Jet Algorithms

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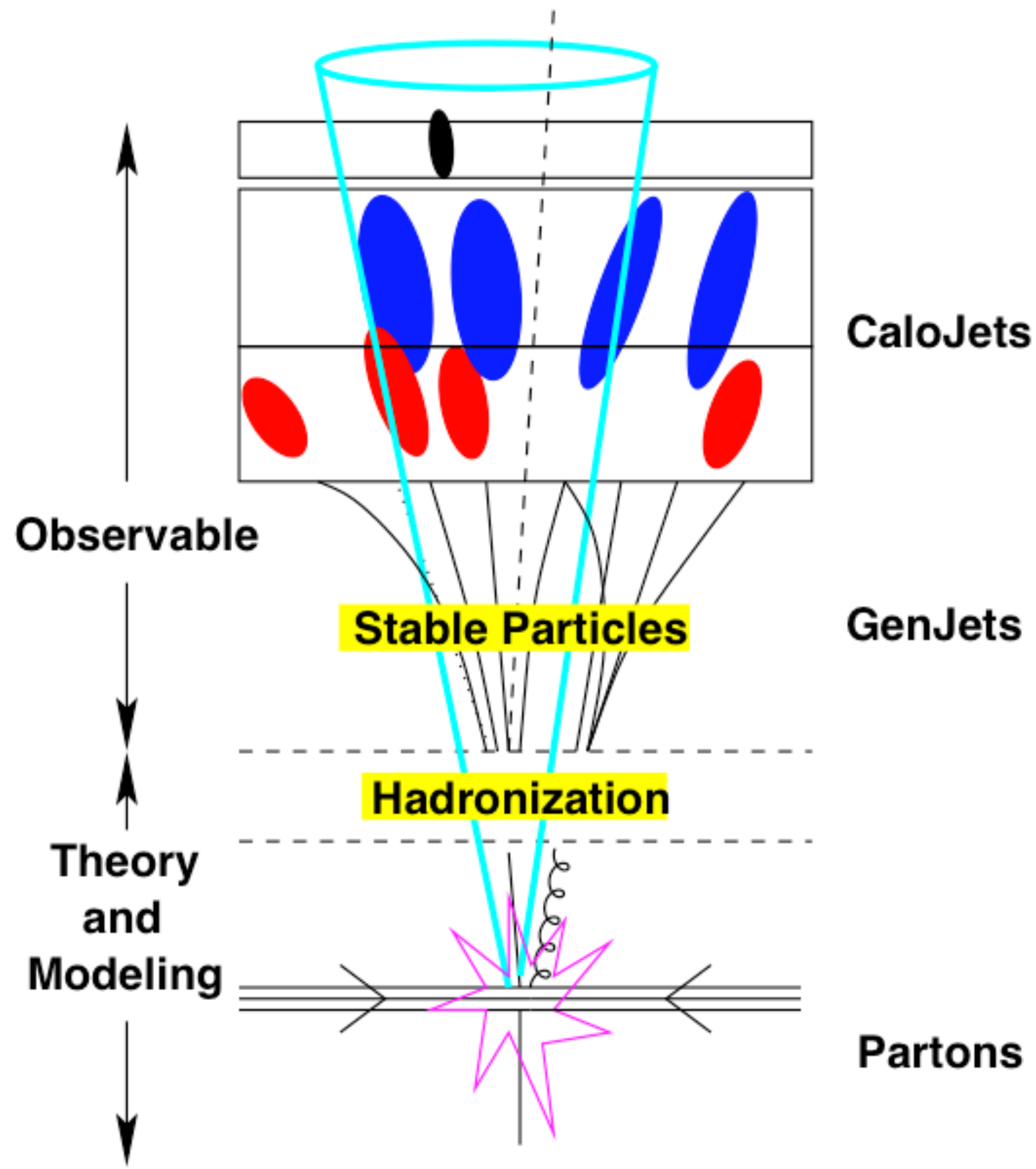
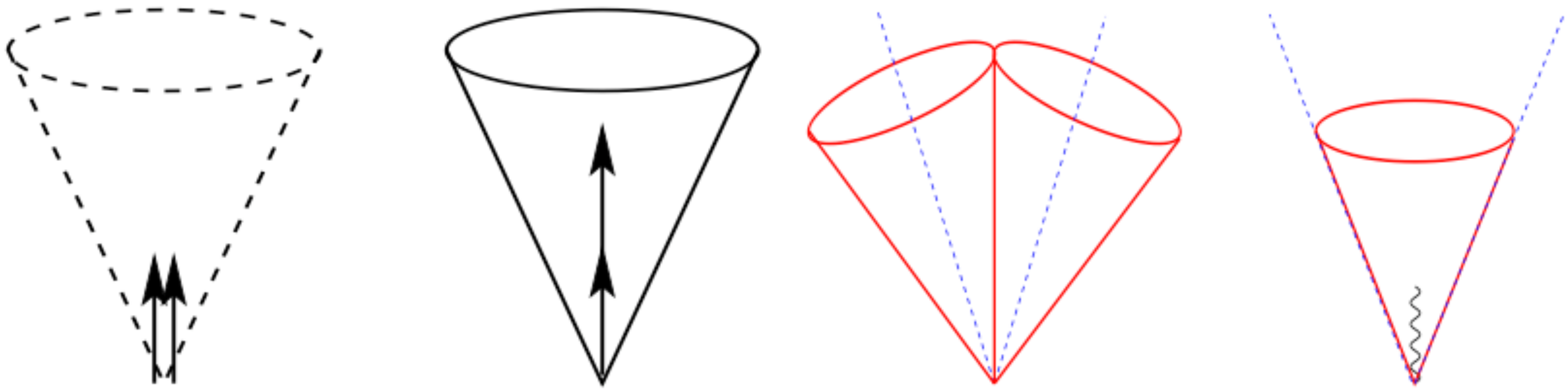
What are Jets?

