LHC monojets & direct detection

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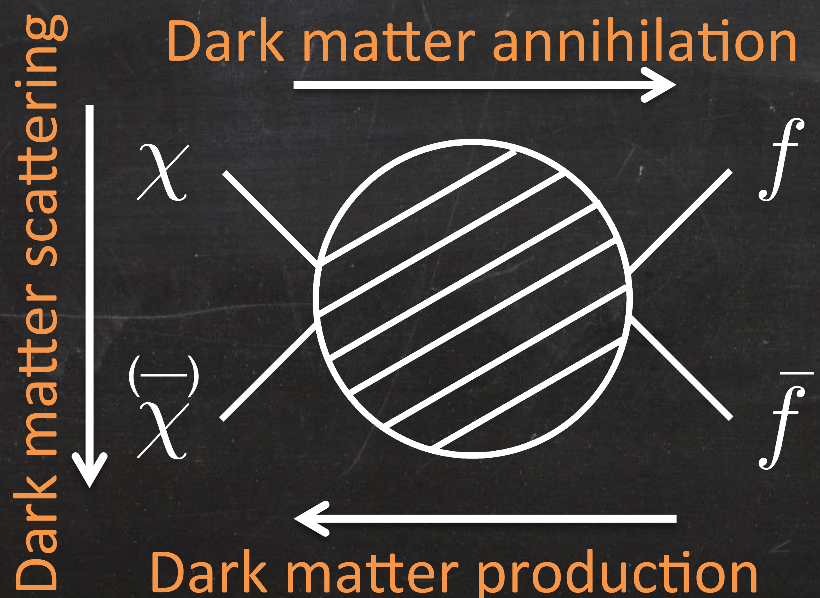
Outline

1. Introduction and motivation
2. Effective operators and their problems
3. Resonant production of vector mediators
4. How to extract bounds for direct detection
5. Example: The dark *Z'*
6. Conclusions

Introduction

If dark matter particles scatter on nuclei to 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

Introduction

Problem: Separation of scales

- Dark matter direct detection probes the non-relativistic limit ($v_{DM} \approx 10^{-3}$), while the LHC probes the TeV scale.
- Interactions that look very similar at the LHC (e.g. coupling to the vector and axial current) may look *very* different in direct detection (spin-independent and spin-dependent).

Effective operators

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

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

- Such an interaction would arise from the exchange of a vector mediator with mass m_R and couplings g_q to quarks and g_χ to DM:

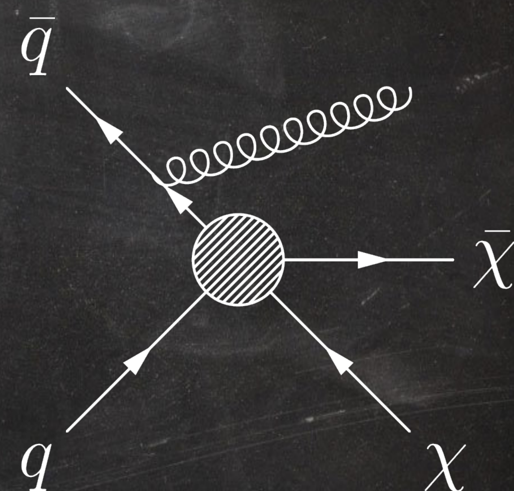
$$\Lambda = m_R/\sqrt{g_q g_\chi}$$

talk by T. Tait

Effective interactions

- For *sufficiently heavy* mediators (m_R > few TeV), effective interactions are valid even at the LHC
- We can *directly* compare LHC searches for dark matter to direct detection experiments

