Unitarity and Gauge Invariance in Dark Matter Models

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CETUP*2016 7 / 8 / 16

THE UNIVERSITY OF MELBOURNE

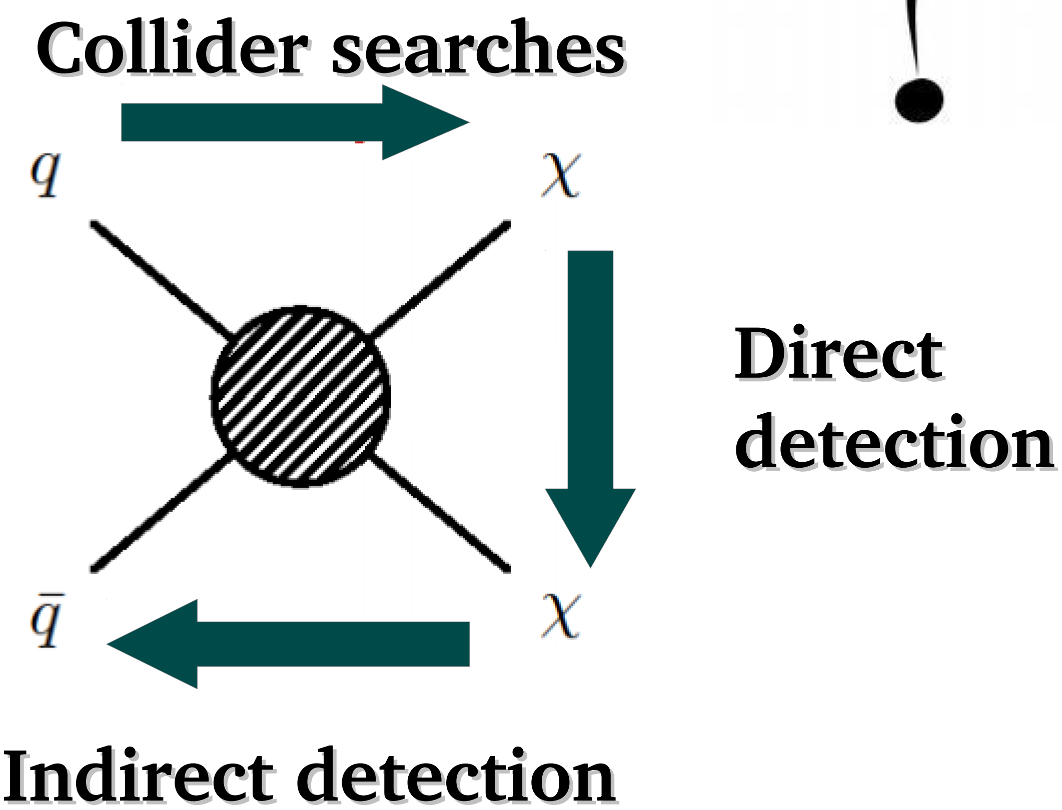
CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Based on:

1503.07874
1512.00476
1605.09382

Probing the nature of DM

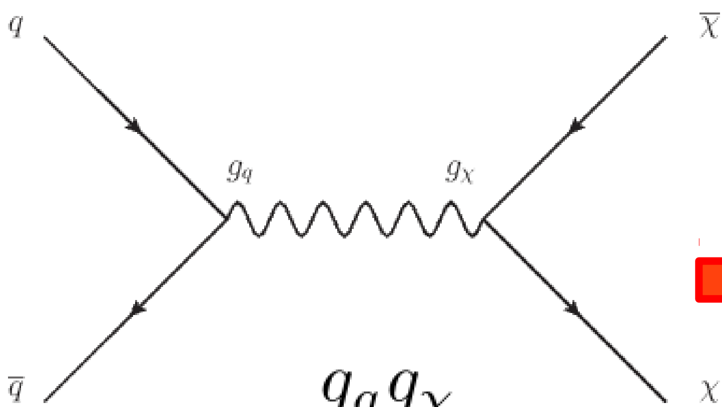
- Still no idea about fundamental nature
- WIMP dark matter well motivated
- Realistic detection prospects



Searches provide complementary information

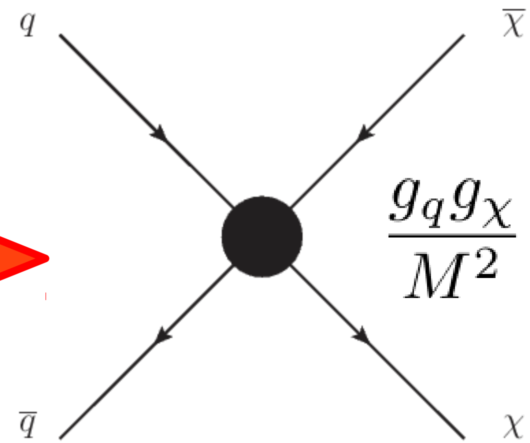
EFTs in a nutshell

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



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

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



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

- 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!

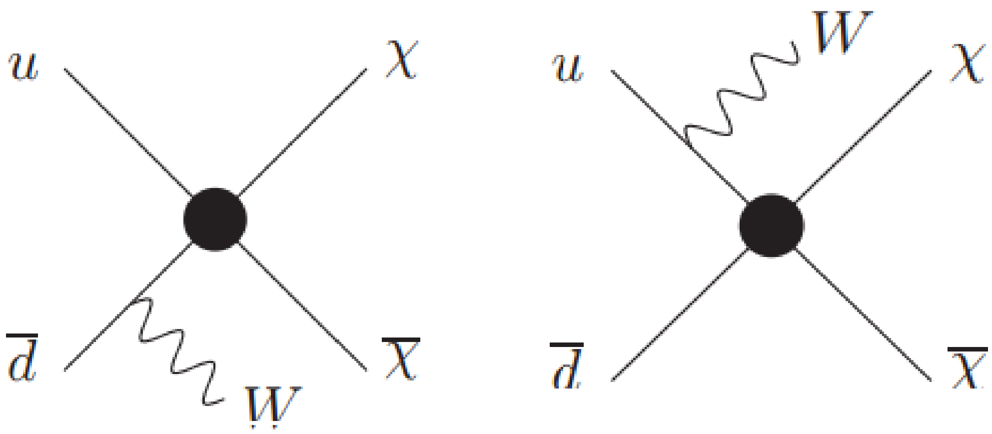
DM-SM effective operators which violate the SM weak gauge symmetries necessarily carry an extra prefactor of the Higgs vev to some power. Origin is the SU(2) scalar doublet

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

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

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

Application to Mono-W EFT



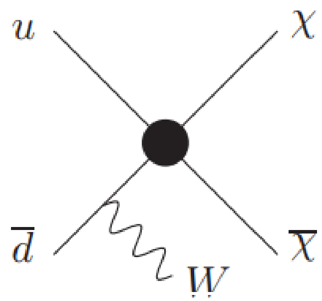
$$\frac{1}{\Lambda^2}\left(\overline{\chi}\gamma^\mu\chi\right)\left(\overline{u}\gamma_\mu u+\xi\overline{d}\gamma_\mu d\right)$$

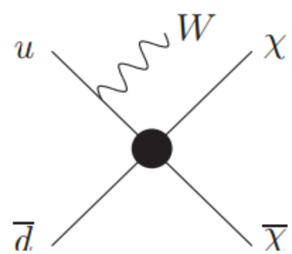
Literature sets $\xi \neq 1$, claims to find interference effect. Analysis is repeated by ATLAS and CMS and it is used to set strong bounds on DM from mono-W searches.

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

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

Polarization vectors





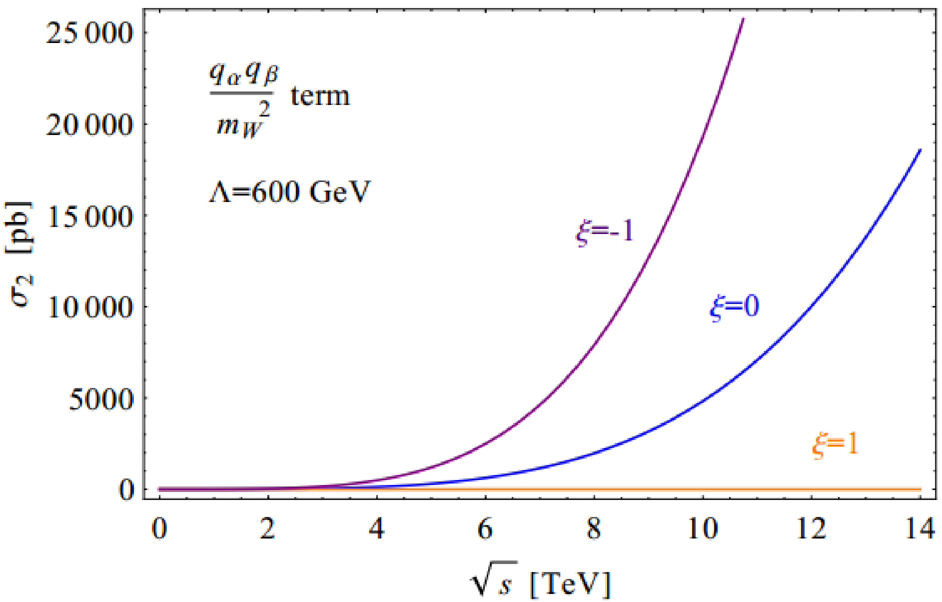
$$\sum_\lambda \epsilon_\alpha^\lambda \epsilon_\beta^{\lambda\,*} = -g_{\alpha\beta} + \frac{q_\alpha q_\beta}{m_W^2}$$

