DARK MATTER SEARCHES AT ATLAS AND CMS:
RUN 1 RESULTS AND RUN 2 POTENTIAL

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On behalf of the ATLAS and CMS Collaborations

16/03/2015 – 50th Rencontres de Moriond (EW)
Dark Matter at the LHC
past and near future searches

1. The heart of the (dark) matter: WIMPs

2. MET+X searches and Effective Field Theories:
   (jet+MET, W+MET, heavy flavors+MET)

3. The case for simplified models and specific examples
   (photon+MET, Z+MET, t+MET, Higgs→MET)

More CMS
and ATLAS
results:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP
THE HEART OF THE MATTER, PRE-LHC

Caterina Doglioni – Dark Matter at the LHC – Moriond EW 2015
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.
THE HEART OF THE MATTER, POST LHC RUN-1

https://cds.cern.ch/record/874049

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EPJC 72 (2012) 2003

2013

First observations of a new particle in the search for the Standard Model Higgs boson at the LHC

https://cds.cern.ch/record/874049
AN EMPIRICAL PROBLEM OF THE SM: DARK MATTER

F. Zwicky – Coma cluster: mass vs light output

V. Rubin – Velocity of gas near Andromeda galaxy

Planck – Dark matter vs standard matter composition using CMB (temperature) fluctuations

Chandra/Hubble (NASA) – Visible mass of bullet cluster vs dark mass inferred from gravitational lensing

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THEORIES OF DARK MATTER

Tim Tait, DM@LHC 2013

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This talk: mostly focus on “model-independent” searches, but still WIMPs (see SUSY talk for more specific neutralino DM, EXO talk for further dark particles)
(Our) preferred DM candidate matches cosmological observations (e.g. thermal relic density): dark, stable, cold, weakly interacting with SM particles, mass of up to a few TeV → a WIMP

Complementary Dark Matter experiments

Indirect detection

Direct detection

Colliders
ATLAS and CMS → physics with jets, leptons, photons
- General-purpose experiments, covering ~ full solid angle
- Excellent tracking, calorimetry, muon spectrometer
Invisible DM particles escape detection:

LHC experiment strategy: tag events using recoiling object(s), measure missing transverse momentum (Missing $E_T$)

$\text{EFT Operators}$ representing types of DM-SM interactions with DM particles

Advantages:
Limited number of degrees of freedom: scale of interaction ($M^*$ or $\Lambda$), DM mass

Disadvantages:
Only applicable at low momentum transfer

arxiv:1008.1783
Invisible DM particles escape detection:

LHC experiment strategy: tag events using recoiling object(s), measure missing transverse momentum (Missing $E_T$)

Dark Matter signature:
excess in tails of $E_T$ distribution

(searches also sensitive to other models)
Jet+MET: look for excess of events with high pT jet(s), high missing transverse momentum.

Signal regions (SR):
Cut and count analysis, varying jet pT and MET thresholds.

Dominant background uncertainties:
W/Z backgrounds (theory, CR stat.)
Object reconstruction (jet/MET)
e.g. SR9: pT > 700 GeV, MET > 700 GeV:
total background uncertainties: 14%

Background estimation (main: Zvv+jets):
use transfer factors from W/Z control regions (CR)

\[ Z \rightarrow \mu\mu + \text{jet} \]
\[ W \rightarrow \mu\nu + \text{jet} \]
\[ Z \rightarrow \nu\nu + \text{jet} \]

Graphics by S. Schramm

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Model-dependent comparison

Needs agreement on benchmarks and assumptions

→ e.g. truncation procedure to ensure EFT validity

Complementarity of direct/indirect detection and colliders:

outlines strengths of each of the experiments
Adopting similar search strategy as 8 TeV

Generator-level backgrounds + smearing for pile-up and detector conditions

Surpassing previous limits within 1st year of data taking
**MET+W/Z/γ**: look for excess of events with high pT boson (decay products), high missing transverse momentum

