LHC Dark Matter Searches

How Useful Are Effective Operators?

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Felix Kahlhoefer

Rudolf Peierls Centre for Theoretical Physics

UNIVERSITY OF OXFORD

In collaboration with

Mads Frandsen, Ulrich Haisch, Philipp Mertsch, Anthony Preston, Subir Sarkar, Kai Schmidt-Hoberg, James Unwin

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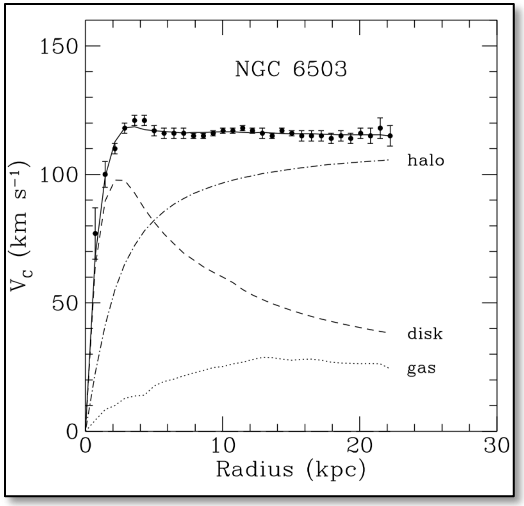
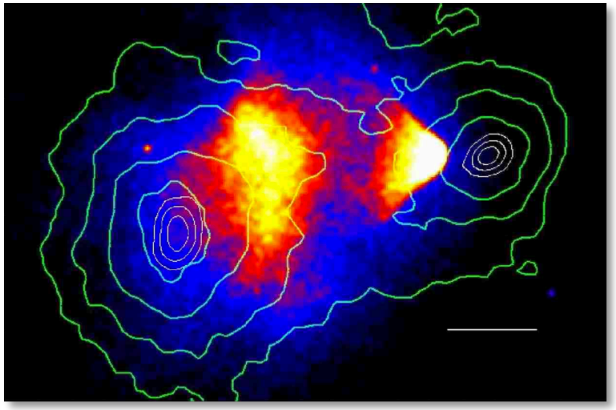
Outline

- Introduction
- Effective operators and their limitations
- How to treat resonances at the LHC
- Operator mixing and heavy-quark loops
- Conclusions

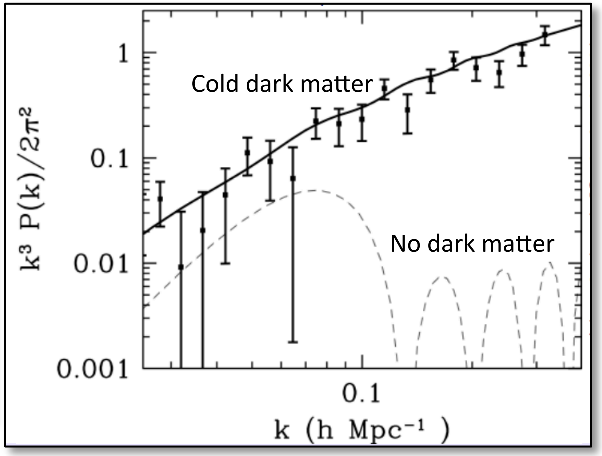
Evidence for dark matter



Galactic scales



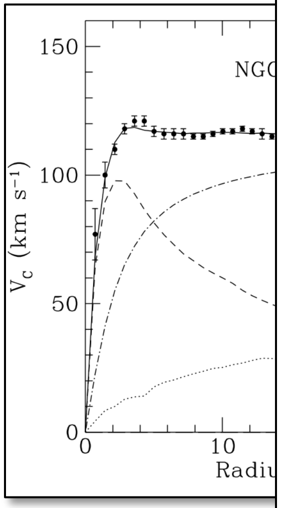
Galaxy cluster scales

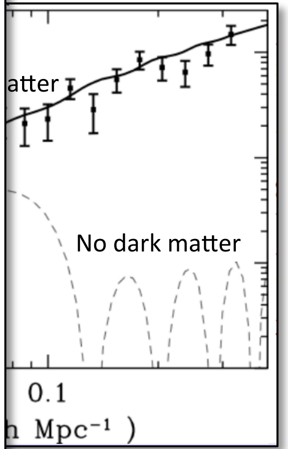


Cosmological scales

Conclusive observational evidence for dark matter over a wide range of astrophysical scales

Evidence for dark matter





Galactic sc gical scales

Conclu matter
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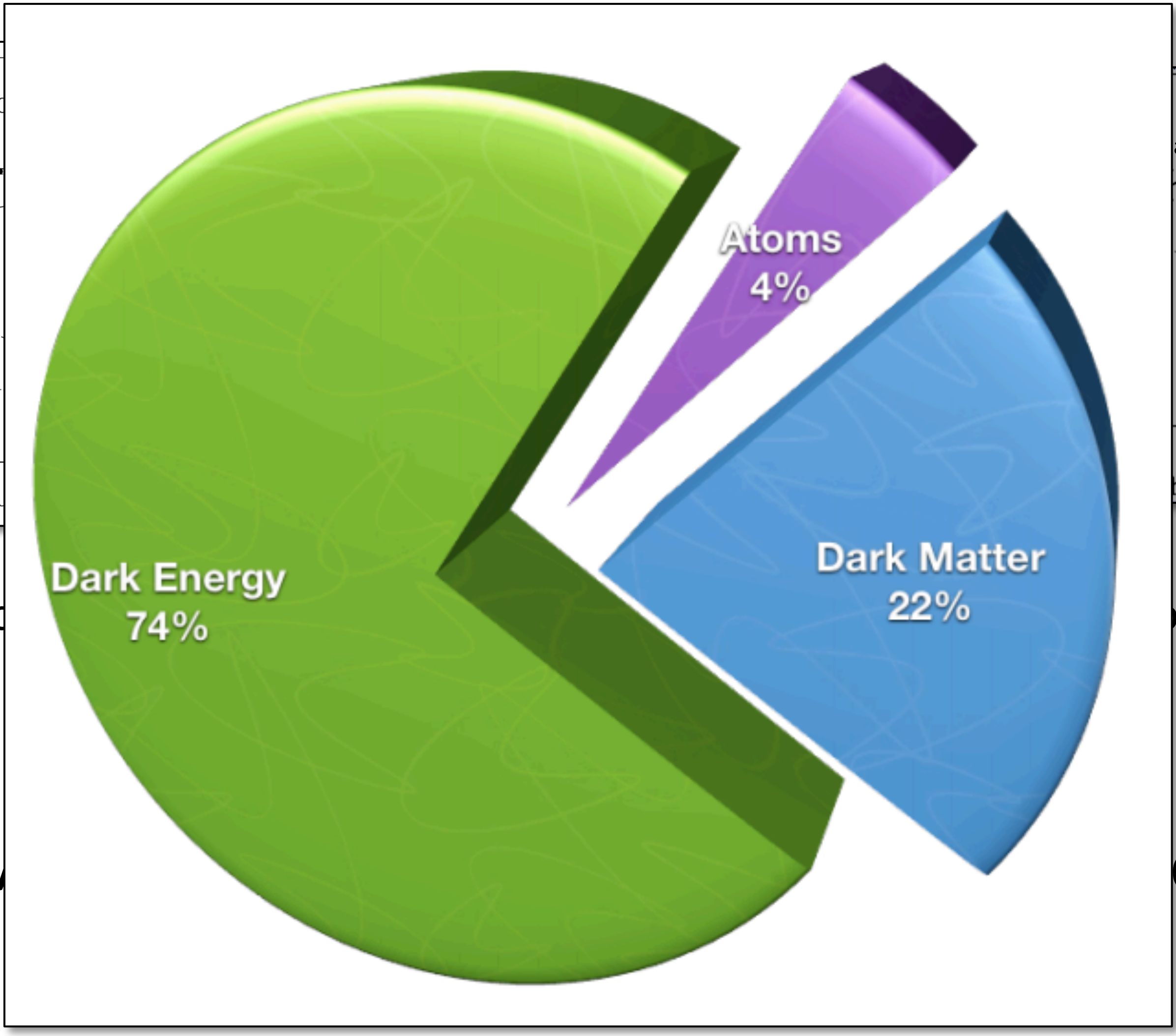
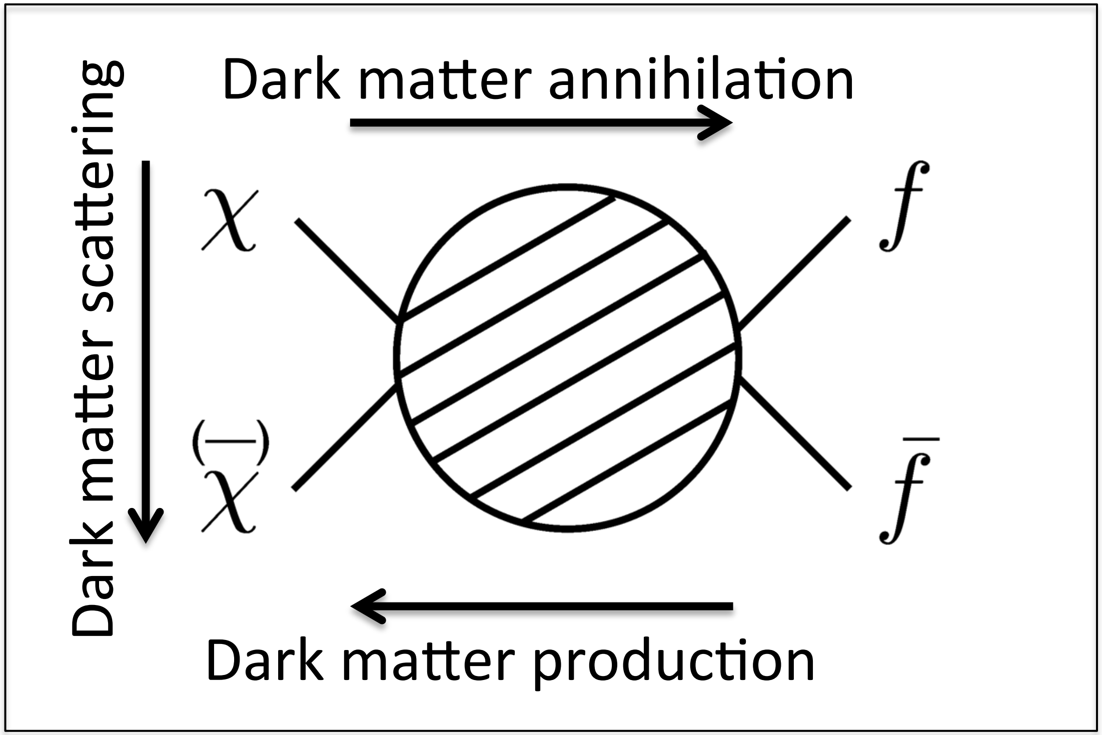