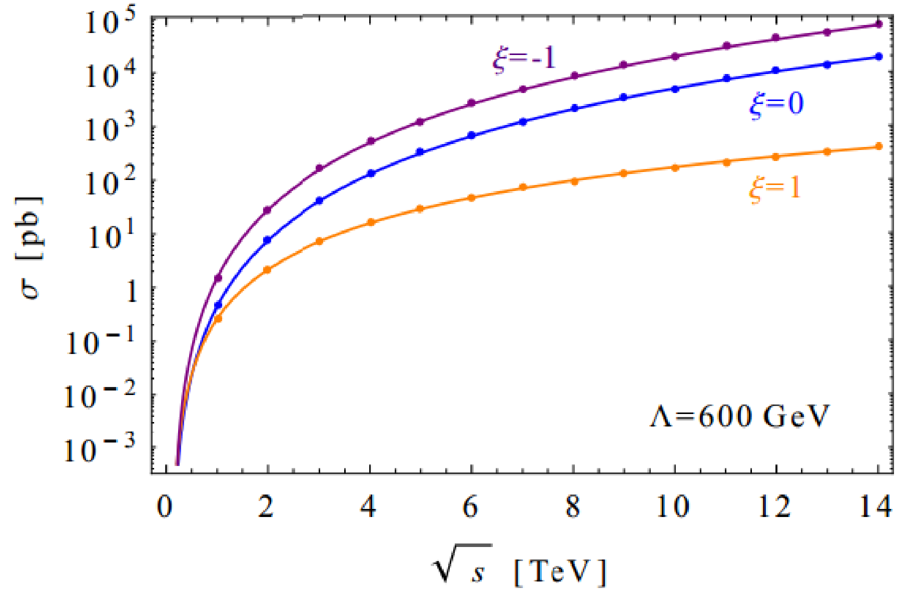
$$\epsilon_\alpha^L = \frac{q_\alpha}{m_W} + \mathcal{O}\left(\frac{m_W}{E}\right) \sim \frac{\sqrt{s}}{m_W}$$

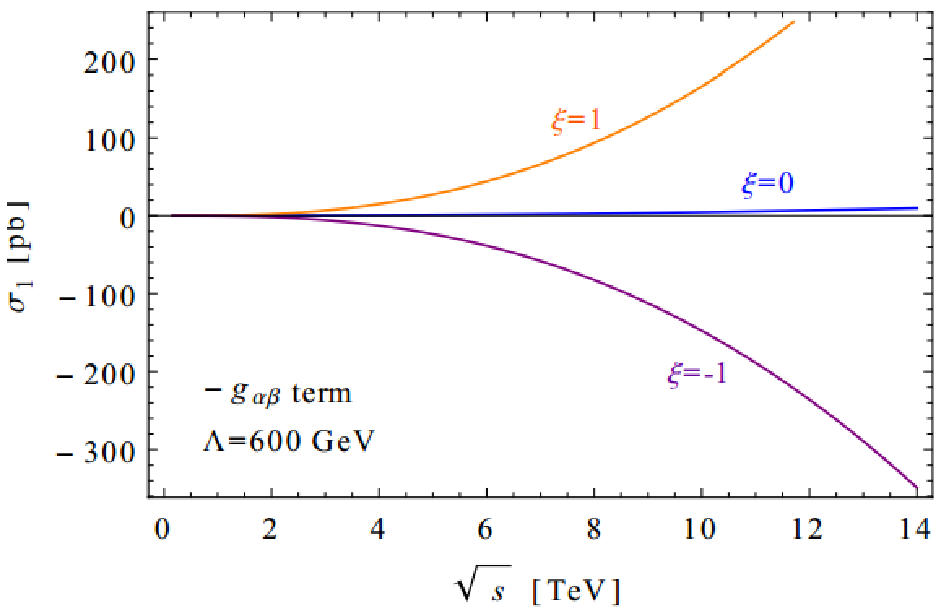
$$\epsilon_\alpha^L \epsilon_\beta^{L\,*} \approx q_\alpha q_\beta / m_W^2 \sim s/m_W^2$$

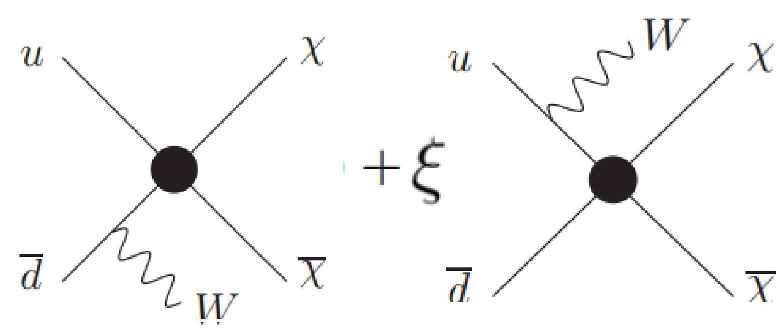
- Goldstone boson equivalence theorem states that, in the high energy limit, the amplitude for emission of a longitudinally polarized W is equivalent to the amplitude for emission of the corresponding Goldstone boson
- Goldstone couples proportionally to mass of quarks, so for longitudinal W emission,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

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









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1503.07874

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 $\xi = -1$ is in fact due to unphysical terms that grow like s/m_W^2, which originate from the term in the polarization sum below:

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

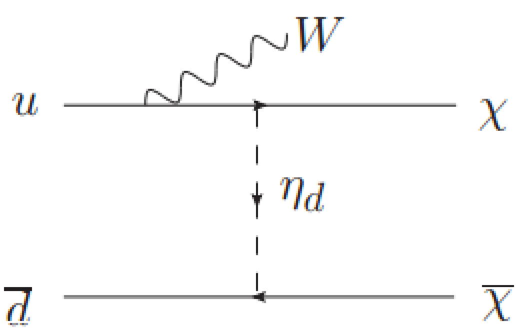
$$\epsilon_\alpha^L \epsilon_\beta^L{}^* \approx \quad q_\alpha q_\beta / m_W^2 \sim s/m_W^2$$

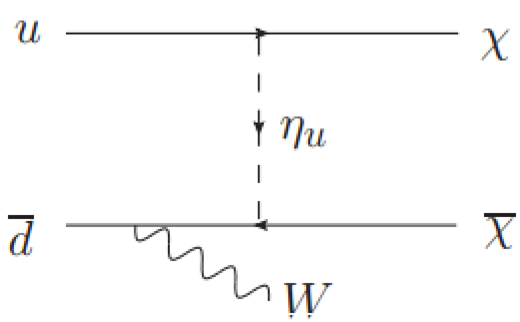
Renormalizable model

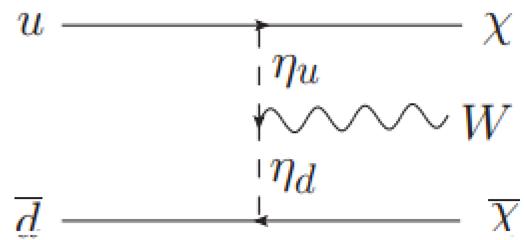
$$\mathcal{L}_{\rm int} = f\overline{Q_L}\eta\chi_R + h.c$$
$$= f_{ud}\left(\eta_u\overline{u}_L + \eta_d\overline{d}_L\right)\chi_R + h.c.$$

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

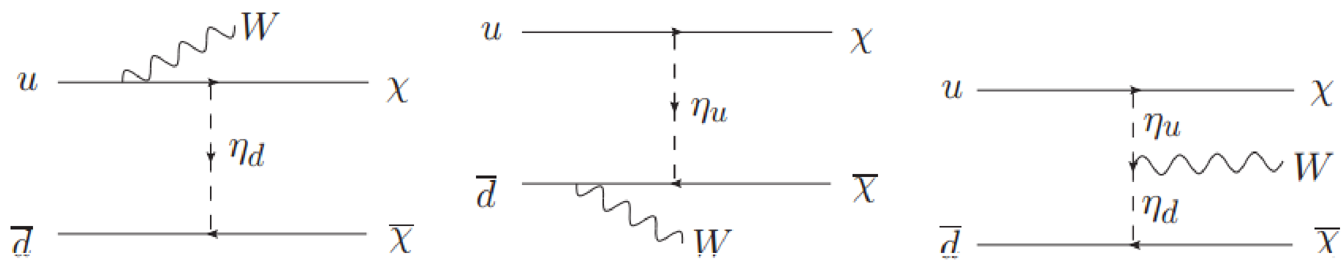
$$m_{\eta_d}^2 = m_2^2 + (\lambda_3 + \lambda_4)v_{\rm EW}^2$$
$$m_{\eta_u}^2 = m_2^2 + \lambda_3 v_{\rm EW}^2$$
$$\delta m_\eta^2 \equiv m_{\eta_d}^2 - m_{\eta_u}^2 = \lambda_4\, v_{\rm EW}^2$$

