On the complementarity in EFT of direct detection and collider DM searches

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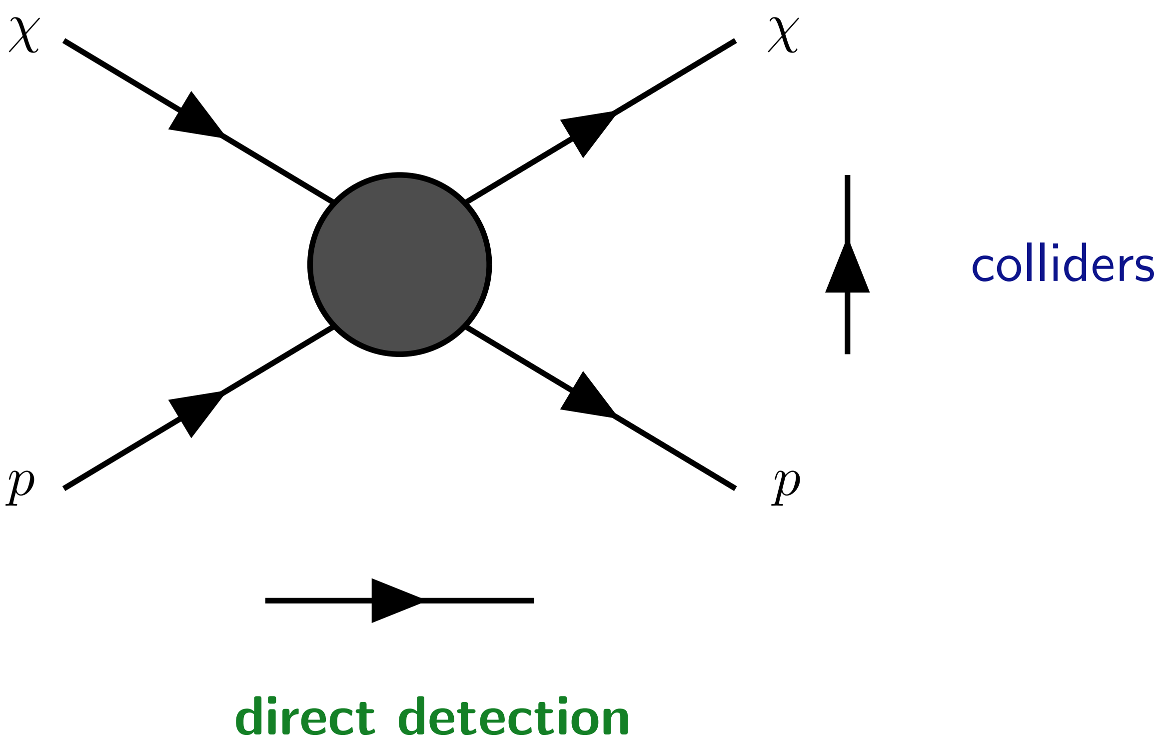
(1403.5161)



Bai Fox Harnik, Kopp, Goodman Ibe Rajaraman Shepherd Tait Yu, Profumo,Frandsen Kahlhoefer Preston Sarkar Schmidt-Hoberg, Papucci Vichi Zurek,Haisch, DeSimone, Shoemaker Vecchi,...

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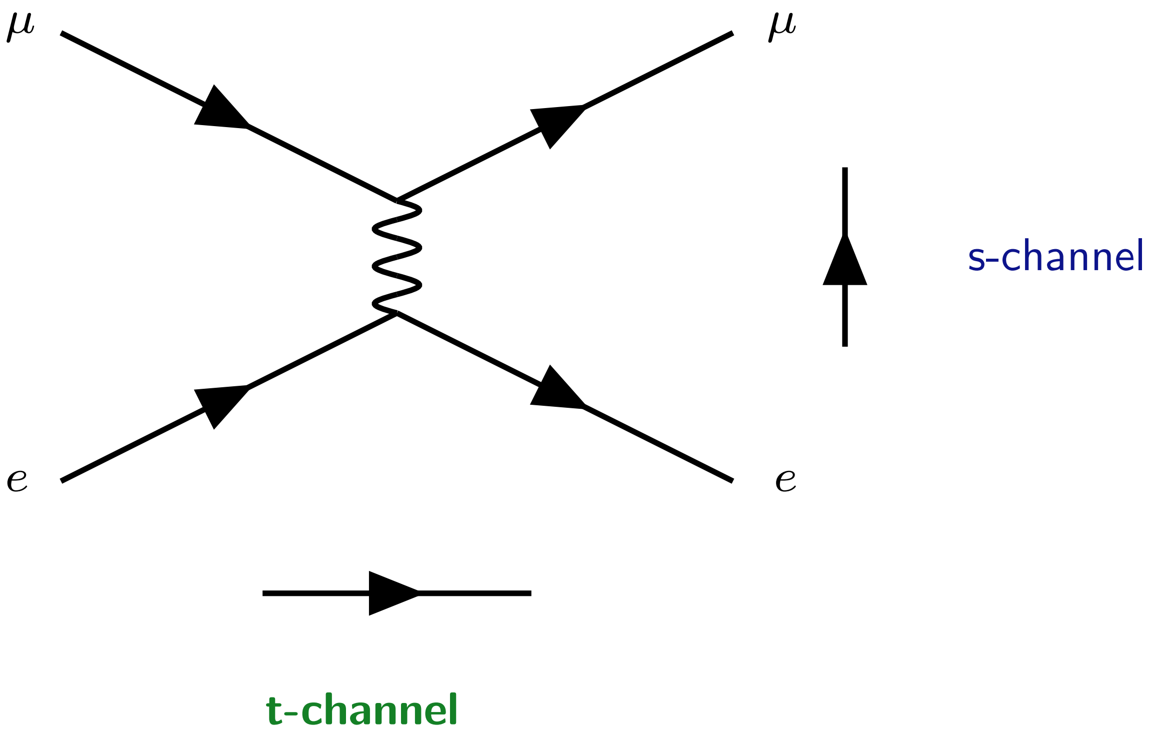

