High p_T π^0 and lepton production in PHENIX at RHIC at $\sqrt{s_{NN}} = 130 - 200$ GeV

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The PHENIX experiment is designed to measure single electron and e^+e^- pairs in a central open spectrometer and muon pairs in two forward shielded spectrometers. Due to the high multiplicity in central Au+Au collisions, the only feasable way to measure jets is via leading single particles (as pioneered by the famous high p_T discoveries at the CERN-ISR). Results on inclusive single π^0's and single prompt electrons (from Charm) show different behavior . The π^0 are suppressed by a factor of 3–5 compared to the scaling expected for point-like collisions (i.e. A^2 in A+A), while the single $e^{\pm}$ p_T spectrum from charm decay follows point-like scaling. Such effects have never been seen at lower energies including the CERN fixed target heavy ion program. Implications of the results in terms of hot, dense, possibly deconfined nuclear matter will be discussed.

Seminar, Pisa, January 15, 2003

Schematic Nuclear Collision Geometry

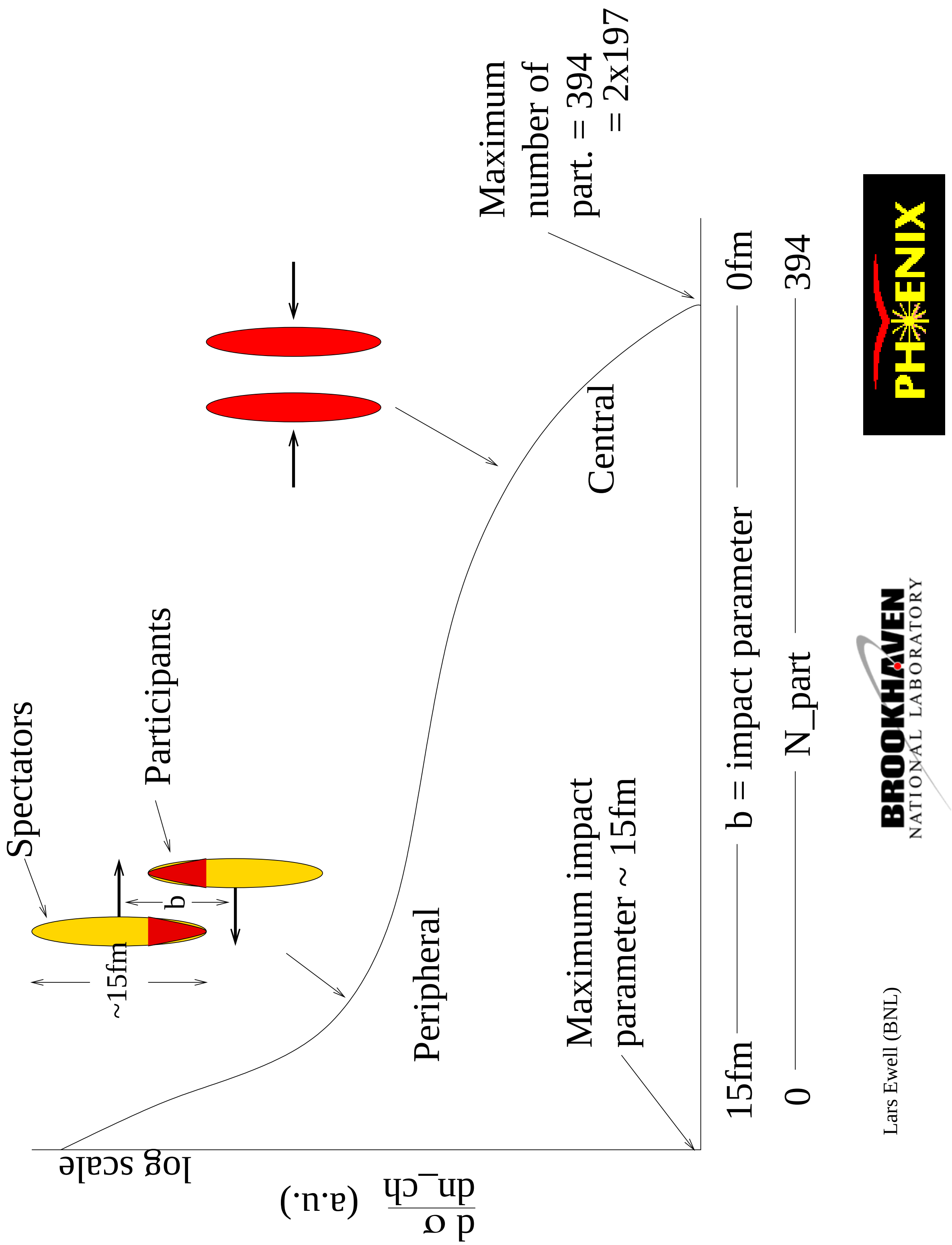


Figure 1: Schematic Nuclear Collision Geometry

High Energy Nucleus-Nucleus Collisions

♡ High Energy Nucleus-Nucleus Collisions provide the means of creating Nuclear Matter in conditions of Extreme Temperature and density

♡ At large energy densities or Baryon Density, a Phase Transition is expected from a state of nucleons containing confined quarks and gluons to a state of "deconfined" (from their individual nucleons) quarks and gluons covering the entire volume of nuclear matter, or a volume that is many units of the characteristic interaction length scale:

$$\Lambda_{\rm QCD}^{-1} \sim (0.1 GeV)^{-1} \sim 2\, fm$$

♡ This state should be in Chemical and Thermal Equilibrium

♡ This is the Quark Gluon Plasma (QGP)

The Major Questions in the Field Are:

♡ How to relate the thermodynamical properties, Temperature (T), energy density (ϵ), entropy (S) ... of the QGP or hot nuclear matter to properties that can be measured in the laboratory.

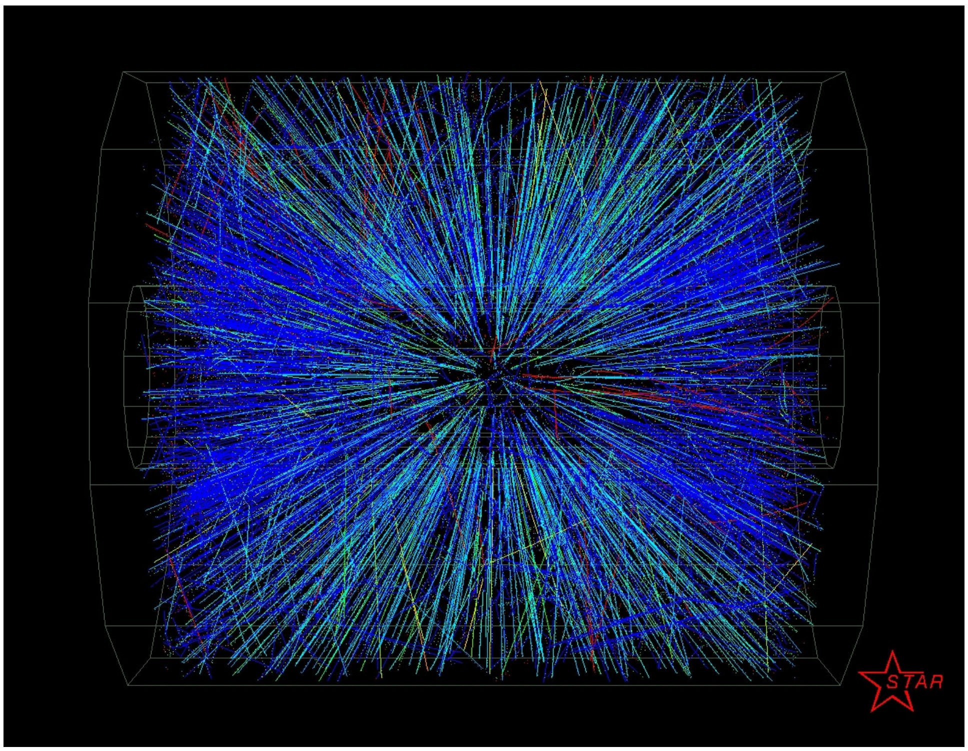
♡ How to detect when/if the QGP is produced and to measure its properties.

