ATLAS Monophoton Results

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DARK MATTER AT THE LHC WORKSHOP
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Outline

• Introduction/Motivation
• LHC and ATLAS
• Monophoton Search
• WIMPS
• ADD LED

• Final notes

"Particles, particles, particles."
The rotation of the stars around the center of the galaxies are not consistent with the amount of mass observed \((L/M)_{\text{SUN}}\).

Spherical dark matter halo

Galaxia M33

M33 rotation curve
Gravitational Lensing

Cluster de galaxias

Large distortion of the images of distant galaxies due to gravitational lensing

→ indication of DM in galaxy clusters

19/9/13
Collisions of clusters of galaxies

Considered the ultimate demonstration of the presence of Dark Matter since this does not involve Newton’s Law.
Increasing $\langle \sigma v \rangle$

$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$

Weak scale for $\chi\chi$ annihilation cross section

$\Omega_{\chi} h^2 \sim \frac{0.1 \text{ pb} \cdot c}{\langle \sigma(\chi\chi \rightarrow \text{SM})v \rangle}$

WMAP results

CMB radiation

380,000 years

13.82 billion years

Planck (20 March 2013)
arXiv:1303.5062v1

4.9% DM

After Planck

Dark Matter: 26.8%
Ordinary Matter: 4.9%
Dark Energy: 68.3%
Dark Matter Candidates

- Neutrinos? ($\Omega_\nu h^2 < 0.0067$ @ 95%CL)
- Sterile Neutrinos
- Axions
- SUSY particles
  - Lightest neutralino
  - Sneutrinos
  - Gravitinos
  - Axinos
- KK states (UED)
- Wimpzillas

General requirements

- Electrically Neutral ("dark")
- Stable (lifetime larger than age of the Universe)
- Massive and Weakly interacting ($\Omega_{CDM} h^2 \sim 0.1$)

$\rightarrow$ WIMPS

Note: No reason DM should be made out of a single component (neutrinos exist)
DM at the LHC

\[ p \rightarrow \text{DM} \rightarrow p \]
WIMP Pair Production at Colliders

At colliders (LHC) WIMPs can be produced in pairs leading to “nothing to detect” in the final state.

Such events are tagged via the presence of an energetic jet or a photon from initial state radiation.

→ Monojets and Monophotons
(complementary....but QCD wins in rate)

Rather spectacular and distinctive signature to search for new physics (also relevant in searches for large extra spatial dimensions, etc... )
LHC

pp collisions at 7 & 8 TeV
LHC Performance (2010-2012)

Spectacular LHC performance (rapid increase of data samples)

LHC ended pp run at 7+8 TeV after delivering more than 28 fb⁻¹

...will come back in 2015 with 13-14 TeV collisions
93.5% efficiency

Challenging pile up conditions for the physics analysis
ATLAS
(relevant to photon ID)

**Inner Detector** - Barrel (B) & End-cap (E) in 2T solenoidal magnetic field:
- Track reconstruction up to $|\eta|<2.47$;
- Conversion vertices reconstruction;
- $e/\gamma$ and $e/\pi^\pm$ separation;
- **Pixel**: (B) 3 layers + (E) 2x3 disks $\sigma_{r\phi}\sim10\ \mu m$, $\sigma_z\sim115\ \mu m$;
- **Semi Conductor Tracker**: (B) 4 layers + (E) 2x9 disks $\sigma_{r\phi}\sim17\ \mu m$, $\sigma_z\sim580\ \mu m$;
- **Transition Radiation Tracker**: (B) 73 layers + (E) 2x160 layers $\sigma_z\sim130\ \mu m$;

**LAr lead sampling calorimeter** with an ‘accordion’ geometry.
- 3 longitudinal layers with cell of $\Delta \eta \times \Delta \phi$:
  - 1st layer $(0.003 \div 0.006) \times 0.1$;
  - 2nd layer $0.025 \times 0.025$;
  - 3rd layer $0.050 \times 0.025$.
- Presampler for $|\eta|<1.8 \Delta \eta \times \Delta \phi \sim 0.025 \times 0.1$.
- Barrel-end-cap crack $|\eta|=1.37\pm1.52$.
- $\sigma(E)/E=(10-17\%)\!/(\eta)/\sqrt{E}$(GeV) $\oplus (1.2\pm1.8\%)$. 
Slicing window algorithm to determine the em-cluster (good photon–$\pi^0$ separation) E-scale known better than 1%