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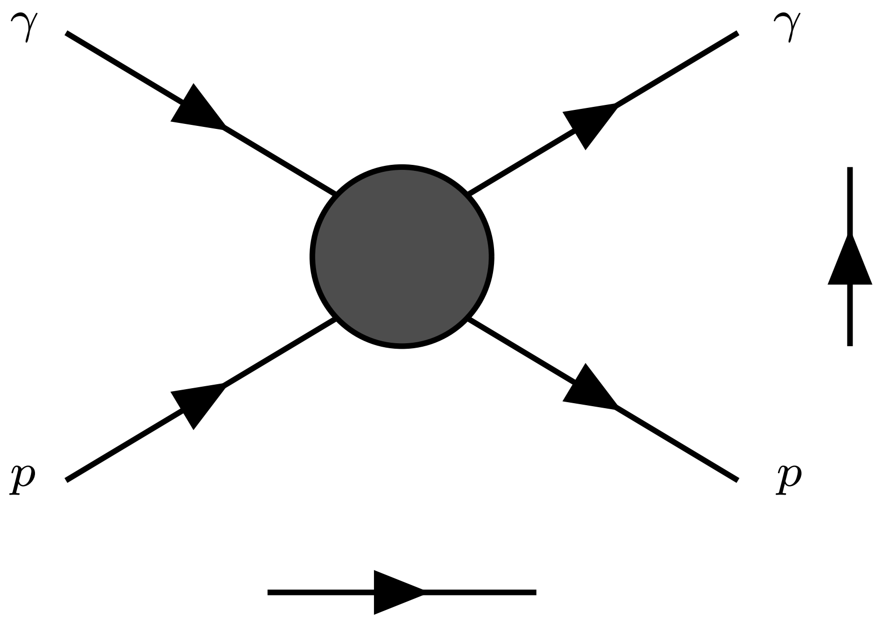

at the TeV, in SM:
$p + \bar{p} \to \gamma + \gamma$
...+ Higgs signal

in QED, at MeV: γ + p $\to$ γ + p

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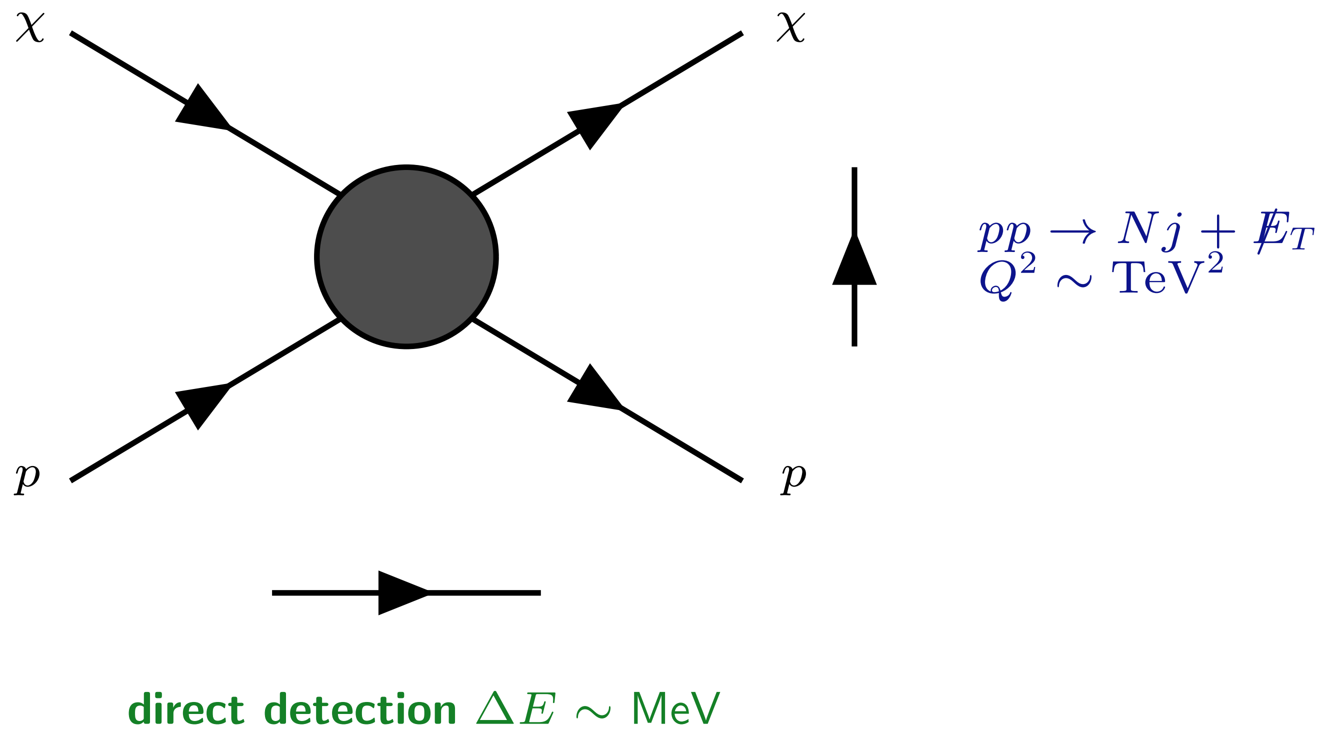
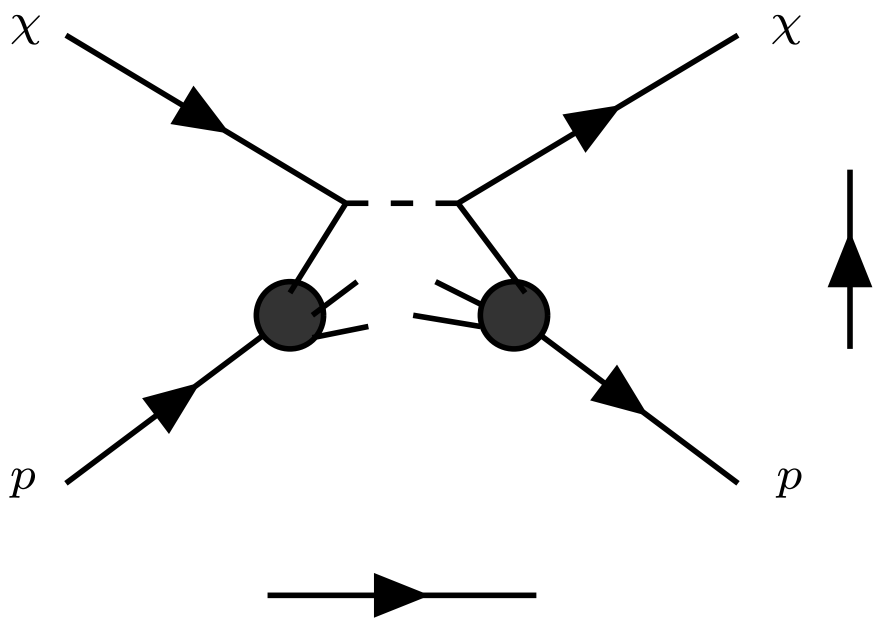


1. particle content is different (H, Z on-shell at LHC)
2. energy scale is different (quantum interferences (are delicate) scale dependent!)

