A critical review of Jet Physics from ISR/FNAL/SpS to LHC

M. J. Tannenbaum
Brookhaven National Laboratory
Upton, NY 11973 USA

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Jets in Hadron Collisions are very complicated with a long learning curve. Probably worse in RHI physics. Hard scattering is better learned with single particle and few particle correlation measurements. The main advantage of jets is rate at large p_T

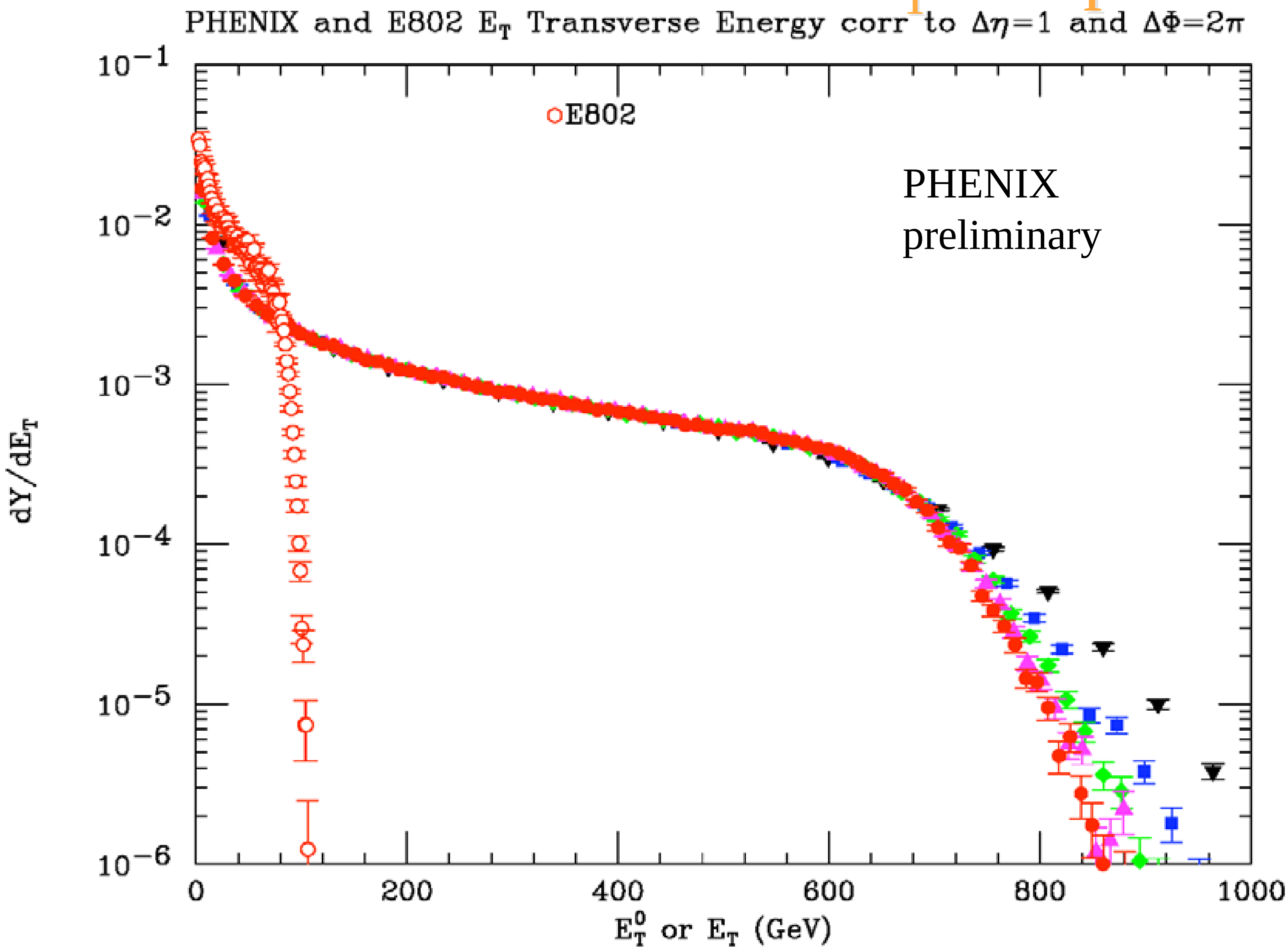
BDMPS 1997-1998

- In 1998 at the QCD workshop in Paris, Rolf Baier asked me whether jets could be measured in Au+Au collisions because he had a prediction of a QCD medium-effect on colored partons in a hot-dense-medium with lots of unscreened color charge.

- As the expected energy in a typical jet cone $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is πR^2 x1/ 2π x $dE_T/d\eta = R^2/2$ x $dE_T/d\eta$ ~ 300 GeV for R=1 at $\sqrt{s_{NN}}$=200 GeV where the maximum Jet energy is 100 GeV, Jets can not be reconstructed in Au+Au central collisions at RHIC.

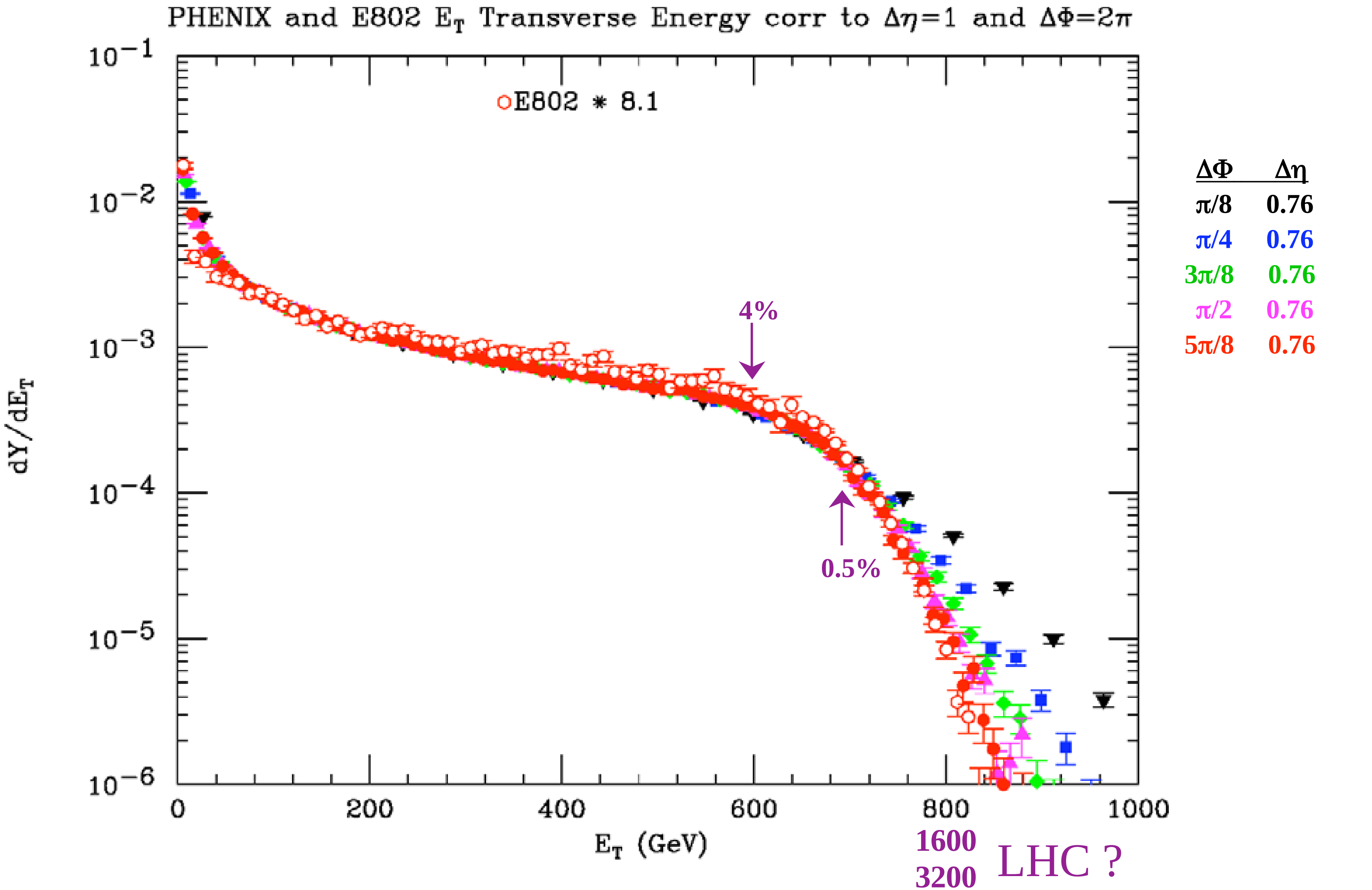
- For LHC Morsch (HP2006) gives ~ 1500 GeV for R=1 at $\sqrt{s_{NN}}$=5500 GeV, a factor of 5 increase, recent predictions [PHENIX PRC**71**(2005)034908, Busza nucl-ex/0410035] give a ratio as low as 2 compared to RHIC.

PHENIX and E802 E_T compared



E877 $dE_T/d\eta$=200 GeV@$\sqrt{s_{NN}}$=4.8 GeV   PHENIX $dE_T/d\eta$~680 GeV@$\sqrt{s_{NN}}$=200 GeV

Au+Au E_T spectra at AGS and RHIC are the same shape!!!



E_T/Jets/hard-scattering Lessons from ISR/FNAL/SPS or why nobody of a certain age believes “proof by Monte Carlo”

[e.g. see M. D. Corcoran, Phys. Rev. D**32** (1985)592-603]

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."*

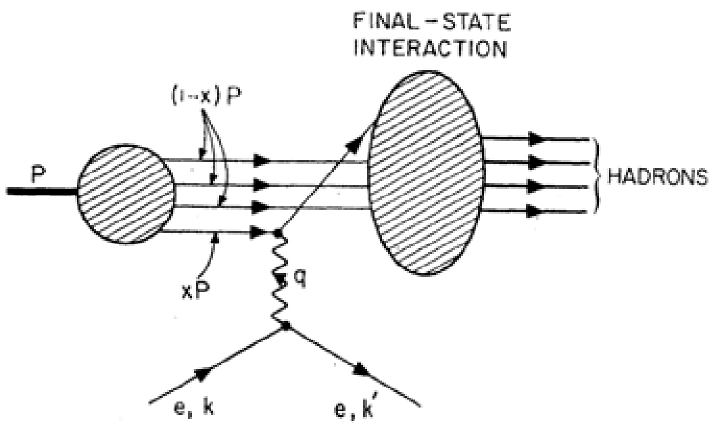
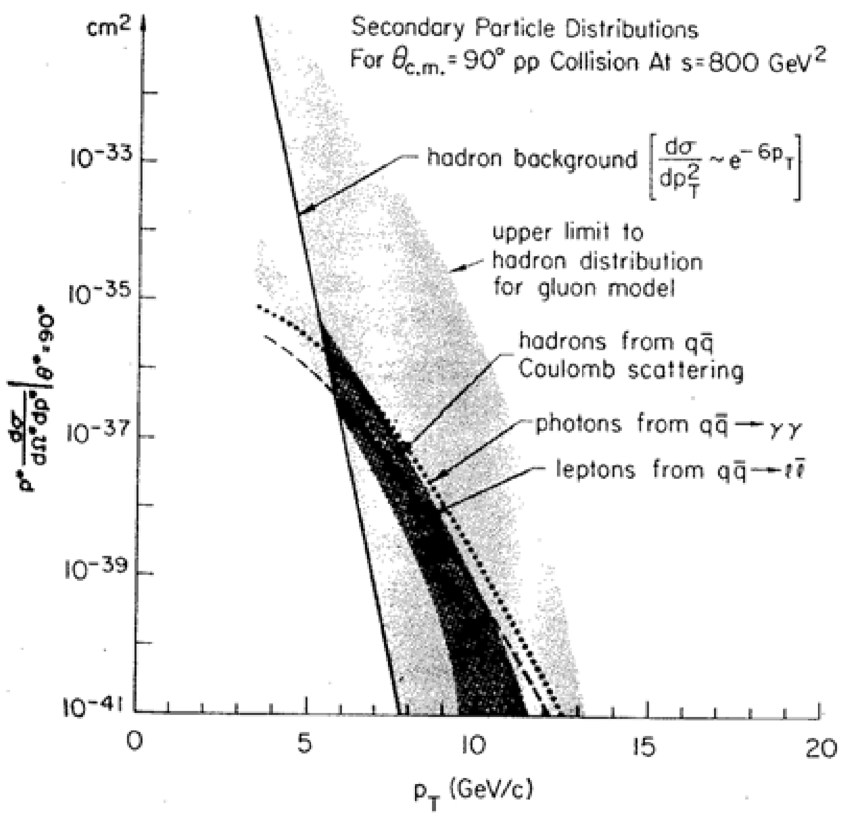


FIG. 1. Kinematics of lepton-nucleon scattering in the parton model.



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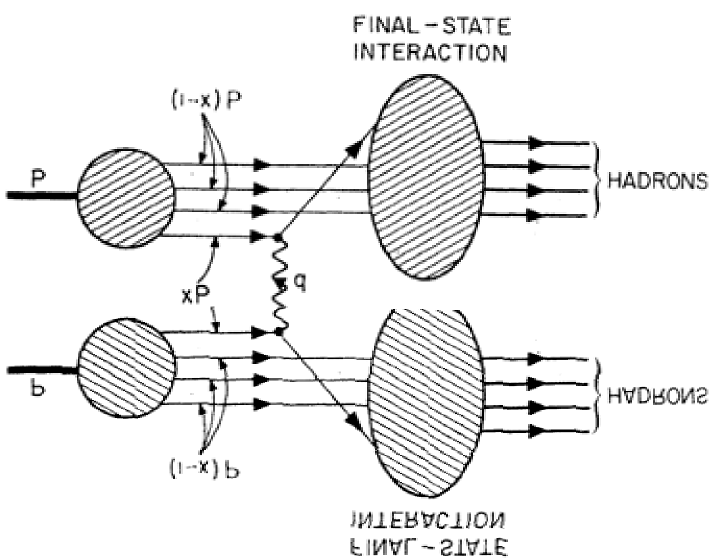
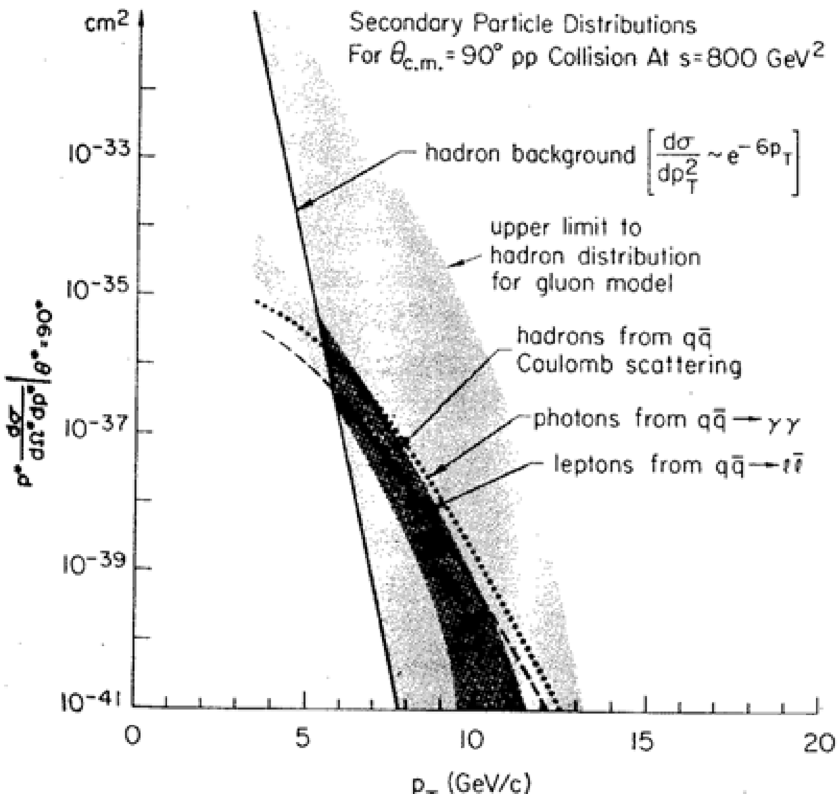
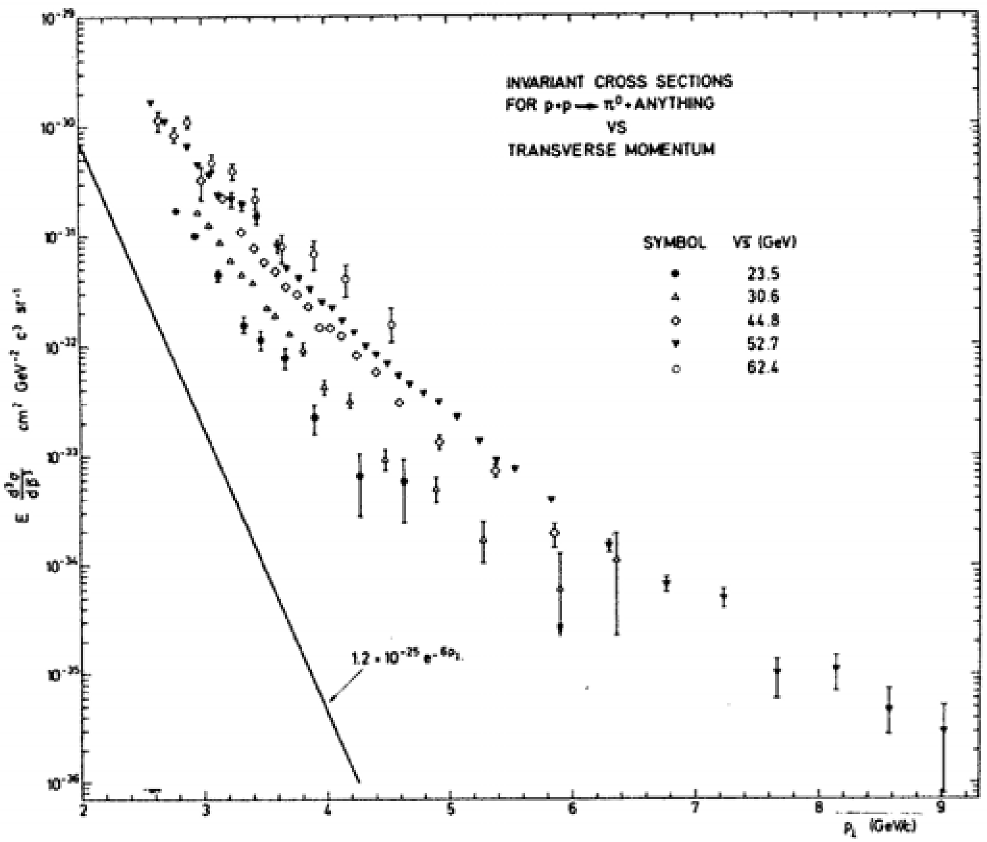




CCR at the CERN-ISR
Discovery of high p_T production in p-p



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

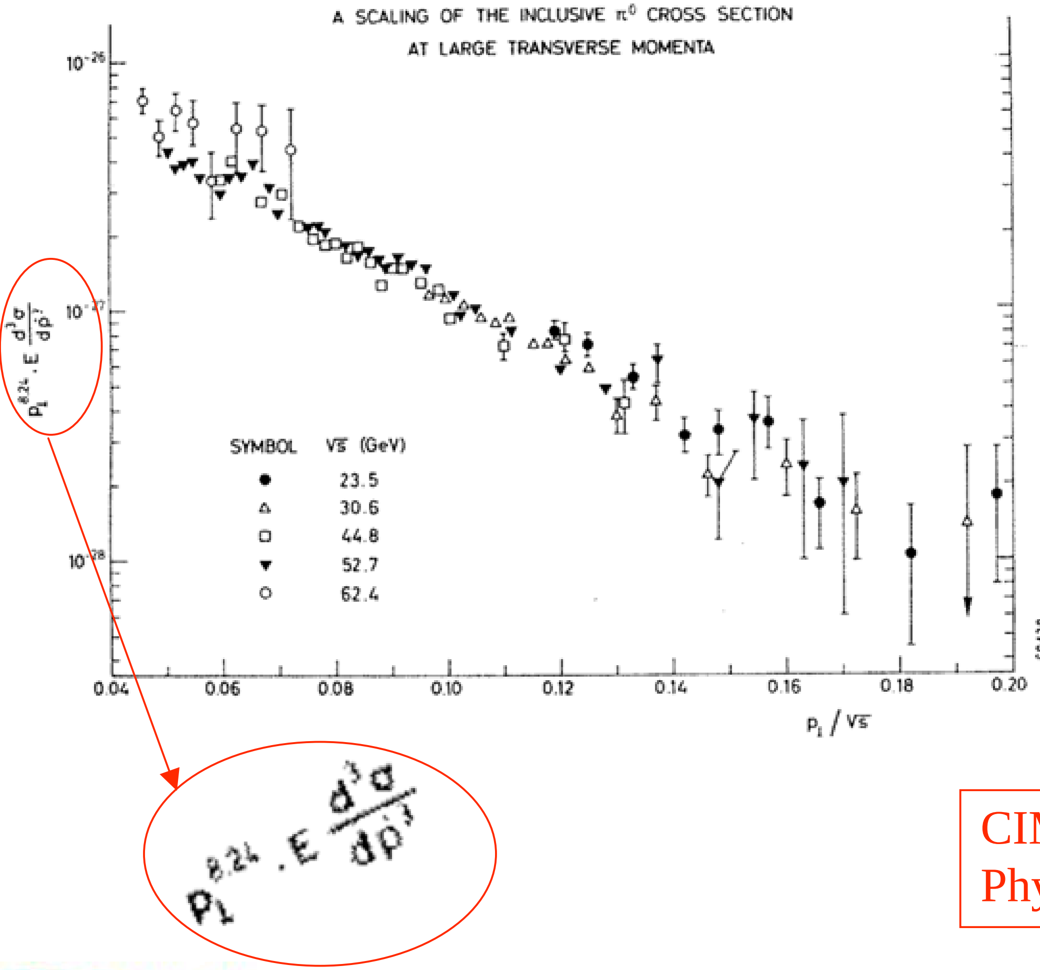
Bj scaling → BBK scaling

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

- 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 scaling but with n=8!, not n=4 as expected for QED

BBK scaling with n=8, not 4
Inspires Constituent Interchange Model

Berman, Bjorken, Kogut, PR**D4**, 3388 (1971)



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

$x_T = 2p_T/\sqrt{s}$

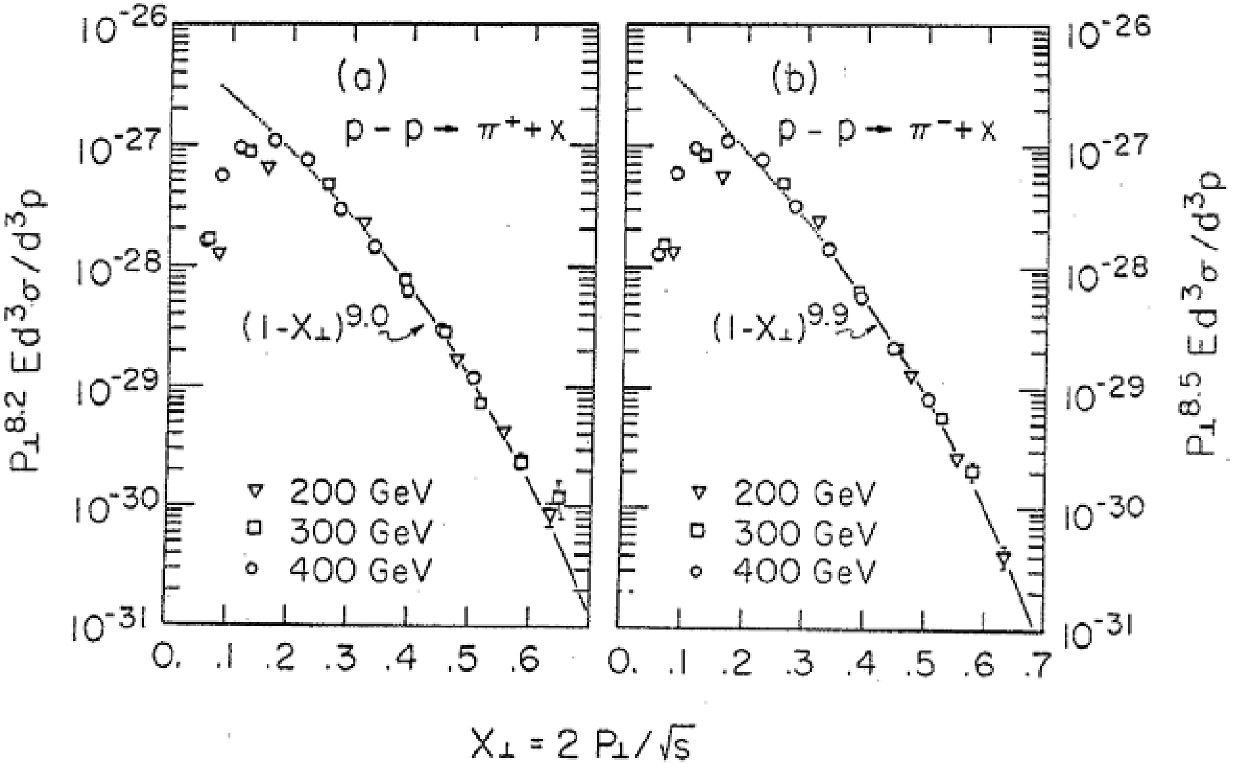
n=4 for QED or vector gluon

n=8 for quark-meson scattering by the exchange of a quark

CIM-Blankenbecler, Brodsky, Gunion, Phys.Lett.**42B**,461(1972)

State of the Art
Fermilab 1977

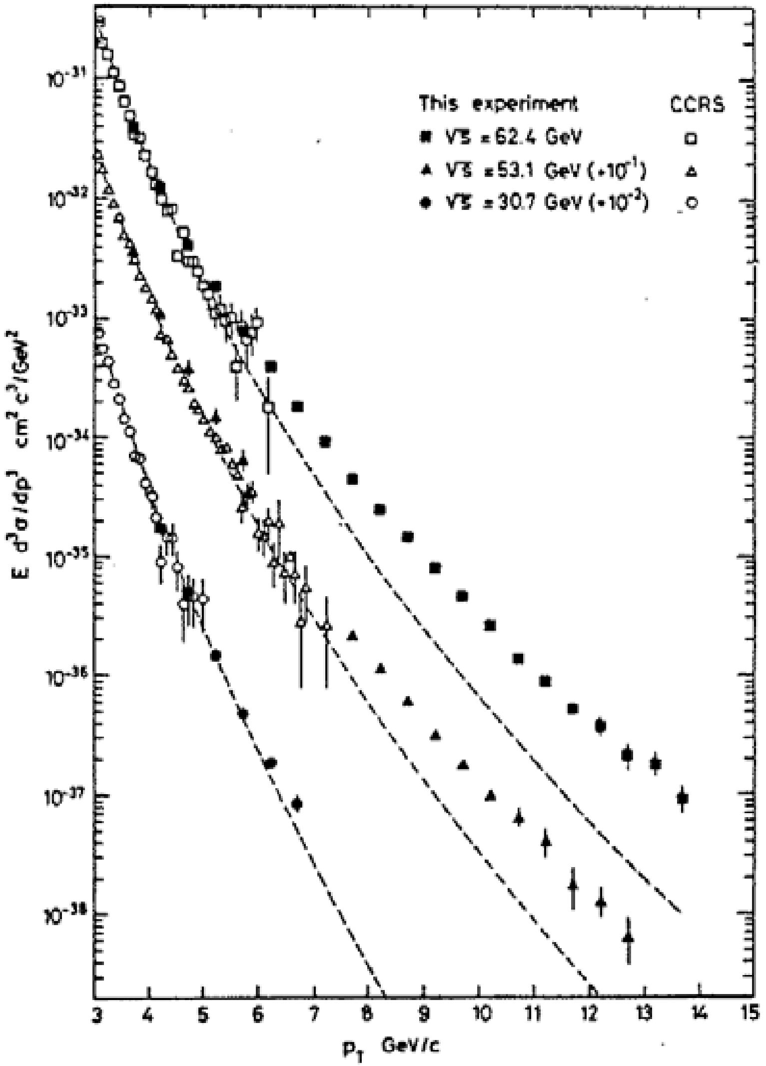
D. Antreasyan, J. Cronin, et al., PRL **38**, 112 (1977)



Beautiful x_T scaling at all 3 fixed target energies with n=8

Totally Misleading--Not CIM or QCD but k_T

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



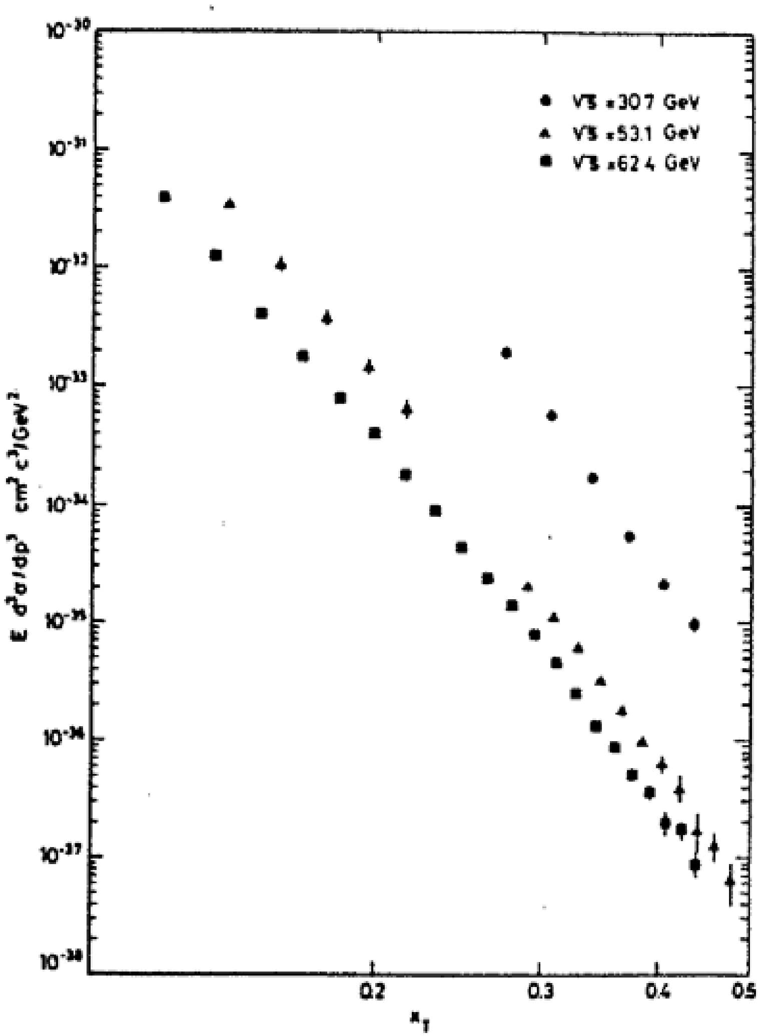
CCOR A.L.S. Angelis, et al, Phys.Lett. **79B**, 505 (1978)

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).

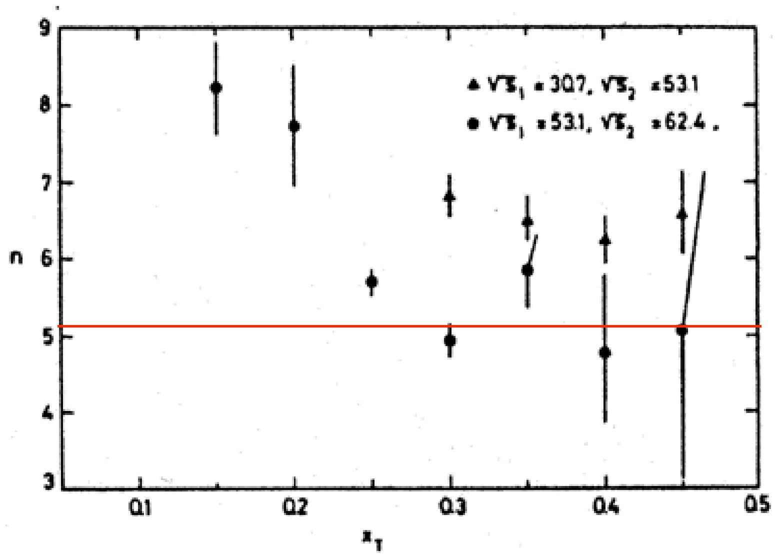
$n(x_T, \sqrt{s})$ WORKS $n \rightarrow 5 = 4^{++}$



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

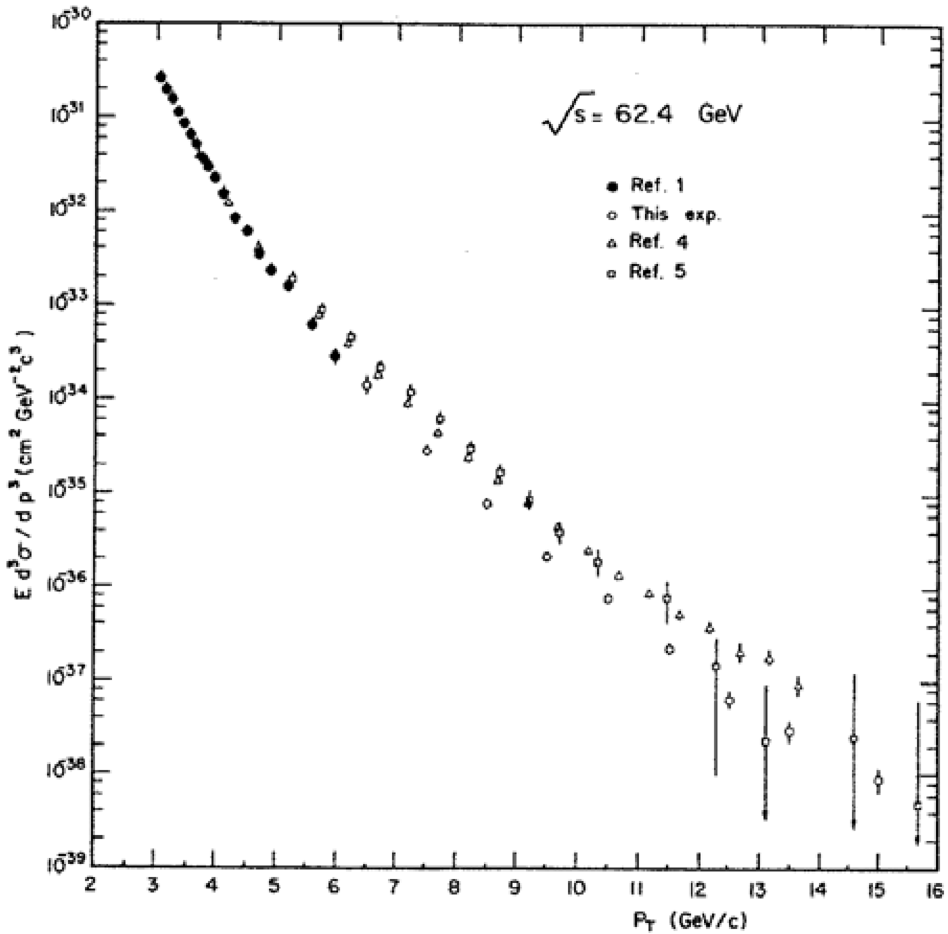
$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^{\,n(x_T,\sqrt{s})}} G(x_T)$$

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



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

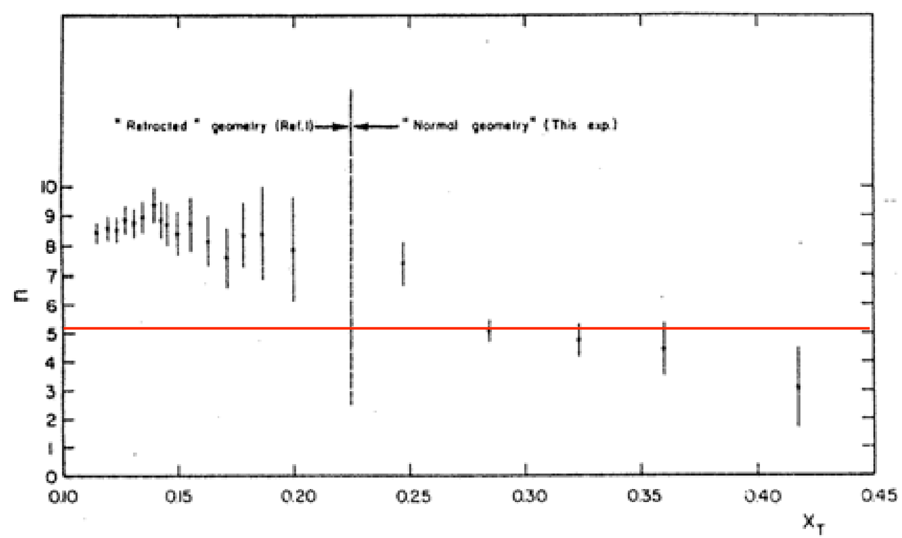
ISR Expt's more interested in $n(x_T,\sqrt{s})$ than absolute cross section



cross sections vary by factor of 2

Athens BNL CERN Syracuse Collaboration,
C.Kourkoumelis, et al
Phys.Lett. **84B**, 279 (1979)

But $n(x_T,\sqrt{s})$ agrees



Status of ISR single particle measurements 1978

♡ Hard-scattering was visible both at ISR and FNAL (Fixed Target) energies by single particle inclusive at large $p_T \geq$ 2-3 GeV/c.

♡ Scaling and dimensional arguments for plotting data revealed the systematics and underlying physics.

♡ The theorists had the basic underlying physics correct; but many (inconvenient) details remained to be worked out, several by experiment.

♡ k_T, the transverse momentum imbalance of outgoing partons (due to initial state radiation), was discovered by experiment.

k_T is what made $n=4^{++} \rightarrow n=8$

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 Jeff Owens.

J. F. Owens, E. Reya, M. Glück
Phys. Rev. **D18**, 1501 (1978)
Detailed quantum-chromodynamic predictions for high-p_T processes

J. F. Owens and J. D. Kimel
Phys. Rev. **D18**, 3313 (1978)
Parton-transverse-momentum effects and the quantum-chromodynamic description of high-p_T processes

♡ Jets in 4π Calorimeters at ISR energies or lower invisible below $\sqrt{\hat{s}} \sim E_T \leq 25$ GeV.

♡ A 'phase change' in belief in Jets with UA2 event at 1982 ICHEP in Paris.

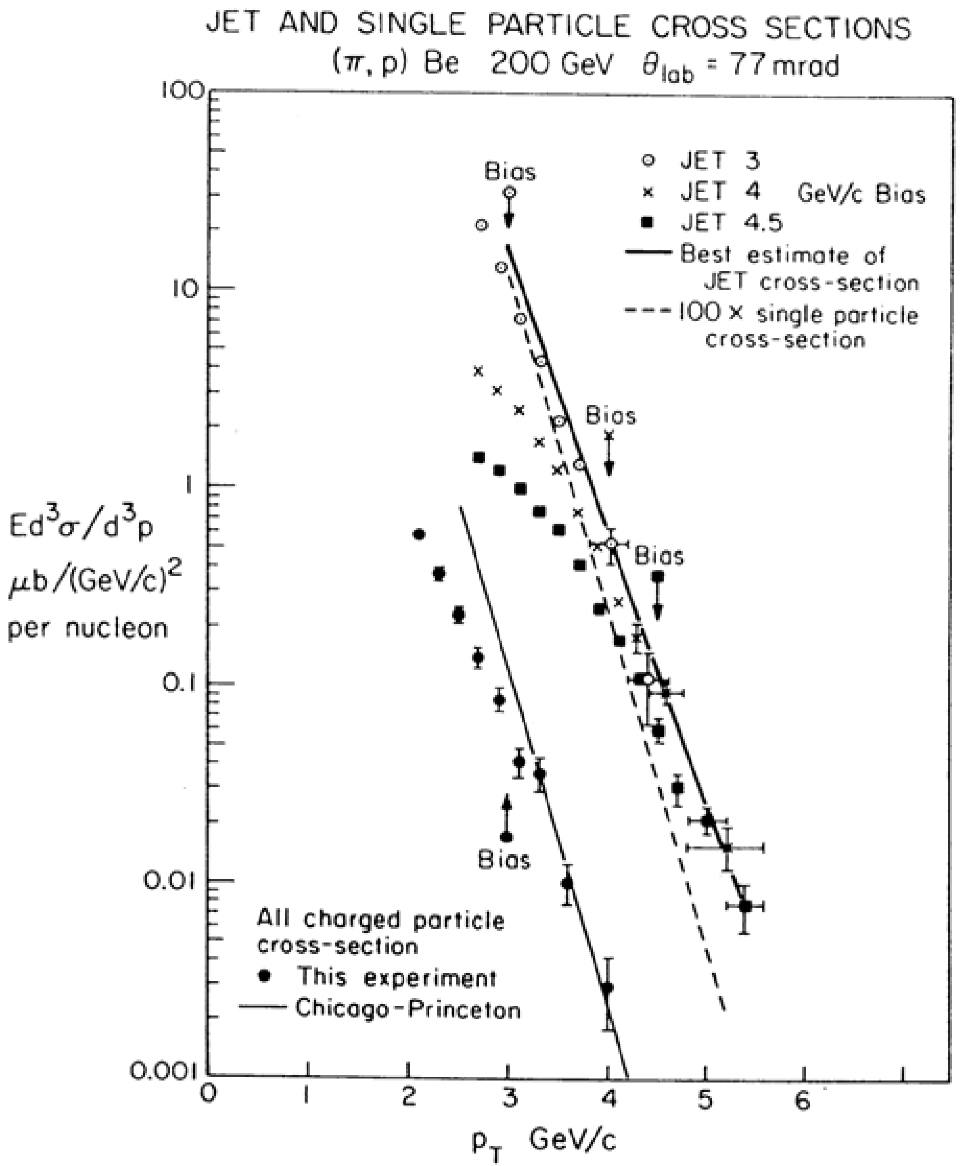
QCD and Jets are now a cornerstone of the standard model

- Incredibly at the famous Snowmass conference in July 1982, many if not most people were skeptical
- The International HEP conference in Paris, three weeks later, changed everything.