Particle candidates for DM

- The most popular candidate is the WIMP: A cold thermal relic with weak scale mass and interactions (e.g. the lightest SUSY particle) which naturally has the required relic abundance – the WIMP miracle
- The *many* alternative options include:
  - Asymmetric dark matter (with same origin as baryons)
  - Warm dark matter (e.g. sterile keV neutrinos)
  - Axion dark matter
  - …

Detecting DM particles

- For most dark matter candidates, we expect some kind of interactions with Standard Model particles leading to thermal equilibrium in the early universe.



Dark matter annihilation

Dark matter scattering

Dark matter production

DM direct detection

Photo: AP

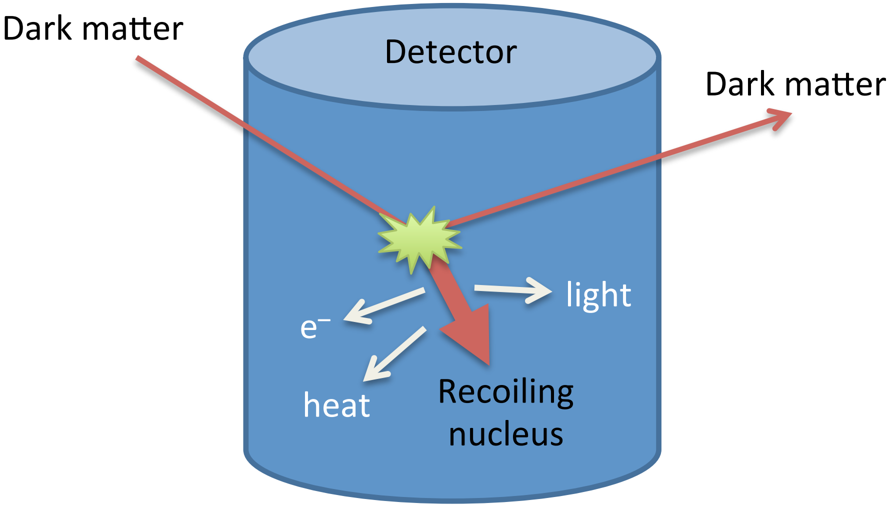
Dark matter particles from the Galactic halo that pass through the Earth will occasionally scatter off nuclei.
The resulting recoil energy of the nucleus can be measured in dedicated low background detectors.

$$\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{nr}}} = \frac{\rho_0}{m_\chi m_\mathrm{N}} \int_{v_\mathrm{min}}^{\infty} \mathrm{d}v\, v f(v, v_\mathrm{E}) \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{nr}}}$$

Typical event rates are less than

1 event per kg per year

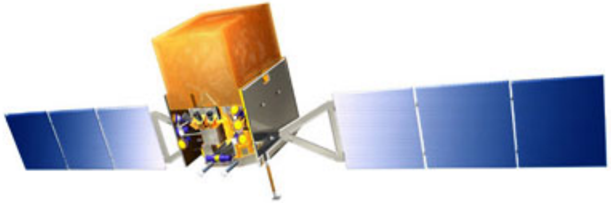
A great experimental challenge!



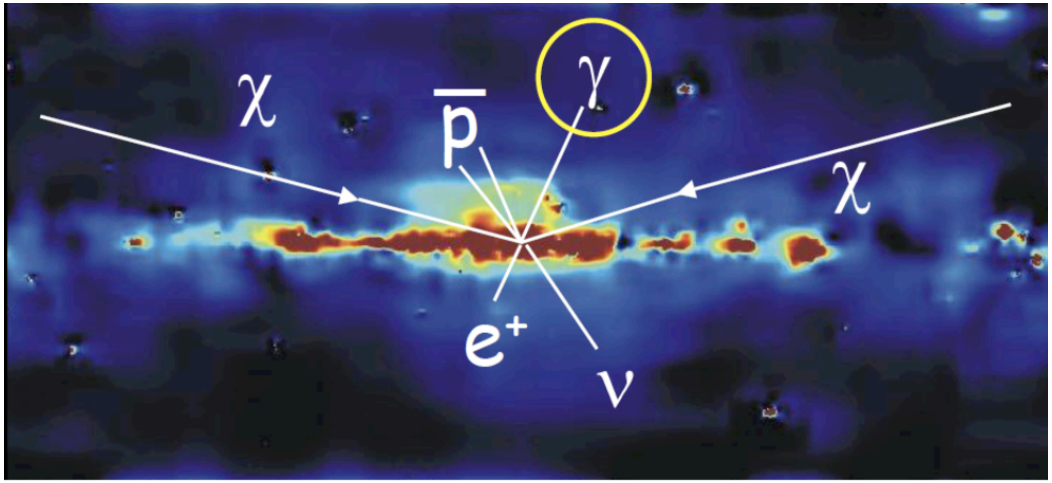
DM indirect detection


© Clay Lipsky

Indirect detection experiments look for the products of DM annihilation in regions of high DM density (e.g. the galactic center) with satellites, balloons and ground based telescopes.

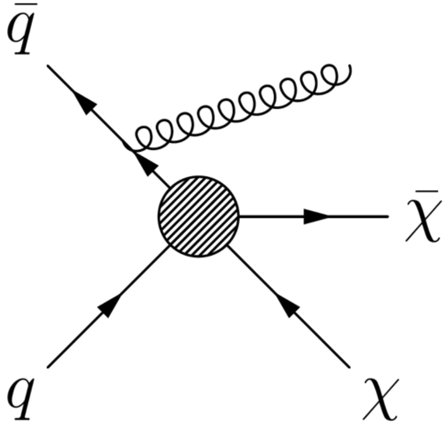


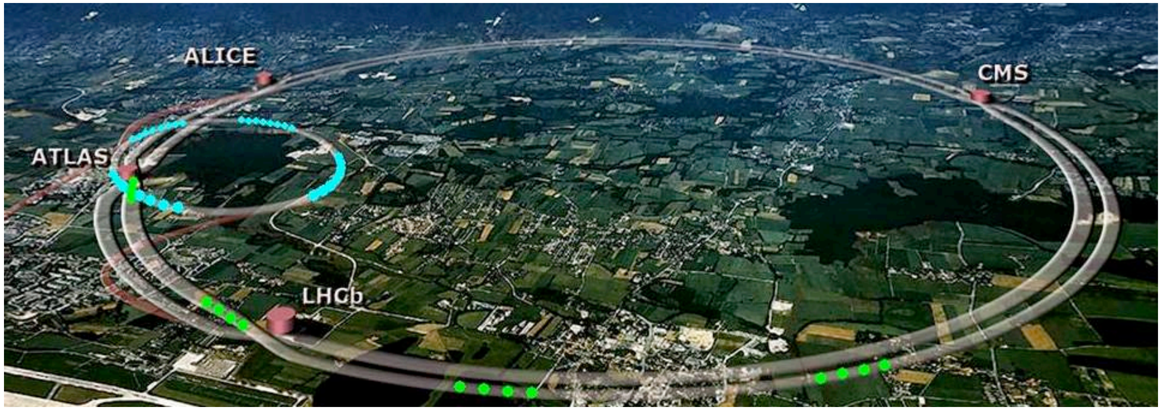
Difficulties arise from astrophysical backgrounds and the DM density profile.



