Hard Scattering in PHENIX at RHIC

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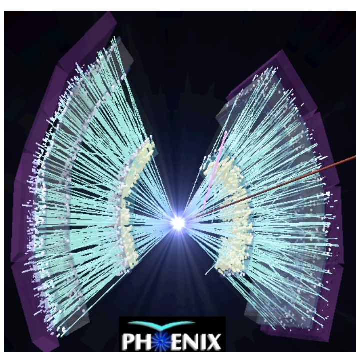


Seminar
MIT, Cambridge MA
March 16, 2007

Bjorken Scaling in Deeply Inelastic Scattering and the Parton Model---1968

- ♡ The discovery that the DIS structure function

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

"SCALED" i.e just depended on the ratio

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

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

- ♡ as originally suggested by **Bjorken** Phys. Rev. **179**, 1547 (1969)
- ♡ Led to the concept of a proton composed of point-like **partons**. Phys. Rev. **185**, 1975 (1969)

$$\nu = \frac{Q^2}{2Mx}$$

- ☐ 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)

- BBK calculated for p+p collisions, the inclusive reaction

$$A+B \rightarrow C + X \qquad \text{when particle } C \text{ has } p_T >> 1 \text{ GeV/c}$$

  - 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."*

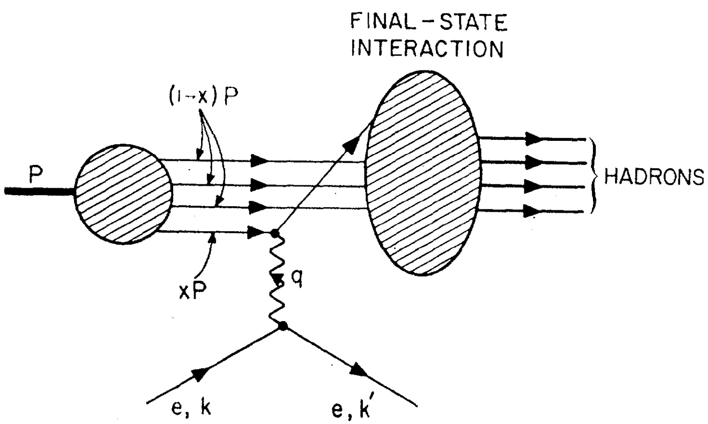
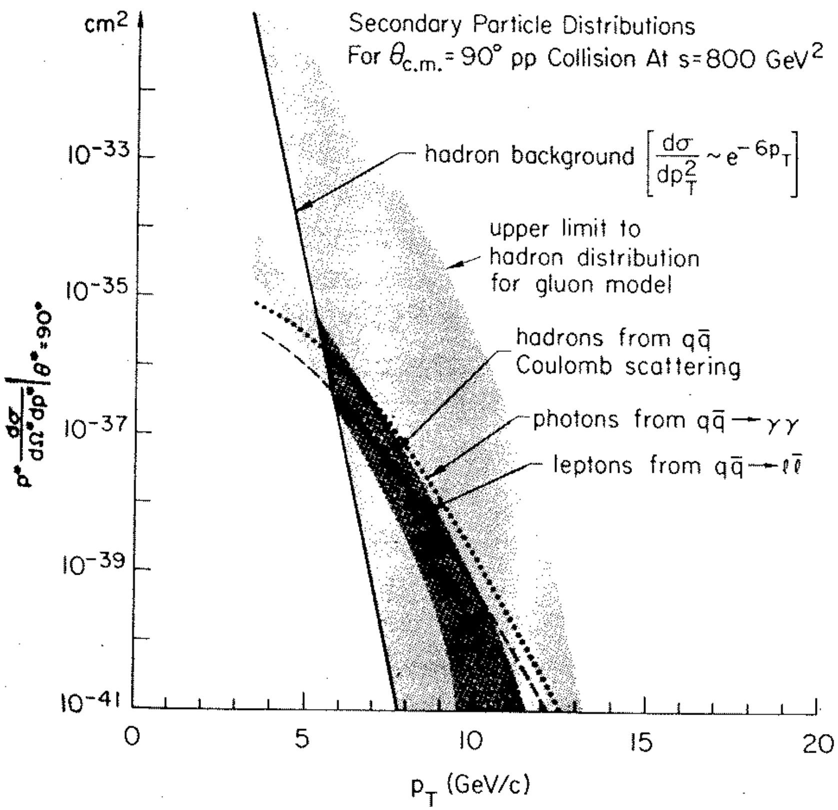


FIG. 1. Kinematics of lepton-nucleon scattering in the parton model.



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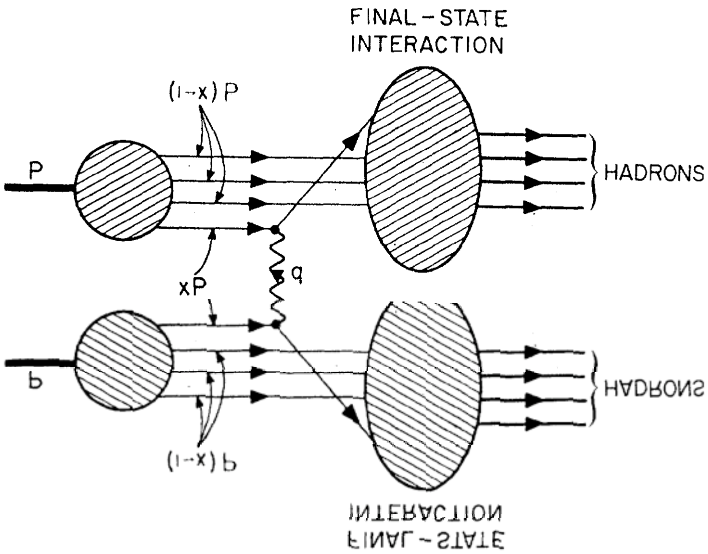
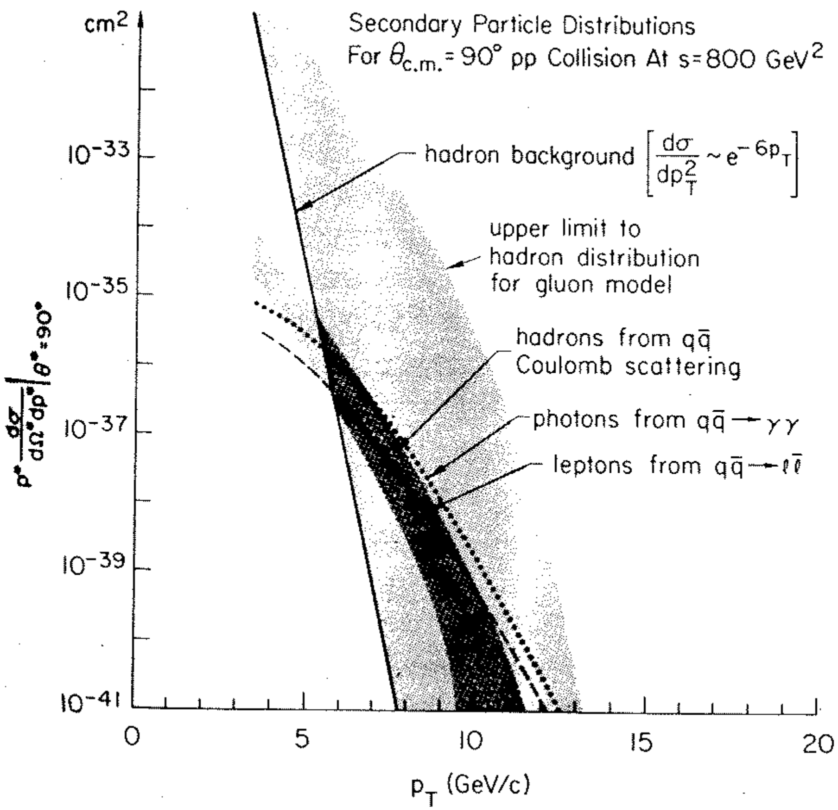
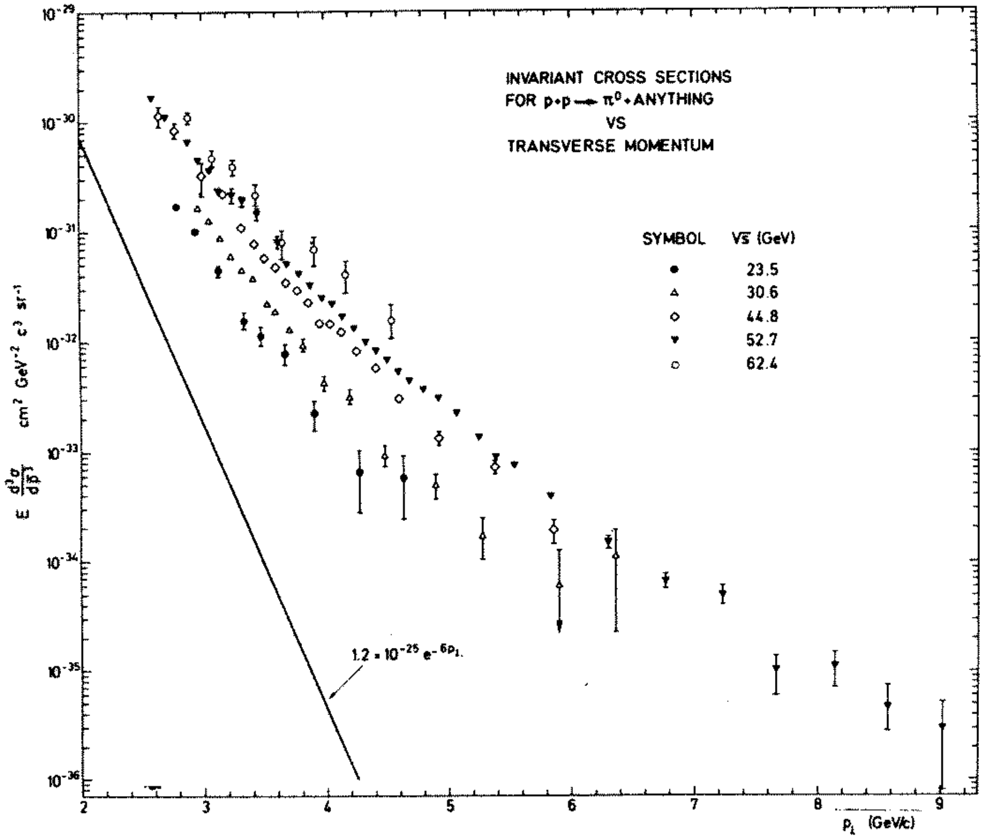




CCR at the CERN-ISR
Discovery of high p_T production in p-p



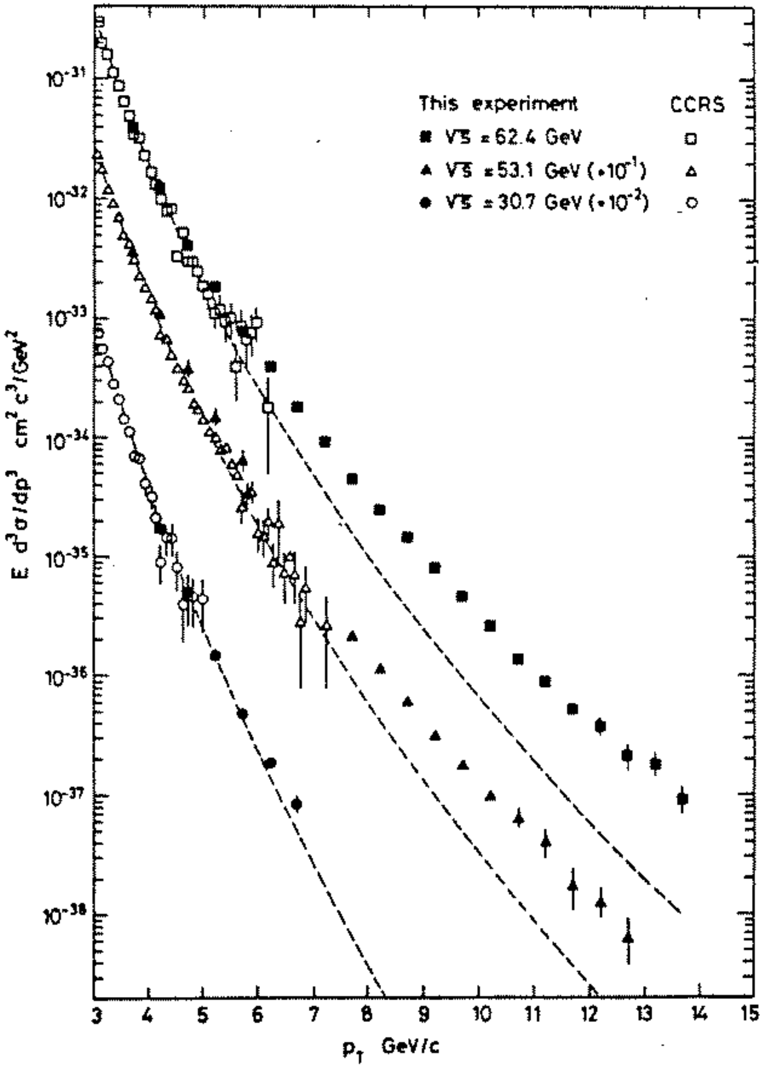
F.W. Busser, *et al.*,
CERN, Columbia, Rockefeller Collaboration
Phys. Lett. **46B**, 471 (1973)

Bj scaling → BBK scaling →
Blankenbecler, Brodsky, Gunion
Scaling PL **42B**, 461 (1972)

$$E\frac{d^3\sigma}{d^3p} = \frac{1}{p_T^n} F\left(\frac{p_T}{\sqrt{s}}\right) = \frac{1}{\sqrt{s}^{\,n}} G(x_T)$$

- e^{-6p_T} breaks to a power law at high p_T with characteristic √s dependence
- Large rate indicates that partons interact strongly (>> EM) with other.
- Data follow BBK-BBG scaling but with n=8!, not n=4 as expected for QED

CCOR 1978--Discovery of “REALLY high p_T>7 GeV/c” at ISR



CCOR A.L.S. Angelis, et al, Phys.Lett. **79B**, 505 (1978)

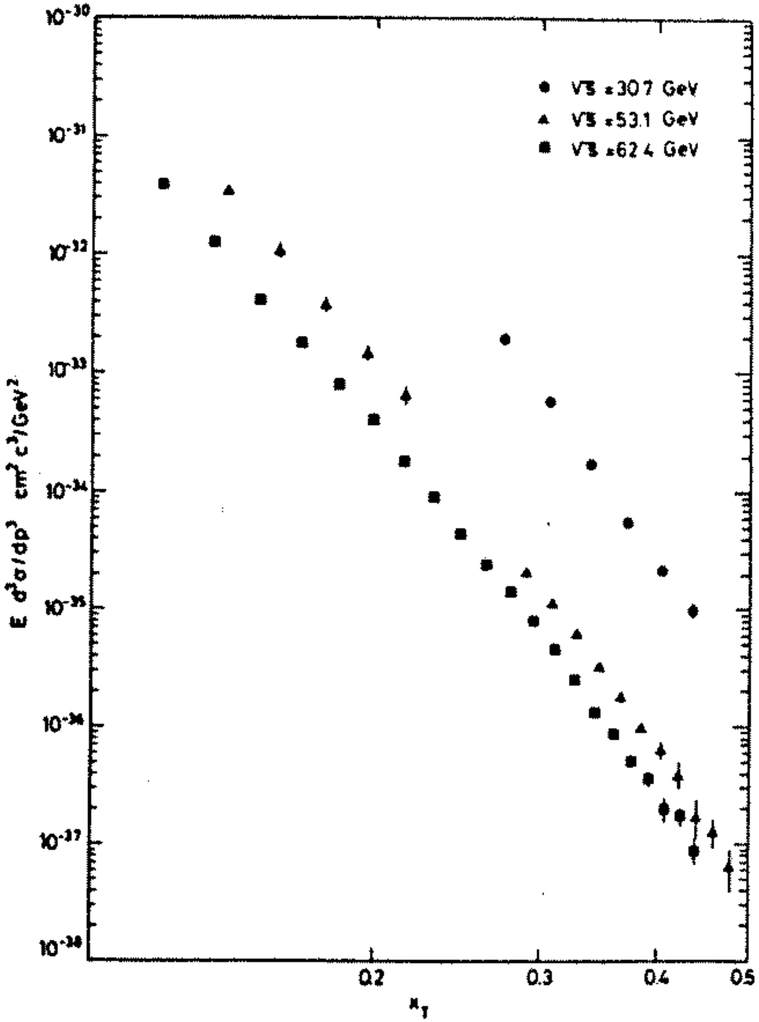
See also A.G. Clark, et al Phys.Lett **74B**, 267 (1978)

- Agrees with CCR, CCRS (Busser) data for $p_T < 7$ GeV/c.
- Disagrees with CCRS fit pT > 7 GeV/c
- New fit is:

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

n=5 (=4^{++}) as predicted for QCD

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

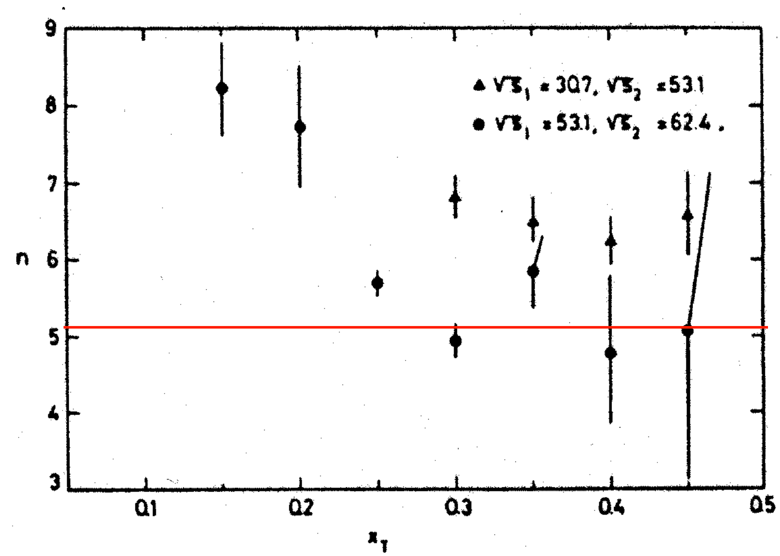


Same data $Ed^3\sigma/dp^3(x_T)$ ln-ln plot

QCD: Cahalan, Geer, Kogut, Susskind, PR**D11**, 1199 (1975)

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

$$\left(\frac{\sqrt{s_1}}{\sqrt{s_2}}\right)^{n(x_T,\sqrt{s})} = \frac{E\frac{d^3\sigma}{dp^3}(x_T,\sqrt{s_2})}{E\frac{d^3\sigma}{dp^3}(x_T,\sqrt{s_1})}$$



Status of ISR single particle measurements 1978

- Hard-scattering was visible both at ISR and and FNAL (Fixed Target Energies) by single particle inclusive production at large p_T>2-3 GeV/c
- Scaling and dimensional arguments showed that the partons of DIS interacted with each other much more strongly than electromagnetically, but with n=4++, characteristic of single-photon exchange, as in coulomb scattering or "J=1 gluon exchange". Experimenters turned their attention to measuring the predicted di-jet structure of the hard-scattered parton-pair using two-particle correlations.
- This configuration was found but it was discovered by the experimenters (with some help from Feynman, Field and Fox, [NPB 128,1 (1977)]) that the jet-pair was not exactly back-to-back in aziumth but had a net transverse momentum imbalance, called $\langle p_{Tpair} \rangle = \surd 2 \langle k_T \rangle$. FFF defined $\langle k_T \rangle$ as the average transverse momentum of a quark inside its parent hadron.
- It was also discovered that k_T is what made n=4++→n=8, "k_T smearing", and that $\langle k_T \rangle$ was not constant i.e. not "intrinsic" but varied with p_T and $\surd s$.

Status of QCD Theory in 1978

- The first modern QCD calculations and predictions for high p_T single particle inclusive cross sections including non-scaling and initial state radiation was done in 1978 by J. F. Owens, E. Reya, M.Gluck, PRD **18**, 1501 (1978), “Detailed quantum-cnromodynamic predictions for high-p_T processes,” and J.F. Owens, J. D. Kimel, PRD **18**, 3313 (1978), “Parton-transverse-momentum effects and the quantum-chromodynamic description of high-p_T processes”.

- This work was closely followed and corroborated by Feynman, Field, Fox PRD **18**, 3320 (1978), “Quantum-chrodynamic approach for the large-transverse-momentum production of particles and jets.”

- However it took until 1982 for the HEP community to believe in jets, but that’s another story.

LO-QCD in 1 slide

Cross Section in p-p collisions c.m. energy $\sqrt{s}$

The overall p-p reaction cross section
is the sum over constituent reactions

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

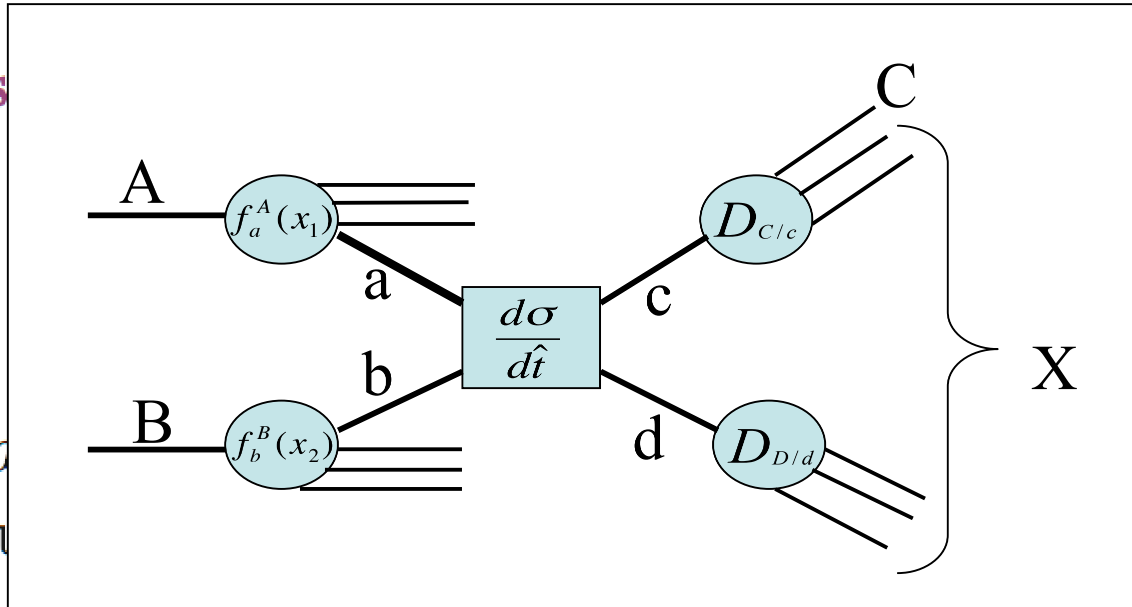
$f_a^A(x_1)$, $f_b^B(x_2)$, are structure functions, the differential probabilities for constituents a and b to carry momentum fractions x_1 and x_2 of their respective protons, e.g. $u(x_1)$,

$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s}\sum_{ab} f_a^A(x_1) f_b^B(x_2) \frac{\pi\alpha_s^2(Q^2)}{2x_1x_2}\Sigma^{ab}(\cos\theta^*)$$

$\Sigma^{ab}(\cos\theta^*)$, the characteristic subprocess angular distributions and $\alpha_s(Q^2) = \frac{12\pi}{25\ln(Q^2/\Lambda^2)}$ are predicted by QCD

LO-QCD in 1 slide

Cross ... gy $\sqrt{s}$



$f_a^A(x_1)$, $f_b^B(x$ ... probabilities
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Relationship to DIS

The quantities $f_a^A(x_1)$ and $f_b^B(x_2)$, the "number" distributions of the constituents, are related (for the electrically charged quarks) to the structure functions measured in Deeply Inelastic lepton-hadron Scattering (DIS), e.g.

$$F_{1\mathrm{B}}(x,Q^2) = \frac{1}{2}\sum_b e_b^2\, f_b^B(x,Q^2) \quad \text{and} \quad F_{2\mathrm{B}}(x,Q^2) = x\sum_b e_b^2\, f_b^B(x,Q^2) \qquad (1)$$

where e_b is the electric charge on quark b.

