Introduction to Jet Reconstruction Algorithms

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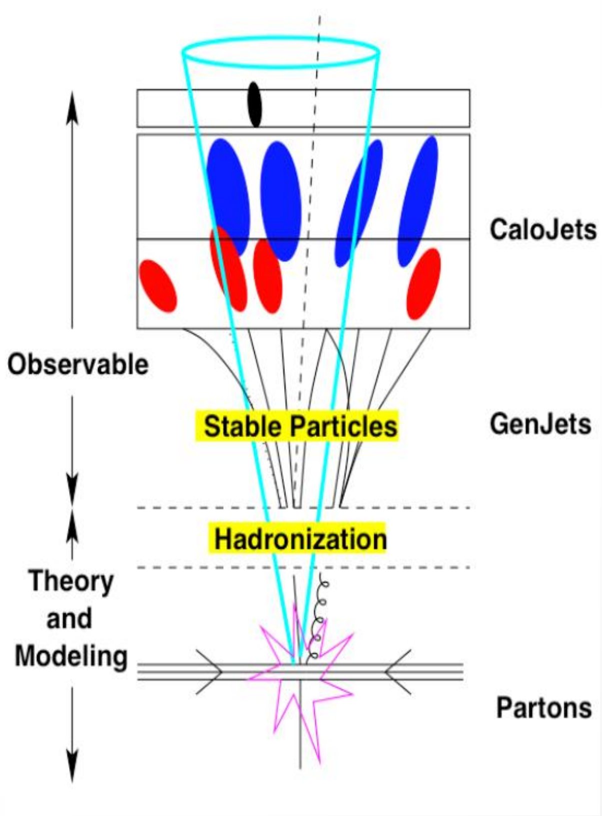
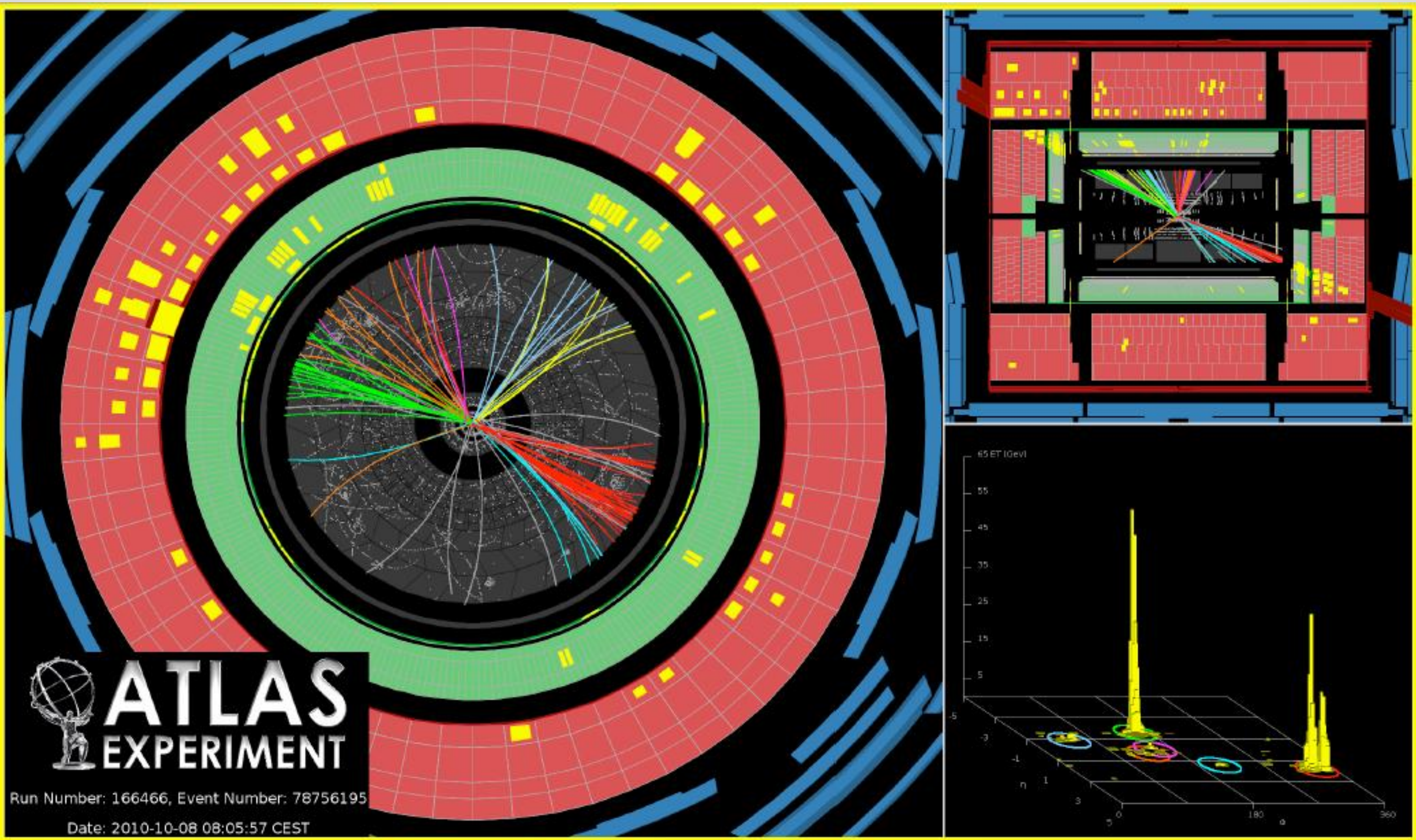
What is a Jet?

- Collimated spray of stable particles
- Jet algorithms are used to define the kinematics and shape of the jets
- Shed light on
  - QCD theory
  - W/Z boson masses
  - Missing energy

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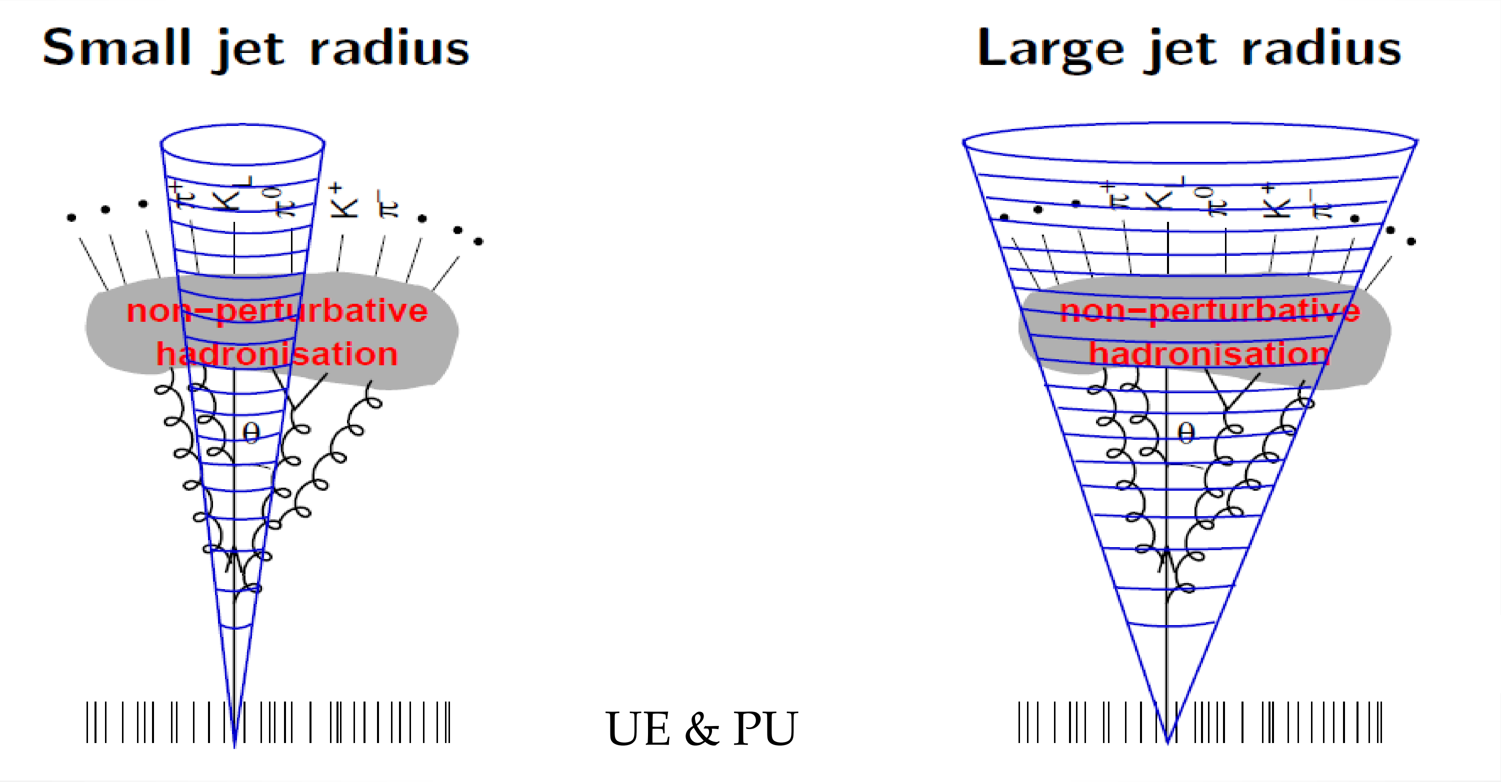
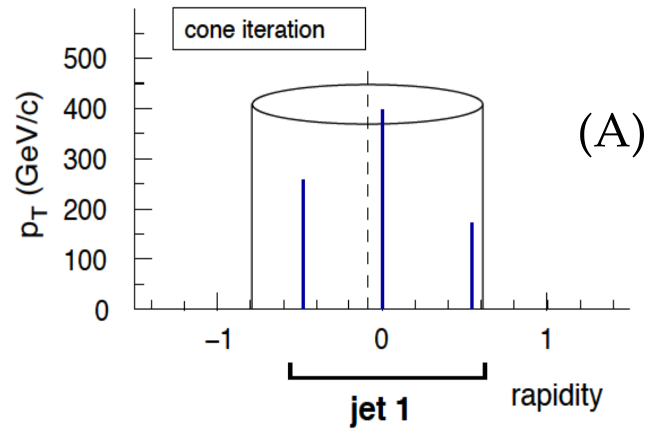
Jet Area

