Probing the Energy Frontier with ATLAS

Séminaire du DPNC

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• These particles we know, and they are the building blocks of the 5% of the universe we roughly understand.

• Described by the Standard Model.
Many open questions:
• What explains the other 95% of the universe? (i.e. Dark Matter, Dark Energy?)
• Why is gravity so weak?
Large Hadron Collider

CMS

ALICE

ATLAS

LHCb
ATLAS Detector

The dashed tracks are invisible to the detector.

Muon Spectrometer

Hadronic Calorimeter

Electromagnetic Calorimeter

Tracking

Muon

Neutron

Proton

Neutrino

Photon

Electron

Solenoid magnet

Transition Radiation Tracker

Pixel/SCT detector
Energy Frontier: Jets

- Newly opened energy regime: $\sqrt{s} = 13$ TeV.

$m=8.12$ TeV dijet event
jet$_{1/2}$ $p_T=3.79$ TeV
Motivation

- Heavy (>1 TeV) resonances to pairs of vector bosons \( (V=W/Z) \) predicted by several extensions of the SM.

- \( V \to \) quark-pair decays most abundant. ➞ Great probe for new physics!

- Mass of jet can identify initiating particle.

\[ m=? \]
Jet Mass Definition (1)

calorimeter-based jet mass:

\[ m^{\text{calo}} = \sqrt{\left( \sum_{i \in J} E_i \right)^2 - \left( \sum_{i \in J} \vec{p}_i \right)^2} \]

• Tracker granularity superior to calorimeter.
  Use tracker in reconstruction of jet mass.
pixel sizes: 50\(\mu\text{m}\times400(250)\mu\text{m}\)

beam pipe

Pixel

Pixel barrel imaged by hadronic interactions
Tracking in Dense Environments

• Common in high energetic jets and decays of particles (e.g. hadronic tau decays).

• Collimation & merged clusters can create confusion. ➔ Bad performance!
Tracking in Dense Environments

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Overview

Performant Tracking → Performant Jet Mass → High Sensitivity Search → Potential Discovery!
Improving Tracking Performance

• Study of previous performance led to algorithmic improvements and novel developments:
  • Use artificial neural network for analysing clusters. → identifies merged clusters. → predicts particles position.
  • Exploit global information.
  • Optimize algorithm and tune parameters.

• Increases:
  accuracy of measurement efficiency of assignment!

Identified as shareable

not identified

→ recover!

arXiv:1704.07983
Improving Tracking Performance

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Improving Tracking Performance

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• Increases: accuracy of measurement efficiency of assignment!
- Efficient hit assignment leads to better performance for physics objects.
• Efficient hit assignment leads to better performance for physics objects.
• Previous results were on simulation
  ➔ performed several studies to measure performance in data!

• Example:
  novel method to measure efficiency of tracking in dense environments in data.

~Energy loss in cluster
Tracking Performance in Data

**ATLAS**

\[ \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \]

- **Data 2015**
- **Fit**
- Single-Track Contribution
- Multiple-Track Contribution

\[ 1000 \text{ GeV} < p_T^{\text{jet}} < 1200 \text{ GeV} \]

- **merged** = 0.028 ± 0.005 (stat)

- **200 \text{ GeV} < p_T^{\text{jet}} < 400 \text{ GeV}**

- **ATLAS**

- **Fit fraction of lost tracks with templates.**

- **Second peak = Inefficiency**
• Results reduce uncertainty from 50% to ~15%.
track-assisted jet mass: $m = m^{\text{calo}}(X)$

- Ratio $\frac{p_T^{\text{calo}}}{p_T^{\text{track}}}$ corrects for charged-to-neutral fluctuations, improving resolution with respect to track-only jet mass.

- $m^{TA}$ uncertainties factor 2 smaller than $m^{\text{calo}}$. 

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Jet Mass Definition (2)

- Rationale for fluctuations of jet mass resolution
- $m^{TA}$ in comparison

\[ \text{Jet Mass} = \begin{cases} \rho \, T \, c_{\text{calo}} & \text{Calorimeter mass} \\ \rho \, T \, t_{\text{track}} & \text{Track assisted mass} \end{cases} \]

*ATLAS* Simulation Preliminary
- $\sqrt{s} = 13 \, \text{TeV}, WZ \rightarrow qqqq$
- anti-$k_t$, $R = 1.0$ jets, $|\eta| < 2.0$
- Trimmed ($f_{\text{cut}} = 0.05$, $R_{\text{sub}} = 0.2$)
- LCW + JES + JMS calibrated

<table>
<thead>
<tr>
<th>Truth jet $p_T$ [GeV]</th>
<th>Calorimeter mass</th>
<th>Track assisted mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
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</tbody>
</table>
Combined Mass: $m^{TA} \oplus m^{calo}$

- $m^{calo}$ not used explicitly in construction of $m^{TA}$
  - Reduce resolution by combining both mass definitions.