**W/Z → jj**: use of single fat jet mass for W/Z tagging

**ATLAS**: 20.3 fb⁻¹ \( \sqrt{s} = 8 \) TeV

- Data
- Z(νν)+jet
- W/Z(ℓ+ℓ+jet)
- Top
- Diboson

\[ \lambda_u \cdot \bar{u} + \lambda_d \cdot \bar{d} \]

**CMS**

- Photon: arXiv:1410.8812

- Spin-independent

- Limits at 90% CL

\[ \xi = \lambda_1 \lambda_2 \]

**ATLAS**

- Z → ℓℓ: PRD 90, 012004 (2014)
- W → ℓν: JHEP 09 (2014) 037

**Advantage for W**: interference
DM with heavy flavors: favoured for some EFT operators

\[ O = \sum_{q} \frac{m_q}{M^3} \bar{q} q \tilde{x} \tilde{x}, \]

Different signal regions, backgrounds normalized from control regions

ATLAS:
- \( \text{ttbar} \rightarrow \text{all-hadronic} \): EPJC (2015) 75:92
- Single lepton stop search: JHEP 11 (2014) 118

CMS:
- \( \text{ttbar} \rightarrow \text{semileptonic} \): CMS-PAS-B2G-14-004
- \( \text{ttbar} \rightarrow \text{dilepton} \): CMS-PAS-B2G-13-004

More details on CMS ttbar+MET searches
Deborah Pinna’s YSF talk

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Beyond MET+X: EFT constraints from dijets

Dijet angular distributions
probe contact interactions

$1/\sigma_{\text{dijet}} d\sigma_{\text{dijet}}/d\chi_{\text{dijet}}$

CMS: arxiv:1411.2646
19.7 fb$^{-1}$ (8 TeV)

- Data
- NLO QCD+EW prediction
- NLO QCD prediction
- $\Lambda_{\text{LL}}^+(\text{NLO}) = 10$ TeV
- $\Lambda_{\text{T}}^+(\text{GRW}) = 7$ TeV

- $M_{jj} > 4.2$ TeV (+0.35)
- $3.6 < M_{jj} < 4.2$ TeV (+0.2)
- $3.0 < M_{jj} < 3.6$ TeV (+0.1)
- $2.4 < M_{jj} < 3.0$ TeV (+0.05)
- $1.9 < M_{jj} < 2.4$ TeV

$\chi_{\text{dijet}}$

$\chi = \exp |y_1 y_2|$

→ can reinterpret constraints in EFT framework for DM

Excluded by Monojet Searches
Excluded by QCD Searches
Excluded by Perturbativity

arxiv:1303.3348

Graphics by N. Zhou, F. Ruehr

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M$_{\chi}$ in TeV
EFT validity issues: sensitivity of LHC to explicit mediators

EFT remains useful benchmark
**RUN-1/RUN-2: MOVING TO SIMPLIFIED MODELS**

**Additional handles at colliders in presence of mediators:**
- Direct searches for mediators
- Constraints on existing mediators
- Additional search signatures

**EFT validity issues:**
→ sensitivity of LHC to explicit mediators

**Run 2 searches**
shift focus to simplified models

- Less Complexity

**Effective Field Theories**

- Contact Interactions
- Higgs portal
- "Squarks"
- Simplified Models
- \(Z'\)
- Dark photon

**CMS: arXiv:1408.3583**
Selected simplified model results: 8 TeV MET+X

Z → ll + MET

ATLAS: PRD 90, 012004 (2014)

Photon + MET

CMS: arXiv:1410.8812

Region excluded wrt thermal relic

ATLAS: $\int L = 20.3 \text{ fb}^{-1}$, $\sqrt{s} = 8 \text{ TeV}$

CMS: Spin Independent, Vector

90% CL limit $M/|g_{\gamma q}|$ [GeV]

Mediator Mass $M$ [TeV]

Caterina Doglioni – Dark Matter at the LHC – Moriond EW 2015
ATLAS/CMS Dark Matter Forum:
experiment/theory discussion towards Run-2 DM searches

Many possibilities to be used as building blocks:

