Constraining simplified dark matter models with the LHC

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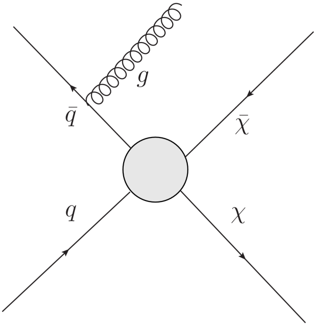
Some brief background:

- The LHC can investigate dark matter (DM) models where there is some way for the dark sector to talk to light quarks
- Can roughly separate searches into two types:
  1. Model-dependent (SUSY searches, ...)
  2. Model-agnostic (typically mono-X)

I will discuss the models used for settings limits on 2. and present some constraints using monojet (a single jet + E_T^{miss}) limits in particular



We will assume:

- Dirac fermion dark matter χ with mass m_{DM}
- A vector mediator Z' with mass M and pure axial-vector[1] couplings g_q, g_{DM}

$$\Rightarrow \mathcal{L}_{\mathrm{MSDM}} \supset -\sum_q g_q Z'_\mu \bar{q}\gamma^\mu\gamma_5 q - g_{\mathrm{DM}} Z'_\mu\, \bar{\chi}\gamma^\mu\gamma_5\chi \qquad (1)$$

This is the interaction term of our minimal simplified dark matter model (MSDM). There are four free parameters (M, m_{DM}, g_q, g_{DM}).

[1] The LHC has little sensitivity to vector couplings compared to direct detection (spin-independent vs spin-dependent).

Can expand the mediator propagator:

$$\frac{g_q g_{\mathrm{DM}}}{Q^2 - M^2} \sim -\frac{g_q g_{\mathrm{DM}}}{M^2}\left(1 + \frac{Q^2}{M^2} + \mathcal{O}\left(\frac{Q^4}{M^4}\right)\right) \tag{2}$$

Let $\Lambda = M/\sqrt{g_q g_{\mathrm{DM}}}$, then:

$$\mathcal{L}_{\mathrm{EFT}} \supset \frac{1}{\Lambda^2}\chi\gamma^{\mu}\gamma_5\bar{\chi}q\gamma_{\mu}\gamma_5\bar{q} \tag{3}$$

where we have integrated out the mediator using (2). This is an effective interaction term which is valid when $Q \ll M$. We've reduced the number of free parameters to two (Λ, m_{DM}).

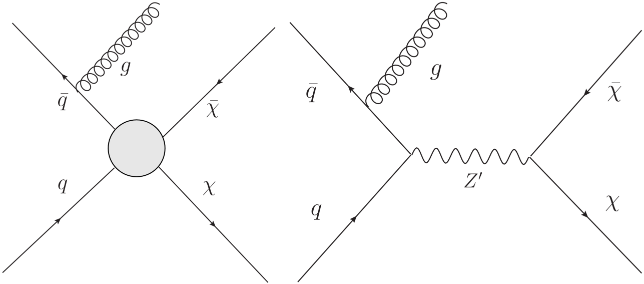


Figure : Example of what we are working with.

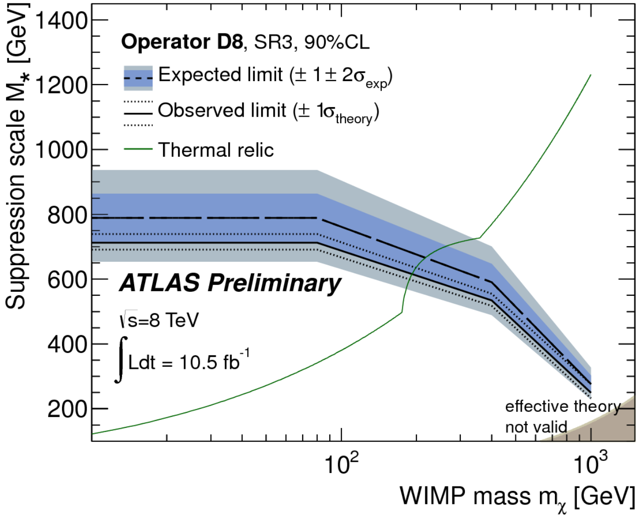


Figure : ATLAS limits on our EFT operator set in ATLAS-CONF-2012-147.

