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

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The experimentalist’s view
(...my view)
A bunch of particles generated by hadronization of a common otherwise confined source
Quark-, gluon fragmentation
What Are Jets?

The experimentalist's view (...my view)

A bunch of particles generated by **hadronization** of a common otherwise confined source

- Quark-, gluon fragmentation

**Consequence of common source**

- Correlated kinematic properties
- Jet reflects the source by sum rules and conservation

Interacting particles in jet generate observable signal in detector

- Protons, neutrons, pions, kaons, photons, electrons, muons, and others with laboratory lifetimes > 10 ps (incl. corresponding anti-particles)

Non-interacting particles in jet do not contribute to directly observable signal

- Neutrinos, mostly

\[
\begin{align*}
(E_{\text{jet}}, \vec{p}_{\text{jet}}) &= \sum_{\text{all particles}} (E_{\text{particle}}, \vec{p}_{\text{particle}}) \\
&= (E_{\text{parton}}, \vec{p}_{\text{parton}}) \\
q_{\text{jet}} &= \sum_{\text{all particles}} q_{\text{particle}} = q_{\text{parton}} \\
m_{\text{jet}} &= \sqrt{E_{\text{jet}}^2 - |\vec{p}_{\text{jet}}|^2} \\
&= \sqrt{\sum_{\text{all particles}} E_{\text{particle}}^2 - \sum_{\text{all particles}} |\vec{p}_{\text{particle}}|^2} = m_{\text{parton}}
\end{align*}
\]
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**Non-interacting particles in jet**

- So not contribute to directly observable signal
  - Neutrinos, mostly

\[
\left( E_{\text{jet}}, \vec{p}_{\text{jet}} \right)_{\text{obs}} = \sum_{\text{interacting particles}} \left( E_{\text{particle}}, \vec{p}_{\text{particle}} \right) \\
\neq \left( E_{\text{parton}}, \vec{p}_{\text{parton}} \right)
\]

\[
q_{\text{jet}}^{\text{obs}} \neq q_{\text{parton}} \\
m_{\text{jet}}^{\text{obs}} \neq m_{\text{parton}}
\]
What is fragmentation?

- Hadronization of partons into particles
  - Confinement in QCD: gluon pair production
  - Gluon radiation

How can fragmentation be measured in an experiment?

- Reconstruct charged tracks in a given jet
  - Momentum fraction carried by these tracks reflects charged (hadron) production in hadronization

High track reconstruction efficiency and low momentum acceptance needed!

- Final state in $e^+e^-$ collisions at LEP ideal – very clean collision environment without underlying event, at center-of-mass energies from 90 to 209 GeV

Fragmentation function are derived from LEP data (1989-2000)

Can we measure the fragmentation of a given jet in hadron colliders?

- Basically impossible, as collision environment is too “messy”
  - Accidental inclusion of charged tracks not from jet (underlying event, pile-up)
  - Loss of relevant tracks hard to detect

Need to rely on models fully describing collision event

- Compare composition of detector jets with particle jets from simulations (generators) like PYTHIA, which implement the LEP fragmentation functions!
Parton jets – what is this?

- Basically a representation of an individual final state parton before hadronization.
- Still called a jet because a jet finding algorithm is applied to the simulated partonic final state.

Jet finders explicitly or implicitly apply spatial and kinematic resolution parameters and (kinematic) thresholds to the interactions.

- Two or more close-by partons can be combined to one jet.
- A parton may not make it into a jet because it is below threshold.

Parton jets are “biased” with respect to the jet finding algorithm and its configuration.

Particle jets

- These are jets from final state particles with lifetime > 10 ps.
- E.g., after hadronization of partons.

Sometimes non-observable particles like neutrinos or particles with very specific signal characteristics (muons) may not be included.

- E.g., the muon generated in semi-leptonic b-decays may not be considered part of the b-jet.

Here a jet finder is mandatory to produce these jets.

- Needs to recombine the bundle of particles coming from the same source (parton).
- Subjects particles to the same resolution parameters and thresholds as used for parton jets.

Attempt to match parton and particle jets may allow to understand effect of fragmentation on jet finding efficiencies, mis-clustering (wrong particles combined), and bias on kinematic reconstruction.

Particle jets are a good “truth” reference for detector jets.

