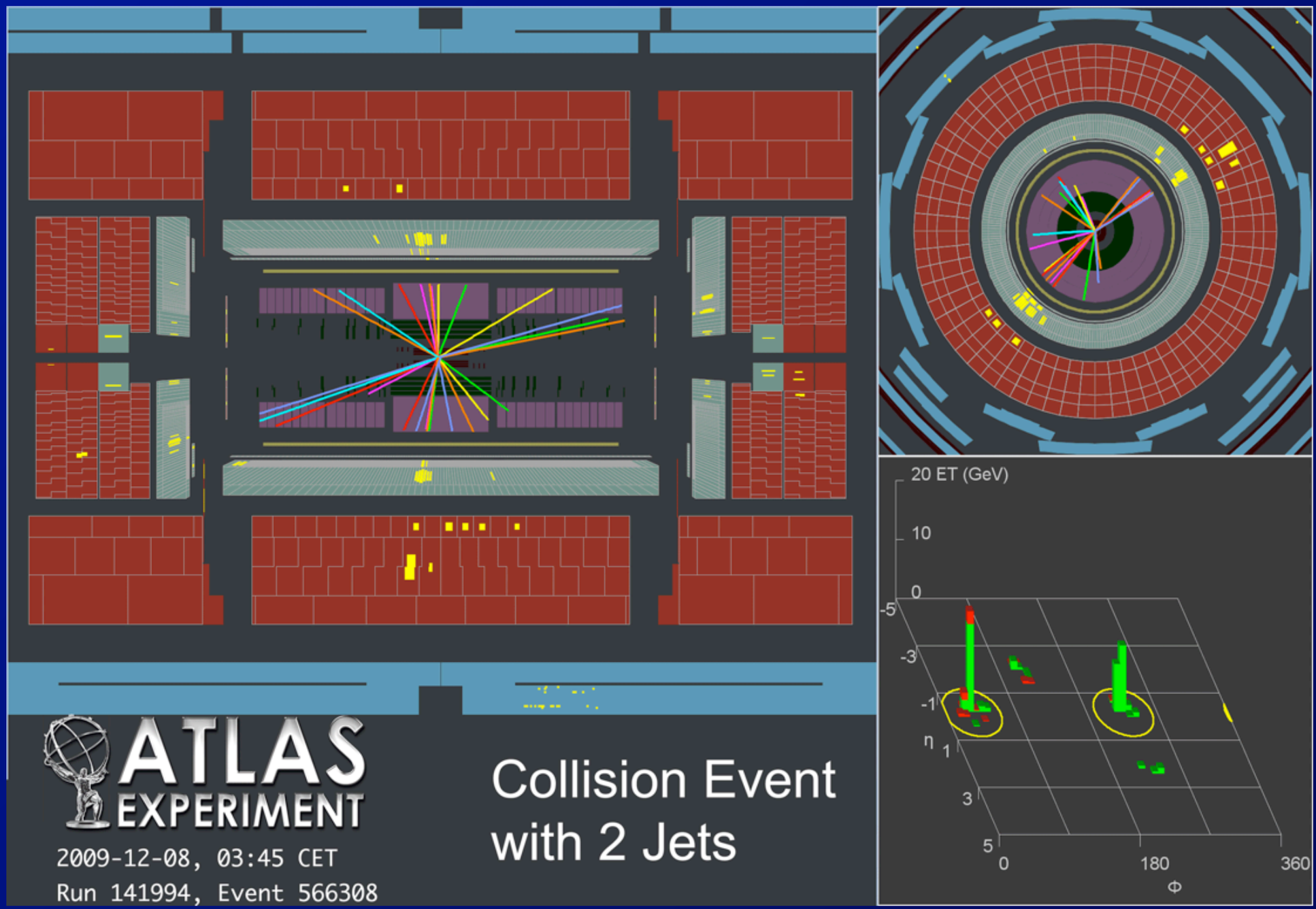
High p_T Physics: LHC Prospects

Brian A. Cole, Columbia University

March 19, 2010

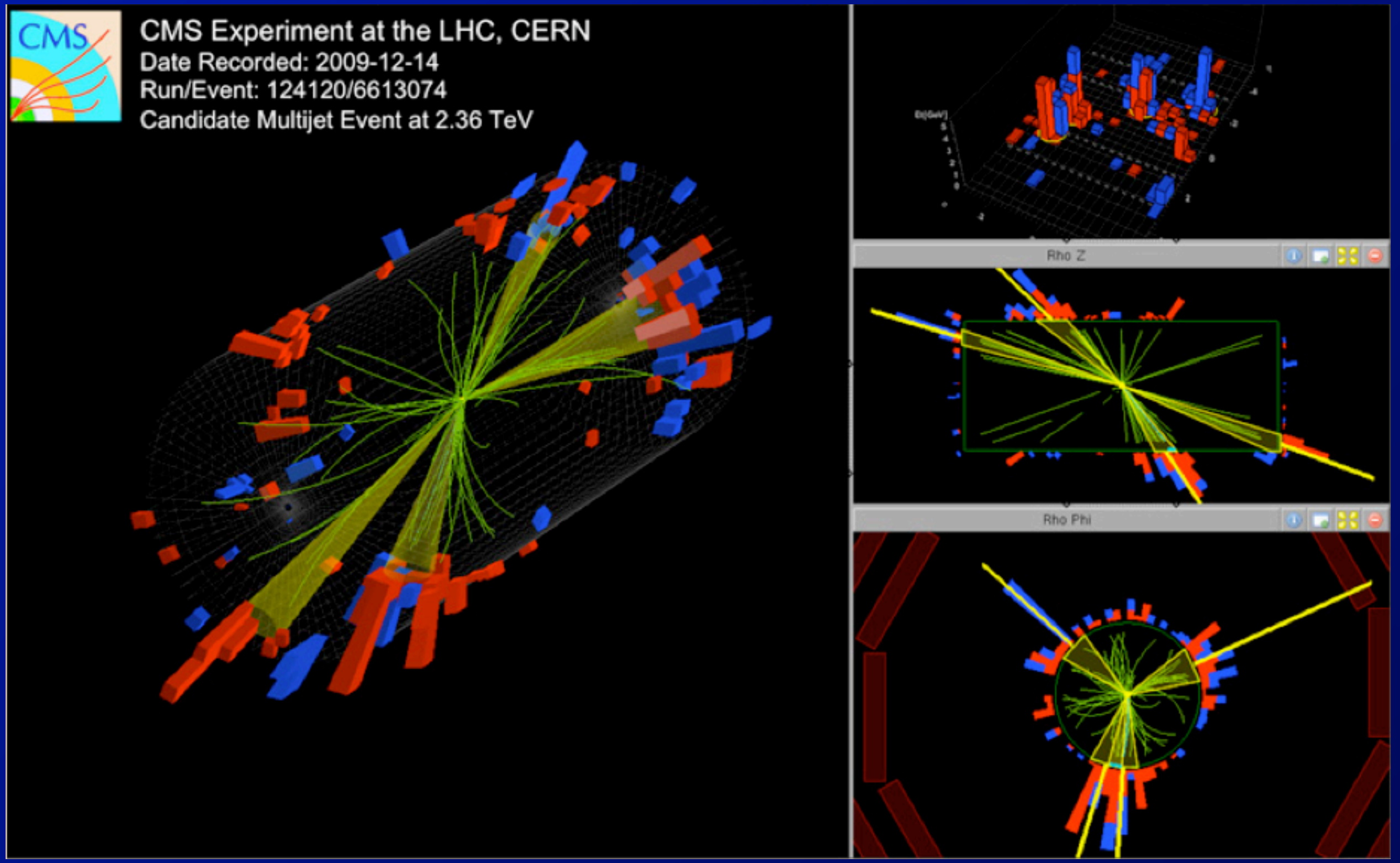


LHC High-p_T Physics (Relevant to this meeting)

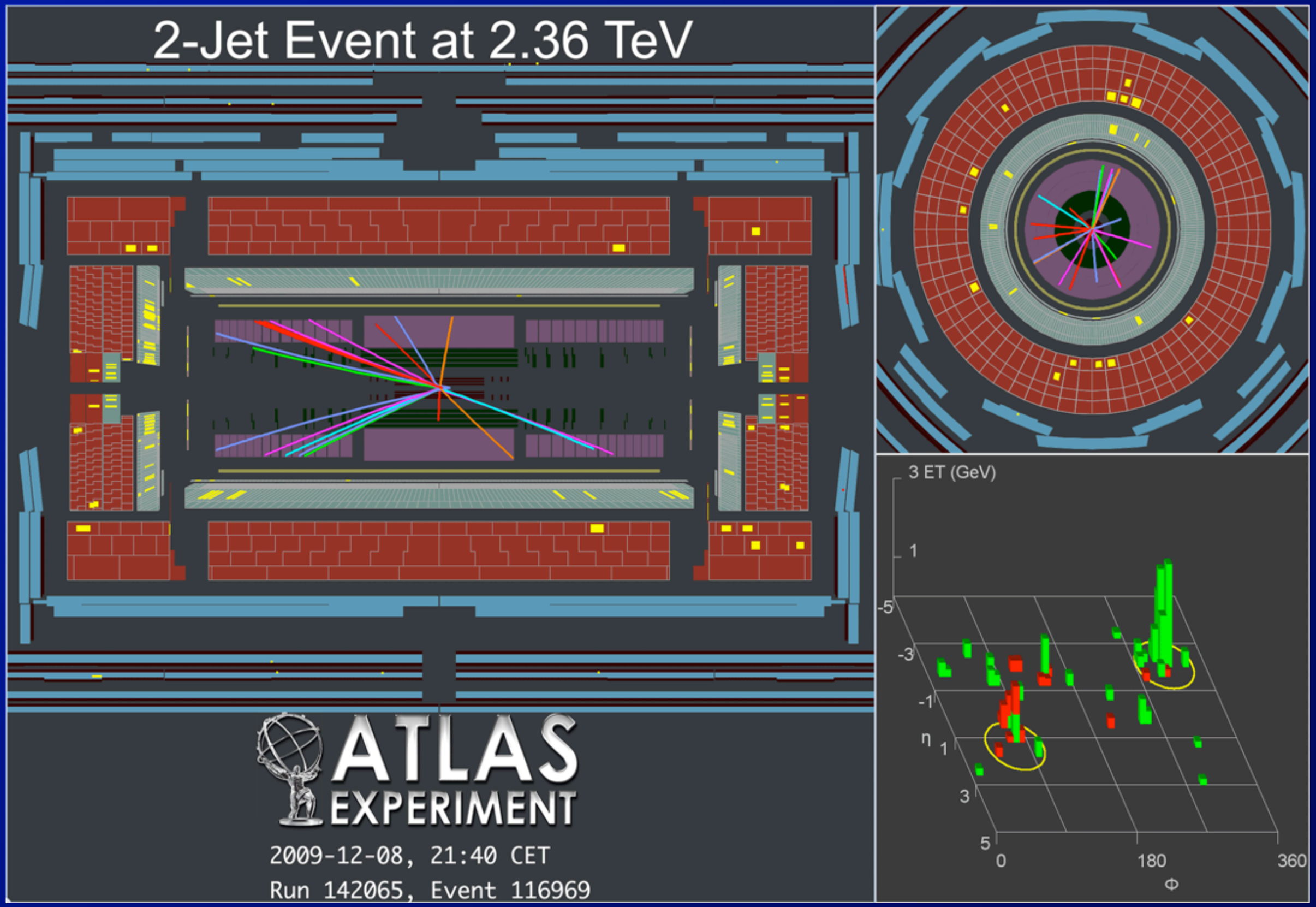
While the primary focus of the LHC is on electro-weak and BSM physics, the LHC will be a powerful tool for studying QCD

- **Very high Q2 hard scattering processes**
  - Production of many-jet final states, heavy flavor
    - ⇒ Tests of understanding of parton showers
- **Hard processes involving low-x partons**
  - In p+p, tests for BFLK physics, diffractive hard physics(?)
  - In p+A, A+A, shadowing measurements, saturation tests
    - ⇒ (semi?)-hard QCD @ large parton densities
- **Jet quenching in A+A**
  - Extended jet p_T range , higher jet yields
  - Jet measurements at very large Q^2
    - ⇒ Modification of extended parton showers in medium

