Interpreting dark matter searches from the LHC

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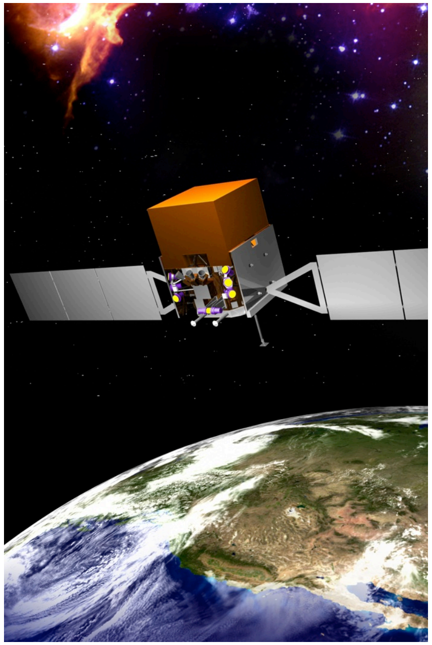
JHEP 1401 025 (arXiv:1308.6799)

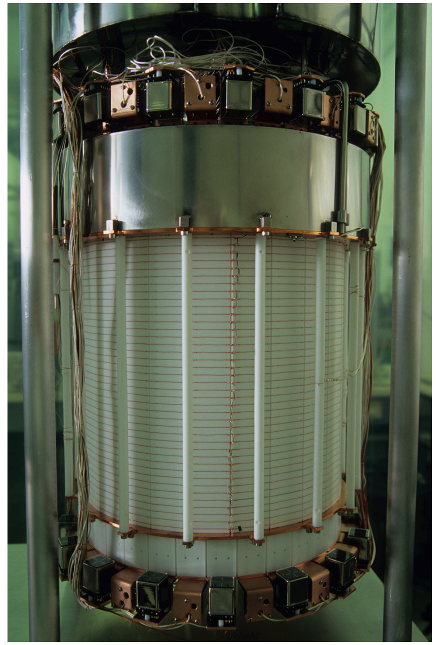
and work in progress

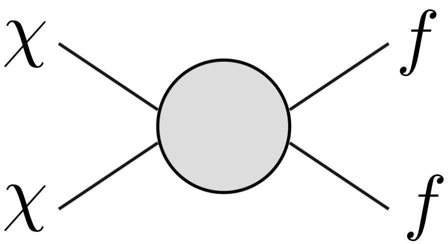
Latest results in dark matter searches, Stockholm – 12th May 2014

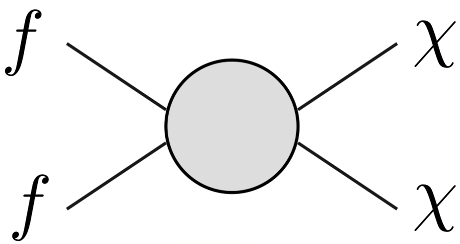
Searches for (WIMP) dark matter

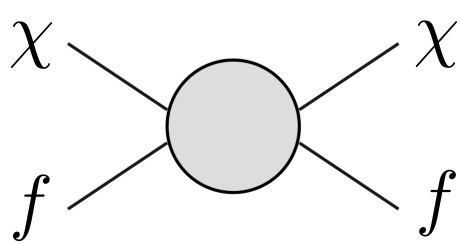
- Indirect detection
- Collider production
- Direct detection