Why nobody (in the U.S.) believed in jets

- In 1972-73, soon after hard-scattering was discovered in p-p collisions, Bjorken PRD**8** (1973) 4098 and Willis (ISABELLE Physics Prospects-BNL-17522) proposed 4π hadron calorimeters to search for jets from fragmentation of scattered partons with large p_T realizing that a substantial increase in rate would be expected in measuring the entire jet at a given p_T rather than just the leading fragment. (Bjorken's parent-child effect)
- It took until 1980 to get a full azimuth $\Delta\eta\sim\pm0.88$ ($\Delta\Theta\sim\pm45^o$) calorimeter but meanwhile experiments were done with smaller back-to-back calorimeters each with aperture $\Delta\Phi\sim\pm45^o$ $\Delta\eta\sim\pm0.55$ and many new trigger biases were discovered, for instance, jets wider than the calorimeter aperture would deposit less energy than narrow jets of the same p_T and be suppressed by the steeply falling spectrum$\Rightarrow$jet structure is dominated by the calorimeter geometry [e.g. see M. Dris NIM **158** (1979) 89]

(In)famous FNAL E260 found "Jets" (1977)

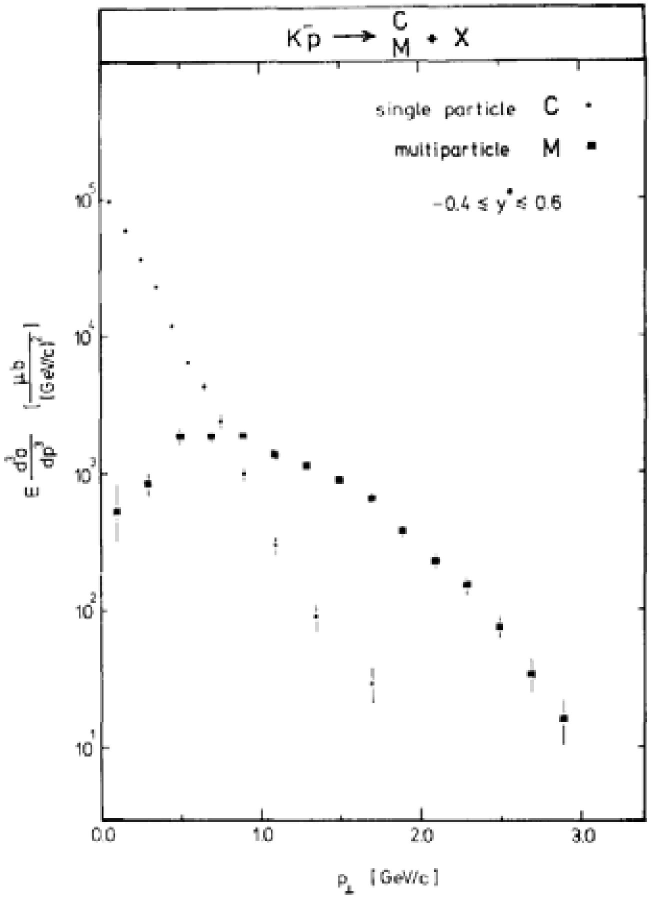


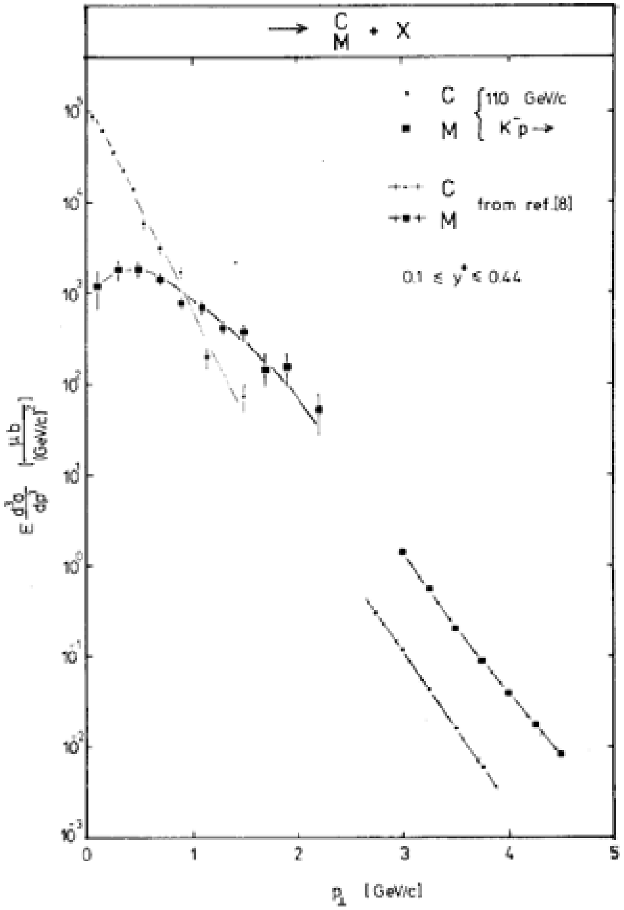
- In each of 2 back to back calorimeters with $\Delta\Phi\sim\pm45^o$ $\Delta\eta\sim\pm0.36$ (same as PHENIX) the invariant cross section of several particles with a vector sum p_T is much larger than a single particle of the same p_T. The authors took this as evidence for the exactly back-to-back in azimuth jets of constituent scattering⇒Never let an interested theorist collaborate on an experiment.

C.Bromberg et al E260, PRL 38 (1977)1447, NPB134 (1978) 189

But, experiments with different apertures got different results

- The first 4π experiment was a bubble chamber(!) 110 GeV/c K^- on p [M. Deutschmann, et al, ABCCLVW collab, NPB**155** (1979)307]

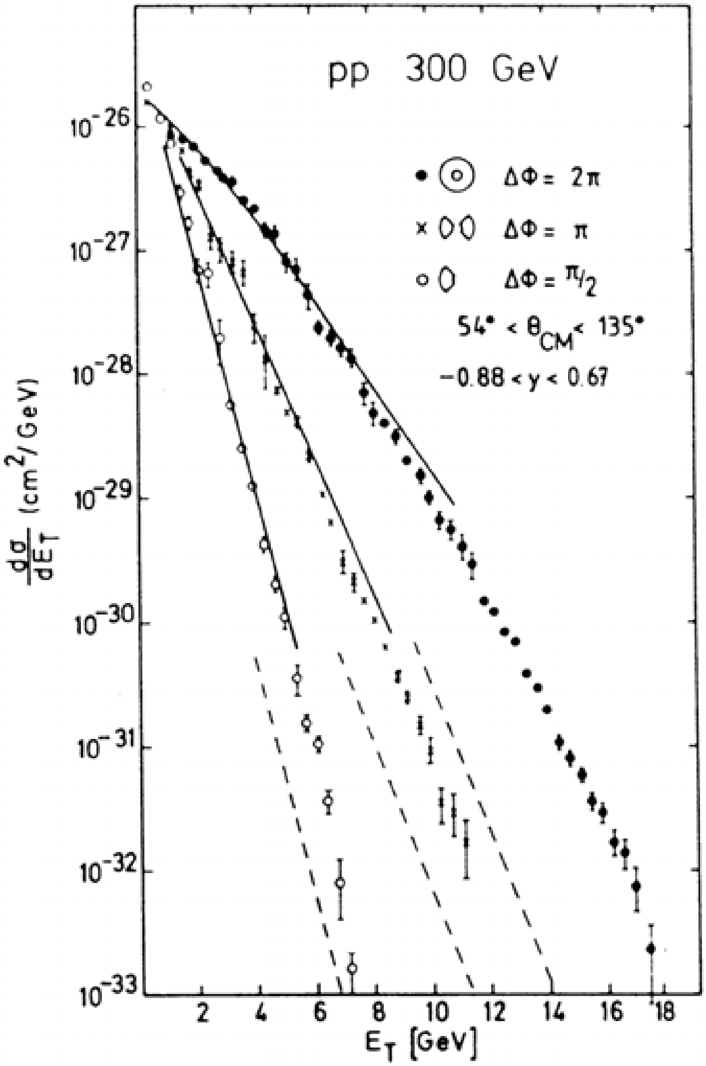




- multiparticle cross section for p_T> 1.5 GeV/c >> single particle
- Data extrapolate nicely to those of E260 [8] in slope and magnitude.
- But ``principal axis" analysis of the data shows "the vast majority of events with large p_T multiparticle systems DO NOT exhibit jet-like structure."

NA5-the coup-de-grâce to jets (1980)

- Full azimuth calorimeter $-0.88<\eta^*<0.67$ ($\rightarrow$ NA35, NA49)



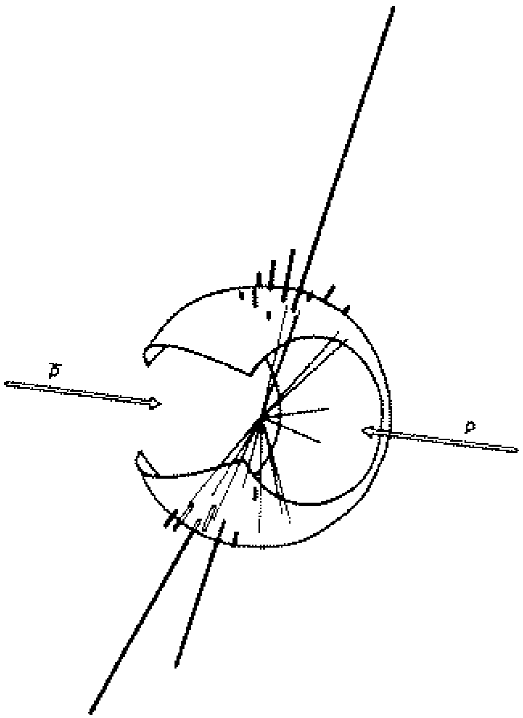
- plus triggered in two smaller apertures corresponding to E260.
- No jets in full azimuth data
- All data way above QCD predictions--------
- The large E_T observed is the result of "a large number of particles with a rather small transverse momentum"--the first E_T measurement in the present terminology.

K. Pretzl, Proc 20th ICHEP (1980)
C. DeMarzo et al NA5, PLB**112**(1982)173

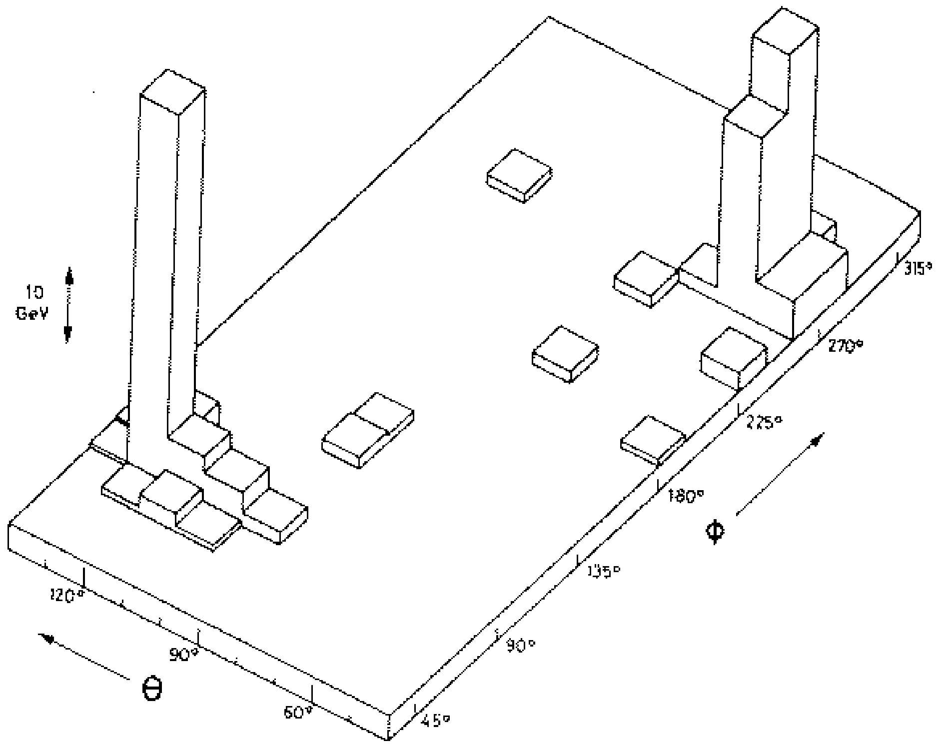
For more on E_T see MJT IJMPA **4** (1989)3377

Back to-THE UA2 Jet-Paris 1982

From 1980--1982 most high energy physicists doubted jets existed because of the famous NA5 E_T spectrum which showed NO JETS. This one event from UA2 in 1982 changed everybody's opinion.

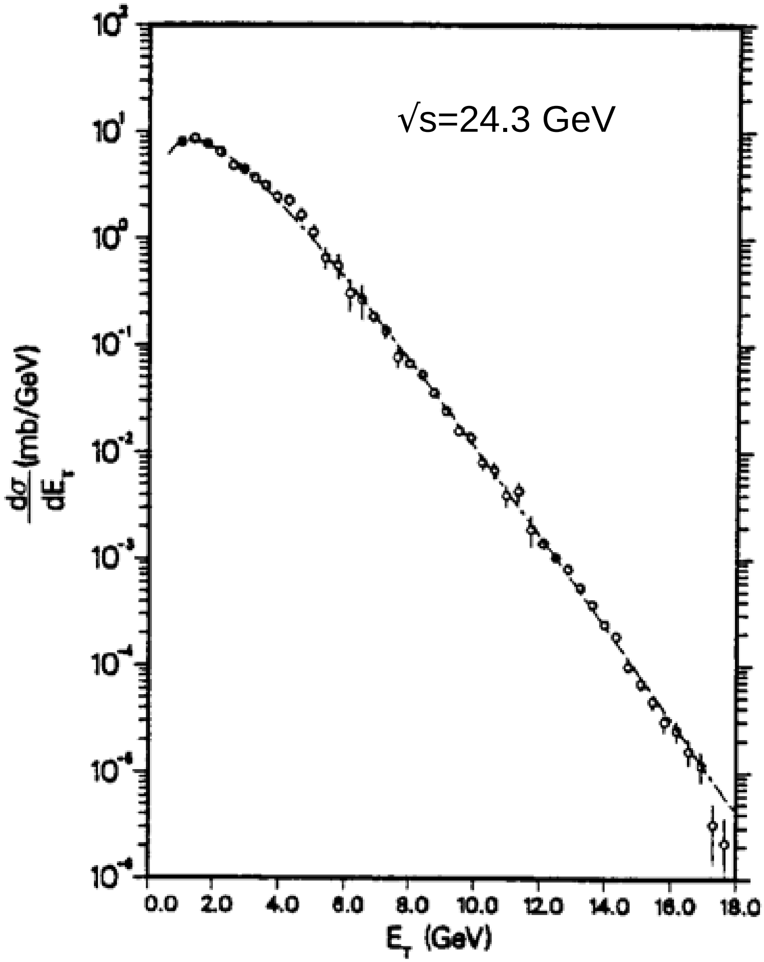


(a)

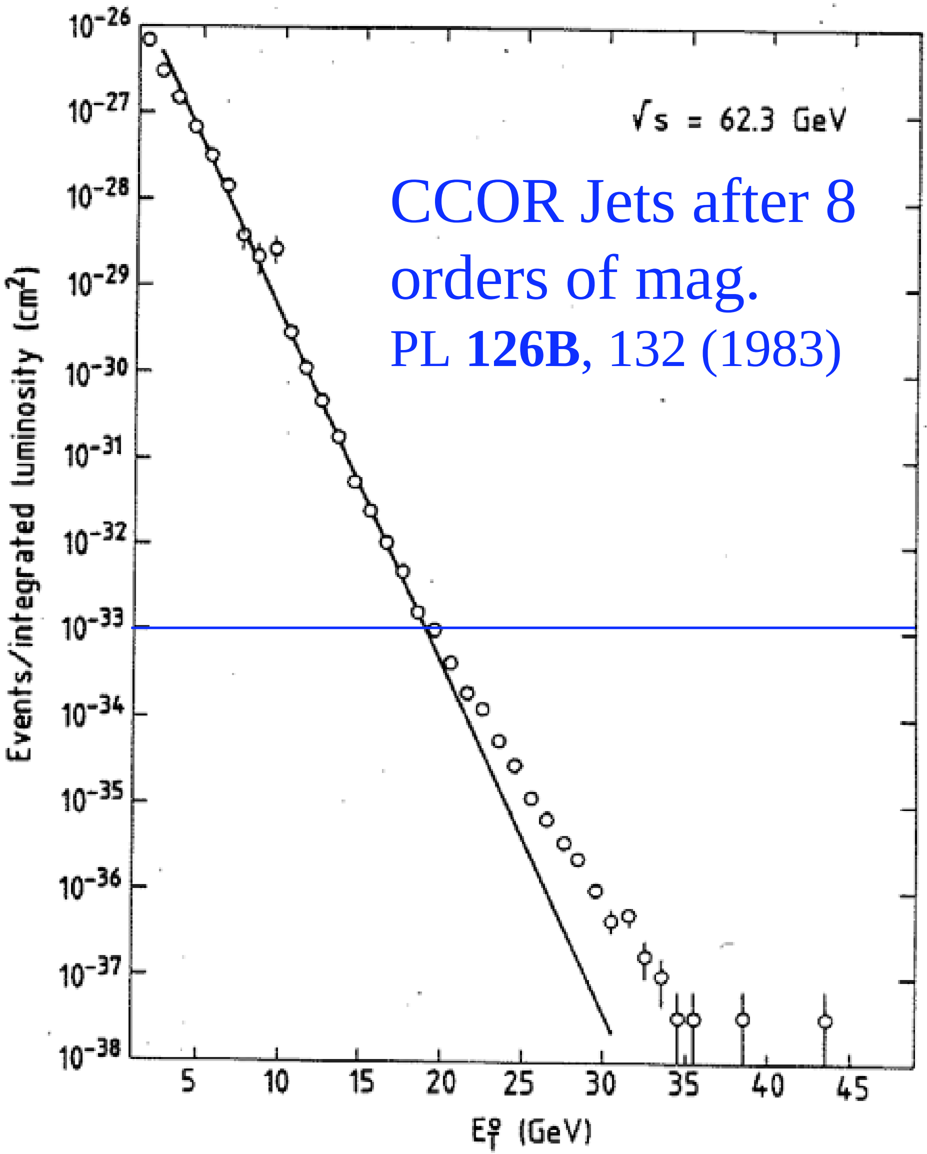


(b)

Also Paris 1982-Jets in E_T distribution



NA5-1980 ICHEP-No Jets
7 orders of magnitude



CCOR Jets after 8 orders of mag.
PL **126B**, 132 (1983)

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

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

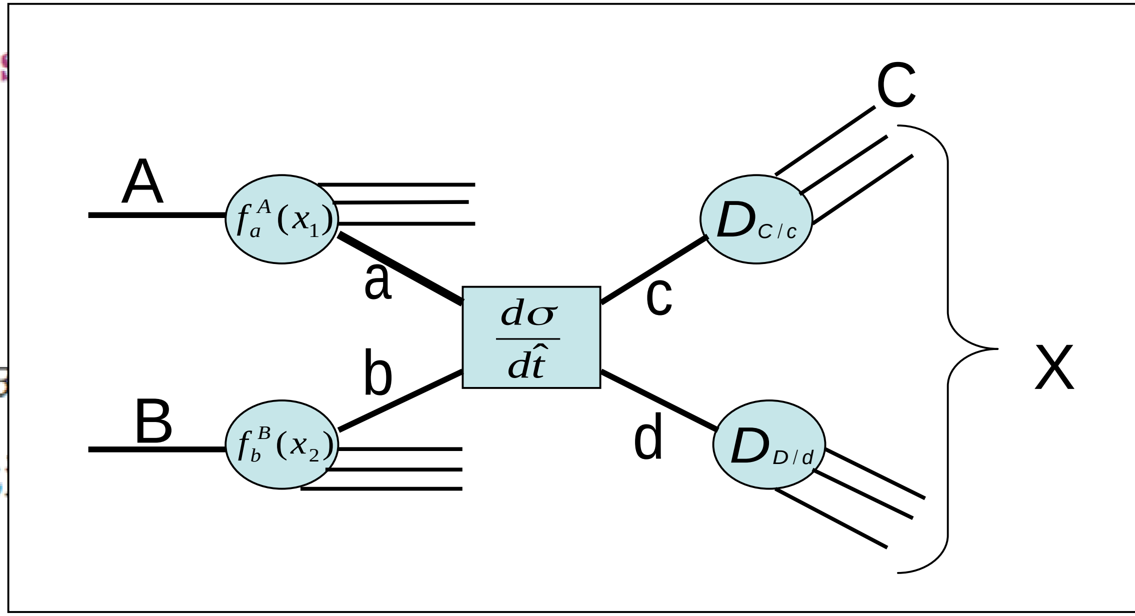
$f_a^A(x_1)$, $f_b^B(x_2)$, are structure functions, the differential probabilities for constituents a and b to carry momentum fractions x_1 and x_2 of their respective protons, e.g. $u(x_1)$,

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

$\Sigma^{ab}(\cos\theta^*)$, 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

Cros ... $\sqrt{s}$



$f_a^A(x_1)$, f_b^B ... robabilities for const ... x_1 and x_2

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

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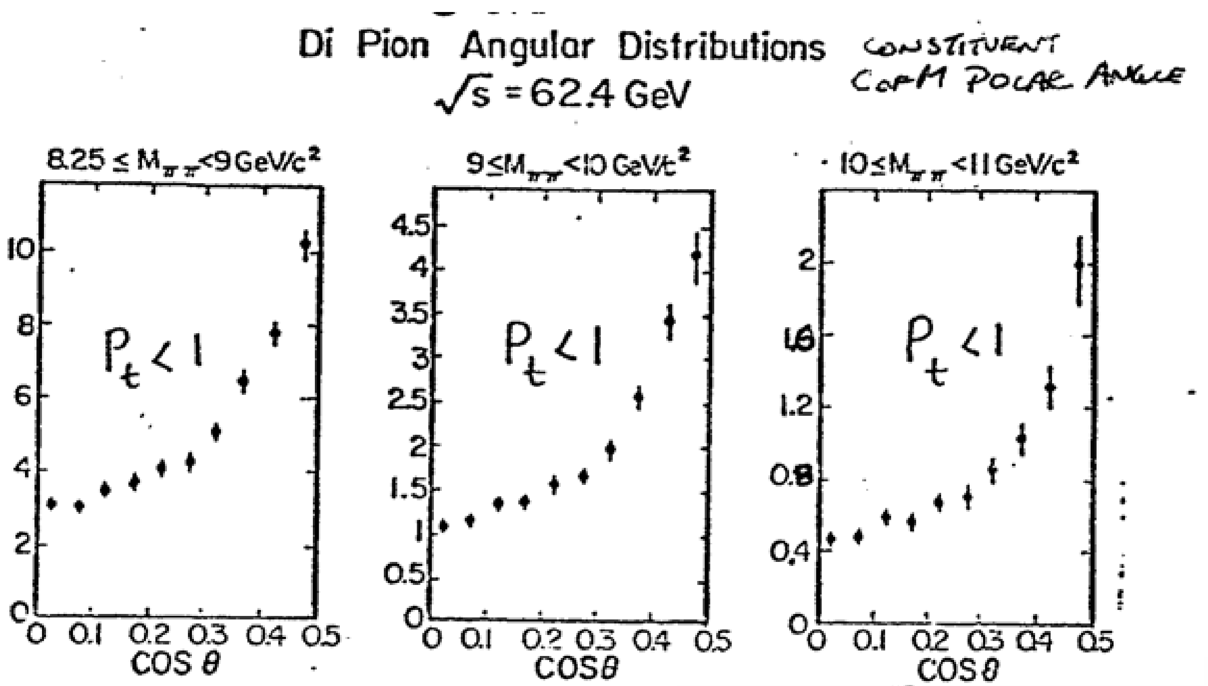
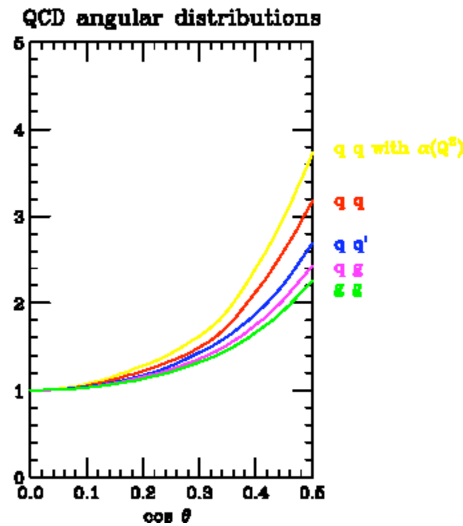
Also Paris1982-first measurement of QCD subprocess angular distribution using π^0-π^0 correlations

DATA: CCOR NPB 209, 284 (1982)



QCD



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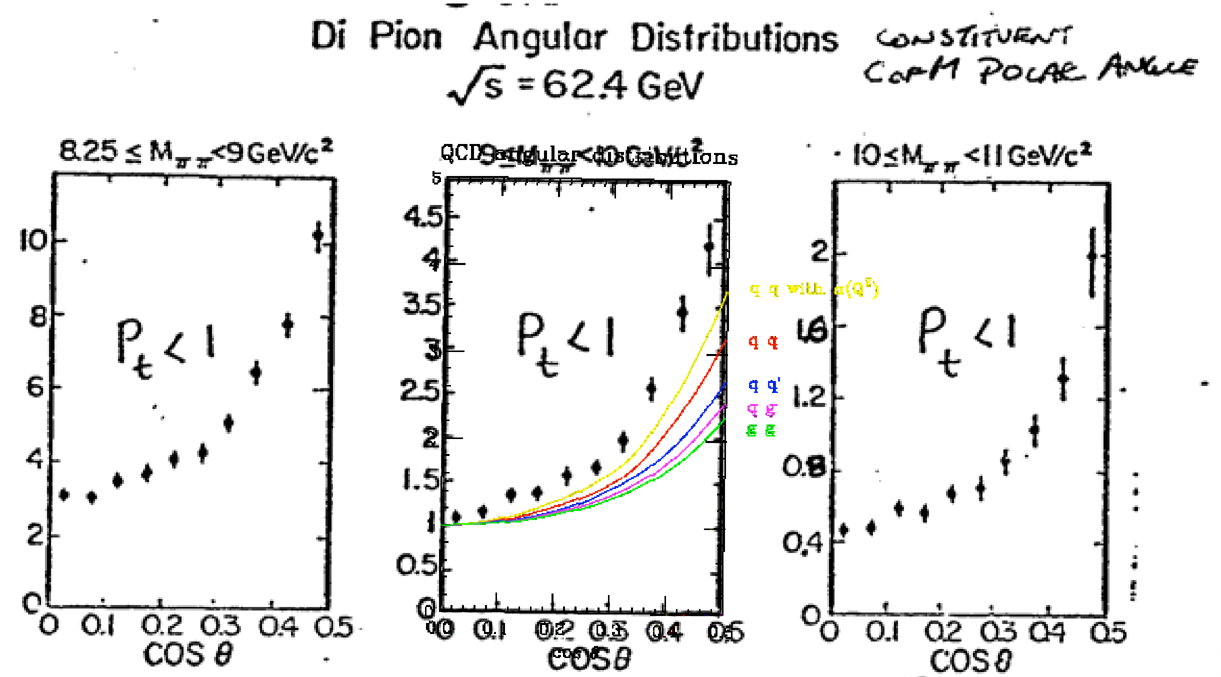
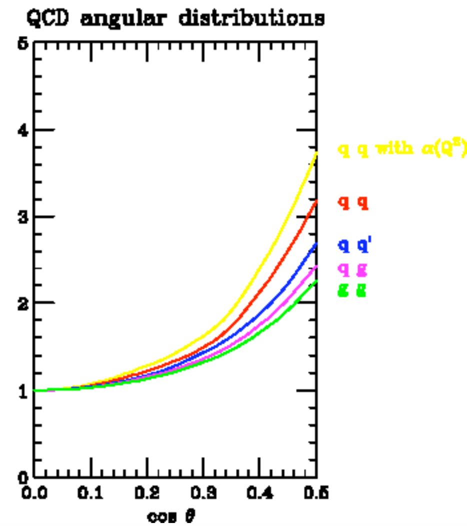


QCD



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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

Eventually this was measured with di-jets

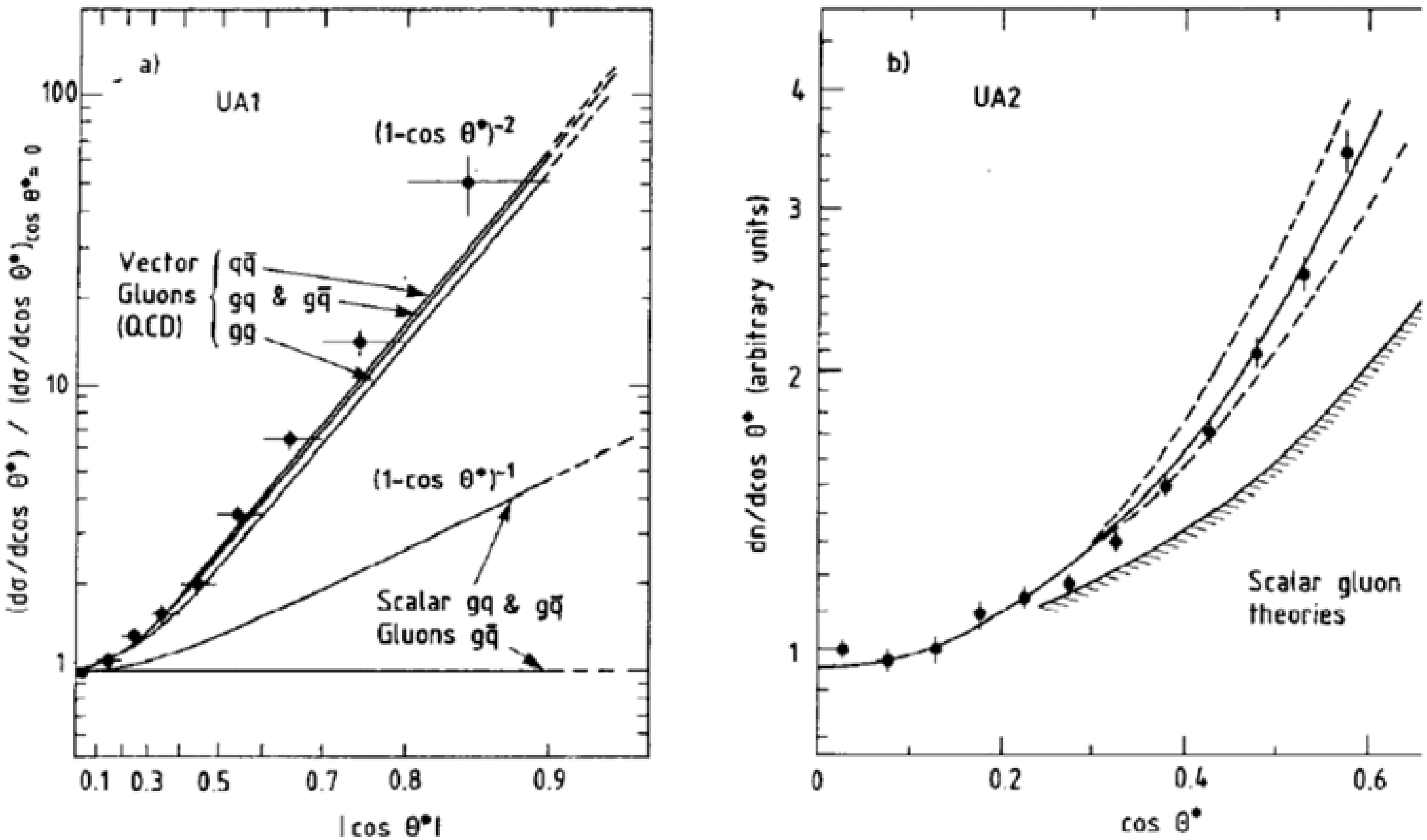


Figure 10 (*a*) Distribution of cos θ^* for hard parton scattering as measured in the UA1 experiment (42). T normalization is defined by setting the value at cos $\theta^* = 0$ equal to 1. (*b*) Distribution of cos θ^* for ha parton scattering as measured in the UA2 experiment (43). All the different QCD processes (except for $\rightarrow q'\bar{q}'$), separately normalized to the data, lie in the area between the two dashed curves. The full line is t overall QCD prediction, normalized to the data.

see L. Di Lella ARNPS **35** (1985) 107--134

When dealing with Jets it is important to remember that QCD couples to color not flavor

- LHC physicists seem to think that because they have a better chance at measuring jets than at RHIC due to the much larger rate and p_T range, they may be able to study the structure of jets and separate medium radiation from normal fragmentation.

- The high jet cross section may not be good news. NLO, NNLO, NN....NLO may cause lots of multi jets instead of di-jets.

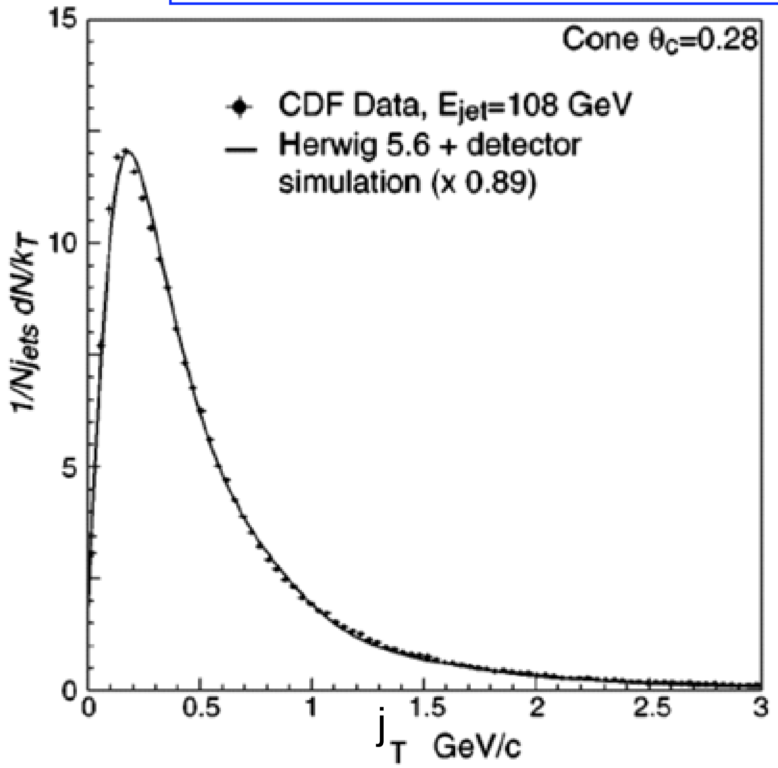
- Also jets will be produced by many different subprocesses:

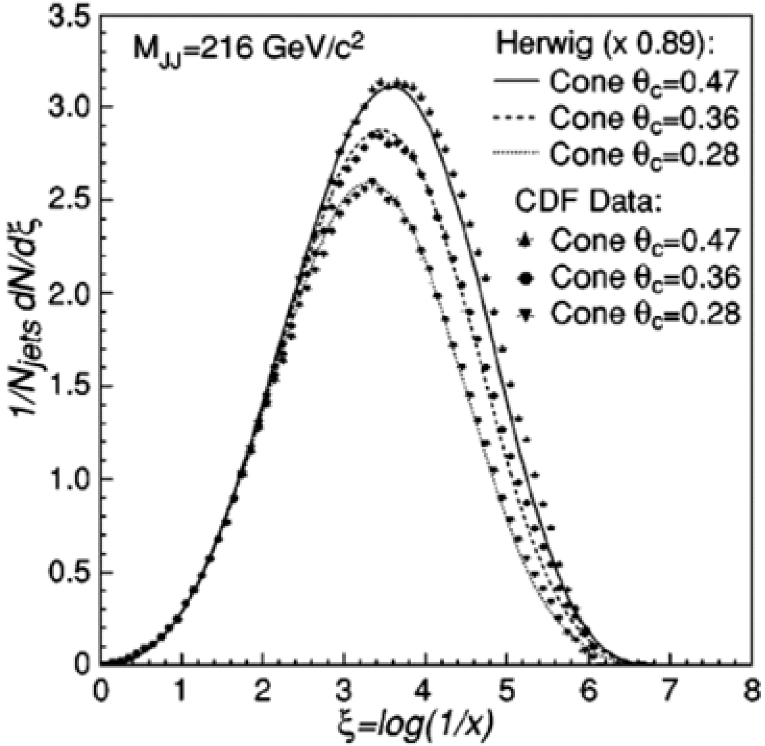
$$gg \rightarrow gg \quad gg \rightarrow u\bar{u} \quad gg \rightarrow d\bar{d} \quad gg \rightarrow c\bar{c} \quad gg \rightarrow b\bar{b} \quad \ldots$$

With all these subprocesses contributing roughly equally at large p_T, the jet structure might be quite complicated to understand.

CDF made such a measurements in p-p collisions but it reads like a legal contract

CDF PRD **68** (2003) 012003-j_T distribution in di-jets





The energy of a jet is defined as the sum of the energies of the towers belonging to the corresponding cluster. Corrections are applied to compensate for the non-linearity and non-uniformity of the energy response of the calorimeter, the energy deposited inside the jet cone from sources other than the parent parton, and the parent parton energy that radiates out of the jet cone. Full details of this procedure can be found in [25].

[25]F.Abe, et al, Phys Rev D45, 1448 (1992)

IV. JET ENERGY CORRECTIONS

The transverse energies and momenta in the above definition (which will henceforth be termed "uncorrected energy") depend only on the energy deposition observed in the calorimeter. These uncorrected quantities differ from the true partonic values for a variety of reasons. Some of these are the result of limitations in detector performance.

(i) The calorimeter response to low-energy charged pions exhibits a nonlinearity for momenta below 10 GeV.

(ii) Charged particles with transverse momenta below ~400 MeV bend sufficiently in the magnetic field that they do not reach the calorimeter. At slightly higher transverse momenta, the magnetic field can bend particles outside the clustering cone.

(iii) Particles that shower in boundary regions of the calorimeter (the ϕ boundaries between modules in the central calorimeter and η_d boundaries between the two halves of the central calorimeter, between the central and plug calorimeters and between the plug and forward calorimeters) will, on average, have a smaller energy reported than for regions of uniform response.

Others result from fundamental elements of the physics process.

(iv) Energy not associated with the hard-scattering process (the so-called "underlying event") will be collected within the clustering cone.

(v) Transverse spreading of the jet due to fragmentation effects will cause particles to be lost outside the clustering cone.

(vi) Energy in neutrinos and muons, which deposit either zero or some small fraction of their energy in the calorimeter.

A. Central jet response

The response of the central calorimeter to pions has been measured both in test beams and *in situ*. Figure 6 shows the measured calorimeter response to charged hadrons as a function of incident momentum for particles hitting the center of a calorimeter tower. The figure also indicates the size of the systematic error associated with this measurement. Note that the measured response deviates substantially from linearity for low incident energy.

Because the calorimeter response to charged hadrons is nonlinear, the observed jet energy is a function not only of the incident parton energy but also of the momentum spectrum of the particles produced in the fragmentation process. It is important that Monte Carlo events used in jet studies reproduce the observed fragmentation properly. We have chosen to use an exact matrix-element calculation for all QCD comparisons in this paper [12]. It was necessary to adjust parameters in the event generator to reproduce the observed jet-fragmentation distributions.

continued

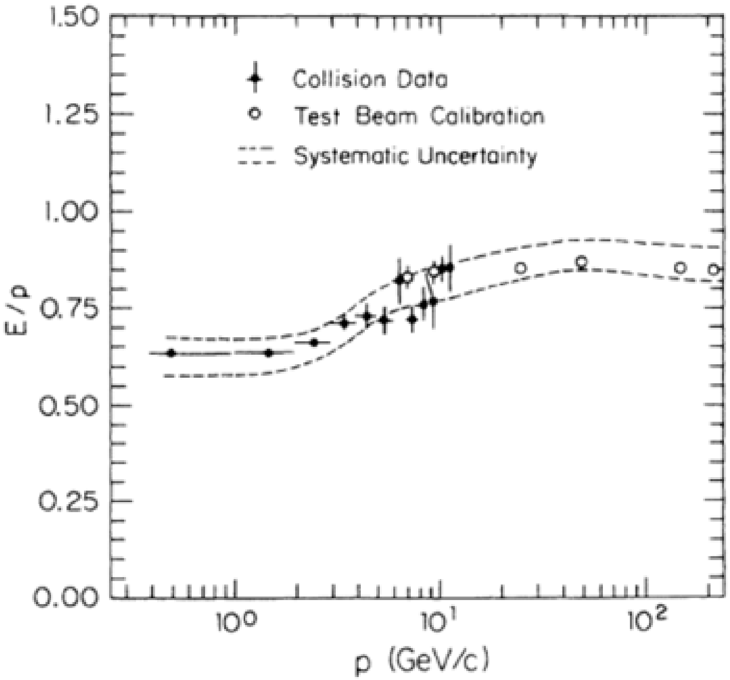


FIG. 6. CDF central calorimeter response (E/p) to pions as a function of incident momentum. The high-energy data come from test beam measurements, and the low-energy data (≤ 12 GeV) comes from isolated tracks in minimum-bias events.

