Complementarities and future of dark matter searches

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Outline

• Dark matter: candidates and complementarity
• The “spectrum of theory space”
• EFT and simplified models: two mono-X Run1 results
• Towards Simplified models: dijets
• A “special” mediator: the Higgs portal
• Perspective for Run2 and beyond: theoretical frameworks and expected sensitivity
• Conclusions
Dark Matter candidates

from Tim M.P. Tait DM@LHC, Chicago 2013
Interpretation of results: “spectrum of theory space”

from Tim M.P. Tait DM@LHC, Chicago 2013
Effective field theories and Simplified Models

**EFT:** details of the particle mediating the interaction have not to be specified.

**SMs:** 4 parameters (mass of DM, mass of mediator, couplings constants)

\[ L \supset \frac{\bar{q} \gamma_{\mu} q}{\Lambda^2} \bar{\chi} \gamma^{\mu} \chi \]

\[ L \supset \frac{g_q \bar{q} \gamma_{\mu} q}{Q^2 - M_{\text{MED}}^2} \frac{g_{\chi} \bar{\chi} \gamma^{\mu} \chi}{Q^2 - M_{\text{MED}}^2} \]

\[ \Lambda = \frac{M_{\text{MED}}}{\sqrt{g_q g_{\text{DM}}}} \]

**Validity of EFTs**

If \( Q^2 \approx O(\text{TeV}^2) \) \( \rightarrow \) a heavy mediator is needed (> 2.5 TeV).

\[ \Lambda \approx 900 \text{ GeV} \Rightarrow g \approx \frac{M_{\text{MED}}}{\Lambda} \approx 3 \rightarrow \text{large couplings} \]

Also large widths of mediators (particle-like?): \( \frac{\Gamma_{\text{MED}}}{M_{\text{MED}}} \geq 1 \)
Dark-matter detection: complementarity

Direct detection

DM → DM
SM → SM

Underground experiments, looking for recoiling atomic nuclei

Collisions

SM → DM
DM → SM

Production of DM pairs

Indirect detection

DM → SM
SM → DM

Ground-based or satellite-borne astroparticle experiments

Astrophysical observations

DM → DM

Star and galaxy surveys, helioseismology

Arxiv references:
- arxiv 1310.8327
- arxiv 1411.1925
- arxiv 1406.5662
- arxiv 1308.0338
Colliders’ favourite candidate: WIMP

We focus here on a DM candidate just:
• stable (or long-lived)
• slow moving (cold)
• complying with the relic density argument: cosmological abundance of order unity today $\rightarrow$ cosmological abundance $10^{-9} \text{GeV}^2$, same order of magnitude one would expect from a typical electroweak cross-section $\rightarrow$ weakly interacting
• large mass if compared with SM particles

Without other assumptions, such a candidate is generically referred to as Weakly Interacting Massive Particle (WIMP)
The “mono-X” strategy at colliders

- DM particles do not leave significant signals in experiments’ detectors.
- “Interesting events” are those with
  - large Missing Energy in the Transverse plane (MET, carried out by the DM pair)
  - a tagging signal, referred to an object from the Initial State Radiation (ISR): the X

Typical Dark Matter signature: feature (excess) in the MET spectrum

CMS arxiv 1408.3583
Mono-jet RUN1 results

Results from ATLAS and CMS are compared with those from direct and indirect measurements:

• **complementarity** of approaches clearly appreciable
• comparisons possible only with the *same assumptions* (special care to implementation details of model and theories, e.g. truncation for EFT).

**Truncation**: events are omitted where the interaction energy scale exceeds the mediator particle mass. This depends on the values adopted for the couplings.

ATLAS arxiv 1502.01518
CMS arxiv 1408.3583
MET+W/Z/γ

Events are looked for with high MET and a high $p_T$ boson, reconstructed directly or from decay products.

**Mono-photon**

Interpretation within simplified models

- $W/Z\rightarrow jj$: PRL 112, 041802 (ATLAS, interesting use of fat jets)
- $Z\rightarrow ll$: PRD 90, 012004 (ATLAS)
- $W\rightarrow lv$: JHEP 09, 037 (ATLAS) and arxiv 1408.2745 (CMS)
- mono-photon: PRD 91, 012008 (ATLAS) and arxiv 1410.8812 (CMS)

**Mono-W**

Interpretation within EFT

Different levels of interpretation between EFTs and SMs.
Dijets angular spectrum

Dijet angular distributions found to be in agreement with the perturbative QCD predictions that include electroweak corrections. Limits on the contact interaction scale from a variety of models at next-to-leading order in QCD corrections were obtained.

