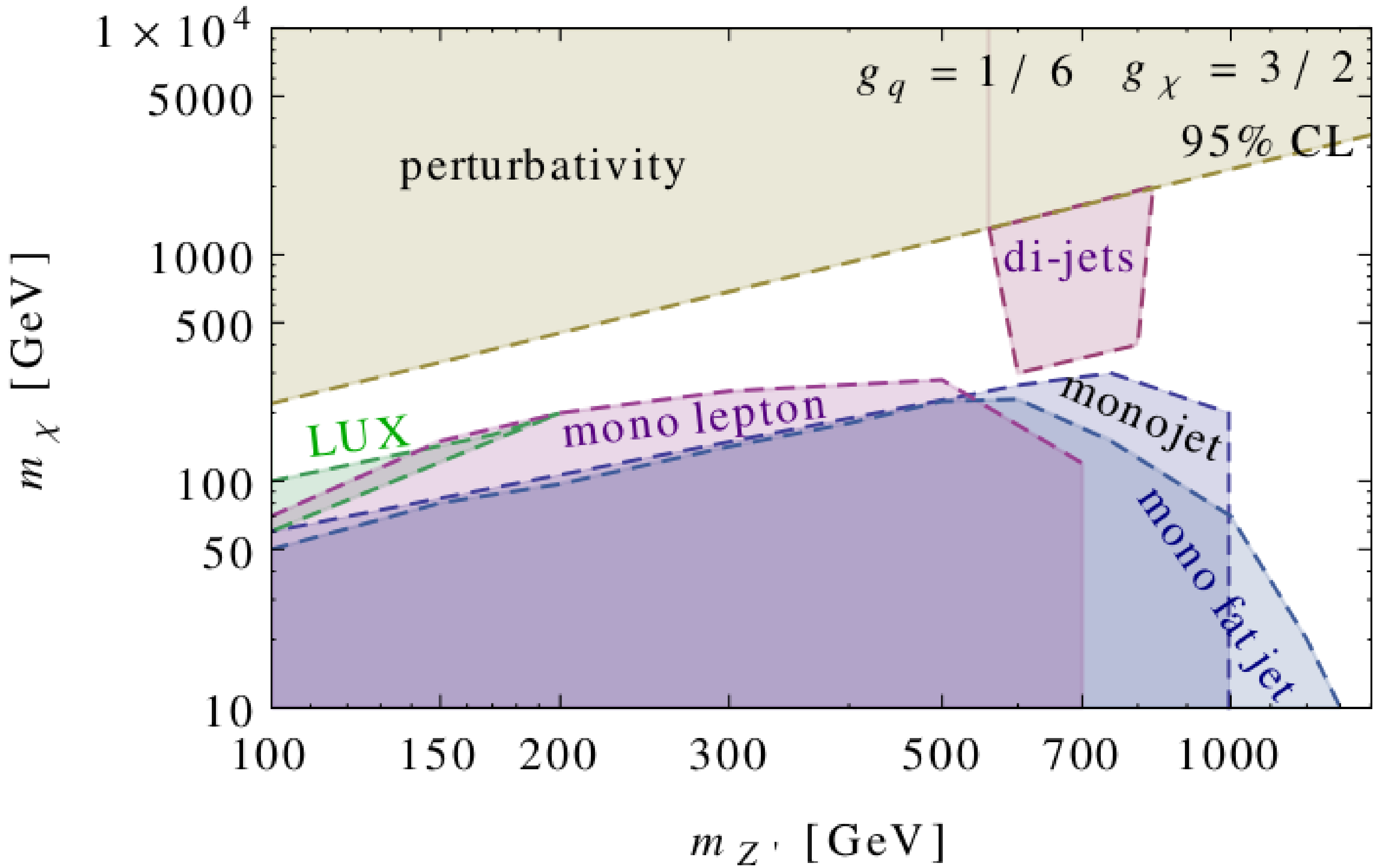
S-channel LHC limits and reach summary



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Other ways to look for DM at the LHC?

