Introduction to Hadronic Final State Reconstruction in Collider Experiments (Part IX)

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Rolf Heuer (Director General, CERN):

“Beams collided at 7 TeV in the LHC at 13:06 CEST today, marking the start of the LHC research program. Particle physicists around the world are looking forward to a potentially rich harvest of new physics as the LHC begins its first long run at an energy three and a half times higher than previously achieved at a particle accelerator. ...”

That was at 4:06am (Arizona) this morning...

We were probably not awake but are as excited!

... and we already see two-jet events!

See event displays on the right!

Two different events!
Top: Muon candidate

Two collisions at the same time

Pile-up!
Recall: the experimentalists' view on jets

A bunch of particles generated by hadronization of a common source
- Quark, gluon fragmentation
As a consequence, the particles in this bunch have correlated kinematic properties
  - Reflecting the source by sum rules and Conservation laws
The interacting particles in this bunch generated an observable signal in a detector
  - Protons, neutrons, pions, photons, electrons, muons, other particles with laboratory lifetimes $\sim 10\text{ps}$, and the corresponding anti-particles
The non-interacting particles do not generate a directly observable signal
  - Neutrinos, mostly

What is jet reconstruction, then?

Model/simulation: particle jet
- Attempt to collect the final state particles described above into objects (jets) representing the original parton kinematic
  - Re-establishing the correlations
Experiment: detector jet
- Attempt to collect the detector signals from these particles to measure their original kinematics
  - Usually not the parton!
Detector Effects On Jets

**Change of composition**
- Radiation and decay inside detector volume
- "Randomization" of original particle content

**Defocusing changes shape in lab frame**
- Charged particles bend in solenoid field

**Attenuation changes energy**
- Total loss of soft charged particles in magnetic field
- Partial and total energy loss of charged and neutral particles in inactive upstream material

**Hadronic and electromagnetic cascades in calorimeters**
- Distribute energy spatially
- Lateral particle shower overlap
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**Hadronc and electromagnetic cascades in calorimeters**
Distribute energy spatially
Lateral particle shower overlap

- 10 GeV
- 1 GeV
- 100 MeV

$\eta$ $\phi$
Detector Effects On Jets

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\[ \phi \]

\[ \eta \]
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**Hadronic and electromagnetic cascades in calorimeters**
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Experiment ("Nature")

Jet Reconstruction Challenges

- Longitudinal energy leakage
- Detector signal inefficiencies (dead channels, HV...)
- Pile-up noise from (off- and in-time) bunch crossings
- Electronic noise
- Calo signal definition (clustering, noise suppression...)
- Dead material losses (front, cracks, transitions...)
- Detector response characteristics ($e/h \neq 1$)
- Jet reconstruction algorithm efficiency
- Lost soft tracks due to magnetic field

- Added tracks from underlying event
- Added tracks from in-time (same trigger) pile-up event
- Jet reconstruction algorithm efficiency

Physics reaction of interest (interaction or parton level)
Jet Reconstruction Challenges

Experiment ("Nature")

Jet calibration task is to unfold all this to reconstruct the particle level jet driving the signals...

- added tracks from underlying event
- added tracks from in-time (same trigger) pile-up event
- jet reconstruction algorithm efficiency
- longitudinal energy leakage
detector signal efficiencies (e/g for EM, EM, HV...)
pile-up noise from (off- and in-time) bunch crossings
detector response characteristics (e.g. e/h ≠ 1)
lost soft tracks due to magnetic field
dead material losses (front, cracks, transitions...)
detector signal definition (clustering, noise suppression...)
calo signal definition (clustering, noise suppression...)

physics reaction of interest (interaction or parton level)
Jet Reconstruction Challenges

Experiment ("Nature")

Jet reconstruction challenges:
- Added tracks from underlying event
- Added tracks from in-time (same trigger) pile-up event
- Jet reconstruction algorithm efficiency
- Longitudinal energy leakage
- Detector signal inefficiencies (dead channels, HV...)
- Pile-up noise from (on- and in-time) bunch crossings
- Calorimeter signal definition (turbid, noise suppression...)
- Pile-up noise from (off- and in-time) bunch crossings
- Detector response characteristics (e/h ≠ 1)
- jet reconstruction algorithm efficiency
- Lost soft tracks due to magnetic field
- Jet calibration task is to unfold all this to reconstruct the particle level jet driving the signals...

