Physics 290E - 11/9/22

What makes a good jet finding algorithm?

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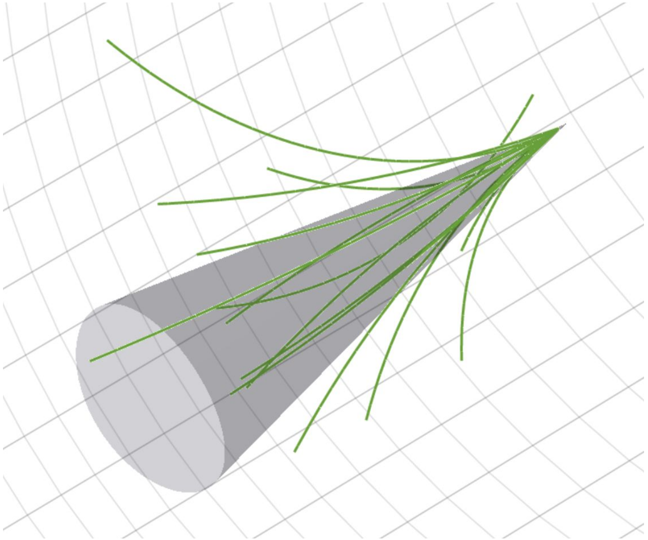
Outline

1. Jets and their characteristics
2. Jet reconstruction
3. Common algorithms

Part I: Jets and their characteristics

What is a jet?

- A **jet** is defined as a collection of hadrons produced by the **hadronization** of a quark or gluon
- Quarks hadronize when their composite particle fragments (into partons)
    - This occurs in high-energy interactions
- Experimentally, it looks like a cone of particle tracks



Particle jet observed by CMS

Why do we care about jets?

- Jets give us a window into studying quarks
  - Other particles (i.e. the Higgs) can be studied via their decays into quarks
- Quarks cannot exist as free particles due to color confinement
  - QCD: 3 color charges (red, green, blue)
  - All free particles must be colorless - quarks can only propagate in qqq or $q\bar{q}$ bound states
    - Mesons:
    - Baryons:

$$\psi^c(q\bar{q}) = \frac{1}{\sqrt{3}}(r\bar{r} + g\bar{g} + b\bar{b}).$$

$$\psi^c(qqq) = \frac{1}{\sqrt{6}}(rgb - rbg + gbr - grb + brg - bgr),$$

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A sketch of hadronization

- When quarks separate, the energy in their color fields increases, allowing for the creation of new quark antiquark pairs (parton branching)
- These quark pairs turn to hadrons when their energy becomes low enough (i.e. when this happens enough times)

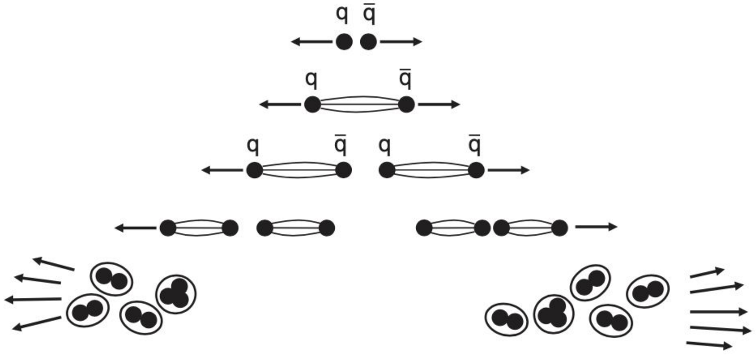
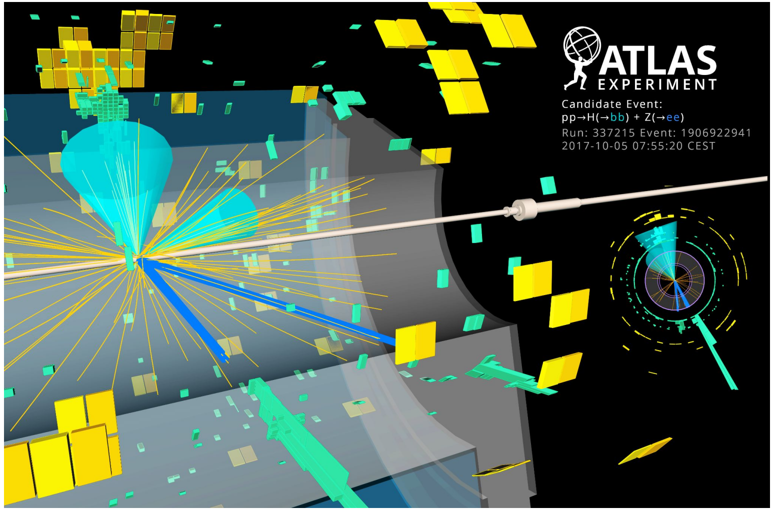