- Approximate independence and Gaussian nature of responses.
  - (Nearly) optimal combination of variables is linear.

- Choose $a$ and $b$ mass according to individual mass resolutions.

$m^{comb} = a \times m^{calo} + b \times m^{TA}$
Jet Mass Definition (2)

- Rationale for using a calorimeter mass fluctuation, calculated as $m^{TA}$.
- $m^{TA}$ is defined as

\[
m^{TA} = (p_T + \text{track mass}) - \text{calorimeter mass}
\]

**ATLAS Simulation Preliminary**

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\[\text{Fractional jet mass resolution} \]

Truth jet $p_T$ [GeV]

- Calorimeter mass
- Track assisted mass
- Combined mass

-50% decrease
Analysis Overview

• Search for R-S graviton

• Results

• Find empirical background fitting function:
  \[ p_1 (1-x)^{p_2} \cdot x^{p_3}, \quad x = m_{JJ}/\sqrt{s}. \]

Events

Background

Invariant mass

Bump!
Analysis Overview

- Search for processes related to W bosons
- Results from previous studies
- Findings and observations
- Improved reconstruction increases sensitivity.

Events vs. Invariant mass

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Analysis Overview

- Search for new physics by probing the energy frontier.
- Results in improved constraints on the R-S graviton.
- Uncertainty in jet energy/mass scale can shift bump.

Events

Invariant mass

Background falling background.

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Analysis Overview

- Search for new physics
  - Results
- Final analysis

- Uncertainty in jet energy/mass resolution change bump's width.

Events vs. Invariant mass

Basic assumption: falling background.
• Search for heavy resonances decaying to WZ, ZZ and WW.

• Results interpreted in terms of:
  ➔ bulk Randall-Sundrum graviton decaying to WW/ZZ.
  ➔ Heavy Vector Triplet (W', Z') decaying to WZ and WW.

• **Final state oriented analysis.**
  ➔ Hadronic decays are important.
    ➔ 3/10× more hadronic W/Z decays than into light leptons.

  ➔ High-\(p_T\) region.
    ➔ hadronic decays can provide great sensitivity.
    ➔ QCD dijet background low or can be suppressed.

**Basic idea:** Bump-Hunting in smoothly falling background.
Analysis Selections

- Kinematic selections enhance diboson signal over background. Example:
  - **Rapidity separation**: signal events more central than QCD background.

Rapidity Separation

- Identify jets as Boson-like:
  - Jet mass.
  - Substructure ($D_2$).
  - Track-multiplicity.

- Signal regions: $WZ$, $WW$ and $ZZ$. 

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Control Regions

- Following CRs used:
  - Jets in a low (50-65 GeV) or high (110-140 GeV) mass sideband.
  - Partial boson selection (only mass, $D_2$, or track-multiplicity).
  - $V+$jets CR allows for derivation of uncertainty on track-multiplicity.

- Why CRs for data-driven analysis?
  - Ensure selections are not sculpting the background.
  - Test the robustness of fitting function.
• No excess over fitted background observed in any signal region.
Results: Fitted Signal Regions

- No excess!
Results: Limits for Benchmark Models

- Able to set best exclusion limits on new resonances of HVT model with 95% confidence level:
  - $W'\rightarrow WZ$: masses between 1.2 - 2.0 TeV.
  - $Z'\rightarrow WW$: masses between 1.3 - 1.7 TeV.

- Not able to exclude bulk RS graviton with current sensitivity.

Previous HVT limit: $W'\rightarrow WZ$ 1.38 - 1.6 TeV

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Summary

• Developments provide excellent performance of track reconstruction in dense environments.
  ➔ New studies helped vastly reduce tracking related uncertainties.

• Improved tracking performance and uncertainties allow for novel methods of jet mass reconstruction.
  ➔ Provides superior performance and reduces related uncertainties.

• Utilizing these performance optimizations a search for heavy diboson resonances was performed.
• No excess observed.
  ➔ But best exclusion limits yet set!