A Brief, But Biased History of Jets and Jet Substructure (including at the LHC) 50 Years of Exciting Physics!

January 23, 2017

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(The oldest person in the room)

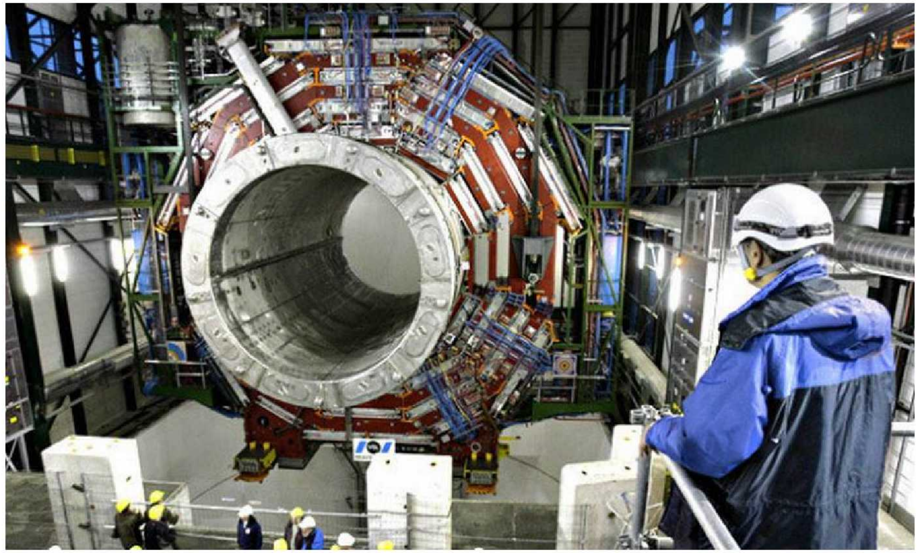
Department of Physics
University of Washington

First – Congratulations to the HEP community of India !!

THE HINDU

SCIENCE

India becomes Associate member of CERN

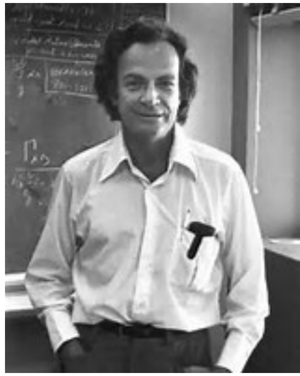


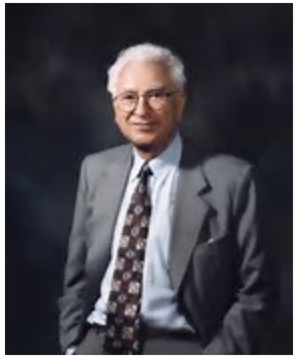
R. Prasad

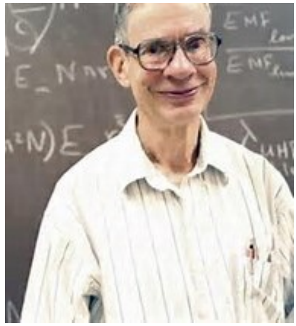
CHENNAI JANUARY 17, 2017 17:51 IST
UPDATED: JANUARY 17, 2017 19:37 IST

India became an Associate member of CERN on Monday with the Indian government completing its internal approval procedures in respect of the agreement it had signed with CERN on November 21, 2016.

In the “Dark Ages” (late 1960’s) there was only QED







- At Caltech, where I was a grad student, Dick Feynman taught a ONE(!) quarter course in QED (there was little understanding of renormalization at that time) and that was all the Quantum Field Theory (QFT) offered.

  The argument was that QFT was not relevant for either the Weak or Strong interactions and QED was a solved(!) problem!! (Wrong on all points!) Still in the 1 hour per week that Murray Gell-Mann taught (a course I called “what Murray did last night”) it was clear that QFT was the language used by the “Grand Old Men”.

  ASIDE: Eventually I led a student revolt of Particle Theory Students demanding that QFT be formally taught, and so Steven Frautschi was enlisted to teach it.

