High Energy Physics and Jets

Jacob Miner

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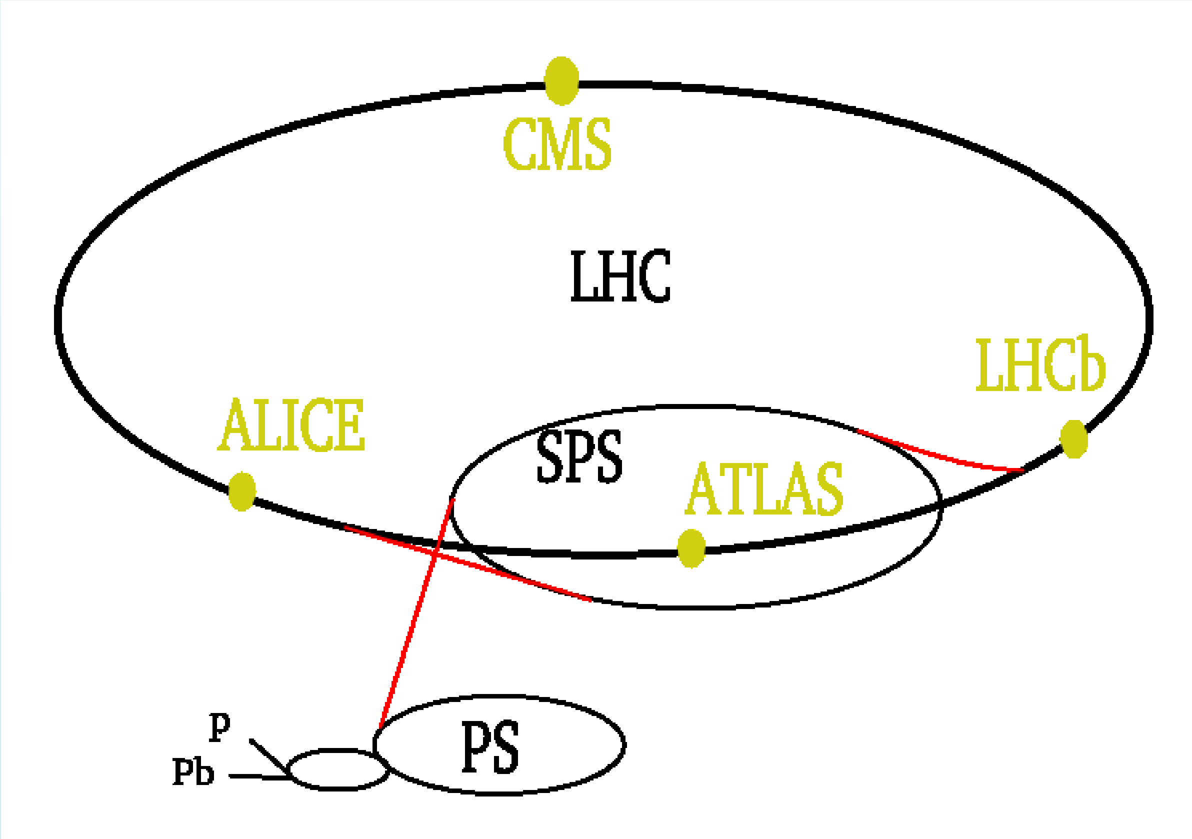
Outline

- Inside Colliders and Detectors
- What is Phenomenology?
- Data Analysis
- Jets
- Jet Algorithms