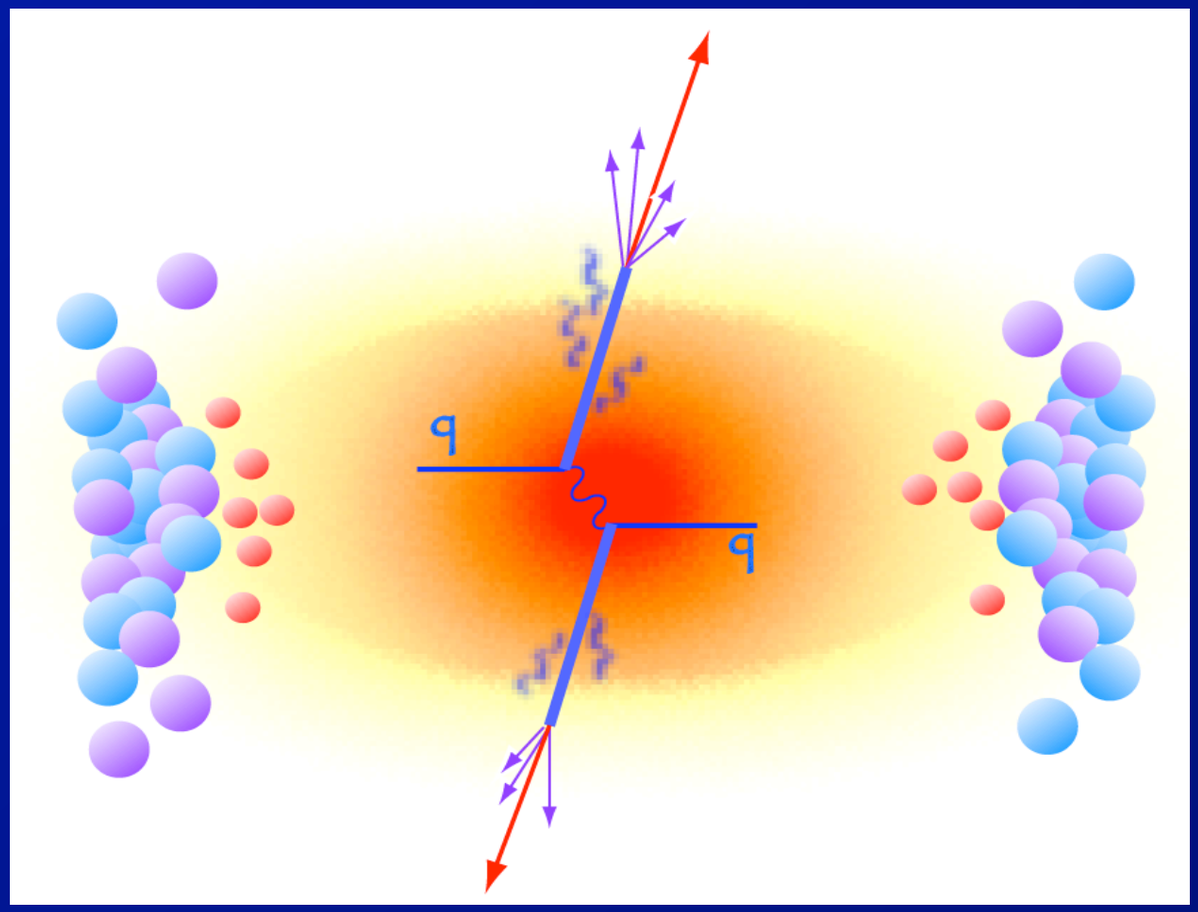
CMS Event Display



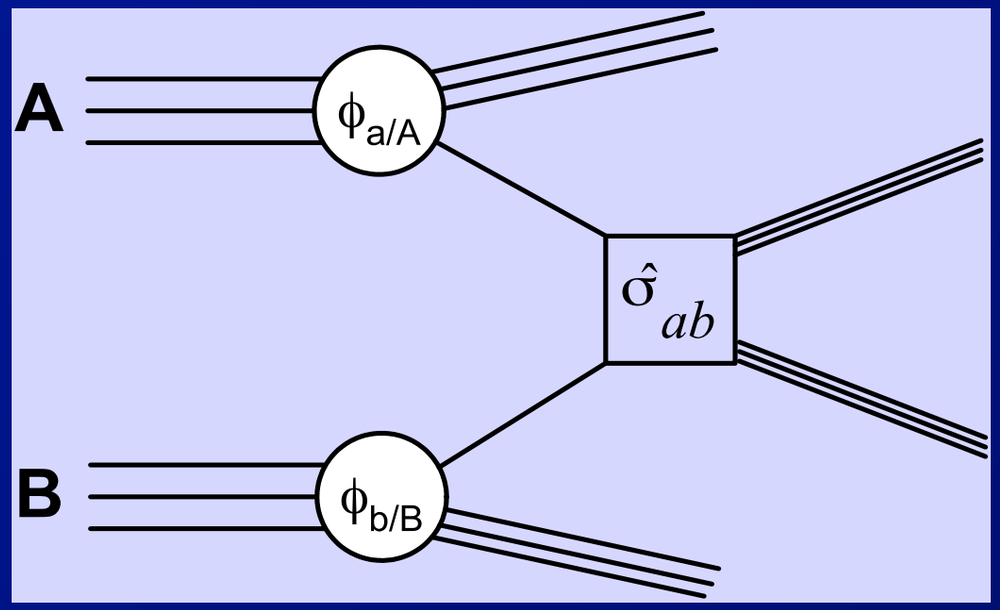
ATLAS Event Display

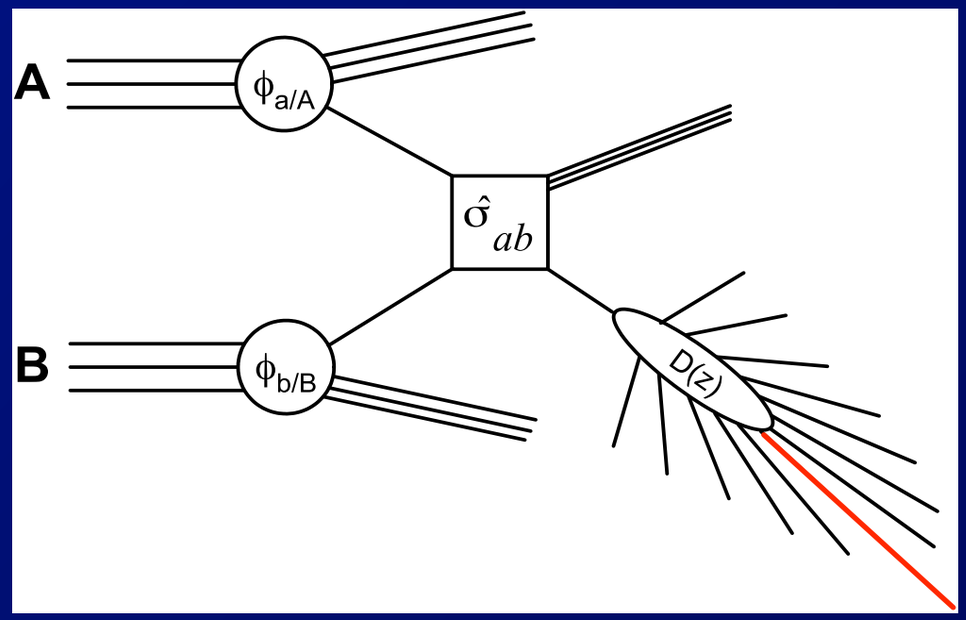


Picturing (and understanding) high-p_T physics



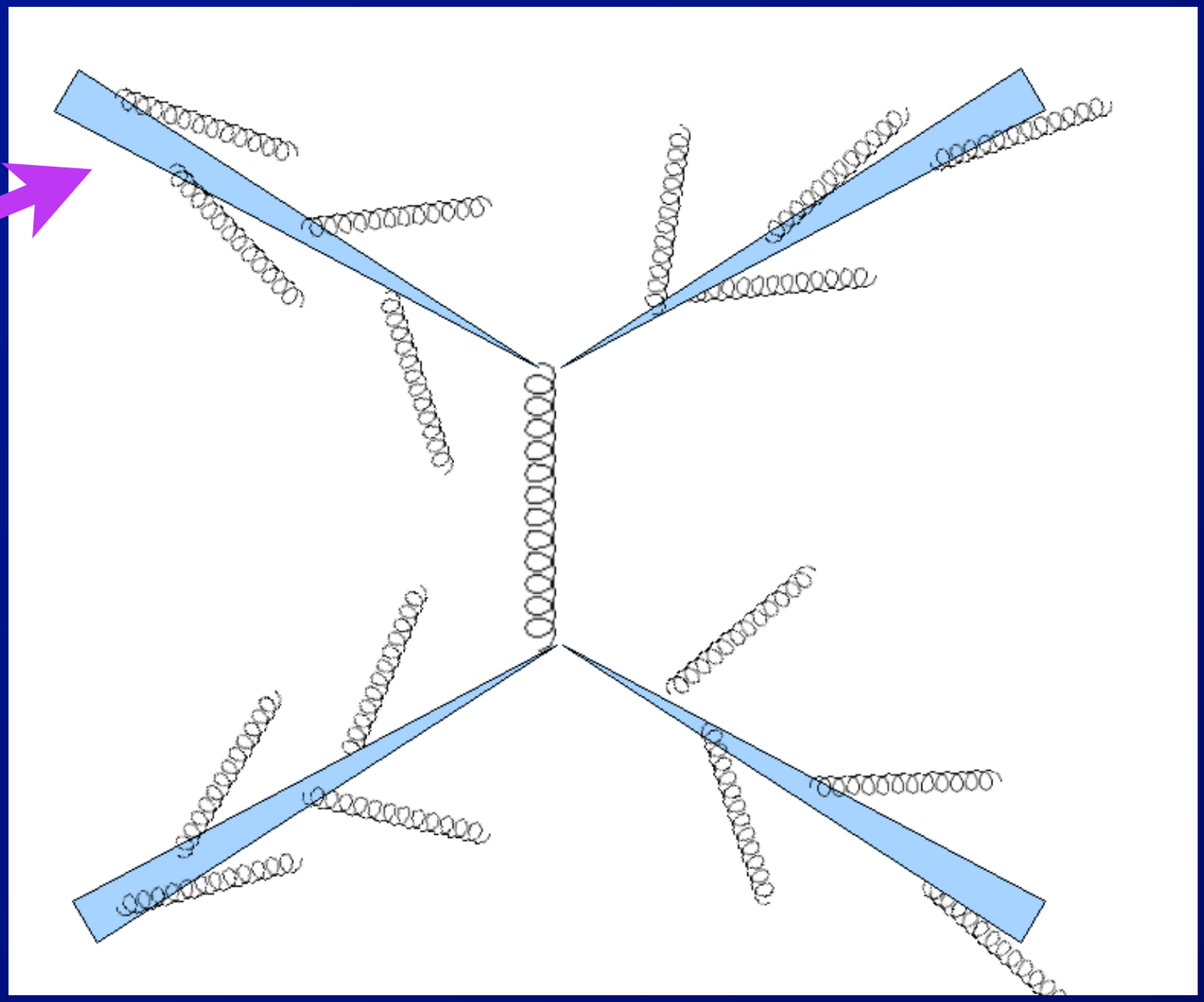
- RHIC community has been conditioned by exposure to cartoons or schematics of physics applicable only at LO
  - ⇒Mea Culpa
  - Even in hard processes QCD is more complicated





Picturing (and understanding) high-p_T physics

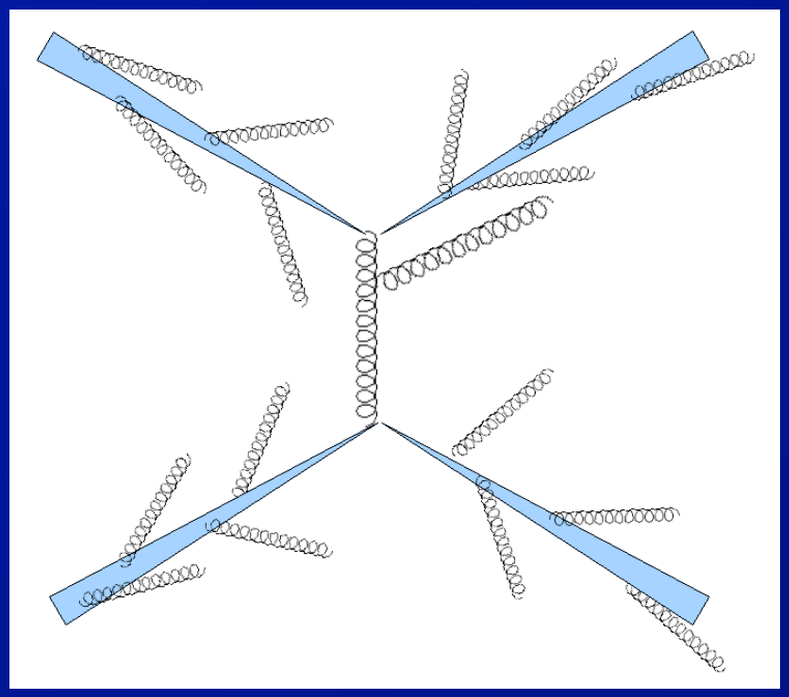
Virtuality evolution:
low → high resolution



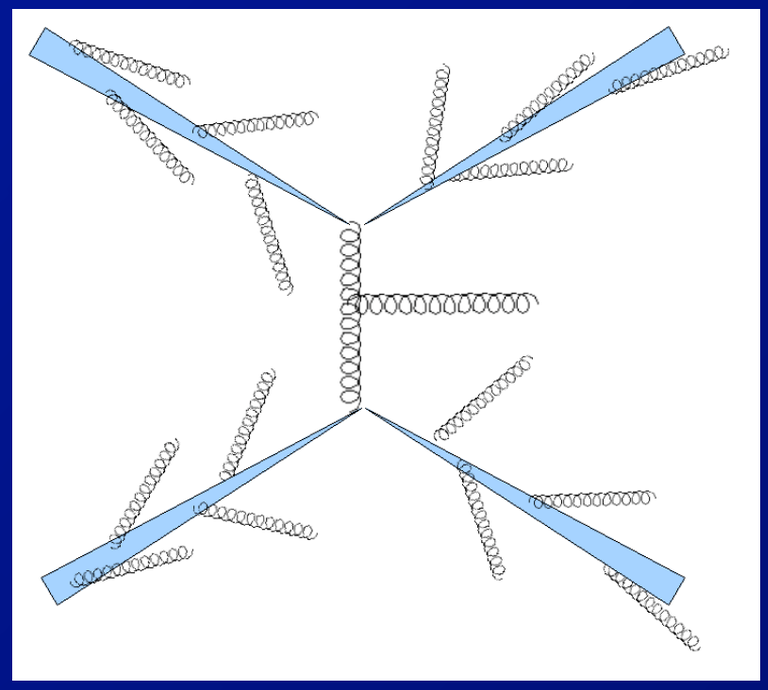
- **Copious radiation by all color charges**
  - Angular ordered initial, final state parton showers
    ⇒ For high-Q^2 processes, hard radiation (jets) in ⟶ shower
  - Subtle physics in QCD description of soft radiation

Picturing (and understanding) high-p_T physics

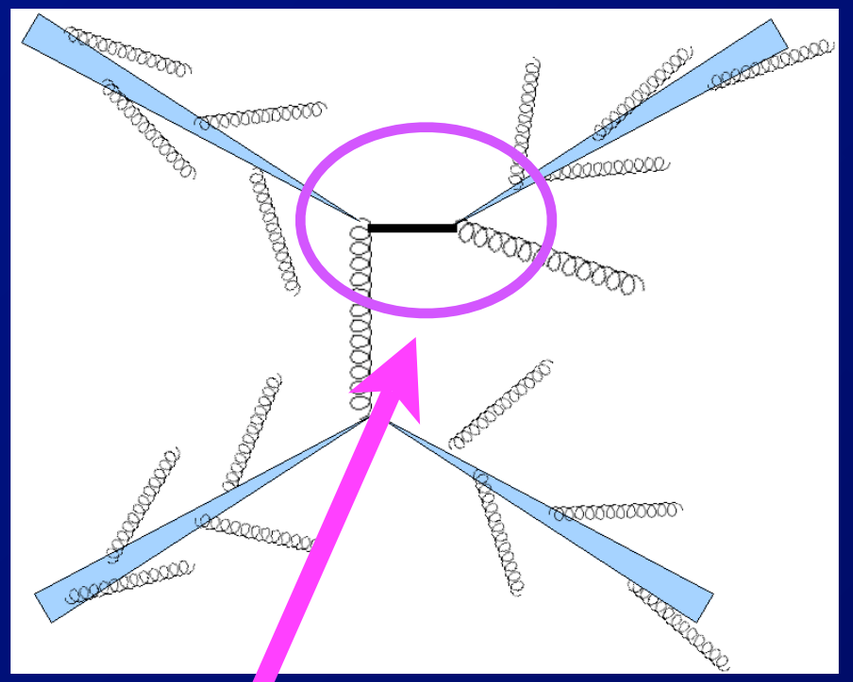
2 jet event (?)



3 jet event (?)



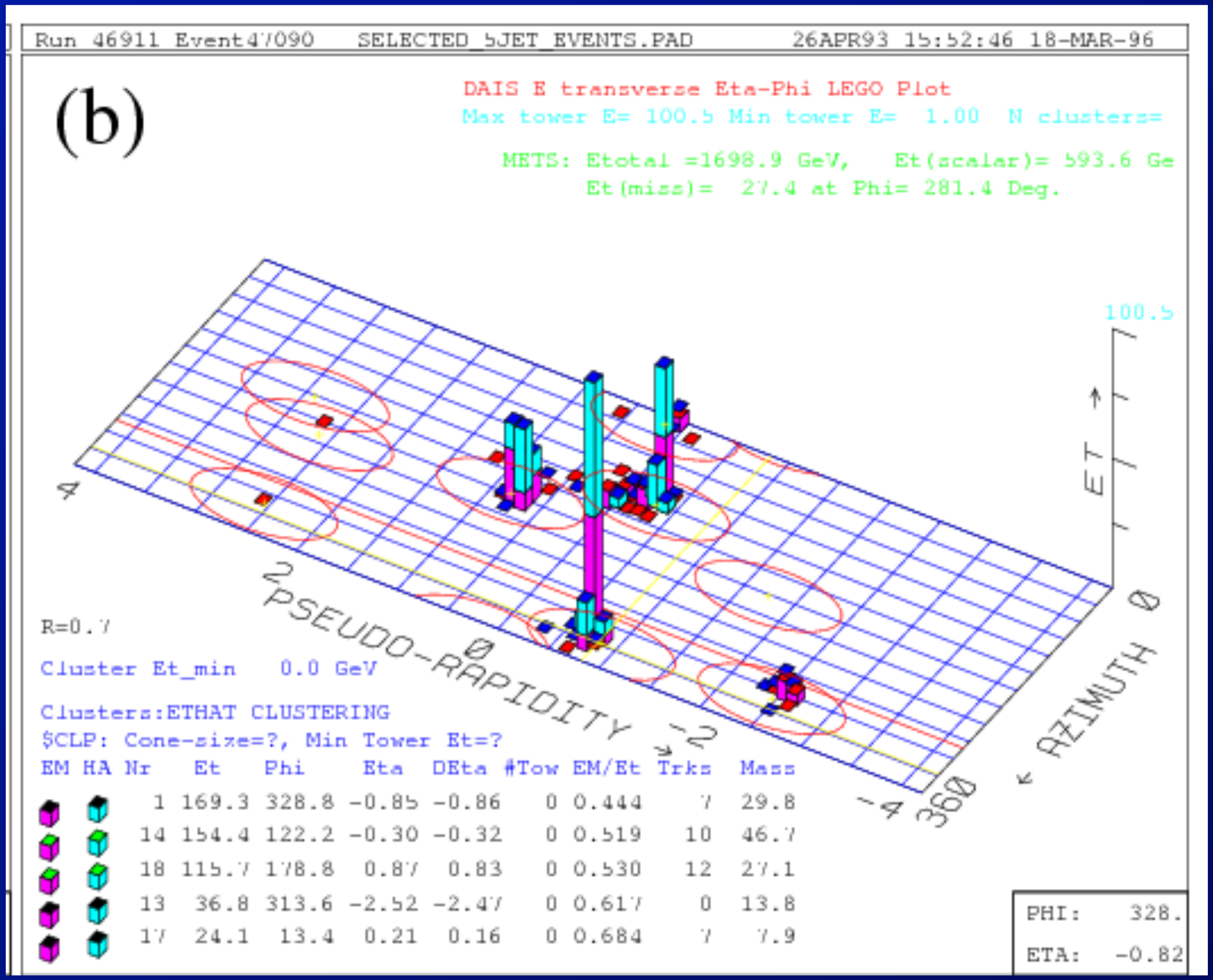
2, 3, ? jet event



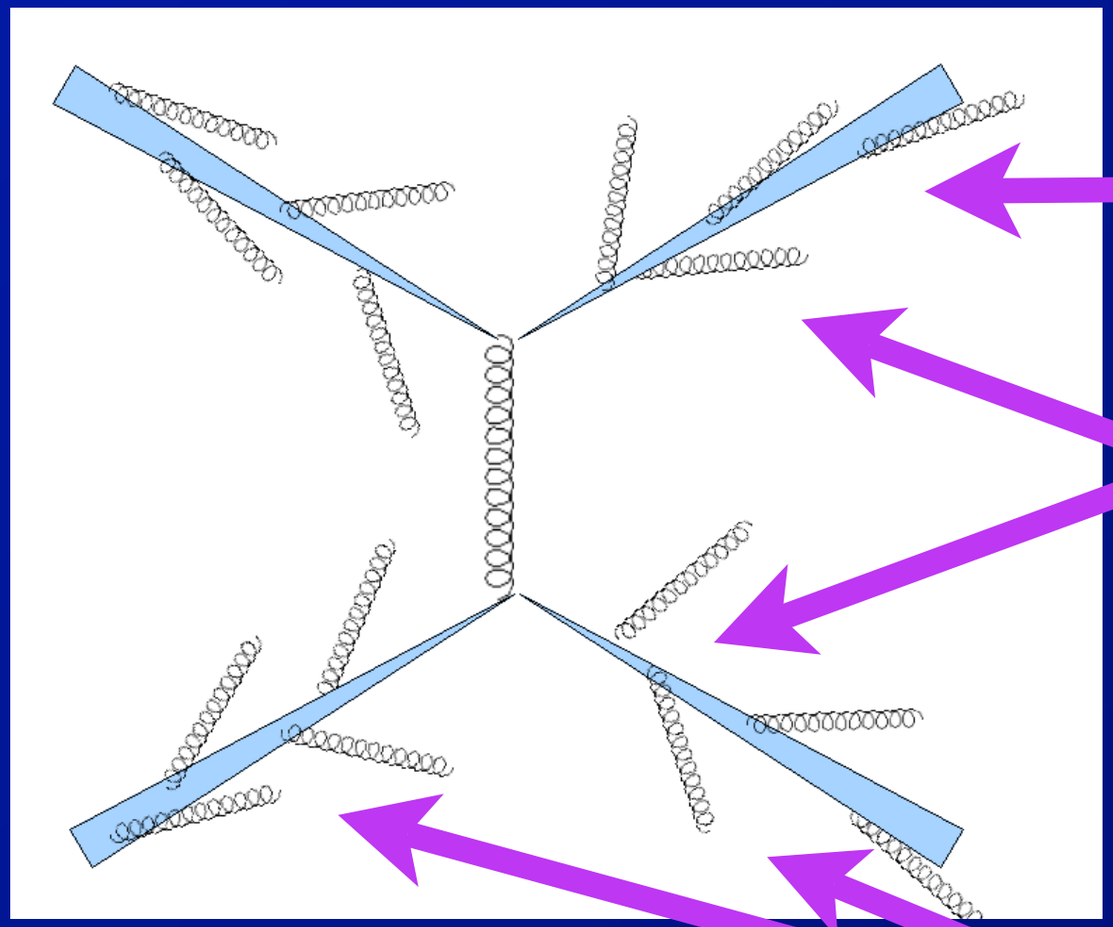
- There is no unique relation between diagrams and numbers of jets
- There is no unique separation between the hard scattering and the parton shower(s)