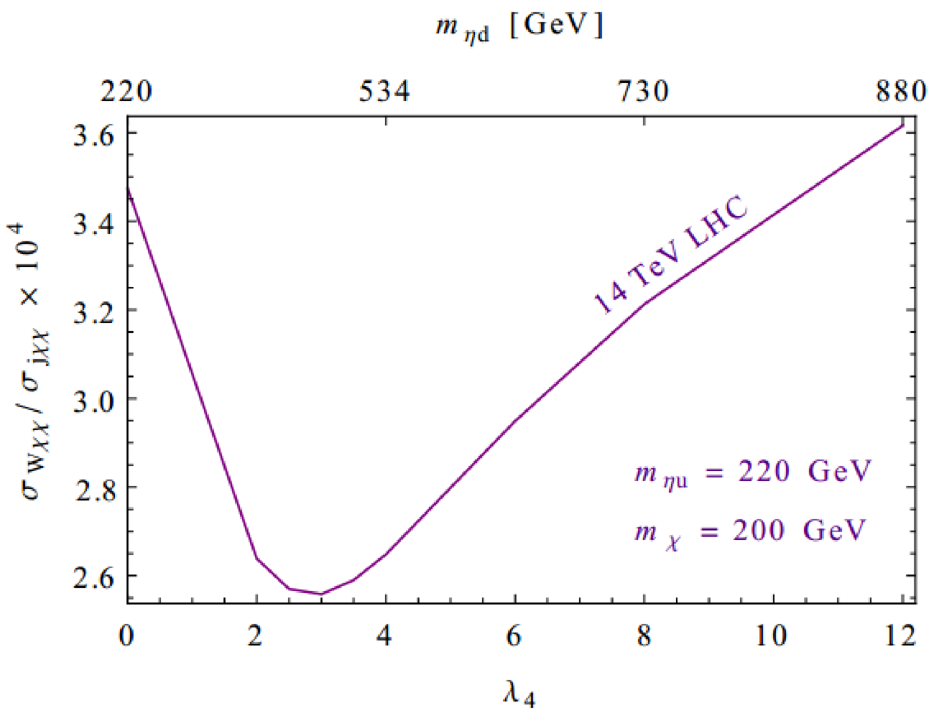






Longitudinal effects





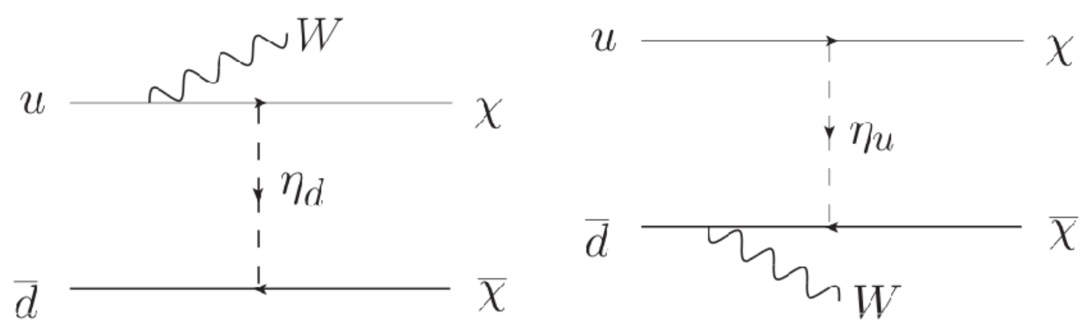
Cross section first suppressed due to increase in propagator mass, then increases when third diagram begins to dominate.

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

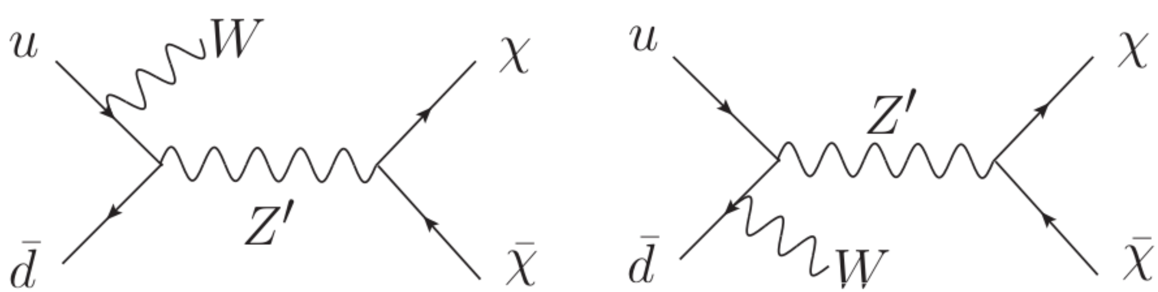
N.Bell, Y.Cai, R.Leane, 1512.00476

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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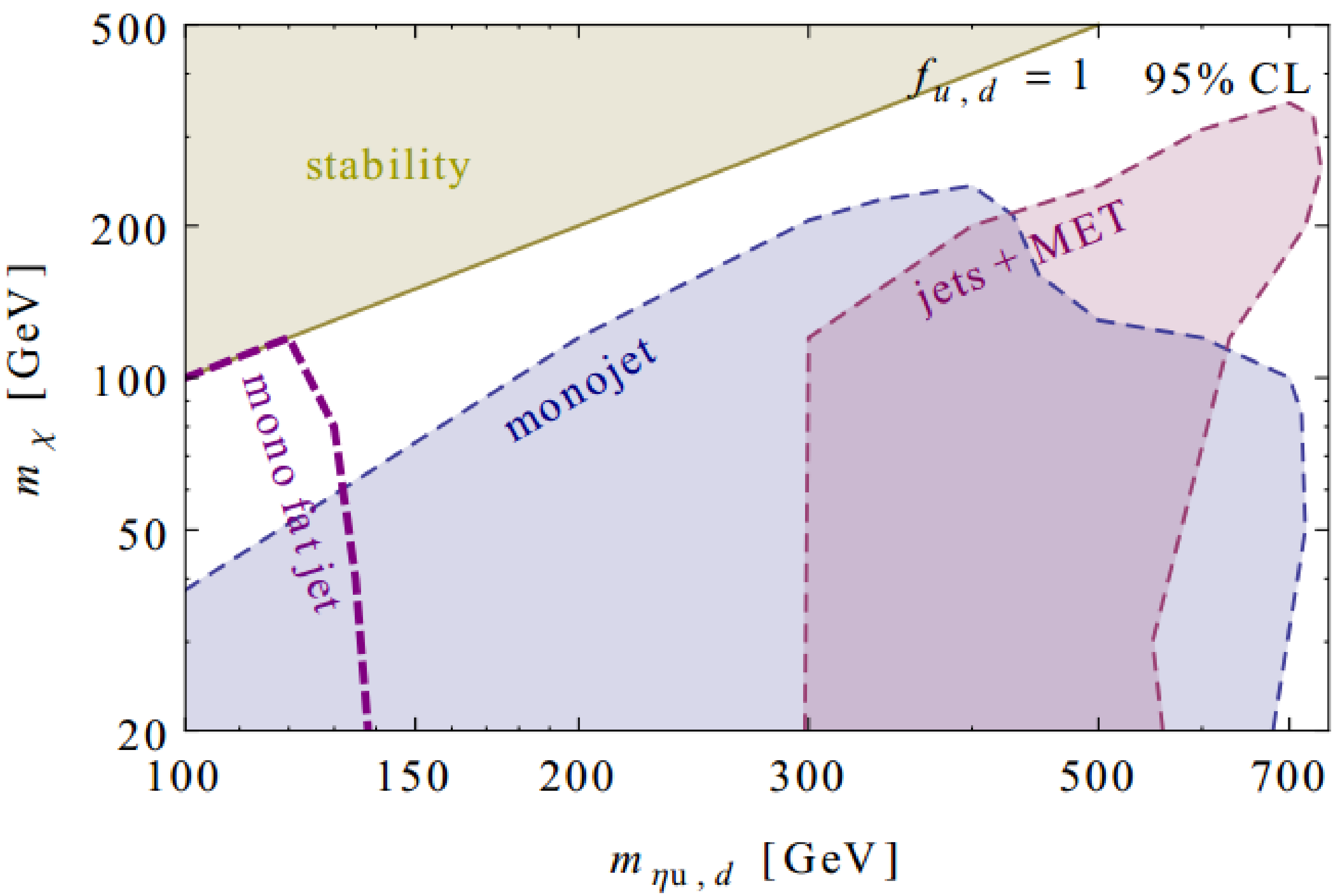
T-channel LHC limits and reach summary



