x_T scaling for high p_T π^0 production in Au+Au collisions at RHIC

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Mid-rapidity transverse momentum (p_T) spectra of pions from p-p$^{\pm}$ collisions of c.m. energy $\sqrt{s}$ from 23 to 1800 GeV exhibit a characteristic shape: an exponential tail at low $p_T \leq 1$ GeV/c which depends very little on $\sqrt{s}$, changing to a power-law tail which depends very strongly on $\sqrt{s}$ with a characteristic scaling behavior indicative of fragmentation of jets produced by hard-scattering. The scaling law is of the form

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^{\,n(x_T,\sqrt{s})}}\, G(x_T) \quad \text{where} \quad x_T = 2p_T/\sqrt{s} \quad .$$

Values of $n(x_T, \sqrt{s})$ are in the range 5–8. Suppression of high p_T π^0 has been observed in Au+Au collisions at RHIC with respect to point-like scaling from p-p collisions. If the effect is due to shadowing of the structure functions, rather than a final state interaction with the hot medium, then, presumably, the cross sections at a given x_T should all exhibit the same suppression, so that the values of $n(x_T, \sqrt{s})$ should remain unchanged from p-p to Au+Au collisions. This is investigated with the latest PHENIX π^0 data from Au+Au collisions at $\sqrt{s_{NN}} = 130$ and Au+Au and p-p collisions at 200 GeV.

Systematics of inclusive π^0 or $\pi^\pm$ production in p-p collisions

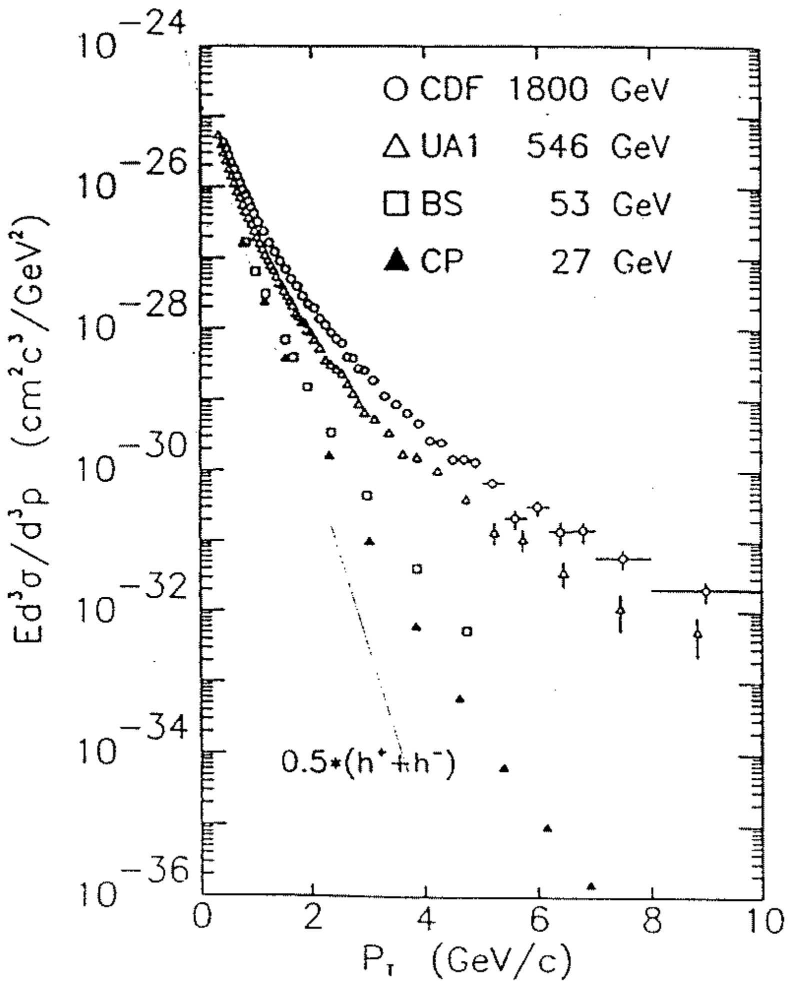


Figure 1: Invariant cross section for non-identified charged-averaged hadron production at 90° in the c.m. system as a function of the transverse momentum p_T tablulated by CDF for a range of c.m.energies $\sqrt{s}$.