On the complementarity **in EFT** *of direct detection and collider DM searches*

if you know fundamental theory...just calculate!
A fundamental DM-SM interaction generates signal in DDetection and @LHC



$pp \to Nj + \not{E}_T$
$Q^2 \sim \mathrm{TeV}^2$

direct detection $\Delta E \sim$ MeV

This talk is about parametrising ignorance with EFT

Outline

1. the ingredients
   - why dark matter...meet χ
   - when to use contact interactions
   - what is Effective Field Theory
2. (contact) interactions of χ with the SM @ LHC
   - with $u, d,_{(c,\, s,\, b,\, g,\, H)}, Z$

   $*$ choose $_{(H)}, Z$ operators $\propto \hat{s}$
3. LHC constraints (sans Madgraph, Pythia...)
   - compare to $(q\bar{q} \to Z \to \nu\bar{\nu})$
4. From TeV to MeV:
   - @m_W, match out H, Z (...later, match out c, b)
   - ?somewhere?, match $u, d, s, g \to p, n$
   - ?? somewhere later?? match $p, n \to$ nuclei

   $\Rightarrow$ what does direct detection constrain?
5. summary:
   - Z unimportant wrt (axial) vector dark-matter quark contact int.

   $\star$ careful about applicability of contact int. @ colliders!

   $\star$ conservative bounds: include only everything that interferes

There is some dark matter:

1. structure of the Universe:
    - need dark matter halos to explain galactic "flat rotation curves"
      (angular velocity of outlying stars $\Leftrightarrow$ they feel more mass than we see)
    - ...
2. evolution of the U
    - need dark matter to grow galaxies
    - see Baryon Acoustic Oscillations in the matter power spectrum
    - MCMC fits to CMB data+etc $\Rightarrow$ in U today: dark mass $\sim 6\times$ baryonic mass

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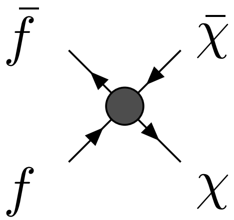
Lets suppose:

- dark matter is a particle
- it has no QCD or QED charge
- it has no $SU(2)$ charge, but is "weakly interacting" with SM gives the right relic density, allows to detect in direct detection/LHC.
- that the mass is $\approx$ 100 GeV want *cold* thermal relic, I did not do scan...
- that the DM has a "conserved parity" (tis not ν_R), cannot decay

$\Rightarrow$ dark matter as an SM-singlet fermion χ (with contact int. to SM)

When to use contact interactions ?



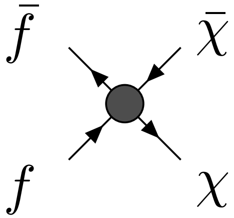
point interaction with non-renorm coupling $\frac{C}{\Lambda^n}$

⋆ assume SM gauge symmetries respected in blob $\Leftrightarrow$

$$\mathcal{L}_{SM} \supset \frac{C}{\Lambda^n} \times \text{SM gauge invariant operator}$$

not usually required for DM EFT

When to use contact interactions ?



point interaction with non-renorm coupling $\frac{C}{\Lambda^n}$

⋆ assume SM gauge symmetries respected in blob ⇔

$$\mathcal{L}_{SM} \supset \frac{C}{\Lambda^n} \times \text{SM gauge invariant operator}$$

not usually required for DM EFT

⋆ minimal self-consistency: $C < 4\pi$ (not more than strongly coupled)

$\Lambda^2 > \hat{s} \equiv |\text{4-p transfer}|^2$

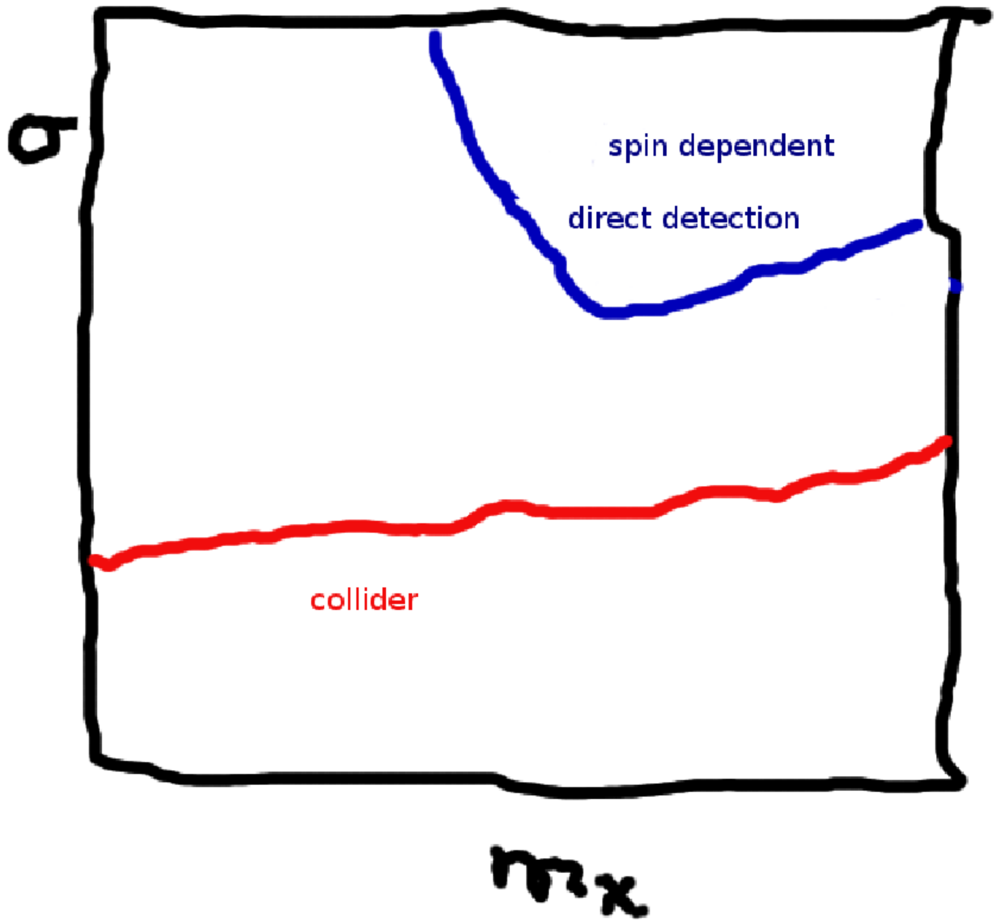
⇒ if $\hat{s} \to 0$, no distinction C vs $1/\Lambda^2$, expts exclude above sensitivity

⇒ **upper** bound to collider exclusions. Colliders exclude:

