Simplified models vs EFTs for DM searches at the LHC

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TeVPA ‘16
Less complete

- Dark Matter 
  - Effective Field Theories
- Contact Interactions

Dipole Interactions

“Sketches of models”

- Simplified Dark Matter Models
  - Higgs Portal
  - “Squarks”
  - Dark Photon
  - Z’ boson

More complete

- Complete Dark Matter Models
- Minimal Supersymmetric Standard Model
- Universal Extra Dimensions

Tim Tait, via Worm et al arXiv:1506.03116
Ensuring Validity of EFTs

\[ \frac{g_q g_\chi}{M^2 - Q_{tr}^2} \sim \frac{g_q g_\chi}{M^2} \equiv \frac{1}{M^*_2} \]
Ensuring Validity of EFTs

\[
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\]

\[
Q_{tr} < M \equiv \sqrt{g_q g_\chi M_*}
\]
Ensuring Validity of EFTs
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• For a given choice of $\sqrt{g_q g_\chi}$, only use events that satisfy

$$M \equiv \sqrt{g_q g_\chi} M^* \geq Q_{tr}$$

$$Q_{tr} = (g_q g_\chi)^{1/2} M^*$$
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Ensuring Validity of EFTs

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Moving Beyond EFTs

- EFTs remain a useful as a benchmark, as a general constraint on DM as long as we are careful not to over-interpret the results.

- A more general set of models is required:
  - EFTs are only a valid description of simplified models for heavy mediators and large couplings.
  - EFTs are designed to be as model-independent as possible and give a generic hard MET spectrum, leaving us blind to other signatures of the dark sector.
Moving Beyond EFTs

- Constraints apply to lower mediator masses
- Increased phenomenology!
  - Dijet, dilepton resonances
  - Resonant enhancement of rate around mediator mass
  - Increased number of channels
- Comes at the cost of increased parameter space

\[
\{ m_{\text{DM}}, M_\star \} \rightarrow \{ m_{\text{DM}}, M_{\text{med}}, g_q, g_{\text{DM}} \}
\]

See talk by Uli Haisch, Monday 12th
Solving the ‘4D Problem’

Benchmark coupling

3-D scan

Vector, Dirac, $g_q = 0.25$, $g_{DM} = 1$

Observed 95\% CL

Uncertainties

Expected 95\% CL

Relic density

$500 \ 1000 \ 1500 \ 2000$

$200 \ 400 \ 600 \ 800 \ 1000$

$M_{med} \ [\text{GeV}]$

$m_{DM} \ [\text{GeV}]$

Figure 1: 95\% CL exclusion contours in the mass-mass plane for a simplified model with a vector mediator, Dirac DM and couplings $g_q = 0.25$ and $g_{DM} = 1$. The black solid (dashed) curve shows the median of the observed (expected) limit, while the yellow curves indicate an example of the uncertainties on the observed bound. A minimal width is assumed and the excluded parameter space is to the bottom-left of all contours. The dotted magenta curve corresponds to the parameters where the correct DM relic abundance is obtained from standard thermal freeze-out for the chosen couplings. DM is overproduced to the bottom-right of the curve. The shown LHC results are intended for illustration only and are not based on real data.

when interpreting supersymmetry searches at the LHC. The parameter space shown in the mass-mass plots can be divided into three regions:

On-shell region:

The on-shell region, $M_{med} > 2m_{DM}$, is the region where LHC searches for MET signatures provide the most stringent constraints. The production rate of the mediator decreases with increasing $M_{med}$ and so does the signal strength in mono-jet searches. In this region the experimental limits and the signal cross sections depend in a complex way on all parameters of the simplified model, and it is therefore in general not possible to translate the CL limit obtained for one fixed set of couplings $g_q$ and $g_{DM}$ to another by a simple rescaling procedure.

