Jets and MET with ATLAS and CMS
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Jets …

- New Physics???
- t/W/Z/H mass
- Hard process
- Jet algorithm
- Jet shapes
- Jet mass
- Heavy quark masses
- Temperature in qgp
- Diffraction / UE
- Hadronization

- $m_{EW}$
- $p_T$
- $p_T R$
- $p_T r$
- $m$
- $m_{b,c}$
- $T$
- $\Lambda_{QCD}$

- Mysteries!!
- >NLO calculations
- NLL/resummed calculations
- Mysteries?
- PDFs
- Tuning

- Jets “today” are [also] experimental signatures of quarks/gluon

- Hadronic final states are a major part of the LHC physics program: Backgrounds/signals/pileup

- Jets / Parton level
- q, g
- π, K, ...
- Energy depositions in calorimeters

https://www.particlezoo.net/
... and missing transverse momentum

- Negative vector sum of $p_T$ of objects in the event
- CMS: all PF candidates (weighted in the case of PUPPI MET)

\[ p_T^{\text{miss}} = - \left( \sum_{\text{selected electrons}} p_T^e + \sum_{\text{accepted photons}} p_T^\gamma + \sum_{\text{accepted } \tau-\text{leptons}} p_T^\tau + \sum_{\text{selected } \mu} p_T^\mu + \sum_{\text{accepted jets}} p_T^{\text{jet}} + \sum_{\text{unused tracks}} p_T^{\text{track}} \right) \]

- ATLAS: Lower-level detector calibration crucial for $p_T^{\text{miss}}$
… and missing transverse momentum

- Negative vector sum of $p_T$ of objects in the event
  - CMS: all PF candidates (weighted in the case of PUPPI MET)
  - ATLAS: Always: Lower-level detector calibration crucial for $p_T^{\text{miss}}$

- Reconstruction
  - Object based approach built in a specific order.
  - Analyses decide on what definitions to use for muons/electrons/...;
  - Input them to MET reconstruction algorithm
  - Algorithm adds objects to $p_T^{\text{sum}}$ in this order to use the best energy measurement/interpretations available:
    - Performing its own overlap removal on whole/parts of objects, removing tracks/clusters that have been used already in the $p_T^{\text{sum}}$.
      - Avoids double-counting!
    - Remaining unused tracks become the 'Track soft term'.

- MET Performance 2015
- METNet as machine learning
  - Considers different WPs for jets to output improved estimate
  - Better resolution
  - Also investigating MET significance
CMS detector (for jets)

CMS specifics
- Very precise tracker and ECAL
- Highly granular ECAL
- Tracking and calorimeters contained within superconducting magnet
- Strong magnetic field (3.8 T)

Tracker: Silicon Pixel and Strip detector
\[
\frac{\sigma(p_T)}{p_T} \sim 0.7\% \text{ at 10 GeV}
\]
\rightarrow \text{Charged particles}

Barrel region

HCAL: Brass/scintillator (|\eta| < 3)
\[
\frac{\sigma(E)}{E} \sim 18\% \text{ for 50 GeV } \pi^+/\pi^-
\]
\rightarrow \text{Hadrons}

ECAL: PbWO}_4\text{Crystal calorimeter}
\[
\frac{\sigma(E)}{E} \sim 2\% \text{ for 50 GeV } e^-
\]
\rightarrow \text{Electrons, photons}
CMS (jets and MET) reconstruction

Try to reconstruct individual particle candidates, combining information from various detectors
- Charged hadrons (tracker)
- Photons (ECAL)
- Neutral hadrons (HCAL)
- +Electrons/muons

- Form jets and MET using particle candidates
- PF greatly improves CMS jet energy resolution as compared to calorimeter-only reconstruction.

JINST 12 (2017) no.10, P10003
CMS (jets and MET) reconstruction

ECAL pulse reconstruction

Particle Flow cluster reconstruction and calibration

HCAL pulse reconstruction

Particle Flow linking and particle reconstruction

Track reconstruction

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Schematic by J. Dolen
Introduction

• Searches with boosted bosons → decay products merged into a single jet (V jets)
• Techniques used to identify these objects will be discussed in detail in other talks this week - only a quick summary today
• V jets occur in many BSM models, some of which have dedicated talks at BOOST (VV resonances, V+MET etc.), therefore I will concentrate on top partner models which produce a very rich phenomenology containing boosted V

Thomas will cover Flavor tagging and boosted objects

Schematic by J. Dolen

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Particle Flow Charged Hadron Subtraction (CHS)

- Majority of pileup is from charged particles
- CHS removes individual charged hadrons from pileup vertices (ca. 2/3 of offset energy in barrel)
- Inherent limitation: Only works in tracker-covered region, only works on charged component
Run 3: PUPPI consistently used for AK4, too

Concept: neutral particles close to charged particles from LV are likely to be from LV.