To facilitate the comparison to direct detection constraints[2] LHC experiments have generally interpreted model-agnostic searches using EFTs.

But:

- Direct detection: $Q \sim \mathcal{O}(10 \text{ keV}) \Rightarrow$ EFT valid $\sim$ always
- LHC: $Q \sim \mathcal{O}(1 \text{ TeV}) \Rightarrow$ EFT valid $\sim$?

Answer (1307.2253, 1308.6799 + others): EFT is only valid for $M \gtrsim 2.5$ TeV at $\sqrt{s} = 8$ TeV.

[2] And also just because there are fewer parameters $\Rightarrow$ cheaper, easier.

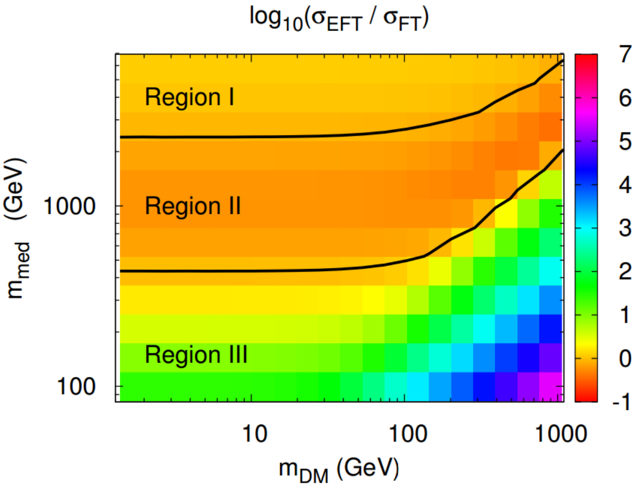


Figure : Ratio of simplified model to EFT cross-section for $g_q, g_{\mathrm{DM}} = 1$ (from 1308.6799).

- Some recent studies using the CMS limits and NLOPS predictions for $\chi\bar{\chi} + 1$ jet (1407.8257, 1411.0535)
- Generally present constraints in e.g. the $M - m_{\rm DM}$ plane as an exclusion contour for a particular choice of $g_q, g_{\rm DM}$
- Note that the minimum width $\Gamma_{\rm min} \propto \sum_f N_{C,f} g_f^2$ can be calculated from the input parameters and needs to be taken into account!

We have studied constraints using ATLAS limits and LOPS predictions scanning $g_q/g_{\rm DM}$ and $g_q.g_{\rm DM}$ assuming $\Gamma_M = \Gamma_{\rm min}$.

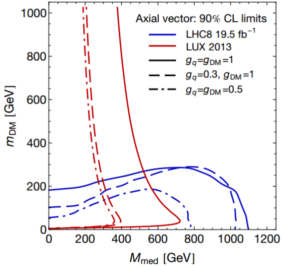
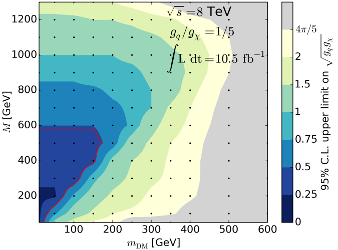
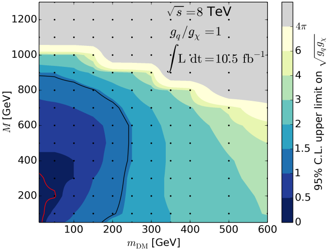
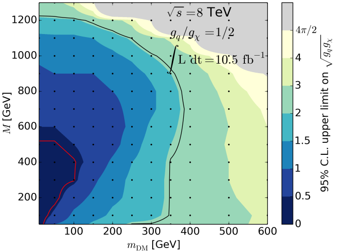


Figure : Example of constraints from 1407.8257.