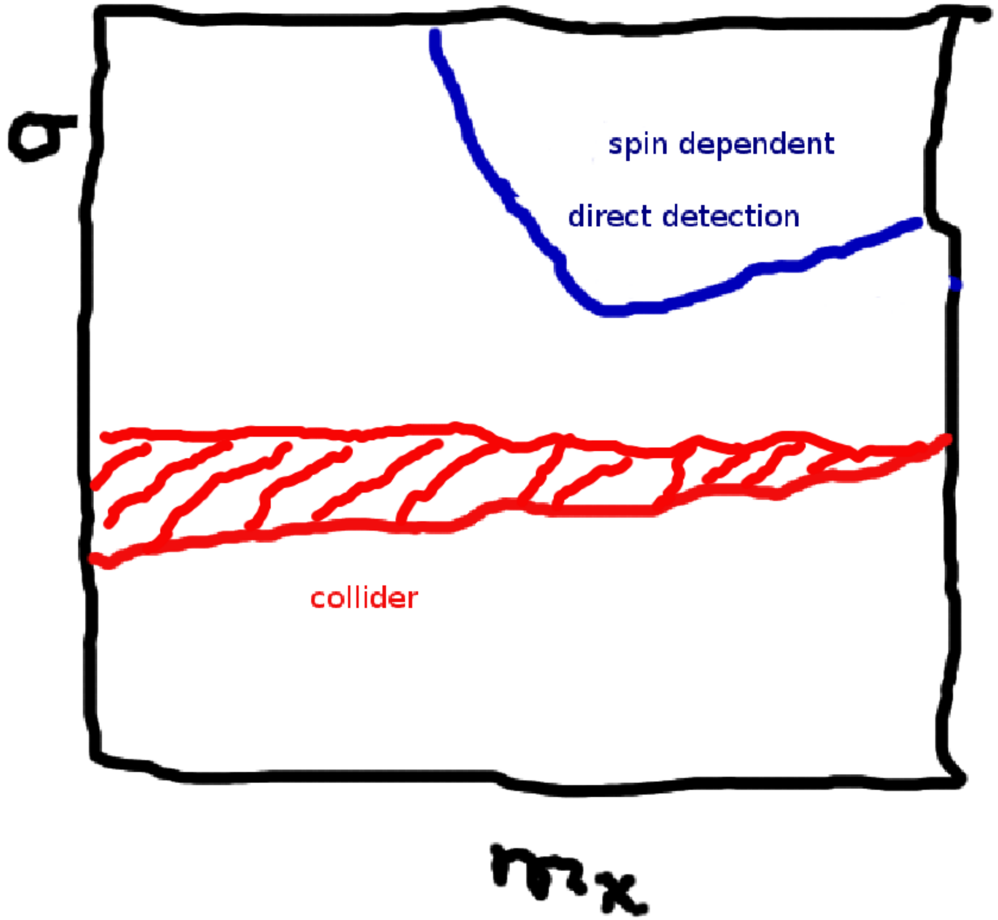
$$\frac{4\pi}{\hat{s}} > \frac{C}{\Lambda^2} > \text{sensitivity}$$

⇔ What is $\hat{s}$ at the LHC? ($\sim$ TeV^2)

For example...you have surely seen plots like



But if remember that colliders not exclude above $4\pi/\hat{s}$:



What is Effective Field Theory ?

idea = describe anything with few equations for relevant variables
technical= how to remove heavy particles (propagators, loops!), retaining effects correctly

here: tool to compare χ-proton interactions at MeV vs TeV not sophistication of B-physics

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how it works (reminder):
* Above the scale $\Lambda \gtrsim$TeV, is $\mathcal{L}_{SM}$ (part. + int.), χ, and New Physics (new part./int.) causing χ to interact with SM

* Below Λ, at the LHC, are SM (part + int), χ, and χ-SM contact interactions

What is Effective Field Theory ?

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how it works (reminder):
* Above the scale $\Lambda \gtrsim$TeV, is $\mathcal{L}_{SM}$ (part. + int.), χ, and *known* NP (new part./int.) causing χ to interact with SM

...if know NP, compute contact interactions coeffs at Λ by matching Greens fns of theories above/below Λ

* Below Λ, at the LHC, are SM (part + int), χ, and predicted χ-SM contact interactions

What is Effective Field Theory ?

idea $=$ describe anything with few equations for relevant variables
technical$=$ how to remove heavy particles (propagators, loops!), retaining effects correctly

here: tool to compare χ-proton interactions at MeV vs TeV not sophistication of B-physics

how it works (reminder):
* Above $\Lambda \gtrsim$TeV, is $\mathcal{L}_{SM}$ (part. $+$ int.), χ, and *unknown* NP (new part./int.) causing χ to interact with SM

...if not know NP...

* Below Λ, at the LHC, are SM, χ and a complete set of χ-SM contact interactions with arbitrary coefficients

* at m_W, m_Z, m_h, remove W, Z, h, replace their exchange by contact interactions

* (remove heavy quarks)

* put quarks in nucleons, nucleons in nuclei...

?? "a complete set of contact interactions" ??

= all possible SM gauge invariant operators involving $\overline{\chi}\Gamma\chi$

?? "a complete set of contact interactions" ??

$=$ all possible SM gauge invariant operators involving $\overline{\chi}\Gamma\chi$

1. organise in powers of $1/\Lambda$

$$\sum_{n=1}^{\infty} \frac{\mathcal{O}_i^{(4+n)}}{\Lambda^n}$$

   (a) **start at operator dimension 5,6,7**

   (b) are higher dimension small?

      i. more legs cost phase space $\sim 1/4\pi^2$ per particle

      ii. Higgs vev costs $v/\Lambda \sim .2$

      iii. derivatives... $\hat{s}/\Lambda^2$ **??**

?? “a complete set of contact interactions” ??

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      iii. derivatives... $\hat{s}/\Lambda^2$ **??**

2. interested in χ-proton interactions, so

   (a) restrict to light-quark-χ and gluon-χ interactions
   (b) **keep also the Z**
   (c) ...and h, heavy quarks, ...