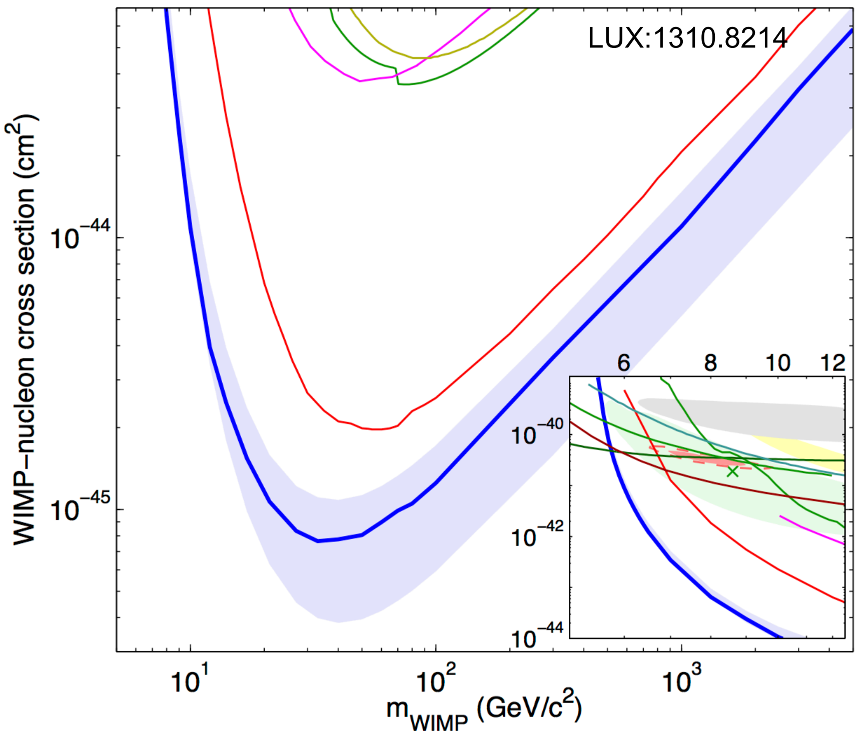




Interpreting searches

- We don't know the correct theory of particle dark matter
- Search results should be presented within a general framework that allows a large number of theories to be constrained
- Interpret results from
    1. Direct detection searches
    2. *LHC monojet searches*

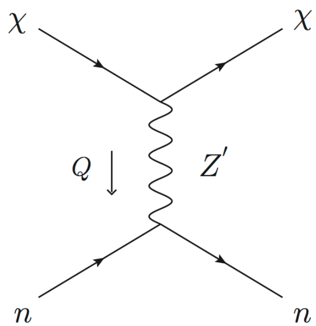
Direct detection searches

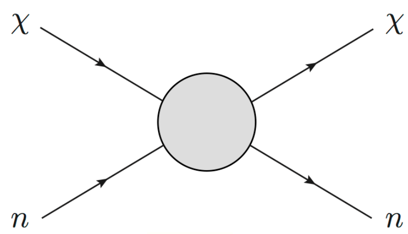


- Limits are quoted in terms of σ_n: the ‘WIMP-nucleon cross section’
  - Is this limit applicable to all theories…? No…

Direct detection searches: assumptions

- Many assumptions made: Spin-independent / spin-dependent /...
- Also assumes a 'contact interaction'

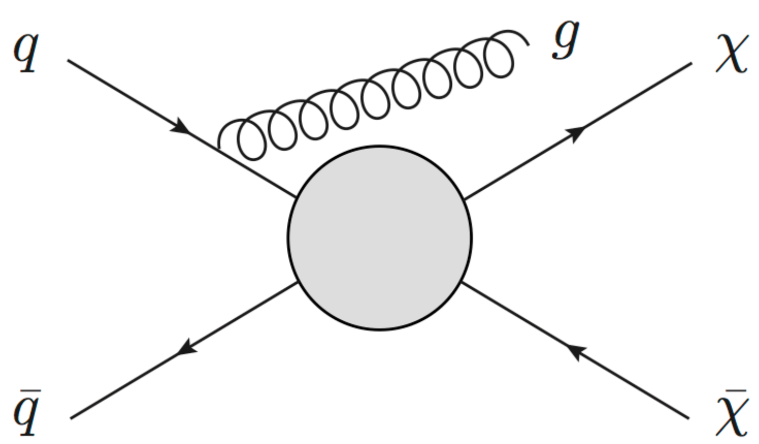


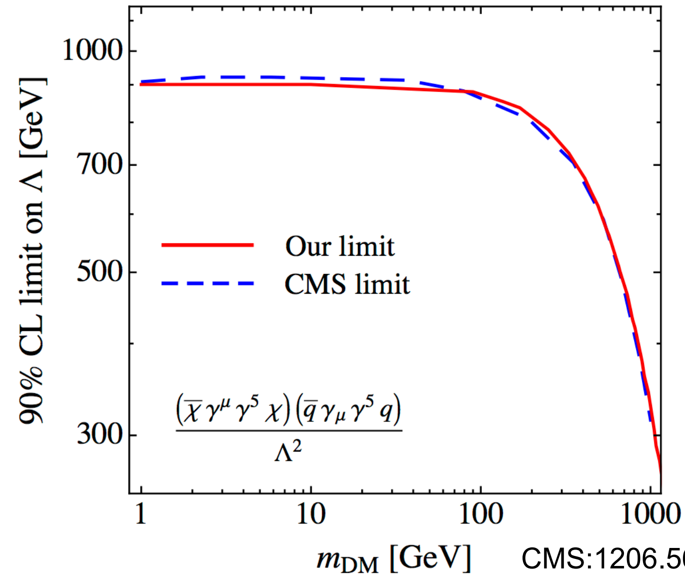


$$\sigma_n \sim \left(\frac{g_n g_\chi}{Q^2 - m_{Z'}^2}\right)^2 \approx \frac{g_n^2 g_\chi^2}{m_{Z'}^4}\left(1 + \frac{Q^2}{m_{Z'}^2} + \cdots\right)^2$$

