Stopping, of various kinds

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The setup: stopping in p+A collisions

The beginning

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NUCLEAR STOPPING POWER

Wit BUSZA
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and

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Received 15 January 1984

Inclusive cross sections for protons emitted in 100 GeV proton–nucleus collisions are used to estimate the stopping power of nuclear matter for fast nucleons. The typical recoil momentum obtained for a nucleon struck by the center of a lead nucleus is 4–10 GeV/*c*, an order of magnitude greater than in p–p collisions, and an order of magnitude smaller than in a naive cascade model. Possible implications for high energy heavy ion collisions are discussed.

- The starting point for my entry into (high energy) heavy ion physics 28 years ago.

A template for the future

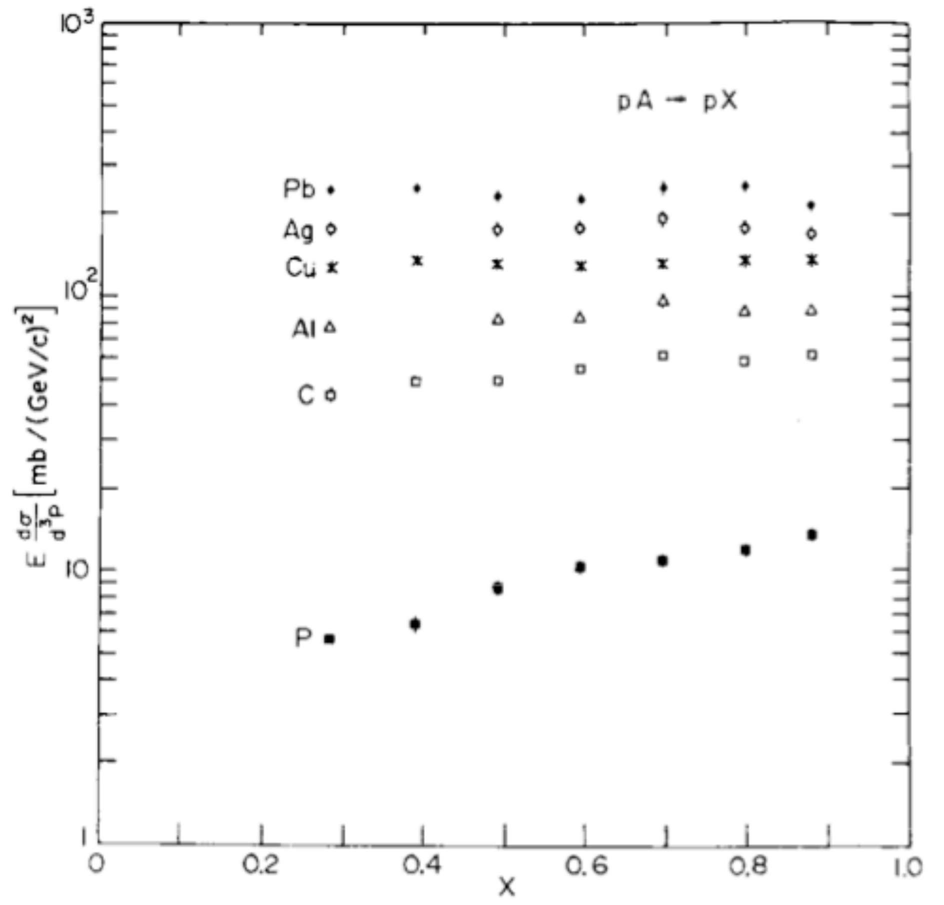


Fig. 1. Inclusive cross sections $E\,d\sigma/d^3P$ at $P_T = 0.3$ GeV/c, as functions of x for pA → pX, obtained from data of ref. [2]. We shall focus on the results for a lead target.

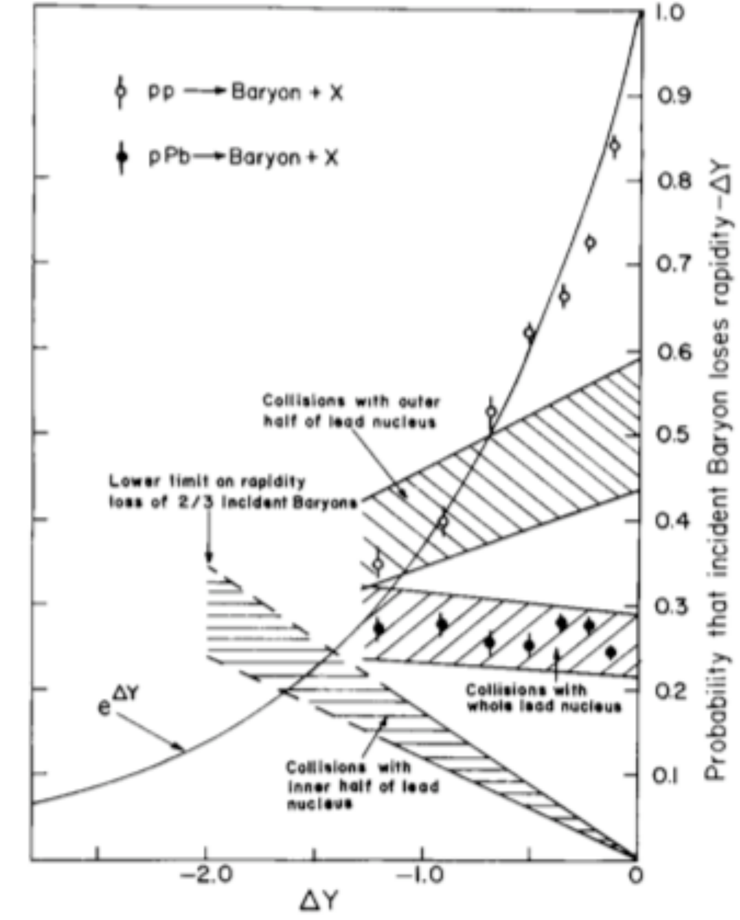


Fig. 2. Probability distributions for protons to lose rapidity $-\Delta y$ in collisions with protons or with lead nuclei. The distributions were calculated from the data shown in fig. 1 by methods discussed in the text. The solid line $e^{\Delta y}$ corresponds to a uniform probability distribution in x.

– Use p-p data to establish empirical baseline
– Understand the role of geometry

Extracting the most from the data

- Classic example of how to extract information from an experimental measurement.

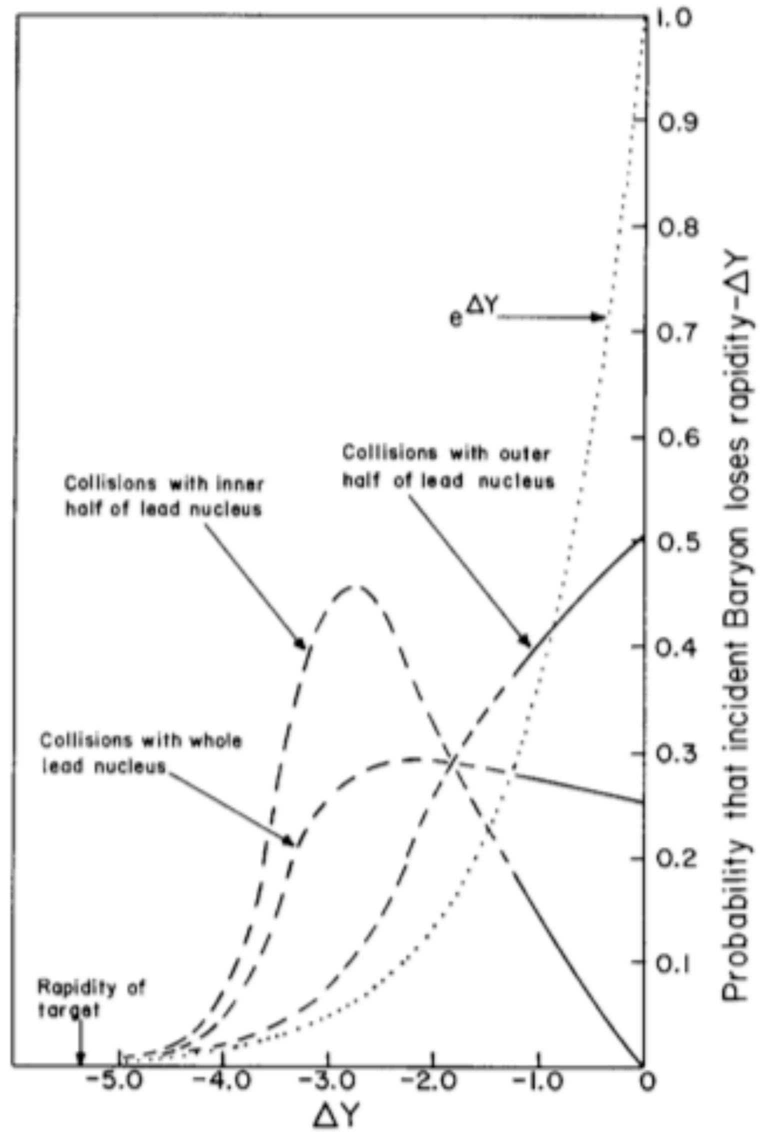


Fig. 3. Extrapolated probability distributions for rapidity loss of protons striking lead nuclei. The dashed lines are the extrapolated portions. The constraint that the normalized total, central, and peripheral inclusive cross sections should all be smooth makes the extrapolations nearly unique.

One of my first papers (with Wit)

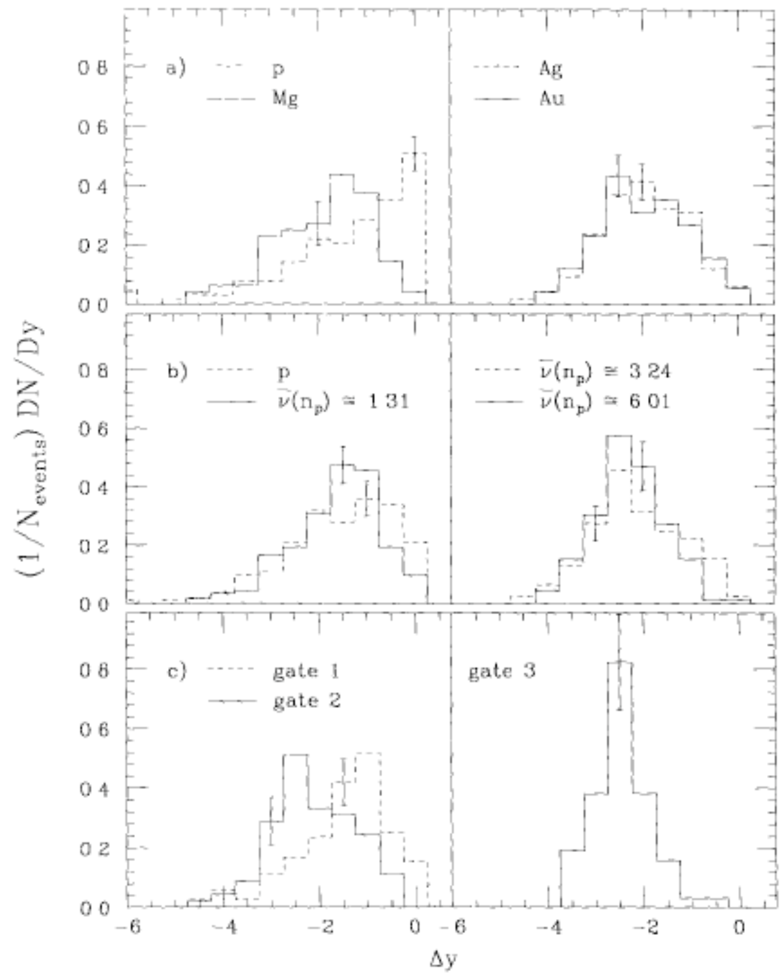
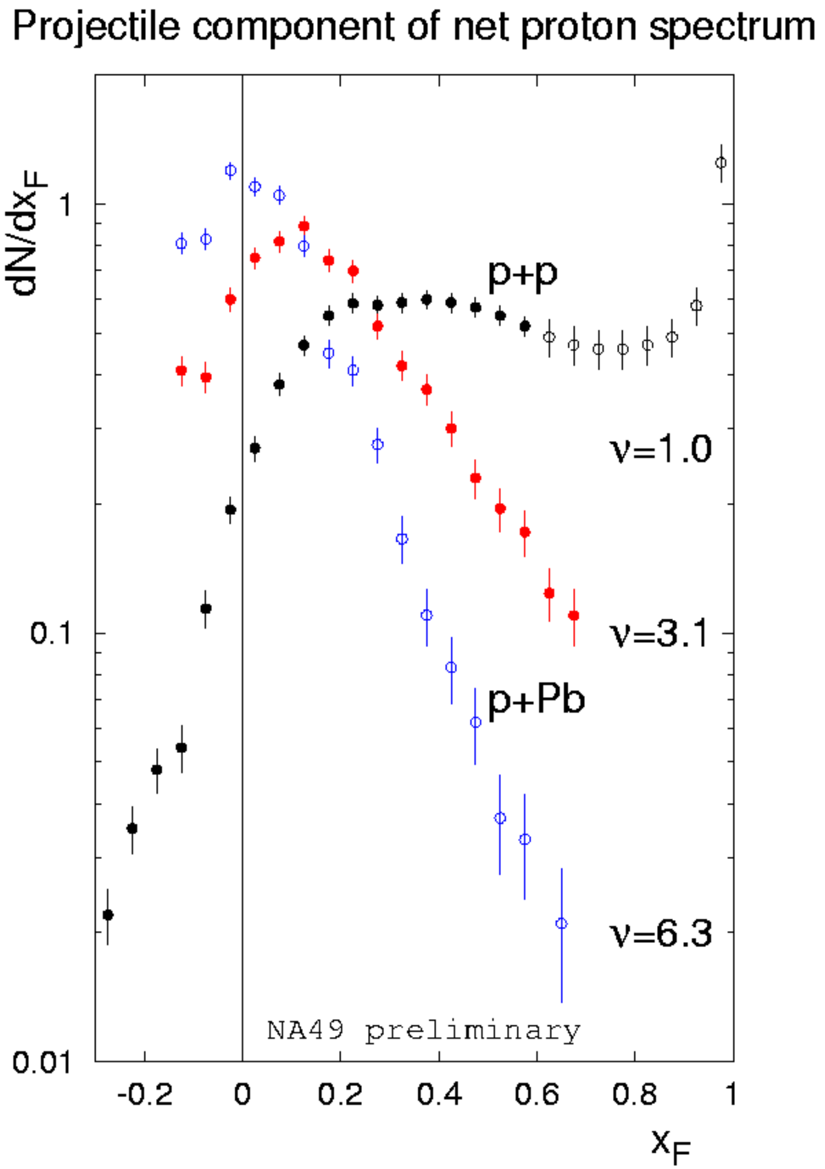
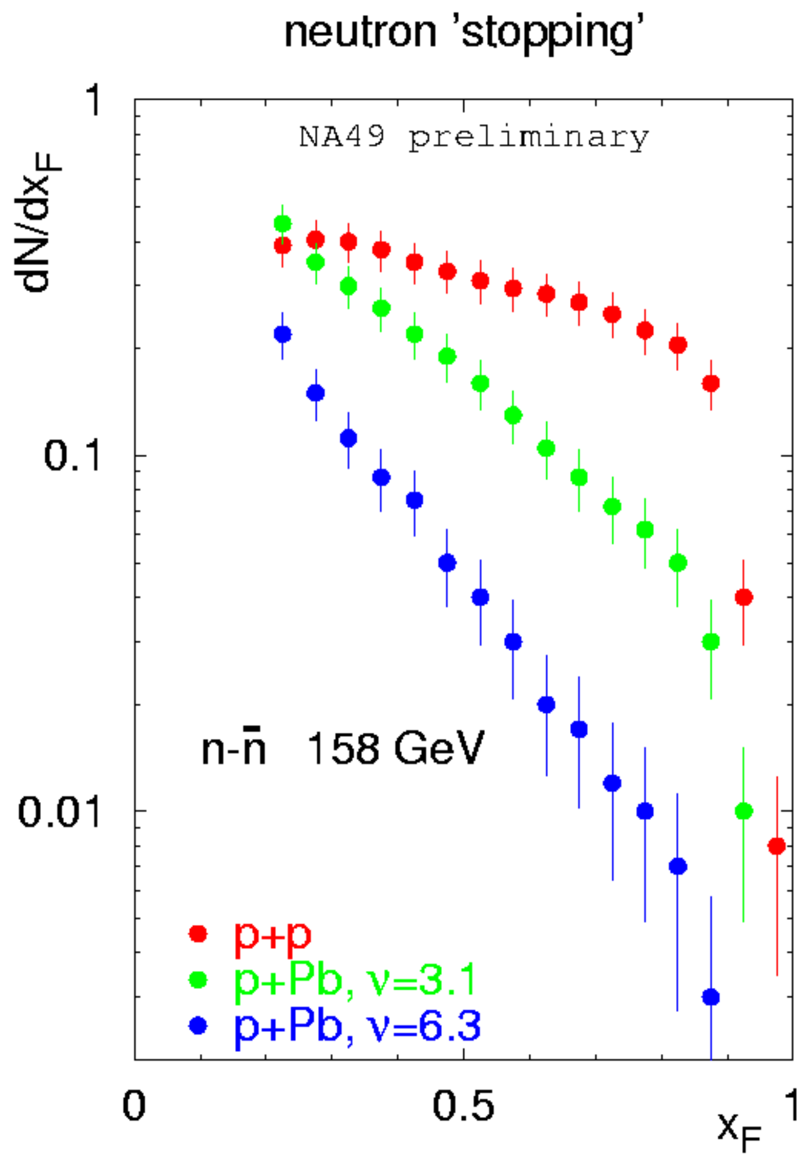


Fig 1. Normalized rapidity loss distributions for the leading positive particle (a) p, Mg, Ag and Au targets (b) p target and nuclear targets gated on $\bar{\nu}(n_p)$ (c) Nuclear targets gated on $\bar{\nu}(n_p)$ and negative particle multiplicity The leading positive particle is assigned the mass of a proton $\Delta y = y_{beam} - y_{leading\ particle}$, where $y_{beam} = 6.06$ for a 200 GeV/c proton beam All distributions are normalized to unity See table 1 for more information

- Measurement of "centrality" dependence of stopping with hybrid spectrometer

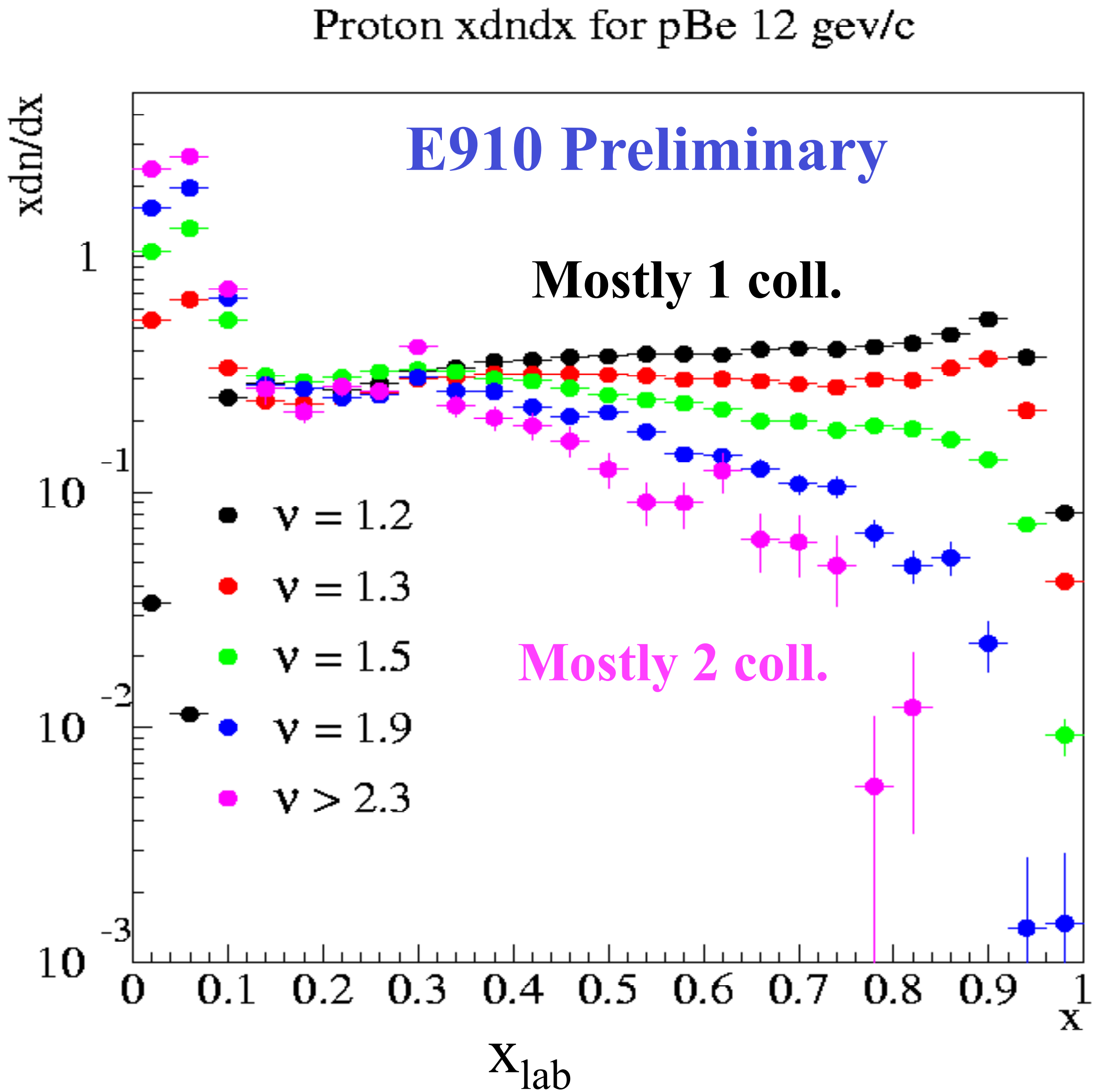
NA49 Proton & Neutron





- After 3 collisions, neutron & proton similar.
- See talk by A. Tei from E941 in parallel session.