Data binned coarsely in \( m_{jj} \), expecting low-\( m_{jj} \) bins dominated by QCD processes and new physics (also quark compositeness) in higher dijet invariant mass bins.

Dijet angular distribution will be potentially important for DM models foreseeing chiral interference with SM interactions.
Resonances in dijet mass spectrum

The limits for resonances with gluons in the final states are less restrictive than those with quarks because the signal shapes are wider.

Prospects in ATL-PHYS-PUB-2015-004

Dominant systematics:
~10% Jet Energy Resolution
The Higgs portal

The Higgs boson could couple also to DM particles, in which case invisible decays would be enhanced. Higgs production in channels VBF and W/Z H are considered with subsequent decay $H \rightarrow$ invisible.

Important: total Higgs boson decay constrainable with global fits to other measurements (basically $W$ and $Z$ couplings, relevant for VBF, assumed not to change). Under this assumption there is still room for $BR_{inv/undet} < 32\%$ for CMS (41% from ATLAS).

If the DM candidate has a mass below $m_H/2$, the invisible Higgs boson decay width, $\Gamma_{inv}$, can be directly translated to the spin-independent DM-nucleon elastic cross section, for scalar ($S$), vector ($V$), and fermionic ($f$) DM.
VBF $H \rightarrow \text{inv.}$

<table>
<thead>
<tr>
<th>Process</th>
<th>Event yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z(\nu\nu)$+jets</td>
<td>$99 \pm 29$ (stat) $\pm 25$ (syst)</td>
</tr>
<tr>
<td>$W(\mu\nu)+$jets</td>
<td>$67 \pm 5$ (stat) $\pm 16$ (syst)</td>
</tr>
<tr>
<td>$W(\tau\nu)+$jets</td>
<td>$63 \pm 9$ (stat) $\pm 18$ (syst)</td>
</tr>
<tr>
<td>$W(\tau\tau)+$jets</td>
<td>$53 \pm 18$ (stat) $\pm 18$ (syst)</td>
</tr>
<tr>
<td>QCD multijet</td>
<td>$31 \pm 5$ (stat) $\pm 23$ (syst)</td>
</tr>
<tr>
<td>Sum ($t\bar{t}$, single top quark, $VV$, $DY$)</td>
<td>$20.0 \pm 8.2$ (syst)</td>
</tr>
<tr>
<td>Total background</td>
<td>$332 \pm 36$ (stat) $\pm 45$ (syst)</td>
</tr>
<tr>
<td>VBF $H(\text{inv})$</td>
<td>$210 \pm 29$ (syst)</td>
</tr>
<tr>
<td>$ggF H(\text{inv})$</td>
<td>$14 \pm 10$ (syst)</td>
</tr>
<tr>
<td>Observed data</td>
<td>$390$</td>
</tr>
<tr>
<td>$S/B$</td>
<td>$70%$</td>
</tr>
</tbody>
</table>

see also ATLAS-COM-PHYS-2015-004
ZH → ll+inv

ATLAS arxiv 1402.3244, PRL 112, 041802

see EPJC 74:2980 for CMS
The Higgs portal: results

For a given value of $M_{\chi}$, an upper limit on $\Gamma_{\text{inv}}$, directly translates to an upper limit on the cross section.

arxiv 1402.3244

EPJC 74:2980 (Z(bbar) also)
Perspectives at 14 TeV

It is a difficult task to assess performance and sensitivity at 14 TeV, as most of numbers needed for an estimation are still unknown (performance of the upgraded detector, energy and luminosity).

A study by CMS (arxiv 1407.8257) performs an extrapolation of CMS results to RUN2. It discusses in detail EFT and simplified models for the interpretation.