RHIC Experiments at a Glance

- **PHENIX**
  - High Granularity, High Resolution Central Spectrometer for electrons, photons and charged hadrons, $|\eta| < 0.35$, $\Delta\Phi = \pi$
  - Electron ID at the trigger level with RICH, EMCal, tracking
  - high segmentation $\gamma - \pi^0$ separation for $p_T \leq 25$ GeV/c
  - Two Endcap Di-Muon Spectrometers $1.1 \leq |y| \leq 2.5$
  - study of J/Ψ Ψ' via e^+e^-, $\mu^+\mu^-$
- **STAR**
  - large acceptance TPC tracking detector
  - good PID for $p_T \leq 1$GeV/c
  - central TPC full tracking in $\Delta\Phi = 2\pi$ $|\eta| < 1$
  - endcap TPC extends tracking to $|\eta| \leq 2$
  - upgrade to Barrel/Endcap EMCalorimeter $|\eta| \leq 1 - 2$
  - Silicon Vertex Detector for short lived hyperons
- **PHOBOS**
  - large area silicon tracking ($dN_{ch}/d\eta$ over 4π)
  - momentum and particle ID at midrapidity $p^\pm$, $K^\pm$, $\pi^\pm$
  - interested in long lived sources, HBT at very low p_T
- **BRAHMS**
  - moveable 2-arm spectrometer
  - small solid angles, excellent PID
  - $p^\pm$, $K^\pm$, $\pi^\pm$ over wide kinematic and rapidity range

Our First Event, June 12, 2000

Au+Au $\sqrt{s_{NN}} = 56$ GeV



STAR—l'Étoile Thousands of particles are produced

Typical Variables Used

• **Longitudinal and Transverse momentum:** For any particle, the momentum is resolved into transverse (p_T) and longitudinal (p_L) components; and in many cases the mass (m) of the particle can be determined.

• **Rapidity and Transverse mass:** Rapidity is used for the longitudinal component since it transforms linearly under a Lorentz transformation

$$y = \ln\left(\frac{E + p_L}{m_T}\right)$$

where

$$m_T = \sqrt{m^2 + p_T^2} \quad \text{and} \quad E = \sqrt{p_L^2 + m_T^2}$$

• **Pseudorapidity:**
In the limit $m \ll E$ the rapidity reduces to the pseudorapidity(η)

$$\eta = -\ln\tan\theta/2$$

• **Invariant Cross Section** The Lorentz invariant differential single particle inclusive cross section is:

$$\frac{Ed^3\sigma}{dp^3} = \frac{d^3\sigma}{p_T dp_T dy d\phi} \qquad \text{where} \quad dy = \frac{dp_L}{E}$$

• **Beam Rapidity and Mid-Rapidity**

$$Y_{\rm Beam} = \ln\left(\frac{p + \sqrt{p^2 + M_{\rm N}^2}}{M_{\rm N}}\right) \qquad y_{\rm NN} = Y_{\rm Beam}/2$$

Typical Quantities Measured and Their Interpretation

- **Temperature (T) :**

$$<p_T> \sim \; T$$

- **Entropy (S) :** The number of particles n produced on a collision, the multiplicity, is taken as proportional to the entropy.

  - ***dn/dy* :** dn/dy the multiplicity density in rapidity is the most commonly used variable

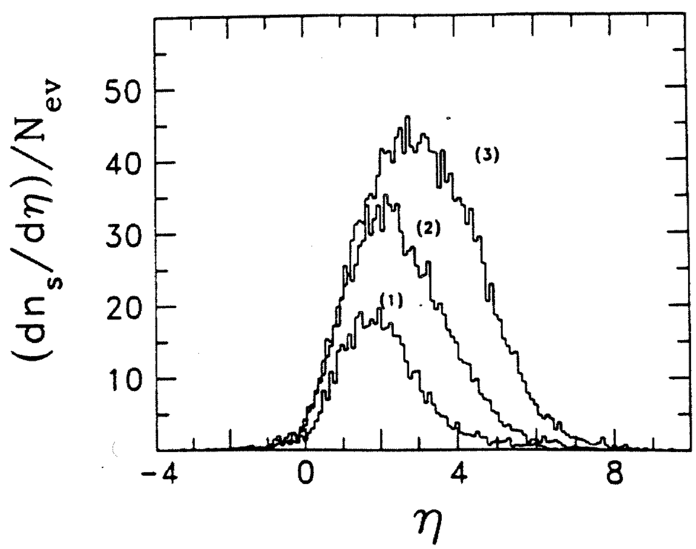


Figure 2: $dn/d\eta$ of relativistic particles for ^{16}O+AgBr Central Collisions. (1) 14.6 GeV/c, (2) 60, (3) 200 GeV/nucleon

- **Comoving Energy Density (ϵ) :**

$$<p_T> \times dn/dy \equiv dE_T/dy \sim \epsilon$$

According to Bjorken, this measures the spatial energy density.

PHENIX $dN_{ch}/d\eta|_{\eta=0}$ $dE_T/d\eta|_{\eta=0}$ Au+Au

Phys. Rev. Lett. **86**, 3500 (2001),Phys. Rev. Lett. **87**, 052301 (2001)

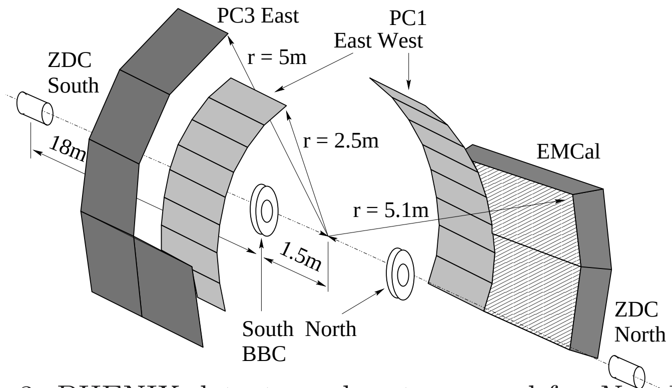
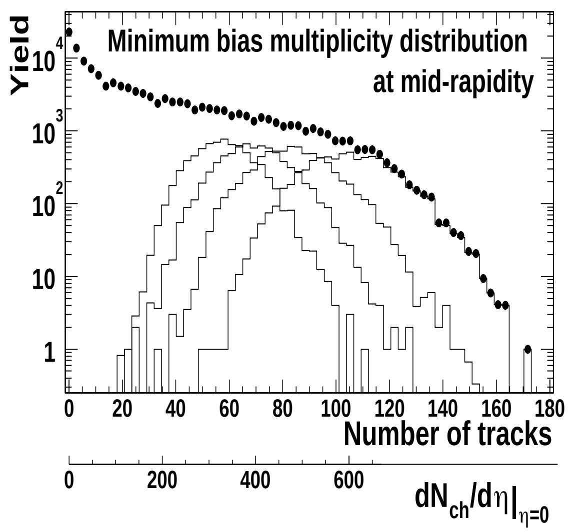
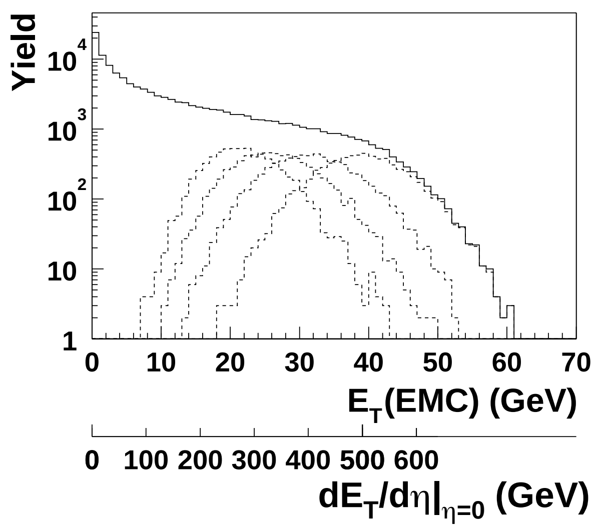
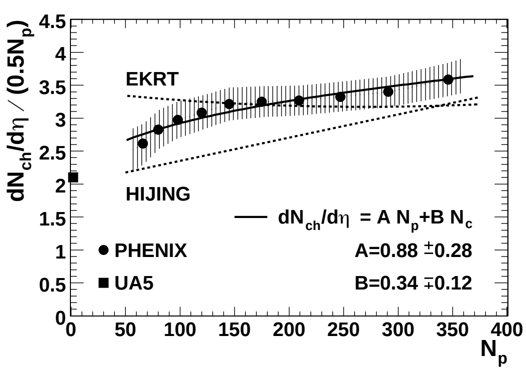
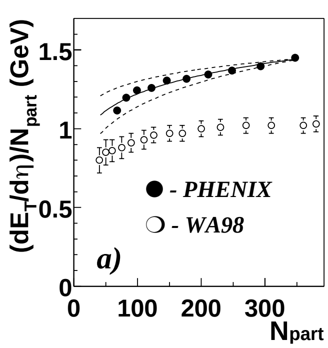