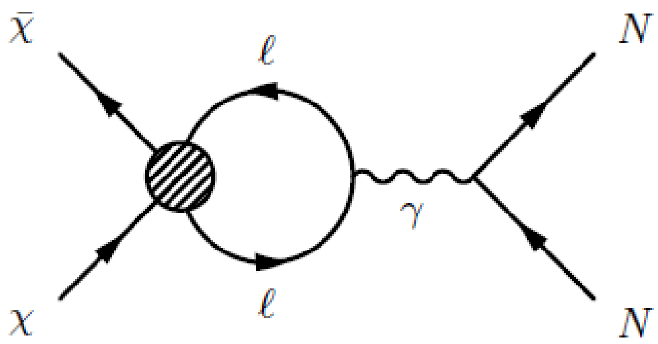
- WIMPs becoming more constrained, but constraints are based on DM-hadron interactions

….perhaps DM does not interact this way?

- Indirect detection experiments observed excess in cosmic ray positron fraction, suggesting DM annihilates to leptonic final states
- Suggest scenario where DM couples exclusively to leptons at tree level. Standard Mono-X LHC searches are not applicable!

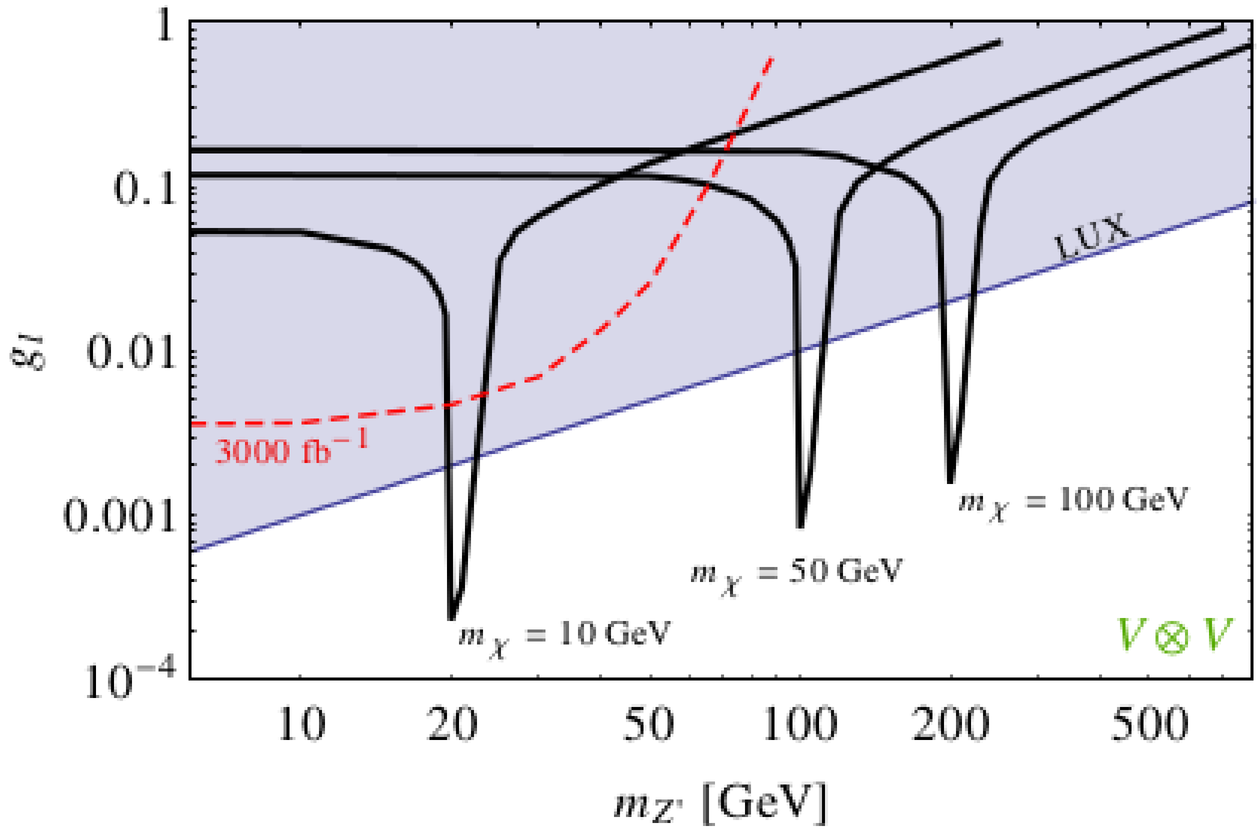
Leptophilic DM Model

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} - \frac{\epsilon}{2} Z'_{\mu\nu} B^{\mu\nu} + i\bar{\chi}\gamma_\mu \partial^\mu \chi$$
$$+ \bar{\chi}\gamma^\mu (g_\chi^V + g_\chi^A \gamma^5)\chi Z'_\mu + \bar{\ell}\gamma^\mu (g_\ell^V + g_\ell^A \gamma^5)\ell Z'_\mu$$
$$- m_\chi \bar{\chi}\chi + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu,$$