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

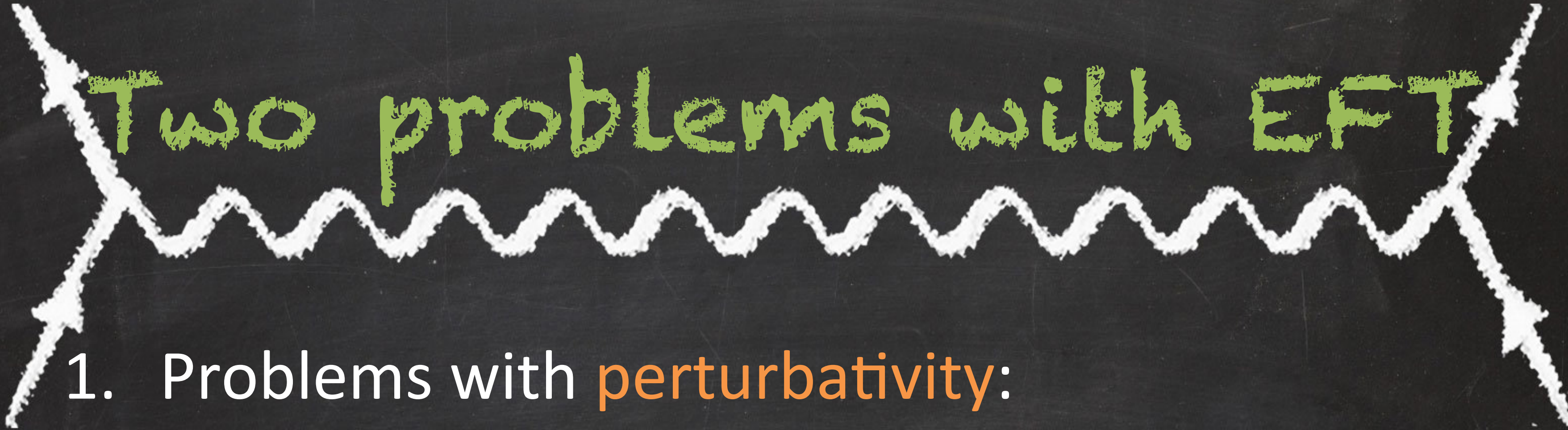


- Current monojet bounds give Λ > 700 GeV, corresponding to

  $\sigma_p \approx 10^{-39}\ \mathrm{cm}^2$

talks by: S. Caron & A. Tapper

Two problems with EFT



1. Problems with perturbativity:

   From g_q, $g_\chi < (4\pi)^{1/2}$ we get $m_R < 2.5$ TeV

   for $\Lambda = 700$ GeV, so we require $\sqrt{s} < 2.5$ TeV.

2. Problems with unitarity:

   $$\boxed{\mathcal{M} = 2\sqrt{3}\frac{s}{\Lambda^2}}$$

   The requirement

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

   holds *only* for $\sqrt{s} < 2.7\,\Lambda \approx 1.9$ TeV.

Shoemaker, Vecchi, arXiv:1112.5457

Fox, Harnik, Primulando, Yu, arXiv:1203.1662

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*:

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

- 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 get 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

