ATLAS Monojet Run-II Analysis & MinBias Measurements with the ATLAS Tile Calorimeter

R Rosten (IFAE)

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MonoJet Analysis Outline

• ATLAS Detector
• Monojet Signature
• Signal Region
• Backgrounds
  • Non-Collision Background
  • anti-Scale Factors
  • Control Regions
• 2015+2016 Results
• Analysis Improvements
The ATLAS Detector
MonoX Signatures

Signature with a **single high energy object X** and large $E_T^{miss}$

MonoJet, MonoPhoton, MonoV, etc

X may be result of initial state radiation (ISR) or associated production

“Traditional” Mono-X dark matter search assumes **pair produced DM particles** with ISR X as the detectable object

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Mono-X Shape Search

Resonance Peak Search
MonoJet Overview

Target models with a **single high energy jet back-to-back** with large $E_T^{miss}$

Other low $E_T$ jets may be present, but veto on leptons and photons

Can arise from physics associated with many models, such as WIMP DM, Compressed SUSY, ALPs, Dark Energy, etc.

Dominate background is $Z \to \nu\nu$, followed by $W \to l\nu$
MonoJet Signal Region

- Perform analysis in bins of $E_T^{\text{miss}}$

Signal region

- Multiple ISR happens
- up to 3 jets with $p_T > 30$ GeV $|\eta| < 2.8$
- $\Delta\phi(jet, p_T^{\text{miss}}) > 0.4$
- Reduce QCD multijet background to negligible levels

$tight$ jet with $p_T > 250$ GeV $|\eta| < 2.4$

- lepton veto
- Veto on electrons and muons
- $E_T^{\text{miss}} > 250$ GeV

- Many signals have harder $E_T^{\text{miss}}$ spectra than SM backgrounds
- Identify the monojet as a good jet not from beam-induced background
- Not an inherent part of interpreted models, present in some backgrounds
- Trigger efficiency + high backgrounds at low $E_T^{\text{miss}}$
Estimating MonoJet Backgrounds

- MC/data fit in control regions (CR)
- Non-collision Background
  - Negligible but non-zero in all MET regions
  - Dominant $Z \rightarrow \nu\nu$ background dominates MORE at higher MET bins
  - Negligible, but would become less so at lower METs
- Data-driven based on flipping tight criteria
- Data-driven based on smearing jet $p_T$
- QCD Multijet Background
  - DiBoson: MC only
Non-Collision Backgrounds

MET triggers especially sensitive to Beam-Induced Background (BIB)

Muon travelling *in-time with proton bunch* and *parallel to the beampipe* emits hard bremsstrahlung radiation, resulting in a fake jet/fake MET

Jets are usually *trackless* and have most of their *energy in a single layer*, properties targeted by the *tight cleaning*
Dominate MonoJet Backgrounds

- $Z \to \nu\nu$: Dominate and irreducible, ISR boosted just like signal
- $W \to l\nu$: ISR boosted + lost lepton
Control Regions & Simultaneous Fit

- Require a good muon with $p_T > 10$ GeV, but veto b jets
- Add muon to $E_T^{\text{miss}}$
- Require $30 < m_T < 100$ GeV where
  \[ m_T = \sqrt{2p_T^l p_T^\nu [1 - \cos(\phi^l - \phi^\nu)]} \]

- Require two good muons with $p_T > 10$ GeV, but veto b jets
- Add muons to $E_T^{\text{miss}}$
- Require $66 < m_{\mu\mu} < 116$ GeV

Can use the same $E_T^{\text{miss}}$ as the signal region!

- Require a good muon with $p_T > 10$ GeV
- Require at least one b jets
- Add muon to $E_T^{\text{miss}}$
- Require $30 < m_T < 100$ GeV where
  \[ m_T = \sqrt{2p_T^l p_T^\nu [1 - \cos(\phi^l - \phi^\nu)]} \]
Lepton Scale Factors

ATLAS
\(\sqrt{s} = 13 \text{ TeV}, 81 \text{ fb}^{-1}\)
Electrons
- Blue: Loose
- Red: Medium
- Black: Tight

ATLAS
\(\sqrt{s} = 13 \text{ TeV}, 81 \text{ fb}^{-1}\)
Electrons, \(E_T > 4.5 \text{ GeV}\)
- Blue: Loose
- Red: Medium
- Black: Tight
anti-Scale Factors – An Explanation

Apply scale factors (SF) to the leptons in an analysis if selecting leptons

Apply ??? in an analysis if you vetoing on leptons

For us, the “???” are what we call “anti-SF”, and are applied per-region to the full sample based on the mean SF of the vetoed leptons

