Lecture 1:
Basics, hard scattering processes in nuclei

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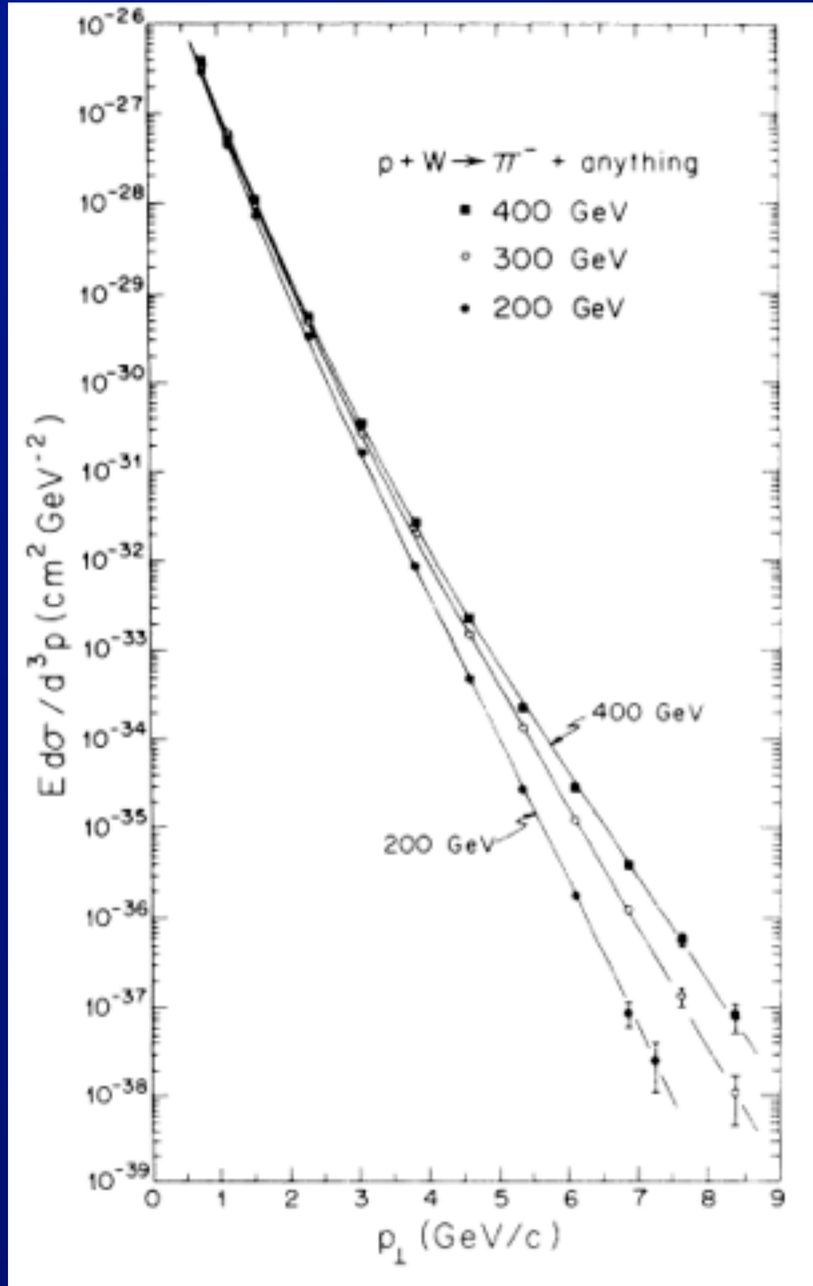
Cronin effect: a “case study”

An early measurement

Cronin *et al*,
Phys. Rev. D11 (1975) 3105

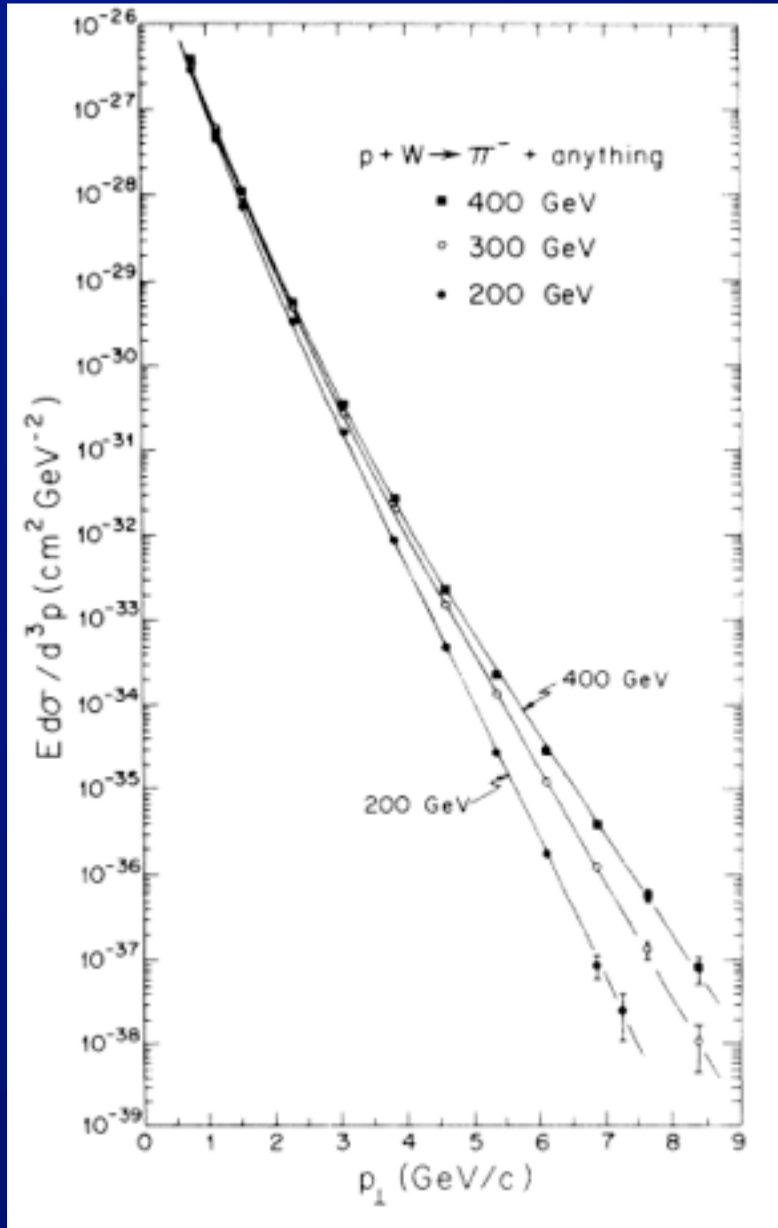
- Inclusive invariant cross-section for π^- production as a function of p_T
  - At 90° in center of mass
  - For three different fixed target collision energies
    - ⇒Clear variation in yield at high p_T with collision energy.



Some basics

- First, center of mass energies:
  - 200 Gev → $\sqrt{s} = 19.4\ \mathrm{GeV}$
  - 300 Gev → $\sqrt{s} = 23.7\ \mathrm{GeV}$
  - 400 Gev → $\sqrt{s} = 27.4\ \mathrm{GeV}$
- Kinematic limits:
  - At nucleon-nucleon level single particle p_T must satisfy $p_T < \sqrt{s}/2$

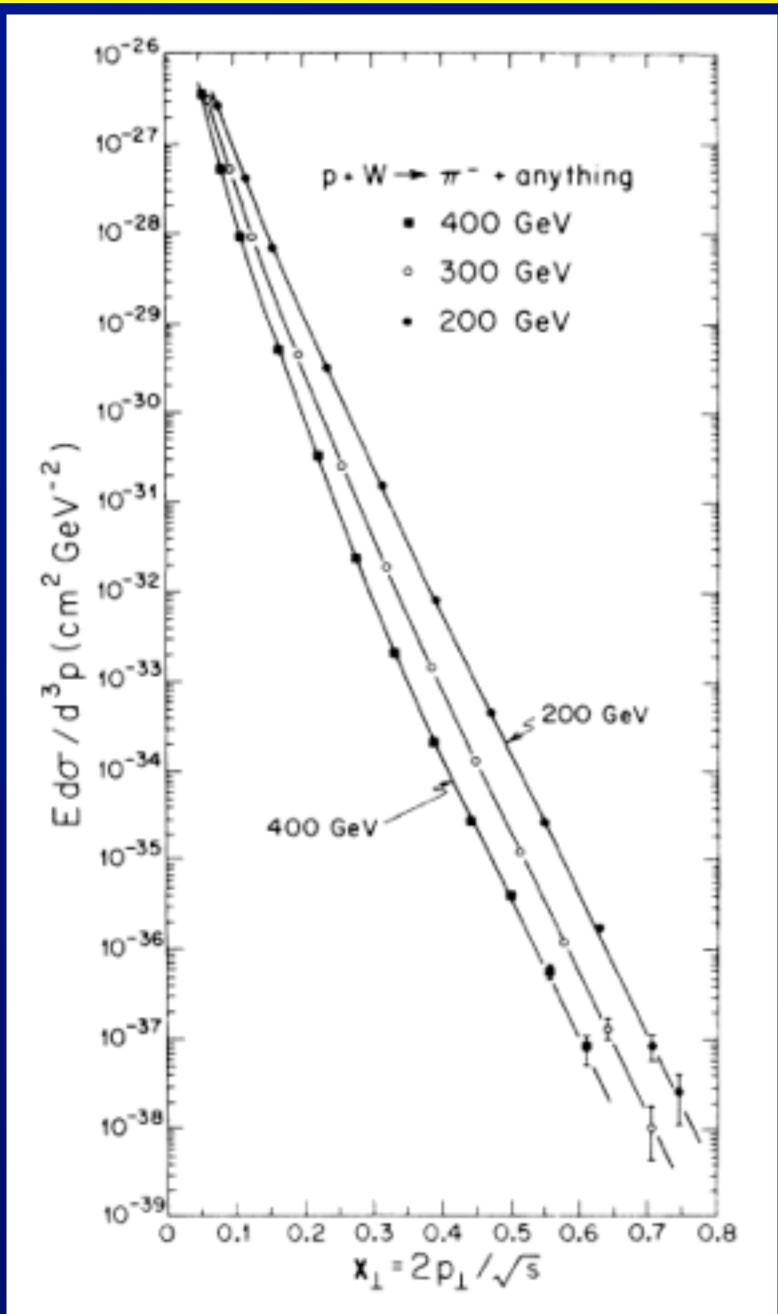
    $\Rightarrow$ 12.0, 13.9, 15.6 GeV
- Invariant cross-section
  - $E\, d^3p$ is Lorentz invariant



Early measurement: x_T

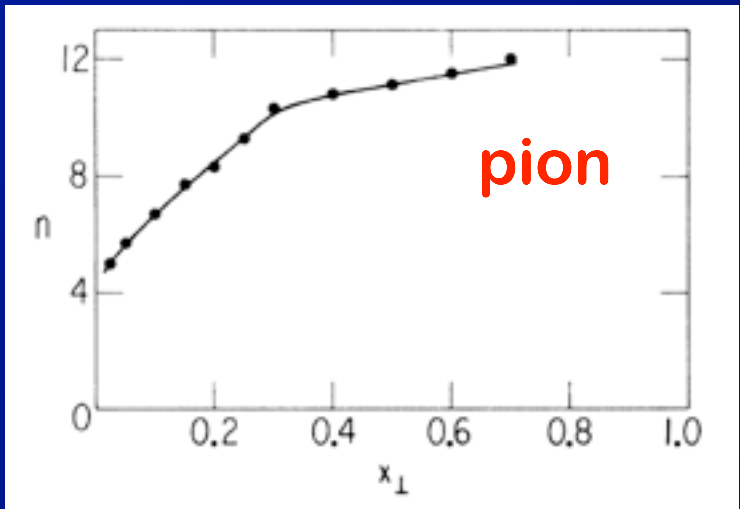
- Define a scaling variable:
  - $x_\perp = p_T/(\sqrt{s}/2)$
  - Measurements extend to significant fraction of kinematic limit.
- Shapes of x_T spectra between different energies are similar.
  - But have different normalization.

    ⇒Correct for $\sqrt{s}$ in $p_T \rightarrow x_\perp$ transformation

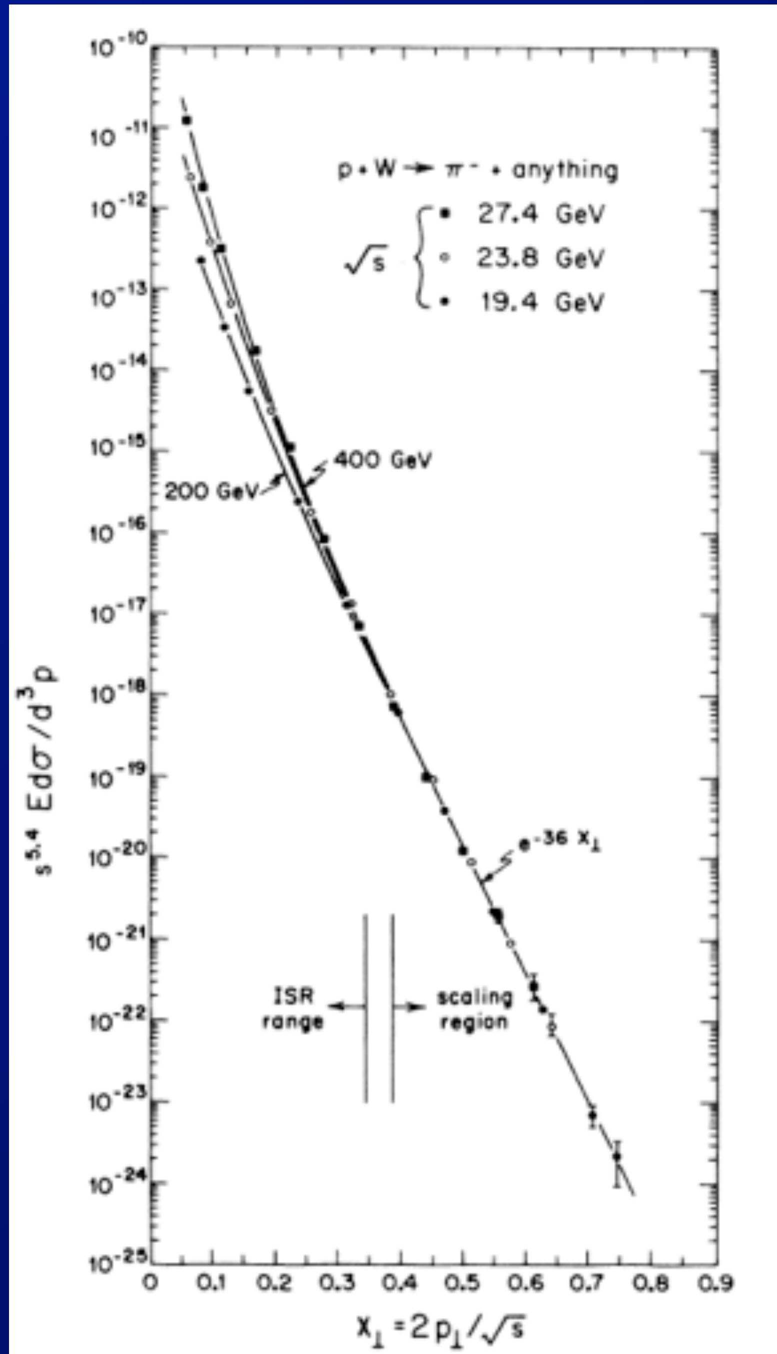


x_T scaling

- High-p_T invariant cross-sections have power-law shape:
  - $$E\frac{d^3\sigma}{dp^3} \propto \left(\frac{1}{p_T}\right)^n$$



- Then, under $p_T \rightarrow x_\perp$ pick up factor of $\left(\frac{1}{\sqrt{s}}\right)^n$



A dependence

- Cross-sections were observed to vary (inclusively) as A^{α}.

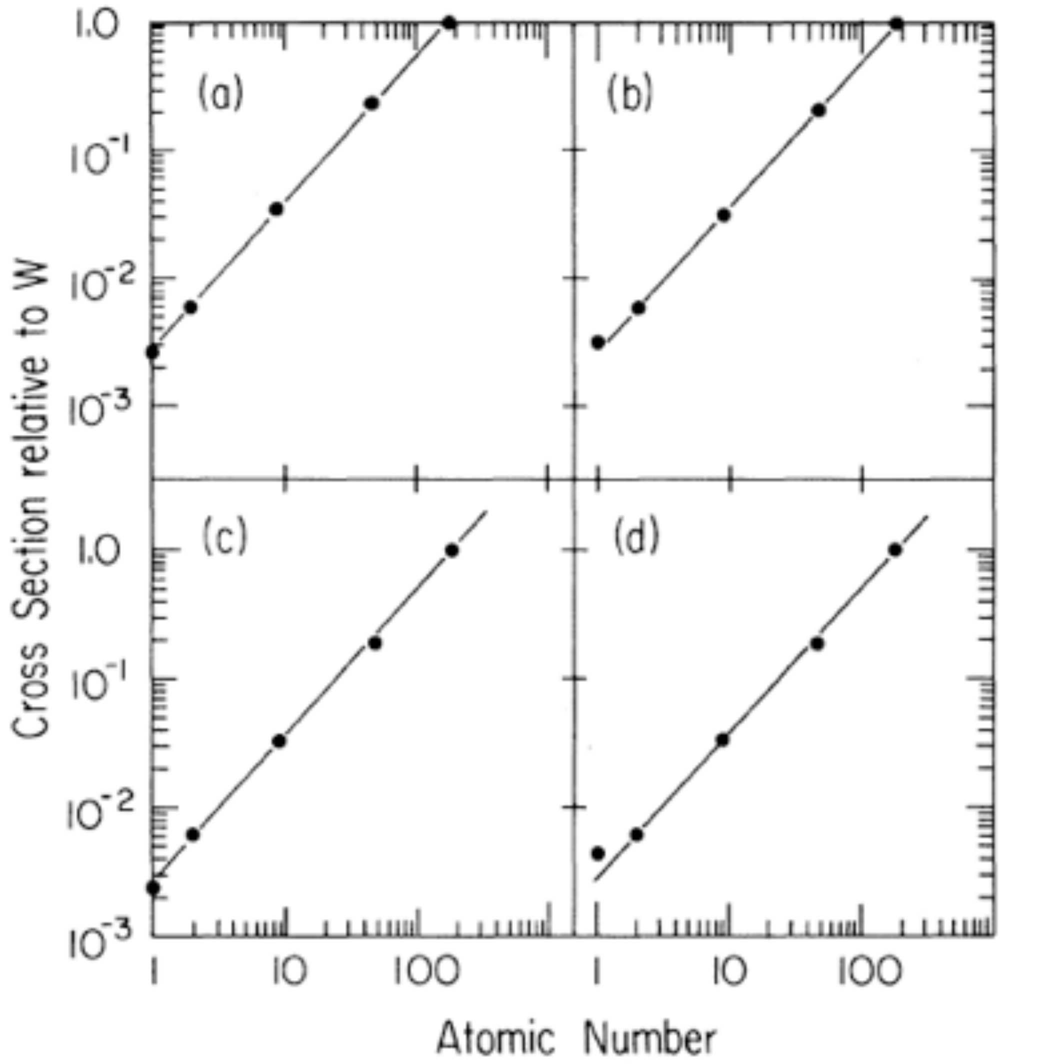
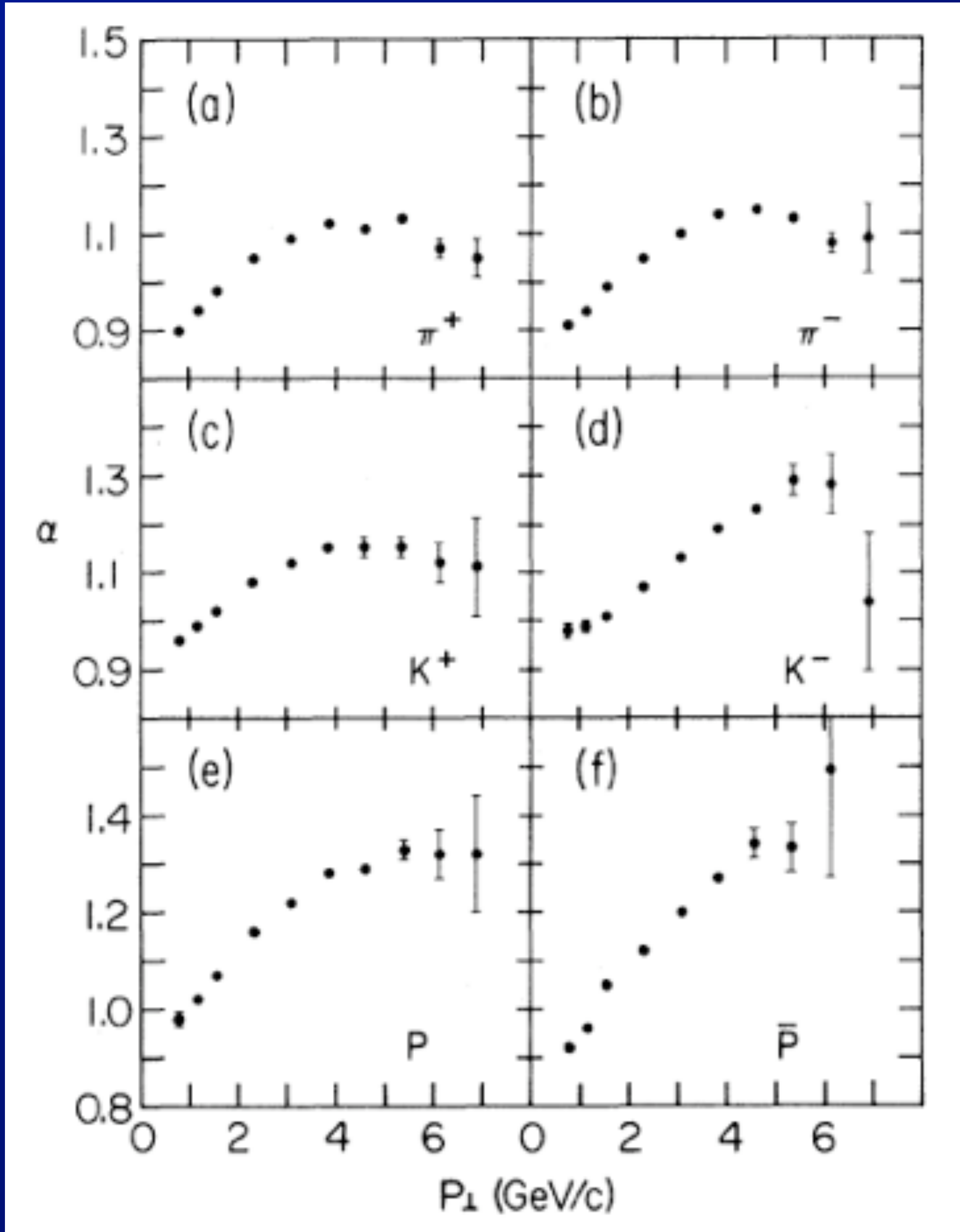