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

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

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

More difficult to constrain

Decay channels

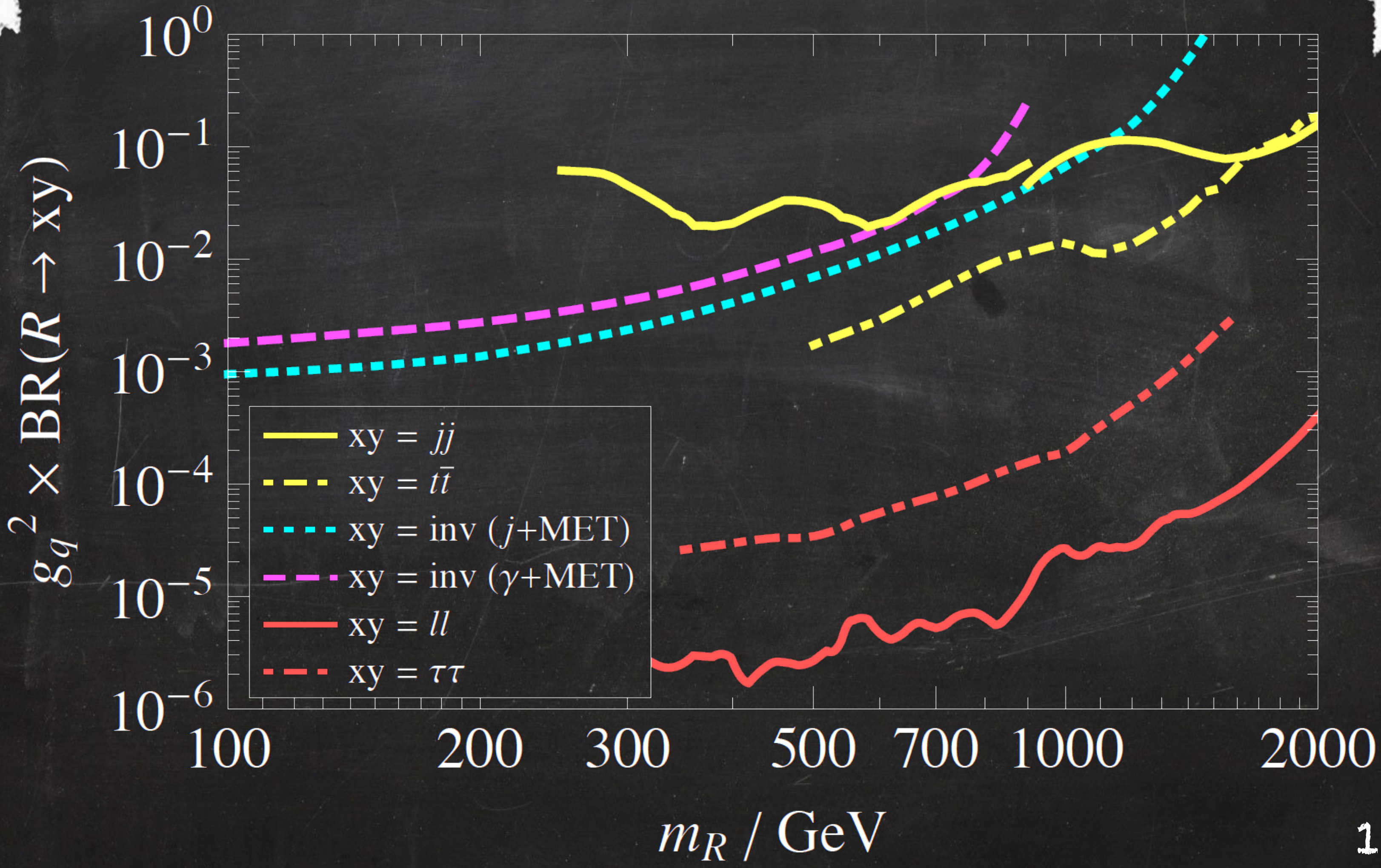
R can decay into fermions, bosons