Where does “hard” scattering end and the parton shower (fragmentation) begin

CDF: Example Multi-jet event



Picturing (and understanding) jets



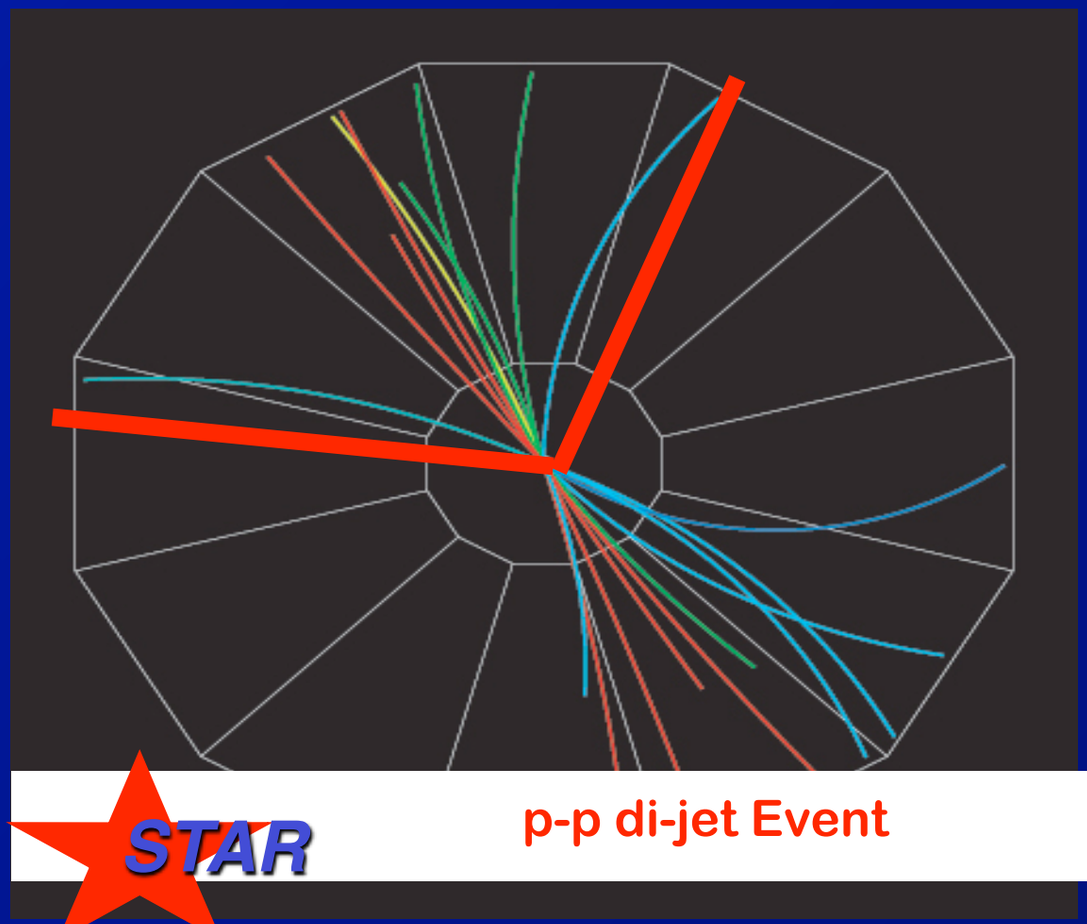
Radiation extends over (beyond) full hemisphere in jet direction

Color connection between outgoing partons and between those partons and beam remnants

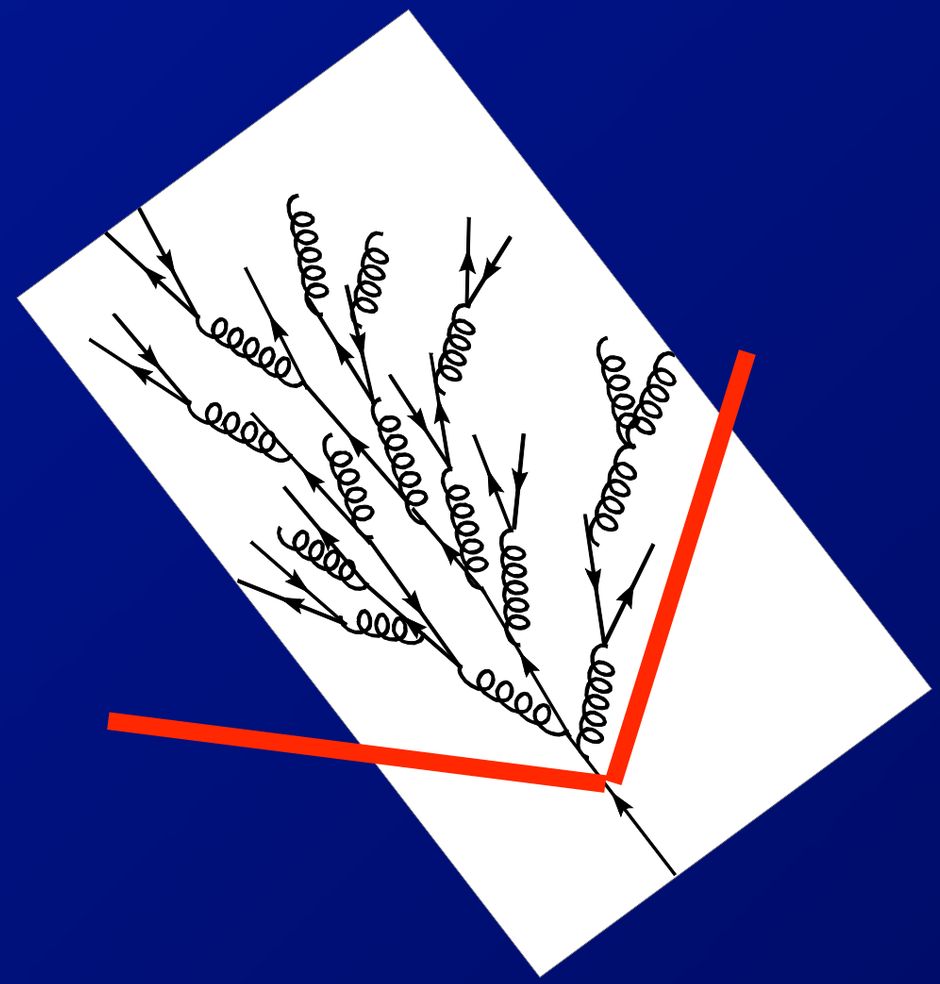
Overlap between initial, final parton showers

- Even theoretically, not possible to uniquely associate a "jet" (measured correlated collection of hadrons) with individual partons
  - NO such thing as a "true" (parton) jet cross-section

Jet Definitions, angular coverage

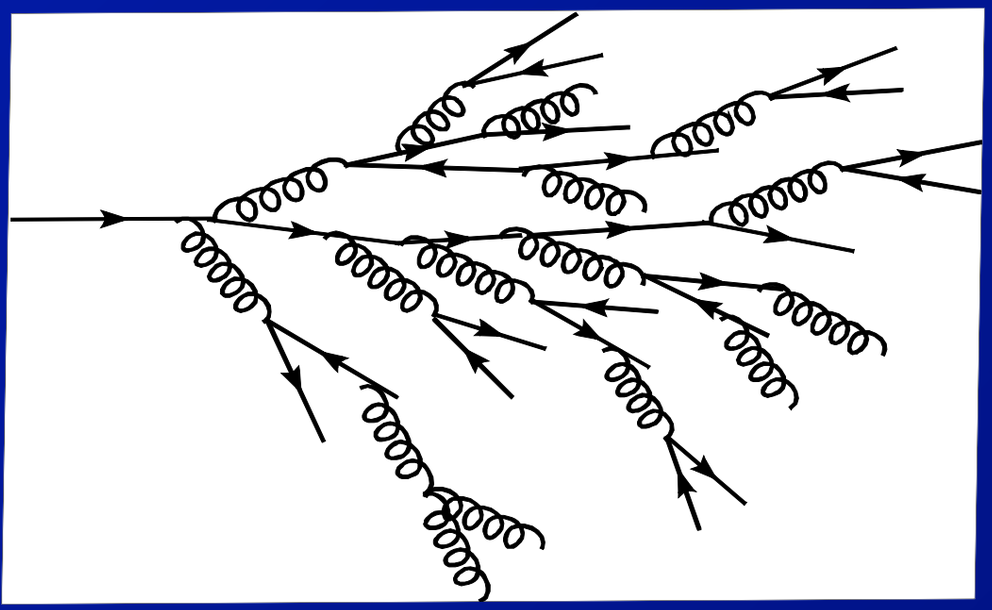


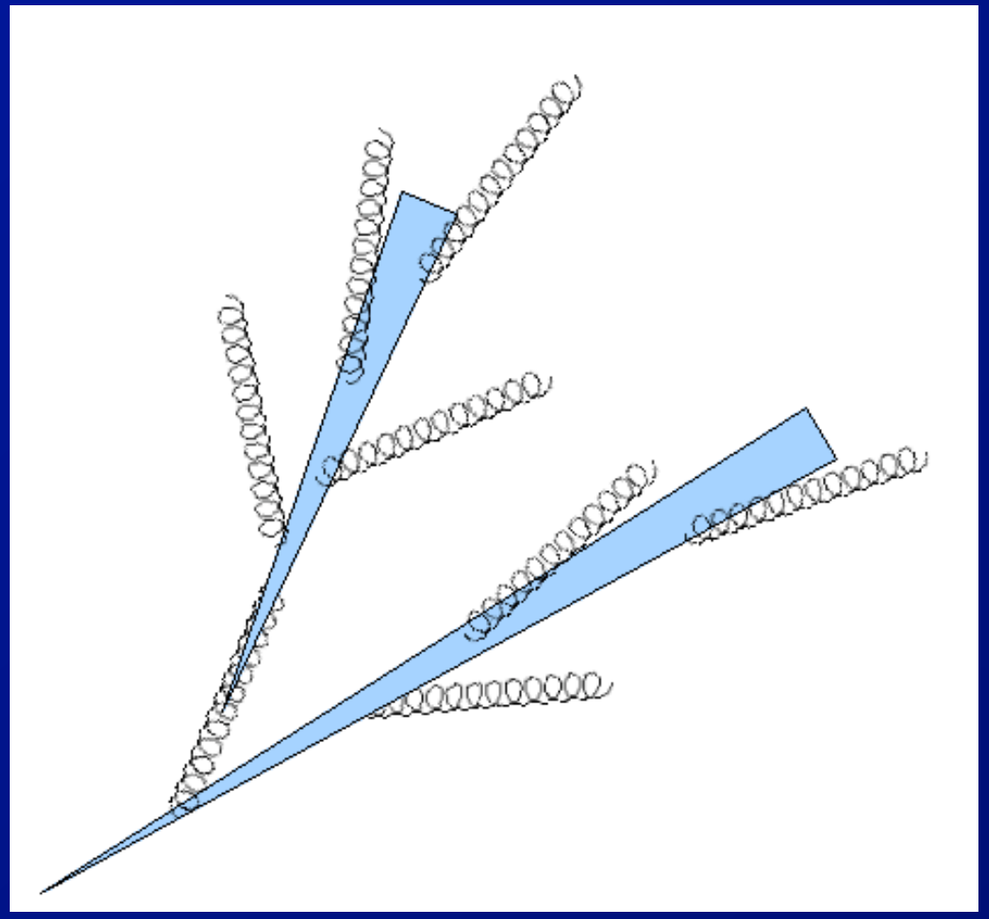
p-p di-jet Event



- **Trade-offs in jet definition:**
  - Larger angular coverage collects more of the jet
    ⇒Smaller losses due to radiation (soft and hard)
  - Larger angular coverage increases overlap of showers
    ⇒And increases contribution of underlying event
- **Changing angular scale can change # of jets**

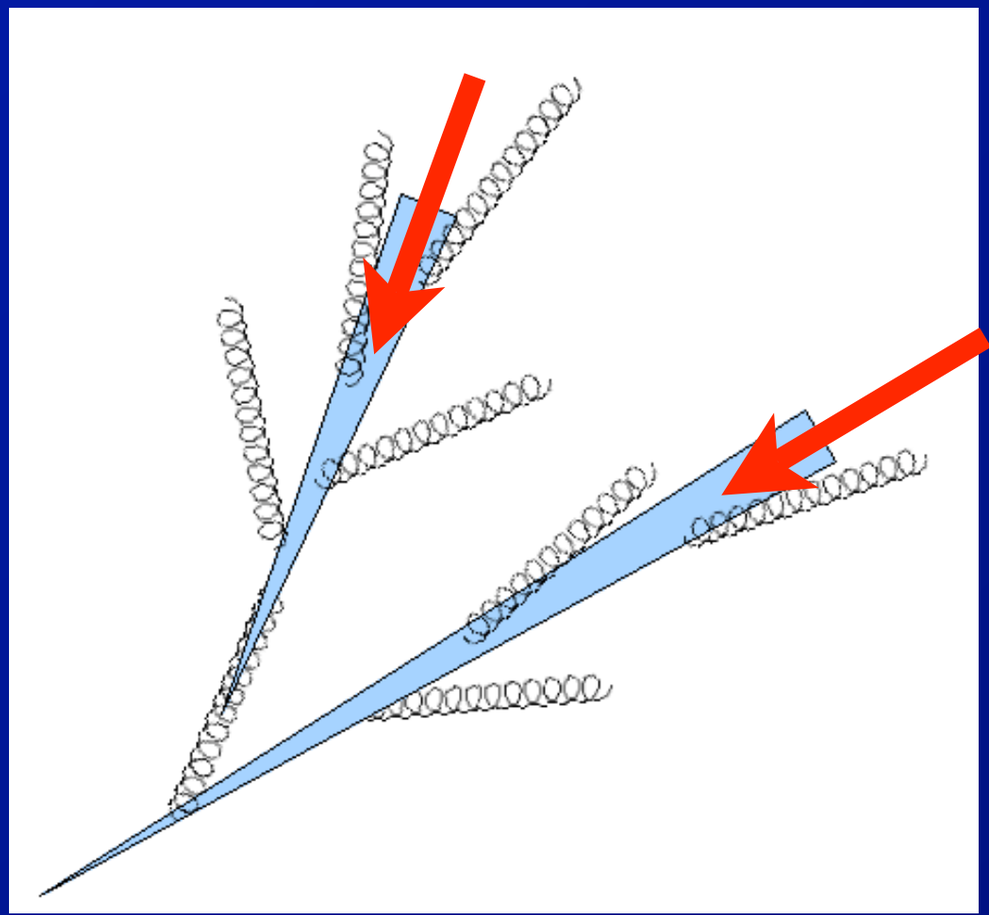
Jet Algorithms, considerations





- Jets defined by the algorithm
- To be calculable in pQCD algorithm should be
  - Collinear safe
    - ⇒Insensitive to small-θ splitting
  - Infrared safe
    - ⇒ #, position, energy of jets insensitive to soft hadrons
  - Well-defined procedure for distinguishing between 1, 2 jets at a given angular scale
- In last 5 years:
  - Death of seeded cone, mid-point
  - New: SIScone, Anti-K_T, +
    - ⇒SIS = Seedless, infrared safe

Sequential Recombination Algorithms



$$R^2 = (\phi_i - \phi_j)^2 + (\eta_i + \eta_j)^2$$

$$d_{ij} = min((k_{T\,i})^p, (k_{T\,j})^p) R^2$$

$$d_{iB} = (k_{T\,i})^p$$

Sequentially combine pairs of particles ("proto-jets") according to smallest d_{ij}

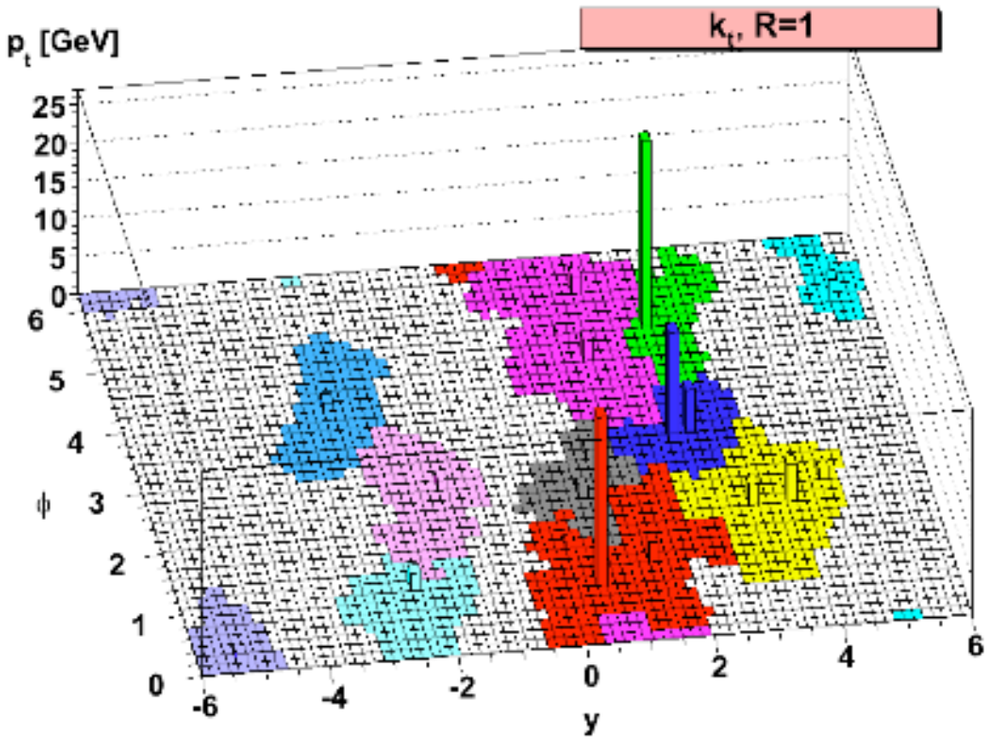
p = 1 - k_T algorithm (QCD-like)

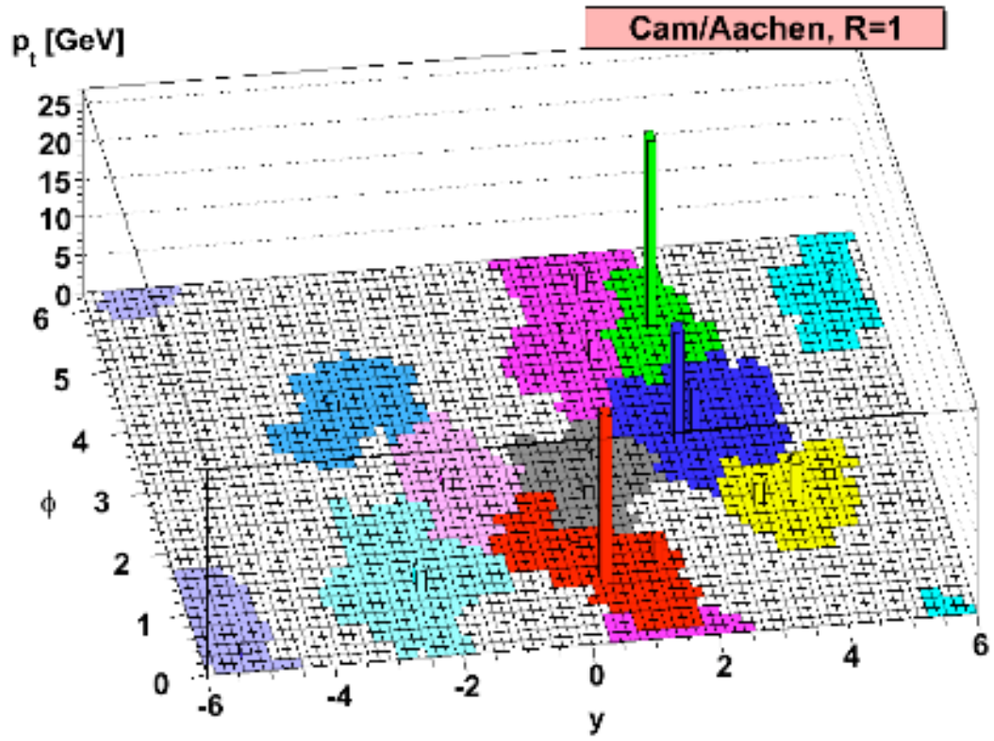
p = -1 - anti-k_T (cone-like)