Diagram showing hadronization of a quark antiquark pair [Thompson]

Jets in practice

- Jets are messy objects
  - They are defined by the algorithms used to reconstruct them
- Jets come in multiples, often overlap
  - Proton proton collisions radiate partons
  - H, Z and W bosons decay to quark pairs
  - Gluons can also create jets
  - Pileup results in multiple interactions per event



Part II: Jet reconstruction

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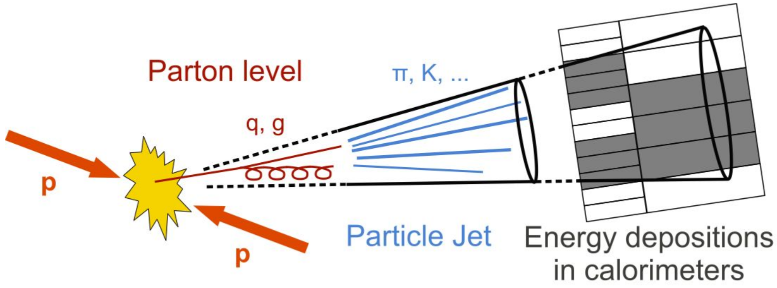
Setting up the problem



- Jets are measured in the tracker and calorimeter of a detector
  - Neutral particles only visible to calorimeter
  - Calorimeter has good energy resolution, tracker good position resolution
- Calorimeter clusters are matched to reconstructed tracks via ParticleFlow
  - Details of this depend on specific experiment
  - Allows for easier subtraction of pileup in calorimeter
- ParticleFlow objects are used as inputs to jet reconstruction algorithms
  - Algorithms also need to be able to work on partons - for theoretical calculations

Jet reconstruction requirements

Several important properties that should be met by a jet definition are:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross sections at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronisation.

Snowmass accord 1990

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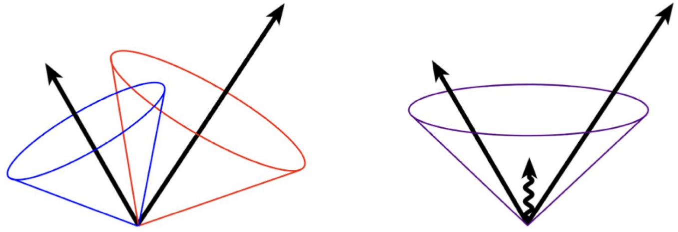
Overview of jet reconstruction

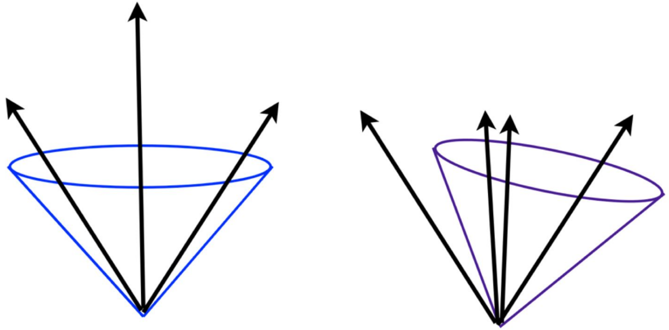
- Two general types: **cone** and **sequential clustering** algorithms
    - Cone algorithms group tracks in (η, ϕ) space and result in jets with circular boundaries
    - Sequential clustering algorithms group tracks in momentum space
        - They try to invert QCD parton branchings and combine two particles into one
- Jet radius **R** is an input parameter
- Also need a **recombination scheme**
    - Tells us how to get kinematic properties of a jet from its constituents
    - Mostly use “E-scheme”: sum up the components of 4-vectors

Infrared and collinear (IRC) safety

- Infrared safety: reconstructed jets are unaffected by the addition of soft partons
- Collinear safety: reconstructed jets are unaffected by the splitting of a parton into collinear partons
- Both of these things happen in higher-order perturbation theory



Infrared unsafety



Collinear unsafety

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Part III: Common algorithms

IC-PR and IC-SM

- Cone algorithms attempt to find “stable cones”
  - Use largest momentum track as seed jet axis and associate all tracks within a given radius before recalculating the axis based on the recombination of these tracks
  - Repeat until axis doesn’t shift anymore
- IC-PR: “iterative cone with progressive removal” (collinear unsafe)
  - Remove relevant tracks once “stable cone” is found and repeat until there are no more seeds that pass the momentum threshold
- IC-SM: “iterative cone with split-merge” (infrared unsafe)
  - Start with a set number of seeds and run split-merge once all cones are stable

