Search for new phenomena in jet+MET and $\gamma+$MET final states at the ATLAS detector

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Motivation for jet+MET search

- Weakly interactive massive particles (WIMPs), dark matter candidates, can be produced in pair at colliders.
  - Large missing transverse energy (MET) from WIMPs.
- An energetic visible object is needed to tag these events.
  - Jets, from gluon initial state radiation, are dominating.
- Jet+MET final state is the most sensitive channel in general dark matter search at LHC.
  - Same event signature can be interpreted in other searches
    - Large extra dimension or SUSY signatures

Effective field theory (EFT) 2

Simplified models
Event selection and backgrounds


- **Cut-and-count** analysis
- A good primary vertex, MET>150 GeV, $p_T^{j1}>120$ GeV
- Jet should be balancing the MET and in opposite direction
- Reject events with bad jets
  - Cosmic rays, detector noise or beam-related background
- Reject events with electrons, muons or isolated tracks
- Scan on MET to increase sensitivities

Event signature to be looked for

jet (after hadronization)

Missing transverse momentum
Event selection and backgrounds


- Major backgrounds:
  - $Z(\nu\nu)/W(l\nu)+\text{jets}$
  - Estimated with control regions (CR) data/MC transfer factors
  - $Z(ll)/W(e\nu)/W(\mu\nu)+\text{jets CRs}$
- Minor backgrounds:
  - Estimated from MC: $Z/\gamma^*(ll)+\text{jets}$, $t\bar{t}$bar, diboson
  - Estimated with data-driven method: multijets, non-collision backgrounds
8 TeV results

- No discrepancy between observation and Standard Model (SM) expectation.
- Limits are set on various signal models.
  - Tune MET cuts against models, use the most sensitive one

![Graph showing ATLAS results with data comparisons and signal models](image-url)
• The 90% CL limit is set on EFT models.
  • Interpretations in WIMP-nucleon cross section.
• Better sensitivity compared to direct detection experiments:
  • Low WIMP mass region for spin-independent models
  • Uniformly powerful for spin-dependent models
• 95% CL limit set on coupling strength in simplified models
• 95% CL limits on suppression scale (M*) is compared between simplified models and EFT
  • Limits the same at high mediator mass, where the mediator is off-shell
• \( M_* = \frac{M_{\text{mediator}}}{\sqrt{g_\chi g_f}} \)
Interpretation for extra dimension search


- Arkani-Hamed, Dimopoulos, and Dvali (ADD) model allows the graviton to propagate in additional dimensions.
  - MET from the missing graviton
- 95% CL limit on fundamental Plank scale $m_D$ in $4+n$ dimensions
  - $\sigma(n, M_D) \propto M_D^{-n-2}$
  - $n$ is the number of extra dimensions
Interpretation for SUSY


- Associated production of a gravitino ($\tilde{G}$) and a gluino ($\tilde{g}$) or a squark ($\tilde{q}$)
- Similar final state as jet+MET signature
- 95% CL limit on gravitino mass $m_{\tilde{G}}$
- Various $m_{\tilde{g}}/m_{\tilde{q}}$ configurations tested

NWA = narrow width approximation
14 TeV prospects
jet+MET, ATL-PHYS-PUB-2014-007

- Study based on MC. EFT models only.
- With the increase of $\sqrt{s}$, the signal cross sections increase much faster than $Z(\nu\nu)$+jets background at high MET.
14 TeV prospects

jet+MET, ATL-PHYS-PUB-2014-007

- Compared to 8 TeV:
  - More sensitive, greater potential for discovery.
  - LHC Run-II operates at 13 TeV, close sensitivity with 14 TeV

Suppression Scale $M$ [GeV]

<table>
<thead>
<tr>
<th>$E_T^{miss}$ threshold [GeV]</th>
<th>400</th>
<th>600</th>
<th>800</th>
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<tbody>
<tr>
<td>14 TeV, 25 fb$^{-1}$</td>
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<td>8 TeV, 20 fb$^{-1}$</td>
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<td>5% syst</td>
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<td>$m_\chi = 50$ GeV</td>
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<td>$m_\chi = 400$ GeV</td>
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Significance [\sigma]