FIG. 1. The invariant cross section for π production relative to tungsten for various atomic numbers at 400 GeV; (a) π^- at $p_\perp = 3.85$ GeV/c, (b) π^+ at $p_\perp = 3.85$ GeV/c, (c) π^- at $p_\perp = 5.38$ GeV/c, (d) π^+ at $p_\perp = 5.38$ GeV/c.

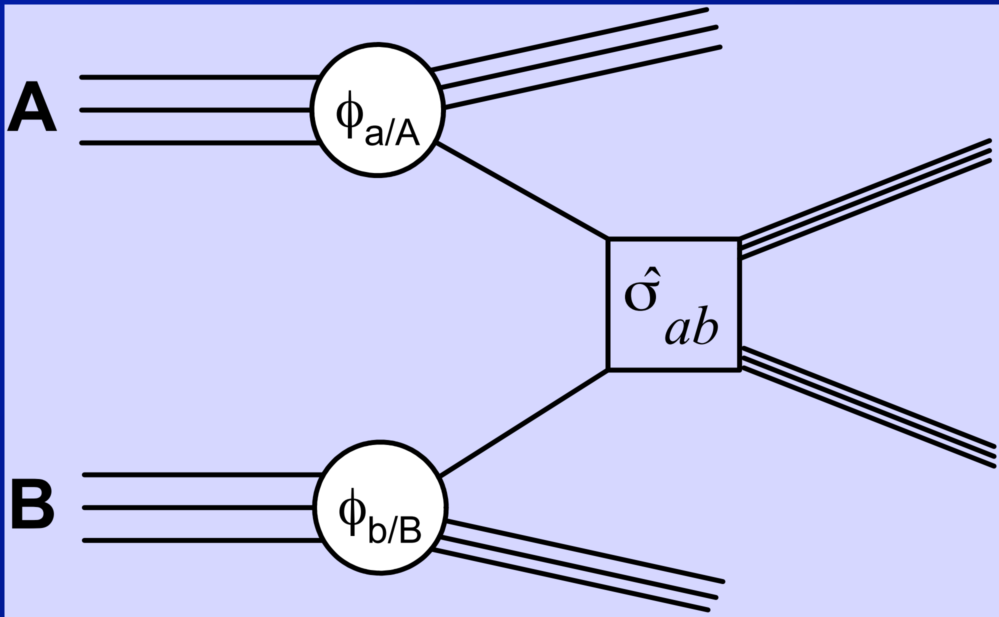
A dependence

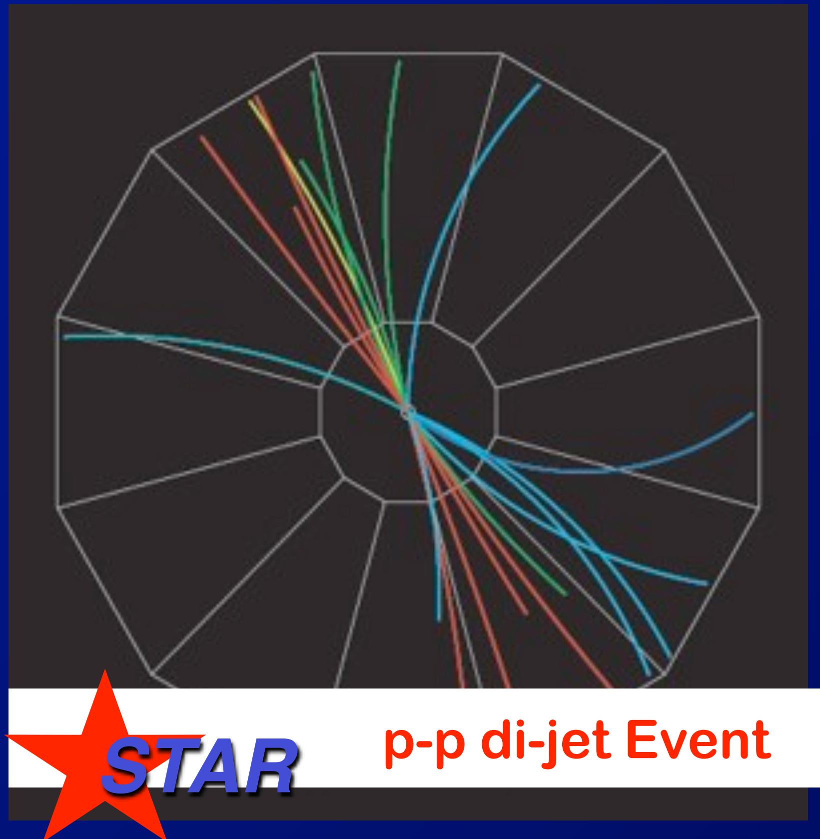
- Extracted values of $\alpha(p_T)$ for pions, kaons and protons.
  - $0.9 < \alpha(pT) < 1.1$ for pions
    - ⇒Surprise: $\alpha > 1$
    - ⇒Varies with particle type
- This is the well-known "Cronin effect"
    - ⇒Why?



Physics: pQCD, geometry

Hard Scattering in p-p Collisions



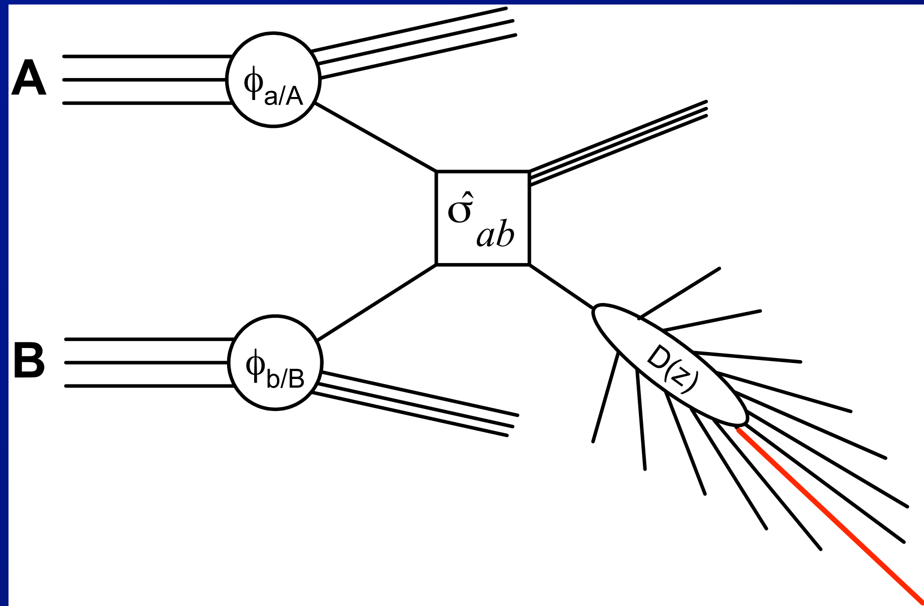


From **Collins, Soper, Sterman**
Phys. Lett. B438:184-192, 1998

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

- Factorization: separation of σ into
  - Short-distance physics: $\hat{\sigma}$
  - Long-distance physics: φ's (universal)

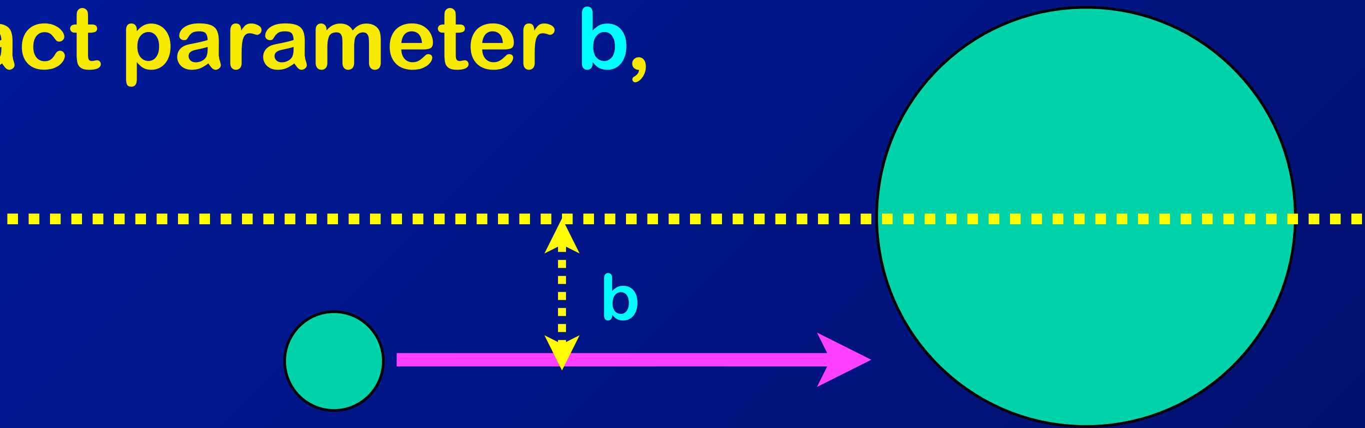
Single High-pt Hadron Production



- For single hadron production need fragmentation functions
  - Describe inclusive hadron longitudinal momentum distribution inside a jet
    - ⇒ $D_i^a(z)$ for parton *i* → hadron *a*
    - ⇒ z is fraction of parton/jet momentum carried by the hadron
- Fragmentation functions satisfy sum rule
  - $\sum_a \int_0^1 dz\, z D_i^a(z) = 1$

e/p-A: nuclear geometry

- Starting point, nuclear nucleon density distribution: $\rho(r)$
- Then, assuming straight-line trajectory at impact parameter b,



  – electron or proton passes through "thickness"

$$T(b) = \int_{-\infty}^{\infty} dz\, \rho(\sqrt{b^2 + z^2})$$

  – *T(b)* has dimensions $1/L^2$

  ⇒ *T(b)* x cross-section = number of scatterings

e/p-A: nuclear geometry

- Then, e.g. produce high-p_T hadrons in p-A collisions at rate/event:
  - $$E\,\frac{d^3 n^{pA(b)}}{dp^3} = T(b) \times E\,\frac{d^3\sigma^{pp}}{dp^3}$$
- With a corresponding differential cross-section per impact parameter:
  - $$E\,\frac{d\sigma^{pA}}{db\,d^3p} = 2\pi b\left(E\,\frac{d^3 n^{pA(b)}}{dp^3}\right) = 2\pi b\left(T(b) \times E\,\frac{d^3\sigma^{pp}}{dp^3}\right)$$
- Integrate over b:
  - $$E\,\frac{d\sigma^{pA}}{d^3p} = \int db\; 2\pi b T(b) \;\times E\,\frac{d^3\sigma^{pp}}{dp^3}$$

e/p-A: nuclear geometry

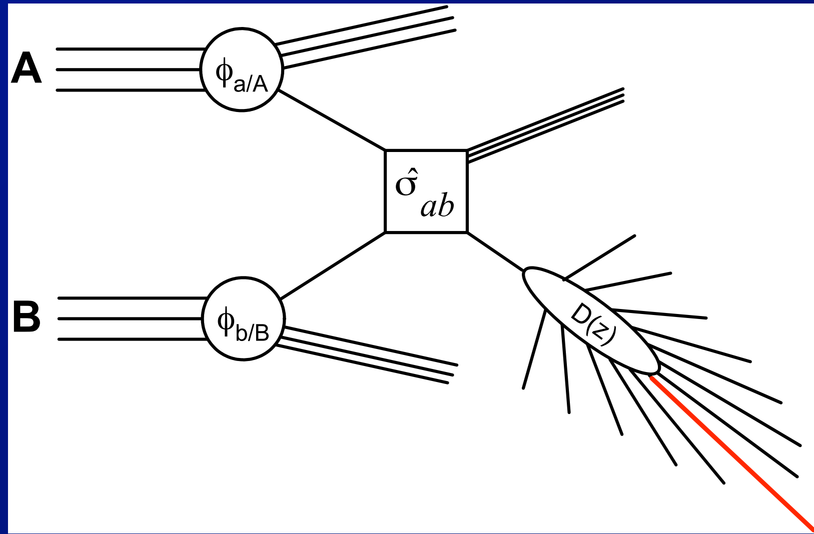
- But,
  - $\int db\, 2\pi b T(b) = \int db dz\, 2\pi b \rho(\sqrt{b^2+z^2}) = \int d^3 r \rho(r) = A$
- So,
  - $E\frac{d\sigma^{pA}}{d^3p} = A \times E\,\frac{d^3\sigma^{pp}}{dp^3}$
- You'll sometimes here that this result depends on small p-p cross-section

  ⇒complete nonsense!
- In principle, can have a total hard scattering rate/event $n^{pA(b)} = T(b)\sigma^{pp}$ that is > ~ 1

  ⇒especially in p+Pb @ LHC

e/p-A: nuclear geometry

- So what assumptions did we make in:



$$E\,\frac{d^3 n^{pA(b)}}{dp^3} = T(b) \times E\,\frac{d^3\sigma^{pp}}{dp^3}$$

- That *ϕ's*, *D's* are the same when colliding with proton and nucleus
- That *ϕ's*, *D's* are the same everywhere along the path (z) of the proton through the nucleus.
  - ⇒Universality
- That multiple hard scatterings are incoherent
- That the hard scattering occurs over a small transverse distance.
- That *T(b)* is constant over transverse size of p

Factorization (crudely)

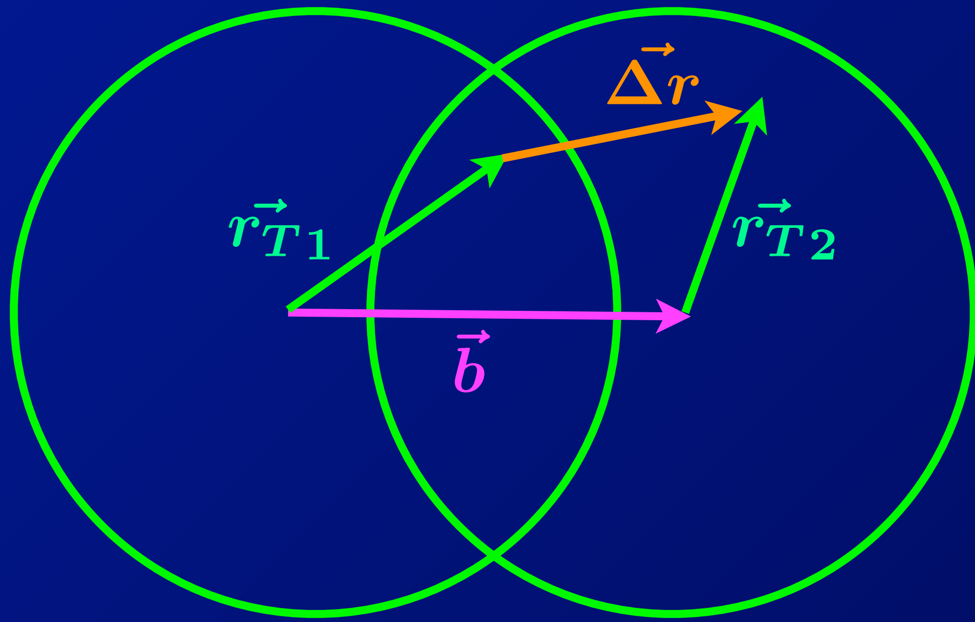
- Why is there no knowledge of the finite (transverse) size of the proton in

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

- Suppose we consider some spatial distribution of partons in proton: $\eta(z, r_T)$
  - longitudinal physics complicated but it's the transverse part of the problem that matters
- Define proton thickness
  - $t(r_T) = \int_{-\infty}^{\infty} dz \, \eta(\sqrt{r_T^2 + z^2})$
- Consider proton-proton collision in transverse plane.