E910 - Projectile Fragmentation

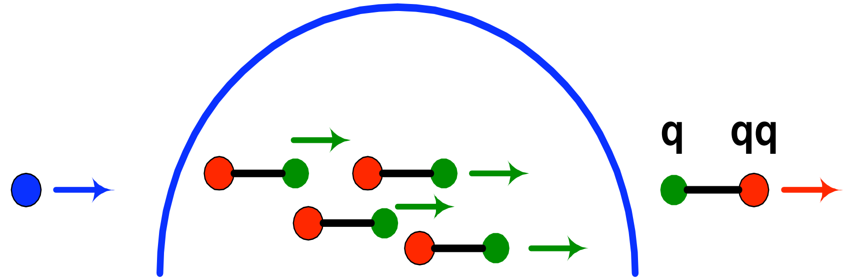


Dramatic change in proton spectrum between 1st, 2nd collision

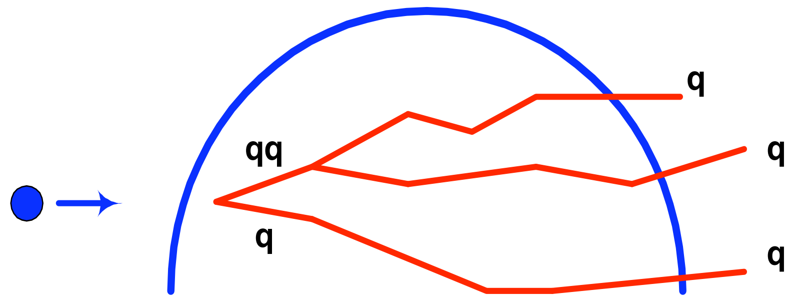
Analysis by H. Hiejima

“Pictures” of p-A Dynamics

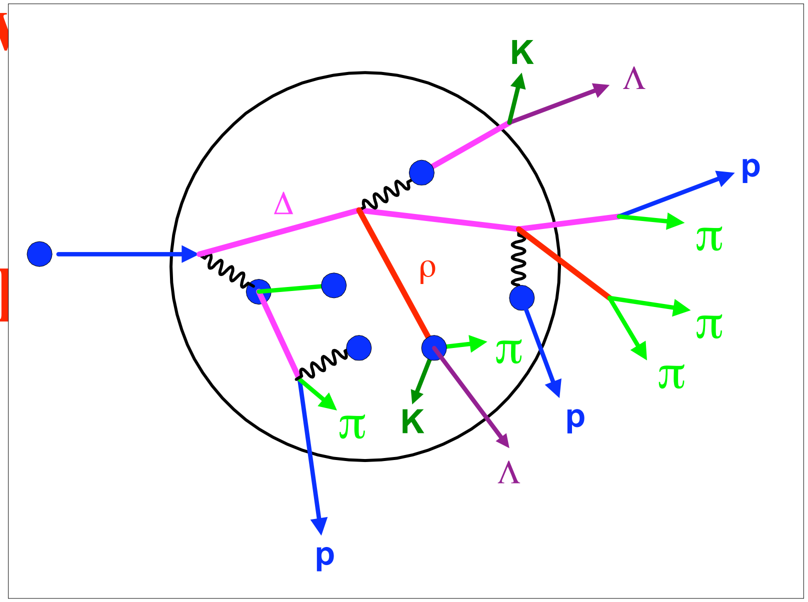
- Color dipole model
  - Excitation via qq – q string.
  - + string overlap (Ropes) ??



- Constituent quark model
  - Valence quarks relevant DOF.
  - Additive or not ?



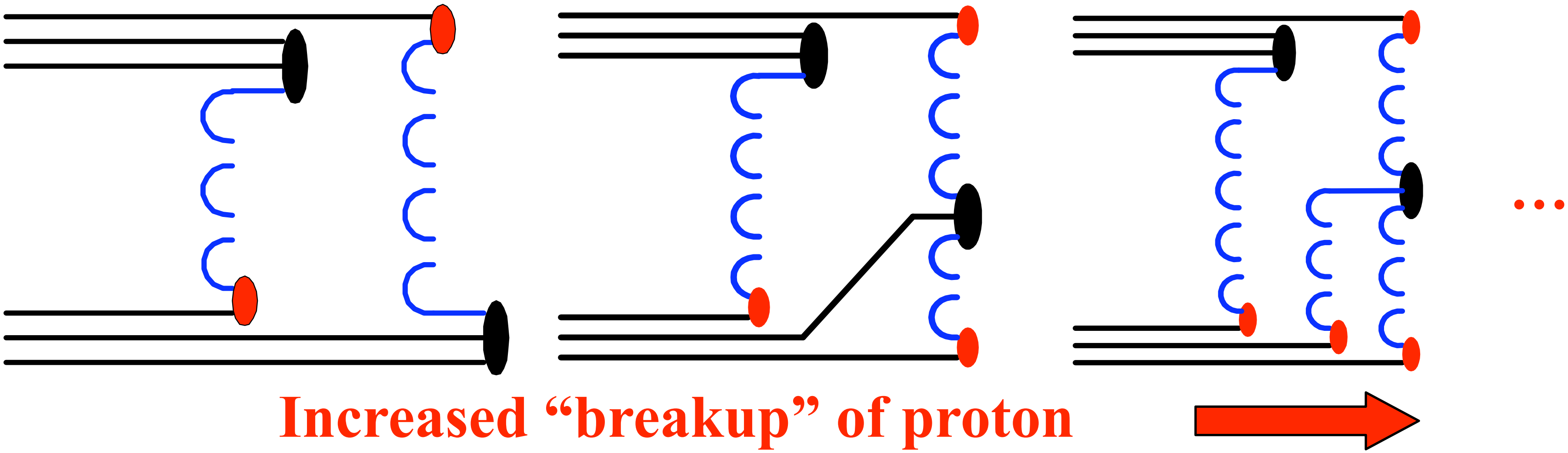
- Resonance Model
  - Δ, N*, ρ excitation, decay.
- **Critical issue: (talk focus) how does proton respond ?**
  - **Esp: in first few collisions**
- **How does response affect final state observables ?**



From p-p to p-A

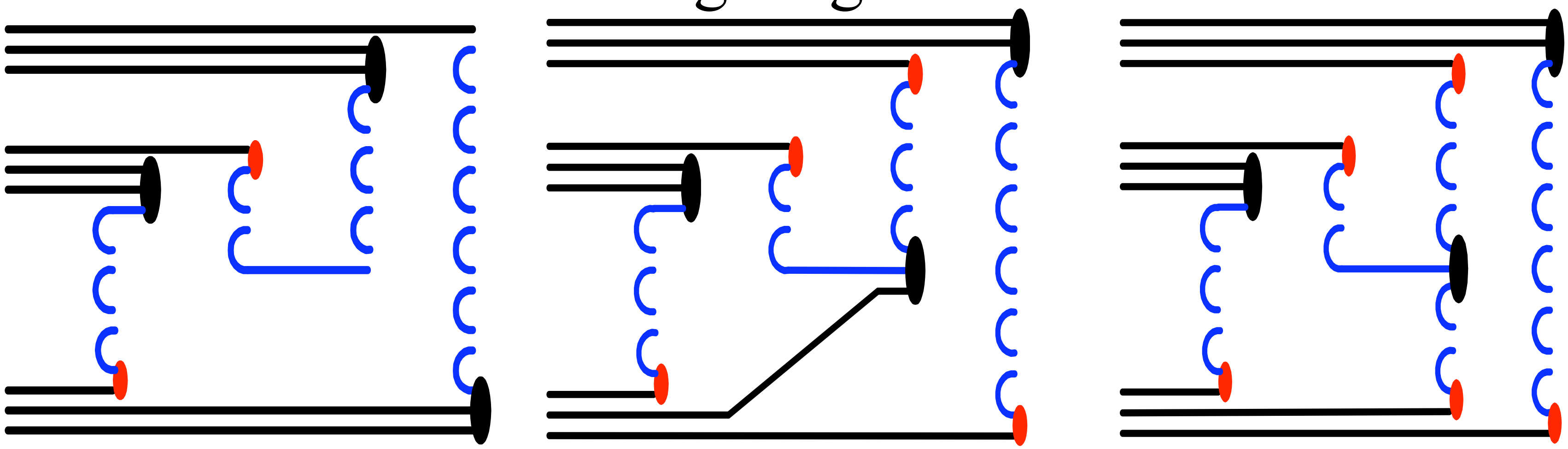
- (more) rigorous model of p-p: “topological” expansion

two-string **Diquark splitting** **Junction**



Increased “breakup” of proton

- Possible double scattering diagrams

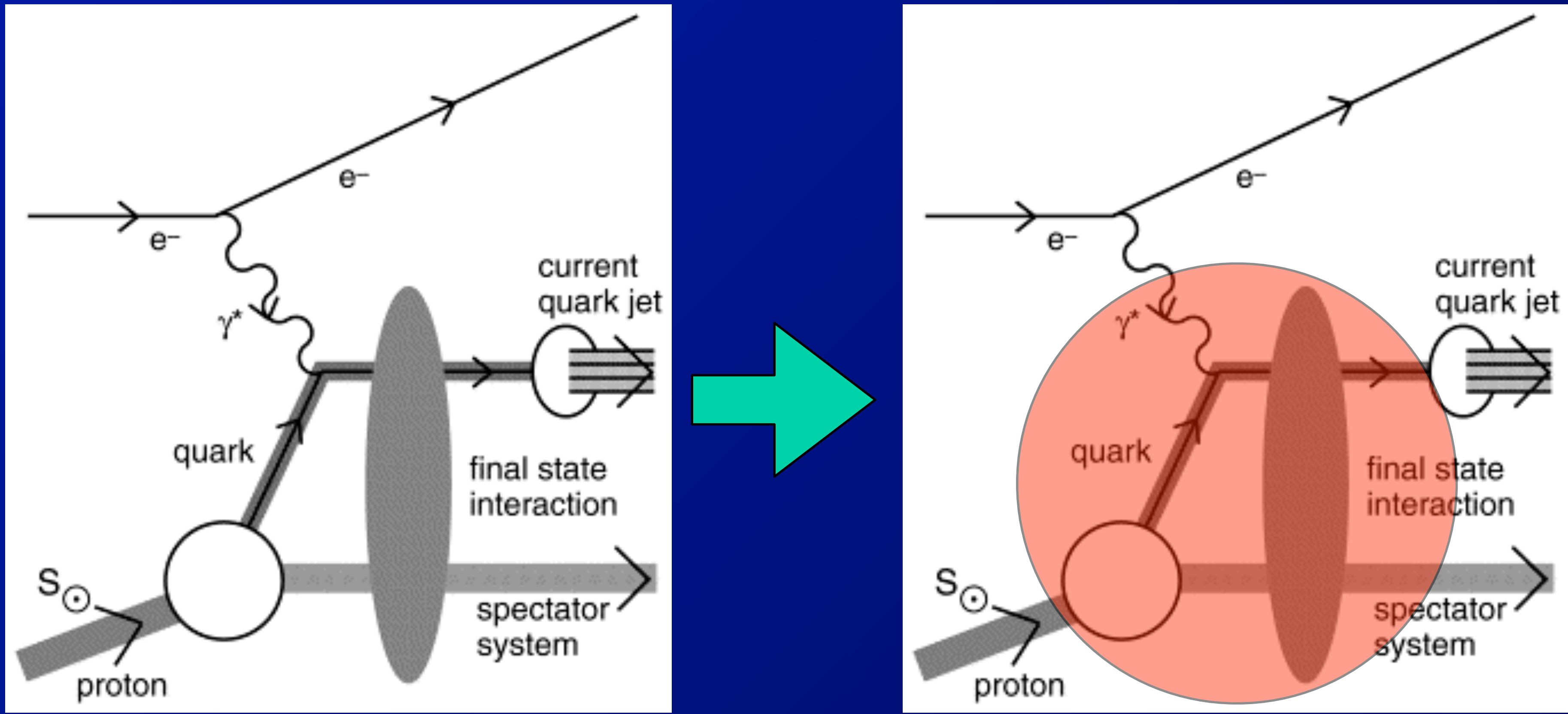


Proton more efficiently broken up ?

A different kind of stopping:

stopping high-momentum quarks and gluons in cold nuclear matter

"Stopping" quarks in nuclei

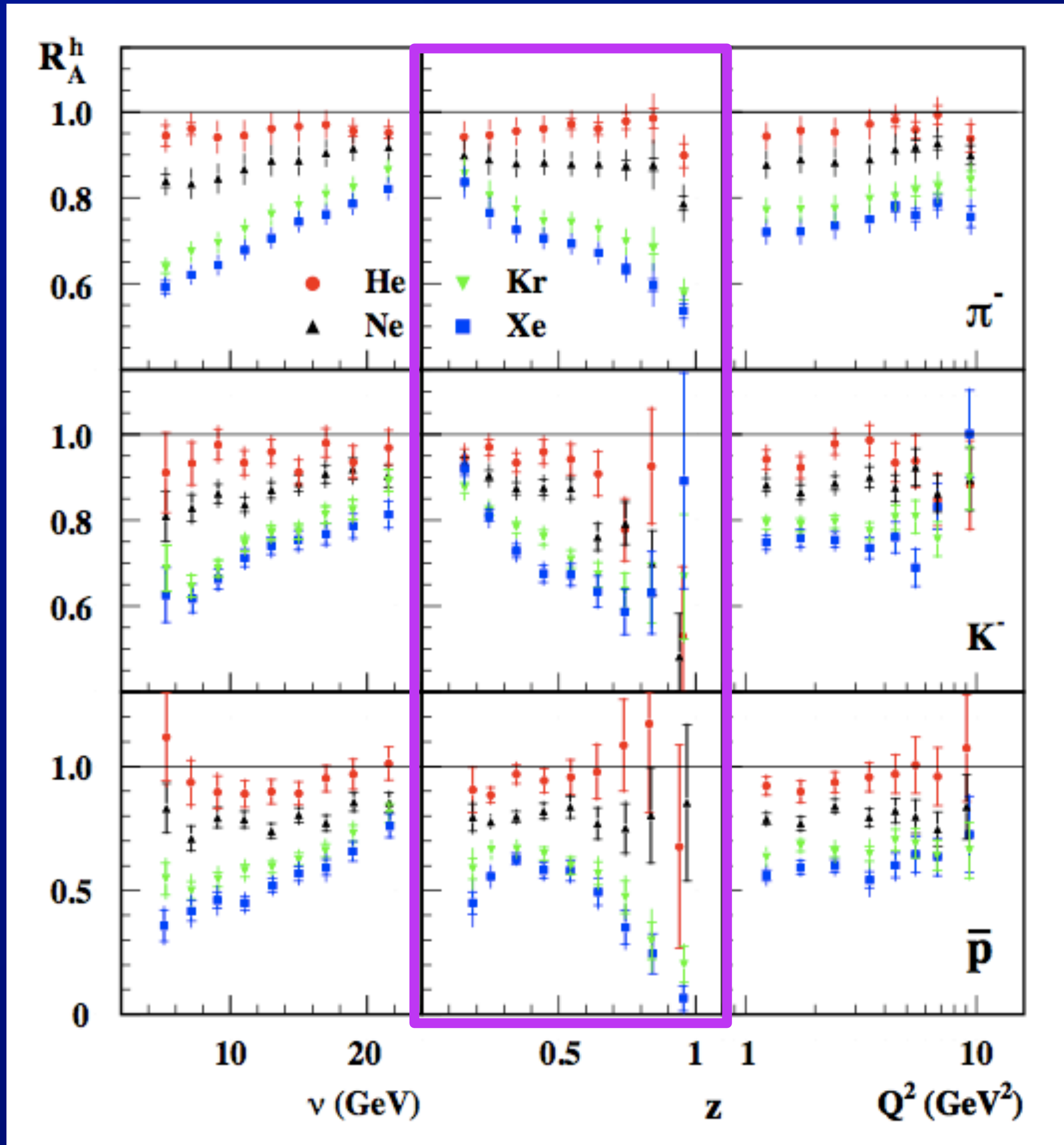


- Study the energy loss of quarks (?) in the target using nuclear semi-inclusive deep inelastic scattering