- Contact interaction if $m_{Z'} \gg Q = \sqrt{2 m_n E_{\mathrm{R}}} \approx 50\ \mathrm{MeV}$
- Lots of theories satisfy this constraint
  - A useful way to parameterize the results

Dark matter searches at LHC

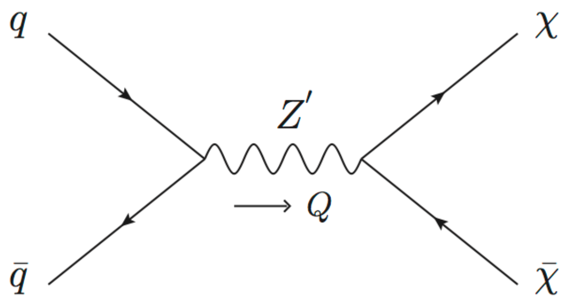




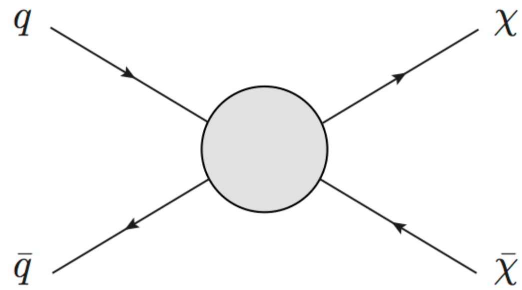
CMS:1206.5663
CMS-PAS-EXO-12-048

- Monojet search: look for a hard jet and missing energy
- Make use of effective field theory (EFT) to place a limit on the ‘contact interaction scale’ Λ .

Effective field theory (EFT)



'Integrate out the mediator'



$$\mathcal{L} \sim g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi + g_q Z'_\mu \bar{q}\gamma^\mu q + \frac{1}{2} m^2_{Z'} Z'_\mu Z'^\mu + \cdots$$

$$\mathcal{L} \sim \frac{1}{\Lambda^2} \bar{q}\gamma_\mu q \, \bar{\chi}\gamma^\mu \chi$$

- Parameter of interest is Λ
- Λ related to parameters in the full theory: $\Lambda \equiv \dfrac{m_{Z'}}{\sqrt{g_q g_\chi}}$

This is not a new idea

- Fermi could describe β-decay without knowing the $W^{\pm}$ mass or the gauge couplings:

$$\mathcal{L} = \frac{G_{\mathrm{F}}}{\sqrt{2}} \left[\bar{\psi}\gamma^{\mu}(1-\gamma^{5})\psi\right] \left[\bar{\psi}\gamma_{\mu}(1-\gamma^{5})\psi\right] \text{ where } G_{\mathrm{F}} \propto \frac{g_{\mathrm{weak}}^{2}}{M_{W}^{2}}$$

- It is a very useful idea - we don't need to know all details of the full theory

- Can (in principle) constrain many different theories:

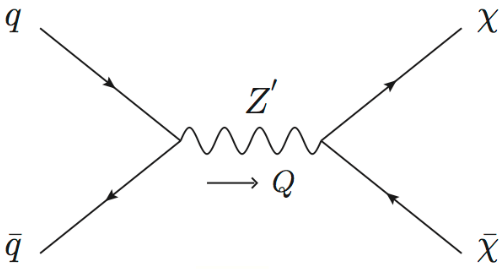
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

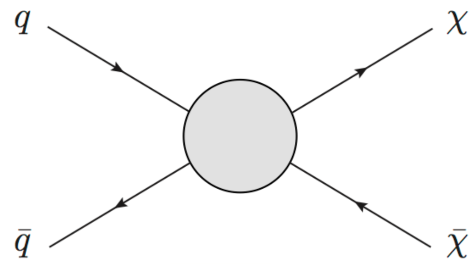
Goodman et al:1008.1783

When is EFT valid?