Contact interactions of χ with the SM (at scale of LHC)

operators with partons, higgs and Z

$derivative$ operators to higgs and Z
(restrict to axial χ operaters)

Wishlist for interactions of $\overline{\chi}\chi$ with the SM

1. SM gauge invariant (many unknowns in EFT; use all available info!)
   Lorentz tensors build with chiral fermions
2. relevant at the LHC or in Direct Detection (neglect leptons)
   interactions with two partons, or Z, or H
3. flavour diagonal (simple + relevant) and forget CP! eg no scalar*pseudo. Tis simpler

   KamenikSmith
4. of not-to-high dimension (≤ 7) (recall $\overline{\chi}\Gamma\chi$ of mass dim 3, SM singlet)

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$\Rightarrow$ DM Lorentz tensors $\overline{\chi}\Gamma\chi$ × quark tensors (no t), $\Gamma \in \{I, \gamma_5, \gamma^\mu, \gamma^\mu\gamma_5, \sigma^{\mu\nu}\}$:

$$\mathcal{O}^{(6)}_{iX,V} = \overline{Q_i}\gamma^\mu P_X Q_i \overline{\chi}\gamma_\mu\chi \quad , \quad \boldsymbol{\mathcal{O}^{(6)}_{iX,A} = \overline{Q_i}\gamma^\mu P_X Q_i \overline{\chi}\gamma_\mu\gamma_5\chi}$$

$$\mathcal{O}^{(7)}_{i,S} = \left(\overline{q_i}\tilde{H}u_i + [\overline{q_1}\tilde{H}u]^\dagger\right)\overline{\chi}\chi$$

$$\mathcal{O}^{(7)}_{i,P} = \left(\overline{q_i}\tilde{H}u_i + [\overline{q_1}\tilde{H}u]^\dagger\right)\overline{\chi}\gamma_5\chi$$

$$\mathcal{O}^{(7)}_{i,T} = \left(\overline{q_i}\tilde{H}\sigma_{\mu\nu}u_i + [\overline{q_i}\tilde{H}\sigma_{\mu\nu}u_i]^\dagger\right)\overline{\chi}\sigma^{\mu\nu}\chi$$

$Q \in \{q_L, u_R, d_R\}$, (and similar @ dim 7 for d quarks with H^c contraction)

Wishlist for interactions of $\overline{\chi}\chi$ with the SM

1. SM gauge invariant (many unknowns in EFT; use all available info!)
   Lorentz tensors build with chiral fermions.

2. relevant at the LHC or in Direct Detection (neglect leptons)
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4. of not-to-high dimension (≤ 7) (recall $\overline{\chi}\Gamma\chi$ of mass dim 3, SM singlet)

$\Rightarrow$ with gluons: $\overline{\chi}\chi$, $\overline{\chi}\gamma_5\chi \times$ GG (uncoloured, (pseudo)scalar):

$$\mathcal{O}^{(7)}_{gg,S} = \overline{\chi}\chi G^A_{\mu\nu}G^{\mu\nu,A} \quad , \quad \mathcal{O}^{(7)}_{g\tilde{g},P} = \overline{\chi}\gamma_5\chi G^A_{\mu\nu}\tilde{G}^{\mu\nu,A}$$

Wishlist for interactions of $\overline{\chi}\chi$ with the SM

1. SM gauge invariant (many unknowns in EFT; use all available info!)
   Lorentz tensors build with chiral fermions.

2. relevant at the LHC or in Direct Detection (neglect leptons)
   interactions with two partons, or Z, or H

3. flavour diagonal (simple + relevant) and forget CP! *eg* no scalar*pseudo. Tis simpler. Constraints??

4. of not-to-high dimension (≤ 7)   (recall $\overline{\chi}\Gamma\chi$ of mass dim 3, SM singlet)

$\Rightarrow \overline{\chi}\Gamma\chi$ interactions with H,Z:

$$\begin{aligned}
\mathcal{O}^{(6)}_{Z,T} &= B^{\mu\nu}\overline{\chi}\sigma_{\mu\nu}\chi \\
\mathcal{O}^{(6)}_{Z,V} &= D^{\mu}B_{\mu\nu}\overline{\chi}\gamma_{\mu}\chi \quad \to \quad -s_W p_Z^2 Z^{\mu}\overline{\chi}\gamma_{\mu}\chi \\
\mathcal{O}^{(6)}_{Z,A} &= \boldsymbol{D^{\mu}B_{\mu\nu}\overline{\chi}\gamma_{\mu}\gamma_5\chi} \quad \to \quad -s_W p_Z^2 Z^{\mu}\overline{\chi}\gamma_{\mu}\gamma_5\chi \\
\mathcal{O}^{(7)}_{h,S} &= H^{\dagger}D^{\mu}D_{\mu}H\overline{\chi}\chi \quad \to \quad \ldots \\
\mathcal{O}^{(7)}_{h,P} &= H^{\dagger}D^{\mu}D_{\mu}H\overline{\chi}\gamma_5\chi \quad \to \quad \ldots
\end{aligned}$$

$B_{\mu\nu} = \partial_{\mu}B_{\nu} - \partial_{\nu}B_{\mu}, B_{\mu} = c_W A_{\mu} - s_W Z_{\mu}.$

Why derivative operators?

- Eqns of Motion can be (=are) used to reduce the operator basis, *eg*, for Higgs:

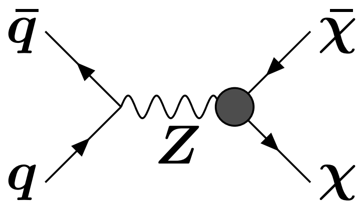
$$D_\mu D^\mu H = \mu^2 H - \lambda H^\dagger H H - \overline{e} Y_e^\dagger \ell - \overline{d} Y_d^\dagger d + \varepsilon \overline{q} Y_u u$$

Usually, use EoM to get rid of derivative operators.

- For EFT @ LHC :$H, W^\pm, Z$ can propagate on-shell, need contact interactions with χ.

- To make contact with low energy EFT, need to match EFT@LHC onto low-EFT (no $H, W^\pm, Z$).
  $\Rightarrow$ choose additional operators at the LHC to be derivative operators:

1. they do not contribute at low energy (match at zero-external-p)
2. they look $\sim$ contact interaction @LHC ($\hat{s} \gg m_Z^2$)



$$\sim \frac{g g_L^q}{2c_W} \frac{1}{\hat{s}^2 - m_Z^2} \frac{\hat{s}\, C}{\Lambda^2} \sim \frac{C g_L^q g}{2 c_W \Lambda^2}$$

Operator basis and Eqns of Motion

On-shell S-matrix elements induced by an operator containing EoM $vanish$.