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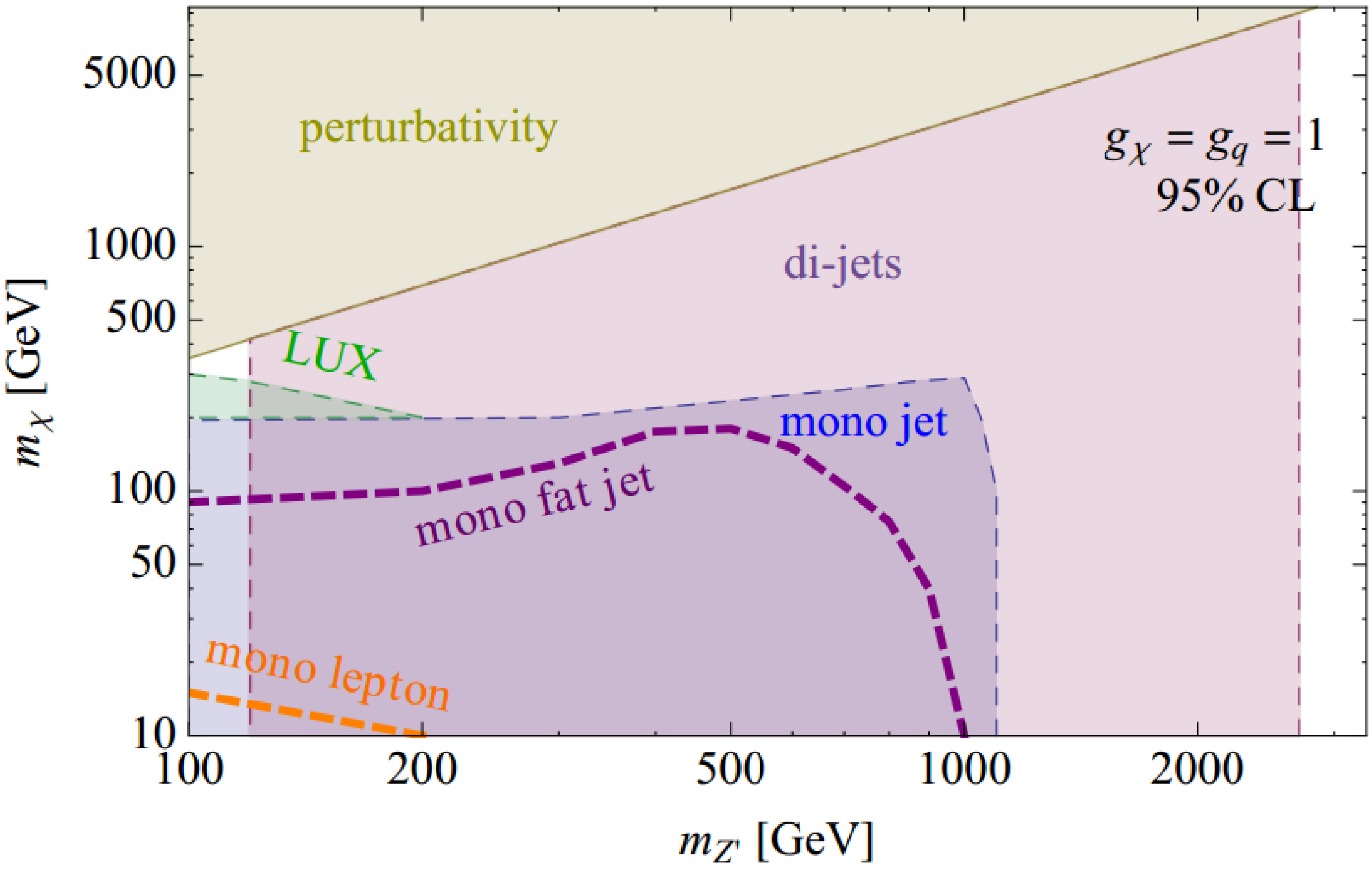

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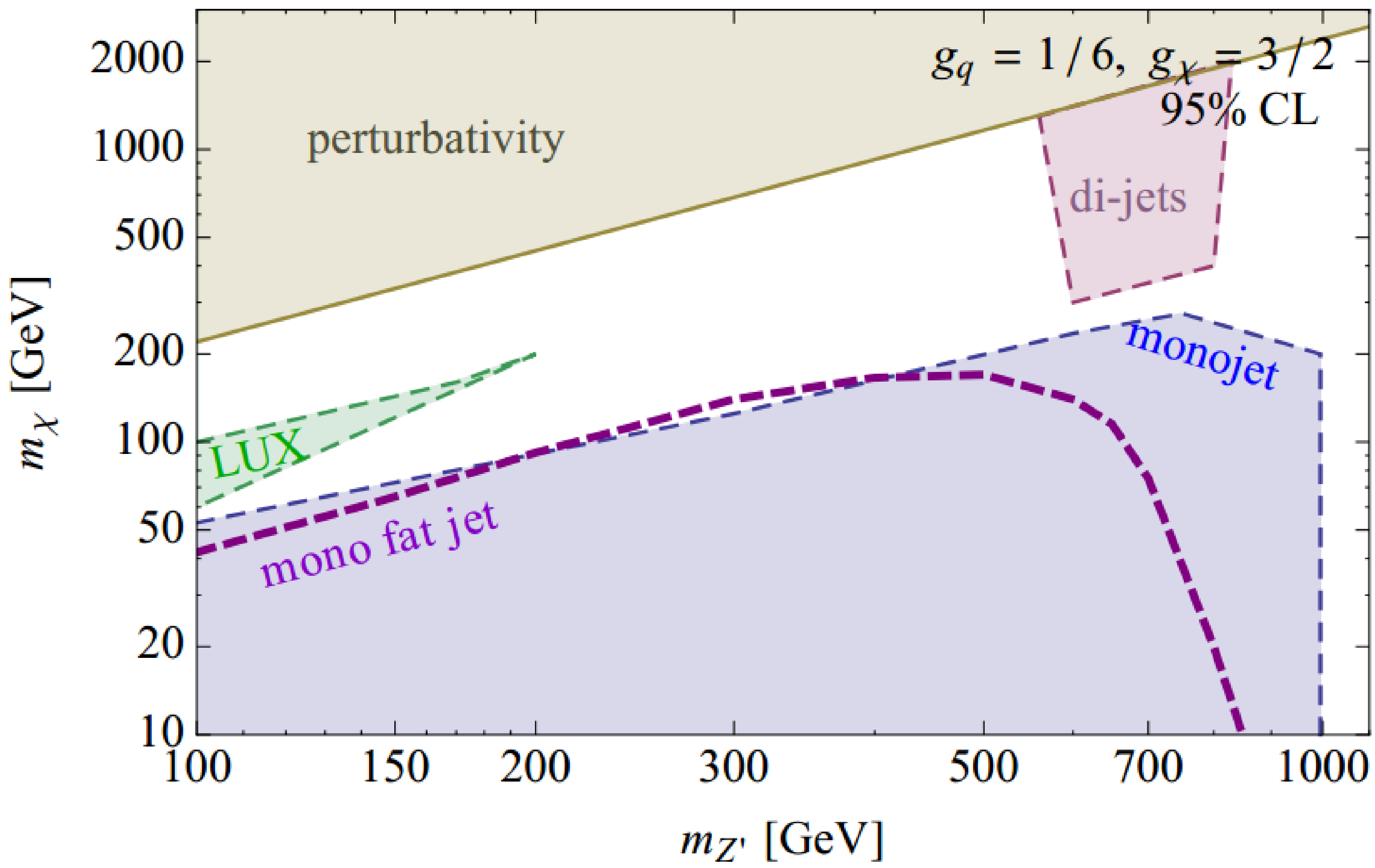
S-channel LHC limits and reach summary



N.Bell, Y.Cai, R.Leane, 1512.00476

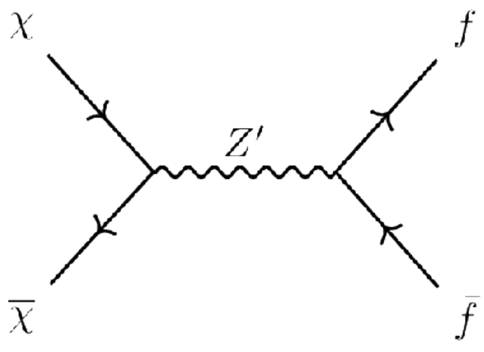
Implications of gauge invariance in other searches?

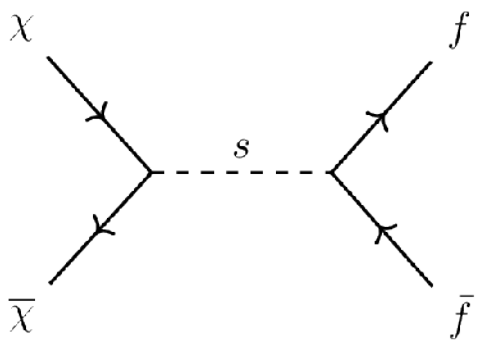
Simplified Models for Dark Matter

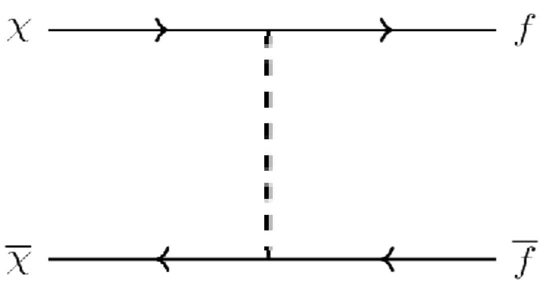
- Still no idea about fundamental nature of DM, model independent framework desirable where possible
- EFTs → issues at high momentum transfer, not generically applicable
- Simplified models: only lightest mediator is retained, set limits on couplings and mediators. Allow for richer phenomenology.

<u>Benchmark simplified models:</u>

s-channel spin-1 s-channel spin-0 t-channel spin-0.







…this can run into problems!

- Not intrinsically capable of capturing full phenomenology of UV complete theories.

- Separate consideration of these benchmarks can lead to physical problems and inconsistencies.

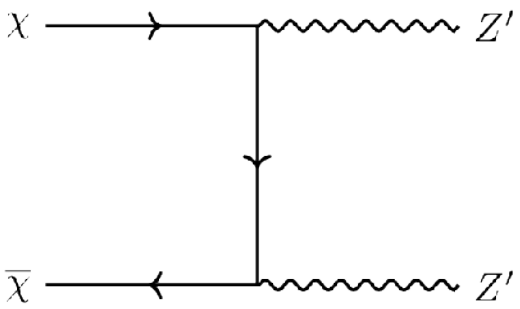
These issues motivate a scenario in which the vector and the scalar mediators appear together within the same theory.