DM searches at colliders

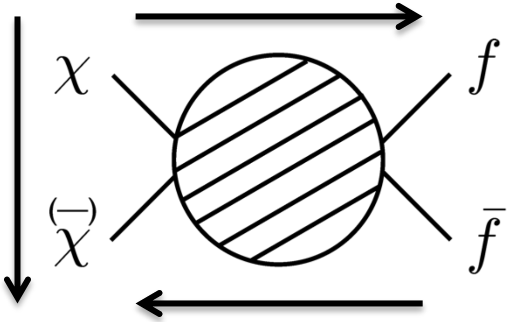
Any DM particles produced at colliders will escape from the detector unnoticed. But if other particles (such as jets) are produced in association with a pair of DM particles, we may observe large amounts of missing transverse energy.





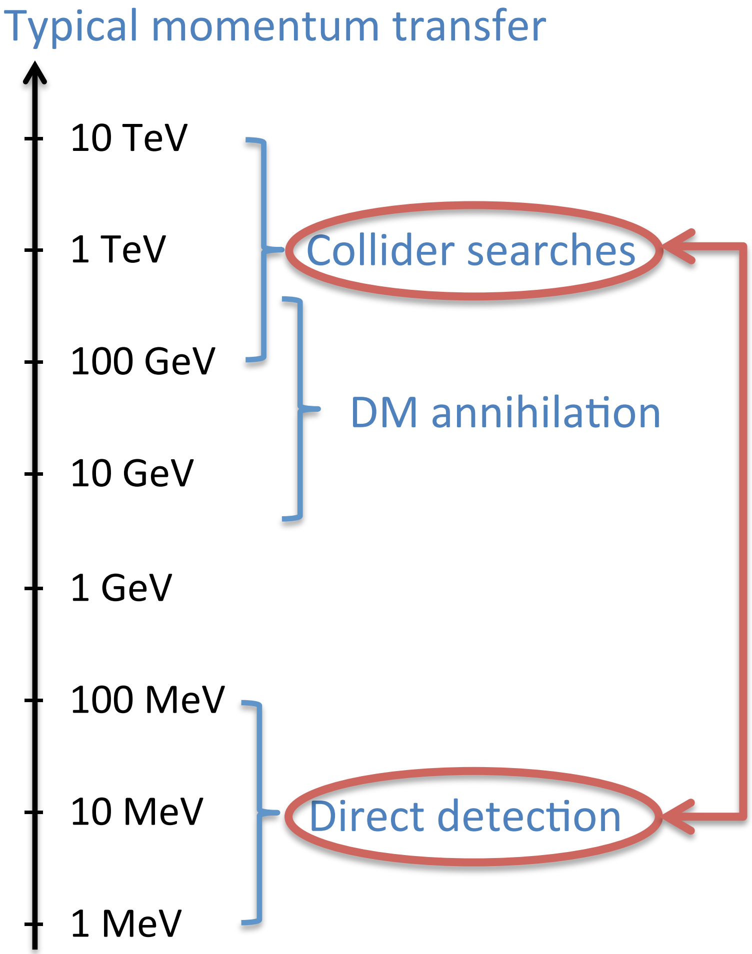
Detecting DM particles

If dark matter particles give a direct detection signal, we also expect to see related processes with distinctive signatures.



Experiments searching for these signatures can constrain the direct detection cross section.

Separation of scales



Dark matter direct detection probes the non-relativistic limit ($v_{\mathrm{DM}} \approx 10^{-3}$), while the LHC probes the TeV scale.

Interactions that look very similar at the LHC may look very different in direct detection.

Example

- Assume that DM interacts with quarks via the exchange of a vector mediator R which can couple to the vector current $\chi\gamma^\mu\chi$ or the axial current $\chi\gamma^5\gamma^\mu\chi$ (or a combination).
- At the LHC: Impossible to distinguish VC and AC.
- In direct detection:

Vector couplings → Spin-independent

Axial couplings → Spin-dependent

Mixed couplings → Momentum suppressed

Effective operators

To compare bounds from the LHC to direct detection, we describe interactions between DM and quarks with effective operators, e.g.

$$\mathcal{L}_\chi^{\text{eff}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

This effective operator could arise from integrating out a vector mediator with mass m_R and vector couplings g_q to quarks and g_χ to DM:

$$\Lambda = m_R/\sqrt{g_q g_\chi}$$

Effective interactions

For $\mathcal{L}_\chi^{\text{eff}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$ the direct detection cross section is given by $\sigma_p^{\text{SI}} = \frac{f^2\mu_{\chi n}^2}{\pi\Lambda^4}$, where $f = 3$ for $g_u = g_d$.

Provided the effective operator remains valid at the LHC, we can use it to calculate the cross section for monojet production.

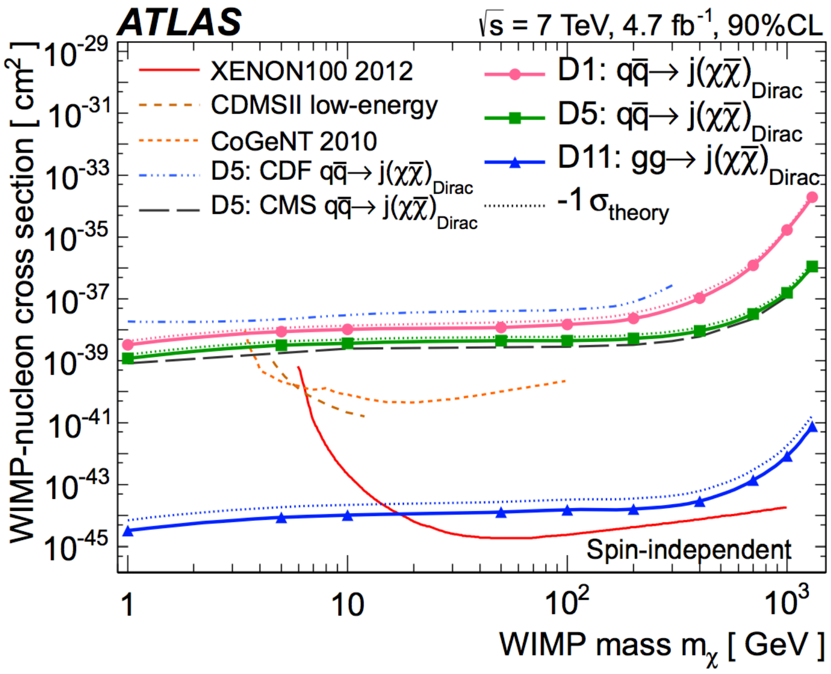
$\sigma\,(j + \text{MET}) \sim 1/\Lambda^4 \sim \sigma_p$

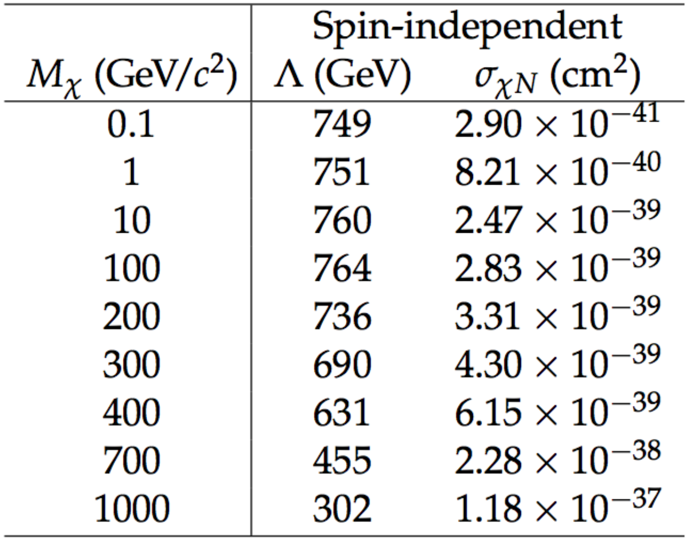
We can *directly* compare LHC searches for dark matter to direct detection experiments

Monojet searches at the LHC

Search for dark matter candidates and large extra dimensions in events with a jet and missing transverse momentum with the ATLAS detector

arXiv:1210.4491





	Spin-independent	
M_χ (GeV/c^2)	Λ (GeV)	$\sigma_{\chi N}$ (cm^2)
0.1	749	2.90×10^{-41}
1	751	8.21×10^{-40}
10	760	2.47×10^{-39}
100	764	2.83×10^{-39}
200	736	3.31×10^{-39}
300	690	4.30×10^{-39}
400	631	6.15×10^{-39}
700	455	2.28×10^{-38}
1000	302	1.18×10^{-37}

CMS Collaboration, arXiv:1206.5663

See also

Goodman et al.	arXiv:1005.1286
Bai et al.	arXiv:1005.3797
Goodman et al.	arXiv:1008.1783
Fox et al.	arXiv:1103.0240
Rajaraman et al.	arXiv:1108.1196
Fox et al.	arXiv:1109.4398

Problems with perturbativity

- Current monojet searches at CMS & ATLAS probe $\Lambda \approx 700$ GeV, corresponding to $\sigma_p \approx 10^{-39}\,\mathrm{cm}^2$.
- To have perturbativity, we require $g_q, g_\chi < (4\pi)^{1/2}$
- From $\Lambda = m_R/\sqrt{g_q g_\chi}$ we then get $m_R < 2.5$ TeV.