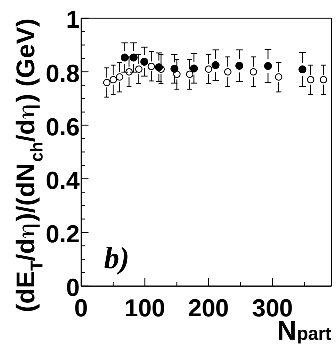
Figure 3: PHENIX detector subsystems used for N_{ch}, E_T, π^0











WNM fails, term $\propto N_{coll}$ indicated

$\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\pi R^2} \rightarrow 4.6$ **GeV/fm^3 at RHIC (top 2%) cf 2.9 CERN**

due to increase in multiplicity $\langle E_T\rangle/\langle N_{ch}\rangle$ stays constant

Experimental Probes of the QGP

• **Collision Geometry :** is determined from charged particle multiplicity, dn/dy, and Transverse Energy Flow, dE_T/dy

♡ **Comoving Energy Density :** is also determined by dE_T/dy

♡ **Entropy :** is also determined by dn/dy

• **Yields and m_T distributions :** of identified hadrons of various species give information on Freezout Temperature ($<p_T>$), and possible Chemical Equilibrium and Thermal Equilibrium

• **Single Photons and Lepton Pairs :** are penetrating probes from the early stage of the collision and their yields are sensitive to the initial temperature and the time evolution of the system

• **J/Ψ suppression :** probes deconfinement, a key feature of a Quark Gluon Plasma

• **Net Baryon Density :** is probed by the rapidity distribution of the nucleons

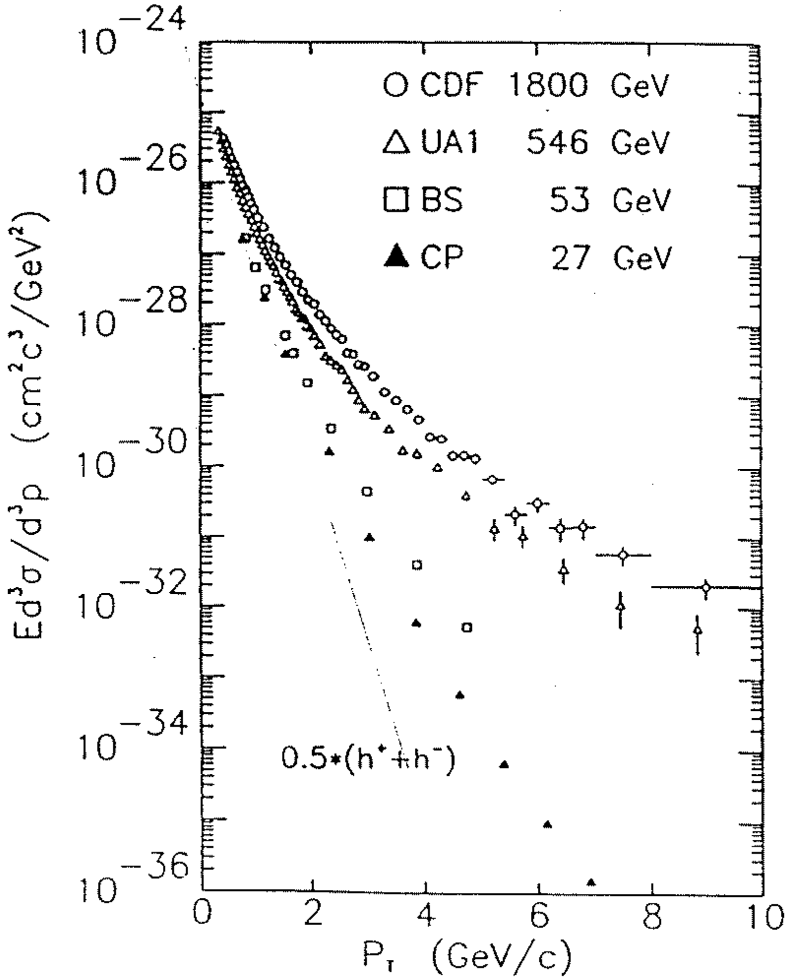
• **Hanbury-Brown Twiss Effect :** The Quantum Mechanical interference due to symmetry (Bose) or antisymmetry (Fermi) of the wave function of 2 (or more) identical particles e.g. K^+K^+ is sensitive to the dimensions of the system at freezeout ...

• **Dense Medium Effects :**

♡ **Mass Shifts :**

♡ **Jet Quenching at large p_T :** ...

From 1998—My Best Bet on Discovering QGP
Utilizes semi-Inclusive π^0 or $\pi^{\pm}$ production



Invariant cross section for non-identified charged-averaged hadron production at 90° in the c.m. system as a function of the transverse momentum p_T tablulated by CDF for a range of C.M. energies $\sqrt{s}$. There is an exponential tail (e^{-6p_T}) at low p_T, which depends very little on $\sqrt{s}$. This is the soft physics region, where the hadrons are fragments of 'beam jets'. At higher p_T there is a power-law tail which depends very strongly on $\sqrt{s}$. This is the hard-scattering region, where the hadrons are fragments of the high p_T QCD jets from constituent-scattering. **My hope is that the QGP causes the high p_T quarks to lose all their energy and stop, so that the high p_T tail will 'vanish' for central Au+Au collisions**

In RHI central collisions, leading particles are the only way to find jets because in one unit of Δr there is $\pi \times \frac{1}{2\pi}\frac{dE_T}{d\eta} \sim 375$ GeV **!!!**.

Some History–Bjorken Scaling in Deeply Inelastic Scattering and the Parton Model—1968

♡ The discovery that the DIS structure function

$$F_2(Q^2, \nu) = F_2(\frac{Q^2}{\nu}) \tag{1}$$

"SCALED" i.e just depended on the ratio

$$x = \frac{Q^2}{2M\nu} \tag{2}$$

independently of Q^2 ($\sim 1/r^2$)

♡ as originally suggested by **Bjorken**

♡ Led to the concept of a proton composed of point-like **partons**.