Spin-1 Simplified Model

Kahlhoefer et al, 1510.02110

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

Consider high energy production of longitudinal Z' bosons:



$$\epsilon_L^\mu(k) = k^\mu / m_{Z'}$$

violates unitarity at high energies, for axial-vector Z'-DM couplings.

Introduces a unitarity bound.

$$\sqrt{s} \lesssim \frac{\pi m_{Z'}^2}{g_\chi^2 m_\chi}$$

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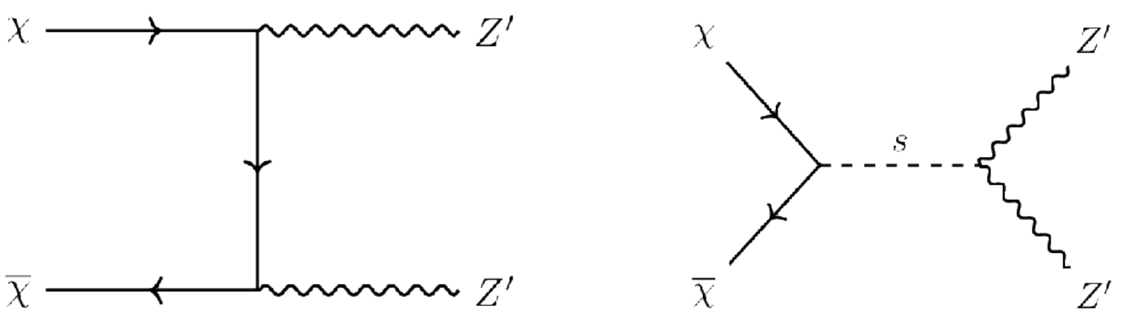

Bad high energy behaviour cancelled by additional scalar!

Introduces a unitarity bound.

$$m_s \lesssim \frac{\pi m_{Z'}^2}{g_\chi^2 m_\chi}$$

$$\sqrt{s} \lesssim \frac{\pi m_{Z'}^2}{g_\chi^2 m_\chi}$$

Spin-1 Simplified Model

Consequences for both Majorana and Dirac DM.

Majorana DM: vector current is vanishing, leaving pure axial-vector interactions.

*** Inclusion of the dark Higgs is unavoidable! ***

Furthermore, can't write down Majorana mass term without breaking the $U(1)_\chi$ symmetry.

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Majorana DM: vector current is vanishing, leaving pure axial-vector interactions.

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Furthermore, can't write down Majorana mass term without breaking the $U(1)_\chi$ symmetry.

Dirac DM: axial-vector Z' interactions will yield same issues.

However, possible to have pure vector couplings to a Z'. Stueckelberg mechanism may give mass to the Z', and a bare mass term for the DM is possible.

Higgs mechanism is what is realized by nature, well motivated to consider dark Higgs together with Dirac DM.

Simple renormalizable theory

For Majorana DM, the model lagrangian is:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{i}{2}\overline{\chi}\partial\!\!\!/\chi - \frac{1}{4}g_\chi Z'^{\mu}\overline{\chi}\gamma_5\gamma_\mu\chi - \frac{1}{2}y_\chi\overline{\chi^c}\chi S - \frac{\sin\epsilon}{2}Z'^{\mu\nu}B_{\mu\nu}$$
$$+ \left[(\partial^\mu + ig_\chi Z'^{\mu})S\right]^\dagger\left[(\partial_\mu + ig_\chi Z'_\mu)S\right] - \mu_s^2 S^\dagger S - \lambda_s(S^\dagger S)^2 - \lambda_{hs}(S^\dagger S)(H^\dagger H)$$

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After symmetry breaking and mixing, relevant terms are:

$$\mathcal{L} \supset \frac{1}{2}m_{Z'}^2 Z'^\mu Z'_\mu - \frac{1}{2}m_s^2 s^2 - \frac{1}{2}m_\chi\overline{\chi}\chi - \frac{1}{4}g_\chi Z'^\mu\overline{\chi}\gamma_5\gamma_\mu\chi - \frac{y_\chi}{2\sqrt{2}}s\overline{\chi}\chi$$
$$+ g_\chi^2 w Z'^\mu Z'_\mu s - \lambda_s w s^3 - 2\lambda_{hs}(hvs^2 + swh^2) + g_f\sum_f Z'^\mu\overline{f}\Gamma_\mu f,$$

Component fields of S and H, in broken phase, are:

$$S \equiv \frac{1}{\sqrt{2}}(w + s + ia) \qquad\qquad H = \left\{G^+, \frac{1}{\sqrt{2}}(v + h + iG^0)\right\}$$

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- New field content: Z', dark Higgs, DM candidate.
- Interactions with visible sector via Higgs portal or hypercharge portal
- Mass generation achieved with the dark Higgs.
- Well behaved at high energies.

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$$+ g_\chi^2 w Z'^\mu Z'_\mu s - \lambda_s w s^3 - 2\lambda_{hs}(hvs^2 + swh^2) + g_f\sum_f Z'^\mu\overline{f}\Gamma_\mu f,$$

Couplings and masses in the theory are all related to each other!

$$m_{Z'} = g_\chi w,$$
$$m_\chi = \frac{1}{\sqrt{2}}w y_\chi, \qquad y_\chi = \frac{\sqrt{2}g_\chi m_\chi}{m_{Z'}}.$$

How does this compare to simplified models?

Indirect Detection with Simplified Models

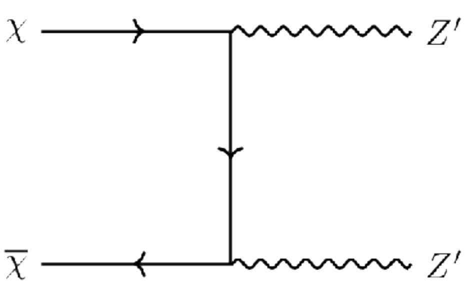
- In universe today, only s-wave contributions to the annihilation cross section are relevant. P-wave contributions are negligible, suppressed as DM velocity $v_\chi^2 \approx 10^{-6}$.

$$\sigma v = a + bv^2 + \cdots$$

- Collider and direct detection experiments introducing increasing tension between allowed DM parameters and the thermal WIMP paradigm.

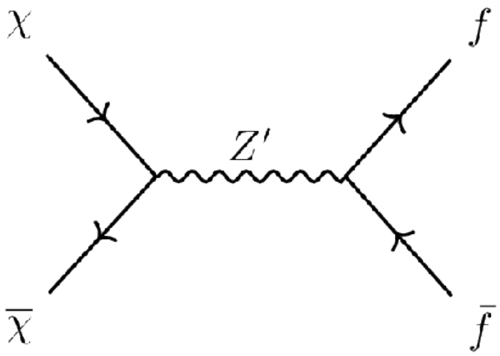
- Hidden on-shell models popular way to avoid this.

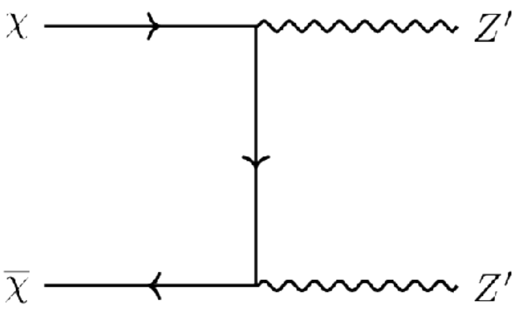
(Abdullah et al, 1404.6528)



Spin-1 Indirect Detection

For fermionic DM:



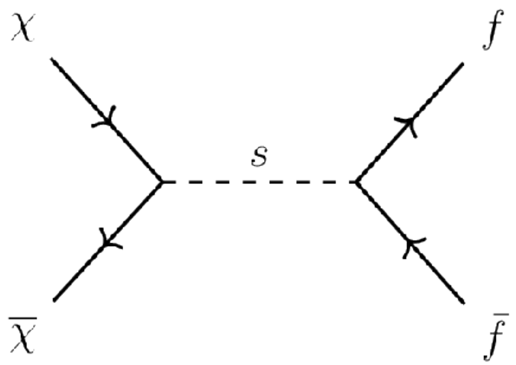


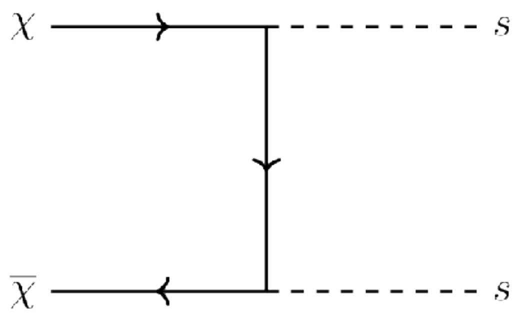
Vector: p-wave
Axial-vector: s or p-wave

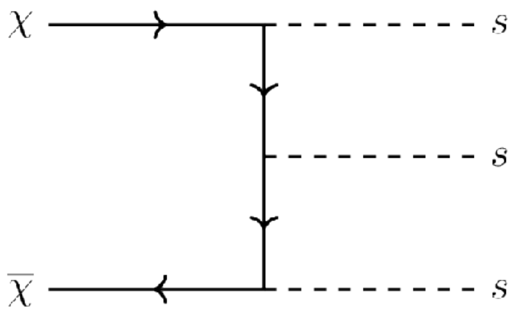
s-wave for all couplings!

