Jets, $E_{T}^{\text{miss}}$, and boosted jet identification in high-pileup conditions with ATLAS

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The Problem with Pileup

- Pileup from additional collisions is a big problem, and will be even worse at the High Luminosity LHC.

- Particles from pileup collisions can:
  - Add **additional jets** not from the hard-scatter
  - Overlap with **hard scatter jets**, altering their energy & structure

Every year the **# of interactions per event (μ)** increases, and will reach ~200 at the HL-LHC!
The Effect of Pileup

Bias mass, resolution, & substructure

More jets vs # vertices ($N_{\text{PV}}$)

Bias event-level observables ($E_{\text{T}}^{\text{miss}}$)

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Jet Vertex Tagger

- **Multivariate JVT** connects jets to pileup vertices using tracking information
  - Large reduction in pileup jets within tracker ($|\eta| < 2.4$)
  - HL-LHC: improve & **extend tracker to** $|\eta| = 4.0$
  - Proposed **High Granularity Timing Detector** (HGTD) aims for **30 ps timing resolution** to match jets to pileup vertices
  - Beyond tracker use **Forward JVT**:
    - Remove **forward QCD jets** that balance a pileup vertex
    - Remove **stochastic jets** (from many vertices) using spatial and timing correlations of clusters

**ATLAS Simulation**

- Tracks from HS vertex
- Tracks from PU vertex 1
- Tracks from PU vertex 2
- Jets
- Vertices

- $p_T = 26$ GeV
- Stochastic pile-up, $\Delta R_{pt} = 0.10$
- $p_T = 40$ GeV
- QCD pile-up, $\Delta R_{pt} = 0.53$
- $p_T = 49$ GeV
- Hard-scatter

**See HGTD talk by Ariel Schwartzman**

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**ATLAS Preliminary**

2017, $\sqrt{s} = 13$ TeV, 20.8 fb$^{-1}$

Anti-$k_t$, $R=0.4$ EM+JES

$p_T^{jet} > 20$ GeV, $|\eta| < 2.4$

**pileup jet reduction w/ JVT**

**ATLAS Simulation Preliminary**

Powheg+Pythia8 $Z \rightarrow \mu\mu$

$\sqrt{s} = 13$ TeV

- TST
- TST and $p_T^{foward jet} > 30$ GeV
- TST and fJVT

**fJVT improves** $E_T^{miss}$

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Area-based subtraction

- Hard-scatter jets can include overlapping pileup energy & pileup clusters
- Event-wide ambient $p_T$ density ($\rho$) taken from median $p_T$ of (pileup sensitive) $k_t$ jets
- Subtract $\rho$ from each anti-$k_t$ jet according to its area

![Graph showing the difference between before and after corrections](image)

- Residual correction vs NPV and $\mu$ due to changing calorimeter geometry
- Works well currently, but difficult at HL-LHC
Cluster-level Subtraction

Translate area-based subtraction to clusters. **How to define cluster area?**

- **Constituent Subtraction:** Add fake “ghost particles” uniformly to event, and **cluster alongside cells**
  - Number of clustered ghosts ∼ area
  - Correct topoclusters according to $N_{\text{ghost}}$ & event $\rho$ (i.e. give ghosts negative $p_T$)

- **Voronoi Area:** $\eta$-$\phi$ area closest to each cluster
- Subtract $\rho$ from each cluster according to Voronoi area
- **1σ suppression:** remove all clusters with low significance above noise
SoftKiller

- SoftKiller targets individual pileup clusters surviving Constituent or Voronoi subtraction.
- Reject all clusters below an event-specific $p_T$ cut.
- $p_T$ cut chosen so detector is half empty for the event.

SoftKiller in action:

Event w/ pileup

Voronoi Subtraction

VS + SoftKiller

$\mu = 200$

Topoclusters

Cluster-level Performance

- **Large reduction in jet energy resolution** compared to jet-area subtraction in high pileup conditions
- **Gains even at lower μ** → ongoing studies for use Run 2 & 3 data
Jet Tagging Performance

- Correcting clusters also improves jet substructure
- Essential for tagging boosted top, W, Z, & Higgs
- Scan over clusters types & grooming methods for best combination
- Tagging efficiency, fake rejection, and mass stability w.r.t. pileup
- Good performance from trimmed LCtopo & soft drop CS+SK / VS+SK jets
- Final algorithms will be calibrated with full in situ chain used for small-R jets