"Stopping" quarks in nuclei

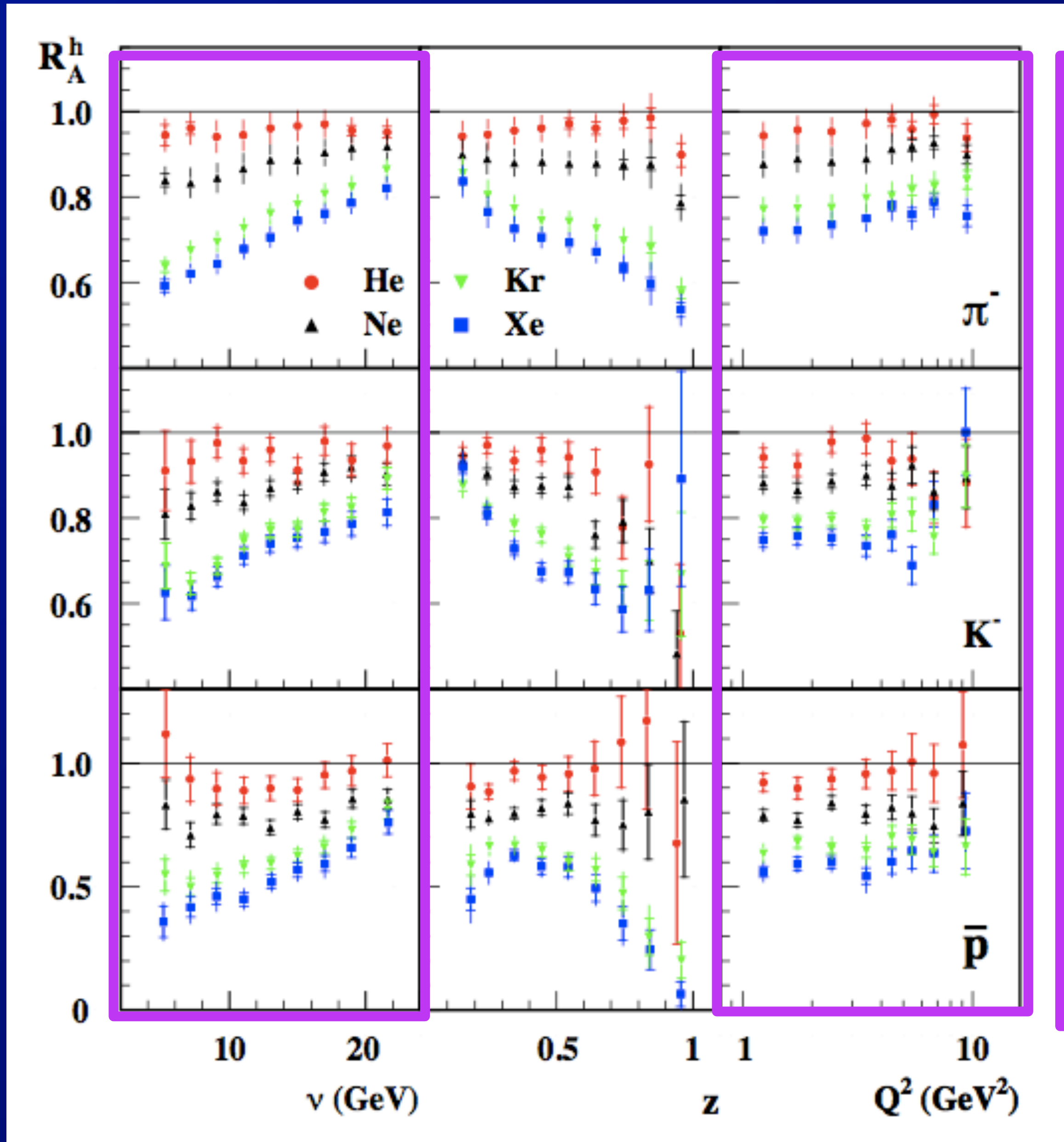
- z = fraction of quark energy carried by hadron
- Clear A-dependent reduction in yield of high-z hadrons
- But physics is complicated

  ⇒hadronization (pre-hadrons)



"Stopping" quarks in nuclei

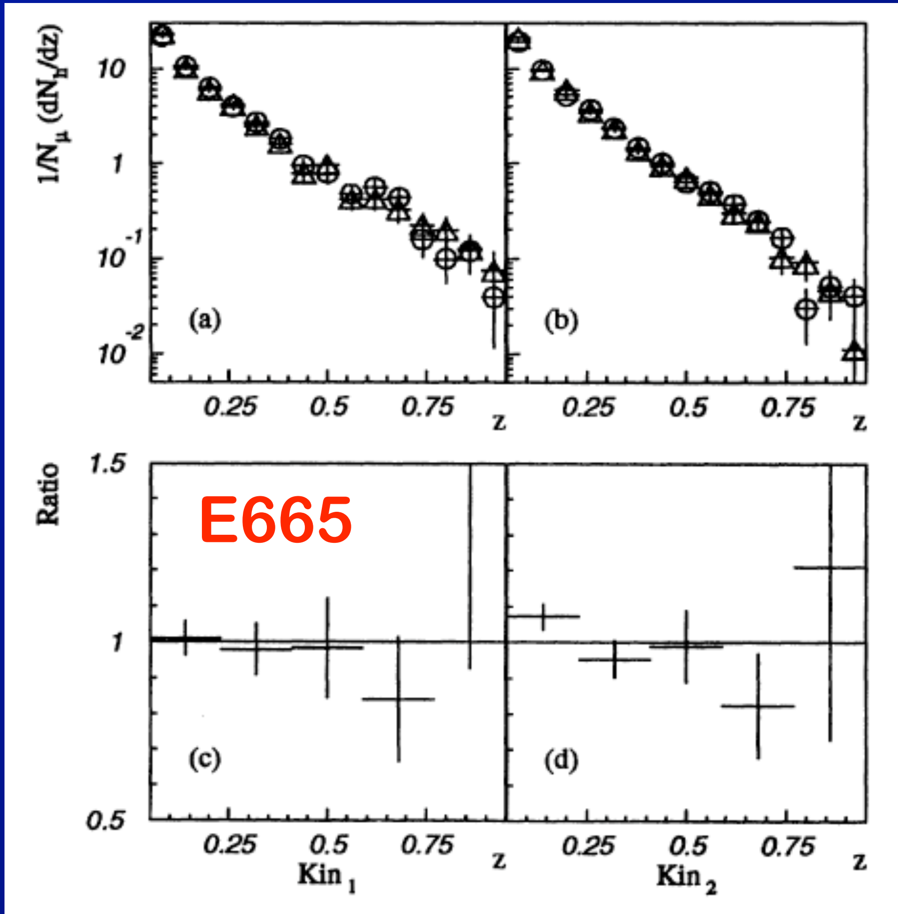
- Weak Q^2 dependence
- "Stopping" decreases with increasing quark energy.

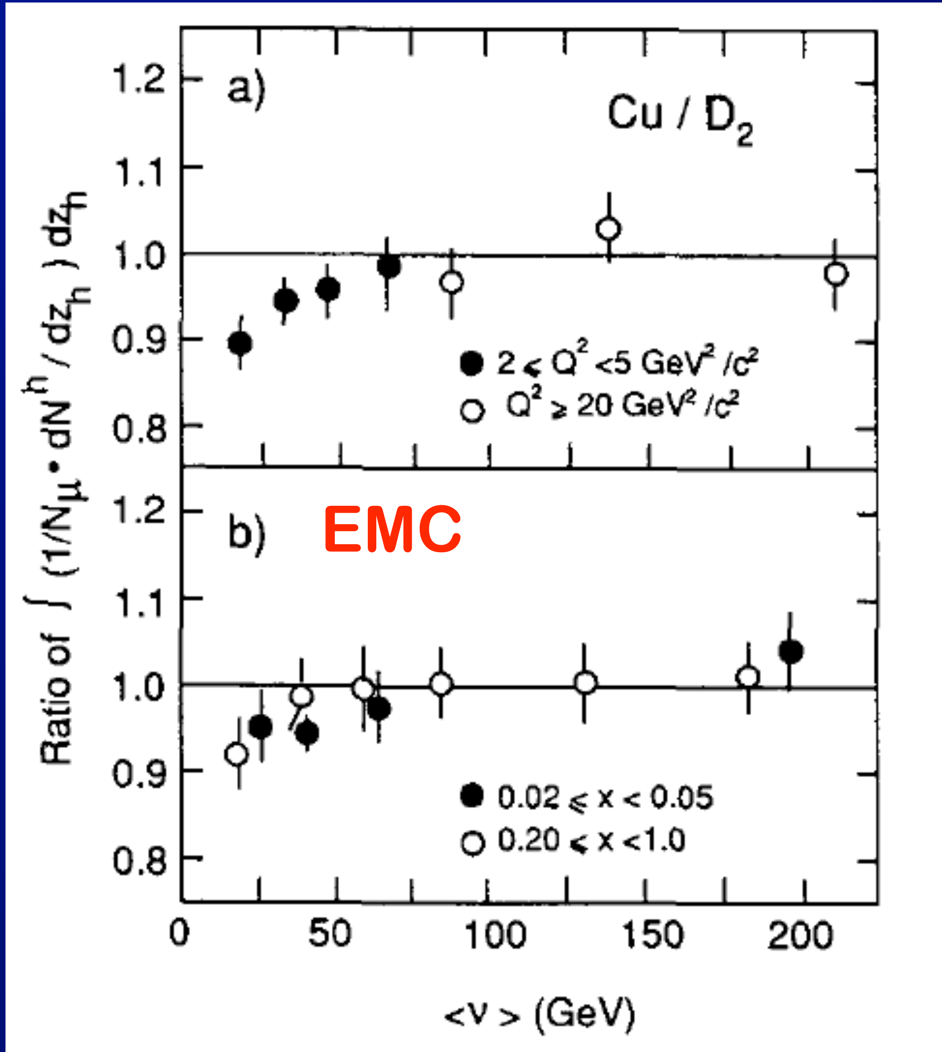


"Stopping" quarks in nuclei

$$\mathrm{Kin}_1 \equiv \begin{cases} x_{\mathrm{Bj}} < 0.005, \\ Q^2 < 1\ \mathrm{GeV}^2/c^2. \end{cases}$$

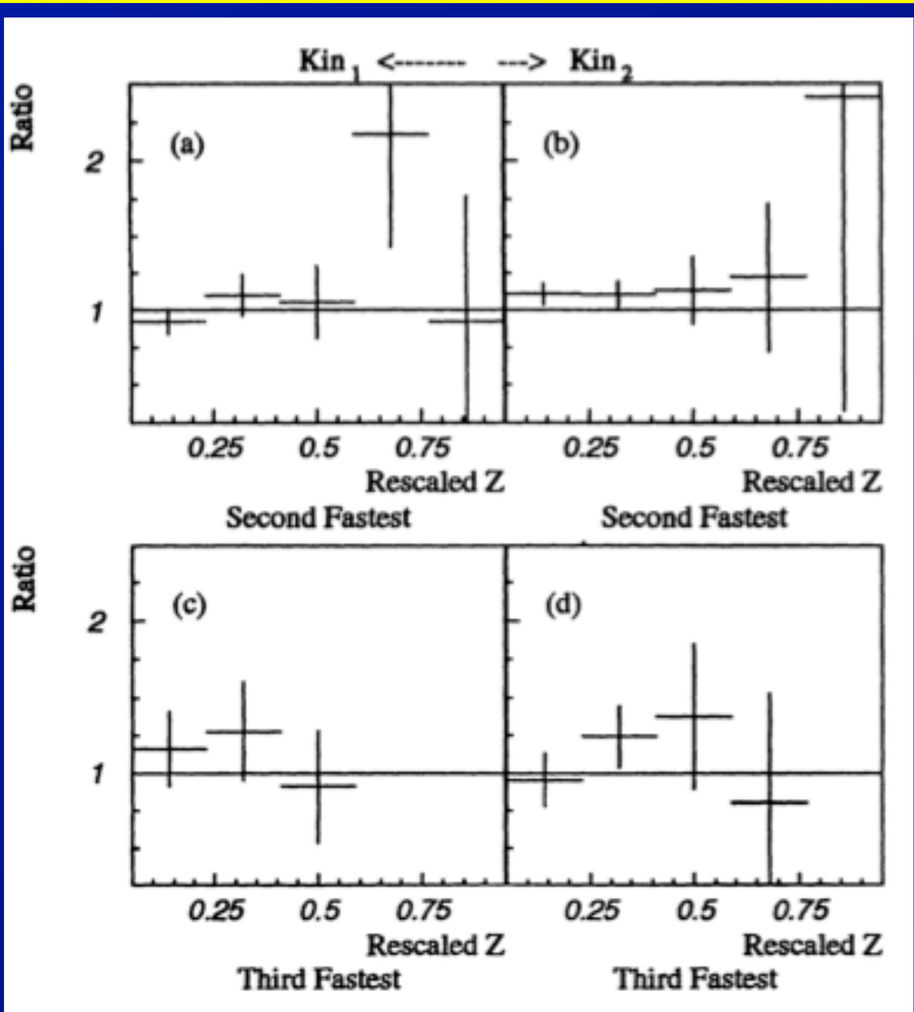
$$\mathrm{Kin}_2 \equiv \begin{cases} x_{\mathrm{Bj}} > 0.03, \\ Q^2 > 2\ \mathrm{GeV}^2/c^2. \end{cases}$$

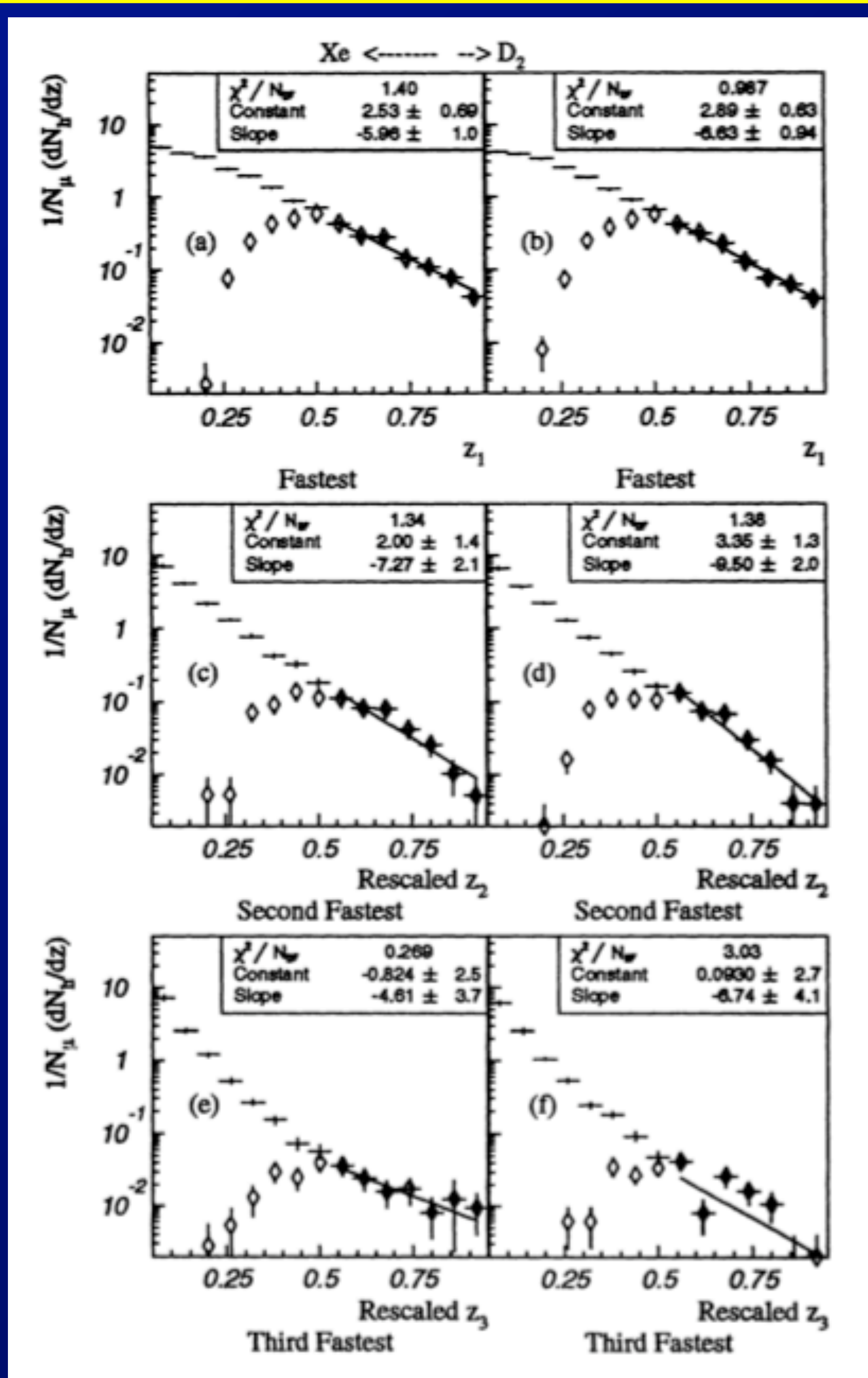




- E665 (ν > 100 GeV) and EMC see little/no stopping of quarks in nucleus

E665: beyond leading hadron





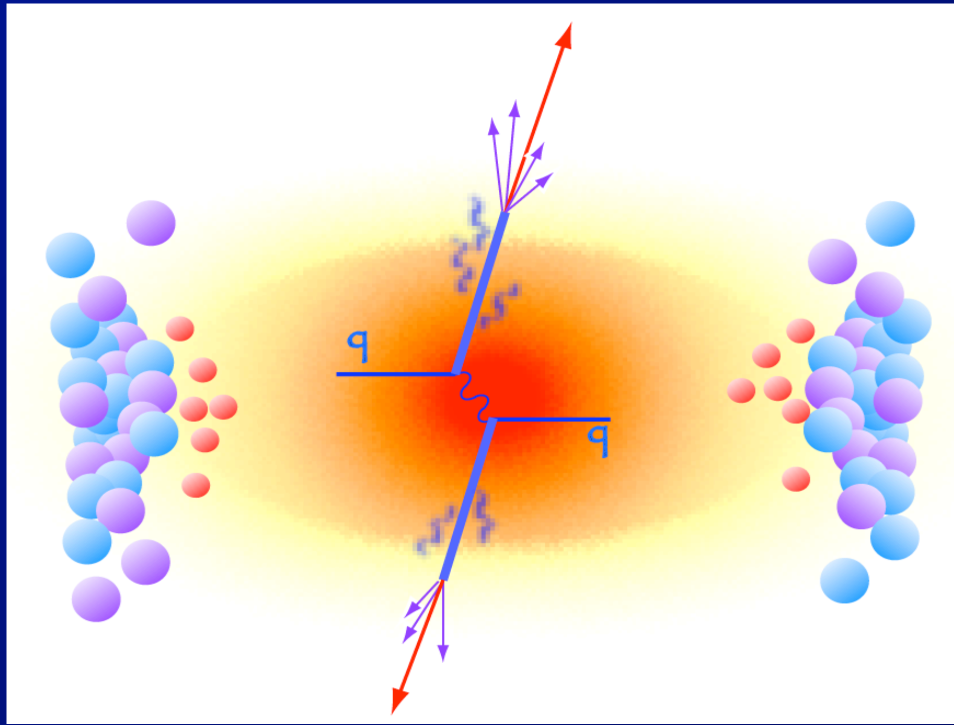
- Ingenious analysis
  - ⇒Relevant for LHC jet quenching?!