Reconstruction of both unconverted/converted photons

Photon isolation against multijet background

High purity/efficiency at large photon $p_t$
Monophotons

Event Selection

Events selected online with
\( E_{\text{t miss}} > 70 \text{ GeV} \) at the trigger level ( \( > 98\% \) efficient for this analysis)

Well-reconstructed primary vertex
\( P_{t \gamma} > 150 \text{ GeV}, \ |\eta_{\gamma}| < 2.37 \), isolated
\( E_{t \text{miss}} > 150 \text{ GeV} \)
\( N_{\text{jet}} < 2 \ (p_{T} > 30 \text{ GeV}) \) (anti-\( k_{t} \) 0.4)
\( \Delta\phi (\gamma, E_{t \text{miss}}) > 0.4, \ \Delta\phi (\text{jet, } E_{t \text{miss}}) > 0.4 \)

Veto on leptons
(rejects W/Z backgrounds)
No electrons with \( p_{T} > 20 \text{ GeV} \), \( |\eta| < 2.47 \)
No muons with \( p_{T} > 10 \text{ GeV}, \ |\eta| < 2.4 \)
Backgrounds

Background dominated by $Z/W+\gamma$ processes (estimated using MC normalized in control regions)

$\gamma + \mu + E_{T}^{\text{miss}}$ control sample (on top of signal region kinematics)

$W/Z+$jets with $e$ or jets faking photons (determined from data)

e $\rightarrow$ $\gamma$ (fake rate from data)
Jet $\rightarrow$ $\gamma$ (isolation vs $\gamma$ ID plane)

$\gamma+$jets and multijet background from data (using $\gamma+$jet sample with $\Delta \phi$ (jet, $E_{T}^{\text{miss}}$) < 0.4)

Small contributions from top, $\gamma\gamma$, dibosons (Taken from MC normalized to NLO/NNLO)
## Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Impact on total prediction</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma ) E-scale</td>
<td>0.9%</td>
<td>Some of the studies on systematics suffer from limited statistics in control samples</td>
</tr>
<tr>
<td>( \gamma ) isolation/ID/resolution</td>
<td>1.1%</td>
<td>Room for improvement in the 8 TeV analysis</td>
</tr>
<tr>
<td>Jet E-scale/resolution</td>
<td>0.9% - 1.2%</td>
<td></td>
</tr>
<tr>
<td>Leptons</td>
<td>0.3%</td>
<td></td>
</tr>
<tr>
<td>Low-pt jets/uncluster energy</td>
<td>0.8%</td>
<td></td>
</tr>
<tr>
<td>Pileup subtraction</td>
<td>0.3%</td>
<td></td>
</tr>
<tr>
<td>W/Z+( \gamma ) modeling</td>
<td>6.9%</td>
<td>Conservative (ALPGEN vs SHERPA)</td>
</tr>
<tr>
<td>Others Sources</td>
<td>&lt; 0.5%</td>
<td>Trigger, Luminosity, lepton ( p_T ), normalization of small backgrounds (top, diboson) ...</td>
</tr>
<tr>
<td>Statistical Component</td>
<td>14%</td>
<td>Due to limited size control samples in data</td>
</tr>
</tbody>
</table>
Results

Good agreement with SM

Results translated into model-independent limits on $\sigma \times A \times \varepsilon$

$\sigma \times A \times \varepsilon < 5.6 \text{ fb} @ 90\% \text{ CL}$
$\sigma \times A \times \varepsilon < 6.8 \text{ fb} @ 95\% \text{ CL}$