Background rejection of W tagger at 50% signal efficiency for various jet types

Jet Grooming Method

<table>
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<th>Soft Drop</th>
<th>Recursive Soft Drop</th>
<th>Bottom-up Soft Drop</th>
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ATLAS Simulation Preliminary

Anti-$k_t$, $R=1.0$ jets, LCW, no JES or JMS calibration applied

$\sqrt{s} = 13$ TeV, 68% mass window + $D_2$ W tagger

$300 \text{ GeV} < p_{\text{T}}^{\text{true}} < 500 \text{ GeV}$, $|y|^{\text{true}} < 1.2$

$\langle \mu \rangle \sim 20$
Jet Tagging Performance

- Correcting clusters also improves jet substructure
- Essential for tagging boosted top, W, Z, & Higgs
- Scan over clusters types & grooming methods for best combination
- Tagging efficiency, fake rejection, and mass stability w.r.t. pileup

- Good performance from trimmed LCTopo & soft drop CS+SK / VS+SK jets
- Final algorithms will be calibrated with full in situ chain used for small-R jets
Particle flow jets

Match tracks to topoclusters, removing charged energy while keeping neutral component

Topoclusters consistent with pileup tracks are rejected, reducing pileup

Improved energy resolution at low $p_T$, driven by accurate track measurements

Jet Resolution

Better $E_T^\text{miss}$ resolution
• At high-$p_T$, track $p_T$ resolution degrades, but extrapolated angular resolution improves

• TCC uses tracks to correct spatial resolution of coarser calorimeter clusters, not their energy

• Retains benefits of pileup vertex rejection

• Large improvement to substructure variables (like $D_2$), benefiting taggers

• Robust against pileup

TCC jets improve $D_2$ resolution

ATLAS Simulation Preliminary

$\sqrt{s} = 13$ TeV

anti $k_T$ R=1.0, WZ $\rightarrow$ qqqq

$|\eta^{\text{jet}}| < 2.0$, $p_T^{\text{jet}} > 200$ GeV

$\langle \mu \rangle \sim 24$
Conclusions

- **High pileup environment** now & at the HL-LHC offers challenges for jet calibration & tagging

- **Various new techniques** for mitigating pileup impact on jet measurements, $E_T^{\text{miss}}$, and identification of high-$p_T$ jets (boson & top tagging)

- Great deal of experimentation - significant effort by software team to ease implementation

- Plan to converge in Run 3 on optimal combination of techniques

- **Significant HL-LHC upgrades** will improve track-based pileup tagging
Backup
Jet Reconstruction

- Inputs to jets are clusters (collections of neighboring calorimeter cells)
- **Inherent noise suppression** from 4-2-0 clustering algorithm:
  - Low energy pileup rejected
  - **Anti-\(k_T\)** jet-finding algorithm focuses on hardest energy deposits, w/ reduced shaping by pileup
- However:
  - Higher-pt pileup jets still get through
  - Selected clusters are still affected by pileup

Most **low-significance cells** removed by clustering
High granularity timing detector

- HL-LHC will see $\langle \mu \rangle = 200$, with $\sim 1.8$ vertex per mm
- Impossible to distinguish pileup vs hard-scatter tracks via geometry only
- Within a bunch crossing, collisions occur with $\sigma_t = 180$ ps
- HGTD can resolve track time within 30 ps
- Large reduction in tracks from pileup vertices close to hard scatter
Jet Vertex Tagger (JVT)


- Multivariate using $R_{pT}$ and $\text{corrJVF}$
- $R_{pT}$ is ratio of jet’s $p_T$ matched to hard scatter tracks
- $\text{corrJVF}$ compare fraction of hard scatter tracks against pileup tracks
- Corrected by # pileup tracks to remove $N_{PV}$ dependence

\[ R_{pT} = \frac{\sum_{k} p_T^{trk}(PV_0)}{p_T^{jet}} \]

\[ \text{corrJVF} = \frac{\sum_{k} p_T^{trk}(PV_0)}{\sum_{l} p_T^{trl}(PV_0) + \sum_{n \geq 1} \sum_{l} p_T^{trl}(PV_n) (k \cdot n_{trk}^{PU})} \]
Jet Grooming: Trimming

- ATLAS standard grooming procedure
- Target softer radiation from pileup, MPI, & ISR
- Recluster constituents into small-R sub-jets $R_{\text{sub}} \sim 0.2$
- Remove sub-jets with fractional $p_T < f_{\text{cut}} \sim 3\%$
Jet Grooming: Pruning