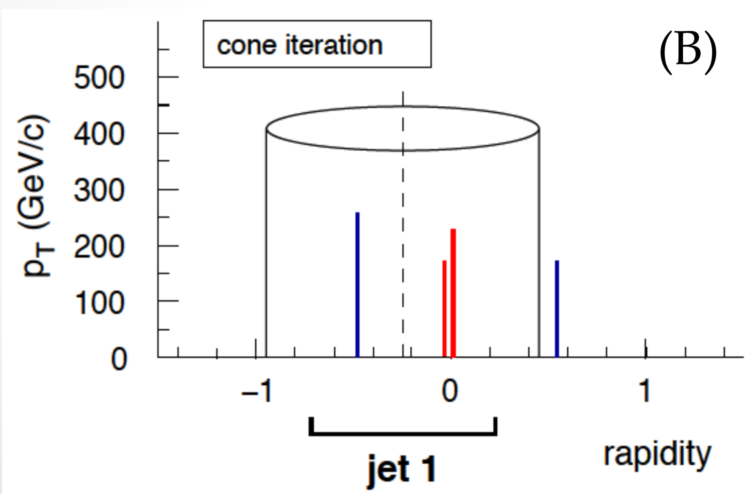
- Jets susceptibility to soft radiation

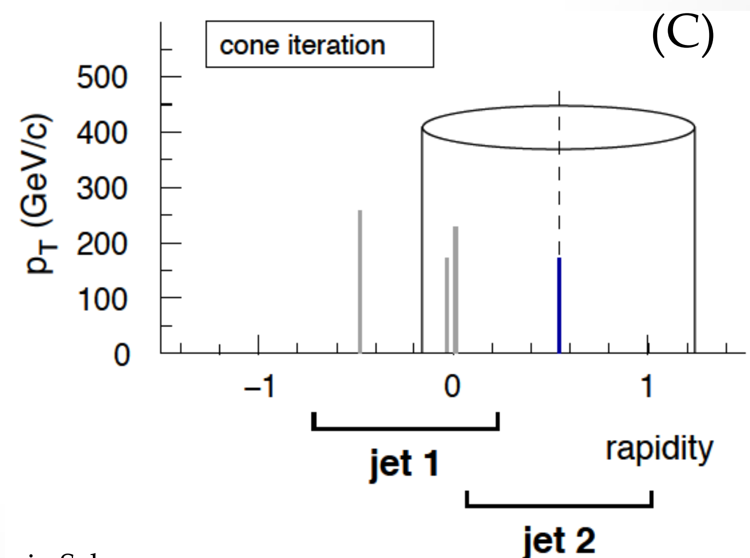


Collinear safety

- An algorithm insensitive to the splitting of a hard particle

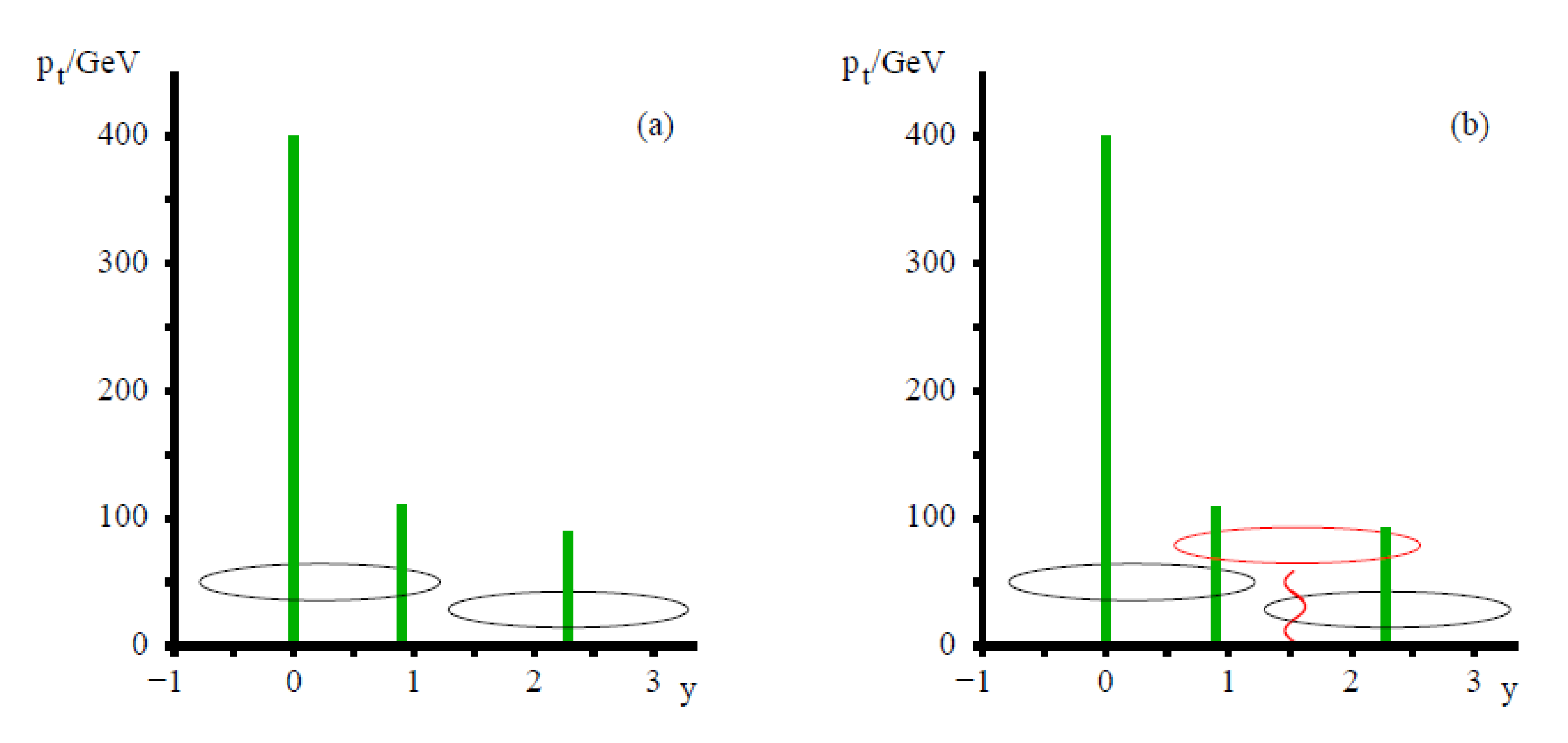






Infra-red Safety

- An algorithm insensitive to the emission of a soft gluon



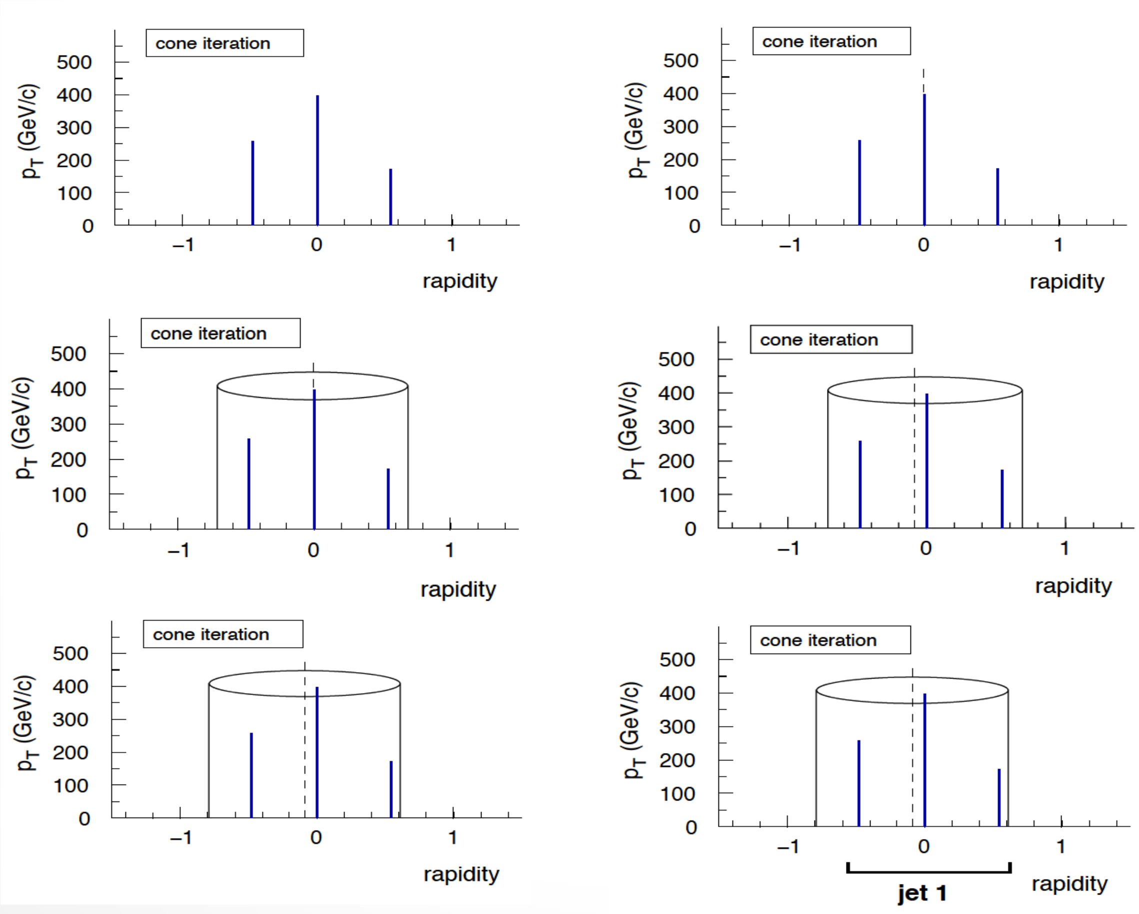
Jet Algorithms

- Two main types
  - Sequential Clustering Algorithms
    - K_t
    - Anti-K_t
    - Cambridge Aachen (C/A)
  - Cone algorithms
    - Iterative cone with progressive removal (IC-PR)
    - Iterative cone with split-merge procedure (IC-SM)
    - Seedless infrared-safe cone (SIScone)