- In summary: theoretically no Standard Model (just the S-matrix and Regge poles), and experimentally no colliders, no jets!!! Just low energy fixed-target hadron collisions yielding resonances and soft pions.

Also: no email, no arXiv, no cellphones, no Facebook and computers communicated thru punched cards.

But importantly -

- Theory: Feynman was already at work interpreting the resonances and soft pions as indicating that hadrons are bound states of what he called partons, including (importantly) soft or “wee” (dE/E) partons. These partons were treated as “dynamical objects”, and not necessarily Gell-Mann’s quarks, which were “algebraic objects”.

- The (James) Bjorken (bj) *scaling* observed in electron-proton scattering at SLAC during this period suggested that the electrically charged partons are fermions and essentially free at short distances.

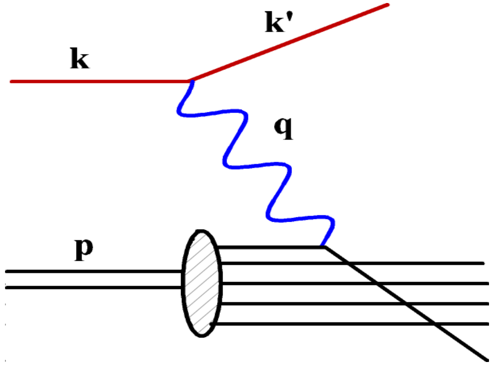
Deeply Inelastic electron-proton scattering:

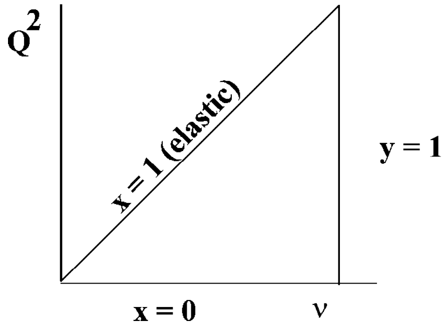
$$p^{\nu} = \left(m, \vec{0}\right), k^{\mu} = \left(E, \vec{k}\right) = \left(E, 0, 0, k\right),$$

$$k'^{\mu} = \left(E', \vec{k}'\right) = \left(E', k' \sin\theta, 0, k' \cos\theta\right),$$

$$q^{\mu} = k^{\mu} - k'^{\mu}, \left|q^2\right| = Q^2, \nu = \frac{p \cdot q}{m} = \left(E - E'\right)$$

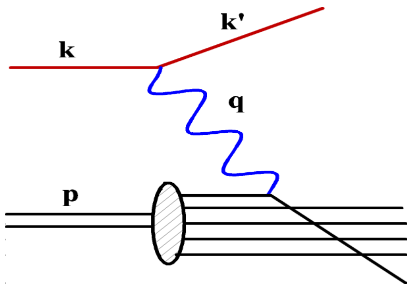
$$x_{bj} \equiv \frac{Q^2}{2m\nu} = \frac{Q^2}{2p \cdot q} = \frac{Q^2}{2m\left(E - E'\right)}, y = \frac{q \cdot p}{k \cdot p} = 1 - \frac{E'}{E}$$





Details -

- Deeply Inelastic electron-proton scattering (DIS):