A different kind of stopping:

stopping high-momentum quarks and gluons in HOT nuclear matter

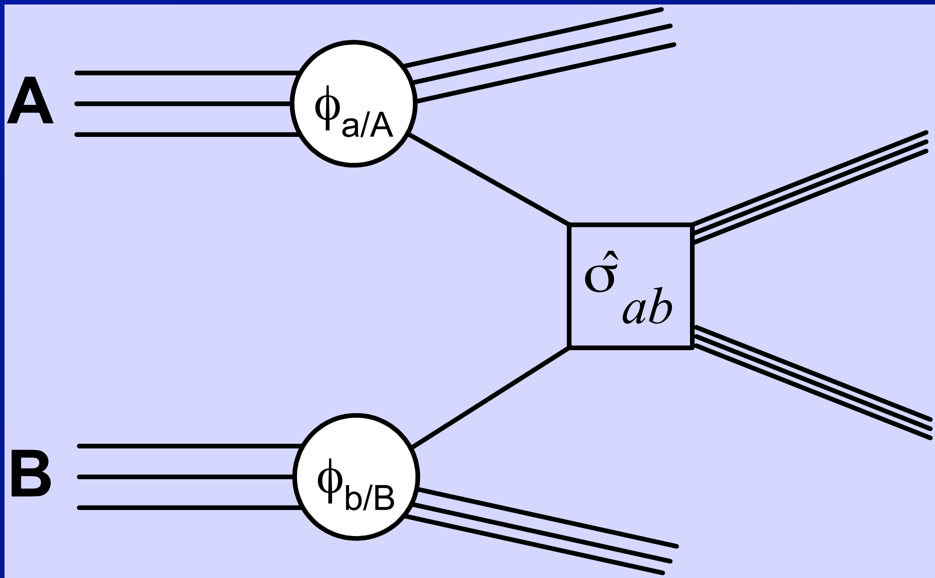
Jet probes of the quark gluon plasma

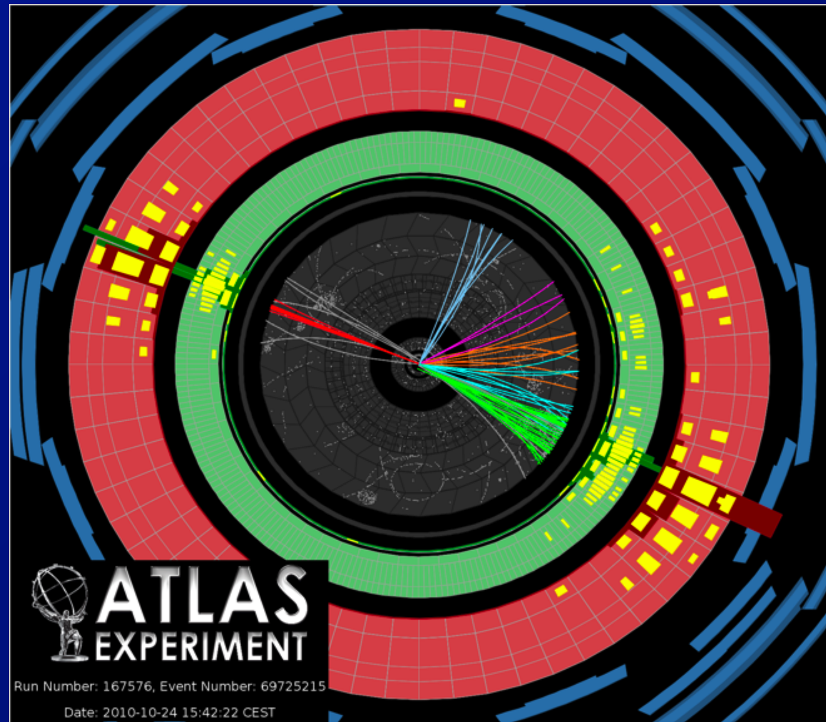
- Use jets from hard scattering processes to directly probe the quark gluon plasma (QGP)



- Key experimental question:
  - ⇒How do parton showers in quark gluon plasma differ from those in vacuum?
- Use vector bosons -- for which the QGP is transparent -- to calibrate hard scattering rates in Pb+Pb collisions.

Hard Scattering in p-p Collisions





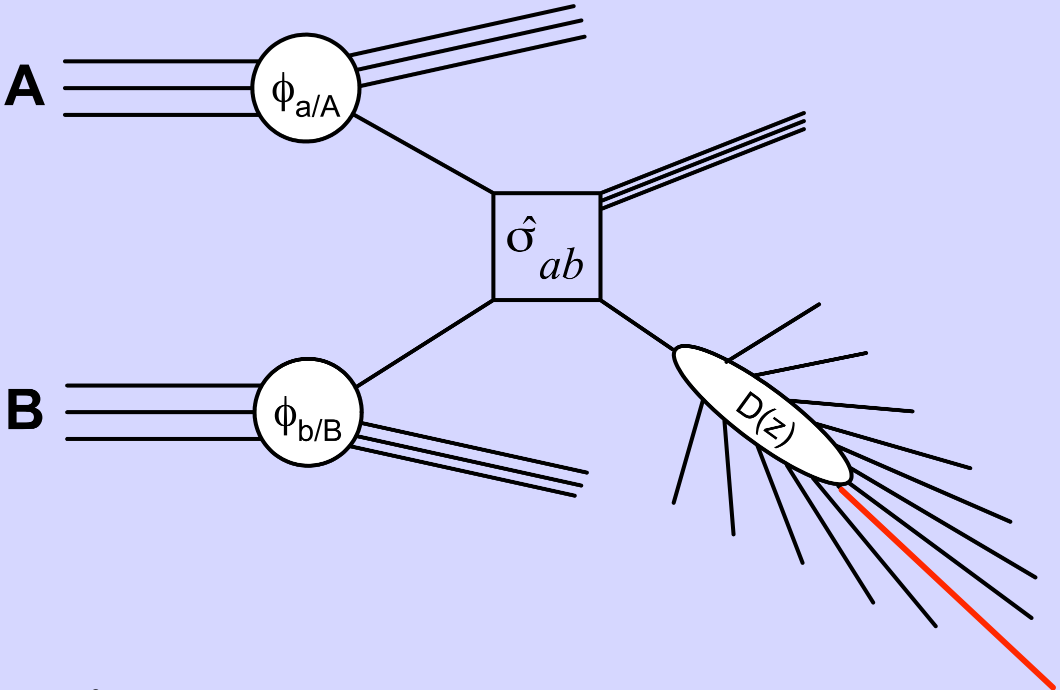
From **Collins, Soper, Sterman**
Phys. Lett. B438:184-192, 1998

$$\sigma_{AB} = \sum_{ab} \int dx_a dx_b \, \phi_{a/A}(x_a, \mu^2) \, \phi_{b/B}(x_b, \mu^2) \, \hat{\sigma}_{ab}\left(\frac{Q^2}{x_a x_b s}, \frac{Q}{\mu}, \alpha_s(\mu)\right) \left(1 + \mathcal{O}\left(\frac{1}{Q^P}\right)\right)$$

- **Factorization:** separation of σ into
  - Short-distance physics: σ_{ab}
  - Long-distance physics: φ's

pQCD – Single Hadron Production

Add fragmentation to hadrons

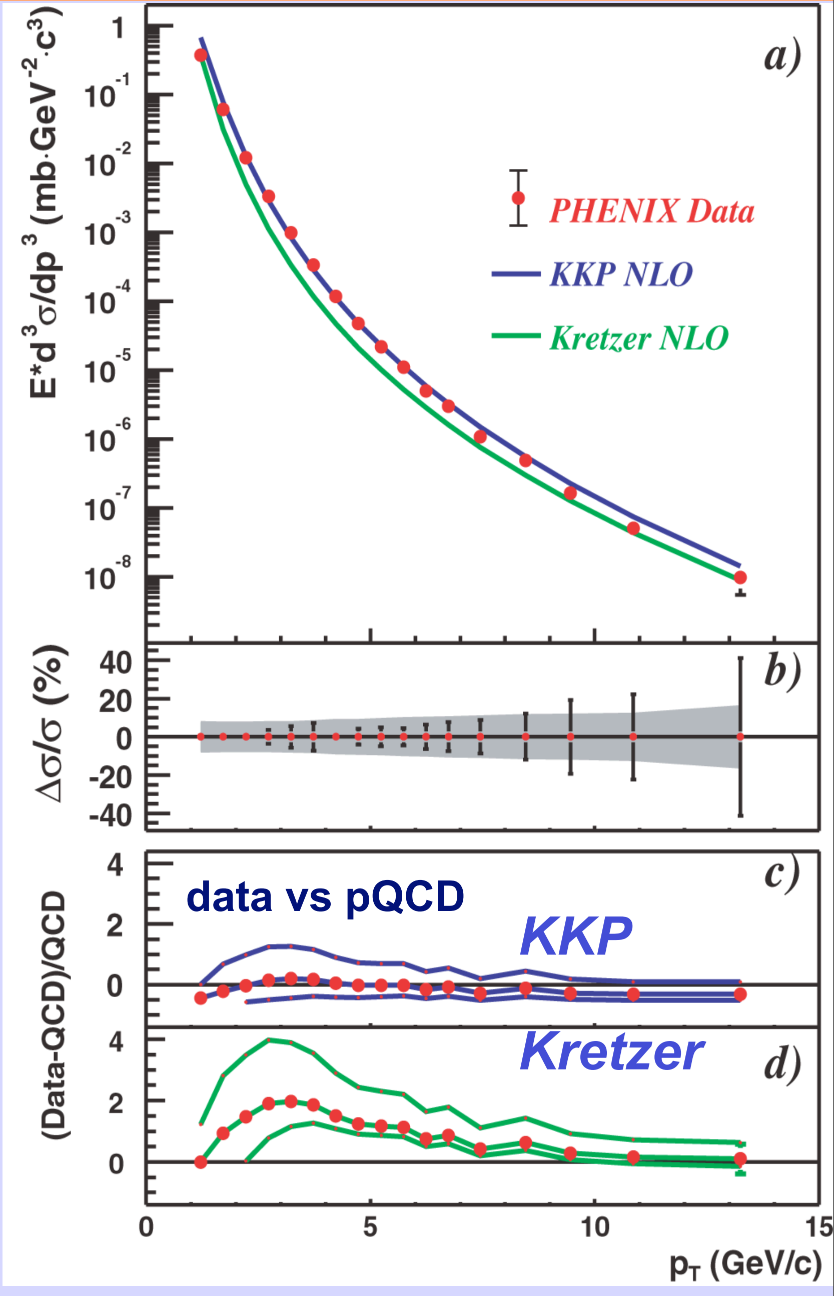


$$E\frac{d^3\sigma}{dp^3} = \sum_{abc}\int dx_a dx_b\, \phi_{a/A}(x_a, Q^2, \mu)\phi_{b/B}(x_a, Q^2, \mu)$$

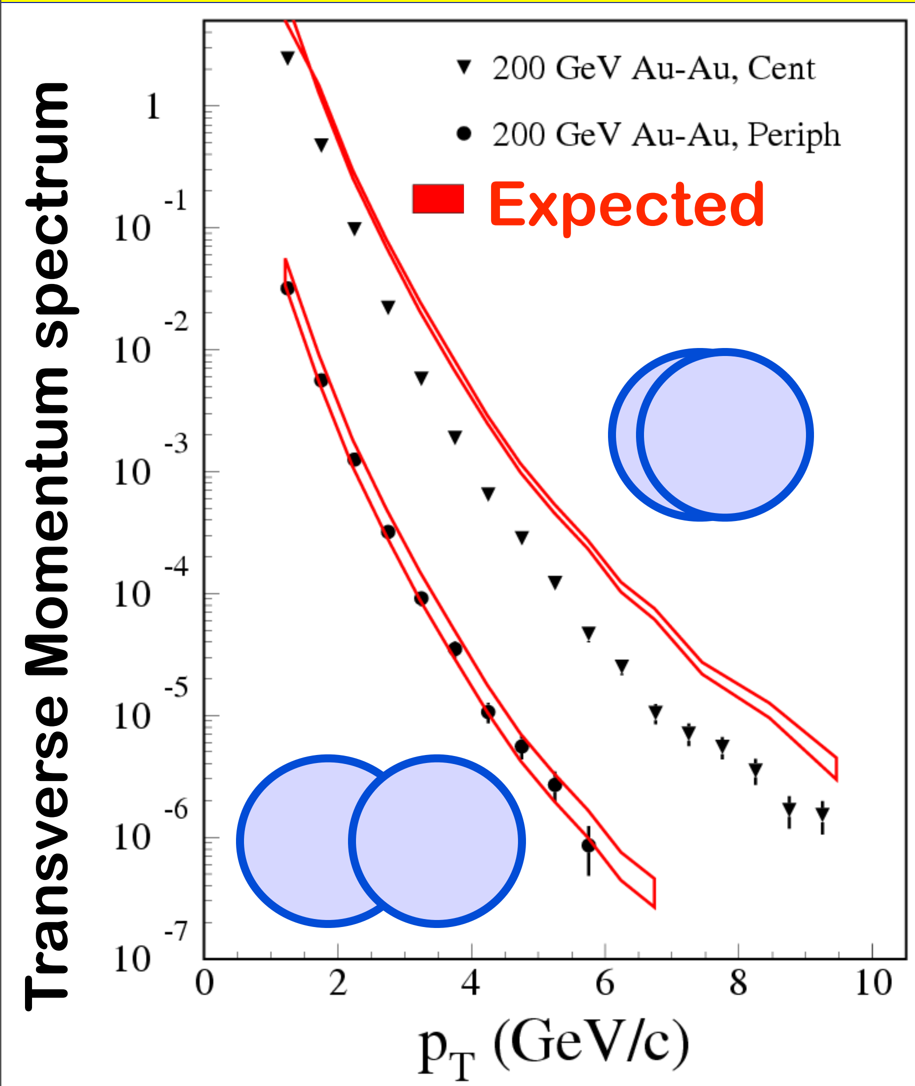
$$\times \frac{D_{\pi^0/c}(z, Q^2, \mu)}{z\pi}\frac{d\hat{\sigma}}{dt}$$

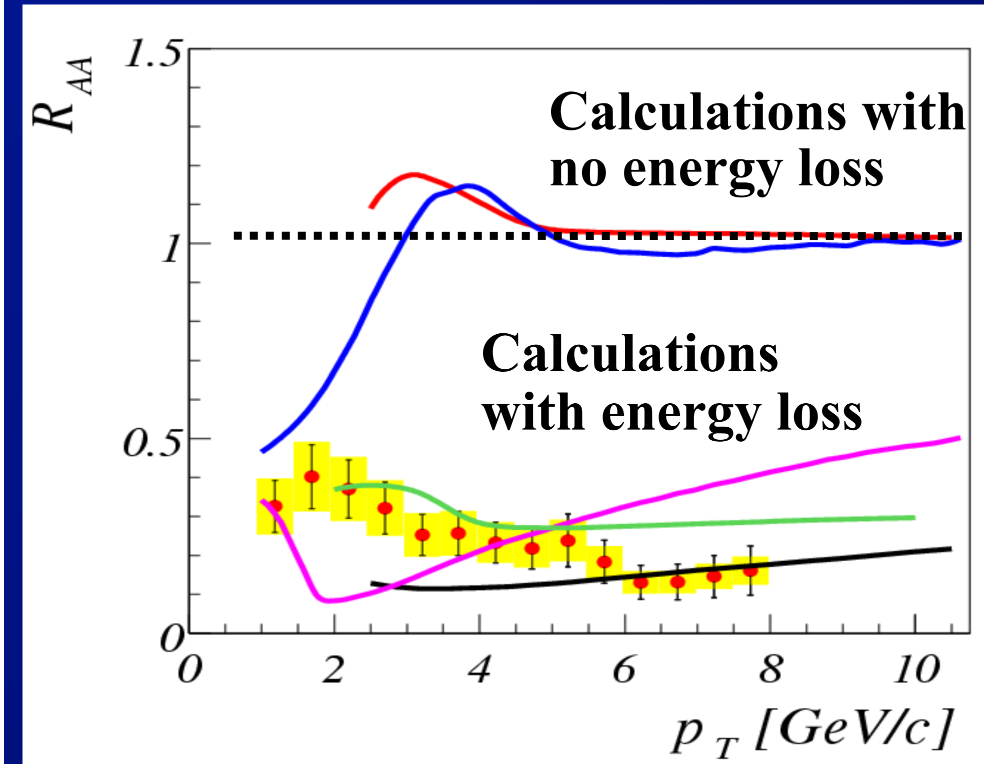
- **D(z) – fractional momentum dist. of particles created by outgoing quark or gluon**

Phys. Rev. Lett. 91, 241803 (2003)



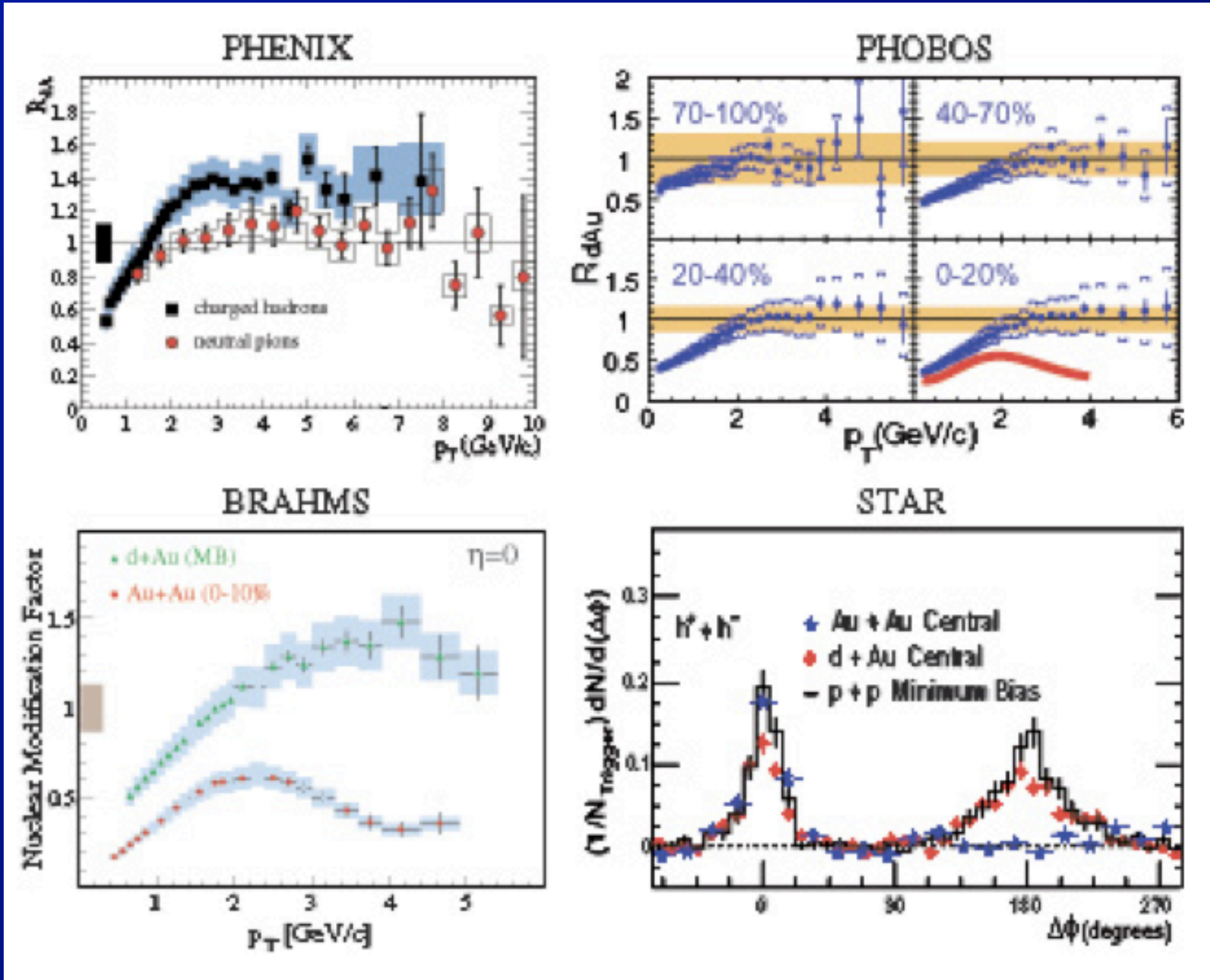
“Jet quenching”, CA. 2002(?)