The Mandelstam invariants $\hat{s}$, $\hat{t}$ and $\hat{u}$ of the constituent scattering have a clear definition in terms of the scattering angle θ^* in the constituent c.m. system:

$$\hat{t} = -\hat{s}\,\frac{(1-\cos\theta^*)}{2} \qquad \text{and} \qquad \hat{u} = -\hat{s}\,\frac{(1+\cos\theta^*)}{2} \quad . \qquad (2)$$

The transverse momentum of a scattered constituent is:

$$p_T = p_T^* = \frac{\sqrt{\hat{s}}}{2}\,\sin\theta^*\,, \qquad (3)$$

and the scattered constituents c and d in the outgoing parton-pair have equal and opposite momenta in the parton-parton (constituent) c.m. system. A naive experimentalist would think of $Q^2 = -\hat{t}$ for a scattering subprocess and $Q^2 = \hat{s}$ for a Compton or annihilation subprocess.

Relationship to inclusive high p_T production in hadron collisions

$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{s d^3\sigma}{d\hat{s} d\hat{y} d\cos\theta^*} =$$

$$= \frac{s}{2}\frac{d^3\sigma}{dp_T^2\, dy_c\, dy_d} = \frac{1}{s}\sum_{ab} f_a^A(x_1) f_b^B(x_2) \frac{\pi\alpha_s^2(Q^2)}{2x_1x_2}\Sigma^{ab}(\cos\theta^*)$$

where

$$\cos\theta^* = \tanh\frac{(y_c - y_d)}{2} \qquad \sin\theta^* = 1/\cosh\frac{(y_c - y_d)}{2}$$

$$x_1 = x_T \frac{e^{y_c} + e^{y_d}}{2} \qquad x_2 = x_T \frac{e^{-y_d} + e^{-y_c}}{2} \quad .$$

For comparison with the literature, e.g. Renk and Eskola, hep-ph/0601059, note:

$$\frac{d\sigma}{d\hat{t}} = \frac{\pi\alpha_s^2(Q^2)}{\hat{s}^2}\Sigma^{ab}(\cos\theta^*) \qquad \frac{d\sigma}{d\cos\theta^*} = \frac{\pi\alpha_s^2(Q^2)}{2\hat{s}}\Sigma^{ab}(\cos\theta^*)$$

$\Sigma^{ab}(\cos\theta^*)$ and Spin Asymmetry -- Fundamental predictions of QCD

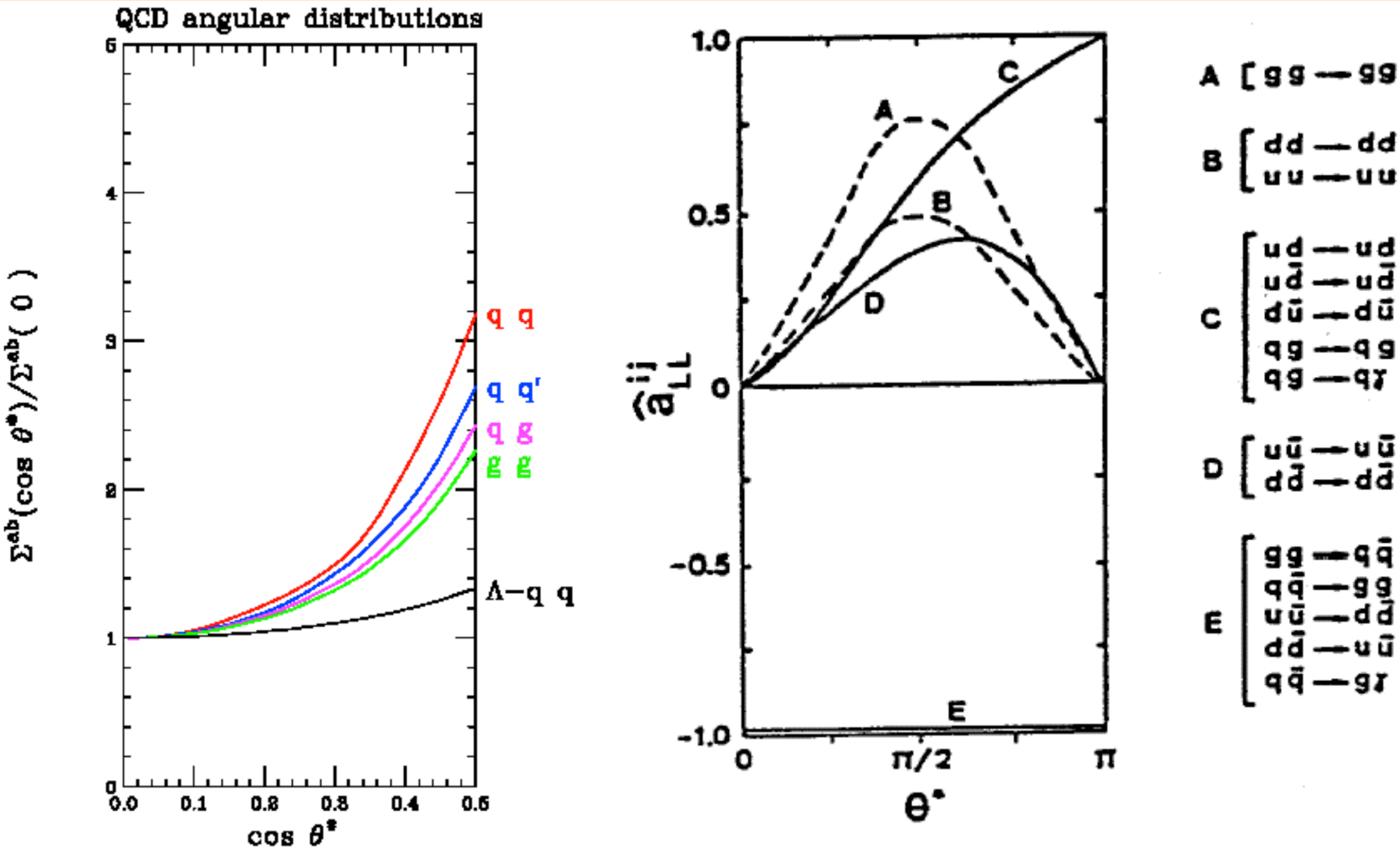
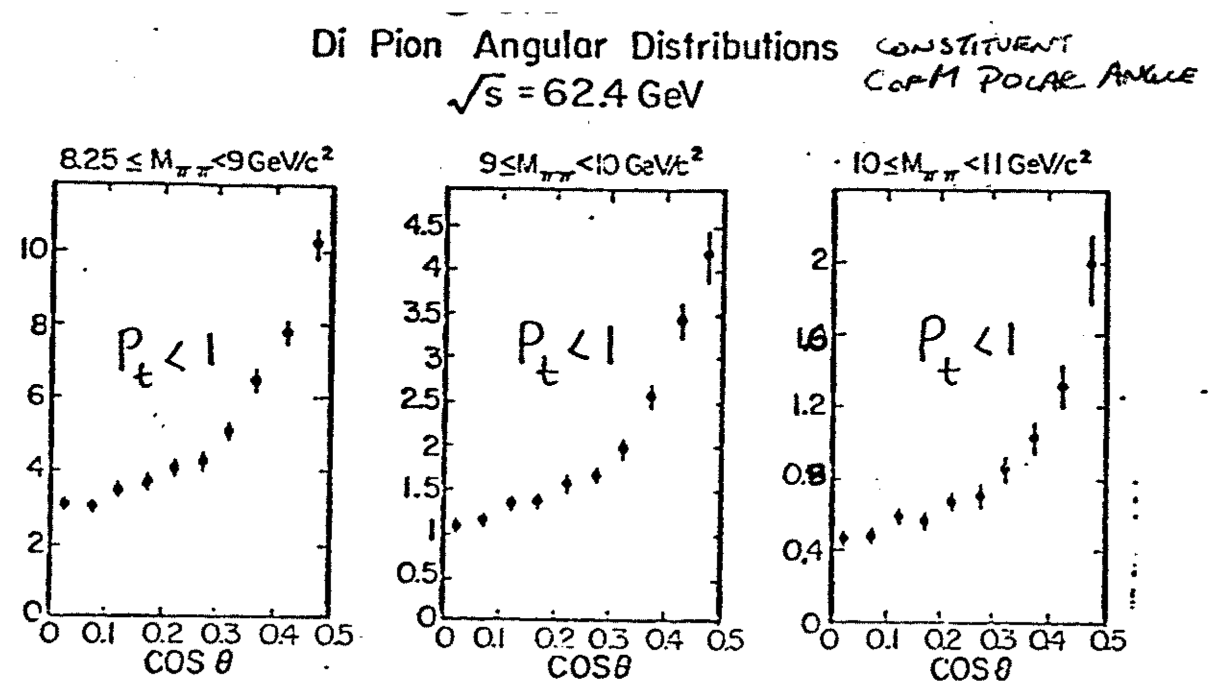


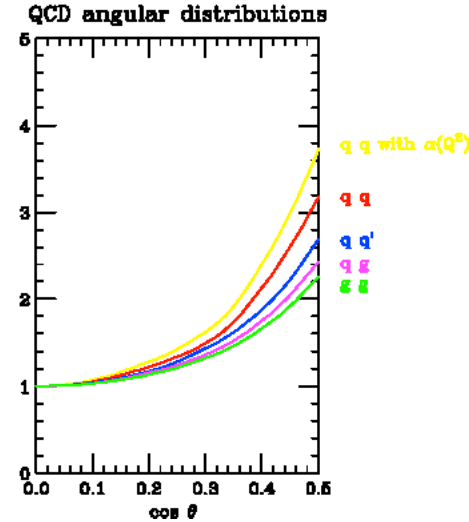
Fig. 2. Characteristic QCD Subprocess angular distributions: (a) scattering; (b) spin asymmetry

Paris1982-first measurement of QCD subprocess angular distribution using π^0-π^0 correlations

DATA: CCOR NPB 209, 284 (1982)



QCD



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$\Sigma^{ab}(\cos\theta^*)$, the characteristic subprocess angular distributions and $\alpha_s(Q^2) = \frac{12\pi}{25\ln(Q^2/\Lambda^2)}$ are predicted by QCD

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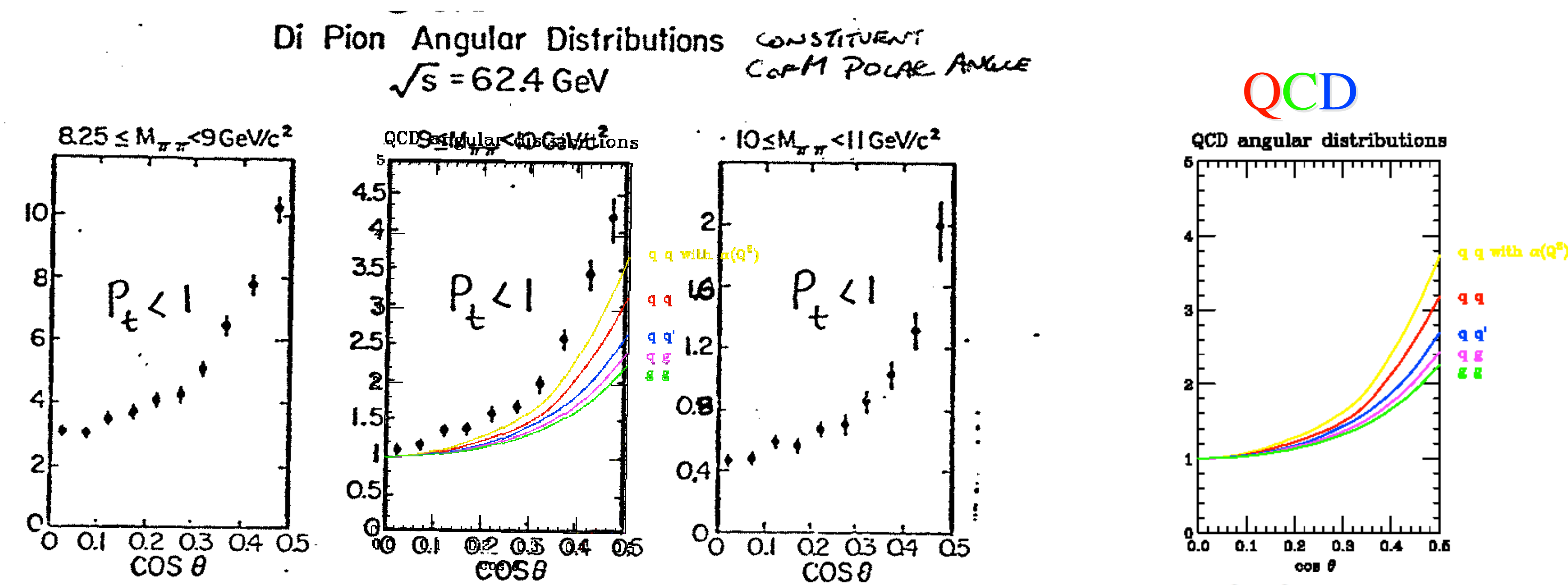

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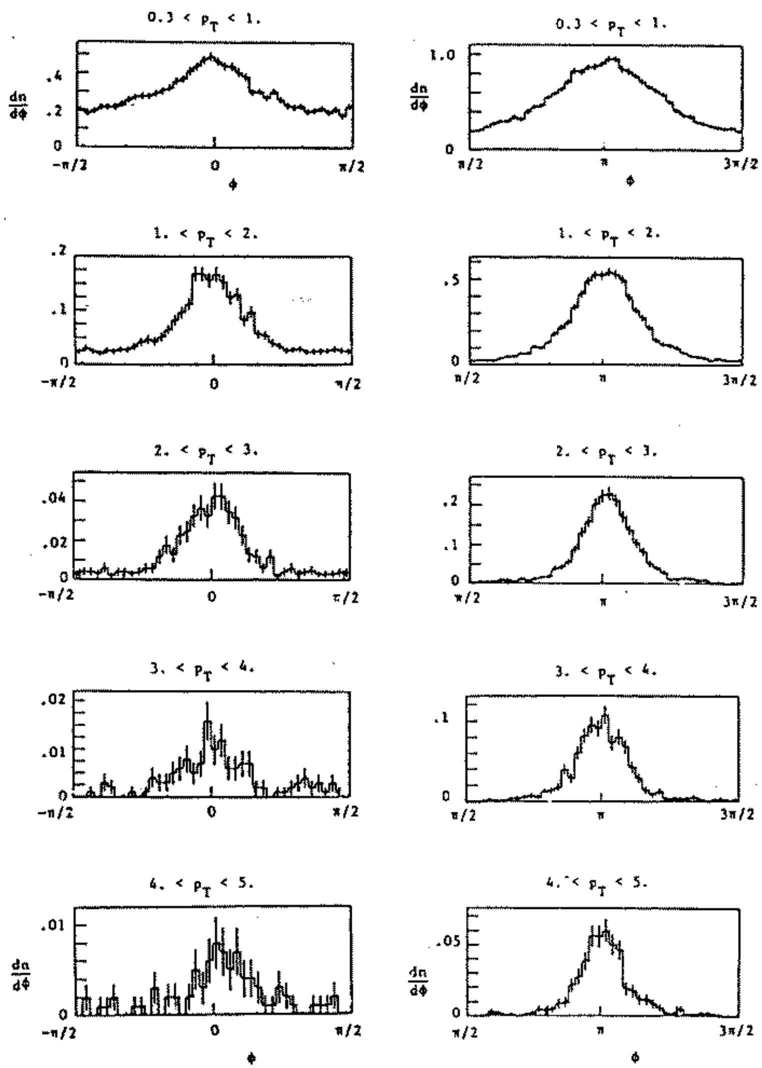
Everything you want to know about JETS can be measured with 2-particle correlations

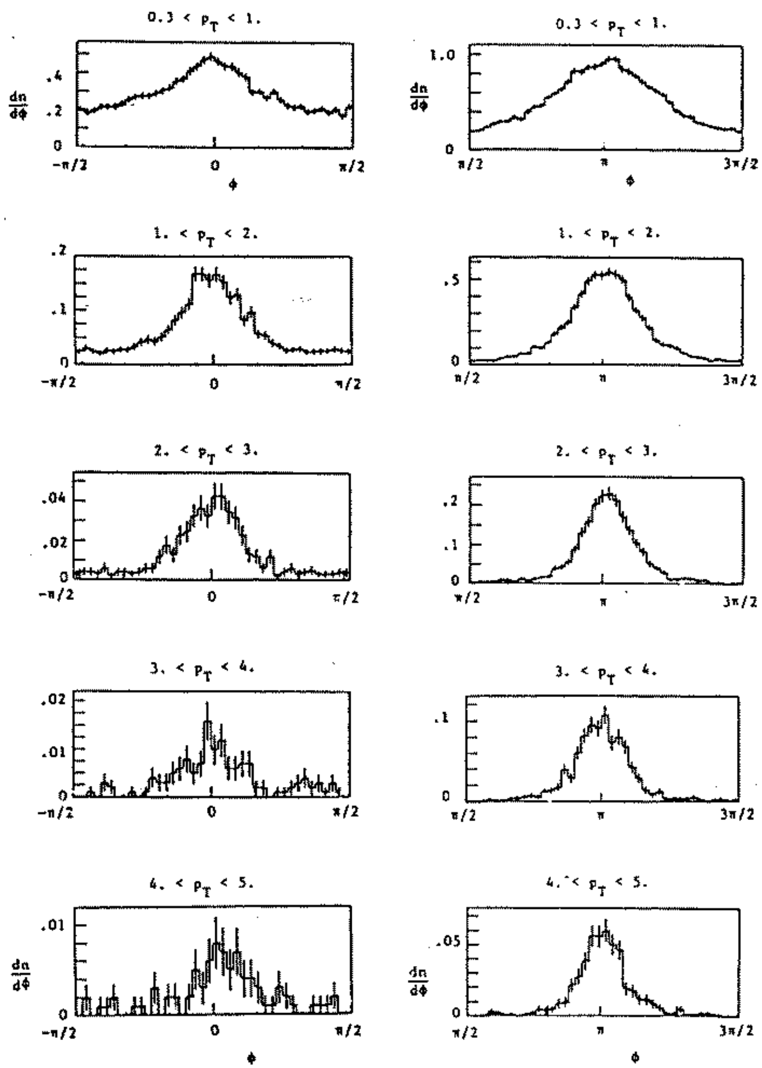


CCOR, A.L.S.Angelis, et al
Phys.Lett. **97B**, 163 (1980)
PhysicaScripta **19**, 116 (1979)

$p_{Tt} > 7$ GeV/c vs p_T

From RHIC97--HP04-CFRNC05

Everything you want to know about JETS can be measured with 2-particle correlations



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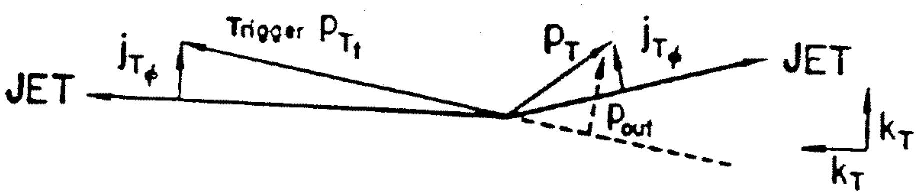

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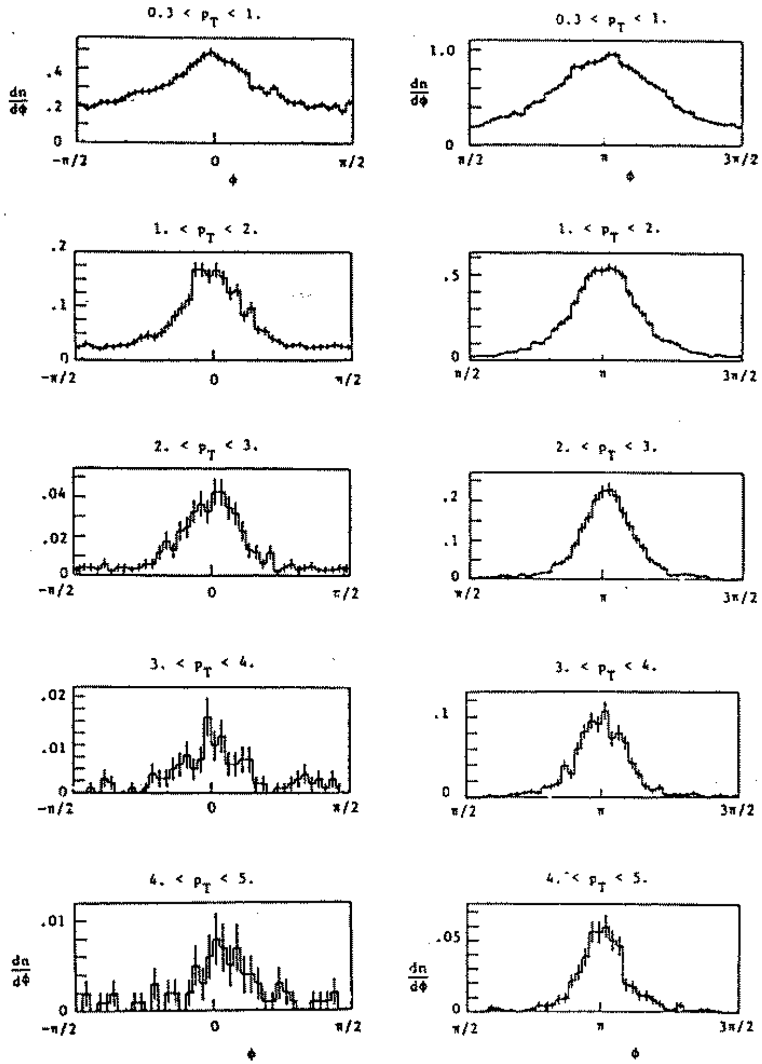

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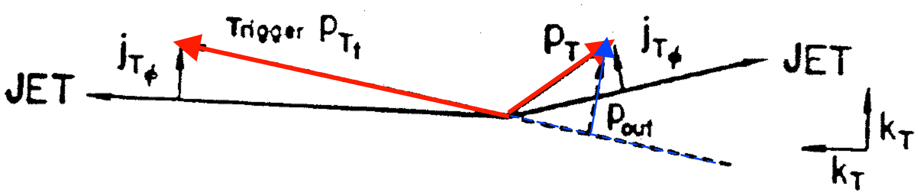

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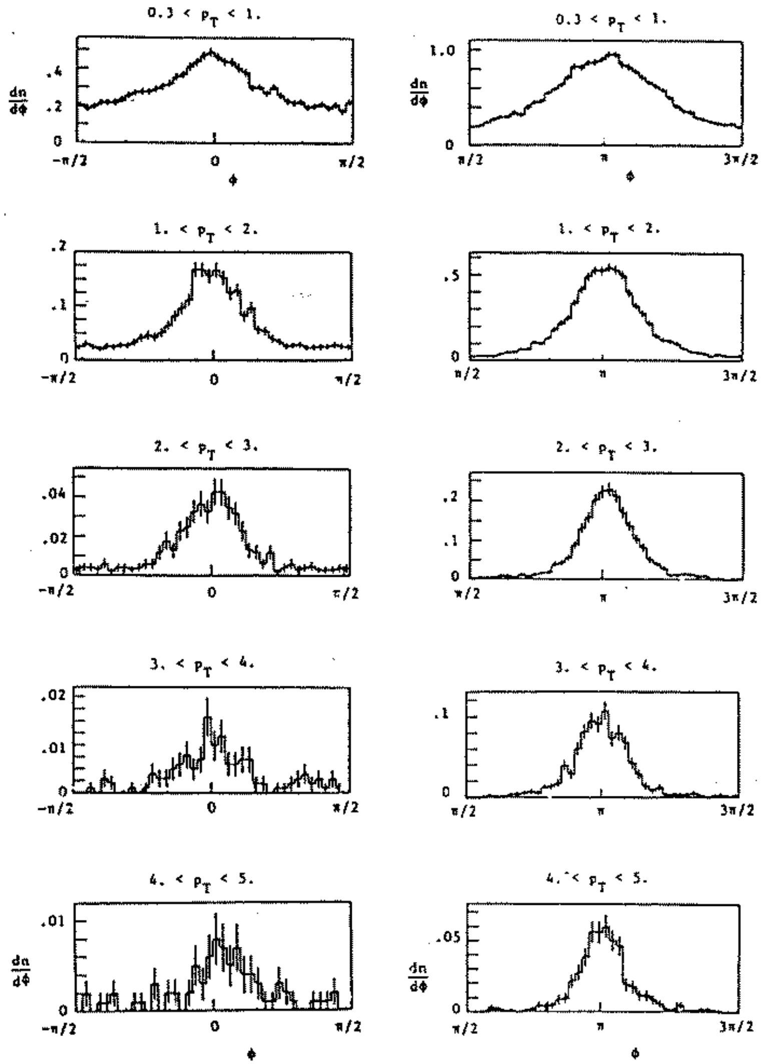