Another study has been performed (ATLAS-PHYS-PUB-2014-007) for this purpose. For the mono-jet channel:

- **harder selection cuts** to cope with **harsher pile-up conditions** (higher MET thresholds, higher jet $p_T$ thresholds)
- same vetoes as for 8 TeV
- **narrower jet acceptance** $|\eta|<3.6$, to avoid forward regions, where variations of performance are expected to be larger

Sensitivity will be sufficient to start investigating simplified models in a systematic way, keeping EFT as a necessary benchmark.
The authors introduce a Minimal Simplified Dark Matter (MSDM) framework to quantitatively characterise DM searches at the LHC. The model is characterised by four parameters: \( m_{DM} \), \( M_{med} \), \( g_{DM} \) and \( g_{q} \), the DM and mediator masses, and the mediator couplings to DM and quarks respectively.
Perspectives: simplified models

arxiv 1407.8257

The use of simplified models allows an equal-footing comparison and clearly shows complementarity between different approaches to DM search. Direct detection is more sensitive to vector-mediated interactions, while collider searches are more sensitive for axial vector-like mediators.
Perspectives: simplified models

Comparison between 90% C.L. limits obtained with the proposed minimal simplified model and those obtained within the EFT framework.

The MSDM mono-jet production cross-section is resonantly enhanced in the low \( m_{DM} \) region. This enhancement is not accounted for in the EFT limits, which explains why the MSDM limit is more constraining than the EFT limit in this mass range.

No limit is obtained in the MSDM model for \( m_{DM} > 300 \) GeV while a naive application of the EFT limit gives the false impression that the limit extends beyond \( m_{DM} = 1 \) TeV. This overstating of the limit at high values of \( m_{DM} \) has sometimes led to the wrong conclusion that for spin-dependent interactions, the mono-jet searches outperform direct detection searches.

EFT and SMs are equivalent for DD experiments, as long as \( M_{\text{med}} > Q (~100 \) MeV).
Perspectives: gain due to higher energy

Expected \( \sim 25 \text{ fb}^{-1} \) in 2016-2017 (10 fb\(^{-1}\) by the end of 2015)

Phase1-upgrade, planned by the end of 2018, will increase luminosity to reach 300 fb\(^{-1}\) within 2022 (\(\mu \sim 60\))

Phase2-upgrade \( \rightarrow 3000 \text{ fb}^{-1}\) within 2030
Perspectives: higher energy and luminosity

ATLAS-SIMULATION-PRELIMINARY

ATLAS Simulation Preliminary

D5, $m_\chi = 50$ GeV

5% syst

$\pi < \frac{g_{SDM}}{\sqrt{S_{SM}}D_{\chi}^4}$

Suppression scale $M_\chi$ [GeV]

MET > 400 GeV
MET > 600 GeV
MET > 800 GeV

8 TeV, 14 TeV, 5 fb$^{-1}$, 25 fb$^{-1}$, 300 fb$^{-1}$, 3000 fb$^{-1}$

ATLAS Simulation Preliminary

D5, $m_\chi = 400$ GeV

5% syst

$\pi < \frac{g_{SDM}}{\sqrt{S_{SM}}D_{\chi}^4}$

Suppression scale $M_\chi$ [GeV]

MET > 400 GeV
MET > 600 GeV
MET > 800 GeV

8 TeV, 14 TeV, 5 fb$^{-1}$, 25 fb$^{-1}$, 300 fb$^{-1}$, 3000 fb$^{-1}$

ATLAS Simulation Preliminary

D5, $m_\chi = 50$ GeV

1% syst

$\pi < \frac{g_{SDM}}{\sqrt{S_{SM}}D_{\chi}^4}$

Suppression scale $M_\chi$ [GeV]

MET > 400 GeV
MET > 600 GeV
MET > 800 GeV

8 TeV, 14 TeV, 5 fb$^{-1}$, 25 fb$^{-1}$, 300 fb$^{-1}$, 3000 fb$^{-1}$

ATLAS Simulation Preliminary

D5, $m_\chi = 400$ GeV

1% syst

$\pi < \frac{g_{SDM}}{\sqrt{S_{SM}}D_{\chi}^4}$

Suppression scale $M_\chi$ [GeV]

MET > 400 GeV
MET > 600 GeV
MET > 800 GeV

8 TeV, 14 TeV, 5 fb$^{-1}$, 25 fb$^{-1}$, 300 fb$^{-1}$, 3000 fb$^{-1}$
Perspectives: expected sensitivity

expected after phase 1 upgrade (2022)

expected after proposed phase 2 upgrade (2030)
Run2 preparation

The ATLAS/CMS Dark Matter forum hosts discussions among theorists and experimentalists oriented to Run2 DM searches

from C. Doglioni, Dark Matter at the LHC – Moriond EW 2015

Important work of agreement on:
• simplified models to investigate (and how to do it)
• procedure of assessment of EFT validity

https://twiki.cern.ch/twiki/bin/view/LHCDMF/WebHome
Conclusions

• LHC results on DM searches are complementary to achievements from Direct and Indirect experiments
• ATLAS and CMS results are mostly limits on WIMPs, obtained by looking for MET+X events (mono-X strategy)
• Run1 results allowed to widely test EFTs, but detailed studies have shown the potential of simplified models in terms of validity and applicability
• The extension of kinematics in Run2 will increase the sensitivity of mono-X searches, but special care will have to be devoted to control of systematics
Backup
# EFT operators