Cones	Sequential clustering
$\eta - \varphi$ space	Momentum space
Rigid circular boundaries	Area fluctuates
Was preferred by experimentalists	Preferred by theorists
Generally suffer from IRC	All are IRC safe

Cone algorithm: IC-PR

- Collinear unsafe



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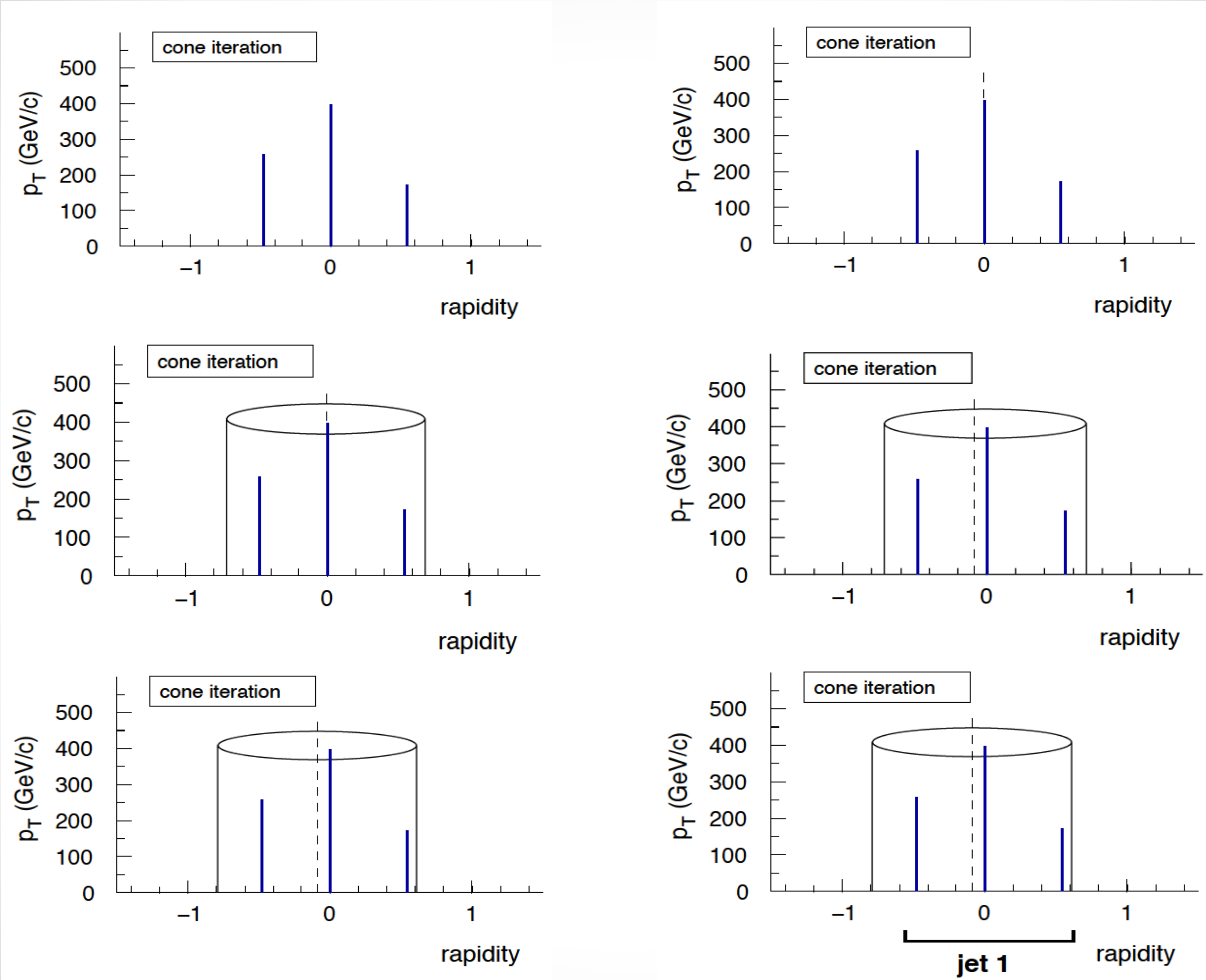


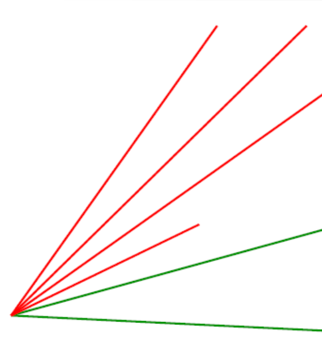
cone iteration
pT (GeV/c)
rapidity
500
400
300
200
100
0
–1
0
1
jet 1

Cone algorithm: IC-SM

- Infra-Red unsafe
- Algorithm
  - Make all cells above E_{cut} a seed and find all stable cones
  - Once all stable cones are found they are labelled as protojets
  - Run split merge procedure