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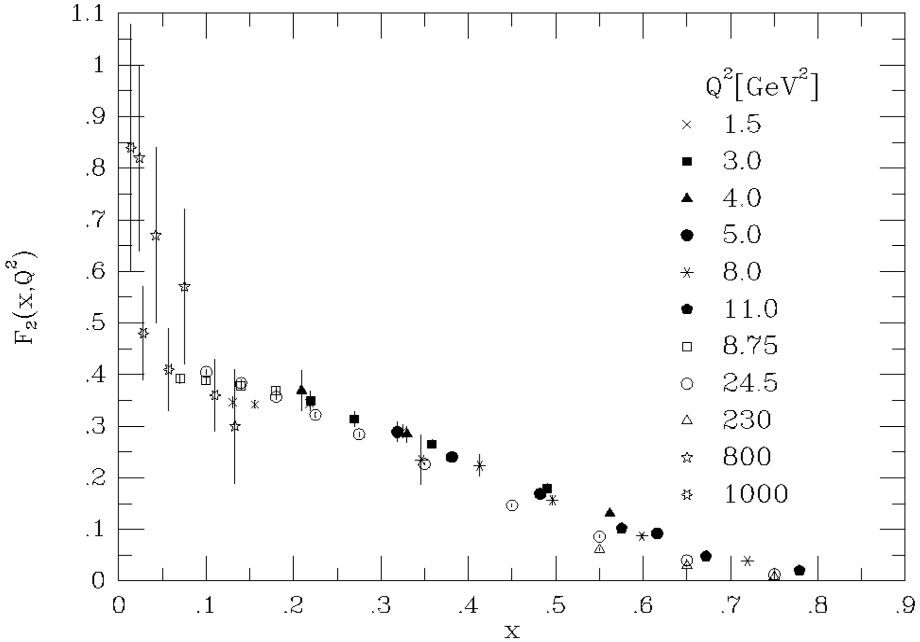


"Observed"   Spin-Flip ↓   Spin-NonFlip ↓

$$\frac{Q^4}{s}\frac{d\sigma}{dxdy} = 4\pi\alpha^2 \left[xy^2 F_1\left(x,Q^2\right) + \left(1-y\right) F_2\left(x,Q^2\right)\right]$$

$$\xrightarrow[x,y\,\text{fixed}]{Q,\nu\to\infty} 4\pi\alpha^2 \left[xy^2 F_1\left(x\right) + \left(1-y\right) F_2\left(x\right)\right] \left[\text{Scaling}\right]$$

➡ Charged partons are pointlike – fermions with nonzero probability to carry finite fraction, $x_F = x_{bj}$, of proton's momentum (at least approximately)

Seemed like Gell-Mann's quarks? But ~ free??

- ASIDE: This stimulated an industry to look for "free" fractionally charged particles, for example, produced by cosmic rays and trapped in the shells of mollusks. A big player was George Zweig (of Aces, fame), also then at Caltech. No luck finding quarks, but George went on to *very* successfully study the physics of ears!

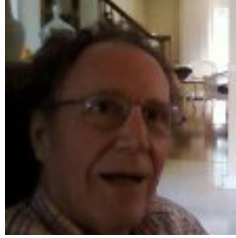
- Still, as already suggested by Feynman, such partons could be pair-wise produced in electron-positron annihilation and generate "jetty" final states, which were eventually observed experimentally.

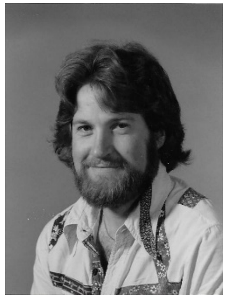
So Parton Picture (~1970):

- Confining interactions soft (~ 100 MeV) and slow (time dilated in CM frame)
- hard interactions rare but fast
- Partons are always confined in hadrons at long distance (compared to a fermi) but act nearly freely at short times/distances
- Describe hadrons in terms of (approximately scale invariant) parton distributions (pfd's) describing the sharing of longitudinal momentum with limited transverse momentum – measured in DIS
- Outgoing isolated partons fragment into hadrons described by (approximately) collinear sharing of momentum – Fragmentation functions, jetty structure built in.
- No QFT basis!!

Early 1970's

- THEORY: Idea of jets of hadrons from rare (large angle) scattered partons more clearly spelled out:
  Berman, Bjorken and Kogut (1971); Ellis and Kislinger (1974)
  Still no real underlying theory or jet definitions!





- First proton collider – the ISR (Intersecting Storage Ring) at CERN, 23.5 < √s/GeV < 62.4. Detectors were reused single-arm versions from fixed target world.