- Collimated bunches of stable hadrons, originating from **partons** (quarks & gluons) after **fragmentation** and **hadronization**
- Jet Finding is the **approximate** attempt to reverse-engineer the quantum mechanical processes of fragmentation and hadronization
  - ★ not a unique procedure -> **several** different approaches
- Jets are the observable objects to relate experimental **observations** to theory **predictions** formulated in terms of quarks and gluons



Jet Requirements

- Collinear- and Infrared-Safe
  - ★ collinear splitting shouldn't change jets
  - ★ soft emissions shouldn't change jets



Collinear-Safety Infrared-Safety

- Identical proceduer on parton- and hadron-level
  - ★ To compare theory calculations to experimental measurements
- Minimal sensitivity to hadronization, underlying event (UE), Pile-Up(PU)
  - ★ we dont' know how to model these effects all that well
- Applicable at detector-level
  - ★ good computational performance
  - ★ not to complex to correct

IRC-Safety

arXiv:0704.0292

"Infrared unsafety is a serious issue, not just because it makes impossible to carry out meaningful (finite) perturbative calcuations, but also because it breaks the whole relation betweeb the (Born or low-order) partonic structure of the event and the jets that one observes, and it is precisly this relation that a jet algorithm is supposed to codify: it makes no sense for the structure of multi-hndred GeV jets to change radically just because hadronisation, the underlying event or pileup threw a 1 GeV particle in between them."