□ The probability for a parton to carry a fraction x of the proton's momentum is measured by $F_2(x)$

♡ **BBK 1971**—S. M. Berman, J. D. Bjorken and J. B. Kogut, Phys. Rev. **D4** 3388 (1971) **predicted the existence of high p_T particle production in p-p collisions,** since:

□ The charged partons of DIS **must scatter electromagnetically**, *"which may be viewed as a* **lower bound** *on the real cross section at large p_T."*

♡ High p_T π^0 and $\pi^\pm$ production discovered at the CERN ISR in 1972-73 was much larger than the BBK prediction, indicating that the partons of DIS strongly interacted with each other. This was before QCD, but BBK had envisaged 'Vector Gluon Exchange'.

BBK 1971—pQCD 1975
The ERA of SCALING

• S. M. Berman, J. D. Bjorken and J. B. Kogut, Phys. Rev. **D4** 3388 (1971) **BBK**

•R. Blankenbecler, S. J. Brodsky, J. F. Gunion, Phys. Lett. **42B** 461 (1972) **BBG**

•R. F. Cahalan, K. A. Geer, J. Kogut and Leonard Susskind, Phys. Rev. **D11**, 1199 (1975) **first QCD prediction**.

develop a **General Form** for high p_T cross sections with a dimensional factor and a scaling factor:

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^{\,n(x_T,\sqrt{s})}}\, G(\frac{2p_T}{\sqrt{s}}) \qquad (3)$$

♡ The **dimensional factor** is $1/\sqrt{s}^{n}$: where n gives the form of the force-law between constituents

□ $n = 4$ for QED or Vector Gluon

□ BBG predict n=**8** for the case of quark-meson scattering by the exchange of a quark.

□ In QCD $n(x_T, \sqrt{s})$ is an "effective index" ~ 4 which varies with x and $\sqrt{s}$ to account for 'scale breaking'.

♡ The **scaling factor** is $G(x)$:

□ where the key point is that $G(x)$ **scales**, i.e. is only a function of the ratio of momenta, $x_T = 2p_T/\sqrt{s}$.

CCOR 1978
"REALLY" High p_T $\pi^0 > 7$ GeV/c

A. L. S. Angelis, et al., Phys. Lett. **79B**, 505 (1978)
See also, A. G. Clark, et al., Phys. Lett. **74B**, 267 (1978)

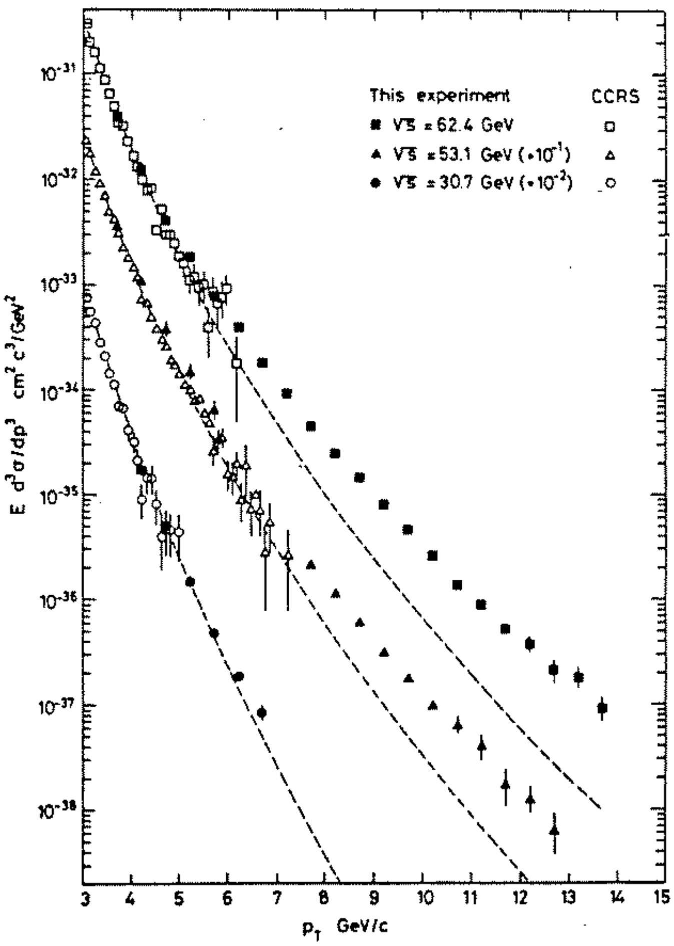


Figure 4: CCOR transverse momentum dependence of the invariant cross section for $p + p \to \pi^0 + X$ at three center of mass energies. Cross sections are offset by the factors noted. Open points and dashed fit are from a previous experiment, CCRS, F. W. Büsser, et al., Nucl. Phys. **B106**, 1 (1976).

♡ Discovery of x_T scaling with $n = 5.1 \pm 0.4$

$n(x_T, \sqrt{s})$ **WORKS,** $n \to 5 = 4^{++}$

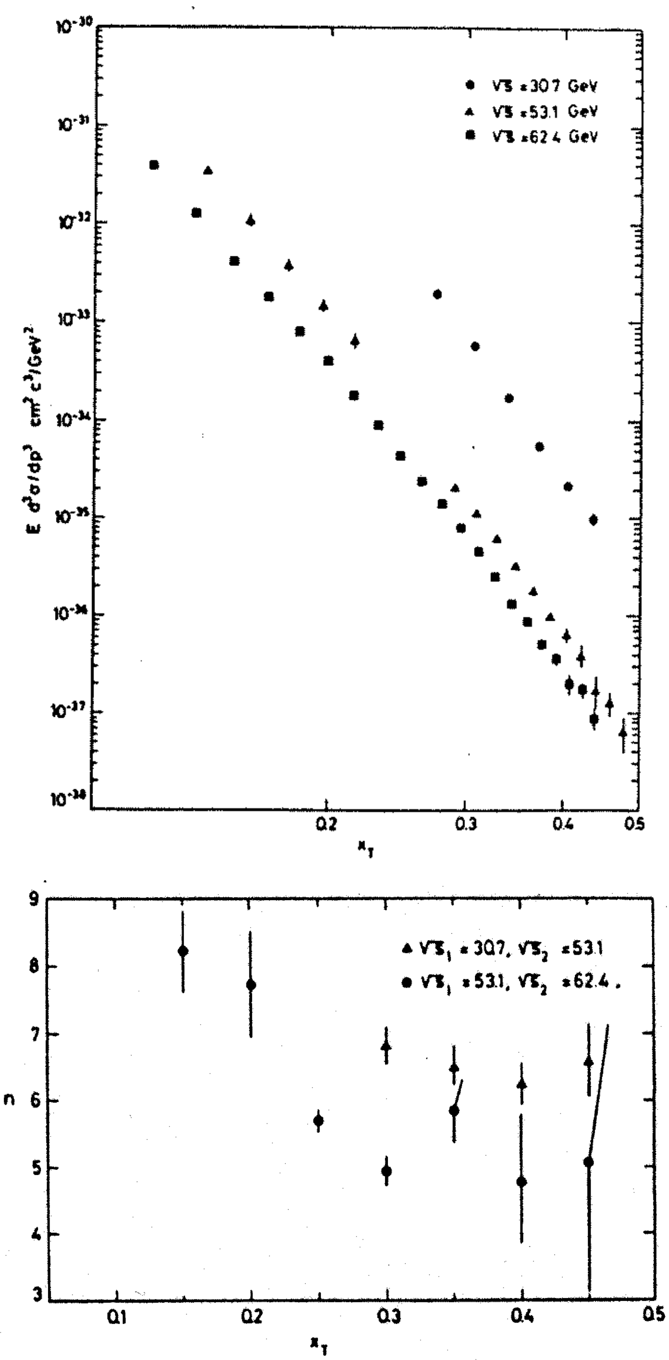


Figure 5: Top(t): CCOR invariant cross section vs $x_T = 2p_T/\sqrt{s}$. Bottom(b): $n(x_T, \sqrt{s})$ derived from the combinations indicated. *The systematic normalization at* $\sqrt{s} = 30.6$ *has been added in quadrature. Note: the absolute scale uncertainty cancels!*

