Jet Physics

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What are jets?

Definition:

Jets are collimated sprays of hadrons

A jet is the detector picture of the parton that initiated it (to a good approximation)
Jets play central role in new physics searches

Papers by ATLAS collaboration

1. Measurements of $W$ and $Z$ boson production in $pp$ collisions at $\sqrt{s} = 5.02$ TeV with the ATLAS detector
   CERN EP-2018-269
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvard | EndNote
   ADS Abstract Service
   Detailed record

2. Physics of Ridge and Hard Processes in Proton-Lead and Lead-Lead Collisions with ATLAS
   DOI: 10.5506/A Phys.Pol Suppl.11.595
   Conference: C18-02-11 Proceedings
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvard | EndNote
   Detailed record

3. Searches for Exotic Phenomena with the ATLAS Detector
   DOI: 10.5506/A Phys.Pol Suppl.11.419
   Conference: C18-03-11 Proceedings
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvard | EndNote
   Detailed record
Introduction to jets

Jets play central role in new physics searches

Papers by ATLAS collaboration which cite the anti-$k_t$ jet clustering algorithm, a widely used jet algorithm [22%]


Is LHC a CoM frame?

In hadron colliders, collisions are **not symmetric** (Lab frame \( \neq \) CoM frame).

Need to define **boost-invariant** momentum coordinates
Rapidity

Lorentz transformations for $E$ & $p_z$ along $z$ axis with speed $\beta = \tanh \varrho$

\[
\begin{align*}
E &= E' \cosh \varrho + p_z' \sinh \varrho \\
p_z &= p_z' \cosh \varrho + E' \sinh \varrho
\end{align*}
\]
\[
\begin{align*}
\frac{E + p_z}{E - p_z} &= \frac{E' + p_z'}{E' - p_z'} e^{2\varrho}
\end{align*}
\]

Define rapidity:

\[
y \equiv \frac{1}{2} \ln \frac{E + p_z}{E - p_z}
\]

Then $y \rightarrow y' = y + \varrho$, with $\varrho$ constant.

Rapidity differences $\Delta y$ are boost-invariant. Then for all particles in an event, can shift rapidities by same constant, and consider rapidity as boost-invariant.
Rapidity

Lorentz transformations for $E$ & $p_z$ along $z$ axis with speed $\beta = \tanh \varrho$

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\begin{align*}
E &= E' \cosh \varrho + p'_z \sinh \varrho \\
p_z &= p'_z \cosh \varrho + E' \sinh \varrho
\end{align*}
\]

\[\rightarrow \frac{E + p_z}{E - p_z} = \frac{E' + p'_z}{E' - p'_z} e^{2\varrho}\]

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Pseudo rapidity

For massless particles (or very energetic particles), we have $p \approx E$

$$\cos \theta = \frac{p_z}{p} \approx \frac{p_z}{E}$$

Then

$$y = \frac{1}{2} \ln \frac{1 + \cos \theta}{1 - \cos \theta} = \ln \cot \frac{\theta}{2}$$

Define pseudo-rapidity:

$$\eta = \ln \cot \frac{\theta}{2}$$

which equals rapidity in the massless (or high energy) limit. Useful quantity for experiment.
Pseudo-rapidity vs $\theta$
Pseudo-rapidity vs $\theta$

Strong coupling running

The renormalised coupling constant depends on diagrams like these:

\[
\mu^2 \frac{\partial \alpha_s}{\partial \mu^2} = \beta(\alpha_s) = -b_0 \alpha_s^2 + b_1 \alpha_s^3 + b_2 \alpha_s^4 + \cdots
\]

with \( b_0 = \frac{(11C_A - 4T_R n_f)}{12\pi} = \frac{(33 - 2n_f)}{12\pi} > 0 \),
\( b_1 = \frac{(153 - 19n_f)}{24\pi^2} \), \ldots

Notice First term in \( \beta \) function is negative (as apposed to that in QED).
Thus \( \alpha_s \) runs oppositely to \( \alpha_{\text{EM}} \).
At one loop $\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2)b_0 \ln(Q^2/\mu^2)}$
Asymptotic freedom

2004 Nobel Prize: David Gross, H. David Politzer and Frank Wilczek for “discovery of asymptotic freedom in the theory of the strong interactions”.

At high energy, quarks behave as free particles (perturbation theory applicable)
Confinement
But quarks/gluons not observed in particle detectors

When $Q \rightarrow \Lambda_{\text{QCD}}$ (large time scales), then $\alpha_s \rightarrow \infty \Rightarrow$ PT breaks.
Quarks undergo a hadronization: quarks and gluons are (eventually) confined into hadrons (confinement).

Hadronization (MC) Models
- Lund String Model
- Flux tube model
- Cluster model
- Independent fragmentation model
What happens when quarks hadronize?

