Dark Matter at the LHC: EFTs and Gauge Invariance

Rebecca Leane

In collaboration with Nicole Bell, Yi Cai, James Dent and Tom Weiler

arXiv: 1503.07874

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

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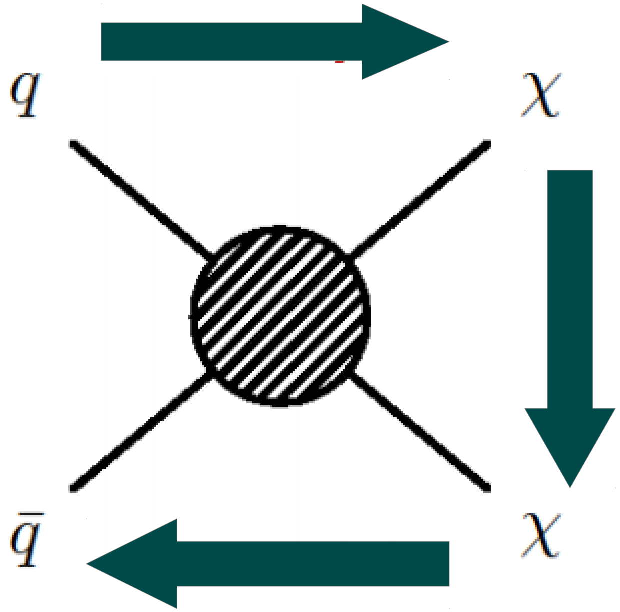
What is dark matter?

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

Collider searches

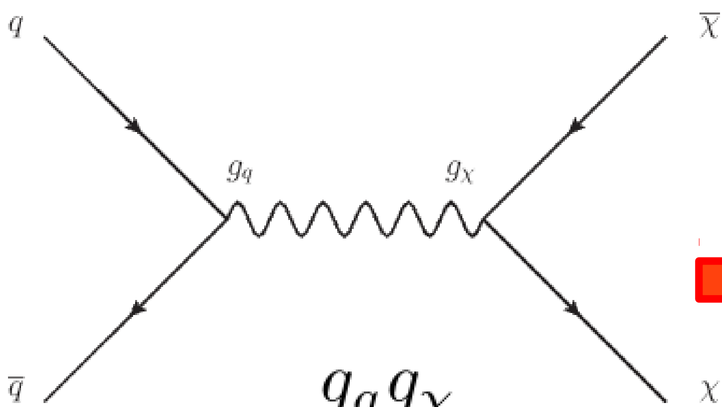


Direct detection

Indirect detection

Searches provide complementary information

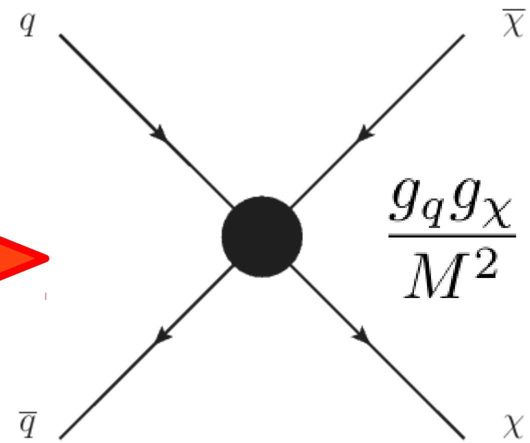
EFTs in a nutshell



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

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

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



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

- 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!