Large Hadron Collider

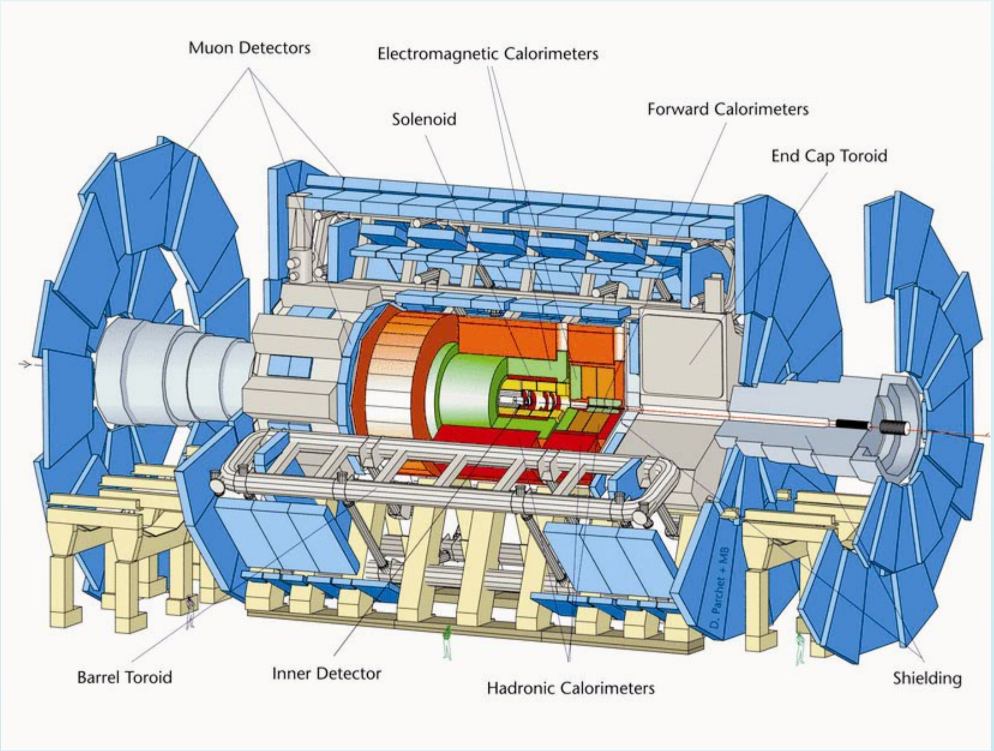
- 14 TeV p^+p^+ collider
- LHC Olympics -
  - community-wide competition
  - given an unknown data set to analyze and explain



Colliders

- **Linear** or **Circular** particle accelerators
  - accelerate charged particles using magnets $+$ E-fields
  - either collides 2 beams or a beam with a fixed target

- colliders produce $e^{\pm}$, γ, gluons, quarks etc.
  - quarks $+$ gluons shower into **jets** - a cone of hadronic particles ($\pi^{\pm,0}$ ...)



Detectors

- **trackers** - designed to locate charged particles
  - semiconductor based for charged particles
  - pixel tracker for vertex location

- **calorimeters** - designed to measure energy of particles
  - stops all particles except μ, ν
  - inner electromagnetic calorimeter for e, γ
  - outer calorimeter for hadrons

- **triggers** - determines if an event is worth recording
  - Hardware and Software based -programmed to ‘know’ what is an interesting event (is this a dangerous bias?)
  - Reduces Standard Model background - records less than 1 in 10^5 events

Phenomenology

- **Goal** is to connect theory and experiment
- detection errors - e vs. μ
- smearing of the event
- geometry - two “holes” on the ends of the detector
- initial state
  - net charge (ie. p^+p^+)
  - net momentum (ie. e^+e^-)

Data

- What does the compiled data look like?

$\#$	typ	eta	phi	pt	$jmas$	$ntrk$	$btag$	$had\backslash em$
1	4	-3.491	6.118	6.92	0.99	25.0	0.0	41.14
2	1	-0.085	1.151	210.39	0.00	-1.0	0.0	0.00
3	6	0.000	3.194	519.76	0.00	0.0	0.0	0.00

- Typ $=$ particle type 0$= \gamma, \ldots$

- $\eta =$ pseudorapidity $= -\ln(\tan(\frac{\theta}{2}))$

Data

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- ϕ = azimuthal angle
- p_t = transverse momentum $\sim$ p orthogonal to the beam axis
- j_{mass} = invariant mass $\sim \sqrt{p^\mu p_\mu}$
- ntracks = number of tracks and charge information

Data

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- btag $=$ (for jets) does the jet contain a b-quark
- $\frac{had}{em}$ $=$ ratio of energy dumped in hadronic and electromagnetic colorimeters
  - $\frac{had}{em} > 1$ for jets, $\ll 1$ for γ, e