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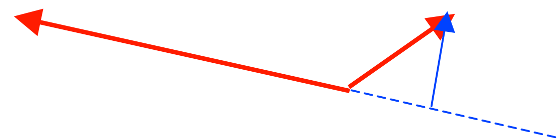

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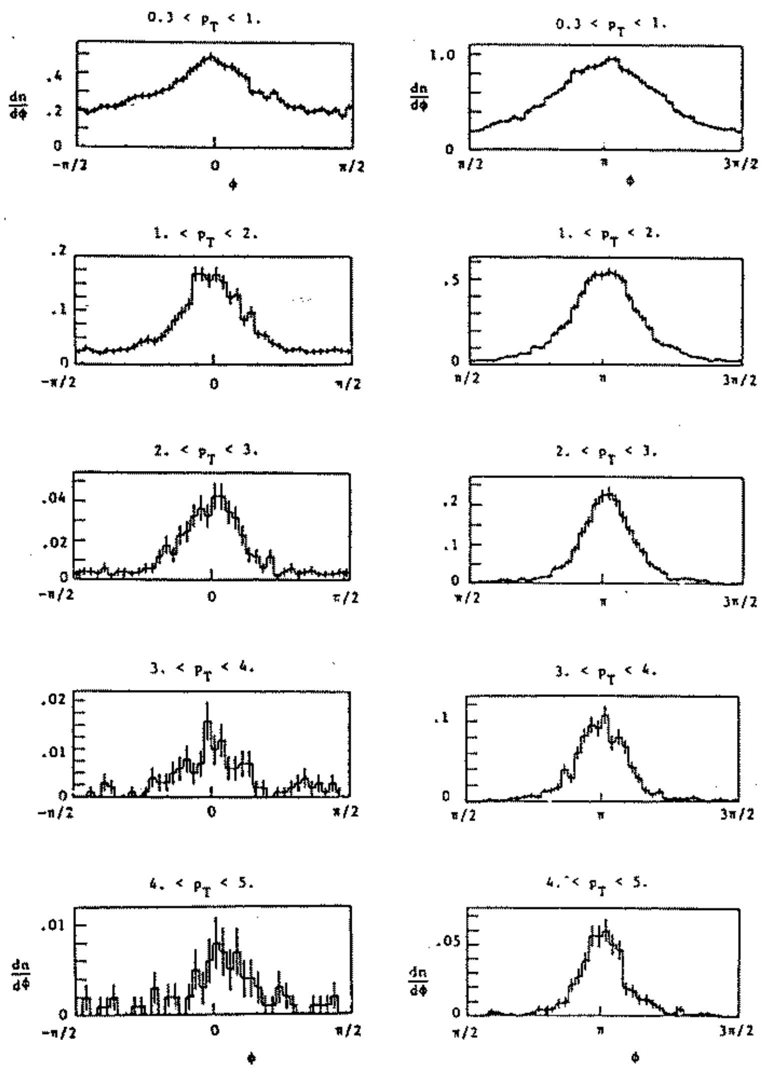

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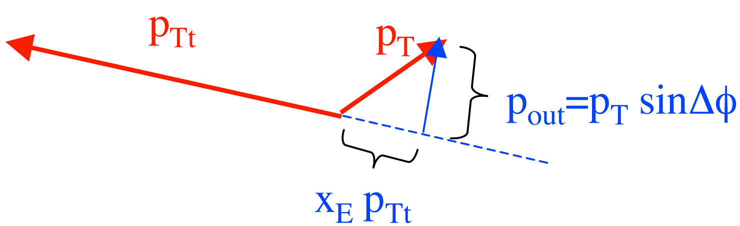
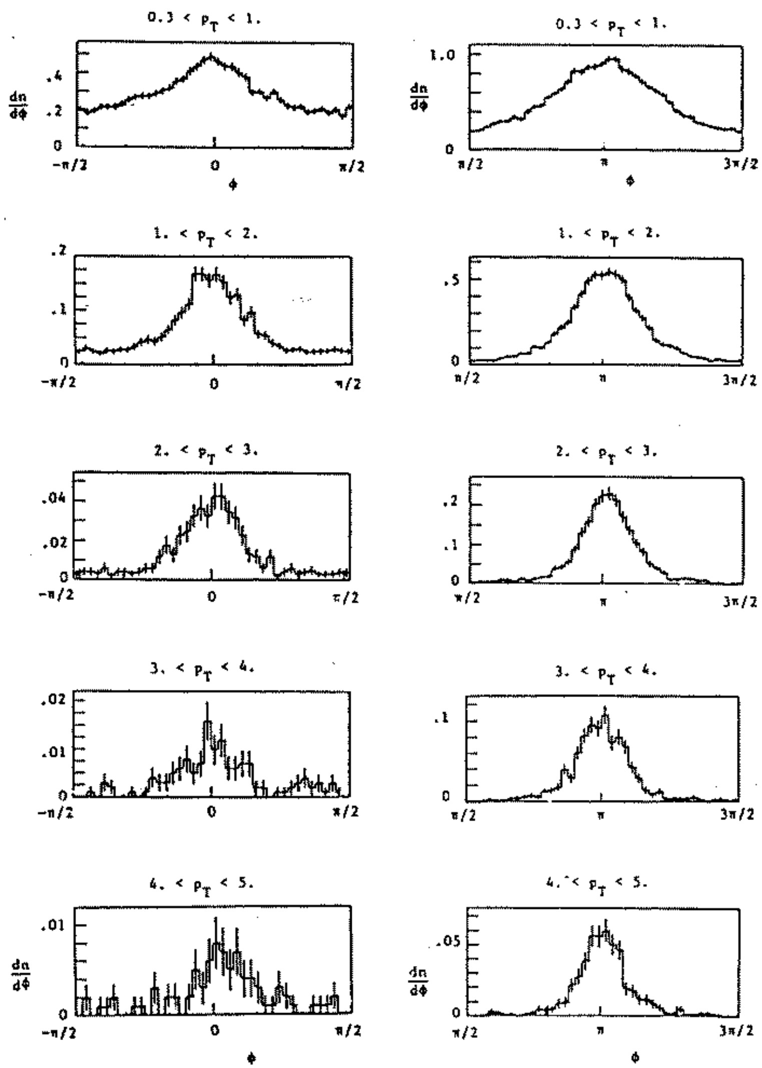


$p_{Tt} > 7$ GeV/c vs p_T

From RHIC97--HP04-CFRNC05

Everything you want to know about JETS can be measured with 2-particle correlations--NOT



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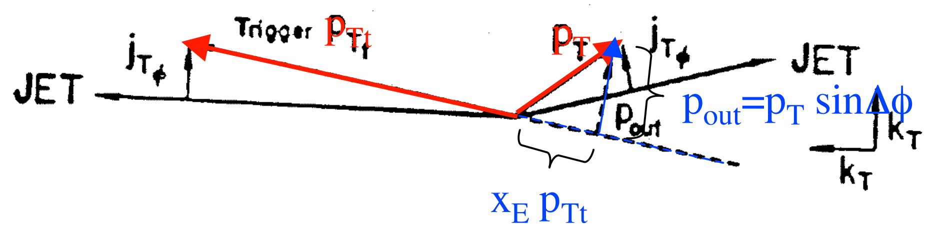
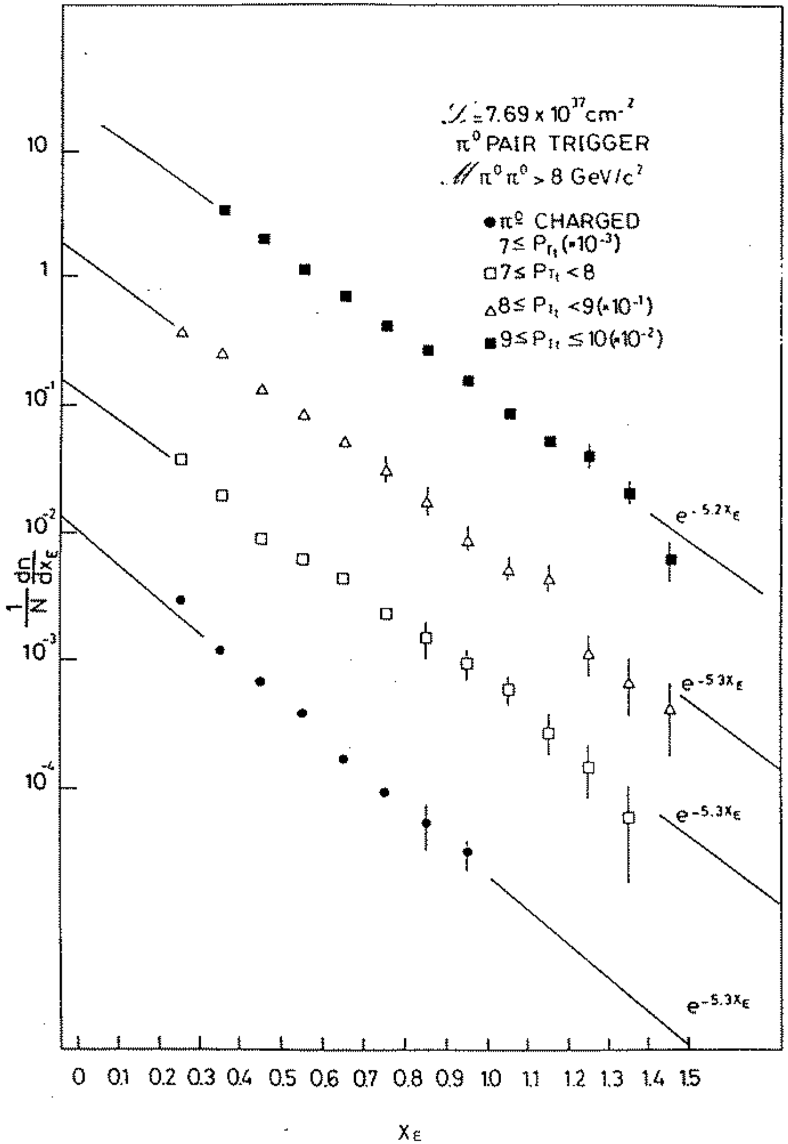


$p_{Tt} > 7$ GeV/c vs p_T

From RHIC97--HP04-CFRNC05

x_E distribution measures fragmentation fn



$$x_E \sim p_{Ta}/p_{Tt} \sim z/\langle z_{trig}\rangle$$

$\langle z_{trig}\rangle = 0.85$ measured

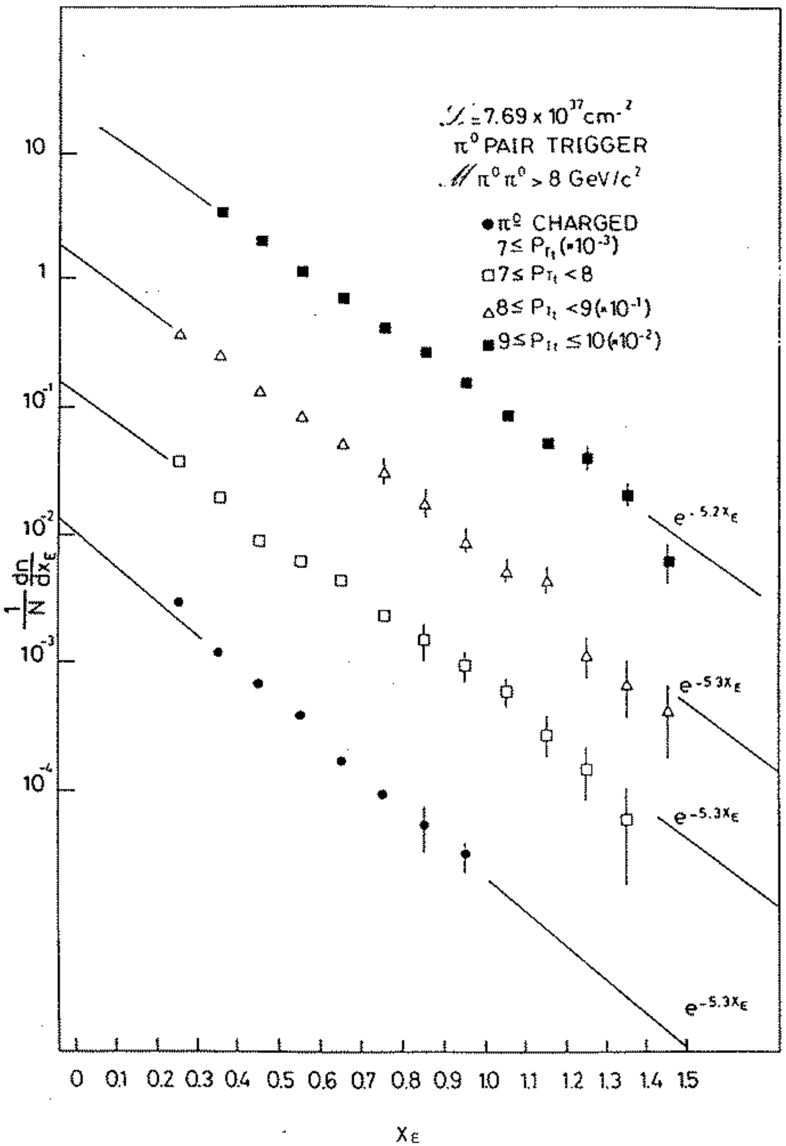
$$\Rightarrow D^q_\pi(z) \sim e^{-6z}$$

- independent of p_{Tt}

See M. Jacob's talk EPS 1979 Geneva

From RHIC97--HP04-CFRNC05

x_E distribution measures fragmentation fn.-NOT



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See M. Jacob's talk EPS 1979 Geneva

From RHIC97--HP04-CFRNC05

Where did I (and everybody in HEP) get this idea?---from Feynman, Field and Fox

38 *R.P Feynman et al. / Large transverse momenta*

FFF Nucl.Phys. **B128**(1977) 1-65

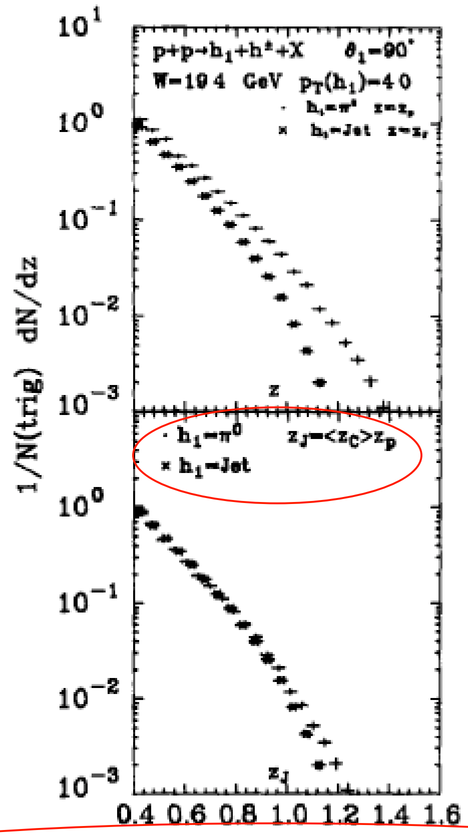


Fig. 23. Comparison of the π^0 and jet trigger away-side distribution of charged hadrons in pp collisions at $W = 19.4$ GeV, $\theta_1 = 90°$, and $p_\perp$ (trigger) = 4.0 GeV/c from the quark-quark scattering model. The upper figure shows the single-particle (π^0) trigger results plotted *versus* $z_p = -p_x(h^\pm)/p_\perp(\pi^0)$ and the jet trigger plotted *versus* $z_j = -p_x(h^\pm)/p_\perp(\text{jet})$ (see table 1). In the lower figure, we plot *both versus* z_J, where for the jet trigger $z_J = z_j$ but for the single-particle trigger $z_J = \langle z_c\rangle z_p$. The away hadrons are integrated over all rapidity Y and $|180° - \phi| \leqslant 45°$ and the theory is calculated using $\langle k_\perp\rangle_{h\to q} = 500$ MeV. • $h_1 = \pi^0$, × h_1 = jet.

"There is a simple relationship between experiments done with single-particle triggers and those performed with jet triggers. The only difference in the opposite side correlation is due to the fact that the 'quark', from which a single-particle trigger came, always has a higher $p_\perp$ than the trigger (by factor $1/z_{trig}$). The away-side correlations for a single-particle trigger at $p_\perp$ should be roughly the same as the away side correlations for a jet trigger at $p_\perp$ (jet)= $p_\perp$ (single particle)/ $\langle z_{trig}\rangle$".

As measured at the ISR by Darriulat, etc.

P. Darriulat, et al, Nucl.Phys. **B107** (1976) 429-456

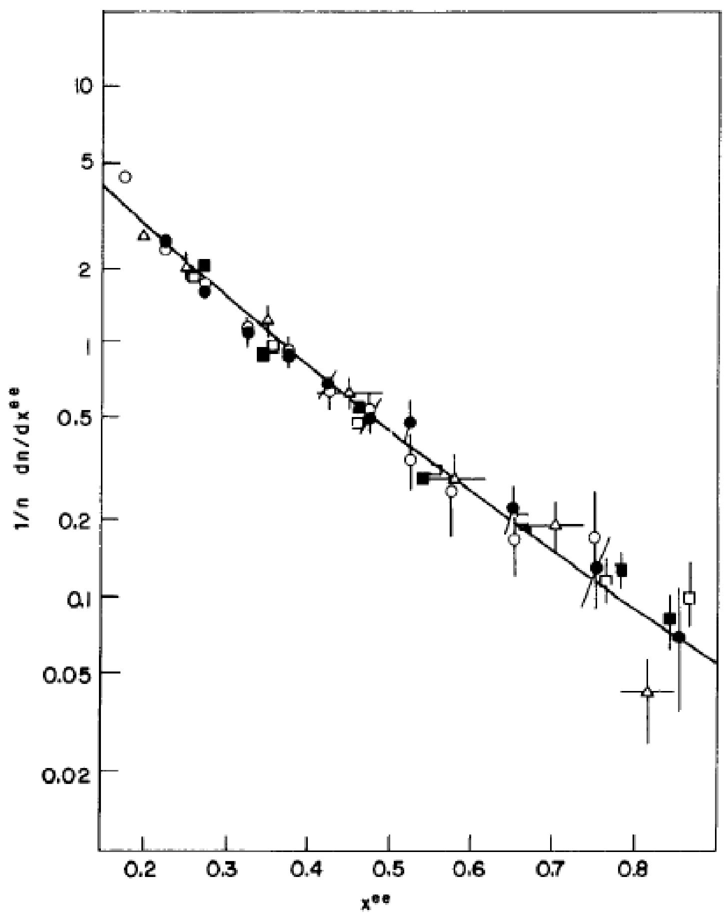


Figure 21 Jet fragmentation functions measured in different processes: ν-p interactions (*open triangles*, Van der Welde 1979); e^+e^- annihilations (*solid line*, Hanson et al 1975); and pp collisions (*full circles* CS, $p_T < 6$ GeV/c, *open circles* CS, $p_T > 6$ GeV/c, *full squares* CCOR, $p_T > 5$ GeV/c, *open squares* CCOR, $p_T > 7$ GeV/c).

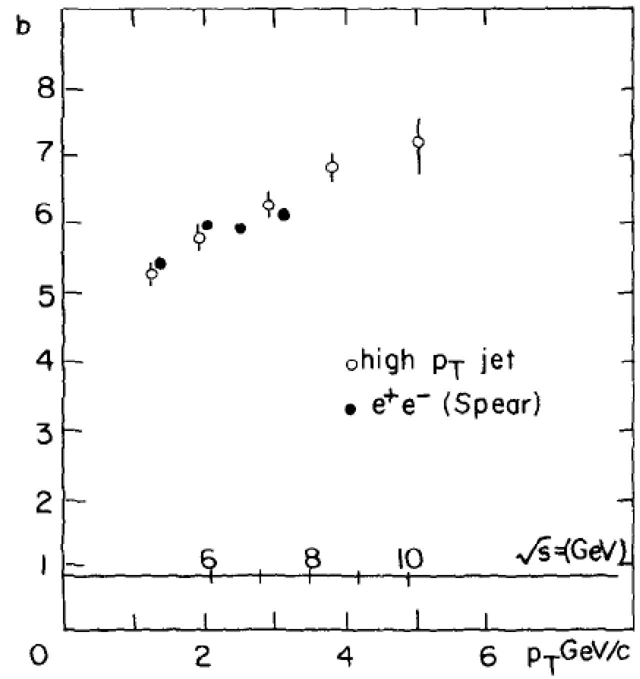
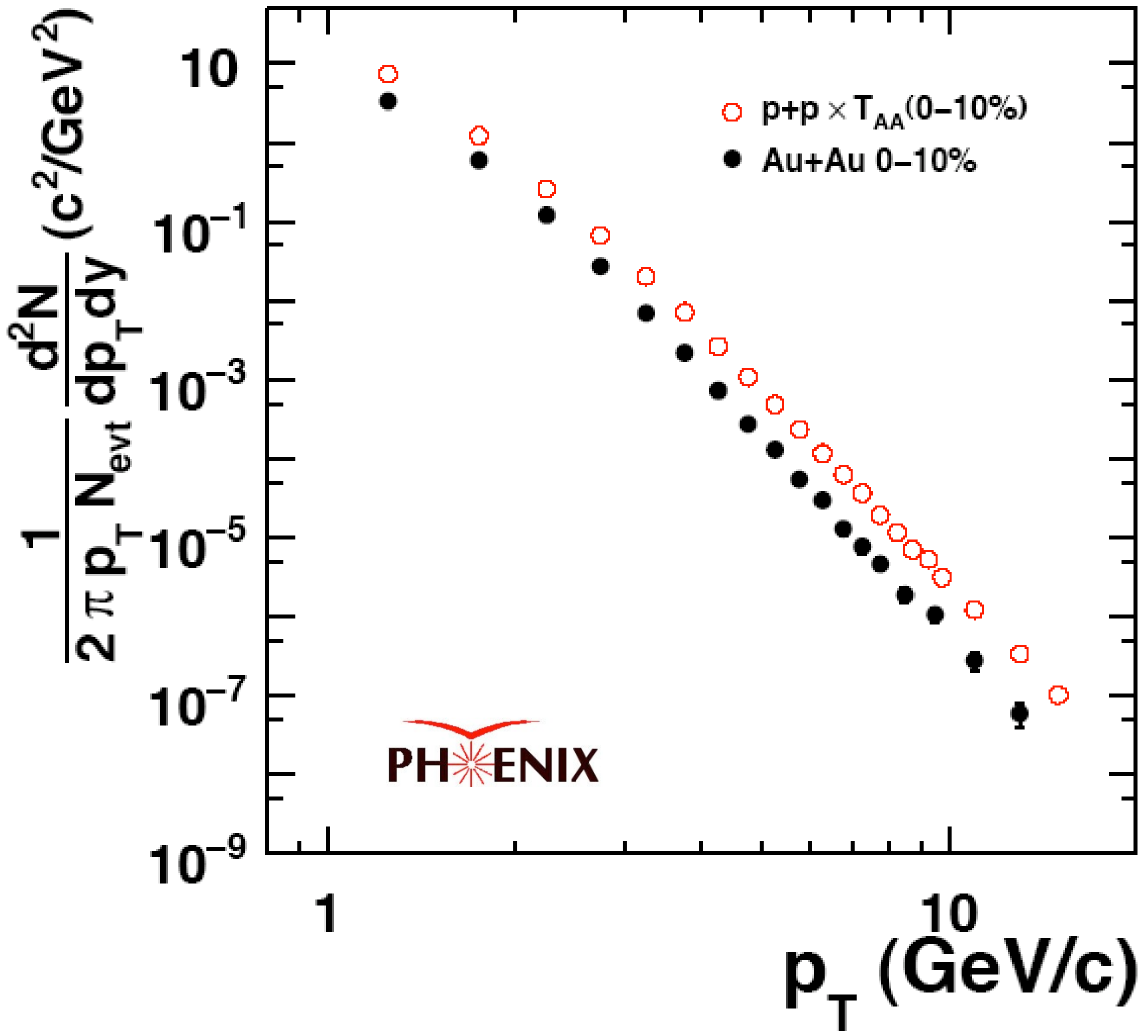


Figure 19 The slopes b obtained from exponential fits to the jet fragmentation function in the interval $0.2 < z < 0.8$ in e^+e^- annihilation (*full circles*) and LPTH data of the BS Collaboration (*open circles*).