  Primarily observe: p + p → $\pi^{0,\pm}$ + X (inclusive pion production)

  Exciting early CCOR collaboration result (1973)

$$s^2 \frac{d\sigma}{d^3p/E}\bigg|_{pp\to\pi^0+X} \approx F\left(\frac{2p_T}{\sqrt{s}} \equiv x_T\right) \quad \text{[Scaling again!]}$$

Alas, correct for detector aging

$$s^{4.12} \frac{d\sigma}{d^3p/E}\bigg|_{pp\to\pi^0+X} \approx G(x_T) \quad \text{[non-Scaling!]}$$

Rest of 1970's

- THEORY: QCD "discovered" – non-Abelian SU(3) theory found to have desired properties, Gross, Politzer and Wilczek: QCD running coupling $\alpha_s(\mu)$ [2004 Nobel Prize]

$$\mu \frac{d\alpha_s(\mu)}{d\mu} ; -\frac{\beta_0}{2\pi}\alpha_s(\mu) \Rightarrow \alpha_s(\mu) = \frac{2\pi}{\beta_0 \ln\left(\mu/\Lambda_{QCD}\right)}, \quad \beta_0 = 11 - \frac{2}{3}n_f, \quad \Lambda_{QCD} = \mu_0 e^{-2\pi/\alpha_s(\mu_0)} : 200\,\mathrm{MeV}$$

$$\xrightarrow[\mu\to\infty]{} 0$$ Asymptotic Freedom

$$\xrightarrow[\mu\to\Lambda_{QCD}]{} \infty$$ Infrared Slavery

Immortalized in an early (2012) episode of the *Big Bang Theory*!

This is UV (short distance) behavior, QCD also has soft and collinear divergence in the infrared (massless quarks and gluons).

- Perturbative QCD was enthusiastically tested via the calculation of infrared safe "event shape" measures in e^+e^- annihilation at PETRA at DESY – Thrust, Jet Broadening, Energy-Energy Correlations.

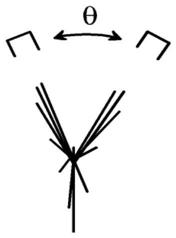
  While not using the exclusive jet definitions common today, the PETRA discussion did use the language of jets (or clusters), see *e.g.*, Sterman and Weinberg, "*Jets from QCD*" (1977).





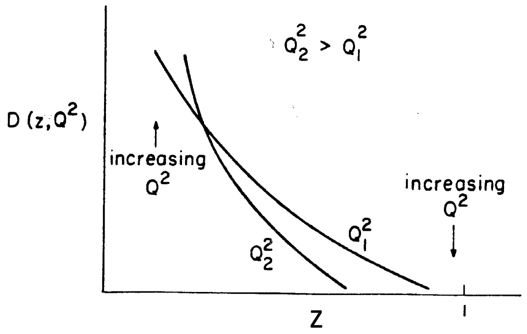
1980's

- THEORY: QCD improved parton model – same basic structure as original parton model but now "understood" asymptotic freedom (small short-distance coupling) and infrared slavery (confinement). Plus

  Partons are quarks AND gluons (vector bosons) → "confirmed" by "3-jet events" at PETRA (1979) - found in distributions of event shapes.

  QCD is NOT scale invariant (bj scaling was only approximate), but coupling and pdf's vary slowly with resolution (momentum) scale, as expected for an interacting theory where charges and momentum are shared – But this behavior is PREDICTABLE in QCD (the anomalous dimensions are calculable)!
  And agrees with data.

  The soft and collinear singularities in a theory with massless gluons can (must) be factored into the (measurable) pdf's and fragmentation functions and make them run.

  But play no role for appropriately defined Infrared Safe quantities (insensitive to soft or collinear partons)!