Jets

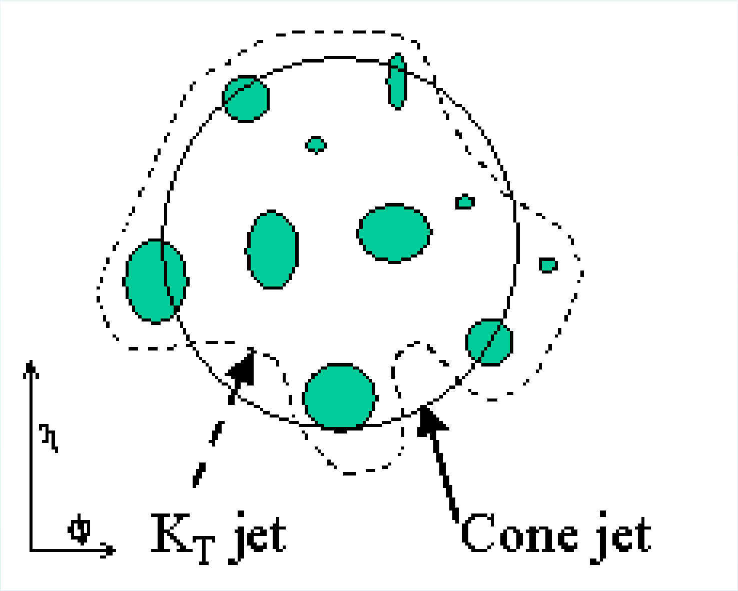
- come from quarks or gluons showering
  - both carry color, which must be confined into color-neutral objects
  - the hadrons can also decay into more hadrons
- inherently amorphous - there is **no** strict mapping from the short distance quark/gluon state to the long-distance final state particles

Jet Algorithms

- Need a specific definition to find jets

- Debate - what is the most consistent with experiment and theory

  - Cone ∼ finds energy within a circular region in the calorimeters
  - KT ∼ combines particles using 4-momentum as a gauge of proximity



Cone Algorithm

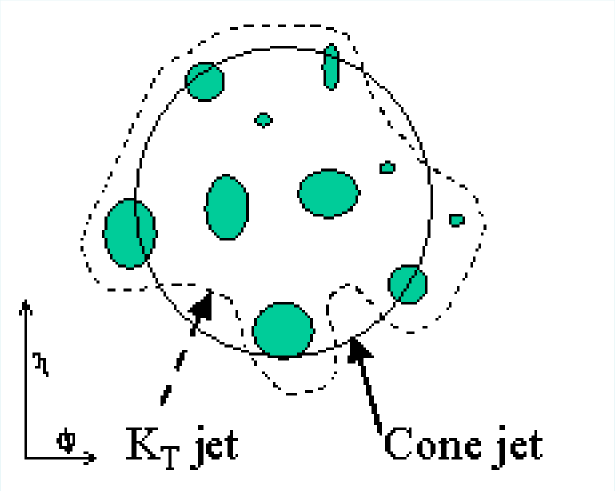
1. defines seeds as a calorimeter readings above a pre-defined value (say 1 GeV)
   - technically we should look everywhere but this is simpler
2. Sums the energy within a certain radius of each seed
3. calculates the cone's centroid
   - if $\eta^{centroid} = \eta^{cone}$ and $\phi^{centroid} = \phi^{cone}$ then this is a jet (ie it is stable)
   - If not we move to the position of the centroid and iterate
4. repeated until only stable cones (jets) are left

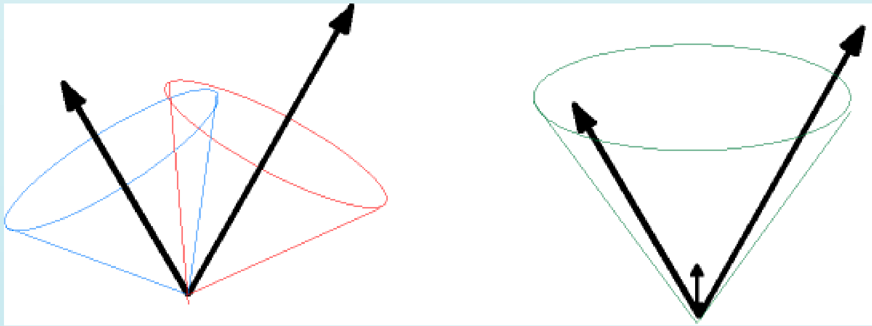
Cone Algorithm Problems

- What do we do if cones overlap?