D. Uncertainties in energy scale

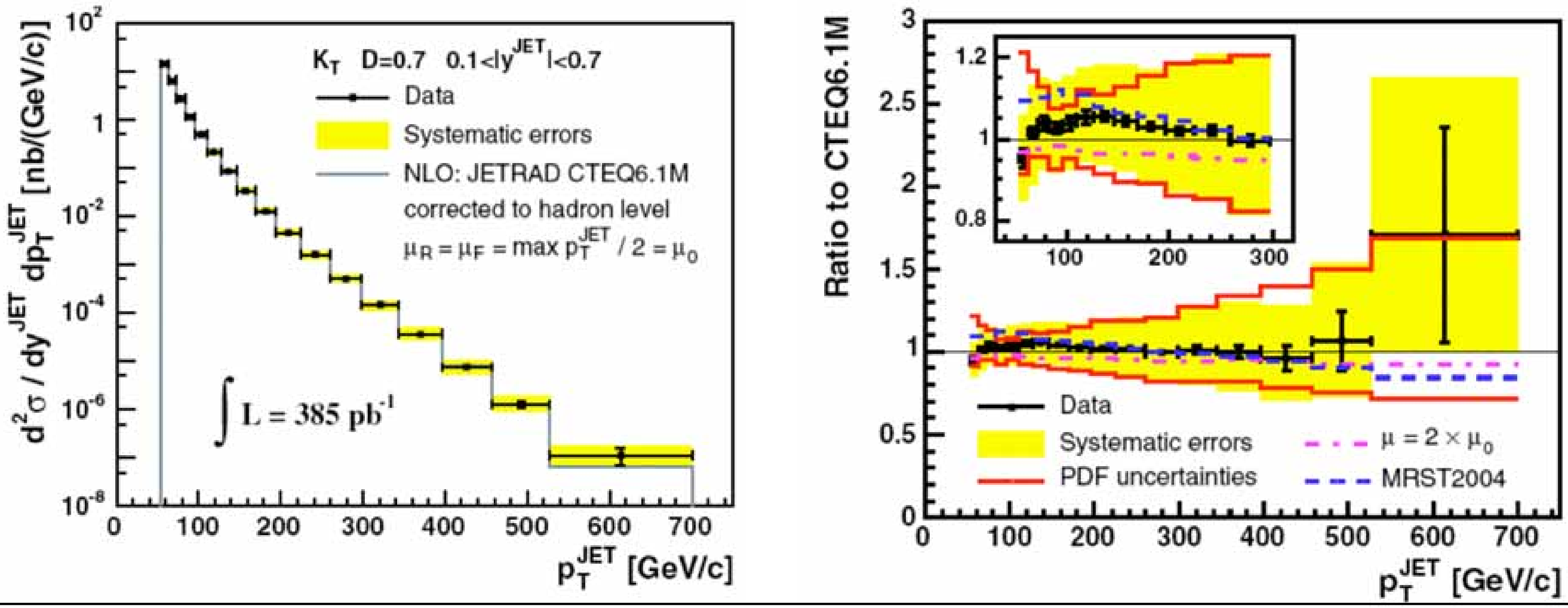
The dominant systematic uncertainty in the central jet energy scale results from the uncertainty in the single-pion response when convoluted with the jet fragmentation function [15]. The uncertainty in single-pion response is indicated by the dashed lines in Fig. 6. The uncertainty in the central energy scale for jets can be expressed as a 40% E_t-independent term, plus an E_t-dependent term which can rise as high as 7% at low E_t ($\approx$25 GeV). The E_t dependent part of the uncertainty results from both the uncertainties in the jet fragmentation, and in the shape of the low energy part of the single pion response. The E_t independent part of the uncertainty comes from two main sources. The first is our ability to properly model the variation of the single-pion response over the face of a calorimeter tower. The second is from the agreement of test beam and *in situ* calibrations for pions of the same momentum, which provides a check of the reproducibility of the energy scale calibration.

C. Underlying event and clustering corrections

The underlying event is the ambient energy produced in hadron collisions associated with the soft interactions of spectator partons. The energy from the underlying

etcetera...

Jet measurements of QCD in pp collisions are now standard after a ~30 year learning curve



The measured crosssection is in agreement with NLO pQCD predictions after the necessary nonperturbative parton-to-hadron correction sare taken into account.

A. Abulencia, et al, CDF PRL 96 (2006) 122001-k_T algorithm

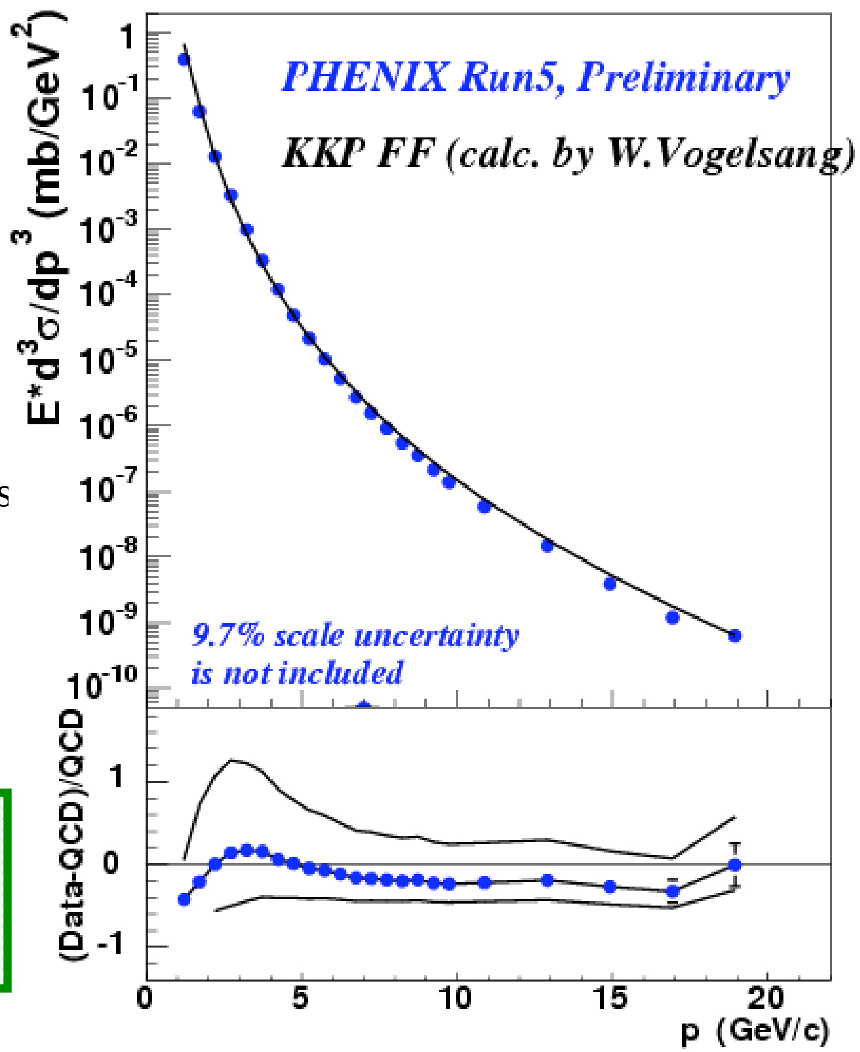
At RHIC, inclusive single particles provide a precision pQCD probe, well calibrated in pp, dAu… collisions

π^0's in p+p: Data vs. pQCD

- Result from run2 published-a classic
  - ✓ PRL91 (2003) 241803
- New result from run5
  - ✓ preliminary
- Comparison of π^0 cross section
  - ✓ Next-to-leading order(NLO) pQCD
    - CTEQ6M + KKP or Kretzer
    - Matrix calculation by Aversa, et. al.
    - Renormalization and factorization scales are set to be equal and set to

      $1/2p_T$, p_T, $2p_T$

    - Calculated by W.Vogelsang



NLO-pQCD described very well down even to p_T ~ 1 GeV/c

Theorists have a tough job---Experimentalists can use scaling rules

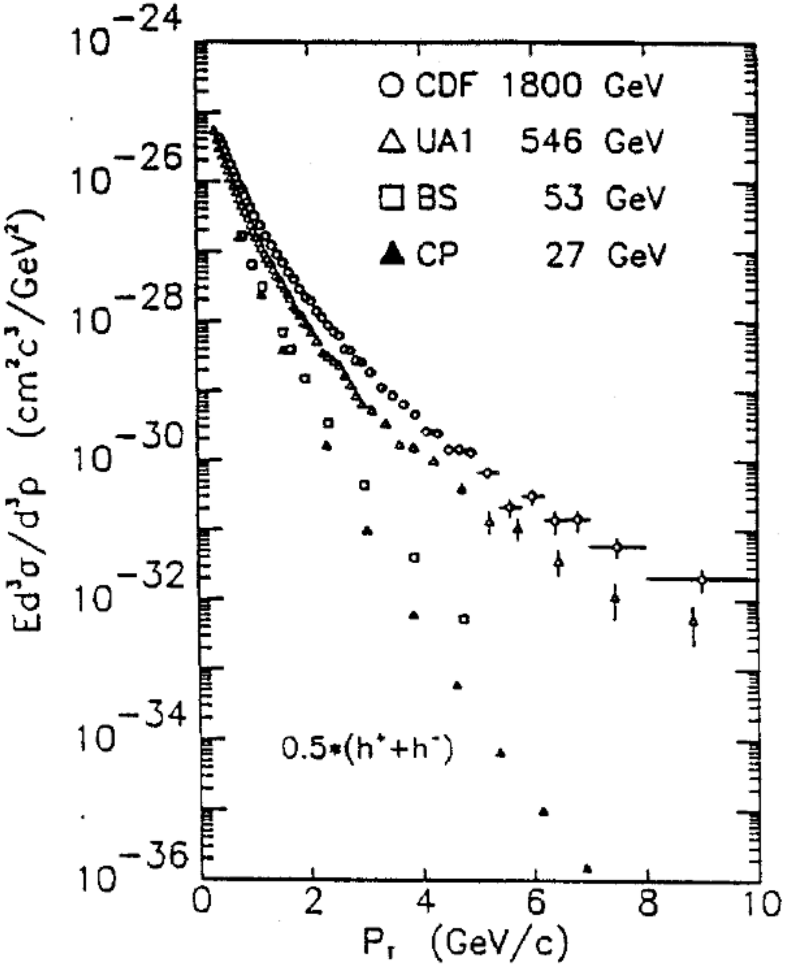
QCD follows x_T scaling-very powerful tool

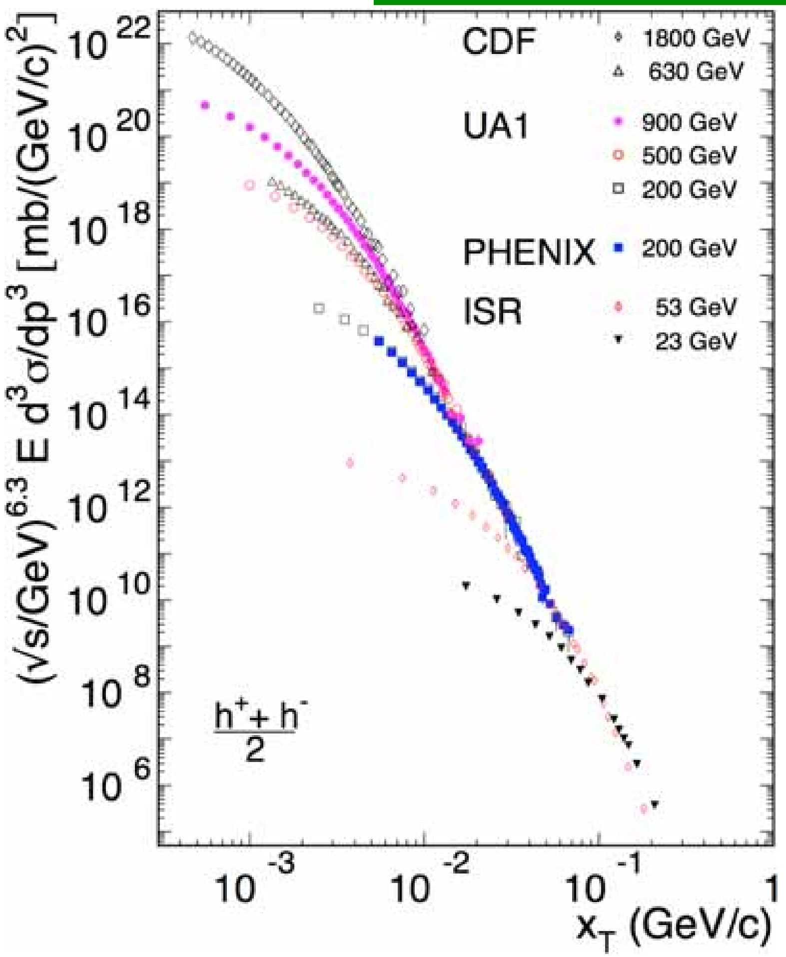
$$E\frac{d^3\sigma}{d^3p} = \frac{1}{p_T^n}F\left(\frac{p_T}{\sqrt{s}}\right) = \frac{1}{\sqrt{s}^{\,n}}G(x_T)$$

$$x_T = \frac{2p_T}{\sqrt{s}}$$

LOQCD, QED: n=4

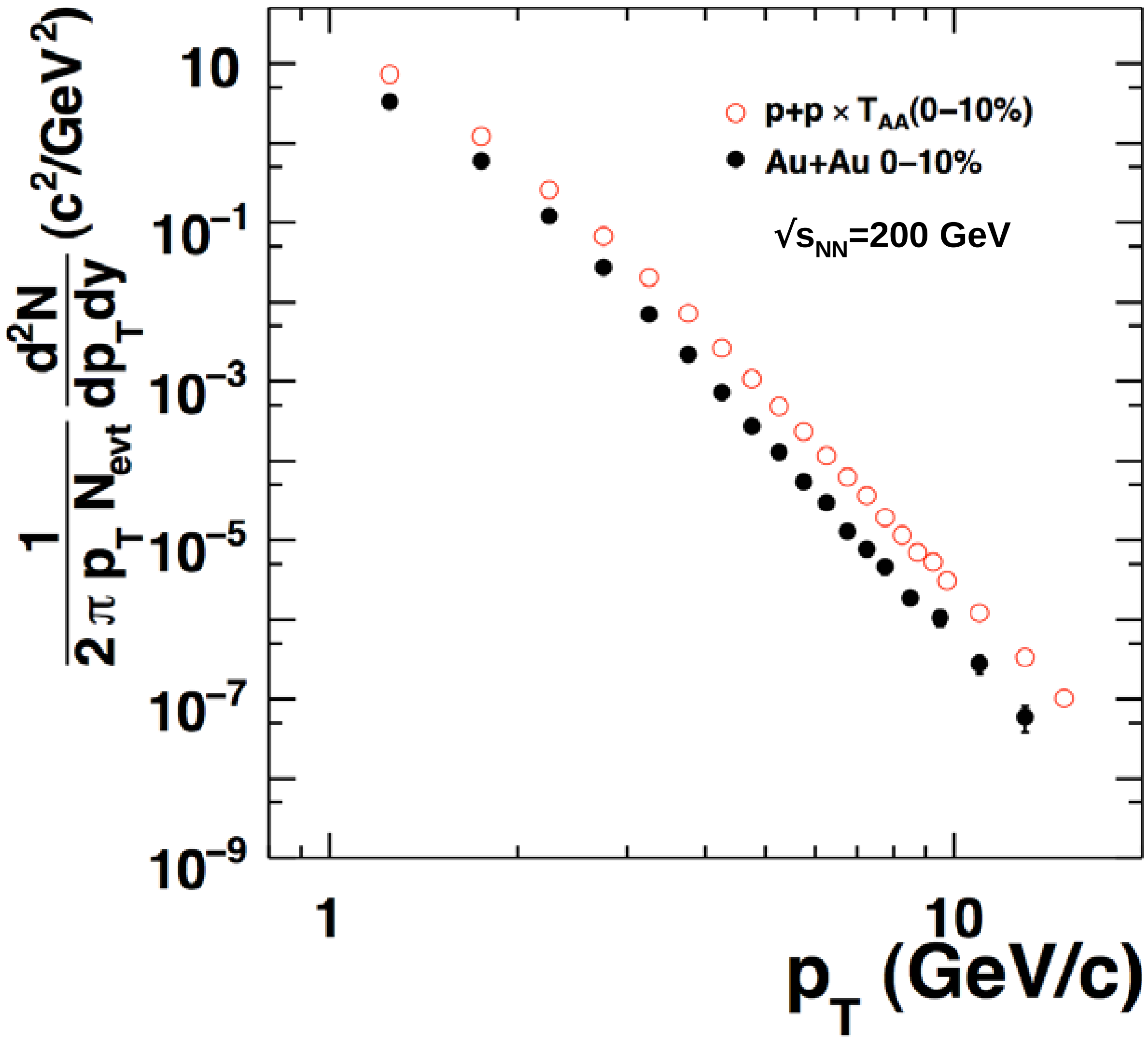
QCD $n(x_T, \sqrt{s}) = 4^{++}$





Structure and Fragmentation fns., which `scale', i.e. are functions only of ratios of momenta, are in F (G)

Inclusive invariant π^0 spectrum is power law for $p_T \geq 3$ GeV/c n=8.1±0.1 in p+p and Au+Au

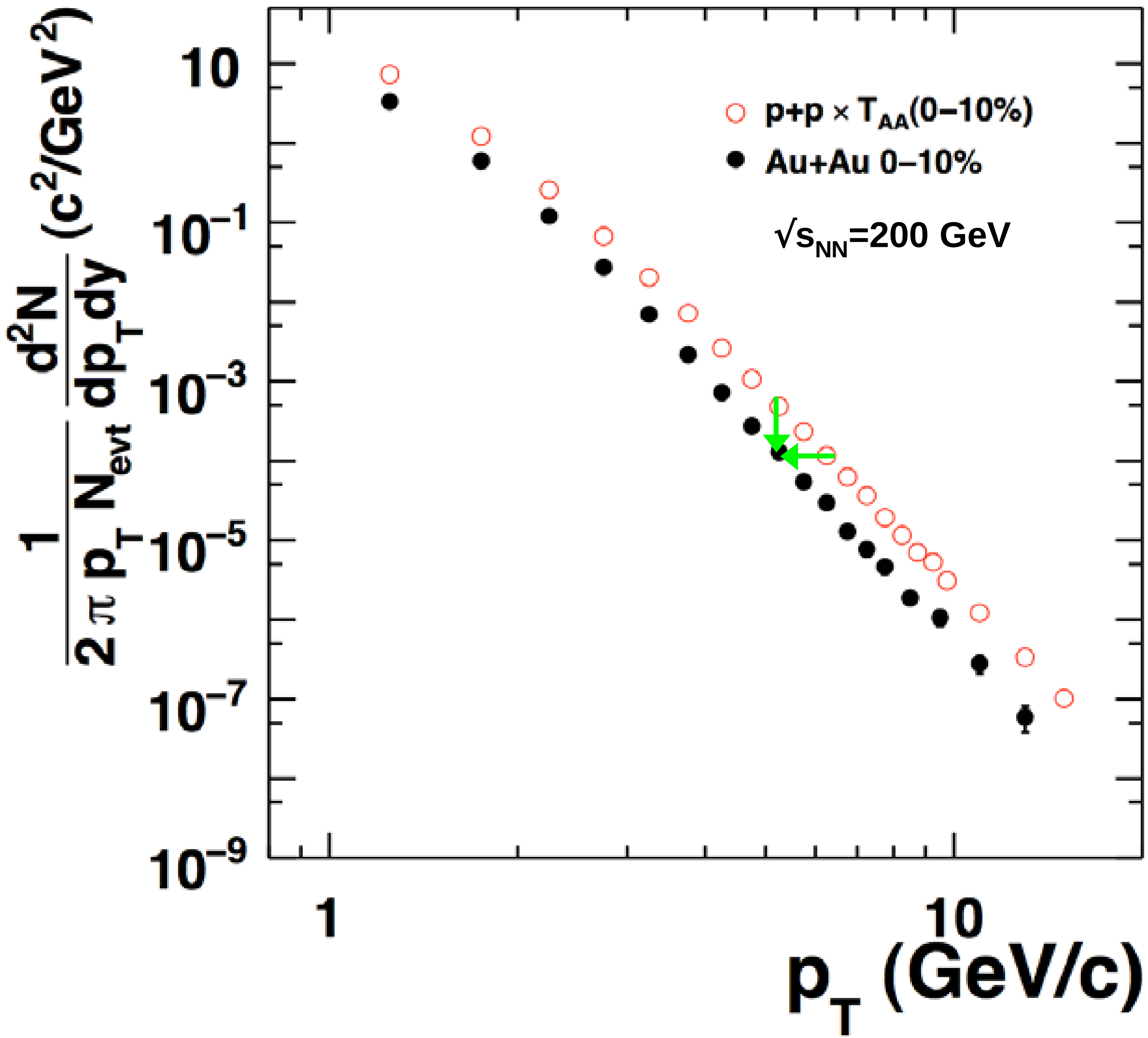


Nuclear Modification Factor

$$R_{BA} = \frac{\left[d^2N^{\pi}_{BA}/dp_T dy dN^{inel}_{BA}\right]}{\langle T_{BA}\rangle \times \left[d^2\sigma^{\pi}_{pp}/dp_T dy\right]}$$

$$R_{BA} = \frac{\left[d^2N^{\pi}_{BA}/dp_T dy dN^{inel}_{BA}\right]}{\langle N_{coll}\rangle \big/ \sigma^{inel}_{pp} \times \left[d^2\sigma^{\pi}_{pp}/dp_T dy\right]}$$

Inclusive invariant π^0 spectrum is power law for $p_T \geq 3$ GeV/c n=8.1±0.1 in p+p and Au+Au



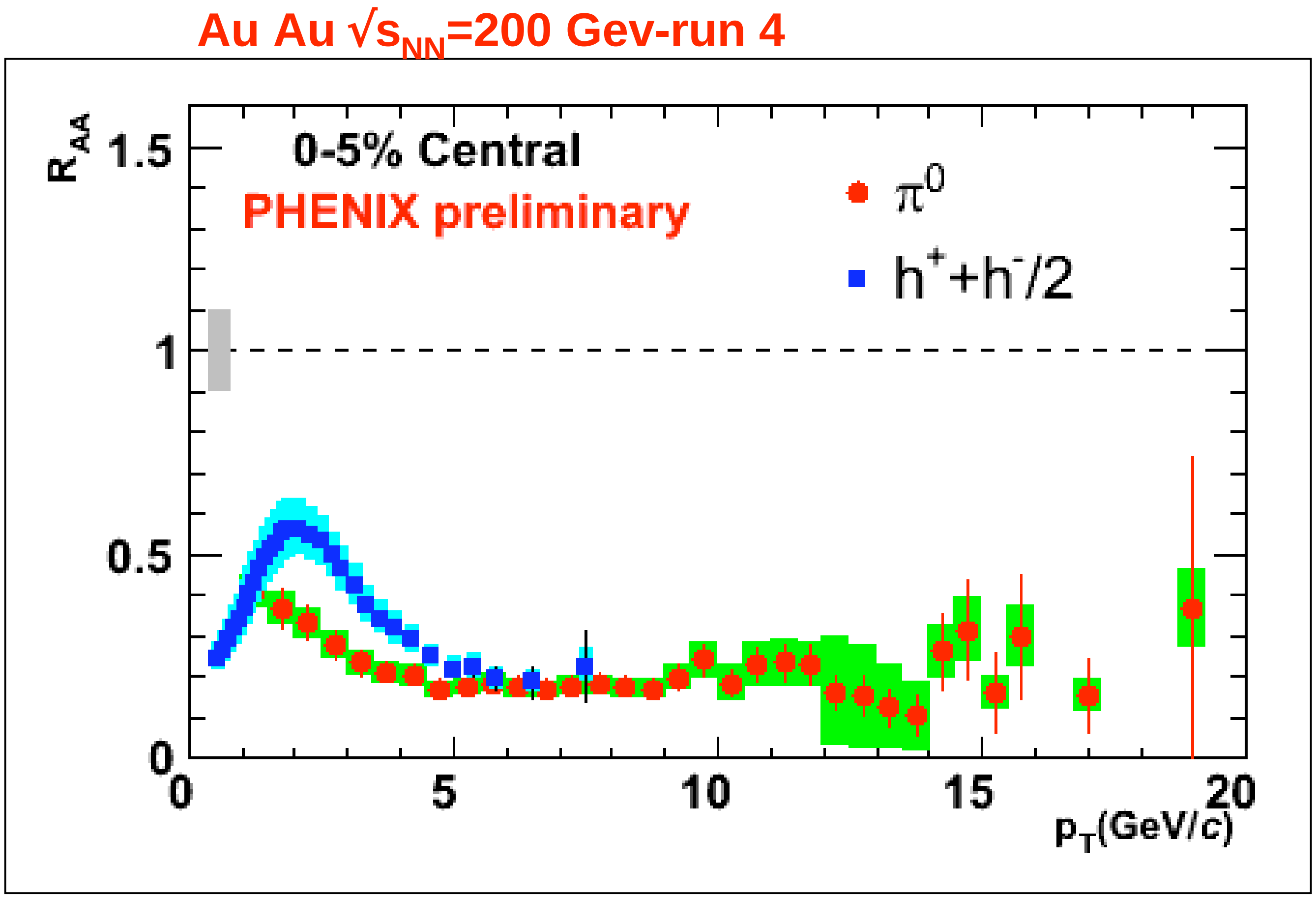
Nuclear Modification Factor

$$R_{BA} = \frac{\left[d^2N^{\pi}_{BA}/dp_T dy dN^{inel}_{BA}\right]}{\langle T_{BA}\rangle \times \left[d^2\sigma^{\pi}_{pp}/dp_T dy\right]}$$

$$R_{BA} = \frac{\left[d^2N^{\pi}_{BA}/dp_T dy dN^{inel}_{BA}\right]}{\langle N_{coll}\rangle / \sigma^{inel}_{pp} \times \left[d^2\sigma^{\pi}_{pp}/dp_T dy\right]}$$

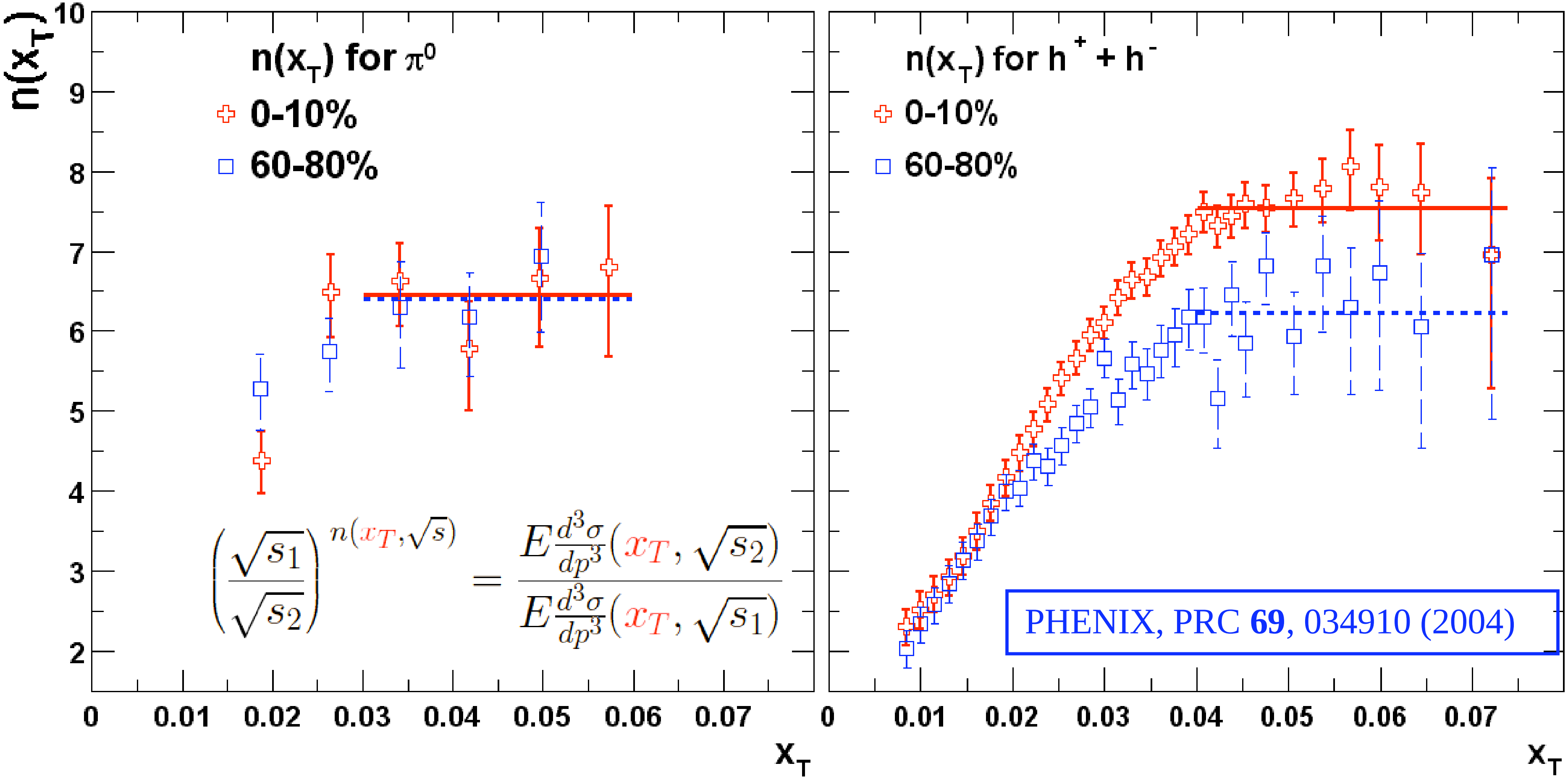
Impossible to distinguish reduction in the number of partons (due to e.g. stopping in medium) from fractional downshift in spectrum (due to e.g. energy loss of parton in medium)

R_{AA}: π^0 and non-identified charged are different



Does either obey QCD? We tried x_T scaling AuAu 200 cf 130 GeV

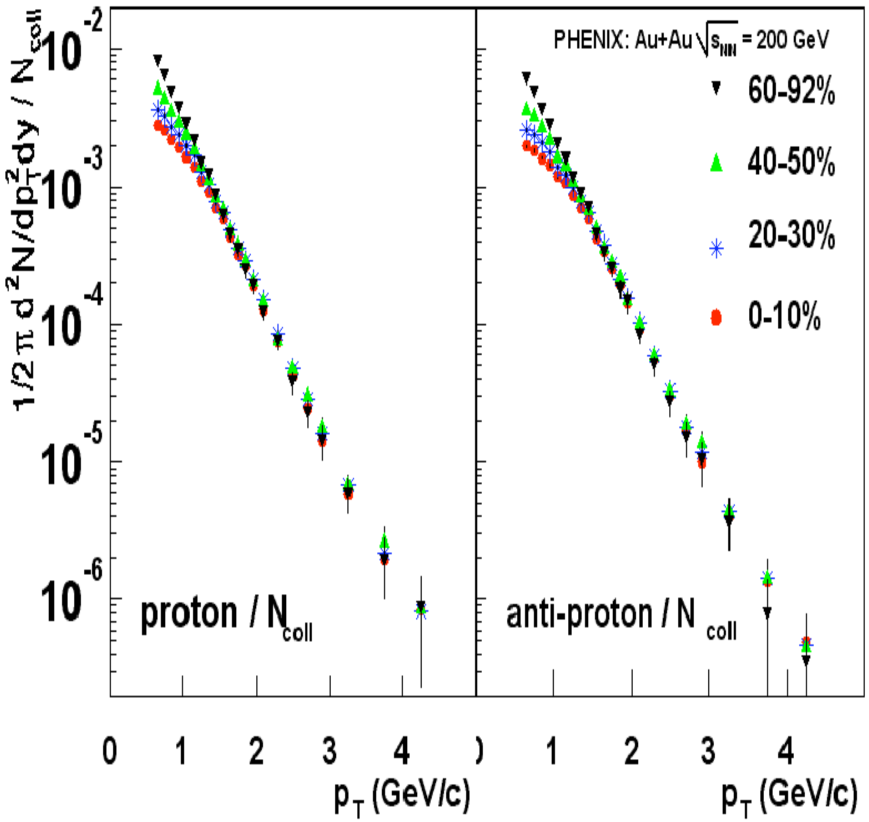
x_T scaling $\sqrt{s_{NN}}$=200/130 AuAu shows $h^{\pm}$ are anomalous

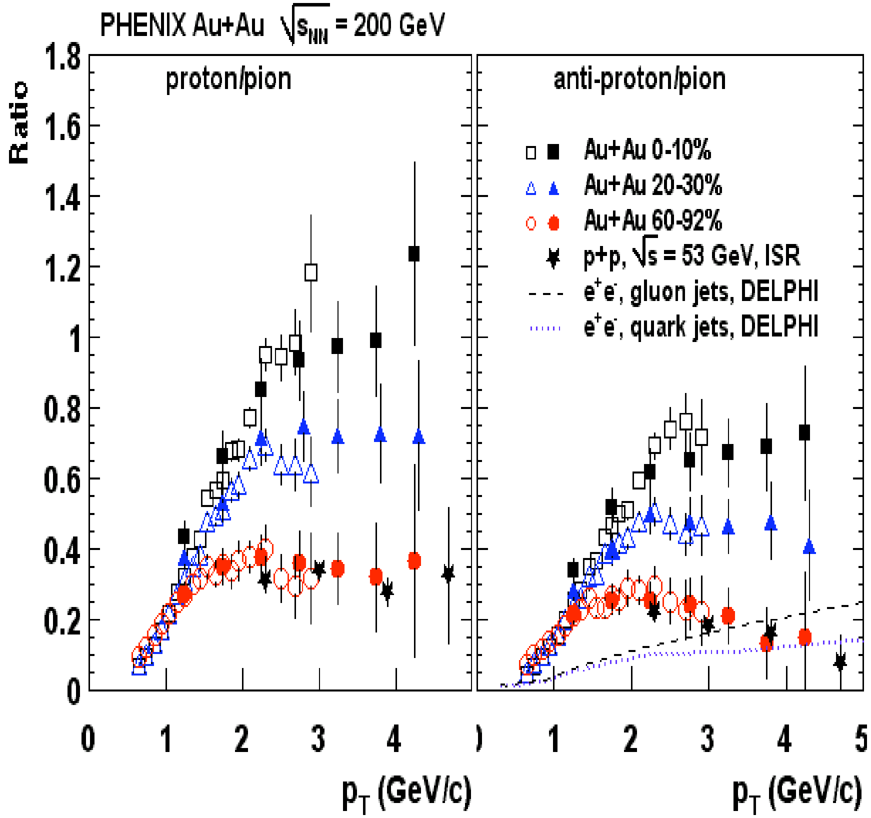


- π^0 x_T scales in both peripheral and central Au+Au with same value of n=6.3 as in p-p indicates that structure and fragmentation fns. (including any energy loss) scale in AuAu i.e. energy loss is fractional
- $(h^+ + h^-)/2$ x_T scales in peripheral same as p-p but difference between central and peripheral is significant

This is the Baryon Anomaly $2<p_T<4.5$ GeV/c

PHENIX PRL 91(2003) 172301



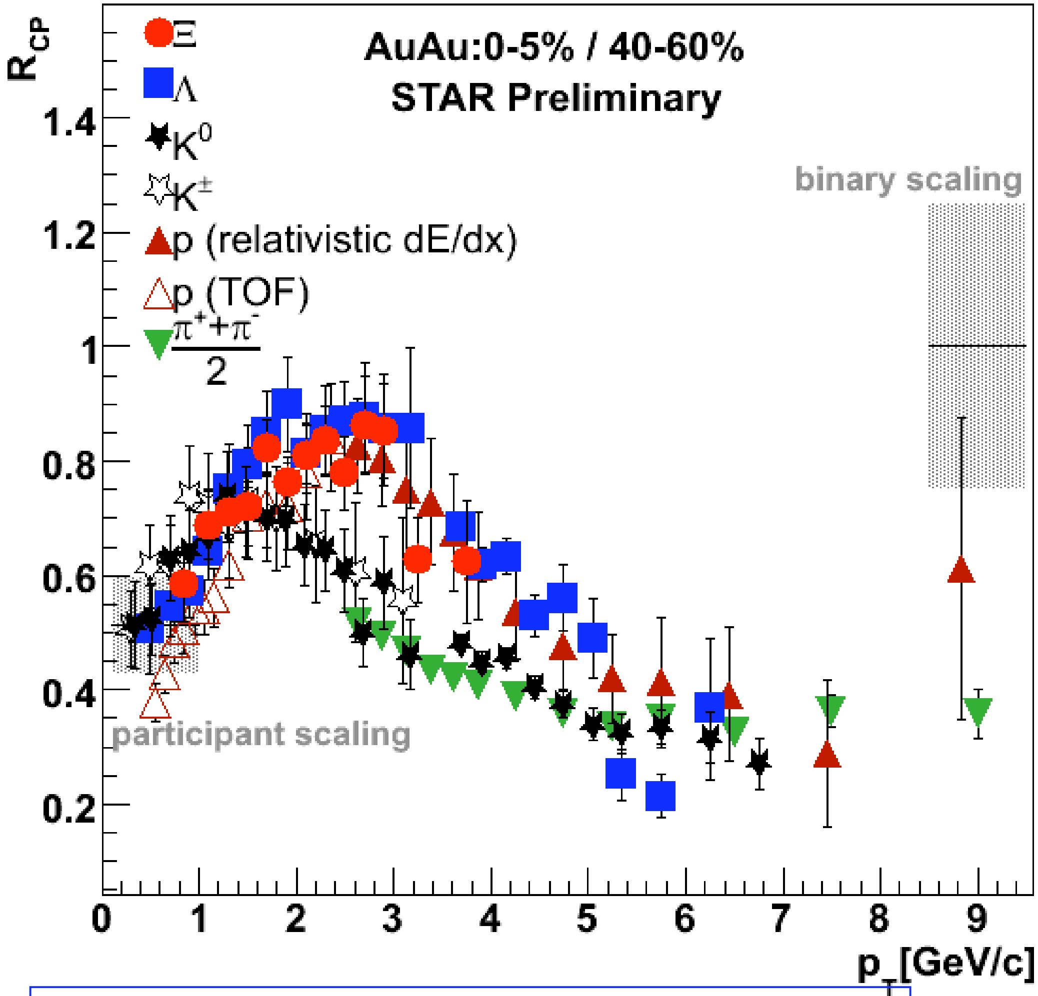


$p^{\pm}$ are not suppressed

$p^{\pm}/\pi^{\pm}$ ratio much larger than from jet fragmentation

Is this ‘recombination’ ⇒ QGP: Fries,Muller, Nonaka PRL **90** 202303 (2003)

Rcp of Baryons & mesons become equal (⇒fragmentation) for p_T>6 GeV/c at 200 GeV



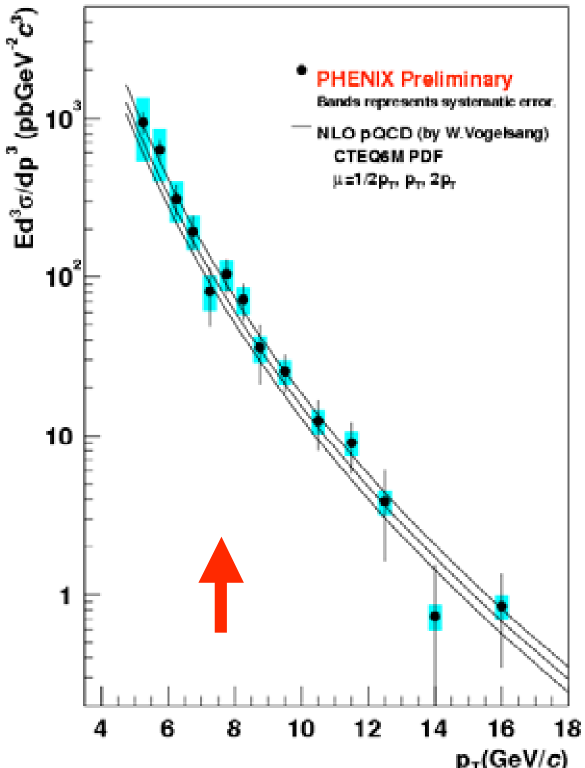
STAR-Jana Bielcikova Hard Probes 2006

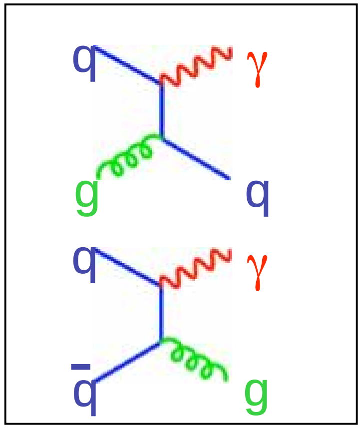
- In agreement with recombination predictions
- Balance between recombination and fragmentation should be different at LHC

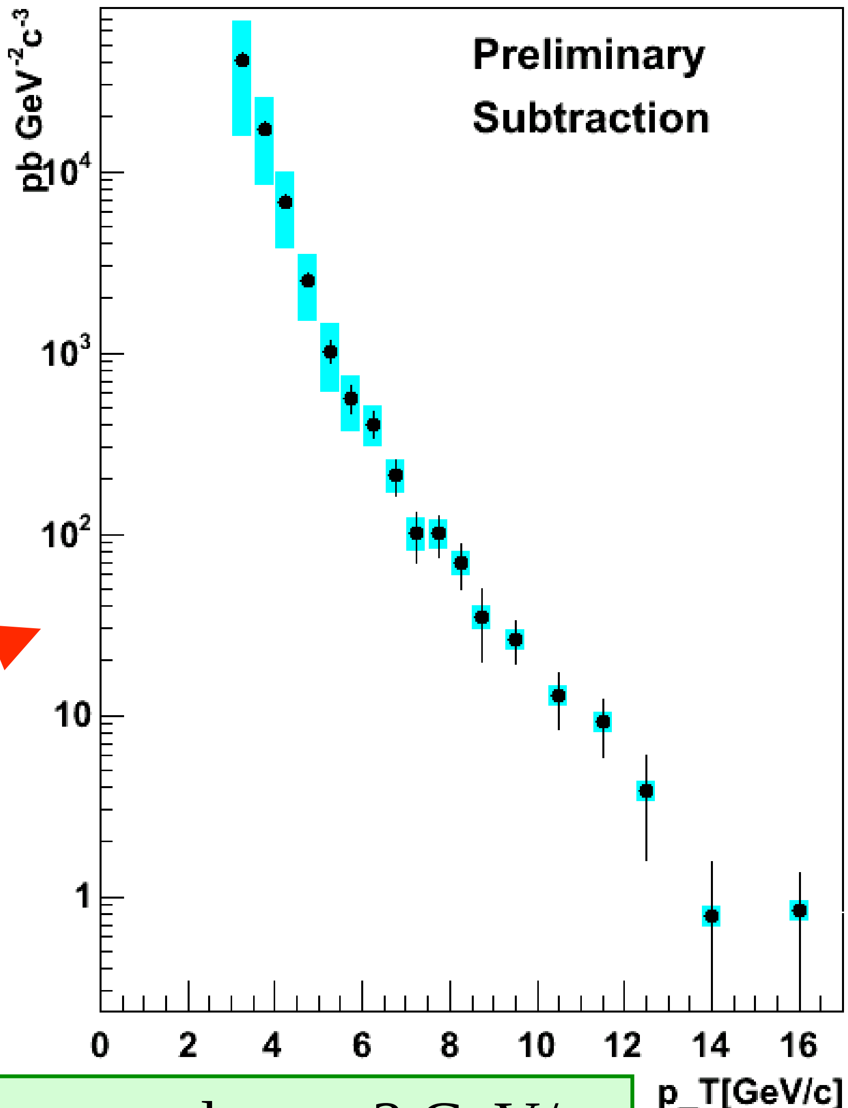
- Hwa & Yang nucl-th/0603053 predict $p/\pi \sim 10$ out to $p_T \sim 20$ GeV/c at LHC due to recombination of partons from the many jets produced⇒ p have no associated jet structure !!