- After all, particles generate the detector signal.
**Parton “Jets”**

Theoretical concept converting matrix element calculations into jet picture

- Depends on the order of the calculation
- Useful tool to link experimental results to calculations in di-quark resonance reconstruction
  - E.g., hadronic decays of the $W$ boson and heavier new particles like $Z'$

Much less meaningful concept in QCD analysis like inclusive jet cross-section

- Jet counting as function of $p_T$
- Number of parton jets not strictly linked to number of particle jets
  - Boundary between matrix element, radiation, parton showering, and underlying event washed out at particle level

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**QCD LO:**

$N_{jets} = 2$

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**QCD NLO:**

$N_{jets} = 3$
Parton “Jets”

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- Useful tool to link experimental results to calculations in di-quark resonance reconstruction
  - E.g., hadronic decays of the W boson and heavier new particles like Z' at LO

Much less meaningful concept in QCD analysis like inclusive jet cross-section

- Jet counting as function of pT
- Number of parton jets not strictly linked to number of particle jets
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LO decays are easy to tag:

- $W \rightarrow q\bar{q}'$ (2-prong decay)
- $Z' \rightarrow q\bar{q}'$ (2-prong decay)
- $t \rightarrow Wb \rightarrow q\bar{q}'b$ (3-prong decay)

→ expectations for number of jets from decayed particle hypothesis at given order
  + mass of jet system pointing to certain source!
Parton “Jets”

**Theoretical concept converting matrix element calculations into jet picture**
- Depends on the order of the calculation

**Useful tool to link experimental results to calculations in di-quark resonance reconstruction**
- E.g., hadronic decays of the $W$ boson and heavier new particles like $Z'$

**Basic QCD $2 \rightarrow 2$ processes at LO:**
- $gg \rightarrow gg$, $gq \rightarrow gq$, $q\bar{q} \rightarrow q'\bar{q}'$

but often observe more than 2 jets in final state due to higher order contributions, initial and final state radiation, and additional interactions from the underlying event

→ no obvious additional constraint on the appropriate parton level model from the observable final state, like in case of heavy particle decays!

→ experimental final state "includes" all orders of calculations and collision environment!!
Particle Jets

Collection of particles from common source

Several sources in each collision

- Hard scattering, multiple parton interactions in the underlying event, initial and final state radiation

Describe the simulated collision viewed with a microscope (idealized)

- Microscope technology – jet finding algorithm
- Resolution – ability of a jet finder to (spatially) resolve jet structures of collision, typically a configuration parameter of the jet finder
- Sensitivity – kinematic threshold for particle bundle to be called a jet, another configuration parameter of the jet finder
Usefulness of Particle Jets

**Good reconstruction reference for detector jets**

- Provide a truth reference for the reconstructed jet energy and momentum
  - E.g., can be used in simulations together with fully simulated detector jets to calibrate those (we will follow up on this point later!)
- Extract particle jets from measurement by calibration and unfolding signal characteristics from detector jets
  - Understand effect of experimental spatial resolution and signal thresholds at particle level
    - Remember: electromagnetic and hadronic showers have lateral extension → diffusion of spatial particle flow by distributing the particle energy laterally!
    - Remember: noise in calorimeter imply a “useful” signal threshold → may introduce acceptance limitations for particle jets!

**Good reference for physics**

- Goal of all selection and unfolding strategies in physics analysis
  - Reproduce particle level event from measurement as much as possible!
- Require correct simulations of all aspects of particle spectrum of collision right
  - Matrix element, parton showers, underlying event (non-perturbative soft QCD!), parton density functions,...
    - Parton shower matching to higher order matrix calculation in complex pp collision environment is a hot topic among theorists/phenomenologists today!
- Allow to compare results from different experiments
  - Specific detector limitations basically removed
    - Also provides platform for communication with theorists (LO and some NLO)
- Important limitations to be kept in mind
  - NLO particle level generators not available for all processes (more and more coming)
  - NNLO etc. not in sight
Jet Finding

Basic idea

Attempt to collect all particles coming from the same source in a given collision

Re-establishing the original correlations between these particles to reconstruct the kinematics and possibly even the nature of the source

Is an algorithmic challenge

Many algorithms on the market, with different limitations
No universal algorithm or algorithm configuration for all final state analysis

More later, but good to know right away!

Requires theoretical and experimental guidelines

Theory – physical features of particle jets addressed by sum (recombination) rules, stability of algorithm, validity for higher order calculations,…

Experiment – requirements for features of measured jets to allow most precise unfolding of particle jet, drives detector designs!

Guidelines often not very appreciated by older analysis/experiments

Often focus on extracting signal structures from experiment without worrying too much about theoretical requirements

LO analysis: apply any jet algorithm to measured signals and corresponding simulations with expectations to get the same physics

LHC kinematic reach and phase space need considerations of higher order calculations – need jet finders valid to (arbitrary!) order!
Very important at LHC

Often LO (or even NLO) not sufficient to understand final states

Potentially significant K-factors can only be applied to jet driven spectra if jet finding follows theoretical rules

E.g., jet cross-section shapes

Need to be able to compare experiments and theory

Comparison at the level of distributions

ATLAS and CMS will unfold experimental effects and limitations independently – different detector systems

Theoretical guidelines

Infrared safety

Adding or removing soft particles should not change the result of jet clustering

Collinear safety

Splitting of large pT particle into two collinear particles should not affect the jet finding