- Cone algorithms have a splash-out effect (data effect)

- Seeds cause Infrared sensitivity (perterbation theory)





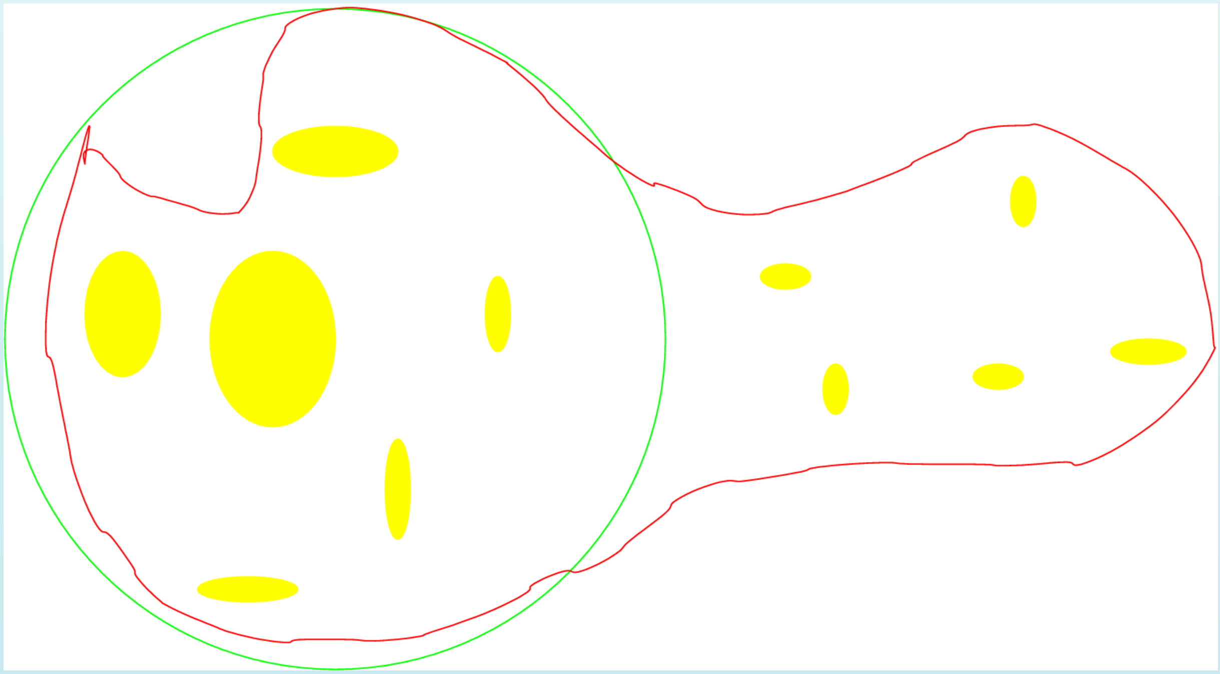
k_t Algorithm

1. combines particles i,j pairwise based on proximity in momentum space (starting with lowest energy)

   - calculates distance for i,j $d_{ij} = min(k_{ti}^2, k_{tj}^2)\frac{R_{ij}^2}{D^2}$
   - $R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$
   - distance from the beam, $d_{iB} = k_{ti}^2$
   - finds min. of all d_{ij}
     - if it is between two particles, they are merged
     - if it is between a particle and the beam, we have a jet

k_t Algorithm Problems

- the k_t algorithm has a splash-in effect



Solutions to Algorithm Problems

- **ALL** jet algorithms have their own quirks
- Seedless Algorithms $\sim$ place trial cones everywhere
- Split/Merge phase puts energy in one cone based on f_{merge} (ie. which cone has more of the overlapping energy)
- Midpoints for cone $\sim$ search between cones less than 2 cone radii apart