Factorization (crudely)

- Consider two partons at transverse positions relative to proton centers of $\vec{r_{T1}}$ and $\vec{r_{T2}}$



- Separated by a distance $\vec{\Delta r}$

$$\vec{\Delta r} = \vec{b} + \vec{r_{T2}} - \vec{r_{T1}}$$

- Write differential cross-section for scattering between the two partons
  - $d^2\sigma / d\vec{\Delta r}^{\,2}$

- Then, $\sigma^{pp}_{hard} = \int d^2b \int d^2r_{T1} \int d^2r_{T2}\, t(r_{T1}) t(r_{T2}) \dfrac{d^2\sigma}{d\vec{\Delta r}^{\,2}}$

Factorization (crudely)

- But, large momentum transfer scattering occurs over small transverse distance

  $$\Rightarrow \frac{d^2\sigma}{d\vec{\Delta r}^2} \propto \delta^2(\vec{\Delta r})$$

- Then,
  - $\sigma_{hard}^{pp} \to \int d^2 r_{T1} \int d^2 r_{T2}\, t(r_{T1}) t(r_{T2}) \to n_1 \times n_2$
  - Of course neglects all QM, kinematics, etc

    $\Rightarrow$ But gets the essence of the transverse physics right.

- So, what happens in p+A collisions?
  - In principle, replace: $\eta(z, \vec{r_{T2}}) \to \eta_A(z, \vec{r_{T2}})$

    $t(\vec{r_{T2}}) \to t_A(\vec{r_{T2}})$

Factorization (crudely)

- But, write in terms of convolution of nucleon parton density and nuclear density function:

$$\eta_A(z, \vec{r_T}) = \int dz_A \int d^2 r_{T\,A}\, \rho(z_A, \vec{r_T}_A)\, \eta(z - z_A, r_T - r_{T\,A})$$

$$t_A(z, \vec{r_T}) = \int d^2 r_T{}'\, T(\vec{r_T} - \vec{r_T}')\, t(\vec{r_T}')$$

- Now write the p+A hard scattering probability at an impact parameter b

$$P_{hard}(b) = \int d^2 r_{T1} \int d^2 r_{T2} \int d^2 r_{T\,A}\, t(\vec{r_T}_1) T(\vec{r_T}_A) t(\vec{r_T}_2 - \vec{r_T}_A) \frac{d^2\sigma}{d\vec{\Delta r}^2}$$

- If everything works as above this should reduce to $\sigma_{pp}^{hard}\, T(b)$

Factorization (crudely)

- **Put in the delta function**

$$P_{hard}(b) = \int d^2 r_{T1} \int d^2 r_{T2} \int d^2 r_T{}' \, t(\vec{r}_{T1}) T(\vec{r}_{T2} - \vec{r}_T{}') t(\vec{r}_T{}') \frac{d^2\sigma}{d\vec{\Delta r}^2}$$

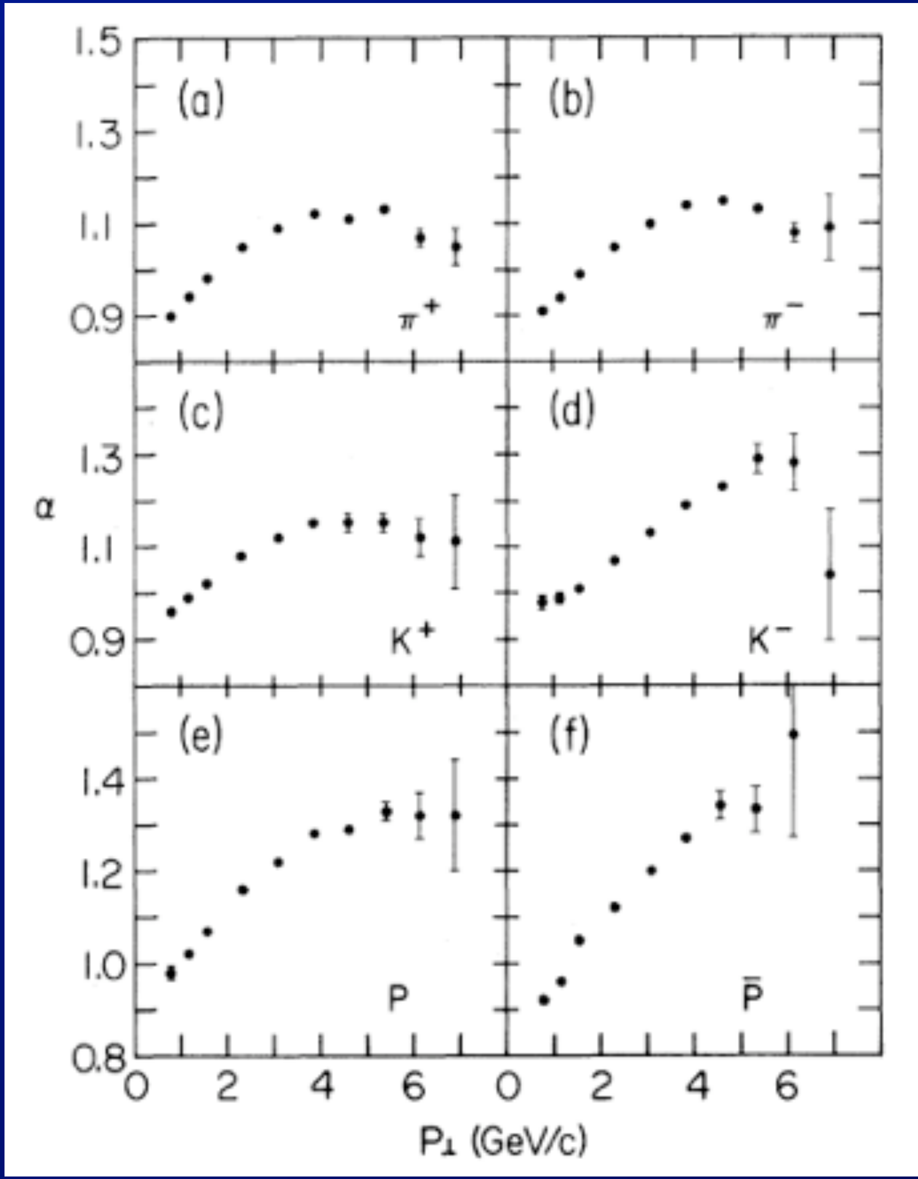
$$P_{hard}(b) = \int d^2 r_{T1} \int d^2 r_T{}' \, T(\vec{r}_{T1} - \vec{r}_T{}' - \vec{b}) t(\vec{r}_{T1}) t(\vec{r}_T{}')$$

  – No simple reduction.

- **But, the ranges of $\vec{r}_{T1}$ and $\vec{r}_T{}'$ over which $t(\vec{r}_{T1})$ and $t(\vec{r}_T{}')$ are finite are small (< 1 fm).**
  – we are sampling nuclear thickness over a small region around $\vec{b}$
- **If T is $\approx$ constant over that region:**
  – $P_{hard}(b) \approx T(b) \int d^2 r_{T1} \int d^2 r_T{}' \, t(\vec{r}_{T1}) t(\vec{r}_T{}') \rightarrow T(b)\sigma_{hard}$

Go back to Cronin

- So hard scattering rates in p+A varying as A^1 make sense.
  - What about < 1?
  - What about > 1?
  - Why particle species dependent?



Why $\alpha < 1$ @ low p_T ?

Cronin *et al*,
Phys. Rev. D 29,
2476–2482 (1984)

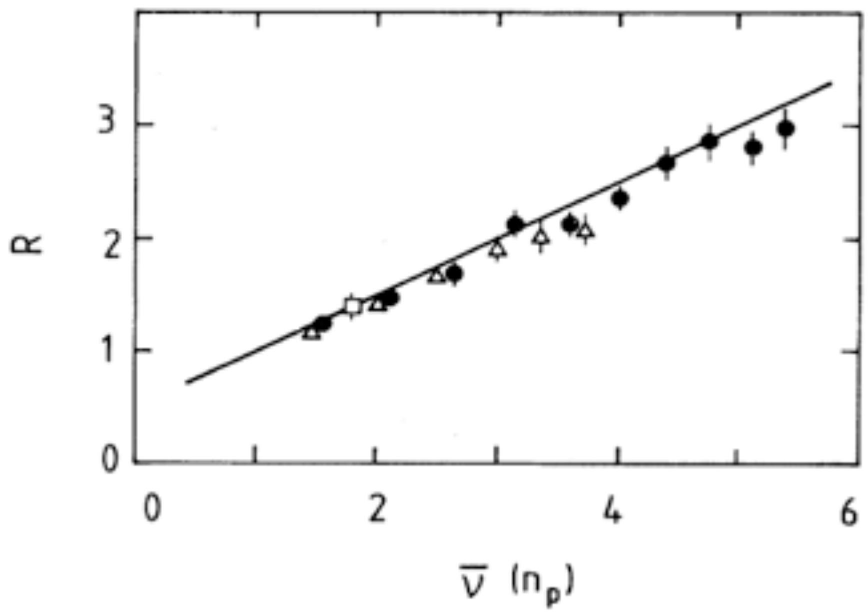


FIG. 4. The ratio $R = \langle n \rangle_{pA} / \langle n \rangle_{pp}$ versus the average number $\overline{\nu}(n_p)$ of projectile collisions for pXe (circles), pAr (triangles), and pNe (squares) collisions. A line of the form $R = 0.5[\overline{\nu}(n_p) + 1]$ is shown for comparison.

- **Soft particle production does not grow proportional to number of soft N-N scatterings, $\nu = \sigma_{inel}\, T(b)$**
  - ⇒**Instead varies like number of wounded nucleons (participants), $N_w = \frac{1}{2}(1 + \nu)$**

Why $\alpha < 1$ @ low p_T ?

- If we integrate over impact parameter the contribution from the "1" is proportional to the total p+A inelastic cross-section

  $\Rightarrow A^{2/3}$

- While the contribution proportional to ν varies like A^1

  ⇒ So the soft production varies with A at a power between 2/3 and 1.

- Strictly, pure wounded-nucleon scaling only applies for total multiplicities
  - Depending on kinematic region covered soft A dependence can be closer to 2/3 or 1.

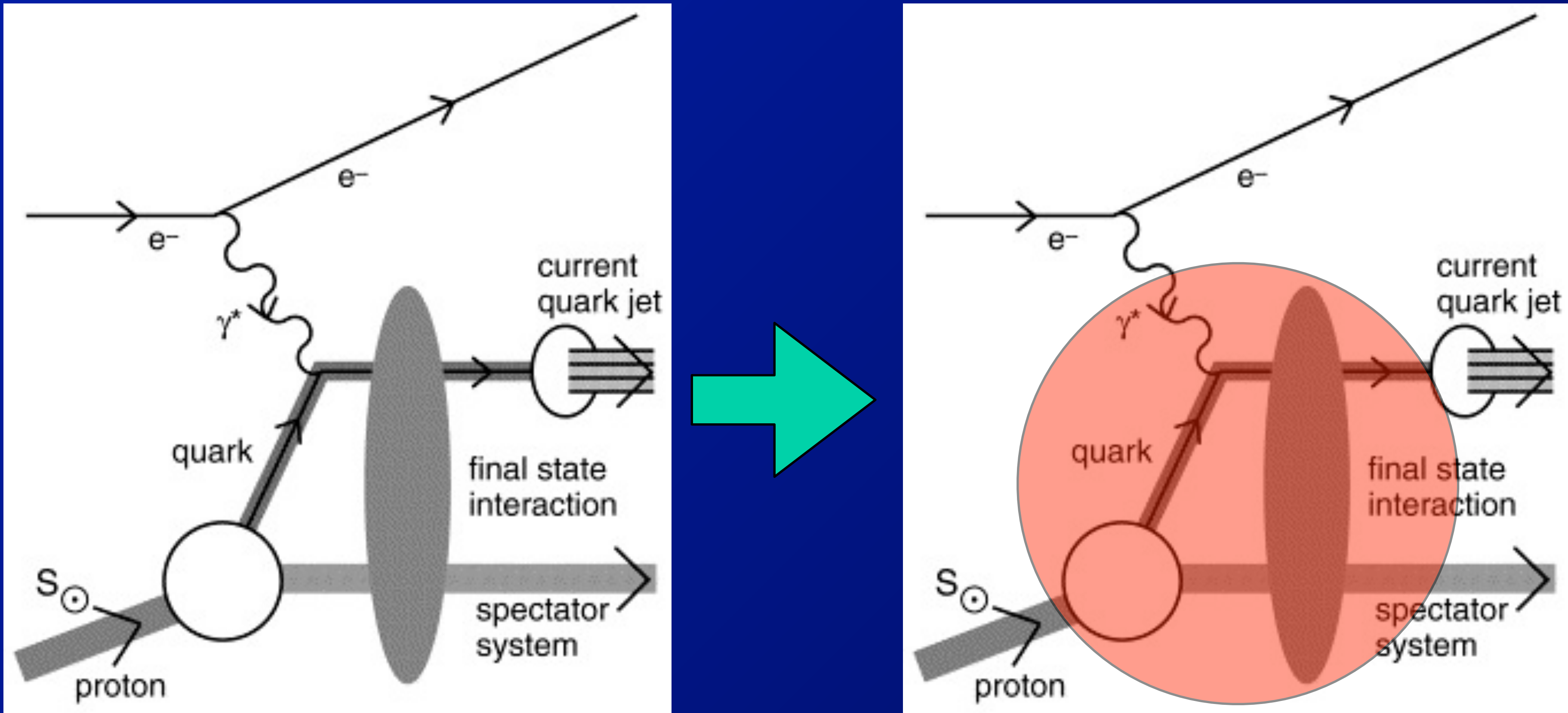
  ⇒ Beware, $\alpha \neq R_{pPb}$

Why α > 1 @ high p_T ?

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

- The α > 1 results from higher twist terms
  - ⇒involve additional soft (<< Q^2) exchanges between ingoing/outgoing parton of hard scattering and other partons from target
- In case of Cronin effect:
  - Usual explanation is soft multiple scatterings of ingoing and outgoing partons
    - ⇒broadens the p_T distribution
  - fragmentation no longer universal!
    - ⇒hadron species dependence
    - ⇒Poorly understood

Quarks fragmenting in nuclei

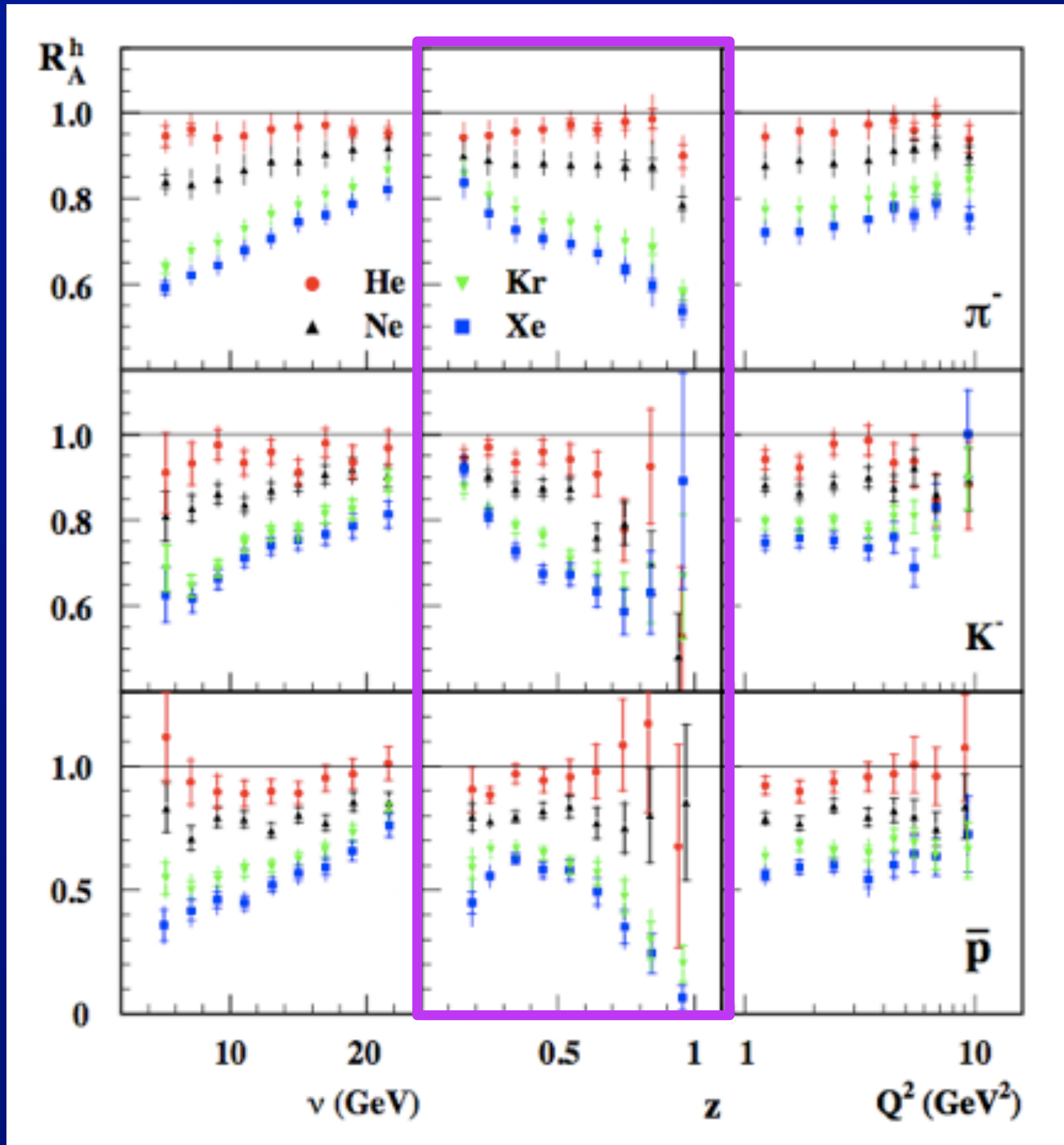


- Study the fragmentation of quarks (?) in nucleus using semi-inclusive deep inelastic scattering

"Stopping" quarks in nuclei

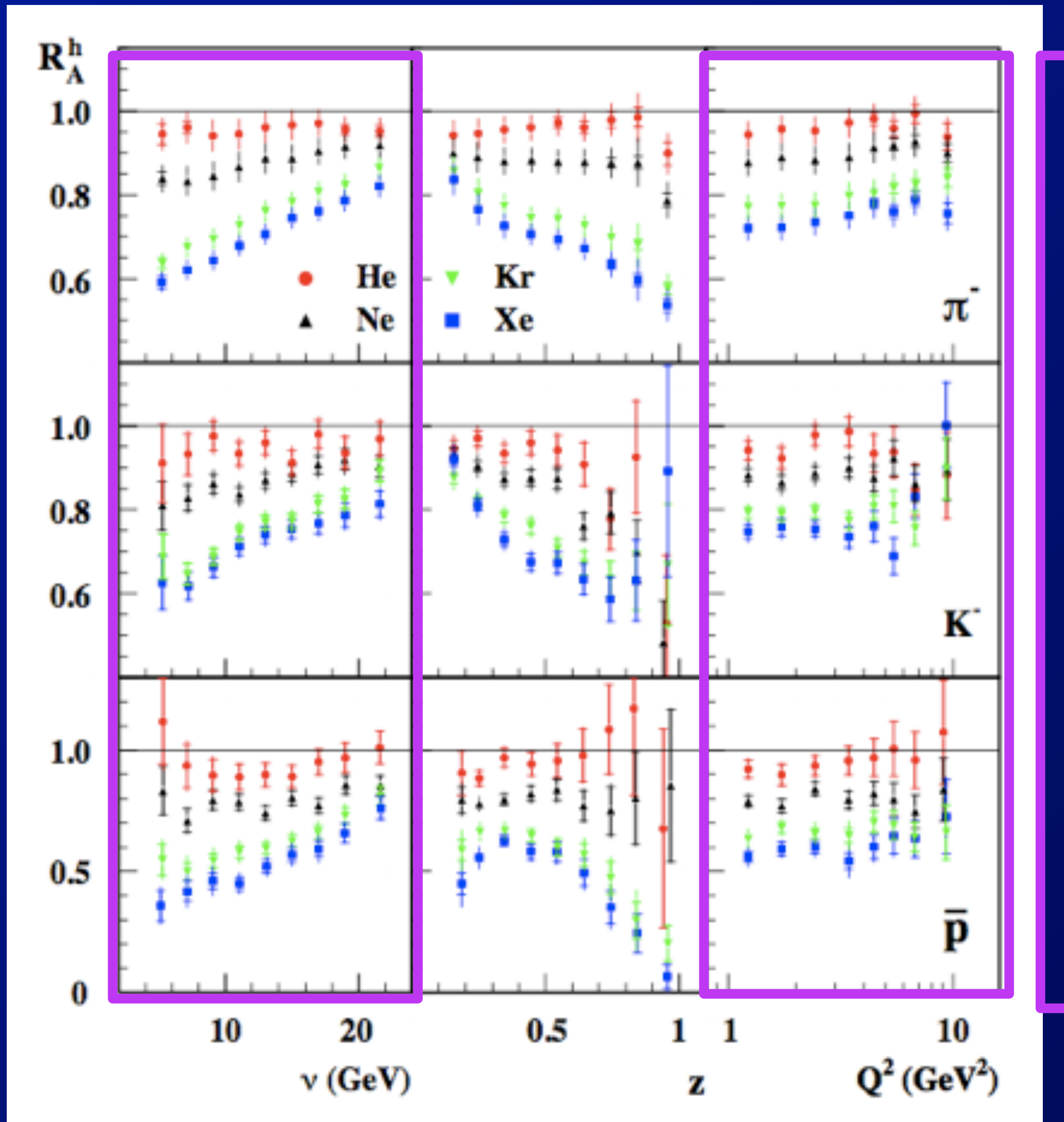
- z = fraction of quark energy (ν) carried by hadron
- Ratio of yields relative to those on deuterium