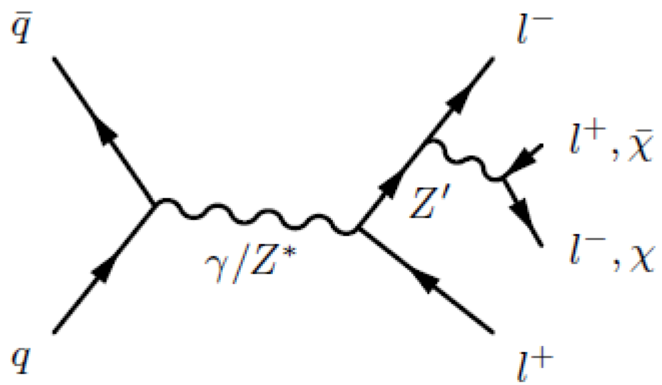


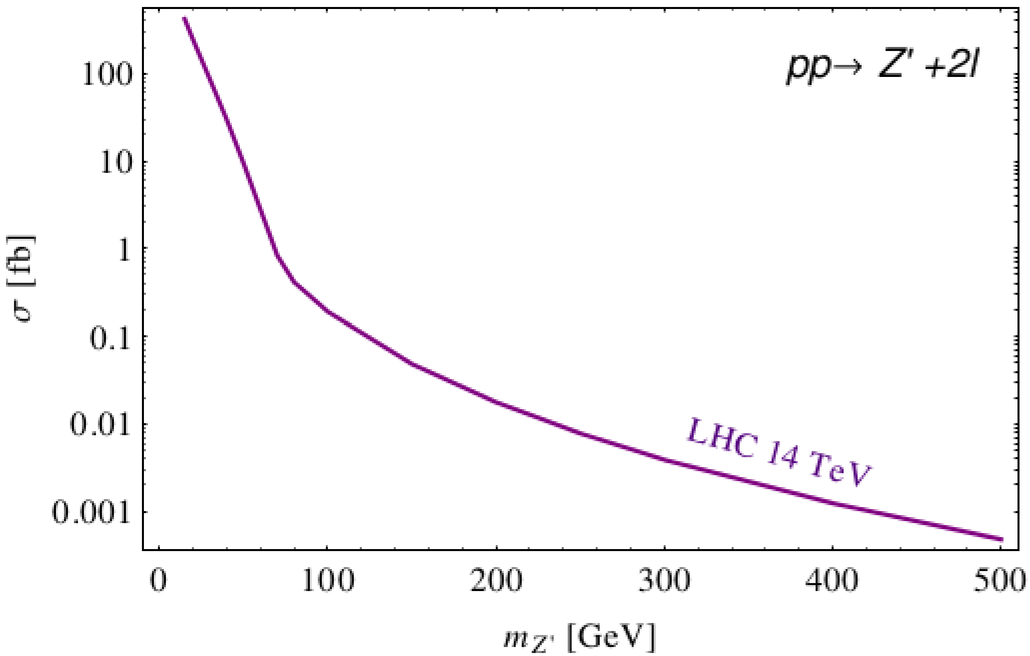
$\Gamma_\chi \otimes \Gamma_\ell$	$\sigma(\chi\chi \to \bar{\ell}\ell)$	$\sigma(\chi N \to \chi N)$	Gauge invariant?
$V \otimes V$	s-wave	1 (1-loop)	Yes
$A \otimes V$	p-wave	v^2 (1-loop)	Yes
$V \otimes A$	s-wave	-	No
$A \otimes A$	p-wave	-	No