Figures from P. Darriulat, ARNPS **30** (1980) 159-210 showing that Jet fragmentation functions in νp, e^+e^- and pp (CCOR) are the same with the same dependence of *b* (exponential slope) on "$\hat{s}$"

Inclusive invariant π^0 spectrum is beautiful power law for $p_T \geq 3$ GeV/c n=8.1±0.1



PHENIX, S.S.Adler, et al., nucl-ex/0611007 subm. PRC

The leading-particle effect a.k.a. trigger bias

- Due to the steeply falling power-law spectrum of the scattered partons, the inclusive particle p_T spectrum is dominated by fragments biased towards large z. This was unfortunately called trigger bias by M. Jacob and P. Landshoff, Phys. Rep. **48C**, 286 (1978) although it has nothing to do with a trigger.

$$\frac{d^2\sigma_\pi(\hat{p}_{T_t}, z_t)}{d\hat{p}_{T_t} dz_t} = \frac{d\sigma_q}{d\hat{p}_{T_t}} \times D^q_\pi(z_t)$$

Fragment spectrum given $\hat{p}_{T_t}$

$$= \frac{A}{\hat{p}_{T_t}^{n-1}} \times D^q_\pi(z_t)$$

Power law spectrum of parton $\hat{p}_{T_t}$

$$\text{let } \hat{p}_{T_t} = p_{T_t}/z_t \qquad d\hat{p}_{T_t}/dp_{T_t}|_{z_t} = 1/z_t$$

$$\frac{d^2\sigma_\pi(p_{T_t}, z_t)}{dp_{T_t} dz_t} = \frac{1}{z_t}\frac{A}{(p_{T_t}/z_t)^{n-1}} \times D^q_\pi(z_t)$$

$$= \frac{A}{p_{T_t}^{n-1}} \times z_t^{n-2} D^q_\pi(z_t)$$

Fragment spectrum given p_{T_t} is weighted to high z_t by z_t^{n-2}

$$\text{where } z_{t\min}|_{p_{T_t}} = x_{T_t} \qquad D^q_\pi(z_t) = B e^{-6z_t}$$

2 particle Correlations

$$\frac{d^2\sigma_\pi(\hat{p}_{T_t}, z_t)}{d\hat{p}_{T_t} dz_t} = \frac{d\sigma_q}{d\hat{p}_{T_t}} \times D^q_\pi(z_t)$$

Prob. that you make a jet with $\hat{p}_{Tt}$ which fragments to a π with $z_t=p_{Tt}/\hat{p}_{Tt}$

Also detect fragment with $z_a = p_{T_a}/\hat{p}_{T_a}$ from away jet with $\hat{p}_{T_a}/\hat{p}_{T_t} \equiv \hat{x}_h$

$$\frac{d^3\sigma_\pi(\hat{p}_{T_t}, z_t, z_a)}{d\hat{p}_{T_t} dz_t dz_a} = \frac{d\sigma_q}{d\hat{p}_{T_t}} \times D^q_\pi(z_t) \times D^q_\pi(z_a)$$

Prob. that away jet with $\hat{p}_{Ta}$ fragments to a π with $z_a=p_{Ta}/\hat{p}_{Ta}$

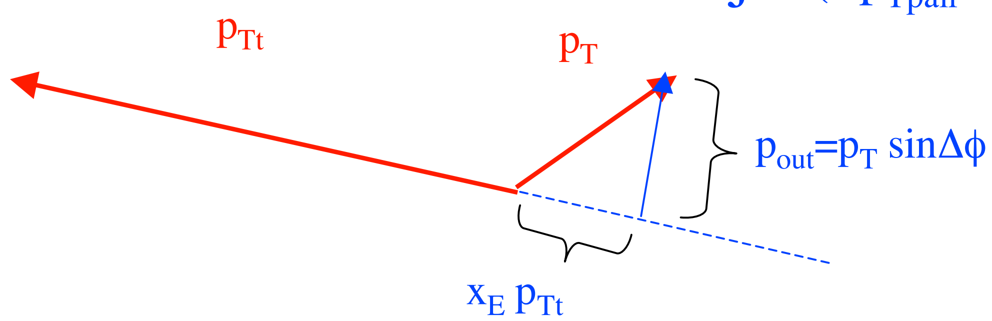
$$z_a = \frac{p_{T_a}}{\hat{p}_{T_a}} = \frac{p_{T_a}}{\hat{x}_h \hat{p}_{T_t}} = \frac{z_t\, p_{T_a}}{\hat{x}_h\, p_{T_t}}$$

(1)
$$\frac{d\sigma_\pi}{dp_{T_t} dz_t dp_{T_a}} = \frac{1}{\hat{x}_h\, p_{T_t}} \frac{d\sigma_q}{d(p_{T_t}/z_t)} D^q_\pi(z_t) D^q_\pi\left(\frac{z_t p_{T_a}}{\hat{x}_h p_{T_t}}\right)$$

Appears to be sensitive to away jet Frag. Fn.

How we found the problem in PHENIX

Following FFF and CCOR PLB**97**(1980)163-168 we were trying to measure the net transverse momentum of the di-jet ($\langle p_{Tpair} \rangle = \sqrt{2} \times \langle k_T \rangle$)



$$\frac{\langle z_t(k_T, x_h)\rangle \sqrt{\langle k_T^2\rangle}}{\hat{x}_h(k_T, x_h)} = \frac{1}{x_h}\sqrt{\langle p_{out}^2\rangle - \left\langle j_{Ty}^2 \right\rangle (1 + x_h^2)} \qquad x_h \equiv \frac{p_{T_a}}{p_{T_t}} \qquad \hat{x}_h \equiv \frac{\hat{p}_{T_a}}{\hat{p}_{T_t}}$$

- j_T is parton fragmentation transverse momentum
- k_T is transverse momentum of a parton in a proton (2 protons)
- $x_E = -p_T \bullet p_{Tt}/|p_{Tt}|^2$ represents away jet fragmentation z
- p_{out} is component of away p_T perpendicular to trigger p_{Tt}

We needed $\langle z_t \rangle$ to solve for k_T. Tried to get it from x_E dist.

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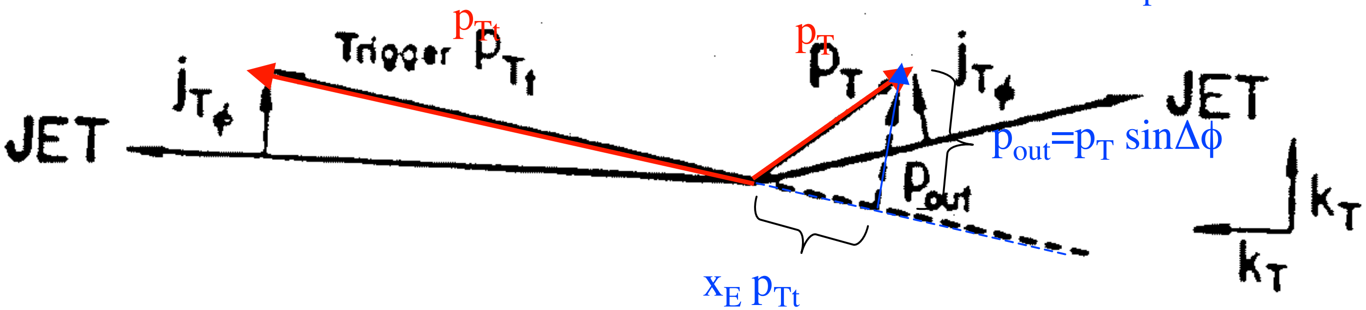

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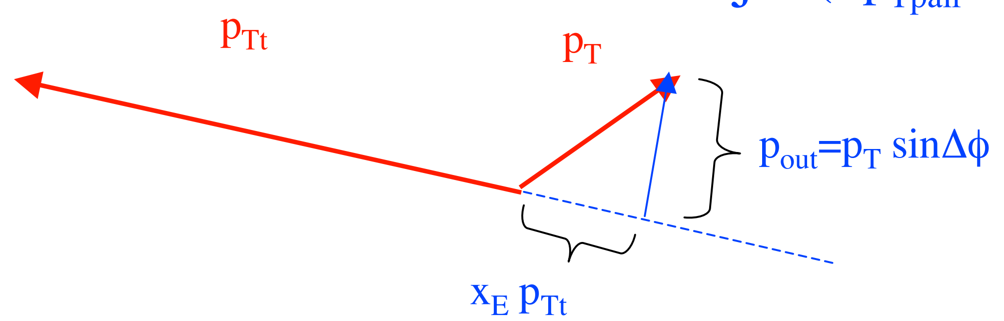

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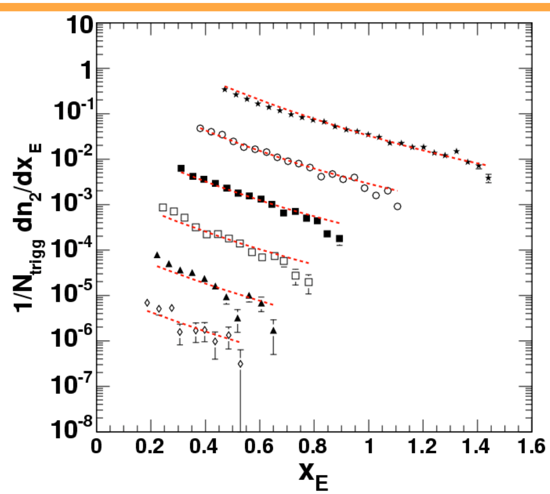
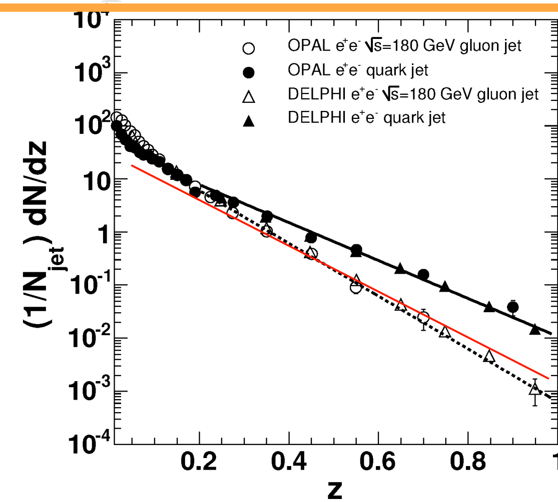
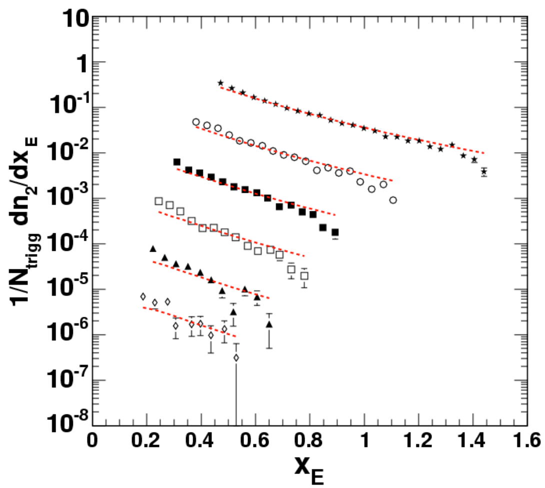
Fit x_E distributions to form of D(z) used by LEP measurements by integrating Eq (1) numerically

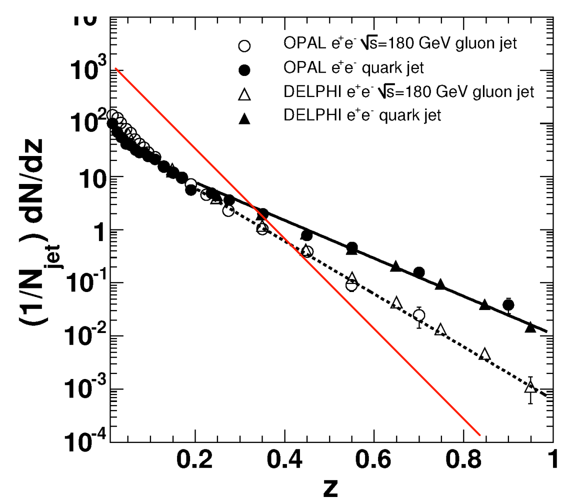


$D(z)=\exp(-10z)$





$D(z)=\exp(-20z)$



After many convergence difficulties, two vastly different fragmentations functions tried⇒No effect on calculated x_E distributions---Mike, can you check this analytically?!

Amazingly, I could; and got a neat result

$$\frac{d\sigma_\pi}{dp_{T_t} dz_t dp_{T_a}} = \frac{1}{\hat{x}_h \, p_{T_t}} \frac{d\sigma_q}{d(p_{T_t}/z_t)} D^q_\pi(z_t) D^q_\pi\left(\frac{z_t p_{T_a}}{\hat{x}_h p_{T_t}}\right) \qquad (1)$$

Take: $D(z) = B \exp(-bz)$ $\qquad \frac{d\sigma_q}{d\hat{p}_{T_t}} = \frac{A}{\hat{p}_{T_t}^{\,n-1}} = A \frac{z_t^{n-1}}{{p_{T_t}}^{n-1}}$

$$(2) \quad \frac{d\sigma_\pi}{dp_{T\mathrm{t}} dp_{T\mathrm{a}}} = \frac{B^2}{\hat{x}_\mathrm{h}} \frac{A}{p_{T_t}^n} \int_{x_{T_t}}^{\hat{x}_\mathrm{h} \frac{p_{T\mathrm{t}}}{p_{T\mathrm{a}}}} dz_\mathrm{t} \, z_\mathrm{t}^{n-1} \exp -bz_\mathrm{t}\left(1 + \frac{p_{T\mathrm{a}}}{\hat{x}_\mathrm{h} p_{T\mathrm{t}}}\right)$$

$$\frac{d\sigma_\pi}{dp_{T\mathrm{t}}} = \frac{AB}{p_{T_t}^{n-1}} \int_{x_{T_t}}^{1} dz_\mathrm{t} \, z_\mathrm{t}^{n-2} \exp -bz_\mathrm{t}$$

Using: $\Gamma(a, x) \equiv \int_x^\infty t^{a-1} \, e^{-t} \, dt$ $\qquad$ Where Γ(a,0)= Γ(a)=(a-1) Γ(a)

The final result

$$\frac{d^2\sigma_\pi}{dp_{T\mathrm{t}}dp_{T\mathrm{a}}} \approx \frac{\Gamma(n)}{b^n}\frac{B^2}{\hat{x}_{\mathrm{h}}}\frac{A}{p_{T_t}^n}\frac{1}{(1+\frac{p_{T\mathrm{a}}}{\hat{x}_{\mathrm{h}}p_{T\mathrm{t}}})^n}$$

$$\frac{d\sigma_\pi}{dp_{T\mathrm{t}}} \approx \frac{\Gamma(n-1)}{b^{n-1}}\frac{AB}{p_{T_t}^{n-1}} \quad ,$$

$$\left.\frac{dP_\pi}{dp_{T\mathrm{a}}}\right|_{p_{T\mathrm{t}}} \approx \frac{B(n-1)}{bp_{T\mathrm{t}}}\frac{1}{\hat{x}_{\mathrm{h}}}\frac{1}{(1+\frac{p_{T\mathrm{a}}}{\hat{x}_{\mathrm{h}}p_{T\mathrm{t}}})^n} \quad . \qquad (42)$$

In the collinear limit, where $p_{T\mathrm{a}}=x_{\mathrm{E}}p_{T\mathrm{t}}$:

$$\left.\frac{dP_\pi}{dx_{\mathrm{E}}}\right|_{p_{T\mathrm{t}}} \approx \frac{B(n-1)}{b}\frac{1}{\hat{x}_{\mathrm{h}}}\frac{1}{(1+\frac{x_E}{\hat{x}_{\mathrm{h}}})^n} \quad . \qquad (43)$$

Where B/b≈<m>≈b is the mean charged multiplicity in the jet

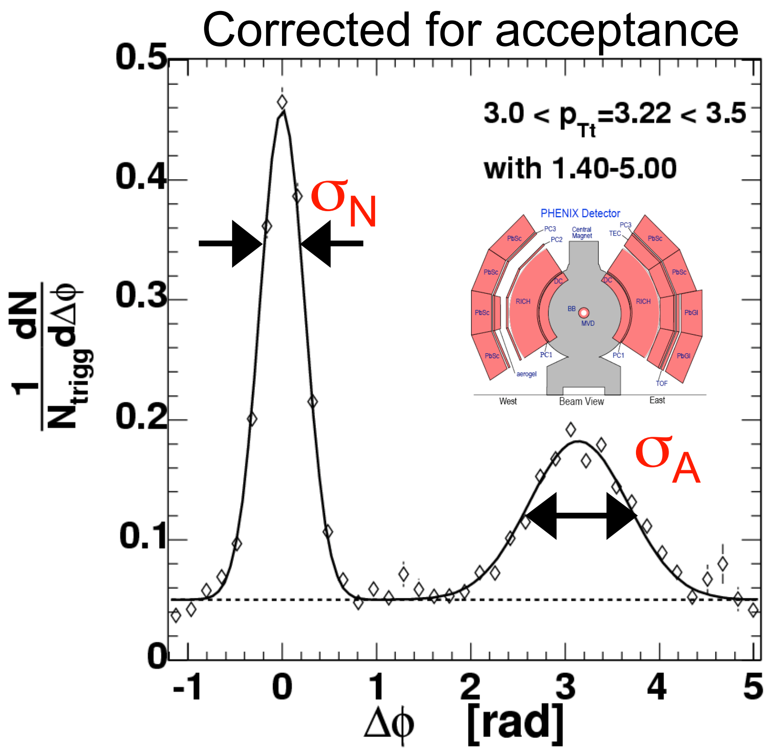
Why dependence on the Frag. Fn. vanishes

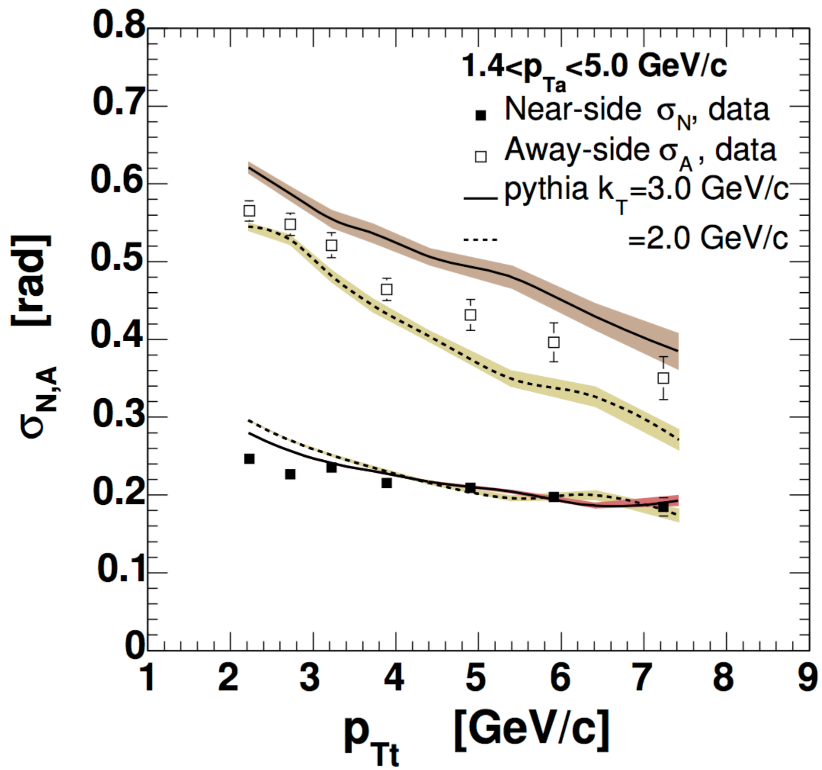
- The only dependence on the fragmentation function is in the normalization constant B/b which equals <m>, the mean multiplicity in the away jet from the integral of the fragmentation function.

- The dominant term in the x_E distribution is the Hagedorn function $1/(1+x_E/\hat{x}_h)^n$ so that at fixed p_{Tt} the x_E distribution is predominantly a function only of x_E and thus exhibits x_E scaling, as observed.

- The reason that the x_E distribution is not sensitive to the shape of the fragmentation function is that the integral over z_t in (1, 2) for fixed p_{Tt} and p_{Ta} is actually an integral over jet transverse momentum $\hat{p}_{T_t}$. However since the trigger and away jets are always roughly equal and opposite in transverse momentum (in p+p), integrating over $\hat{p}_{T_t}$ simultaneously integrates over $\hat{p}_{T_a}$. The integral is over z_t, which appears in both trigger and away side fragmentation functions in (1).

Oh yes--PHENIX π^{o} - $h^{\pm}$ correlation functions p+p $\sqrt{s}$=200 GeV: PRD **74**, 072002 (2006)





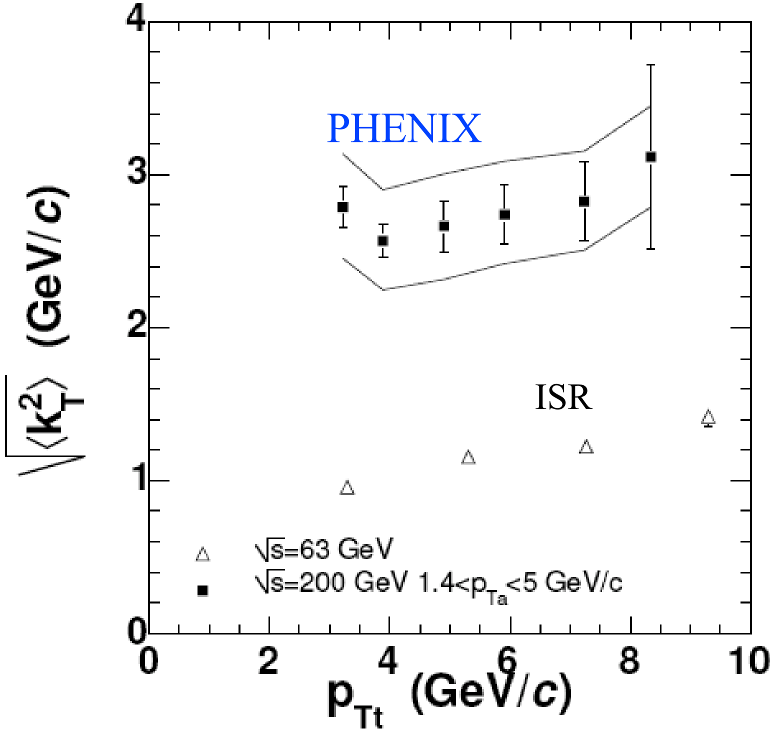
$\sigma_N \propto \langle j_T \rangle$ jet fragmentation transverse momentum-measure directly

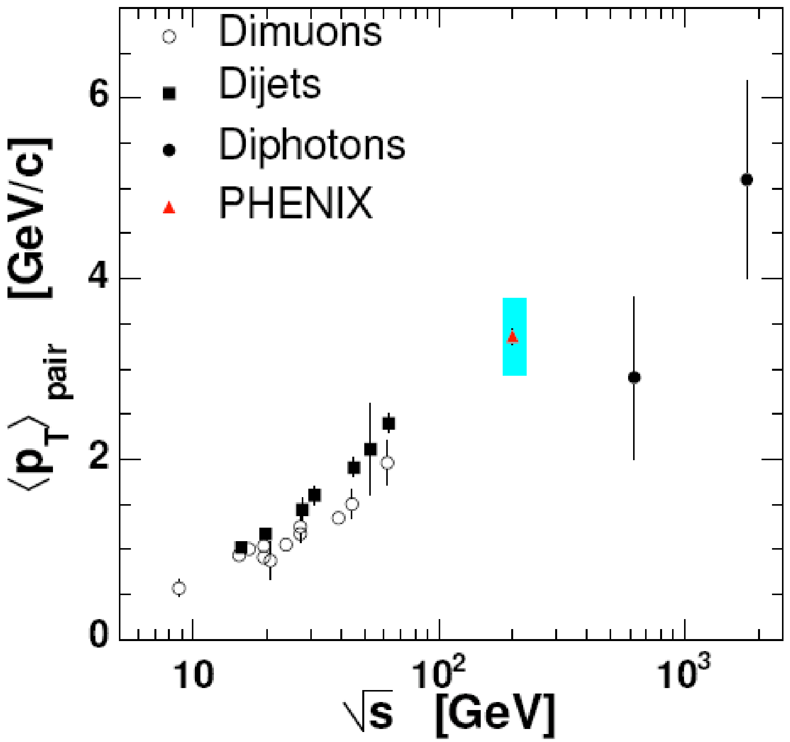
$$\sqrt{\langle j_T^2 \rangle} = 585 \pm 6(\mathrm{stat}) \pm 15(\mathrm{sys})\ \mathrm{MeV}/c$$

$\sigma_F \propto \langle k_T \rangle$ parton transverse momentum-more complicated.