1980's

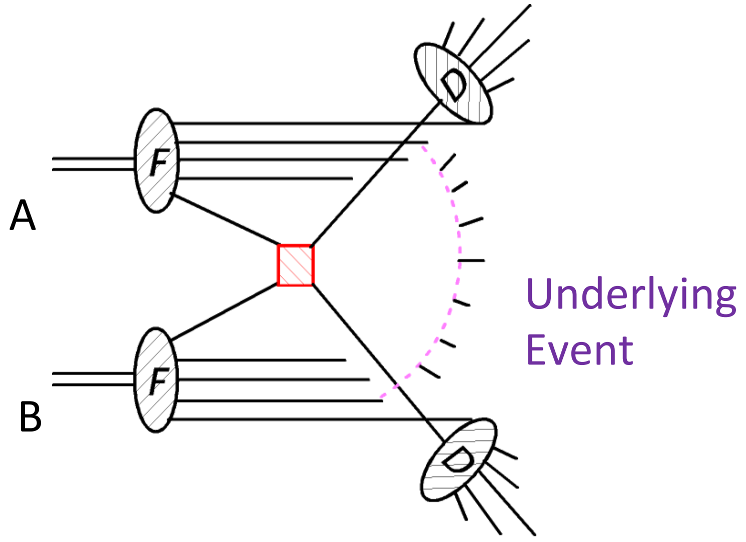
- THEORY: QCD improved parton model -

  QCD is a predictive (and testable) theory - a big change from the dark ages!
  Jet cross section is a convolution

$$\frac{d\sigma}{dp_T dy} = \sum_a \int dx_a F_{a/A}(x_a,\mu) \sum_b \int dx_b F_{b/B}(x_b,\mu) \frac{d\hat{\sigma}(x_a,x_b,\mu;p_T,y)}{dp_T dy}$$

Measure, run

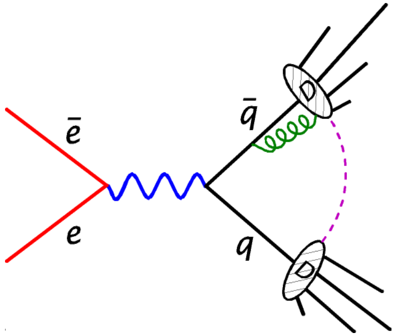
Parton cross section:
Calculate in pQCD, depends on jet definition, sums over Fragmentation D



- But there remains an inherent ambiguity for QCD jets. They are initiated by a colored parton at short distance, but necessarily composed of colorless hadrons at large distances. So we know there is a soft interaction to conserve color, which is not uniquely defined, until given the details of the jet algorithm. There is no single, correct result.

1980's

- EXPERIMENT: "Real" jet identifying algorithms appear for e^+e^- annihilation events in the form of "recombination" algorithms – think recombining the showers from the originally produced quarks (and gluons). Start with a list of observed hadrons (or QCD partons), end with a list of jets. All hadrons are in a jet, since all come from the hard scattering! (unlike pp events)



JADE at PETRA (1986): Define a pairwise distance measure:

$$y_{kl} \equiv 2\left(1-\cos\theta_{kl}\right)\frac{E_k E_l}{E_{vis}^2}\ ;\ \frac{M_{kl}^2}{s}\quad \left[\text{ignoring particle masses}\right]$$

Identify pair with smallest y_{kl} and replace pair in list with cluster with $p_{cl} = p_k + p_l$ yielding a new list

Repeat until all $y_{kl} > y_{cut}$ (the IR cutoff)
The remaining clusters in the list are then the jets.

By 1990 it was recognized (at a meeting in Durham) that higher orders in the theory were better behaved for the Durham (also kT) algorithm with distance measure

$$y_{kl}\left(k_T\right) \equiv 2\left(1-\cos\theta_{kl}\right)\frac{\min\left(E_k^2, E_l^2\right)}{E_{vis}^2}\quad \left[\text{cluster soft parton with closest other parton}\right]$$

The application to the lists is just as above.

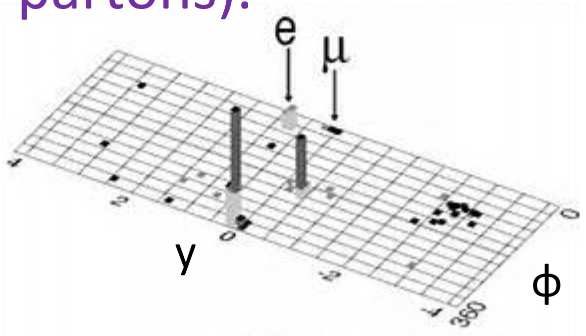
1980's into 1990's

- EXPERIMENT: pp collisions became important. The experiences at the SpbarpS at CERN in the mid 1980's (with nearly 4π detectors) indicated that jets would be important also in hadron-hadron collisions. The jets at UA1 and UA2 were rudimentary (and detector dependent) but useful in finding the W and Z (but not SUSY – see the book "Nobel Dreams" by Taubes). However, the mindset was that jets represented a *single* parton; color conservation guarantees that cannot be true in detail.