...modeling and calculations establish the link between particle and interaction level...

physics reaction of interest (interaction or parton level)
Jet Reconstruction Challenges

Jet calibration task is to unfold all this to reconstruct the particle level jet driving the signals...

...modeling and calculations establish the link between particle and interaction level...

...but how is this really done?

physics reaction of interest (interaction or parton level)
The experiment starts with the actual collision or the generator...

- Triggered collision with signal parton collision, fragmentation & underlying event (experiment), or:
- Interaction level calculation with fragmentation and underlying event modeling (simulations)

... go to the particles in the simulation ...

Here particle level event represent the underlying interaction and the full complexity of the physics of the collision in the experiment

... collect the detector signals ...

- From the readout (experiment), or:
  - Take the stable (observable) particles and simulate the signals in the detector (e.g., the calorimeter and tracking detector)(simulations)

... and compare them!

- Complex – need to include all experimental biases like event selection (trigger bias), topology and detector inefficiencies

This establishes particle jet references for the detector jets!

- Of course only in a statistical sense, i.e. at the level of distributions!
Jet Reconstruction Task

Experiment ("Nature")

Modeling Particle Jets

- Generated Particles
- Particle Jets

Jet Finding
Stable Particles
Decays
Particles
Fragmentation

\[ |M|^2 \otimes pdf (Q^2, x) \]

Multiple Interactions
Jet Reconstruction Task

Experiment ("Nature")

Modeling Calorimeter Jets

Reconstructed
Jets

Identified
Particles

Jet Finding

Reconstructed Calorimeter Signals

Signal Reconstruction

Raw Calorimeter Signals

Detector Simulation

Stable Particles

Reconstructed Calorimeter Signals

Jet Finding

Identified Particles

Reconstructed Jets

Stable Particles

Jet Finding

Raw Calorimeter Signals

Detector Simulation

Stable Particles

Reconstructed Calorimeter Signals

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Detector Simulation

Stable Particles

Reconstructed Calorimeter Signals

Jet Finding

Identified Particles

Reconstructed Jets

Stable Particles
Jet Reconstruction Task

Experiment ("Nature")

Measuring Calorimeter Jets

Reconstructed Jets

Identified Particles

Jet Finding

Reconstructed Calorimeter Signals

Signal Reconstruction

Raw Calorimeter Signals

Measurement

Observable Particles
What is jet calibration?

Straightforward: attempt to reconstruct a measured jet such that its final four-momentum is close to the true jet kinematics generating the signal.

Why is it needed?

Could compare simulated and measured calorimeter signals at any scale and deduct the true kinematics from the corresponding particle jet in simulation.

Remember energy scales in calorimeters?

But need to reconstruct any jet in the experiment

Even (or especially) the ones in events we have not simulated – which probably means new physics?

To understand these events the best measurement of the true jet independent of the availability of simulations for this specific event – no simulation bias allowed in general!

Can we calibrated without simulations at all?

Complex physics and detector environment – hard to avoid simulations for precision reconstruction!

But there are in-situ jet calibrations (more at another time from a special guest speaker!)

So jet reconstruction needs to include a calibration

Use a simulated calibration sample representing simple final state

Chose a somewhat understood Standard Model topology like QCD di-jets

Calibrate using measurable jet features

Establish functions using jet observables as parameters to calibrate calorimeter jets from a basic scale to the final jet energy scale

If done right, simulation biases can be reduced, especially concerning the correct simulation of the event topology

Understand the limitations (systematic error) in the context of the analysis

All this is the global subject of the remaining lectures!
Any jet calibration needs to be validated

First step is the initial closure test – apply the calibration to the same samples which were used to extract it

Residual (average) deviations from the expected or true jet energy should be small – can be considered a first input to the systematic error!