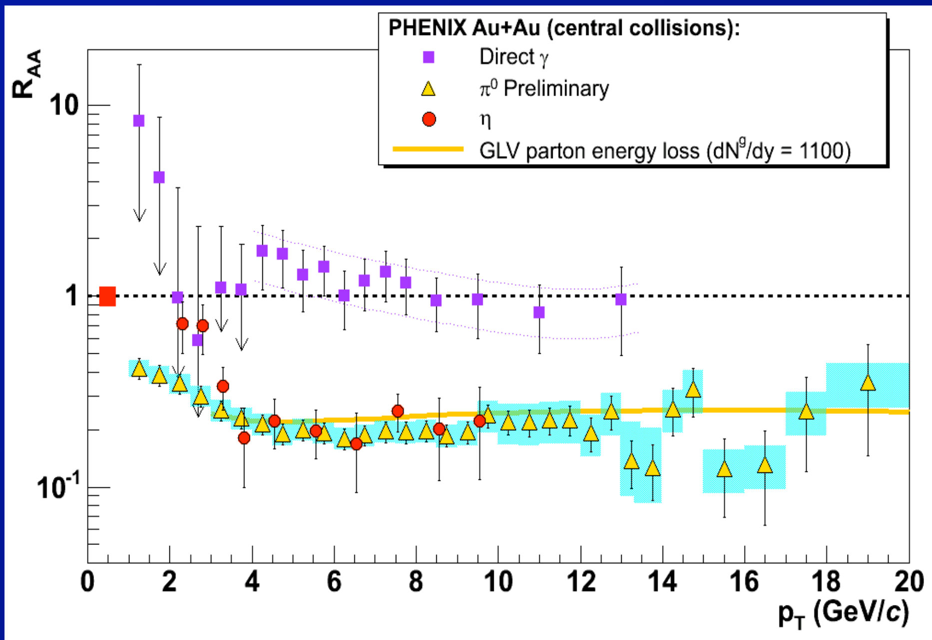


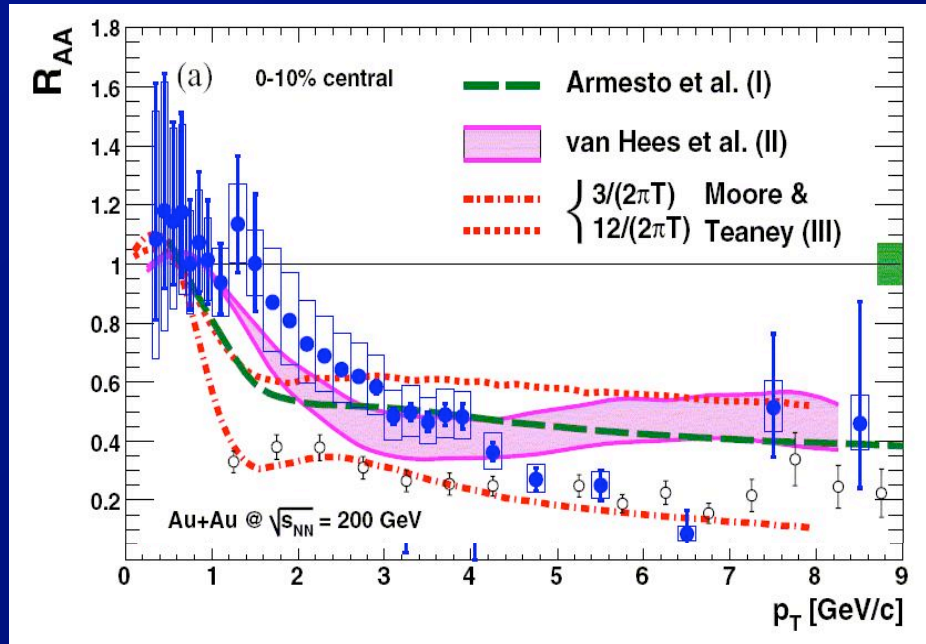
- In the days of jet quenching innocence ...

Single/di-hadron suppression w/ control



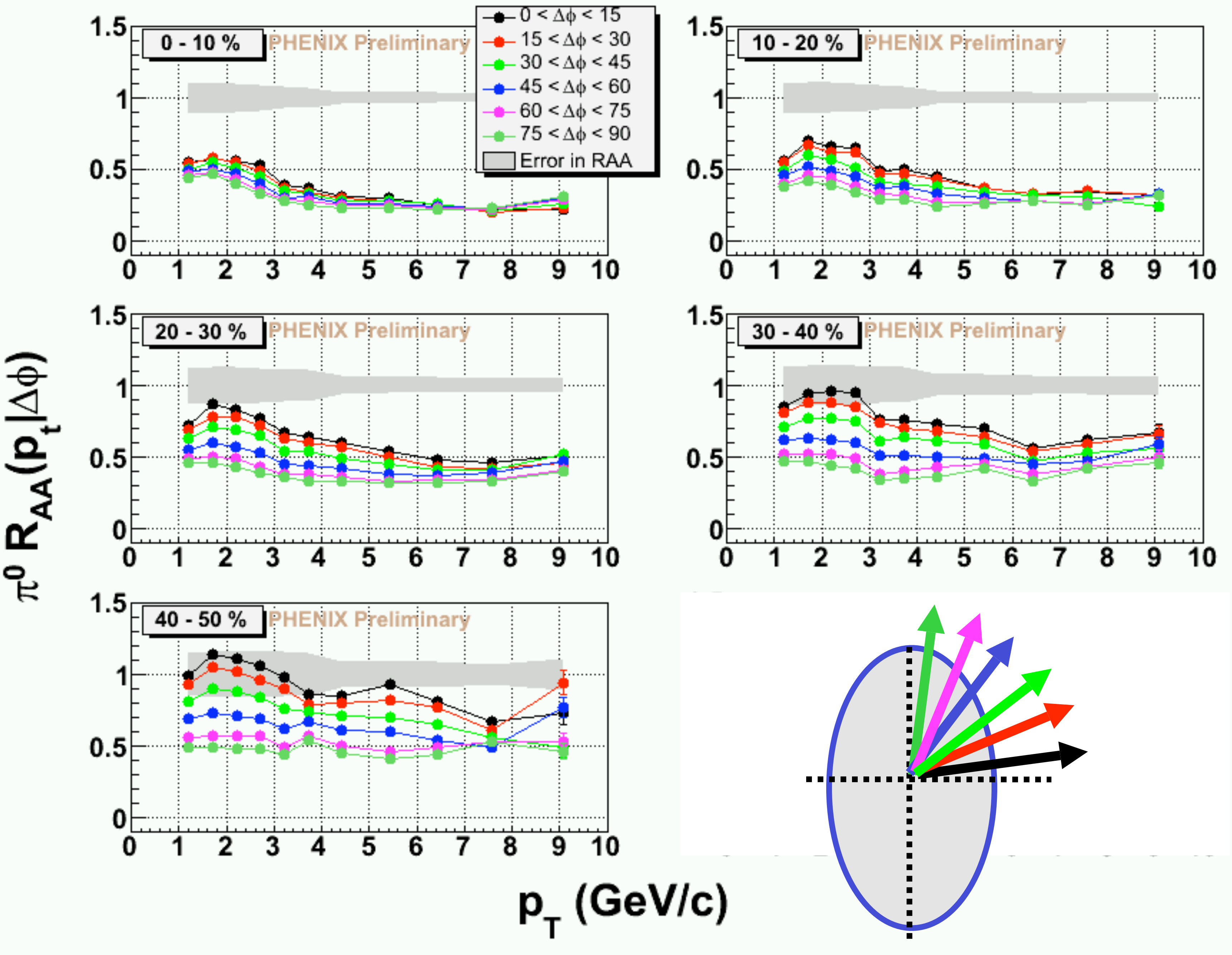
More progress ...





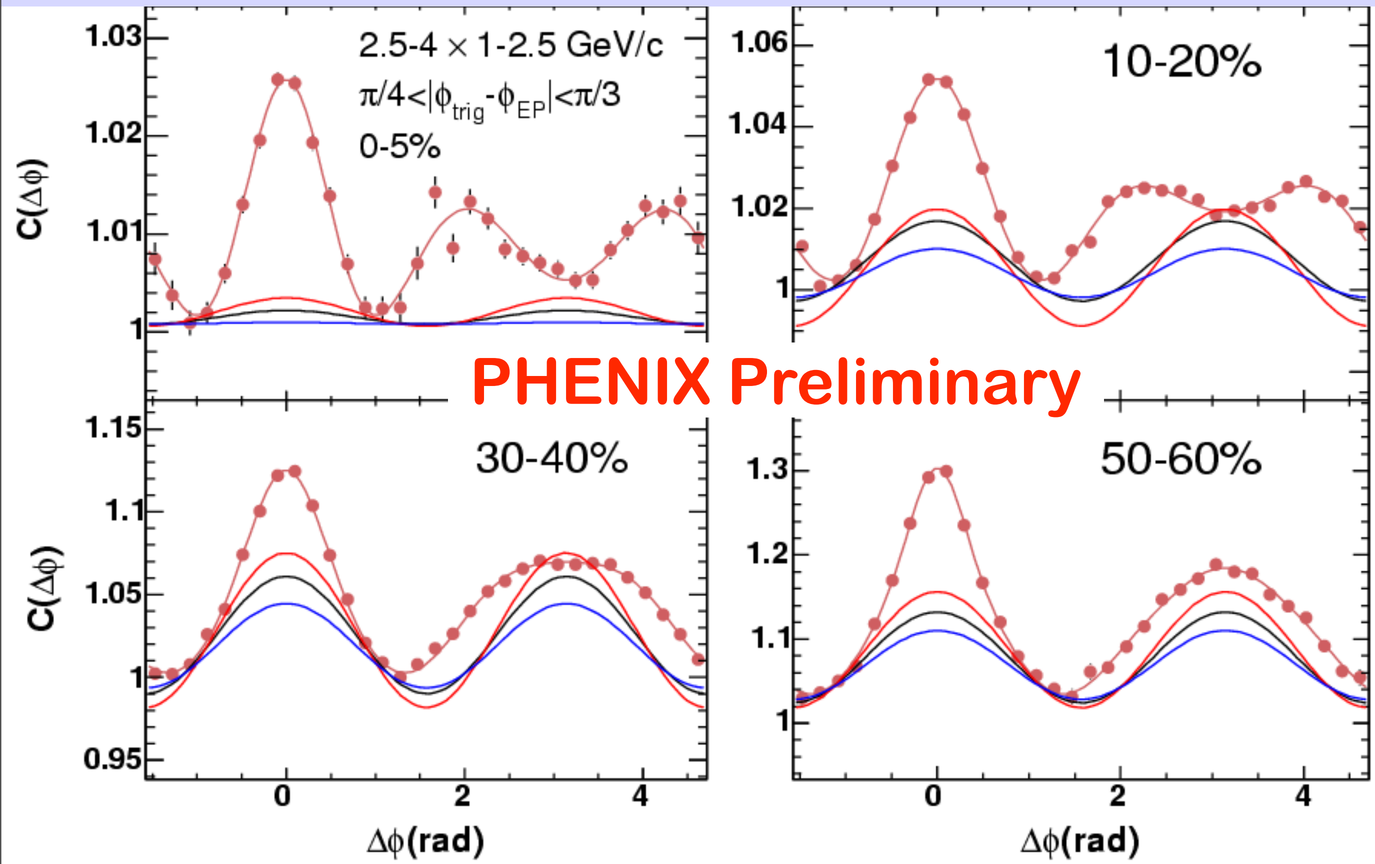
- Additions of photon control measurement and heavy quark suppression provide stronger evidence for quenching
  - ⇒But heavy quark results were a challenge to theory

Quenching “sees” the geometry

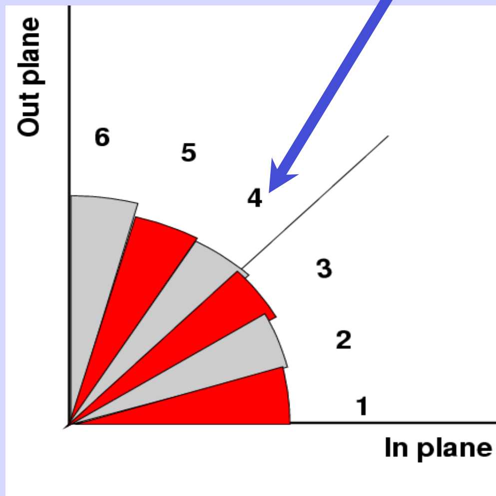


Into the wilderness …

From Quark Matter 2005



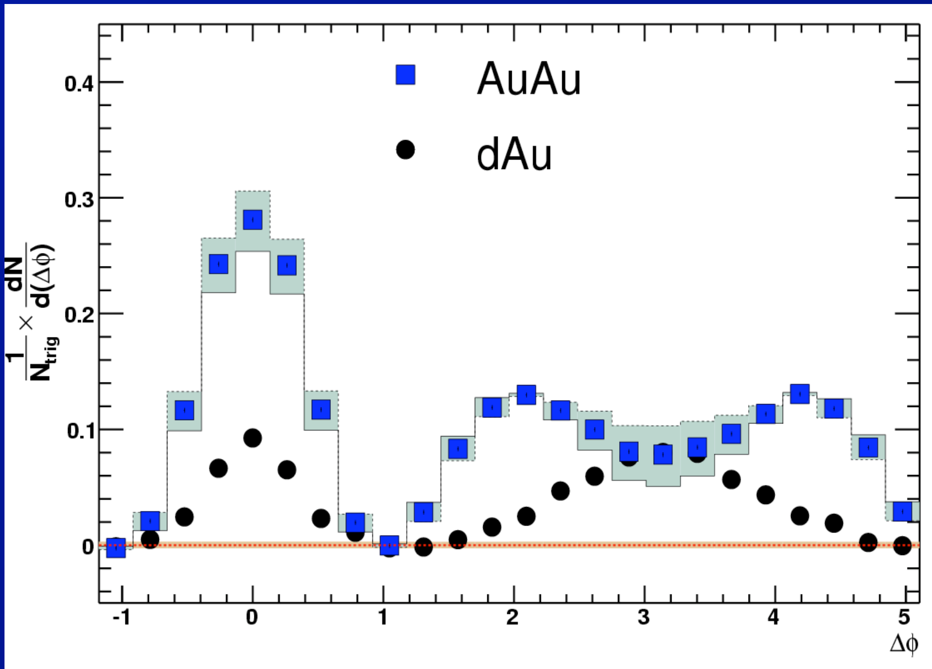
Look in bin #4

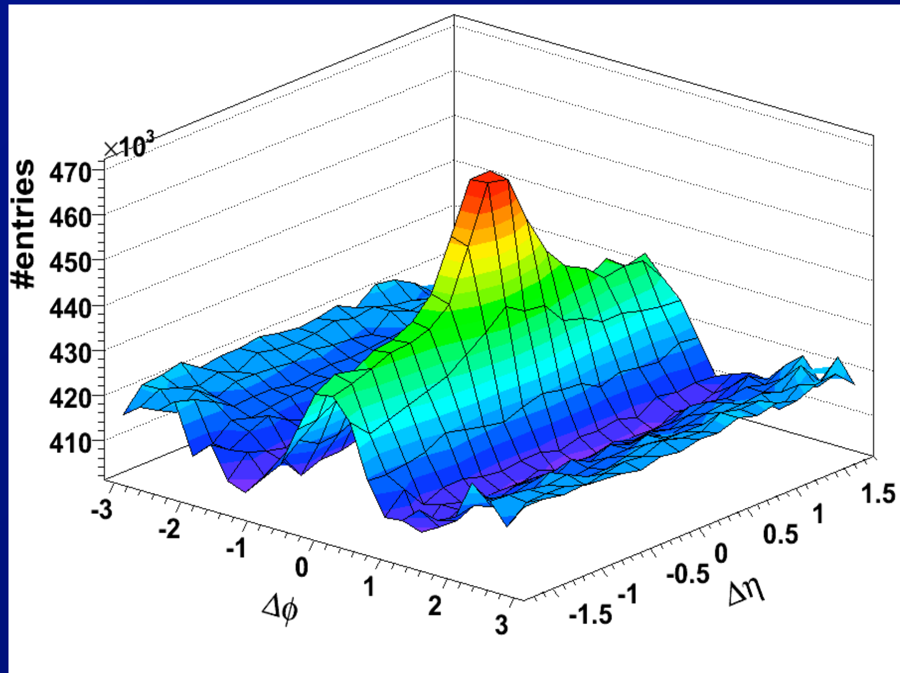


- For PHENIX reaction plane resolution & chosen bin sizes, $\Delta\phi_{trig}$ bin 4 has smallest flow effects.
- Even without subtracting flow contribution, a dip is seen for central collisions.

Jet Quenching, Medium Response(?)

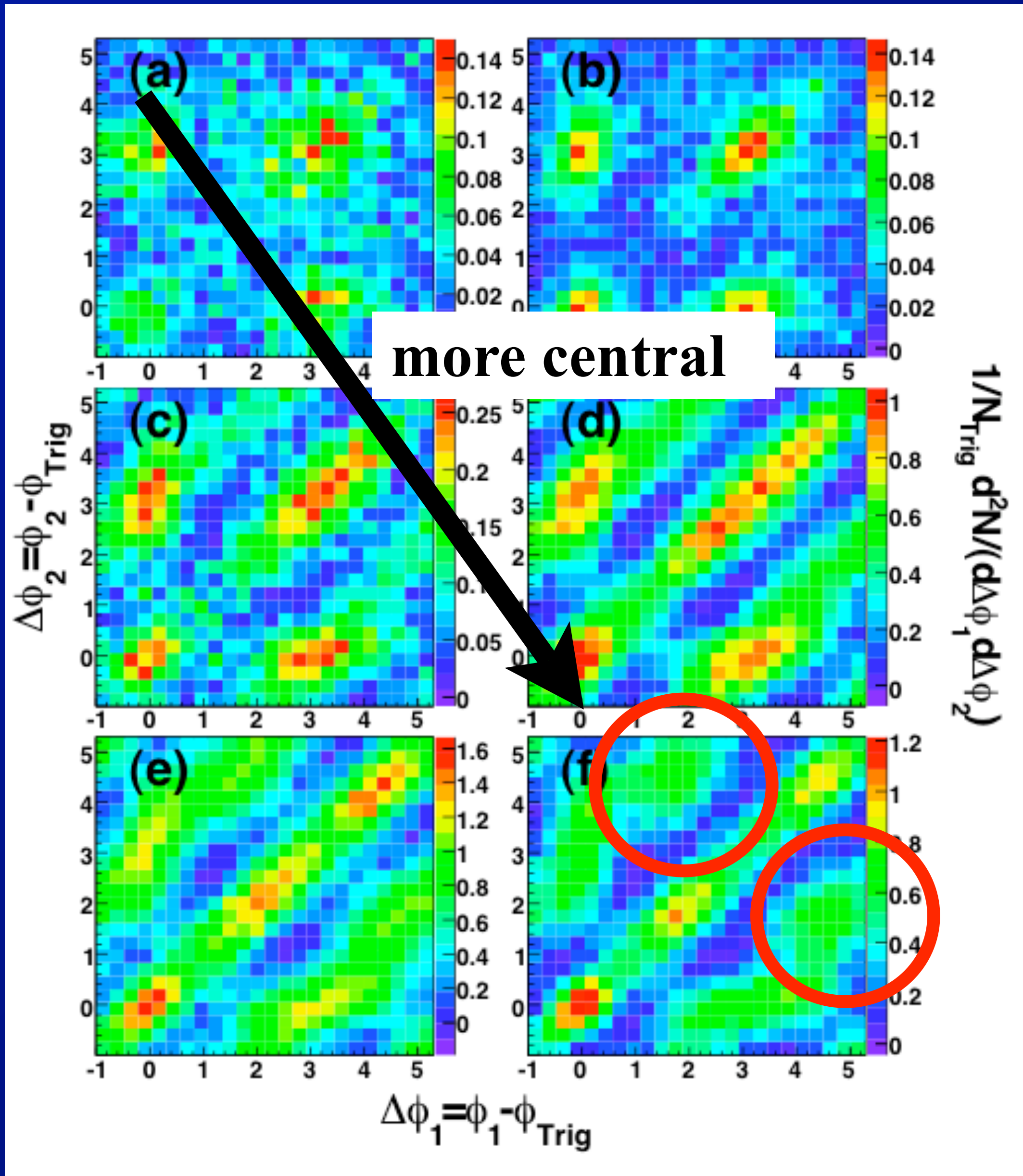
So what about these features in the data?