- 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 c.1997 was that the QGP would cause the high p_T quarks to lose all their energy and stop, so that the high p_T tail would 'vanish' for central Au+Au collisions**

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

♡ The discovery that the DIS structure function

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

"SCALED" i.e just depended on the ratio

$$x = \frac{Q^2}{2M\nu} \quad (2)$$

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)

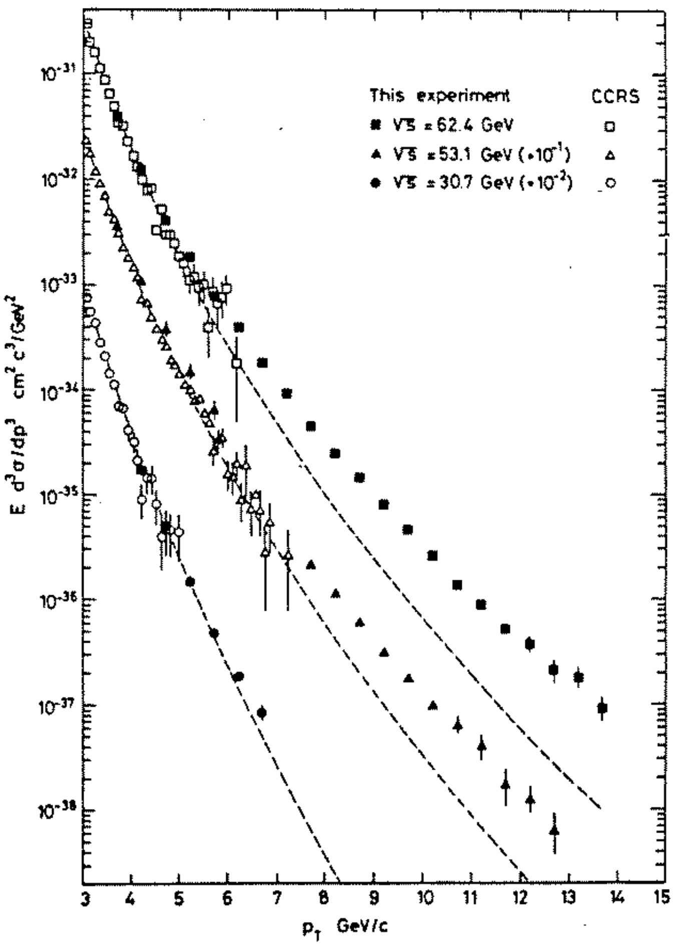


Figure 2: CCOR transverse momentum dependence of the invariant cross section for $p + p \rightarrow \pi^0 + X$ at three center of mass energies. Cross sections are offset by the factors noted. Open points and dashed fit are from a previous experiment, CCRS, F. W. Büsser, et al., Nucl. Phys. **B106**, 1 (1976).