For instance, the equations of motion (EoM) for the hypercharge boson ($B \simeq Z$) are

$$\partial_\mu B^{\mu\nu} - g'^2 H^\dagger H B^\nu + \sum_f Q_Y^f \overline{f}\gamma^\nu f = 0$$

so the operator:

$$\mathcal{O} = \overline{\chi}\gamma_\nu\chi(\partial_\mu B^{\mu\nu} - g'^2 H^\dagger H B^\nu + \sum_f Q_Y^f \overline{f}\gamma^\nu f)$$

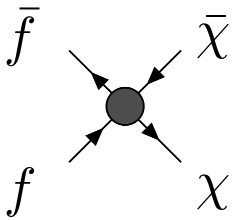
induces vertices

$\overline{\chi}\gamma_\nu\chi\overline{f}\gamma^\nu f$, $\propto Q_Y^f$

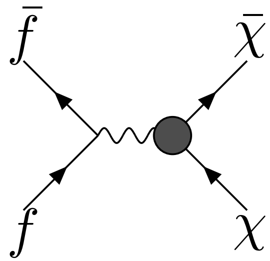
$B^\nu\overline{\chi}\gamma_\nu\chi$, $\propto p_B^2 - m_B^2$ $(m_B = g'\langle H\rangle)$.

These vertices cancel in on-shell S-matrix elements :

$\langle f\bar{f}|\mathcal{O}|\bar{\chi}\chi\rangle = \quad Q_Y^f$



$-$ $\quad Q_Y^f \frac{p^2-m_B^2}{p^2-m_B^2}$



From now on...

...focus on dimension six operators that can be relevant in Spin-Dependent (SD) Direct Detection :

$$\overline{q}\gamma^\mu P_L q\,\overline{\chi}\gamma_\mu\gamma_5\chi \quad , \quad \overline{d}\gamma^\mu P_R d\,\overline{\chi}\gamma_\mu\gamma_5\chi \quad , \quad \overline{u}\gamma^\mu P_R u\,\overline{\chi}\gamma_\mu\gamma_5\chi$$

$$D^\mu B_{\mu\nu}\overline{\chi}\gamma_\mu\gamma_5\chi \quad (\rightarrow \quad - s_W p_Z^2 Z^\mu \overline{\chi}\gamma_\mu\gamma_5\chi)$$

because:

- LHC limits on such quark-χ interactions are more restrictive than SD DD so want to know: can one evade the LHC limit on the quark operators, by including interference with the Z operator?

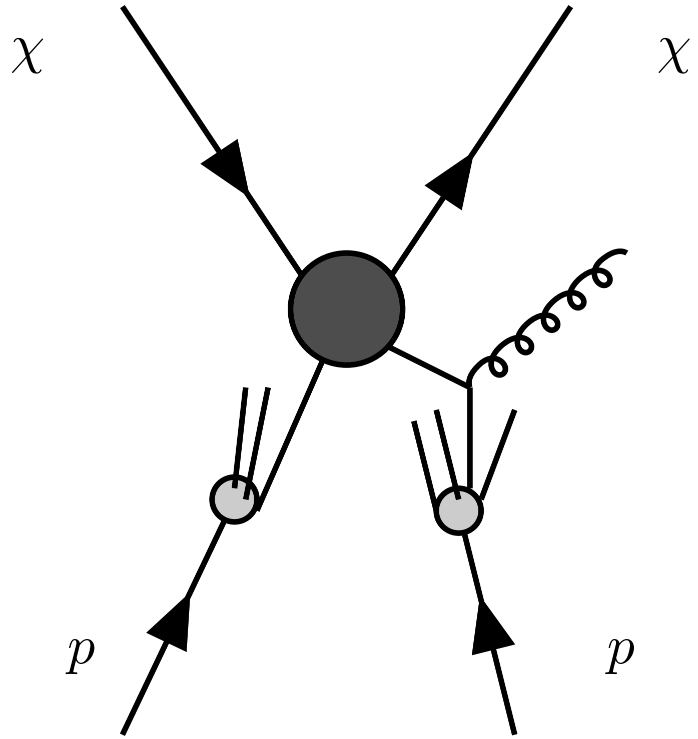
(almost) consistent with including only everything that interferes(gives conservative bounds):

- not interfere at the LHC with other operators
- but axial and tensor $\overline{\chi}\Gamma\chi$ currents interfere in Spin Dep Direct Detection

Constraints from the LHC

translating CMS bound to my operators

$\bar{\chi}\chi$ are missing energy ($\not{E}_T$) at the LHC:what to measure?



$$pp \to j + \not{E}_T + X$$

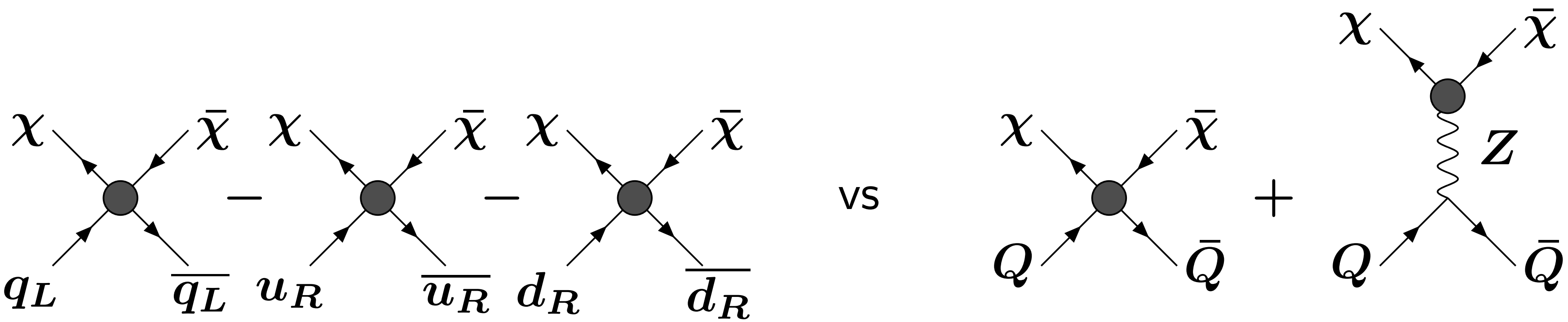
(but... $pp \to j + Z(\bar{\nu}\nu) + X$)

CMS-PAS-EXO-12-048
ATLAS-CONF-2012-147

CMS puts $\frac{1}{\Lambda^2}\sum_{q=u,d} \overline{q}\gamma^\mu\gamma_5 q\,\overline{\chi}\gamma_\mu\gamma_5\chi$ in blob, obtains $\Lambda > 950$ TeV

$$(\overline{q}\gamma^\mu P_L q\,\overline{\chi}\gamma_\mu\gamma_5\chi \ \ , \ \ \overline{d}\gamma^\mu P_R d\,\overline{\chi}\gamma_\mu\gamma_5\chi \ \ , \ \ \overline{u}\gamma^\mu P_R u\,\overline{\chi}\gamma_\mu\gamma_5\chi \ \ , \ \ -s_W p_Z^2\overline{\chi}\not{Z}\gamma_5\chi)$$