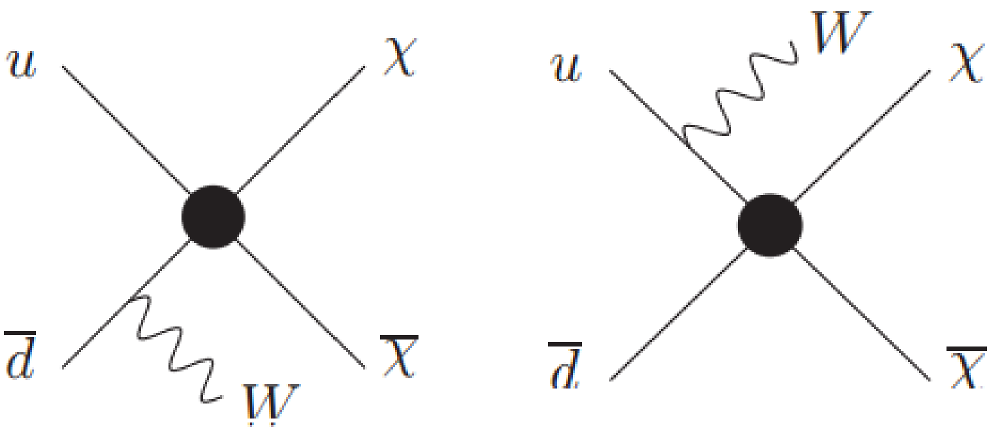
DM-SM effective operators which violate the SM weak gauge symmetries necessarily carry an extra prefactor of the Higgs vev to some power. Origin is the SU(2) scalar doublet

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

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

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

Application to Mono-W EFT



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

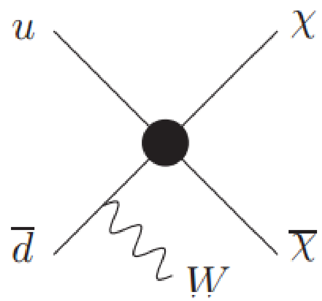
Literature sets $\xi \neq +1$, claims to find "interference effect". Analysis is repeated by ATLAS and CMS and it is used to set strong bounds on DM from mono-W searches.

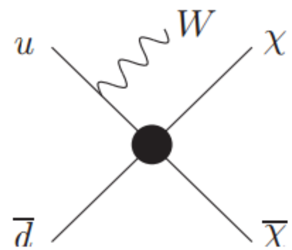
$$\frac{v_{\mathrm{EW}}^2}{\Lambda^4}(\overline{\chi}\gamma^\mu\chi)(\overline{u_L}\gamma_\mu u_L) \qquad \boxed{\begin{pmatrix} u \\ d \end{pmatrix}_L}$$

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





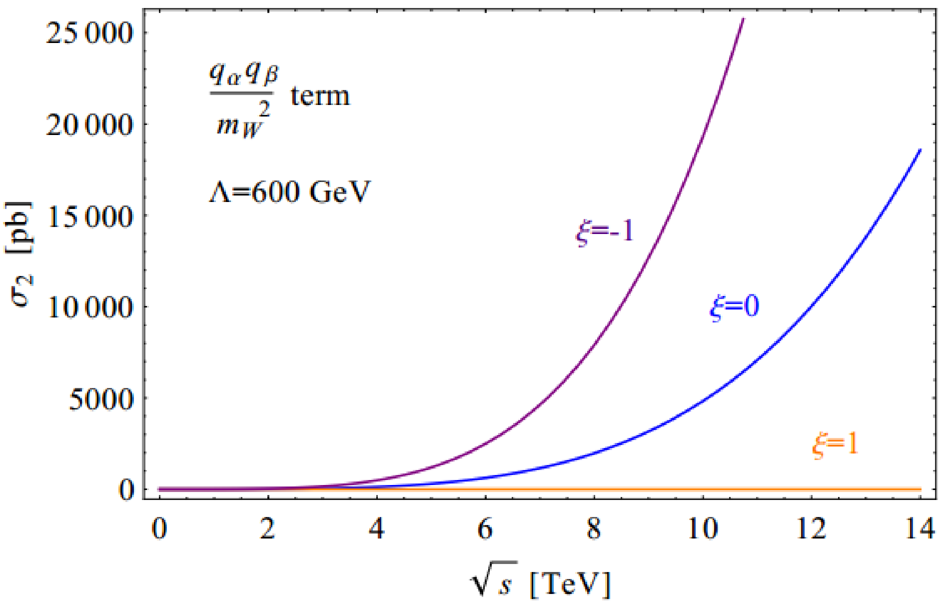
$$\sum_\lambda \epsilon^\lambda_\alpha \epsilon^{\lambda\,*}_\beta = -g_{\alpha\beta} + \frac{q_\alpha q_\beta}{m_W^2}$$