Vector-vector Z’ couplings



LHC phenomenology





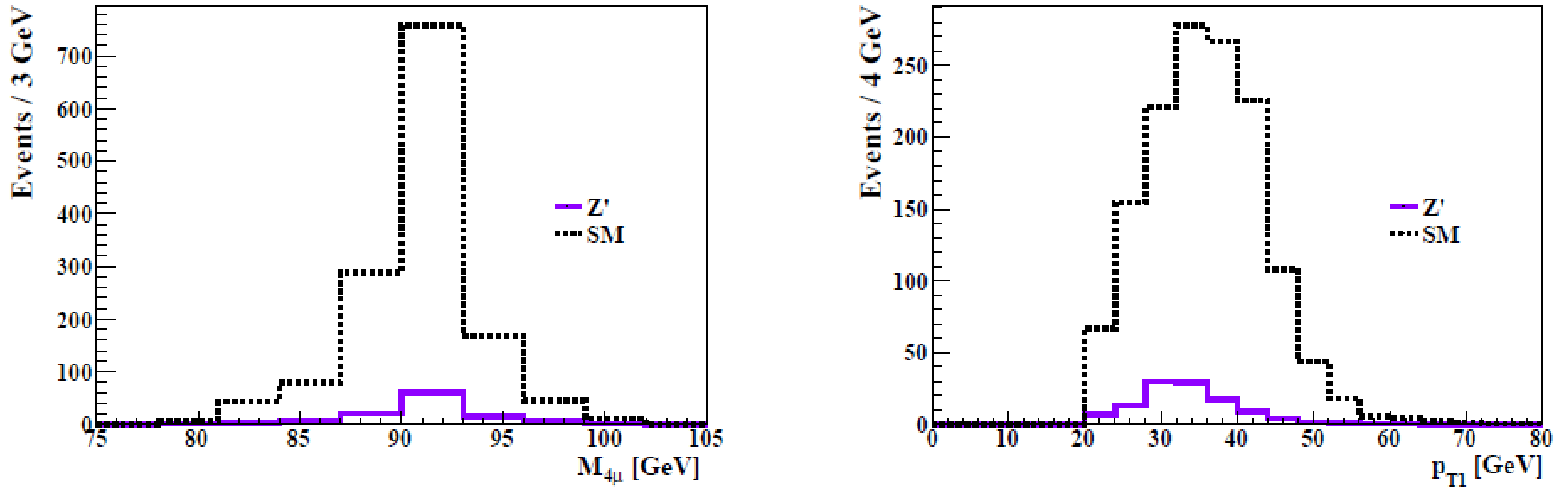


FIG. 9. Invariant mass for four muons (left) and transverse momentum p_T for leading in p_T muon (right) for $pp \to 4\mu$ in the SM and Z' model (with $m_{Z'} = 60$ GeV, $m_\chi = 10$ GeV, $g_\mu = g_\chi = 0.1$), at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 300\ fb^{-1}$. The peak in the four muon invariant mass spectrum is a reconstruction of the Z mass.