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

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

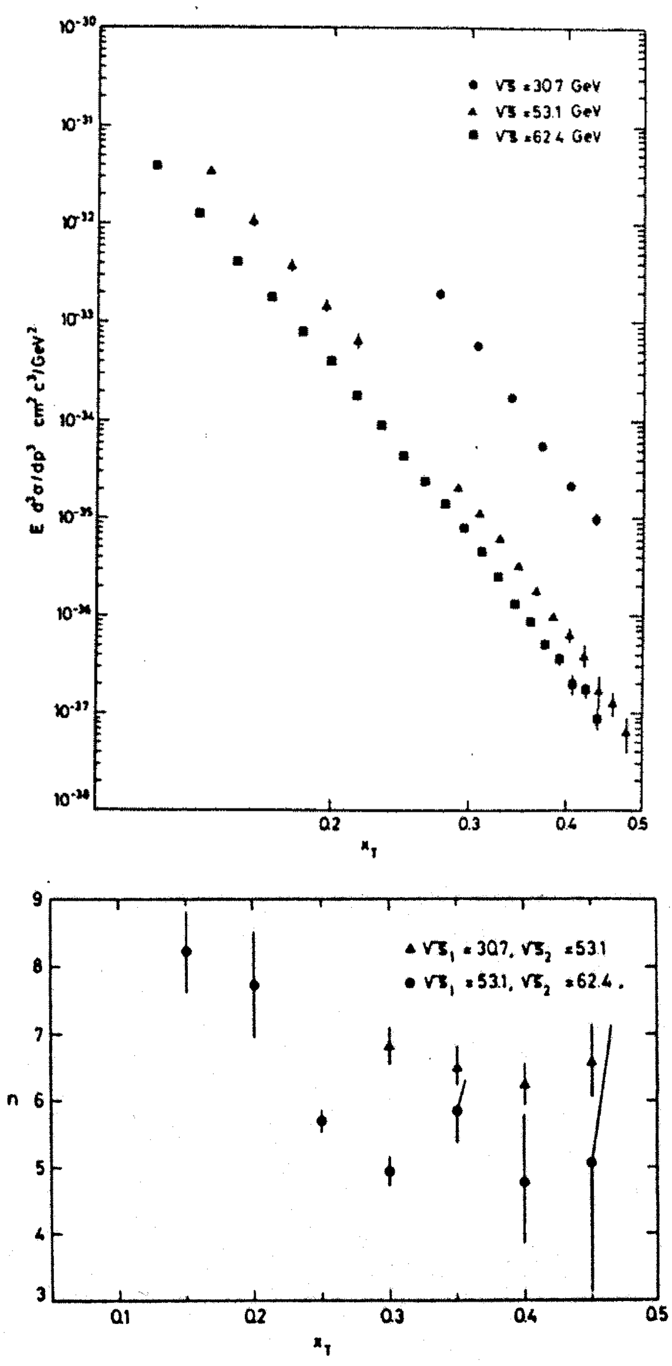


Figure 3: Top(t): CCOR invariant cross section vs $x_T = 2p_T/\sqrt{s}$. Bottom(b): $n(x_T, \sqrt{s})$ derived from the combinations indicated. *The systematic normalization at* $\sqrt{s} = 30.6$ *has been added in quadrature. Note: the absolute scale uncertainty cancels!*

♡ $Ed^3\sigma/dp^3 \simeq p_T^{-5.1\pm0.4}(1-x_T)^{12.1\pm0.6}$, 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.

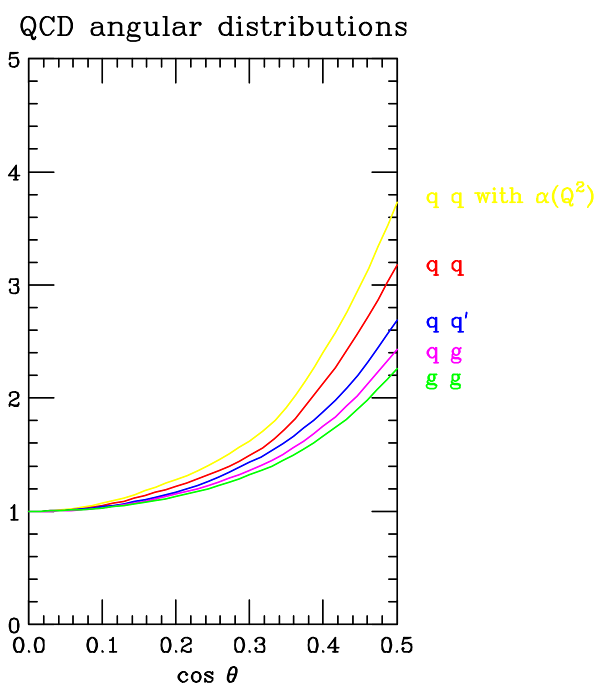


Figure 4: Characteristic QCD Subprocess scattering angular distributions.