  Learned pp collision (unlike ee) events are cylindrical (not spherical).
  Appropriate kinematic variables are E, P_T, ϕ (azimuth around beam) and rapidity $y = 0.5 \ln[(E+p_z)/(E-p_z)]$ or pseudorapidity $\eta = \ln[\cot(\theta/2)]$ (≈ y, instead of θ).
  The appropriate angular separation variable is $\Delta R^2 = \Delta y^2 + \Delta\phi^2$ (instead of Δθ).

  The partons not participating in the large angle scatter interact (softly) and generate a largely uncorrelated "underlying" event along with the jets. This underlying event is much like a typical minimum bias (low pT) event (just at lower total energy) with a fairly uniform (in ϕ and y) distribution of soft hadrons (recall the "wee" partons).

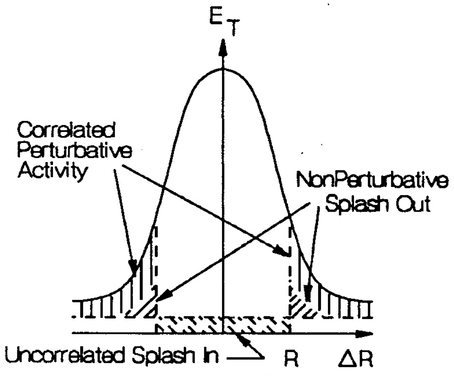
  Learned to use LEGO plots – energy on the surface of the (y,ϕ) cylinder



1980's into 1990's

- EXPERIMENT:

  An idealized UA1 style jet looked like – (but QM)

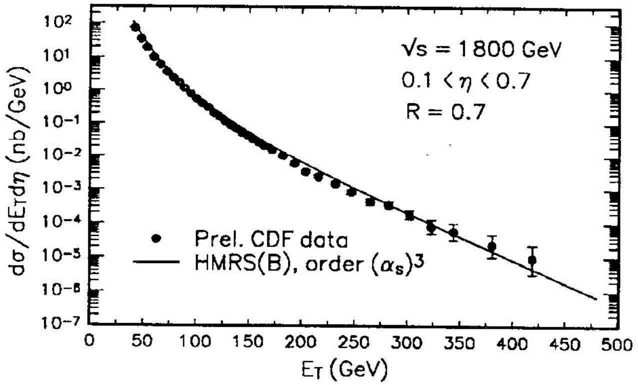


Since most of the particles in the event are not in the jets, felt the need for a different (non-recombination) style jet algorithm.

1990 – the Snowmass Accord – Iterative Cone Algorithm: Agreed to by Theorists and Experimenters to be used at the Tevatron (CDF and D0). Actually was not full – 4-vector definition until Run II. Worked OK for 10% agreement, but ….

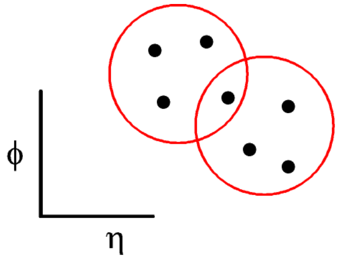
- **CONE center -** $\left(y^C, \varphi^C\right)$
- **CONE i ∈ C iff** $\Delta R^i \equiv \sqrt{\left(y^i - y^C\right)^2 + \left(\varphi^i - \varphi^C\right)^2} \leq R$
- **Cone Contents ⇒ 4-vector** $P_\mu^C = \sum_{i \subset C} p_\mu^i$
- **4-vector direction** $\bar{y}^C = 0.5 \ln\left[\frac{P_0^C + P_z^C}{P_0^C - P_z^C}\right]$; $\bar{\varphi}^C = \arctan\left[\frac{P_y^C}{P_x^C}\right]$
- **Jet = stable cone** $\left(\bar{y}^C, \bar{\varphi}^C\right) = \left(y^C, \varphi^C\right)$