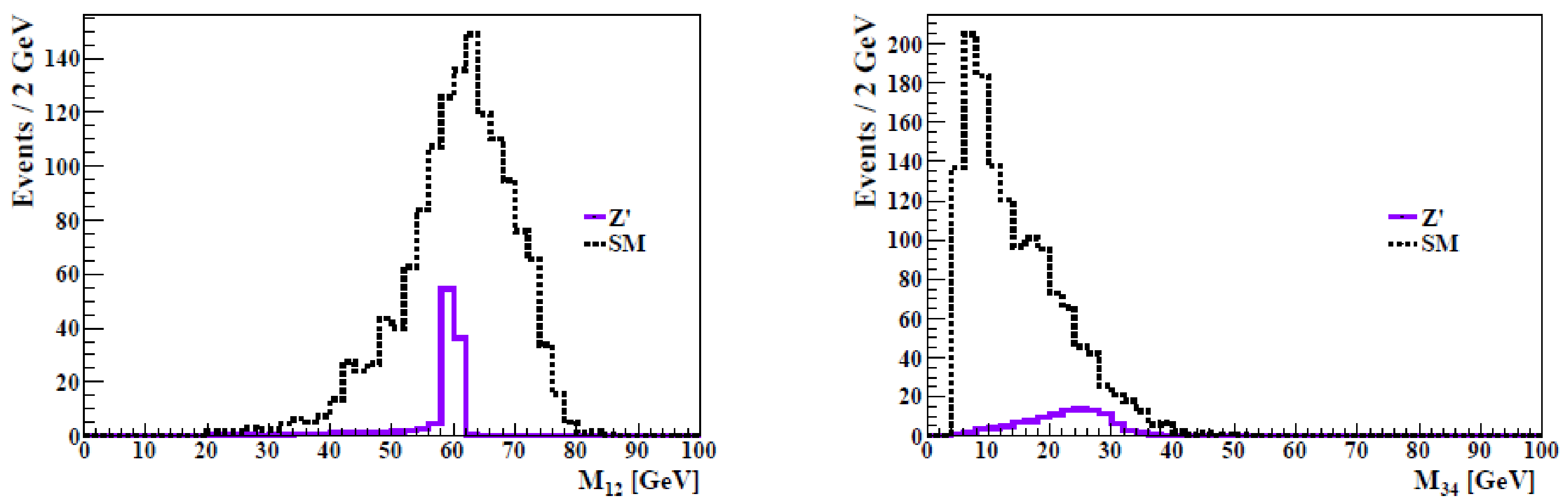


FIG. 10. Invariant mass for first and second leading muons in p_T (left) and third and fourth leading muons in p_T (right) for $pp \to 4\mu$ in the SM and Z' model (with $m_{Z'} = 60$ GeV, $m_\chi = 10$ GeV, $g_\mu = g_\chi = 0.1$), at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 300\ fb^{-1}$. The mass of the Z' can be seen clearly as the resonance at $m_{Z'} = 60$ GeV in the invariant mass spectrum M_{12}.

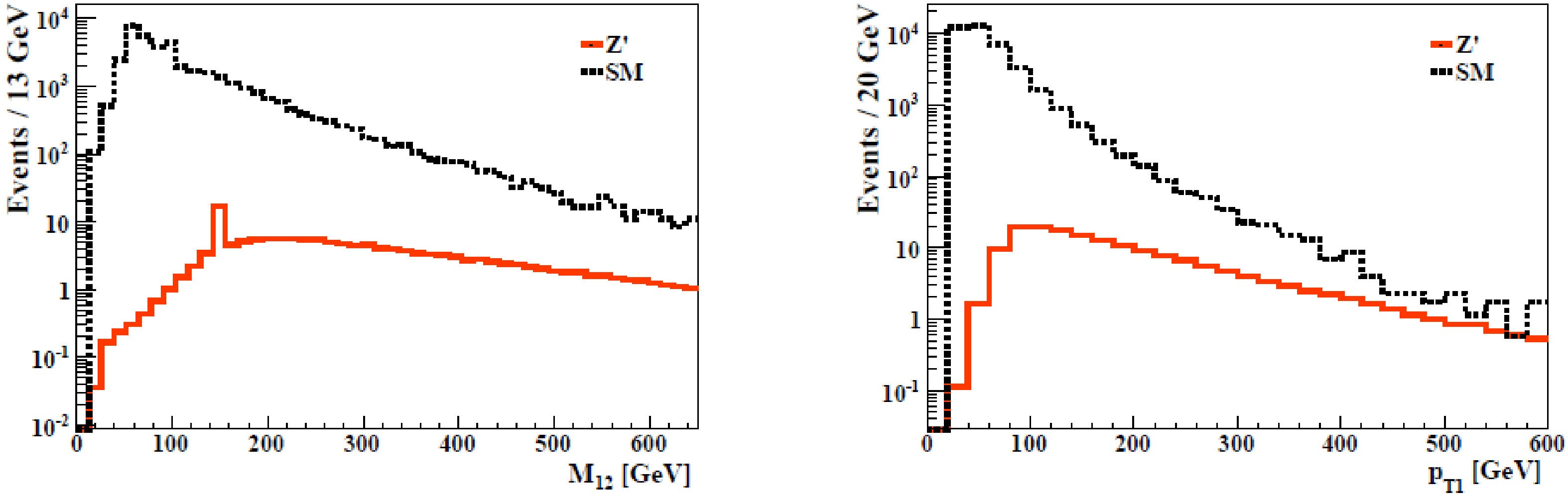


FIG. 11. Invariant mass for first and second leading muons in p_T (left) and transverse momentum p_T for p_T leading muon (right) both before cuts, for $pp \to 4\mu$ in the SM and Z' model (with $m_{Z'} = 150$ GeV, $m_\chi = 10$ GeV, $g_\mu = g_\chi = 0.19$), at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3000\ fb^{-1}$.