For $W \rightarrow \mu \nu$ in the SR: $antiSF \approx 1.05$

**MC** – fraction of IDed and reconstructed muons in e.g. $W \rightarrow \mu \nu$

**Data** – fraction of IDed and reconstructed muons in e.g. $W \rightarrow \mu \nu$

$SF = \frac{\epsilon_{data}}{\epsilon_{MC}}$
2015+2016 Results

- $\kappa_\ell = 1.31$
- $\kappa_V = 1.27$
- Set most stringent model-independent limits yet on benchmark DM model
- Additional interpretations were large extra spatial dimensions and SUSY
- Dominate systematics are:
  - Pre-fit: PDF, JES, and theoretical uncertainty on top-quark production
  - Post-fit: Muon, electron ID efficiencies, pileup reweighting
- Projections suggest more to gain by improving analysis (reducing systematics, increasing signal to background) than by gathering more data
MonoJet Interpretations: Benchmark DM

- At higher $g_q$, resonance searches dominate
- Search complementarity especially clear in leptophilic model

ATLAS/CMS Dark Matter Forum: 1507.00966
ATLAS Mediator DM Summary Paper: 1903.01400
**Monojet Interpterion: Compressed SUSY**

\[ \Delta m_{\tilde{q}\tilde{\chi}_1^0} \sim \text{small} \]

**ATLAS**

- \( \tilde{t}_1 \) production, \( \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 \)
- **Observed limits at 95% CL**
  - ATLAS \( \sqrt{s} = 13 \text{ TeV}, \ 3.2 \text{ fb}^{-1} \)
  - ATLAS \( \sqrt{s} = 13 \text{ TeV}, \ 36.1 - 139 \text{ fb}^{-1} \)
  - \( m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0} \leq m_t \)
  - Expected limit \( \pm 1 \sigma_{\text{exp}} \)
  - Expected limit \( \pm 2 \sigma_{\text{exp}} \)

**July 2019**

- Observed limits
- Expected limits
- \( \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0 \) \( \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0 \)
- \( \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 \) \( \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0 \)
- \( \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 \) \( \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0 \)

**Run 1, \( \sqrt{s} = 8 \text{ TeV}, 20 \text{ fb}^{-1} \)**

\[ m(\tilde{t}_1), [\text{GeV}] \]

\[ m(\tilde{\chi}_1^0), [\text{GeV}] \]
Possible Upcoming Improvements

Lower minimum MET cut & analyze the trigger turn on

Add a tau veto

Consider new interpretations, such as axion-line particles and invisible Higgs

Veto on softer leptons

Add new control regions, such as $Z \rightarrow ee$

Try splitting top control region
Part 1 Conclusions:
ATLAS MonoJet Search

• Monojet analysis looks for enhancement or distortion of missing energy spectrum resulting from new invisible particles recoiling off of an energetic jet

• Both larger backgrounds and trigger limitations drive the lower cut on missing energy

• Analysis utilizes control regions for dominate backgrounds

• Other backgrounds reduced by cleaning criteria

• Largest gain in limits in the future likely to come from analysis evolution more than extra data
Tile MinBias Outline

• Tile Calorimeter
• Energy and Aging
• Tile Minbias Measurements
• Luminosity
  • Why it matters
  • What systems can measure it
• Lucid Calibration
• Long Term Stability
• Possible Tile Advancements
Tile Calorimeter Revisited

- Tile is a sampling calorimeter composed of alternating steel absorbers and scintillator tiles
- Calorimeter consists of four partitions each with 64 wedge shaped modules
- Modules made up of cells
- Cells defined by bundles of fibers from scintillators fed into the same PMT
Tile Energy Measurements and Aging

- Particles passes through scintillators, which absorb some of the energy and emit light
- Light collected by the wavelength shifting fibers, which pass it to the PMTs
- PMTs pass a current to the electronics, which yield a recorded signal
- Ideally, the relationship between energy and current is independent of time
- In reality, aging is a major issue and frequent calibration is necessary
MinBias Measurements

- Tile readout electronics include low-current integrators that average current from each PMT over $O(10 \text{ ms})$
- Originally intended to measure low currents from Cs during calibration, but readout from physics runs as well
- Can supplement (or replace) Cs measurements in physics runs, good for luminosity!
Why Luminosity Matters

- 139 fb$^{-1}$ pp data for Run-II
- Preliminary uncertainty for Run-II dataset at 1.7%
- Luminosity uncertainty is the dominant uncertainty for many precision measurements