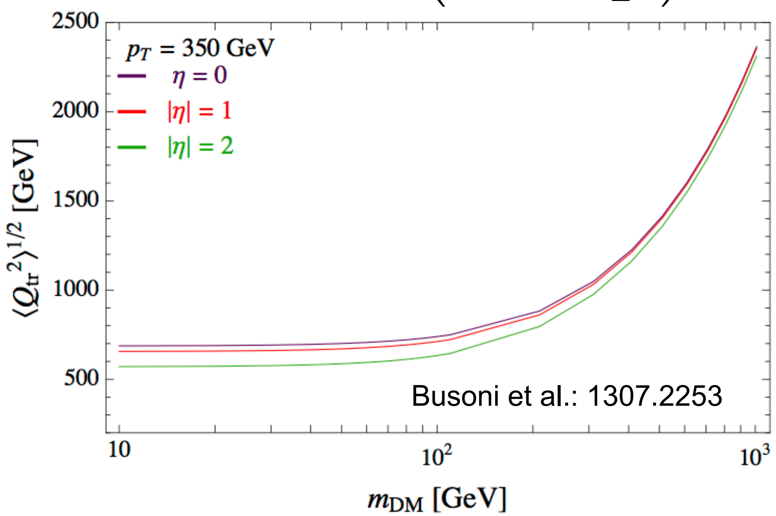
- Back of the envelope estimate:



'Integrate out the mediator'



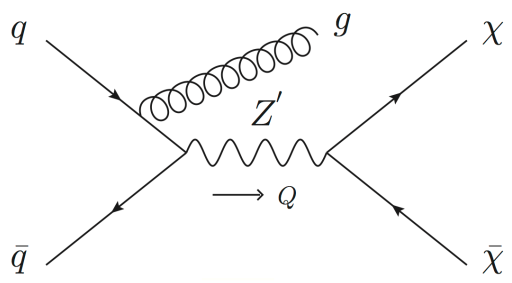
$$\sigma \sim \left(\frac{g_q g_\chi}{Q^2 - m_{Z'}^2}\right)^2 \approx \frac{g_q^2 g_\chi^2}{m_{Z'}^4}\left(1 + \frac{Q^2}{m_{Z'}^2} + \cdots\right)^2$$

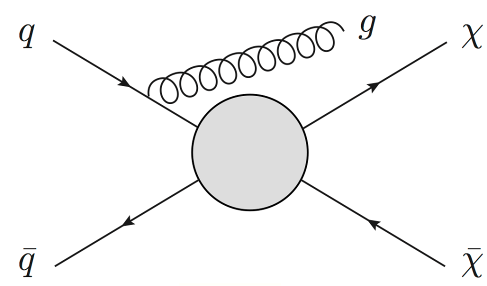


- Requires $m_{Z'} \gg Q \sim$ TeV

When is EFT valid?

- Better estimate: Compare a 'simplified model' with EFT result





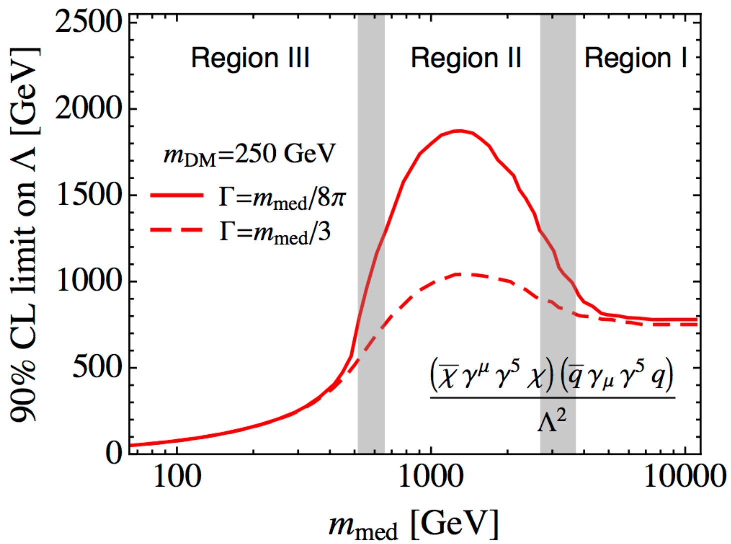
- Assumptions:
  1. s-channel axial-vector mediator
  2. Equal coupling to all quarks
  3. No coupling to leptons or SM gauge bosons

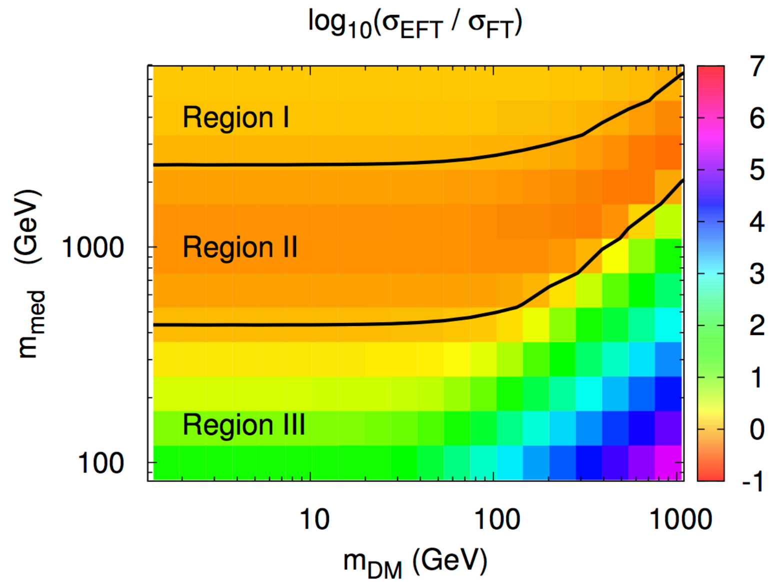
- For those who like Lagrangians:

$$\mathcal{L} \supset g_\chi Z'_\mu \bar{\chi}\gamma^\mu\gamma^5\chi + g_q Z'_\mu \bar{q}\gamma^\mu\gamma^5 q \quad \text{vs} \quad \mathcal{L} \supset \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{\chi}\gamma_\mu\gamma^5\chi$$

When is EFT valid?

- Look at limit on $\Lambda = \frac{m_{\rm med}}{\sqrt{g_q g_\chi}}$





- Region I: EFT limit is good $m_{\rm med} \gtrsim 3~\rm TeV$
- Region II: EFT limit is too weak
- Region III: EFT limit is too strong $m_{\rm med} \lesssim 500~\rm GeV$

Region I: when EFT applies

- Mediator mass is large:

$$m_{\rm med} \gtrsim 3 \text{ TeV}$$

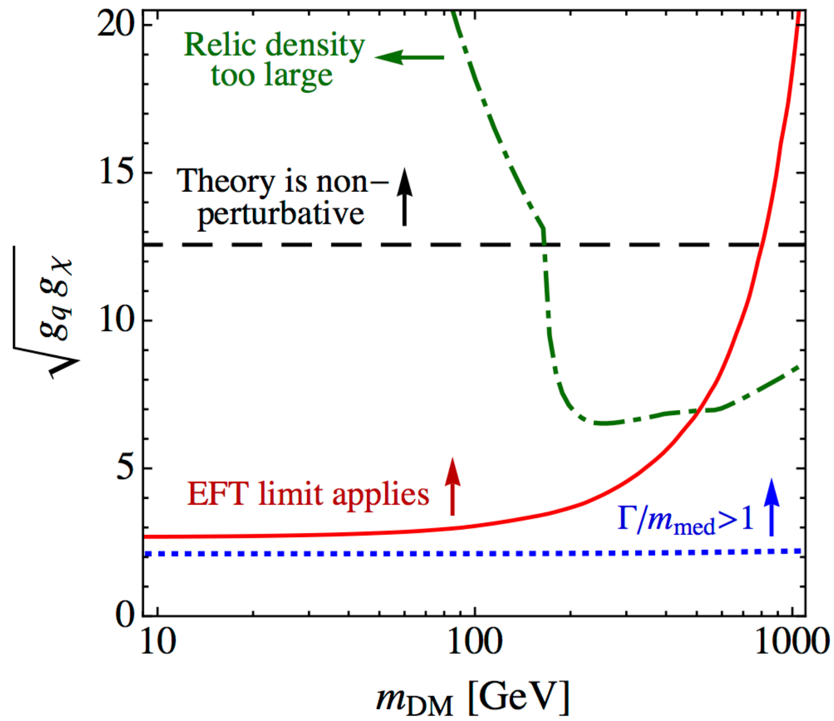
- What about the couplings?

$$\sqrt{g_q g_\chi} = \frac{m_{\rm med}}{\Lambda}$$

...they must be large

- Compare with known couplings:

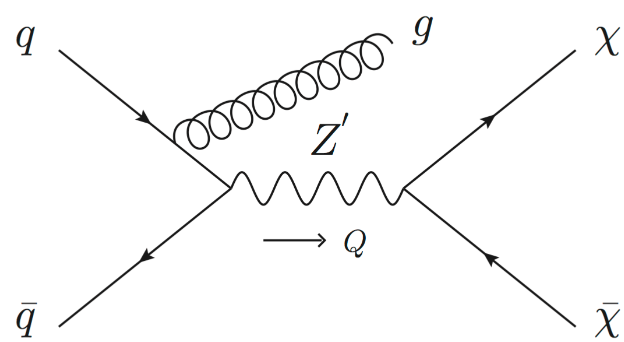
$$g_{\rm strong} \approx 1.2$$
$$g_{\rm weak} \approx 0.6$$
$$g_{\rm hypercharge} \approx 0.4$$



- Couplings of this size typical in strongly interacting theories
  – EFT limit applies to a small class of theories