and new hidden sector states

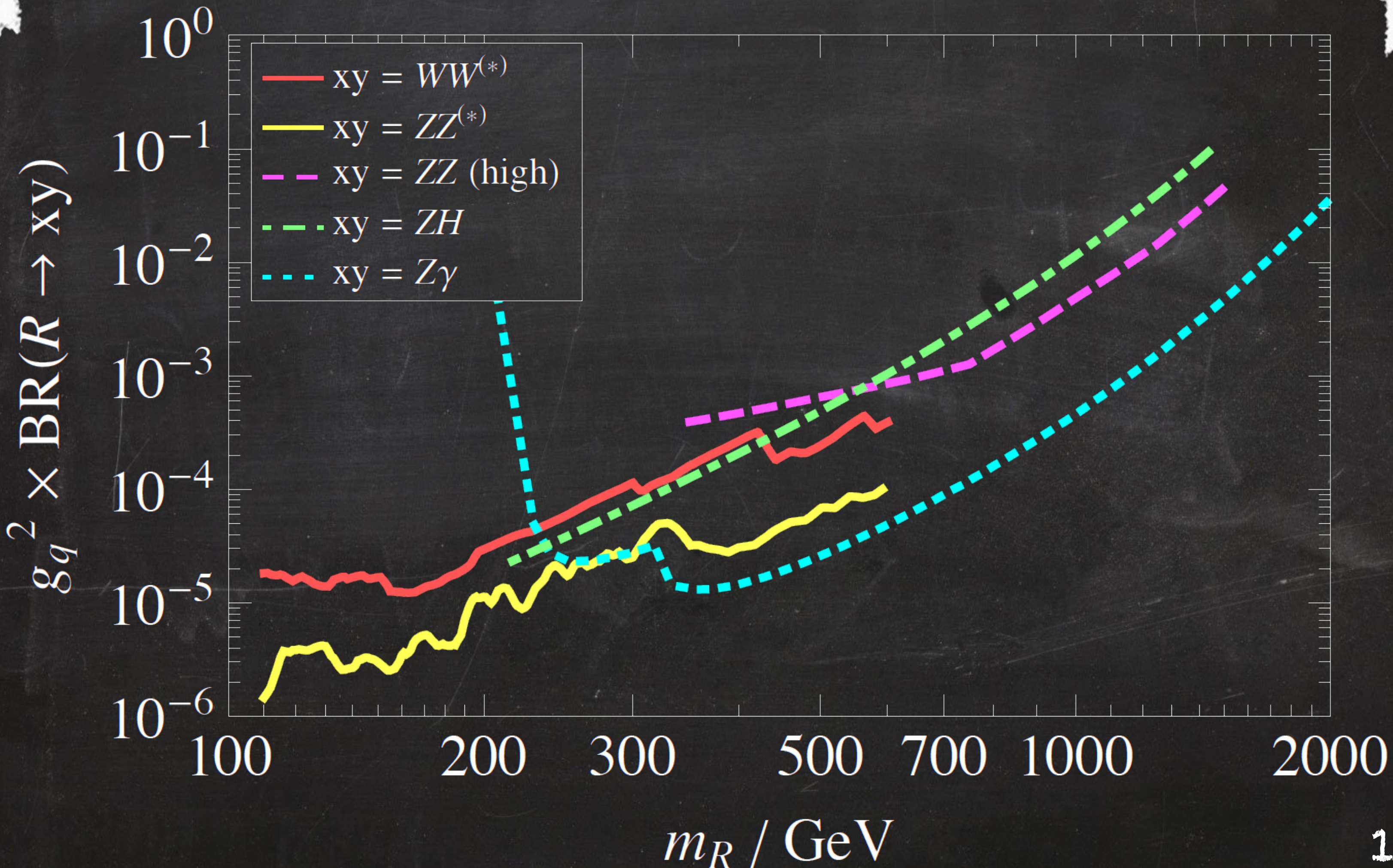
$$\Gamma_R = \Gamma^{\chi\bar{\chi}} + \sum_q \Gamma^{q\bar{q}} + \sum_l \Gamma^{l\bar{l}} + \sum_\nu \Gamma^{\nu\bar{\nu}} + \Gamma^{W^+W^-} + \Gamma^{ZZ} + \Gamma^{\gamma Z} + \Gamma^{ZH} + \Gamma^X$$