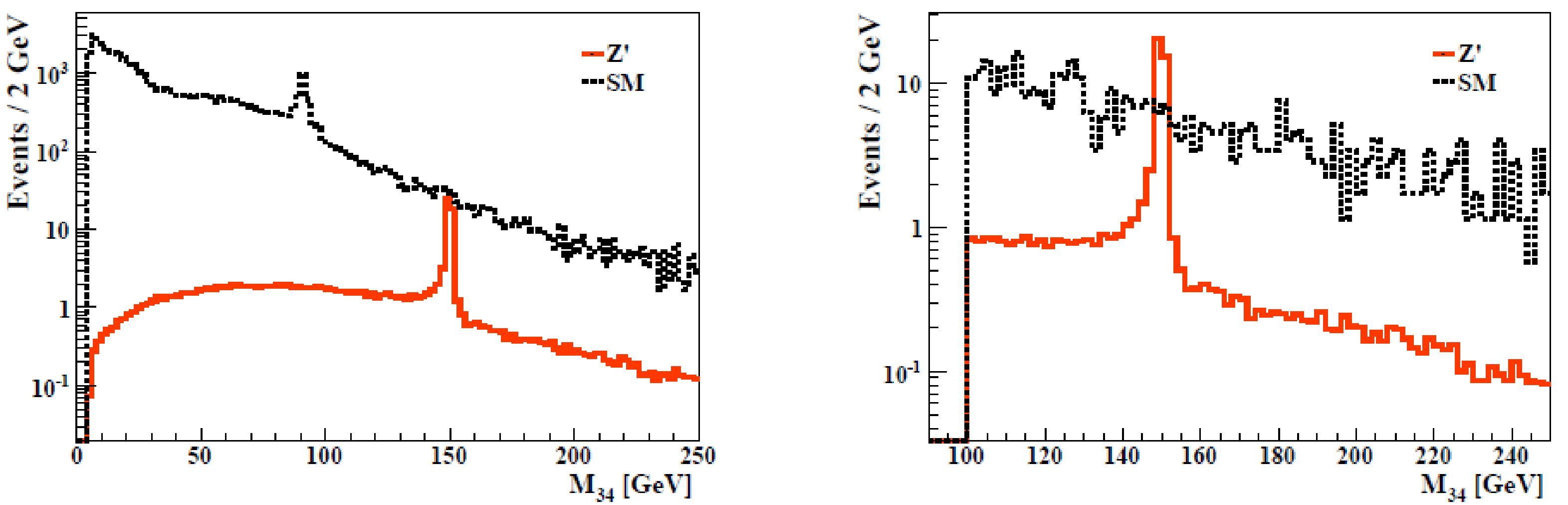
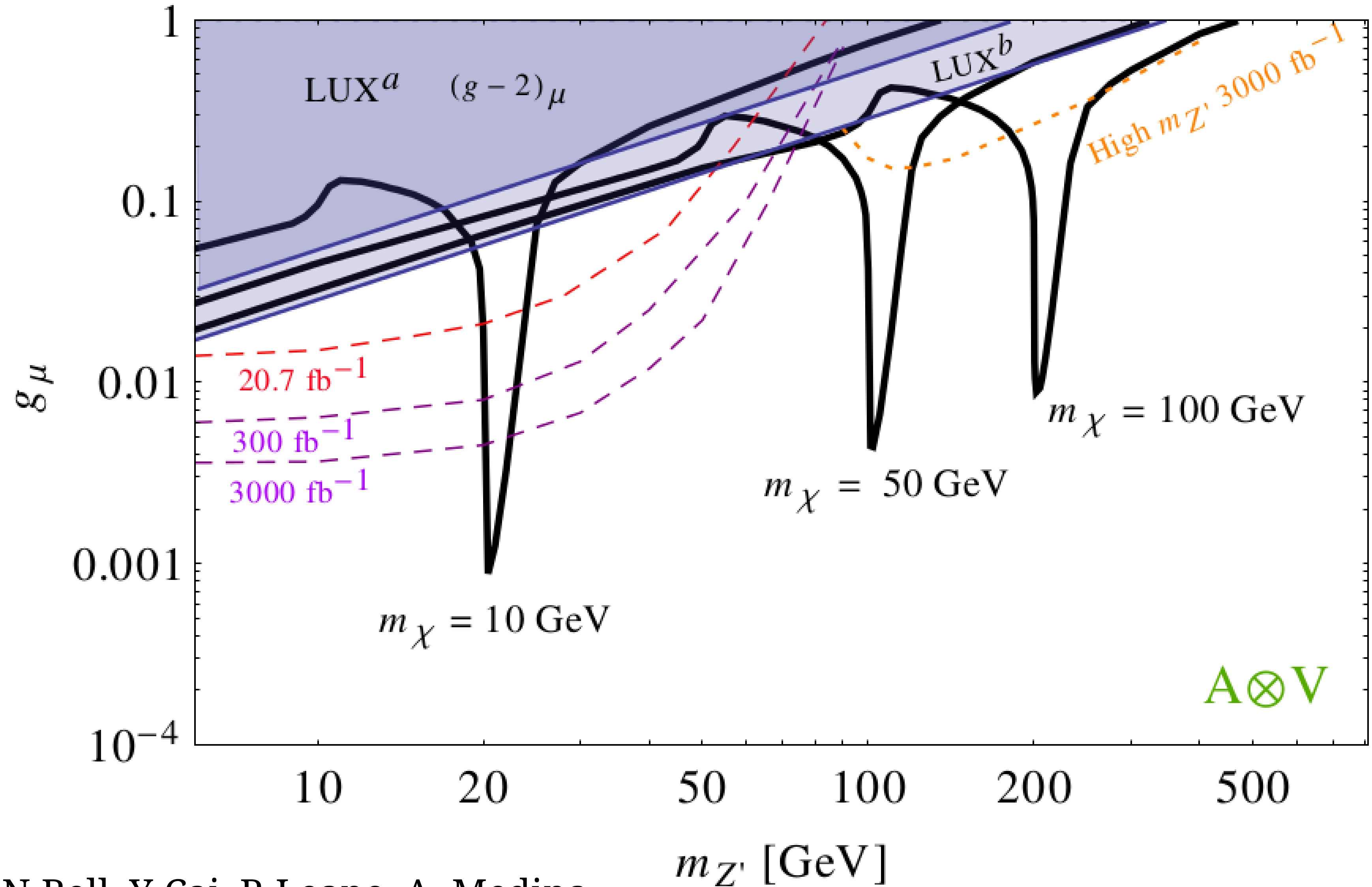