  ⇒ A and flavor dependent reduction in yield of high-z hadrons



"Stopping" quarks in nuclei

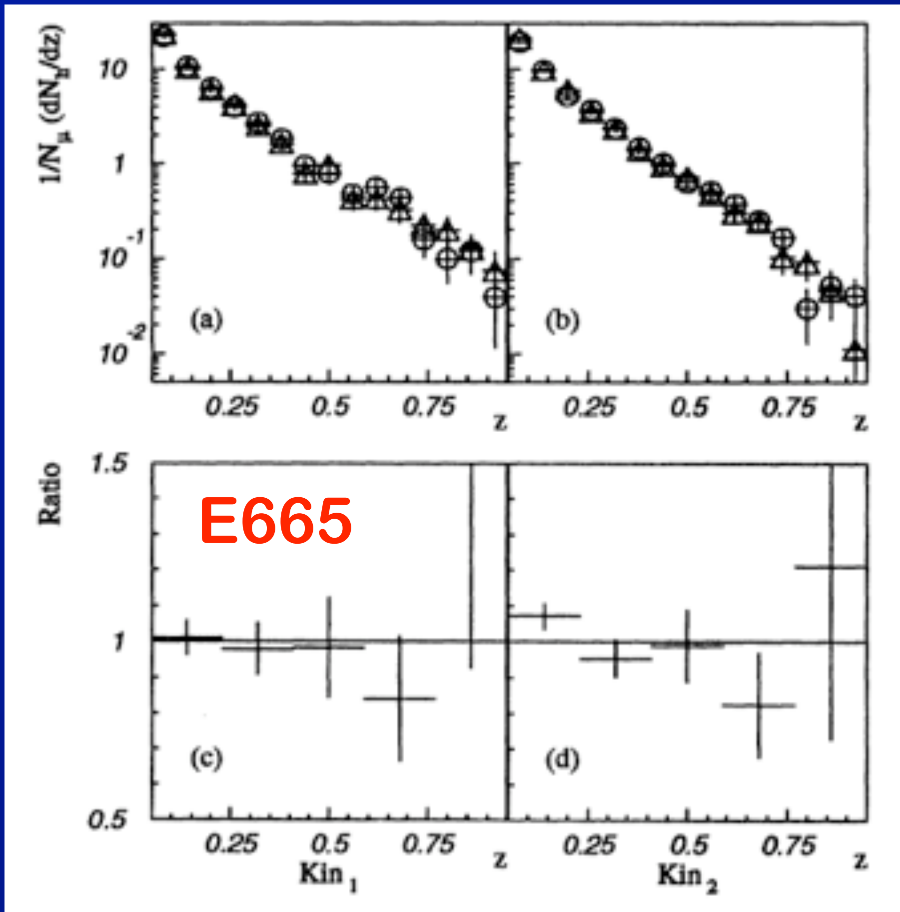
- Weak Q^2 dependence
- "Stopping" decreases with increasing quark energy.

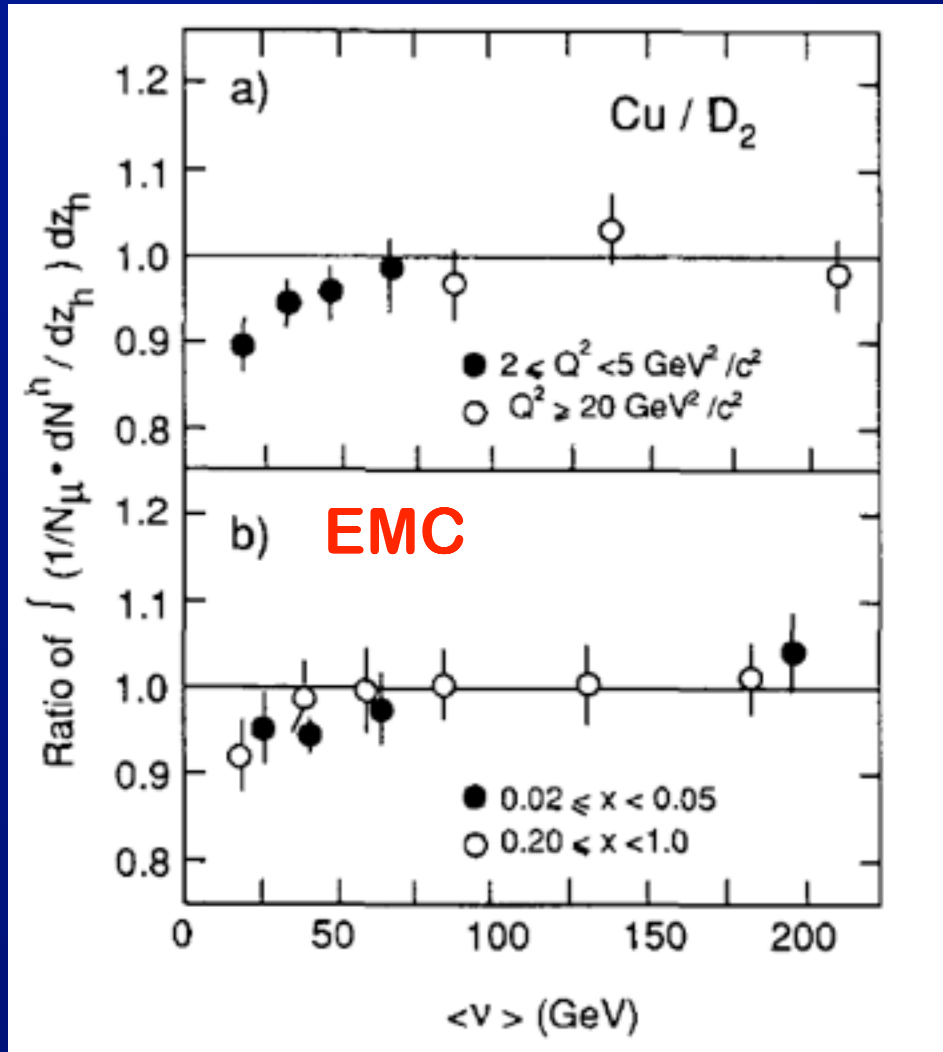


"Stopping" quarks in nuclei

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

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





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

"Cold nucleus" energy loss

- Existing data suggest that cold nucleus energy loss is small for quark energies greater than ~ 100 GeV.
  - Better data needed → EIC.
- Consider effects in d/p+A at RHIC, LHC.
  - mid-rapidity jets with transverse mass $m_T = \sqrt{p_T^2 + m^2}$
  - Have energies in the nuclear rest frame given by $E = m_T \cosh \Delta y$
  - With Δy the rapidity difference between the jet and the nucleus.
- For RHIC @ mid-rapidity, $E = m_T \times 106$

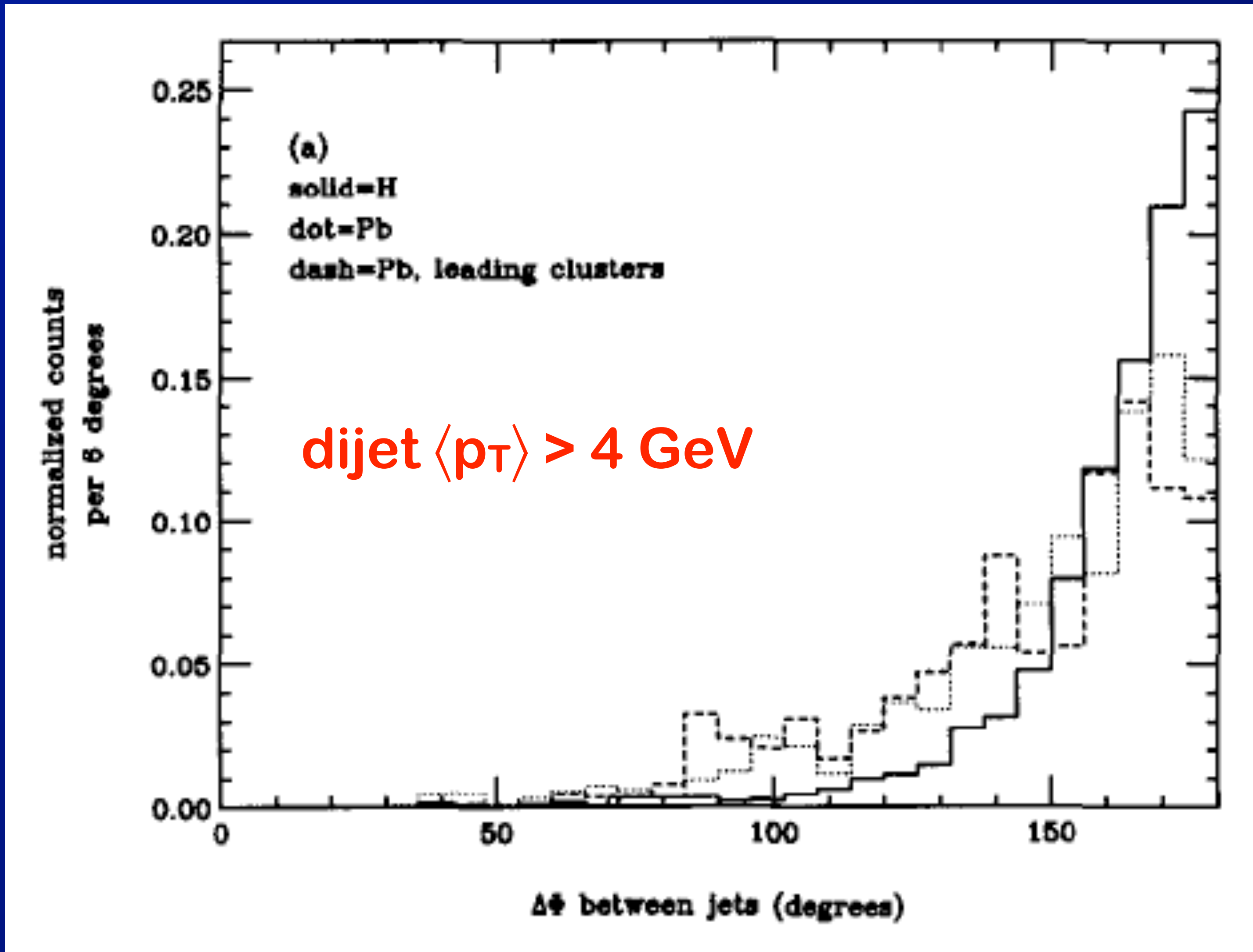
  ⇒ weak cold nucleus energy loss

  ⇒ even less @ LHC except maybe at large y.

Jets in p+A @ fixed-target energies

E609, Corcoran *et al*, PLB 259 (1991) 209

400 GeV
(fixed target)
p+p and p+Pb

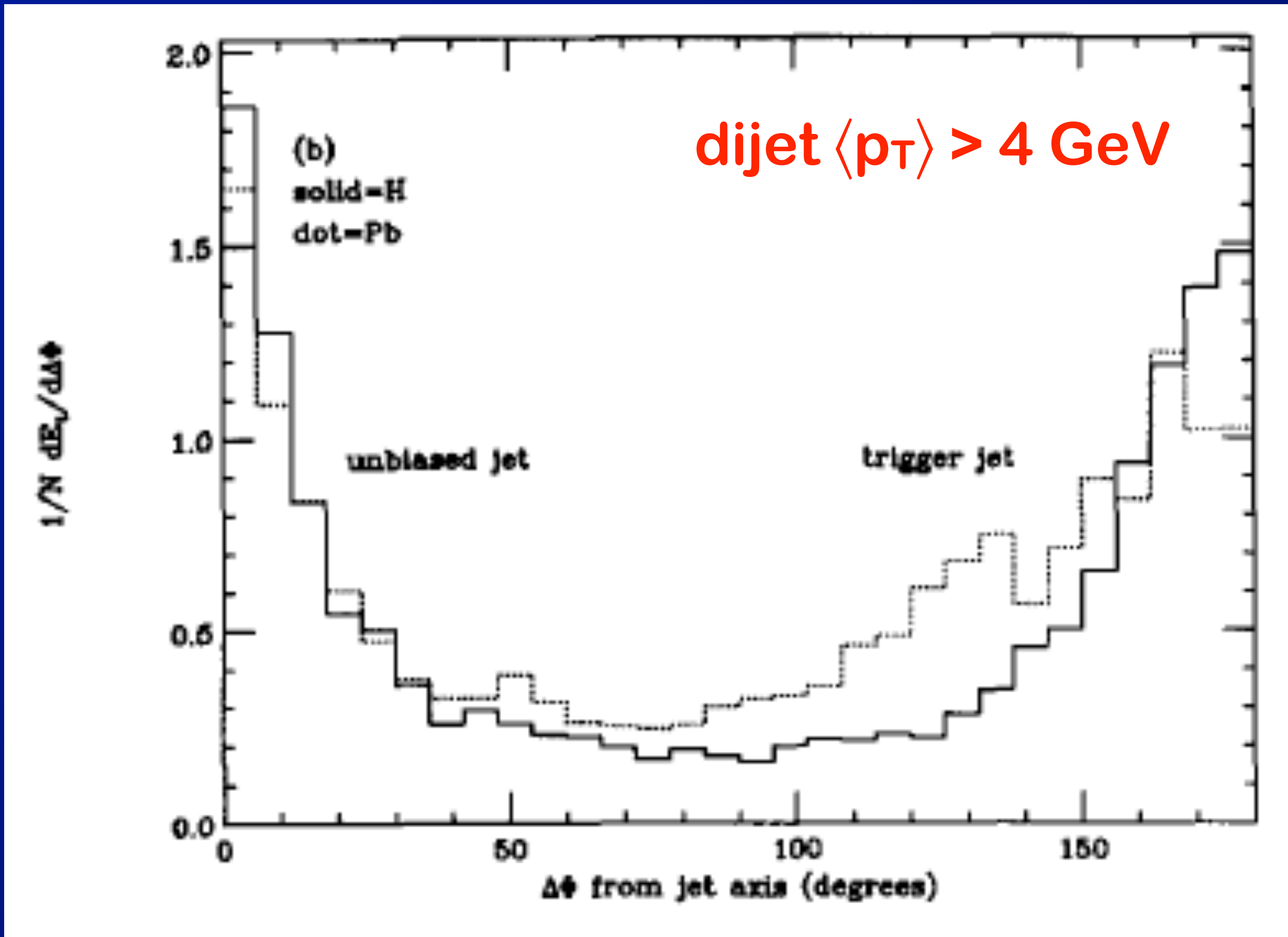


- Broadening of the dijet Δφ distribution

Jets in p+A @ fixed-target energies

E609, Corcoran *et al*, PLB 259 (1991) 209

400 GeV
(fixed target)
p+p and p+Pb



- Similar results with calorimetric energy flow instead of jets.

Jets in p+A @ fixed-target energies

E557, Stewart *et al,* Phys. Rev. D 42, 1385–1395 (1990)

800 GeV (fixed target) p+p, Be, C, Cu, and Pb

Single jets

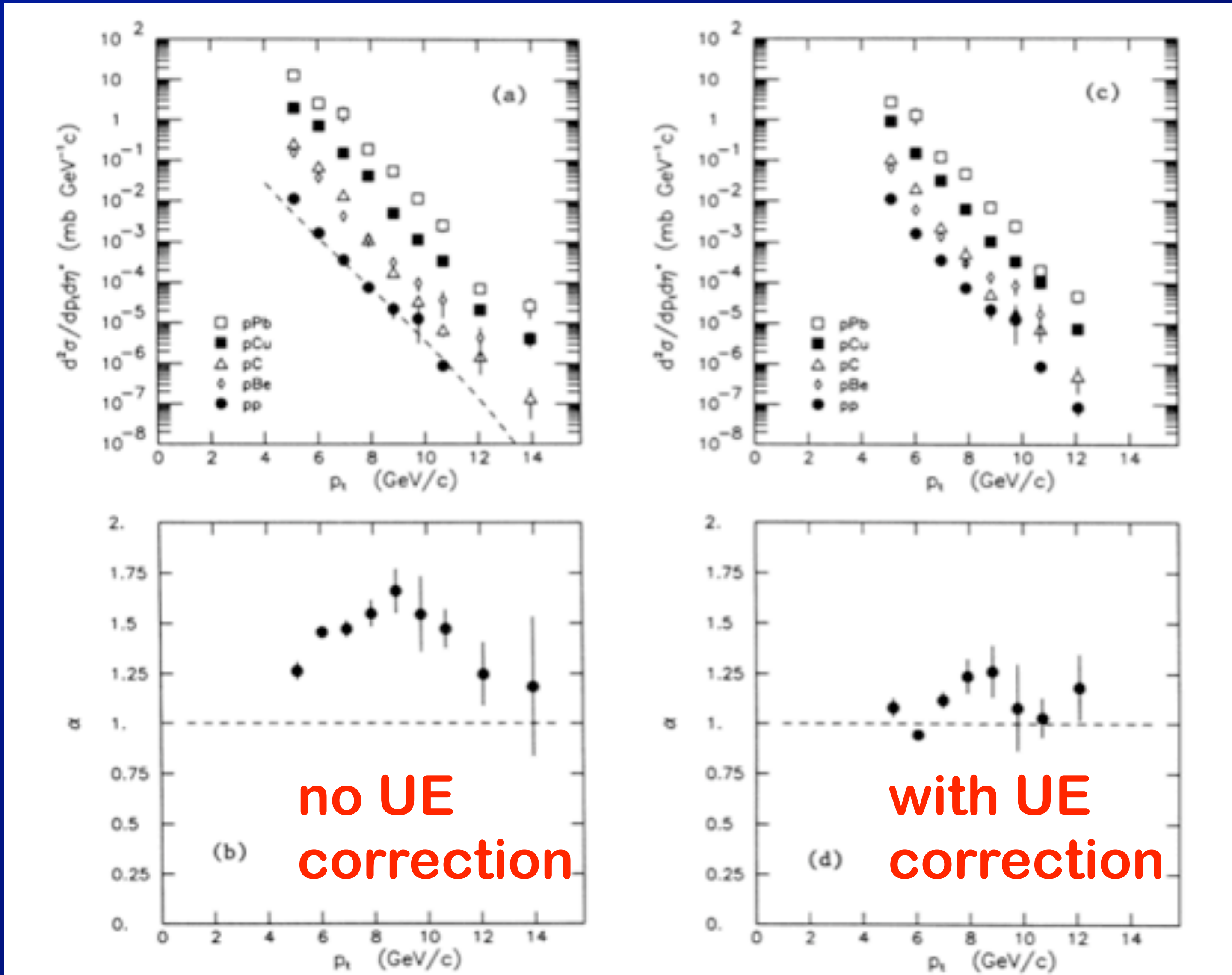


FIG. 7. (a) Dependence of $d^2\sigma/dp_t d\eta^*$ on jet p_t for pA interactions at 800 GeV/c. The dashed line represents the c.m. energy-dependent parametrization of jet cross sections for the pp interactions.[6] (b) α vs p_t. (c) and (d) Same as (a) and (b) after correction for the underlying event (see text) was applied to the heavier nuclei data.