Jet Algorithms

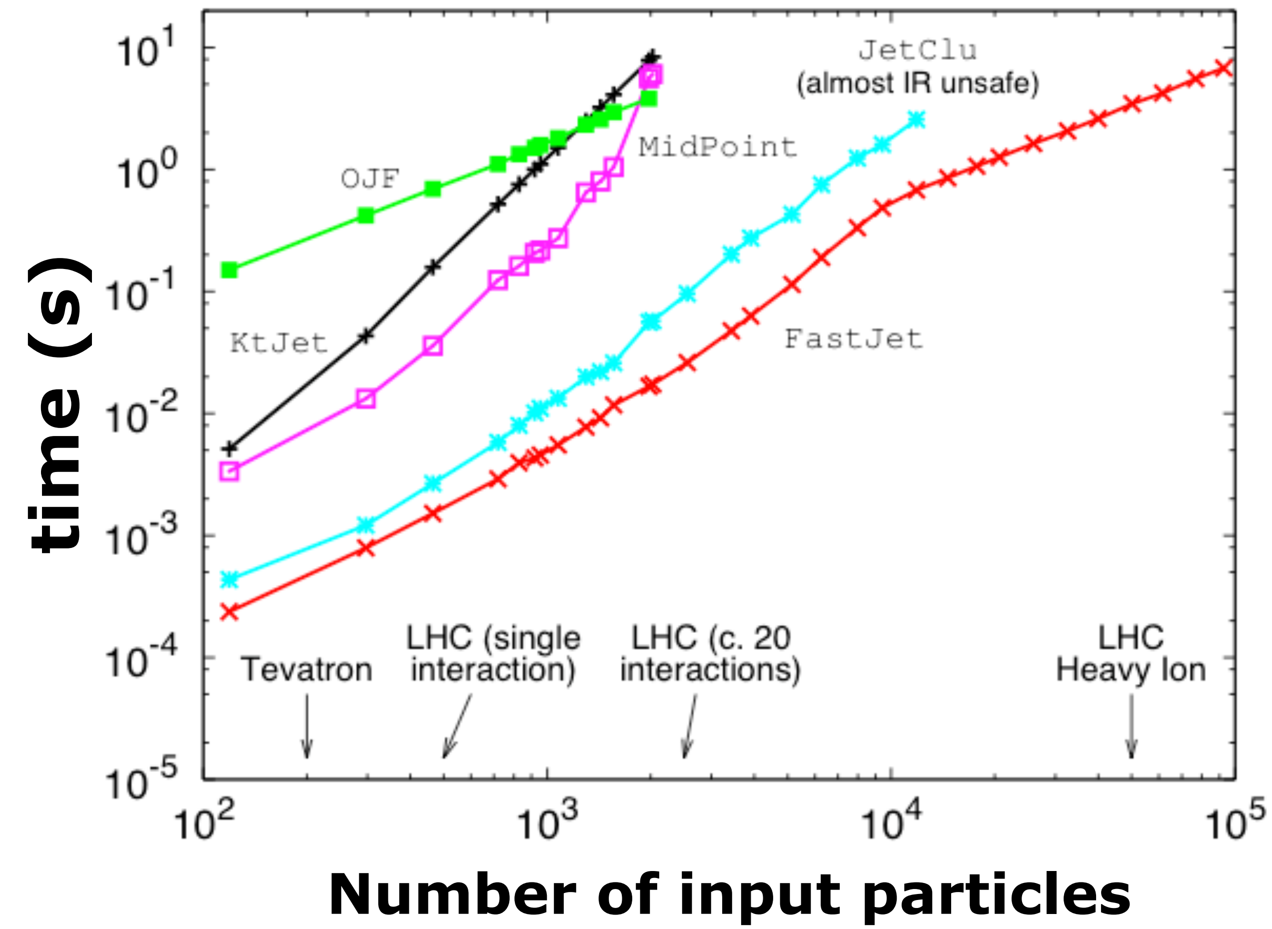
Two kinds of mainstream algorithms:

- **Cone-Type Algorithms**
  - ★ Midpoint Cone (Tev), Iterative Cone (CMS), SISCone (LHC)
  - ★ Typically not Infrared- & Collinear-Safe (exception: SISCone)
  - ★ Typically complex, invoving several (non-phyiscal) parameters
  - ★ Favored at hadron colliders (computational performance?)
  - ★ Strongly disfavored by theorists