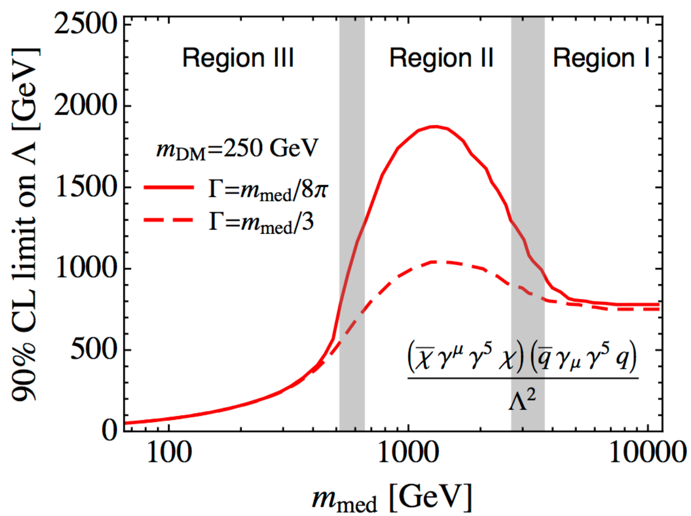
Region II: EFT limit conservative

- The mediator s-channel production is resonantly enhanced



- Enhancement when

$$m^2_{\text{med}} \approx 4m^2_{\text{DM}} + E^2_{T,\text{miss}}$$



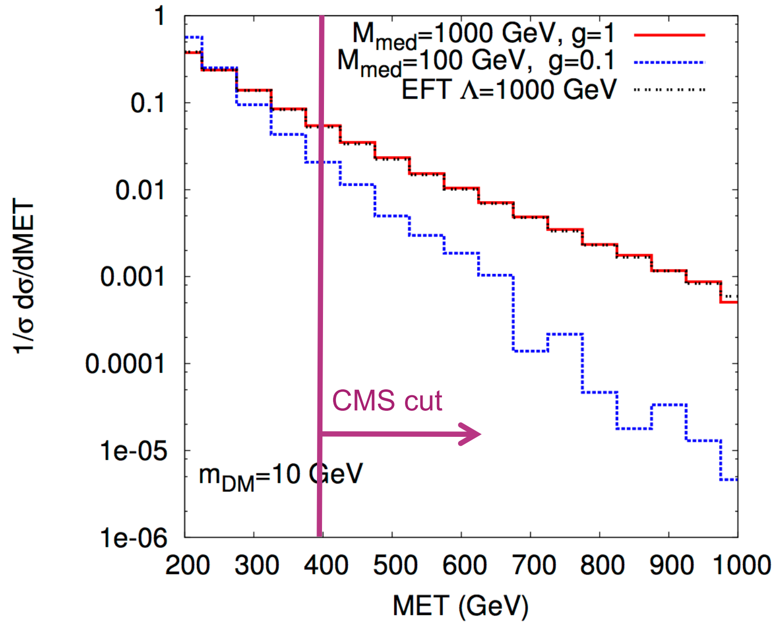
- Peak height scales as $\Gamma^{-1/4}$

Region III: EFT limit too strong

- Mediator mass is small:

$$m_{\rm med} \lesssim 500 \text{ GeV}$$

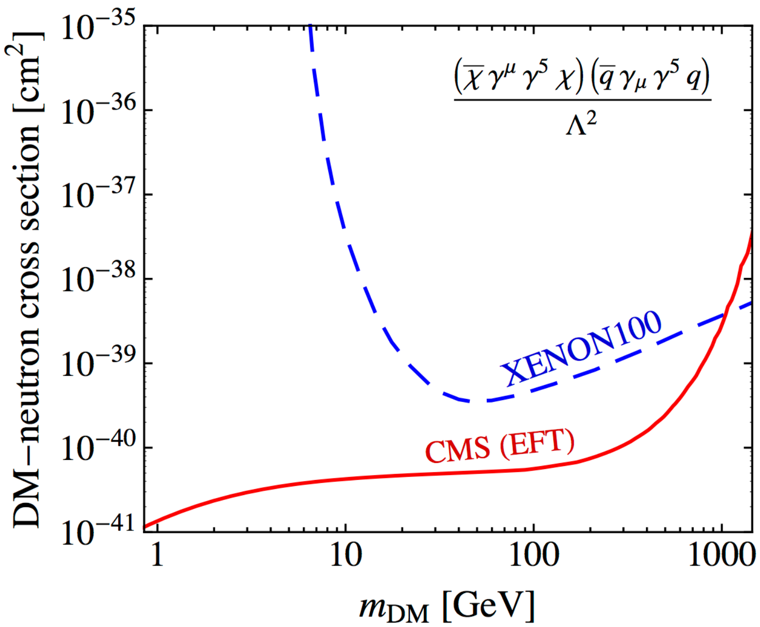
- Events with a light mediator are much softer