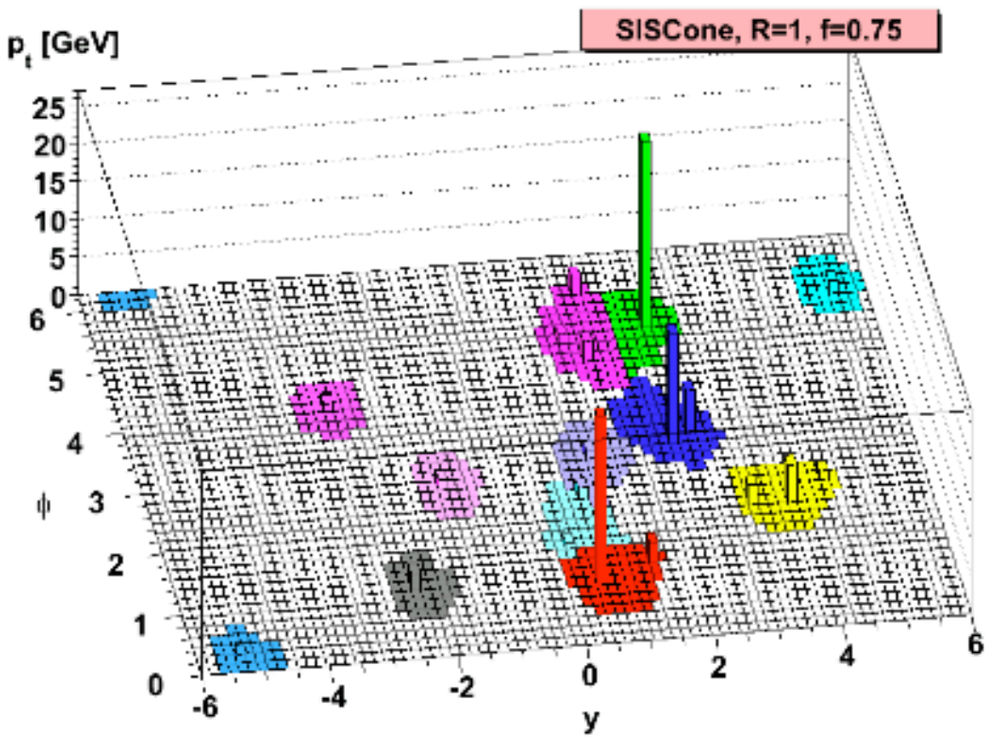
- **Sequential recombination algorithms:**
  - Infrared and collinear safe
  - Original kT algorithm motivated by angular-ordered PS
  - Anti-k_T inspired twist to produce cone-like behavior

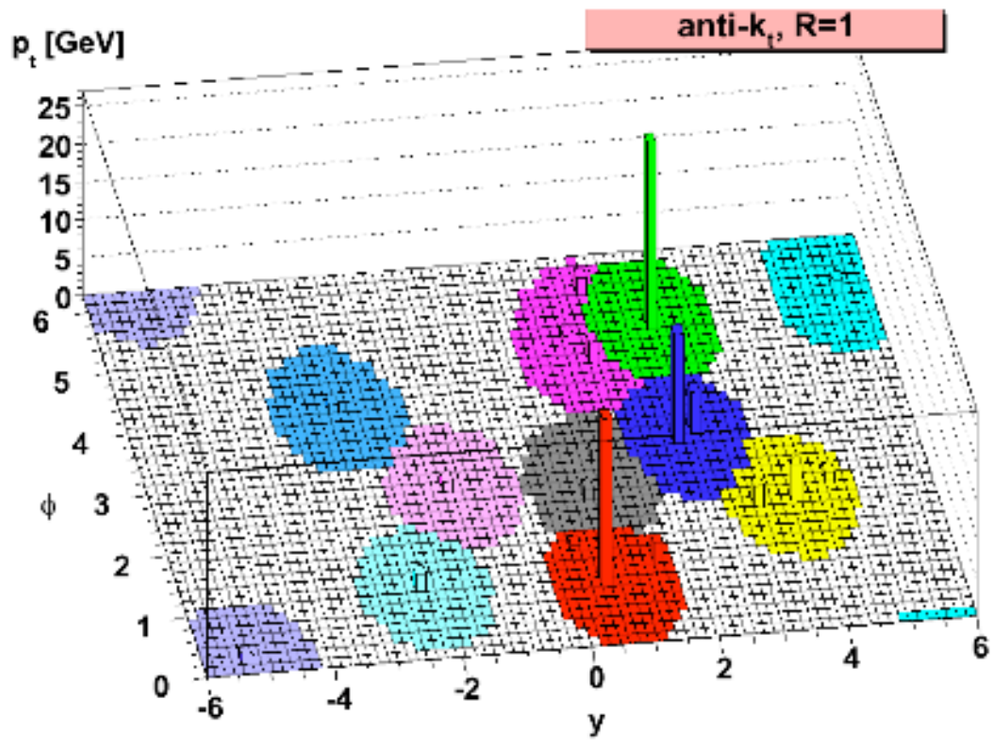
    ⇒But without (less) ad-hoc split-merge

Different Jet Algorithms



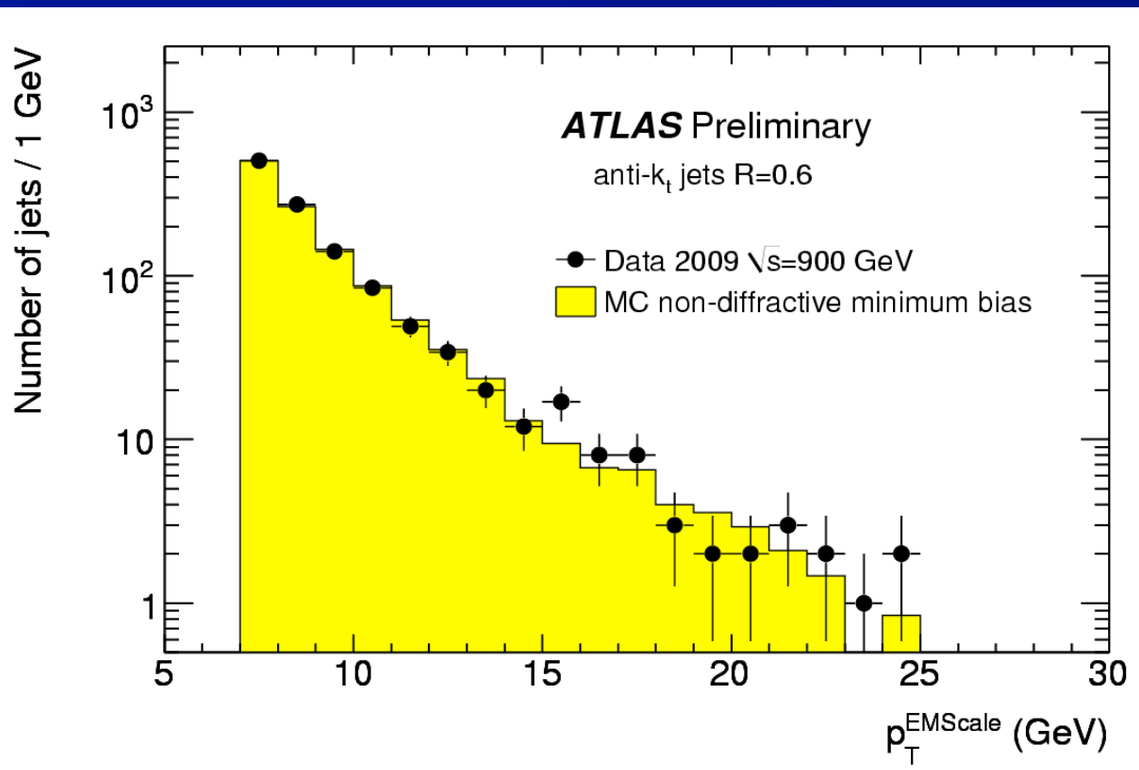


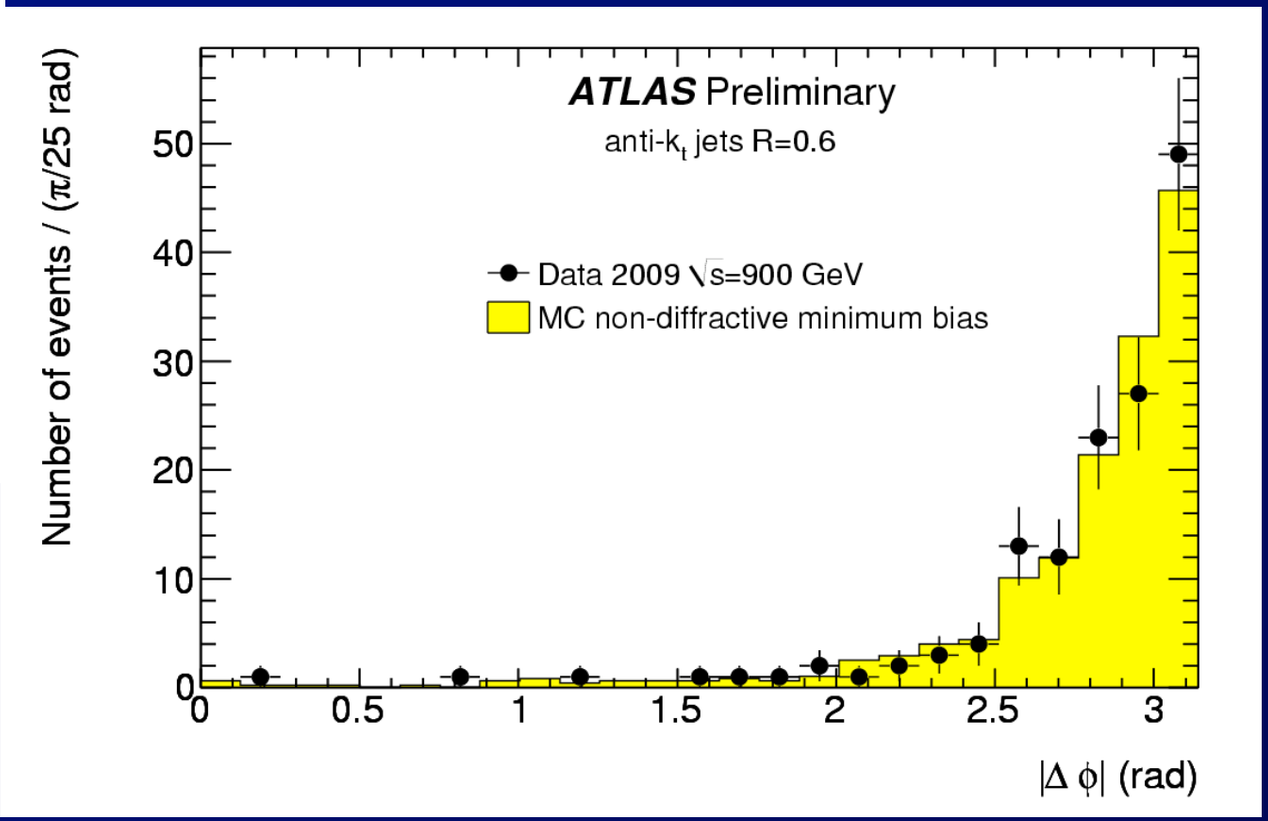




(very) Preliminary LHC Jet Data: ATLAS

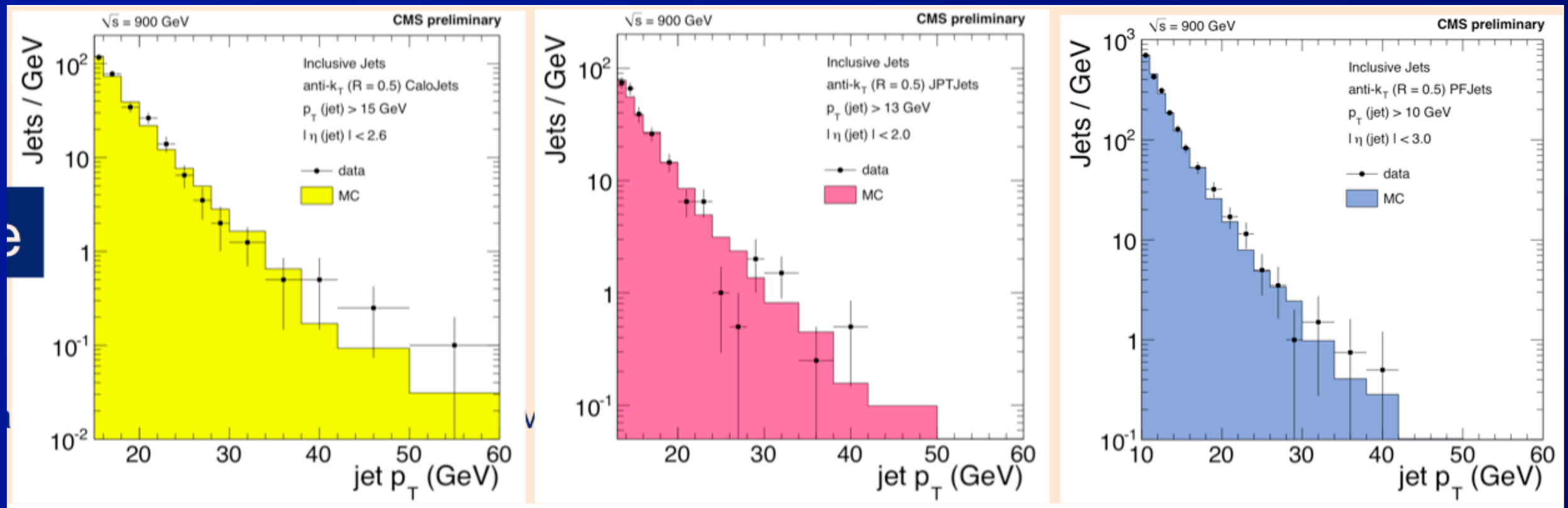
- Reconstructed using anti-k_T algorithm (R = 0.6)
  - ATLAS "topo-tower" algorithm (similar to D0 4-2-0)
- Jet energies only at EM scale
- ~ 10's k jets reconstructed from first beam data