Spin-0 Indirect Detection

Analogous diagrams not quite the same.







Pseudoscalar: s-wave
Scalar: p-wave

Always p-wave!

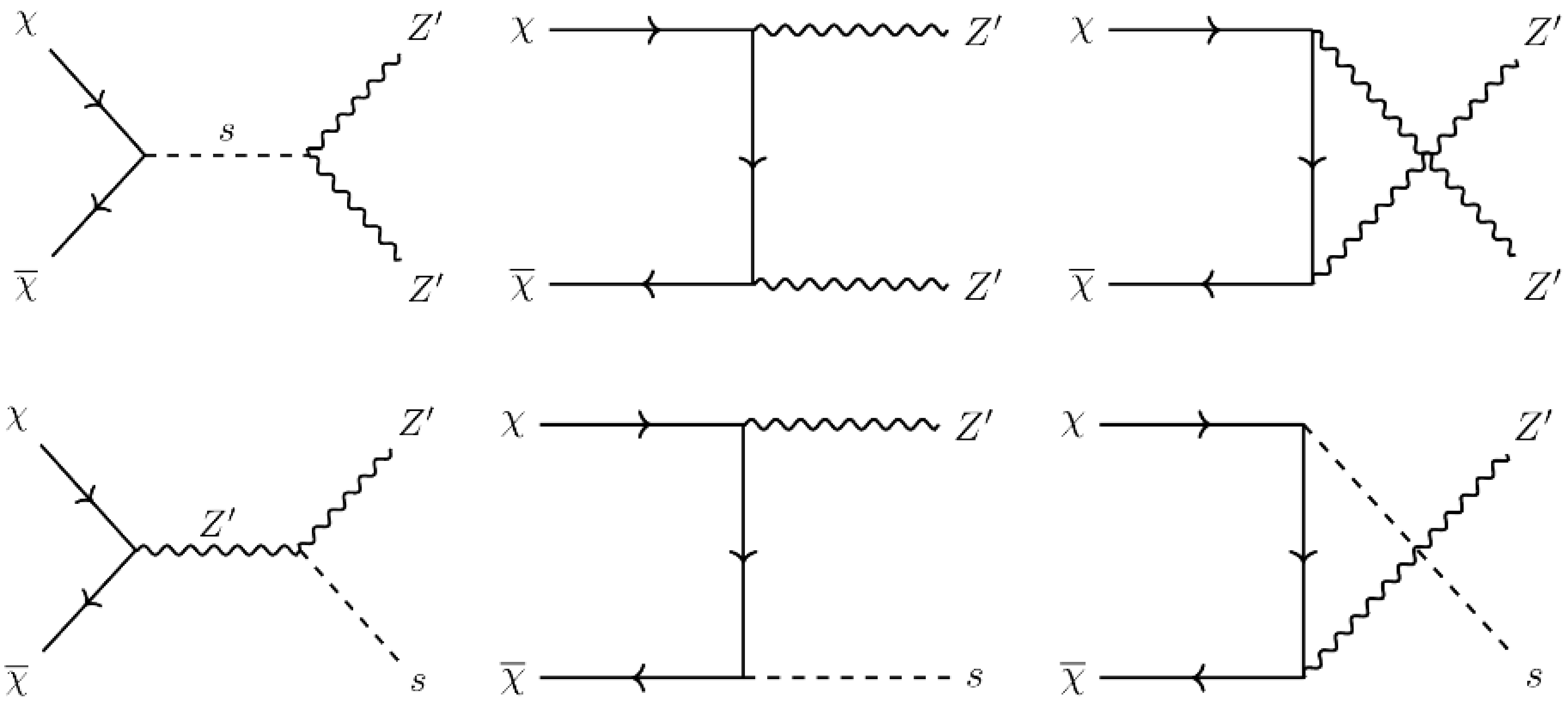
Pseudoscalar: s-wave
Scalar: p-wave

No s-wave diagram for scalars!

What happens when we consider the self-consistent dark sector?

Annihilation Processes

N.Bell, Y.Cai, R.Leane, 1605.09382

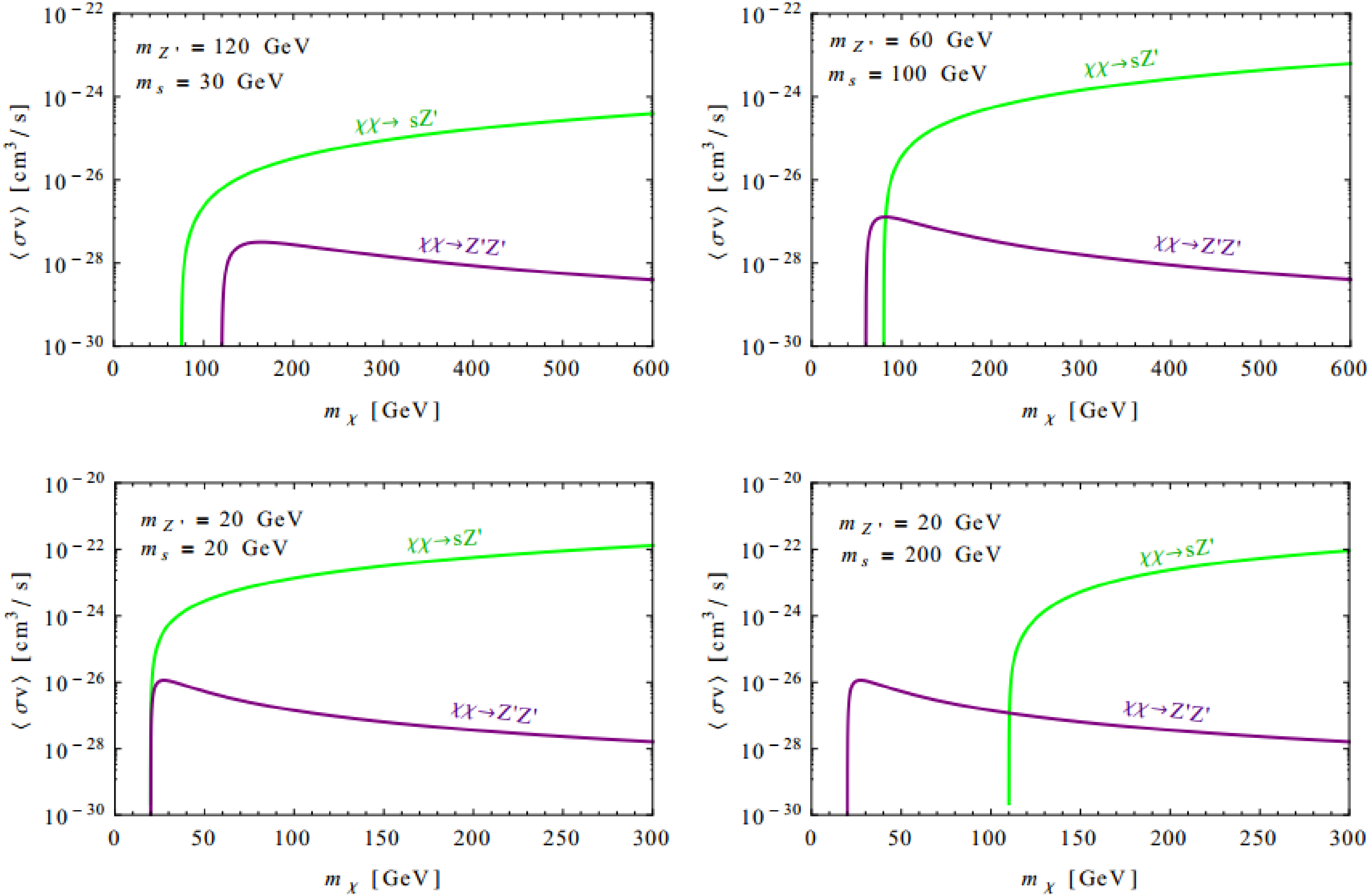


This opens up a new s-wave annihilation process!
Further, this allows us to probe the nature of the scalar with comparable strength to the Z', that is not ruled out by other exps.

So we know we have a new s-wave process….

but how large is its annihilation rate?