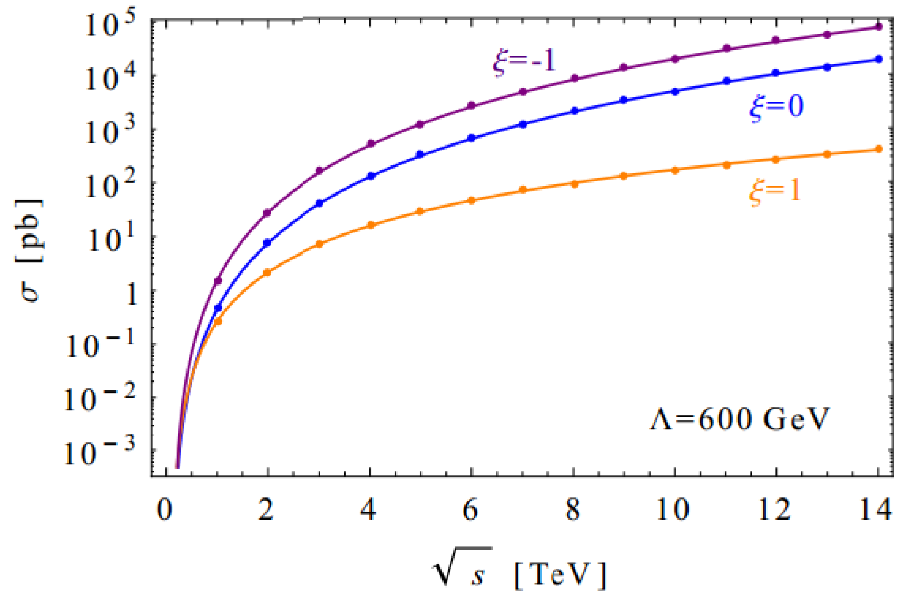
$$\epsilon^L_\alpha = \frac{q_\alpha}{m_W} + \mathcal{O}\left(\frac{m_W}{E}\right) \sim \frac{\sqrt{s}}{m_W}$$

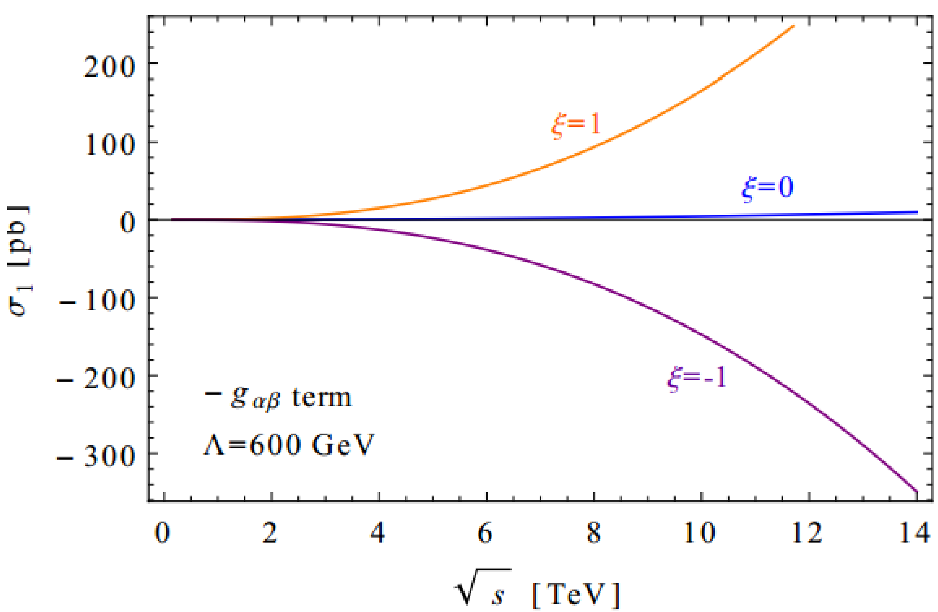
$$\epsilon^L_\alpha \epsilon^{L\,*}_\beta \approx q_\alpha q_\beta / m_W^2 \sim s/m_W^2$$

