Search for Dark Matter in Mono-Photon events with ATLAS

Maria Giulia Ratti
In collaboration with Silvia Resconi, Leonardo Carminati, Donatella Cavalli

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Why Dark Matter at the LHC?

- Compelling evidence of Dark Matter from astrophysical probes

- But what is the nature of the Dark Matter? How does it interact with Standard Model particles?

- Complementary strategies for the detection of DM particles:
  - Direct searches
  - Indirect searches
  - Production at colliders

- Grounding assumption:
  - DM and SM interact other than gravitationally, otherwise none of the strategies is effective
Mono-X Signatures

- DM goes out undetected
Mono-X Signatures

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  => need a visible SM particle to tag the event

- Mono-X signatures: $E_T^{\text{miss}} + X = \text{jet, } \gamma, W, Z, H$
Mono-X Signatures

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  - => need a visible SM particle to tag the event

- Mono-X signatures: $E_{T}^{\text{miss}} + X=\text{jet, } \gamma , W, Z, H$

- $X$ object irradiated by the initial state or, in the case of electroweak bosons, involved in the interaction
Mono-Photon Search

- Cut & Count analysis
- Look for a deviation in data from prediction of the SM => Signal over Background
- Essential a very accurate background estimation
- Quantify the level of agreement/disagreement by means of a statistical analysis
- Set limits on parameter space of various models

Which SM processes have the same signature?

- $Z(\rightarrow \nu \nu) + \gamma$ irreducible background $O(70\%)$
- $W(\rightarrow l \nu) + \gamma$ $O(15\%)$
- $W/Z + \text{jets}$ electron or jet taken as a photon $O(15\%)$
- $\gamma + \text{jets}$ and other remaining bkgs $O(1\%)$

How are they estimated?

- from DATA/MC RATIOS in appropriate Control Regions
- purely DATA-DRIVEN techniques
- pure MC simulation
Mono-Photon Search

**Signal Region (SR)**
- Trigger and Event cleaning
- Jet cleaning
- Energetic photon with $p_T > 150$ GeV
- $E_T^{\text{miss}} > 150$ GeV
- $\Delta \varphi (\gamma, E_T^{\text{miss}}) > 0.4$
- Leading photon “tight”, isolated
- At most one jet well separated from the $E_T^{\text{miss}}$
- Veto on electrons and muons

**Control Regions (CRs)**
- Keep the same cuts as SR
- **revert one or more cuts** at a time to define regions enriched in a particular source of background

**W/Z + $\gamma$ Backgrounds**

1 $\mu$ CR
- $W(\mu \nu) + \gamma$

2 $\mu$ CR
- $Z(\mu \mu) + \gamma$

2 ele CR
- $Z(\text{ee}) + \gamma$

- Data/MC ratios in the CRs
- Extrapolate to the SR
- Normalize the yields in the SR
**Mono-Photon Search**

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**Jets faking Photons**
- Two-dimensional Sideband method
- $N_A^{bkg} = N_B \frac{N_D}{N_C}$

**Electrons faking Photons**
- $EFR = \text{probability of electron to fake a photon with a Tag & Probe method}$
- Scale a mono-electron CR with this probability

$1\text{ele CR}$ no photon $\times$ $EFR$
Data Analysis in ATLAS

- A huge and continuously evolving framework is needed for data analysis:
  - Big amount of data in various formats spread over the grid
  - Smaller datasets, called “derivations”, optimized for each analysis, to be replicated at local sites
  - Reconstruction software maintained by the Combined Performance groups
  - Analysis software developed by each analysis group for their needs
What is $E_T^{\text{miss}}$?

- $E_T^{\text{miss}} = \text{Missing Transverse Momentum}$
  - Negative vector sum of the transverse momenta of all detected particles
  - Global quantity of the event
  - In a parton-parton scatter the initial transverse momentum is $\sim 0$

  => Measured imbalance of the total transverse momentum is the handle for the invisible part of the event

Real $E_T^{\text{miss}}$:
- New particles
- Neutrinos

Fake $E_T^{\text{miss}}$:
- Miscalibrations
- Mismeasurements
- Limited detector acceptance
- Detector Noise

$E_T^{\text{miss}}$ is the discriminating variable for many searches for new physics
Reconstructed and calibrated "physics objects":

- electrons, photons, taus, muons
  - Selected as recommended from the various CP groups
  - analyses can optimize the selections for their needs

- Jets:
  - Fully calibrated Anti-kt4 with $p_T > 20$ GeV
  - Anti-kt4 with $p_T > 7$ GeV for handling the overlap between physics object

Signal objects:

- tracks and clusters
\[ \text{Reconstruction: Term by Term} \]

\[ E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss}, e} + E_{x(y)}^{\text{miss}, \gamma} + E_{x(y)}^{\text{miss}, \tau} \]

\[ + E_{x(y)}^{\text{miss, jets}} + E_{x(y)}^{\text{miss, } \mu} + E_{x(y)}^{\text{miss, Soft}} \]

\[ E_{x(y)}^{\text{miss, } k} = - \sum_k p_{x(y)}^k \]

- **Reconstructed and calibrated** "physics objects":
  - electrons, photons, taus, muons
    - Selected as recommended from the various CP groups
    - analyses can optimize the selections for their needs
  - **Jets:**
    - Fully calibrated Anti-kt4 with \( p_T > 20 \text{ GeV} \)

- **Tracks** from primary vertex  => **TST** \( E_T^{\text{miss}} \)
- **Unmatched** clusters + soft jets  => **CST** \( E_T^{\text{miss}} \)
$E_T^{\text{miss}}$ Performance