Scale momentum by its PUPPI weight:

\[ P_T^{\text{PUPPI}} = P_T^i \times \omega_{\text{PUPPI}}(\alpha^i) \]

PUPPI is extendable to the forward region by redefining alpha with charged+neutral particles. Use for Run 3 as default (also AK4)
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- First public result with 13.6 TeV was top cross section measurement (Sep 2022)
- Use W mass to control jet-energy scale for early measurement
- Smooth commissioning of AK4PUPPI for Run 3

ArXiv:2303.10680
ATLAS: Calorimeter hits as starting point

- ATLAS LAr calorimeters more finely segmented
- TopoClusters as main input for jets: 3D clusters of noise-suppressed calo. cells
- With Run 2 Particle Flow became default, Track Calo Clusters, and Unified Flow Objects to improve substructure: Large-R jet paper
- ML Pion reconstruction

### Inner Detector
- Charged particle tracks
- Decay vertices e.g. Hard-Scatter vertex "PV"
- $|\eta| < 2.5$

### EM Calorimeter
- EM Showers
- $e/\gamma$ Energy & direction
- $|\eta| < 4.9$
- $\Delta\eta \times \Delta\phi = 0.025 \times \pi/128$

### Hadronic Calorimeter
- HAD showers
- Charged & neutral hadron Energy & direction
- $|\eta| < 4.9$
**ATLAS: Different jet types**

**Particle Flow: improve low $p_T$**
- Combine calorimeter + tracks without double counting
  - Associate tracks with $\geq 1$ topoclusters
  - Subtract calo energy deposits matching a track.
  - Remove PU tracks at the end using Charged Hadron Subtraction (CHS)

**Track Calo Clusters: Improve subjets**
- **Unified Flow Objects: Combine PF+TCC**
  - **TCC** to improve angular resolution at high $p_T$
  - **UFO** to optimize performance across whole $p_T$ range
    1. Start with tracks and PF objects
    2. Reduce PU
    3. Sparse environment PFOs $\rightarrow$ UFO
    4. Remainder $\rightarrow$ TCC split $\rightarrow$ UFO
  - Improves jet mass res. and PU dependence
  - **Run 3:** UFO with CS + SK and SoftDrop default large-R jets (and good for narrow-R jets)
Jet energy corrections (base schema)

Jet energy corrections (JEC) correct reconstructed jets on average back to particle level:

\[
\frac{\langle p_T^{\text{reco}} \rangle}{\langle p_T^{\text{gen}} \rangle} = 1
\]

(vs. \( p_T^{\text{gen}}, \eta, A, \text{pileup } \mu \))
Jet energy corrections (new developments)

- Change rho definition, use jets in impact-parameter sideband → reduced bias, smaller uncertainty
- 1D → 3D residual correction: adds correlation, corrections for extra detector effects
- Improved closure
Jet energy corrections (new developments)

Reconstructed jets
Jet finding applied to tracking, and/or calorimeter-based inputs.

$p_t$-density-based pile-up correction
Applied as a function of event pile-up $p_t$ density and jet area.

Residual pile-up correction
Removes residual pile-up dependence, as a function of $\mu$ and $N_{\mu}$.

Absolute MC-based calibration
Corrects jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated.

Global sequential calibration
Reduces flavour dependence and energy leakage effects using calorimeter, track, and muon-segment variables.

Residual in situ calibration
A residual calibration is applied only to data to correct for data/MC differences.

Global Sequential Calibration → Global Neural Network Calibration

Add more observables
Account for correlations
Improves Response & Resolution & JES Flavour uncs.

b-jet JES via $\gamma$+jet

ATLAS Simulation
$\sqrt{s} = 13$ TeV, Pythia 8 dijet
Anti-$k_t$, $R = 0.4$ jets (PFlow)
$0.7 < |\eta_{\text{det}}| < 1.3$

ATLAS Simulation
$\sqrt{s} = 13$ TeV, Pythia 8 dijet
Anti-$k_t$, $R = 0.4$ jets (PFlow)
$0.2 < |\eta_{\text{det}}| < 0.7$
Jet energy corrections (new developments)

- Not applied to PUPPI jets in Run 3, just monitored
- More inputs to global fit of residual corrections
- Transition to PUPPI for Run 3 (and first Run 3 publication with AK4 PUPPI jets)
Hadronic final states are a major part of the LHC physics program: Backgrounds/signals/pileup

- Improved “defaults” for Run 3, improved methods
- Close interplay with low-level reconstruction
- Machine learning crucial tool to improve performance

Also important: HL-LHC around the corner - new playground for exploiting detector upgrades
Backup
Standard heavy object tagging

Two main questions:
A. What is the mass of the object?

Need to remove softer constituents (QCD radiation)

CMS “baseline”: PUPPI soft drop mass

Softdrop/mMDT
- C/A declustering, stop if

\[
\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R_0} \right)^\beta
\]

CMS: \( \beta = 0 \) and \( z = 0.1 \)

Jet mass: \( m_{QCD} \to 0 \)
Standard heavy object tagging

- Quantify how well a jet can be subdivided into sub-jets
- CMS “baseline”: N-subjettiness ratio

Two main questions:
A. What is the mass of the object?
B. What is inside this object?

- Fully merged hadronic top jet
- Partially merged hadronic top (W jet + b jet)
For optimal performance access to jet-constituents more powerful than high-level observables (cf. e.g. JME-18-002)

Recent comprehensive comparison study ATL-PHYS-PUB-2022-039 on dataset made publicly available

ParticleNet best, though some increase in modelling uncs.