Jets in p+A @ fixed-target energies

E557, Stewart *et al*, Phys. Rev. D 42, 1385–1395 (1990)

800 GeV (fixed target) p+p, Be, C, Cu, and Pb

dijets (Ejj is scalar sum of dijet E_T's)

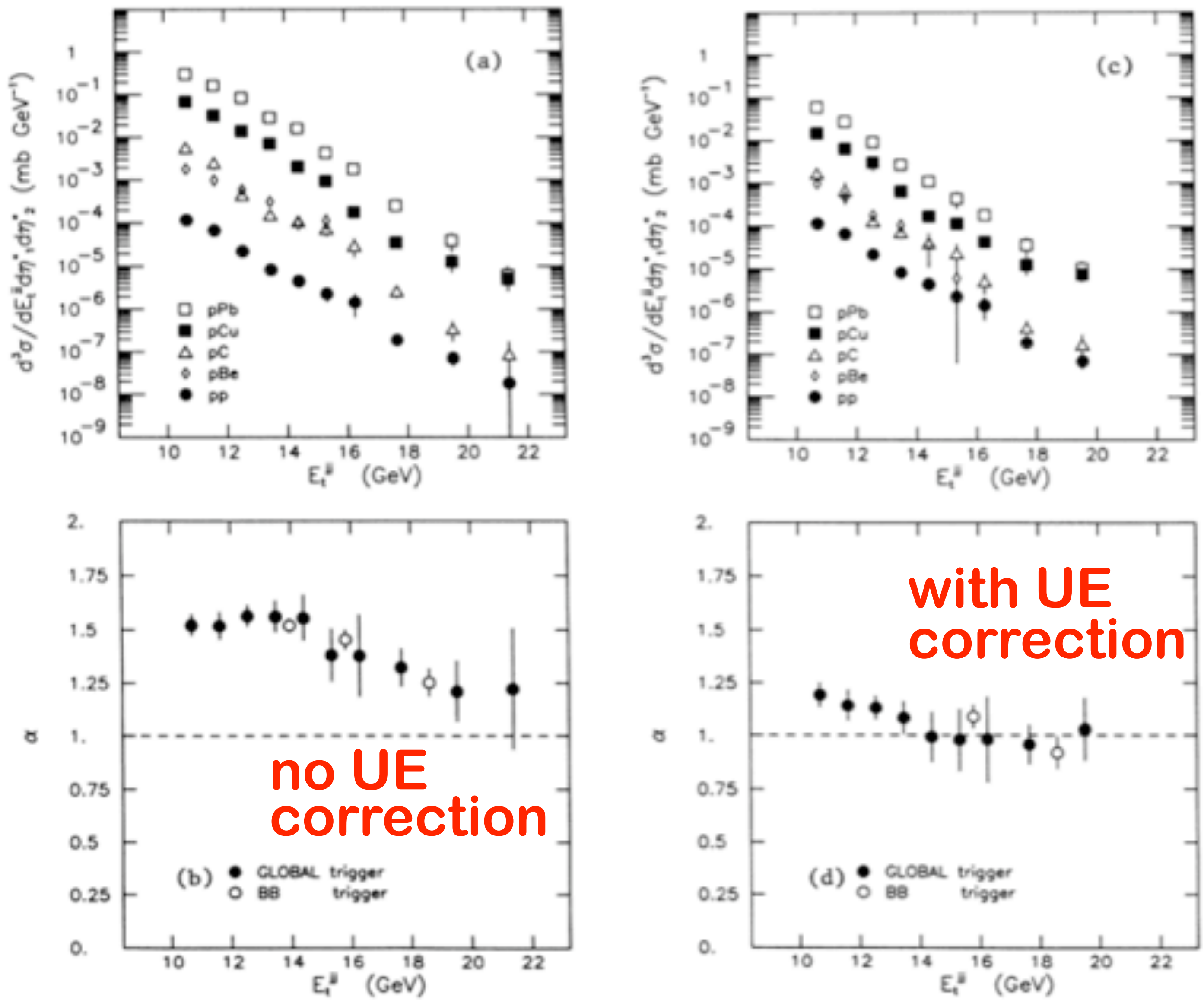


FIG. 8. (a) Dependence of $d^3\sigma/dE_t^{jj}d\eta_1^*d\eta_2^*$ on dijet E_t^{jj} for pA interactions at 800 GeV/c, where E_t^{jj} is the scalar sum of transverse energy of the two jets. (b) α vs E_t^{jj}. (c) and (d) Same as (a) and (b) after correction for the underlying event (see text) was applied to the heavier nuclei data.

Jets in fixed-target p+A

- Data suggest that in p+heavy nucleus collisions, for jets with p_T ~ 4-6 GeV
  - "nuclear enhancements" are observed in the single jet, dijet rates
  - and dijet acoplanarity.
- But, E557 data show that at higher jet p_T, at most weak modifications

  ⇒once underlying event is subtracted
- "nuclear effects" are dying away more rapidly with jet energy in p+A than in e+A?

  ⇒due to larger Q^2 in p+A vs DIS?

Summary

- Studies of hard scattering processes in proton-nucleus and lepton-nucleus collisions show non-trivial A dependence
  - Separate from nuclear PDF modifications
- Those effects are consistent with initial and/or final-state transverse momentum broadening
  - Cronin effect, Dijet broadening
- And cold nuclear energy loss
  - semi-inclusive deep inelastic scattering
- Confined to p_T scales <~ 10 GeV

    ⇒Though relevant scales for broadening & energy loss may be different

Geometry, again

- Go back to:
  - $$E\,\frac{d^3n^{pA(b)}}{dp^3} = T(b) \times E\,\frac{d^3\sigma^{pp}}{dp^3}$$
  - Most fundamental expression of the impact of the nuclear geometry on hard scattering
    $\Rightarrow$assuming factorization
- Often, the right-hand side is reinterpreted
  - $$E\,\frac{d^3n^{pA(b)}}{dp^3} = T(b) \times \sigma^{pp}_{inel} \times E\,\frac{d^3n^{pp}}{dp^3}$$
- Then, N_{coll} is defined $N_{coll} = T(b)\,\sigma^{pp}_{inel}$
  - Yielding, $$E\,\frac{d^3n^{pA(b)}}{dp^3} = N_{coll} \times E\,\frac{d^3n^{pp}}{dp^3}$$

Geometry, again

- Which might motivate a definition of R_{pA}
  - $$R_{pA} \equiv \frac{d^3 n^{pA(b)} / dp^3}{N_{coll}\ d^3 n^{pp} / dp^3}$$
- This is an abomination!
  - Measuring $E\ d^3 n^{pp} / dp^3$ is difficult due to
    - ⇒diffraction (in inelastic cross-section)
    - ⇒inefficiencies in triggering on or reconstructing low-multiplicity events.
- But, if we use T(b) and p-p cross-section for hard process, R_{pA} is robust
  - $$R_{pA} \equiv \frac{d^3 n^{pA(b)} / dp^3}{T(b)\ d^3 \sigma^{pp} / dp^3}$$

RHIC: a new regime

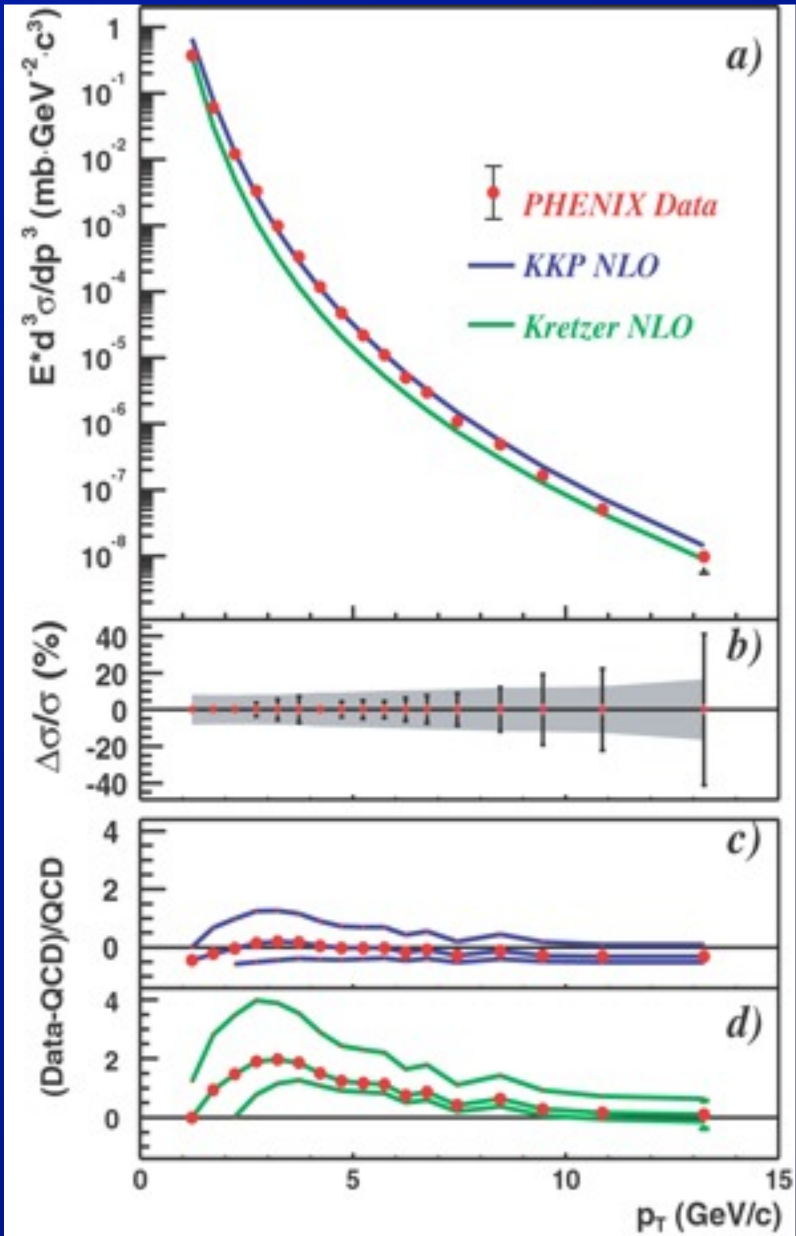
7-200 GeV/A Au+Au, d+Au, Cu+Cu
32-500 GeV p+p, ...

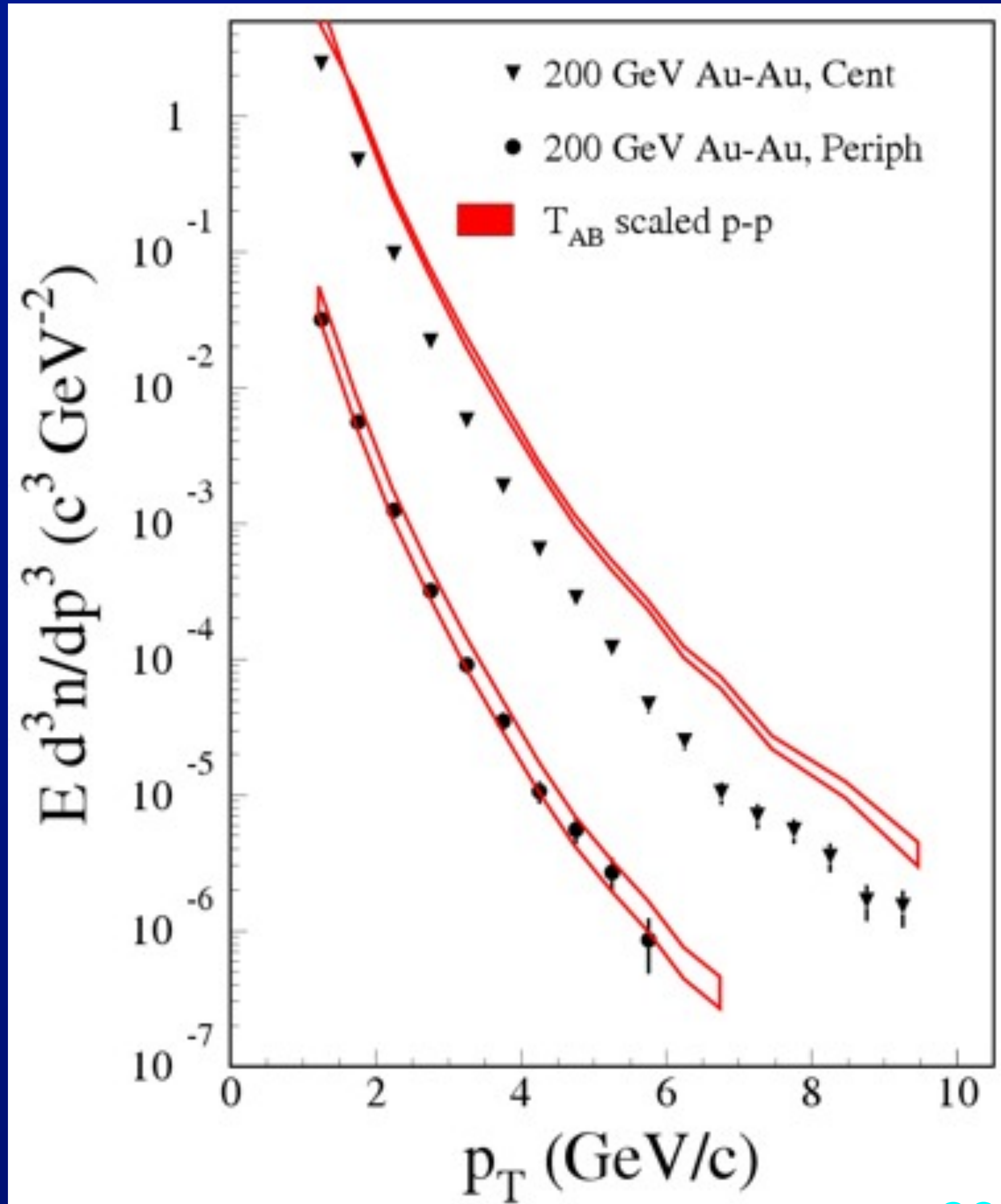
PHENIX

STAR

The early days of jet quenching

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





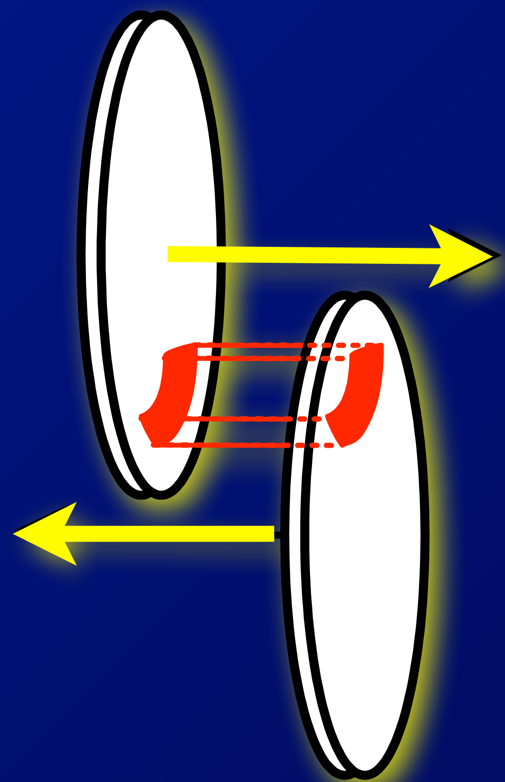
A-A Hard Scattering Rates

- For "partonic" scattering or production processes, rates are determined by T_{AB}

$$T(r_t) = \int_{-\infty}^{\infty} dz\, \rho_A^{nucleon}(z, r_t)$$

$$T_{AB}(b) = \int d\vec{r}\, T_A(|\vec{r}|)\, T_B(|\vec{b} - \vec{r}|)$$

  - t-integrated A-A parton luminosity
  - Normalized relative to p-p



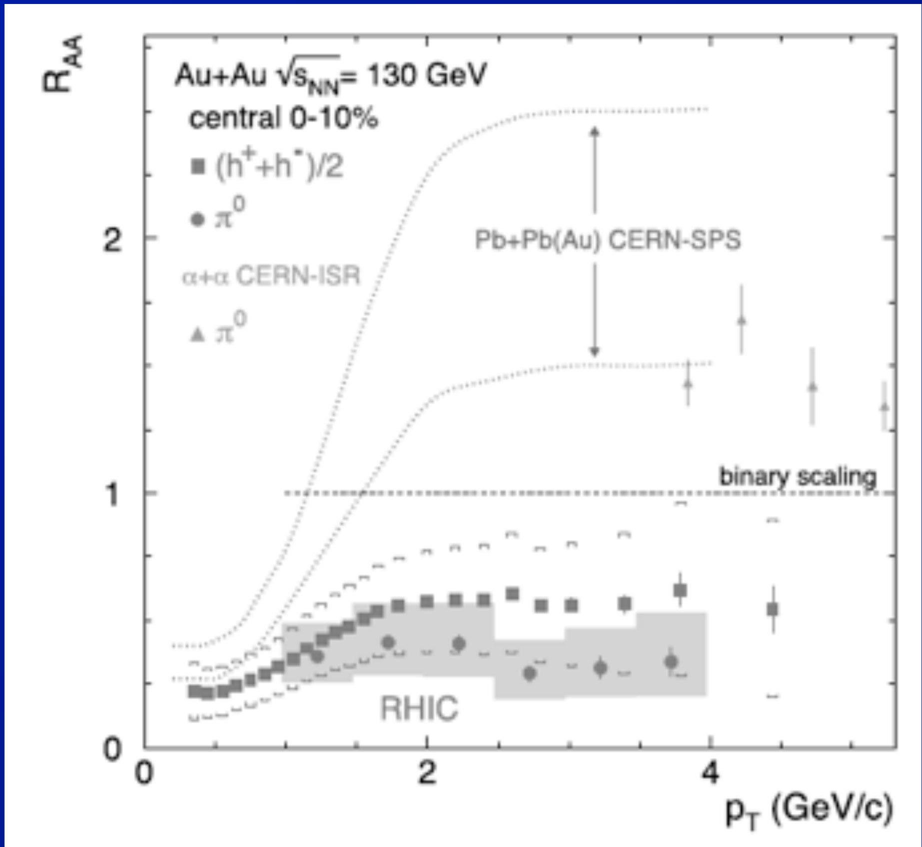
- If factorization holds, then

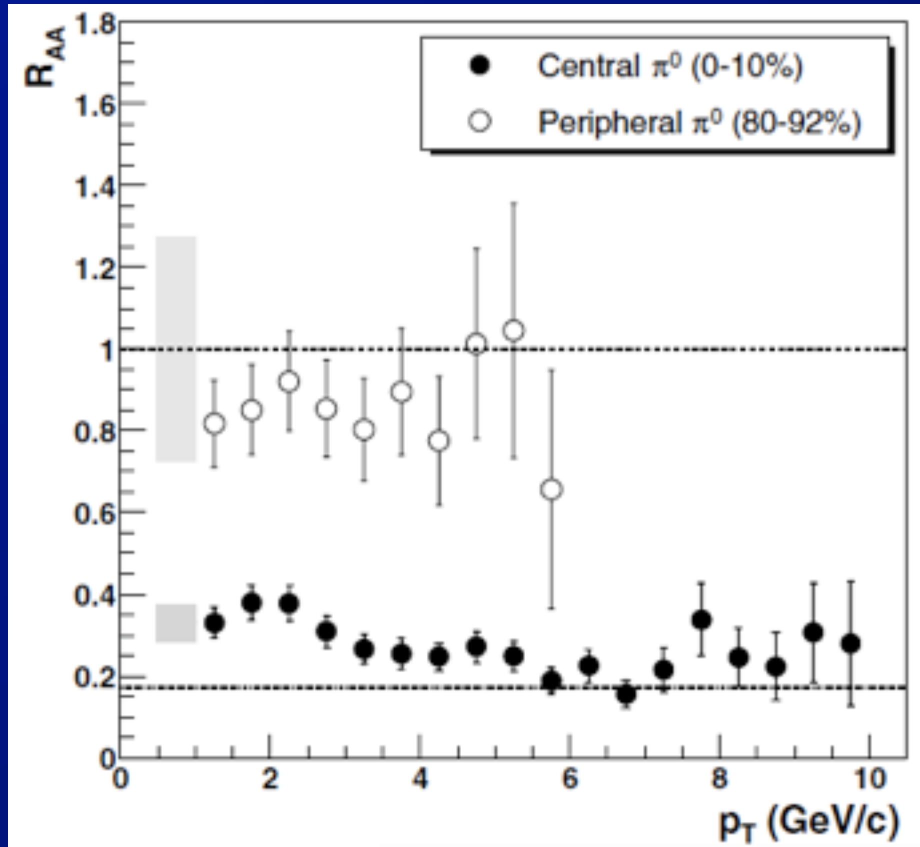
$$\frac{dn_{hard}^{AB}}{dp_\perp^2} = \frac{d\sigma_{hard}^{NN}}{dp_\perp^2} T_{AB}(b)$$