O-shell region:

In the o-shell region, $M_{med} < 2m_{DM}$, pair-production of DM particles turns on and the constraints from MET searches rapidly lose power. The cross sections become proportional to the combination $g_q^2 g_{DM}$ of couplings, so that in principle the LHC exclusions corresponding to different coupling choices can be derived by simple rescalings. Deviations from this scaling are observed on the interface between on-shell and o-shell regions $M_{med}' < 2m_{DM}$. Note that for $M_{med} < 2m_{DM}$ an
Solving the ‘4D Problem’

Only 2 parameters to scan
Solving the ‘4D Problem’

✅ Only 2 parameters to scan

❌ Less comprehensive: Difficult to translate to other couplings
Solving the ‘4D Problem’

- **Only 2 parameters to scan**
- **Less comprehensive:** Difficult to translate to other couplings
- **More comprehensive**

**Benchmark coupling**

**3-D scan**

![Graph showing 95% CL exclusion contours in the mass-mass plane for a simplified model with a vector mediator, Dirac DM and couplings $g_q = 0.25$, $g_{DM} = 1$. The black solid (dashed) curve shows the median of the observed (expected) limit, while the yellow curves indicate an example of the uncertainties on the observed bound. A minimal width is assumed and the excluded parameter space is to the bottom-left of all contours. The dotted magenta curve corresponds to the parameters where the correct DM relic abundance is obtained from standard thermal freeze-out for the chosen couplings. DM is overproduced to the bottom-right of the curve. The shown LHC results are intended for illustration only and are not based on real data.**

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**Off-shell region:** In the off-shell region, $M_{med} < 2m_{DM}$, pair-production of DM particles turns off and the constraints from MET searches rapidly lose power. The cross sections become proportional to the combination $g_q^2 g_{DM}$ of couplings, so that in principle the LHC exclusions corresponding to different coupling choices can be derived by simple rescalings. Deviations from this scaling are observed on the interface between on-shell and off-shell regions $M_{med} \approx 2m_{DM}$. Note that for $M_{med} < 2m_{DM}$ an

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Solving the ‘4D Problem’

- Only 2 parameters to scan
- Less comprehensive: Difficult to translate to other couplings

- More comprehensive
- Scan over parameter space challenging
Benchmark Coupling

Axial-vector mediator, Dirac DM
\( g_q = 0.25, g_{DM} = 1 \)

\( \Omega_c h^2 < 0.12 \)

\( 2 \times DM \text{ Mass} = \text{Mediator Mass} \)

Thermal relic \( \Omega_c h^2 = 0.12 \)

Perturbative unitarity

ATLAS: CONF-2016-009

ATLAS: CONF-2016-030

JHEP 06 (2016) 053

Benchmark Coupling

Axial-vector mediator, Dirac DM

\[ g_q = 0.25, \quad g_{DM} = 1 \]
Benchmark Coupling
Benchmark Coupling

DM Simplified Model Exclusions  ATLAS Preliminary  August 2016

DM Mass [TeV]

Dijet TLA
ATLAS:CONF-2016-030

Dijet 8 TeV

Thermal relic $\Omega_c h^2 = 0.12$

Perturbative unitarity

$2 \times$ DM Mass = Mediator Mass

Thermal relic $\Omega_c h^2 = 0.12$

Axial-vector mediator, Dirac DM

$g_a = 0.1, g_{DM} = 1.5$
Solving the 4D Problem: Rescaling

\( \{ m_{DM}, M_{med}, g_{DM}, g_{SM} \} \rightarrow \{ m_{DM}, M_{med}, g_{DM} \cdot g_{SM}, g_{DM} / g_{SM} \} \)

For each \( \{ m_{DM}, M_{med}, g_{q} / g_{DM} \} \), simulate signal cross section \( \sigma_{\text{sim}} \) for a range of \( g_{q} \cdot g_{DM} \), compare with the experimental limit \( \sigma_{\text{lim}} \).

Value of \( g_{q} \cdot g_{DM} \) where \( \sigma_{\text{sim}} = \sigma_{\text{lim}} \) defines the constraint on \( g_{q} \cdot g_{DM} \).
Solving the 4D Problem: Rescaling

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Solving the 4D Problem: Rescaling

If we know how $\sigma_{\text{sim}}$ varies with $g_q g_{\text{DM}}$, we can simulate for one (or few) value(s) of $g_q g_{\text{DM}}$, avoiding the full scan.

\[ \sigma_{\text{sim}} \propto (g_q g_{\text{DM}})^2 \]
If we know how $\sigma_{\text{sim}}$ varies with $g_q g_{\text{DM}}$, we can simulate for one (or few) value(s) of $g_q g_{\text{DM}}$, avoiding the full scan.
Solving the 4D Problem: Testing Rescaling

- What is the rescaling relation?