Typical $\varepsilon \sim 75\%$

<table>
<thead>
<tr>
<th>Background source</th>
<th>Prediction</th>
<th>± (stat.)</th>
<th>± (syst.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z(\rightarrow \nu\bar{\nu}) + \gamma$</td>
<td>68%</td>
<td>93</td>
<td>± 16</td>
</tr>
<tr>
<td>$Z/\gamma^* (\rightarrow l^+ l^-) + \gamma$</td>
<td>18%</td>
<td>0.4</td>
<td>± 0.2</td>
</tr>
<tr>
<td>$W(\rightarrow l\nu) + \gamma$</td>
<td>18%</td>
<td>24</td>
<td>± 5</td>
</tr>
<tr>
<td>$W/Z + \text{jets}$</td>
<td>13%</td>
<td>18</td>
<td>–</td>
</tr>
<tr>
<td>Top</td>
<td>0.07</td>
<td>0.07</td>
<td>± 0.07</td>
</tr>
<tr>
<td>$WW, WZ, ZZ, \gamma\gamma$</td>
<td></td>
<td>0.3</td>
<td>± 0.1</td>
</tr>
<tr>
<td>$\gamma + \text{jets and multi-jet}$</td>
<td></td>
<td>1.0</td>
<td>–</td>
</tr>
<tr>
<td>Total background</td>
<td></td>
<td>137</td>
<td>± 18</td>
</tr>
</tbody>
</table>

Events in data (4.6 fb$^{-1}$) 116
Effective Theory
(model independent approach)

Effective Lagrangian approach (contact interaction)
with parameters $M_*$ and $m_\chi$

$$M_*^2 \sim M^2/g_1g_2$$
assuming the interaction is mediated
by a heavy particle with mass $M$ and
couplings $g_1$ and $g_2$

Different operators are considered
with different structures and here $\chi$
will be taken as Dirac fermions

Important note:
Not clear whether the effective approach
under- or over-estimates the cross
sections since this depends on the details
of the unknown UV limit of the theory

Strictly speaking theory only applicable
when $M$ is much larger than the energy
scale present in the reaction $[Q^2 \ll (4\pi M_*)^2]$
90% CL Limits on $M_*$

$A \times \varepsilon$ in the range between 11% (D1) and 23% (D9) (due to different $E_T^{\text{miss}}$ spectrum)

On signal yields:
Experimental uncertainties (7%)  
Theoretical uncertainties  
ISR/FSR (4% – 10%)  
PDFs (5% - 30%)  
$\mu_{R,F}$ (8%)

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Name} & \text{Initial state} & \text{Type} & \text{Operator} \\
\hline
D1 & q\bar{q} & \text{scalar} & \frac{m_{\chi}^2}{M_*^2} \chi \chi q \bar{q} \\
D5 & q\bar{q} & \text{vector} & \frac{1}{M_*^2} \chi \gamma^\mu \chi \gamma_\mu q \\
D8 & q\bar{q} & \text{axial-vector} & \frac{1}{M_*^2} \chi \gamma^\mu \gamma^5 \chi \gamma_\mu \gamma^5 q \\
D9 & q\bar{q} & \text{tensor} & \frac{1}{M_*^2} \chi \sigma^{\mu\nu} \chi \sigma_{\mu\nu} q \\
D11 & g\bar{g} & \text{scalar} & \frac{1}{4M_4^4 M_5^4} \chi x \chi x \chi_4 (G_{\mu\nu})^2 \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{WIMP MASS} & M_\ast \text{ in D1 (GeV)} & M_\ast \text{ in D5 (GeV)} & M_\ast \text{ in D8 (GeV)} & M_\ast \text{ in D9 (GeV)} \\
\hline
1 \text{ GeV} & > 31 & > 585 & > 585 & > 794 \\
1.3 \text{ TeV} & > 5 & > 156 & > 100 & > 188 \\
\hline
\end{array}
\]

Results are translated into 90% CL limits on $M_\ast$ for different operators and as a function of WIMP mass.
Different operators contribute either to spin-dependent or spin-independent WIMP-nucleon cross sections.

Within the assumption of the validity of the effective theory the LHC results complement direct detection searches (particularly relevant at $m_\chi < 10$ GeV)

\[
\sigma^{D1} = 1.60 \times 10^{-37} \text{cm}^2 \left( \frac{\mu_\chi}{1 \text{ GeV}} \right)^2 \left( \frac{20 \text{ GeV}}{M^*} \right)^6 \\
\sigma^{D5} = 1.38 \times 10^{-37} \text{cm}^2 \left( \frac{\mu_\chi}{1 \text{ GeV}} \right)^2 \left( \frac{300 \text{ GeV}}{M^*} \right)^4 \\
\sigma^{D8,D9} = 4.7 \times 10^{-39} \text{cm}^2 \left( \frac{\mu_\chi}{1 \text{ GeV}} \right)^2 \left( \frac{300 \text{ GeV}}{M^*} \right)^4
\]
Very significant improvement on limits compared to Tevatron
For \( m_\chi < 100 \text{ GeV} \): WIMPS-nucleon cross sections above
3 \( \times 10^{-40} \text{ cm}^2 \) (\( 10^{-39} \text{ cm}^2 \)) are excluded for spin–dependent (spin-independent) operators