♡ $Ed^3\sigma/dp^3 \simeq p_T^{-5.1\pm0.4}(1 - x_T)^{12.1\pm0.6}$, for $7.5 \leq p_T \leq 14.0$ GeV/c, $53.1 \leq \sqrt{s} \leq 62.4$ GeV (including *all* systematic errors).

x_T scaling in QCD

In p-p collisions at c.m. energy $\sqrt{s}$, the overall reaction cross section is the sum over constituent reactions (with $\sqrt{\hat{s}}$, $\hat{t}$)

$$a + b \rightarrow c + d$$

$a(x_1)$, $b(x_2)$, are structure functions, the differential probabilities for constituents a and b to carry momentum fractions x_1 and x_2 of their respective protons, e.g. $u(x_1)$,

$$\frac{d^3\sigma}{dx_1 dx_2 d\hat{t}} = \frac{1}{s^2} \sum_{ab} a(x_1) b(x_2) \frac{\pi \alpha_s^2(Q^2)}{{x_1}^2 {x_2}^2} \Sigma^{ab}(\cos\theta^*)$$

$\Sigma^{ab}(\cos\theta^*)$, the characteristic subprocess angular distributions and $\alpha_s(Q^2) = \frac{12\pi}{25} \ln(Q^2/\Lambda^2)$ are fundamental predictions of QCD. x_1, x_2, $\cos\theta^*$ are dimensionless, functions of ratios of momenta.

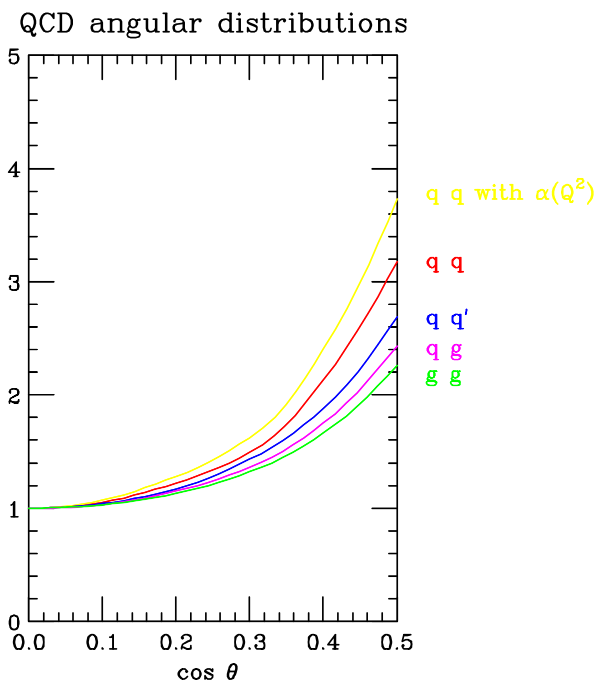
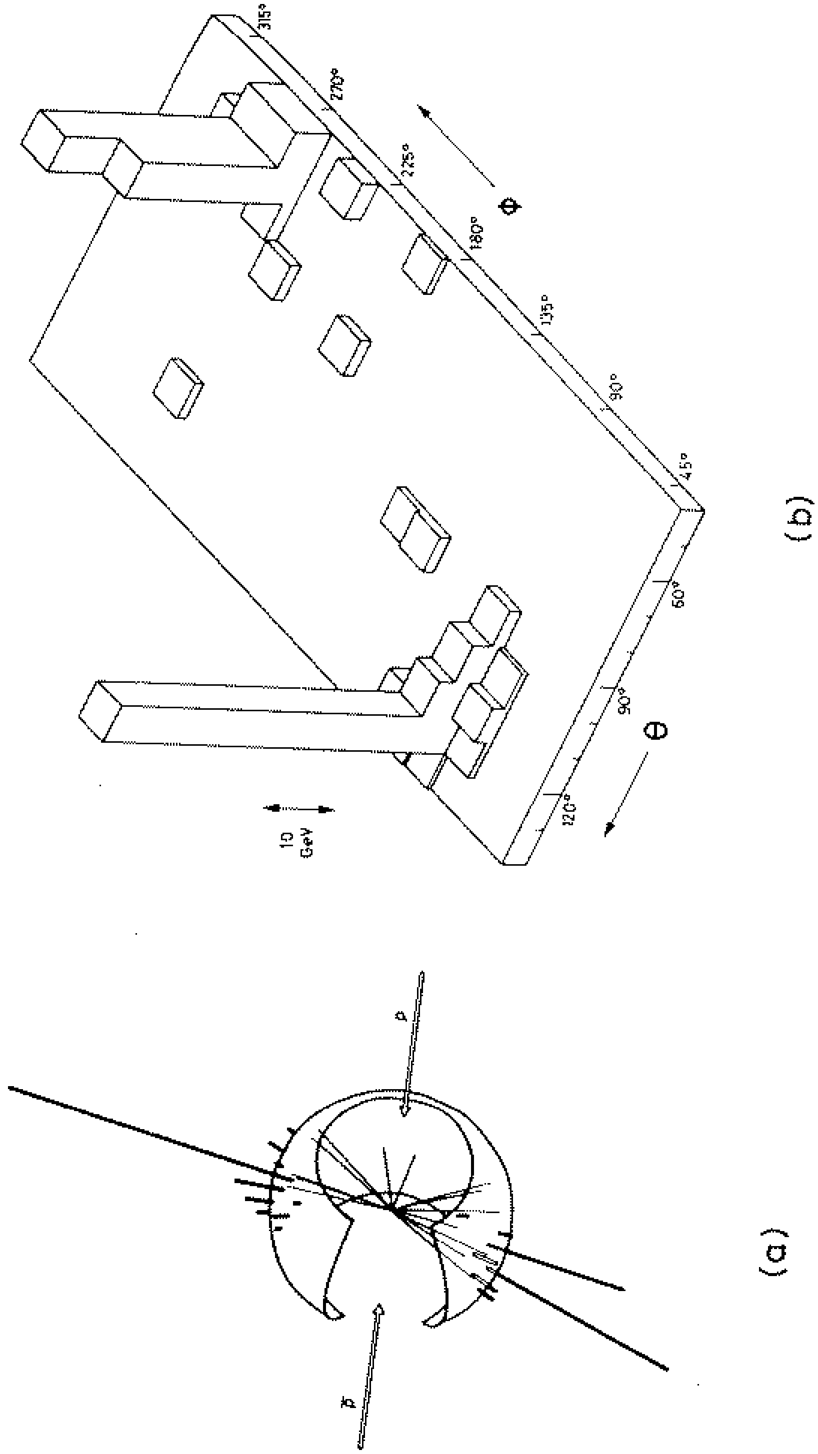
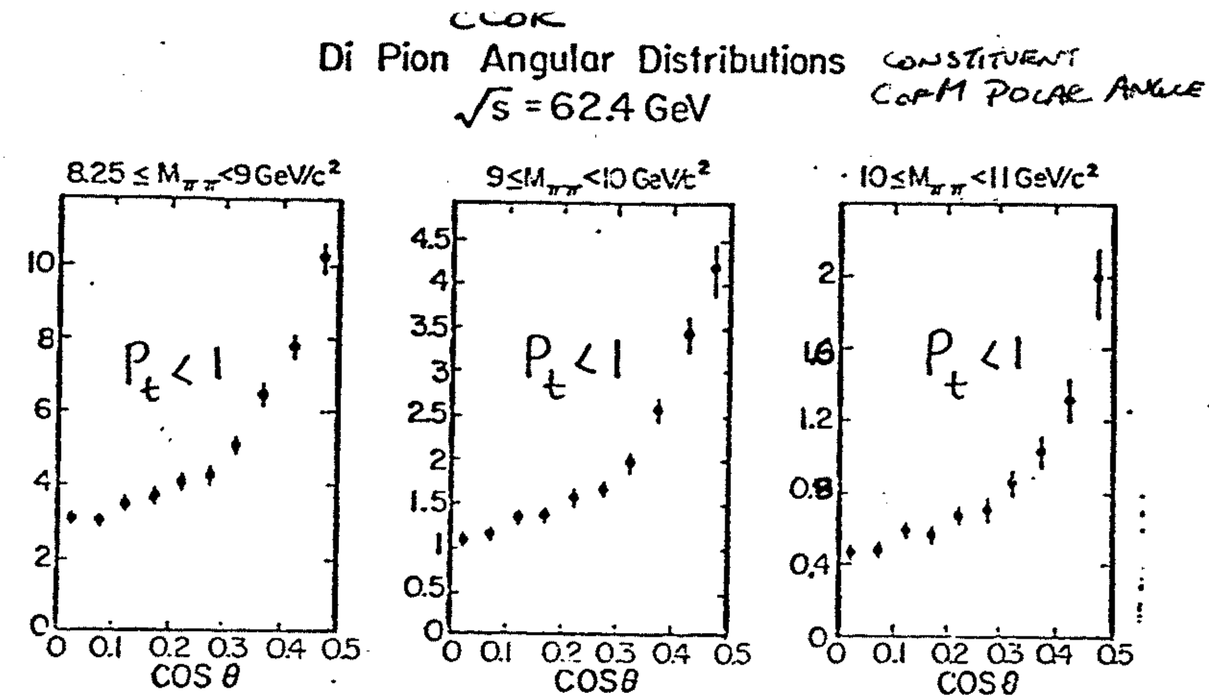