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

E. Gabathuler, Total cross-section

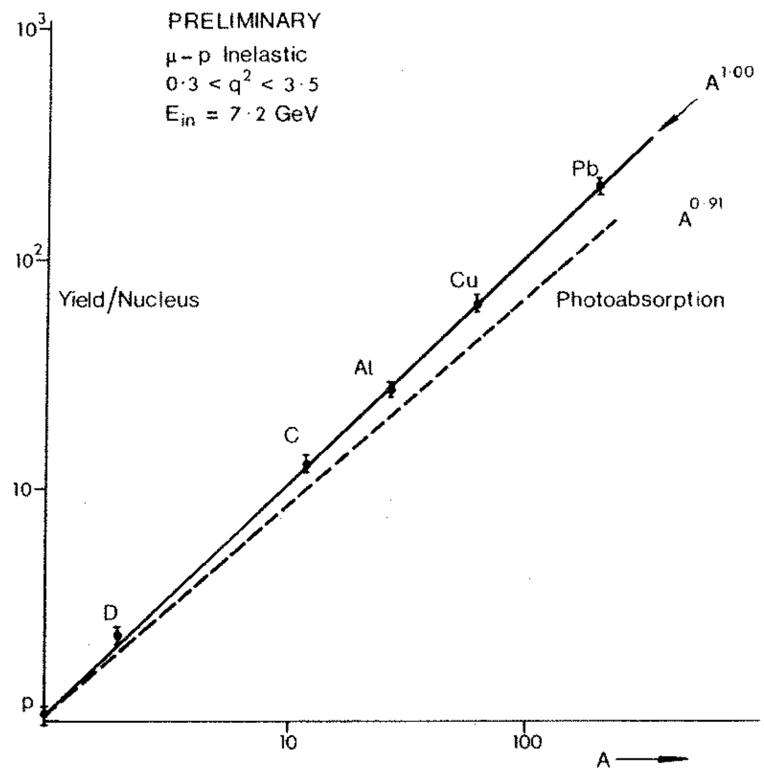


Fig. 14. The *A* dependence of the inelastic muon cross-section as presented by Tannenbaum (see discussion).

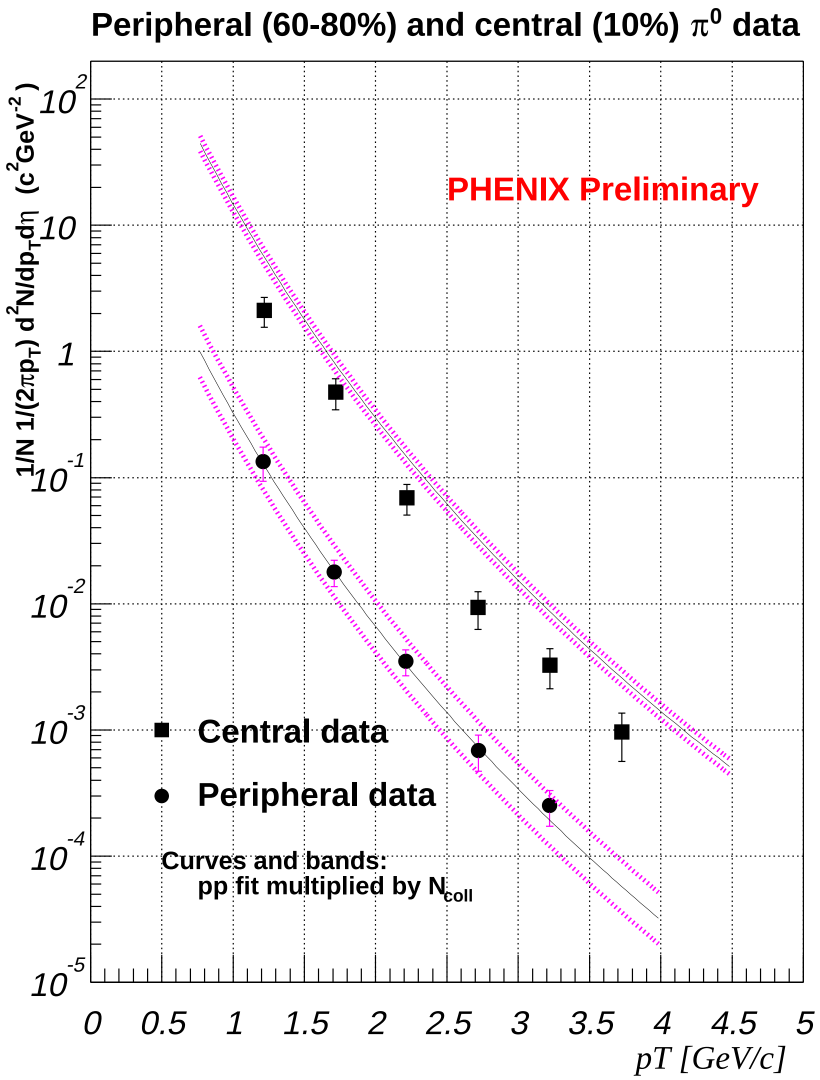
AGS $\mu - A$ scattering data, from E. Gabathuler's talk, [Proc. 6th Int. Symposium on Electron and Photon Interactions at High Energies, Bonn (1973)].