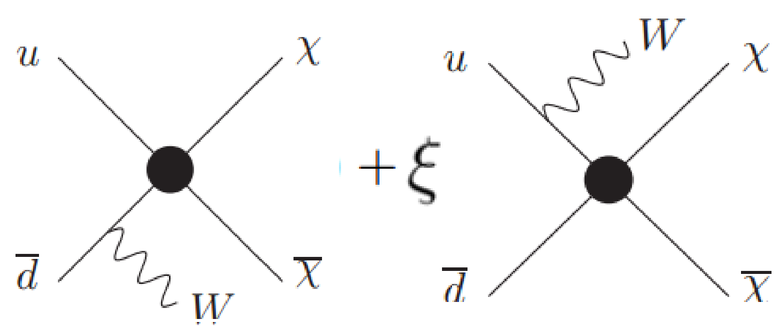
- Goldstone boson equivalence theorem states that, in the high energy limit, the amplitude for emission of a longitudinally polarized W is equivalent to the amplitude for emission of the corresponding Goldstone boson
- Goldstone couples proportionally to mass of quarks, so for longitudinal W emission,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

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


$\frac{q_\alpha q_\beta}{m_W^2}$ term
Λ=600 GeV
ξ=-1
ξ=0
ξ=1
σ_2 [pb]
25 000
20 000
15 000
10 000
5000
0
0 2 4 6 8 10 12 14
$\sqrt{s}$ [TeV]


ξ=-1
ξ=0
ξ=1
Λ=600 GeV
σ [pb]
10^5
10^4
10^3
10^2
10^1
1
10^{-1}
10^{-2}
10^{-3}
0 2 4 6 8 10 12 14
$\sqrt{s}$ [TeV]


ξ=1
ξ=0
ξ=-1
$-g_{\alpha\beta}$ term
Λ=600 GeV
σ_1 [pb]
200
100
0
− 100
− 200
− 300
0 2 4 6 8 10 12 14
$\sqrt{s}$ [TeV]


u
χ
$\bar{d}$
$\bar{\chi}$
W
$+\xi$
u
W
χ
$\bar{d}$
$\bar{\chi}$

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/m_W^2 , which originate from the term in the polarization sum below:

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

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

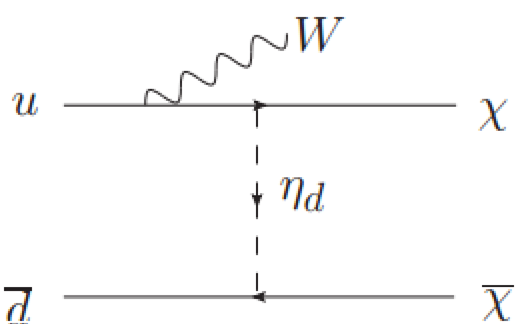
Renormalizable model

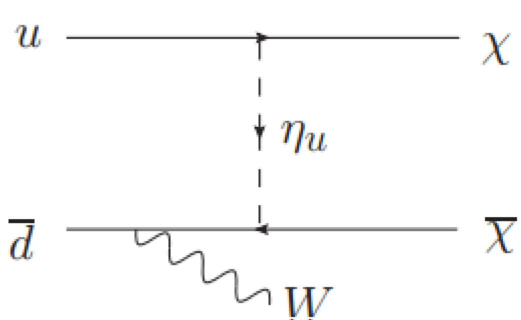
$$\mathcal{L}_{\text{int}} = f\overline{Q_L}\eta\chi_R + h.c$$
$$= f_{ud}\left(\eta_u\overline{u}_L + \eta_d\overline{d}_L\right)\chi_R + h.c.$$

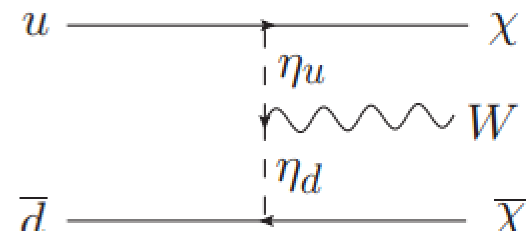
$$V = m_1^2(\Phi^\dagger\Phi) + \frac{1}{2}\lambda_1(\Phi^\dagger\Phi)^2 + m_2^2(\eta^\dagger\eta) + \frac{1}{2}\lambda_2(\eta^\dagger\eta)^2$$
$$+ \lambda_3(\Phi^\dagger\Phi)(\eta^\dagger\eta) + \lambda_4(\Phi^\dagger\eta)(\eta^\dagger\Phi)$$