Results RMS k_T in p+p @ 200 GeV

$$\sqrt{\langle k_T^2 \rangle} = 2.68 \pm 0.07(\text{stat}) \pm 0.34(\text{sys})\ \text{GeV}/c$$





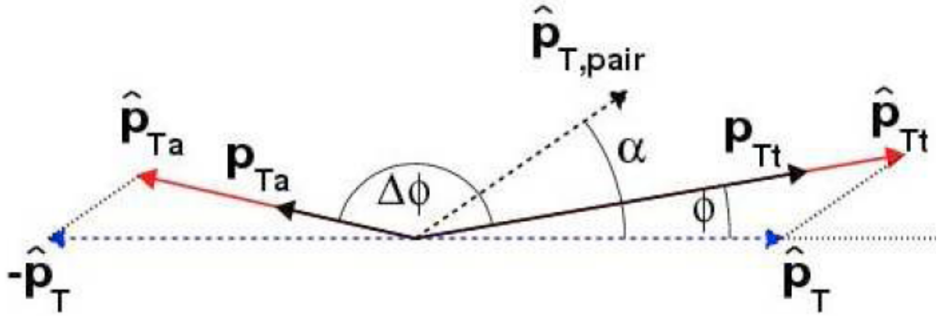
$$\langle p_T \rangle_{pair} = 3.36 \pm 0.09(\text{stat}) \pm 0.43(\text{sys})\ \text{GeV}/c$$

Main contribution to the systematic errors comes from unknown ratio gluon/quark jet => D(z) slope =><m>

Discussion
Application

A very interesting formula

$$\left.\frac{dP_\pi}{dx_\mathrm{E}}\right|_{p_{T\mathrm{t}}} \approx \langle m\rangle\,(n-1)\frac{1}{\hat{x}_\mathrm{h}}\frac{1}{(1+\frac{x_E}{\hat{x}_\mathrm{h}})^n}$$

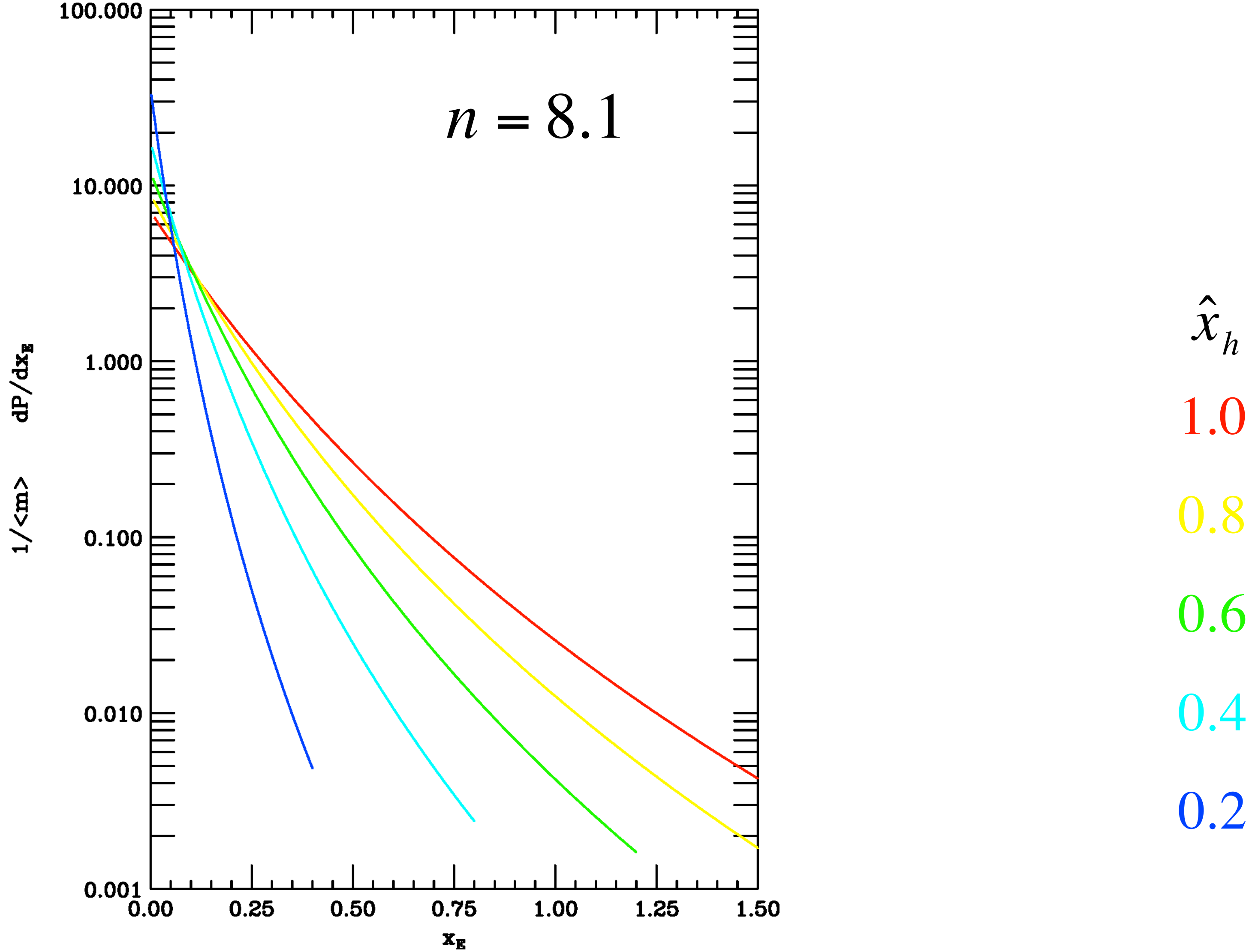


$$x_E = \frac{-p_{T_a}\cos\Delta\phi}{p_{T_t}} \simeq \frac{p_{T_a}}{p_{T_t}} \quad\longrightarrow\quad \hat{x}_h = \frac{\hat{p}_{T_a}}{\hat{p}_{T_t}}$$

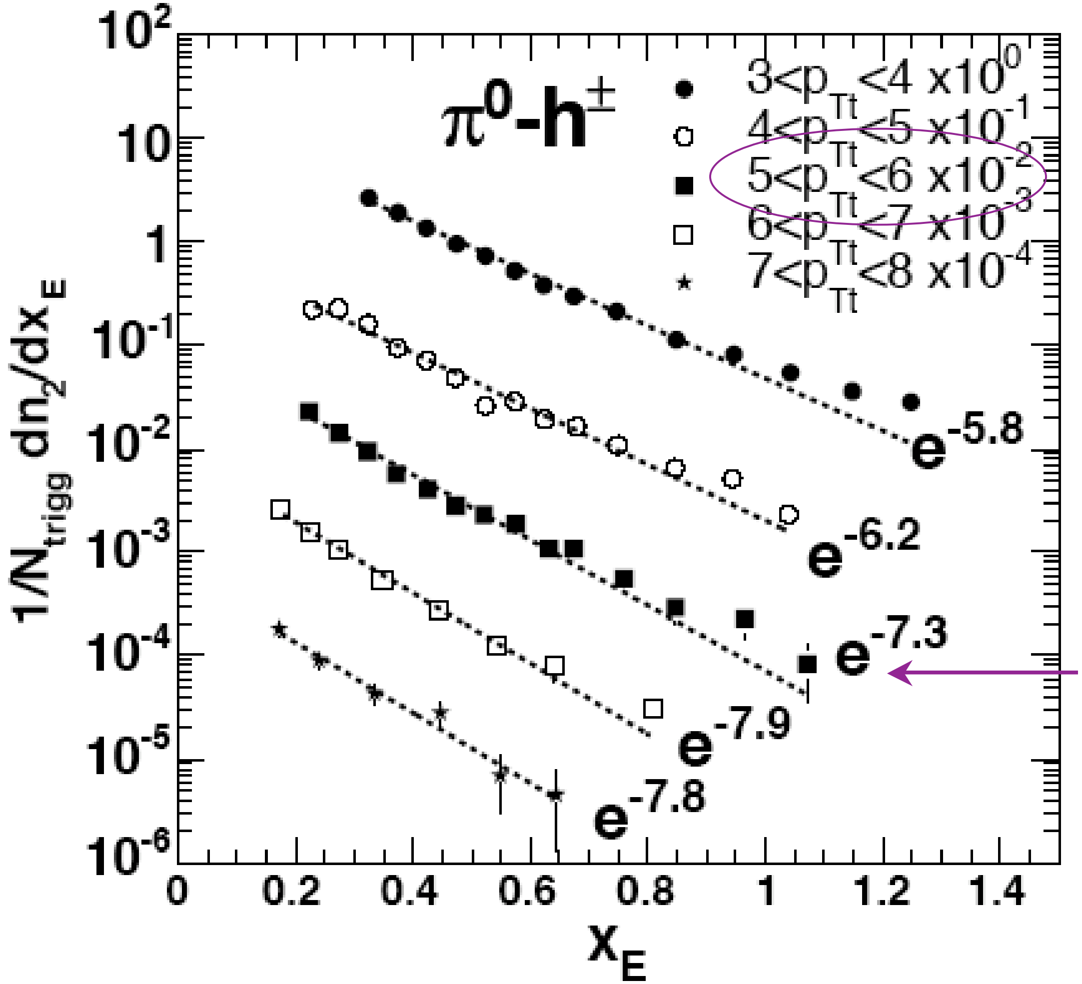
measured

Ratio of jet transverse momenta

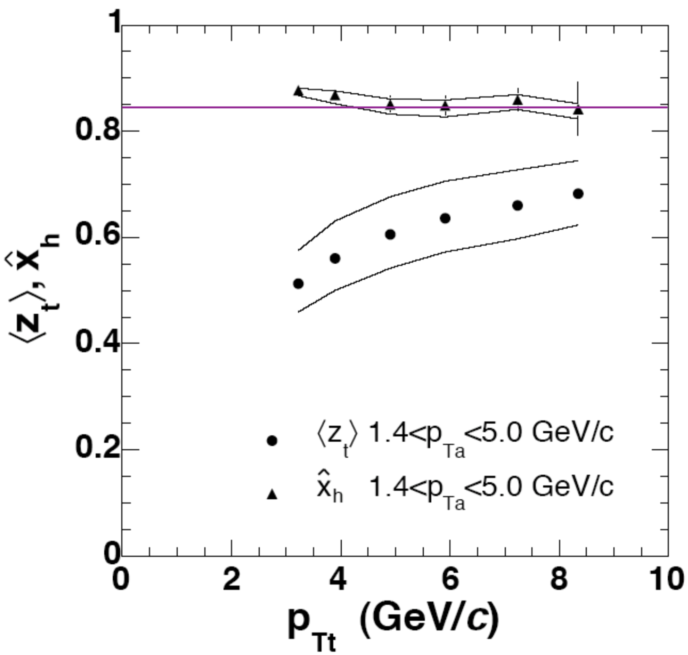
Shape of x_E distribution depends on $\hat{x}_h$ and *n* but not on *b*



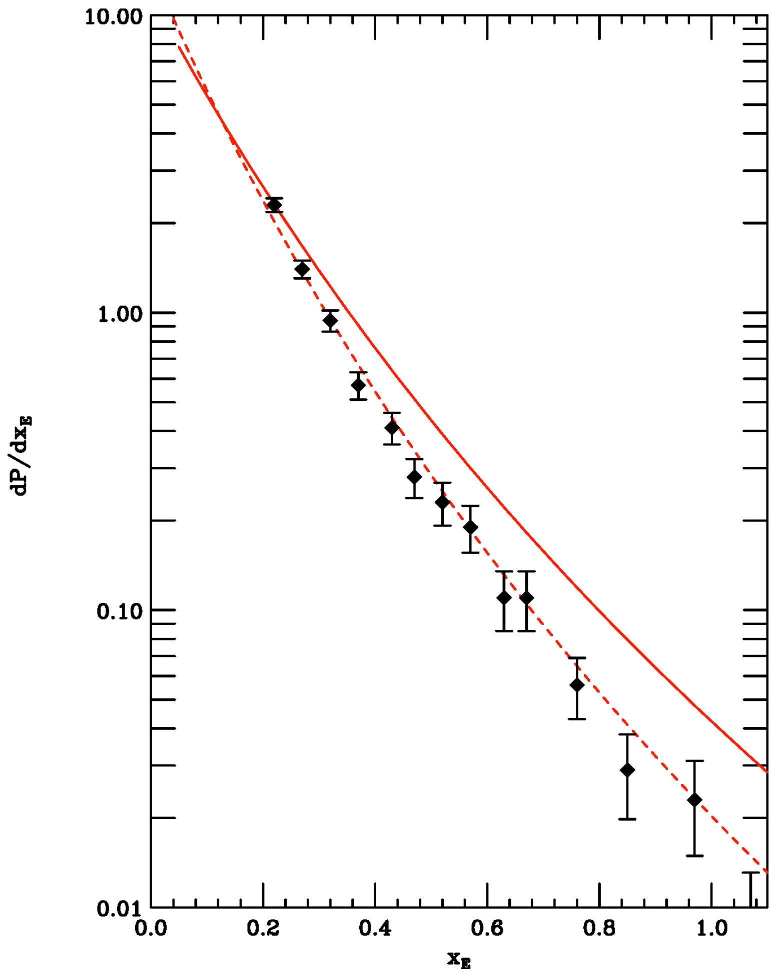
Does the formula work?



PHENIX p+p
PRD **74**, 072002
(2006)



It works for PHENIX p+p PRD **74**, 072002

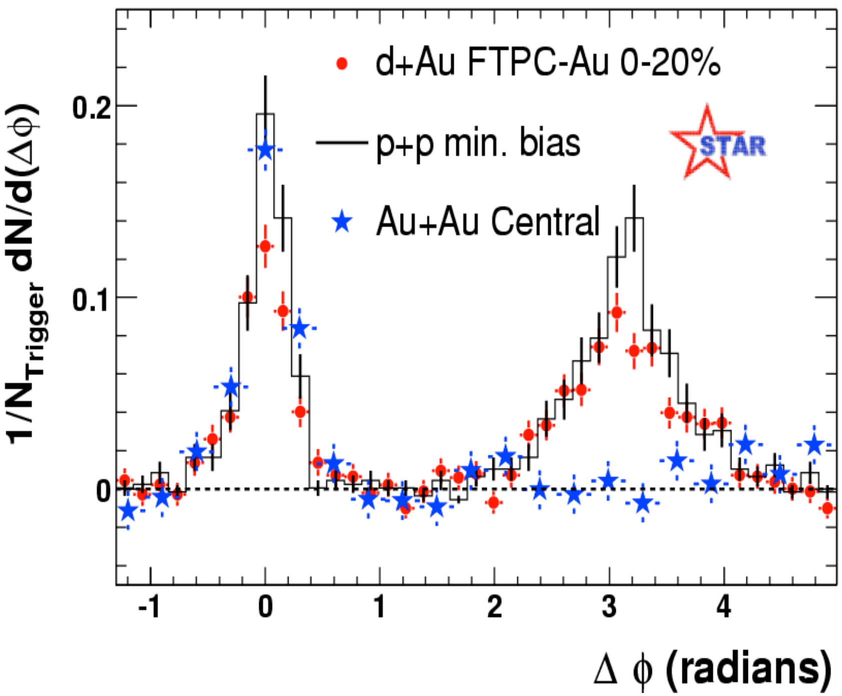


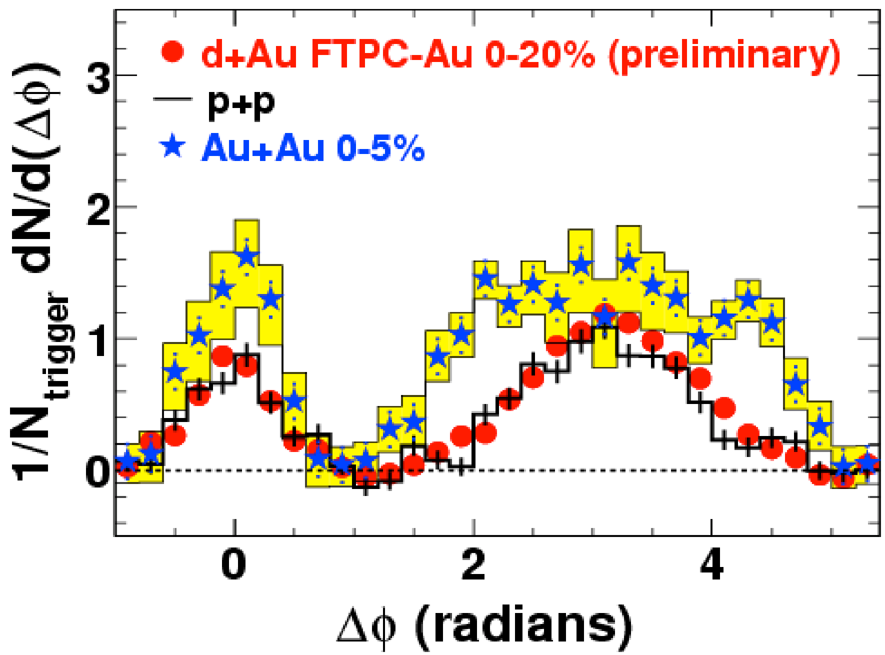
$$f(y) = 1.63 \times \frac{7.1}{(1+y)^{8.1}}$$

(solid line) $x_E = y$

(dashed line) $x_E = \hat{x}_h\, y = 0.8\, y$

STAR showed that the away jet really didn't vanish--it just lost energy and widened





STAR-PRL**91**(2003)072304

$4 < p_{Tt} < 6$ GeV/c $2 < p_{Ta} < p_{Tt}$

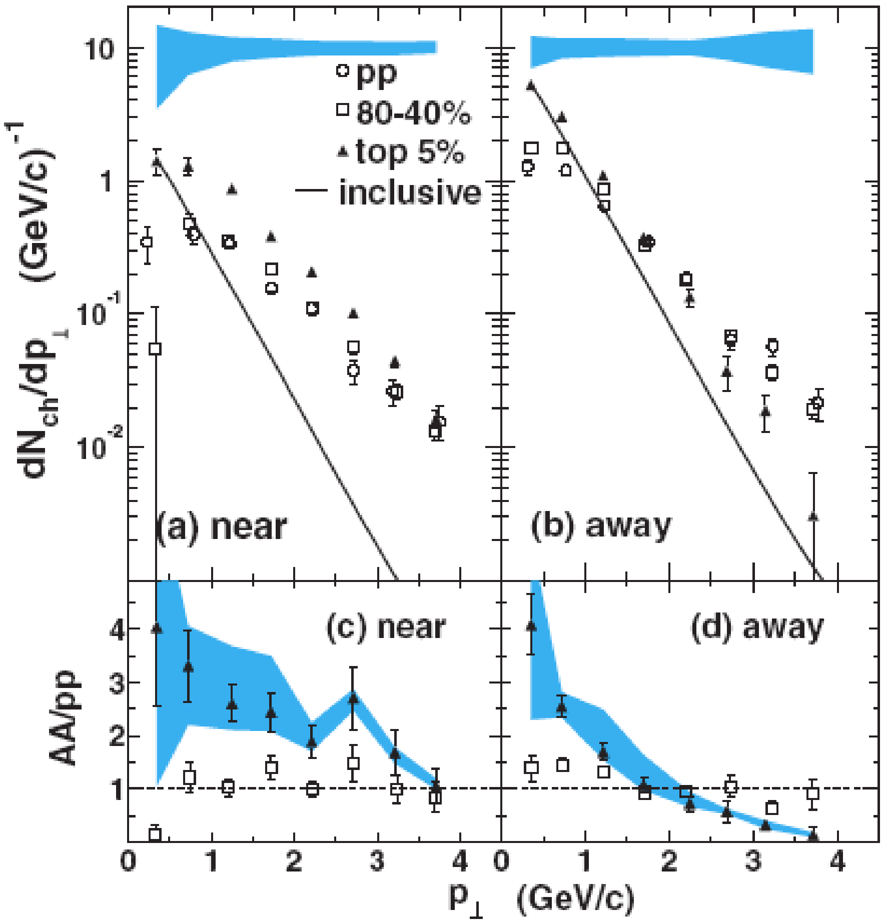
$x_h = p_{Ta}/p_{Tt} \sim 0.5$

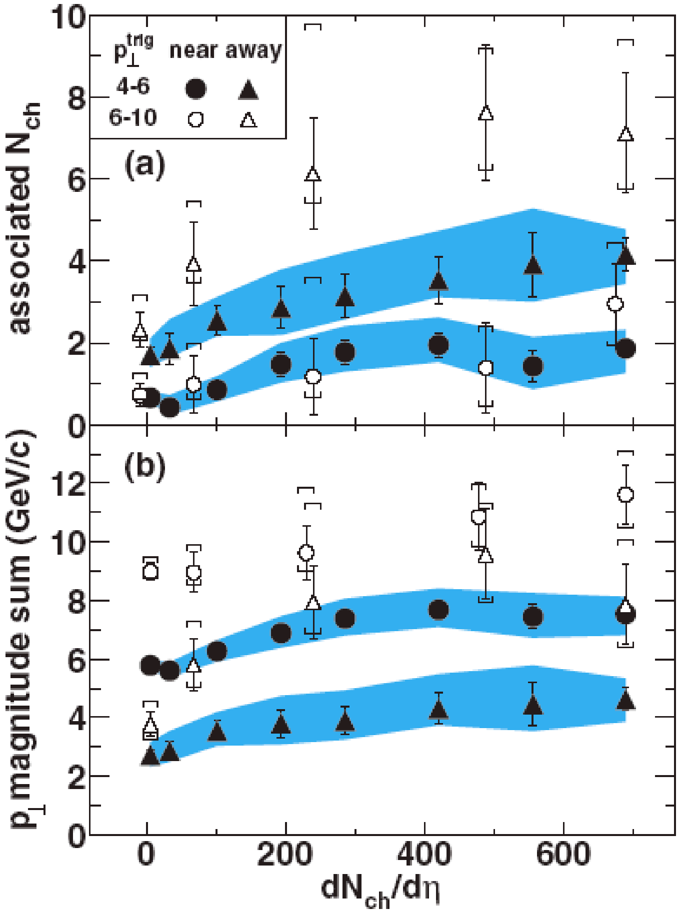
STAR-PRL**95**(2005)152301

$4 < p_{Tt} < 6$ GeV/c $0.15 < p_{Ta} < 4$ GeV/c

$x_h = p_{Ta}/p_{Tt} \sim 0.04$

Now Apply Eq. To (STAR) Au+Au data



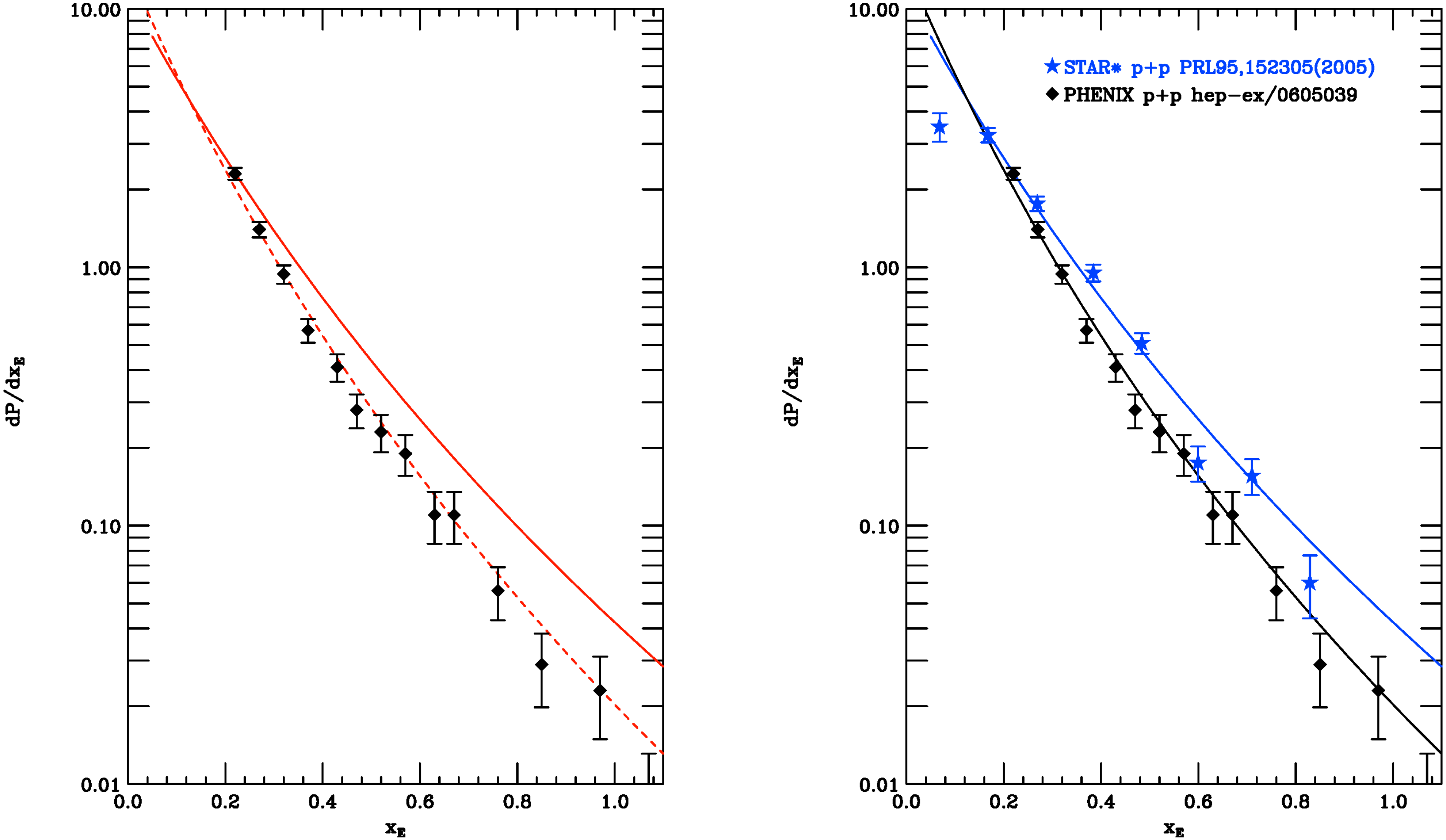


$4 < p_{Tt} < 6$ GeV/c $\langle p_{Tt} \rangle$=4.56 GeV/c

pp, AuAu $\sqrt{s_{NN}}$=200 GeV

STAR, J. Adams, Fuqiang Wang, et al PRL **95**, 152301 (2005)

