Portorož - 8 apr 2015

DM @ LHC
Status & Outlook

Andrea De Simone

MOSTLY BASED ON:
Busoni, DS, Morgante, Riotto - arXiv:1307.2253
DS, Giudice, Strumia - arXiv:1402.6287
ATLAS - ATLAS-PHYS-PUB-2014-007
ATLAS - arXiv:1502.01518
3 Pillars of Dark Matter Searches

**INDIRECT DETECTION**
DM DM → $e^+ e^-$, ...

**DIRECT DETECTION**
DM Nucleus → DM Nucleus

**COLLIDER**
$pp \rightarrow \text{DM} + X$
(in LHC we trust...)
• Dark Matter searches @ LHC:
  mono-jets, effective operators and all that...

• *dead ends? way out?*

• outlook for the next LHC Run
Some trivial considerations:

- Dark Matter in a collider is like a neutrino (missing $E_T$)

- if stabilized by a $Z_2$ symmetry, Dark Matter produced in pairs

- Difficult search, unless correlating missing $E_T$ with other handles

  [ - jets/photons from initial state radiation?  
    - displaced vertices?  
    - accompanying particles? ]

- NEED NEW IDEAS!
✓ constrain **DM-quarks** interactions and translate into limits on **DM-nucleon** cross-section

✓ **complementary/competitive** with direct detection

✓ **no astrophysical uncertainties**
More complete/more parameters

Complete Models

MSSM, Composite Higgs, Extra-Dim...

pMSSM scan

lots of parameters...

Figure 9: Comparisons of the models surviving or being excluded by the various searches in the LSP mass-scaled SI cross section plane as discussed in the text. The SI XENON1T line is shown as a guide to the eye.
Theory Space

Complete Models

More complete/
more parameters

Effective Theories

less complete/
less parameters
Effective Field Theory Description

- Effective low-energy description
  - \( \Lambda \sim 1 \text{ TeV} \)

- New States
  - \( (\text{say, } 10 \text{ TeV}) \)

LHC can access regions beyond the validity of the eff. description

Integrate out the UV physics connecting Dark Matter-SM

\[
\frac{1}{M^2_*} (\bar{\chi} \Gamma^A \chi) (\bar{q} \Gamma_A q)
\]

Need to use EFT carefully and consistently
Effective Field Theory Description

- The momentum transfer in the relevant process must be
  \[ Q_{\text{tr}} \lesssim M_{\text{med}} \]

- \( Q_{\text{tr}} / M_{\text{med}} \) measures the badness of the truncation of the tower of effective ops to the lowest dimensional ones.

- Usually, lowest order is OK. Not a problem for direct/indirect searches.
  Situation can be different @ LHC.

\[
\begin{align*}
\frac{1}{Q_{\text{tr}}^2 - M_{\text{med}}^2} &= -\frac{1}{M_{\text{med}}^2} \left[ 1 + \frac{Q_{\text{tr}}^2}{M_{\text{med}}^2} + \mathcal{O} \left( \frac{Q_{\text{tr}}^4}{M_{\text{med}}^4} \right) \right], \\
\sum_{d>4} \frac{1}{M_*^{d-4}} \mathcal{O}_d &= M_{\text{med}} = f(g_i, M_*)
\end{align*}
\]
Number of valid events are a fraction

$$\left[ R_{M_*}^{\text{tot}} \right] = \sigma \left| Q_{\text{tr}} < M_*/\sigma \right.$$ of the total events

So the new limits are found by:

$$M_{\text{valid}}^{\text{exp}} = \left[ R_{M_*}^{\text{tot}} \right]^{1/4} M_{\text{exp}}^{\text{valid}}$$

Implications for LHC Limits

Signal cross section scales as:

$$\sigma \propto M_*^{-4}$$
(for dim-6 ops)
The “money plots”

- after truncation: theoretically robust limits
- still relevant at low DM masses