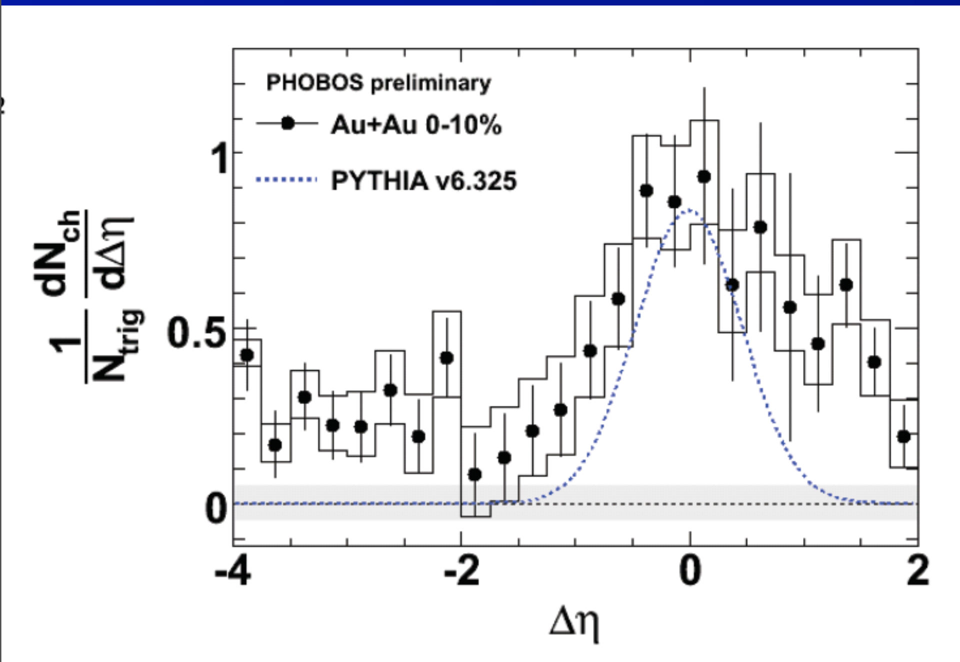
- **One general comment (as someone who has worked on these measurements)**
  - Doing these analyses with jet "triggers" instead of hadrons will help tremendously
  - Both at RHIC and LHC

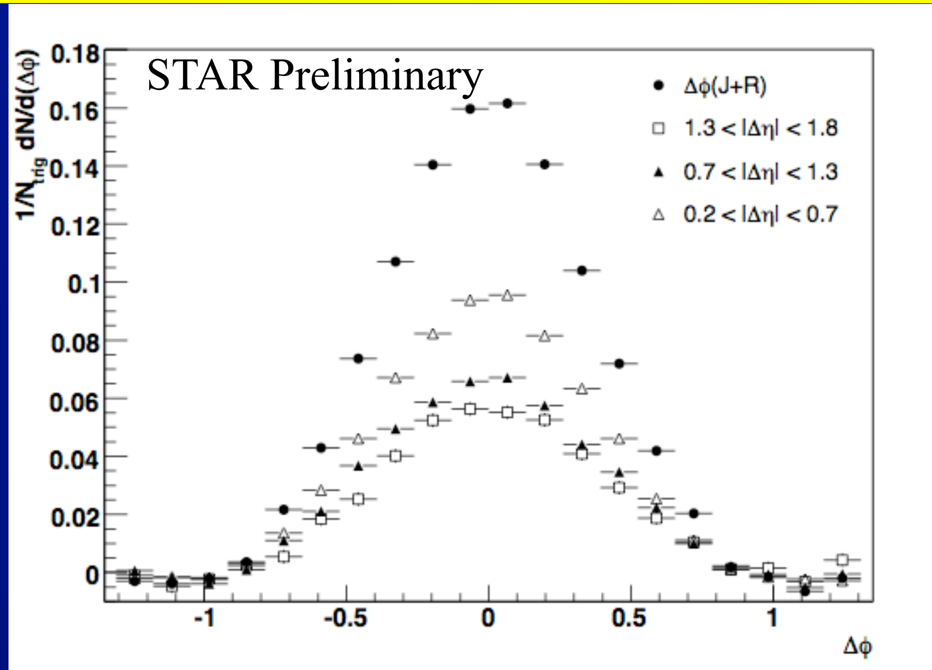
STAR: 3-hadron correlations



- Data look pretty clear, even to a skeptic …

The Ridge: new insights

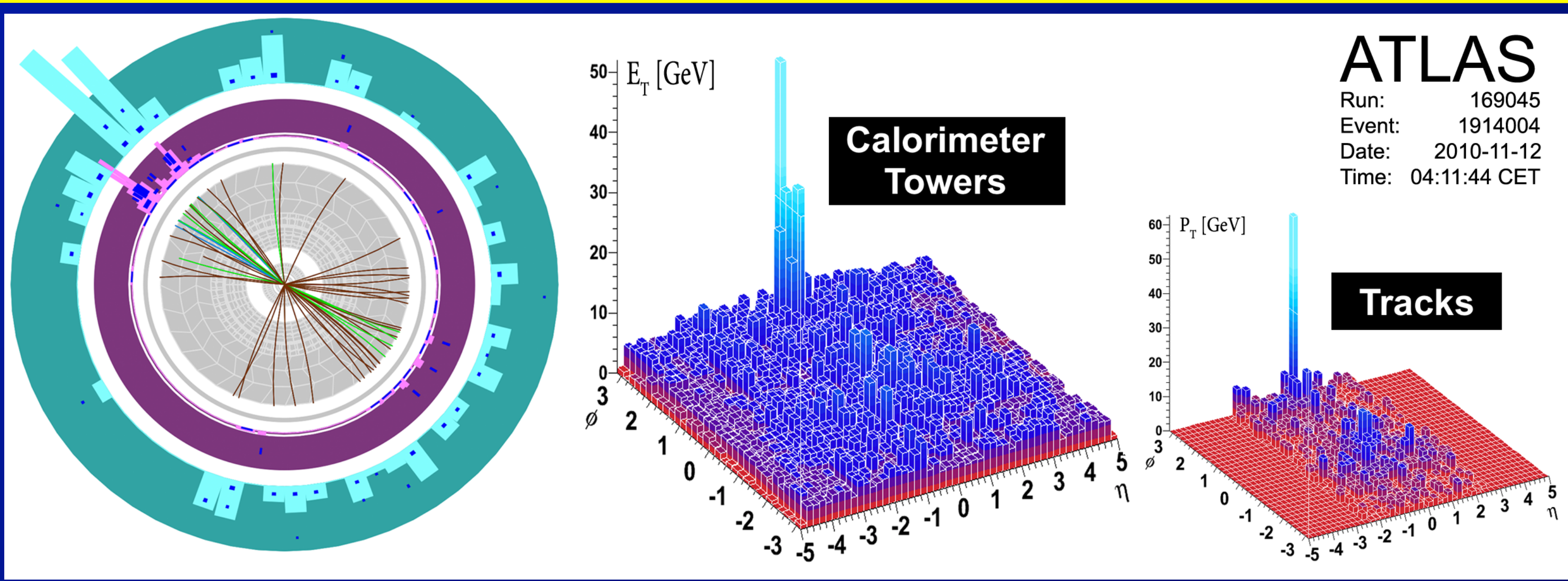


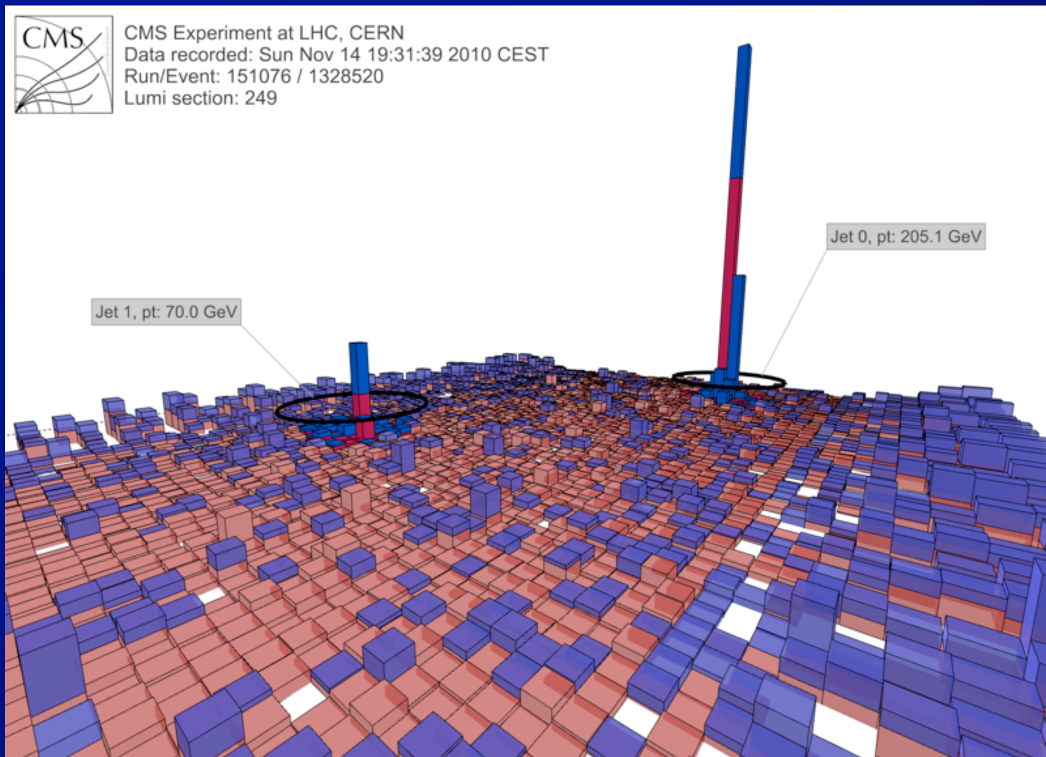


- Ridge extends over loooooong range in Δη.
- How close is the Δφ distribution to that of jets?
  – A crucial question to be answered (quantitatively)
- Momentum and flavor dist. characteristic of medium.
  – (data not shown for brevity)

Out of the wilderness …

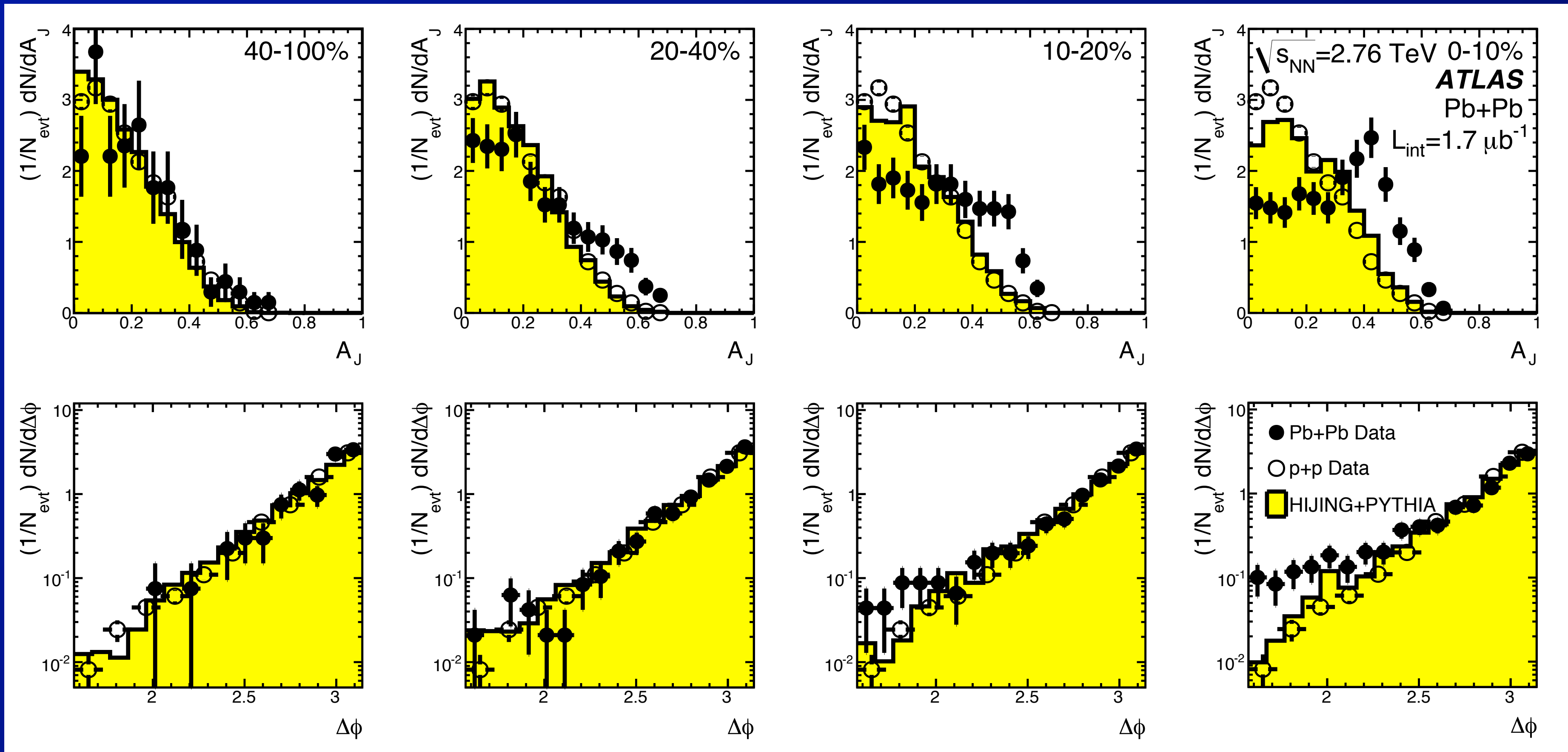
Dijet asymmetry





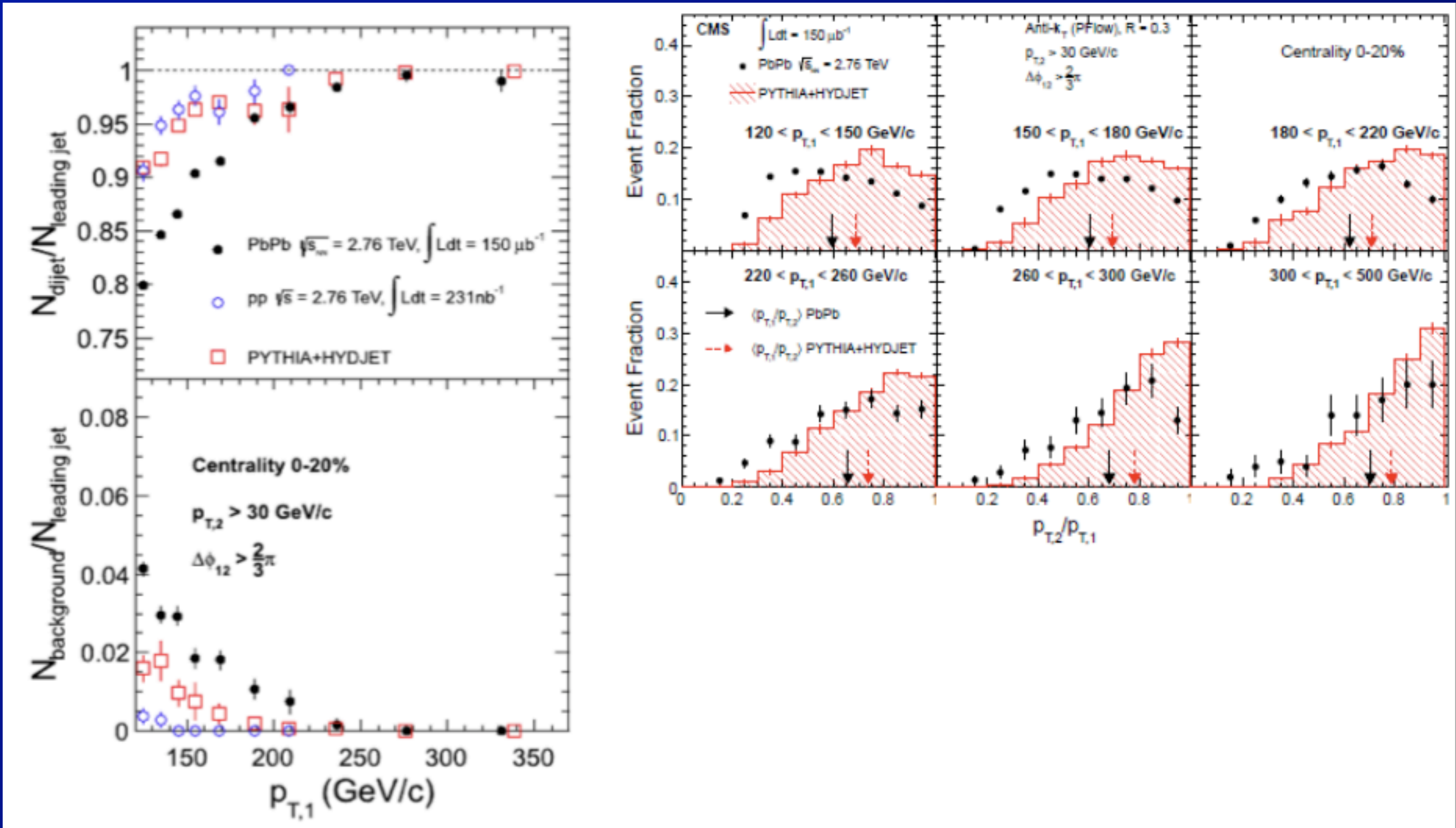
- 1st time that we can "see" jet quenching in individual events

Di-jet asymmetry & acoplanarity



- For more central collisions, see:
  - Change in distribution of dijet asymmetry
  - While no change in the distribution of Δφ
    - ⇒Except for combinatoric pairs in central