- Very important to measure at LHC--needs pid over a large p_T range

New direct γ's in p+p: Data vs. pQCD





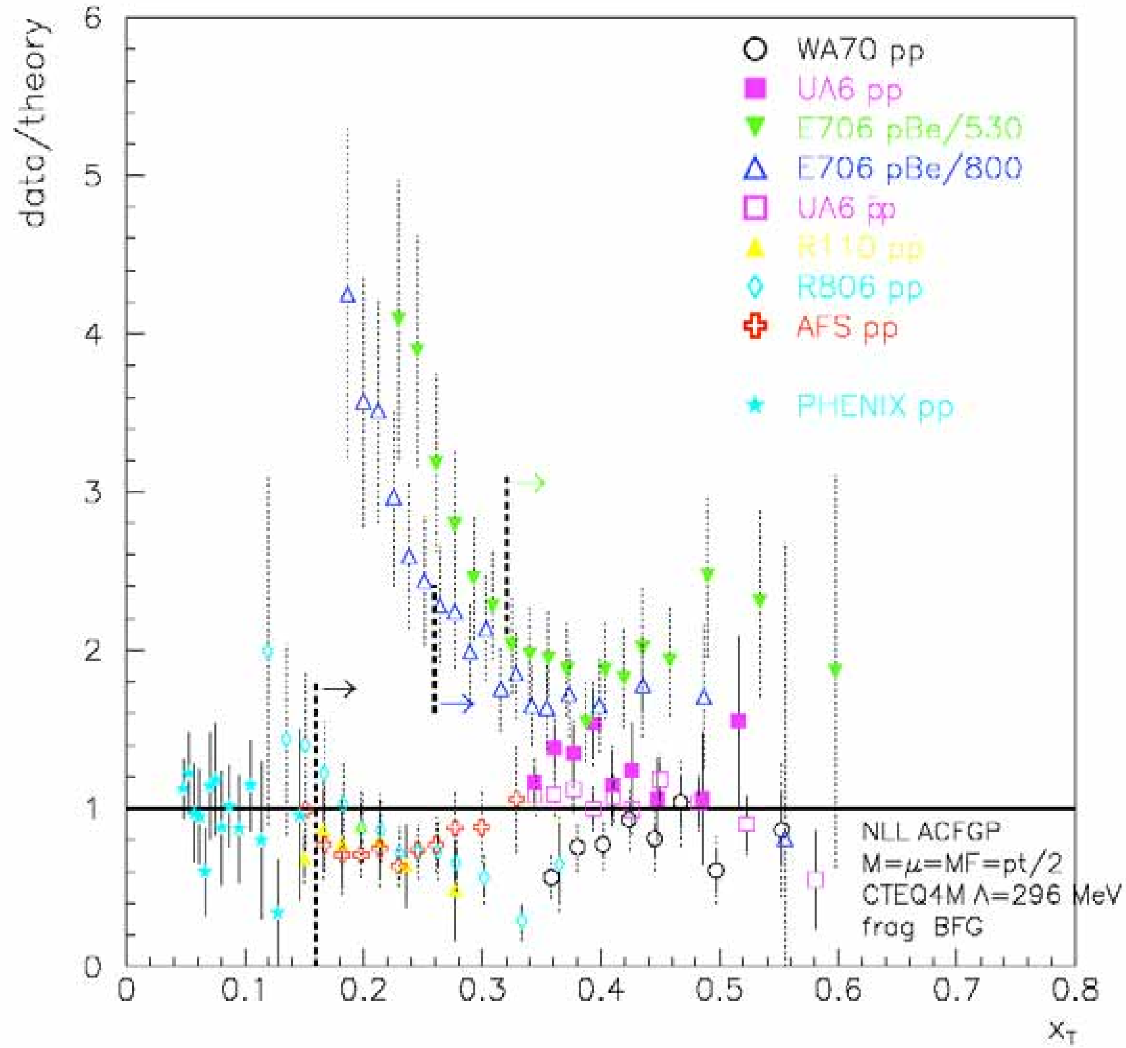


- PHENIX run3 preliminary result.
  - ✓ Recent Update down to 3GeV/c
  - ✓ Publication is coming soon.
- NLO-pQCD calculation
  - ✓ Private communication with W.Vogelsang
  - ✓ CTEQ6M PDF.
  - ✓ Sum of direct γ + Bremsstrahlung γ
  - ✓ 3 scales (1/2pT,1pT,2 pT)

Previous results for p_T> 5GeV/c new results p_T>3 GeV/c

Comparison with other data and pQCD

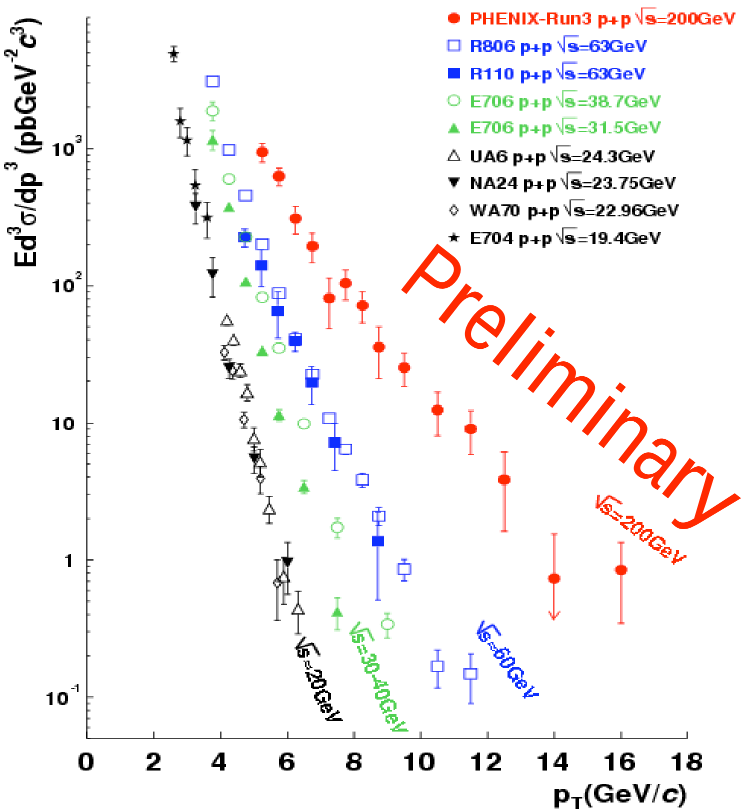
Aurenche et al Eur. Phys. JC**9** (1999)107

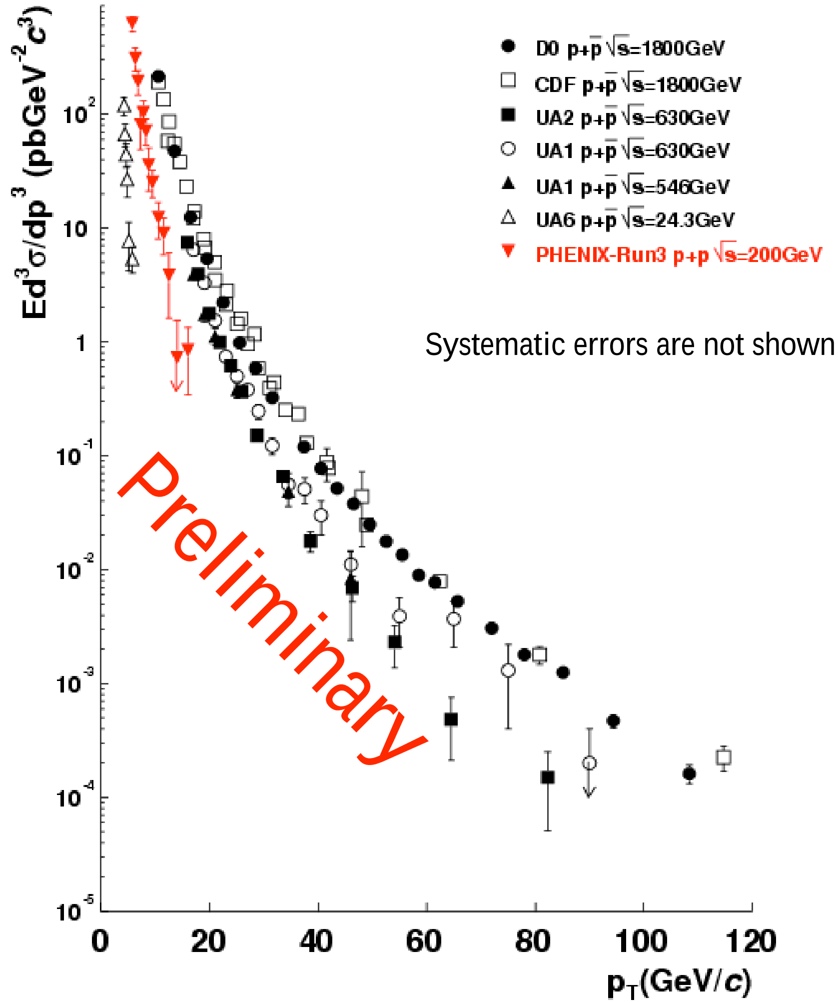


Talk by Monique Werlen at RHIC&AGS users meeting 2005

PHENIX data clarifies longstanding data/theory puzzle

Comparison with Other Experiments

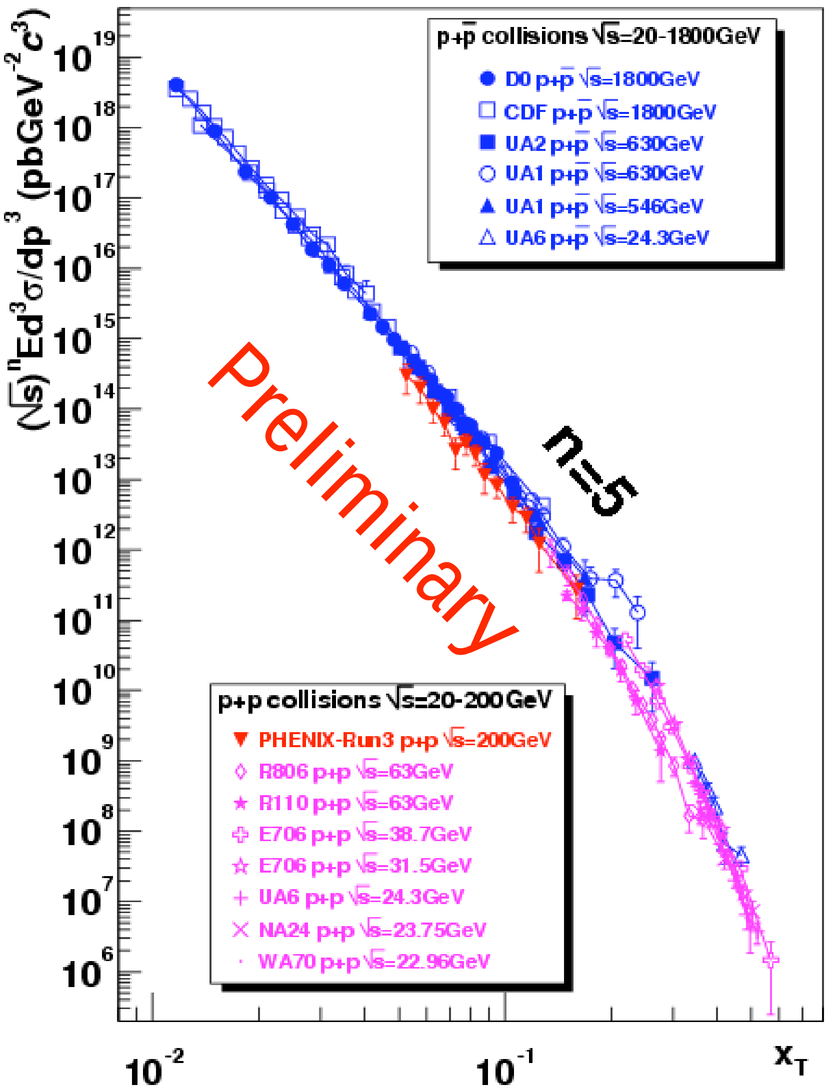




proton-proton collisions

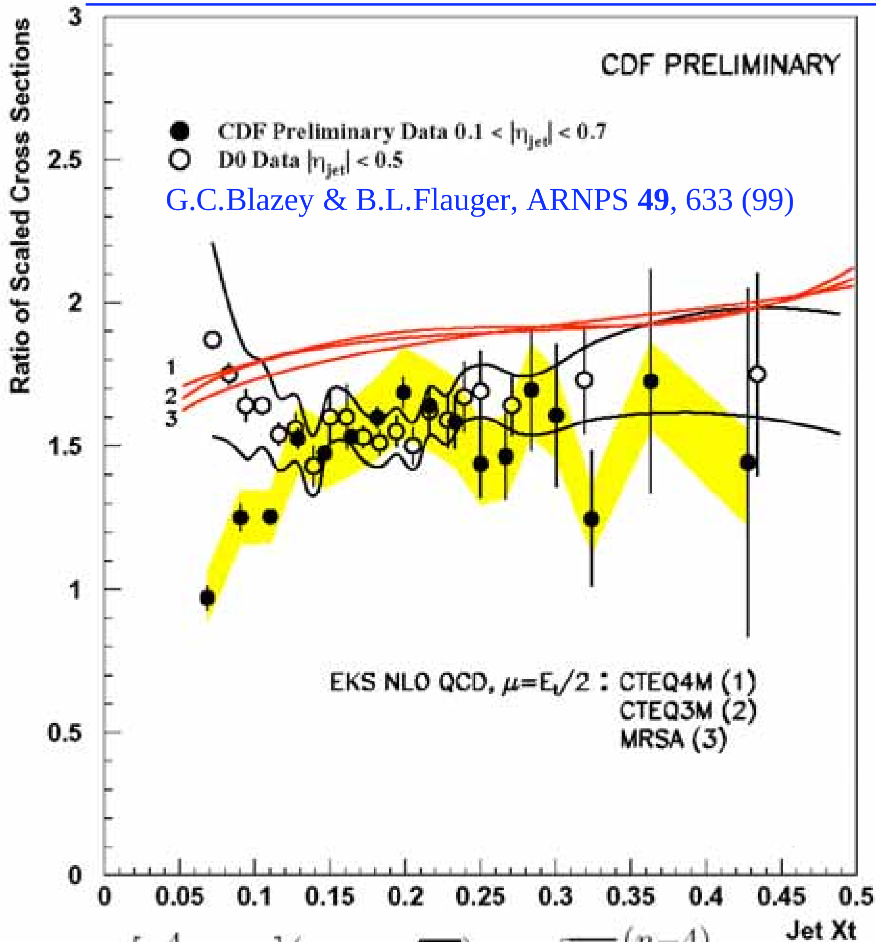
proton-antiproton collisions

x_T scaling: a) Direct-γ b) Jets



Direct γ n≈5

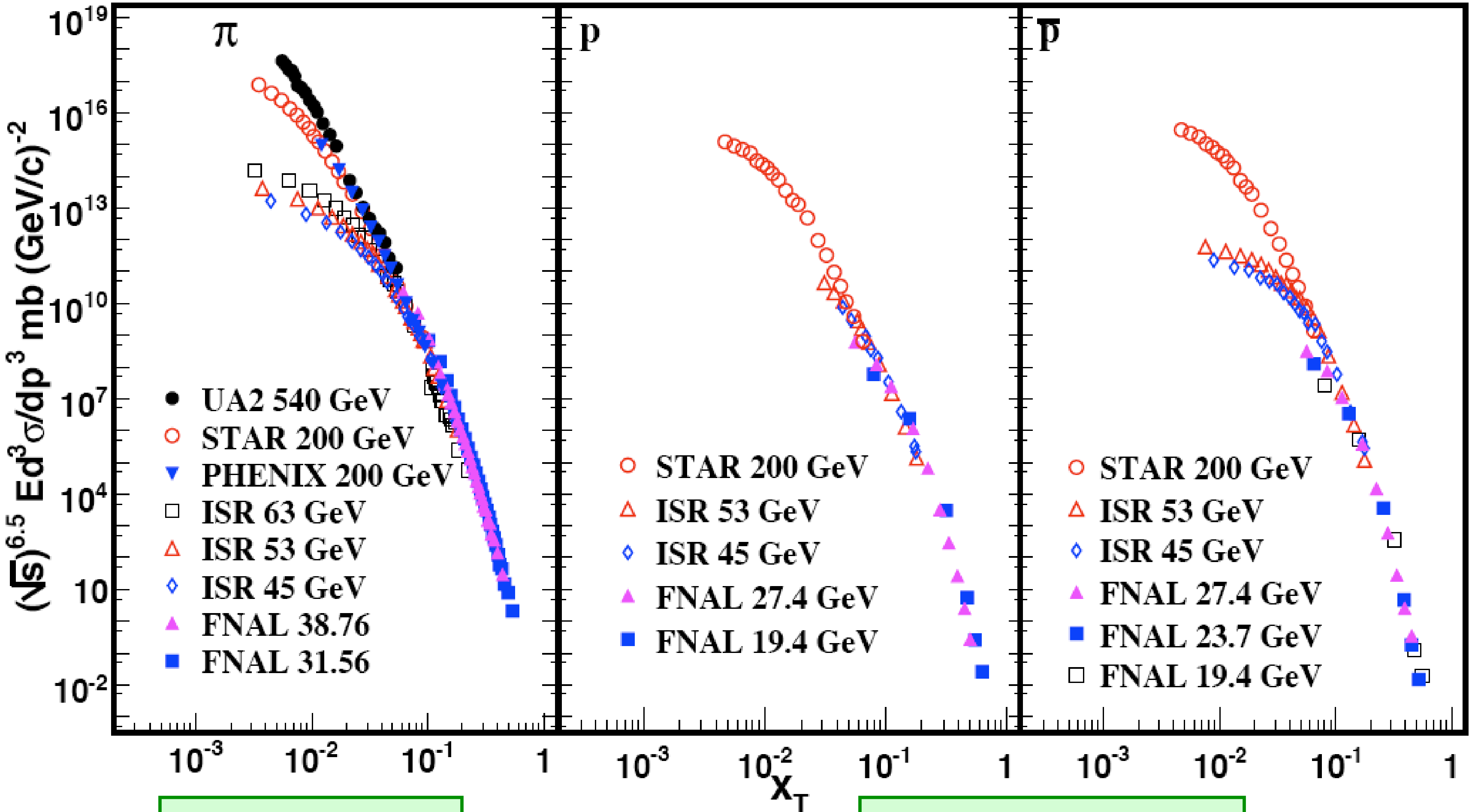
Jets-Ratio of Scaled Cross Sections 630/1800



$$\frac{[p_T^4\,\sigma_{\rm inv}](x_T,\sqrt{s_1})}{[p_T^4\,\sigma_{\rm inv}](x_T,\sqrt{s_2})} = \sqrt{\frac{s_2}{s_1}}^{(n-4)}$$

Jets n≈4.5

New: STAR x_T scaling result for (anti-)protons in p+p collisons $\sqrt{s_{NN}}$=200 GeV



$\pi^{\pm}$ n=6.8 ± 0.5

p, $\bar{p}$ n =6.5 ± 1.0

STAR, nucl-ex/0601033. It appears that Brodsky, et al PLB**637**, 58 are likely wrong

New STAR Jet measurement in p-p collisions---first at RHIC-hep-ex/0608030

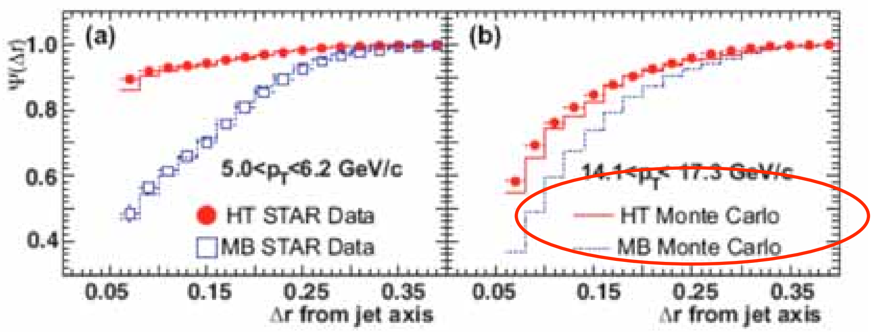


FIG. 1: Jet profile $\Psi(\Delta r, r_{\mathrm{cone}}, p_T)$ versus inner cone size Δr at $r_{\mathrm{cone}} = 0.4$ for MB (open squares) and HT (filled circles) data compared with STAR Monte Carlo simulation in two jet p_T bins (a) $5.0 < p_T < 6.2$ and (b) $14.1 < p_T < 17.3\,\mathrm{GeV/c}$. The MB jet yield is insufficient in the latter range.

"Jets were reconstructed using a midpoint-cone algorithm"

See Kilgore, Giele PRD**55** (1997) 7183 for a critical review of jet algorithms

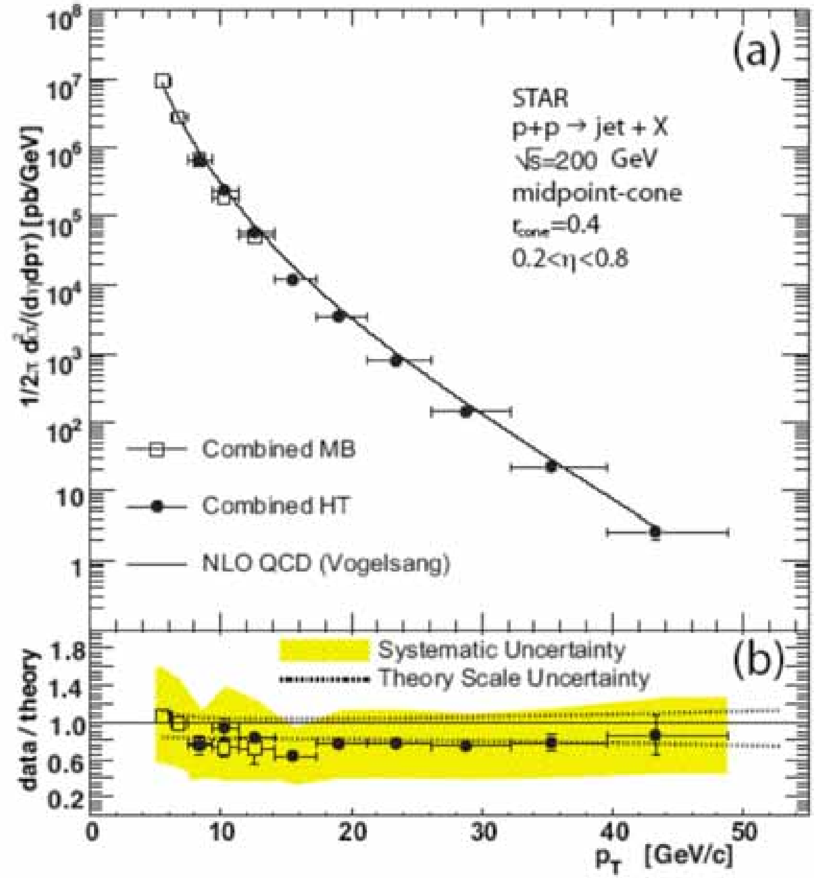
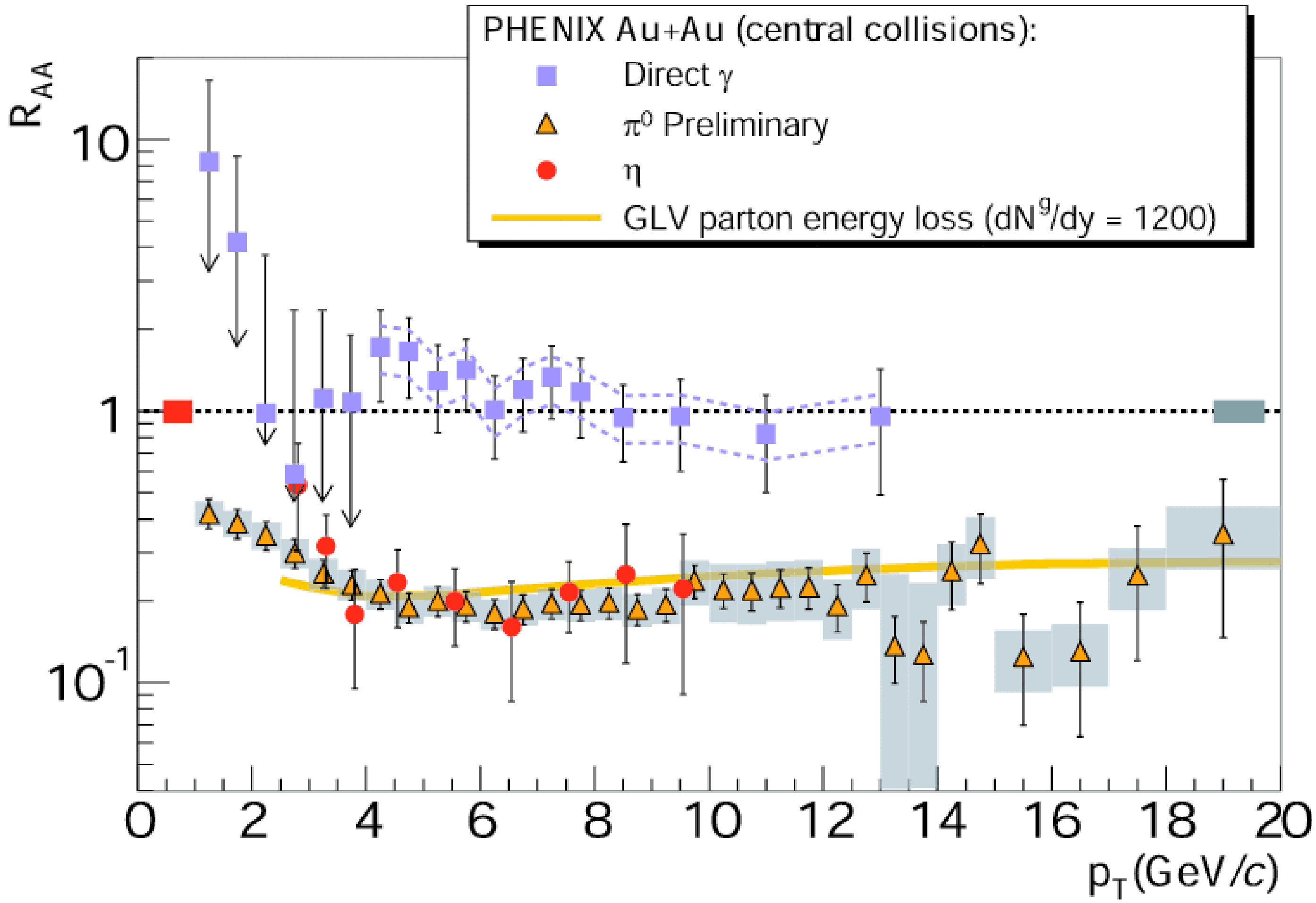


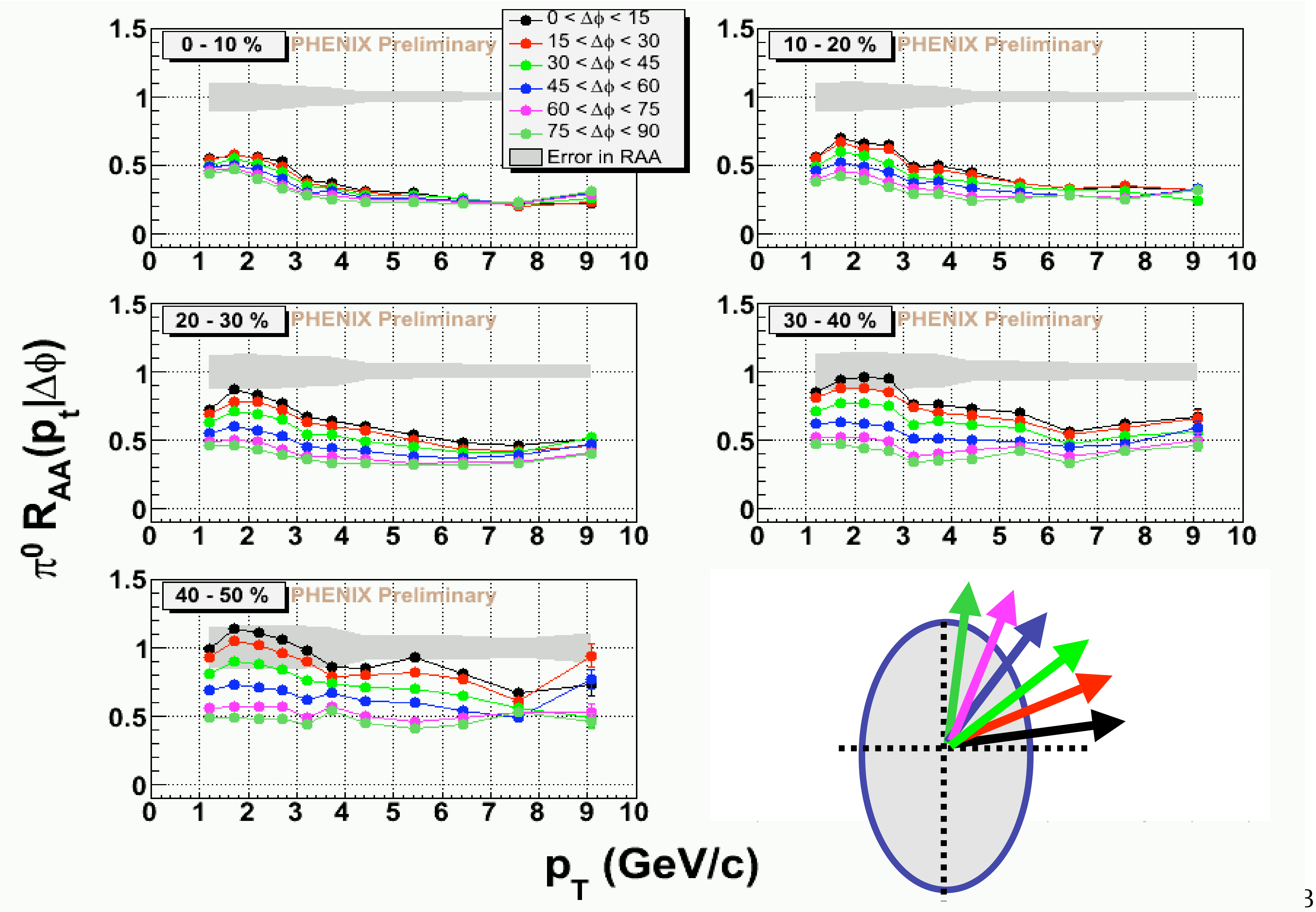
FIG. 2: (a) Inclusive differential cross section for $p+p \rightarrow \mathrm{jet}+X$ at $\sqrt{s} = 200$ GeV versus jet p_T for a jet cone radius of 0.4.

Status of R_{AA} in AuAu at $\sqrt{s_{NN}}$=200 GeV

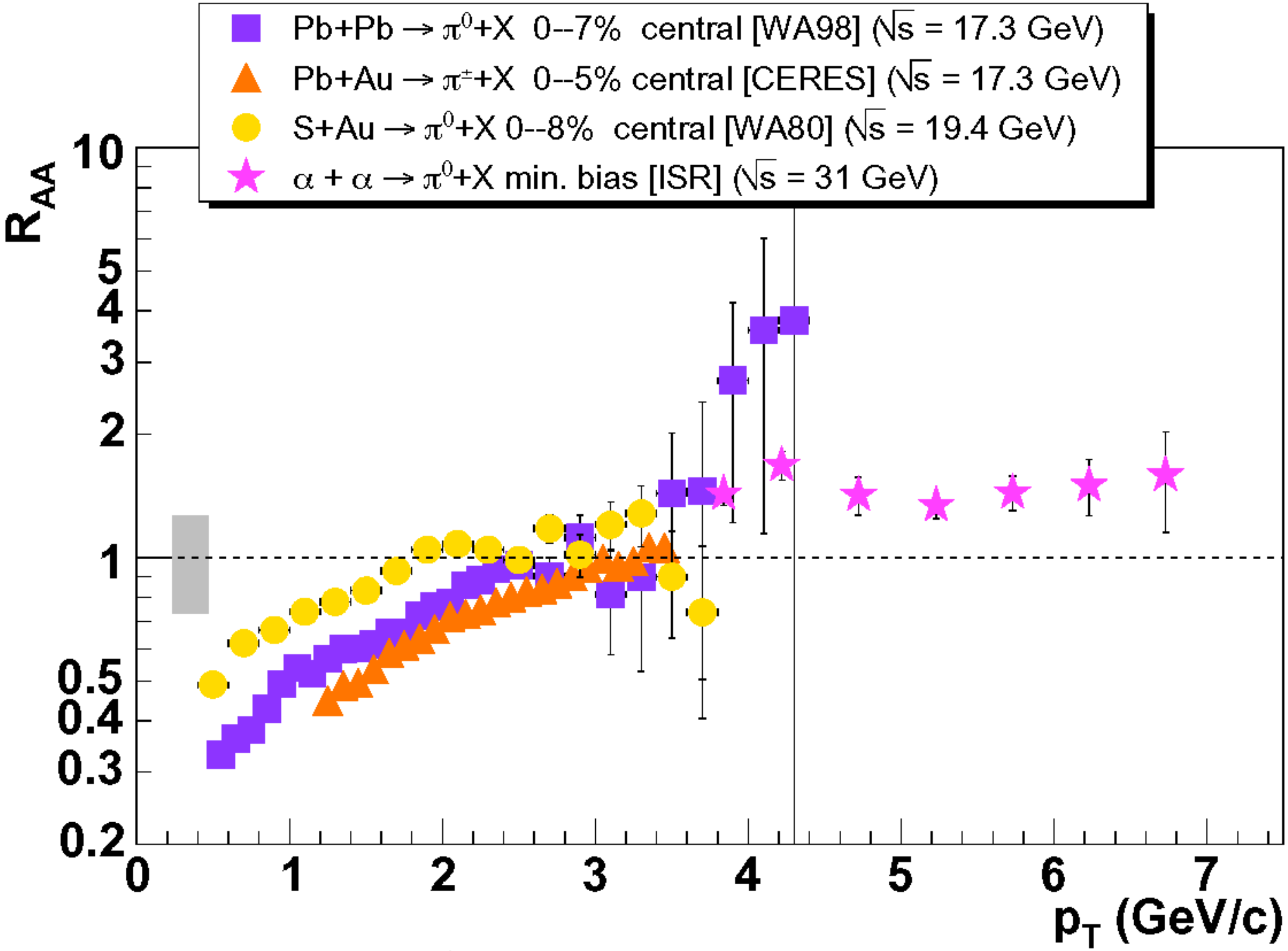


Direct γ are not suppressed. π^0 and η suppressed even at high p_T
Implies a strong medium effect (energy loss) since γ not affected.
Suppression is flat at high p_T. Are data flatter than theory?

To test details of Theory⇒$R_{AA}(\Delta\phi, p_T)$-π^0

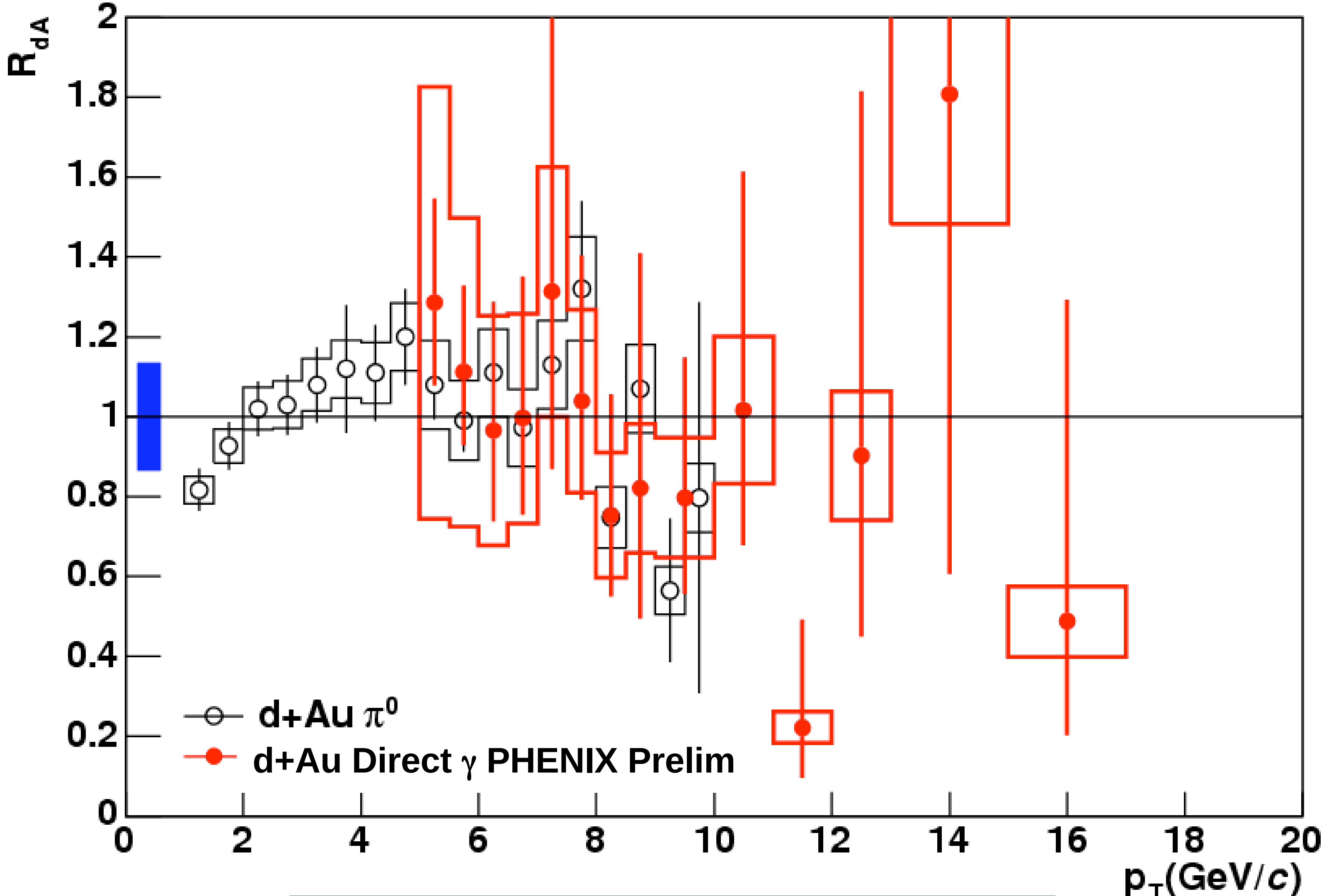


For A+A: $R_{AA} \geq 1$ before RHIC



- The importance of comparison data!