SISCone

- Seedless cone algorithm that generates jets with smaller areas
  - Not rigidly limited to R like other cone algorithms
- Builds protojets by going through each track and considering all of its neighbors in a certain radius
  - Multiple circles are then drawn containing or excluding each of these particles and the jet axis is recalculated for each
  - Cones that include the same particles once their axis is updated are marked as stable
- Only IRC safe cone algorithm

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Generalized k_t algorithm

1. Start with a list of particles and calculate all *inter-particle* and *beam* distances: $d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p})\Delta R_{ij}^2, \quad d_{iB} = p_{t,i}^{2p} R^2,$
    a. Here, p is a free parameter, R is the jet radius and $\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta\phi_{12}^2}.$
2. Find the smallest distance among all d_{ij} and d_{iB}
    a. If a d_{ij} is the smallest, *i* and *j* are combined using a recombination scheme
    b. If a d_{iB} is the smallest, *i* is marked as a jet and removed from the list
3. Repeat steps 1 and 2 until the list is empty

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Variation of generalized k_t

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p})\Delta R_{ij}^2,$$
$$d_{iB} = p_{t,i}^{2p} R^2,$$

- k_t: p = 1
  - Low-momentum tracks get recombined first
  - Follows QCD branching structure
- Cambridge-Aachen: p = 0
  - Recombination does not depend on momentum, only on angular separation
- anti-k_t: p = -1
  - High-momentum tracks get recombined first
  - Generally used in ATLAS/CMS

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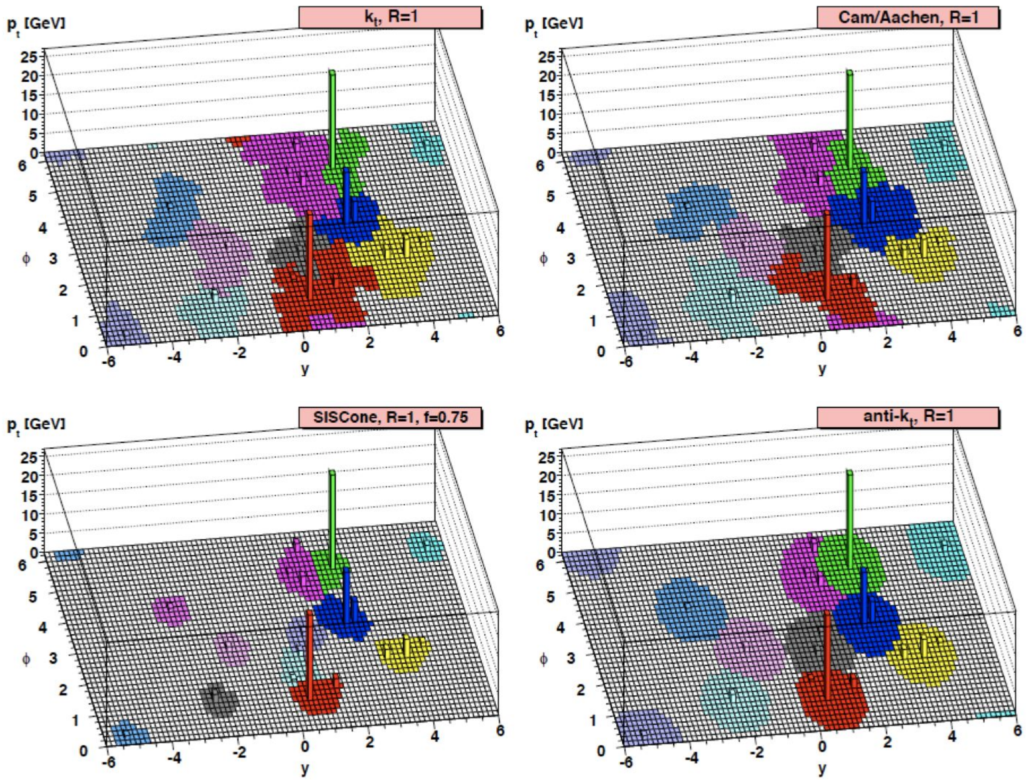
Why anti-k_t?

- Look at "catchment area" of jets
  - Jet area with addition of large number of "ghost particles" (soft radiation) to an event
- Anti-k_t jet shapes show the most resilience



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Conclusions

- Anti-k_t algorithm produces jets that are the most resilient to soft radiation and is therefore used primarily
  - Also much faster than e.g. SISCone
- Cambridge-Aachen and k_t are useful for jet substructure analysis since they are more connected to the physics
- These algorithms are fairly new
  - Probably more to come!

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