Figure 6: Characteristic QCD Subprocess scattering angular distributions.

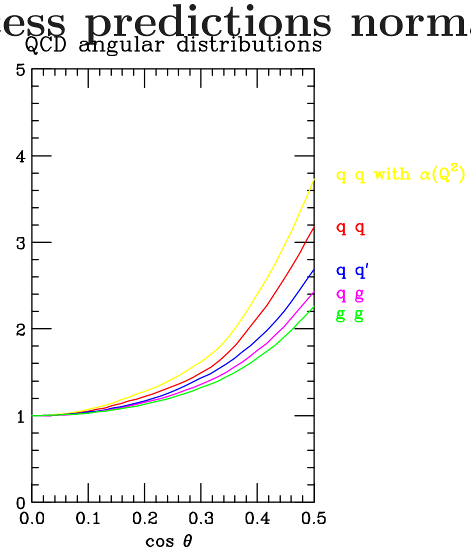
Int'l HEP Conference, Paris, 1982
The UA2 Two-Jet Event



Int'l HEP Conference, Paris, 1982— First measurement of QCD subprocess angular distributions



QCD Subprocess predictions normalized at 90°



Angular distributions of pairs of nearly back-to-back π^0 as a function of the invariant mass $M_{\pi\pi}$ of the pair. The net P_t of the pion pair is restricted as indicated on the figure and the net rapidity of the di-pion system is restricted to $|Y_{\pi\pi}| < 0.35$. The distribution plotted is the polar angular distribution of the dipion axis in the frame with zero net longitudinal momentum. The important feature of the analysis in these variables, which are more typically used for lepton pairs, is that the di-pion angular distribution at fixed mass corresponds closely to the distribution of scattered partons at fixed $\hat{s}$, thus the data and QCD prediction at the parton level can be directly compared without recourse to a Monte Carlo. [see Nucl Phys **B209** (1982) 284].

To go from p-p to A+A collisions: We know from DIS that Hard Scattering is Point-Like

E. Gabathuler, Total cross-section

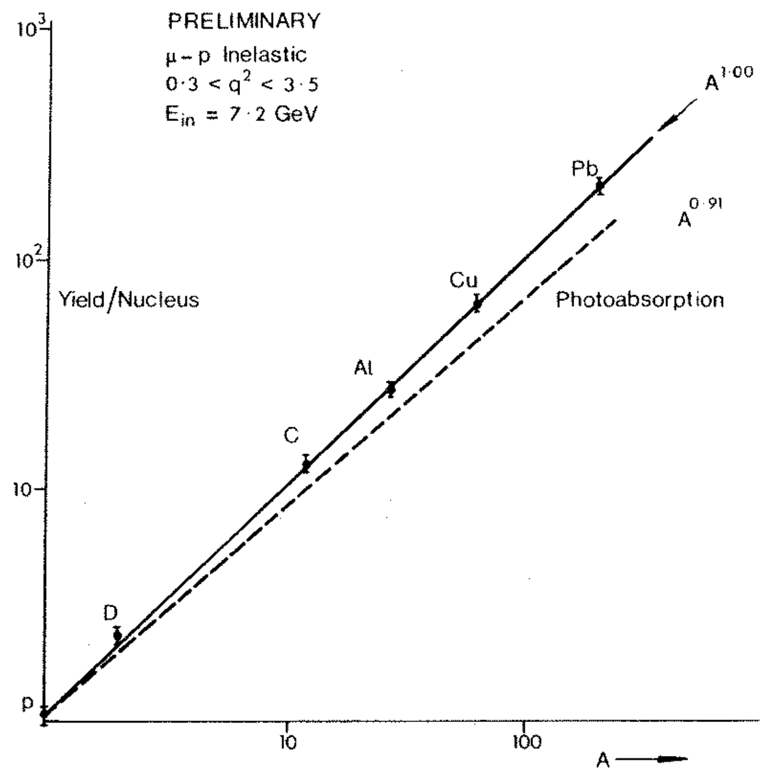


Fig. 14. The *A* dependence of the inelastic muon cross-section as presented by Tannenbaum (see discussion).

AGS $\mu - A$ scattering data, from E. Gabathuler's talk, [Proc. 6th Int. Symposium on Electron and Photon Interactions at High Energies, Bonn (1973)].

♡ DIS is pointlike $A^{1.00}$ even at modest q^2—no shadowing.

♡ Photoproduction is shadowed—$A^{0.91}$

♡ In the region of hard scattering ($p_T > 2$ GeV/c) scaling from p-p to nuclear collisions should be simply proportional to the relative number of point-like encounters, corresponding to A (p+A), $A \times B$ (A+B) for the total rate and to T_{AB}, the overlap integral of the nuclear profile functions, as a function of centrality.