Parallels to EFT effect via mass splitting

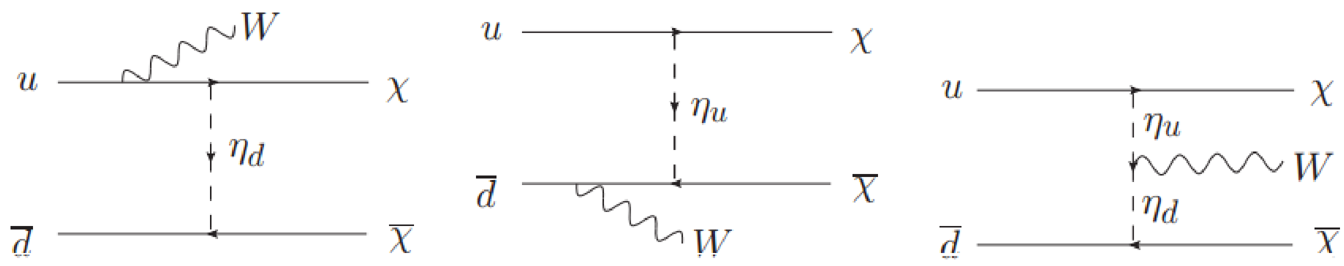
$$\delta m_\eta^2 \equiv m_{\eta_d}^2 - m_{\eta_u}^2 = \lambda_4\, v_{\text{EW}}^2$$