Split-merge procedure

- Repeat
  - Remove all protojets with $p_t < p_{tcut}$
  - Find hardest protojet i (scalar sum of constituents)
  - Find hardest protojet j that shares particles with i
  - If overlap == true
    - If $p_{tshared} < f * p_{tj}$
      - Share particles
    - Else
      - Merge protojets
  - Else
    - Make protojet i a final jet
- Until no protojets left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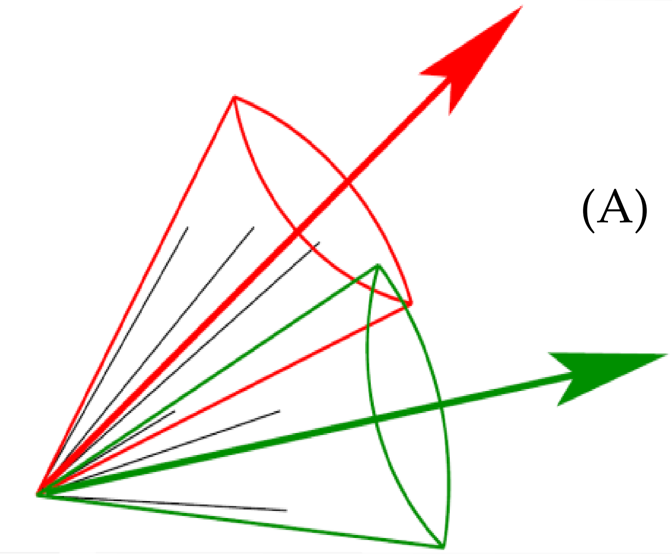
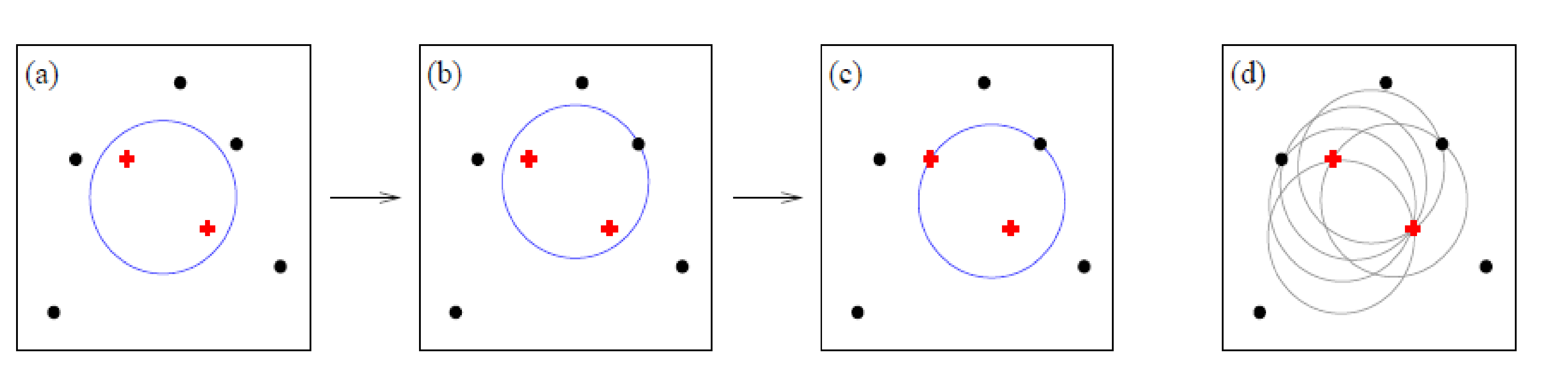

(A)

Cone algorithm: SIScone

- IRC safe cone
- Has a relatively smaller area so is not badly affected by the UE and PU
- Has a good resolution but is bad for multijets

Cone algorithm: SIScone

- Method
  - Find all distinct, different content, circles
    - For the current cones not previously found, determine whether edge points are appropriately included/excluded in the circle around the axis
  - Explicitly check for stable cones
  - Run split-merge procedure on all stable cones



A practical Seedless Infrared-Safe Cone jet algorithm; Gavin Salam, Gregory Soyez

Sequential clustering Algorithms

- $d_{ij} = \min\left({p_{ti}}^{a}, {p_{tj}}^{a}\right) * \frac{{R_{ij}}^{2}}{R}$
- $d_{iB} = {p_{ti}}^{a}$
- ${R_{ij}}^{2} = (\varphi_i - \varphi_j)^2 + (\eta_i - \eta_j)^2$
- Radius parameter R is generally between 0.4 – 0.7

Sequential Clustering Algorithms

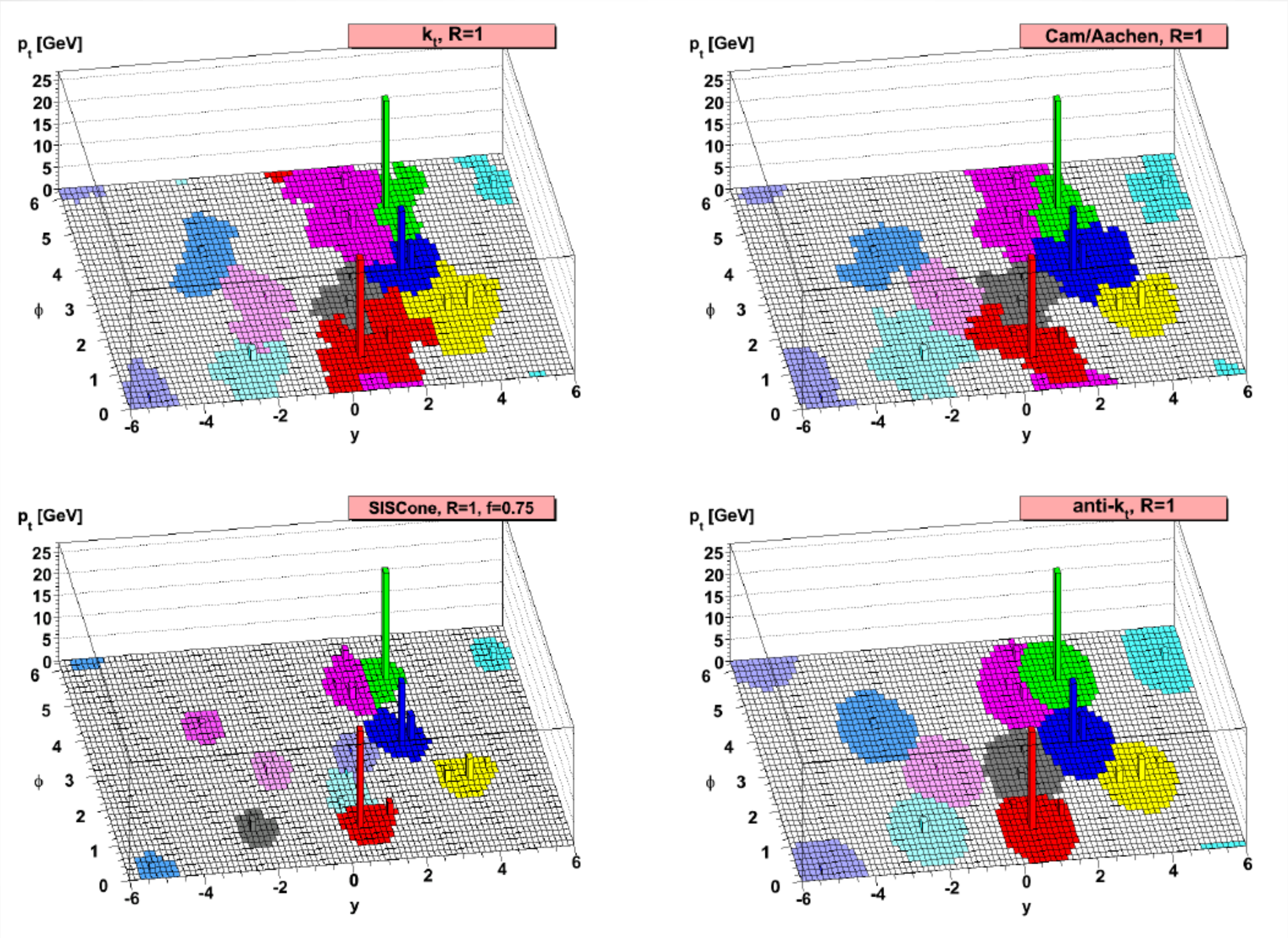
a = 2 (K_t)	a = 0 (C/A)	a = -2 (Anti-K_t)
$d_{ij} = \min(p_{ti}{}^2, p_{tj}{}^2) * \frac{R_{ij}{}^2}{R}$	$d_{ij} = \frac{R_{ij}{}^2}{R}$	$d_{ij} = \min\left(\frac{1}{p_{ti}{}^2}, \frac{1}{p_{tj}{}^2}\right) * \frac{R_{ij}{}^2}{R}$
$d_{iB} = p_{ti}{}^2$	$d_{iB} = 1$	$d_{iB} = \frac{1}{p_{ti}{}^2}$

Kt	C/A	Anti-Kt
d_{ij} dominated by soft	d_{ij} independent of pt	d_{ij} dominated by hard
Area fluctuates considerably	Area fluctuates somewhat	Area fluctuates slightly
Susceptible to UE & PU	Somewhat susceptible to UE & PU	Only slightly susceptible to UE & PU
Good for jet sub structure	Best for jet sub structure	Worst for jet substructure

Sequential Clustering Algorithms

- Find $\min\{d_{ij}, d_{iB}\}$
- If d_{ij} == min
  - Combine i and j
- Else
  - Make i a final jet

- Repeat process until
  - Inclusive clustering – all particles are part of a jet with $R_{ij} > R$
  - Exclusive clustering – a certain number of jets have been found



A sample parton-level event illustrating the active catchment areas, calculated through the addition of a uniform coverage of infinitesimally soft particles.