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<th>M [TeV]</th>
<th>1</th>
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<th>1.4</th>
<th>1.6</th>
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<th>2</th>
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<tr>
<td>$\sqrt{s} = 14$ TeV $\int Ldt = 25$ fb$^{-1}$ D5, $m_\chi = 50$ GeV $\pi &lt; \sqrt{g_{SM} g_{DM}} &lt; 4\pi$</td>
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<td>5\sigma discovery</td>
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<td>3\sigma evidence</td>
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Motivation for $\gamma$+MET search

- Well measured $\gamma$ object. Cleaner background from electro-weak processes
- Complements the initial state radiation search
- Exclusively sensitive to certain dark matter models
- $\gamma$ can be directly involved in dark matter vertex

\[ \bar{q} \gamma q \bar{\chi} \rightarrow \chi \gamma \] vertex

\[ \bar{q} \gamma q \bar{\chi} \rightarrow \chi \gamma \] vertex
Event selection and backgrounds

\( \gamma + \text{MET}, \text{Phys. Rev. D 91, 012008 (2015)} \)

- Selection: (**no MET tuning** on models, cut-and-count analysis)
  - Similar to jet+MET, replacing the jet with \( \gamma \)
  - Lepton veto. No more than 1 jet.
- Backgrounds:
  - Major backgrounds: \( Z(\nu\nu) + \gamma, W(l\nu) + \gamma \) (estimated with CRs)
  - \( W/Z + \text{jets} \) (estimated with data-driven jet\( \rightarrow \gamma \) factor)
  - \( \text{ttbar, single top, diboson} \) (estimated with MC)
- Simultaneous fit with signal region and CRs (\( \mu\mu\gamma, e\epsilon\gamma, \mu\nu\gamma \))
  - \( N = \text{Poiss}(N|\mu \times N_{\text{sig}} + k_Z \times N_{Z\gamma} + k_W \times N_{W\gamma} + N_{\text{other}}) \)
  - \( k_Z/k_W \): shared scale factor in all regions for \( Z\gamma/W\gamma \) process
  - \( N_{Z\gamma}/N_{W\gamma} \): MC yields for \( Z\gamma/W\gamma \) processes in each region
  - \( N_{\text{other}} \) from data-driven or MC
8 TeV results

- No excess is observed compared to SM expectation.
- Upper limit of model-independent cross section on possible excess: 5.3 fb at 95% CL
90% CL limit on EFT models translated into WIMP-nucleon cross section.

Similar with jet+MET compared to direct detections.

Less sensitive compared to jet+MET analysis.

\[
\chi m \frac{1}{10^{12}} \chi m \frac{1}{10^{13}} \chi m \frac{1}{10^{14}}
\]

\[
\int L dt = 20.3 \text{ fb}^{-1} \sqrt{s} = 8 \text{ TeV}
\]
Interpretation for ADD/squark

• ADD model
• 95% CL limit on Plank Scale vs. number of extra dimensions
• ~2.2 TeV for all number of extra dimensions

- Squark search:
  - pair production of squark
  - $\tilde{q} \rightarrow q + \text{LSP}$, Lightest SUSY Particle can be invisible
• 95% CL limit on cross section for pair production.
• $m_{\tilde{q}} \hspace{1mm} \text{vs} \hspace{1mm} \Delta m$ plane:
• Left region of plane excluded

![Graph showing ATLAS ADD model, 95% CL limit on M_D lower limit [TeV].](image)

- Numbers give 95% CL excluded cross section [fb]
Interpretation in $\gamma\gamma\chi\chi$ EFT

Inspired by Fermi-LAT observed $\gamma$-ray spectrum at 130 GeV
- \textit{APJ} 750 3 doi:10.1088/0004-637X/750/1/3
- 95% CL limit on suppression scale $M^*$.  
- Exclusion is set on $(k_1,k_2)$ plane to generate Fermi-LAT observation in the rate of $\chi\bar{\chi} \rightarrow \gamma\gamma$ annihilation.
  - $\sigma \propto (k_1 \cos^2 \theta_w + k_2 \sin^2 \theta_w)/M^*_6$
- Upper region of plane is excluded $\rightarrow M^{F-LAT}_* < M_* $ lower limit from this analysis

\[ \bar{\chi}\chi \rightarrow \gamma\gamma \]

\[
\frac{1}{M^*_6} \left( k_1 \cos^2 \theta_w + k_2 \sin^2 \theta_w \right)
\]
Models in Run-II