FIG. 12. Invariant mass of third and fourth leading in p_T muons before cuts (left) and after cuts (right), for $pp \to 4\mu$ in the SM and Z' model (with $m_{Z'} = 150$ GeV, $m_\chi = 10$ GeV, $g_\mu = g_\chi = 0.19$), at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3000\ fb^{-1}$.



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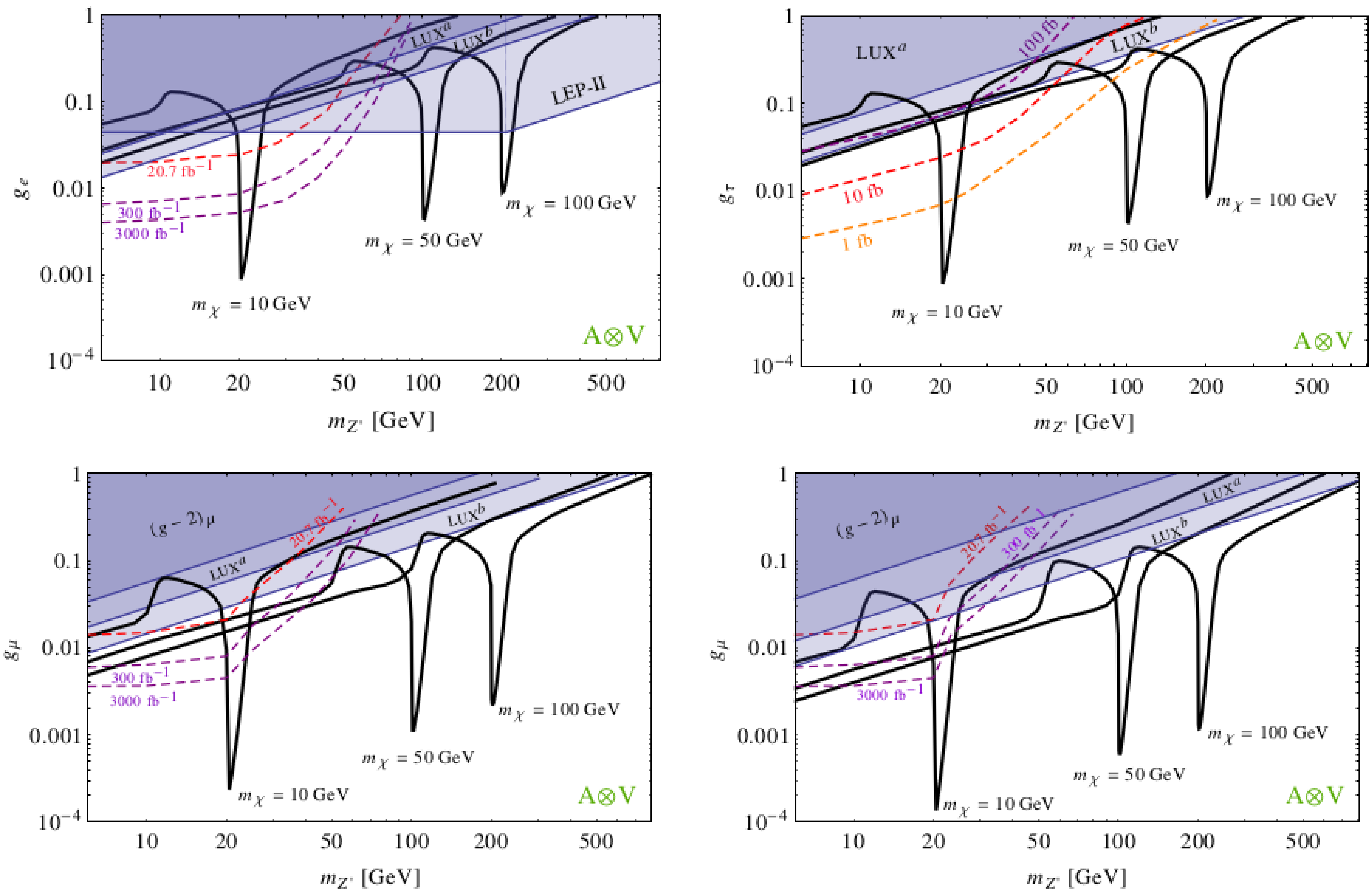