Find by iteration, *i.e.*, put next trial cone at $\left(\bar{y}^C, \bar{\varphi}^C\right)$



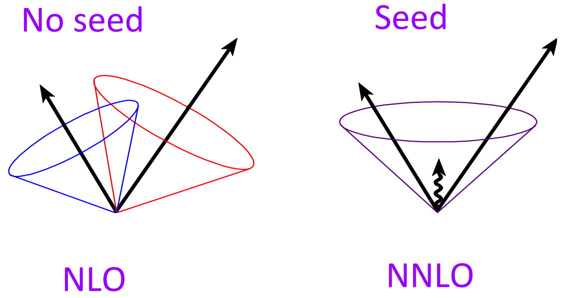
Ellis, Kunszt and Soper, pQCD NLO, 1989-92
Coded in Fortran!!

Cone Issues arose as things became detailed



1) Stable Cones can and do Overlap: need rules for merging and splitting, but NOT the same for D0 and CDF

2) Seeds – experiments only look for jets around active regions (save computer time, which was an issue then)



$\Rightarrow$ problem for theory, IR sensitive (Unsafe?) at NNLO

This is a BIG deal philosophically – but not a big deal numerically (in data)

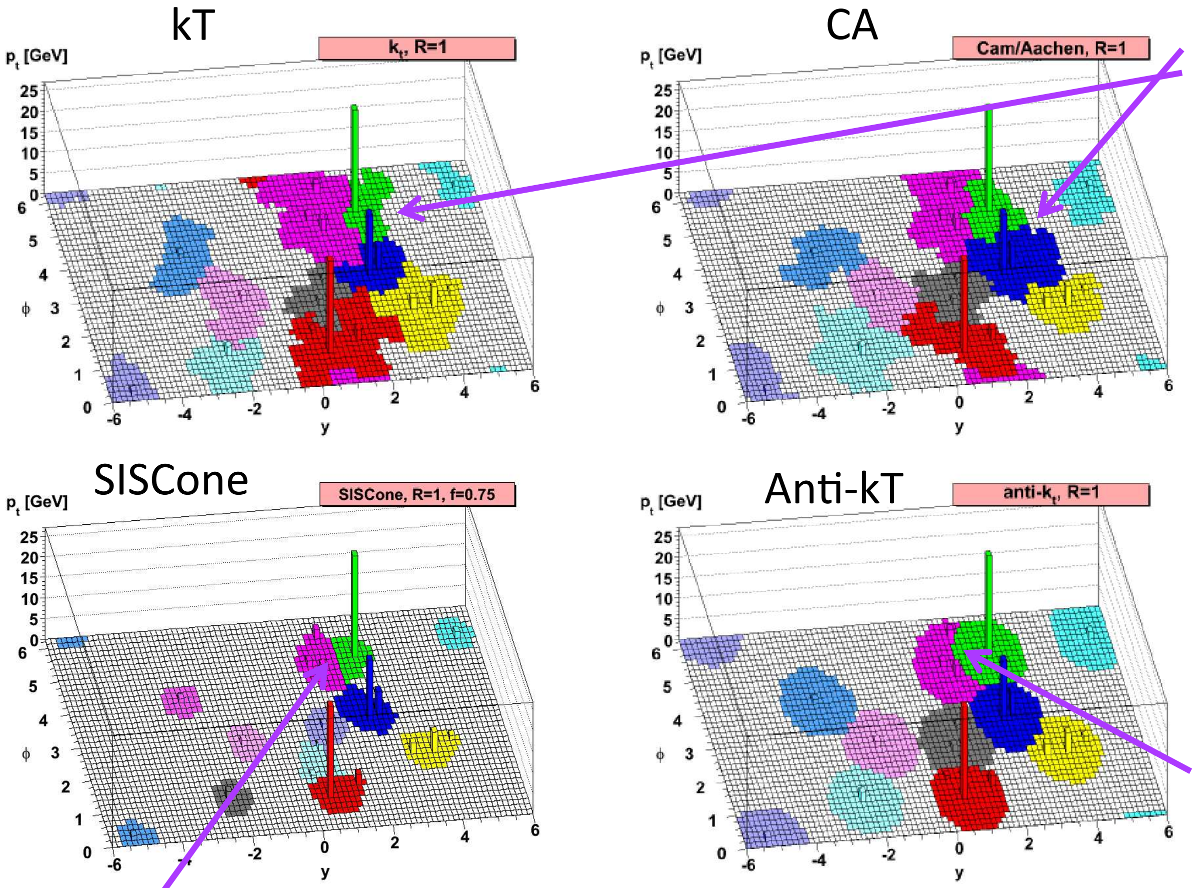
$\Rightarrow$ Could use SEEDLESS version (SISCone) at the LHC