- Limit on g stronger, so limit on $\Lambda \sim \dfrac{m_{\rm med}}{g^2}$ is weaker

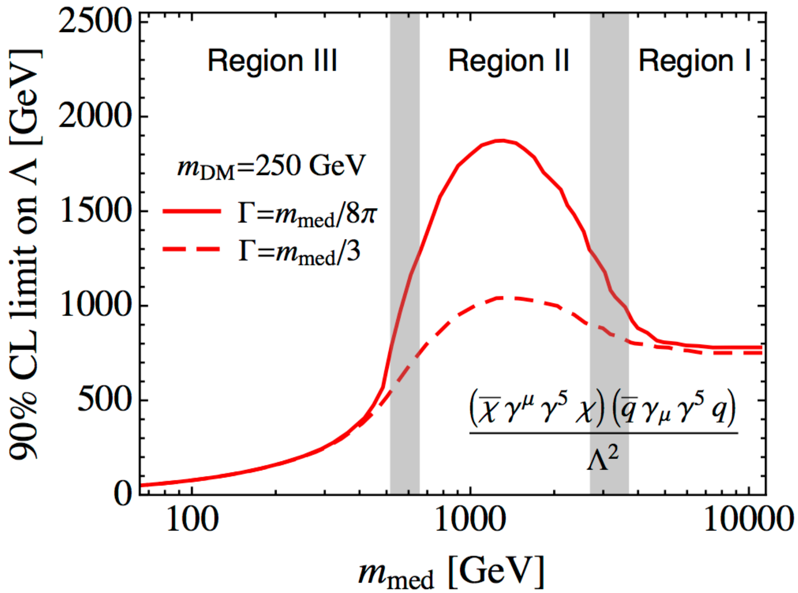
Other problems

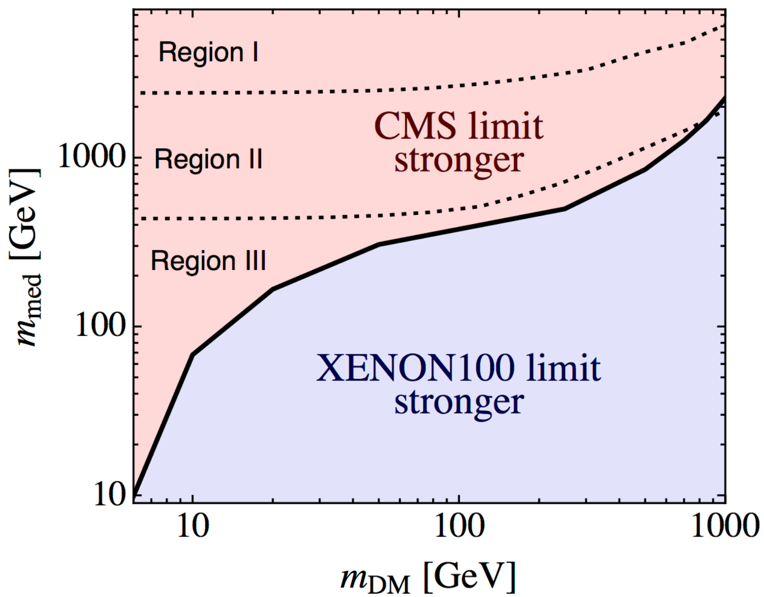
- Comparison with direct detection
  - Naïve application of EFT limit gives the impression that colliders give a stronger limit when $m_{\mathrm{DM}} \lesssim 1\ \mathrm{TeV}$



Other problems

- Comparison with direct detection
  - Important to remember the dependence on $m_{\rm med}$
- Scattering cross section $\sigma_n \propto \Lambda^{-4}$