Comparing to the CMS search



CMS combines 3 operators who *not* interfere.
Conservative=consider separately $Q \in \{q_L, u_R, d_R\}$...add Z, *does* interfere

$$\frac{1}{\Lambda^2_{CMS}} \quad \Leftrightarrow \quad \sqrt{\frac{f_Q}{f_u + f_d}} \left[C^{(6)}_{QX,A} + g^Q_X \frac{g s_W}{c_W} \frac{p_Z^2 C^{(6)}_{Z,A}}{(p_Z^2 - m_Z^2)} \right] \frac{1}{2\Lambda^2_{me}}$$

if $p_Z^2 = M^2_{inv} \gg m_Z^2$ then can compare

$$\frac{1}{\Lambda^2_{CMS}} \quad \Leftrightarrow \quad \sqrt{\frac{f_Q}{f_u + f_d}} \left[C^{(6)}_{QX,A} + g^Q_X \frac{g s_W}{c_W} C^{(6)}_{Z,A} \right] \frac{1}{2\Lambda^2_{me}}$$

also, $M^2_{inv} = |\text{4-p transfer}|^2$, require $\Lambda^2_{me} > M^2_{inv}$

To guess M^2_{inv} ...

Have $|\mathcal{M}|^2$ for partonic process $qg, q\bar{q} \to Nj + \chi\overline{\chi}$

1. to show that most events have large M^2_{inv}
   ⋆ neglect spin correlations and m_χ. Then the trace over χs $\propto M^2_{inv}$
   ⋆ integrate 2-bdy phase space of $\chi\overline{\chi}$, replace by "inv" of variable mass $p^2 = M^2_{inv}$:

$$d\Phi_{N+2}(j_1, ..j_N, \chi, \bar{\chi}) = d\Phi_{N+1}(j_1, ..j_N, inv(p)) \times (2\pi)^3 dp^2 \delta^4(p - p_\chi - p_{\bar{\chi}}) \frac{d^3 p_\chi}{2E_\chi (2\pi)^3} \frac{d^3 p_{\bar{\chi}}}{2E_{\bar{\chi}} (2\pi)^3} .$$

$$\Rightarrow \int d\Phi_{N+2} |\mathcal{M}|^2 \propto M^4_{inv}$$

2. to estimate the upper limit of M^2_{inv}:
   consider 3bdy phase space for (massless) jets $+ \chi\bar{\chi}$... $M^2_{inv}\Big|_{max} \lesssim 4{\not{E}_T}^2$
   CMS uses data with 400 GeV $\leq \not{E}_T \lesssim$ TeV

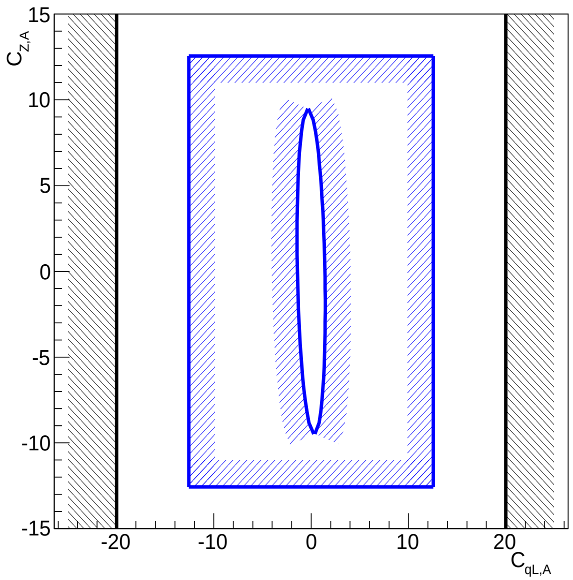
$$M^2_{inv}\Big|_{max} \lesssim 1 - 4\text{TeV}^2 \quad \Rightarrow \Lambda_{me} = \text{TeV}$$

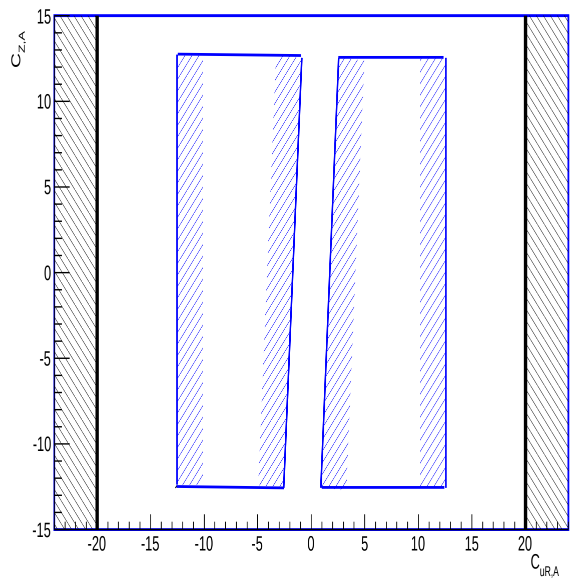
Translating CMS limits to my operators (for $\Lambda_{me} =$ TeV)

$$4\pi \lesssim \sqrt{\frac{2}{3}|C_{qL,A} + \frac{2}{15}C_{Z,A}|^2 + \frac{1}{3}|C_{qL,A} - \frac{1}{6}C_{Z,A}|^2} \lesssim \sqrt{2}$$

$$4\pi \lesssim |C_{uR,A} - \frac{1}{15}C_{Z,A}| \lesssim \sqrt{3}$$

$$4\pi \lesssim |C_{dR,A} + \frac{1}{30}C_{Z,A}| \lesssim \sqrt{6}$$





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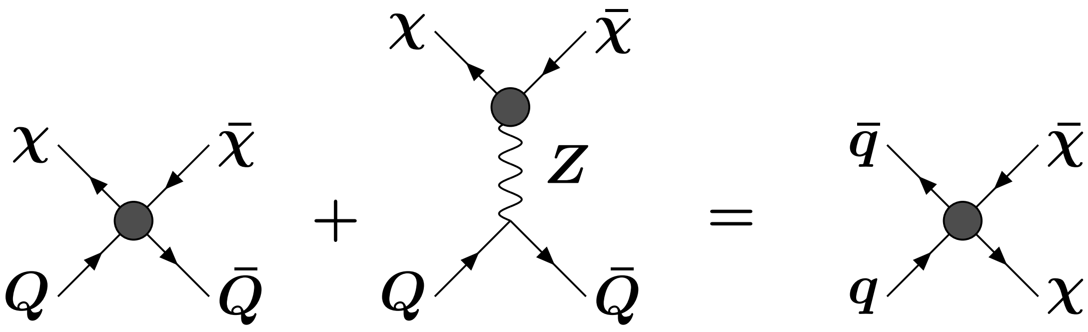
From TeV to MeV and Direct Detection bounds