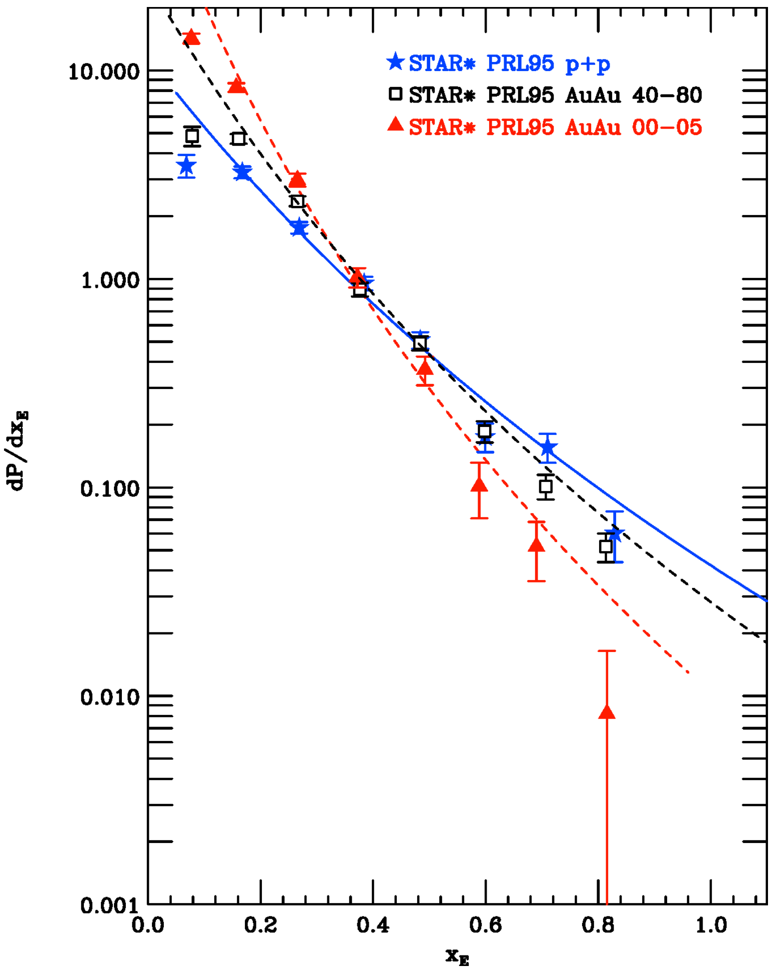
It works for STAR p+p and:



a) * means data normalized to agree with hep-ex/0605039-PRD **74**, 072002

b) $\hat{x}_h = 1.0$

STAR Au+Au--Clear effect with centrality

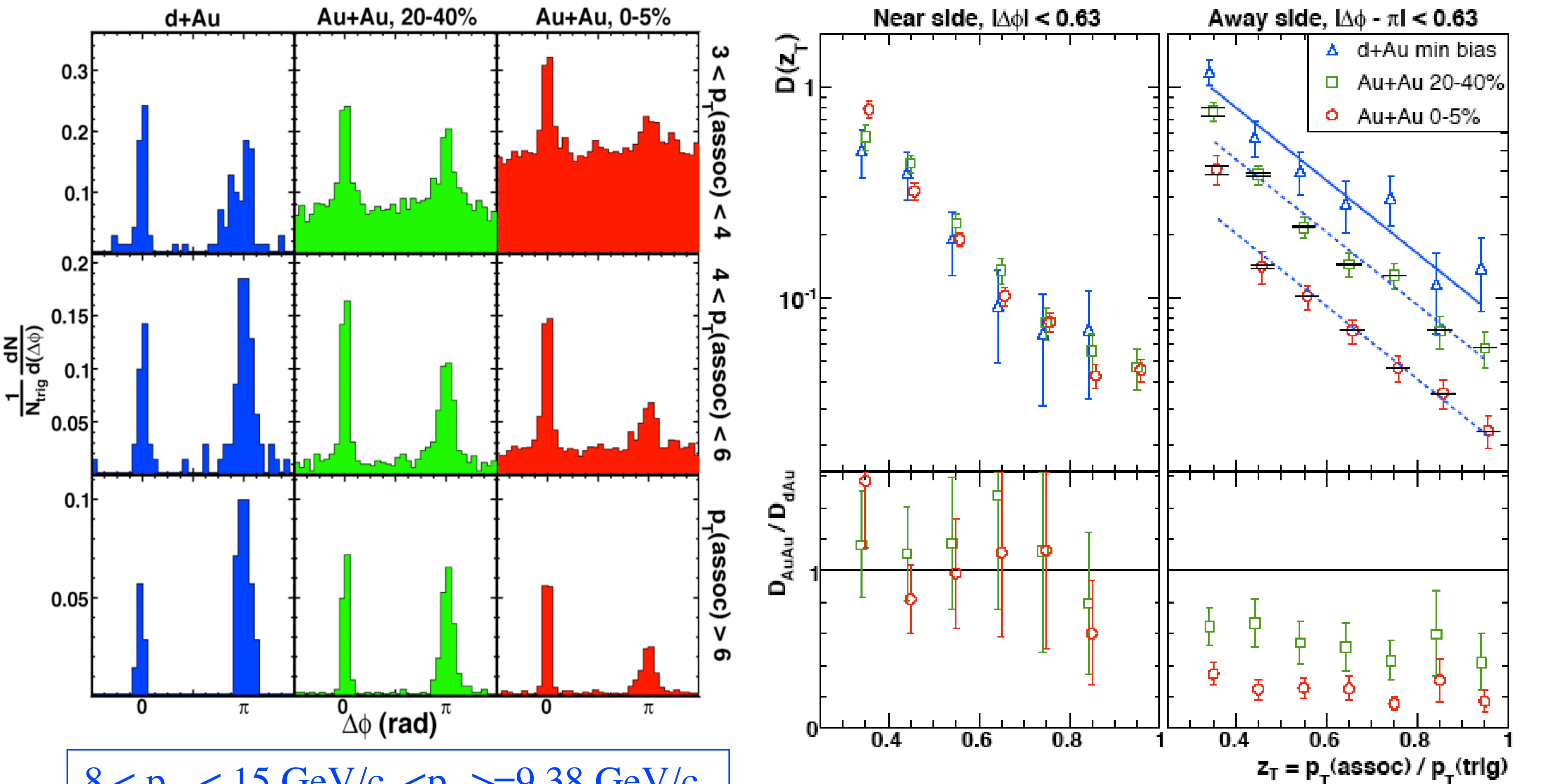


p+p	data*0.6	fit*1.0	$\hat{x}_h$ =1.0
AuAu40-80	data*0.6	fit*1.75	$\hat{x}_h$ =0.75
AuAu00-05	data*0.6	fit*4.0	$\hat{x}_h$ =0.48

- Away jet $\hat{p}_{Ta}$/trigger jet $\hat{p}_{Tt}$ decreases with increasing centrality
- consistent with increase of energy loss with distance traversed in medium

STAR, J. Adams, Fuqiang Wang, et al PRL **95**, 152301 (2005)

Newer STAR data AuAu: nucl-ex/0604018

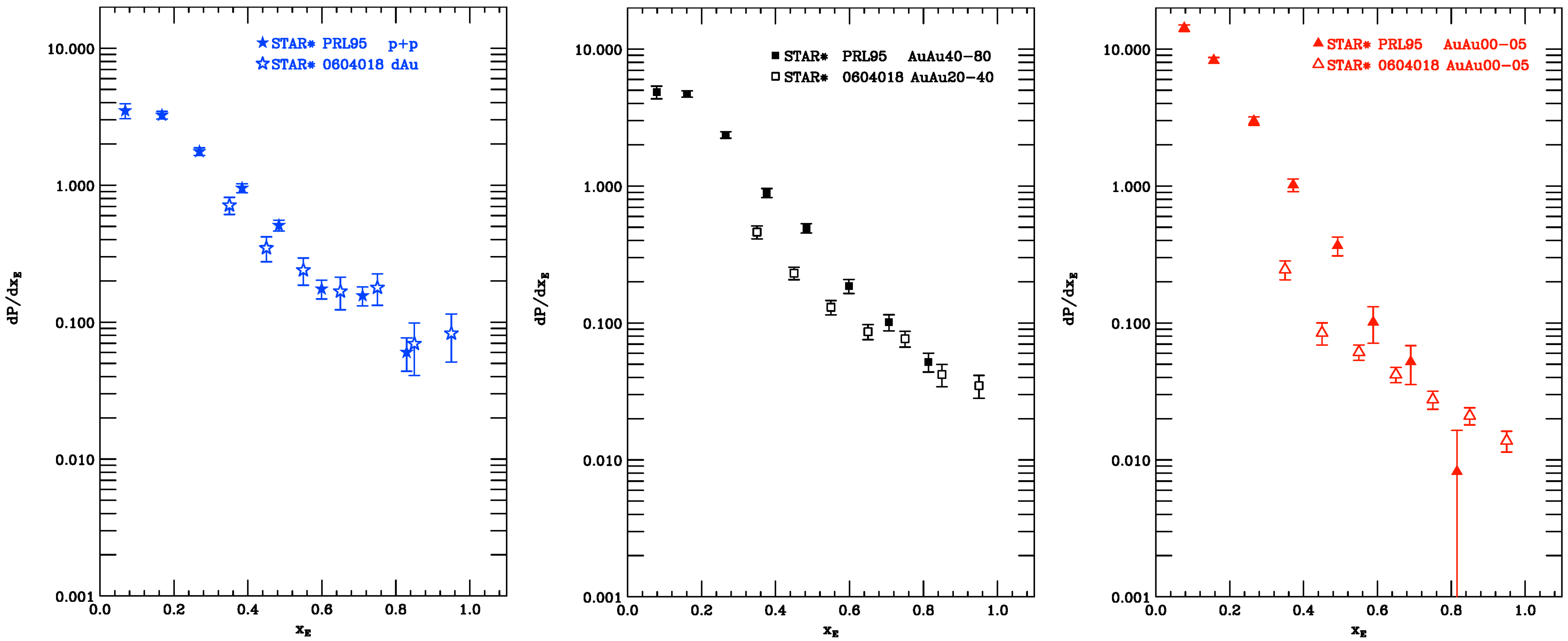


$8 < p_{Tt} < 15$ GeV/c $\langle p_{Tt} \rangle = 9.38$ GeV/c

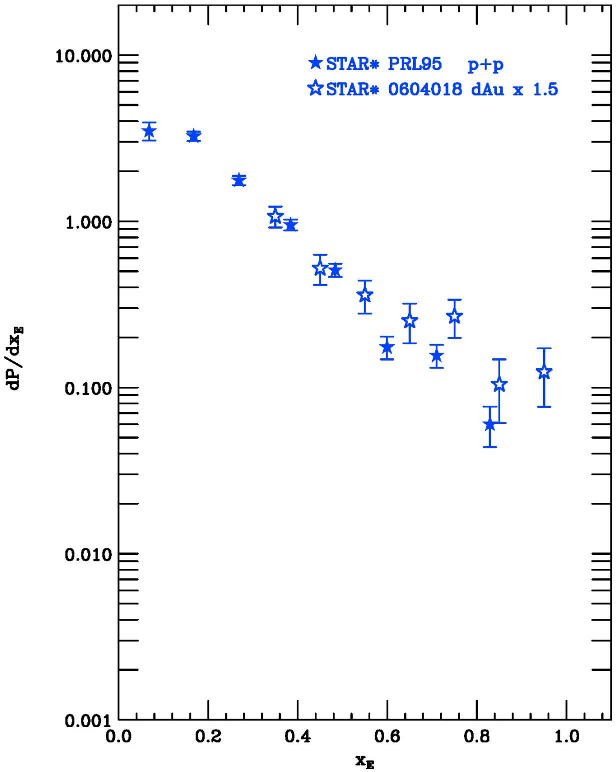
STAR, J. Adams, D. Magestro, et al PRL **97**, 162301 (2006)

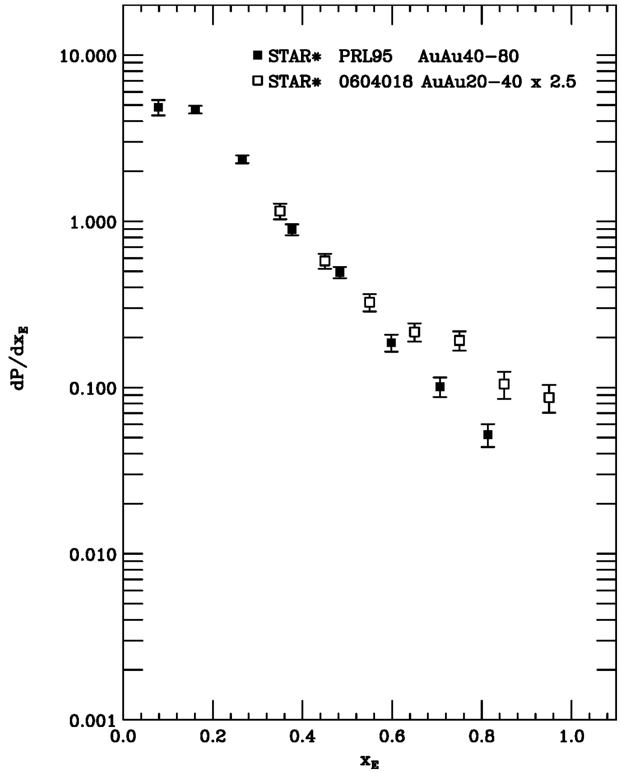
Thanks to Dan Magestro for table of data points

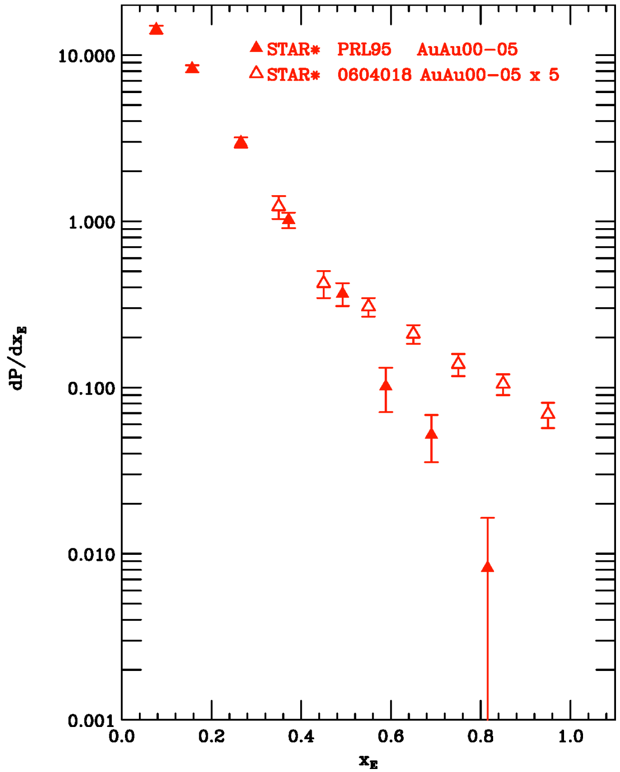
STAR(nucl-ex/0604018) differs from STAR (PRL95) in normalization and SHAPE



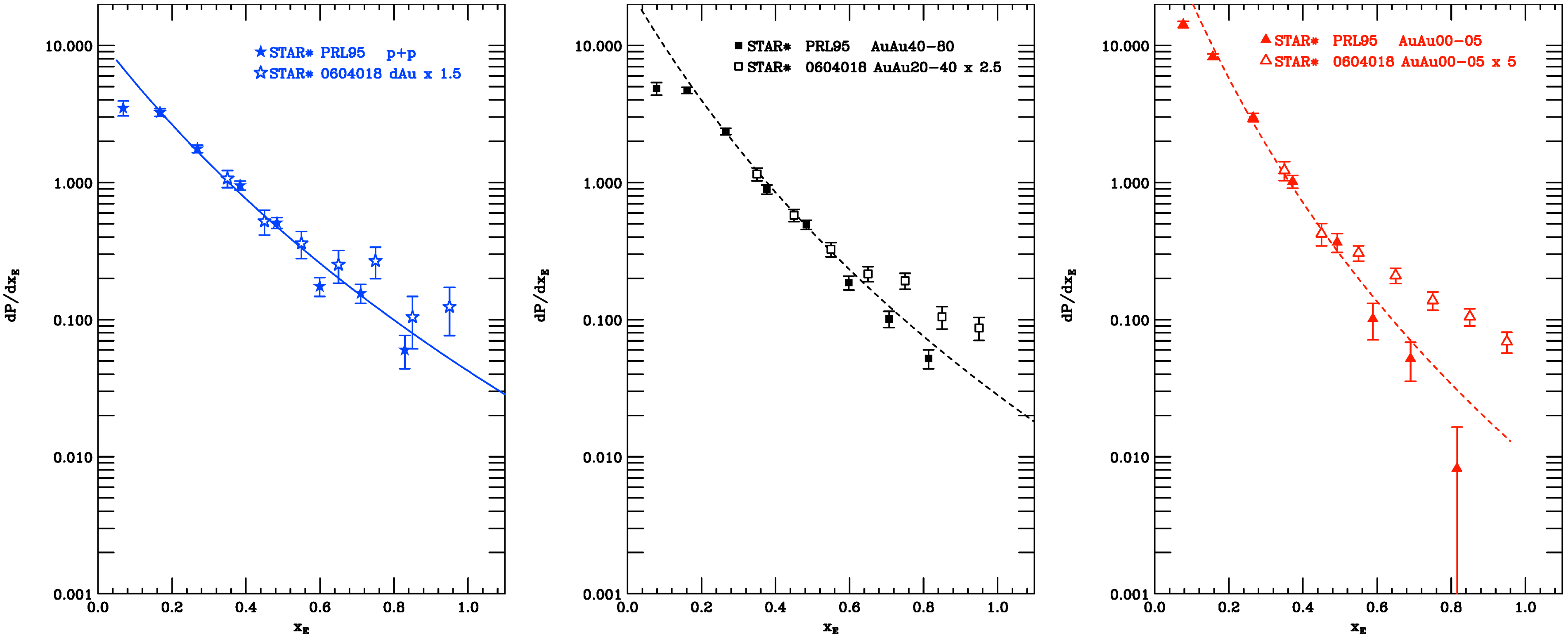
Normalize 064018 to PRL95 by eye



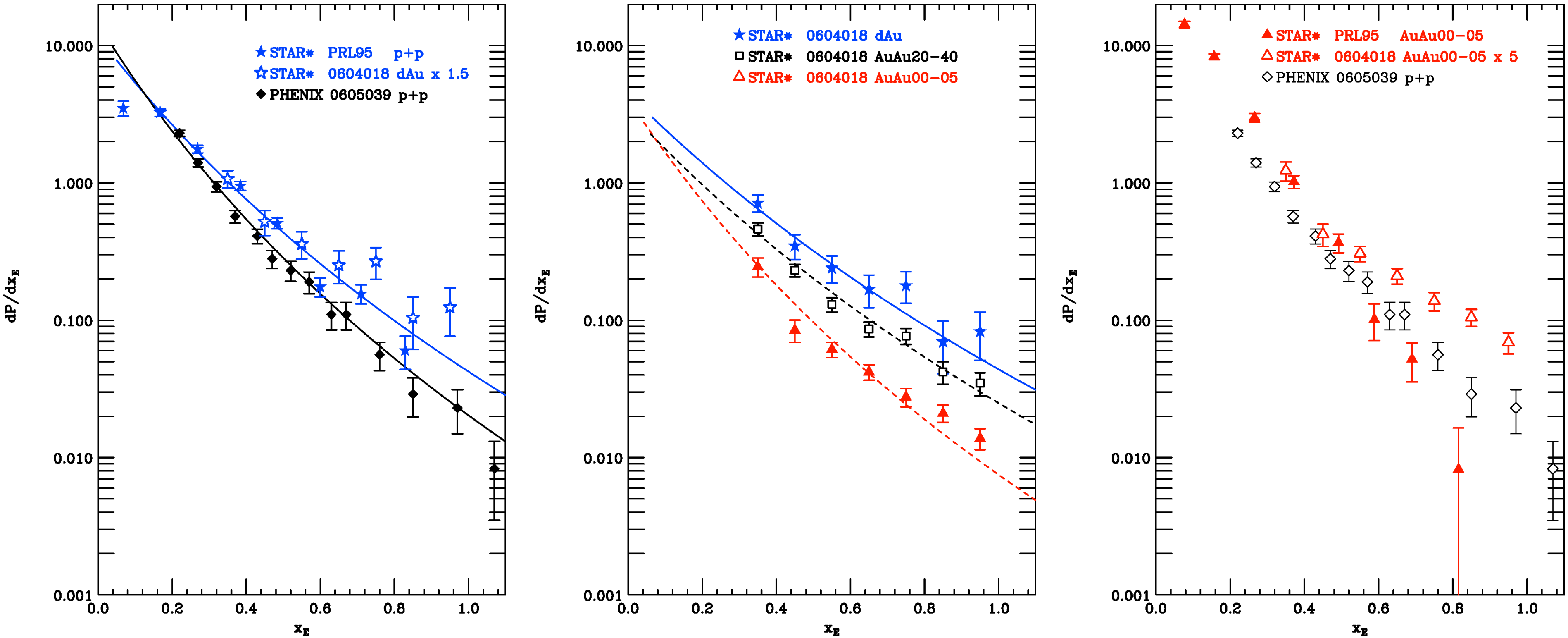




Normalized data with PRL95 curve



STAR 0604018 AuAu central flatter than PHENIX 0605039 p+p for x_E>0.5!