- TST $E_T^{\text{miss}}$ performing best
- Higher value of the $E_T^{\text{miss}}$ and Soft Term at higher jet multiplicity
**$E_T^{\text{miss}}$ Performance: Resolution**

- Width of the $E_{x,y}^{\text{miss}}$ is a sensitive quantity to pile-up effects
- Measured as a function of the number of primary vertices, $N_{PV}$, in 0-jet (left) and inclusive jet (right) topologies

In 0-jet events TST and Track $E_T^{\text{miss}}$ perform very similar, insensitive to pile-up

In inclusive jet events, CST and TST $E_T^{\text{miss}}$ both depend on pile-up

Track $E_T^{\text{miss}}$ stable wrt pile-up
$E_T^{\text{miss}}$ Performance: *Scale in $Z \rightarrow ll$*

- Well calibrated $E_T^{\text{miss}}$ in $Z \rightarrow ll$ events projected along any axis should be zero.
- Projection of the $E_T^{\text{miss}}$ onto the Z axis is sensitive to the imbalance between Hard and Soft part of the event.

Bias is bigger in 0-jet events indicating underestimation of the Soft Term.
- In events with jets, TST $E_T^{\text{miss}}$ performs best.
Conclusions and Plans

- Analysis of mono-photon events in good progress:
  - Most analysis tools in place: derivations, software, selections and background estimation techniques
  - Big effort in understanding the $E_T^{\text{miss}}$, invisible part of the collision event
  - Work in progress in the statistical interpretation of the results
  - Almost 2.5 fb$^{-1}$ of data already collected by ATLAS and ready for analysis
    => will need the entire 2015 data to improve the Run 1 results
Background projections with 5 fb$^{-1}$

<table>
<thead>
<tr>
<th>table(results).yields channel</th>
<th>SR</th>
<th>ONEmuCR</th>
<th>TWOneleCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitted bkg events</td>
<td>277.06 ± 28.72</td>
<td>134.08 ± 11.58</td>
<td>28.87 ± 3.91</td>
</tr>
<tr>
<td>Fitted Zmunu gamma events</td>
<td>188.08 ± 28.28</td>
<td>0.79 ± 0.12</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>Fitted Zgamma events</td>
<td>2.76 ± 0.42</td>
<td>10.89 ± 1.62</td>
<td>26.38 ± 3.91</td>
</tr>
<tr>
<td>Fitted Wgamma events</td>
<td>43.67 ± 5.16</td>
<td>102.44 ± 11.74</td>
<td>0.52 ± 0.06</td>
</tr>
<tr>
<td>Fitted Wjets events</td>
<td>23.18 ± 0.54</td>
<td>15.90 ± 0.21</td>
<td>0.21 ± 0.00</td>
</tr>
<tr>
<td>Fitted Zjets events</td>
<td>1.31 ± 0.03</td>
<td>0.26 ± 0.00</td>
<td>1.09 ± 0.03</td>
</tr>
<tr>
<td>Fitted gammajets events</td>
<td>17.70 ± 0.42</td>
<td>3.81 ± 0.05</td>
<td>0.66 ± 0.02</td>
</tr>
<tr>
<td>Fitted dijets events</td>
<td>0.37 ± 0.01</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
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<td>MC exp. SM events</td>
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Tabella 2: SR expected yields for 5 fb$^{-1}$, fixed isolation cut on the photon
M.G. Ratti - Search for Dark Matter in mono-photon events with ATLAS

**Mono-Photon Studies**

**ATLAS Preliminary**

Data 2015

\[ \sqrt{s} = 13 \text{ TeV}, \int L dt = 71 \text{ pb}^{-1} \]

Photon + \( E_T^{\text{miss}} \) selection

**ATLAS Work in Progress**

- \( Z(\rightarrow \nu
\nu) + \gamma \)
- \( Z(\rightarrow \mu
\mu) + \gamma \) muons invisible
- \( Z(\rightarrow ee) + \gamma \) electrons invisible

**Jet Veto Efficiency**

- \( p_T > 30 \text{ GeV} \)
- \( p_T > 40 \text{ GeV} \)
- \( p_T > 50 \text{ GeV} \)
TST Soft term systematics

- Systematics on the $E_T^{\text{miss}}$ measurement quantify the level of agreement between data and MC.
- Component originated from the measurement of the other physics objects can be propagated through the $E_T^{\text{miss}}$ computation.
- TST Soft term uncertainties are provided on MC-based studies.
- Expected to cover discrepancies between data and MC at 13 TeV:
  - Modelling of the generators
  - Full vs Fast simulation
  - Experimental conditions: geometry of the detector, bunch spacing …
TST Soft term systematics

Soft Term projections onto $p_T^{\text{hard}}$:
- Mean of longitudinal component
  => scale uncertainty
- RMS of transverse and longitudinal components
  => resolution uncertainty
$E_T^{\text{miss}}$ Performance: Resolution

- $W \rightarrow l\nu$ inclusive jets (left), ttbar inclusive jets (right)

- In inclusive jet events, all variants suffer by the increased event activity in higher pile-up regions
- TST and CST show similar values of the resolution among various topologies, while Track resolution suffers in high-jet multiplicity events
**TST** $E_T^{\text{miss}}$: Resolution and Scale in 2015 data and MC

- Agreement between data and MC with very first data, $Z \rightarrow \mu\mu$ events
Higher $p_T$ threshold for jets going into the jet term can improve the resolution at high $N_{PV}$

but also increases the bias at all $p_T^Z$
There must be a mechanism to keep track of the overlaps between physics/signal objects:

- **Run 2 Association Map**:  
  - Contains the spatial association of each physics object to anti-kt4 jets  
  - Within each jet, object overlaps are identified  
  - Unassociated tracks/clusters go into the core soft terms