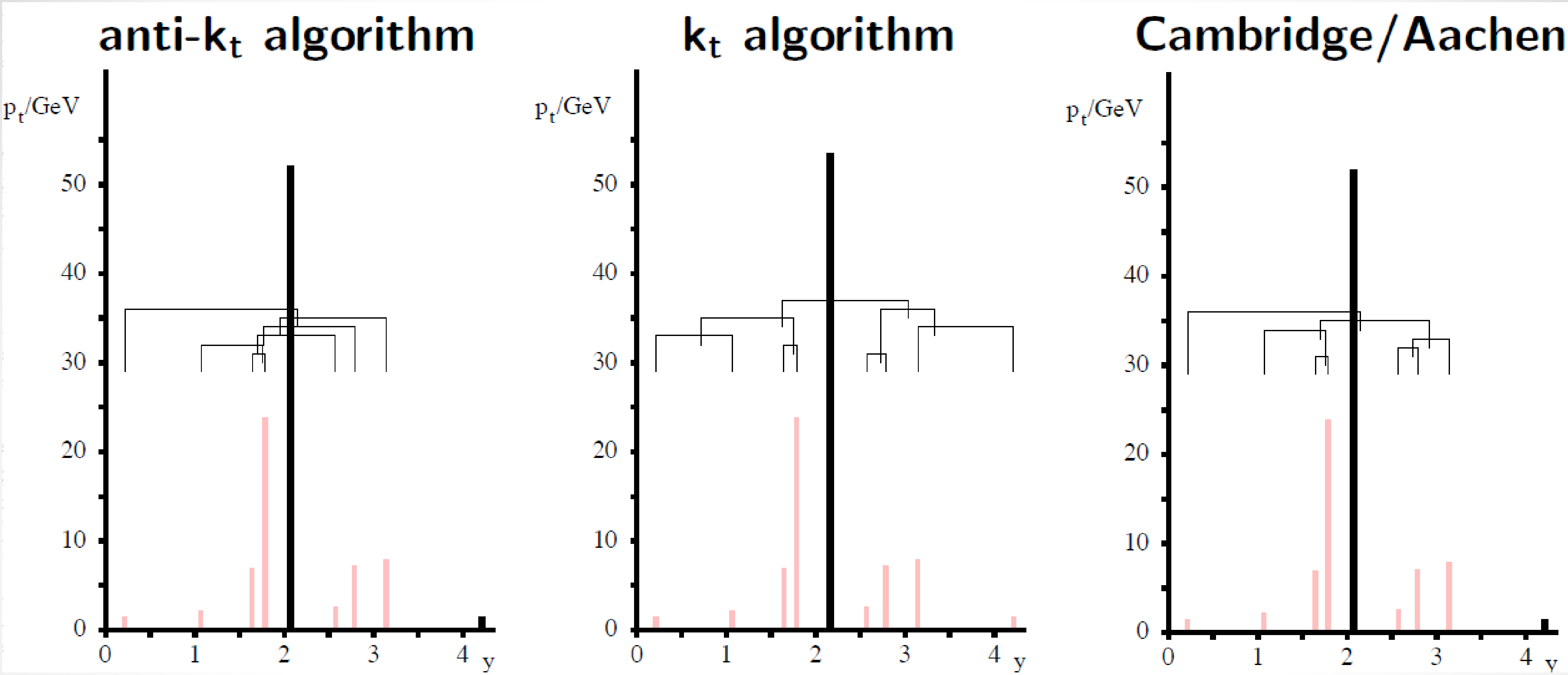
The Anti-k_t jet clustering algorithm; Matteo Cacciari, Gavin Salam, Gregory Soyez

Conclusion

- IC-PR and IC-SM are no longer widely used as infra-red and collinear unsafe, which are important obstacles an algorithm has to overcome
- Most successful algorithm for jets is Anti-K_t whereas for jet substructure it is Cambridge/Aachen
- Jet size and shape is important as we need a large enough jet to capture the non-perturbatively hadronised particles but not too large that we capture UE and PU
- Accurate jet reconstruction is the only way we are able to study the quarks and gluons directly