Algorithm Timing

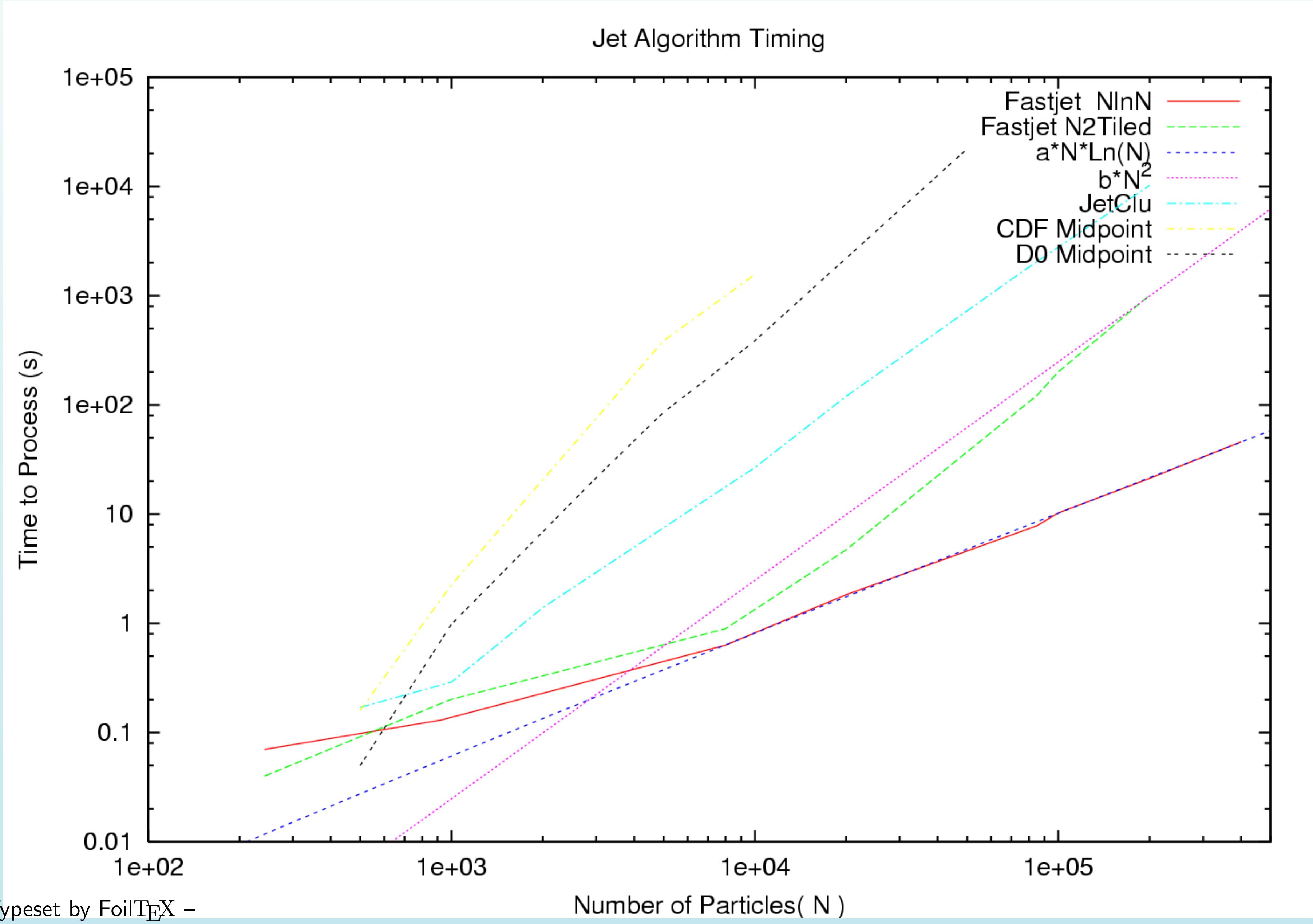
- With so many events occurring and large numbers of particles, processing jets needs to be fast
- Need to understand how time scales with N (the number of particles in an event)
- In particular what part of the algorithm takes the longest and can we optimize this?