Fox, Harnik, Kopp, Tsai, arXiv:1109.4398
Fox, Harnik, Kopp, Tsai, arXiv:1103.0240

For collisions with √s > 2.5 TeV, we can no longer rely on an effective operator description, because new physics becomes relevant.

Problems with unitarity

- For a sensible theory, all predicted probabilities should be smaller than unity.
- More formally, we require partial wave unitarity

$$|a^J(s)| = \left| \frac{1}{32\pi} \int_{-1}^{1} \mathrm{d}(\cos\theta) \mathrm{P_J}(\cos\theta) \mathcal{M}(\mathrm{s}, \cos\theta) \right| < 1$$

- For the effective operator from above $\mathcal{M} = 2\sqrt{3}\frac{s}{\Lambda^2}$ leading to $\sqrt{s} < 2.7\,\Lambda \approx 1.9$ TeV.

Shoemaker, Vecchi, arXiv:1112.5457
Fox, Harnik, Primulando, Yu, arXiv:1203.1662

For collisions with √s > 1.9 TeV, the effective operator makes nonsensical predictions.

Resonant production

- Effective operators may *not* be valid at the LHC
- It is quite possible that the mediator mass is comparable to LHC energies ($m_R \sim$ TeV)
- The LHC can produce such a mediator *on-shell*:

$$\sigma\,(j + \text{MET}) \sim \sigma\,(pp \rightarrow R + j) \times \text{BR}\,(R \rightarrow \text{invisible})$$

- As a consequence, the monojet cross section is *no longer proportional* to the direct detection cross-section and the analysis is more involved.

How to extract a bound

$$\sigma_p \sim \frac{\mu_{\chi n}^2}{\pi} \frac{g_q^2 g_\chi^2}{m_R^4}$$

g_q: Coupling to quarks
g_χ: Coupling to the DM particle
m_R: Mass of the mediator
$\mu_{\chi n}$: Reduced mass

$$\Gamma(R \to \chi\bar{\chi}) \sim \frac{m_R}{12\pi} g_\chi^2$$

$$\Gamma(R \to \chi\bar{\chi}) \leq \Gamma_R \times \mathrm{BR}(R \to \mathrm{inv})$$

$$\sigma_p \lesssim 12 \frac{\mu_{\chi n}^2 \boxed{\Gamma_R}}{m_R^5} \underbrace{g_q^2 \cdot \mathrm{BR}(R \to \mathrm{inv})}_{\text{Constrained by monojet searches}}$$

More difficult to constrain

Decay channels

R can decay into fermions, bosons

and new hidden sector states

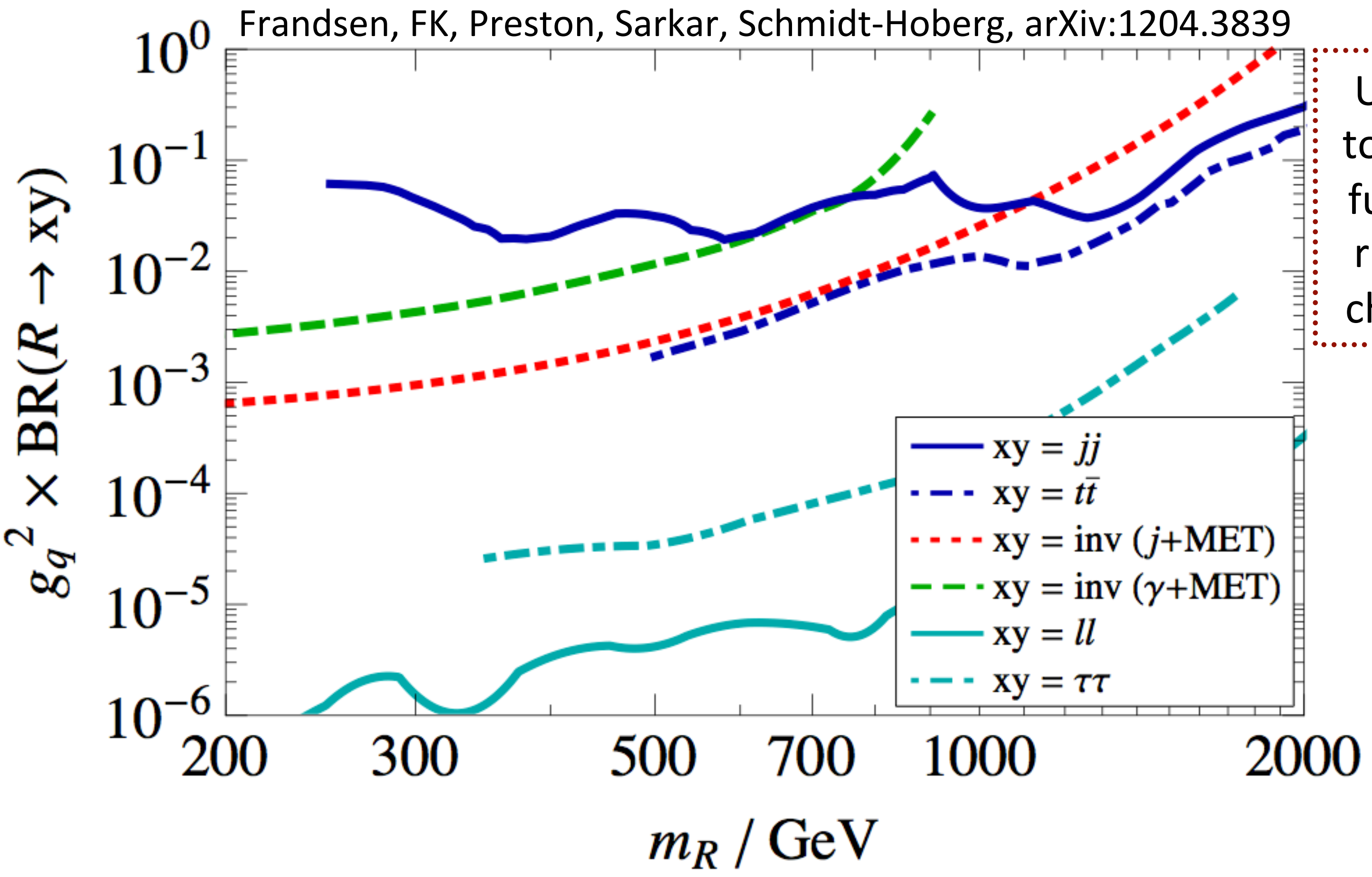
$$\Gamma_R = \Gamma^{\chi\bar{\chi}} + \sum_q \Gamma^{q\bar{q}} + \sum_l \Gamma^{l\bar{l}} + \sum_\nu \Gamma^{\nu\bar{\nu}}$$

$$+ \Gamma^{W^+W^-} + \Gamma^{ZZ} + \Gamma^{\gamma Z} + \Gamma^{ZH}$$

$$+ \Gamma^{X}$$

All of these channels can be constrained by the LHC!