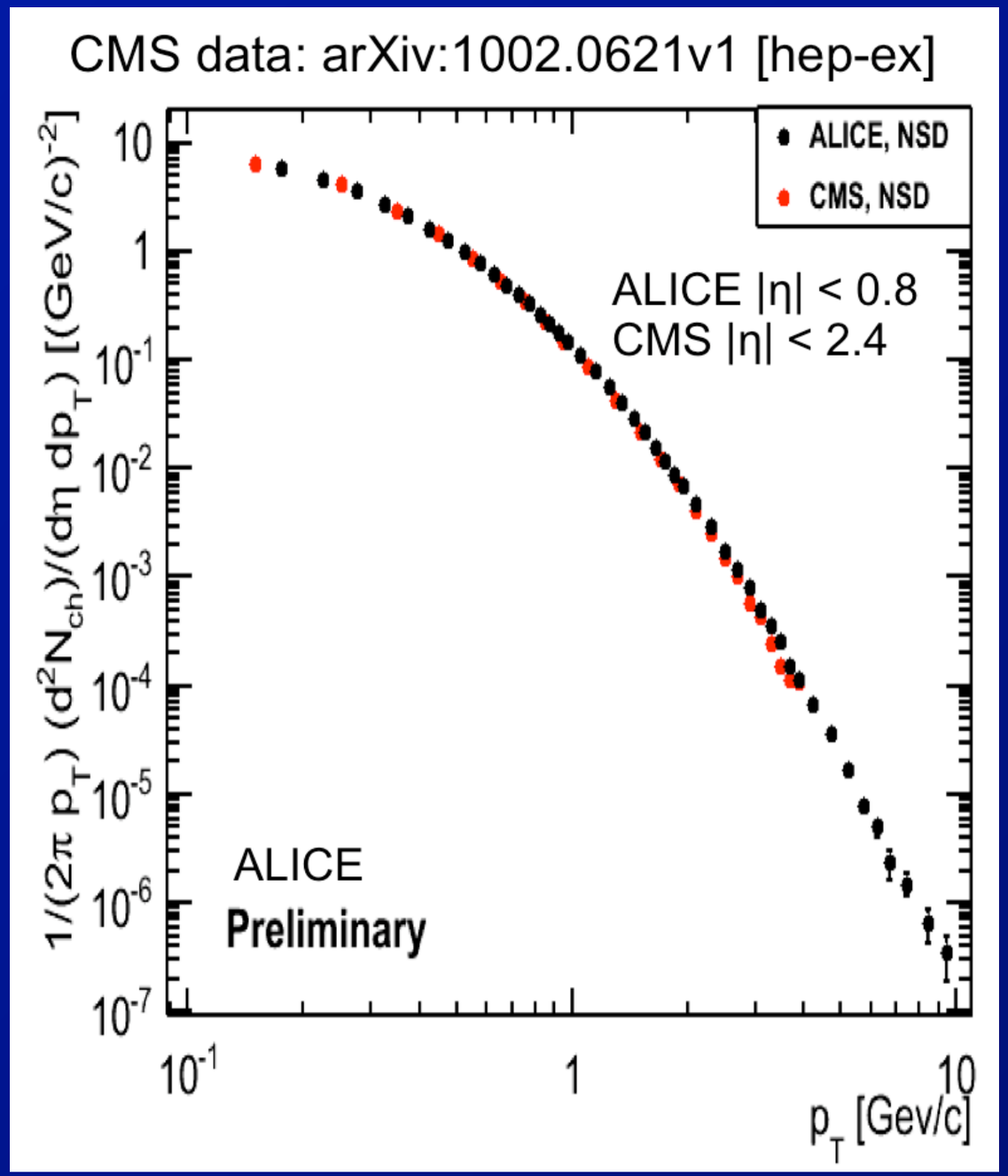
(very) Preliminary LHC Jet Data: CMS

Salvatore Rappocio, Moriond (QCD) Talk

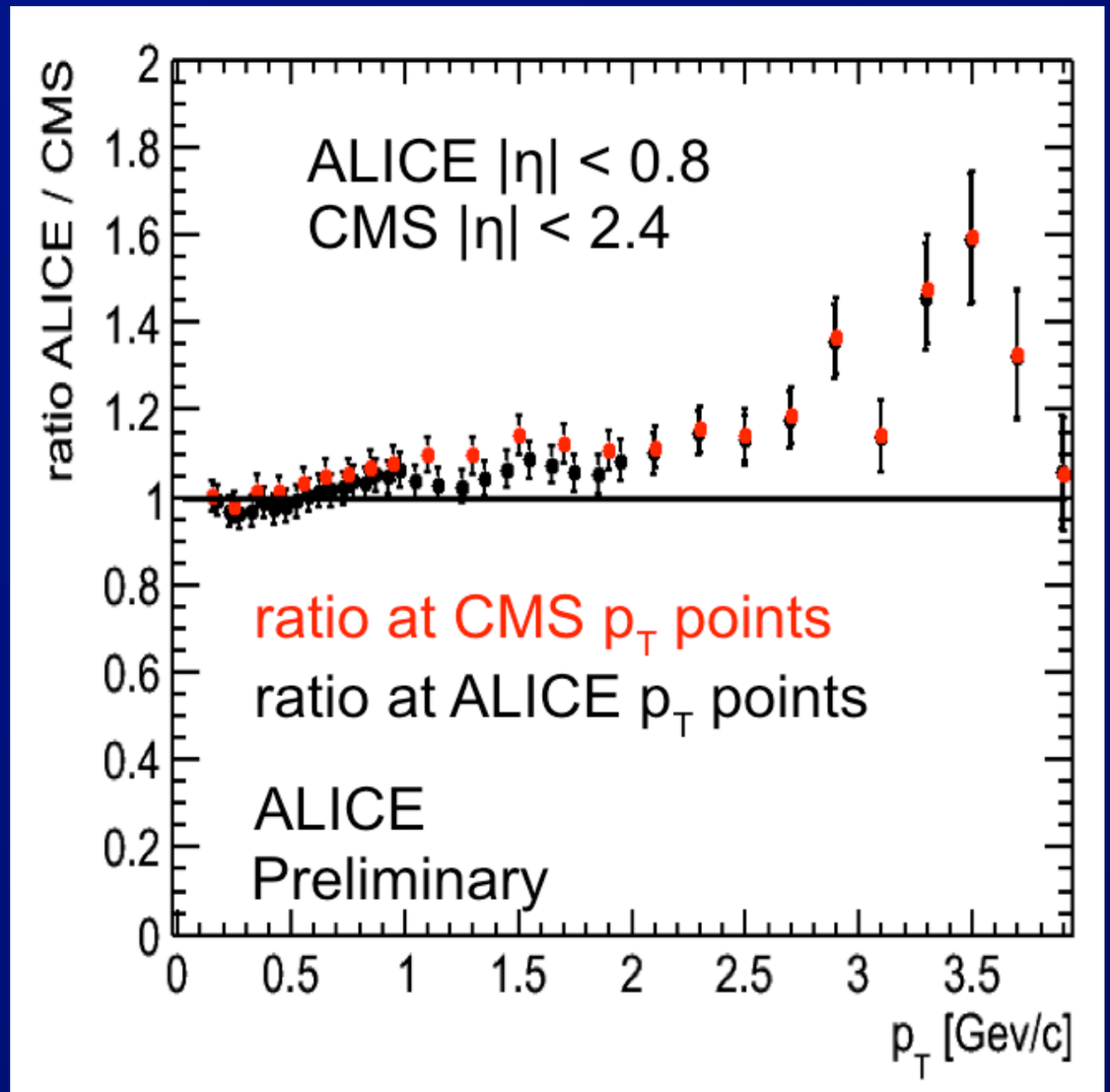


- Anti-k_T, R = 0.5
- From left to right:
  - Calorimeter only, track-improved calo, particle flow
    - ⇒Track-improved & particle flow uses tracking, identification of neutral hadrons, photons, etc to improve jet resolution.

ALICE, CMS Charged Particle Spectra

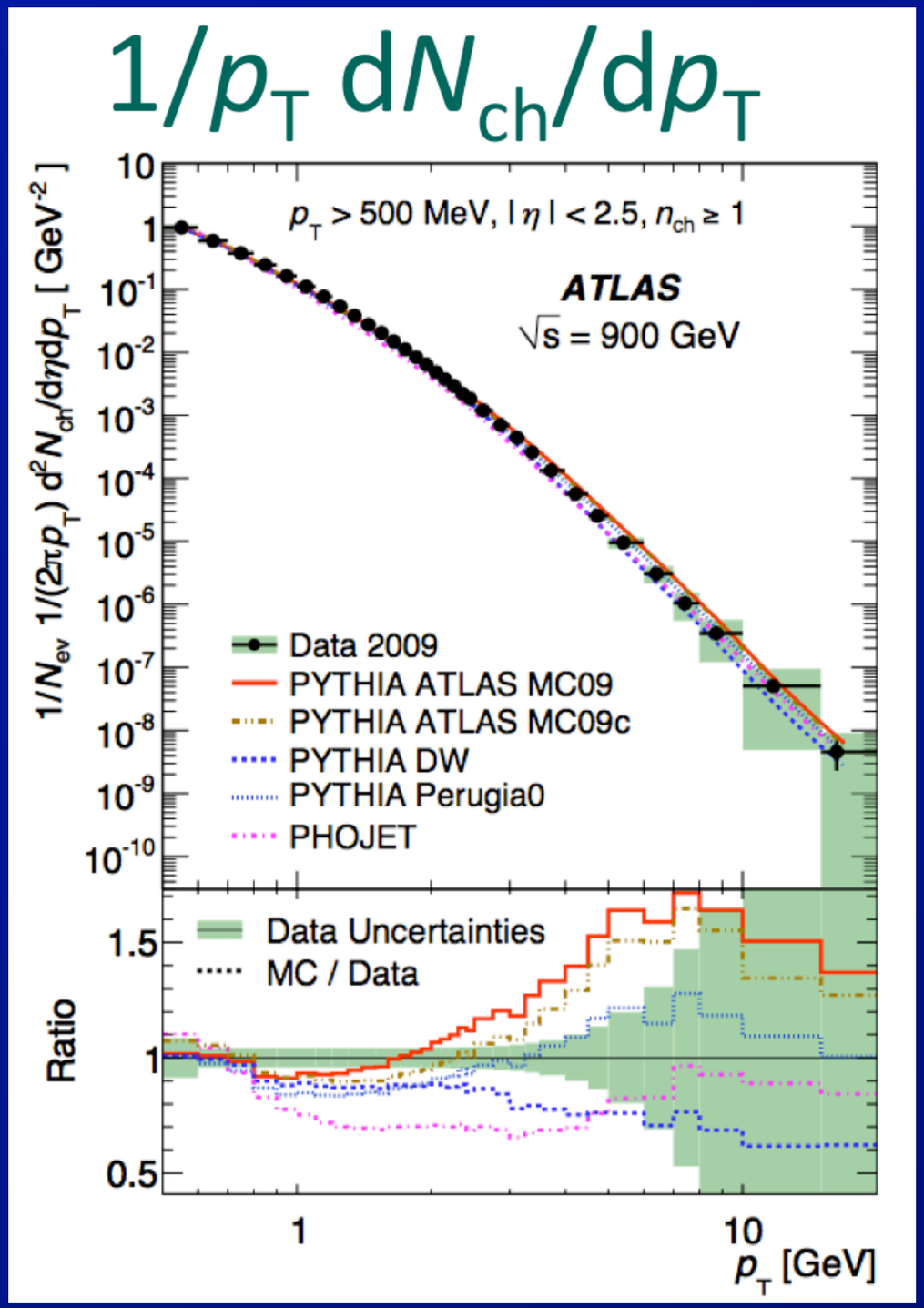


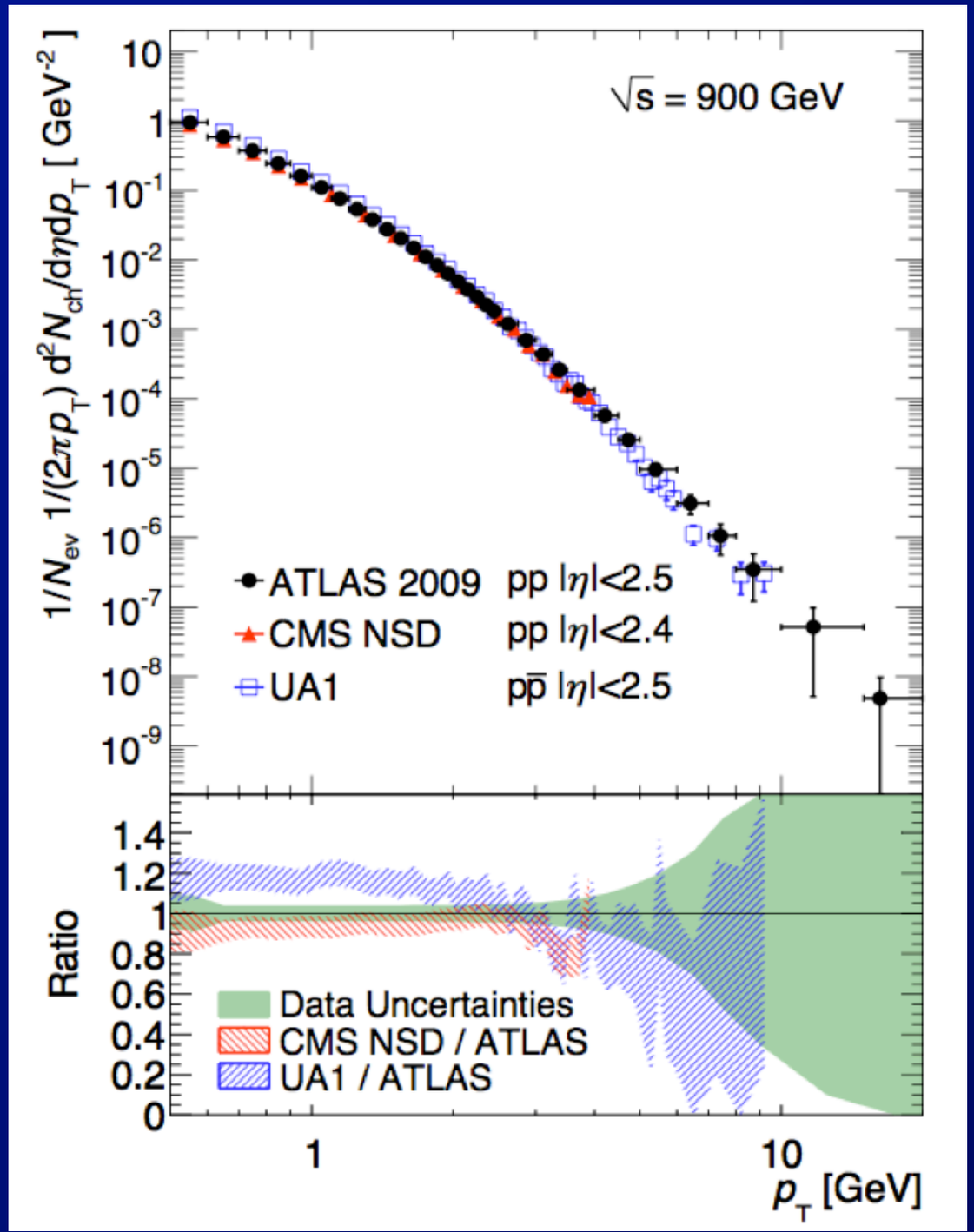
From Jacek Otwinowski (ALICE) Moriod Talk



- **Non-single diffractive charged particle spectra**
  - **⇒Note different pseudo-rapidity coverage**

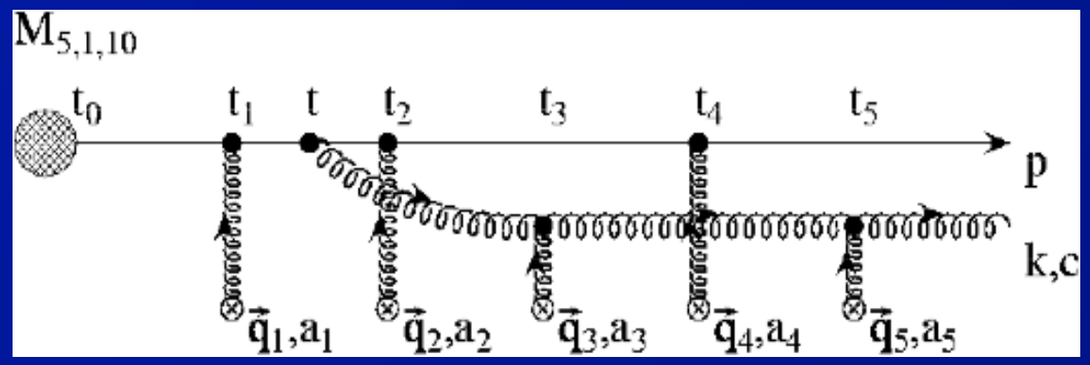
ATLAS Charged Particle Spectrum

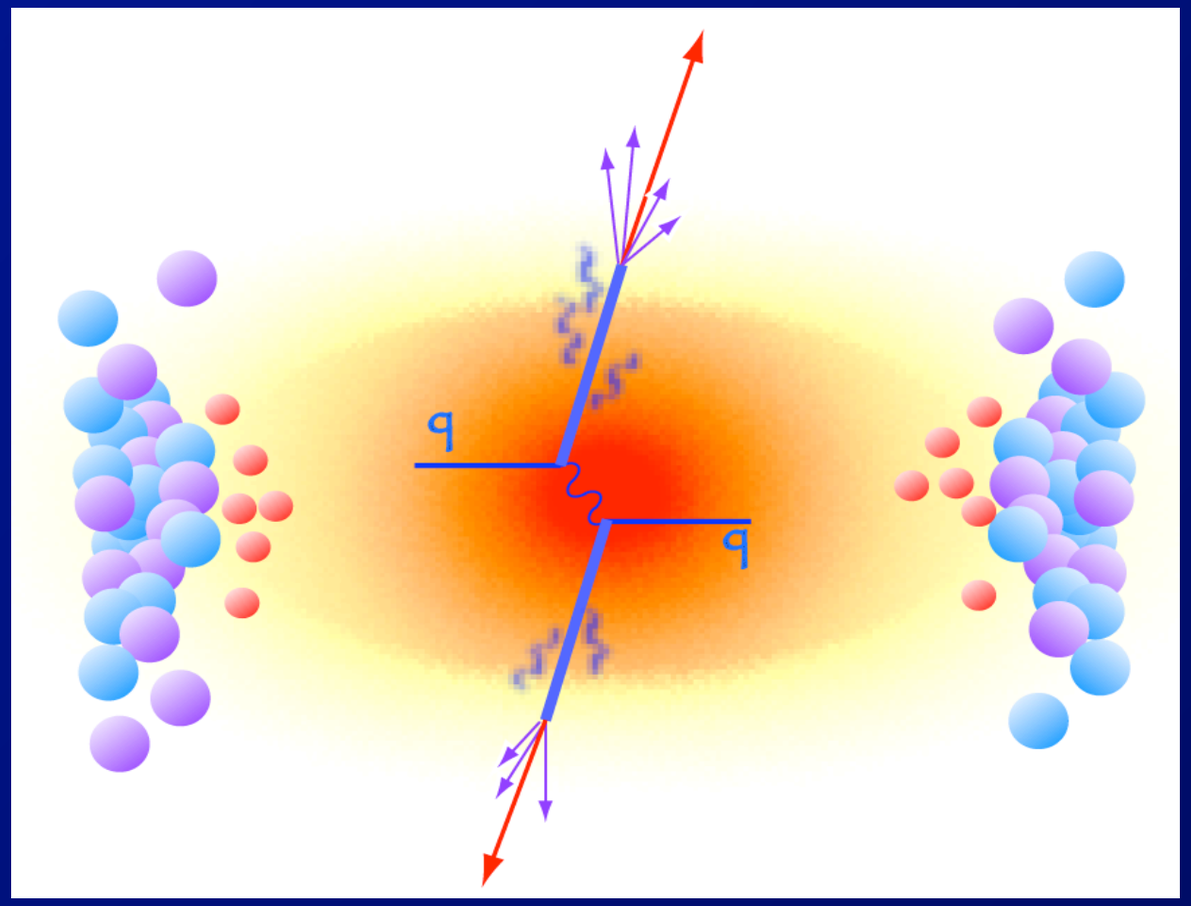




- **Beware ATLAS event selection requirements**
  - 3 tracks, p_T > 0.15 GeV, 1 tracks, p_T > 0.5 GeV