Fastjet

- uses geometry algorithms to speed up the process

- Reduces time from $\mathcal{O}(N^3)$ to $\mathcal{O}(N\ln(N))$

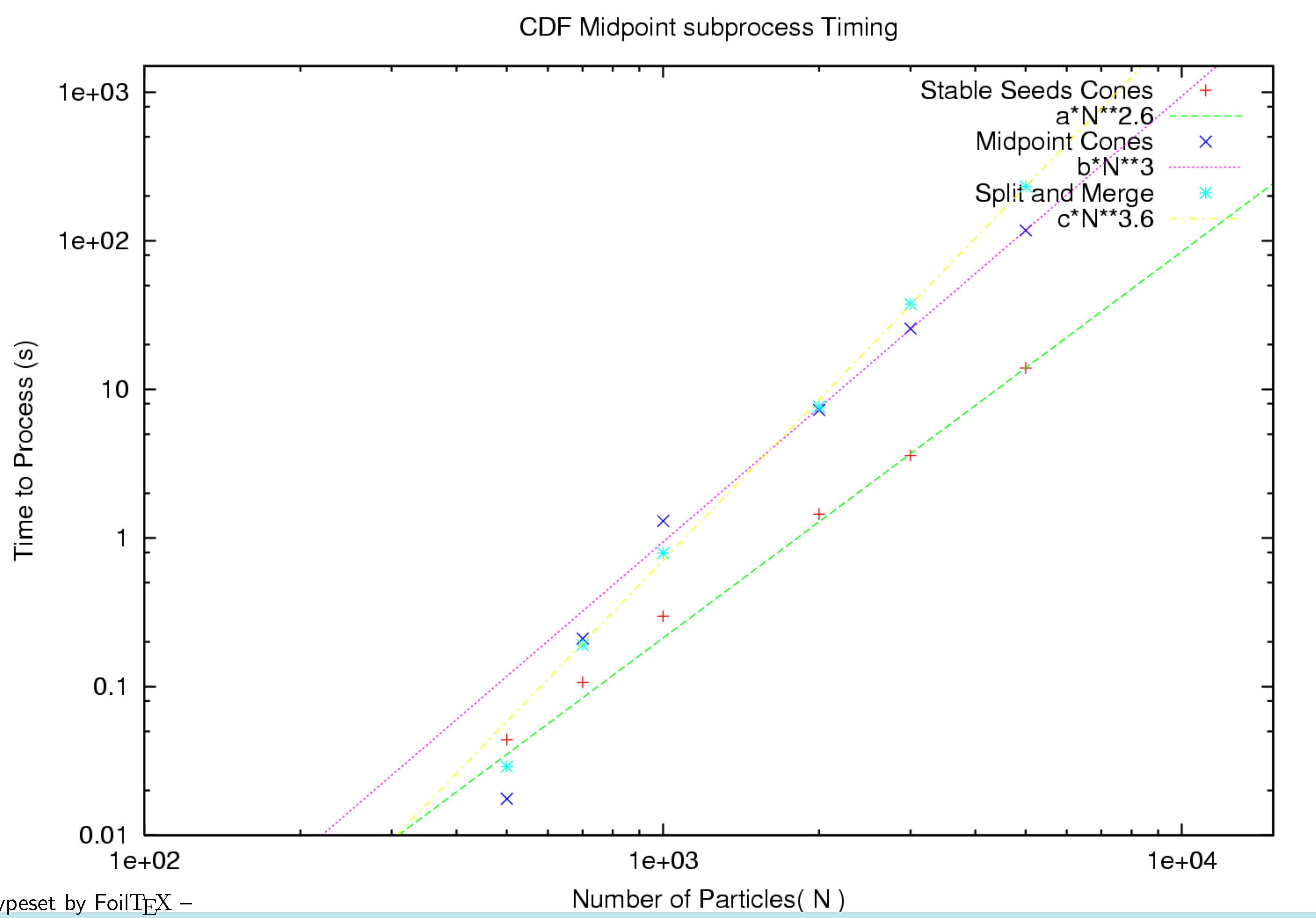
  - KT algorithms take $\mathcal{O}(N^2)$ to compute d_{ij}
  - this is repeated N times for total of $\mathcal{O}(N^3)$
  - Fastjet uses efficient list management (nearest neighbor)


Jet Algorithm Timing
Time to Process (s)
Number of Particles(N)
Fastjet NlnN
Fastjet N2Tiled
a*N*Ln(N)
b*N2
JetClu
CDF Midpoint
D0 Midpoint
1e+05
1e+04
1e+03
1e+02
10
1
0.1
0.01
1e+02
1e+03
1e+04
1e+05