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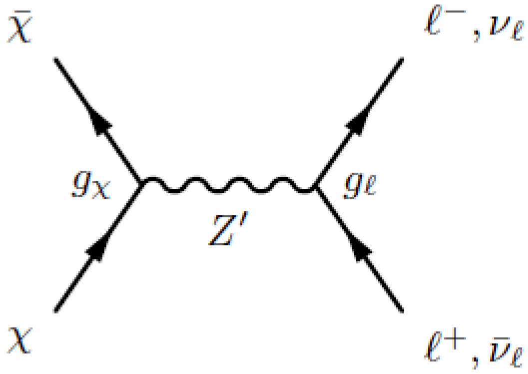
Summary

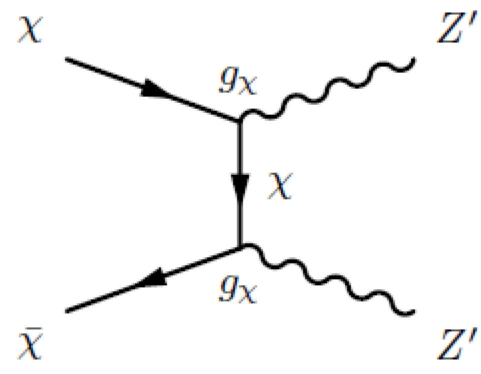
LHC provides a method of dark matter detection… good to know what to look for and how to go about it!

- Mono-X signatures popular. Mono-W signal unique in ability to probe differing DM couplings to u and d quarks
- However any difference is protected by EW scale, cannot be arbitrarily large… there is no huge "interference effect"
- Any SU(2) violating operators should be suppressed by factors relating to the Higgs vev
- Should use UV complete, gauge invariant model rather than EFT to avoid longitudinal W problems.
- Mass splitting does not substantially increase the cross section in the gauge invariant model, but still can probe DM with mono-W, leading to complementary results
- DM can have other LHC signatures other than mono-X. Leptophilic DM is interesting model which can explain lack of signals at many hadron based experiments… but still can be highly constrained!

Run II at the LHC is a crucial time for dark matter… stay tuned!

DM Relic Density





- Larger couplings = subdominant contribution to the relic density,
- Smaller couplings = overclose universe unless additional annihilation channels present

- The Z'Z' channel is kinematically open only for Z' mass < DM mass, while for Z' mass > DM mass, the freeze-out is determined by annihilation to leptons.

- The annihilation cross section to leptons has an s-wave contribution when vector-like Z' coupling to DM, but proceeds via a velocity suppressed p-wave contribution with axial-vector bilinear.