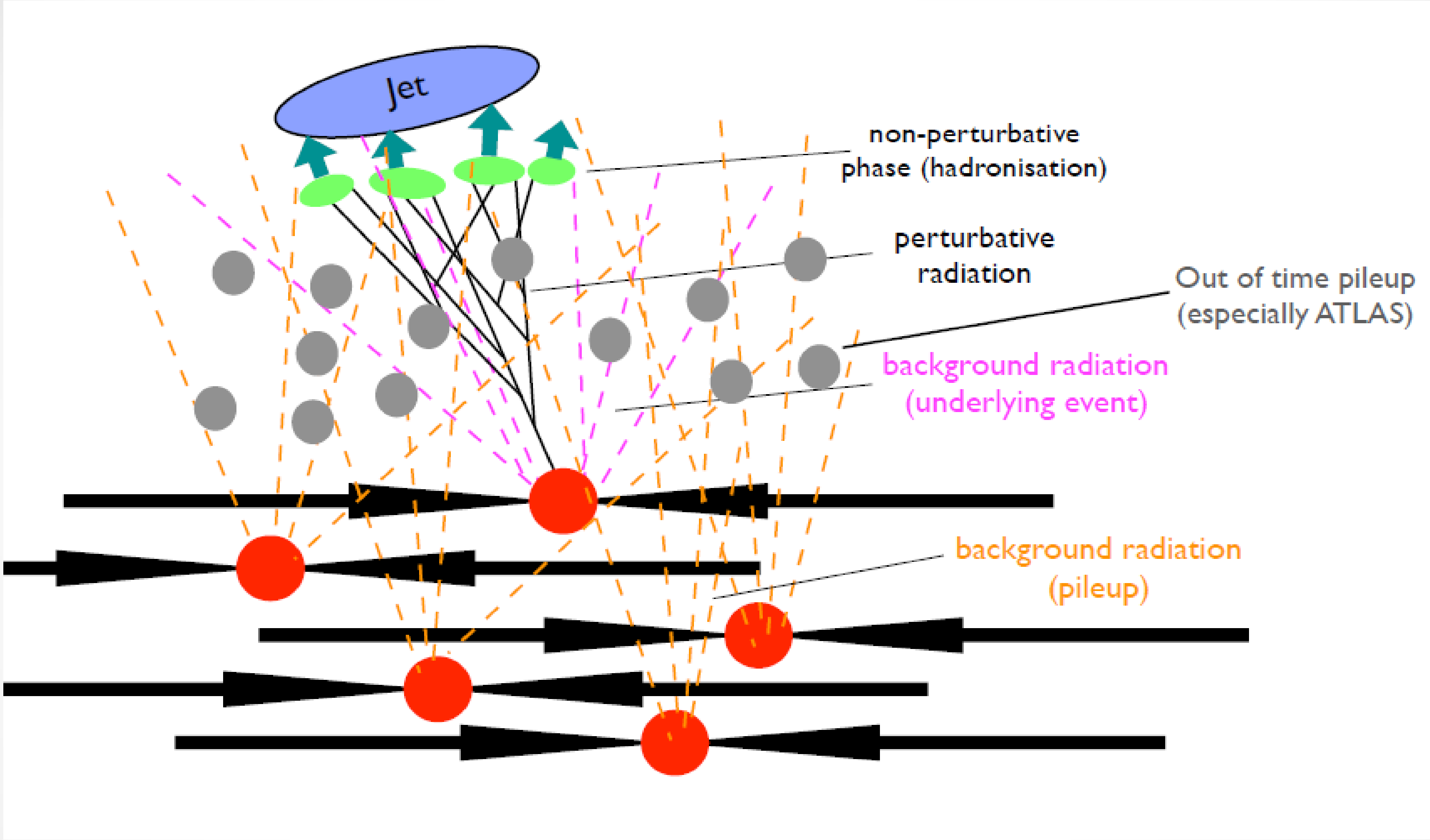
END

EXTRA SLIDES



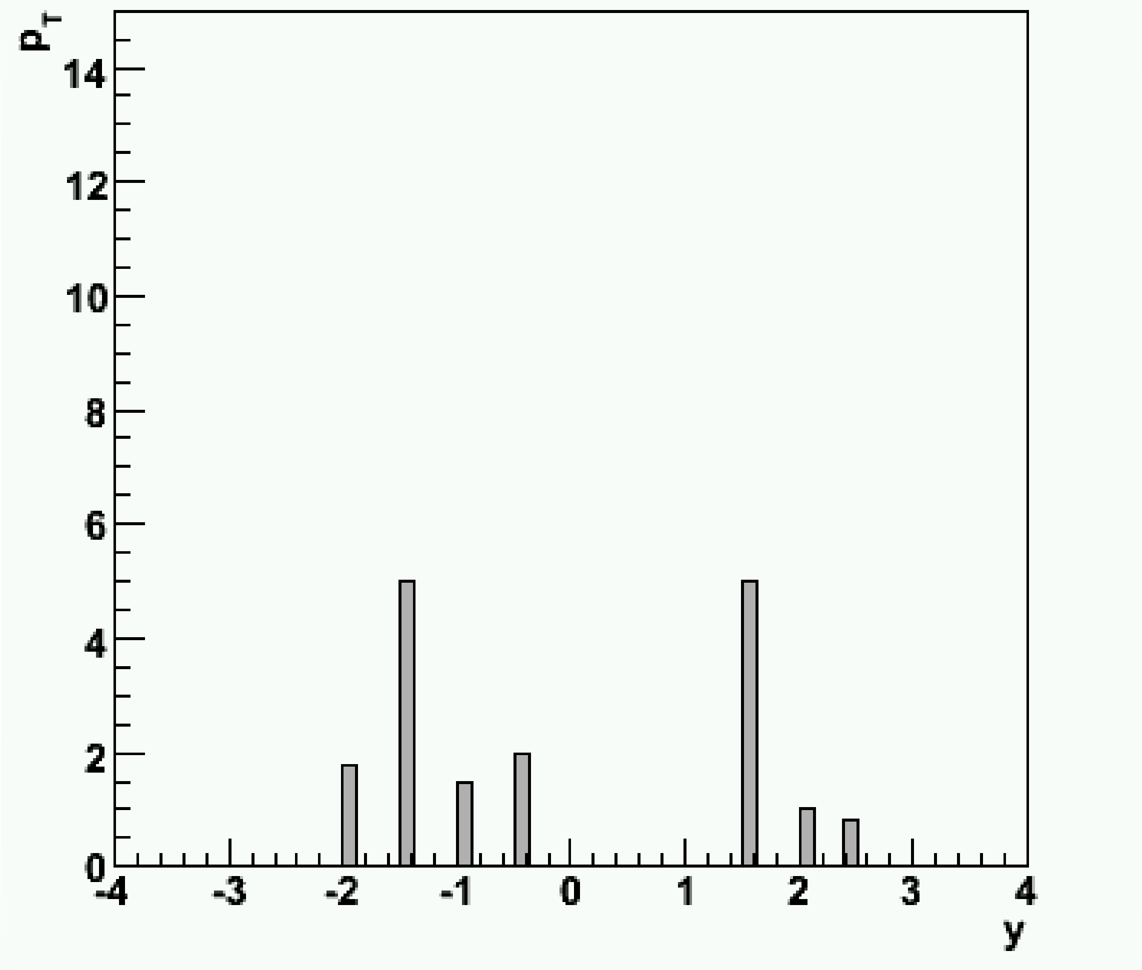
Jets and jet substructure 2: Using jets; Gavin Salam

Simplified one dimensional examples of the clustering order for the different sequential clustering algorithms.



The complexity of data collection

Lecture 4: Jet finding techniques and results, Marco van Leeuwen



Kt algorithm demo

Recombination schemes

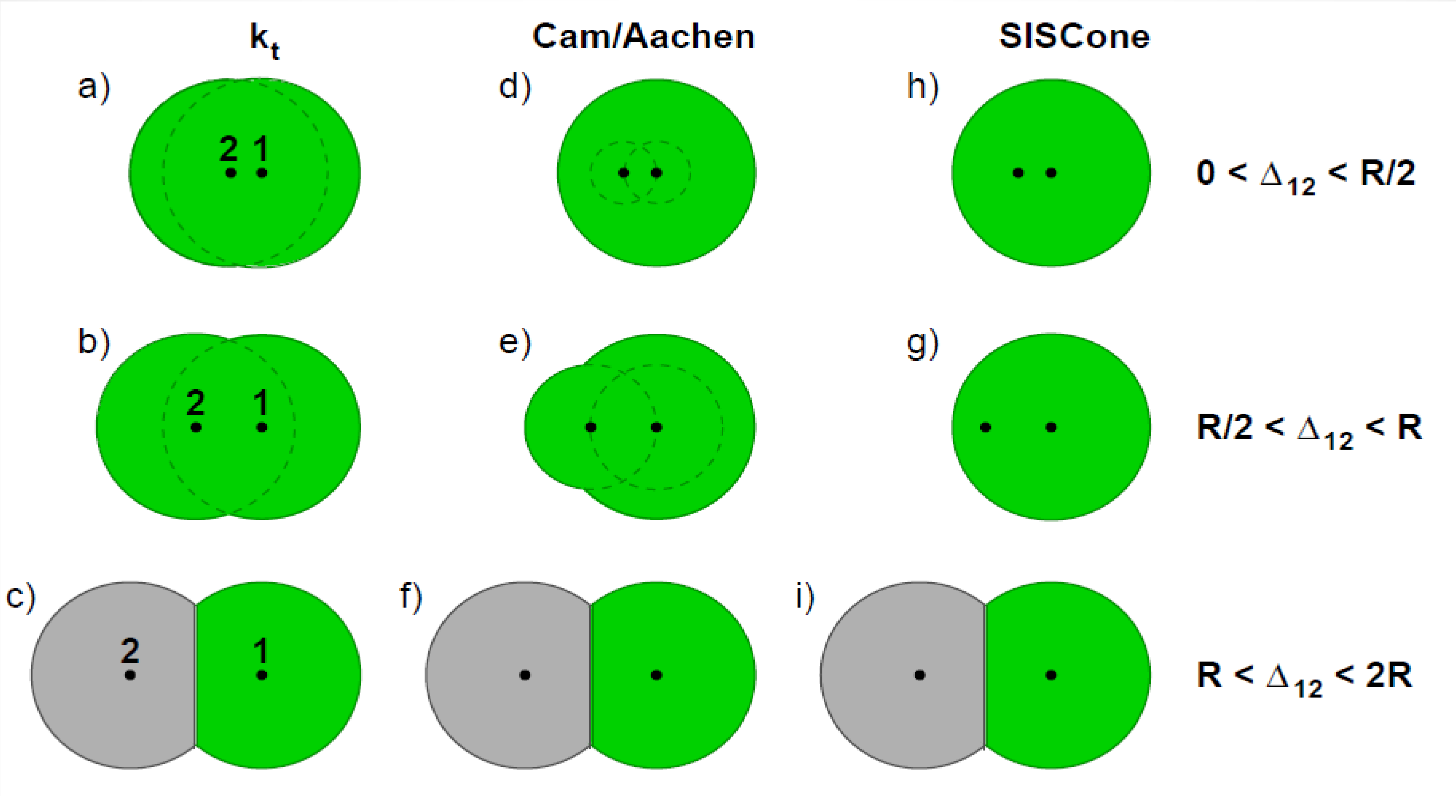
- Covariant E scheme
  - Assumes particles have mass
  - Boost invariant
  - Combine by summing momentum four vectors $(\frac{E}{c}, \boldsymbol{p})$
- p_t weighted scheme
  - Assumes particles are massless
  - Not boost invariant
  - $p_t^{new} = \sum_i p_{ti}$
  - $\eta^{new} = \frac{\sum_i \eta_i * p_{ti}}{p_t^{new}}$
  - $\varphi^{new} = \frac{\sum_i \varphi_i * p_{ti}}{p_t^{new}}$