- Define R_{AA}
  - Degree to which factorization is violated

$$R_{AA} = \frac{dn_{hard}^{AB}}{dp_\perp^2} \Big/ \frac{d\sigma_{hard}^{NN}}{dp_\perp^2} T_{AB}(b)$$

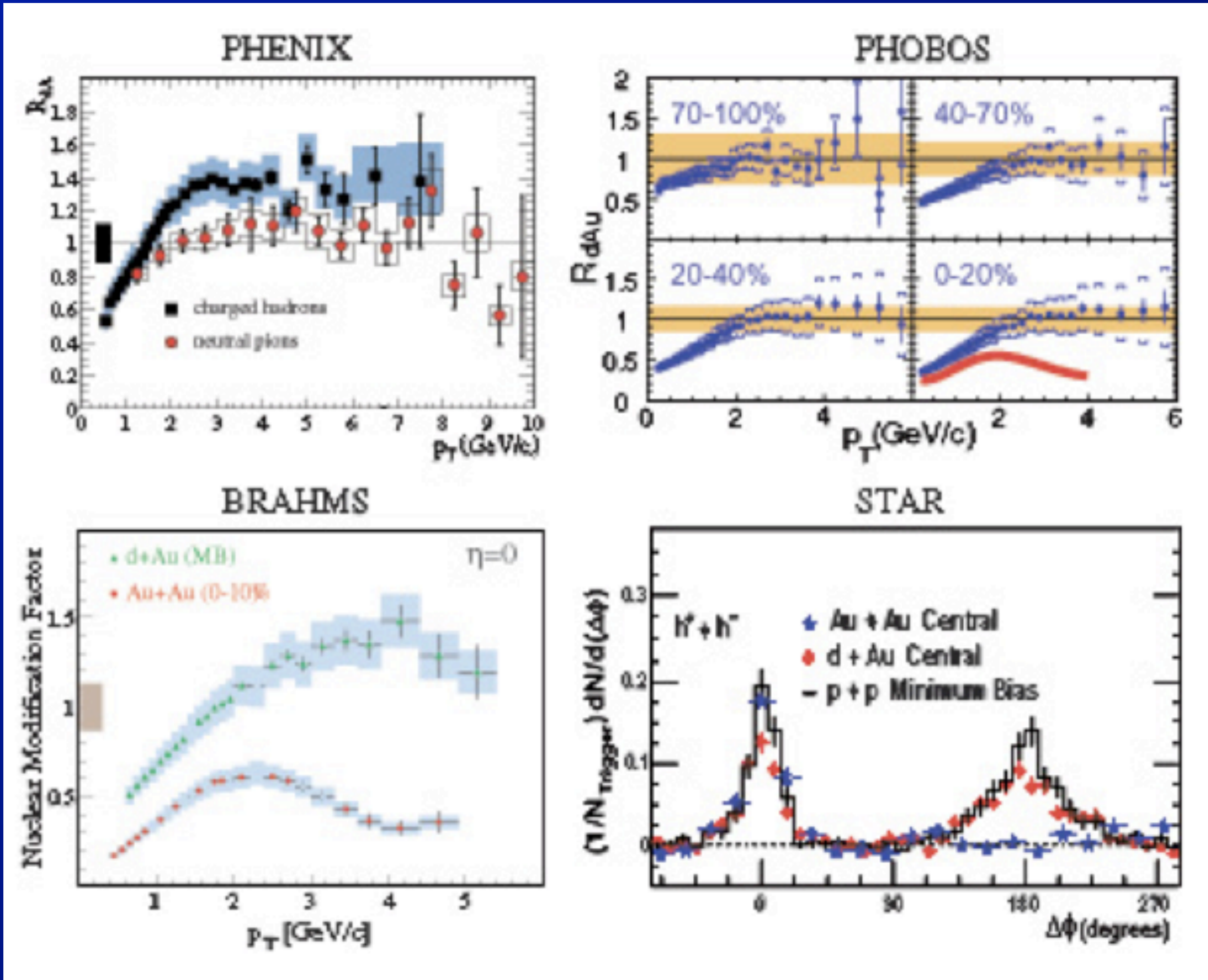
PHENIX: “jet” quenching @ 130, 200 GeV



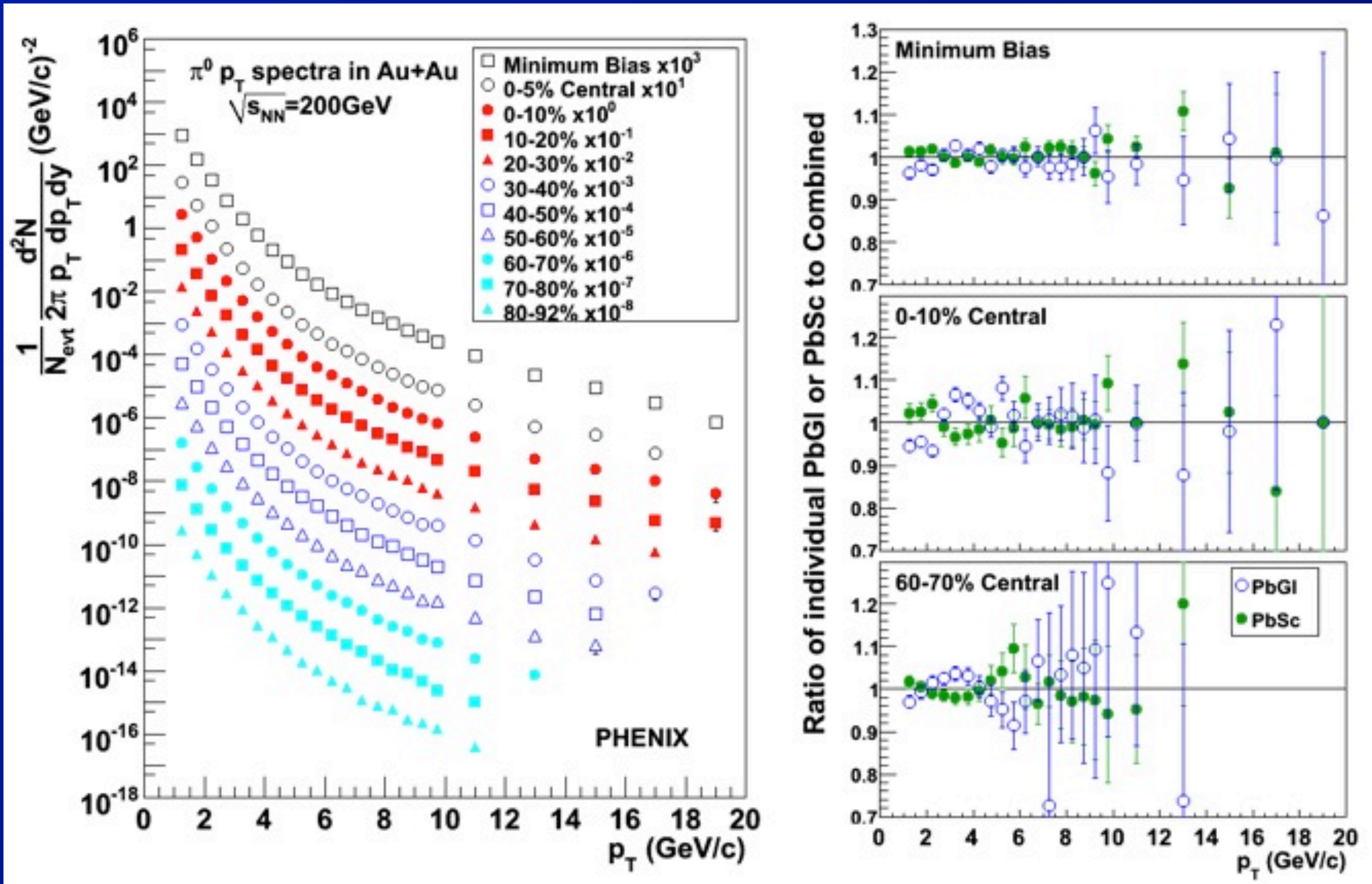


- **Limited reach in pT compared to what we are used to in the LHC era.**
  - **Qualitative features of single hadron suppression already established in 2003.**
    - ⇒ **In particular, apparent weak p_T variation**

Single/di-hadron suppression w/ control

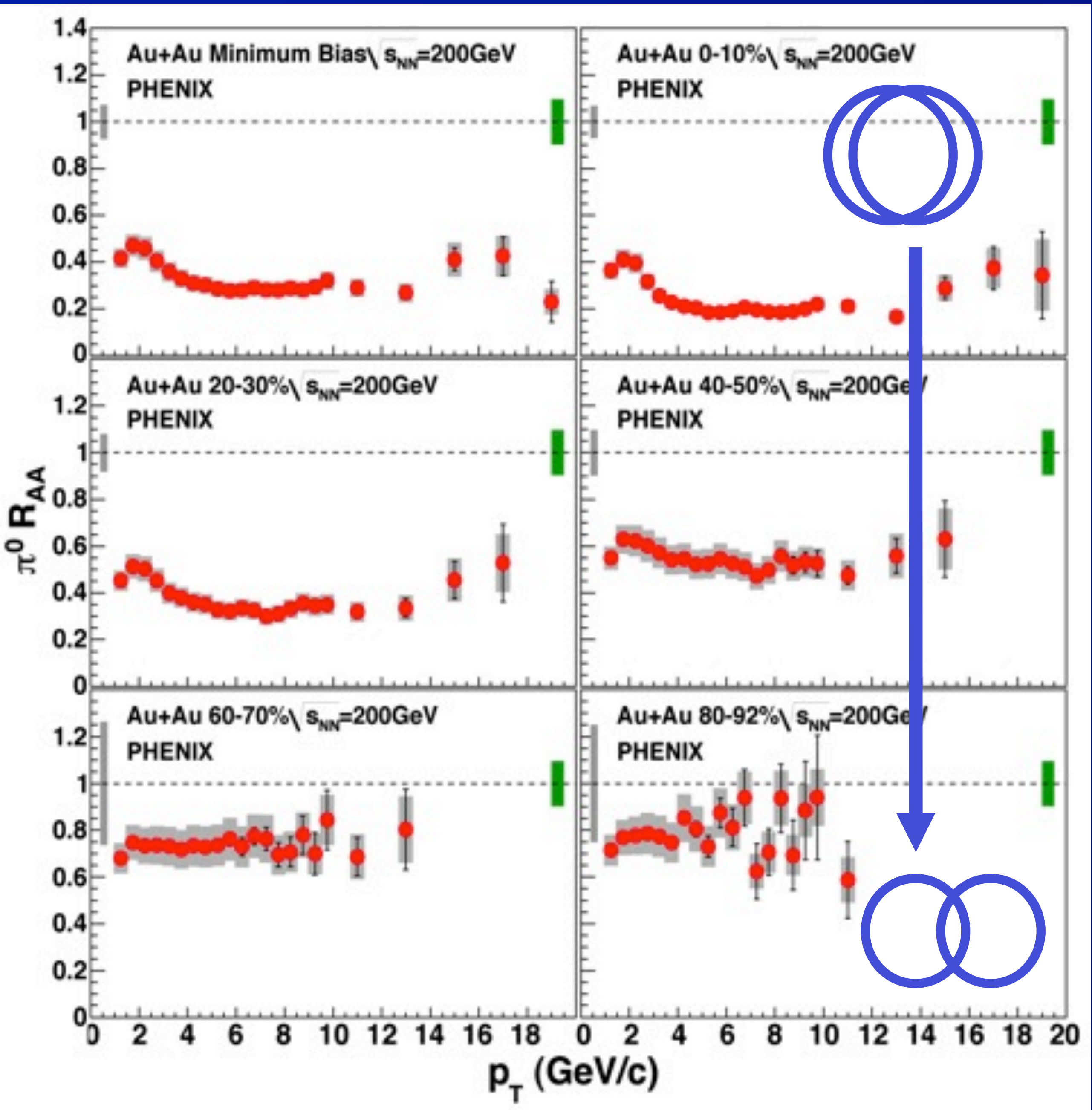


PHENIX Au+Au π^0 Spectra



- Control over systematic errors w/ two measurements using different electromagnetic calorimeter

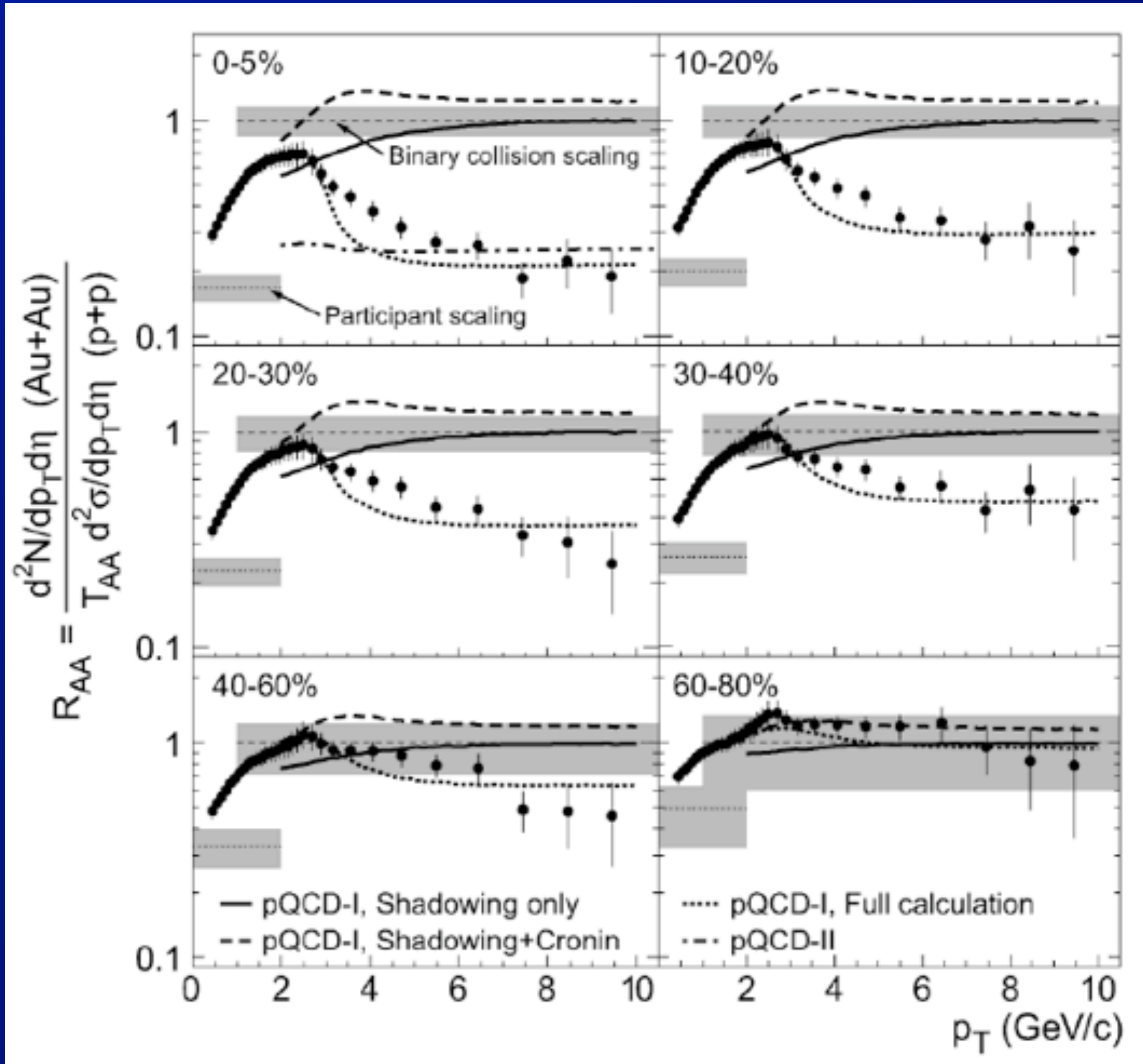
PHENIX Au+Au π^0 R_{AA}



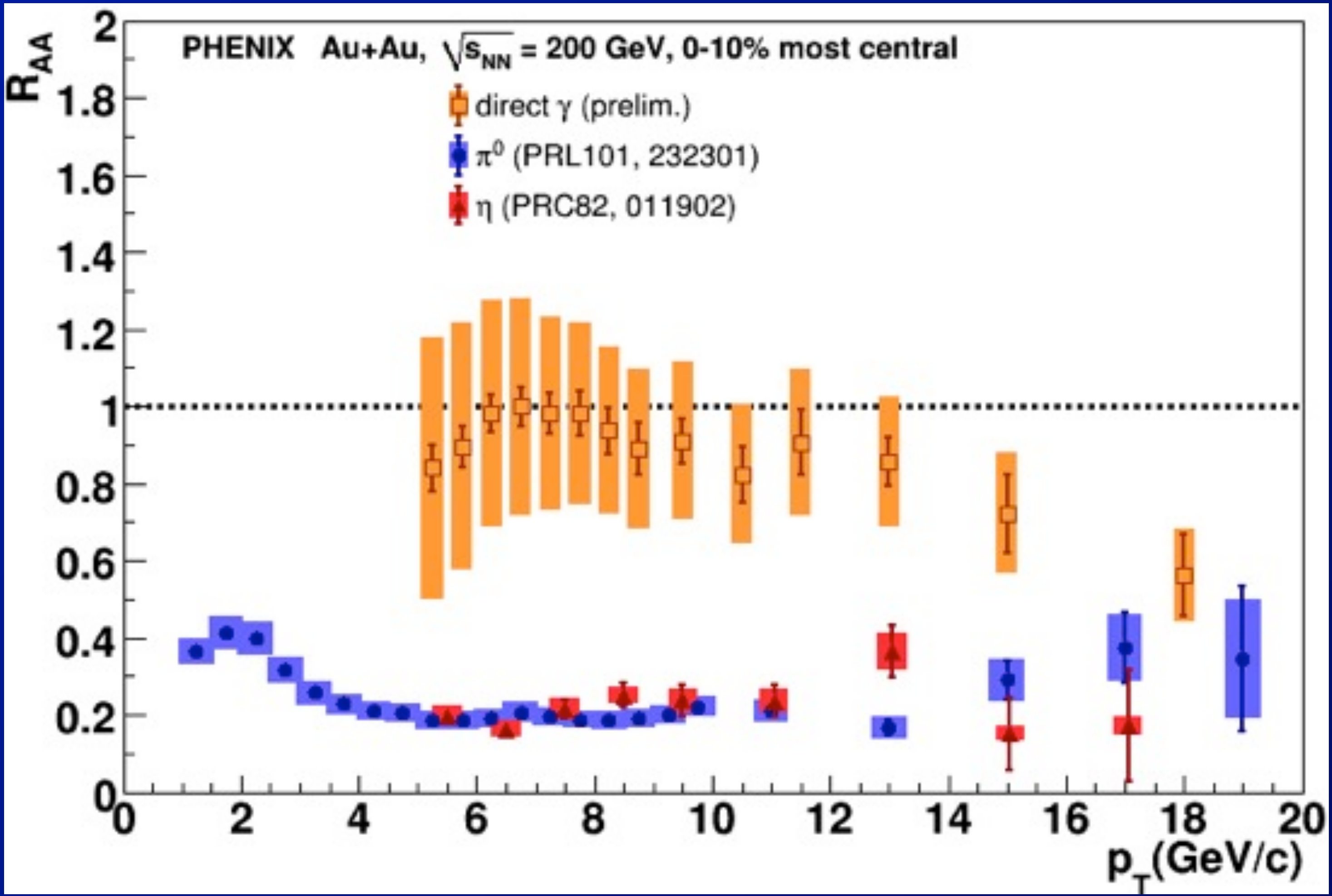
- Factor of ~ 5 violation of factorization in central Au+Au
- Smooth evolution of high-p_T π^0 suppression with centrality.
- ≈ constant for p_T > 4 GeV/c (more on this later).