$\sqrt{s}=8$ TeV
$g_q/g_\chi=1/5$
$\int$L dt = 10.5 fb^{-1}
M [GeV]
$m_{\rm DM}$ [GeV]
95% C.L. upper limit on $\sqrt{g_q g_\chi}$
$4\pi/5$
2
1.5
1
0.75
0.5
0.25
0


$\sqrt{s}=8$ TeV
$g_q/g_\chi=1$
$\int$L dt = 10.5 fb^{-1}
M [GeV]
$m_{\rm DM}$ [GeV]
95% C.L. upper limit on $\sqrt{g_q g_\chi}$
4π
6
4
3
2
1.5
1
0.5
0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M [GeV]
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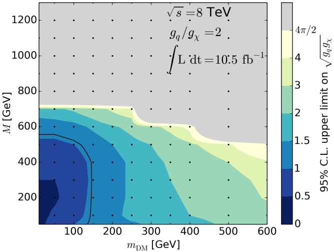
95% C.L. upper limit on $\sqrt{g_q g_\chi}$
$4\pi/2$
4
3
2
1.5
1
0.5
0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4
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0

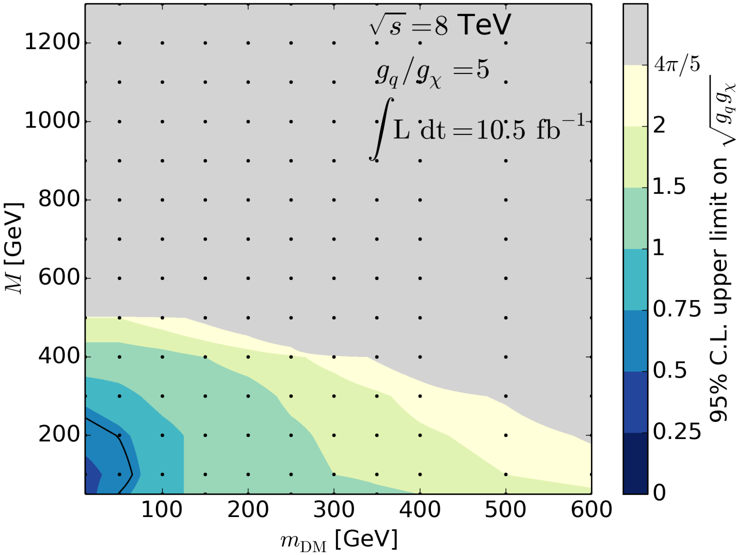
- Dark matter is a Big Thing at 14 TeV LHC
- Need to make sure constraints are robust and can be compared to Direct Detection $\Rightarrow$ EFTs are of limited use
- Simplified Models give a consistent and robust framework at cost of more parameters

1. Implement Lagrangian in FeynRules
2. Generate parton level events with MadGraph5
3. Match to Pythia 8 for showering
4. Perform detector simulation and analysis in ATOM+Rivet
5. Get out visible cross-section, compare to ATLAS limits

Since we assume axial-vector couplings the minimal width[3] is:

$$\Gamma_{\rm min} = \frac{N_C g_{\rm DM}^2 M (1 - 4m_{\rm DM}^2/M^2)^{3/2}}{12\pi}\Theta(M - 2m_{\rm DM}) + \sum_q \frac{N_C g_q^2 M (1 - 4m_q^2/M^2)^{3/2}}{12\pi}\Theta(M - 2m_q)$$

[3] Assuming no additional invisible decays.


$\sqrt{s}$ =8 TeV
g_q/g_χ =5
$\int$L dt =10.5 fb^{-1}
1200
1000
800
600
400
200
M [GeV]
100
200
300
400
500
600
m_{DM} [GeV]
$4\pi/5$
2
1.5
1
0.75
0.5
0.25
0
95% C.L. upper limit on $\sqrt{g_q g_\chi}$