Jet Tomography in A+A Collisions



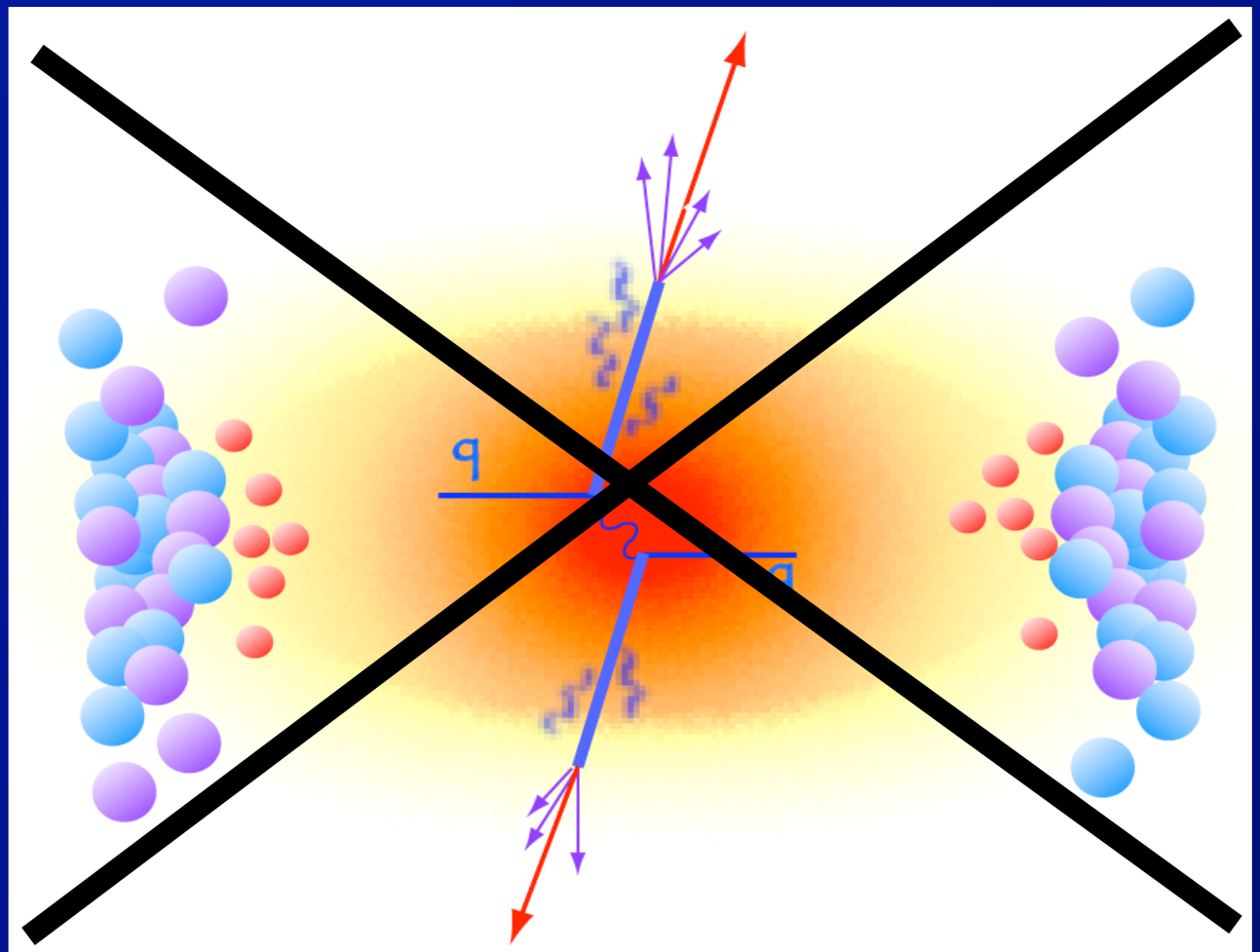


- At RHIC, studied via hadrons (until recently!)
  - Statistics suffer from function ⇒ rates
  - Quenching ⇒ geometric bias
  - No direct measure of frag. function.
- At LHC:
  - Full jets, high p_T, large rates, b jets, di-jet, γ-jet

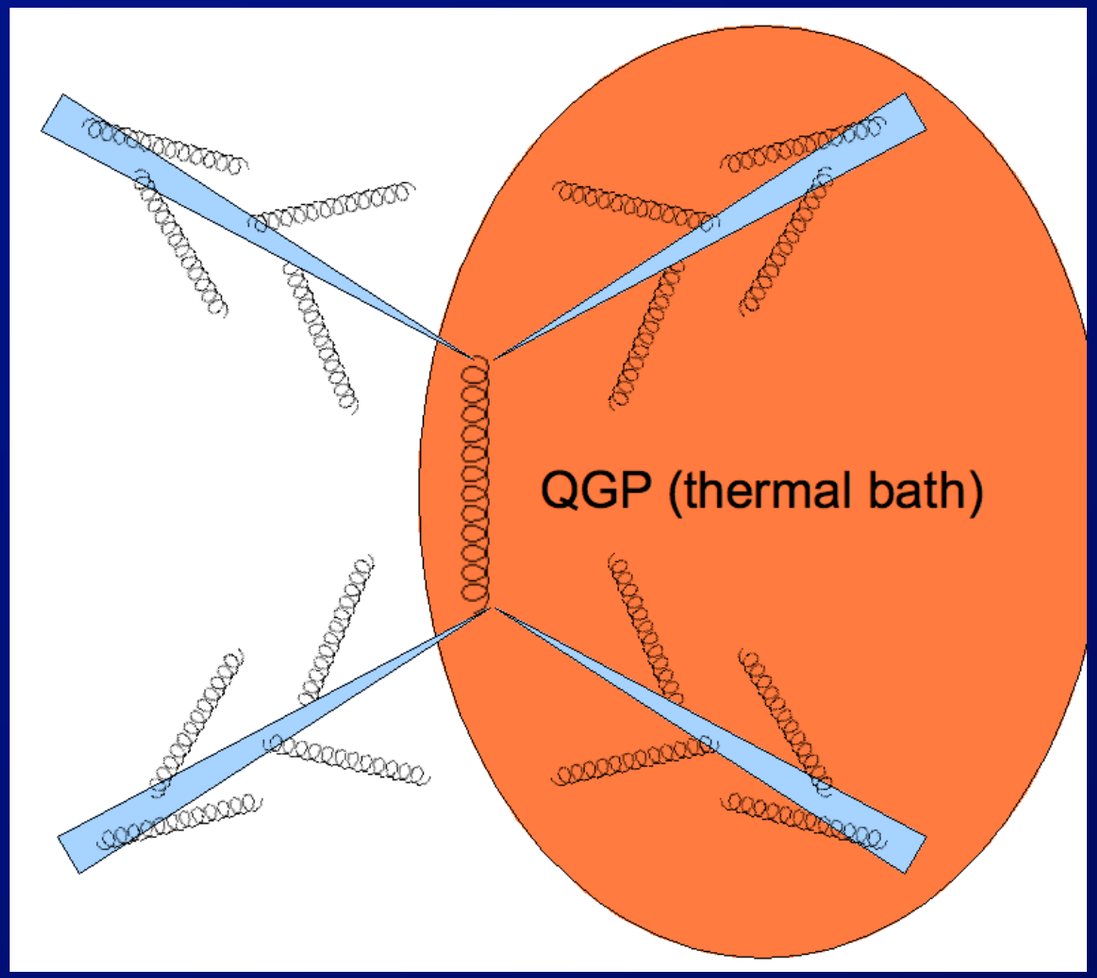
⇒Precision jet tomography

Understanding A+A Jet Measurements

Canonical picture

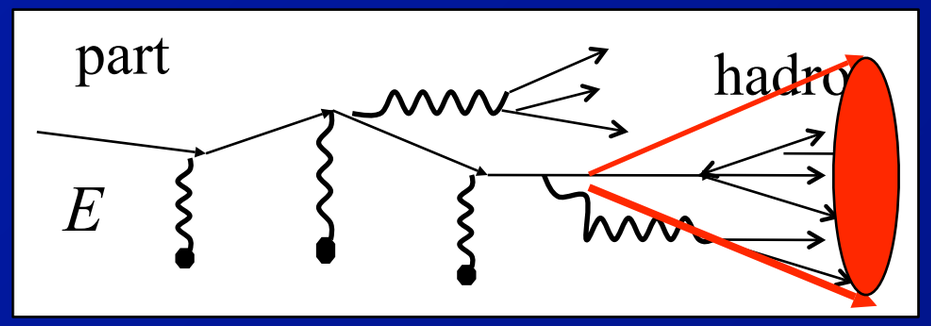


"Jet quenching" = medium modified parton shower



- **Important to remember above discussion:**
  - There is no unique "true jet" measurement (more so now)
  - Some of induced radiation will be outside jet (E loss)
  - The fragmentation of the jet will soften

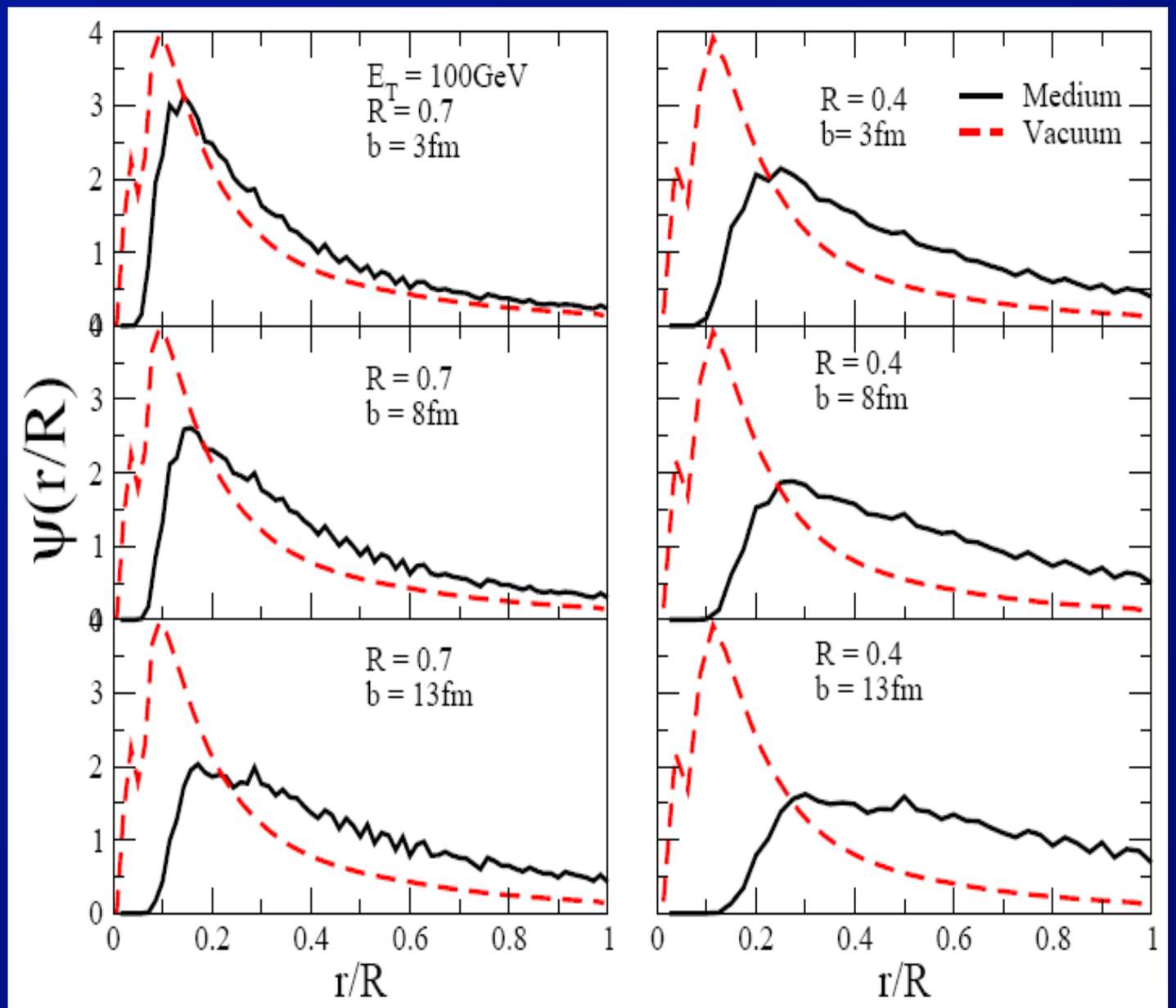
Jet Quenching Calculations



$$\Psi_{\rm int}(r;R) = \frac{\sum_i (E_T)_i \Theta(r-(R_{\rm jet})_i)}{\sum_i (E_T)_i \Theta(R-(R_{\rm jet})_i)} ,$$

$$\psi(r;R) = \frac{d\Psi_{\rm int}(r;R)}{dr} .$$

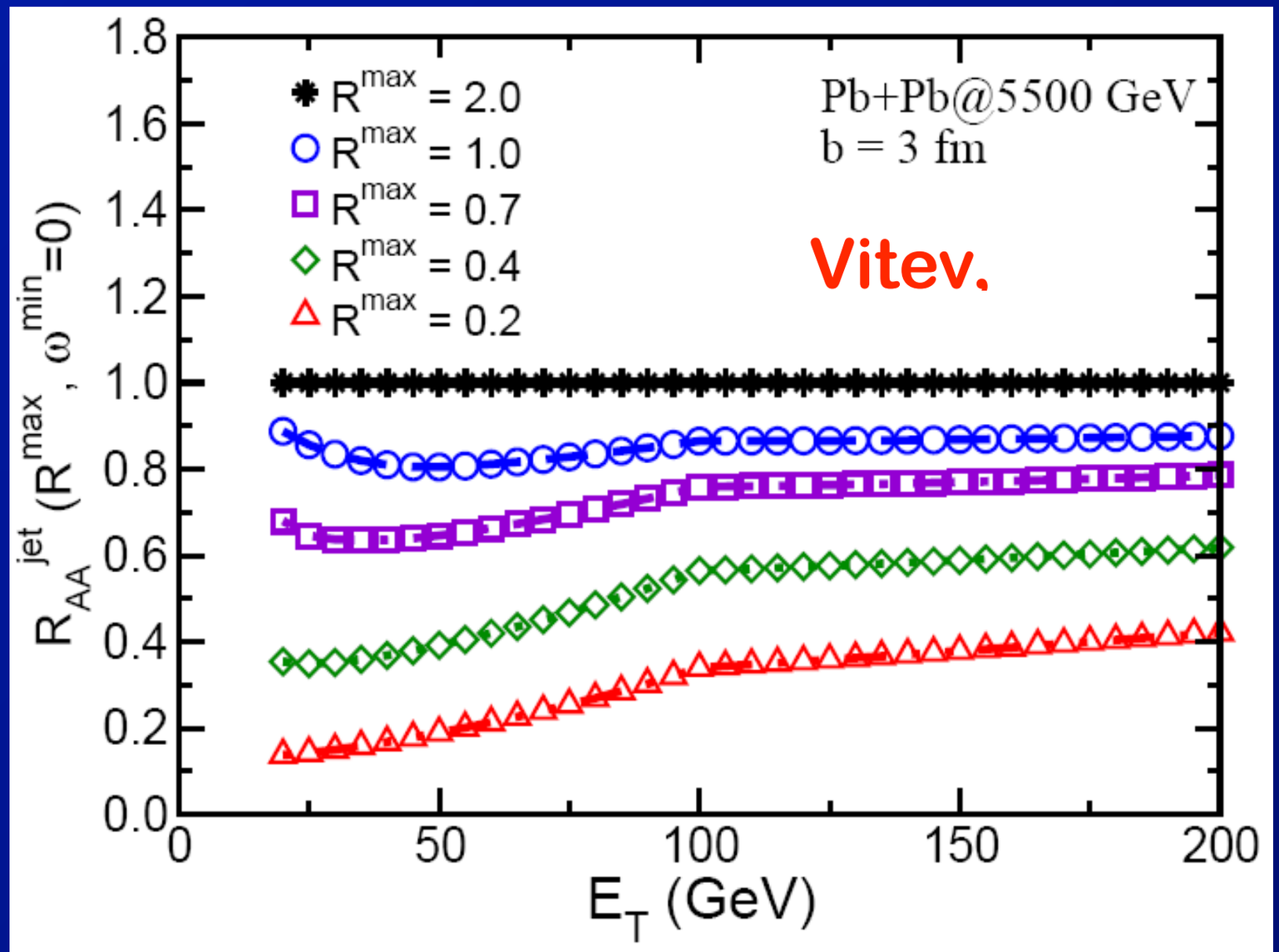
R = 0.7 R = 0.4



Zhang, Vitev
Quark Matter 2009

- Big change in hadron angular distribution due to medium
- Especially important for smaller "cones"

Jet "Suppression"

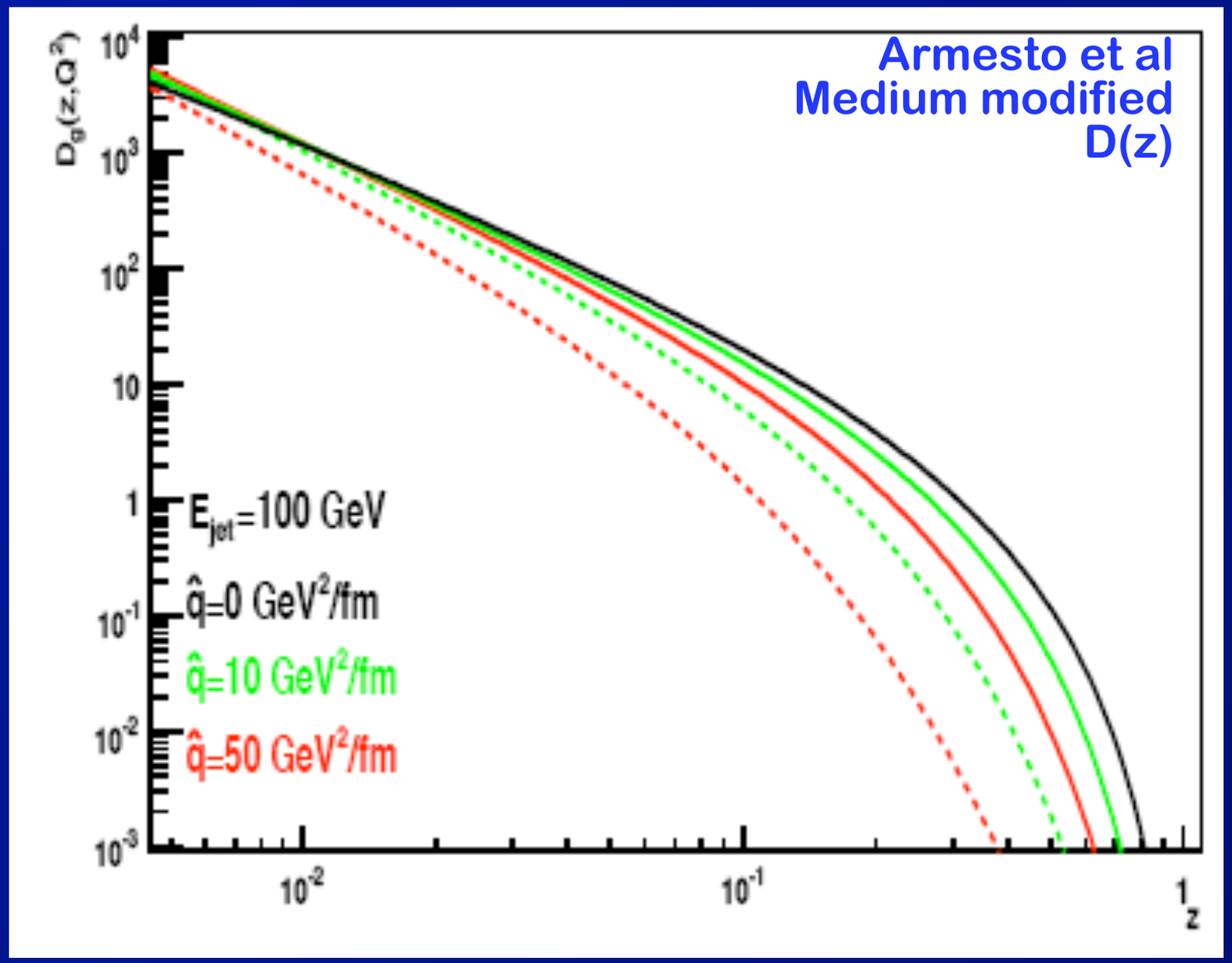


Ratio of in-medium to vacuum jet yield

- **Reduction in jet yield at given E_T due to medium-induced radiation outside the "cone"**
  - **Smaller jet ⇒ larger suppresion, especially below 100 GeV**