- Remove soft low-$p_T$ clusters, but keep large-angle radiation
- Redo jet clustering (C/A or $k_t$), and at each stage cluster if either:
  - Not soft: $p_T$ fraction of second constituent is $> z_{\text{cut}}$
  - Close-by: $\Delta R_{1,2} < R_{\text{cut}}$
- Otherwise, reject 2nd constituent
Jet Grooming: Modified Mass Drop + Filtering

- Iterative declustering of a C-A jet targeting **soft and wide-angle radiation**
- Remove branches with $p_T$ imbalance, provided no large drop in mass
- Requirements on 2 subjets from last clustering stage:
  
  (i - Mass Drop): $m(j_1) < \mu \times m(j_2)$

  (ii - Balanced Splitting): $\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}$

- If either fails, remove softest jet $j_2$, and continue procedure
- If both pass, end procedure and keep jet

- **Filtering**: Recluster constituents into 3 C-A jets of radius $R_{filt}$ (discard extra clusters)

![Diagram](image)

$C/A \ R= R_{filt}$

$R_{filt} = \min[0.3, \frac{\Delta R_{j_1,j_2}}{2}]$

Filtered jet
Jet Grooming: Soft drop

• Extends mMDT to reject wide-angled radiation

• Run backwards through clustering of C/A jet, removing constituent if:
  \[
  \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} < z_{\text{cut}} \left( \frac{\Delta R_{12}}{R_0} \right)^\beta
  \]

• Larger \( \beta \) allows for more soft & wide-angled radiation in a jet

• **Recursive soft drop**: Continue the procedure the soft-drop requirements are passed \( N \) times

• Continues through good constituents, grooming them as well

• **Bottom-up soft drop**: Apply soft drop criteria during jet reconstruction
Jet Reclustering

- Build large-$R$ jets from **fully-calibrated** $R=0.4$ jets
- Benefit from small-$R$ pileup suppression
- Propagate full suite of small-$R$ uncertainties
- No additional large-$R$ calibration needed - flexible choice in large-$R$ radius
- Can use other grooming methods with $R=0.4$ jets

$\sqrt{s} = 8$ TeV PYTHIA $Z' \to t\bar{t}$, $m_{Z'}=1.5$ TeV

![Diagram showing event clustering with $R=1.0$ and reclustering with $R=0.3$](image.png)

Due to the increased catchment area of large radius jets over small radius jets, they are more susceptible to contributions from pileup. Just as there are pileup correction techniques for large radius jets and their subjets, one can benefit from pileup corrections to the small radius jet inputs that propagate to re-clustered jets. In particular, one can remove jets from pileup interactions with techniques like JVT [19] and can correct the remaining jets with methods like the four-vector jet areas subtraction.

In the growing field of jet substructure, there are many jet observables which depend explicitly on the jet constituents, not just the jet four-vector. These techniques are still applicable for re-clustered jets. Section 5 discusses two approaches to jet substructure in the re-clustering paradigm. In a **top-down** approach, large radius re-clustered jets inherit the constituents of the small radius jets clustered within. Clearly, any constituents that might be part of large radius jets that are not clustered within a small radius jets are not considered under this scheme. However, this removal of radiation also impacts trimmed large radius jets. More details on substructure for trimmed and re-clustered trimmed jets is presented in Section 5.1. An alternative **bottom-up** approach to jet substructure is to use the radius $r_{jets}$ directly as the inputs to jet substructure. The advantages and limitations of bottom-up substructure are described in Section 5.2.
• Scan over many clusters types & grooming methods for best combination
• Tagging efficiency, fake rejection, and mass stability w.r.t. pileup
In case of track-cluster-multi-matches, create one TCC object per hard-scatter PV track, and share the energy based on $p_T$ ratios:

$$\text{TCC}_4 = (\alpha p_T^{c2}, \eta^{t2}, \phi^{t2}, \alpha m^{c2} = 0)$$

$$\text{TCC}_5 = (\beta p_T^{c2}, \eta^{t3}, \phi^{t3}, \beta m^{c2} = 0)$$

$$\alpha = \frac{p_T^{t2}}{p_T^{t2} + p_T^{t3}} \quad \beta = \frac{p_T^{t3}}{p_T^{t2} + p_T^{t3}}$$