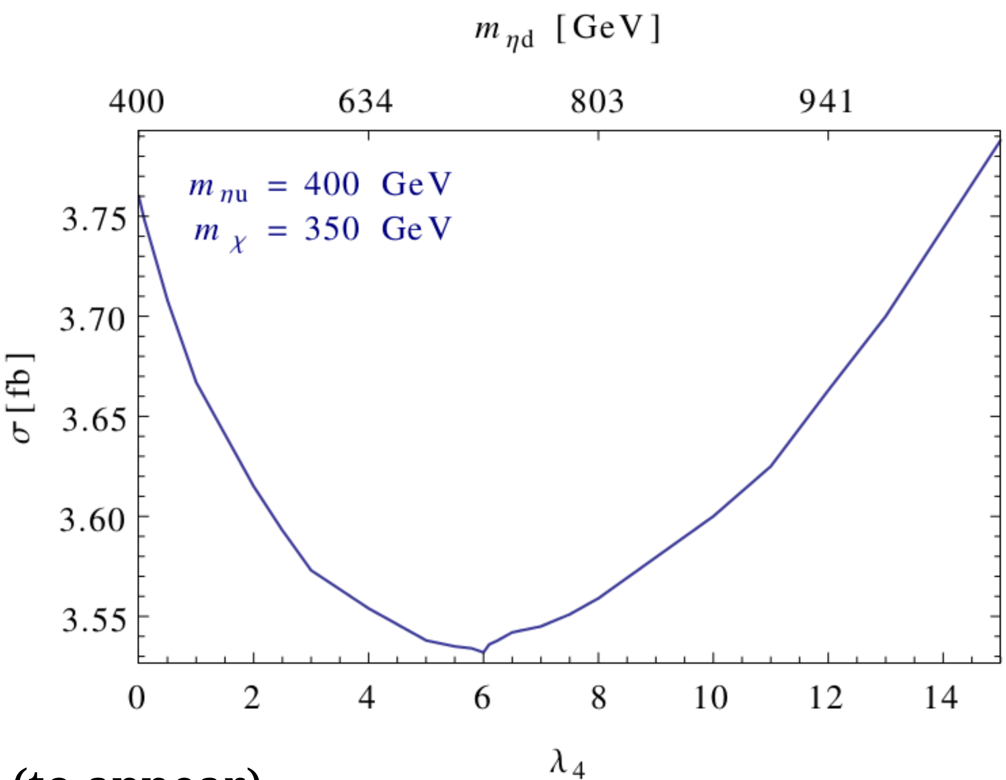






Longitudinal effects



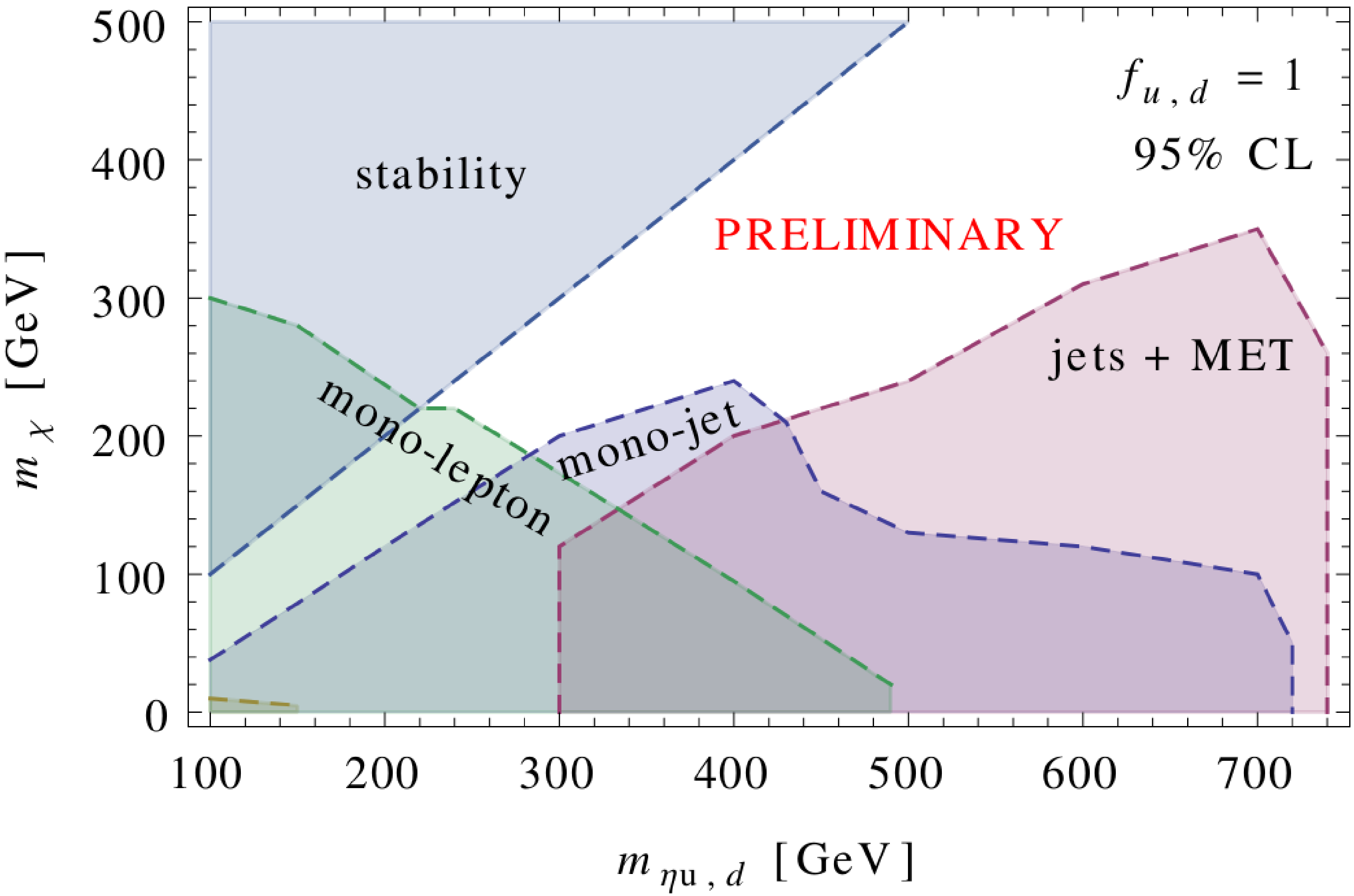


Cross section first suppressed due to increase in propagator mass, then increases when third diagram begins to dominate

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

(to appear)

LHC limits and reach summary



(to appear)

Summary

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

- Mono-W signal unique in ability to probe 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

These observations will be an important guide to LHC collaborations in interpreting current and future mono-W DM searches, and for theorists constructing EFTs.