$L=20.3 \text{ fb}^{-1}$

[ATLAS - 1502.01518]
$\sqrt{s} = 14$ TeV

**EFT Discovery Potential**

$L=25$ fb$^{-1}$

**ATLAS** Simulation Preliminary

$\sqrt{s}=14$ TeV $\int Ldt=25$ fb$^{-1}$

$D5$, $m_\chi = 50$ GeV

$\pi < \sqrt{g_{SM} g_{DM}} < 4\pi$

- 5% systematic

5$\sigma$ discovery

3$\sigma$ evidence

$L=300$ fb$^{-1}$

**ATLAS** Simulation Preliminary

$\sqrt{s}=14$ TeV $\int Ldt=300$ fb$^{-1}$

$D5$, $m_\chi = 50$ GeV

$\pi < \sqrt{g_{SM} g_{DM}} < 4\pi$

- 5% systematic

- 1% systematic

5$\sigma$ discovery

3$\sigma$ evidence

$L=3000$ fb$^{-1}$ (HL-LHC)

**ATLAS** Simulation Preliminary

$\sqrt{s}=14$ TeV $\int Ldt=3000$ fb$^{-1}$

$D5$, $m_\chi = 50$ GeV

$\pi < \sqrt{g_{SM} g_{DM}} < 4\pi$

- 5% systematic

- 1% systematic

5$\sigma$ discovery

3$\sigma$ evidence

EFT validity assumed

Effective Operator

$(\bar{\chi}\gamma^\mu \chi)(\bar{q}\gamma_\mu q)$

$m_{DM} = 50$ GeV

[ATL-PHYS-PUB-2014-0087]
EFT approach

- limited validity
- not entirely model-independent
  (still rather general...)

How to go beyond that (but keeping generality), in view of LHC14?

- **Simplified Models**
- **Selected benchmarks cases**
Complete Models

More complete/
more parameters

Simplified Models

Effective Theories

Other Benchmarks

less complete/
less parameters
Simplified Models

... just means extending the SM with:

- 1 Dark Matter particle
- 1 Mediator particle connecting DM-SM

>> just another parametrization of unknown high energy physics <<

- correspondence
- eff ops \leftrightarrow simplified models

× 1 or 2 more parameters \((g's)\)

✓ exploit other searches for mediators (e.g. di-jet), complementary to mono-jet

✓ theoretically consistent, no worries about EFT, widths, etc.
Simplified Models for Dark Matter and Missing Energy Searches at the LHC

Jalal Abdallah,¹ Adi Ashkenazi,² Antonio Boveia,³ Giorgio Busoni,⁴ Andrea De Simone,⁴ Caterina Doglioni,⁵ Aielet Efrati,⁶ Erez Etzion,² Johanna Gramling,⁵ Thomas Jacques,⁵ Tongyan Lin,⁷ Enrico Morgante,⁵ Michele Papucci,⁸,⁹ Bjoern Penning,³,¹⁰ Antonio Walter Riotto,⁵ Thomas Rizzo,¹¹ David Salek,¹² Steven Schramm,¹³ Oren Slone,² Yotam Soreq,⁶ Alessandro Vichi,⁸,⁹ Tomer Volansky,² Itay Yavin,¹⁴,¹⁵ Ning Zhou,¹⁶ and Kathryn Zurek⁸,⁹

Interplay and Characterization of Dark Matter Searches at Colliders and in Direct Detection Experiments

Sarah A. Malik,¹ Christopher McCabe,²,³ Henrique Araujo,¹ Alexander Belyaev,⁴,⁵ Céline Boehm,² Jim Brooke,⁶ Oliver Buchmueller,² Gavin Davies,² Albert De Roeck,⁶,⁷ Kees de Vries,¹ Matthew J. Dolan,⁵ John Ellis,⁶,⁷ Malcolm Fairbairn,⁶ Henning Flaecher,⁶ Loukas Gouskos,⁸ Valentin V. Khoze,⁵ Greg Landsberg,⁵ Dave Newbold,⁶ Michele Papucci,⁸ Timothy Sumner,² Marc Thomas⁴,⁵ and Steven Worm⁶
Simplified Models

Z’ vector mediator model: \( \mathcal{L} = - \sum_f g_f Z'_\mu [\bar{f} \gamma^\mu f] - g_{\text{DM}} Z'_\mu [\bar{\chi} \gamma^\mu \chi] \)