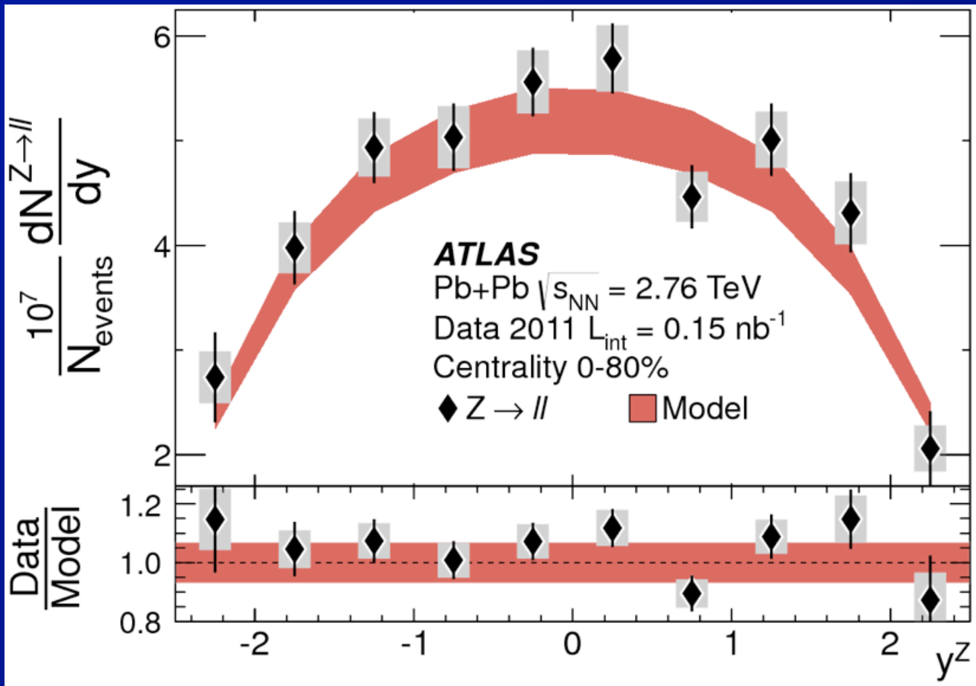
dijet asymmetry: energy dependence

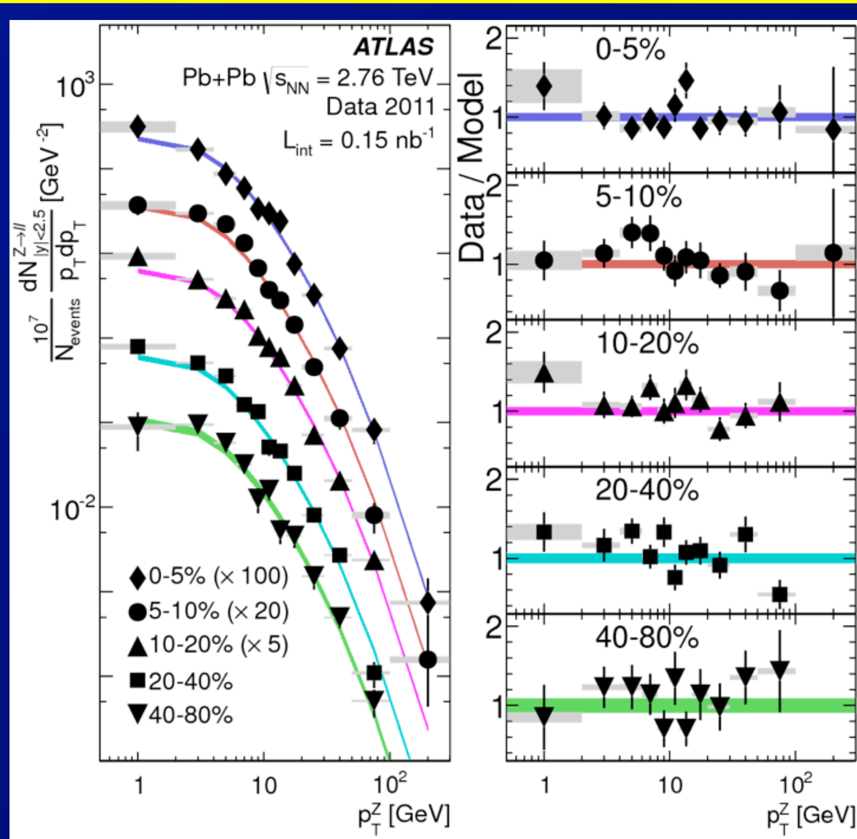


- Shamelessly borrowed from Gunther's talk at WSU jet quenching workshop

Pb+Pb: Z production (2)

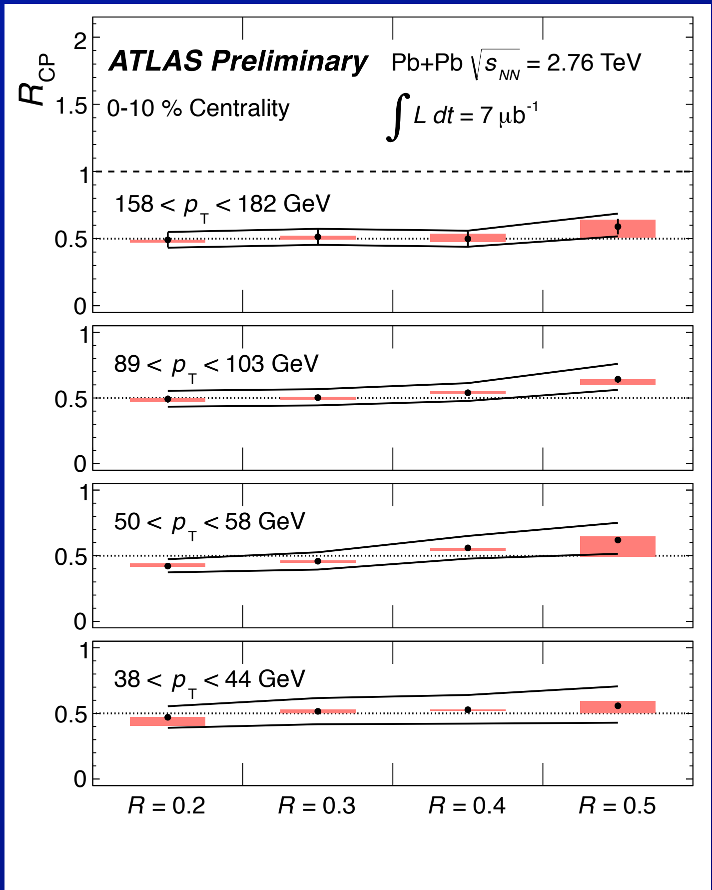
Phys. Rev. Lett. 110, 022301 (2013)



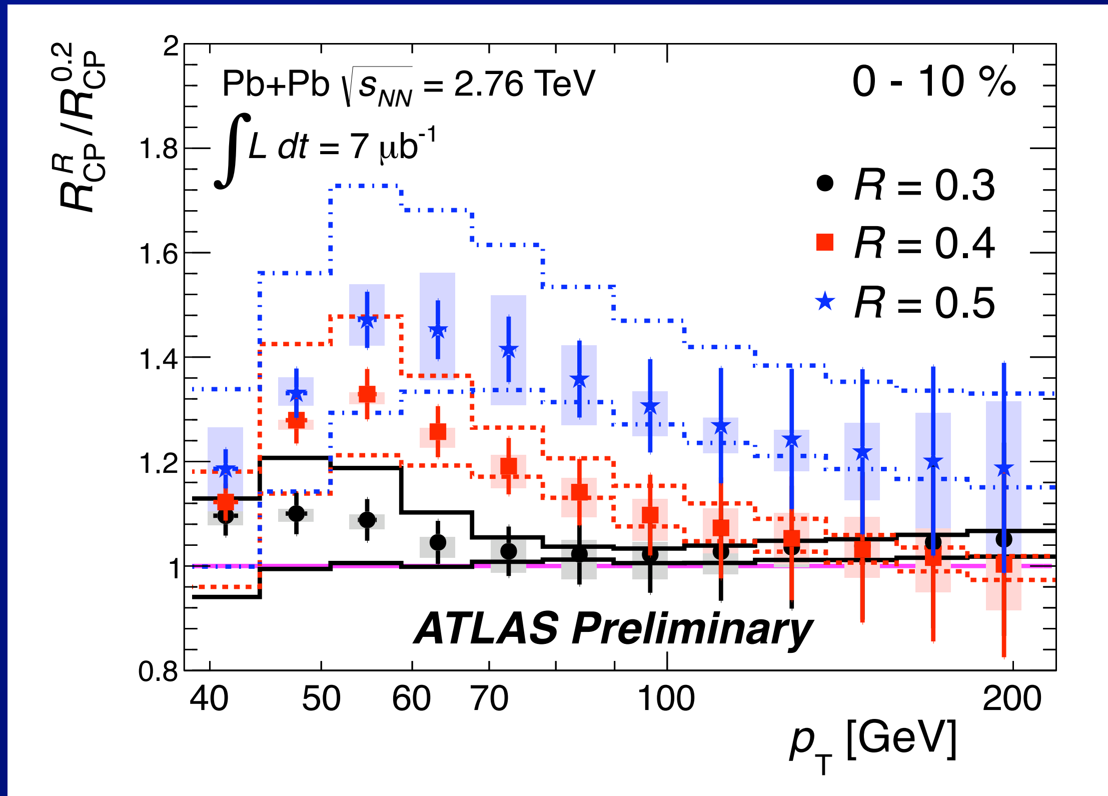


- Compare Pb+Pb Z rapidity distributions (minimum-bias) and pT spectra to PYTHIA scaled to NNLO calculations
  - No nuclear PDFs
    - ⇒ Nuclear PDF effects <~ 20%

Jet radius dependence of R_{cp}

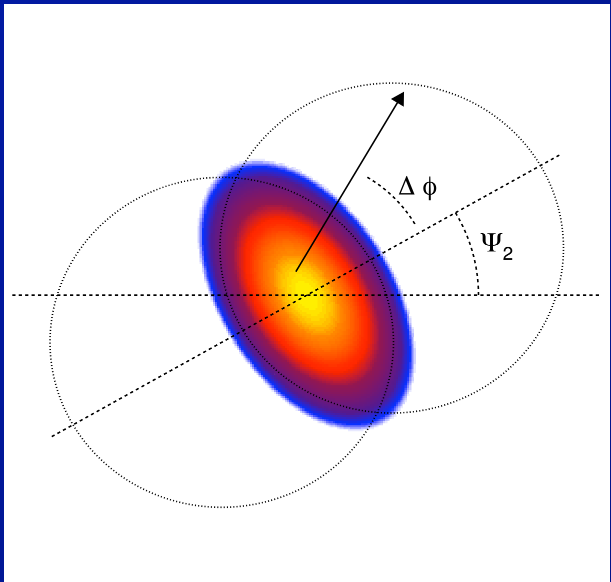


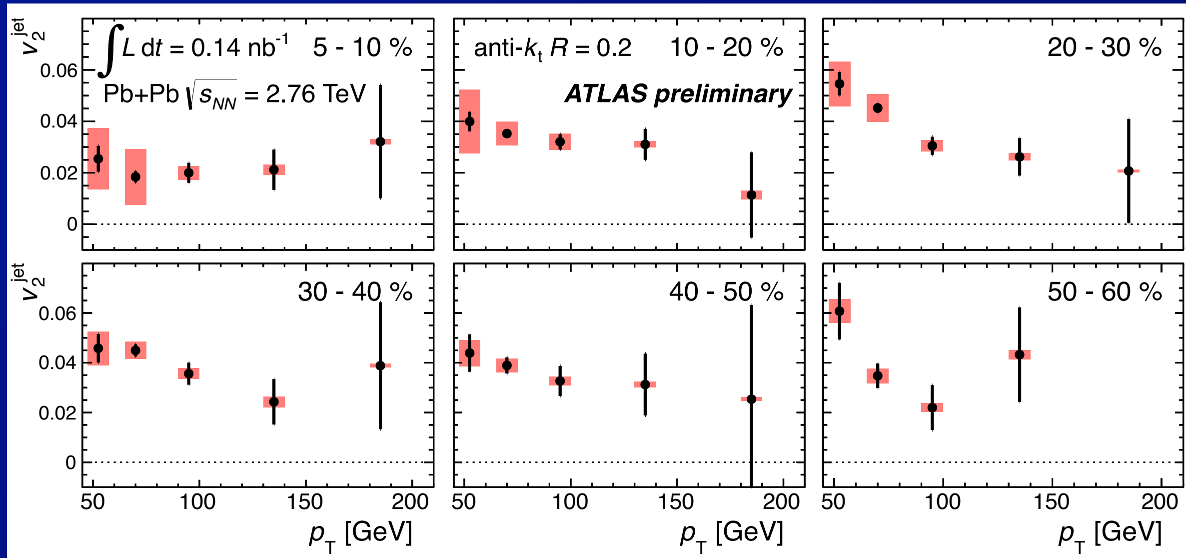
Significant cancellation of correlated errors

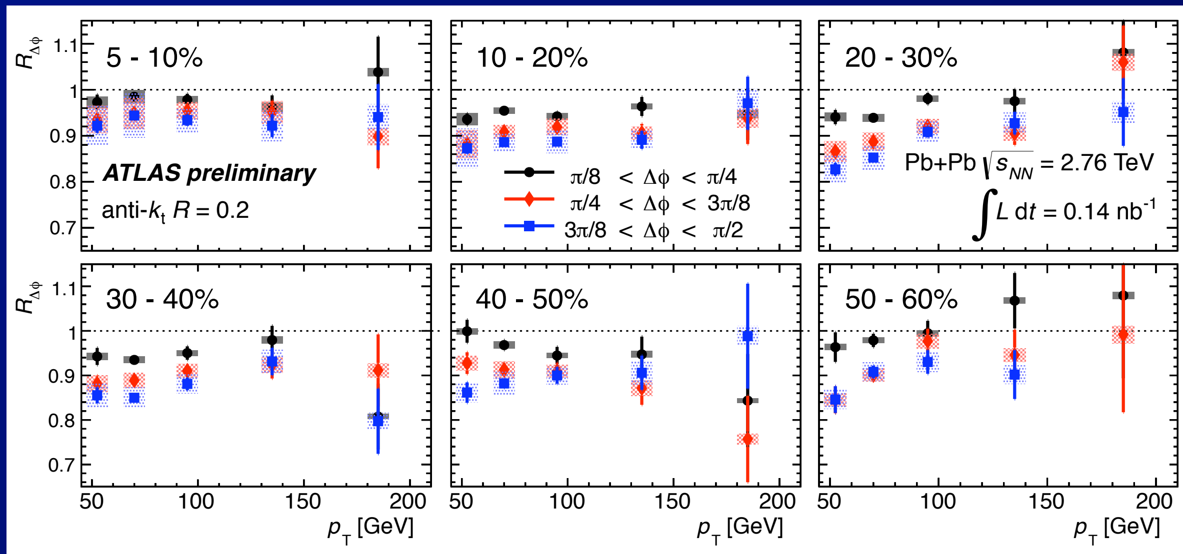


- Evaluate jet radius dependence of R_{cp}
  - Modest but significant variation of R_{cp}
  - Less suppression for larger R
    - ⇒An indication of jet broadening?

Differential jet suppression



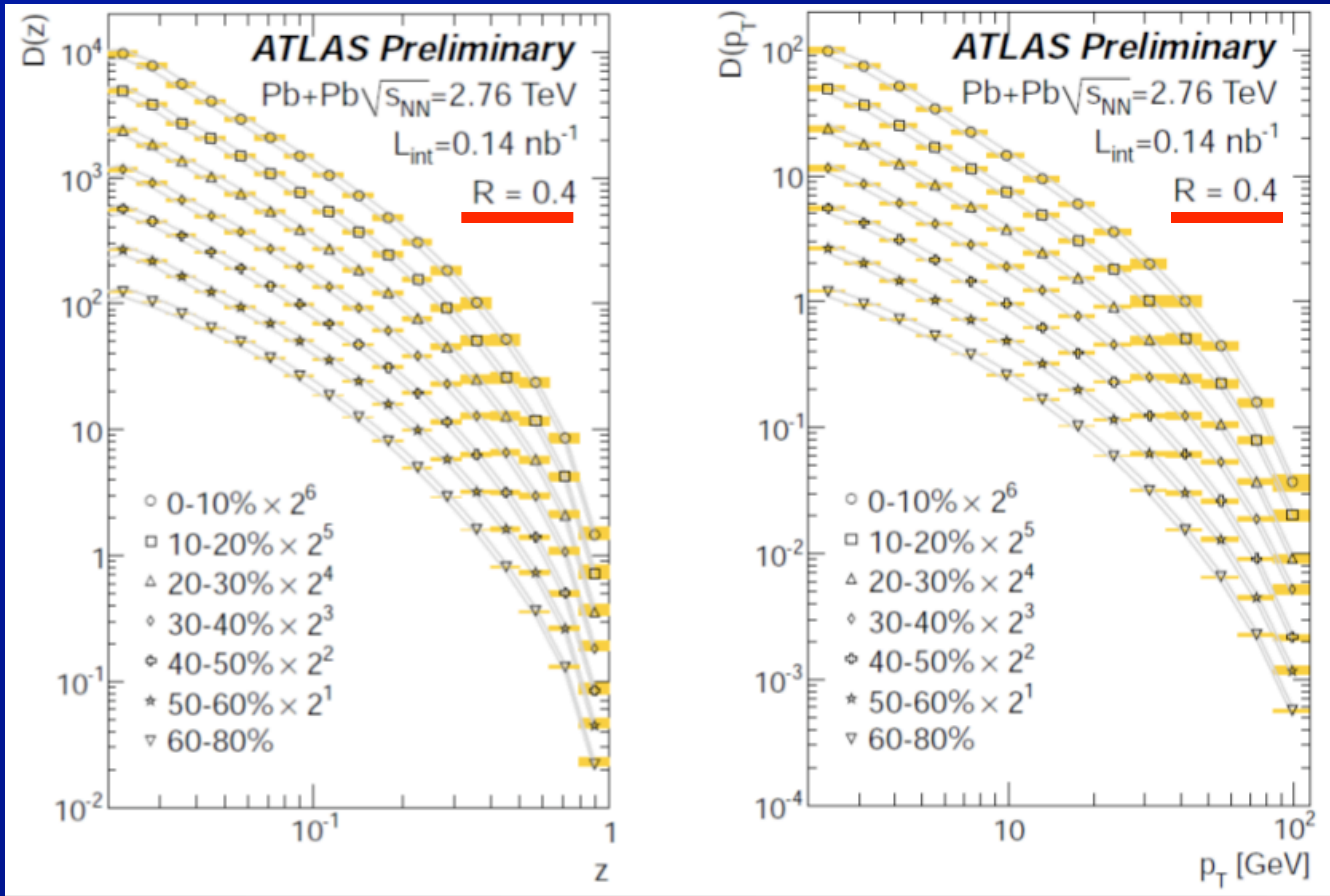




- Measure:
  - Jet v_2
  - Ratios of jet yields in Δφ bins

⇒1st measurement of differential jet quenching using jets.