⇒Significant effect for reasonable R (< 0.4)

Modification of Fragmentation Function

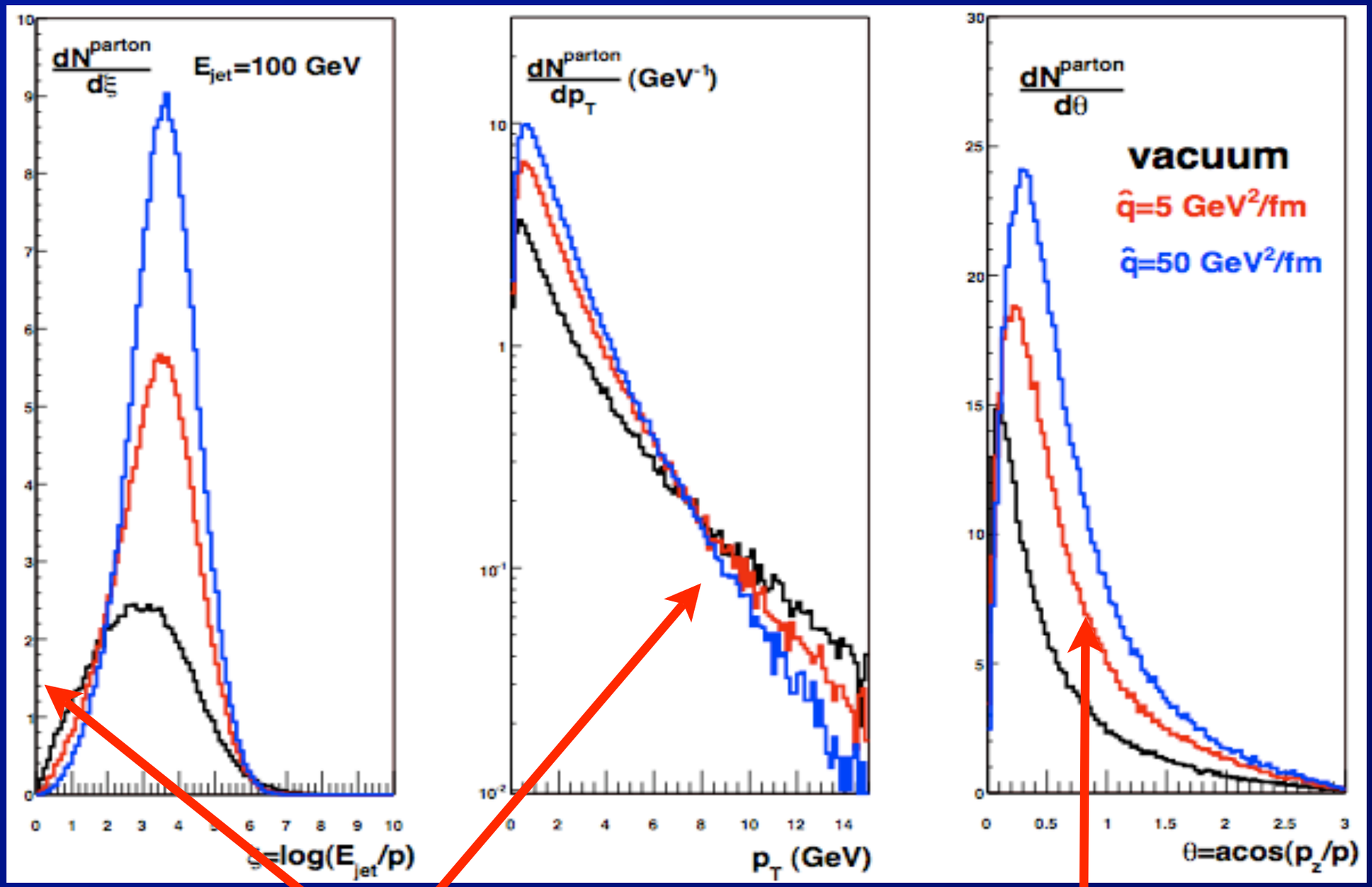


Increasing medium density

- As long as some of induced radiation is "in cone"
  - "Jet" energy will include radiation
    - ⇒But fragmentation hadrons will be shifted down in p_T
    - ⇒Suppressed fragmentation function @ large z

Jet Modifications: Expectations

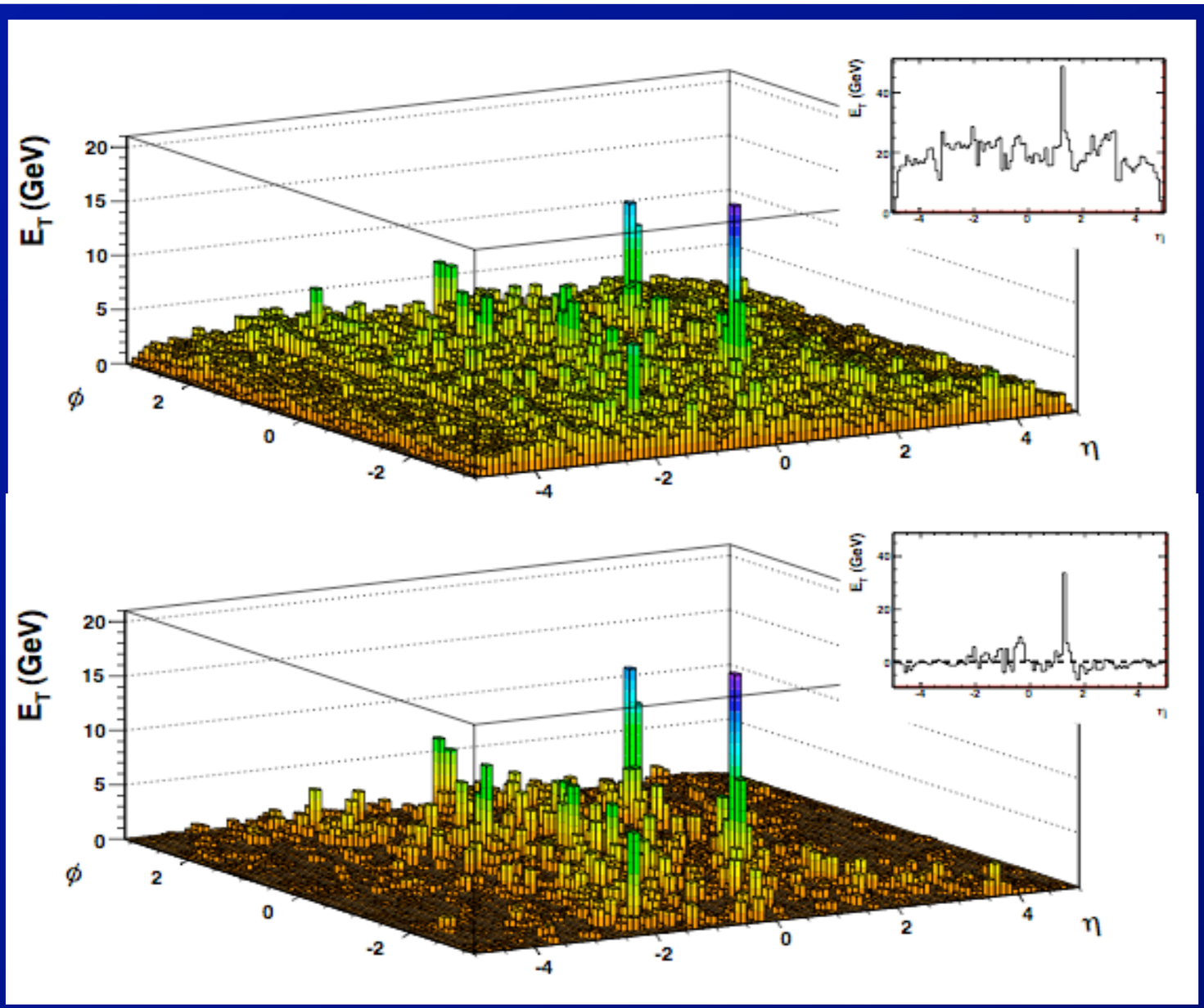
Wiedemann: Quark Matter 2009



Denser medium

- Expect softening and angular broadening of fragmentation due to medium.

Jets in A+A: Underlying event

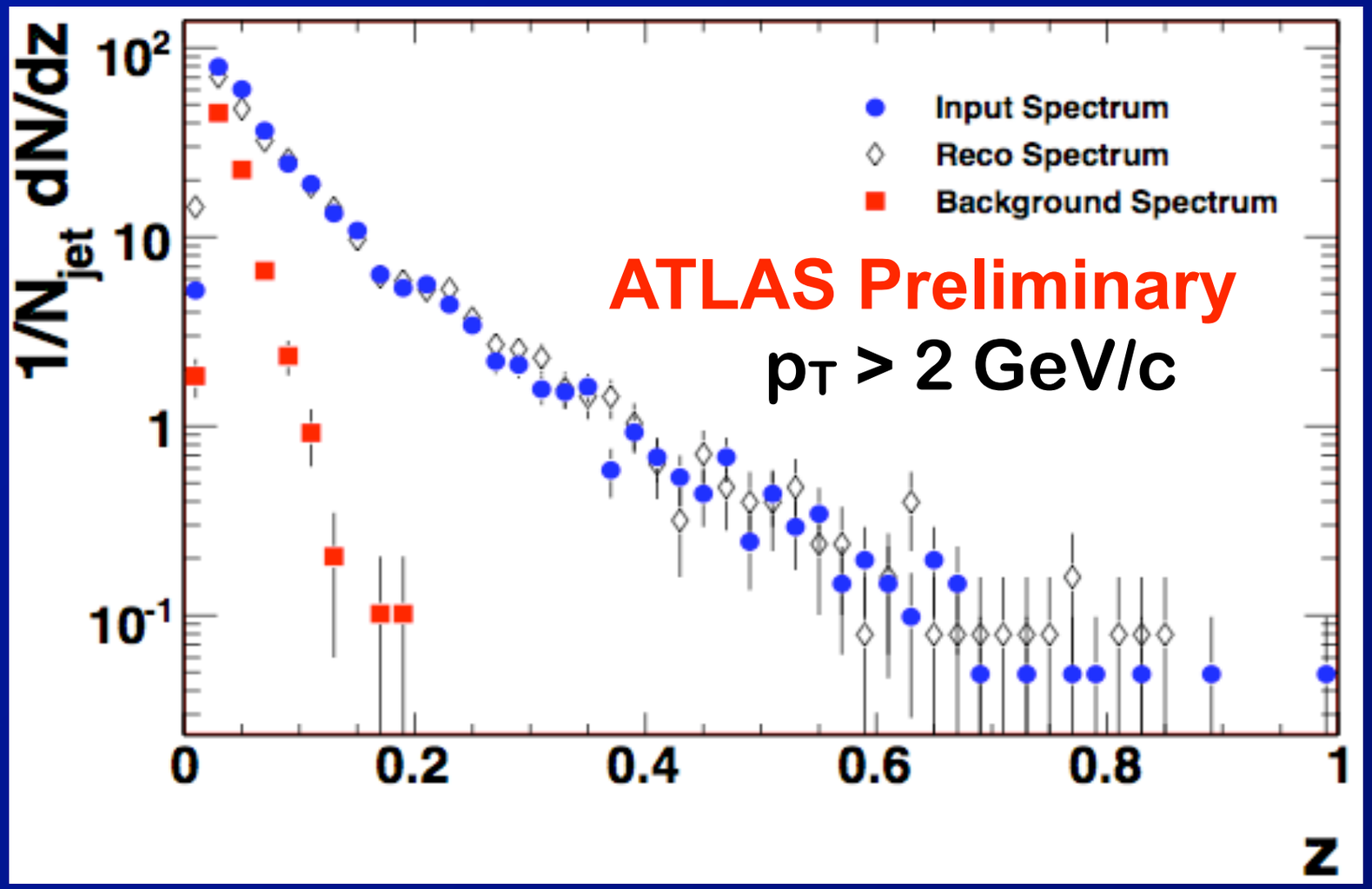


Pb + Pb + 70 GeV jet

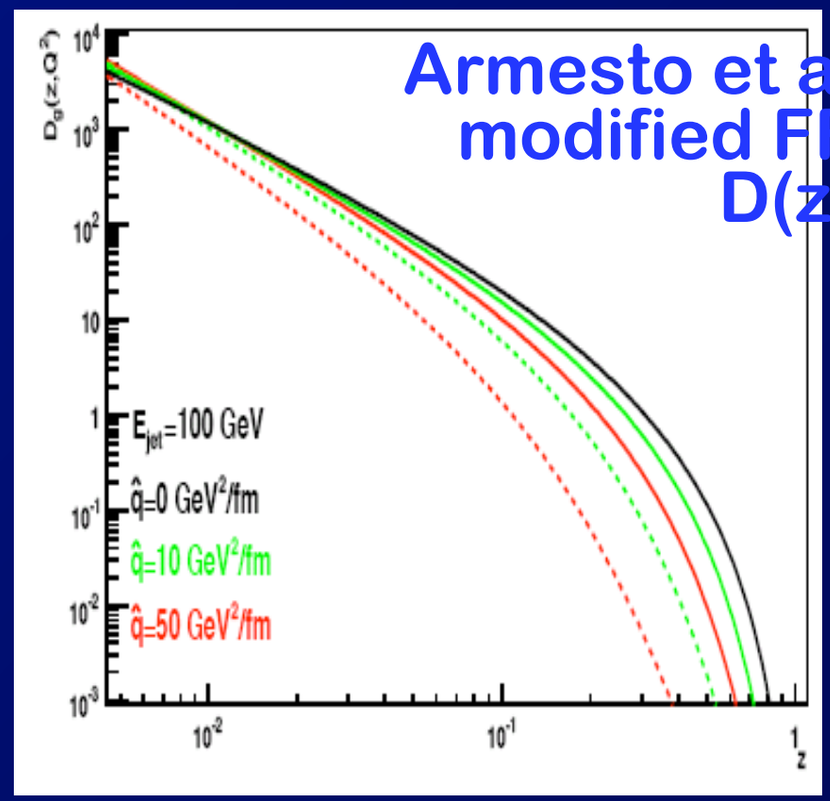
Pb + Pb + 70 GeV jet background subtracted

- Underlying event affects jet energy resolution
- But, far worse, can produce false jets
  - –Crucial issue for A+A jet measurements
    - ⇒ Important to optimize signal/background (smaller “R”)

ATLAS: Modified Fragmentation Func.



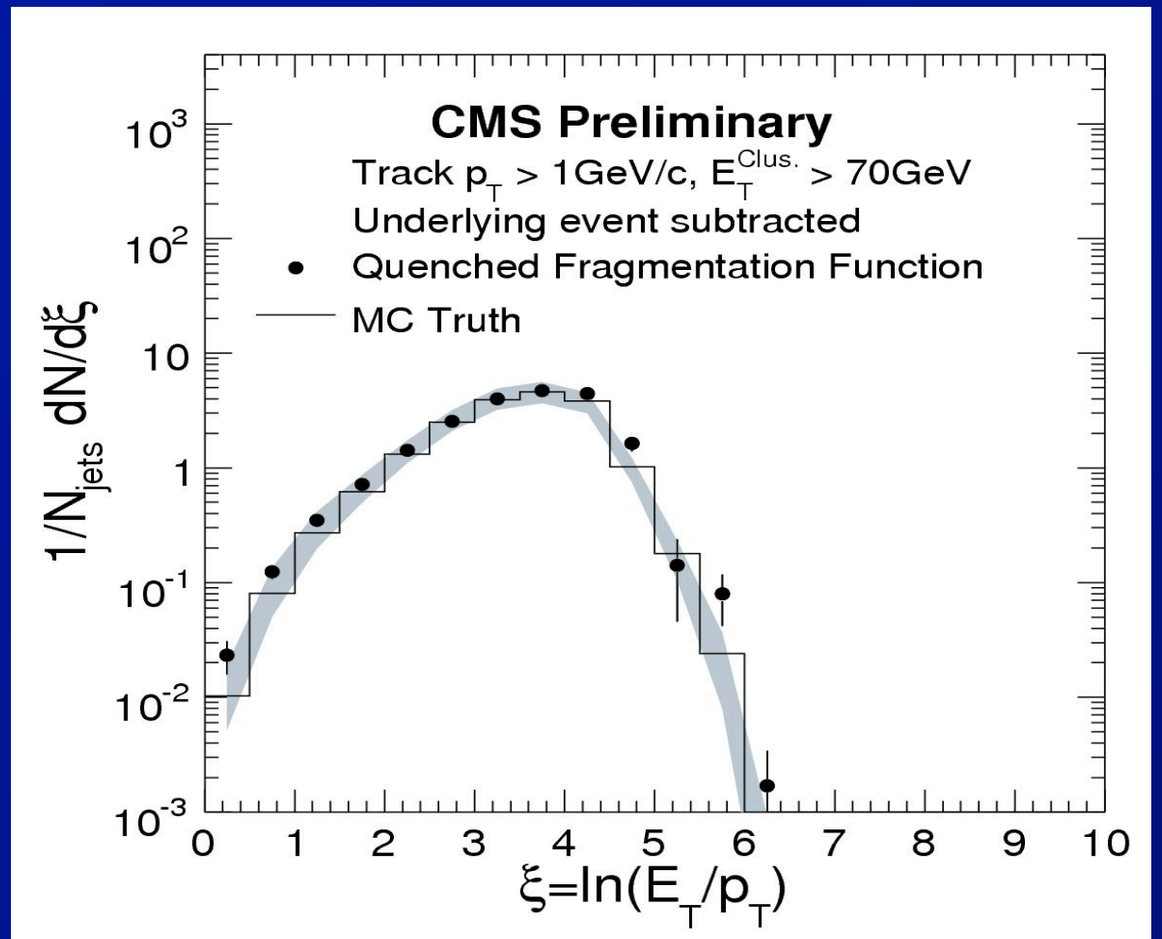
Background = tracks from underlying event

