Jets and jet substructure

Gavin Salam (CERN)
with extensive use of material by Matteo Cacciari and Gregory Soyez

TASI
June 2013
JETS
Collimated, energetic bunches of particles
Jets date back to the late 1970s


To study jets, we consider the partial cross section $\sigma(E, \theta, \Omega, \epsilon, \delta)$ for $e^+e^-$ hadron production events, in which all but a fraction $\epsilon \ll 1$ of the total $e^+e^-$ energy $E$ is emitted within some pair of oppositely directed cones of half-angle $\delta \ll 1$, lying within two fixed cones of solid angle $\Omega$ (with $\pi\delta^2 \ll \Omega \ll 1$) at an angle $\theta$ to the $e^+e^-$ beam line. We expect this to be measurable.

$$\sigma(E, \theta, \Omega, \epsilon, \delta) = (d\sigma/d\Omega)_0 \left[ 1 - \left( g_F^2 / 3\pi^2 \right) \left\{ 3\ln \delta + 4\ln \delta \ln 2\epsilon + \frac{\pi^2}{3} - \frac{5}{2} \right\} \right]$$
And they’ve been used and studied at every collider since

gluon discovery:

event at TASSO
$\sqrt{s} = 27.4$ GeV, in 1979

event at LEP
$\sqrt{s} = 91.2$ GeV, in 1990s
And they’ve been used and studied at every collider since...

gluon discovery:

event at TASSO
\[ \sqrt{s} = 27.4 \text{ GeV, in 1979} \]

event at LEP
\[ \sqrt{s} = 91.2 \text{ GeV, in 1990s} \]
And they’ve been used and studied at every collider since.

gluon discovery:

- event at TASSO: $\sqrt{s} = 27.4$ GeV, in 1979
- event at LEP: $\sqrt{s} = 91.2$ GeV, in 1990s
And they’ve been used and studied at every collider since...
Find all papers by ATLAS and CMS
464 records found

1. Measurement of the W+W- cross section in pp collisions at sqrt(s) = 7 TeV and limits on anomalous WW gamma and WWZ couplings
   References | BibTeX | LaTeX(US) | LaTeX(EU) | HarvMac | EndNote
   ADS Abstract Service
   Detailed record

2. Measurement of the hadronic activity in events with a Z and two jets and extraction of the cross section for the electroweak production of a Z with two jets in pp collisions at $\sqrt{s} = 7$ TeV
   References | BibTeX | LaTeX(US) | LaTeX(EU) | HarvMac | EndNote
   ADS Abstract Service
   Detailed record
Pull out those that refer to one widely used jet-alg

272 records found

60% of papers use jets!
Jet usage at the LHC

- Tree level
- Monte Carlo
- (N)NLO
- BSM searches
- Higgs physics
- top physics
- MC validation
- PDF fits

Jets (theory tool)

- CKKW
- MLM
- MC + Tree
- Detector sim.

Jet X-sct

Detector unfolding

DETECTOR

Jet usage at the LHC
Two key aspects to discussing jets

How jets come to have the structure they do

How we “reconstruct” jets
Two key aspects to discussing jets

How jets come to have the structure they do

How we “reconstruct” jets

Most of the content of these lectures
Why do we see jets?

Parton fragmentation

\[ \int \alpha_s \frac{dE}{E} \frac{d\theta}{\theta} \gg 1 \]

Non-perturbative physics

\[ \alpha_s \sim 1 \]
Why do we see jets?

Gluon emission

\[ \int \alpha_s \frac{dE}{E} \frac{d\theta}{\theta} \gg 1 \]

Non-perturbative physics

\[ \alpha_s \sim 1 \]

soft-collinear structure (no colour)

\[ \frac{i}{p' + k'} ig_s \epsilon \cdot v(p) \]

drop \( k \) in numerator, use \( p'k + k'\epsilon = 2p.k, \ p'v(p) = 0 \)

get \( g_s \frac{p.\epsilon}{p.k} v(p) \) take \( p = (1, 0, 0, 1), \ k = E(\cos \theta, \sin \theta, 0, 1), \ \epsilon = (\sin \theta, -\cos \theta, 0, 0) \)

square the amplitude, put in phasespace:

\[ \frac{d^3k}{2E(2\pi)^3} \rightarrow \frac{E dE d\cos \theta d\phi}{16\pi^3} \]
Reconstructing jets
Jet finding as a form of projection

Projection to jets should be resilient to QCD effects
Reconstructing jets is an ambiguous task
Reconstructing jets is an ambiguous task

2 clear jets
Reconstructing jets is an ambiguous task

2 clear jets

3 jets?
Seeing v. defining jets

Introduction

Background knowledge

Jets are what we see.

Clearly(?) 2 jets here

How many jets do you see?

Do you really want to ask yourself this question for $10^9$ events?

Gavin Salam (CERN)

Reconstructing jets is an ambiguous task

2 clear jets

3 jets?

or 4 jets?
Make a choice: specify a jet definition

\[ \{P_i\} \xrightarrow{\text{jet definition}} \{j_k\} \]

- Which particles do you put together into a same jet?
- How do you recombine their momenta (4-momentum sum is the obvious choice, right?)

“Jet [definitions] are legal contracts between theorists and experimentalists”

-- MJ Tannenbaum

They’re also a way of organising the information in an event

1000’s of particles per events, up to 20,000,000 events per second
Cluster analysis or clustering is the task of grouping a set of objects in such a way that objects in the same group (called cluster) are more similar (in some sense or another) to each other than to those in other groups (clusters). It is a main task of exploratory data mining, and a common technique for statistical data analysis used in many fields, including machine learning, pattern recognition, image analysis, information retrieval, and bioinformatics.