"match out" the Z
put quarks in nucleons

From TeV to Direct Detection @MeV

1. match out the Z, h ,at zero external momentum $\Leftrightarrow p_Z^2 = 0$:



diagrams above m_Z determine operator coefficients in theory below m_Z:

$$\left[C^{(6)}_{QX,A} + g^Q_X \frac{g s_W}{2 c_W} \frac{p_Z^2 C^{(6)}_{Z,A}}{(p_Z^2 - m_Z^2)} \right]_{above} = C^{(6)}_{QX,A}\Big|_{below}$$

2. run (not $\overline{q}\gamma^\mu q$, but $\overline{q}q$ yes)

3. (match out b, c, s)

4. match onto two-χ-two nucleon operators, $N \in \{n, p\}$

$$\{\overline{\psi_N}\Gamma_N\psi_N\overline{\chi}\Gamma_\chi\chi\} \qquad \Gamma \in \{1, \gamma_5, \gamma^\mu, \gamma^\mu\gamma_5\sigma^{\mu\nu}\}$$

- in practise, evaluate quark currents in nucleon states

$$\langle N|\overline{q_i}\gamma^\mu\gamma_5 q_i|N\rangle = 2s^\mu \Delta Q_i^N \quad (= \quad \Delta Q_i^N \langle N|\overline{\psi_N}\gamma^\mu\gamma_5\psi_N|N\rangle)$$

- non-relativistic kinematics! In zero-momentum transfer limit(!),

$$\overline{\psi}\gamma^\mu\gamma_5\psi \sim (0, s_x, s_y, s_z) \quad , \quad \overline{\psi}\gamma^\mu\psi \sim (X, 0, 0, 0)$$

so axial χ operators interact with nucleon spin.
and the only non-zero operators are

$$\boldsymbol{\overline{\chi}\gamma^\mu\gamma_5\chi\overline{\psi_N}\gamma_\mu\gamma_5\psi_N} \qquad \overline{\chi}\sigma^{\mu\nu}\chi\overline{\psi_N}\sigma_{\mu\nu}\psi_N \qquad \text{SpinDep}$$

$$\overline{\chi}\chi\overline{\psi_N}\psi_N \qquad \overline{\chi}\gamma^\mu\chi\overline{\psi_N}\gamma_\mu\psi_N \qquad \text{SpinIndep}$$

Direct Detection Bounds: Spin Dependent

$$\sigma_{SD} \simeq m_p^2 \left[\frac{.42(C_{qL,A} + C_{uR,A} - 2C_{dR,A})}{2\Lambda^2} \right]^2 \lesssim \frac{10^{-10}}{4} \mathrm{GeV}^{-2}$$

(exptal bound for $m_\chi \sim 100$ GeV). For $\Lambda =$TeV:

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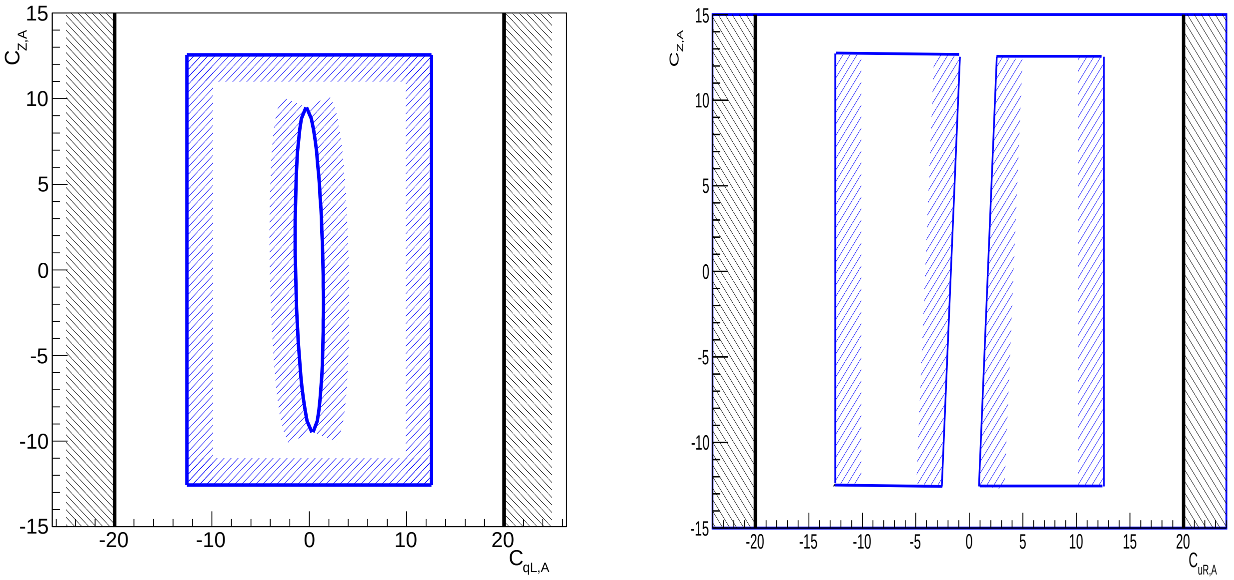
$$|(C_{qL,A} + C_{uR,A} - 2C_{dR,A})| \lesssim 20$$



Summary

There is dark matter. Does it have interactions stronger than gravity with the SM?

Below mediator mass, can parmetrise dark matter interactions with the SM via contact interactions (depends on Q#s of DM...here a SM-singlet fermion χ)

At the LHC, contact interaction approx marginally consistent (? ?? ???) : mediator coupling to DM > 1.
Considered axial vector interaction of DM to u, d, Z : LHC insensitive to $\overline{\chi} \not{Z} \gamma_5 \chi$ coupling. For $\overline{Q}\gamma^\mu Q \overline{\chi}\gamma_\mu\gamma_5\chi$ can exclude $4\pi \gtrsim C \gtrsim \text{few}$ for $\Lambda =$TeV

Some things to remember with contact interactions:

1. Colliders exclude a band:

$$\frac{4\pi}{\hat{s}} \gtrsim \frac{C}{\Lambda^2} \gtrsim \text{sensitivity}$$

** LHC contact interaction analysis not sensitive to parameter space explored by spin dep direct detection**

2. different particles/interferences in DD and at LHC: constrain different linear combinations of operators.

3. recall conservative bounds $\Leftrightarrow$ only include everything that interferes

(in presence of interference, should not set bounds one operator at a time!)

** should not do initial flavour sum for contact interactions at the LHC**