Constraints: Fermions

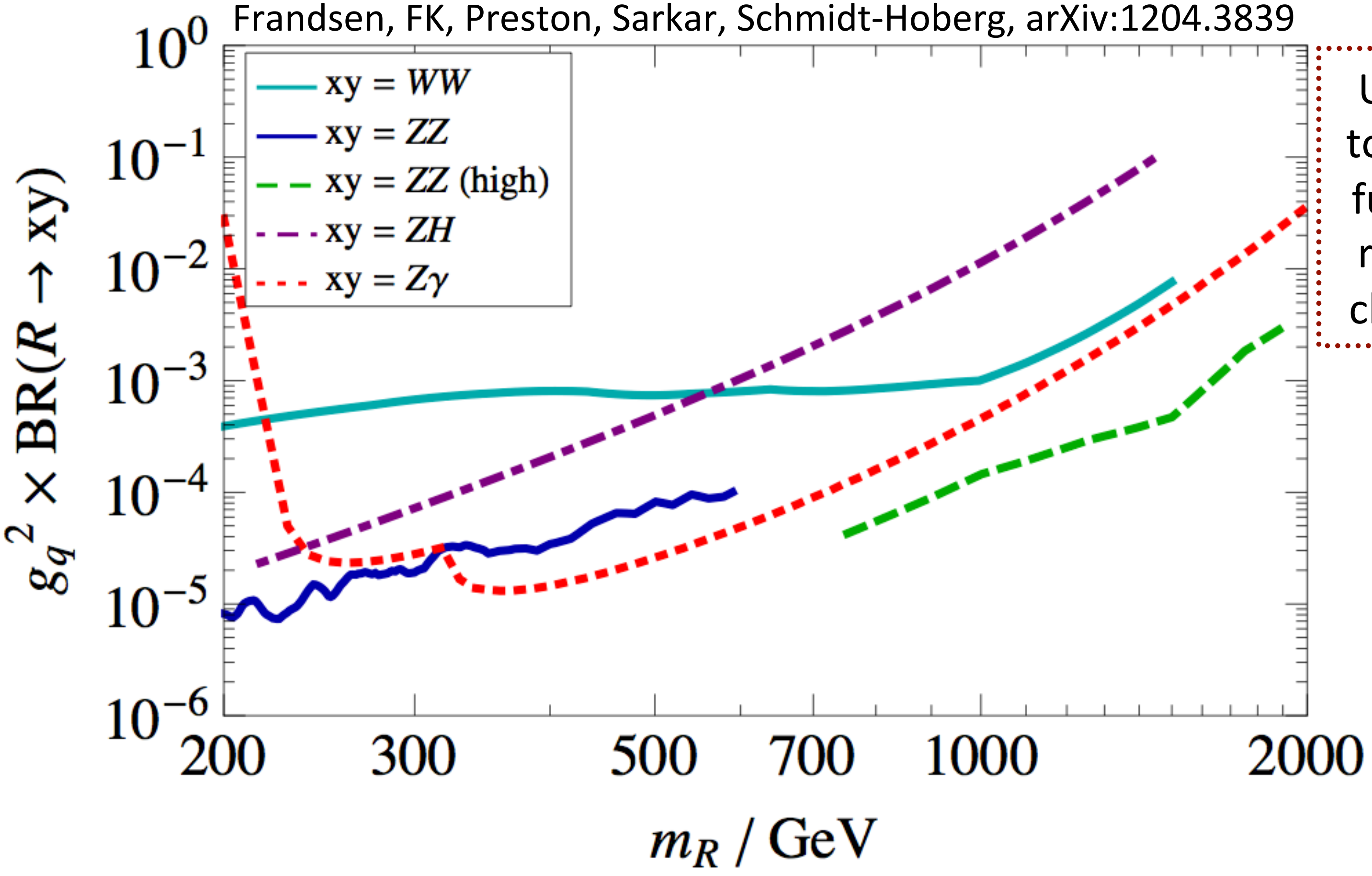


Updated to include full 7 TeV run in all channels!

How Useful Are Effective Operators?

Constraints: Bosons

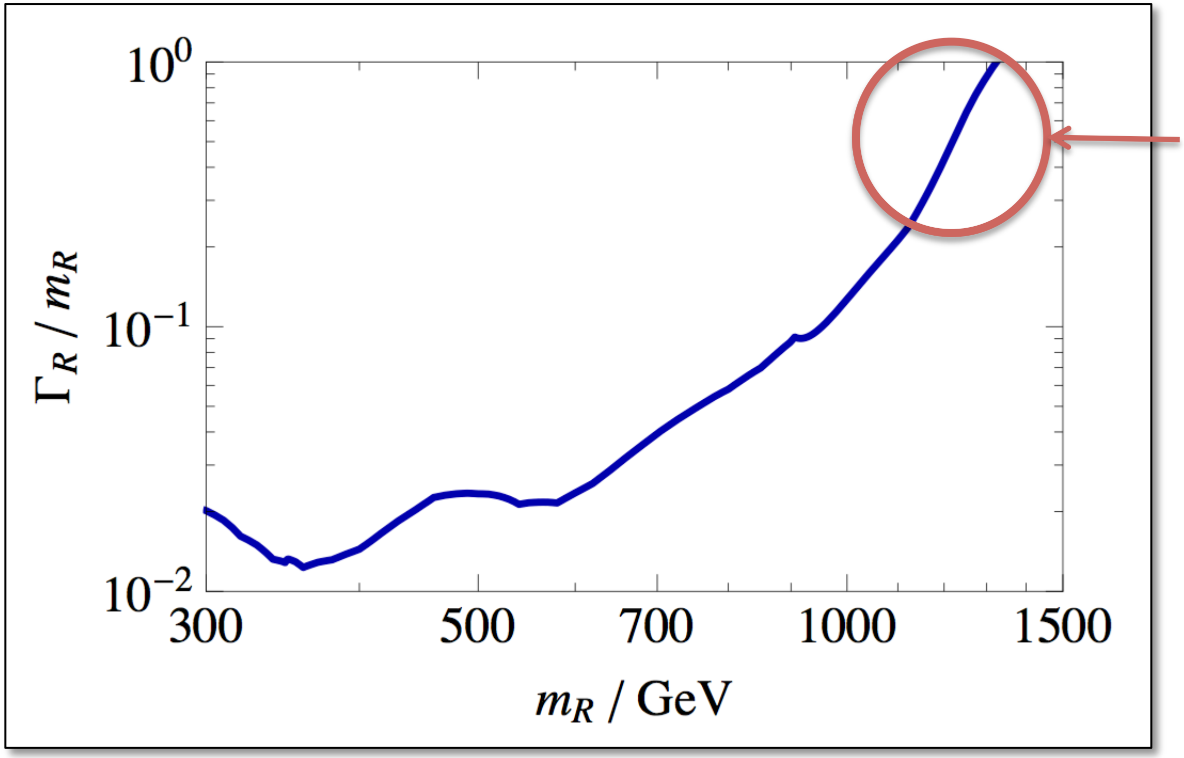
Frandsen, FK, Preston, Sarkar, Schmidt-Hoberg, arXiv:1204.3839



Updated to include full 7 TeV run in all channels!

Combined Constraints

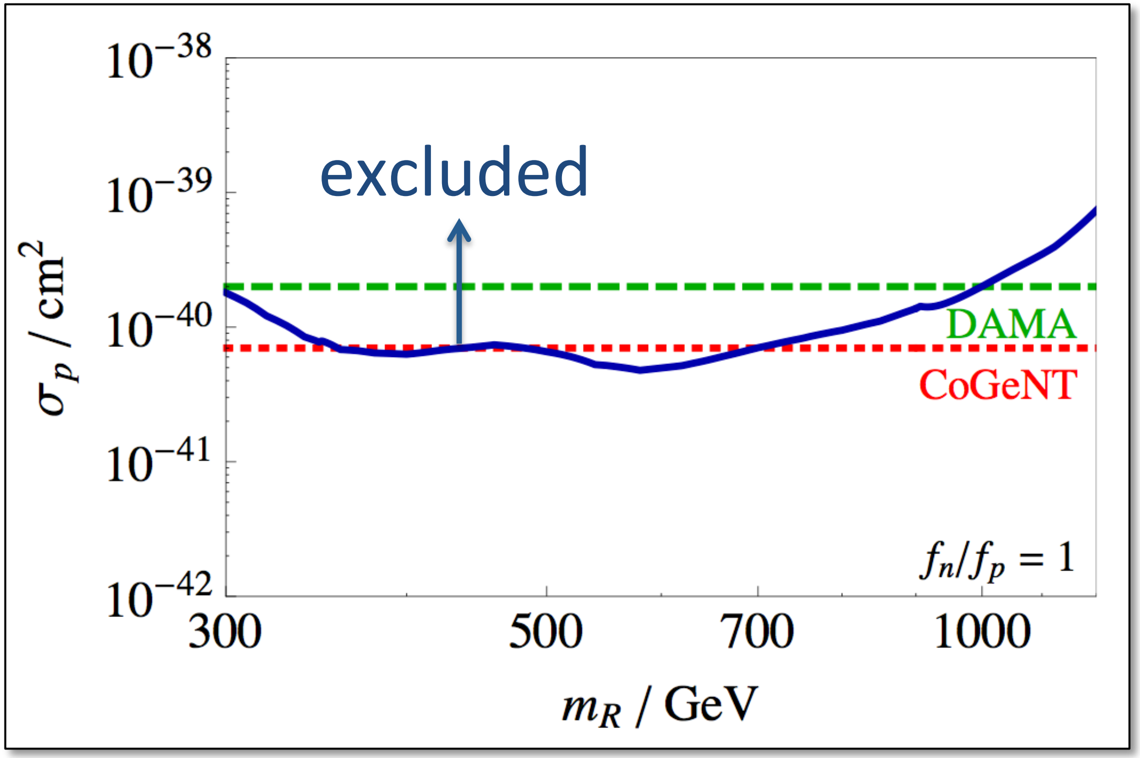
- If *R* decays only into SM particles or invisible states, we can obtain a bound on Γ_R.