♡ 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 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= $\langle N_{coll}(40\text{mb})\rangle/40\text{mb}$

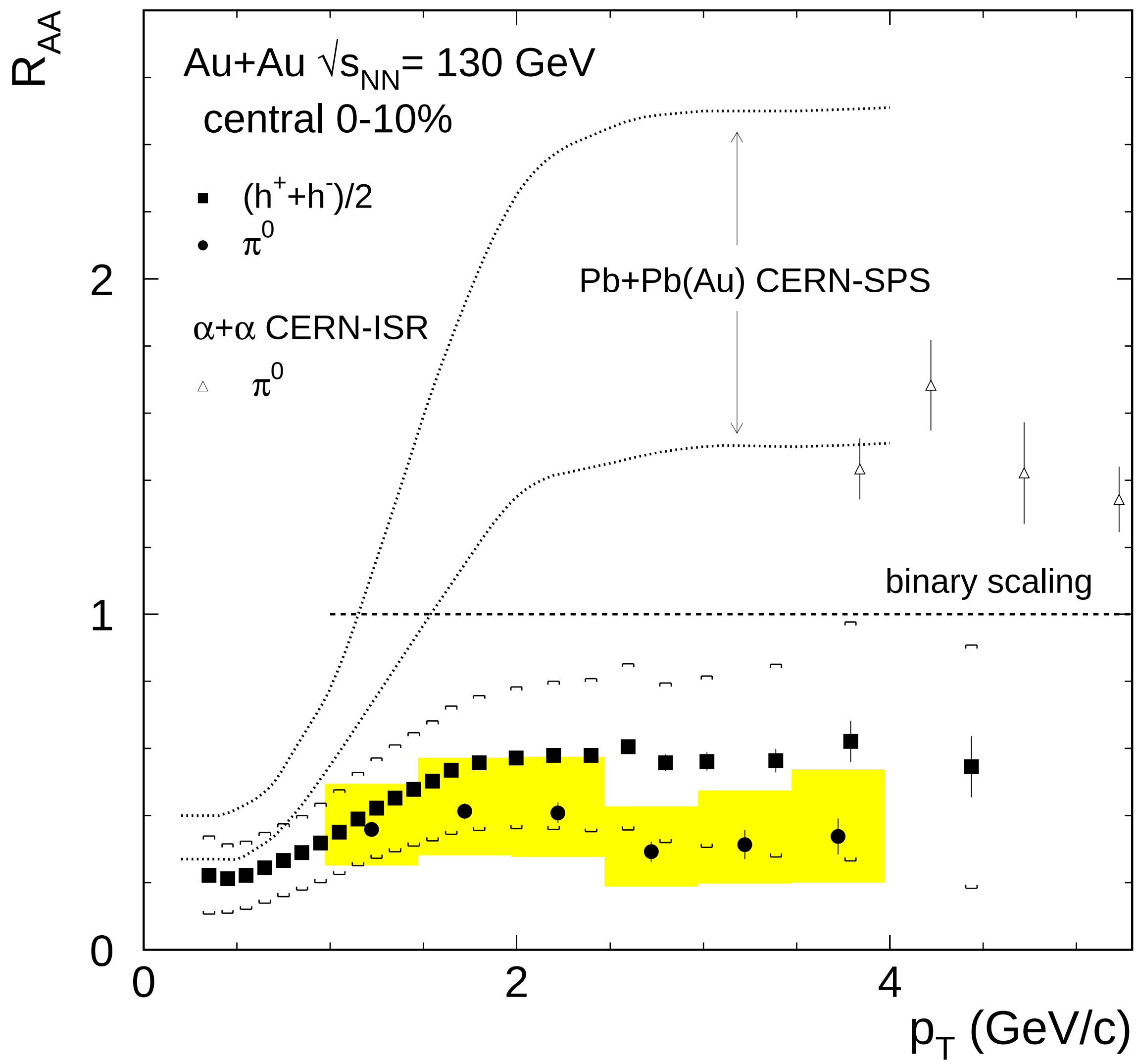
♡ **Central π^0 yield is BELOW the point-like prediction!!**