\( \sqrt{s} = 8 \text{ TeV} \)

\( \sqrt{s} = 14 \text{ TeV} \)

\( M^* = \frac{M_{\text{med}}}{\sqrt{g_f g_{\text{DM}}}} \)

[ATL-PHYS-PUB-2014-0087]
In order for the EFT to be valid we need to ensure that the kinematic distributions are probed at scales less than the EW scale, i.e. fixed at mediator. The ratio is computed for fixed mediator. For the pseudoscalar mediator model we show the indirect detection limits using Fermi data [58].

For the pseudoscalar we show 95% CL exclusion limits while we show limits at 95% CL for the other mediators. For the pseudoscalar mediator we show the spin-dependent and spin-independent cross sections as in Fig. 7, now plotted as functions of the dark matter mass.

Projected 90% CL exclusions (from CMS data) onto direct-detection plane.
Simplified Models: Relic Density

Z' vector mediator model: \[ \mathcal{L} = - \sum_f g_f Z'_\mu \left[ \bar{f} \gamma^\mu f \right] - g_{\text{DM}} Z'_\mu \left[ \bar{\chi} \gamma^\mu \chi \right] \]

**Figure 3:** Over-production and under-production boundary lines for thermal relic dark matter for three different choices of the coupling strength and a $Z'$-type mediator with pure vector couplings. Black lines are ATLAS projected 95% CL lower bounds after 25 fb$^{-1}$ at 14 TeV assuming 5% systematic uncertainties.

**Figure 4:** Over-production and under-production boundary lines for thermal relic dark matter compared with projected ATLAS reach for two values of the dark matter mass and a $Z'$-type mediator with pure vector couplings. Black lines are ATLAS projected 95% CL upper bounds after 25 fb$^{-1}$ at 14 TeV assuming 5% systematic uncertainties.

**Figure 5:** The solution to the ratio $g_{f} / g_{\text{DM}}$ corresponding to the bounds on the product $g_f \cdot g_{\text{DM}}$ combined with fixed mediator widths as represented in Fig. 4. At large mediator masses no solution exists and the widths are unphysical for the coupling strengths in Fig. 4.

**Hypothesis:** $g_f \leq g_{u,d}$

**ATLAS 95% CL bound**

L=25 fb$^{-1}$ at 14 TeV

\[ \langle \sigma v \rangle_{\text{ann}} < \langle \sigma v \rangle_{\ast} \]

\[ \langle \sigma v \rangle_{\text{ann}} > \langle \sigma v \rangle_{\ast} \]
Way Out?

Complete Models

More complete/
more parameters

Simplified Models

Effective Theories

less complete/
less parameters

Other Benchmarks
Some benchmark cases offering prospects for DM discovery
(alternative to EFT or simplified models):

1. **DM co-annihilating with a coloured partner**
   - DM coupled to the Z
   - DM coupled to the Higgs

2. **DM annihilating through a SM mediator**
   - DM coupled to the Z
   - DM coupled to the Higgs

3. **DM near Z/h thresholds**

... ???
EFT fragile

LHC can discover **mediators** more easily than effective operators

**Get ready to fail**

*abandon* WIMP paradigm in *N* years

or

**WIMP obstinacy?**

**Future of LHC searches for DM**

Need to explore **new avenues**

- **beyond EFT**
- **as model-indep. as possible**
BACK UP
In what regions of the parameter space \( \{ \Lambda, m_{\text{DM}} \} \) is the effective description accurate/reliable?

\[
R_{\Lambda}^{\text{tot}} \equiv \frac{\sigma_{\text{eff}} |Q_{\text{tr}} \leq \Lambda |}{\sigma_{\text{eff}}} \tag{valid events}
\]

\( R_{\Lambda}^{\text{tot}} \) fraction of eff. cross section at low momentum transfer.

\( 0 < R < 1 \). \( R \sim 1 \): negligible contribution from higher-dim ops

EFT works better for larger \( \Lambda \) and smaller \( m_{\text{DM}} \).