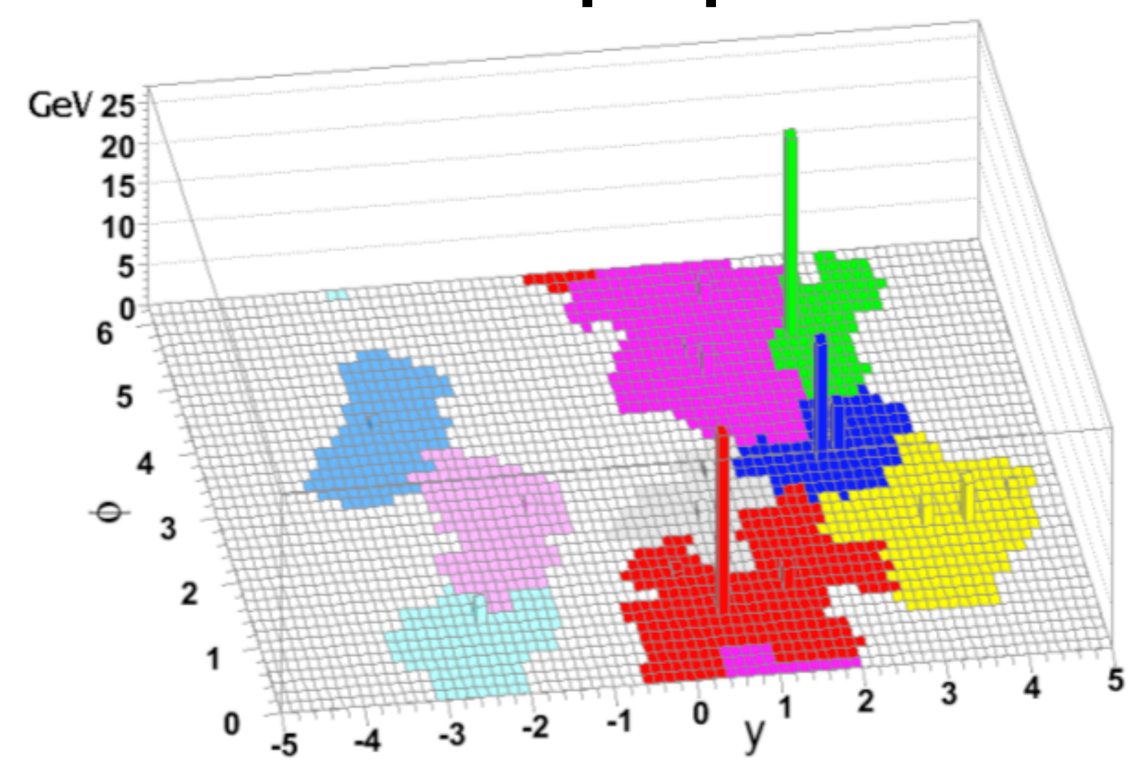
- **Sequential Clustering Algorithms**
  - ★ kT, Cambridge/Aachen, Anti-kT
  - ★ Infrared- & Collinear-Safe by construction
  - ★ Clean & Simple Algorithms
  - ★ Strongly favored by theorists
  - ★ Not widely used at hadron colliders in the past
    - computational performance **(SOLVED)**
    - jet area not trivially accessible **(SOLVED)**

Fastjet

- C++ library providing **fast** (!) JA implementation
  - ★ kT, Cambridge/Aachen, Anti-kT, SISCone
  - ★ Sequential Clustering: yielding bit-**identical results** w.r.t. prior implementations featuring **dramatically improved performance**



- Fastjet also introduces concept of **jet area** for sequential clustering algorithms ("jet catchment area")
  - ★ actually, for **all** IRC-safe algorithms
  - ★ important to address UE & PU contributions which will be significant at the LHC, and are typically measured per unit area of the calorimeter surface