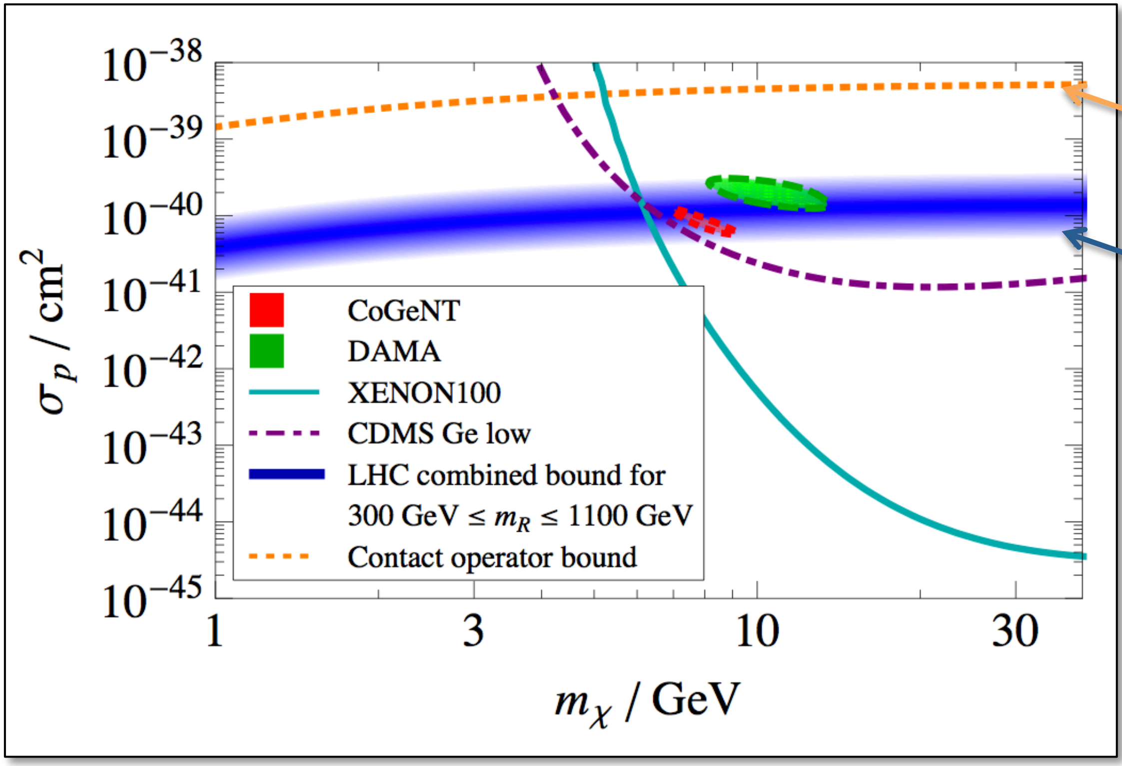
Narrow-width approximation no longer valid

Direct detection limit

$$\sigma_p \lesssim 12 \frac{\mu_{\chi n}^2 \Gamma_R}{m_R^5} g_q^2 \cdot \mathrm{BR}(R \to \mathrm{inv})$$



Direct detection limit



Bound for
$m_R \gg 1.1$ TeV

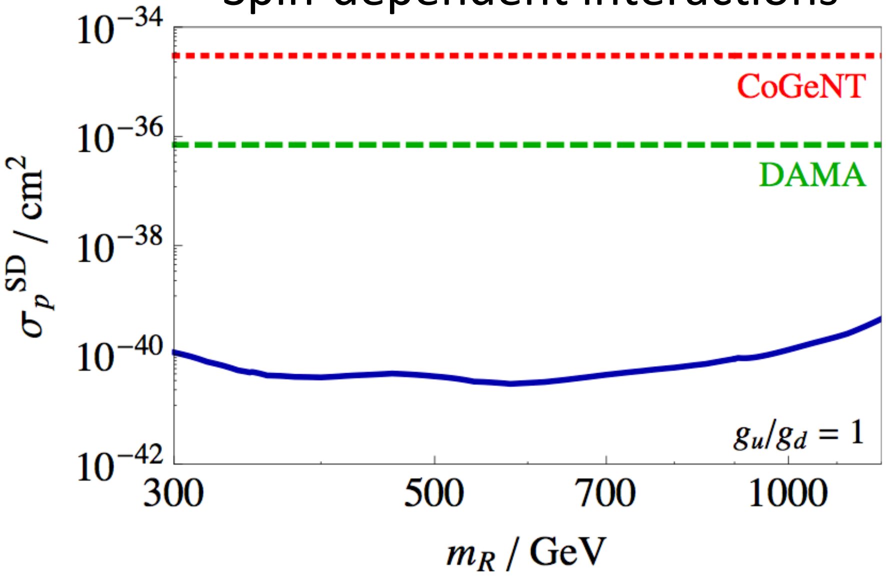
Bound for
$m_R > 300$ GeV
$m_R < 1.1$ TeV

There are strong constraints on the direct detection cross section for vector mediators with $m_R < 1.1$ TeV.

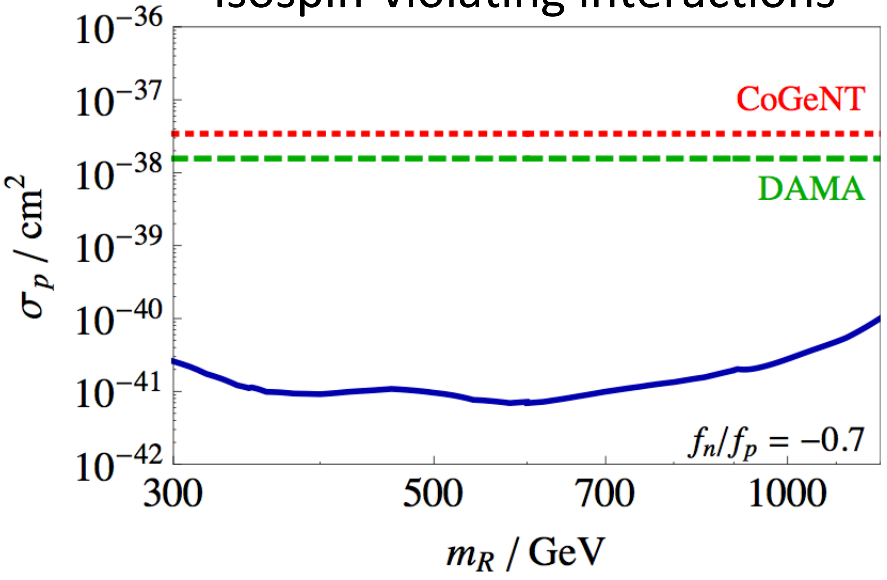
Non-standard interactions

- Collider bounds are largely independent of low-energy effects (e.g. nuclear coherence).
- Very strong bounds arise if σ_p is suppressed.

Spin-dependent interactions



Isospin-violating interactions



Possible caveats

1. If the mediator is lighter than 300 GeV it becomes very difficult to constrain BR($R \rightarrow qq$).
2. If the DM mass is comparable to the mediator mass, decays of R into $\chi\chi$ are suppressed.
3. If R can decay into new hidden sector states with complicated decay modes, Γ_R can be large.
4. If $g_q << g_\chi$ the production of R at LHC is insufficient to constrain Γ_R.

Operator mixing

Operator mixing

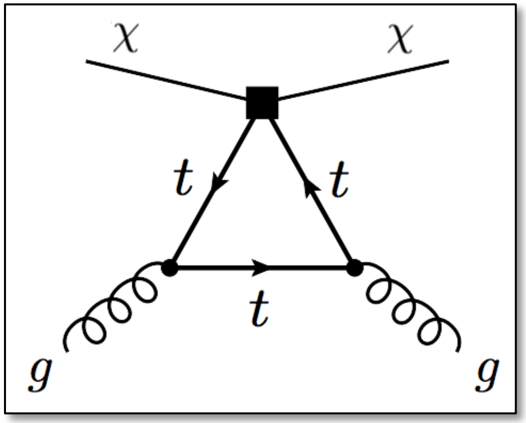
- To calculate direct detection cross sections, we must evolve all effective operators from the TeV scale down to the hadronic scale.
- In the process, new interactions may be induced at loop-level, leading to additional operators, which are absent (or small) at the TEV scale.
- A full calculation should include the mixing of all relevant effective operators under Renormalisation Group evolution.