State of R_{dA} in d+Au at $\sqrt{s_{NN}}$=200 GeV



Both Direct γ and π^0 consistent with 1

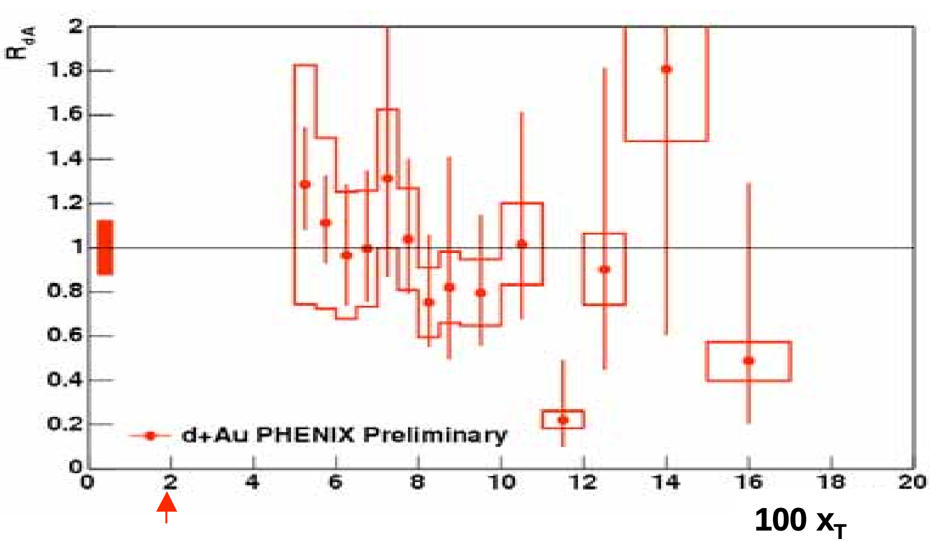
Direct γ is"EMC effect" for gluons

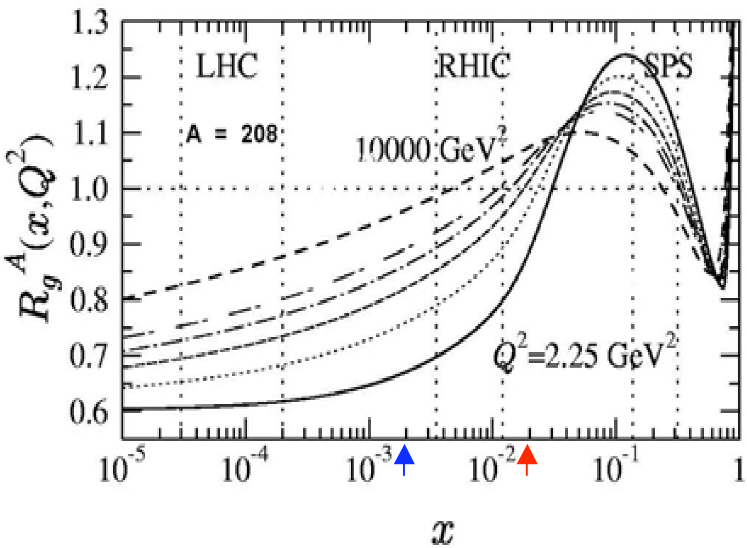
Nuclear Modification Factor-Min Bias

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

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

Eskola, Kolhinen, Vogt hep-ph/0104124



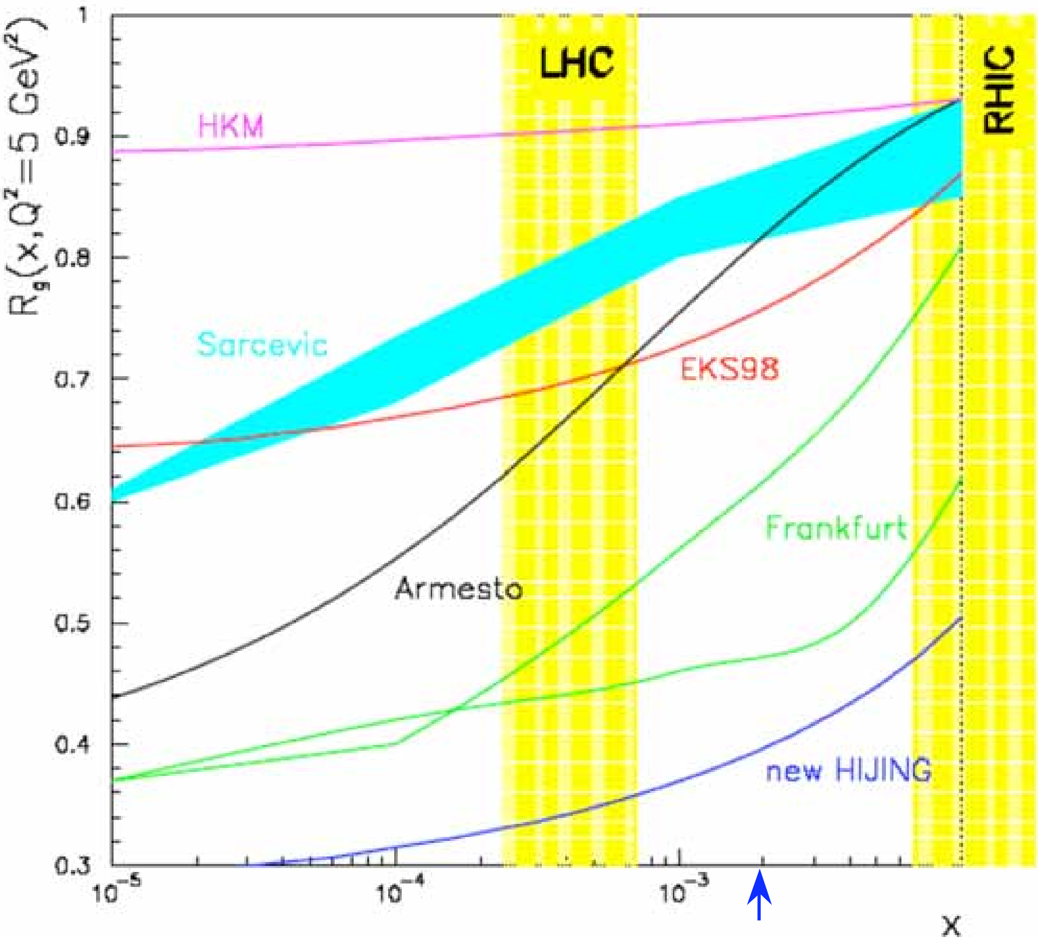


Consistent with 1 ➔ No modification within the error

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

AA measurements at LHC probably useless without pp and pA (dA) comparison data



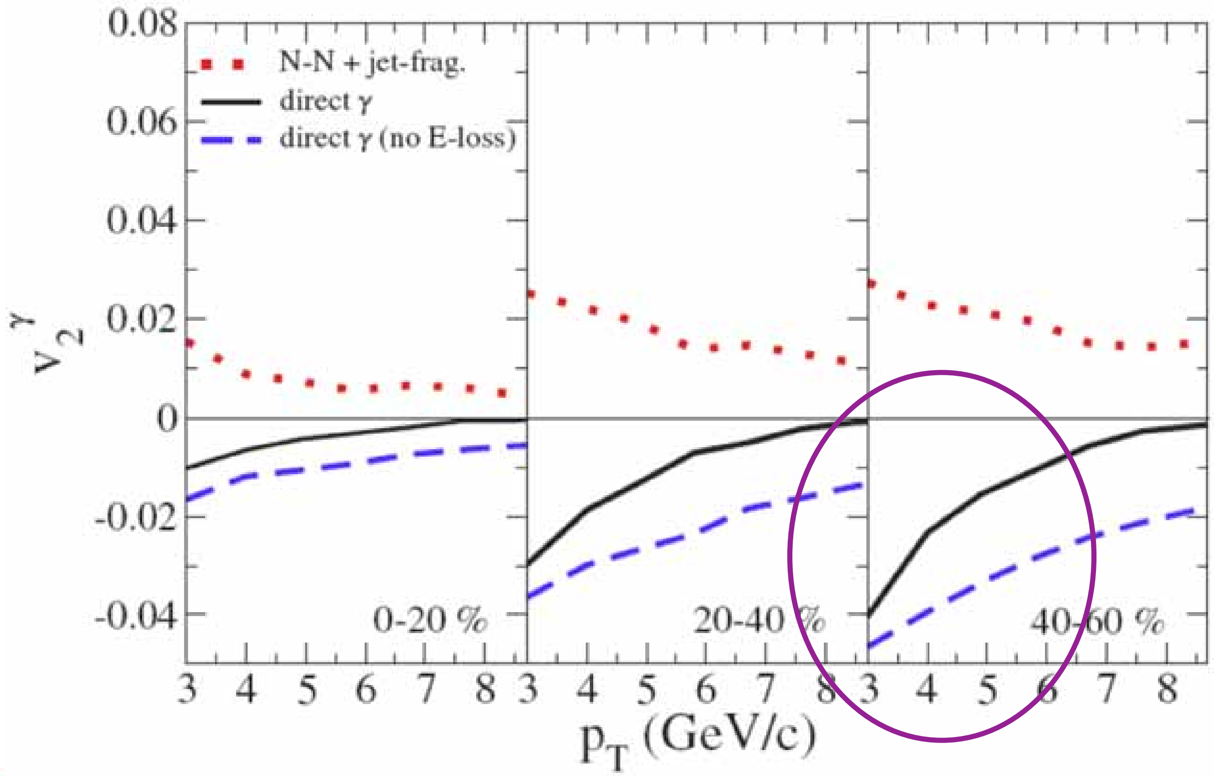
Predictions from CERN-Yellow-report-hep-ph/0308248

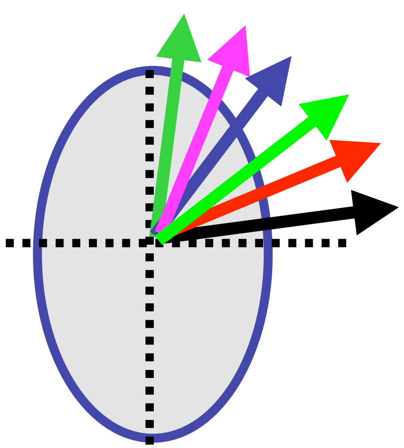
- For pp make sure to run at 900 GeV and 14000 GeV. Interpolation +QCD might be adequate to believe 5500 GeV
- LHC could be the CGC factory. $R_g(x,Q^2)$ not known for any A or any x or Q^2. Forward d+Au measurements at RHIC will be useful.

Need d+Pb or p+Pb runs at $\sqrt{s_{NN}}$=5500 GeV, unless direct γ are not suppressed in Pb+Pb. Direct γ much harder at LHC than at RHIC

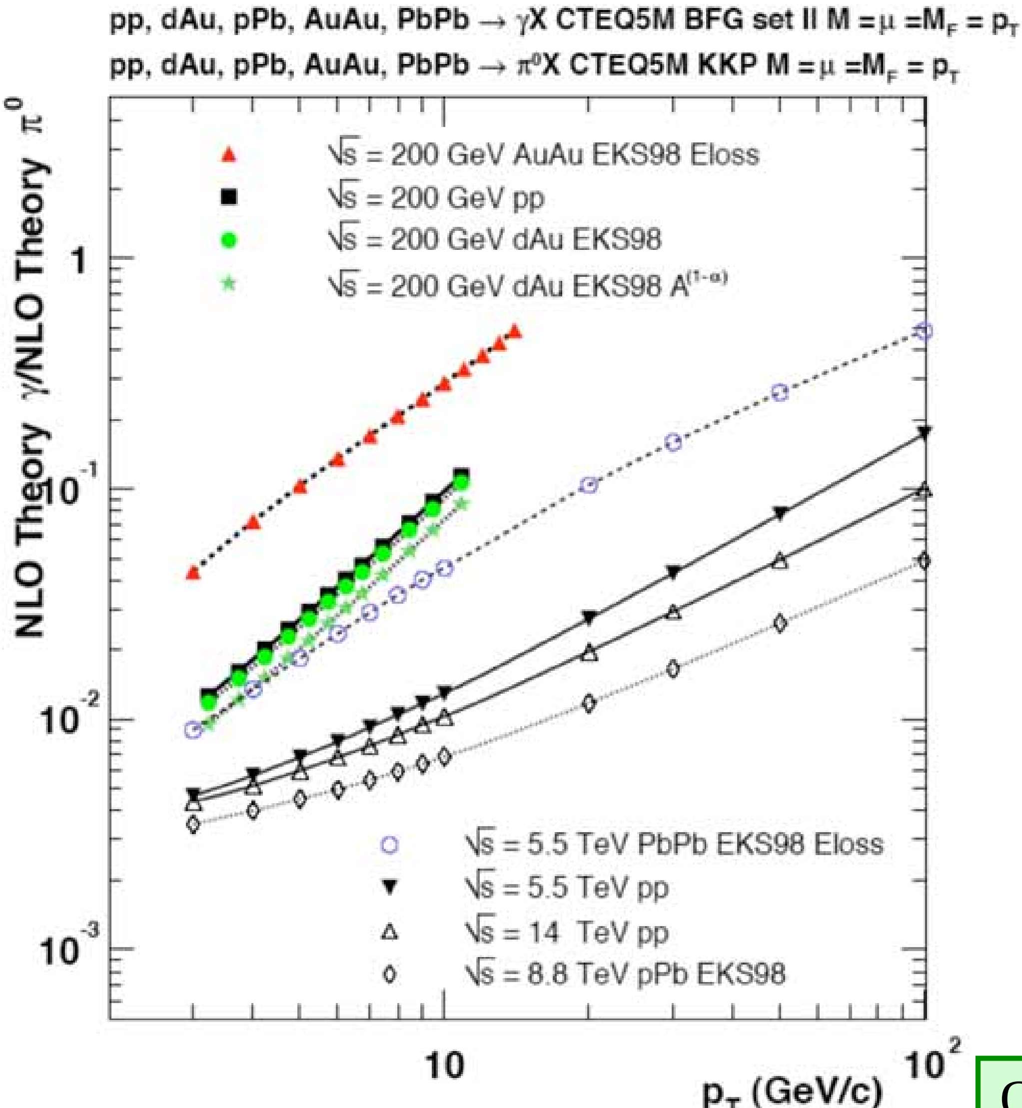
Direct γ with respect to the reaction plane

Turbide, Gale & Fries, PRL 96 (2006) 032303 predict that if jet(parton) suppression is due to g+q-->g+q (+g) in the medium then the reaction g+q--> γ+q should create a source of direct photons proportional to the distance traversed through the medium-fewer on the mid-plane more vertical, the opposite of π^0 and other hadronic jet fragments





MJT-This is a great measurement for LHC



- γ/π^0 much smaller at LHC compared to RHIC. ⇒ Measurement with real photons is much harder
- use external or internal conversions to low mass e^+e^- pairs for p_T <5 GeV/c (contains π^0 and all other decay photon)---nice measurement of hadron $v_2>0$
- compare to low mass $\mu^+\mu^-$ pairs, which have no π^0 and minimal η and should have $v_2<0$ if medium regeneration theory is correct

CERN Yellow Report-hep-ph/0311031

Opposite v_2 for ee and μμ would indicate dramatic physics without need to know all the backgrounds in detail

Correlations

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 $\hat{p}_{T_t}$

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

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

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

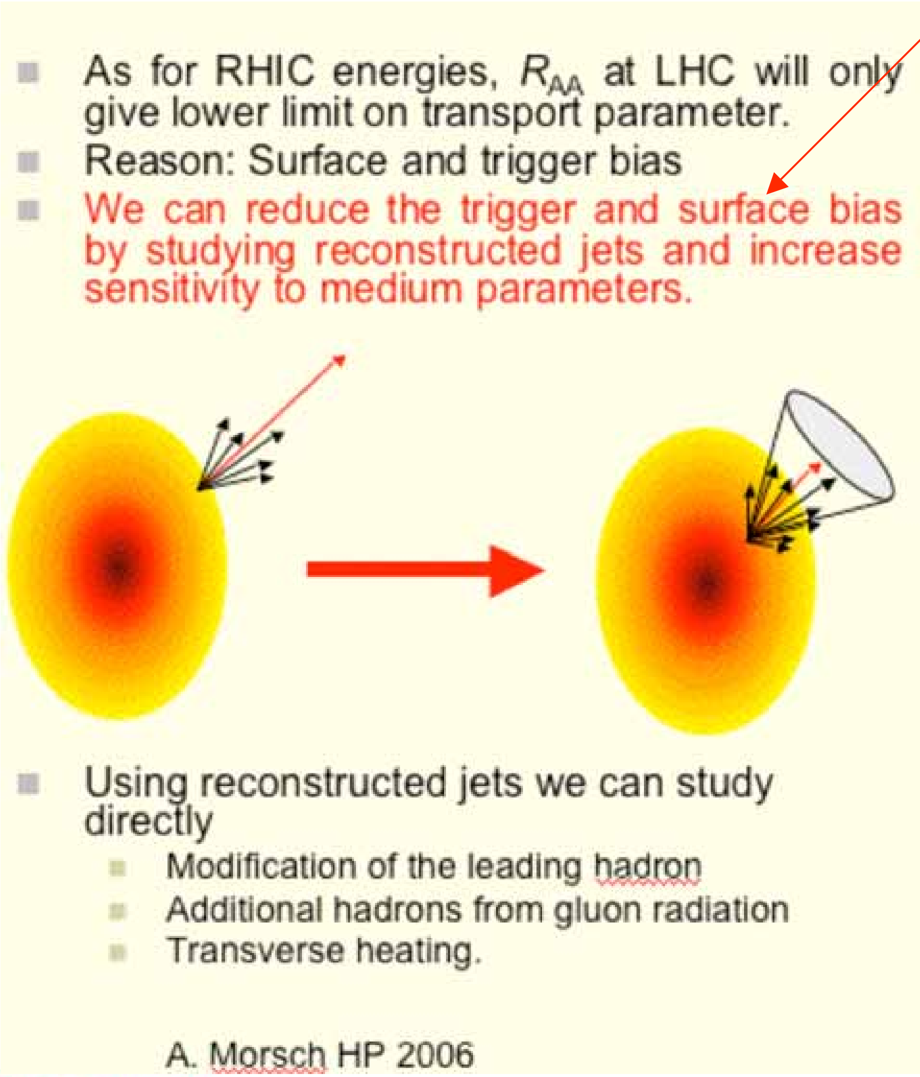
$$\frac{d^2\sigma_\pi(p_{T_t}, z_t)}{dp_{T_t} dz_t} = \frac{1}{z_t} \frac{A}{(p_{T_t}/z_t)^{n-1}} \times D^q_\pi(z_t)$$

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

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

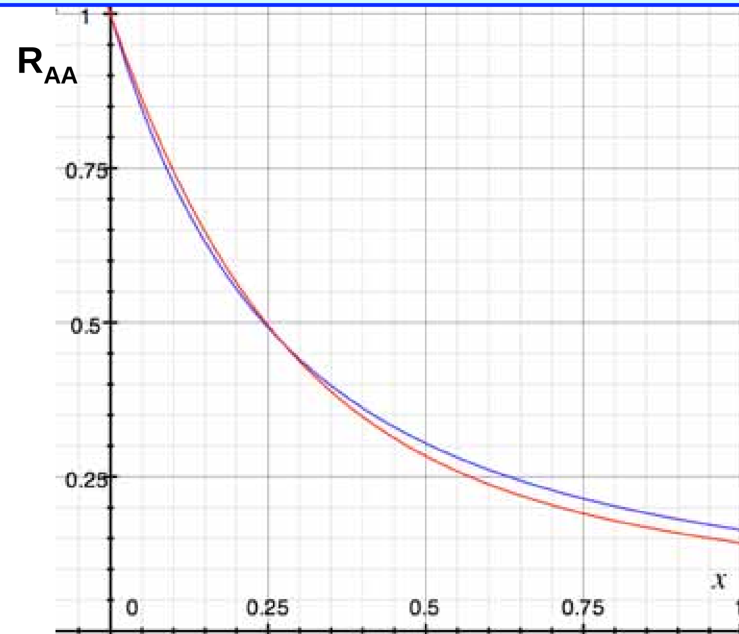
$$\text{where } z_{t\min}|_{p_{T_t}} = x_{T_t} \qquad D^q_\pi(z_t) = Be^{-6z_t}$$

p.s.-The same math shows that surface bias is identical for jets and single particle triggers



i.e. I don't agree if jets fragment outside of medium which they must by Quantum Mechanics

MJT simplistic calc for a uniform opaque medium (x=fraction of energy lost from center to surface≤1):
$R_{AA}(x=1)$ =1/(n-1) or 1/(n-2), n=8.1 RHIC,
LHC n~6.5⇒ less suppression!? Corona Effect?
To theorists: please improve my result.



2 particle Correlations

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

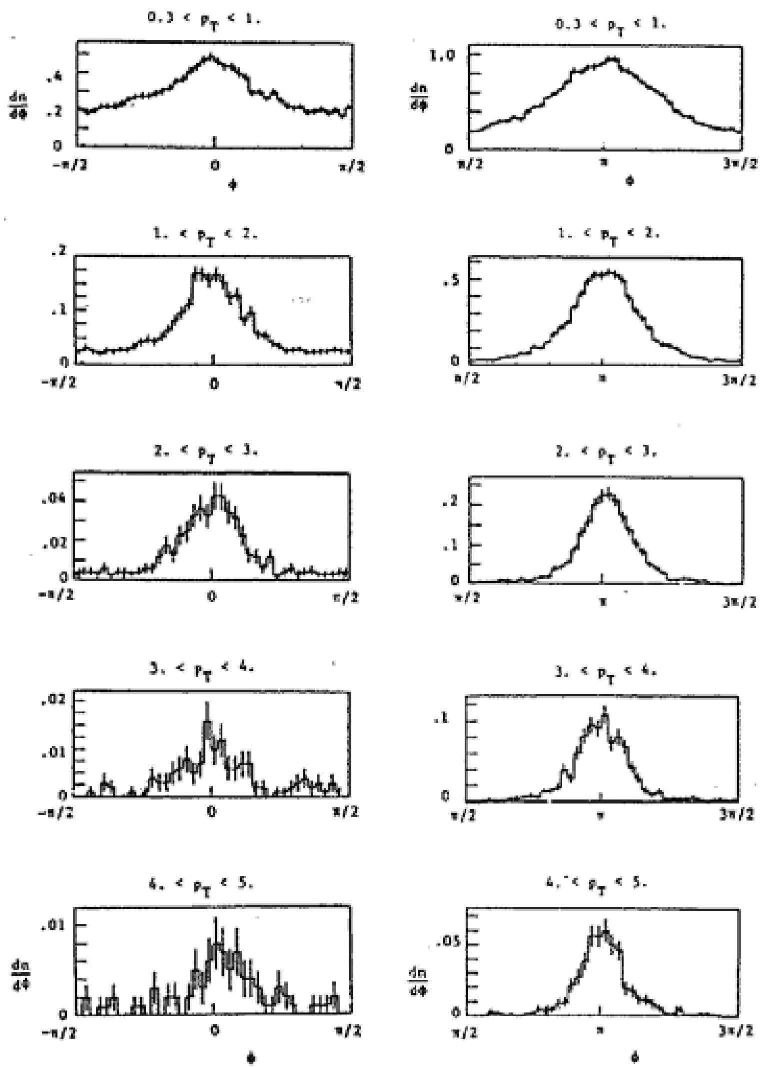
Also detect fragment with $z_a = p_{T_a}/\hat{p}_{T_a}$
from away jet with $\hat{p}_{T_a}/\hat{p}_{T_t} \equiv \hat{x}_h$

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

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

(1) $$\boxed{\frac{d\sigma_\pi}{dp_{T_t} dz_t dp_{T_a}} = \frac{1}{\hat{x}_\mathrm{h}\, p_{T_t}} \frac{d\sigma_q}{d(p_{T_t}/z_t)} D^q_\pi(z_t) D^q_\pi(\frac{z_t p_{T_a}}{\hat{x}_\mathrm{h} p_{T_t}})}$$

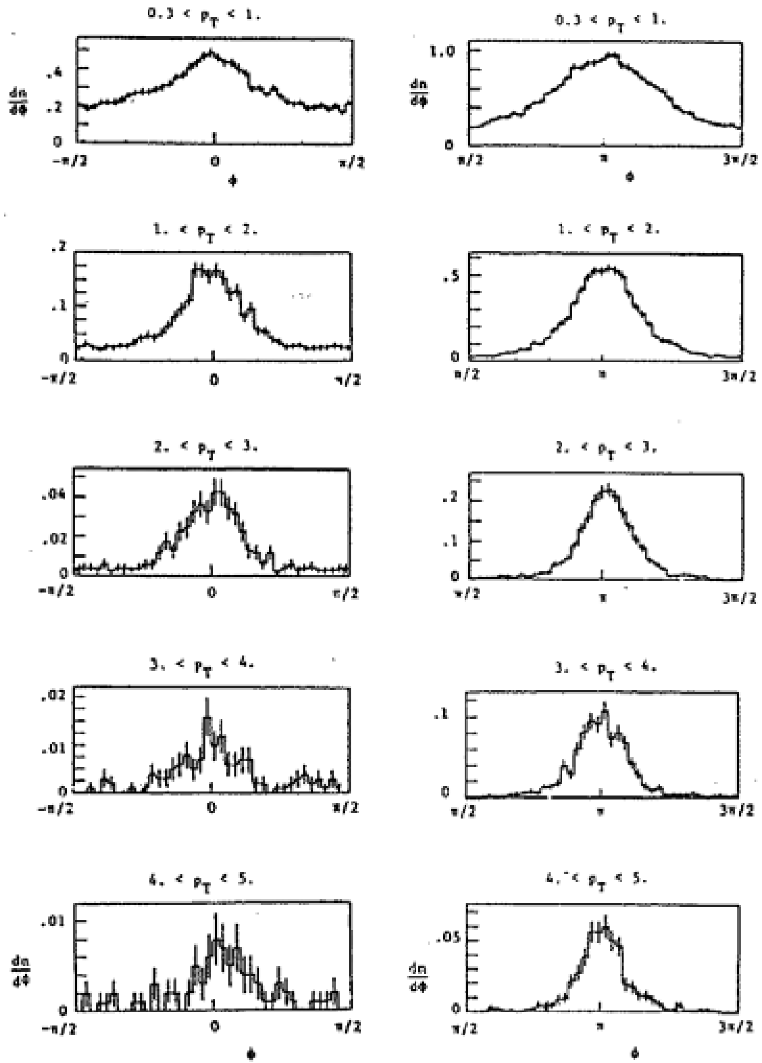
How everything you want to know about JETS was measured with 2-particle correlations



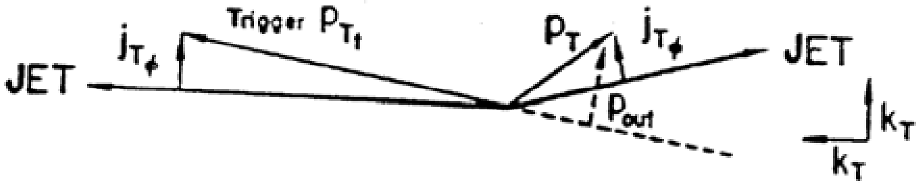
CCOR, A.L.S.Angelis, et al
Phys.Lett. **97B**, 163 (1980)
PhysicaScripta **19**, 116 (1979)

p_{Tt} > 7 GeV/c vs p_T

How everything you want to know about JETS was measured with 2-particle correlations

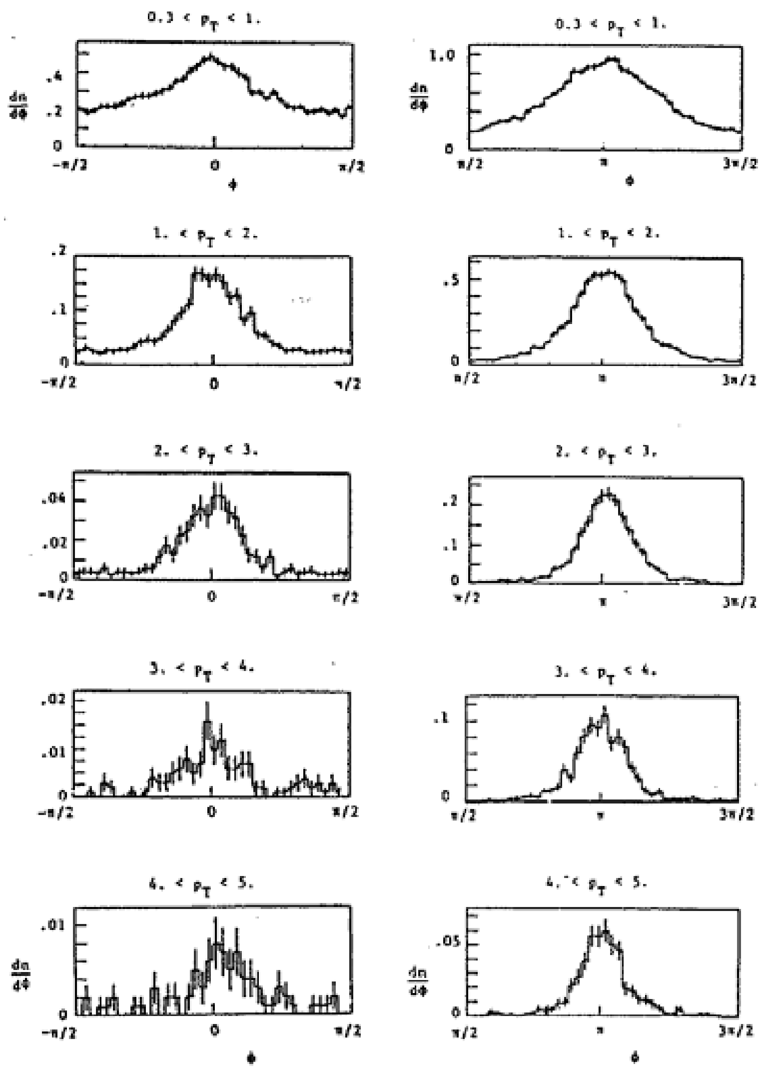


CCOR, A.L.S.Angelis, et al
Phys.Lett. **97B**, 163 (1980)
PhysicaScripta **19**, 116 (1979)

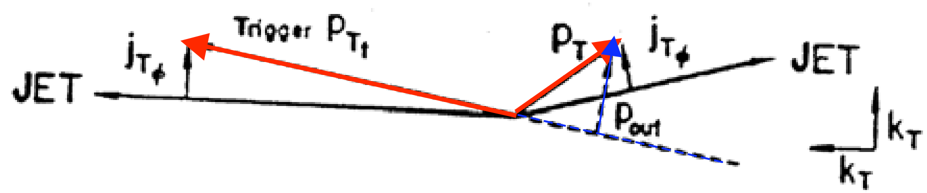


$p_{Tt} > 7$ GeV/c vs p_T

How everything you want to know about JETS was measured with 2-particle correlations

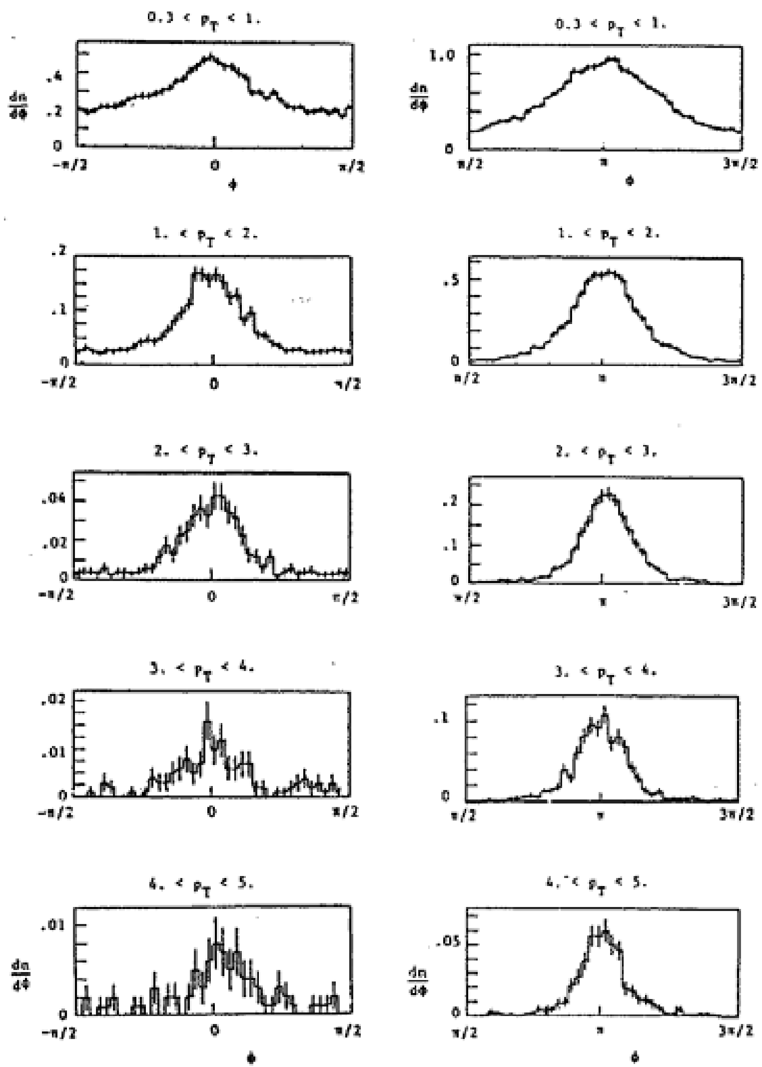


CCOR, A.L.S.Angelis, et al
Phys.Lett. **97B**, 163 (1980)
PhysicaScripta **19**, 116 (1979)

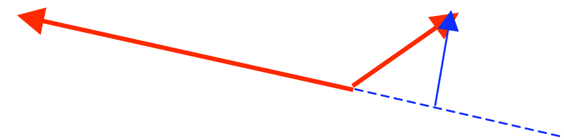


p_{Tt} > 7 GeV/c vs p_T

How everything you want to know about JETS was measured with 2-particle correlations

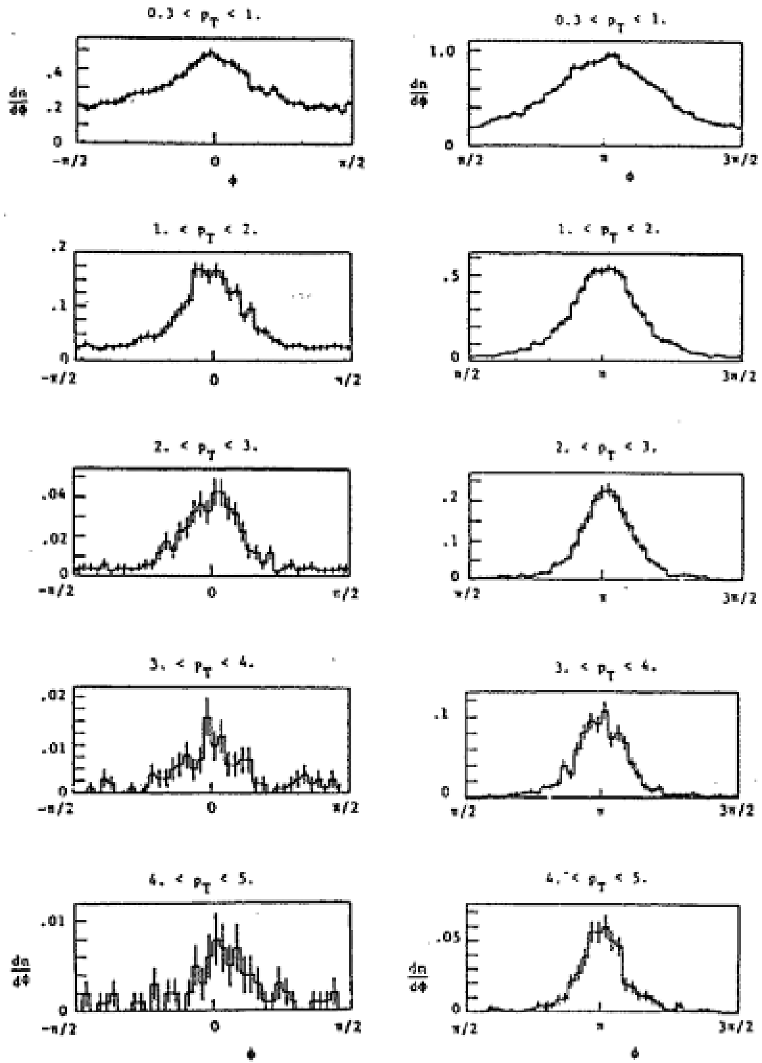


CCOR, A.L.S.Angelis, et al
Phys.Lett. **97B**, 163 (1980)
PhysicaScripta **19**, 116 (1979)

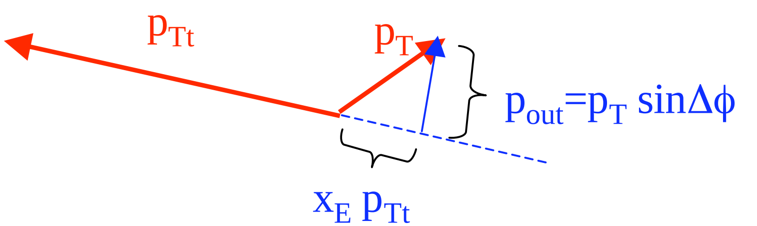


p_{Tt} > 7 GeV/c vs p_T

How everything you want to know about JETS was 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

Feynman, Field and Fox said that x_E distribution from single particle or Jet measures D(z)

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

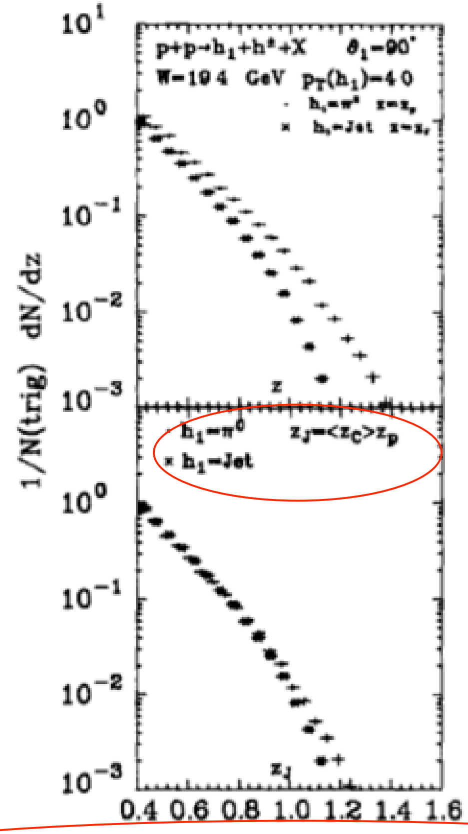


Fig. 23. Comparison of the π^0 and jet trigger away-side distribution of charged hadrons in pp collisions at $W = 19.4$ GeV, $\theta_1 = 90°$, and $p_\perp$ (trigger) = 4.0 GeV/c from the quark-quark scattering model. The upper figure shows the single-particle (π^0) trigger results plotted *versus* $z_p = -p_x(h^\pm)/p_\perp(\pi^0)$ 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 $|180° - \phi| \leq 45°$ and the theory is calculated using $\langle k_\perp\rangle_{h\to q} = 500$ MeV. • $h_1 = \pi^0$, × h_1 = jet.

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

"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

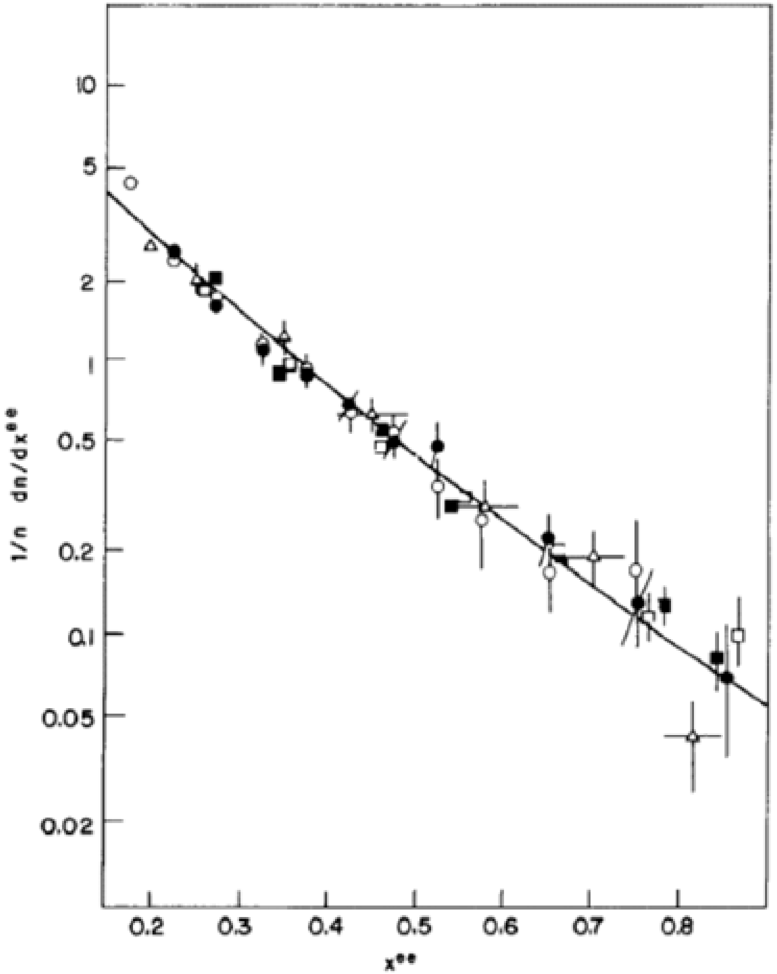


Figure 21 Jet fragmentation functions measured in different processes: ν-p interactions (*open triangles*, Van der Welde 1979); e^+e^- annihilations (*solid line*, Hanson et al 1975); and pp collisions (*full circles* CS, $p_T < 6$ GeV/c, *open circles* CS, $p_T > 6$ GeV/c, *full squares* CCOR, $p_T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

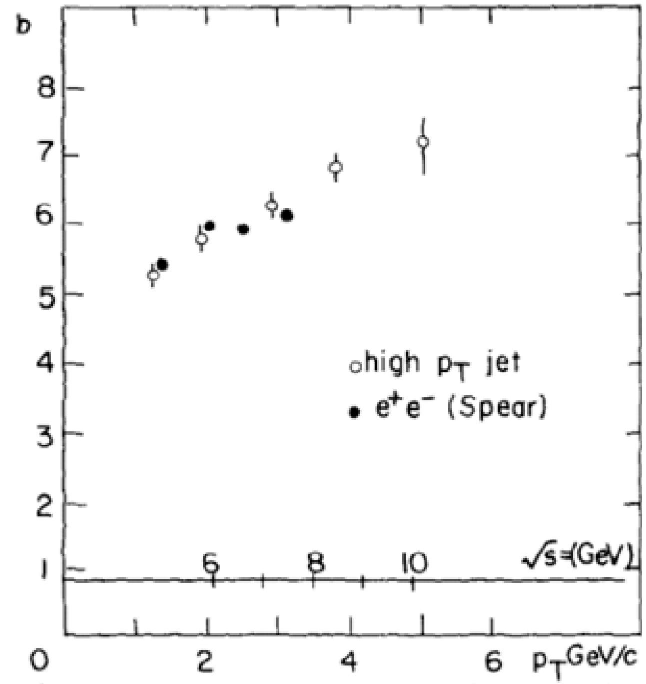
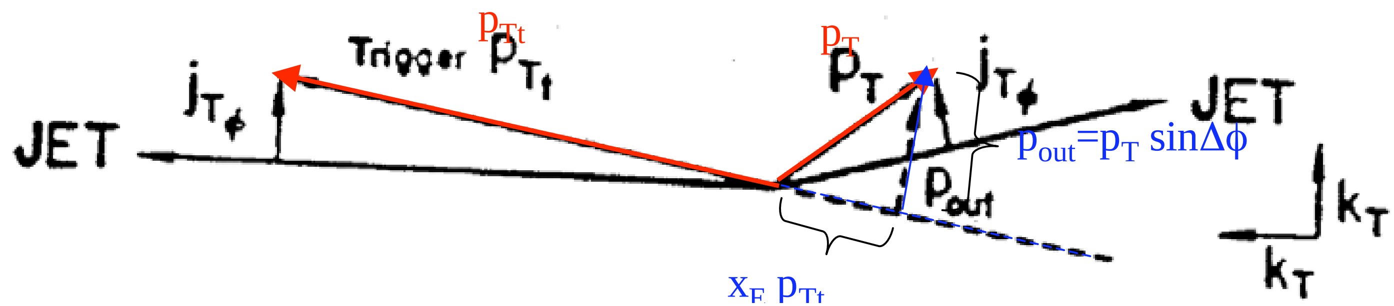


Figure 19 The slopes *b* obtained from exponential fits to the jet fragmentation function in the interval $0.2 < z < 0.8$ in e^+e^- annihilation (*full circles*) and LPTH data of the BS Collaboration (*open circles*).