♡ 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

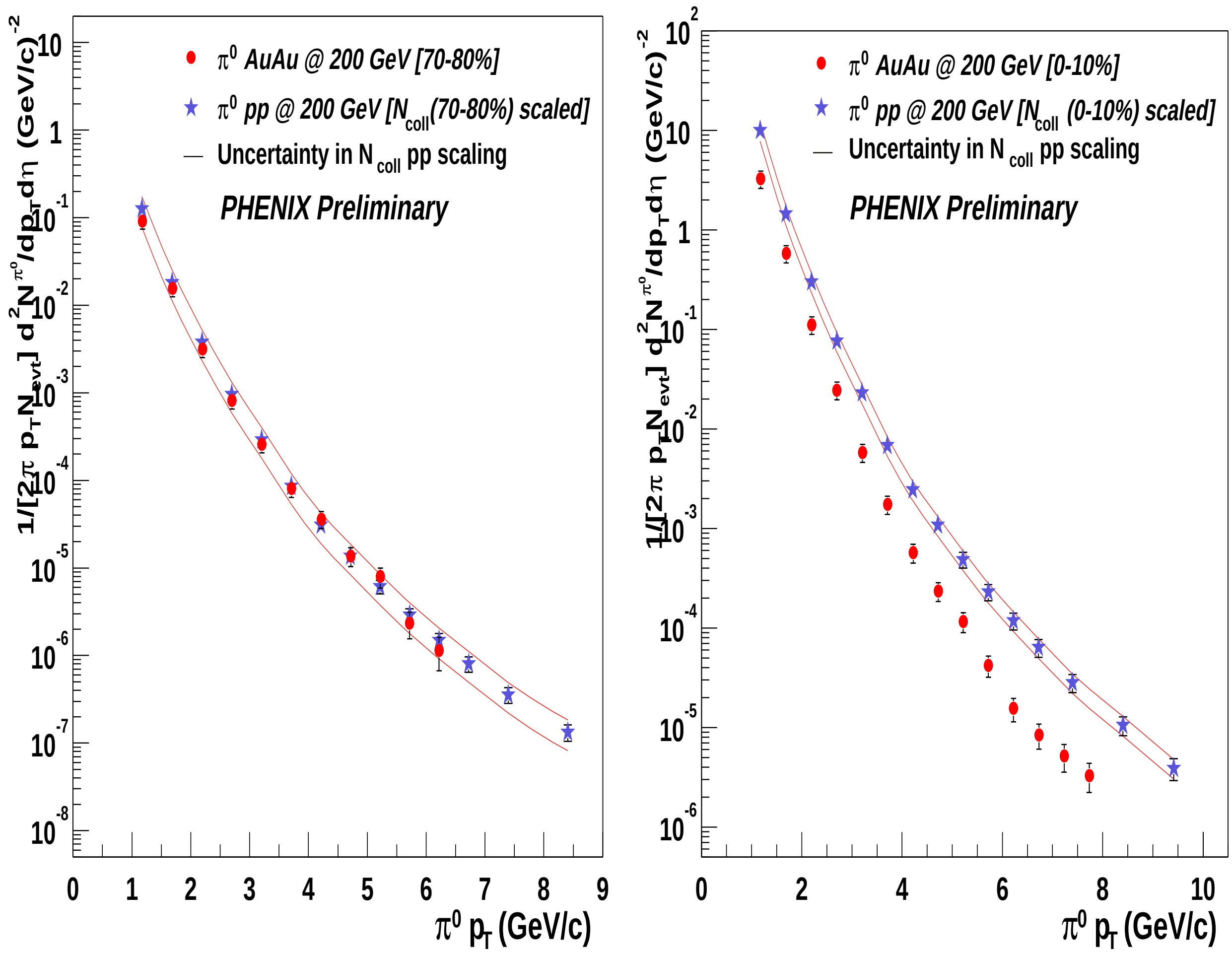


Figure 5: (a) π^0 Invariant yields for peripheral (60-70) and (b) central (0-10) Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of p_T compared to point-like scaled p-p **measurements**.