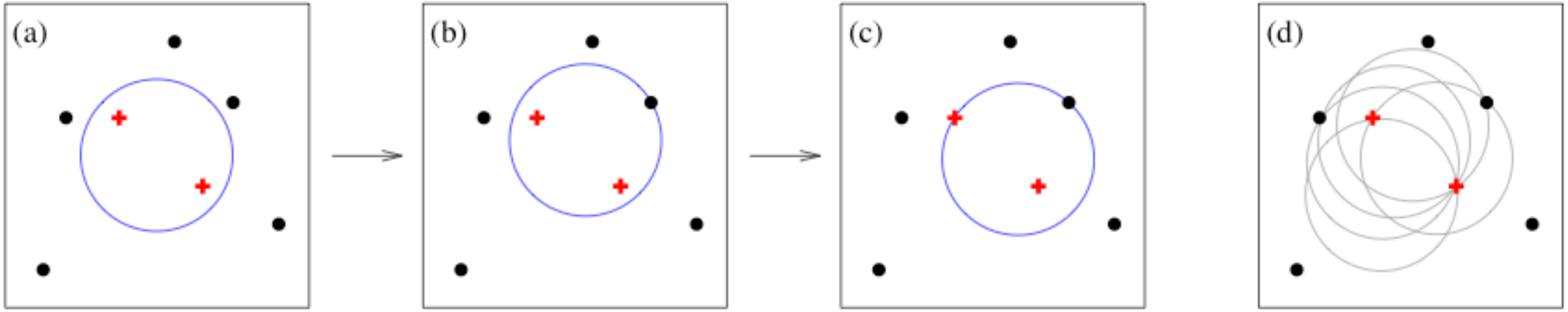


Iterative Cone Algorithm

- Find most energetic particle in event -> SEED
- Put a cone of radius R around the seed, sum up momenta of all particles enveloped by cone -> TRIAL JET
- Compare trial jet axis with seed axis
- if identical within precision -> STABLE CONE -> JET
  - ★ remove all particles belonging to the jet, then proceed with next most energetic particle as seed
- otherwise, iterate with trial jet axis as new seed until convergence
- Until no seeds above certain threshold (CMS: 1GeV) are left

SISCone Algorithm

- "Seedless Infrared-Safe Cone" Algorithm
- Exact seedless cone algorithm which provably finds all stable cones
- Collinear- and Infrafred-Safe
- Acceptable computational performance ($\sim N^2 \ln N$)
  - ★ existing approach: $\sim N 2^N$ -> 10^{17} years (!!) for N=100
- Currently: standard cone-type algorithm at CMS



2D Simplification: Moving (a) initial circular enclosure in a random direction until it some **particle** (b) touches the circle, then pivot the circle around that edge point until (c) a second point touches the edge. (d) all circles defined by pairs of edge points are all stable cones

Sequential Clustering Algs

- Based on the following **distance measures**:
  - ★ distance $\mathbf{d_{ij}}$ between two particles i and j:

$$d_{ij} = \min\left(k_{\mathrm{T}i}^{2p}, k_{\mathrm{T}j}^{2p}\right)\frac{\Delta_{ij}}{D} \qquad \Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

  - ★ distance between any particle i and the beam (B) $\mathbf{d_{iB}}$:

$$d_{iB} = k_{\mathrm{T}i}^{2p}$$

- Compute all distances d_{ij} and d_{iB}, find the **smallest**
  - ★ if smallest is a dij, **combine** (sum four momenta) the two particles i and j, update distances, proceed findint next smallest
  - ★ if smallest is a diB, **remove** particle i, call it a **jet**

- Repeat until all particles are clustered into jet

- Parameter **D**: Scales the dij w.r.t. the diB such that any pair of final jets a and b are at least separated by $\Delta_{ab}^2 = D^2$