What Really Happens in Hadron Scattering

The Anomalous Nuclear Enhancement
aka the 'Cronin Effect'
The unpleasant Nuclear Effect

Due to Multiple Scattering of the initial Nucleons (Constituents?)
Now called k_T broadening.
But don't forget 'shadowing' of the Structure Functions in Nuclei
For latest info see E. Wang and X.-N. Wang nucl-th/0104031

CERN Pb+Pb $\sqrt{s_{NN}} = 17.2$ GeV

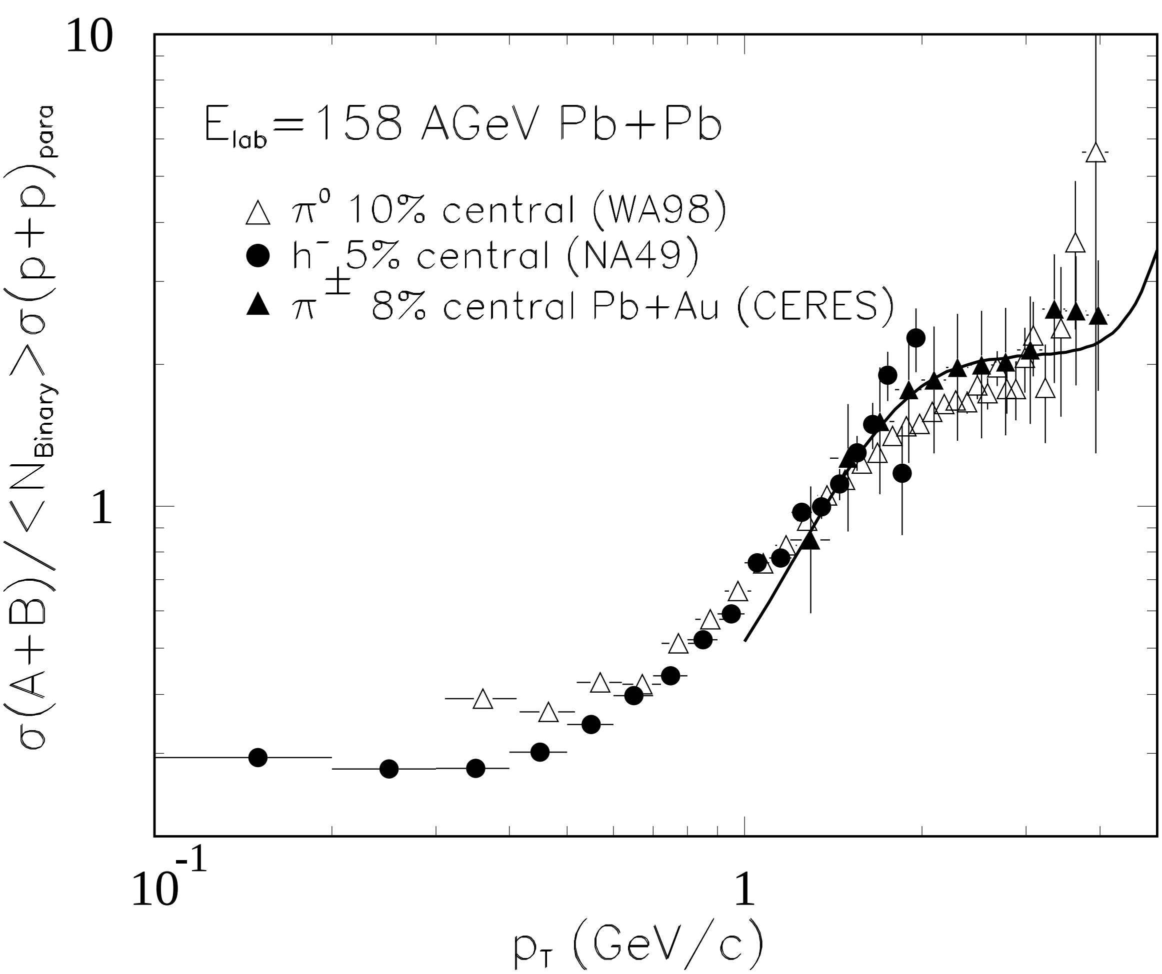
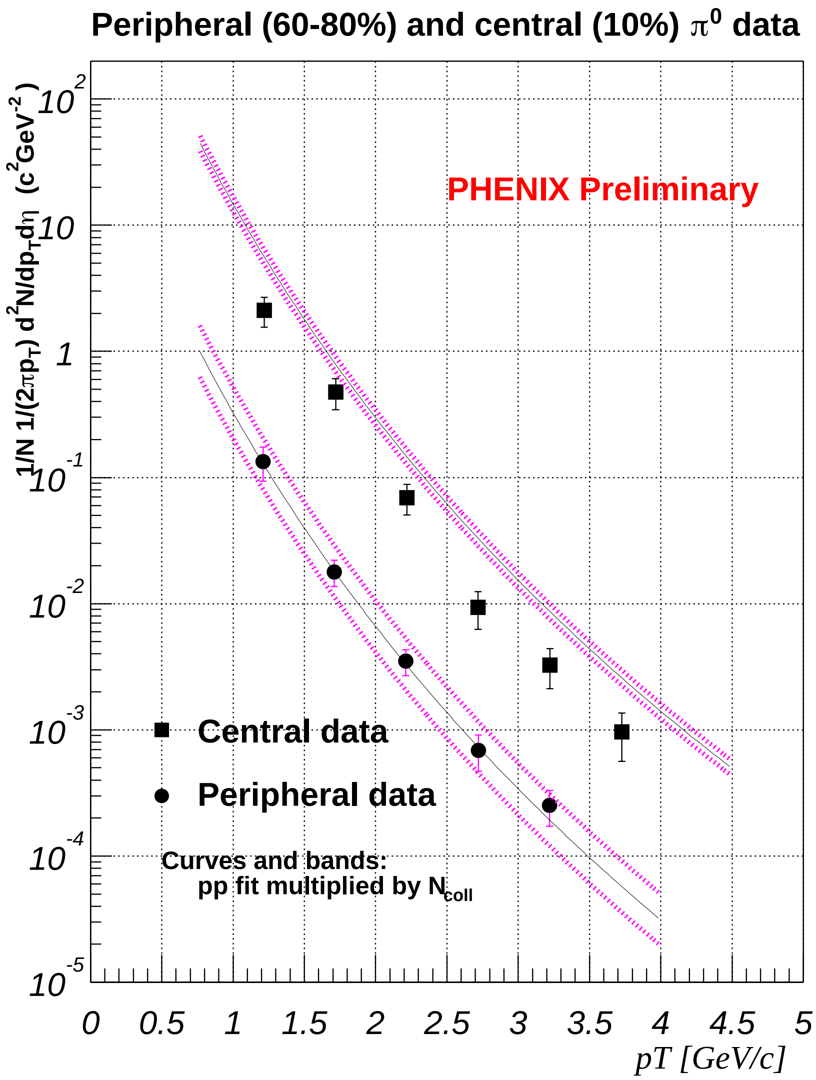


Figure 7: From Wang and Wang nucl-th/0104031

What happens at RHIC—something new!
High $p_T \pi^0$ —PHENIX
Au+Au $\sqrt{s_{NN}}$=130 GeV
π^0 Cent. and Periph.



PHENIX central and peripheral π^0 semi-inclusive yield, scaled by $\langle T_{AB} \rangle$ for the centrality class= $\langle N_{coll}(40\text{mb})\rangle/40\text{mb}$