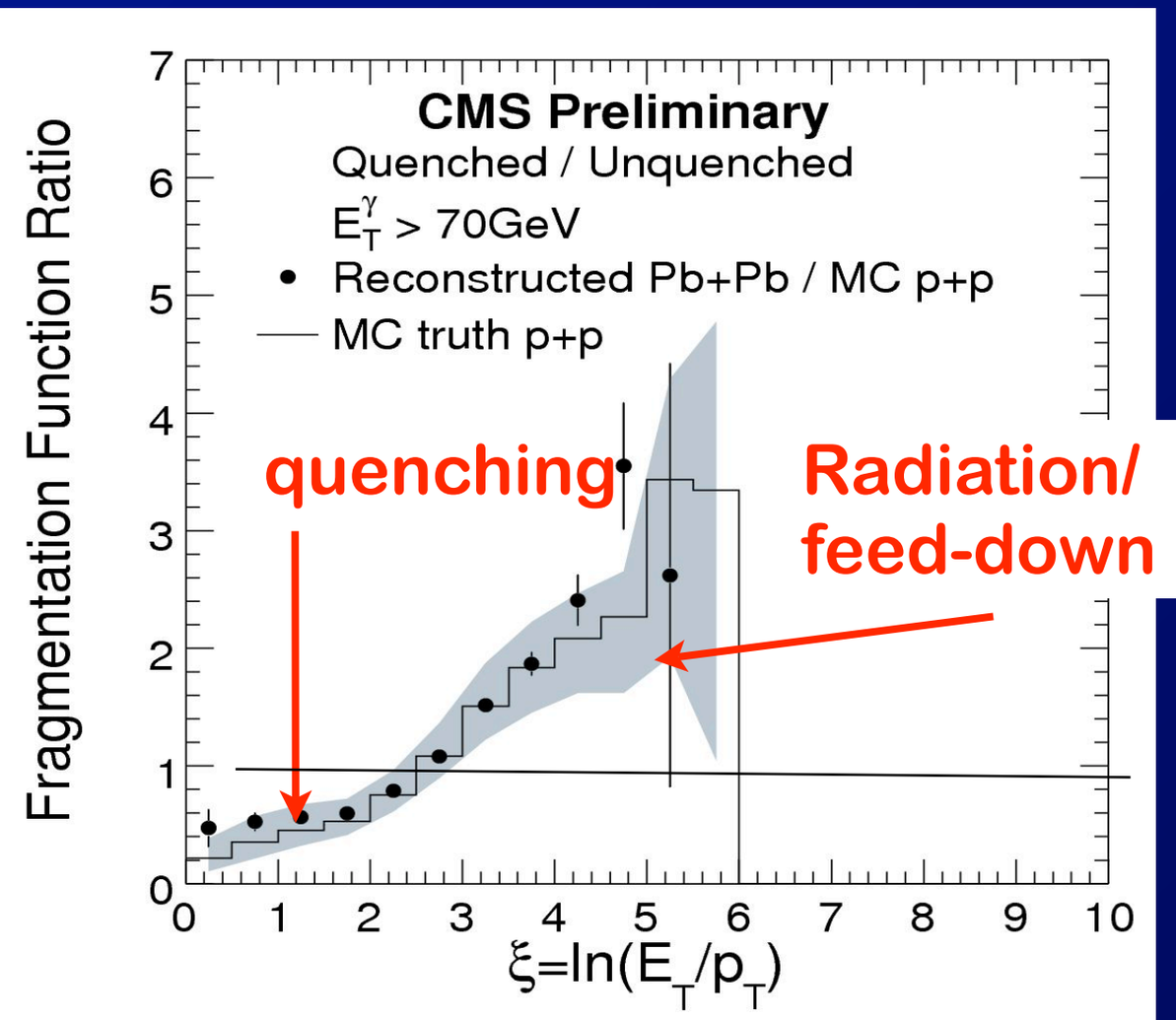


- **Comparison of input hadron z distribution to reconstructed**
  - –With tracking efficiency correction
    - ⇒**But prior to corrections for jet energy resolution**

CMS: γ-jet fragmentation function

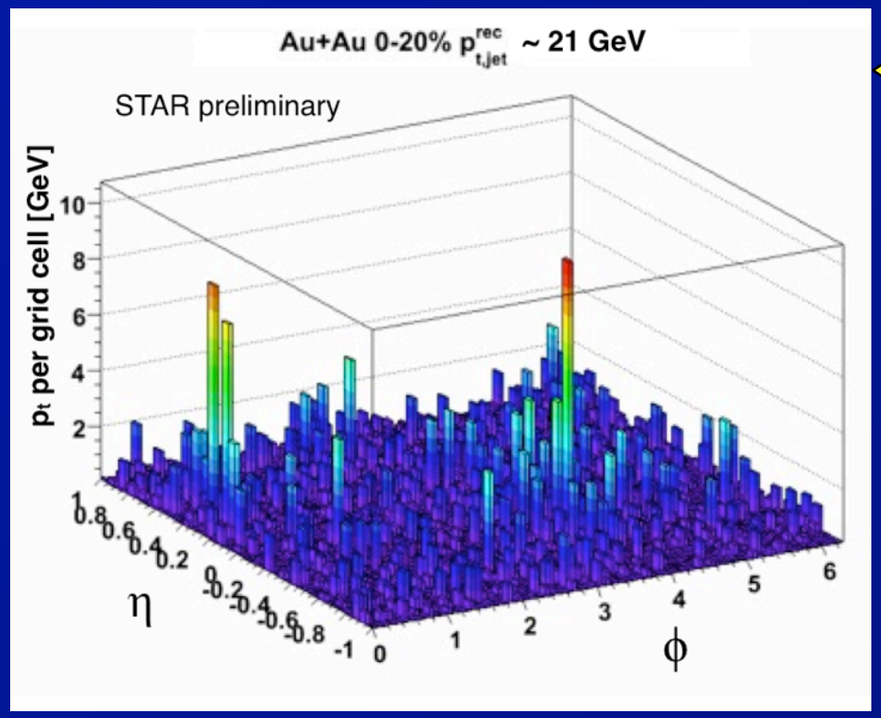
Pb+Pb 0-10% centrality, statistics for 0.5 nb^{-1}





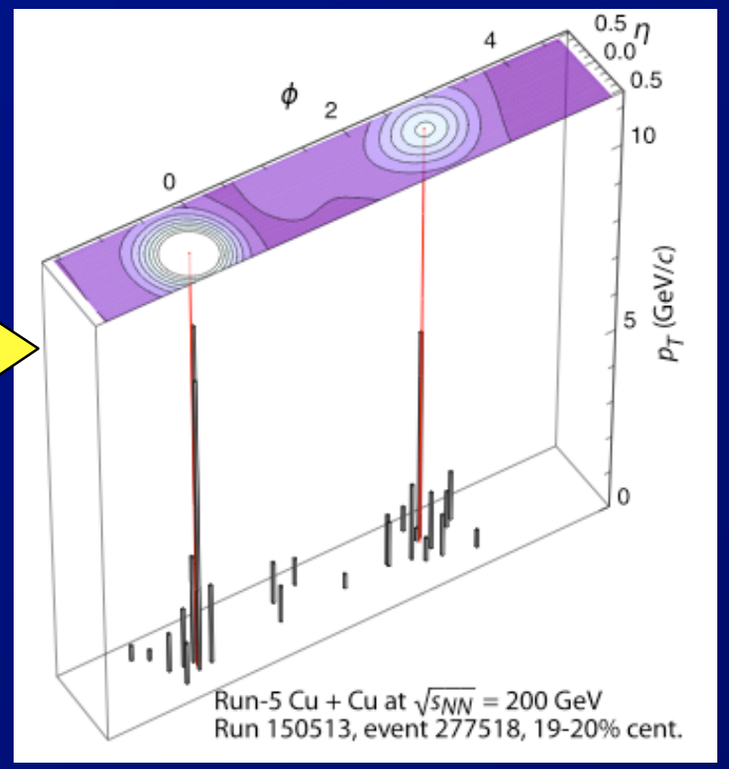
- **Measure fragmentation function in jets opposite a reconstructed photon using photon energy.**
  - $\Delta\phi > 172°$, $E_T^{jet} > 30$ GeV, $|\eta^{jet}| < 2$
  - Photon $E_T > 70$ GeV

True Jet measurements in progress

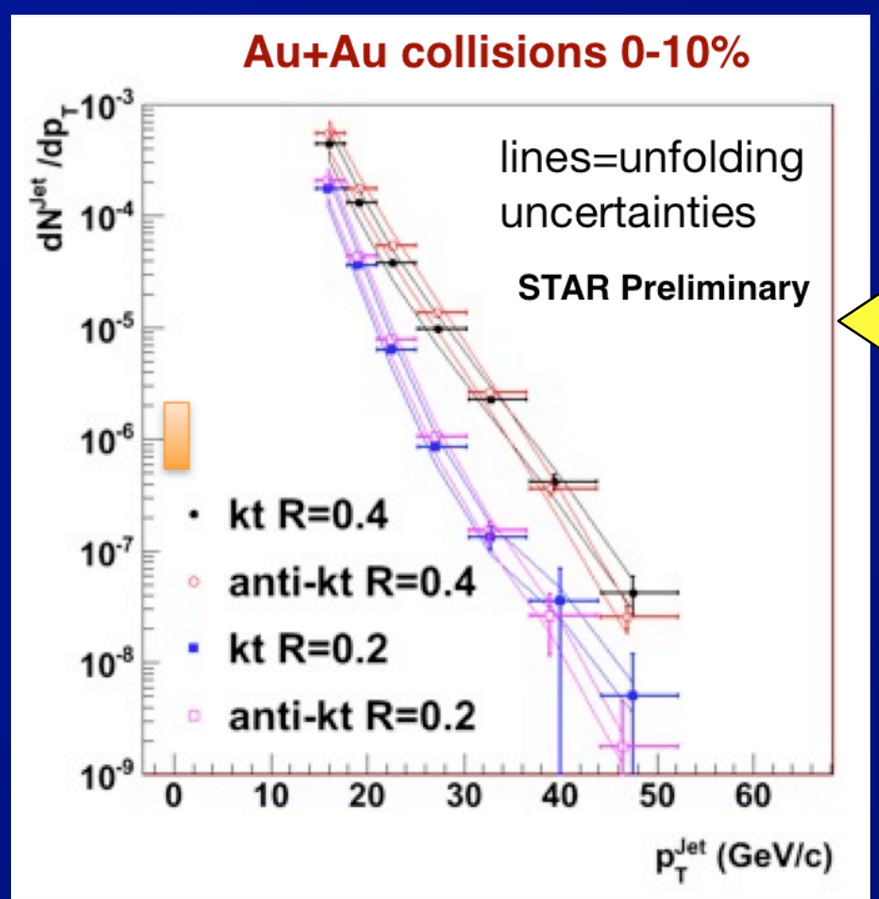


STAR (Au-Au)

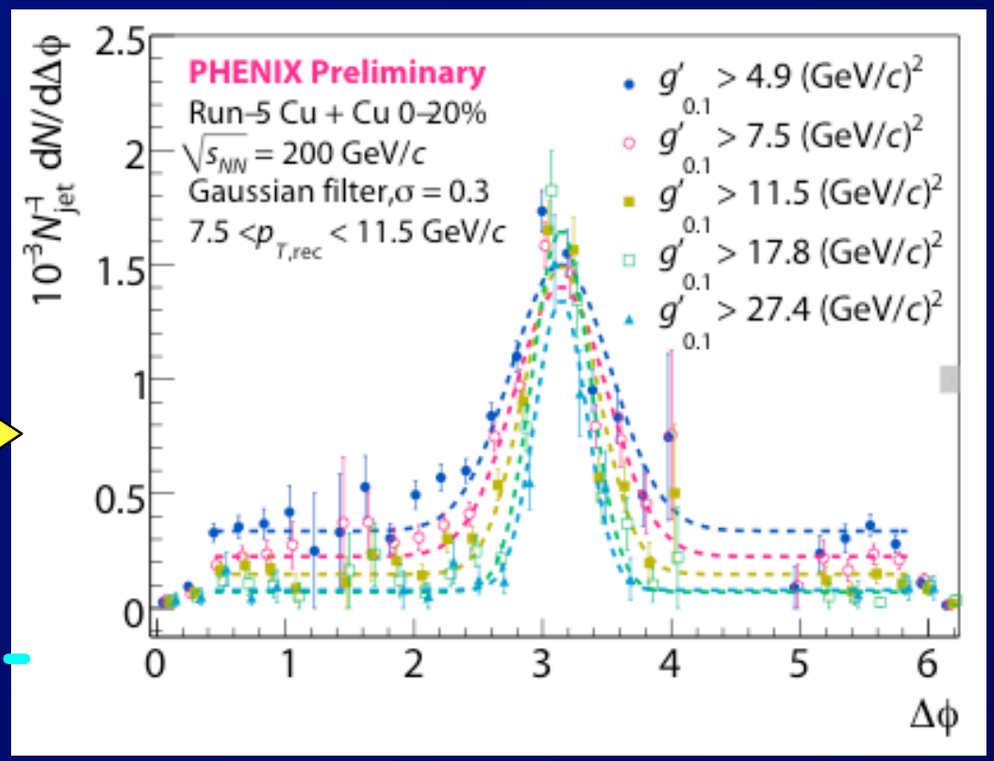
PHENIX (Cu+Cu) jet events



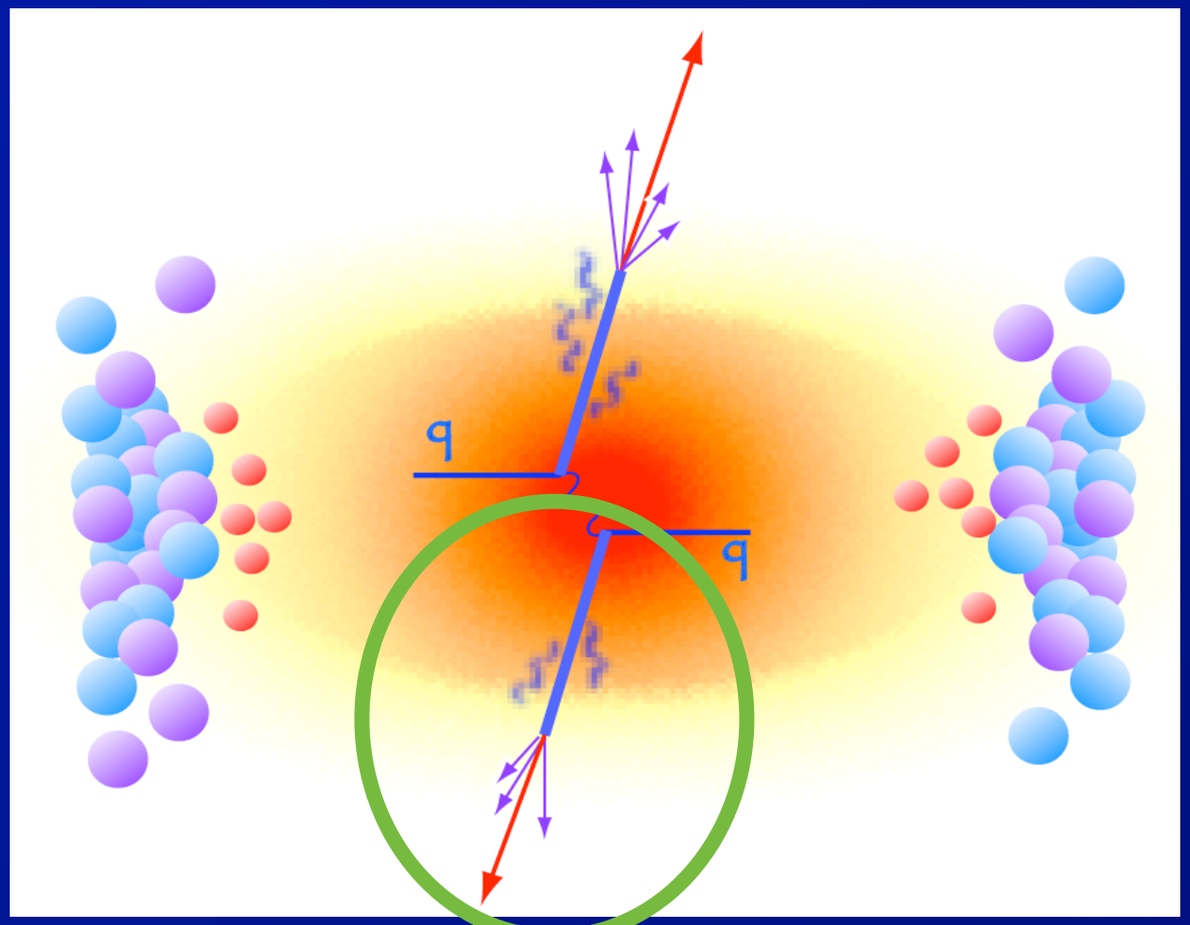
STAR Au+Au spectrum



PHENIX Cu+Cu di-jet Δϕ



Physics of jet quenching



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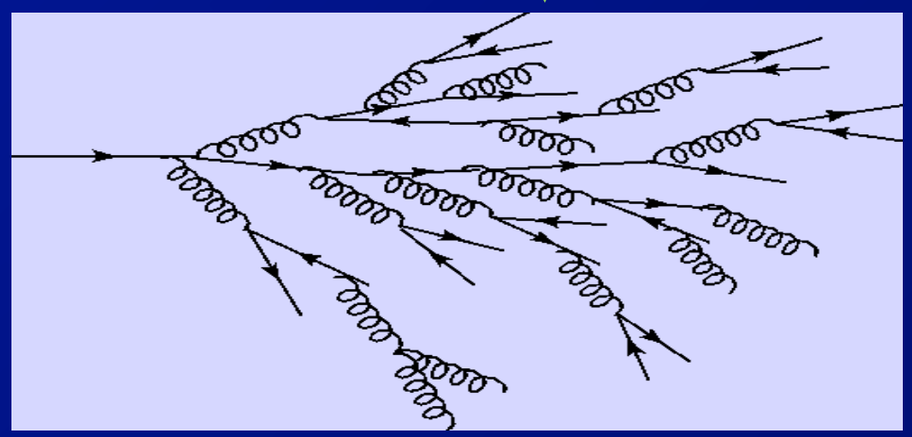

- **Crucial question:**
  - Does parton evolution in medium look anything like a "normal" parton shower?
- **Attempt to distinguish**
  - Weakly coupled radiative + collisional energy loss
  - Strongly coupled/non-perturbative quenching

  ⇒Expect strong coupling effects to produce "non-QCD-like" jets

  ⇒Then should measure large jet suppression

Prospects

- 7 TeV p-p
  - LHC magnets already being ramped to 3.5 TeV
  - 7 TeV operation on few week time-scale
  - Goal for 2010-2011, 1 fb-1

    ⇒Unprecedented sample of jets out to ~ TeV
- 2.6 TeV Pb+Pb
  - Few weeks of low-luminosity ~10^{-25} fall 2010.

Physics

- High-statistics studies of parton showers generated by high-Q^2 processes
- Unique studies of jet quenching in Pb+Pb
  - ⇒ New physics of radiating color charge in medium
  - ⇒ Crucial probe of quark-gluon plasma for $T/T_c > 2$
- Low-x physics (which I didn't have time to discuss)