- Parameter **p**: governs the relative power of of energy vs geometrical scales to distinguish the three algorithms: **2**=kT, **0**=C/A, **-2**=Anti-kT

kT Algorithm

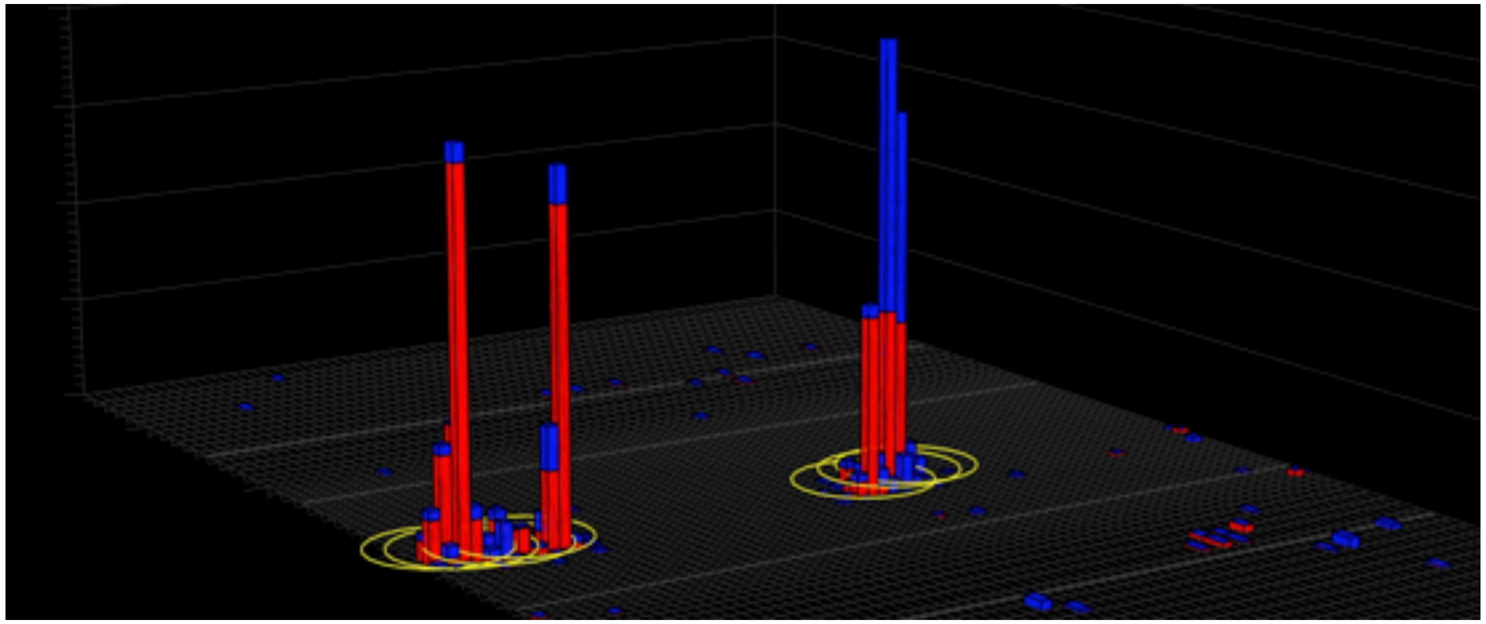
- Sequential clustering algorithm with the longest history, extensively used at LEP
- kT distance measures are closely related to structure of divergences in QCD emissions: **kT attempts approximate inversion of QCD branching process**
- Used to be computationally slow, now **fast like hell** thanks to fastjet implementation!
- Only one single parameter: D
- Available in CMS with D=0.4 and D=0.6

Cambridge/Aachen Alg

- Distance measure only based on geometrical scale: particles are clustered exclusively based on **spatial separation**, without considering energies/momenta

- First CMS studies currently underway, but no striking features/ advantages over existing set expected