Consider for example simple process in LEP $e^+e^- \rightarrow q\bar{q}$. 

\[
\begin{align*}
\text{Process} & : e^+ e^- \rightarrow q\bar{q} \\
\text{Diagram} & : \\
\text{Particles} & : e^+, e^-, q, \bar{q}, K^0, \pi^+ \text{ etc.}
\end{align*}
\]
What happens when quarks hadronize?

In flux tube model we have the following picture:

We get streams of hadrons in the directions of the initial $q\bar{q}$ pair: We get two jets of hadrons
2 Jet production at LEP
2 Jet production at LEP

Run: event 4093, Date 9:30:27, Time 29:7, CTk (N=3, SumPT=73.3), Ecal (N=25, SumE=32.6), Hcal (N=22, SumE=22.6)
Ebeam: 45.55 GeV, Evis: 99.9 GeV, PT (0, 0.06, -0.86), Muon (N=1, 0), Sec Vtx (N=3), Fdisk (N=0, SumE=0.05)
Beam: 3.5, Thrust: 0.9979, Apix: 0.0017, Ob/aj: 0.5246, Sph: 0.3037

Centre of screen is { 0.0000, 0.0000, 0.0000}
3 Jet event?
3 Jet event?
Is it 3 or 4 Jet event?
Jet algorithms

Need concrete definition of a jet, several are available in the market:

**Sequencial recombination (all CIS)**
- $k_t$ clustering algorithm
- anti-$k_t$ clustering algorithm (ATLAS & CMS)
- Cambridge/Aachen algorithm

**Cone algorithms (Mostly not CIS)**
- Mid-point cone algorithm (CMS)
- Iterative cone
- Seed-less infrared-safe cone algorithm (LHC) [CIS]
Sequential Recombination Jet algorithms

- ∀ hadron pairs \((i, j)\), define their distance
  \[ d_{ij} = \min \left( k_{ti}^p, k_{tj}^p \right) \left[ (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \right] ; \]

- ∀ hadrons \(i\), define its beam distance \(d_{iB} = k_{ti}^p R^2\).

- Find smallest of all distances, \(d_{\text{min}}\).

- If \(d_{\text{min}} = d_{iB}\), object \(i\) is a jet and is removed from list.

- If \(d_{\text{min}} = d_{ij}\), objects \(i\) and \(j\) are merged with \(p_{\mu} = p_{\mu i} + p_{\mu j}\) (other schemes available)

- Iterate until all objects are removed.

\(R\): **jet radius** (specified by user).

- \(p = -2\): anti-\(k_t\) algorithm [arXiv:0802.1189 [hep-ph]]
- \(p = 0\): Cambridge/Aachen algorithm [hep-ph/9707323]
Cone-type Jet algorithms

**Seedless infrared-safe Cone algorithm [arXiv:0704.0292 [hep-ph]]**

- Search for all stable cones of radius $R$ (in a seedless way)
  - **Definition**: Stable cone: cone pointing in same direction as 4-momentum of contents
- Resolve jet overlaps with split/merge procedure with overlap parameter $f$.

- An online tool for visualising impact of jet choice on dijet mass distribution (generated with Pythia)

- **FastJet**: a C++ lib for implementing $k_t$, anti-$k_t$, SISCone, and C/A algorithms in MC event generators
  - [https://fastjet.hepforge.org/](https://fastjet.hepforge.org/)
What algorithm, and what jet radius $R$?

**ATLAS’s choice:** Anti-$k_t$ with $R = 0.4, 0.6$

Why? required for jet energy scale calibration. HCal data does not provide 4-momentum of individual hadrons. Energy of jet is calibrated (calibration only available for specific jet radii).

Problematic for theorists: we need jet radius flexibility.

Solution: Particle flow at CMS with PID (and Topo-clusters at ATLAS?)

**CMS’s choice:** Mainly anti-$k_t$ with $R = 0.5, 0.7$

Particle flow can be used to construct jets with arbitrary radii.
Jets at ATLAS

ATLAS dijet event
Jets at ATLAS

ATLAS multi-jet event
Choice of algorithm

- Should project hard partonic structure of event, without much modification from QCD effects (parton shower, hadronization).
- Must be infrared and collinear-safe to be able to apply PT: soft/collinear gluons shouldn’t modify final-state jets.
- We have shown that optimal jet radii should be small in order to minimise so called non-global effects (important for observables defined in limited region of phase space).
How about choice of jet radius vs. NP effects
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Small-$R$ jets have less contamination from pile up and underlying event

$[\propto R^2]$
Jet definition

What choice of Jet algorithm & $R$ (for us theorists)?

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How about choice of jet radius vs. NP effects

However hadronization alters energy content of a small-$R$ jet

[hadronization effects $\propto 1/R$]
Jet substructure

Trimming
Grooming
Pruning
MDT
Filtering
Tagging