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 "$\hat{s}$"

PHENIX (hep-ex/0605039) found this is wrong

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

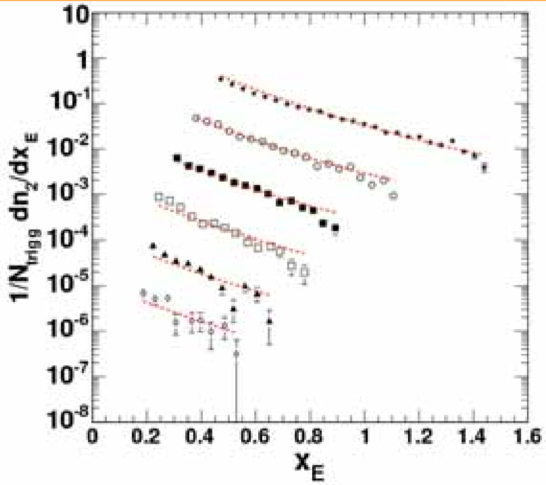


$$\frac{\langle z_t(k_T,x_h)\rangle \sqrt{\langle k_T^2\rangle}}{\hat{x}_h(k_T,x_h)} = \frac{1}{x_h}\sqrt{\langle p_{out}^2\rangle - \left\langle j_{Ty}^2\right\rangle (1+x_h^2)} \qquad x_h \equiv \frac{p_{T_a}}{p_{T_t}} \qquad \hat{x}_h \equiv \frac{\hat{p}_{T_a}}{\hat{p}_{T_t}}$$

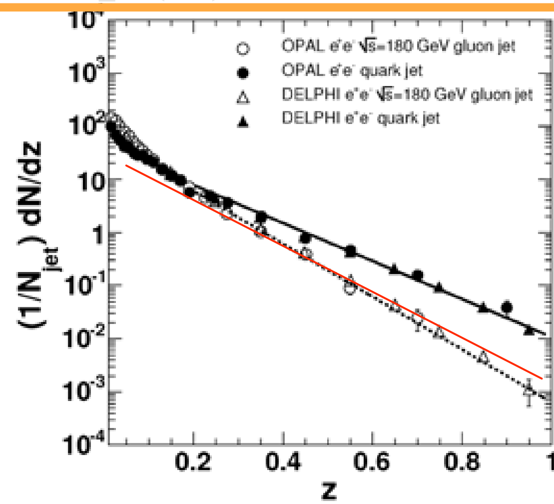
- j_T is parton fragmentation transverse momentum
- k_T is transverse momentum of a parton in a proton (2 protons)
- $x_E = -p_T \bullet p_{Tt}/|p_{Tt}|^2$ represents away jet fragmentation z
- p_{out} is component of away p_T perpendicular to trigger p_{Tt}

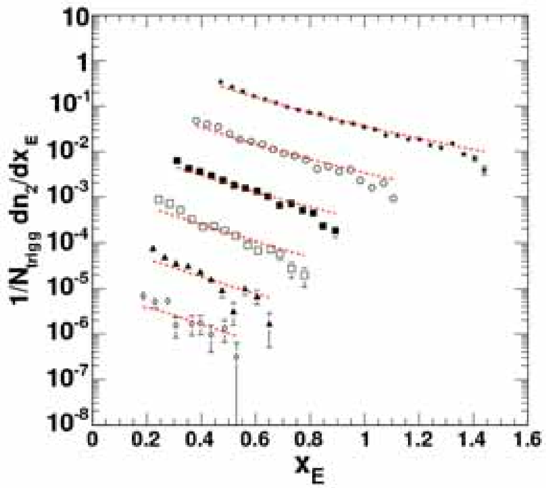
We needed $\langle z_t \rangle$ to solve for k_T. Tried to get it from x_E dist.

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

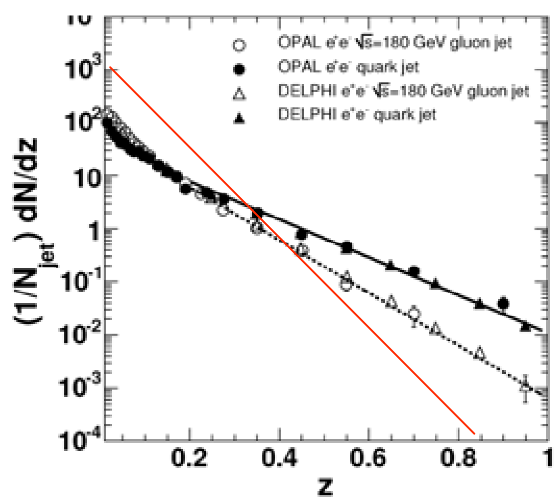


D(z)=exp(-10z)





D(z)=exp(-20z)



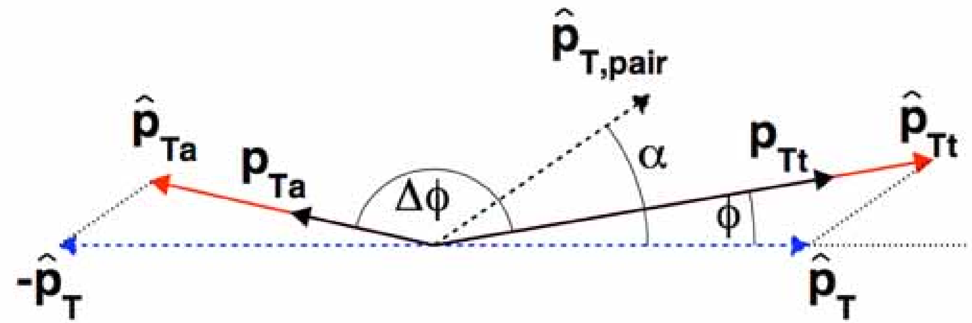
After many convergence difficulties, two vastly different fragmentations Functions tried⇒No effect on calculated x_E distributions---Mike, can you check this analytically?!

Amazingly, I got a simple, interesting formula

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

<m> is the mean multiplicity in the jet, n is the power of the p_{Tt} spectrum

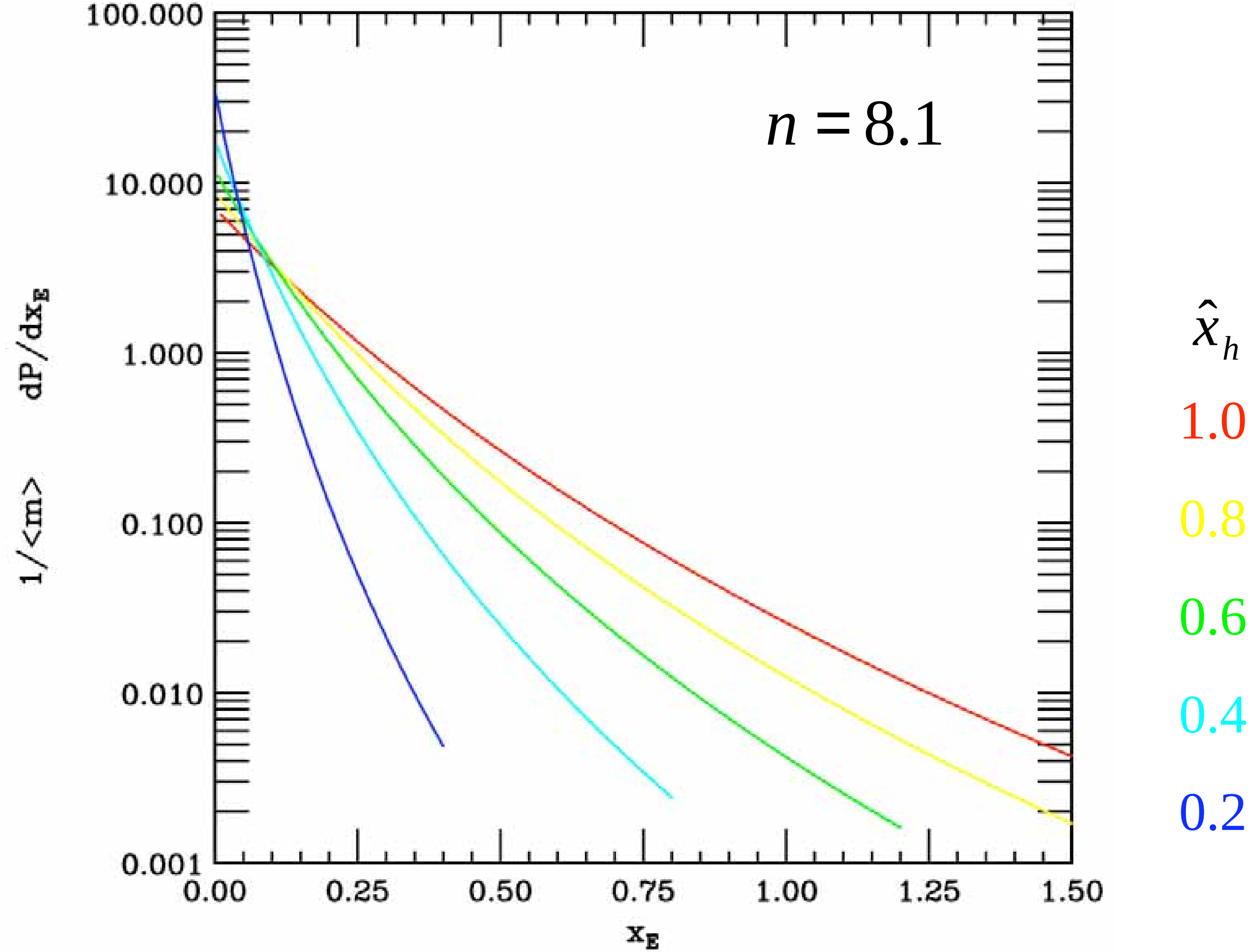
$\Rightarrow$ The x_E spectrum scales in the variable $x_E/\hat{x}_h$



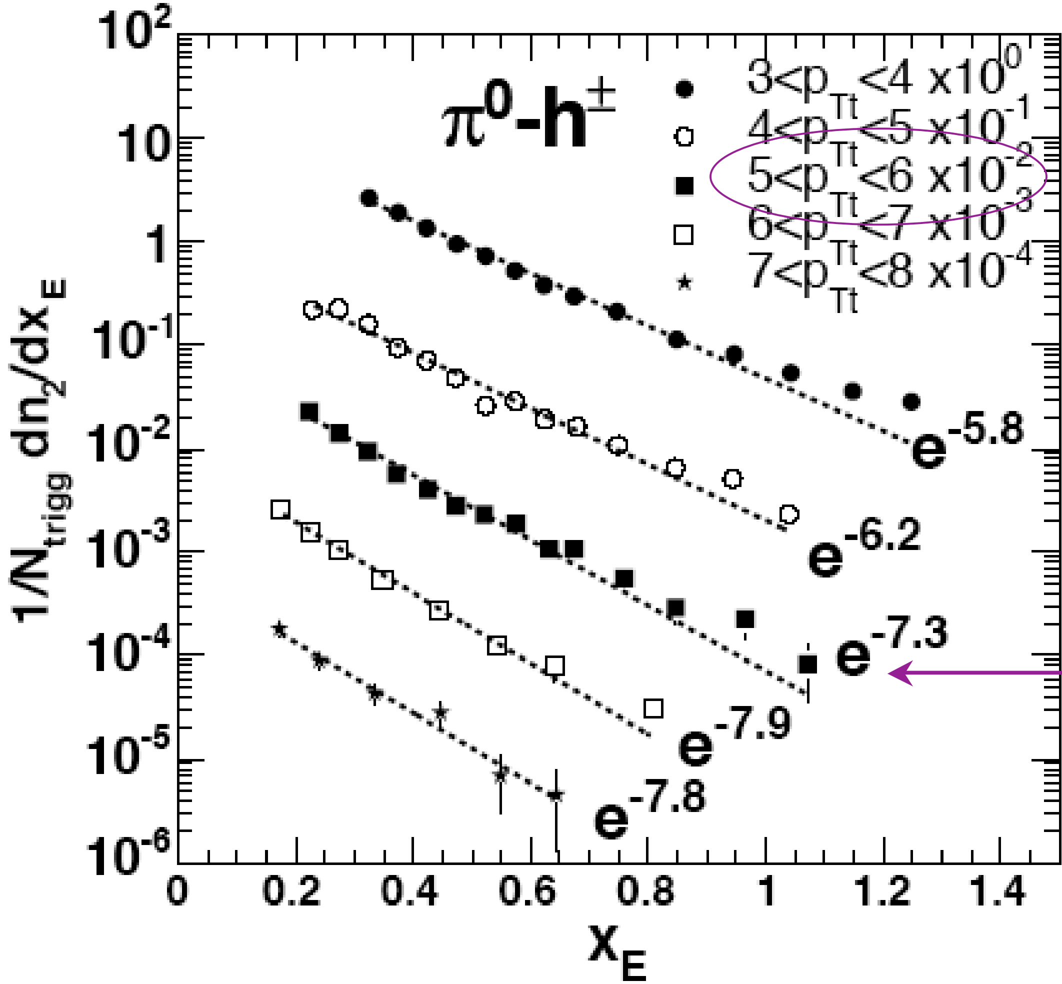
$$x_E = \frac{-p_{T_a}\cos\Delta\phi}{p_{T_t}} \simeq \frac{p_{T_a}}{p_{T_t}} \longrightarrow \hat{x}_h = \frac{\hat{p}_{T_a}}{\hat{p}_{T_t}}$$

Measured ratio of particle p_{Ta}, p_{Tt} $\Rightarrow$ Ratio of jet transverse momenta

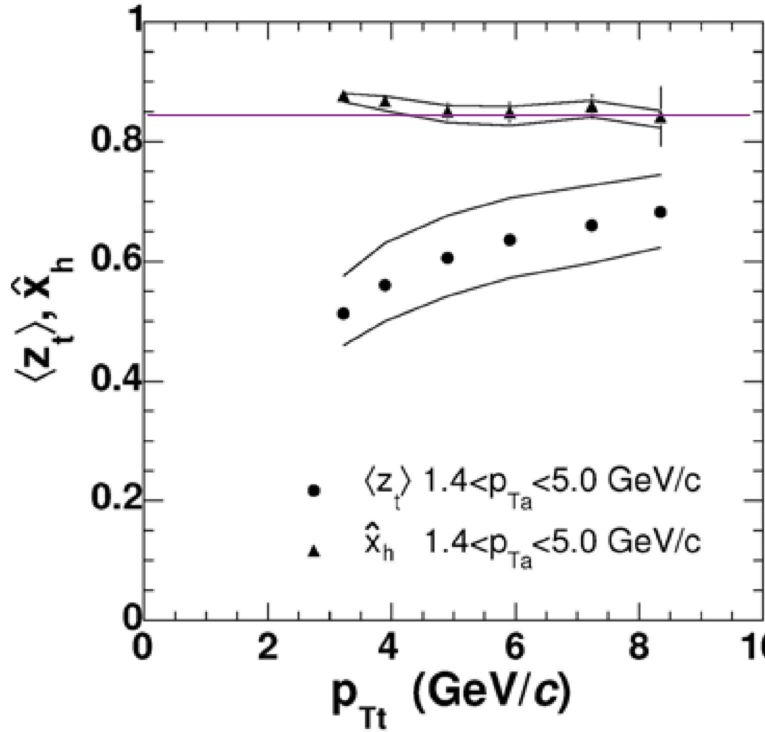
Shape of x_E distribution depends on $\hat{x}_h$ and *n* but not on *b*



Does the formula work?

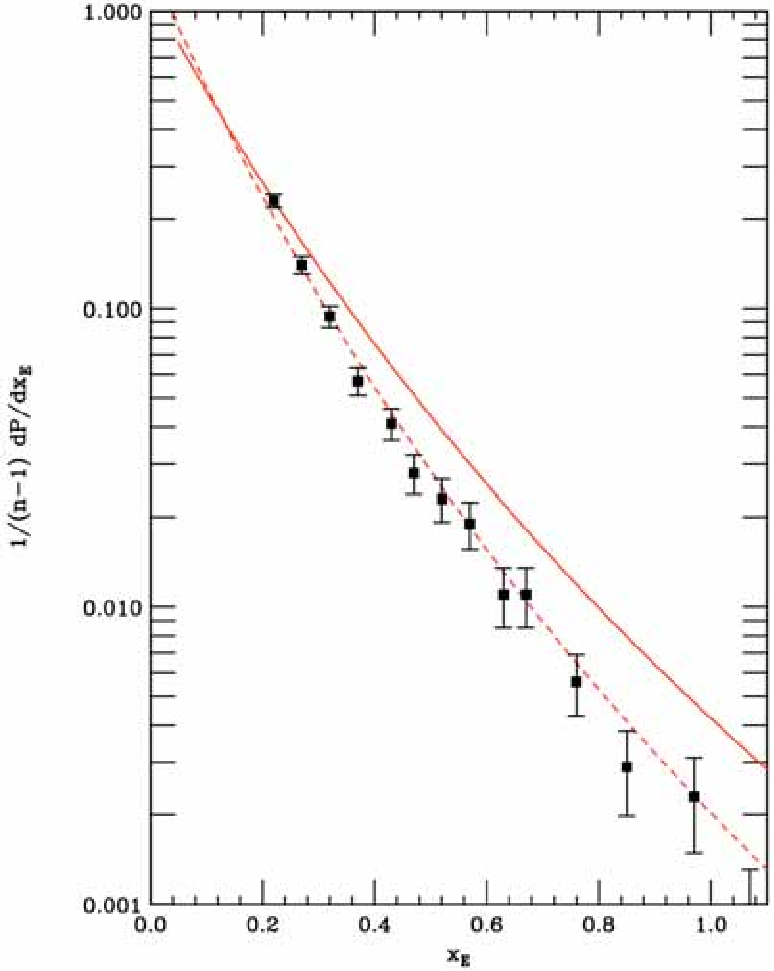


PHENIX p+p
hep-ex/0605039



$\boxed{\hat{x}_h \approx 0.8 \text{ due to } k_T \text{ smearing}}$

It works for PHENIX p+p hep-ex/0605039



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

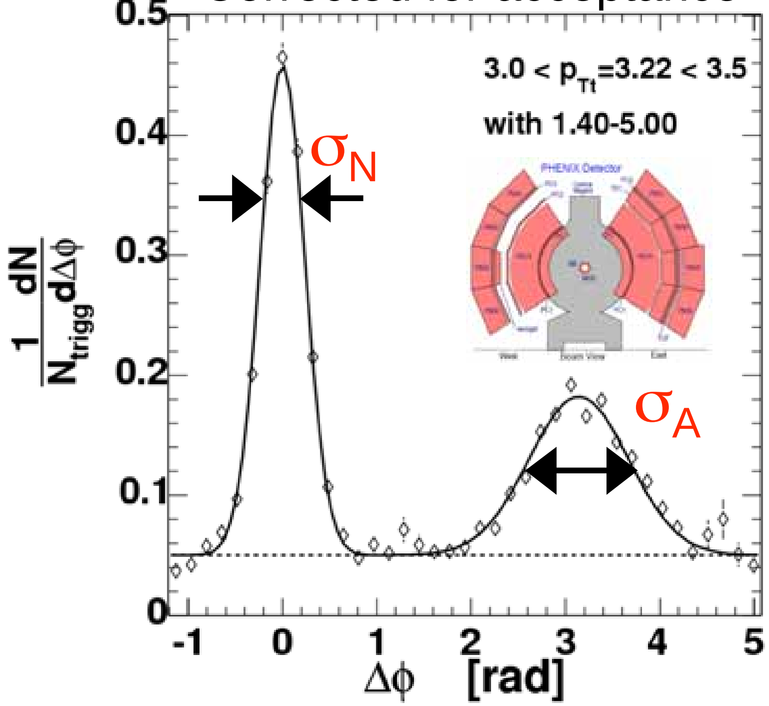
(solid red line) $x_E = y$

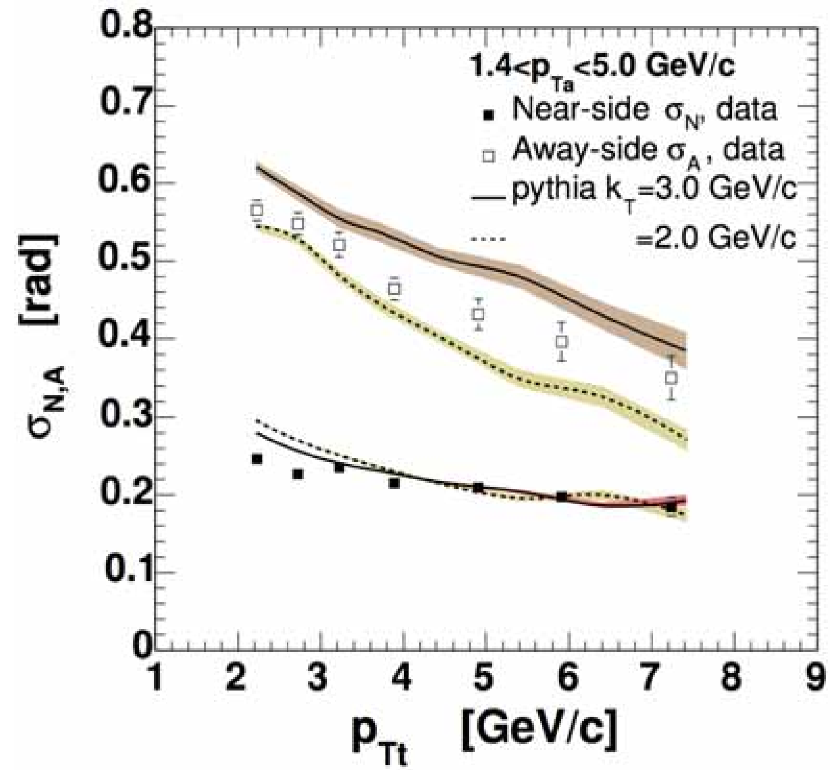
(dashed red line) $x_E = \hat{x}_h\, y = 0.8\, y$

nb: vertical scale labels on this and similar plots should be multiplied by 10

PHENIX π^o - $h^\pm$ correlation functions p+p $\sqrt{s}$=200 GeV hep-ex/0605039

Corrected for acceptance





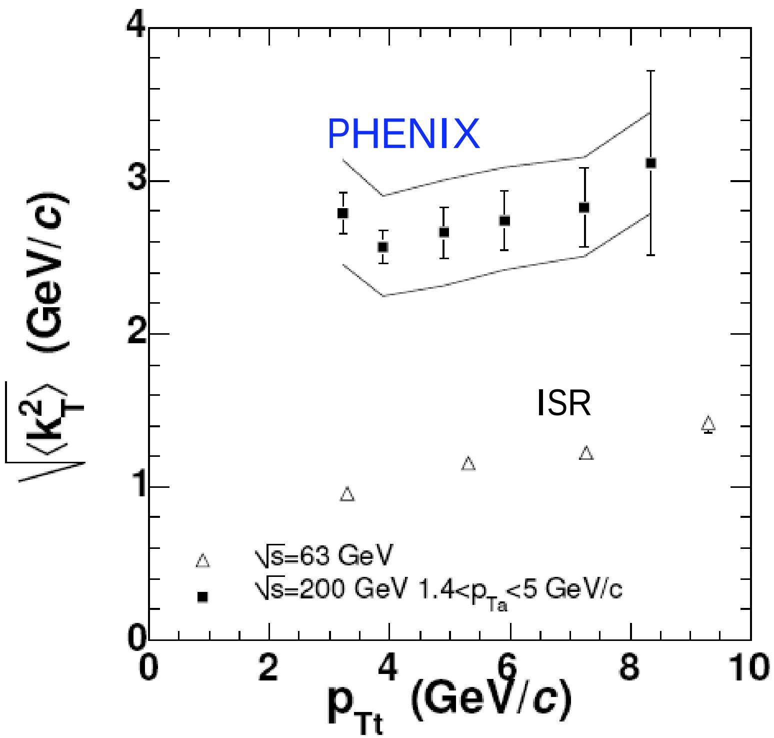
$\sigma_N \propto \langle j_T \rangle$ jet fragmentation transverse momentum-measure directly

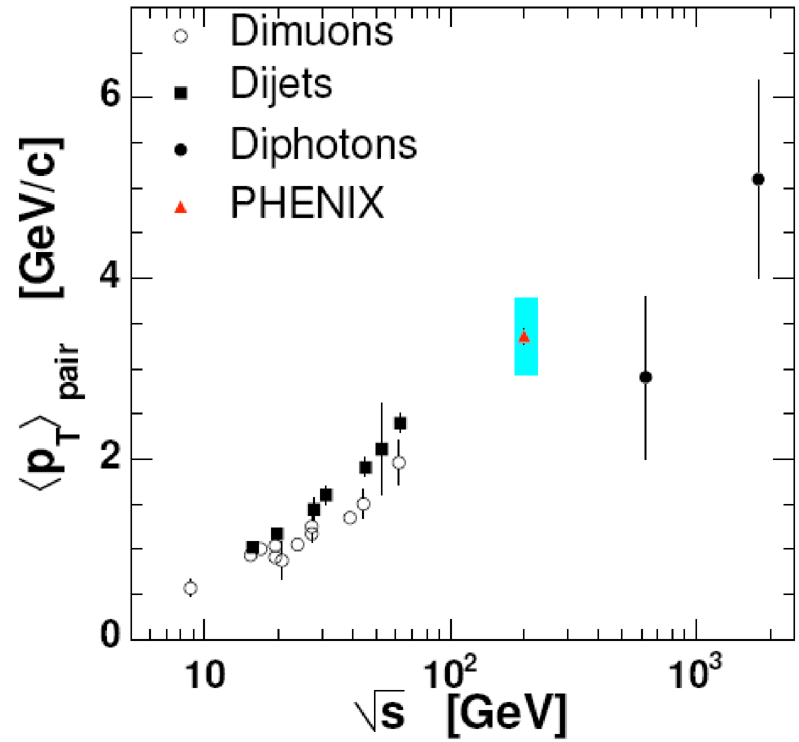
$$\boxed{\sqrt{\langle j_T^2 \rangle} = 585 \pm 6(\mathrm{stat}) \pm 15(\mathrm{sys})\ \ \mathrm{MeV}/c}$$

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

Results RMS k_T in p+p @ 200 GeV

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

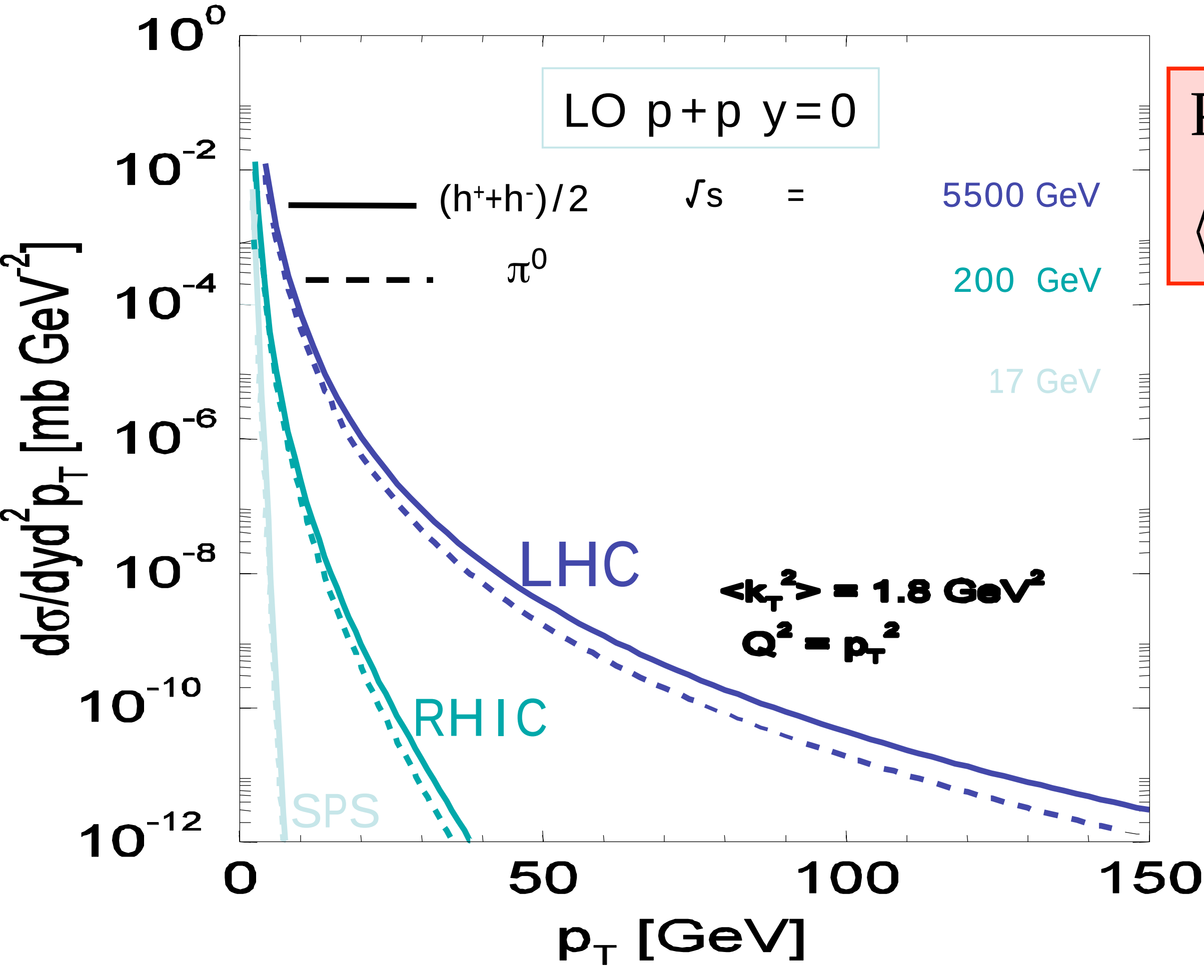




$$\boxed{\langle p_T \rangle_{pair} = 3.36 \pm 0.09(\mathrm{stat}) \pm 0.43(\mathrm{sys})\ \mathrm{GeV}/c}$$

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

LHC prediction from many talks Schutz, Gustaffson, Morsch ...



PHENIX $\sqrt{s}$=200 GeV

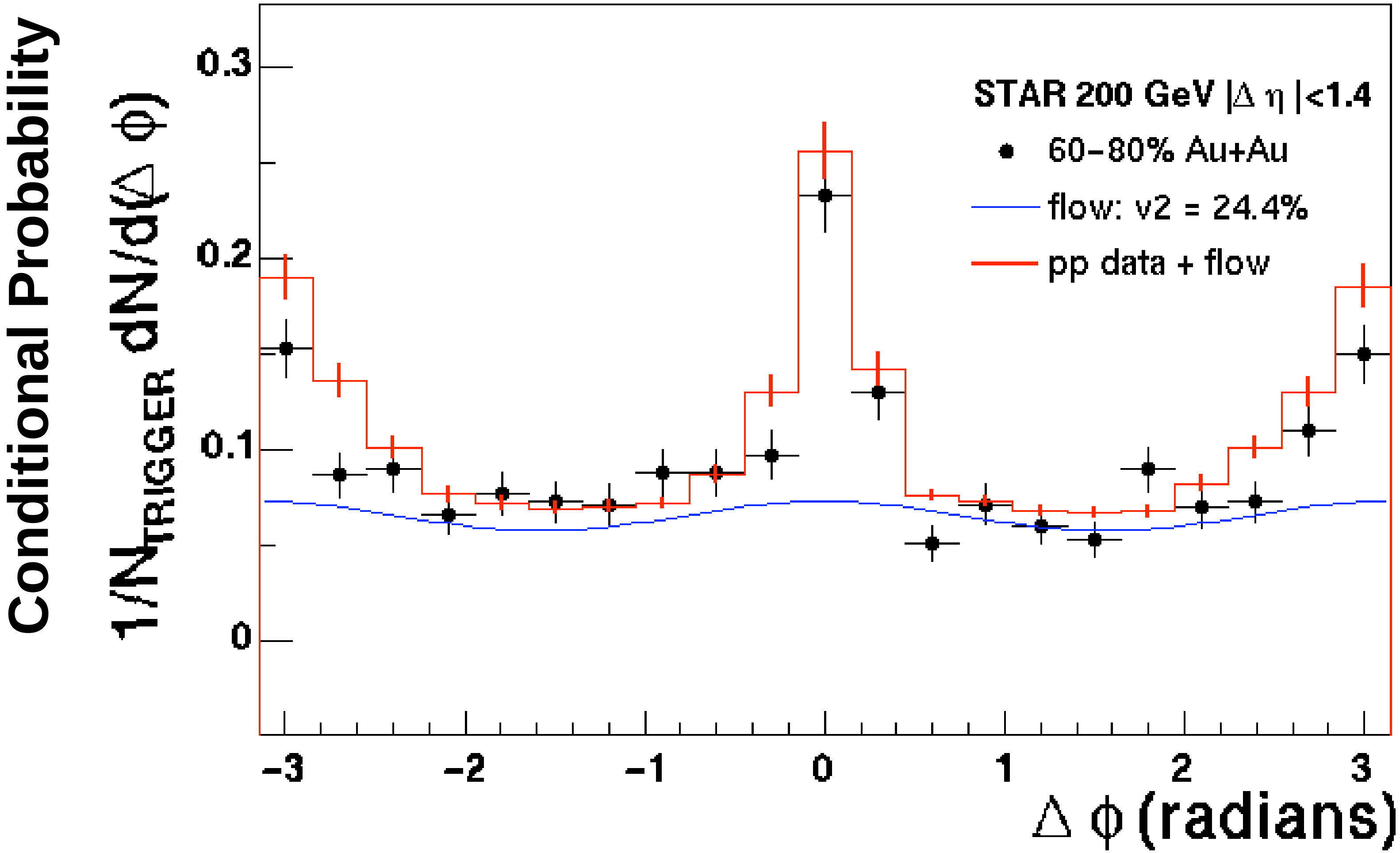
$$\langle k_T^2 \rangle = 7.2 \pm 1.8 \text{ GeV/c}^2$$

Hmmm!

Application 2-particle correlations in Au+Au

STAR-Peripheral Au+Au data vs. pp+flow

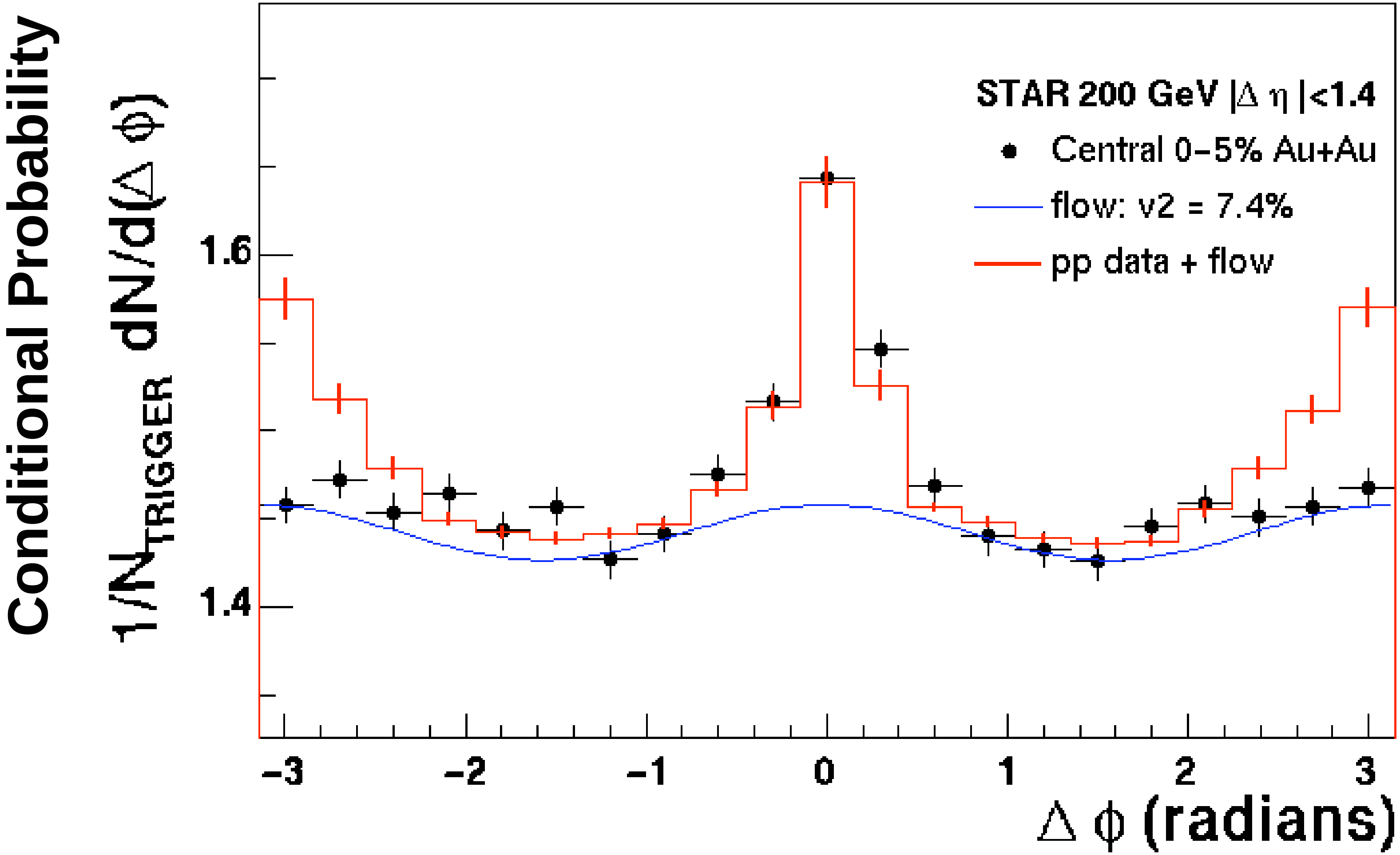
$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2(p_{Tt})v_2(p_{Ta})\cos(2\Delta\phi))$$



STAR-QM2002-Hardke 4< p_{Tt}< 6 GeV/c 2<p_{Ta}<p_{Tt}

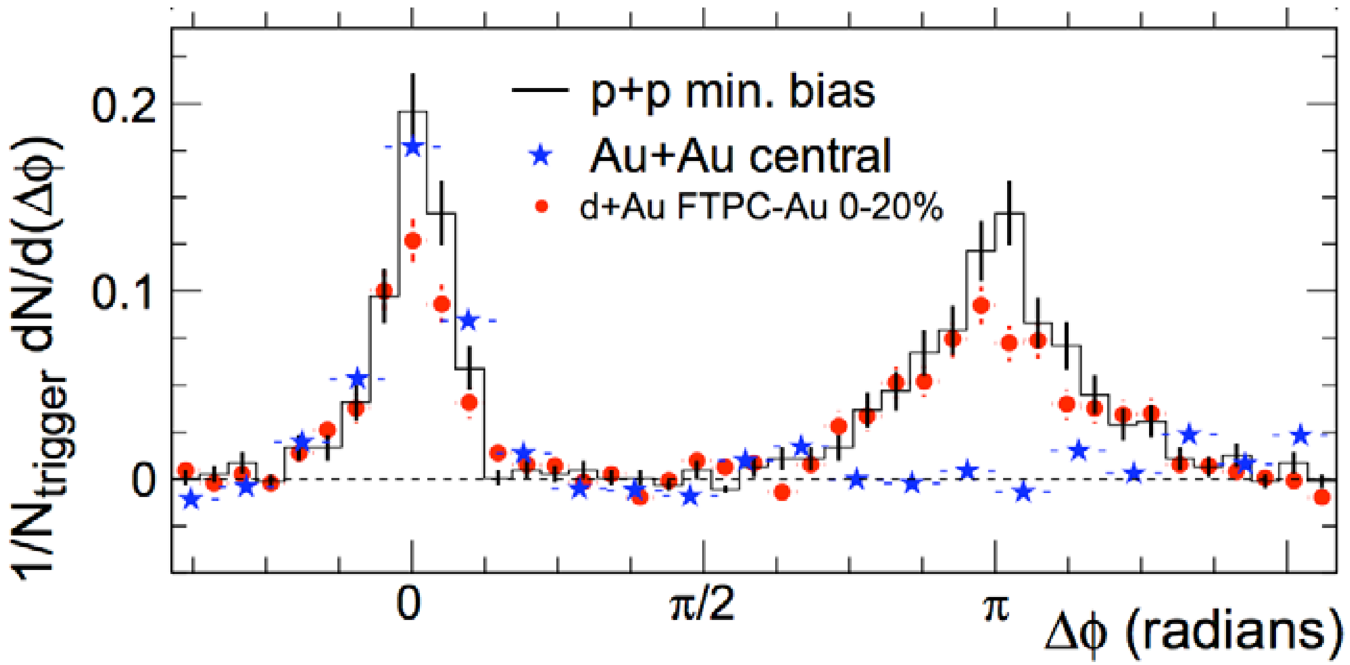
STAR-Central Au+Au data vs. pp+flow

$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2(p_{Tt})v_2(p_{Ta})\cos(2\Delta\phi))$$



STAR-QM2002-Hardke 4< p_{Tt}< 6 GeV/c 2<p_{Ta}<p_{Tt}

Great PR-Is it great Science?