3) Splash-out from smearing of energetic parton at edge of cone – can be quantitatively relevant (the R_{sep} thing)

4) Dark towers – secondary showers may not be clustered in any jet

By the mid-1990's the Recombination Algorithm had been adapted to pp collisions: Ellis and Soper (1993), Catani, *et al.* (1993)

Jet Areas – from Salam & Carriari, Salam & Soyez



Amorphous edges

Anti-kT very regular leading jets,
But bites others

S/M effect

Recombination Algorithms – unlike ee focus on on large p_T, some particles not in a jet

Merge jet constituents pairwise based on "distance" defined by minimum value of d_{ij}, *i.e.* make list of metric values (rapidity y and azimuth ϕ, p_T transverse to beam) [Inclusive Mode]

$$\text{Pair } ij : d_{ij} \equiv \text{Min}\left[\left(p_{T,i}\right)^{\alpha},\left(p_{T,j}\right)^{\alpha}\right]\frac{\sqrt{\left(y_i - y_j\right)^2 + \left(\phi_i - \phi_j\right)^2}}{R} \equiv \text{Min}\left[\left(p_{T,i}\right)^{\alpha},\left(p_{T,j}\right)^{\alpha}\right]\frac{\Delta R_{ij}}{R},$$

$$\text{Single } i : d_i = \left(p_{T,i}\right)^{\alpha} \quad [\text{New}]$$

If d_{ij} is the minimum, merge pair (add 4-vectors), replace pair with sum in list and redo list;

If d_i is the minimum $\rightarrow$ i is a jet! (no more merging for i, it is isolated by R),

1 angular size parameter R, plus

$\alpha = 1$, ordinary k_T (kT), recombine soft stuff first

$\alpha = 0$, *Cambridge/Aachen* (C/A), controlled by angles only

$\alpha = -1$, *Anti-k_T* (AkT) just recombine stuff around hard guys – cone-like (with seeds), Salam, *et al*. (2008)

Recombination Lessons:

- Jet identification is unique – no merge/split stage as with cone
- "Everything (interesting) in a jet", no Dark Towers (soft particles in "beam jet")
- Resulting jets are more amorphous for $\alpha \geq 0$, energy calibration more difficult (subtraction for Underlying Event + PileUp?)
- But for $\alpha < 0$, Anti-kT (Carriari, Salam & Soyez), jet area seems stable and geometrically regular * - the "real" cone algorithm (but large pT jets take a bite out of small pT one)

→ Use Anti-kT at the LHC!

Jet Summary for 2005 at the LHC:

- ATLAS and CMF to primarily use Anti-kT with various (but different) R values (As of summer 2016 there is one shared R value, R=0.4)
- Would like to reliably control the expected impact of high luminosity (large Pile Up), eventually ~ 100 individual pp collisions per bunch crossing!!
- Would like to reliably ID heavy, boosted objects (W, Z, Top, Higgs) that decay hadronically.

→ The era of Jet Substructure !!