Measurement of the $Z \to \ell^+ \ell^-$ production cross-section in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector (1911.04813)

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
<th>Correlation</th>
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</thead>
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<td>Trigger efficiency</td>
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<tr>
<td>Photon identification efficiency</td>
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<td>Muon isolation efficiency</td>
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<td>Muon identification efficiency</td>
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<td>Total uncertainty</td>
<td>3.2 3.0</td>
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## A Matter of Uncertainty

<table>
<thead>
<tr>
<th>Data sample</th>
<th>2015+16</th>
<th>2017</th>
<th>2018</th>
<th>Comb.</th>
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<td>44.3</td>
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<td>Total uncertainty (fb⁻¹)</td>
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<td>1.0</td>
<td>1.2</td>
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<td>Uncertainty contributions (%)</td>
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<td>Bunch-by-bunch $\sigma_{\text{rel}}$ consistency</td>
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<td>0.4</td>
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<td>Scan-to-scan reproducibility</td>
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<tr>
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<td>Afterglow and beam-halo subtraction</td>
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<td>Total uncertainty (%)</td>
<td>2.1</td>
<td>2.4</td>
<td>2.0</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**Systematic is partially correlated between years**

**Systematic is fully correlated between years**

Correlations in uncertainty between years results in a reduced combined uncertainty.
**Luminosity Detectors & Algorithms**

**Tile**
Diverts ~1% of PMT current and integrates over O(10) ms
Sensitive over wide range of luminosities

**Z-counting**
Cross-check of baseline luminosity vs time and $\mu$

**FCal & EMEC**
Read out LAr gap HV currents over O(1) s integration times
Use of HV current bypasses trigger limitations

**BCM and TPX**
BCM only for low ($\mu$) and HI runs
TPX for monitoring radiation

**LUCID-2**
The ATLAS reference luminometer, uses a hit counting algorithm
Provides real-time measurement of luminosity at any number of interactions per LHC bunch crossing ($\mu$)

**Tracks**
Count reconstructed Si tracks in randomly triggered events
Sensitive over wide luminosity range
Luminosity Measurements with Tile

- The minbias current measured by Tile is **directly proportional to the luminosity**, to low order
- The slope of the relationship is the luminosity coefficient
- **Luminosity coefficients ideally constant**, but aging necessitates corrections to the luminosity, especially for the aging and recovery of PMTs
- Tile provides the only luminosity measurement in addition to Track Counting that is **robust against pileup**
Long Term Stability

- Long-term stability uncertainty comes from a comparison of the luminosity measured by other luminometers to LUCID-2

- Reference run chosen for which all systems’ luminosities are normalized to LUCID (red arrow)

- Contributing data from physics data runs, with calibration for LUCID coming from special calibration runs
LUCID Calibration

- vdM scans carried out with very low luminosity and isolated bunches
  - Multiple scans allow for evaluation of scan-to-scan reproducibility
  - Off-axis scans allow for evaluation of non-factorization
- Reference luminosity for calibrating LUCID comes from beam parameters
- $O(10^{-4})$ corrections account for Bi-207 and beam-gas interactions

\[
\mathcal{L} = f_{\text{LHC}} \frac{n_1 n_2}{2 \pi \Sigma_x \Sigma_y} \\
\sigma_{\text{vis}} = f_{\text{LHC}} \frac{\mu_{\text{vis}}}{\mathcal{L}}
\]
Calibration Transfer

- LUCID measurements sensitive to pileup and bunch train running → calibration from VdM run results in an **overestimate** of luminosity in physics running conditions

- **Correction** needed for $\mu_{vis}$ at high luminosities from track counting

- **Uncertainty** on calibration transfer from comparison of track counting and Tile luminosity measurements in same pairs of runs

\[ \frac{\mu_{corr}}{\mu_{raw}} = p_0 + p_1 \mu_{raw} \]
Advancing Tile Measurements

- Tile measurements affected by:
  - Aging – Currently accounted for in calibration transfer
  - Non-linearity of PMTs – PMT gain depends on anode current, higher at high luminosity
  - Activation of material – Radiation produced by activated materials in ATLAS induces a bias in Tile Luminosity measurements

![Graph showing gain vs current](image)