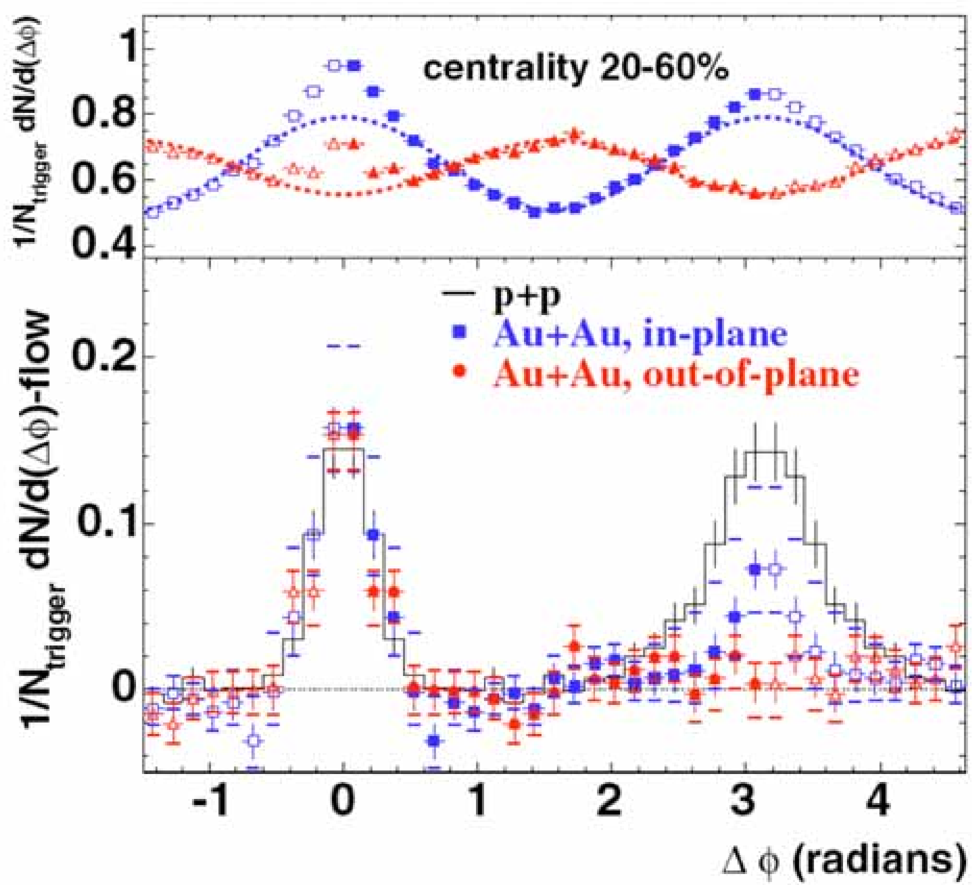
Did the away jet vanish in Au+Au?

STAR-PRL**91**(2003)072304 4< p_{Tt}< 6 GeV/c 2<p_{Ta}<p_{Tt}

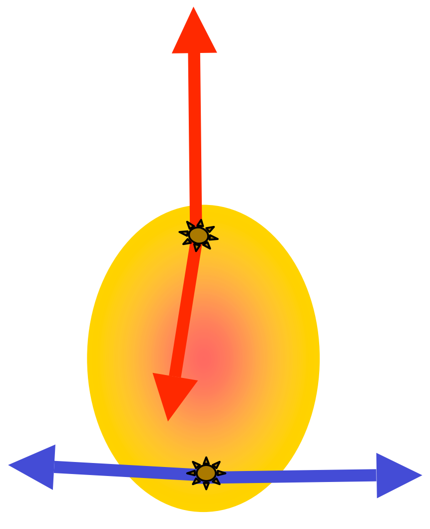
Also serious issues with exact v_2 to use, and exact background level

I-Reaction plane dependence of jet correlation

PRL **93**, 252301 (2004) **STAR** J. Adams, *et al.*,



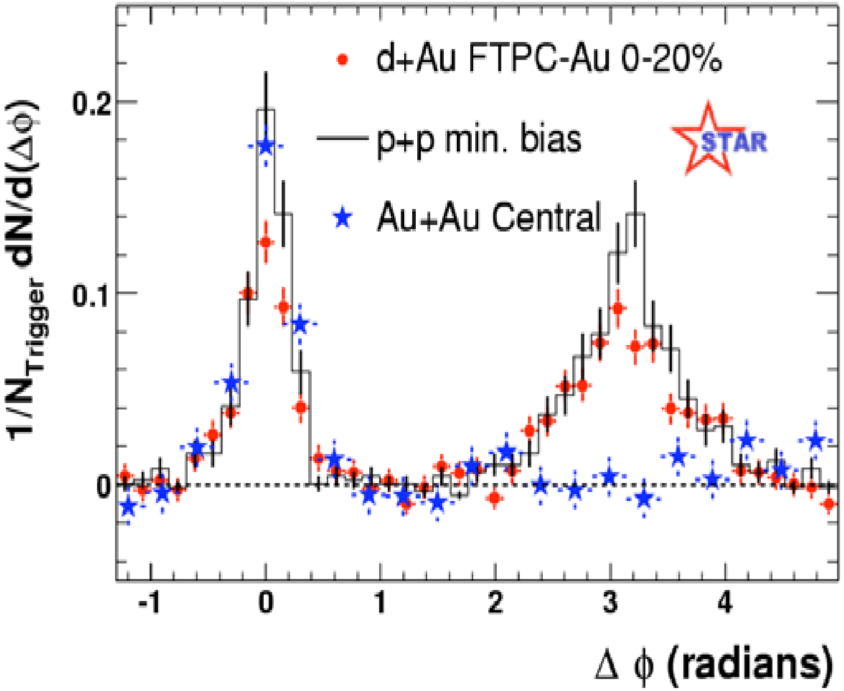
$4 < p_{Tt} < 6$ GeV/c $2 < p_{Ta} < p_{Tt}$

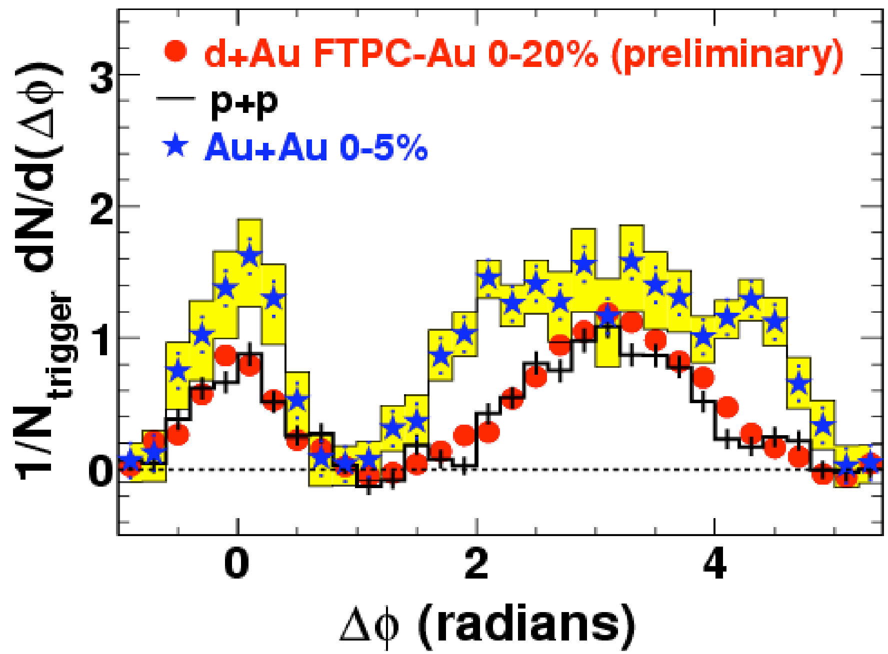


Jet energy loss depends on path-length through the medium

Methodology of J. Bielcikova, S.Esumi, K. Filimonov, S. Voloshin, J.P. Wurm, PRC 69 (2004) 021901(R)

II-Going to lower p_{Ta} showed that the away jet didn't vanish it just lost energy and widened





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

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

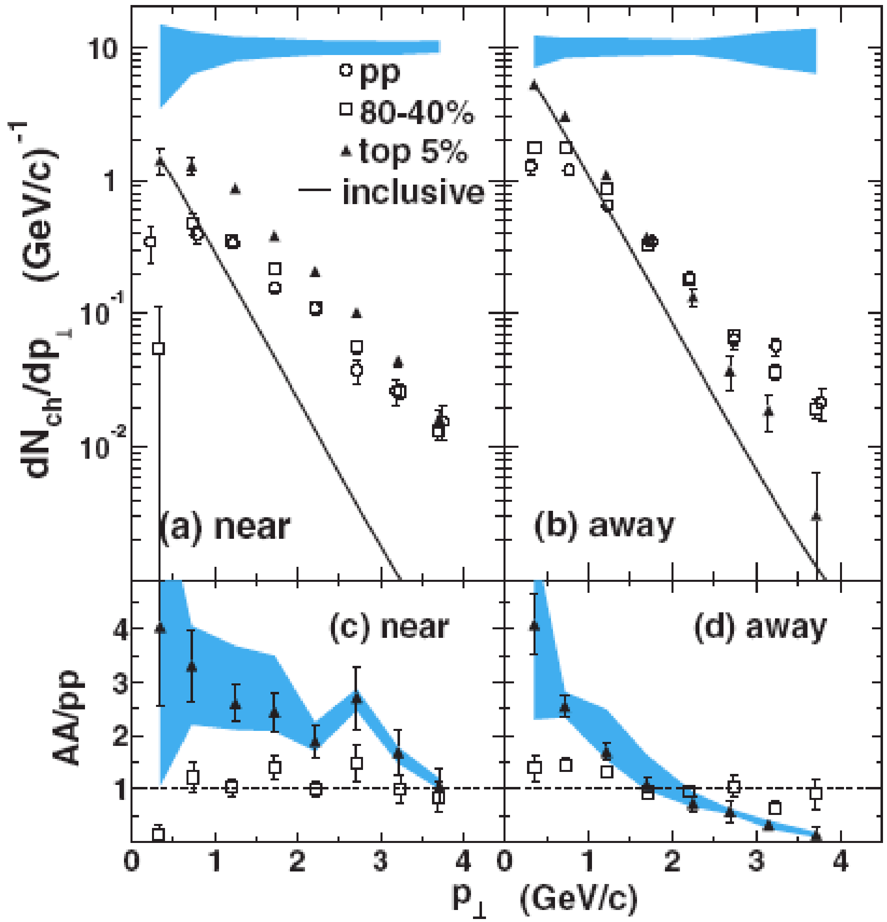
$x_h=p_{Ta}/p_{Tt}$~0.5

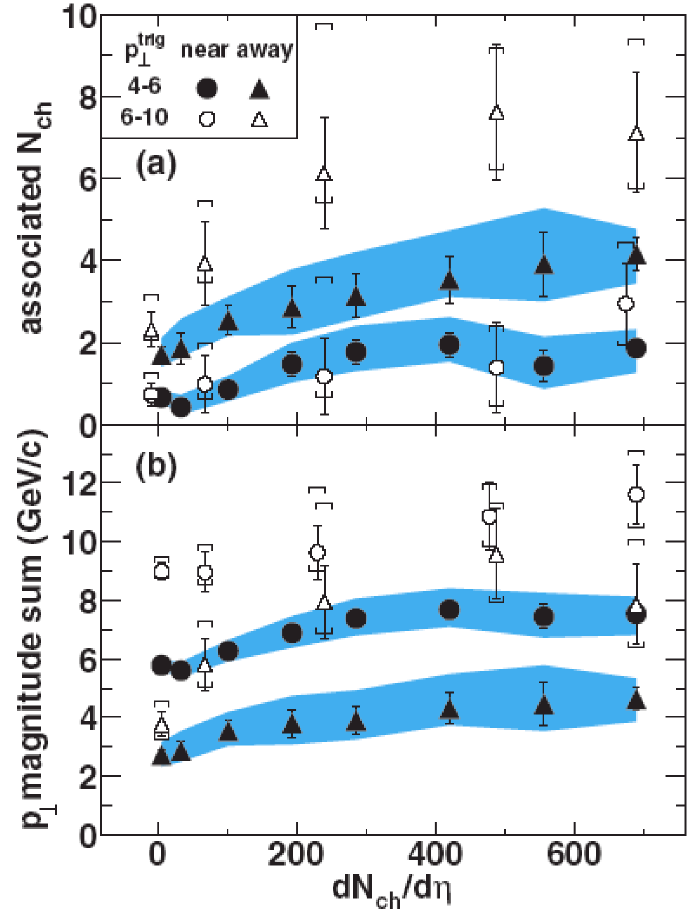
STAR-PRL**95**(2005)152301

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

$x_h=p_{Ta}/p_{Tt}$~0.04

I applied my x_E formula to STAR PRL 95 yields



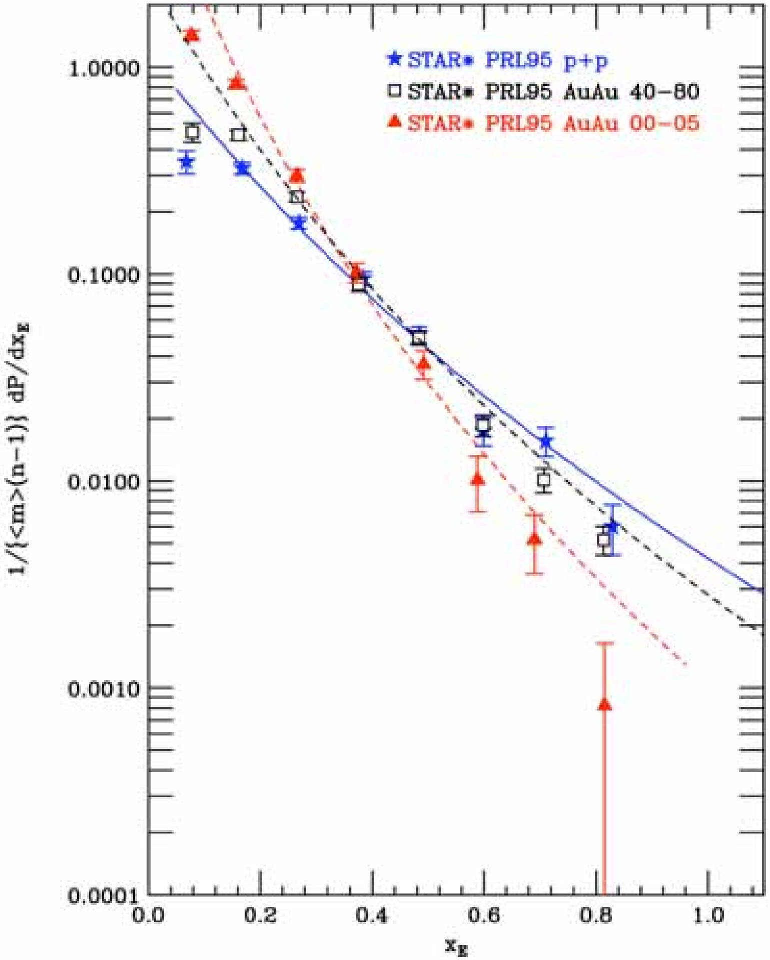


4 < p_{Tt} < 6 GeV/c $\langle p_{Tt}\rangle$=4.56 GeV/c

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

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

Clear $x_E/\hat{x}_h$ scaling 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 $\hat{p}_{Tt}$ ($\hat{x}_h$) decreases with increasing centrality
- consistent with increase of energy loss with distance traversed in medium

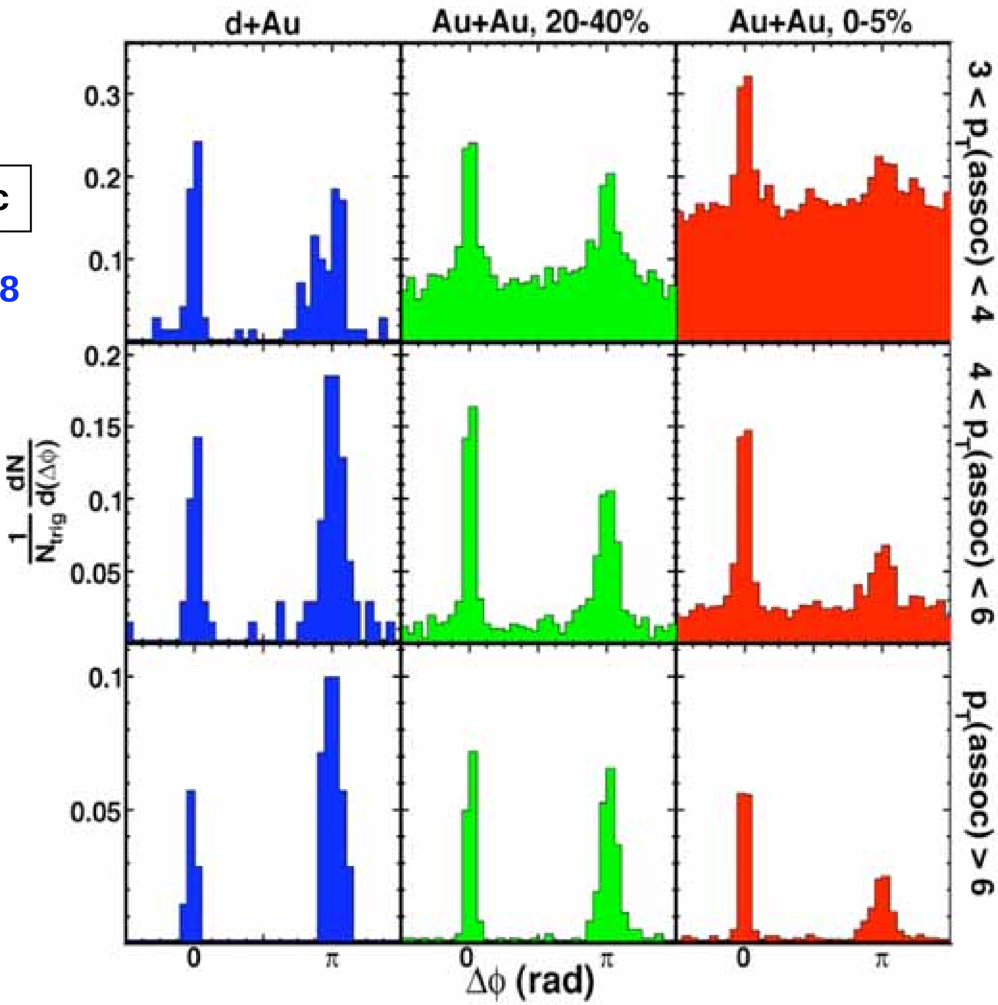
STAR, J. Adams, Fuqiang Wang, et al PRL **95**, 152301 (2005)

Emergence of narrow Di-Jets p_{Ta}>3 GeV/c--- Is the trick p_{Tt}>8 GeV/c? or ??

STAR

8 < p_T(trig) < 15 GeV/c

STAR nucl-ex/0604018



$$x_h = p_{Ta} / p_{Tt}$$

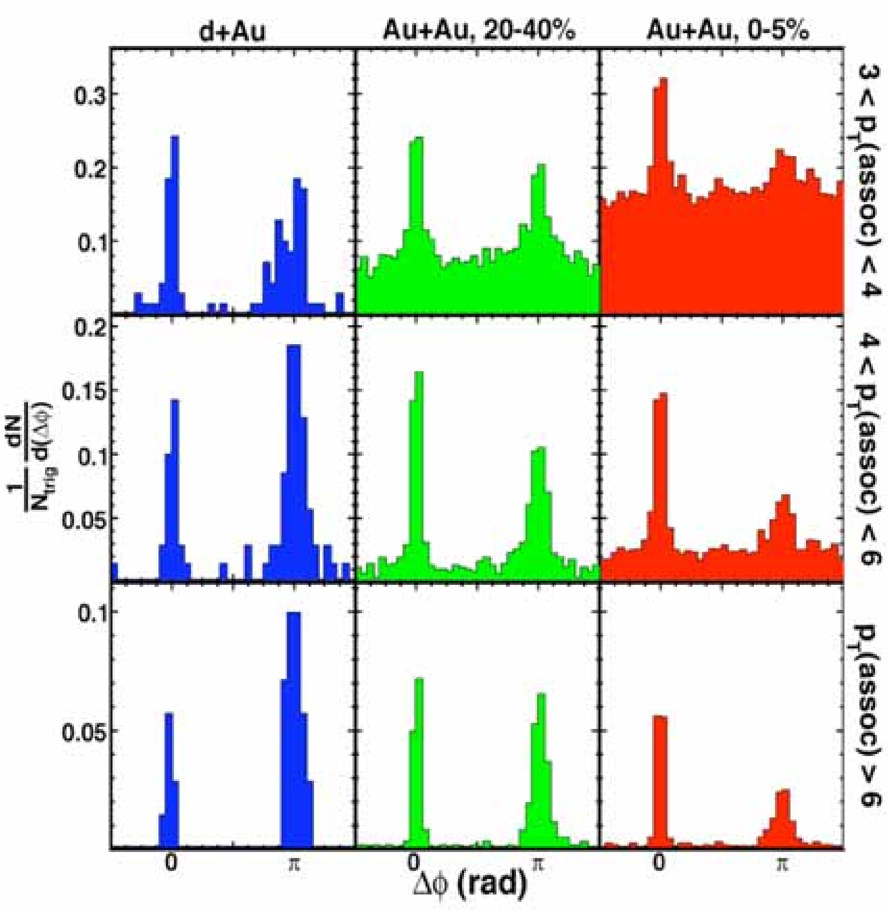
~0.375

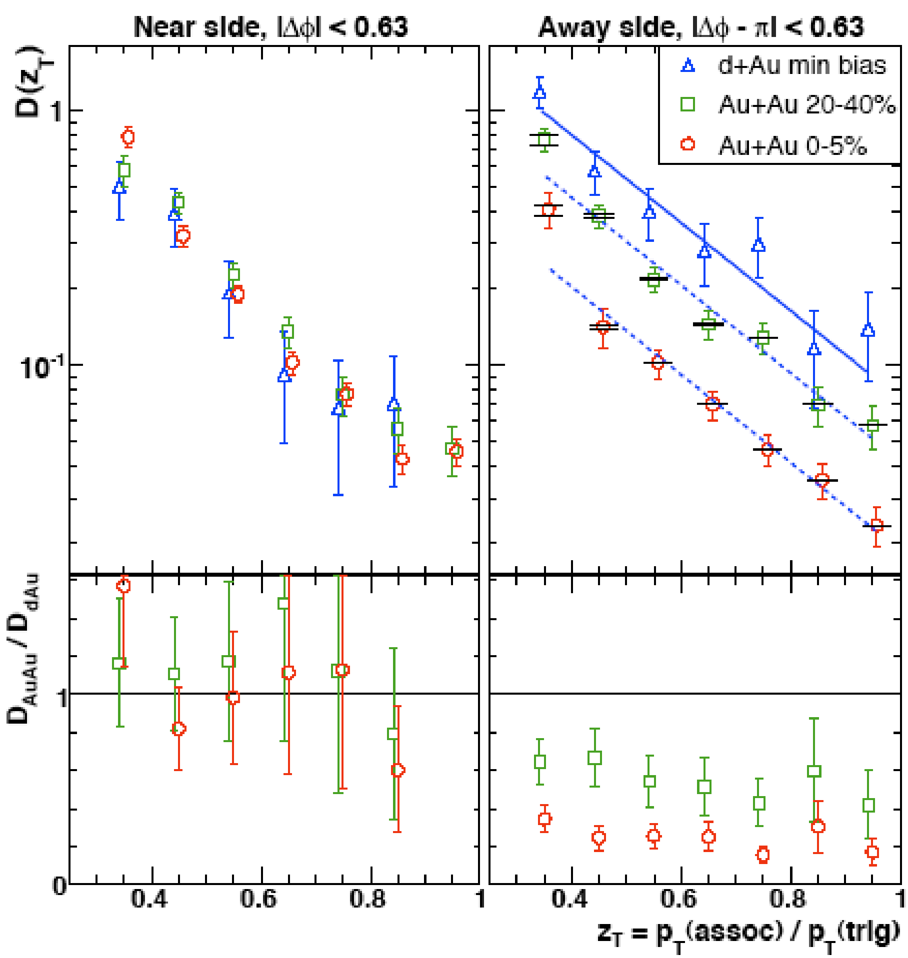
~0.5

~0.75

Remember, charged hadrons are anomalous for $p_T \leq$ 6 GeV/c

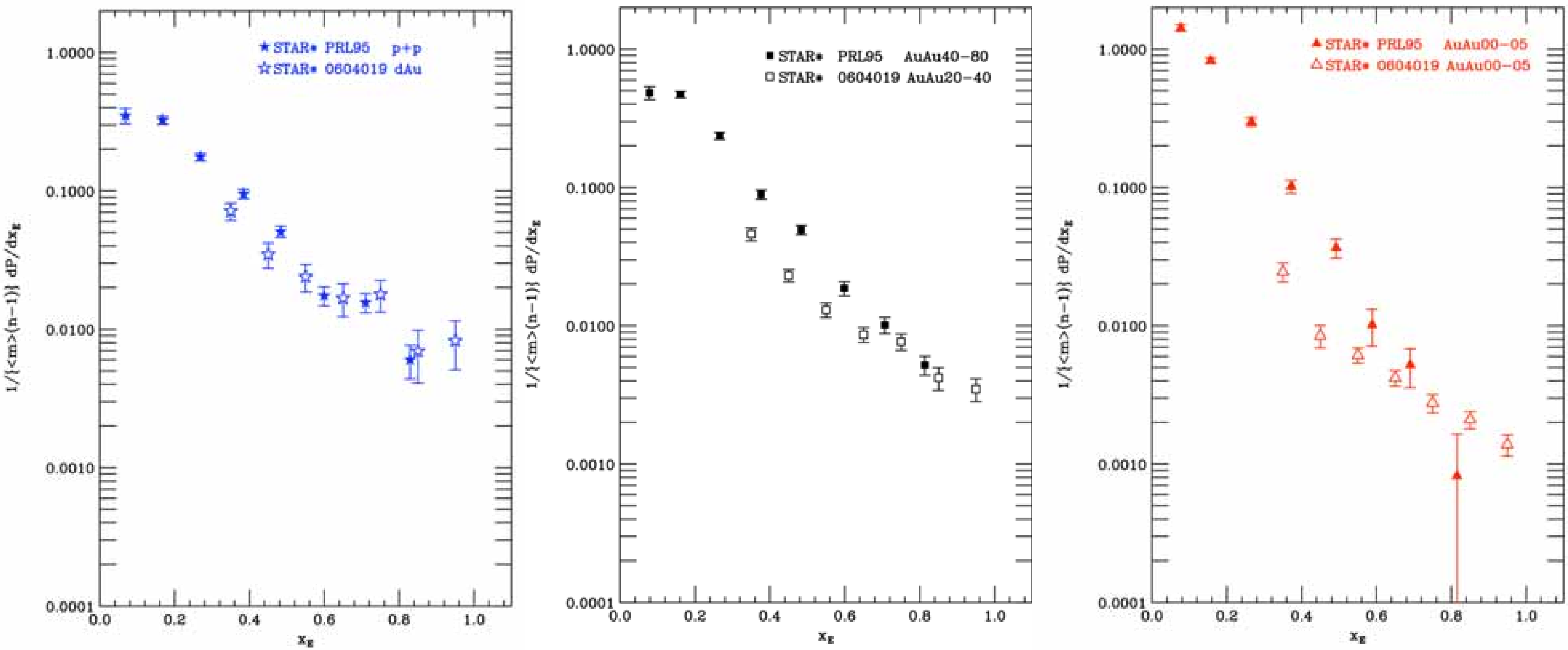
Away side yields from nucl-ex/0604018





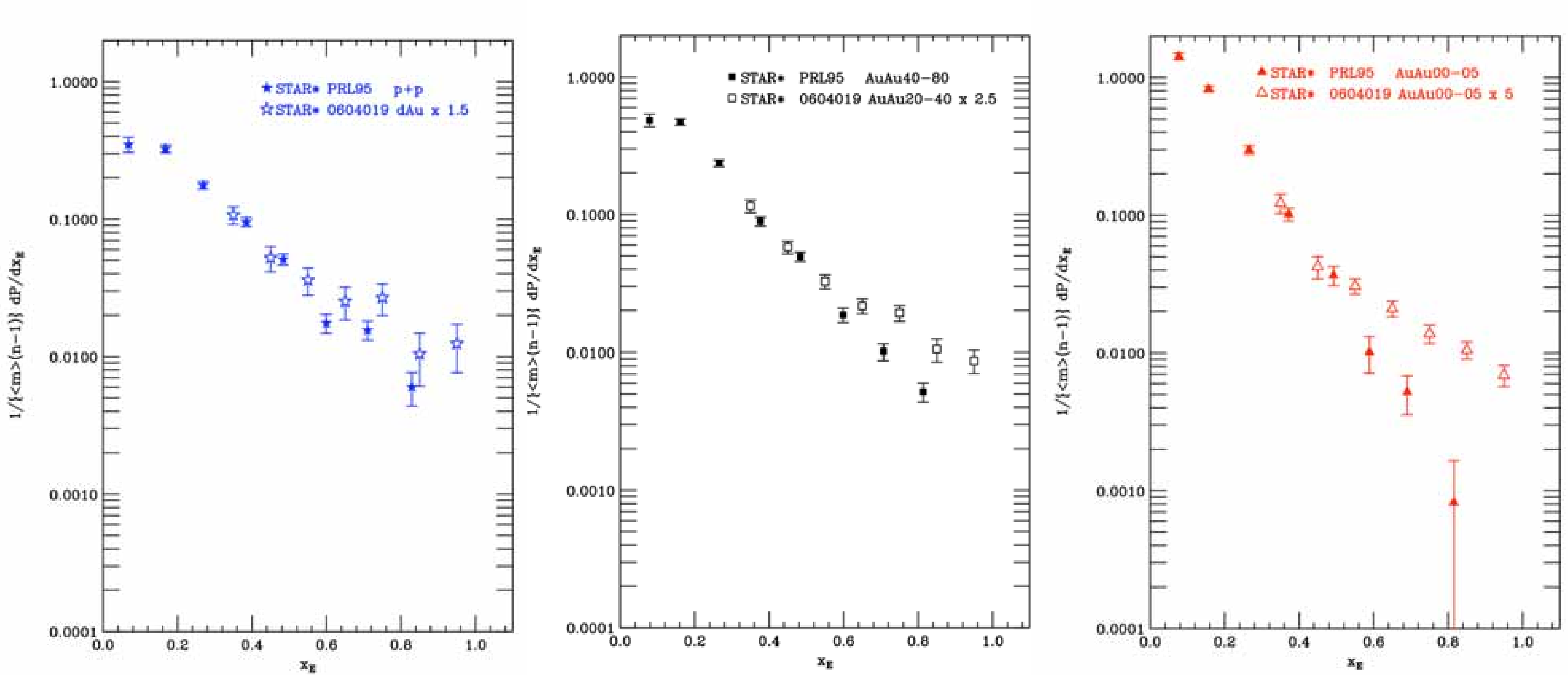
$8 < p_{Tt} < 15$ GeV/c $\langle p_{Tt} \rangle = 9.38$ GeV/c Thanks to Dan Magestro for table of data points

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



nb: vertical scale labels on these and similar plots should be multiplied by 10
STAR* 0604019 label should be STAR* 0604018

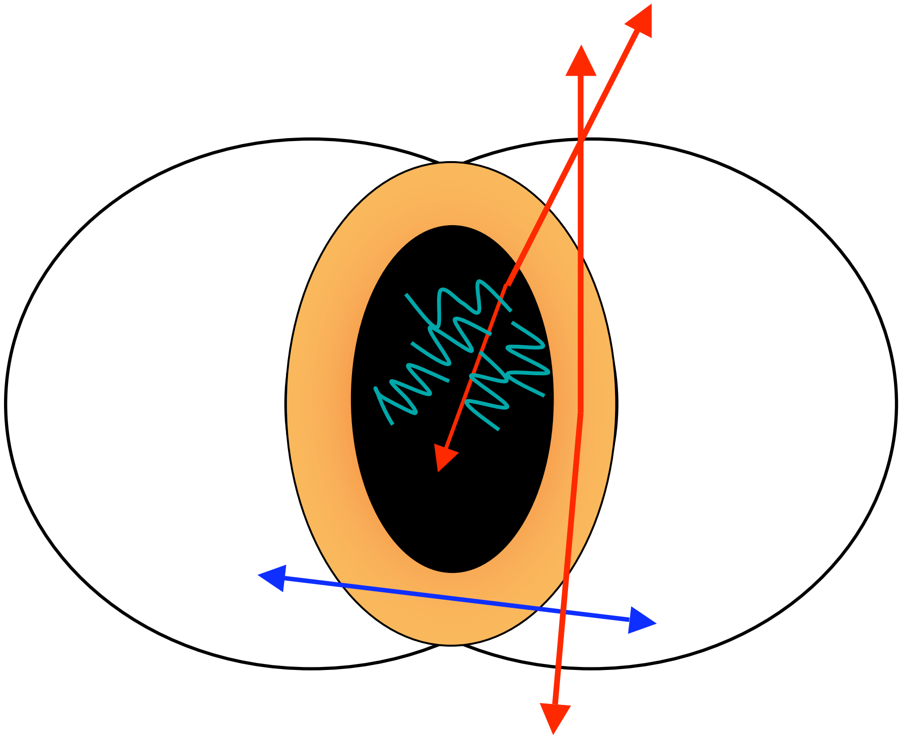
I Normalized 064018 to PRL95 by eye



If this is a real discontinuity in the x_E distribution it could indicate softer away jets that interact and harder jets that have punched through

If this is punch-through due to tangential emission, why does it depend on p_T?

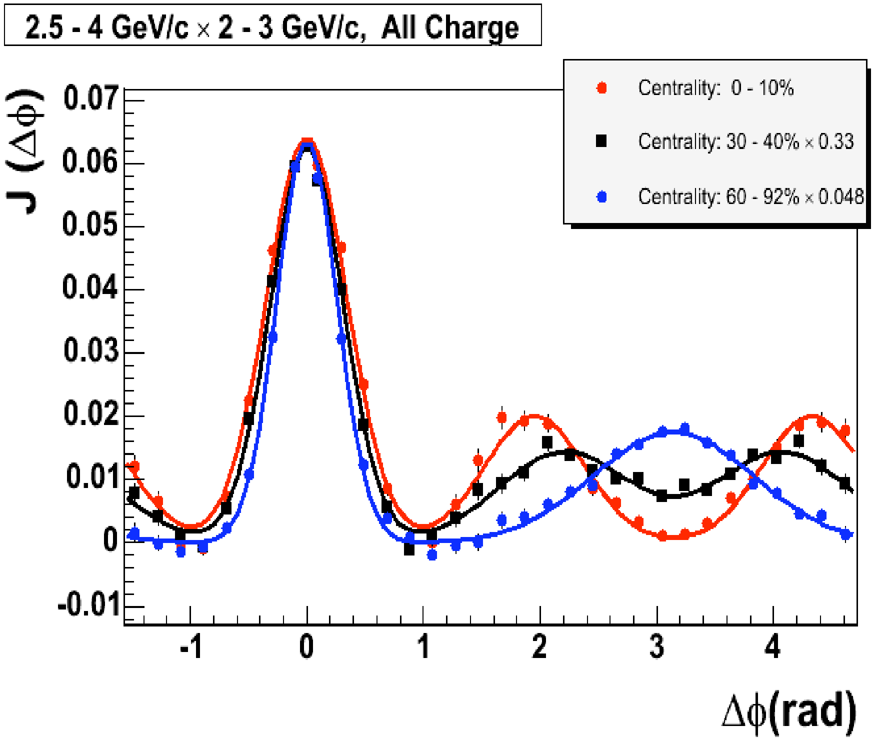
Tangential emission



We must carefully map out how this effect depends on p_{Tt} and p_{Ta} and particle type and angle to the reaction plane...

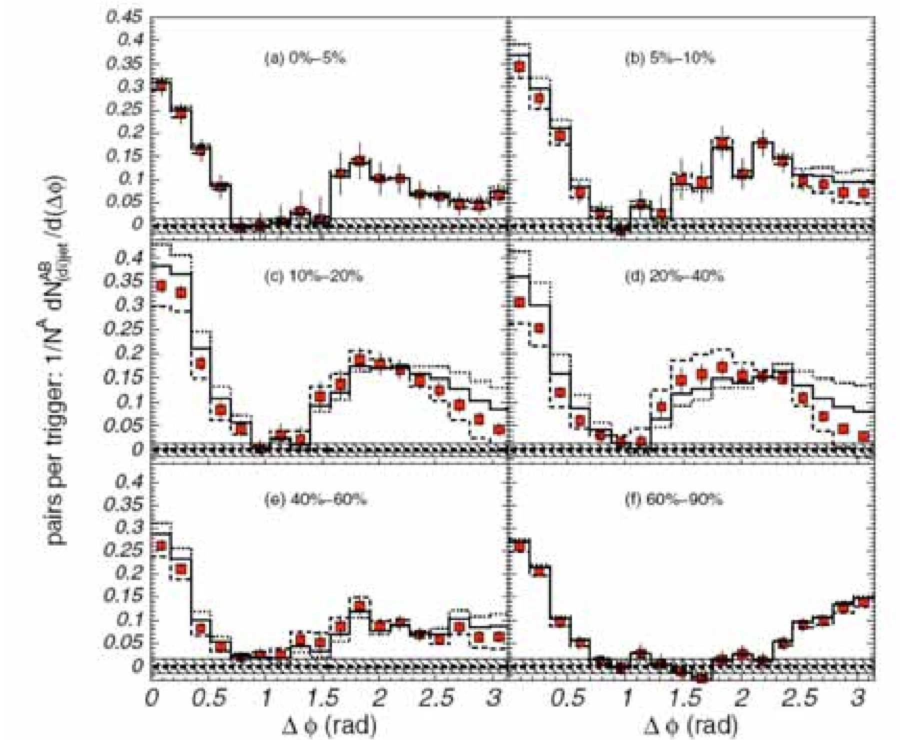
2-particle correlations AuAu at intermediate p_T

Status at QM05: PHENIX PRELIMINARY



$2.5 < p_{T,trigger} < 4.0$ GeV
$1.0 < p_{T,assoc} < 2.5$ GeV

PHENIX
PRL97(2006)052301



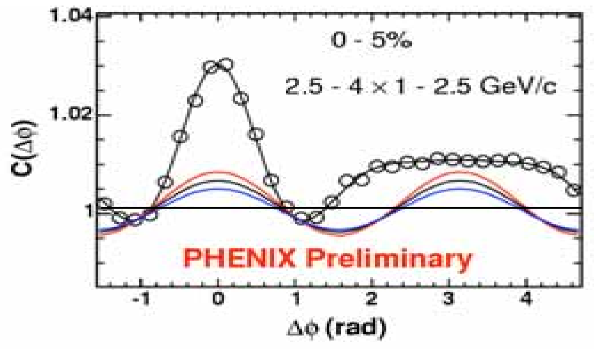
Strong away-side broadening seen at low $p_{T,assoc}$

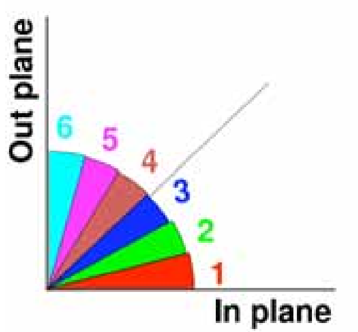
Is there a 'dip' at the away-side?

Conical emission: Mach cone? Cherenkov? Other mechanisms?