All of these channels can be constrained by the LHC!

Constraints: Fermions

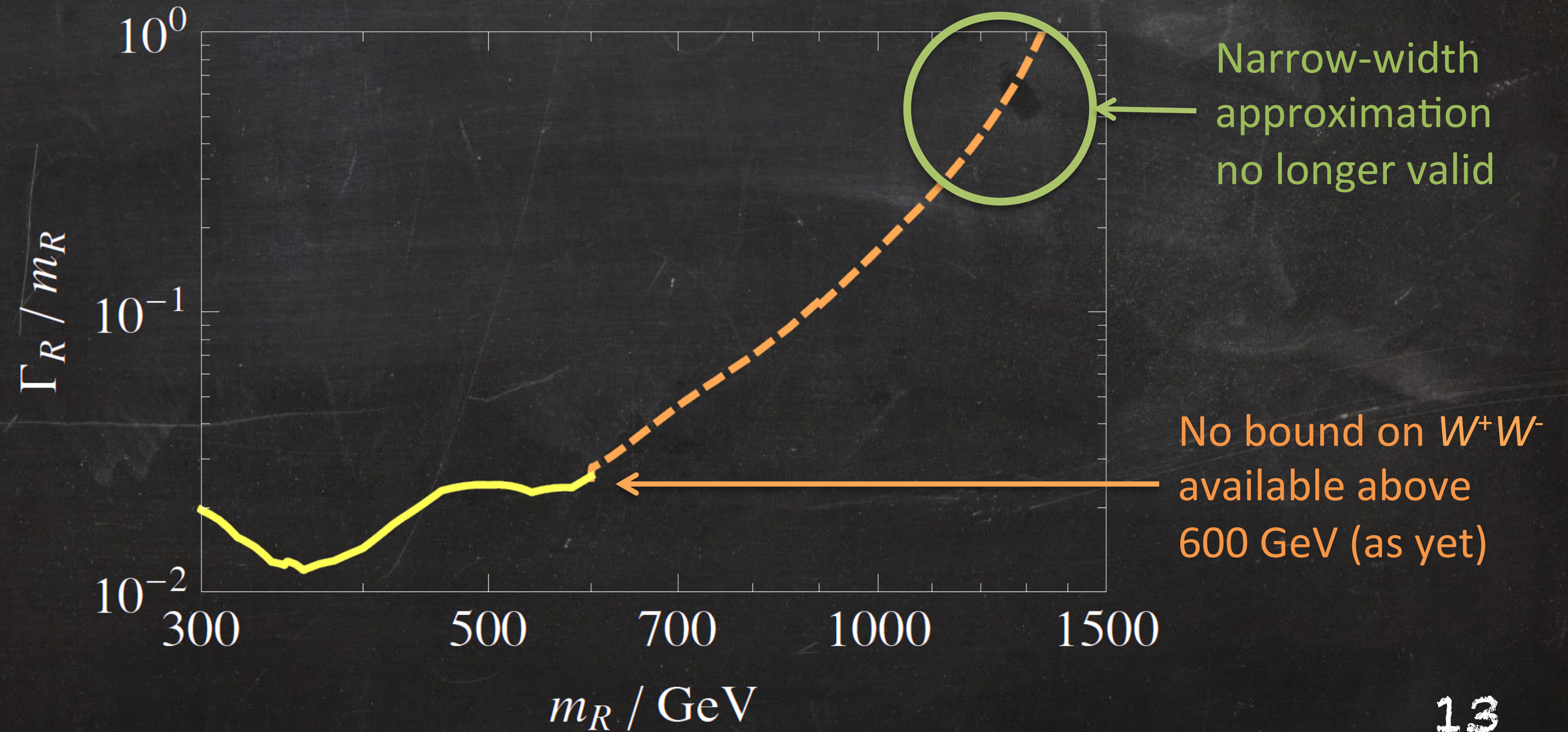


Constraints: Bosons



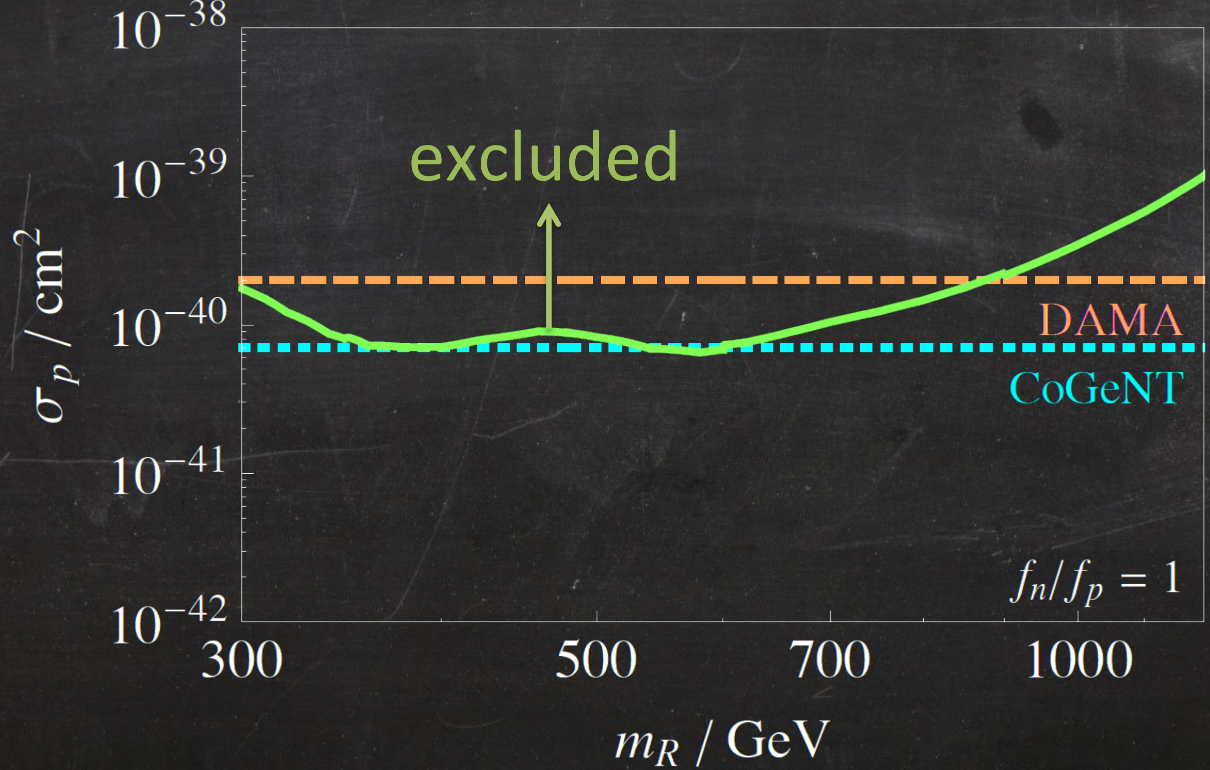
Combined Constraints

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

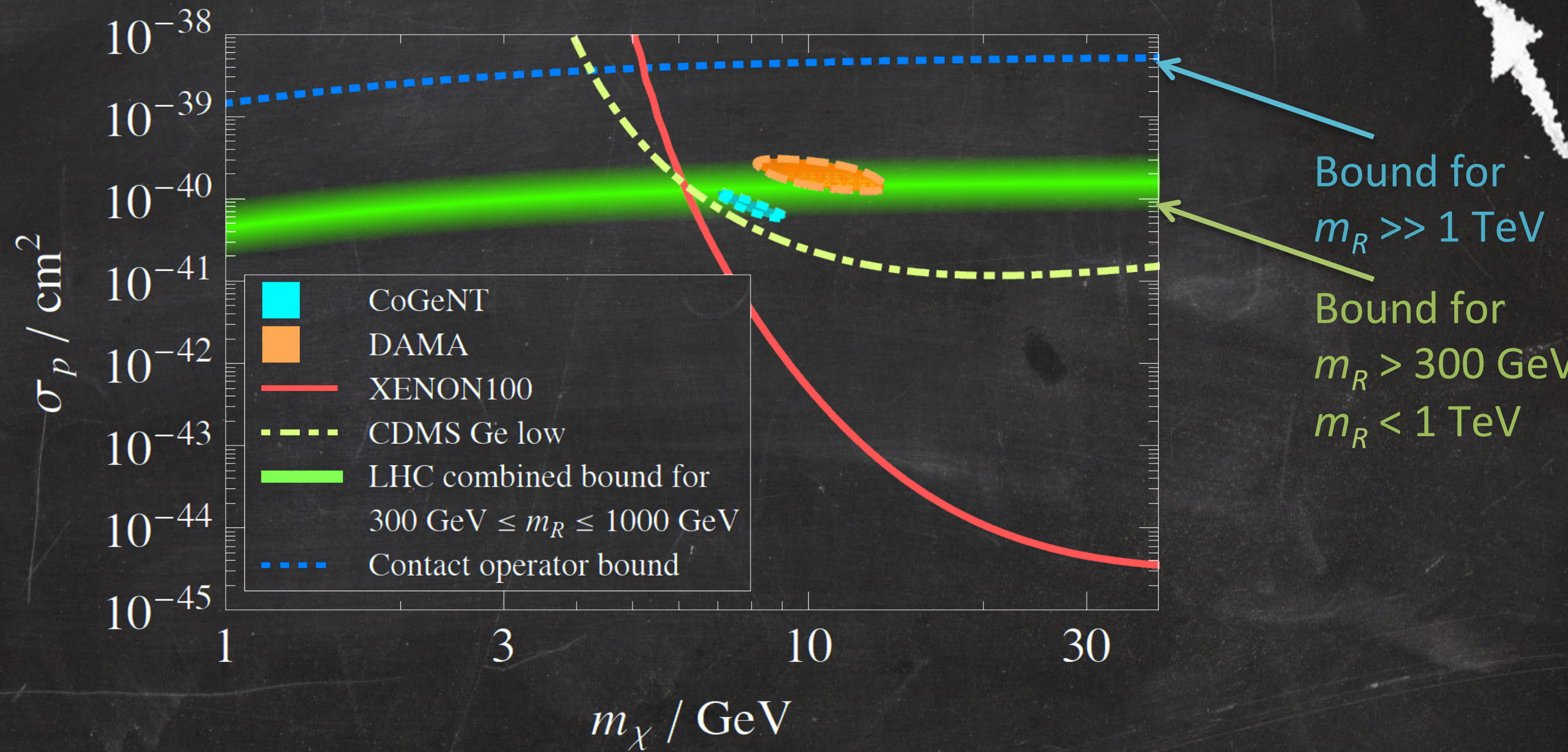


Direct detection limits

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



Direct detection limits



There are strong constraints on the direct detection cross section for vector mediators with m_R < 1 TeV.

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 very large.
4. If $g_q << g_\chi$ the production of R at LHC is insufficient to constrain Γ_R.