- **p-p data at $\sqrt{s} = 200$ GeV is measured by PHENIX**
- **No RHIC p-p data at $\sqrt{s} = 130$ GeV**
- **Test for x_T scaling from $\sqrt{s_{NN}}$=130 to 200 GeV using Au+Au peripheral (60-80%) and central (0-10%).**

Invariant Yield vs x_T in Au+Au at 130 and 200 GeV

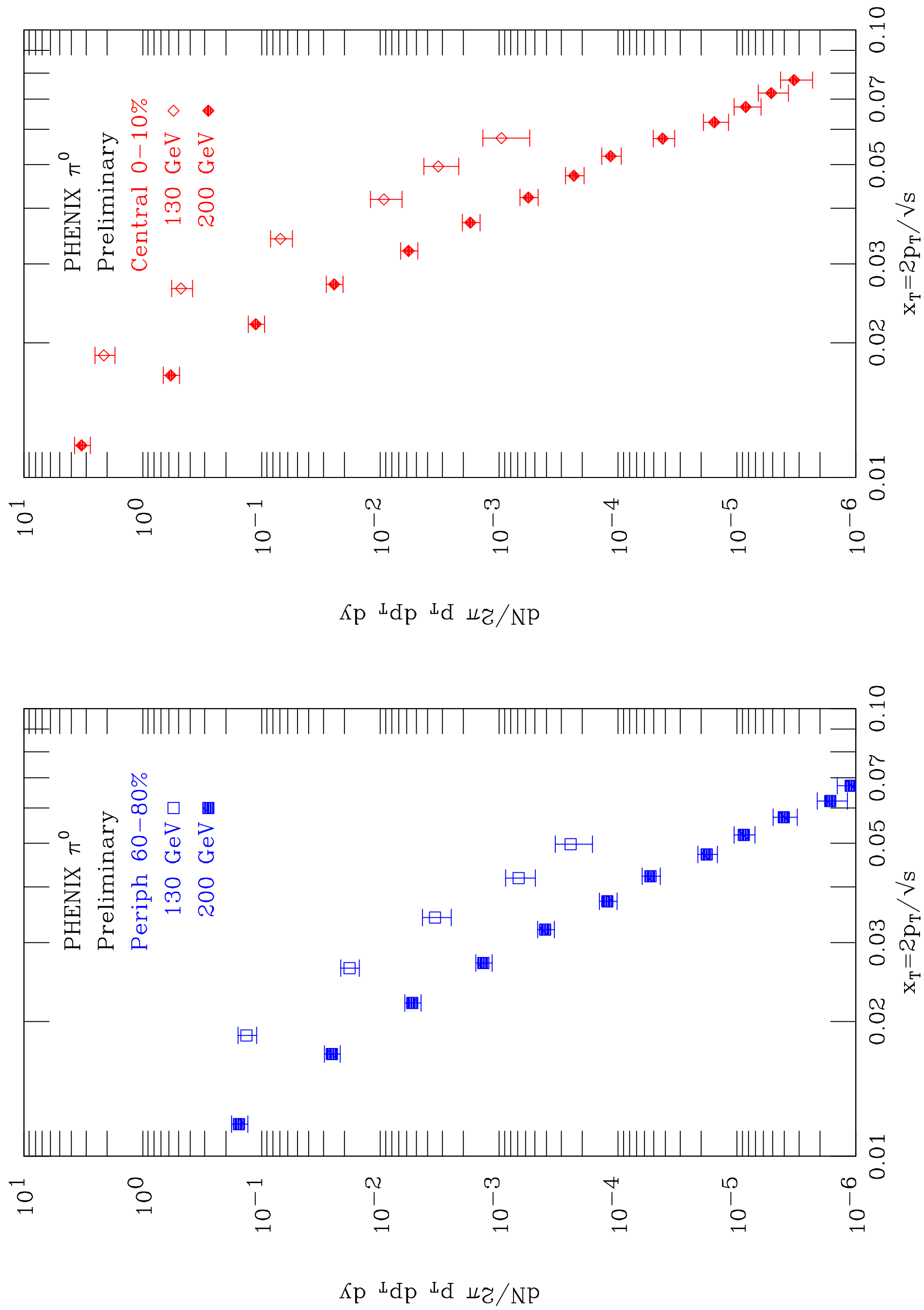


Figure 6: log-log plots of invariant yields vs x_T for peripheral and central Au+Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV.