Annihilation cross sections



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Indirect Detection Limits

- Dwarf Spheriodal Galaxies, most DM dense objects in our sky.
- Can't just take existing limits on the cross section due to different final states and different kinematics

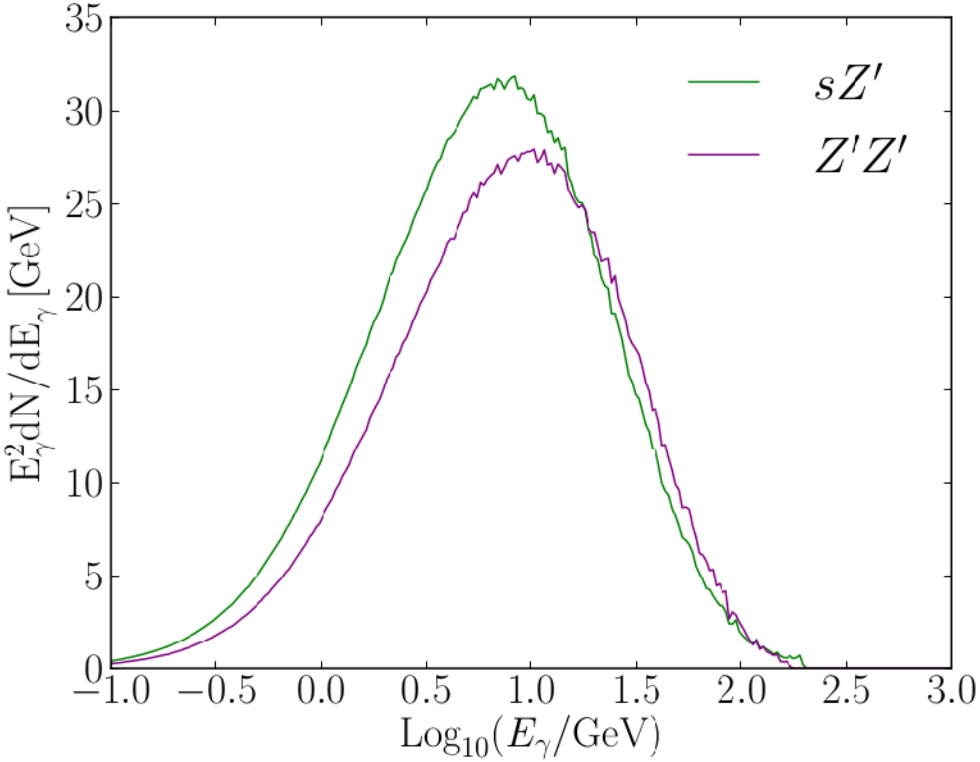
  → generate spectra ourselves, compare to Fermi data and find limits.

- At lower DM masses, and for electron positron final states, AMS-02 can provide stronger limits.

The Photon Energy Spectra

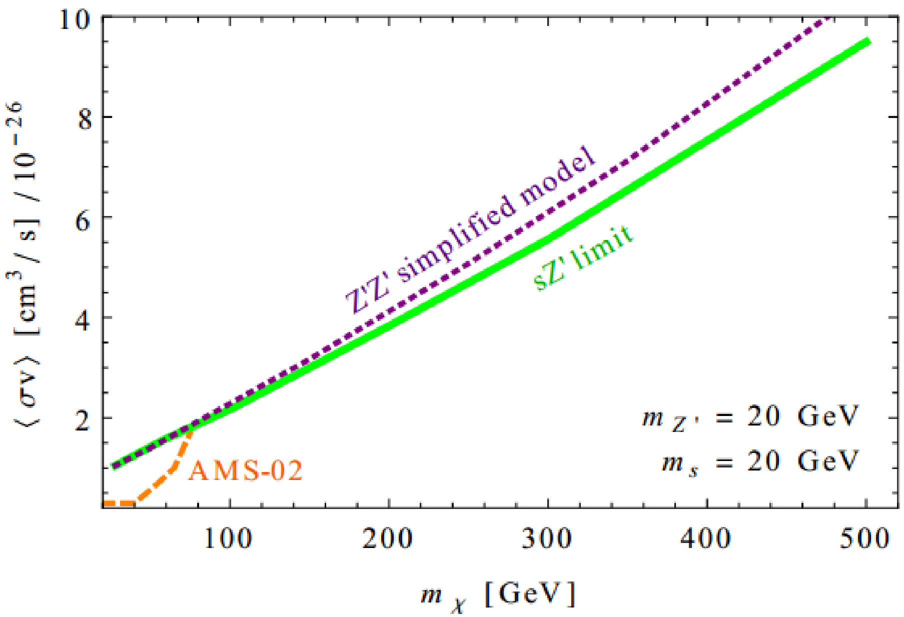
Generate in Pythia, make effective resonance in particle CoM frame, then average the separate spectra.

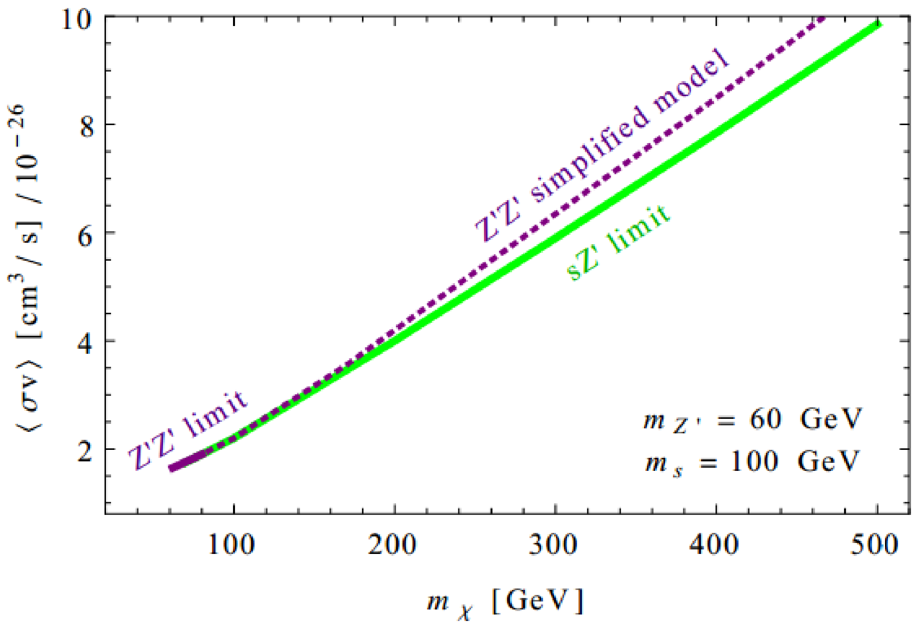
Perform this average again for regions where both sZ' and Z'Z' cross sections are the same, to obtain combined limit.



$$E_{CoM}^{Z'} = \frac{s + m_{Z'}^2 - m_s^2}{2\sqrt{s}}, \quad E_{CoM}^{s} = \frac{s + m_s^2 - m_{Z'}^2}{2\sqrt{s}}.$$

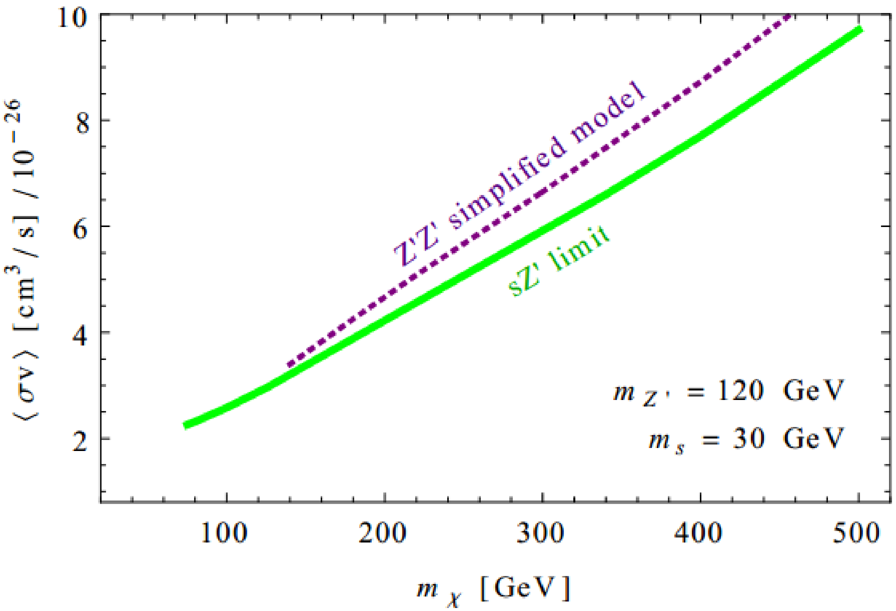
Indirect Detection Limits

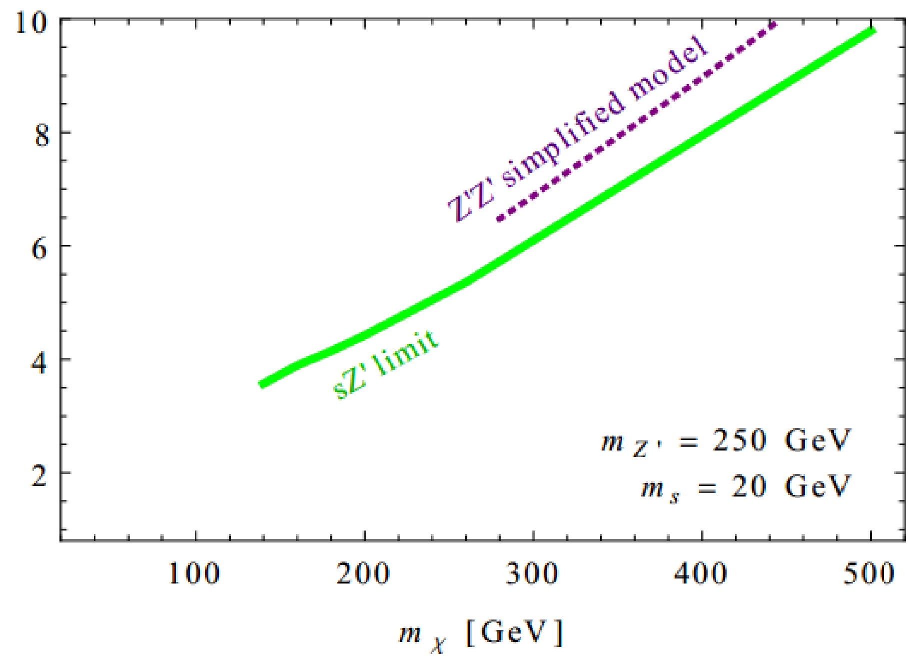




N.Bell, Y.Cai, R.Leane, 1605.09382

Indirect Detection Limits





N.Bell, Y.Cai, R.Leane, 1605.09382

Other Limits?