\[ \sigma \propto \begin{cases} 
g^2 q^2 / \Gamma_{\text{OS}} & \text{if } M > 2m_{\text{DM}} \text{ on-shell} \\
g^2 q^2 & \text{if } M < 2m_{\text{DM}} \text{ off-shell} \end{cases} \]

- Holds only if the width factorises out; ie, kinematic distribution of missing energy is independent of the width

- Kinematic behaviour not greatly affected for on-shell s-channel models when \( \Gamma / M_{\text{med}} < 0.5 \)

- t-channel: additional monojet diagrams with on-shell mediator

  - Peak shape strongly depends on \( \Gamma / M_{\text{med}} \). Coupling scan absolutely needed
Solving the 4D Problem: Testing Rescaling

- Generate constraints on axial-vector model using these two techniques:
  - Full scan over 3D space, Scan over 2D space and rescale
  - Take ratio of these limits to measure validity of rescaling
- Best in central **on-shell** region where constraints are strong and width is small
- Breaks down in **off-shell** and **transition** regions

![Graph showing on-shell and off-shell regions](image)

**Graphical Description:**
- **On-shell** region with strong constraints.
- **Off-shell** region with weaker constraints.

**Equation:**
- $\sqrt{s} = 8 \text{ TeV}$
- $g_q / g_{DM} = 1/5$
- $\mathcal{L} dt = 15.5 \text{ fb}^{-1}$
- $95\%$ C.L. upper limit on $\sqrt{g_q g_{DM}}$

**Color Legend:**
- Bright colors represent higher limits.
- Dark colors represent lower limits.
Predictability of Rescaling Validity

\[ \sigma \propto \begin{cases} 
\frac{g_q^2 g_{DM}^2}{\Gamma_{OS}} & \text{if } M > 2m_{DM} \\
\frac{g_q^2 g_{DM}^2}{\Gamma_{DM}} & \text{if } M < 2m_{DM}
\end{cases} \]

\( \sqrt{s}=8 \text{ TeV} \)
Axial-vector mediator
\( M_{med} = 1 \text{ TeV} \)
\( g_{DM} = 2g_q \)

\( m_{DM} = 10 \text{ GeV} \)
\( m_{DM} = 400 \text{ GeV} \)
\( m_{DM} = 500 \text{ GeV} \)
\( m_{DM} = 700 \text{ GeV} \)
Contours show ratio of $\sigma$ using rescaling vs the true simulated value, independent of limits on $\sigma$.

Rescaling breaks down when width is large and when mediator mass is small.
Morphing

- Method for estimating physical distributions as a continuous function of an arbitrary number of theoretical parameters using non-linear interpolation between a number of input distributions, or factorising out dependence on mediator mass before generation

- Would allow regions where rescaling fails to be investigated for a reasonable computational cost, and to transition between regions of different running

- Only works in regions with smooth change in distribution

Baak et al, arXiv:1410.7388
Conclusion

• Effective operators remain a useful benchmark for DM searches at the LHC if used and interpreted with caution

• Simplified models are the natural next step, but can lead to reduced coverage of the parameter space

• Rescaling + morphing can overcome this issue, and allow constraints to be presented in a full 3D plane
Backup
Rescaling operator constraints

- Some hidden assumptions now made explicit, but should still be interpreted with caution

ATLAS + Busoni, De Simone, TDJ, Morgante, Riotto
Ensuring Validity of EFTs

- This technique relies on a clear definition of the momentum transfer, and a relationship between $M_\star$ and the parameters of an underlying simplified model e.g. $M \equiv \sqrt{g_q g_\chi} M_\star$

- Breaks down if there is no simple UV completion
Model-independent Rescaling

- An alternative, conservative, model independent approach:
  - define a free parameter $g_\star$
  - Substitute $Q_{tr} \rightarrow E_{cm} \geq Q_{tr}$
  - Condition becomes $E_{cm} < g_\star M_\star$
  - Weaker constraints than the model-dependent method

![Graph showing model-independent rescaling](Image 1)

![Graph showing model-independent limits](Image 2)
$\sqrt{s} = 8$ TeV
$\frac{g_q}{g_{DM}} = 1/2$
$\int L \, dt = 20.3 \cdot fb^{-1}$

$\sqrt{s} = 14$ TeV
$\frac{g_q}{g_{DM}} = 1/5$
$\int L \, dt = 20 \cdot fb^{-1}$