There is no objectively "correct" clustering algorithm, but [...] "clustering is in the eye of the beholder."[1] The most appropriate clustering algorithm for a particular problem often needs to be chosen experimentally, unless there is a mathematical reason to prefer one cluster model over another.
Partitioning / centroid-based clustering [cone algorithms]
Example of a partitional algorithm

1) Choose K centroids at random
2) Assign objects to closest centroid, forming K clusters
3) Calculate centroid (mean of distances) of each cluster, update centroids
4) Check if an object in a cluster is closer to another centroid.
   Reallocate in case.
5) Repeat from step 3 until no object changes cluster anymore.

Step 1 (random centroids)
Step 2 (allocate objects)
Step 3 (move centroids)
Step 5 (end of iteration)
Example of a **partitional algorithm**

1) Choose K centroids at random
2) Assign objects to closest centroid, forming K clusters
3) Calculate centroid (mean of distances) of each cluster, update centroids
4) Check if an object in a cluster is closer to another centroid. Reallocate in case.
5) Repeat from step 3 until no object changes cluster anymore.

**One of the main shortcomings:**
result of final convergence can be highly sensitive to choice of initial seeds.
Also, the concept of ‘mean distance’ (to calculate the centroid) must be defined.
One of the simplest of the cone algs
e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a "jet" and remove from event

Notes
- "Hardest particle" is collinear unsafe
  more right away...
One of the simplest of the cone algs

\[ \text{e.g. CMS iterative cone} \]

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a "jet" and remove from event

Notes
- "Hardest particle" is collinear unsafe
- more right away...
Iterative Cone, Prog Removal (IC-PR)

One of the simplest of the cone algs

e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
  more right away...
One of the simplest of the cone algs

e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- **Sum the momenta** use as new seed direction, iterate until stable
- Convert contents into a "jet" and remove from event

Notes
- "Hardest particle" is collinear unsafe
  more right away...
Iterative Cone, Prog Removal (IC-PR)

One of the simplest of the cone algs

\[ \text{e.g. CMS iterative cone} \]

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta \text{use as new seed direction}, iterate until stable
- Convert contents into a "jet" and remove from event

Notes
- "Hardest particle" is collinear unsafe
  more right away...
One of the simplest of the cone algs

e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable

Notes
- "Hardest particle" is collinear unsafe
  more right away...
Iterative Cone, Prog Removal (IC-PR)

One of the simplest of the cone algs

- e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- **Sum the momenta** use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
- more right away...
One of the simplest of the cone algs
e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
  more right away...
One of the simplest of the cone algns
e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- **Draw cone around seed**
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
- more right away...
Iterative Cone, Prog Removal (IC-PR)

One of the simplest of the cone algs
e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
- more right away...
One of the simplest of the cone algs
e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes

- “Hardest particle” is collinear unsafe
  more right away...
One of the simplest of the cone algs (e.g. CMS iterative cone):

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes:
- “Hardest particle” is collinear unsafe... more right away...
One of the simplest of the cone algs

e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
  more right away...
Iterative Cone, Prog Removal (IC-PR)

One of the simplest of the cone algs

e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes

- “Hardest particle” is collinear unsafe
  more right away...

Draw cone

$p_t$/GeV

0 10 20 30 40 50 60

0 1 2 3 4 y
One of the simplest of the cone algs
e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
  more right away...
One of the simplest of the cone algs
\[\text{e.g. CMS iterative cone}\]

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
- more right away...
Iterative Cone, Prog Removal (IC-PR)

One of the simplest of the cone algs
e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe more right away...
Iterative Cone, Prog Removal (IC-PR)

One of the simplest of the cone algs

\begin{itemize}
  \item e.g. CMS iterative cone
  \item Take hardest particle as seed for cone axis
  \item Draw cone around seed
  \item Sum the momenta use as new seed direction, iterate until stable
  \item Convert contents into a “jet” and remove from event
\end{itemize}

Notes

\begin{itemize}
  \item “Hardest particle” is collinear unsafe
  \item more right away...
\end{itemize}
Iterative Cone, Prog Removal (IC-PR)

One of the simplest of the cone algs
\[ \text{e.g. CMS iterative cone} \]

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
  more right away...
Iterative Cone, Prog Removal (IC-PR)

One of the simplest of the cone algs
- e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
- more right away...
One of the simplest of the cone algs
e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
- more right away...

Seed = hardest_particle
One of the simplest of the cone algs
\[\text{e.g. CMS iterative cone}\]

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

**Notes**

- “Hardest particle” is collinear unsafe
  - more right away...
One of the simplest of the cone algs

e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
  
more right away...
One of the simplest of the cone algs

e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
  more right away...
Iterative Cone, Prog Removal (IC-PR)

One of the simplest of the cone algs

e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes

- “Hardest particle” is collinear unsafe
  - more right away...
One of the simplest of the cone algs
e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
  more right away...
Iterative Cone, Prog Removal (IC-PR)

One of the simplest of the cone algs  
e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
  more right away...
Iterative Cone, Prog Removal (IC-PR)

One of the simplest of the cone algs  
e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
  more right away...
One of the simplest of the cone algs
e.g. CMS iterative cone

- Take hardest particle as seed for cone axis
- Draw cone around seed
- Sum the momenta use as new seed direction, iterate until stable
- Convert contents into a “jet” and remove from event

Notes
- “Hardest particle” is collinear unsafe
  more right away...