Example

- Consider the operator which may arise from integrating out a scalar mediator with quark couplings proportional to the quark mass m_q.

$$\mathcal{L}_\chi^{\text{eff}} = \frac{m_q}{\Lambda^3}\,\bar{q}q\,\bar{\chi}\chi$$

- For energies below the top quark mass m_t, the top quark can be integrated out to give an effective interaction between DM and gluons:



$$\mathcal{L}_\chi^{\text{eff}} = \frac{\alpha_s}{4\Lambda_g^3}\,G^a_{\mu\nu}G^{a\,\mu\nu}\,\bar{\chi}\chi$$

Example

- More formally, the operator $\mathcal{O}_q = \mathcal{C}_q m_q \bar{\chi}\chi \bar{q}q$ induces the operator $\mathcal{O}_G = \mathcal{C}_G \bar{\chi}\chi G^{a,\mu\nu} G^a_{\mu\nu}$ with $\mathcal{C}_G(m_t) = -\frac{\alpha_s(m_t)}{12\pi}(1+\delta_t)\,\mathcal{C}_t(m_t)$

$\delta_t = 11\alpha_s(m_t)/(4\pi)$

- A similar threshold correction arises for the bottom quark below m_b and for the charm quark below m_c.

Drees and Nojiri, PRD47, (1993)

Direct detection cross-section

- To calculate the direct detection cross-section, we now need to evaluate $\langle A|\mathcal{O}_q|A\rangle$ and $\langle A|\mathcal{O}_G|A\rangle$ where $|A\rangle$ is the target nucleus state. One finds

$$\langle A|\mathcal{O}_q|A\rangle \simeq 2m_N A\, f^N_{Tq}\, F_{\text{Helm}}(\bar{q})\, \mathcal{C}_q(\mu)$$

and

$$\langle A|\mathcal{O}_G|A\rangle \simeq -2\, \frac{8\pi}{9\alpha_s(\mu)}\, m_N A\, f^N_{TG}\, F_{\text{Helm}}(\bar{q})\, \mathcal{C}_G(\mu)$$

$$\boxed{\sigma^\chi_{\text{SI}} = \frac{\mu_A^2}{\pi}\, |f^\chi|^2 \text{ with } f^\chi = \sum_q \langle A|\mathcal{O}^\chi_q|A\rangle + \langle A|\mathcal{O}^\chi_G|A\rangle}$$

LHC bounds

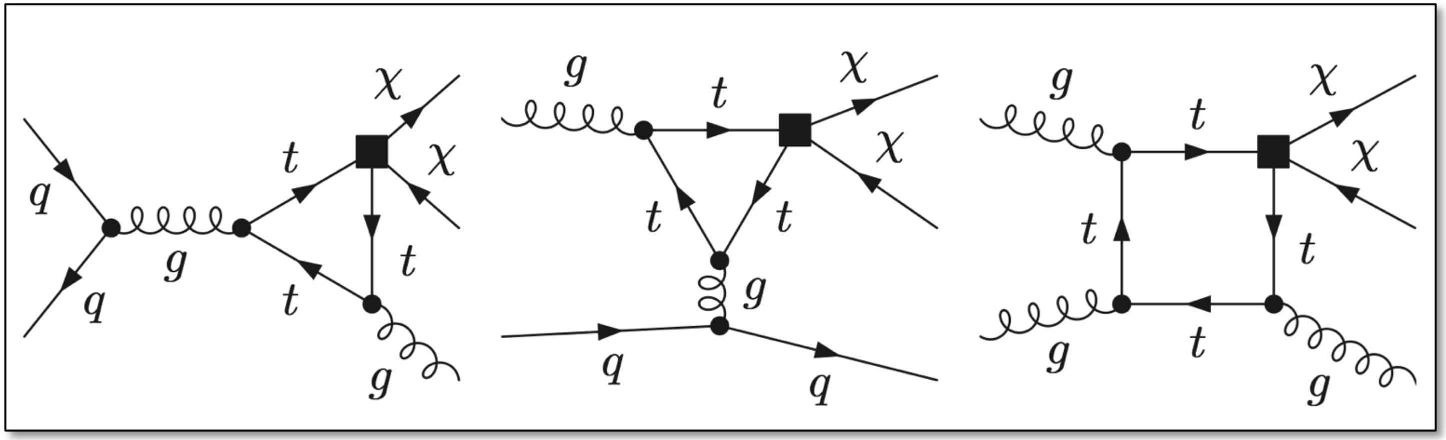
- What is the correct procedure to analyse bounds from monojet searches for the scalar operator?

$$\boxed{\mathcal{L}_\chi^\text{eff} = \frac{m_q}{\Lambda^3}\,\bar{q}q\,\bar{\chi}\chi}$$

- Tree-level cross section are small, because there are no heavy quarks in the initial state.
- We cannot use effective DM-gluon interactions, because the typical energies ($\sqrt{s}$, p_T, …) are large compared to m_t (not to mention m_b and m_c).

LHC bounds

- For an accurate analysis, we must include the full energy dependence of the heavy quark loops using FormCalc + LoopTools (or MCFM).



- While charm and bottom quarks are negligible, top quark loops give the dominant contribution.

Implementation in MCFM

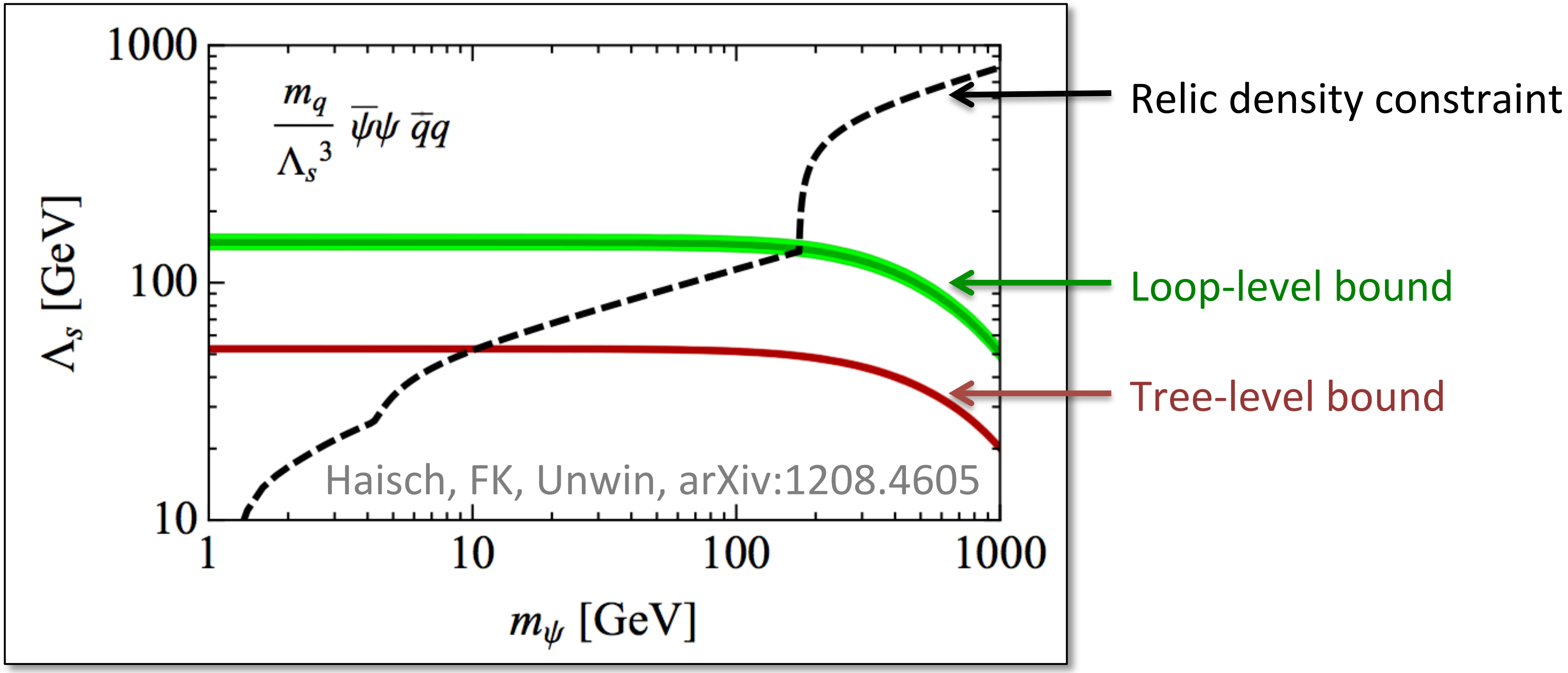
- Our analysis is based on analytical results for the process $p + p \rightarrow H + j \rightarrow \tau^+ \tau^- + j$.

Ellis *et al.*, Nucl.Phys. B297, 221 (1988)

- These results can be extended to the case of an off-shell mediator by replacing m_H with the invariant mass of the DM pair (equal to $s + t + u$).
- Because the primary jet has very large p_T, effects of parton showering and hadronisation are expected to be small.