Example: The dark Z′

- As an example we consider the case where *R* is the gauge boson of a new *U*(1) under which only the dark matter particle is charged

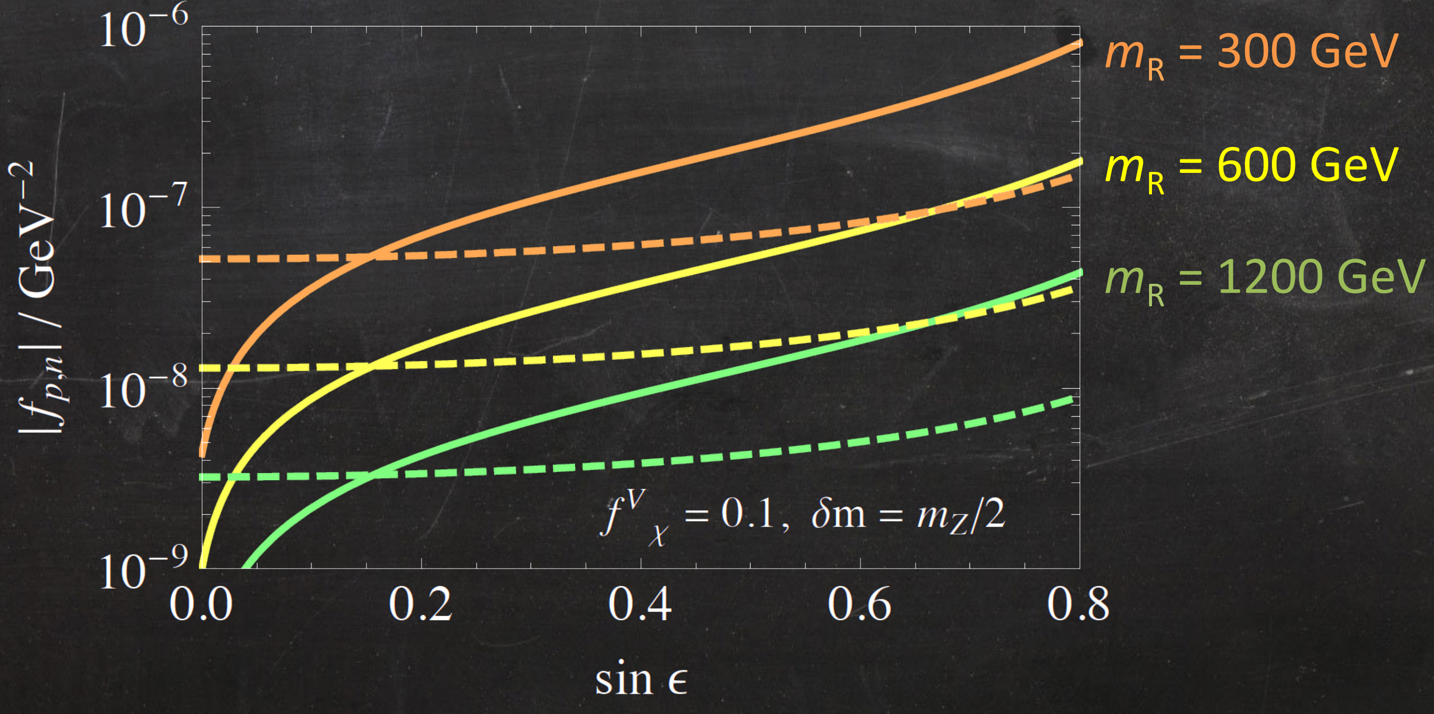
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu$$
$$- \frac{1}{2} \sin\epsilon \, B_{\mu\nu} Z'^{\mu\nu} + \delta m^2 Z_\mu Z'^\mu$$

K. Babu, C. F. Kolda, and J. March-Russell, Phys.Rev. D57 (1998), 6788–6792
Fox, Liu, Tucker-Smith, Weiner, Phys.Rev. D84 (2011) 115006
Frandsen, F.K., Sarkar, Schmidt-Hoberg, JHEP 1109 (2011) 128