♡ Reasonable x_T scaling in the region $0.025 \leq x_T \leq 0.06$: curves at 130 and 200 GeV are parallel for both peripheral and central Au+Au collisions.

x_T scaling in Au+Au Collisions

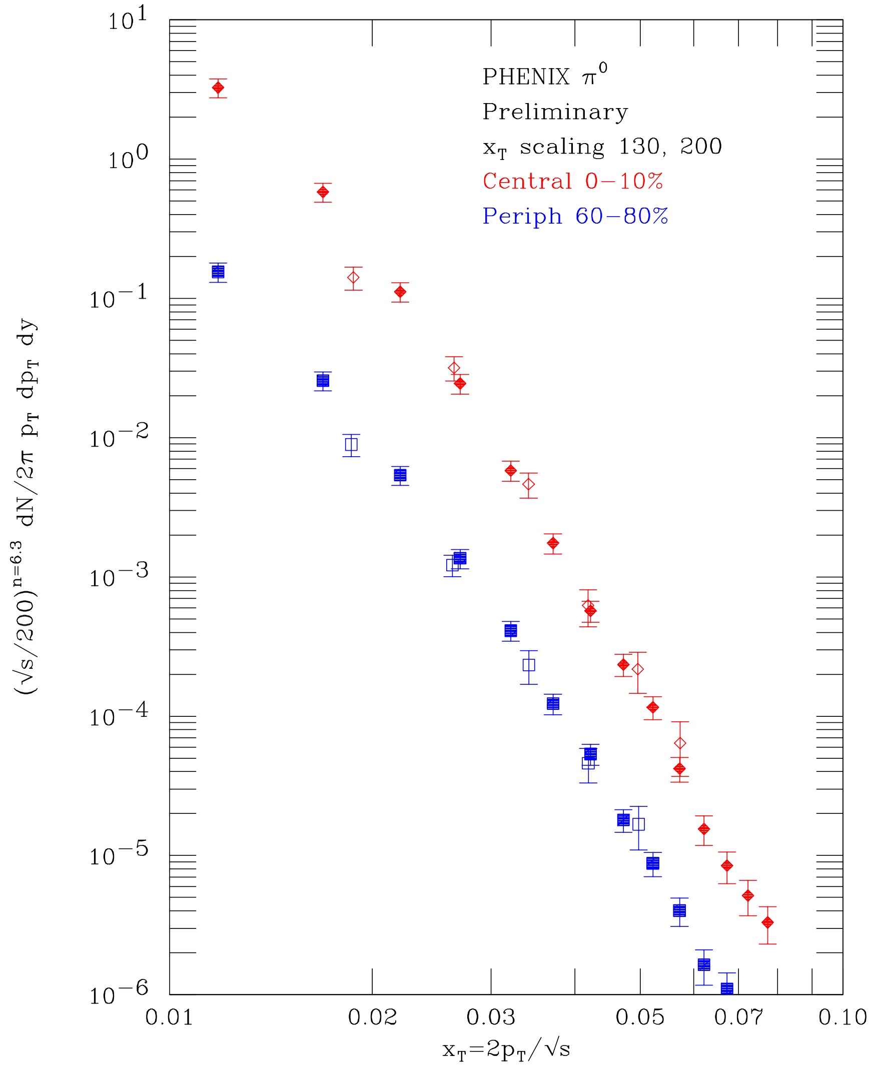


Figure 7: (a) π^0 Invariant yields for peripheral (60-80) and central (0-10) Au+Au collisions at $\sqrt{s_{NN}}$=130 and 200 GeV versus x_T on a log-log plot where the yields have been multiplied by the factor $(\sqrt{s}/200)^{6.3}$, for both peripheral and central collisions.

♡ Ratio of 130 to 200 GeV at fixed x_T is ~ 15 for both peripheral and central collisions, corresponding to $n = 6.3 \pm 0.7$, when correlated systematic errors are included.—Not unreasonable compared to lower energy p-p data.

♡ $\sqrt{s_{NN}}$ dependence consistent with pQCD in Au+Au for both peripheral and central. Precision test is lacking due to missing p-p data at 130 GeV.

♡ Inconclusive on Shadowing versus Quenching. Awaits definitive test in d+Au collisions, where only shadowing is operative: But it's hard for me to believe a factor of 5 suppression from Shadowing!!!