Cutoff scale arbitrary: \( Q_{\text{tr}} < \sqrt{g_q g_\chi} \Lambda \) (conservatively: \( Q_{\text{tr}} < 4\pi \Lambda \) )
Implications for LHC Limits

\((\bar{\chi} \gamma^\mu \chi)(\bar{q} \gamma_\mu q)\) \hspace{1cm} \sqrt{s} = 8 \text{ TeV}

\(\sqrt{s} = 8 \text{ TeV} \hspace{1cm} \int L = 20 \text{ fb}^{-1}\)

\(m_\text{DM} = 50 \text{ GeV}\)

\(m_\text{DM} = 400 \text{ GeV}\)

\(\sqrt{s} = 14 \text{ TeV} \hspace{1cm} \int L = 25 \text{ fb}^{-1}\)

[A. De Simone]

[ATL-PHYS-PUB-2014-0087]
1. Co-Annihilations with a Coloured Partner

- DM accompanied by a nearby coloured state $\text{DM}'$ $\text{DM}$ $M_{DM} + \Delta M$
- $\text{DM}$ $M_{DM}$

- Situation fully characterised (model-independently) by:
  - DM’ quantum numbers (spin, color)
  - $M_{DM}$
  - $\Delta M$

- 4 cases of interest:

<table>
<thead>
<tr>
<th>DM’</th>
<th>Colour triplet</th>
<th>Colour octet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar</td>
<td>S3</td>
<td>S8</td>
</tr>
<tr>
<td>Fermion</td>
<td>F3</td>
<td>F8</td>
</tr>
</tbody>
</table>

- Relic density from co-annihilations in the early Universe (with Sommerfeld enhancement)
Relic density in the limit of mass degeneracy $\Delta M = 0$

Substantial effect of Sommerfeld corrections
1. Co-Annihilations with a Coloured Partner

large QCD cross section:

\[ pp \rightarrow \text{DM}' \ 	ext{DM}' + \text{jet} \]

large enough splitting to tag soft jet?

90\%CL exclusion

\[ \sqrt{s} = 8 \text{ TeV} \]

\[ L = 19.6 \text{ fb}^{-1} \]

LHC will not probe the entire parameter space, \( \sqrt{s} \sim 100 \text{ TeV} \) will.
The DM-quarks interactions are mediated by a SM particle (Z or H)

DM coupled to the Z

\[\mathcal{L} = -\frac{g_2}{\cos \theta_W} Z_\mu \left[ \sum_f \left[ \bar{f} \gamma_\mu (g^V_f) f + \gamma_5 (g^A_f) f \right] + \sum_s g_s \left[ s^* (i \partial_\mu s) - (i \partial_\mu s^*) s \right] \right] \]

some regions still allowed for axial couplings of fermion DM (SD cross section is less constrained)
2. Annihilations Through SM Mediator

DM coupled to the Higgs

\[ \mathcal{L} = -h \frac{1}{\sqrt{2}} \left[ \sum_f y_f \bar{f} f + \bar{\psi}_{\text{DM}} (y_{\text{DM}} + i y_{\text{P}} \gamma_5) \psi_{\text{DM}} + \frac{\lambda_{\text{DM}} v}{2} s_{\text{DM}}^2 \right] \]

some regions still allowed for scalar DM \((M > 100 \text{ GeV})\)
and fermion DM with axial couplings

RULED OUT

A. De Simone
in the early Universe:
DM annihilations with s-channel exchange of a mediator

Near resonance \( (M_{\text{med}} - 2M_{\text{DM}} \lesssim 2\Gamma_{\text{med} \rightarrow \text{DM}}) \), the annihilation cross section is driven by the on-shell term, which is model-independent (Breit-Wigner)

The relic abundance is determined model-independently by the width:

DM freezes out via decays
Simple situation when the mediator is $Z$ or $H$.

Curves for correct DM relic abundance:

- room for improvement, exploring invisible widths of $Z$ and $h$

(LHC, future Higgs factories, GigaZ...)

- motivation to improve on $Z/h$ invisible BRs

Invisible BR suggested by DM thermal relic abundance

DM mass