STAR charged hadron suppression

STAR, PRL 91 (2003) 172302

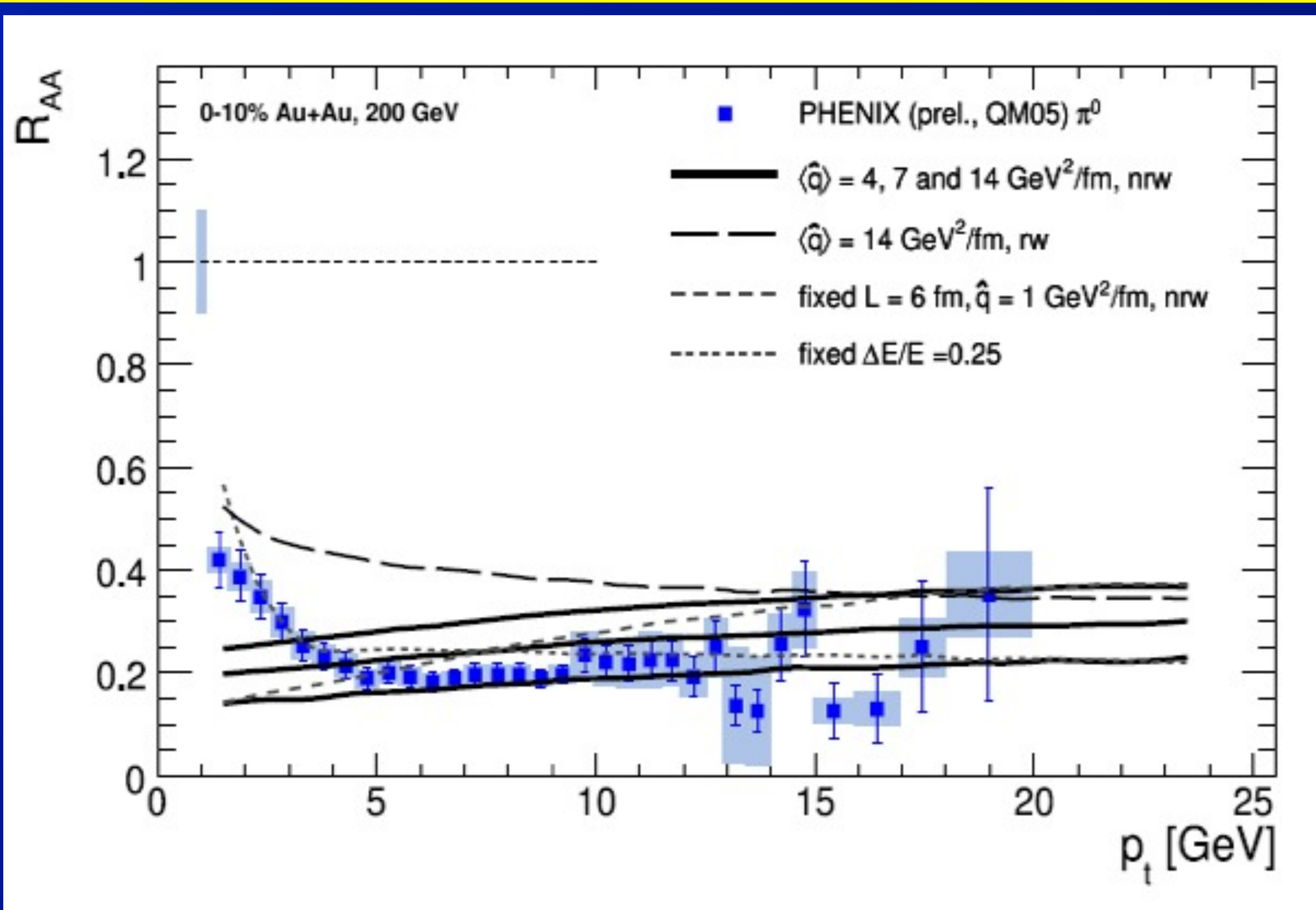


Single hadrons, photon



- "State of the art" in single hadron suppression measurements @ RHIC.

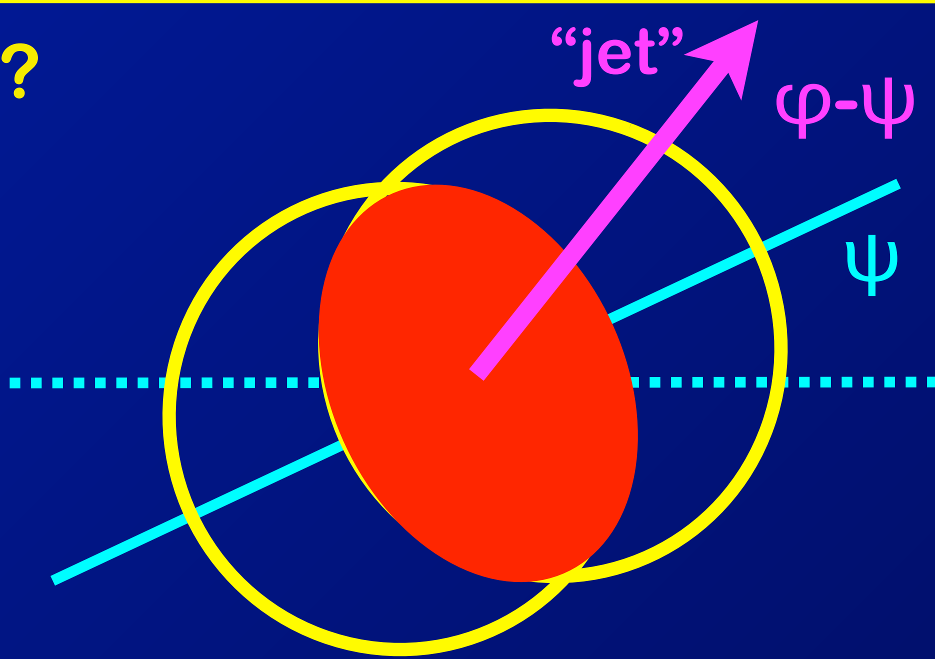
Single hadron and quenching "theory"



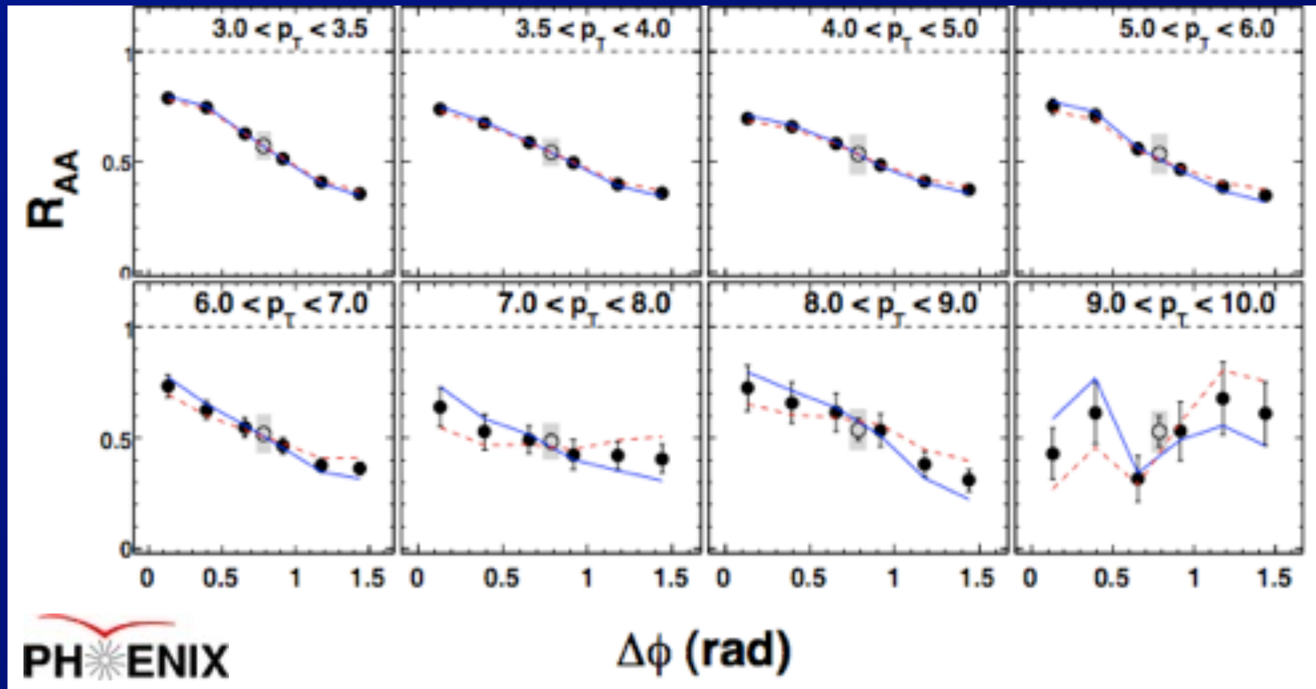
- suggests qhat values >> larger than ones we currently think are appropriate (~ 1 GeV^2/fm)

Jet tomography

- How to probe geometry?
  - Use spatial asymmetry of medium @ non-zero impact parameter
  - Measure orientation (ψ) event-by event

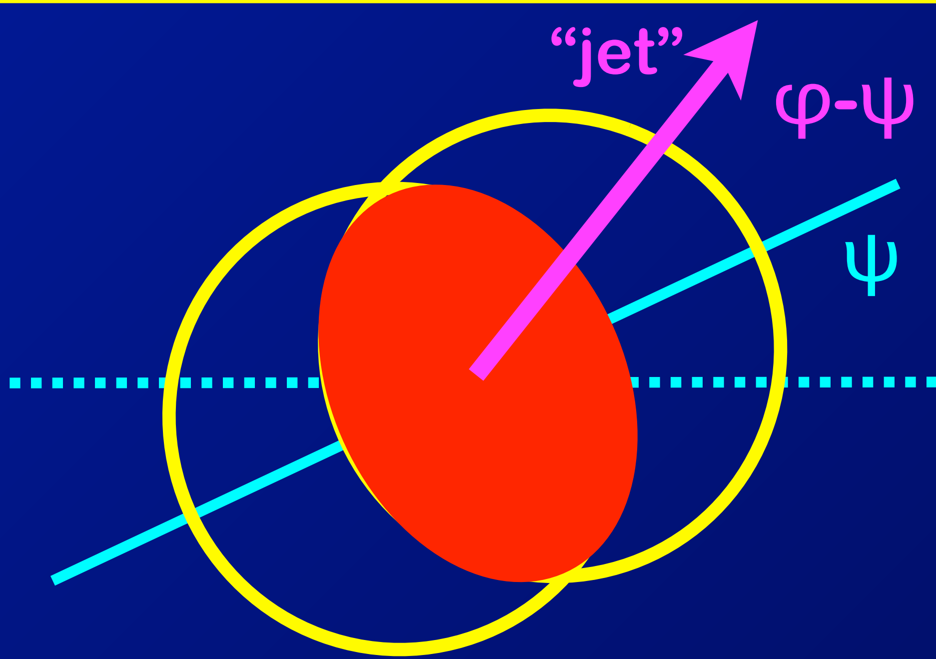


- Measure R_{AA} vs $\Delta\varphi = \varphi - \psi$

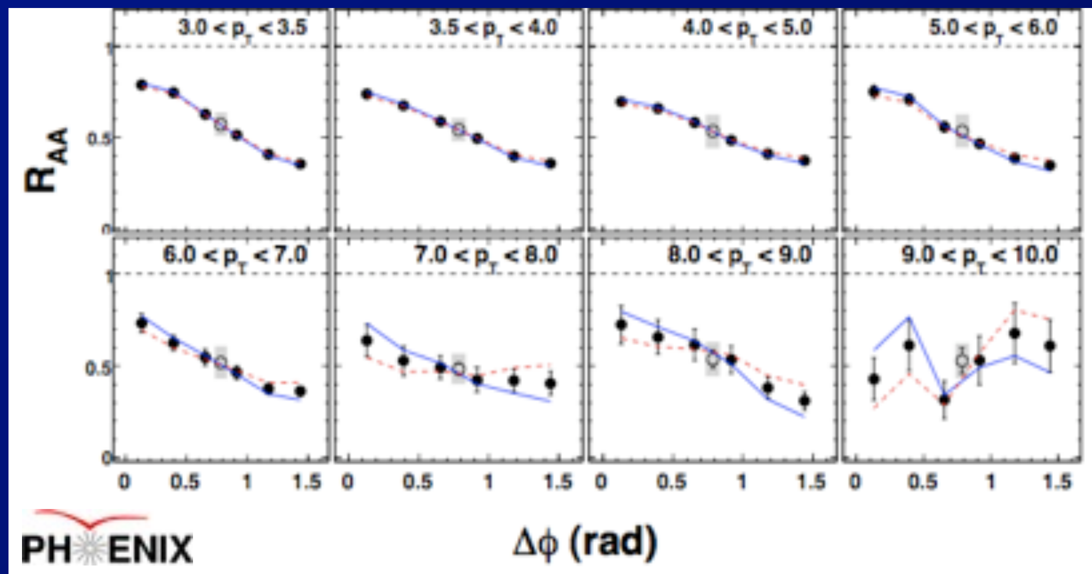


Jet tomography

- How to disentangle two contributions?
  - Use spatial asymmetry of medium @ non-zero impact parameter
  - Measure orientation (ψ) event-by event



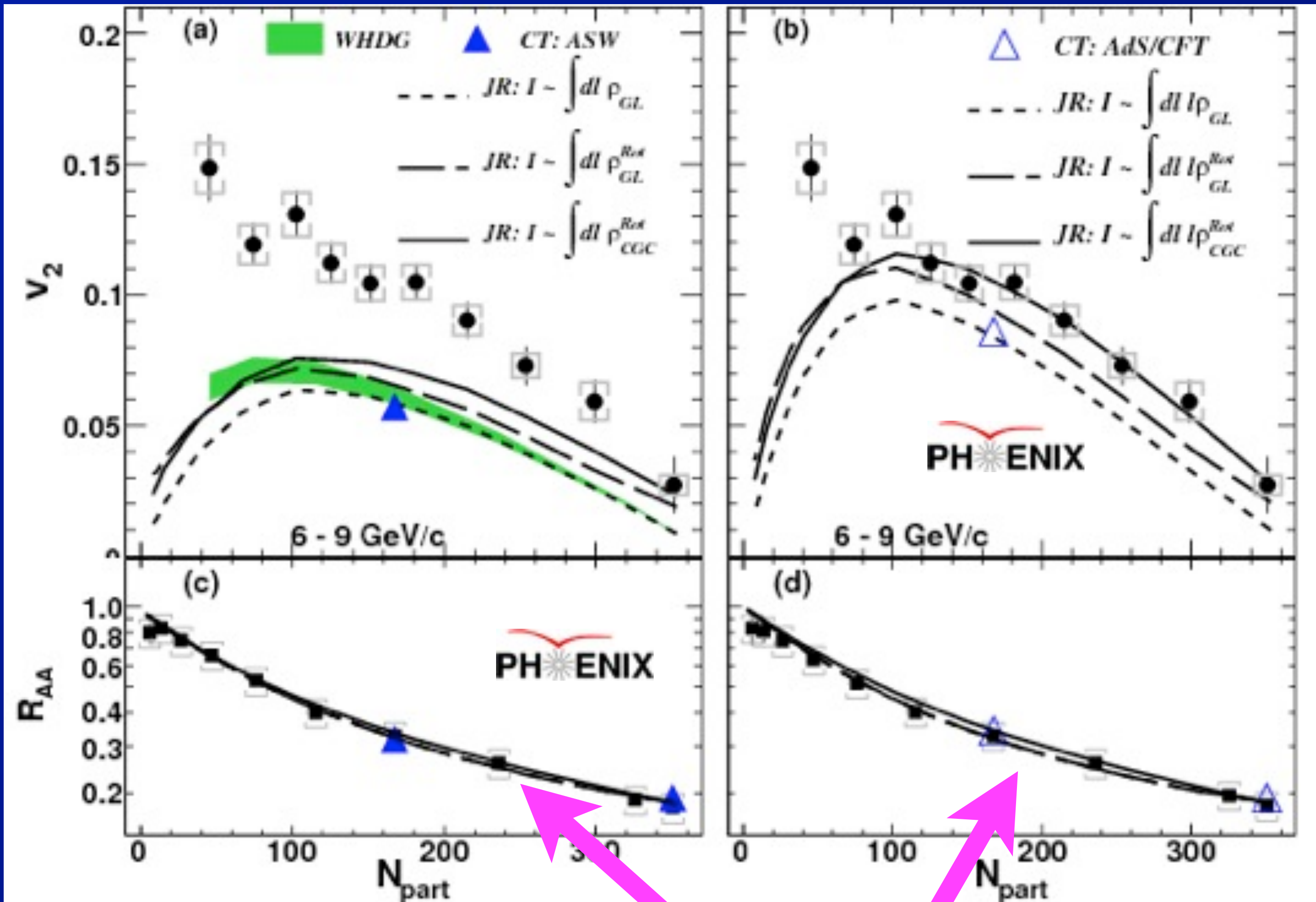
- Measure R_{AA} vs $\Delta\varphi = \varphi - \psi$