Bai, Fox, Harnik, arXiv:1005.3797
Choudalakis, arXiv:1110.5295

LHC bounds



Haisch, FK, Unwin, arXiv:1208.4605

Relic density constraint

Loop-level bound

Tree-level bound

- Including loop-level processes increases predicted monojet cross sections by a factor of around 500.
- Width of the bands reflect scale uncertainties.

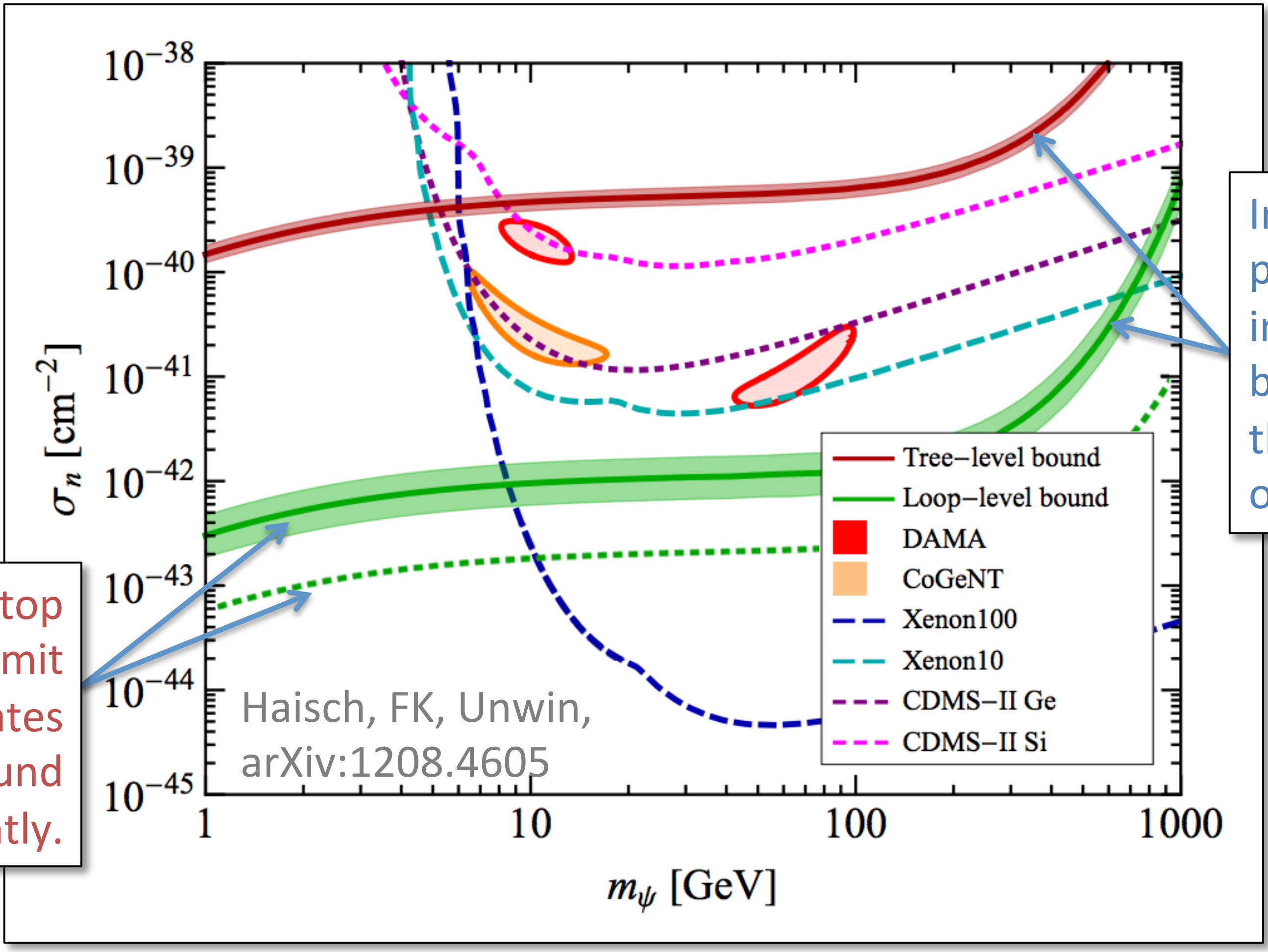
How heavy are top quarks?

- It is tempting to consider only the limit of infinitely heavy top quark and use the effective DM-gluon interaction

$$\mathcal{O}_G = \mathcal{C}_G \, \bar{\chi}\chi G^{a,\mu\nu} G^a_{\mu\nu}$$

- We find that this approximation overestimates cross sections by a factor of 3 for small DM masses.
- For large DM masses, the error grows rapidly, reaching a factor of 40 at $m_\psi = 1$ TeV.
- For accurate results it is essential to allow on-shell top quarks with finite mass in the loops.

LHC bounds



Haisch, FK, Unwin, arXiv:1208.4605

Heavy top quark limit overestimates the bound significantly.

Including loop processes improves the bounds by more than two orders of magnitude

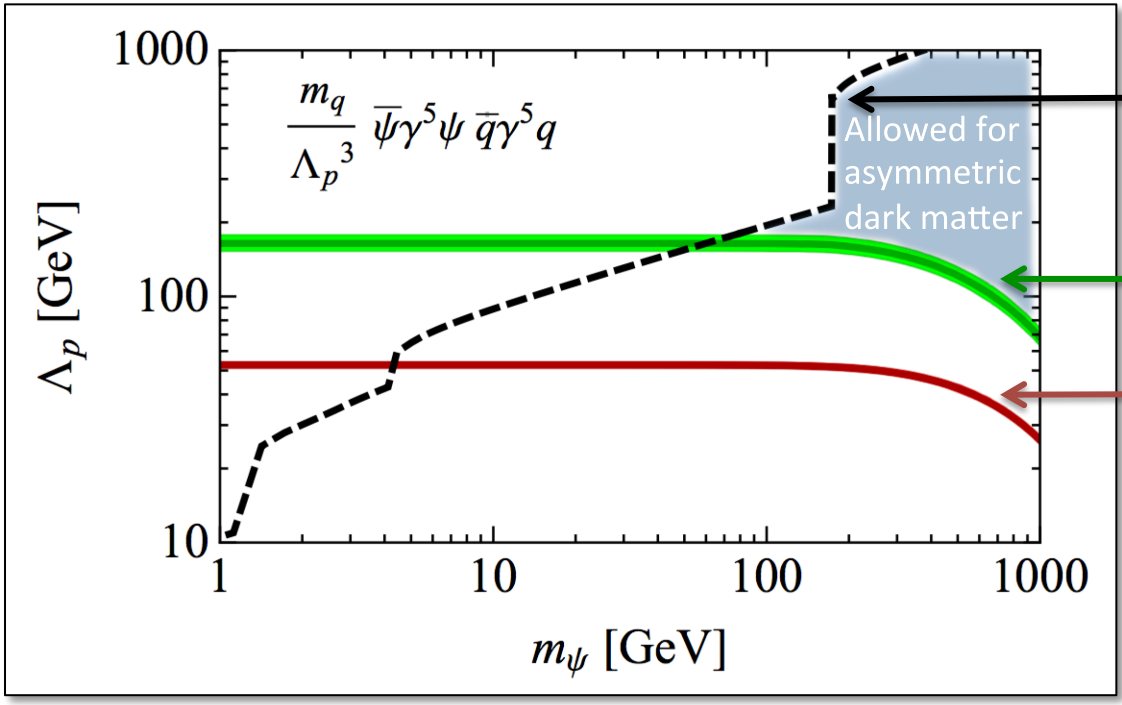
Pseudoscalar interactions

- For the pseudoscalar operator

  $$\mathcal{O}_p^\psi = \frac{m_q}{\Lambda_p^3}\,\bar{q}\gamma^5 q\,\bar{\psi}\gamma^5\psi$$

  detection cross sections are spin-dependent and in addition suppressed by $q^4 / m_N{}^4$.
- Consequently, no relevant constraints on Λ_p arise from direct detection experiments.
- At the LHC scalar and pseudoscalar interactions look very similar, so we obtain strong constraints on Λ_p.

Pseudoscalar interactions



Relic density constraint

Loop-level bound

Tree-level bound

- Imposing that DM is not overproduced leads to the bound $m_\psi > 60$ GeV (Majorana fermion: $m_\psi > 85$ GeV).

Conclusions

- At typical LHC energies effective operators may be insufficient to interpret monojet bounds, because the intermediate particles can be on-shell.
- *Example 1*: Resonant production of vector mediators

  Heavy mediators ($m_R \geq 300$ GeV) can be tested and constrained by current LHC data.
- *Example 2*: Heavy-quark loops for scalar mediators

  Loop-level processes significantly enhance the monojet cross-section, but one needs to include the full top-mass dependence for accurate results.