Midpoint sub-process Timing

- 3 main processes

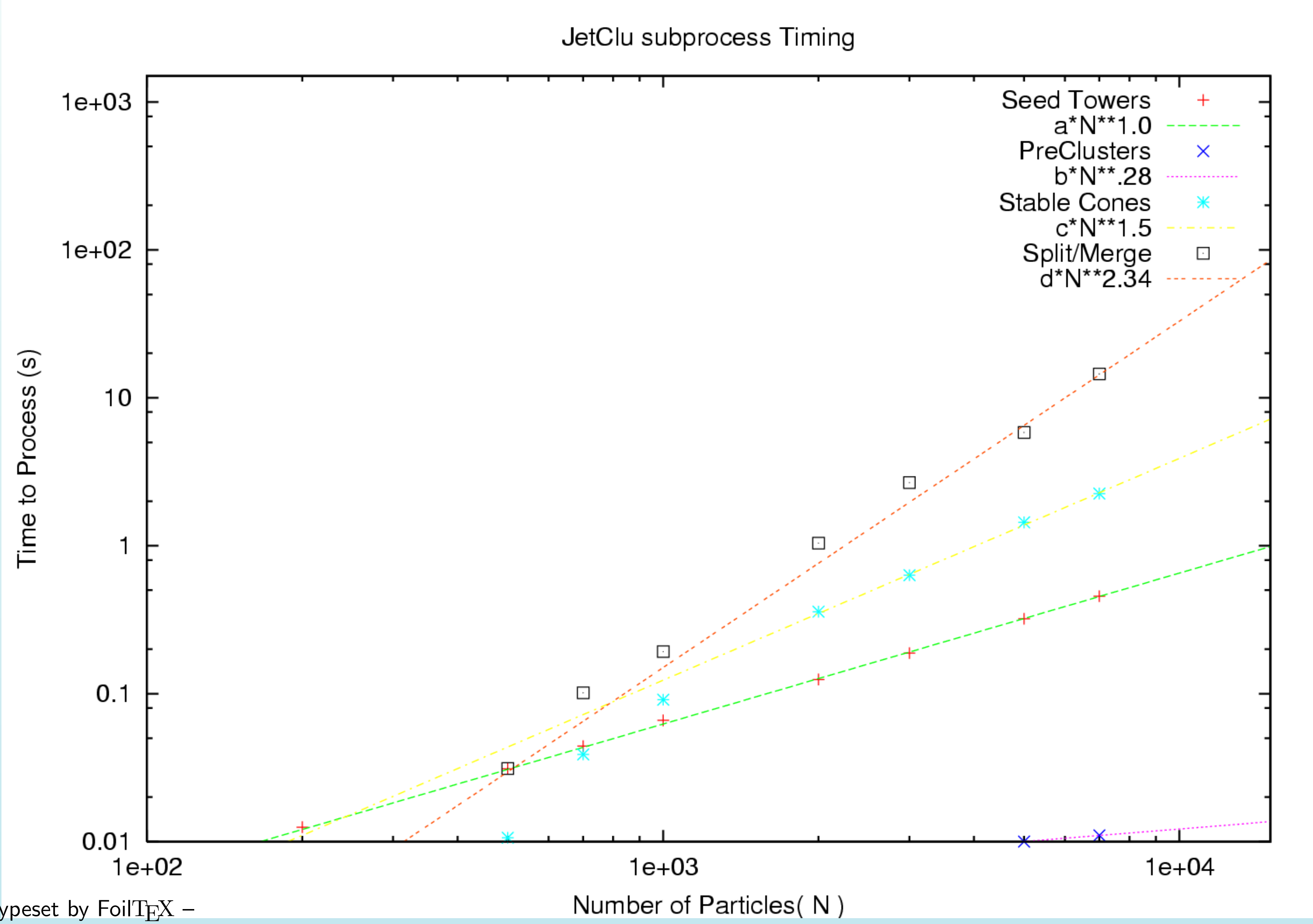
1. Find stable cones from seeds
2. Find Midpoint cones
3. Split/Merge cones


CDF Midpoint subprocess Timing
Stable Seeds Cones
a*N**2.6
Midpoint Cones
b*N**3
Split and Merge
c*N**3.6
Time to Process (s)
1e+03
1e+02
10
1
0.1
0.01
1e+02
1e+03
1e+04
Number of Particles(N)

JetClu sub-process Timing

- 4 main processes

1. Seed Towers
2. Preclusters
3. Stable Cones
4. Split/Merge cones


JetClu subprocess Timing
Time to Process (s)
Number of Particles(N)
1e+03
1e+02
10
1
0.1
0.01
1e+02
1e+03
1e+04
Seed Towers
a*N**1.0
PreClusters
b*N**.28
Stable Cones
c*N**1.5
Split/Merge
d*N**2.34

Summary

- For solid phenomenological predictions we need to understand
  - detector geometry, capabilities
  - The model to be studied
  - Properties of the algorithms used
- Jets play an important role in HEP and a precise and **consistent** definition is important to achieve accurate results
- There is **NO** right answer except that we must match THEORY and EXPERIMENT