Example: The dark Z′

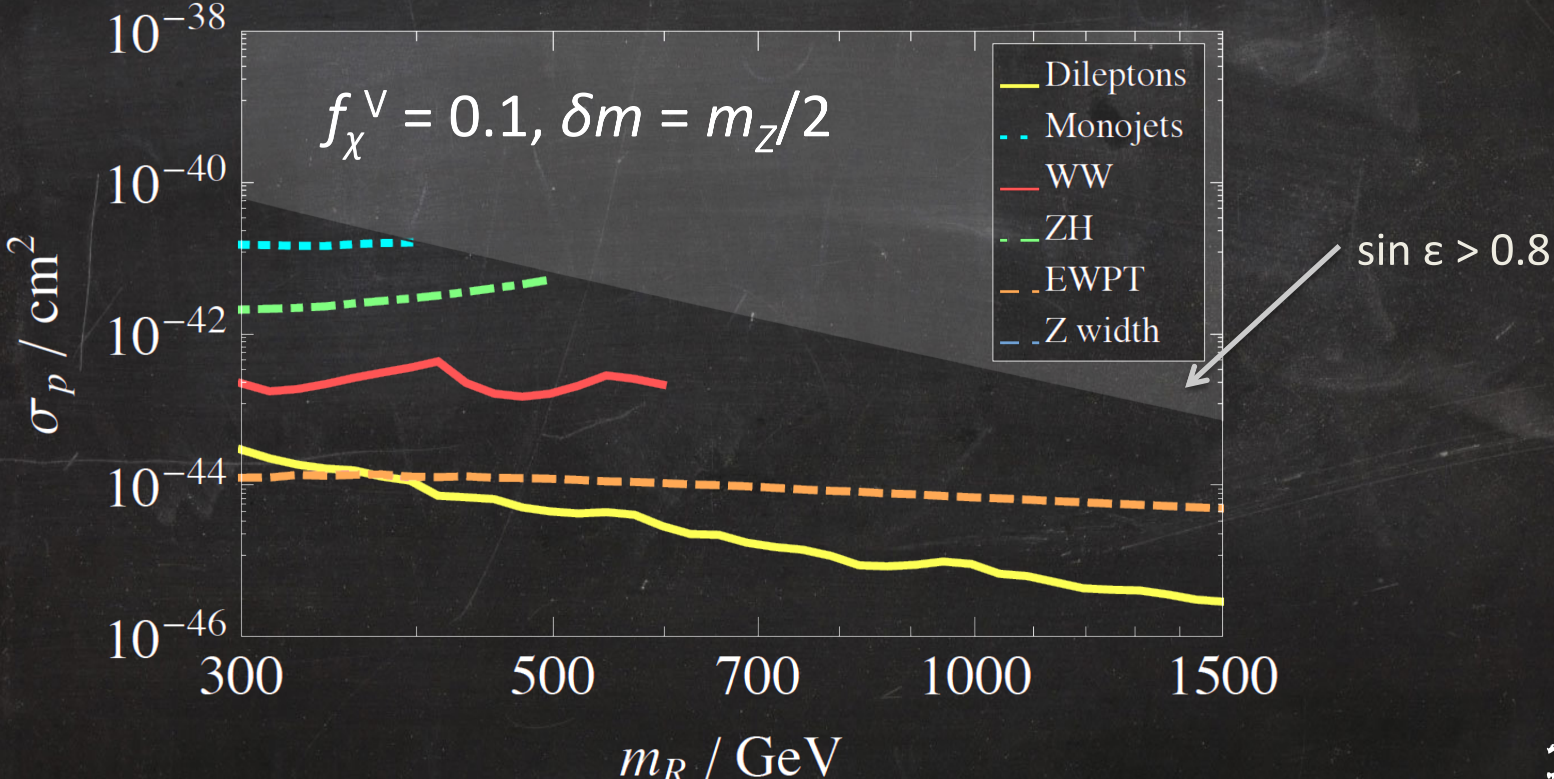
- Attractive feature: Isospin violation ($f_p \neq f_n$)
- $f_n/f_p = -0.7$ *suppresses bounds from XENON100*

Frandsen, F.K., Sarkar, Schmidt-Hoberg, JHEP 1109 (2011), 128



Example: The dark Z′

For 300 GeV < $m_{Z'}$ < 1500 GeV, we can use current LHC data to constrain direct detection cross sections



Conclusions

- If the LHC can resolve the mediator of dark matter interactions, effective operators are insufficient to interpret monojet bounds
- Heavy mediators ($m_R \geq 300$ GeV) can be tested and constrained by current LHC data
- Attractive model: Dark *Z'* with mixing
- Lighter mediators are much more difficult to constrain experimentally

Backup

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.