Norm (data)	Norm fit	hatx_h
Data*0.6	Fit*0.500	1.300
Data*0.6	Fit*0.350	1.200
Data*0.6	Fit*0.300	0.850

Can still fit, but curves too flat x_h>1, but still decreases with increasing centrality

Conclusions-I

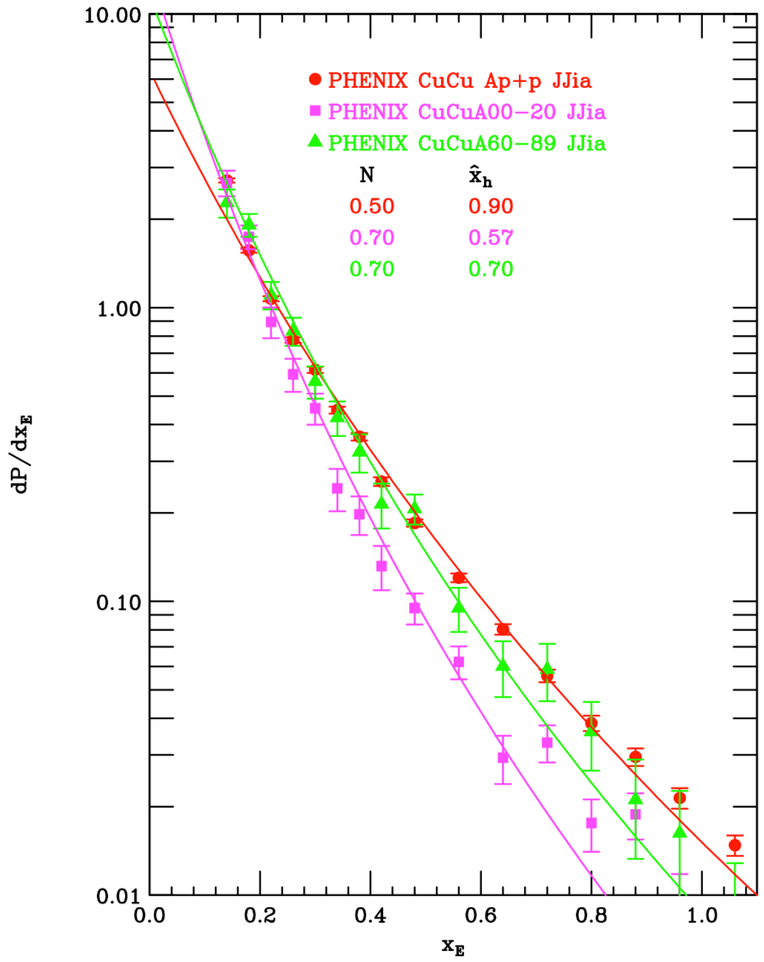
- Nice `fit' of $1/(1+y)^{n=8.1}$ with $x_E = \hat{x}_h\, y$ to PHENIX hep-ex/0605039 (PRD 74, 072002) and PRC73; and STAR PRL95 x_E distributions. But STAR nucl-ex/0604018-PRL97 d+Au much flatter than PHENIX d+Au PRC73,054903 (2006) in same p_{Tt} range.

- Both STAR Au+Au measurements show a decrease in the ratio of the transverse momentum of the away jet relative to the trigger jet with increasing centrality. For both data sets $\hat{x}_h$ decreases by a factor of ~2 from p+p (dAu) to Au+Au central collisions. Much more info than I_{AA}.

- New STAR `punchthrough' data has much too flat shape, an apparent sharp break, and disagrees in normalization with STAR PRL95.

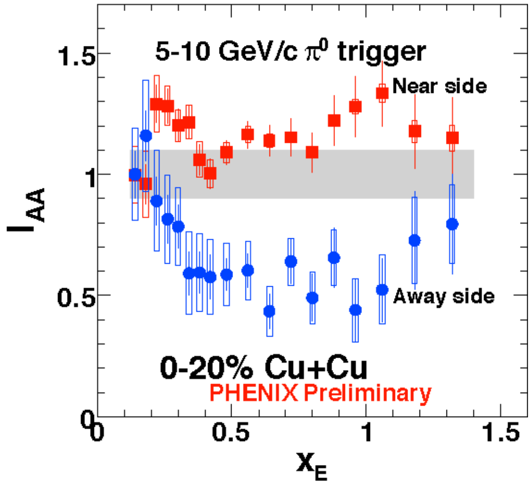
- Comparison of two STAR data sets would benefit by going lower in p_{Ta} (z_T) for the data of nucl-ex/0604018 to see whether slope is really steeper at low z_T, with dramatic break and (unreasonable in my opinion) flattening of the z_T distribution for $z_T \geq 0.5$

PHENIX QM2006-JJia Cu+Cu

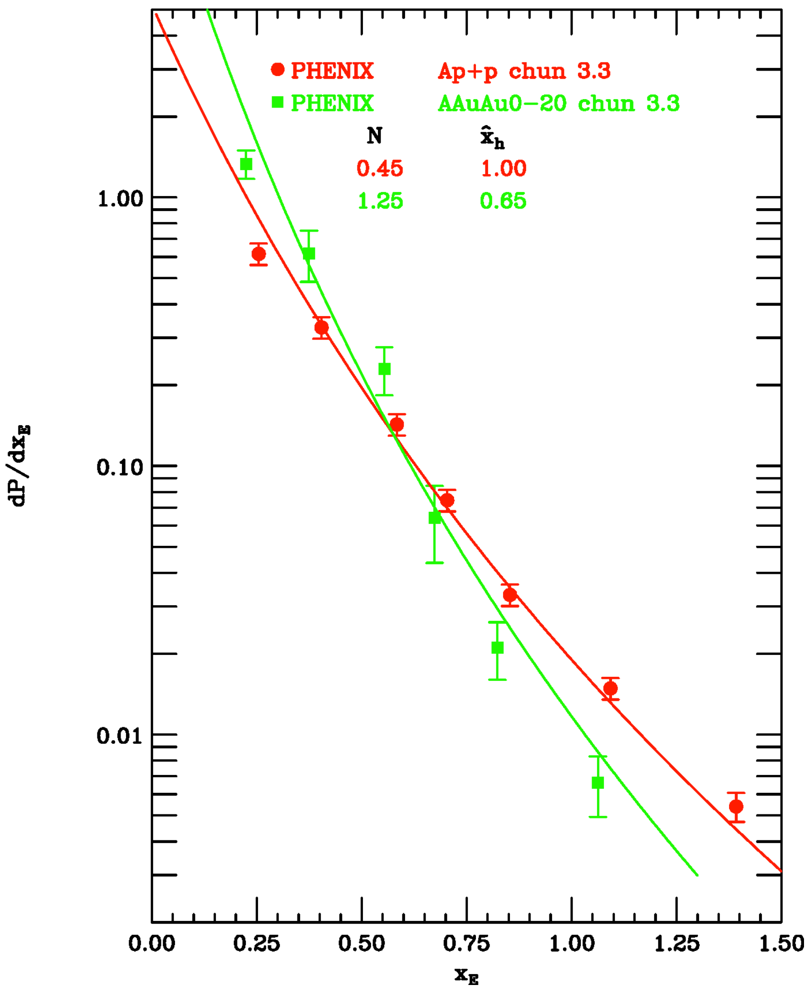


p+p	data*1.0	fit*0.5	$\hat{x}_h$ =0.90
CuCu60-89	data*1.0	fit*0.7	$\hat{x}_h$ =0.70
CuCu00-20	data*1.0	fit*0.7	$\hat{x}_h$ =0.57

π^0 (p_{Tt}>5 GeV/c)--$h^{\pm}$

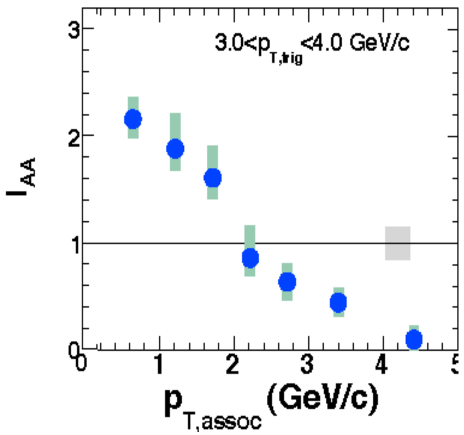


PHENIX QM2006-Chun Zhang AuAu



p+p p_T=3.3	data*1.0	fit*0.45	$\hat{x}_h$ =1.0
AuAu00-20	data*1.0	fit*1.25	$\hat{x}_h$ =0.65

$h^{\pm}$ ($3<p_{Tt}<4$ GeV/c)--$h^{\pm}$



$\hat{x}_h$ Conclusions

- Both the STAR data (FQ.Wang) and PHENIX QM2006 data nicely exhibit the $x_E/\hat{x}_h$ scaling in the range $0.2 < x_E < 0.6$ as the dominant feature. Thus, in my opinion, the simple scaling formula adjusted to fit the data in the range $0.2 < x_E < 0.6$ is a simple and elegant way to characterize the x_E distributions in A+A collisions which gives a quantitative estimate of the relative energy loss of away-jets triggered by a high p_{Tt} hadron (e.g. π^0).

- This is a decent estimate of the energy loss of jets passing through the medium since trigger jets are “surface biased” due to an effect similar to “trigger bias”--jets emitted closer to the surface which have not lost energy are favored over jets emitted deeper in the medium with higher $\hat{p}_{Tt}$ which have lost energy.

- Help on this issue from theorists would be appreciated.

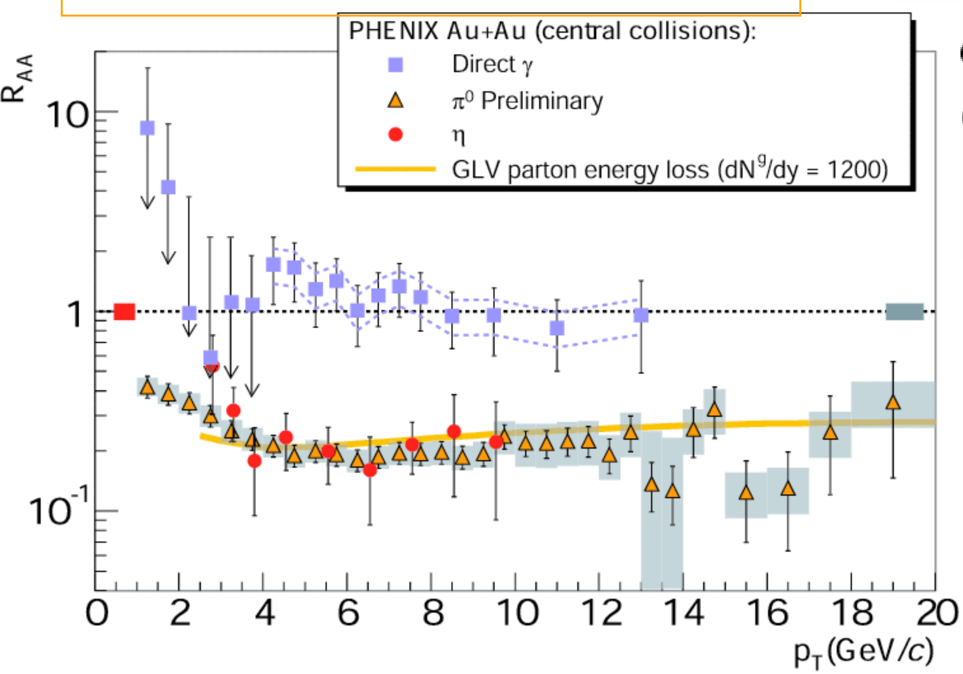
If time permits perhaps the most interesting result from QM2006 PHENIX

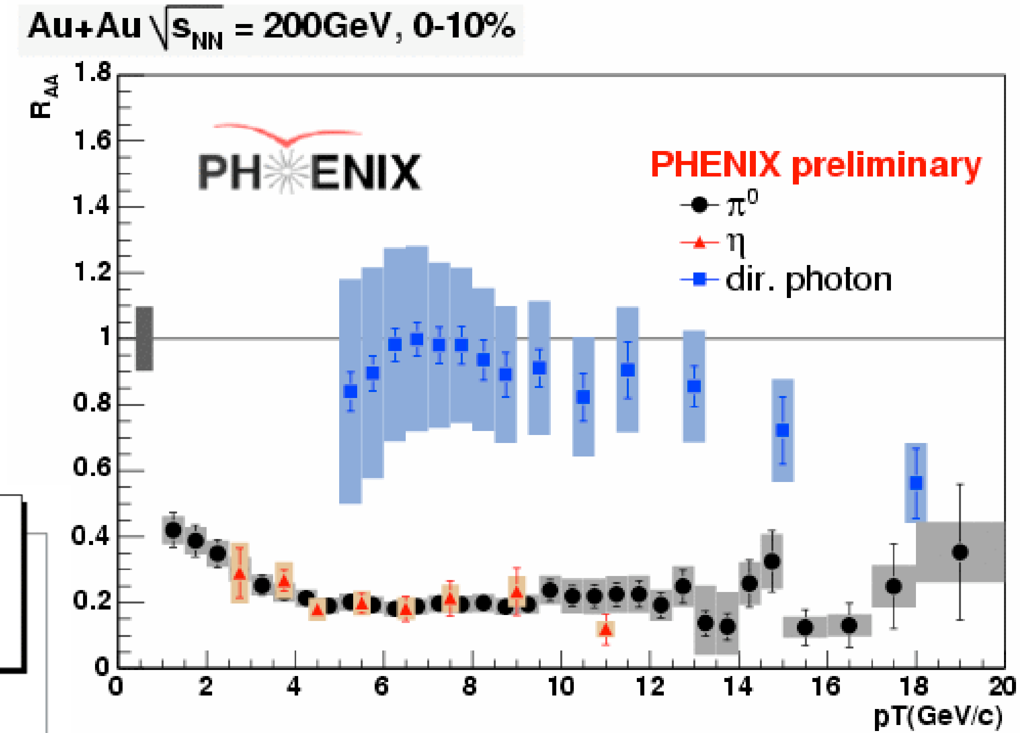
This could be the biggest result at QM2006

$$R_{AA}(p_T) = \frac{d^2Y^{AA}/dp_T dy}{\langle T_{AA}\rangle d^2\sigma^{NN}/dp_T dy}$$

$$T_{AA} = \langle N_{coll}\rangle / \sigma_{inel.}$$

QM2005
-I wanted to make a T-shirt
pp dir γ reference is pQCD



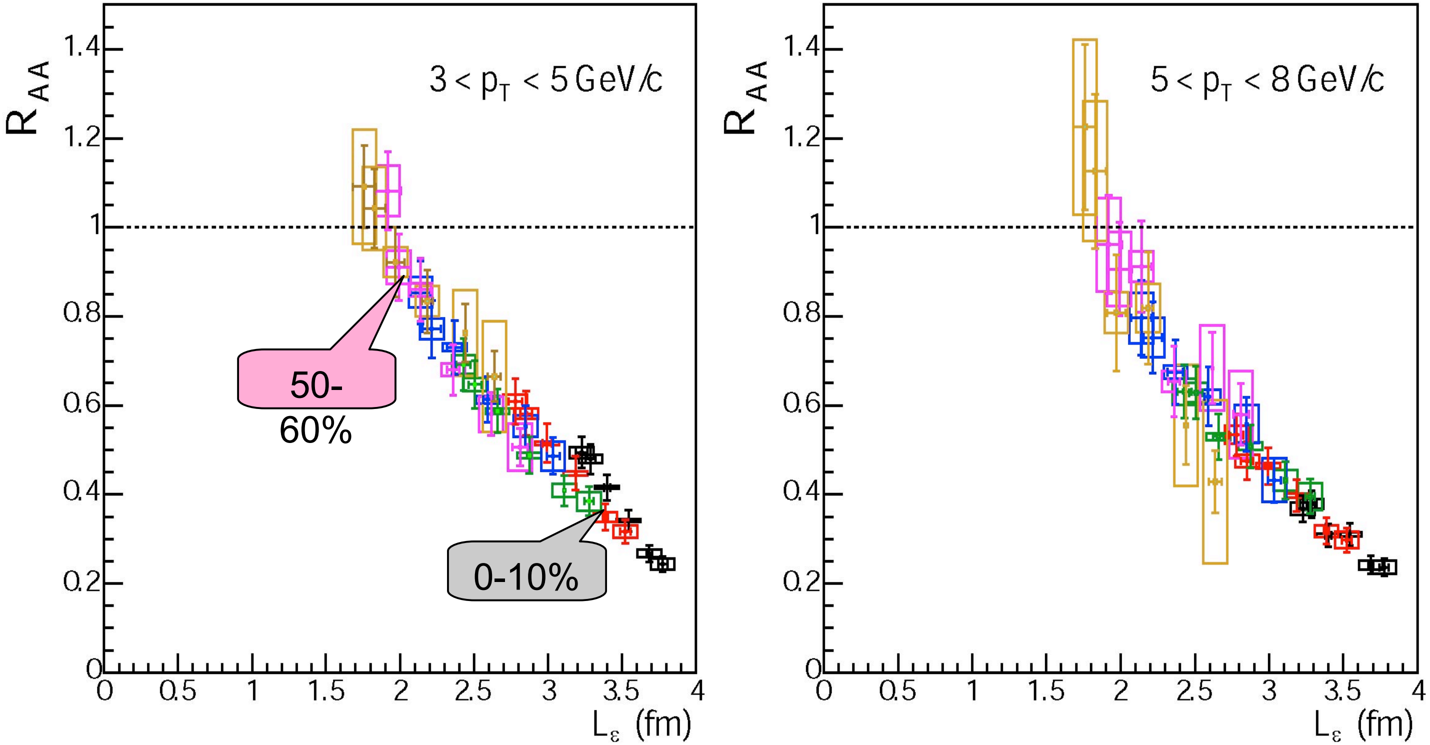


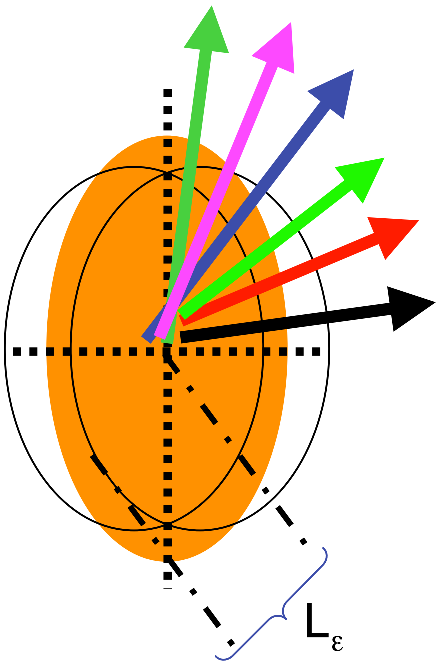
QM2006-
pp dir γ reference is run 5 msmt
If $R^{\pi}_{AA} = R^{\gamma}_{AA}$ the whole concept of energy loss changes

R_{AA} π^0 vs. Reaction Plane-learn something new!

Au+Au collisions at 200GeV
R_{AA} is absolute, v2 is relative

nucl-ex/0611007
(submitted to Phys. Rev. C.)

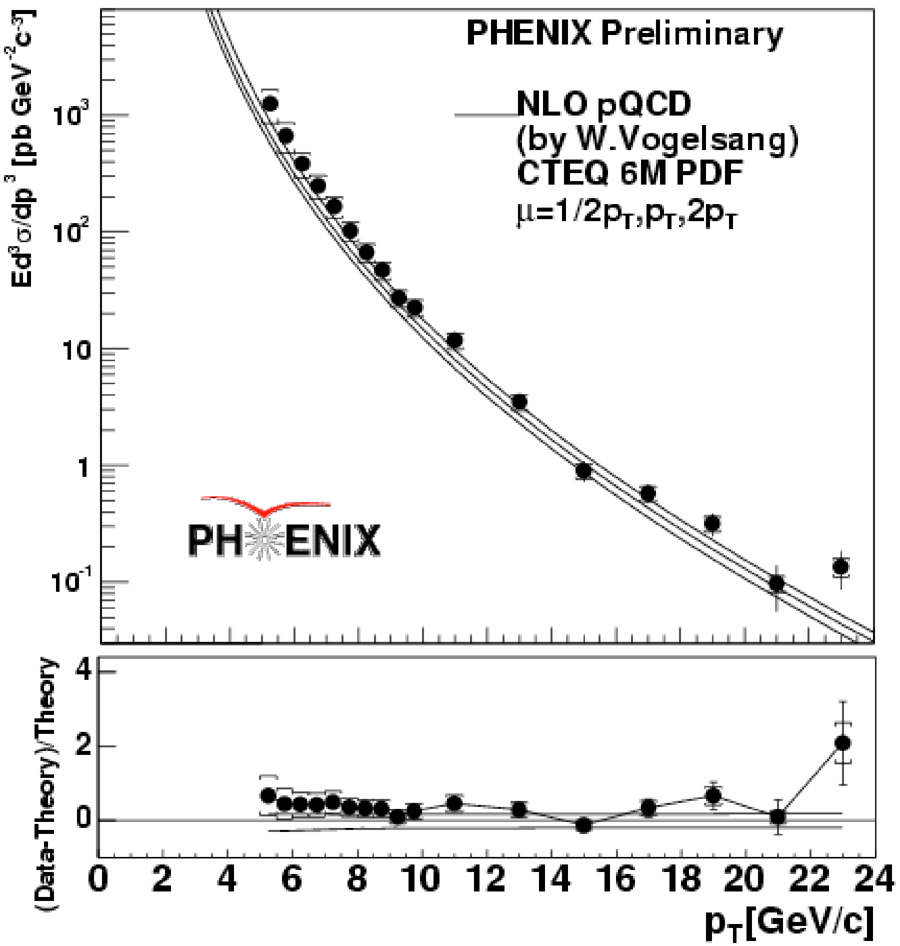




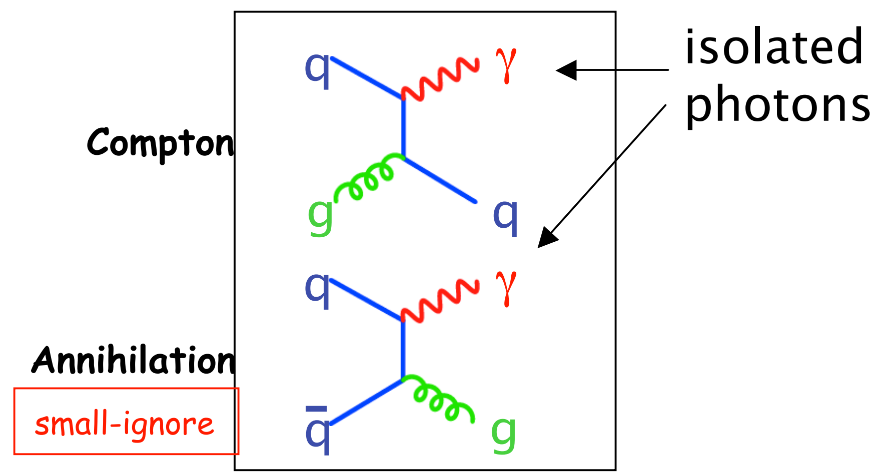
L_ε = distance from edge to center calculated in Glauber model

Little/no energy loss for L_ε < 2 fm

RHIC-PHENIX year-5 direct photon cross-section



- **PHENIX Year-5 preliminary result.**
- p_T region is extended up to 24GeV/*c*.
- Good reference for the evaluation of nuclear effect for high-p_T direct photon production at RHIC.



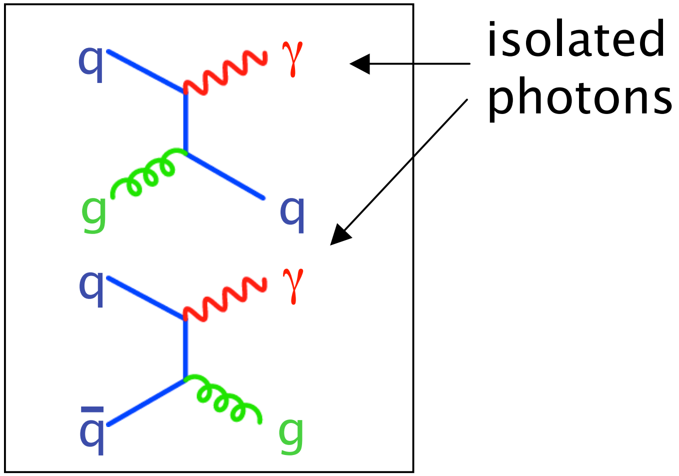
Direct photon production-simple theory hard experiment

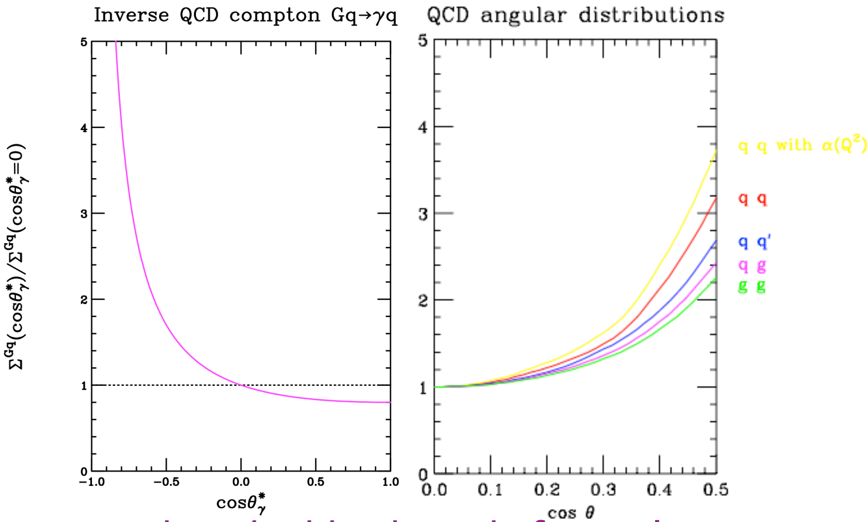
See the classic paper of Fritzsch and Minkowski, PLB **69** (1977) 316-320

Compton

Annihilation

small-ignore





Compton distribution is much flatter than scattering and peaked backwards from gluon

$$\Sigma^{gq}(\cos\theta^*) = \frac{\alpha\, e_q^2}{3\,\alpha_s}\left(\frac{1+\cos\theta^*}{2} + \frac{2}{1+\cos\theta^*}\right)$$

Substitution and Jacobean gives:

$$\frac{d^3\sigma}{dp_T^2\, dy_c\, dy_d} = x_1 f_g^A(x_1)\, F_{2\mathrm{B}}(x_2, Q^2)\frac{\pi\alpha\alpha_s(Q^2)}{3\hat{s}^2}\left(\frac{1+\cos\theta^*}{2} + \frac{2}{1+\cos\theta^*}\right)$$
$$+\; F_{2\mathrm{A}}(x_1, Q^2)\, x_2 f_g^B(x_2)\frac{\pi\alpha\alpha_s(Q^2)}{3\hat{s}^2}\left(\frac{1-\cos\theta^*}{2} + \frac{2}{1-\cos\theta^*}\right)$$

A Brief History of the EMC effect.