Then apply calibration to jets in other topologies/physics channels and measure deviation from expected kinematics – this is the validation

Often done with simulated physics as they have an intrinsic truth reference (particle jets)

Samples with widely different topology than calibration sample preferred, possibly even several topologies

Understanding biases introduced in any given procedure is part of the validation

Need to develop calibrations with least biases

Biases can be introduced by the use of simulations – physics model limitations, inappropriate calorimeter shower simulations and signal extraction modeling, ...

Also experimental biases due to trigger and event selections changing shapes of distributions etc. – more later!

Need to understand if small or hidden biases in calibration sample and chosen calibration model do not increase for other topologies

Calorimeter signal definition can introduce biases due to different sensitivities to noise, jet shape reconstruction, ...
Some obvious procedural requirements

Need the same signal treatment in data and simulation
   Including the same jet finder and jet finder configuration

Need to understand the detector data very well
   Need to unfold all signal extraction inefficiencies and any detector problem
   Can be done by including those into the simulated signal reconstruction (e.g. noise) or by developing corrections for the experimental data

Need to understand the detector simulation very well
   Signal defining electromagnetic and hadronic shower features need to be reproduced to highest possible precision

Jet reconstruction validation

Compare basic performance measures for data and simulation
   Signal linearity, relative energy resolution, jet shapes...

Level of comparison is good estimate for systematic error of a given reconstruction and calibration
   Assumes that simulation reflects state-of-art understanding of physics and detector
   Lack of understanding (data is the “truth”) then reflects measurement error

Ok, but...

Still have not told you how simulation based jet calibration is really done!
   Like to lay down the ground rules first!
Step Back: Calorimeter Signals

**Need to have another look at the calorimeter**

Basically all calorimeters at collider experiments show some level of non-compensation

For sure the ones in ATLAS and CMS are!

**Needs to be corrected for jet calibration**

And all other hadronic final state contributions like isolated hadrons, tau-leptons, and low pT hadronic signals

**Can this be done for highest spatial calorimeter granularity (cells)?**

Not easy to see – individual cell signal without any other context hard to calibrate in non-compensating calorimeters

Better to establish a larger context first to find out which calibration the calorimeter cell signal needs

Reconstructed jet itself – in ATLAS this is called **Global Calibration**

Topological cell clusters without jet context – in ATLAS this is called **Local Calibration**

**Cannot recommend to use cells directly to find jets:**

High multiplicity on input for jet finders

Negative signal treatment required for four-momentum recombination

  Noise can create E<0 in cells

Jets should consistent of significant (relevant) signal objects

  Cell signal not a good image of the particle flow in jets

**Larger calorimeter signal objects clearly preferred**

**Towers** of cells – add cell signal up in projective calorimeter towers

Topological **clusters** of cells – add cell signals following signal correlations in showers
Impose a regular grid view on event

\[ \Delta \eta \times \Delta \varphi = 0.1 \times 0.1 \text{ grid} \]

Motivated by particle Et flow in hadron-hadron collisions

Well suited for trigger purposes

Collect cells into tower grid

Cells signals can be summed with geometrical weights

\[ \text{Depend on cell area containment ratio} \]

\[ \text{Weight} = 1 \text{ for projective cells of equal or smaller than tower size} \]

Summing can be selective

Noise filter can be applied!

Towers have massless four-momentum representation

Fixed direction given by geometrical grid center

\[
\left( E_{\eta \varphi}, \eta, \varphi \right) \mapsto \left( E = p, p_x, p_y, p_z \right)
\]

\[ p = \sqrt{p_x^2 + p_y^2 + p_z^2} \]

\[
E_{\eta \varphi} = \sum_{\left( A_{\text{cell}}^{\eta \varphi} \cap A_{\eta \varphi} \right) \neq 0} w_{\text{cell}} E_{\text{cell}}
\]

\[
w_{\text{cell}} = \begin{cases} 
1 & \text{if } A_{\text{cell}}^{\eta \varphi} \leq \Delta \eta \times \Delta \varphi \\
< 1 & \text{if } A_{\text{cell}}^{\eta \varphi} > \Delta \eta \times \Delta \varphi
\end{cases}
\]