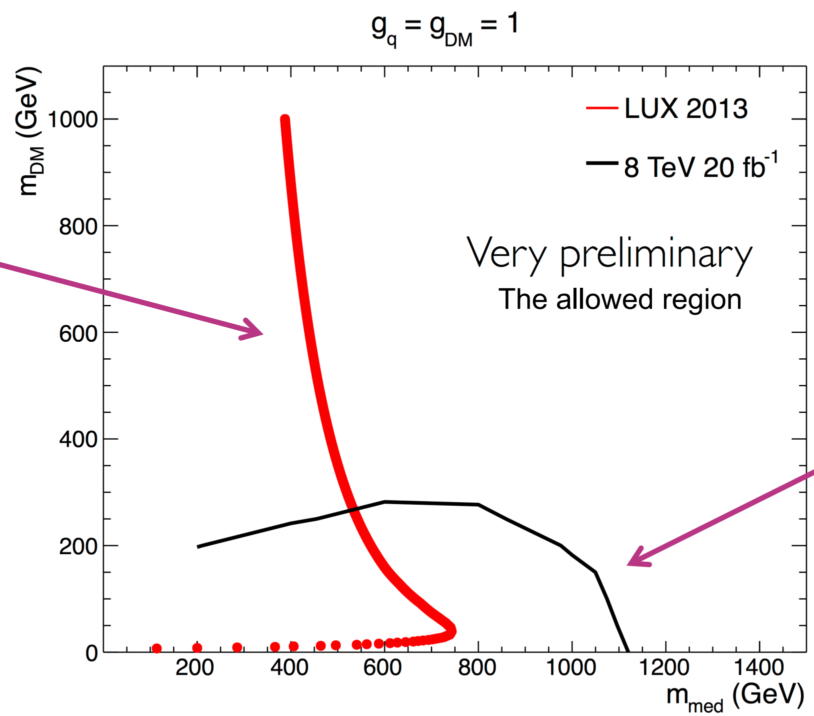


- As $m_{\rm med}$ decreases, direct detection limit is stronger

Beyond EFT: simplified models

- Another way to present the results:

LUX limit
- Extends to large m_{DM}

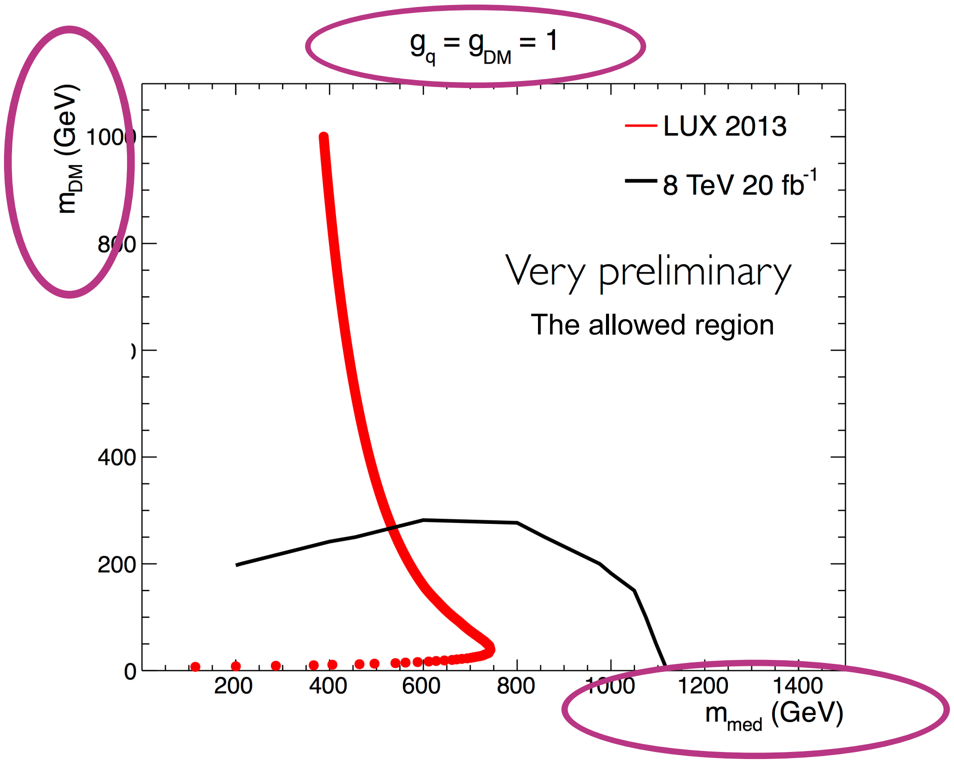


CMS limit
- Extends to large m_{med}

- Shows that searches are complementary

Beyond EFT: simplified models

- Difficulty: representing results in 4D parameter space



1. m_{DM}
2. m_{med}
3. g_{DM}
4. g_q (or Γ)

- Best way to present the results not optimized - in progress!

Summary

- Important to interpret dark matter searches in the right framework
- Direct detection experiments constrain the 'WIMP-nucleon cross section'
  - Very useful: constrains a large number of theories
- LHC monojet searches have been interpreted in an EFT framework
  - Limited use: constrains few theories and comparison with direct detection limits is too naïve
- Need to go beyond EFT – 'simplified models' capture more physics but at the expense of extra parameters