- Characterize by amplitude of Δφ modulation:

$$\frac{dN}{d\phi} = C\left[1 + 2\underline{v_2}\cos(2\Delta\phi)\right]$$

Single hadron suppression

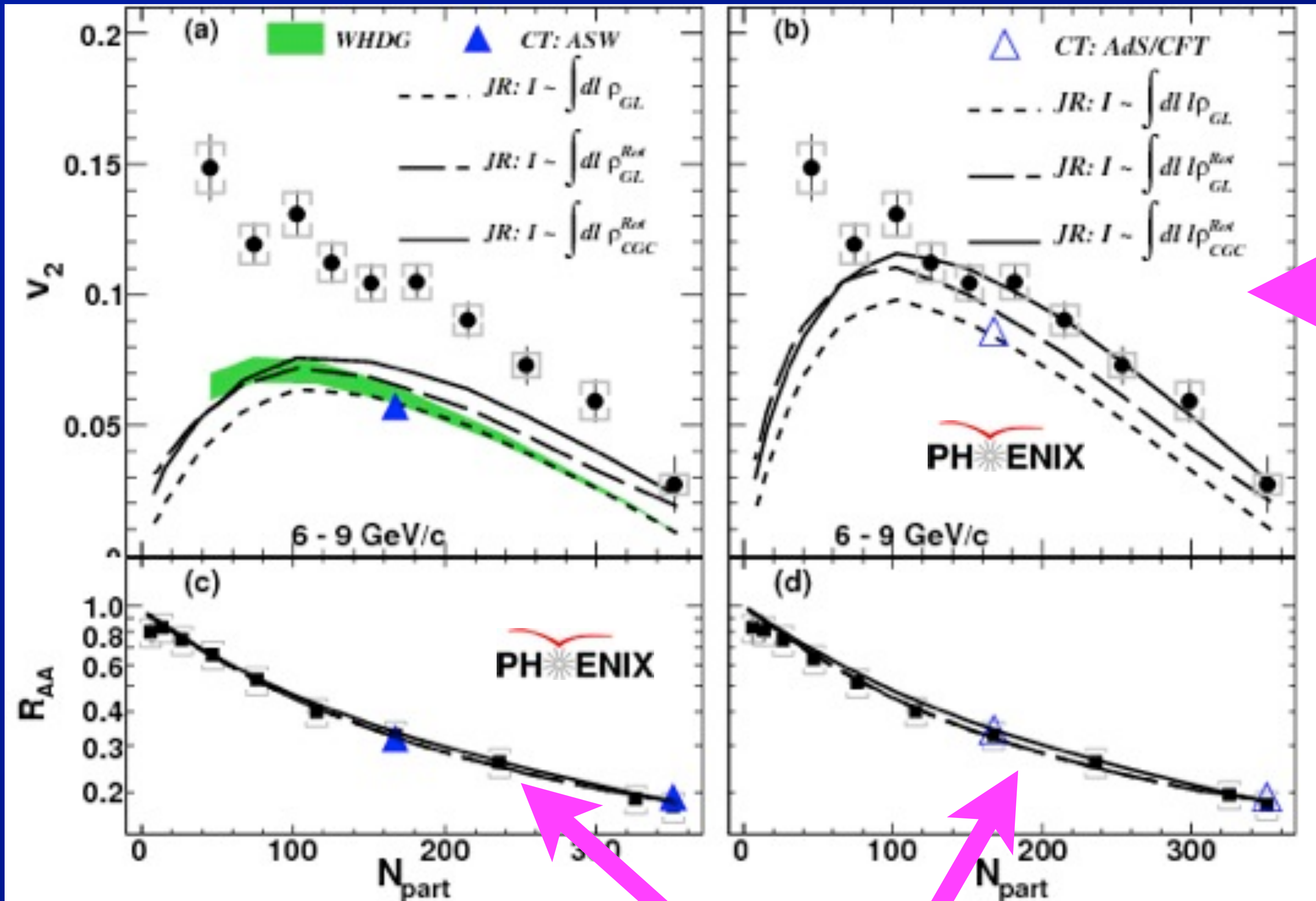


Calculations:

- Wicks *et al.*, NPA784, 426
- Marquet, Renk, PLB685, 270
- Drees, Feng, Jia, PRC71, 034909
- Jia, Wei, arXiv: 1005.0645

- Two calculations: weak, strong coupling
  - N_{part} dependence same for both
  - But v_2 (modulation vs $\Delta\varphi$) prefers strong coupling

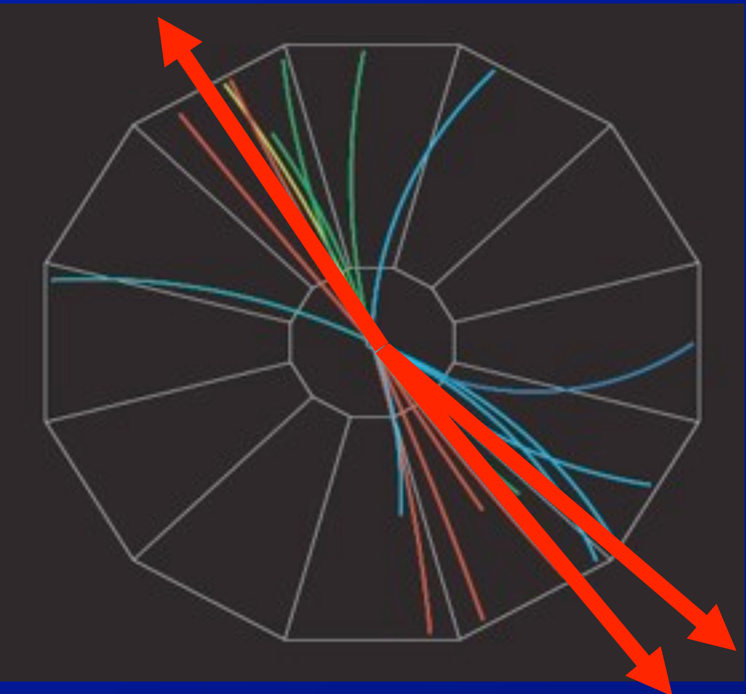
Single hadron suppression



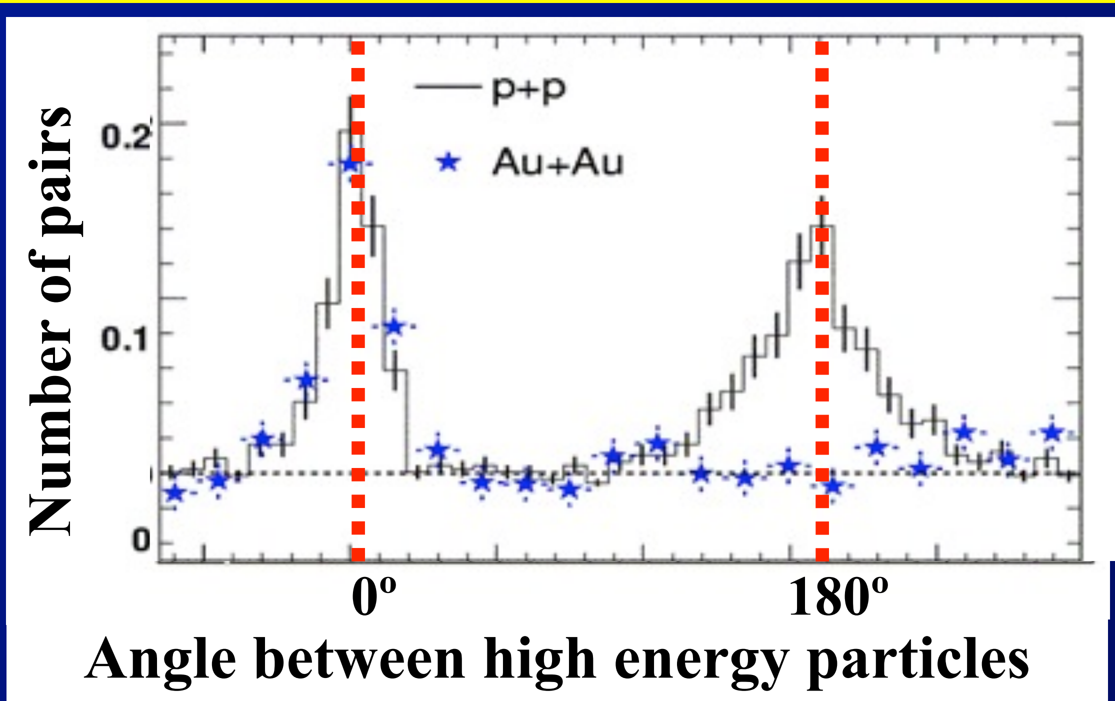
- Two calculations: weak, strong coupling
  - N_{part} dependence same for both
  - But v_2 (modulation vs $\Delta\varphi$) prefers strong coupling

STAR Experiment: "Jet" Observations

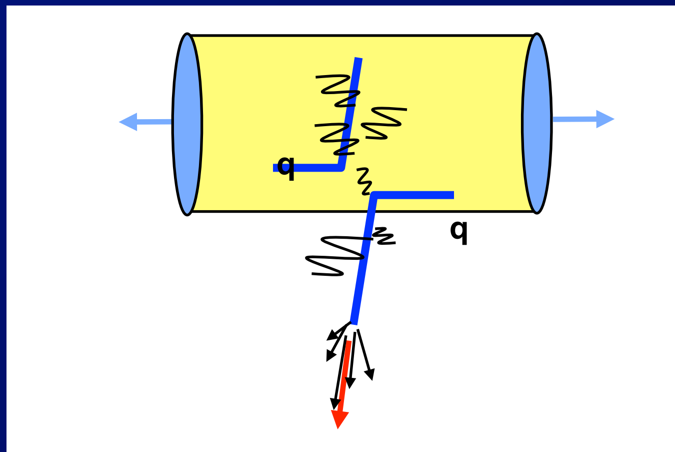
proton-proton jet event



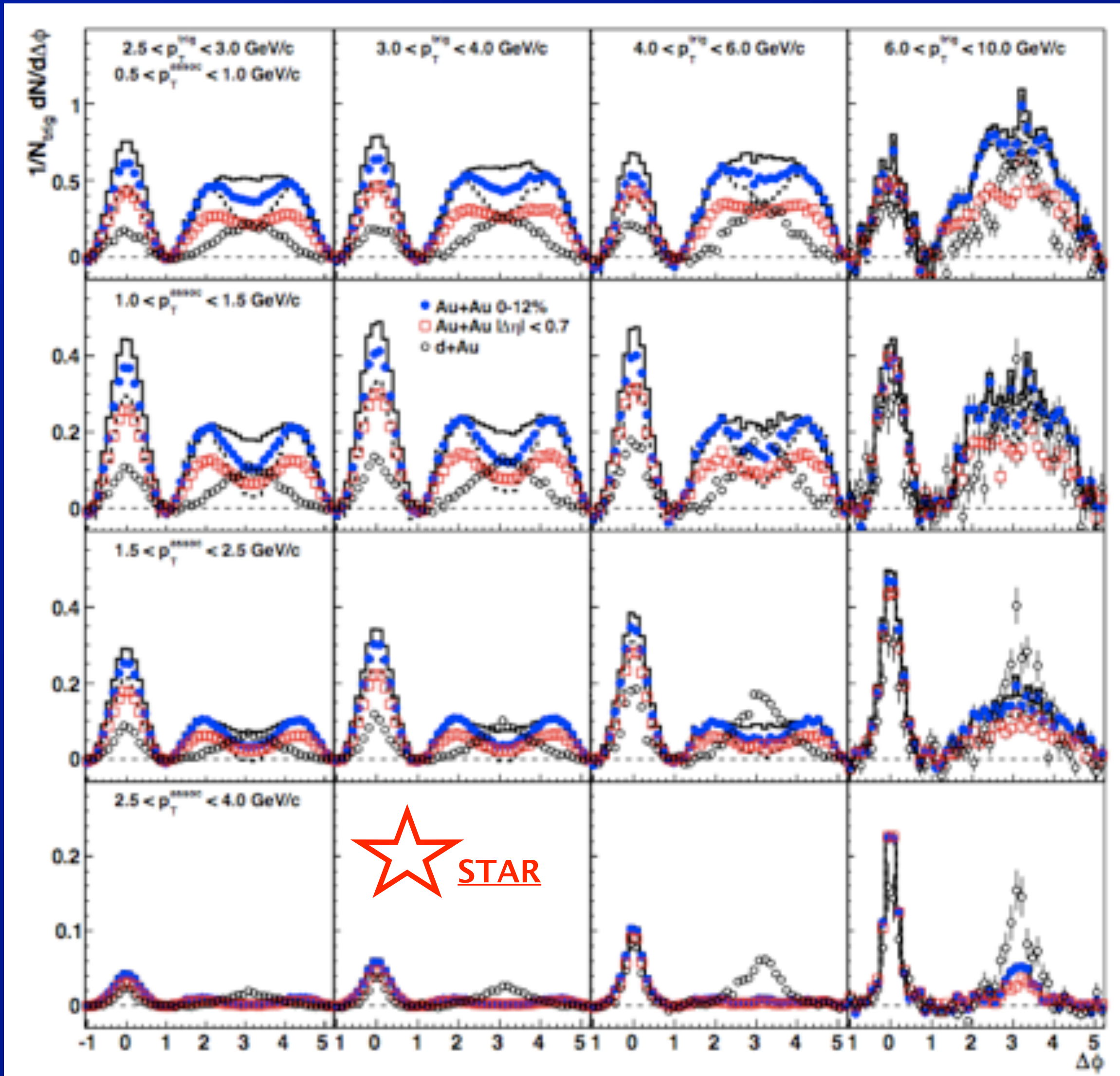
Analyze by measuring (azimuthal) angle between pairs of particles



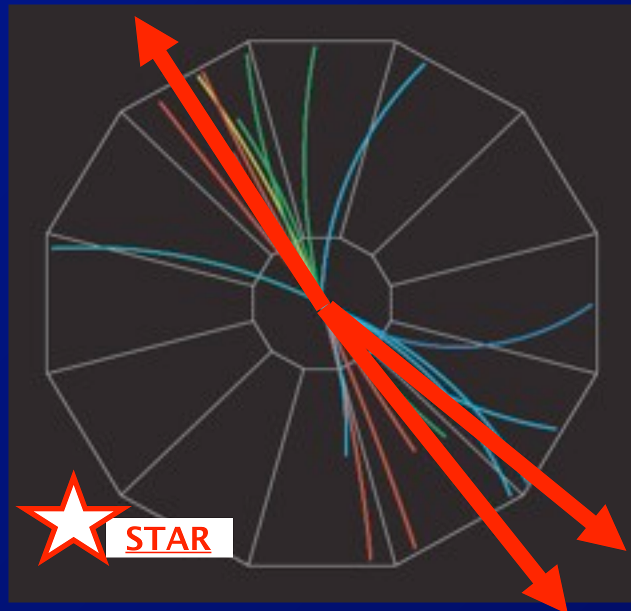
- In Au-Au collisions we see one "jet" at a time
- Strong jet quenching
- Enhanced by surface bias



Two-particle correlations



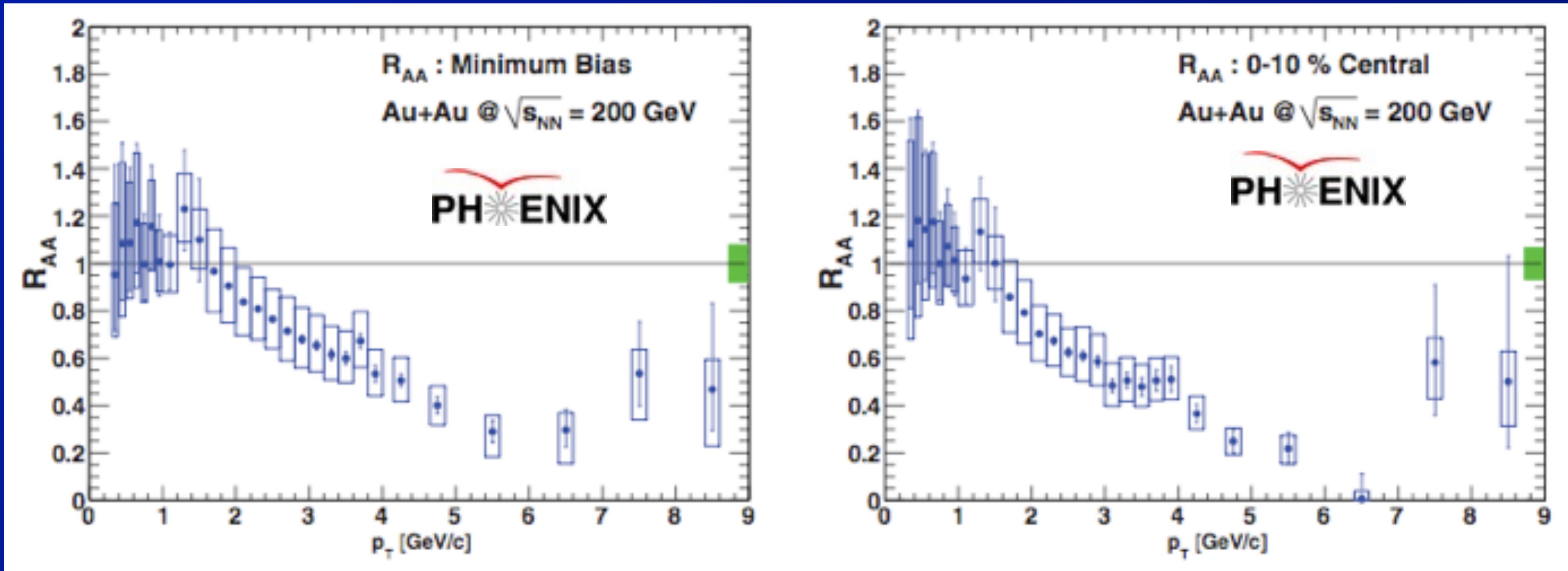
Indirect dijet measurement via dihadron correlations



STAR,
Phys. Rev. C82
(2010) 024912

- Through very detailed measurements from STAR and PHENIX we've learned that most of this has little to do with high-p_T physics, though it is very interesting

Heavy quark suppression



- Measure heavy quark production via semi-leptonic decays (B+D) to electrons
  - See suppression comparable to light mesons
    - ⇒Unexpected due to mass suppression of radiative contributions, especially for b quark.

RHIC – Where We Stand (from 2009)

- **Significant theoretical uncertainties**
  - Role of collisional energy loss.
  - Differences in approximations.
  - Choice of strong coupling constant.
  - Description of medium
  - Incorporating position, time dependence of medium.
  - Fluctuations in # emitted gluons.
  - Energy loss biases.
- **Currently single hadron data do not sufficiently discriminate, test theoretical differences.**
  - Use more "differential" measurements.
  - Use multi-hadron measurements.

Better: use full jet measurements

Where are we?

- Studies of "jet" modification in nuclei show clear, but modest effects in e+A/p+A collisions.
  - Clearly decrease with increasing jet energy
- Geometry plays an critical role in hard scattering in nuclei
  - and influencing initial/final-state interactions
- Start of RHIC program opened a new frontier where much larger effects are observed due to (s)QGP.
  - But single, two-particle, heavy quark measurements have not provided unique understanding of quenching physics ⇒ jets.