- Prioritized set of simplified models
- Common model implementation and details (e.g. matching, scales) towards MC generation of benchmarks
- EFT validity assessment procedure

This Forum will document:
models and choices (arXiv write-up + SVN repository)

https://twiki.cern.ch/twiki/bin/view/LHCDMF/WebHome
Mailing list: lhc-dmf@cern.ch
Run-2 benchmark choices being finalized – examples:

Prioritized list of models for jet+MET search

Study of choice of benchmark points for searches with W/Z/gamma

CMS Simulation

Generator-level plot from talk at DM Forum 16/02/15

http://arxiv.org/abs/1411.0535
http://arxiv.org/abs/1409.2893

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Many BSM models predict single top+MET
→ group main characteristics
in simplified models (resonant/non resonant)

Background estimation (main: V+jets):
use transfer factors from data control regions

CMS: arXiv:1410.1149 (hadronic decay)

ATLAS: EPJC (2015) 75:79 (leptonic decay)

Resonant model
\( m(S) = 500 \text{ GeV} \)
Higgs boson could mediate DM/SM interactions
→ search for enhancements of invisible decays

More details on exotic Higgs decays in Paolo Meridiani's talk

Caterina Doglioni – Dark Matter at the LHC – Moriond EW 2015
Higgs boson discovered, Dark Matter still at large → looking for DM particle candidates at the LHC

Preparing the ground for Run-2 searches:
LHC results complementary to other Dark Matter experiments

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BACKUP SLIDES
<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>$\frac{m_q}{M_*^2} \chi^\dagger \chi \bar{q} q$</td>
</tr>
<tr>
<td>C5</td>
<td>$gg$</td>
<td>scalar</td>
<td>$\frac{1}{4M_*^2} \chi^\dagger \chi \alpha_s (G_{\mu \nu}^a)^2$</td>
</tr>
<tr>
<td>D1</td>
<td>$qq$</td>
<td>scalar</td>
<td>$\frac{m_q}{M_*^3} \bar{\chi} \chi \bar{q} q$</td>
</tr>
<tr>
<td>D5</td>
<td>$qq$</td>
<td>vector</td>
<td>$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q$</td>
</tr>
<tr>
<td>D8</td>
<td>$qq$</td>
<td>axial-vector</td>
<td>$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q$</td>
</tr>
<tr>
<td>D9</td>
<td>$qq$</td>
<td>tensor</td>
<td>$\frac{1}{M_*^2} \bar{\chi} \sigma^{\mu \nu} \chi \bar{q} \sigma_{\mu \nu} q$</td>
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<tr>
<td>D11</td>
<td>$gg$</td>
<td>scalar</td>
<td>$\frac{1}{4M_*^3} \bar{\chi} \chi \alpha_s (G_{\mu \nu}^a)^2$</td>
</tr>
</tbody>
</table>
EFT validity addressed explicitly

Previous papers: only accounting for kinematic constraints and theory perturbativity
This paper: more explicit constraint (stronger for some operators)

\[ Q_{tr}^2 < \Lambda^2 \]
(coupling/operator-dependent statement)

Under discussion in literature and ATLAS/CMS DM Forum

Limit on suppression scale of EFT M*

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Early DM searches: what do we gain/lose from CoM increase?

- Current monojet analysis: systematically limited at low MET, statistically limited at high MET → How high can we reach in $M^*$ at 14 TeV?
- Will we have problems with the EFT validity at a higher CoM energy?

Somehow counterintuitive results! Competing effects: $Q_{tr} < \sqrt{g_{SM}g_{DM}}M^*$

- Higher MET → higher $Q_{tr}$ (weak correlation: MET smeared by detector)
- Increase of reach in $M^*$ → higher limits to start with → increased validity
PHOTON+JET SEARCHES

CMS: arXiv:1410.8812


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CMS TTBAR+MET SEARCHES

Semileptonic channel

CMS-PAS-B2G-14-004

Dilepton channel

CMS-PAS-B2G-13-004

\[ M_T \equiv \sqrt{2E_T^{\text{miss}} p_T^l (1 - \cos(\Delta \phi))} \]