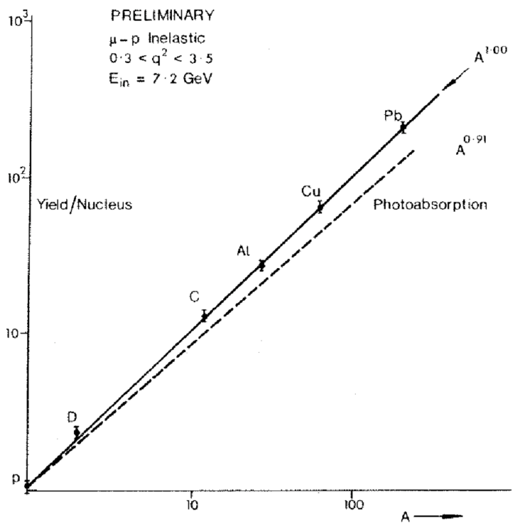
note disagreement

$A^{1.00}$

LETTERS

31 March 1983

E. Gabathuler, Total cross-section



A dependence of the inelastic muon cross-section as presented by Tannenbaum (see d

M.May, et al, PRL 35 (1975) 407. Plot is online result shown by Gabathuler at Electron/Photon 1973

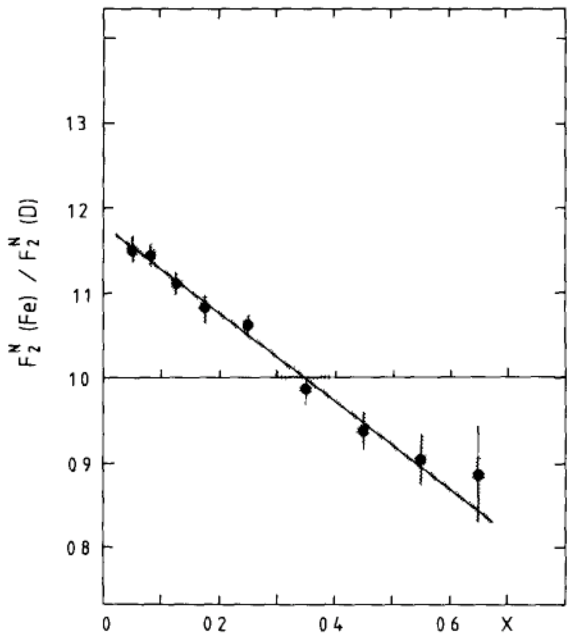
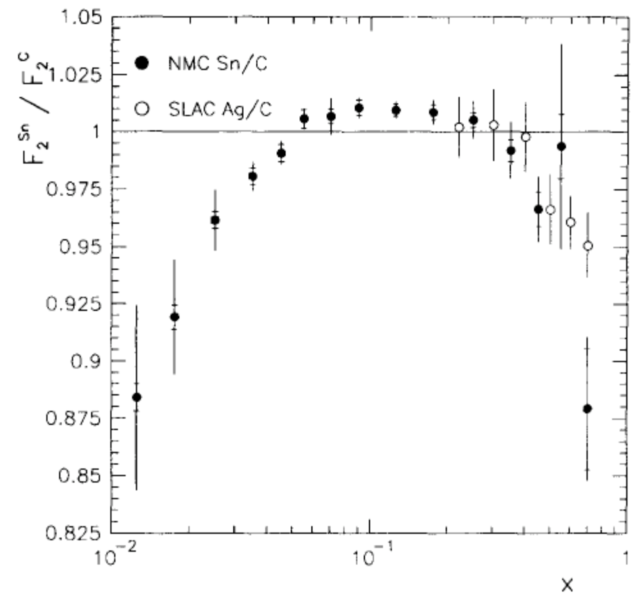


Fig. 2. The ratio of the nucleon structure functions F_2^N measured on iron and deuterium as a function of $x = Q^2/2M_p\nu$. The iron data are corrected for the non-isoscalarity of $^{56}_{26}$Fe,

EMC, J.J.Aubert, et al, PLB 123(1983) 275-278

NMC Collaboration/Nuclear Physics B 481 (1996) 23–39



NMC, M.Arneodo, et al, NPB 481(1996) 23-39

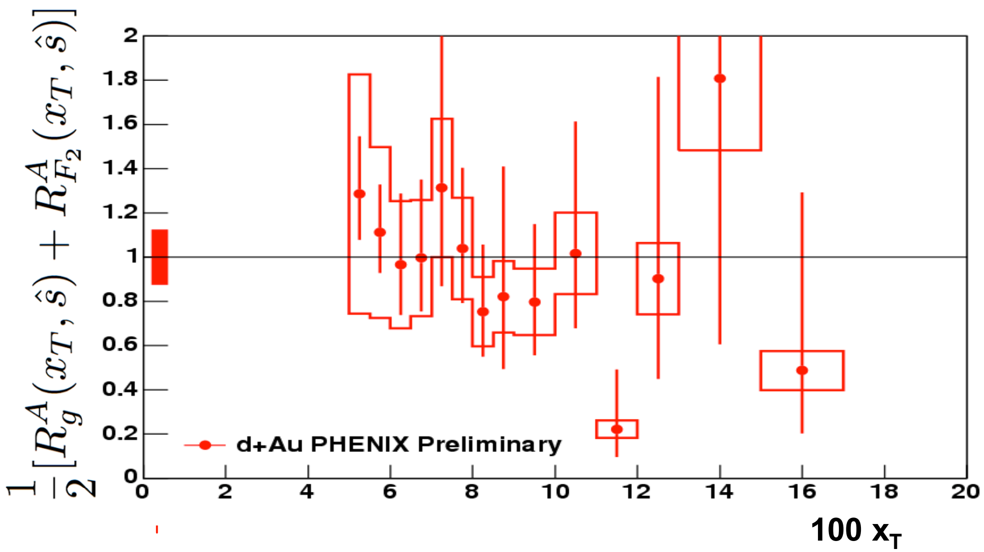
Direct γ is "EMC effect" for gluons

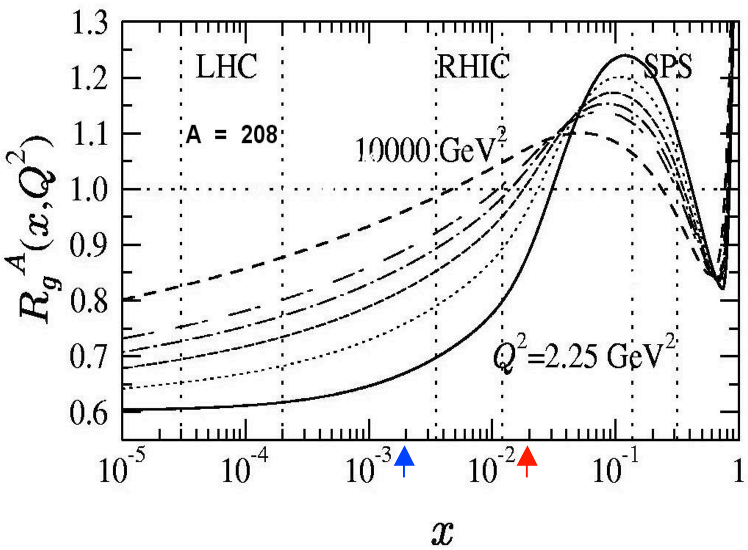
Nuclear Modification Factor-Min Bias

$$R_{dA} = \frac{d\sigma_\gamma^{dA}(p_T)/dp_T}{(2 \times A) \times d\sigma_\gamma^{pp}(p_T)/dp_T}$$

$$R_{dA} \approx \frac{1}{2}\left(\frac{F_{2A}(x_T)}{AF_{2p}(x_T)} + \frac{g_A(x_T)}{Ag_p(x_T)}\right) = R_g^A(x, Q^2)$$

Eskola, Kolhinen, Vogt hep-ph/0104124





Consistent with 1 ➔ No modification within the error

This is first measurement of 'EMC effect' for gluons

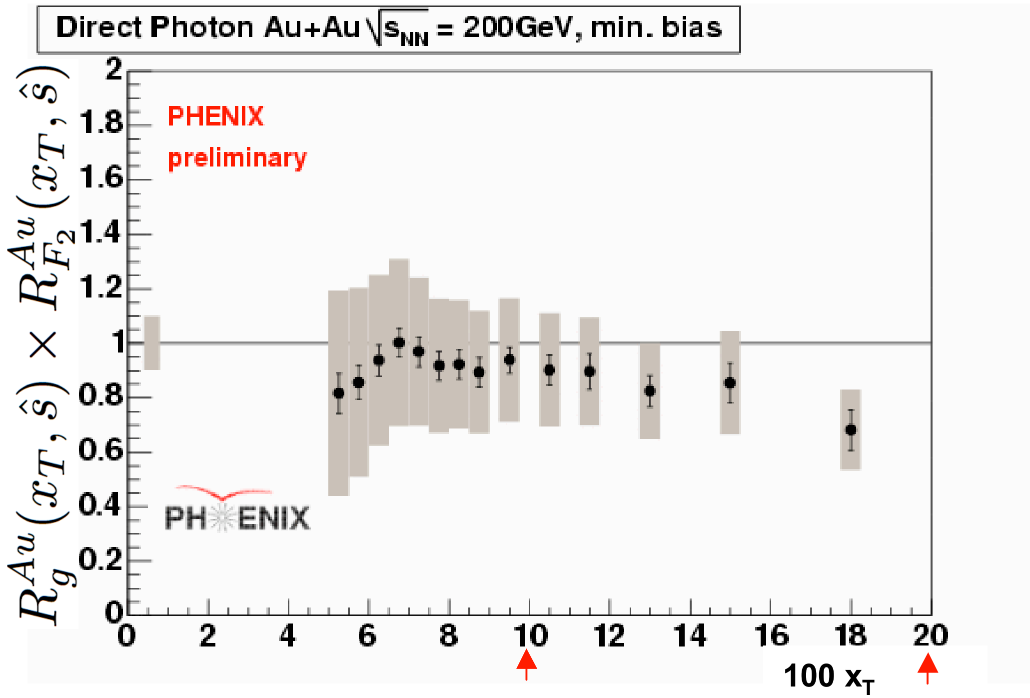
x	p_T(RHIC)	p_T (LHC)
0.02	2 GeV/c	60 GeV/c
0.002	0.2 GeV/c	6 GeV/c

For Au+Au min bias R_{AA} is also simple

Au+Au minimum bias

$$R_{AA} = \frac{d^2\sigma_\gamma^{AA}/dp_T^2\,dy_\gamma}{AA\,d^2\sigma_\gamma^{pp}/dp_T^2\,dy_\gamma} \approx \left(\frac{F_{2A}(x_T)}{AF_{2p}(x_T)} \times \frac{g_A(x_T)}{Ag_p(x_T)}\right)$$

Eskola,Kolhinen,Ruuskanen
Nucl. Phys. B**535**(1998)351



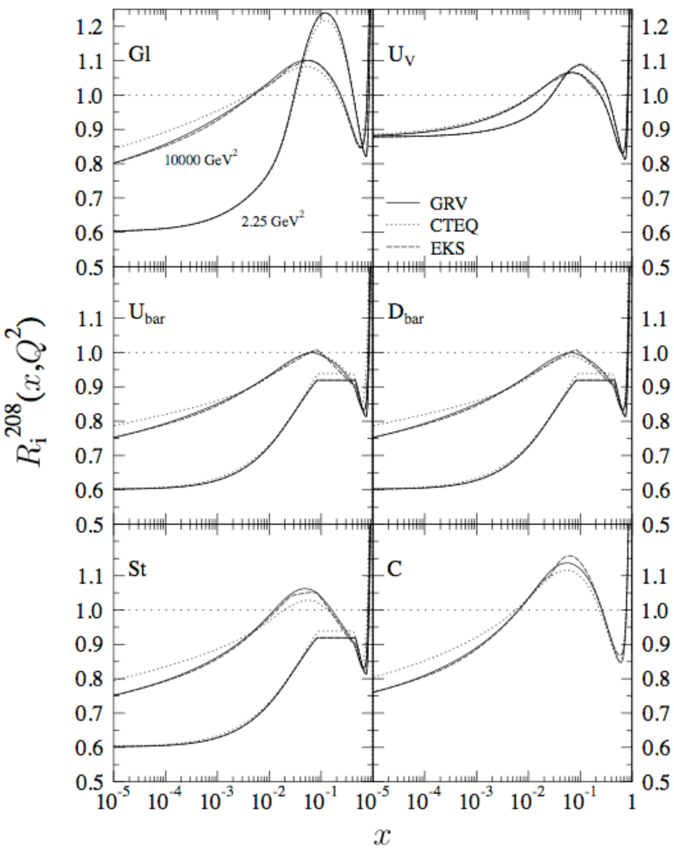


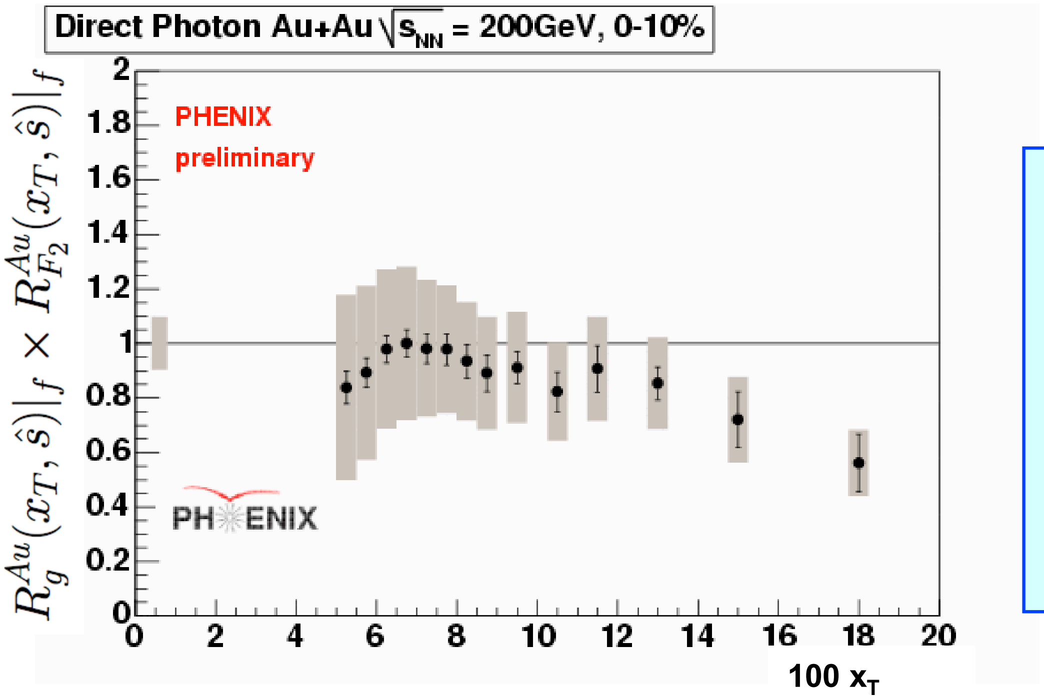
Fig. 1. The nuclear ratios $R_i^A(x,Q^2)$ for individual parton flavours $i = g, u_V, \bar{u}, \bar{d}, s, c$ of a lead nucleus $A = 208$ as functions of x at fixed values of $Q^2 = Q_0^2 = 2.25$ GeV² and $Q^2 = 10000$ GeV² as obtained by using the GRV-LO [25] distri-

Do the structure function ratios actually drop by ~20% from x=0.1 to x=0.2?

Central Collisions---no theory counterpart-yet

Au+Au Central Collisions

$$R_{AA} = \frac{1}{A_f A_f}\frac{d^2\sigma_\gamma^{AA}|_f/dp_T^2\,dy_\gamma}{d^2\sigma_\gamma^{pp}/dp_T^2\,dy_\gamma} \approx \left(\frac{F_{2A}(x_T)|_f}{A_f F_{2p}(x_T)} \times \frac{g_A(x_T)|_f}{A_f g_p(x_T)}\right) = \quad ???$$



Theorists, HELP!

Very few attempts so far for structure function measurements or theory as a function of impact parameter:
E665, ZPC 65, 225 (1995)
Li and Wang, PLB 527, 85 (2002)
Klein and Vogt PRL 91, 142301 (2003)
Emel'yanov, et al. PRC 61, 044904 (2000)
and references therein.

Experimentalists:
RHIC p+A, eRHIC

Nobody has seriously measured nor calculated structure function ratios as a function of centrality!!!

What I still don't understand-I

After 6 runs at RHIC, many discoveries have been made in Au+Au collisions but there is much that is still not known or understood:

- Is the nuclear modification factor R_{AA} for π^0 really constant at a factor of 5 suppression over the range $3< p_T< 20$ GeV/c which would occur for a constant-fractional energy loss analogous to bremsstrahlung, or does the suppression tend to vanish at larger p_T? Is dE/dx constant or a constant fraction or something else?
- Does R_{AA} for direct-γ really approach that of π^0 at large p_T~20 GeV/c as indicated by preliminary data? If true this would argue that the suppression due to a medium effect vanishes at large p_T> 20 GeV/c and the effect observed is due to the structure function. If this is confirmed, it would be VERY BAD for LHC.
- The detailed mechanism of jet suppression due to interaction with the medium is not understood. It is not known whether partons lose energy continuously or discretely, whether they stop in the medium so that the only observed jet fragments are those emitted from the surface or whether partons merely lose energy exiting the medium such that those originating from the interior of the medium with initially higher p_T are submerged (due to the steeply falling p_T spectrum) under partons emitted at the surface which have not lost energy. In either case, there is a surface bias.

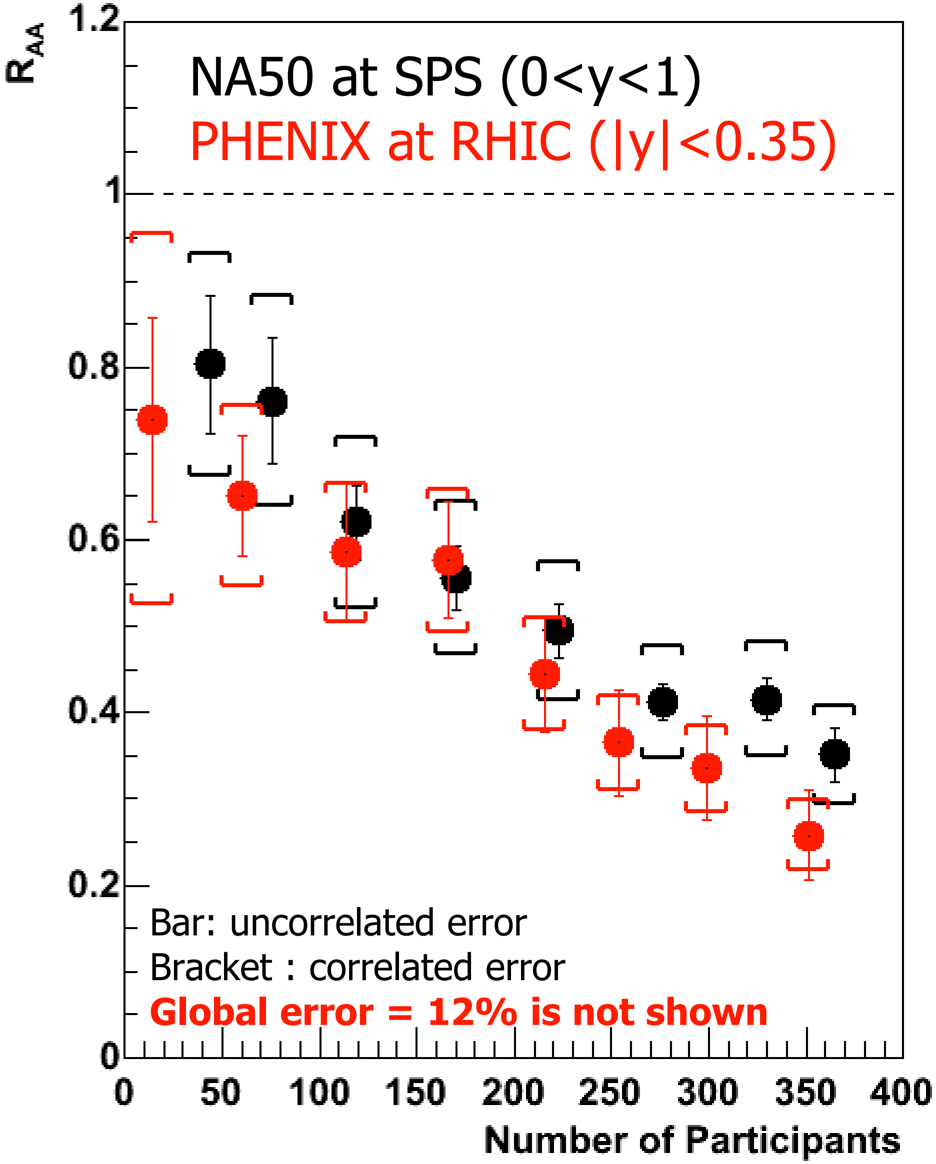
What I still don't understand-II

- The reason why heavy quarks appear to lose the same energy as light quarks is not understood.
- It is not known whether a parton originating at the center of the medium can exit the medium without losing any energy.
- It is not known where the energy from the absorbed jets or parton energy loss goes or how it is distributed.
- The surface bias discussed above complicates the use of two-particle correlations of hard-scattered partons to probe the medium since detecting a particle from an away-side parton changes the surface bias of the trigger parton. This means that detection of both a trigger and away side particle is required in order to constrain the hard-scattering kinematics and the position of the origin of the hard-scattered parton-pair within the nuclear matter. Then, the main correlation information with relatively stable kinematics and origin is obtained by studying correlations with an additional 1 or two particles, i.e. a total of 3 or 4 particle correlations, which is much more complicated and requires much more data than the same studies in p+p collisions.

What I still don't understand-III

- The baryon anomaly, the increase of the $p^{\pm}/\pi^{\pm}$ ratio in the range $2<p_T<6$ GeV/c in Au+Au collisions from the value given by parton-fragmentation in this p_T range in p+p collisions, is not understood. Elegant recombination models fail to explain the similar jet activity correlated to the p and π triggers in this "intermediate" p_T range.
- The wide away-side non-identified hadron correlations for triggers in the intermediate range $2<p_T<6$ GeV/c in Au+Au collisions, with a possible dip at 180^{o} which causes apparent peaks displaced by $\sim 60^{o}$, is not understood. It could represent a Mach cone due to the analogy of a sonic-boom of the parton passing through the medium faster than the speed of sound, or it could indicate jets with large deflections. The effect may be related to the baryon anomaly, which occurs in this p_T range; or the peaks, which are seen also for much softer trigger particles, may not be a hard-scattering effect.
- The ridge is not understood. What causes it? What are its properties? How does it depend on p_{Tt}, angle to reaction plane etc? Why isn't there an away-side ridge?
- Finally, J/Ψ suppression, which for more than 20 years has represented the gold-plated signature of deconfinement, is not understood.

J/Ψ Suppression--R_{AA}
PHENIX mid-rapidity (e+e-) the same as NA50!!!



- R_{AA} vs. N_{part}
  - ✓ NA50 at SPS
    - 0<y<1
  - ✓ PHENIX at RHIC
    - |y|<0.35