- Small couplings between the dark and visible sector… almost vanishing!
- Can effectively remove direct detection and collider bounds.
  - Given WIMP DM is becoming increasingly constrained, this is also nicely motivated.
- Can't have arbitrarily small couplings, as need the mediator to decay within the lifetime of the galaxy, also needs to decay quickly enough to avoid BBN bounds.

Summary

Understanding nature of DM one of foremost goals of physics community. Want to ensure we are searching correctly!

- Both EFTs and simplified models are popular frameworks for setting limits on the nature of DM – but both have shortcomings.
- EFTs: appropriate LHC cutoffs.
- 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.

Summary

Understanding nature of DM one of foremost goals of physics community. Want to ensure we are searching correctly!

- Simplified models are a popular framework, but they are not intrinsically capable of capturing the full phenomenology of UV complete theories.
- In fact, it can be inconsistent to consider benchmarks separately, and Majorana DM it is necessary to include the scalar in the theory.
- Leads to interesting phenomenology: previously unconsidered s-wave process, which for some couplings can dominate the annihilation rate. Different shaped spectra can also lead to stronger cross section limits.
- Also allows the properties of the scalar to be probed in this context with comparable strength to the vector!

Back up slides

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:

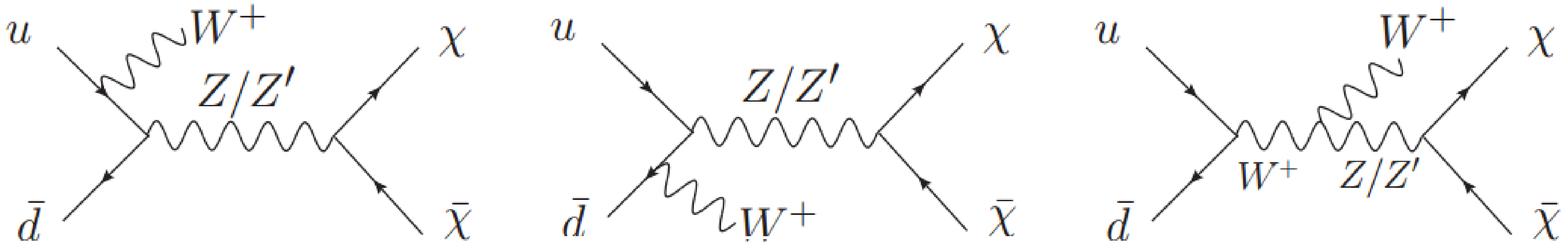
$$\frac{1}{\Lambda^2}\left(\overline{\chi}\gamma^\mu\chi\right)\left(\overline{q}\gamma_\mu q\right) = \frac{1}{\Lambda^2}\left(\overline{\chi}\gamma^\mu\chi\right)\left(\overline{q}_L\gamma_\mu q_L + \overline{q}_R\gamma_\mu q_R\right)$$

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

N.Bell, Y.Cai, J.Dent, R.Leane, T.Weiler, 1503.07874

Other UV model

N.Bell, Y.Cai, R.Leane, 1512.00476



Quark-Z' couplings like that of the Z, which are of opposite sign for u and d quarks due to their weak isospin assignments of $T_3 = \pm 1/2$. In the EFT limit, where the Z' is integrated out, this would give negative value of ξ.

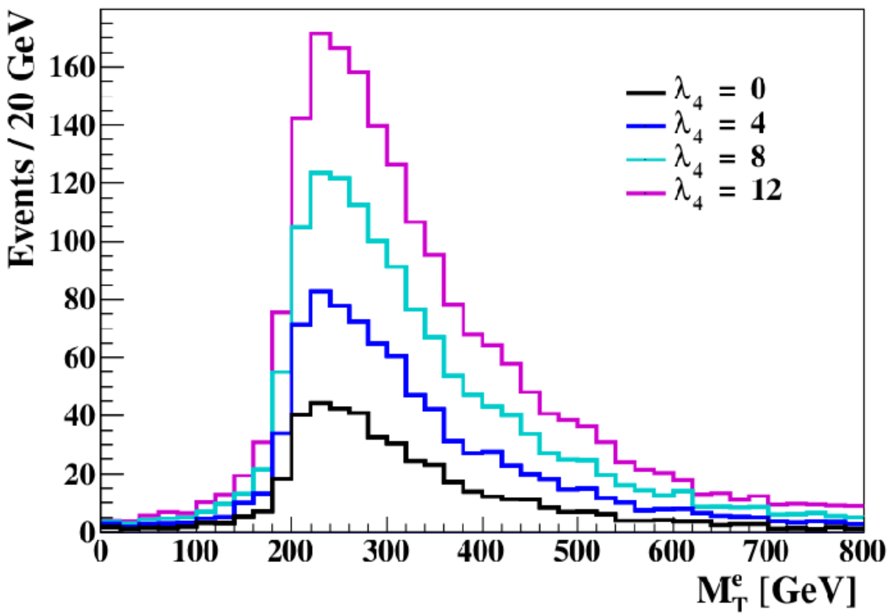
However, the strength of the DM-quark interactions would be suppressed by the Z/Z' mixing angle, which is of order $v_{\rm EW}^2/M_{Z'}^2$ and thus the operator arises only at order $1/\Lambda^4$.

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-lepton cuts

- E_T of the leading electron > 100 GeV
- E_T of the next-to-leading electron < 35 GeV
- At least one electron
- M_T for the electron, $M_T^e > 220$ GeV
- Pseudorapidity for the electron must be in the range $-2.1 < \eta(\ell_e) < 2.1$
- Jet $P_T < 45$ GeV
- The electron P_T and $\not{E}_T$ ratio must be in the range $0.4 < P_T/\not{E}_T < 1.5$
- $\Delta\phi_{e,\not{E}_T} > 2.5$.

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

Mono fat jet cuts

$$\sqrt{y} = min(p_{T1}, p_{T2}) \frac{\Delta R}{m_{jet}}$$

- $\not{E}_T > 350$ GeV
- At least one large radius jet with $P_T > 250$ GeV
- $\sqrt{y} > 0.4$
- $50 < m_{jet} < 120$ GeV
- $-1.2 < \eta < 1.2$
- No more than one narrow jet with $P_T > 40$ GeV and $-4.5 < \eta < 4.5$ which is separated from the leading large radius jet as $\Delta R > 0.9$
- $\Delta\phi(jet, \not{E}_T) < 0.4$ for narrow jets.

Model charges

Gauge symmetry group:

$$SU(3)_c \otimes SU(2)_W \otimes U(1)_Y \otimes U(1)_\chi$$

$$D_\mu = D_\mu^{SM} + iQ' g_\chi Z'_\mu$$

Fermion mass terms generated as

$$\mathcal{L}^{\text{Yuk}} = -y_{ij}\, \overline{\chi}_i P_L \chi_j S + h.c.$$

Charge constraints!

Majorana DM: $Q'_S + 2\, Q'_{\chi_j} = 0$

Dirac DM: $Q'_S - Q'_{\chi_i} + Q'_{\chi_j} = 0$

Dirac DM extensions

Combinations of mass generation mechanisms possible:

- Vectorlike Dirac DM:
  1. Bare DM mass, Z' mass from Stueckelberg.
  2. DM mass from dark Higgs, Z' mass from Stueckelberg.
  3. Bare DM mass, Z' mass from dark Higgs.
- Chiral Dirac DM:
  1. Both DM and Z' get mass from dark Higgs.
  Requires non-zero axial-vector Z'-DM couplings to be present!

If it turns out that any of these scenarios are realized by nature, simplified model constraints and pheno will be different!

The Photon Energy Spectra

$$\frac{d^2\Phi}{d\Omega dE_\gamma} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\left(\sum_f \frac{dN}{dE_\gamma} Br_f\right) J(\phi,\gamma)$$

Z' partial width taken analytically:

$$\Gamma(Z' \to f\bar{f}) = \frac{m_{Z'} N_c}{12\pi}\sqrt{1 - \frac{4m_f^2}{m_{Z'}^2}}\left[g_{f,V}^2\left(1 + \frac{2m_f^2}{m_{Z'}^2}\right) + g_{f,A}^2\left(1 - \frac{4m_f^2}{m_{Z'}^2}\right)\right]$$

For dark Higgs, use Fortran package HDecay, as higher order corrections and loops can be relevant. Ensures accurate calculation of all branching fractions.

Unitarity Bounds

$$\sqrt{s} < \frac{\pi m_{Z'}^2}{g_\chi^2 m_\chi}$$

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

Parameters in the theory are all related to each other. Need to ensure sensible choices are made to avoid unitarity problems, i.e. Yukawas:

$$m_{Z'} = g_\chi w,$$
$$m_\chi = \frac{1}{\sqrt{2}} w y_\chi, \qquad y_\chi = \frac{\sqrt{2} g_\chi m_\chi}{m_{Z'}}.$$