• LHC dark matter forum (DMF) recommends dark matter models for interpretation in run-II for ATLAS and CMS.
  • White paper on arXiv:1507.00966

• Simplified models will be the baseline as EFT models have validity issues, especially at high $\sqrt{s}$
  • Mediators can be vector/axial-vector, scalar/pseudo-scalar
  • Recommendation on the grid to be scanned:
    • Dark matter mass, mediator mass and width

• **POWHEG** as the default generator

• EFT models will be presented with truncation:
  • UV complete
  • Kinematics: $Q_{tr} < \sqrt{g_\Phi g_\chi} M_*$ or $E_{cm} < \sqrt{g_\Phi g_\chi} M_*$
13 TeV fresh data

- Performance plots with first 50 ns data.

Summary

• The jet+MET and γ+MET final states at LHC are powerful to search dark matter candidates:
  • More sensitive compared to direct detections for spin-dependent operators or low $m_\chi$ for spin-independent ones
  • The same signature can also be interpreted in extra dimension or SUSY searches
• 8 TeV analyses show no excess compared to SM background expectations.
  • 95% CL model-independent limit on cross section
    • jet+MET: 726 fb (lowest MET SR), γ+MET 5.3 fb
• Run-II analyses
  • good potential for discovery
  • follow the LHC DMF mandate to interpret the results.
Backup
References

• Search for new phenomena in final states with an energetic jet and large missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

• Sensitivity to WIMP Dark Matter in the Final States Containing Jets and Missing Transverse Momentum with the ATLAS Detector at 14 TeV LHC
  • ATL-PHYS-PUB-2014-007

• Search for new phenomena in events with a photon and missing transverse momentum in pp collisions at $\sqrt{s}=8$TeV with the ATLAS detector

  • arXiv:1507.00966
13 TeV fresh data

- Performance plots with first 50 ns data.
- Effect for jet cleaning shown
  - Jet cleaning not applied.
  - Good jets from hard-collision MC (Zνν+jets, Wlν+jets)

**ATLAS Preliminary**
\[ \sqrt{s} = 13 \text{ TeV} \int \text{Ldt} \sim 78 \text{ pb}^{-1} \]
Anti-\(k_t\) R = 0.4 Jets

Jet\(p_T\) [GeV]

- Data
- Z\(\nu\nu\) + jets
- W\(l\nu\) + jets

\(N_{\text{jets}} = 1\)
\(\text{MET} > 100 \text{ GeV}\)

**jet+MET selection before jet cleaning**

Events / \(16\)

ATLAS Preliminary
\[ \sqrt{s} = 13 \text{ TeV} \int \text{Ldt} \sim 78 \text{ pb}^{-1} \]
Anti-\(k_t\) R = 0.4 Jets

Jet \(\phi\)

- Data
- Z\(\nu\nu\) + jets
- W\(l\nu\) + jets

\(N_{\text{jets}} = 1, p_T^{\text{jet}} > 150 \text{ GeV}\)
\(\text{MET} > 100 \text{ GeV}\)

**jet+MET selection before jet cleaning**

$m_{\tilde{g}}$ limits for jet+MET

**ATLAS**

$\sqrt{s}=8$ TeV, 20.3 fb$^{-1}$

$E_T^{\text{miss}}>500/700$ GeV

$m_{\tilde{g}}=2 \times m_{\tilde{q}}$

- Observed limit
- Expected limit
- $\pm 1\sigma_{\text{exp}}$
- $\pm 2\sigma_{\text{exp}}$
- NWA limit

$m_{\tilde{g}}=4 \times m_{\tilde{q}}$

- Observed limit
- Expected limit
- $\pm 1\sigma_{\text{exp}}$
- $\pm 2\sigma_{\text{exp}}$
- NWA limit

$m_{\tilde{g}}=1/2 \times m_{\tilde{q}}$

- Observed limit
- Expected limit
- $\pm 1\sigma_{\text{exp}}$
- $\pm 2\sigma_{\text{exp}}$
- NWA limit

$m_{\tilde{g}}=1/4 \times m_{\tilde{q}}$

- Observed limit
- Expected limit
- $\pm 1\sigma_{\text{exp}}$
- $\pm 2\sigma_{\text{exp}}$
- NWA limit