Inclusive jet fragmentation

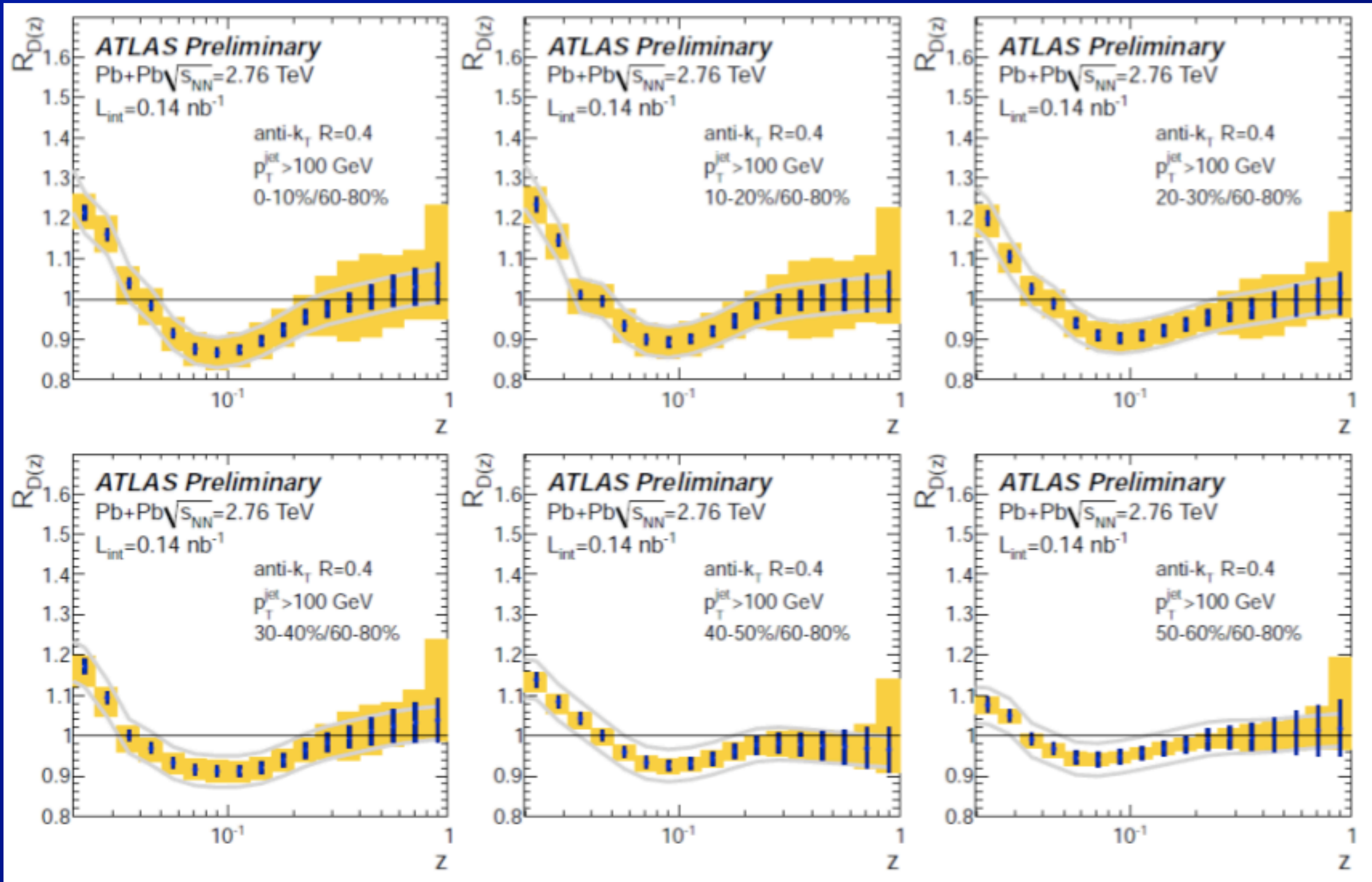


Unfolded for jet and charged particle resolution

$$D(z) = \frac{1}{N_{jet}} \frac{dN_{chg}}{dz}, z = \vec{p}_{chg} \cdot \vec{p}_{jet} / |\vec{p}_{jet}|$$

$$D(p_T) = \frac{1}{N_{jet}} \frac{dN_{chg}}{dp_T}$$

Inclusive jet fragmentation (2)



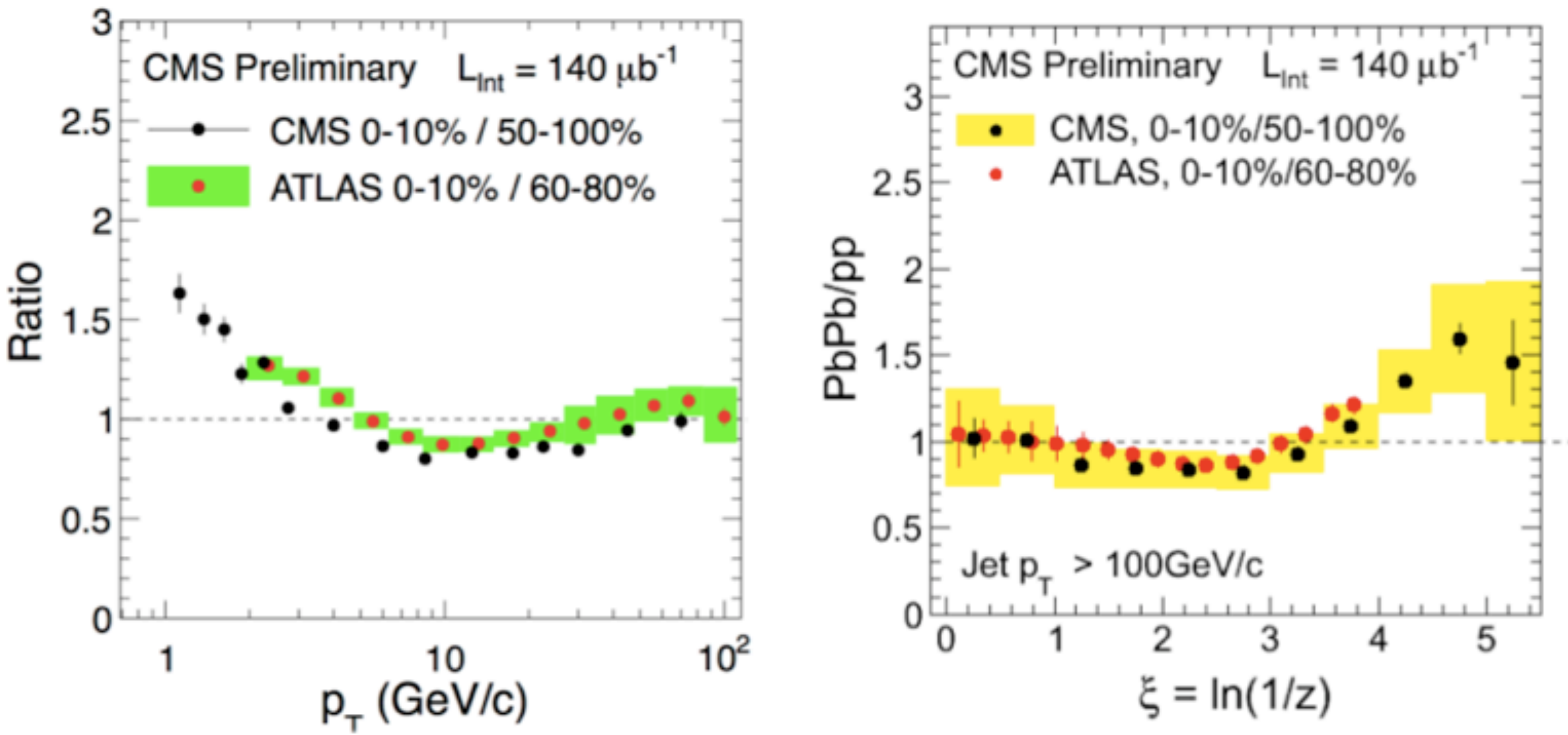
R = 0.4

- **First observation of modified parton shower in inclusive jets**

  ⇒**Not only seeing "left over" unquenched jets.**

Jet fragmentation comparison

Fragmentation function comparison



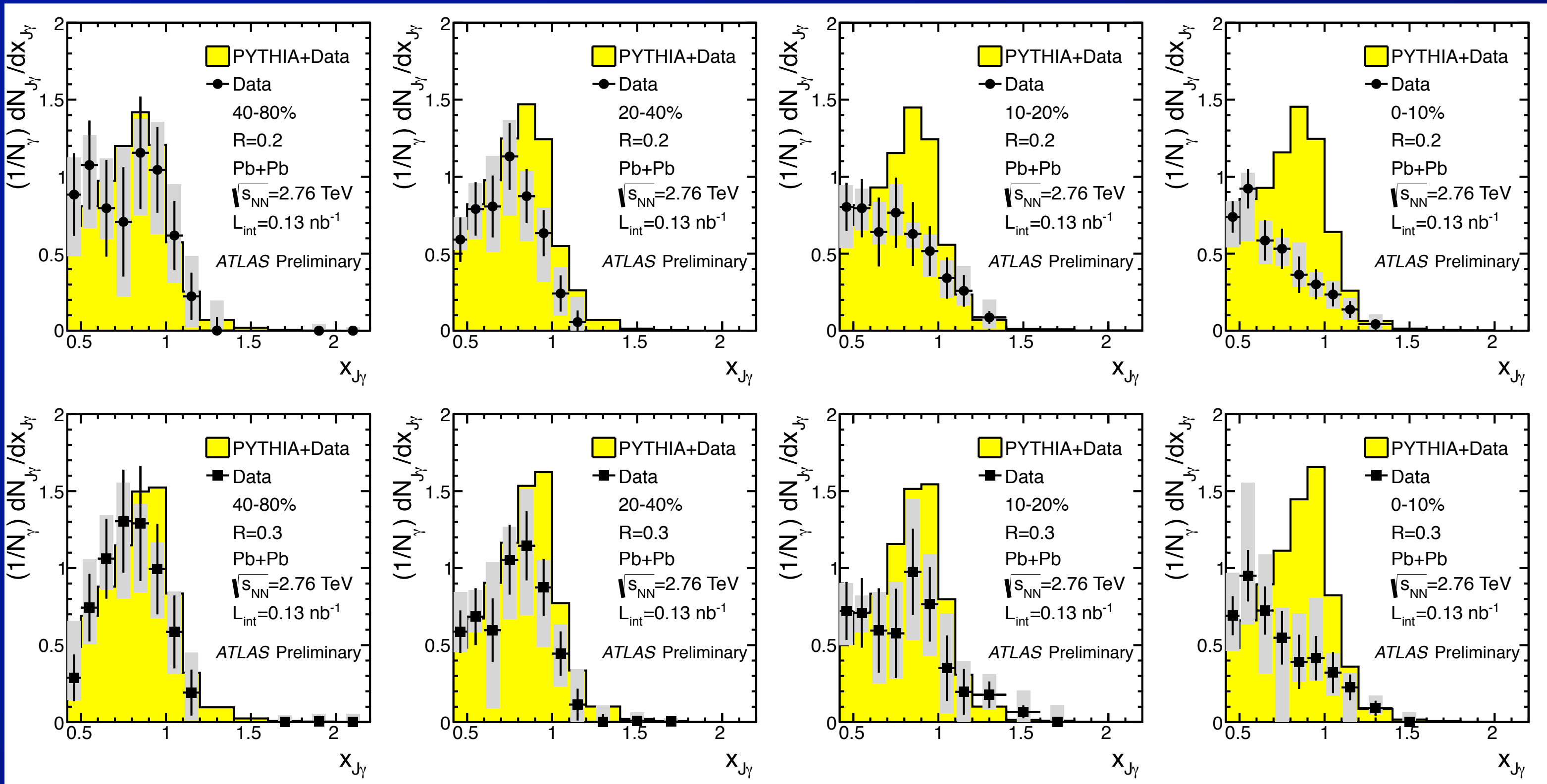
Note: Only one set of syst. uncertainties shown: Good agreement

Depletion from 3-4GeV to 40-50GeV (2-3% of total jet energy)

Enhancement below 3-4GeV (~ 2% of jet energy)

γ-jet momentum balance

Peripheral ⟶ central



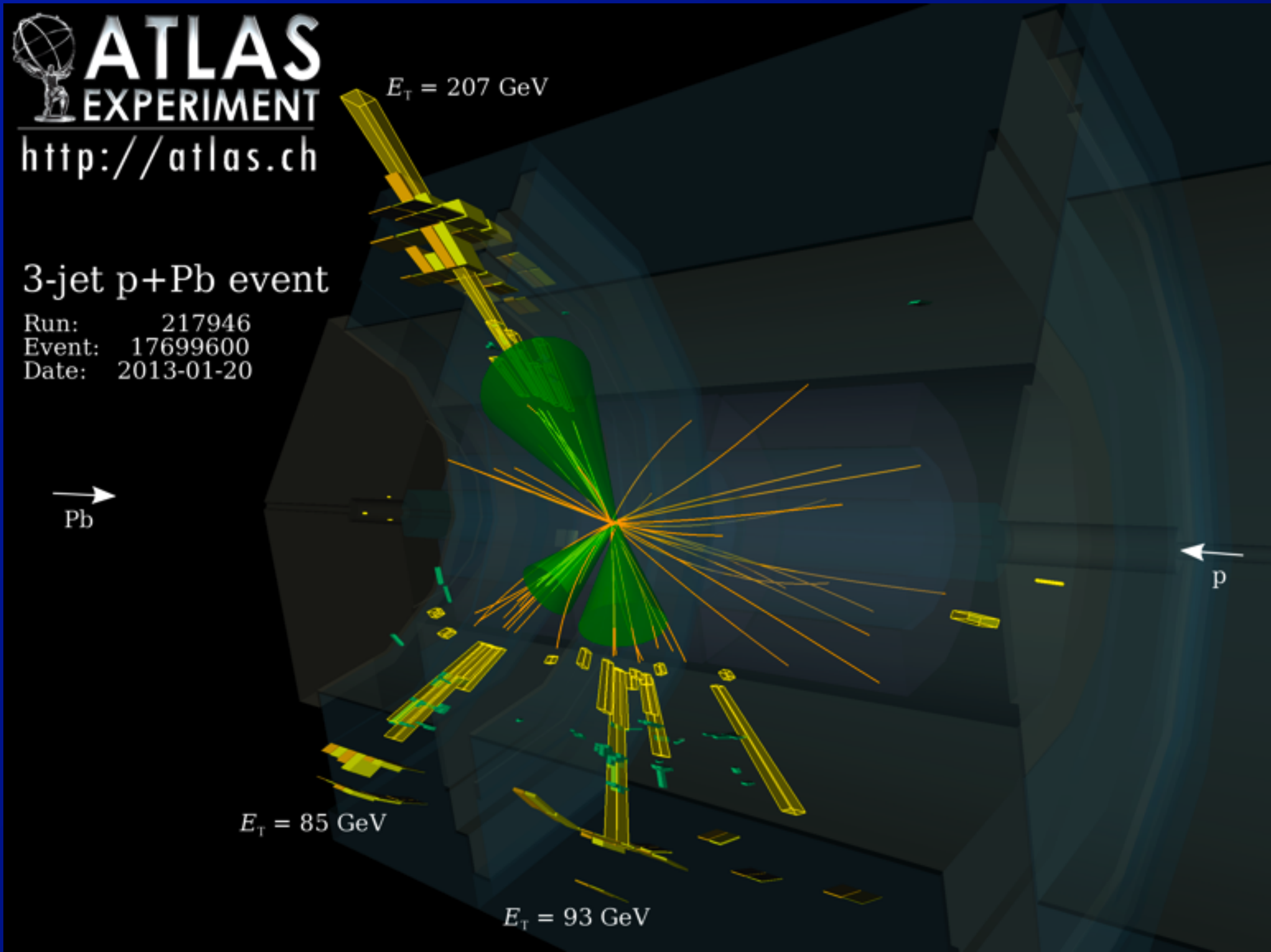
R = 0.2

R = 0.3

- Plot distribution of $x_J = p_T^{\text{jet}} / p_T^{\gamma}$
  - photon background pairs subtracted
  - unfolded for jet energy resolution

⇒Substantial change in γ-jet balance

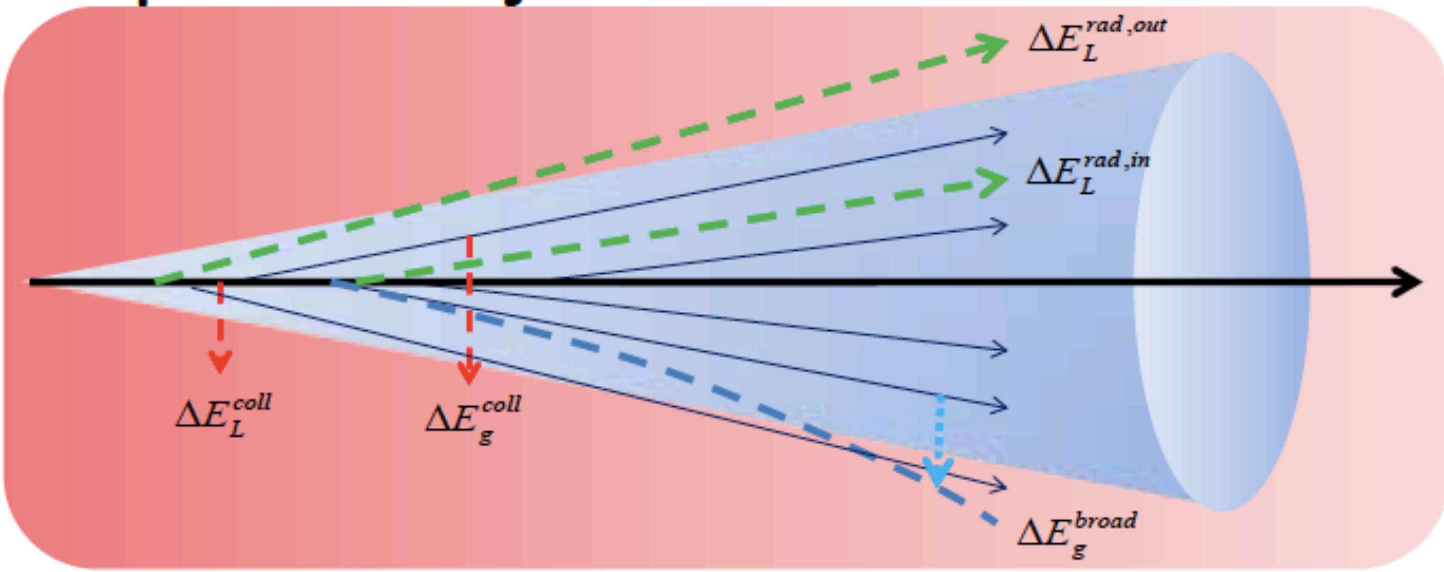
p+Pb @ LHC the next frontier



Summary, Perspectives

Quark stopping in QGP? No!

A partonic jet shower in medium



Leading parton:

Transfers energy to medium by elastic collisions

Radiates gluons due to scatterings in the medium (*inside* and *outside* jet cone)

Radiated gluons (*vacuum* & *medium-induced*):

Transfer energy to medium by elastic collisions

Be kicked out of the jet cone by multiple scatterings after emission

- Jet quenching not as simple as we originally imagined ...

Summary

- Long and venerable history in particle physics of studying “stopping” in strongly interacting “media”
  - Laying the groundwork for studying jet quenching in the quark gluon plasma

    ⇒ Still, a very complicated problem
  - We have left the wilderness

    ⇒ But we are not out of the woods yet

Apropos to this workshop

- My first interaction with Wit was in an 8.03 recitation in 1982.
  - Then 8.05 in 1983.
- We have interacted innumerable times over the many years in between.
  - $\Rightarrow$ And our paths have crossed continually
- p-A physics has been and will continue to be an important part of my career.

Thank you, Wit