**ATLAS Online Luminosity**
- Run 355273

Tile will not measure 0 luminosity here because of activation

2020_06_01 OSU 29
Part 2 Conclusions: Tile Calorimeter MinBias

- Tile Minimum Bias measurements average current over long (on LHC timescales) periods of time
- This can help fill in “missing” data from lack of Cs calibrations to monitor the scintillator aging
- Tile also play an important role in luminosity measurements, especially for the calibration transfer from van der Meer runs to physics running conditions
- Current work in Tile is dedicated to improving the measurement of minbias via measurements of activation and PMT response non-linearities
Building an Analysis – Trigger

1 event/25 ns = 40 MHz

Hardware
(~500 trgs)

100 kHz

Software
(~1500 trgs)

1 kHz

ATLAS Preliminary
Data 2017
\( \sqrt{s} = 13 \text{ TeV}, 1.3 \text{ fb}^{-1} \)

\( W \rightarrow \mu \nu \)

- L1_XE50
- HLT_xe110_pu10_L1XE50
- HLT_xe110_mht_L1XE50

ATLAS Preliminary
Data 2016 / 2017, \( \sqrt{s} = 13 \text{ TeV} \)

- HLT_xe110_mht_L1XE50
- HLT_xe110_pu10_L1XE50

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 3.4 \text{ fb}^{-1} \)

TLA jets
Offline jets selected by any single-jet trigger
Offline jets selected by \( \eta \)110 single-jet trigger

ATLAS Trigger Operations
Data 2017, \( \sqrt{s} = 13 \text{ TeV}, \) p-p runs

- Physics Main
- B Physics and Light States
- Average total rate (1.1 kHz)
- Average rate Physics Main (1.0 kHz)

ATLAS Trigger Operations
Data 2016 / 2017, \( \sqrt{s} = 13 \text{ TeV} \)

- HLT_xe110_mht_L1XE50
- HLT_xe110_pu10_L1XE50

2020_06_01

OSU
MonoJet Interpretations: Compressed SUSY

\[ \tilde{b}_1 \tilde{b}_1 \text{ production, } \tilde{b}_1 \rightarrow b\chi^0_1 \]

**ATLAS**

All limits at 95% CL

- Observed limit (\( \pm 1 \sigma_{\text{SUSY}}^{\text{theory}} \))
- Expected limit (\( \pm 1 \sigma_{\text{exp}} \))
- Expected limit (\( \pm 2 \sigma_{\text{exp}} \))

\( \sqrt{s} = 13 \text{ TeV, } 36.1 \text{ fb}^{-1} \)

\( m_{\tilde{b}_1}, m_{\chi^0_1} \) [GeV]

\( m_{\tilde{b}_1} \) [GeV]
LUCID-2

- LUCID (LUminosity Cherenkov Integrating Detector): Provides real-time measurement of luminosity at any number of interactions per LHC bunch crossing ($\mu$)
  - Primary luminosity detector in ATLAS from 2015+
- 2*4*4 IP-pointing PMTs with small acceptance (Cherenkov radiation from quartz window sufficient) to cope with high occupancy
- Fast read-out electronics to cope with 25 ns bunch spacing
- Radioactive Bi-207 deposited on quartz window allows for continuous monitoring of PMT gains
Luminosity Calibration Procedure: Overview

Use low luminosity van-der-Meer (VdM) scans to determine absolute luminosity of each colliding bunch as related to bunch intensity \( n_1 n_2 \) by measuring beam overlap integral \( \Sigma_x \Sigma_y \).

\[
\mathcal{L}_{\text{bunch}} = f_{\text{LHC}} \frac{n_1 n_2}{2\pi \Sigma_x \Sigma_y}
\]

LUCID-2 measurements relate visible interactions per bunch crossing \( \mu_{\text{vis}} \) and cross section \( \sigma_{\text{vis}} \)

PMT gain stability monitored by Bi-207 calibration

Use linearity of track counting luminosity measurement to extrapolate VdM calibration to “normal” LHC running conditions, i.e. the calibration transfer

\( \mu \sim 0.5 \rightarrow \mu \sim 50 \)

\[
\mu_{\text{vis}} = -(1 - P_{\text{HIT}})
\]

\[
\mathcal{L} = f_{\text{LHC}} \frac{\mu_{\text{vis}}}{\sigma_{\text{vis}}}
\]
Long-Term Stability

- Long-term stability uncertainty comes from a comparison of the luminosity measured by other luminometers to LUCID-2
- Reference run chosen for which all systems’ luminosities are normalized to LUCID (red arrow)
Tile Laser-in-Gap Measurements

- Fire laser pulse in LHC abort gap
- Observe resulting signal in Tile PMTs
- Readout amplitude affected by any change in PMT gain