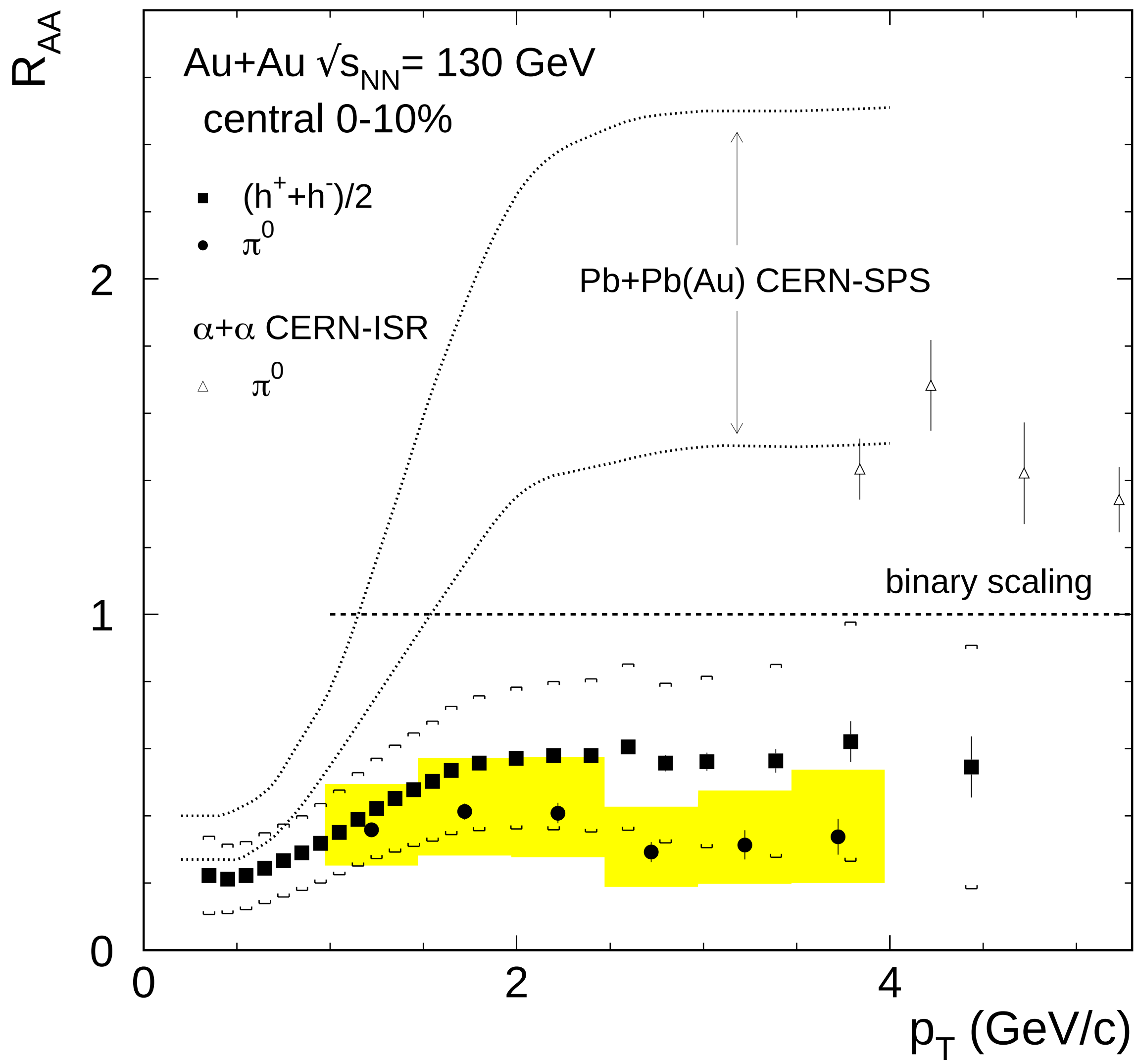
♡ **Central π^0 yield is BELOW the point-like prediction!!**

♡ Made the cover of PRL **88** 14 January 2002!

A New and Interesting High p_T Nuclear Effect

Ratio of PHENIX π^0 and $(h^+ + h^-)/2$ Central to UA1 fit

A deficit for $p_T > 2$ GeV/c—never seen previously!!!



• Do the scattered partons lose energy in hot matter, thus reducing the energy of the fragments, i.e. reducing the number of π^0 at a given p_T—'Jet Quenching'. (may not respect x_T scaling).

• Or is there a huge nuclear shadowing in Au+Au collisions at RHIC (e.g. Gluon Saturation) so that fewer high p_T jets are produced. In this case x_T scaling should hold with the same $n(x_T, \sqrt{s})$ as p-p collisions since the shadowing only affects the $G(x_T)$ term, and will be the same at a given x_T as $\sqrt{s}$ varies.

High p_T π^0 suppression continues in Au+Au at $\sqrt{s_{NN}}$=200 GeV

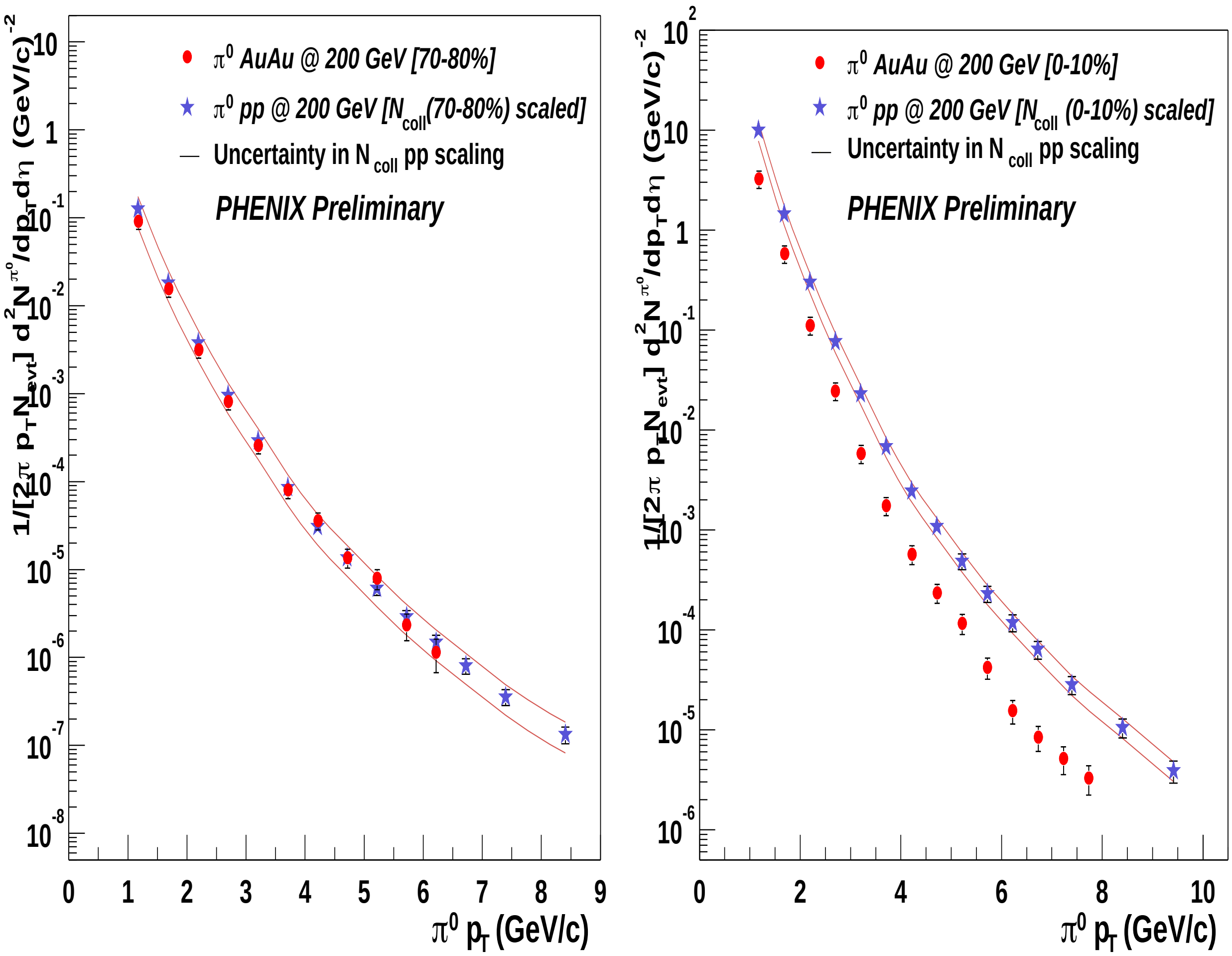


Figure 8: (a) π^0 Invariant yields for peripheral (60-70) and (b) central (0-10) Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV as a function of p_T compared to point-like scaled p-p **measurements**.

- **p-p data at $\sqrt{s} = 200$ GeV is measured by PHENIX**
- **No RHIC p-p data at $\sqrt{s} = 130$ GeV**