Anti-K_t algorithm

- If $2R < R_{ij}$
  - i accumulates all soft particles within R
- If $R < R_{ij} < 2R$
  - If $p_{ti} \gg p_{tj}$
    - i is circular and j is crescent shaped
  - If $p_{ti} \sim p_{tj}$
    - Straight line between i and j
- If $R_{ij} < R$ i and j form one jet
  - If $p_{ti} \gg p_{tj}$, jet centered on i
  - If $p_{ti} \sim p_{tj}$, shape is union of circles ($< R$) around the particles plus circle centered on final jet (R)

SIScone

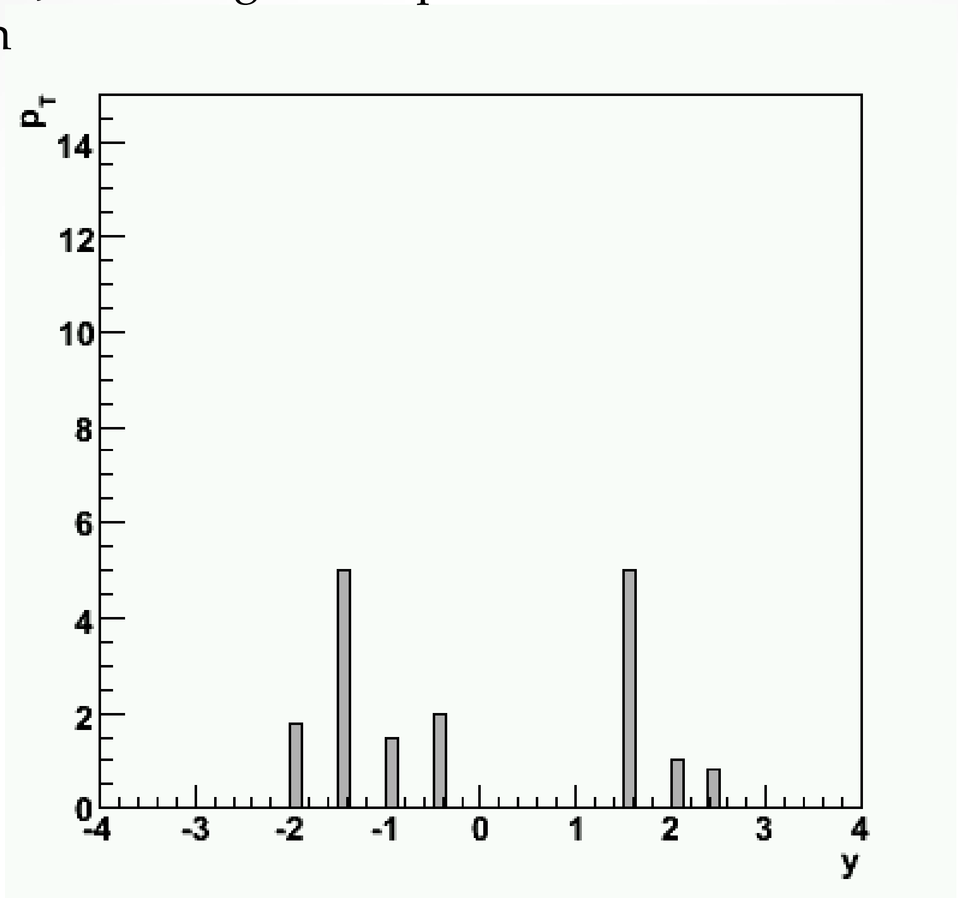
- For all particles i
  - Find all particles j within 2R of i
  - If there is no j
    - i is a stable cone
  - Else
    - Identify the two circles that contain both i and j on their circumference
    - Compute the angle of each circles centre relative to i $\zeta = \tan^{-1}(\frac{\Delta\phi_{iC}}{\Delta y_{iC}})$
    - Sort these circles into increasing angle ζ
    - Call the first circle in this list the current circle
    - Calculate the total momentum and checkxor for the cones that it defines
    - Consider all four permutations of edge points being included or excluded. Call these the current cones
    - Repeat
      - for each of the 4 cones
        - if this cone has not been found, add to list of distinct cones
        - if this cone has not yet been labelled as unstable, establish if the in/out status of the edge particles (with respect to cone momentum axis) is the same as when defining the cone. If it is not, label the cone as unstable
      - Move to next circle. It differs from the previous either by a particle entering or leaving the circle. Calculate the momentum for the new circle and corresponding new current cones by adding or removing the momentum of the particle that has entered or left. The checkxor can be updated by XORing with the label of that particle
    - Until all circles considered
- For each cone not labelled unstable
  - Explicitly check its stability and if stable add to list of protojets



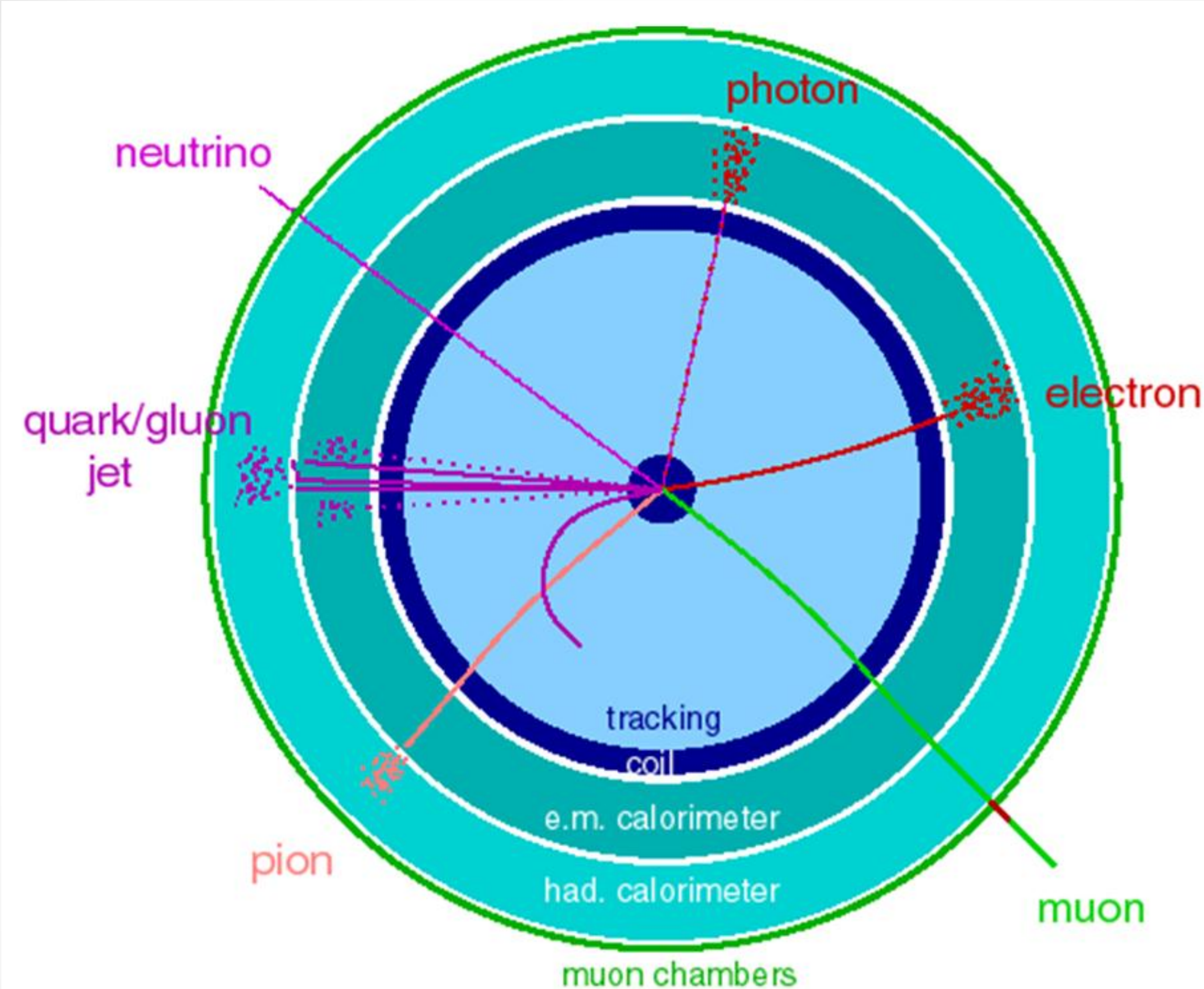
Passive catchment areas of three different algorithms