- BUT: C/A has been shown to provide the best performance when it comes to resolve **jet substructure**!
  - ★ undoing the pair-wise clustering of a jet step-by-step yields its "subjets"
  - ★ Promising strategies to find e.g. **high-pT** top quarks & Higgs bosons are currently studied at CMS based on subjets using the C/A algorithm



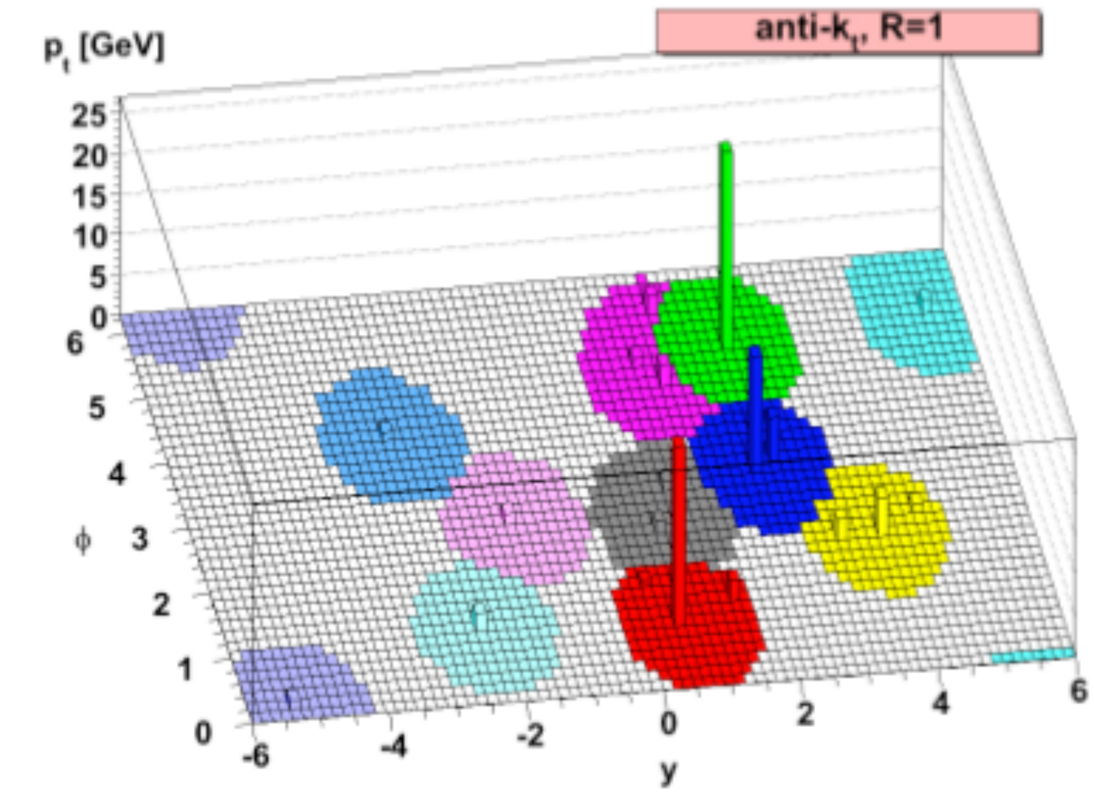
$$Z' \rightarrow t\bar{t}$$

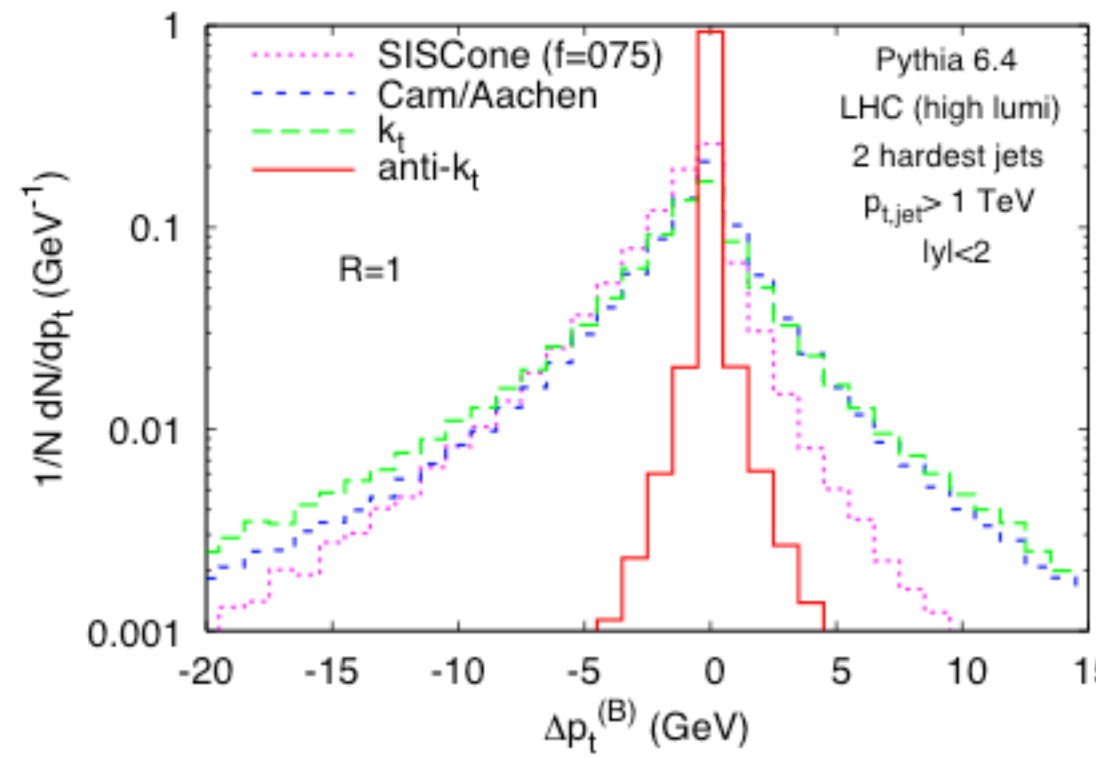
Anti-kT Algorithm

- Despite being a IRC-safe sequential clustering algorithm: produces **cirular cone-shaped jets**!

- Many similar features and performance (expected, under study) as iterative cone, without the assoc. short-commings

- Shown to be particularly **insensitive to UE & PU**
  - ★ "back-reaction": net transverse momentum change of 200GeV leading jets in QCD dijet sample when adding high-lumi PU to the event





Summary

- Jets are the key to revealing nature's secrets from LHC collisions! And FUN! :)
- You should come & participate to the CMS Jet-Algorithm Meetings, which take place bi-weekly on Thursday, 17^{30}
  - ★ Next: April 23rd
  - ★ subscribe to **hn-cms-jet-algorithms@cern.ch**
  - ★ take a look at **https://twiki.cern.ch/twiki/bin/view/CMS/JetAlgorithms**
- You might want to check out this cool page which demonstrates the performance of different JAs for different physics purposes: **http://www.lpthe.jussieu.fr/~salam/jet-quality/**

References

- JA in CMS:
  http://cms.cern.ch/iCMS/jsp/openfile.jsp?tp=draft&files=AN2008_001_v4.pdf
  http://cms.cern.ch/iCMS/analysisadmin/get?analysis=JME-07-003-pas-v2.pdf
  Note in preparation, pre-approval target: May 11th
- **Fastjet**: http://www.lpthe.jussieu.fr/~salam/fastjet/
- **kT:** http://arxiv.org/abs/hep-ph/0512210
- **SISCone**: http://arxiv.org/abs/0704.0292
- **Anti-kT**: http://arxiv.org/abs/0802.1189
- **Jet Areas**: http://arxiv.org/abs/0802.1188