Beyond EFT for DM@LHC

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Based on:
DS, Giudice, Strumia
. EFT approach (see T. Jacques’ talk)
  - limited validity
  - not entirely model-independent, but still rather general
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“you can’t score if you don’t have the ball”

[J. Cruyff]
- **EFT approach** (see T. Jacques’ talk)
  - limited validity
  - not entirely model-independent, but still rather general

- How to go beyond that (but keeping generality), in view of LHC Run II?
  - **Simplified Models**
  - **Selected benchmarks cases**
**Simplified Models**

- **Correspondence**
  - eff ops ↔ simple toy models

- **Exploitation**
  - 1 or 2 more parameters (g’s)
  - Direct detection limits must be re-expressed

- **Upper Limits**
  - Provide upper limits on $g$ (or $M/g$)
    - For each simplified model
    - For given $m_{DM}$

- **Completeness and Reliability**
  - Complete and reliable information
Some benchmark cases offering prospects for DM discovery (alternative to EFT or simplified models):

1. DM co-annihilating with a coloured partner

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

3. DM near Z/h thresholds
1. CO-ANNIHILATIONS WITH A COLOURED PARTNER

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

- Situation fully characterised (model-independently) by:
  - $\text{DM'}$ 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>$S_3$</td>
<td>$S_8$</td>
</tr>
<tr>
<td>Fermion</td>
<td>$F_3$</td>
<td>$F_8$</td>
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- 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
large QCD cross section:

\( pp \rightarrow DM' \ DM' + \text{jet} \)

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

L=19.6 / fb

LHC will not probe the entire parameter space, \( \sqrt{s} \sim 100 \ \text{TeV} \) will.
2. Annihilations through SM mediator

The DM-quarks interactions are mediated by a SM particle (Z or H)

**DM coupled to the Z**

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

*Fermion DM coupled to the Z*  
*Scalar DM coupled to the Z*

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

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

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

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...)

invisible BR

DM mass

Invisible BR suggested by DM thermal relic abundance
Conclusions

- Need to explore new avenues for DM searches @ LHC
  - beyond EFT
  - as model-independent as possible
- Proposed some benchmark cases for DM discovery:
  1. DM co-annihilating with a coloured partner
     - identification of soft jets, tag extra-jets
  2. DM annihilations via SM mediator (Z, h)
     - LHC searches not competitive, but good to improve MET channels (e.g. non-thermal production)
  3. DM near Z/h thresholds
     - motivation to improve on Z/h invisible BRs