catchment area of jets, Matteo cacciari & Gavin Salam

Lecture 4: Jet finding techniques and results, Marco van Leeuwen



Cone algorithm

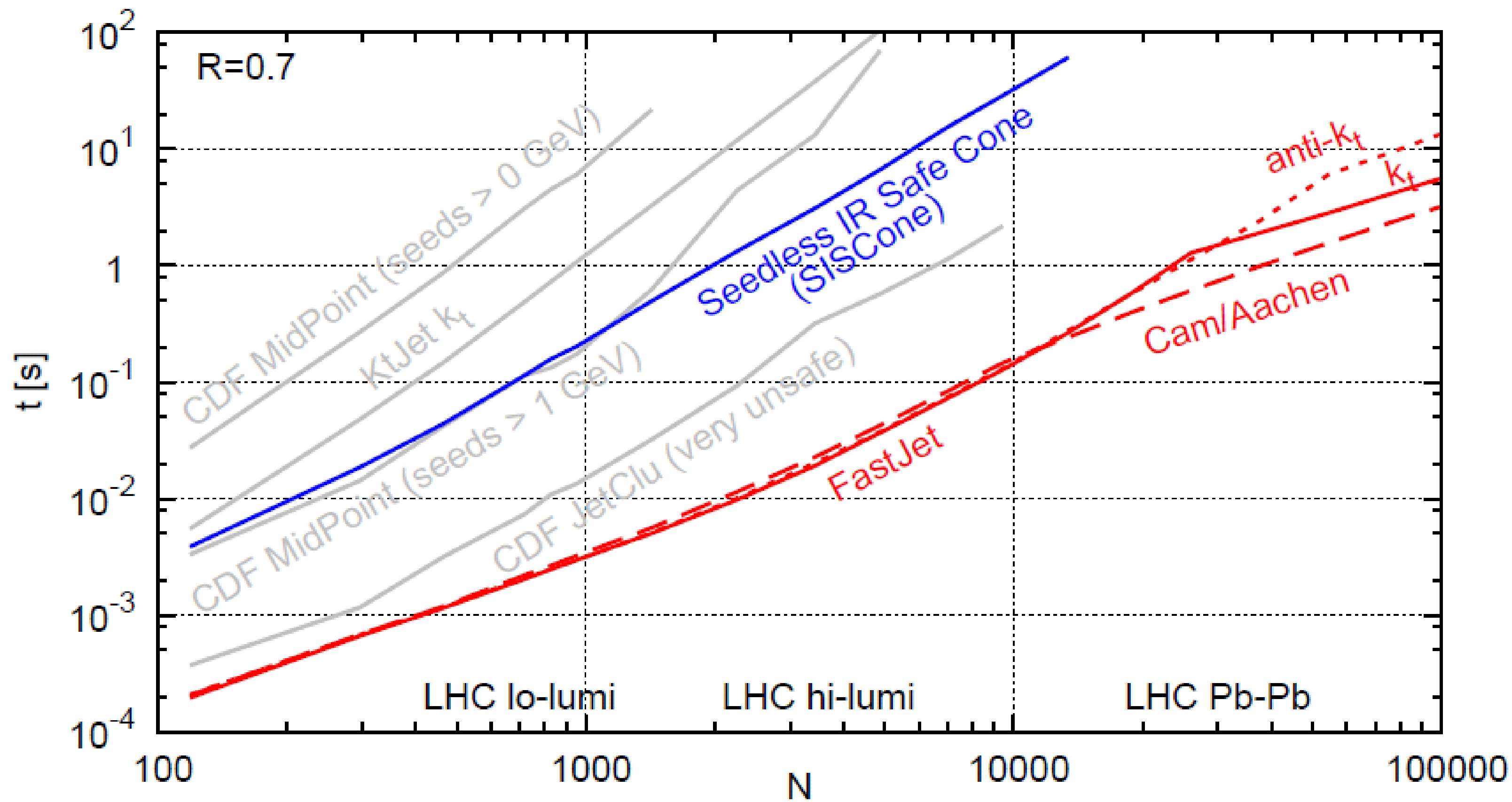


Particle decay signatures

Geometry

- Rapidity $y = 0.5\ln(\frac{E+p_t}{E-p_t})$
- Pseudorapidityη $= 0.5\ln(\frac{p+p_t}{p-p_t}) = -\ln(\tan(\frac{\theta}{2}))$
- Azimuth angle φ
- $E_t = E\sin\theta$
- Hard particle ≡ High momentum

Jets at hadron colliders (1), Gavin Salam



Time taken for algorithm to run as a function of the number of particles

Definitions

- Hadronization
  - The formation of hadrons when free quarks, due to colour confinement, combine with quarks and antiquarks created from the vacuum. Top quarks are unable to hadronize as they have extremely short lives
- Fragmentation
  - Refers to inclusive hadron spectra of the particles that have "broken up" and formed new particles. Similar to hadronization but hadronization refers to the actual process of hadrons being formed.
- Hard scattering scale
  - In an e^-e^+ collision, the centre of mass energy controls the hardness of the process. The hardness scale is the defining and separation of the high p_t scattering from the soft UE in initial state hadron collisions. The necessity of this arrises due to the hadrons having an internal structure that increases the complexity of the interactions.

Definitions

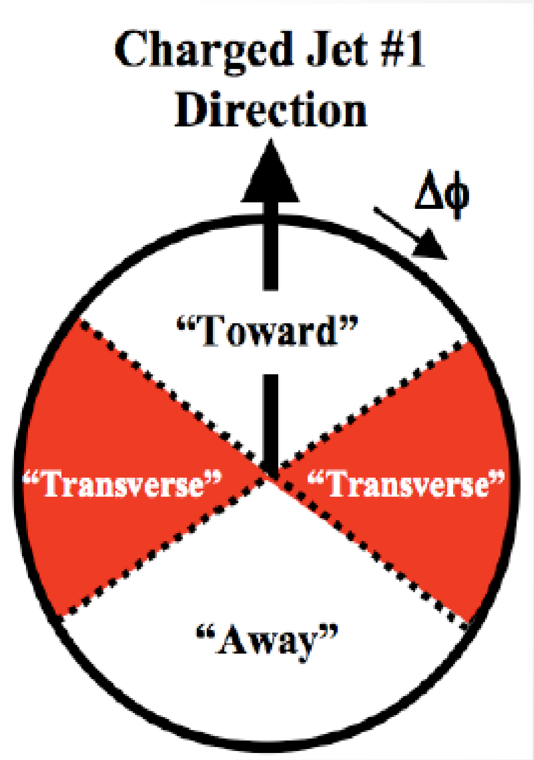
- Collision
  - When two particles interact
  - Elastic collision
    - 2-to-2 colour singlet exchange process where outgoing particles are the same as the incoming particles
  - Inelastic collision
    - Colour singlet exchange process where the outgoing particles differ from the incoming particles
    - Single diffractive collision
      - One of the incoming protons are excited into a high mass colour singlet state and subsequently decays
    - Double diffractive collision
      - Same as single diffraction but occurs for two protons
  - Most observed interactions are non-diffractive as the diffractive collisions tend to carry on through the beam tunnel

Definitions

- Minimum bias
  - Measuring a series of collisions with the minimum possible requirements that ensure an inelastic collision. Consists of a large fraction of the inelastic cross section. Dependant on the trigger used
  - The inelastic cross section is made up of the σ_{sd} (single diffraction), σ_{dd} (double diffraction) and σ_{nd} (non-diffractive) cross sections seen in the equation $\sigma_{tot} = \sigma_{elas} + \sigma_{sd} + \sigma_{dd} + \sigma_{nd}$
  - Ensures that no undue weight is given to a certain kind of event.
- Pile-up
  - Describes the events coming from additional pp interactions other than the one of interest. This increases as luminosity increases.
  - In-time pile-up is the additional pp interactions in the same bunch crossing
  - Out-of-time pile-up is the additional pp interactions from other bunch crossings

Definitions

- Underlying event (UE)
  - Additional interactions originating from the same pp collision. This includes everything from single particle interactions that are not the hard process of interest.
  - Consists of initial and final state radiation, beam-beam remnants, multiple parton interactions and occasionally in-time pile-up. Usually the particles in the transverse plane make up the underlying event. The toward region points in the direction of the hardest jet.
  - This is not to be confused with minimum bias. MB contains events that are chosen with a detected energy above a pre-determined value. UE is studied in events which specifically have a hard scattering occur.



Soft QCD at hadron colliders; Emily Nurse