<table>
<thead>
<tr>
<th>Name</th>
<th>Initial state</th>
<th>Type</th>
<th>Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>$qq$</td>
<td>scalar</td>
<td>$\frac{m_q}{M^2_*} \chi \gamma^\dagger \chi \bar{q}q$</td>
</tr>
<tr>
<td>C5</td>
<td>$gg$</td>
<td>scalar</td>
<td>$\frac{1}{4M^2_*} \chi \gamma^\dagger \chi \bar{q}q \alpha_s (G^a_{\mu\nu})^2$</td>
</tr>
<tr>
<td>D1</td>
<td>$qq$</td>
<td>scalar</td>
<td>$\frac{m_q}{M^3_*} \chi \bar{q}q$</td>
</tr>
<tr>
<td>D5</td>
<td>$qq$</td>
<td>vector</td>
<td>$\frac{1}{M^2_*} \chi \gamma^{\mu} \chi \bar{q} \gamma^{\mu} q$</td>
</tr>
<tr>
<td>D8</td>
<td>$qq$</td>
<td>axial-vector</td>
<td>$\frac{1}{M^2_*} \chi \gamma^{\mu} \gamma^5 \chi \bar{q} \gamma^{\mu} \gamma^5 q$</td>
</tr>
<tr>
<td>D9</td>
<td>$qq$</td>
<td>tensor</td>
<td>$\frac{1}{M^2_*} \chi \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q$</td>
</tr>
<tr>
<td>D11</td>
<td>$gg$</td>
<td>scalar</td>
<td>$\frac{1}{4M^3_*} \chi \chi \alpha_s (G^a_{\mu\nu})^2$</td>
</tr>
</tbody>
</table>
Perspectives: monojet and validity of EFT

Fraction of WIMP events passing the EFT validity requirement $Q_{tr} < M_{\text{med}}$.

Rescaled limits on $M^*$ for valid WIMP events.
Perspects: Run2 monojet sensitivity
MET+heavy quark(s) signal

Events are looked for with high MET and a ttbar pair (yield enhanced for certain EFT operators, as the coupling is proportional to the quark mass)

Analyses differ for the ttbar pair decay mode:

- all-hadronic: EPJ 75:92 (ATLAS)
- semileptonic: CMS-PAS-B2G-14-004

[Graphs and diagrams showing data and limits on dark matter mass]

EPJ 75:92

arxiv 1504.03198
The Large Hadron Collider at CERN, near Geneva, makes proton bunches colliding at center of mass energy up to 14 TeV, with instantaneous luminosity up to $10^{34}$ cm$^{-2}$ s$^{-1}$. Run 1 in 2009-2013. Run 2 starting in 2015 (first collisions in the next months).

ATLAS and CMS are general purpose $4\pi$ experiments.
MET+jet (mono-jet)

Events are looked for with high MET and a jet of high transverse momentum ($p_T$)

*Event selection:*
- one high $p_T$ jet (>120 GeV ATLAS, >80 GeV CMS)
- high MET (>150 GeV ATLAS, >105/120 GeV CMS)
- allow a third jet from ISR ($p_T>$30 GeV)
- veto events with three or more energetic jets
- veto events with identified leptons
- suppress QCD multijet background $\Delta\Phi(j_1,j_2)<2.5$ rad for CMS and $\Delta\Phi(j_1,MET)>0.5$ rad for ATLAS
  (residual contribution estimated from bg-enriched regions)

*Main background* from $Z(\rightarrow vv)+$jets, $W(\rightarrow lv)+$jets estimated in orthogonal control samples.
Non collision background also reduced by specific quality cuts on jets

*Systematics* on the background 5%-15%

See also Luise’s talk.

ATLAS arxiv 1502.01518
CMS arxiv 1408.3583