Not enough sensitivity yet to exclude/confirm the CoGeNT/DAMA excess at \( m_\chi \sim 10 \text{ GeV} \) in case the of D1/D5 models

90% CL, Spin Dependent

90% CL, Spin Independent

Very significant improvement on limits compared to Tevatron
For \( m_\chi < 100 \text{ GeV} \): WIMPS-nucleon cross sections above
3 \( \times 10^{-40} \text{ cm}^2 \) (\( 10^{-39} \text{ cm}^2 \)) are excluded for spin–dependent (spin-independent) operators
Large Extra Dimensions

Extra spatial dimensions explain the apparent weakness of Gravity (relevant scale $\sim$TeV)

$A \times \varepsilon$ about 20%
(approx. independent on n and $M_D$)

On signal yields:
Experimental uncertainties (7%)
Theoretical uncertainties
ISR/FSR (4%)
PDFs (4% - 11% as n increases)
$\mu_{R,F}$ (9% - 5% as n increases)

95% CL limits on $M_D$ vs n

Limits on $M_D$ beyond 1.9 TeV
(a real challenge for the model validity)

Note: Limits sensitive to the truncation strategy
for $s$-hat $> M_D^2$ (15% to 75% of the ADD cross section as n increases)

... LHC probing phase space at large $Q^2$

19/9/13
Final Notes

- Very successful LHC operations

- More than 26 fb-1 of data on tape for ATLAS (7 TeV & 8 TeV)

- 7 TeV results on monophotons

- *Within the effective lagrangian framework* the LHC DM searches are rather competitive & complement direct detection experiments

- Searches continue with 8 TeV dataset including all possible mono-X channels
More Energy and More Data!

El LHC will almost double the centre-of-mass energy in 2015

8 TeV $\rightarrow$ 14 TeV
with increased luminosity

Ready for a new discovery?
Backup Slides
Mono-Z

(ZZ → ll νν)

No jets with $p_T$ above 25 GeV

$$\left( \frac{|p_T^{\ell\ell} - p_T^Z|}{p_T^Z} \right) < 0.6$$

$$-p_T^{\ell\ell} \times \cos(\Delta\phi(p_T^{\ell\ell}, p_T^Z)) > 80 \text{ GeV}$$

In good agreement with SM predictions

This can be used to put limits on $\chi \chi + Z$

arXiv:1211.6096
Un-official combination

ATLAS & CMS Mono-X

As expected the combination is totally dominated by the mono-jet results

VECTOR
Spin Independent

AXIAL-VECTOR
Spin Dependent

Ning Zhou et al., arXiv:1302.3619
Large Extra Dimensions

Extra spatial dimensions explain the apparent weakness of Gravity (relevant scale $\sim$TeV)

Number of Extra Dimensions

Limits on $M_D$ beyond 1.5 TeV (a real challenge of the model validity)

Note: Limits sensitive to the truncation strategy for $s$-hat $> M_D^2$ ... LHC probing phase space at large $Q^2$
Extra Dimensions

Alternative to solve Hierarchy Problem

Extra spatial dimensions explain the apparent weakness of Gravity (relevant scale ~ 1 TeV)

ADD
Arkani-Hamed, Dimopoulos, Dvali, Phys Lett B429 (98)
Many large compactified EDs
In which G can propagate

\[ M_{pl}^2 \sim R^n M_{pl} (4+n)^{(2+n)} \]

Effective \( M_{pl} \sim 1 \text{TeV} \rightarrow \) if compact space \((R^n)\) is large

RS
Randall, Sundrum, Phys Rev Lett 83 (99)
1 highly curved ED
Gravity localised in the ED

\[ \Lambda_\pi = \frac{M_{pl}}{k R_c} e^{-k R_c} \]

\( \Lambda_\pi \sim \text{TeV} \)

if warp factor \( k R_c \sim 11-12 \)
\( k/ M_{pl} \), \( k \): curvature scale

monojet/monophoton

resonances