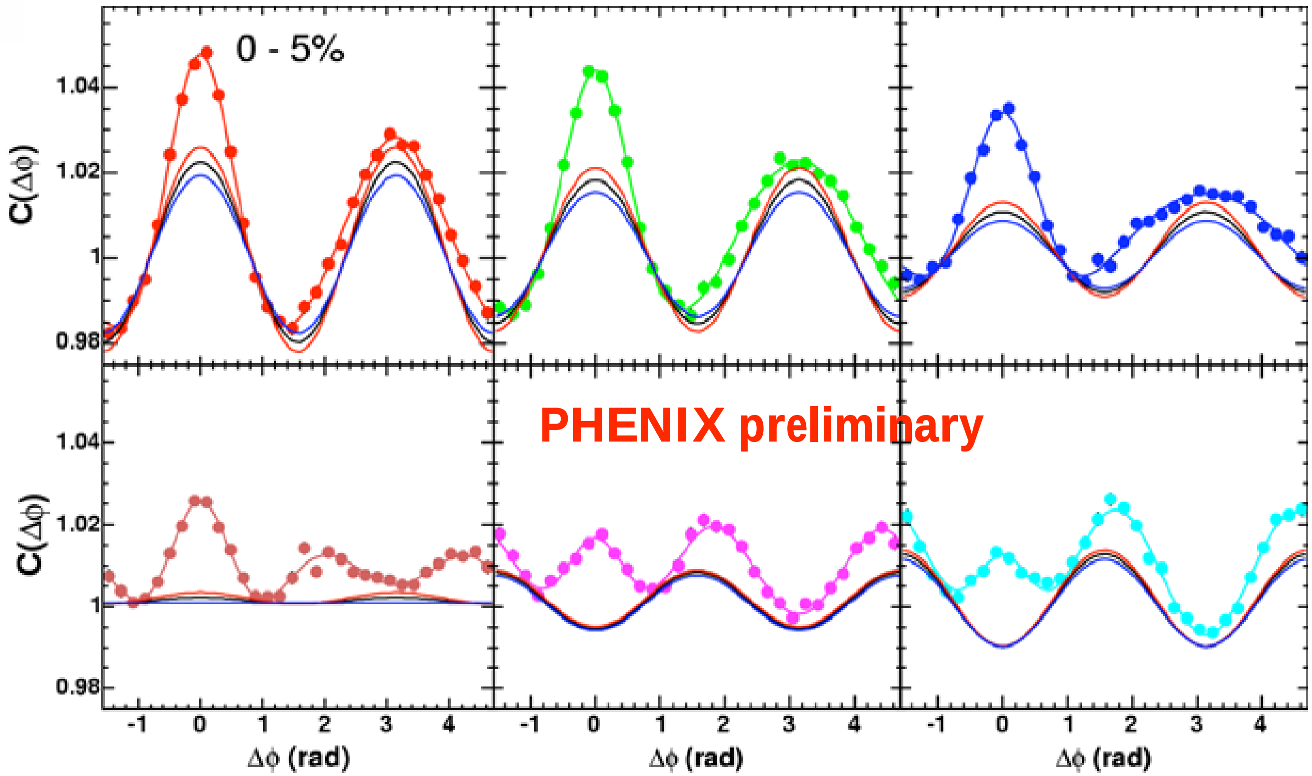
Also note: systematic uncertainties should not be disregarded

Reaction Plane dependence same data



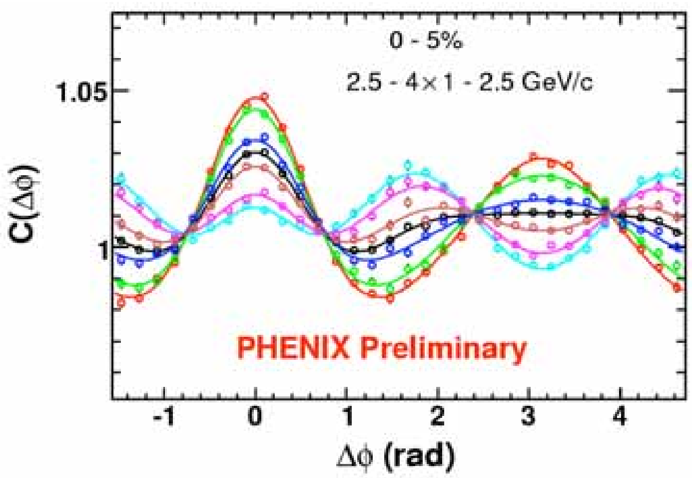


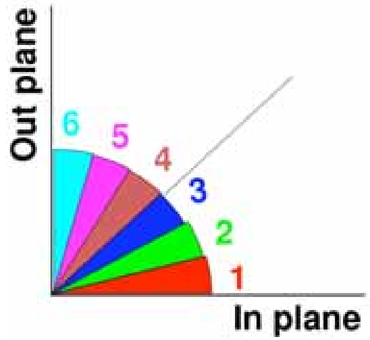
clear variation of correlation function and phase and magnitude of v_2 with angle to reaction plane



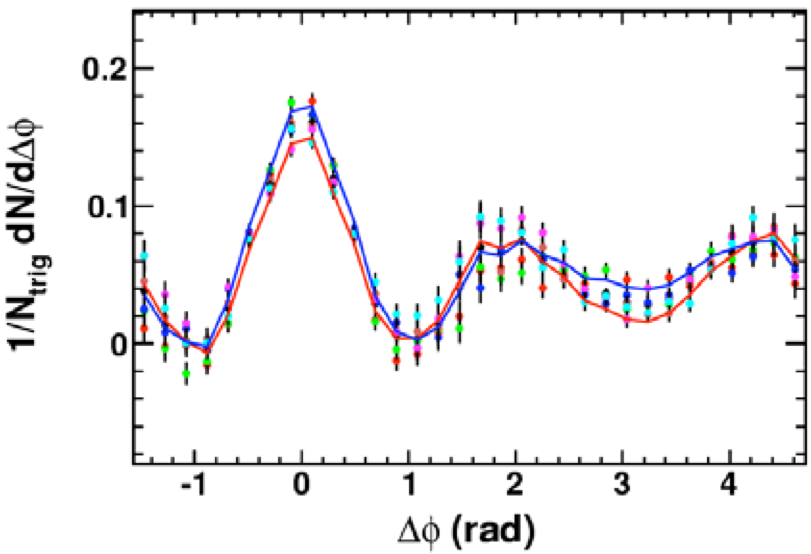
RP dependence confirms corrected Jet function shape

Correlation Function



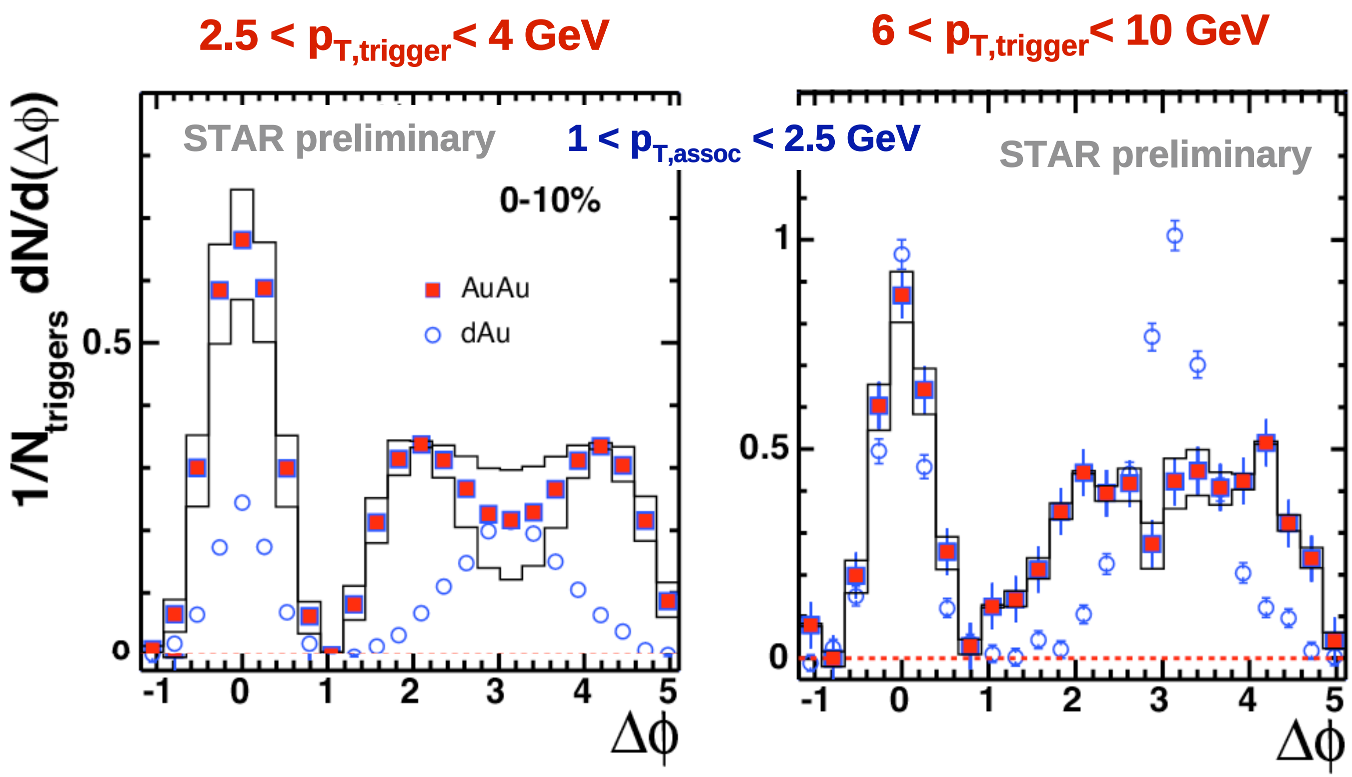


Jet Function corrected for v_2



- Shoulder and dip of wide away jet seen in all bins
- The dip is significant for bin 4 where the v_2 systematic is small

STAR-New 2-particle results-HP2006



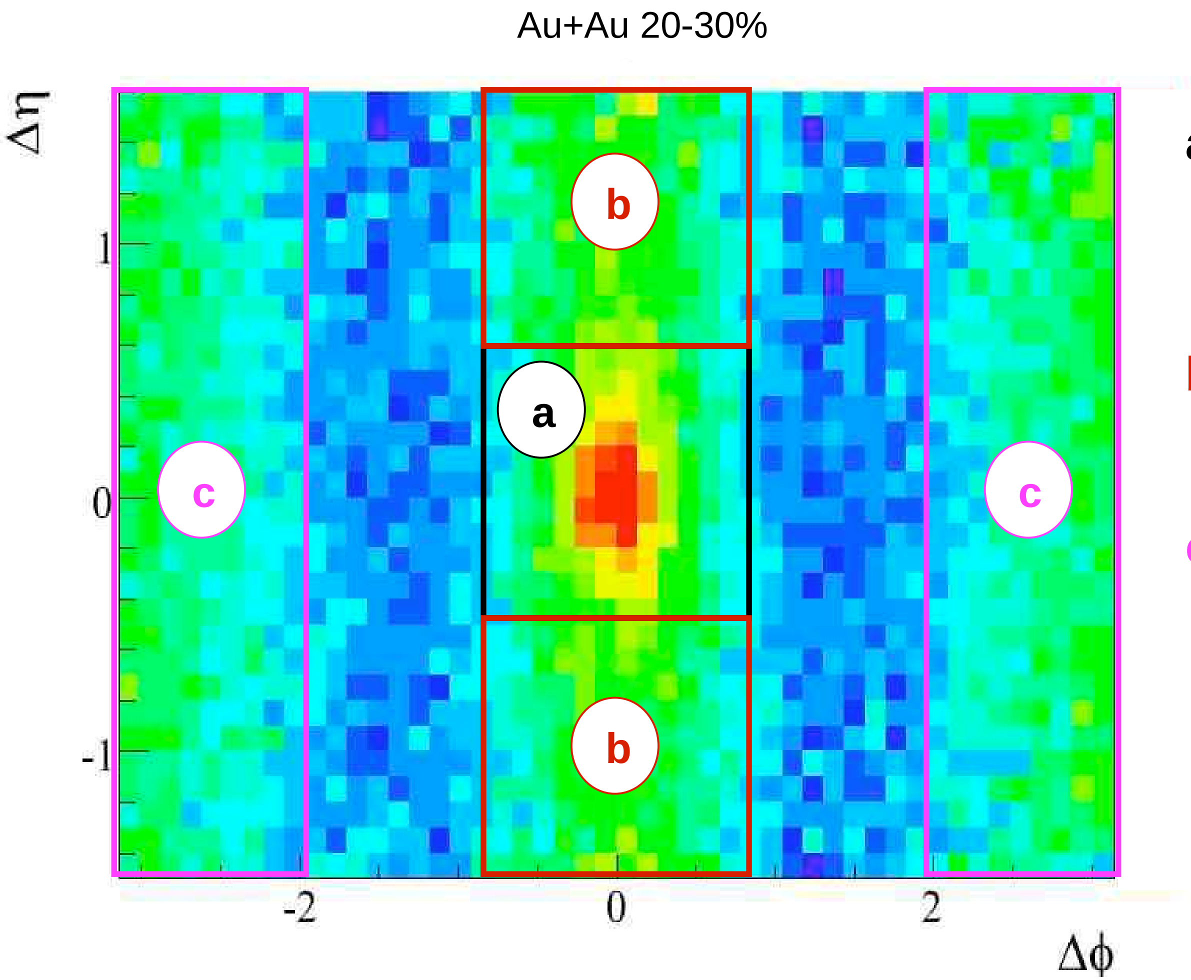
Systematic study of intermediate $p_{T,assoc}$ under way

Broadening persists to higher $p_{T,trigger}$, but not 'dip'

What happens to the away-side at intermediate p_T?

Interaction with medium?
Where does the lost energy go?
Mach Cone? Ridge?
If it is a medium effect look at particles with velocity of the medium

Near-Side Long-Range $\Delta\eta$ Correlation: the Ridge



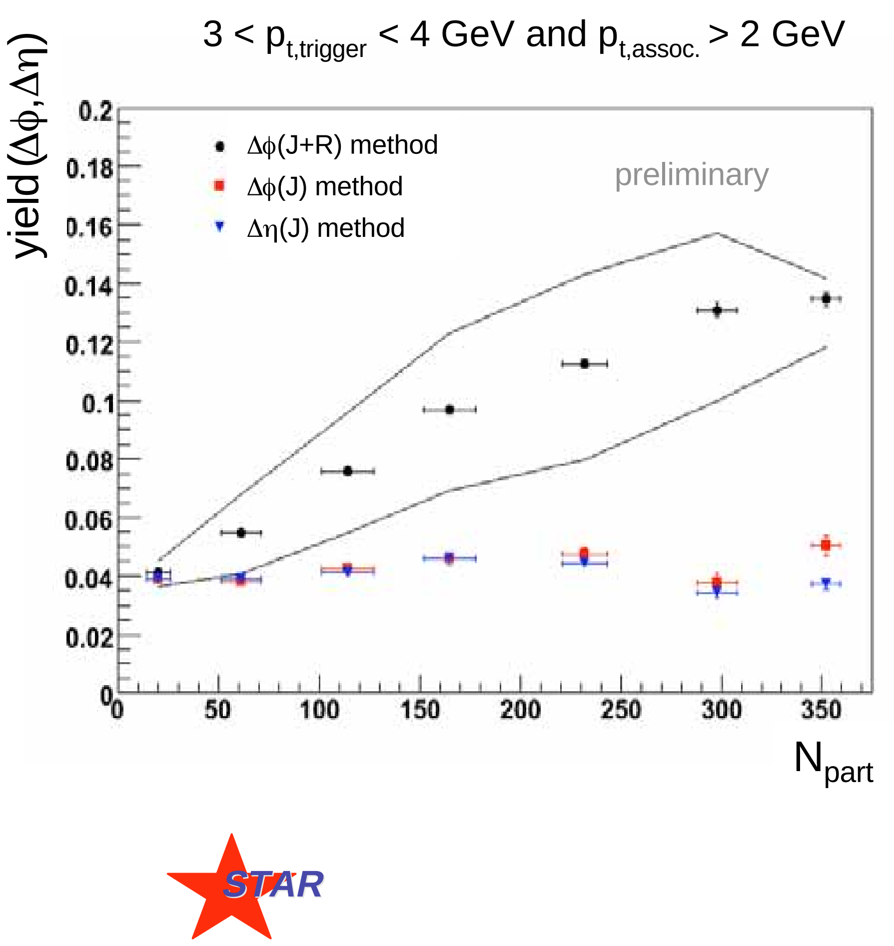
a) Near-side jet-like corrl. + ridge-like corrl. + v_2 modulated bkg.

b) Ridge-like corrl. + v_2 modulated bkg.

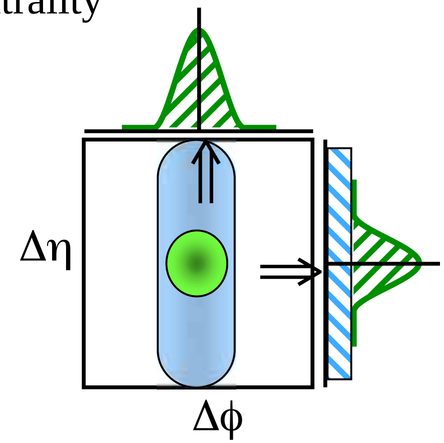
c) Away-side corrl. + v_2 modulated bkg.

STAR-HardProbes 06

Centrality Dependence of the Ridge

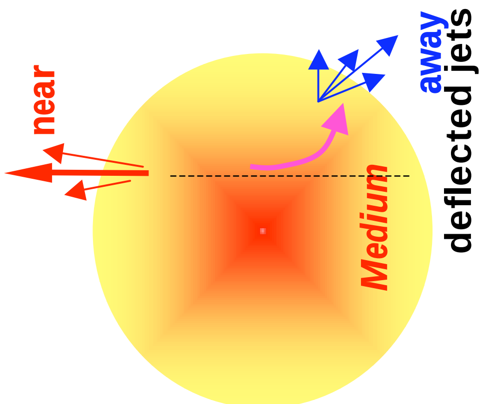


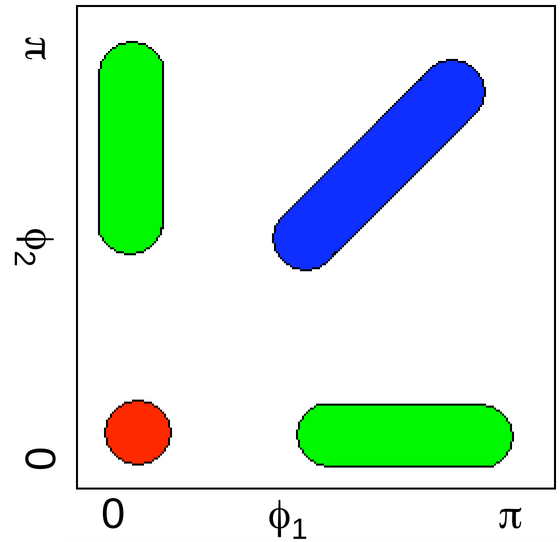
- yield of associated particles can be separated into a jet-like yield and a ridge yield
  - ✓ jet-like yield consistent in η and ϕ and independent of centrality
  - ✓ ridge yield increases with centrality



Conical Flow vs Deflected Jets

STAR 3 particle : Given a trigger, plot plot ϕ_1 vs ϕ_2 for 2 away particles





STAR Preliminary

HP2006≠QM2005

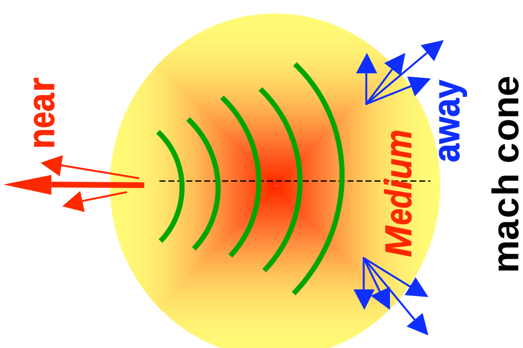
Central Au+Au

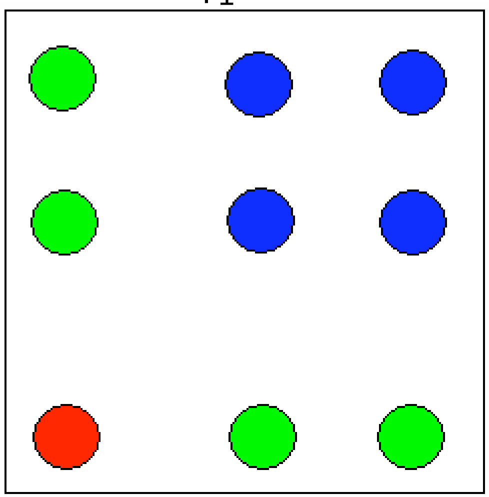
0-12% triggered

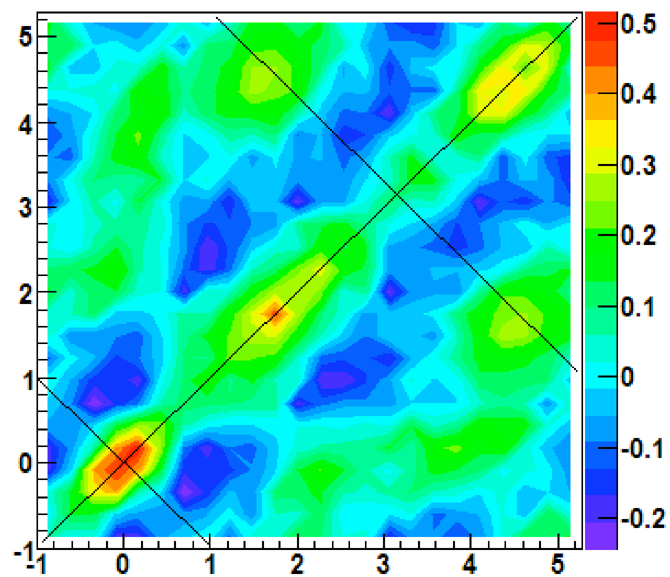
ZYAM/Purdue normalization

$3 < p_{T,trigger} < 4$ GeV

$1 < p_{T,assoc} < 2$ GeV



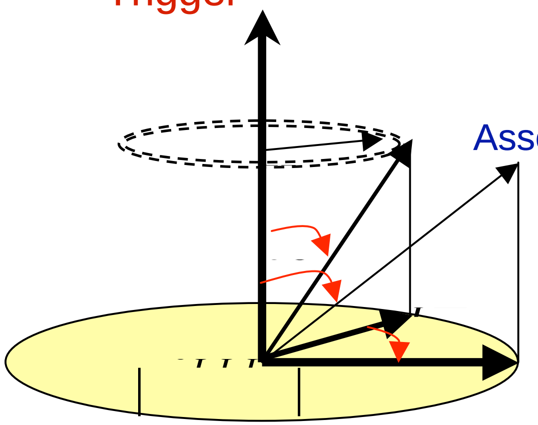




Not obviously the best projection-difficult to understand

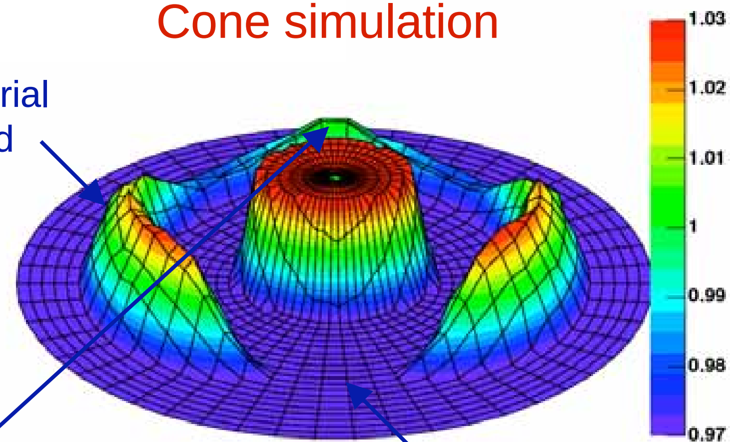
PHENIX-Polar co-ordinates-wrt Cone

Method being developed in PHENIX-Better Projection?



Combinatorial background

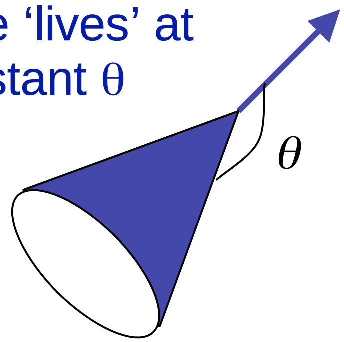
Cone simulation



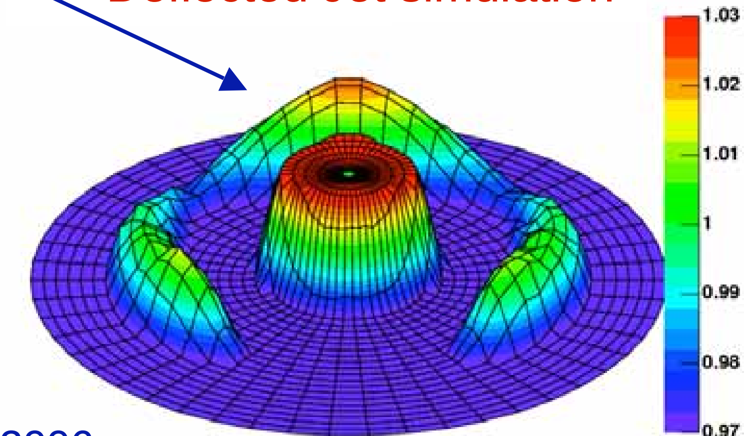
More strength at $\Delta\phi$ =0 for deflected

$\Delta\phi$=180° swamped?

Motivation: cone 'lives' at constant θ



Deflected Jet simulation



Cone is not back-to-back with trigger in 3-space
Must distinguish hollow from solid moving cone

VanLeeuwen-Ajitnand-HP2006

Experimental results: PHENIX

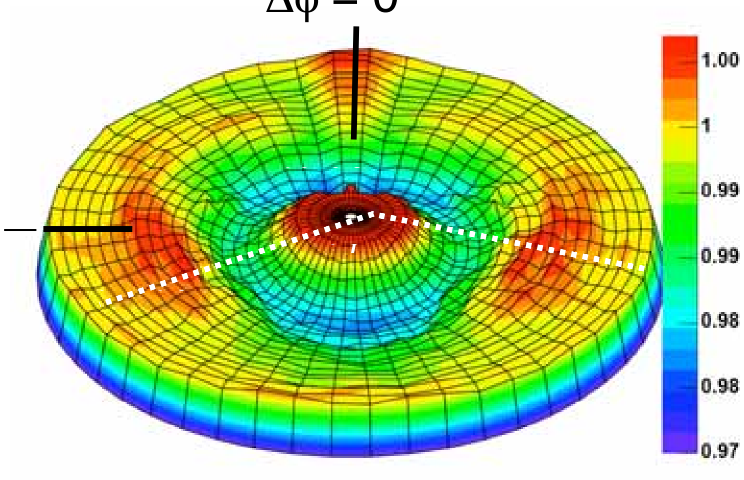
PHENIX Acceptance

PHENIX *Preliminary*

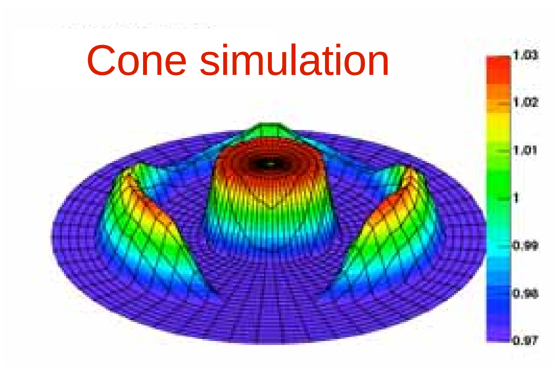
$\Delta\phi = 0$

Cent: 0-5%

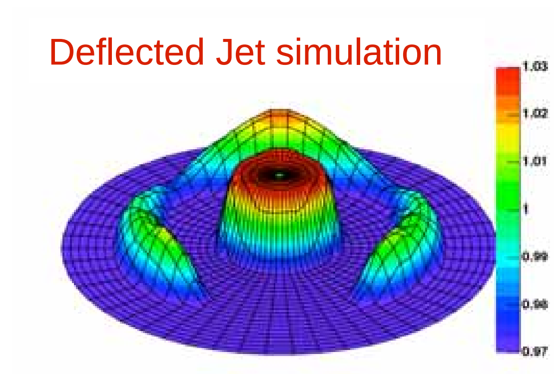
$3 < p_{T,trigger} < 4$ GeV
$1 < p_{T,assoc} < 2$ GeV



Uncorrected,
no v_2 subtraction



Middle of
Long Learning Curve



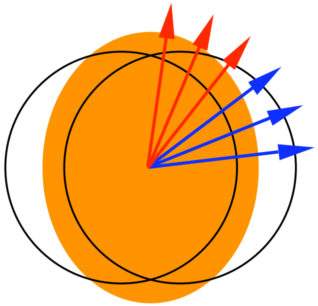
N.N. Ajitanand's Hard Probes 2006

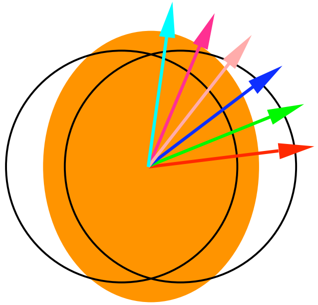
Frankly, until we figure out all these unexplained results at RHIC in the 0.1--10 GeV/c range, I'm not very interested in ~100 GeV jets at LHC nor do I expect much influence of the medium to be observable at such large p_T

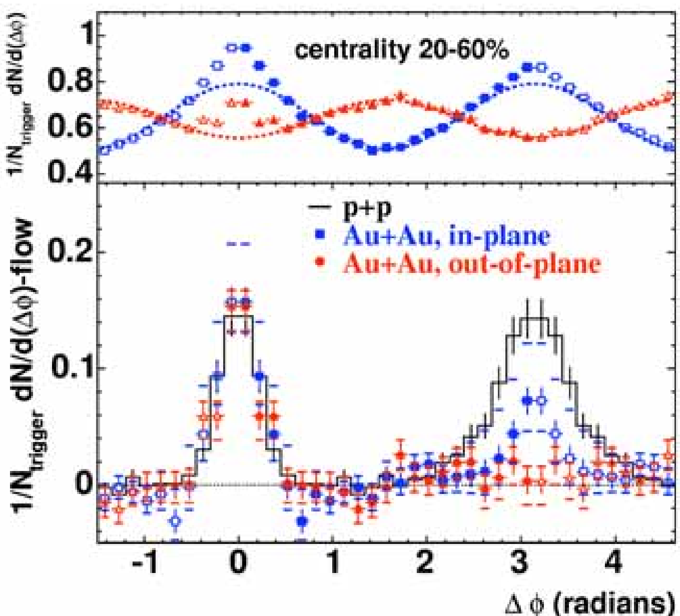
My parting advice

A big lesson learned at RHIC was that flow or anisotropy with respect to the reaction plane is a major complication to jets (via 2-particle correlations). Most likely it is the same for jets at LHC. Then there is the ridge and .... Expect a new long learning curve.

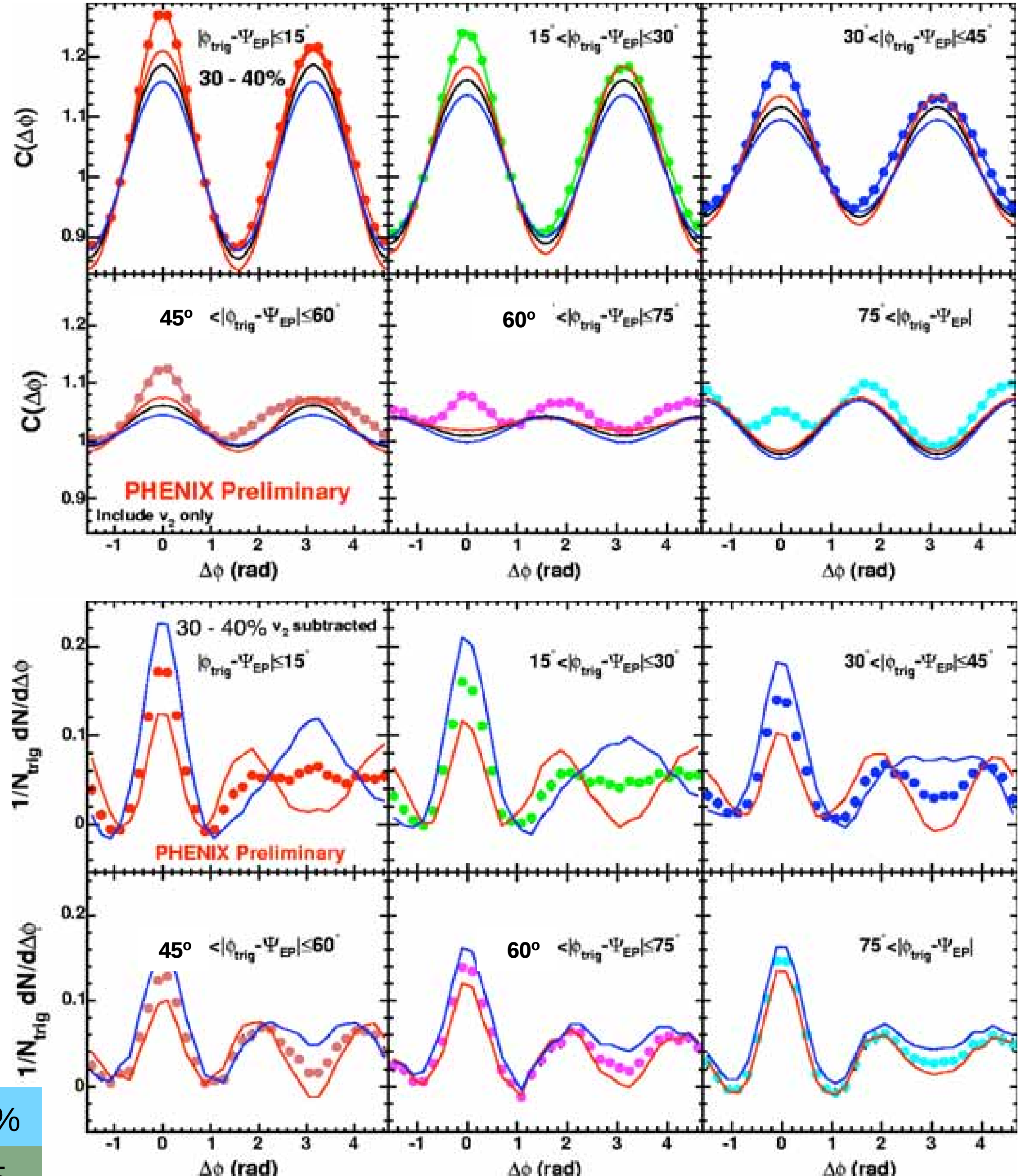
Backup, Extras, what couldn't fit







STAR PRL 91, 072304 (2003)



$h^{\pm} - h^{\pm}$

C: 20-60%

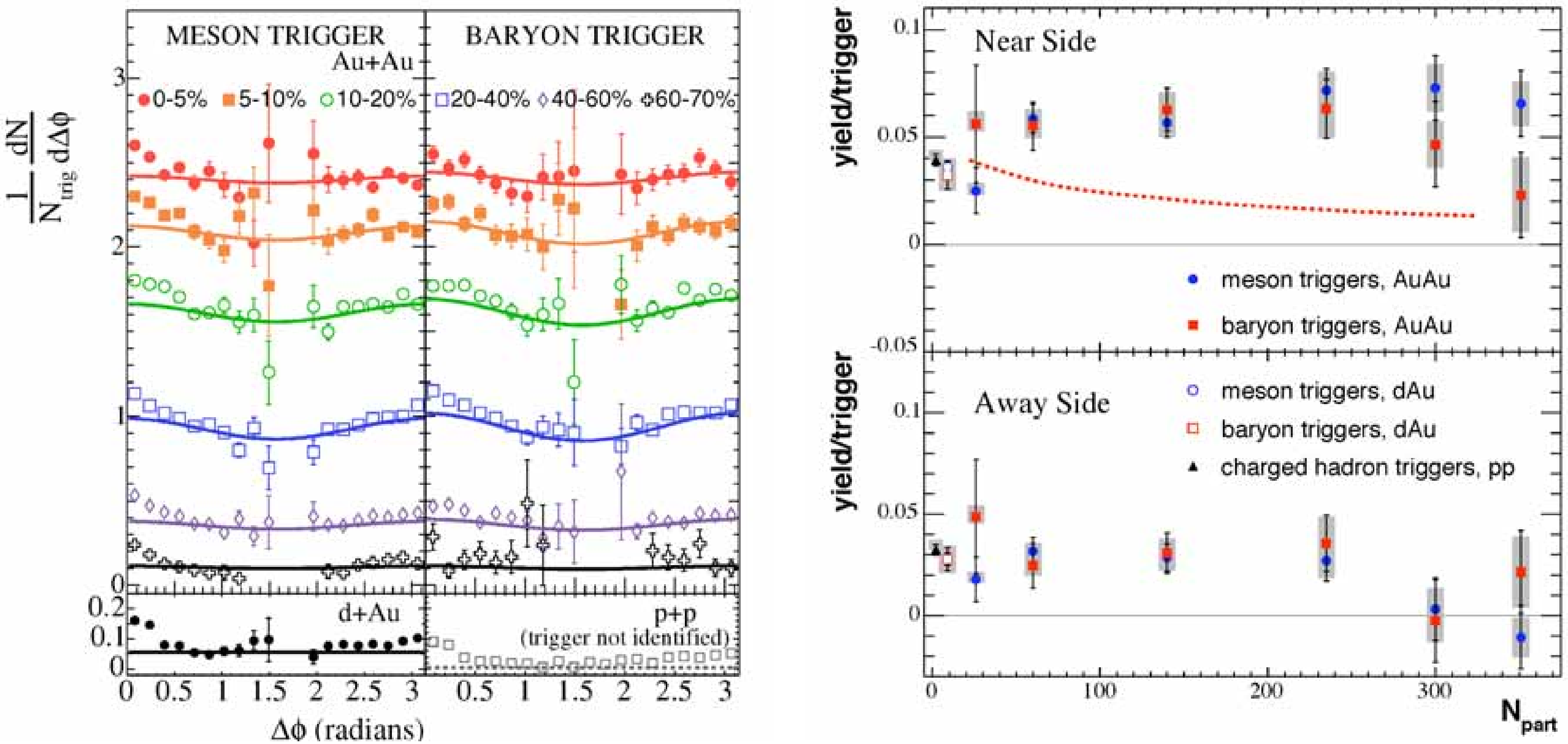
T: 4-6

P: 2-$P_{T\ Trig}$

$h^{\pm} - h^{\pm}$	C: 30-40%
T: 2.5 - 4	P: 1 - 2.5

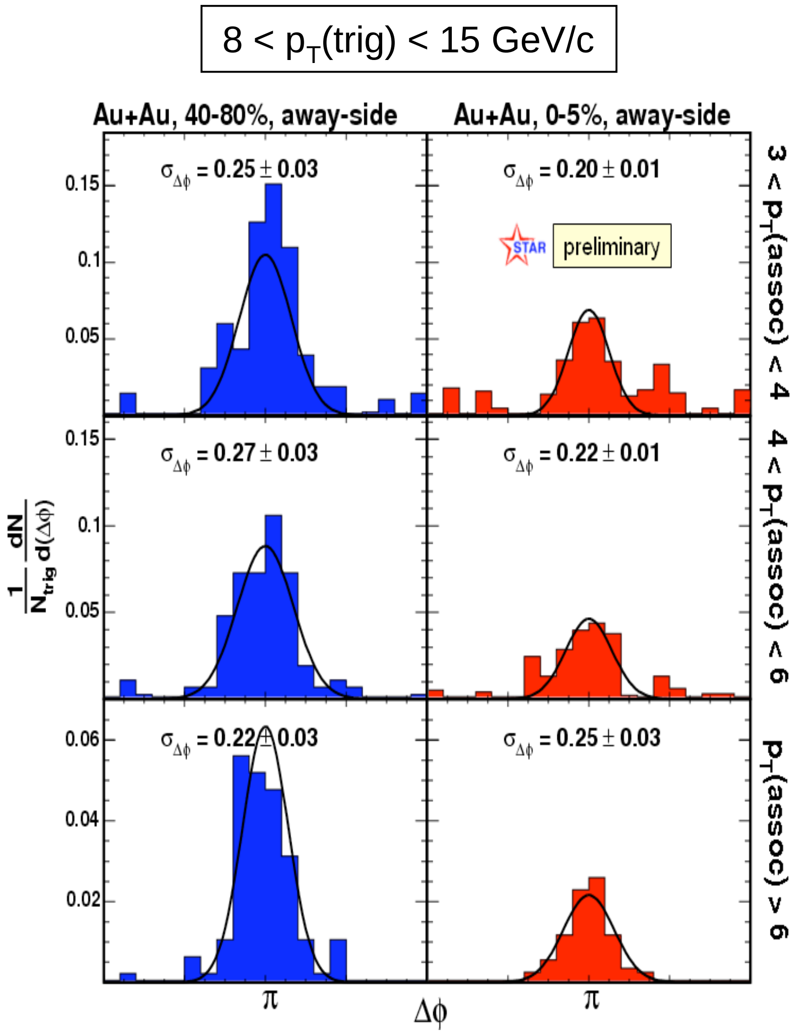
One of the few definitive results

PHENIX PRC **71** 051902 $2.4<p_{Tt}<4$ GeV/c $1.7< p_{Ta}<2.5$ GeV/c



Trigger mesons and baryons in the region of the baryon anomaly both show the same trigger (near) side and away side jet structure. This ‘kills’ the elegant recombination model of the baryon anomaly

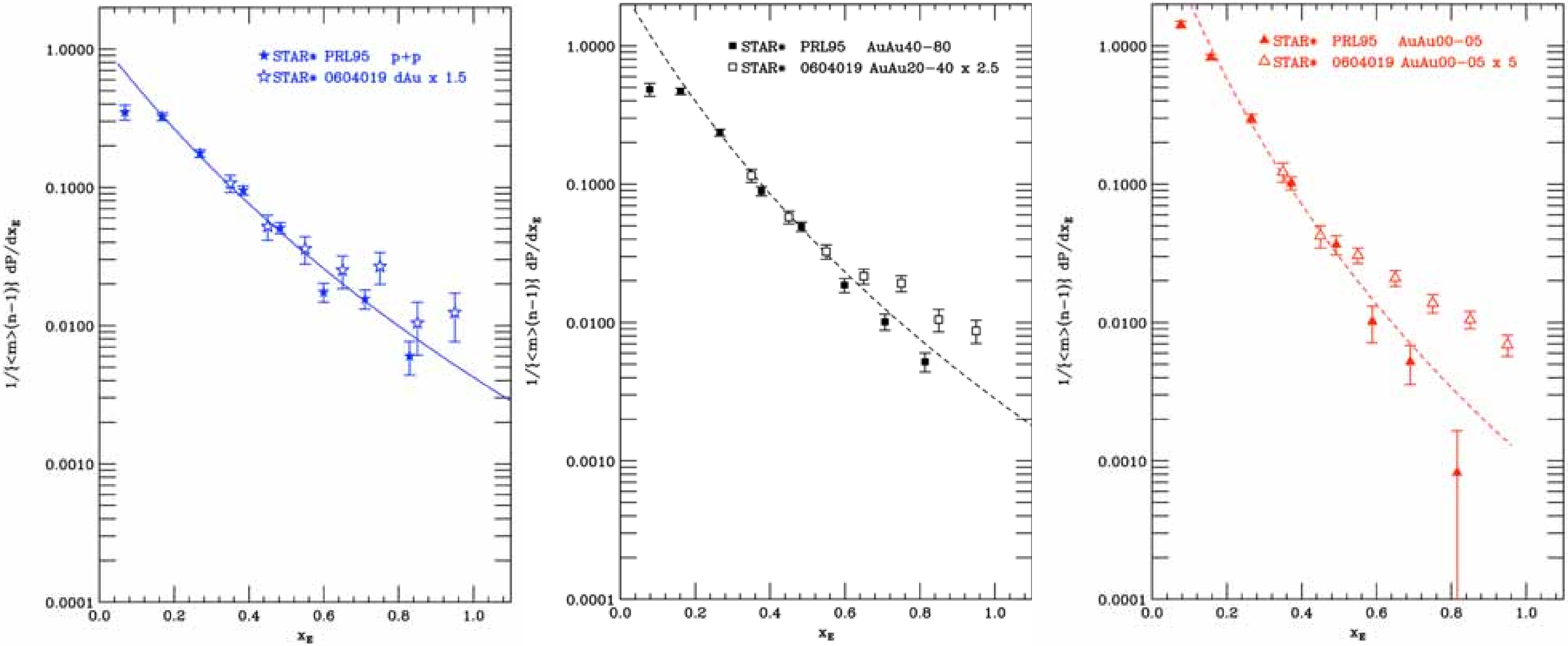
Width of Away-Side Peaks



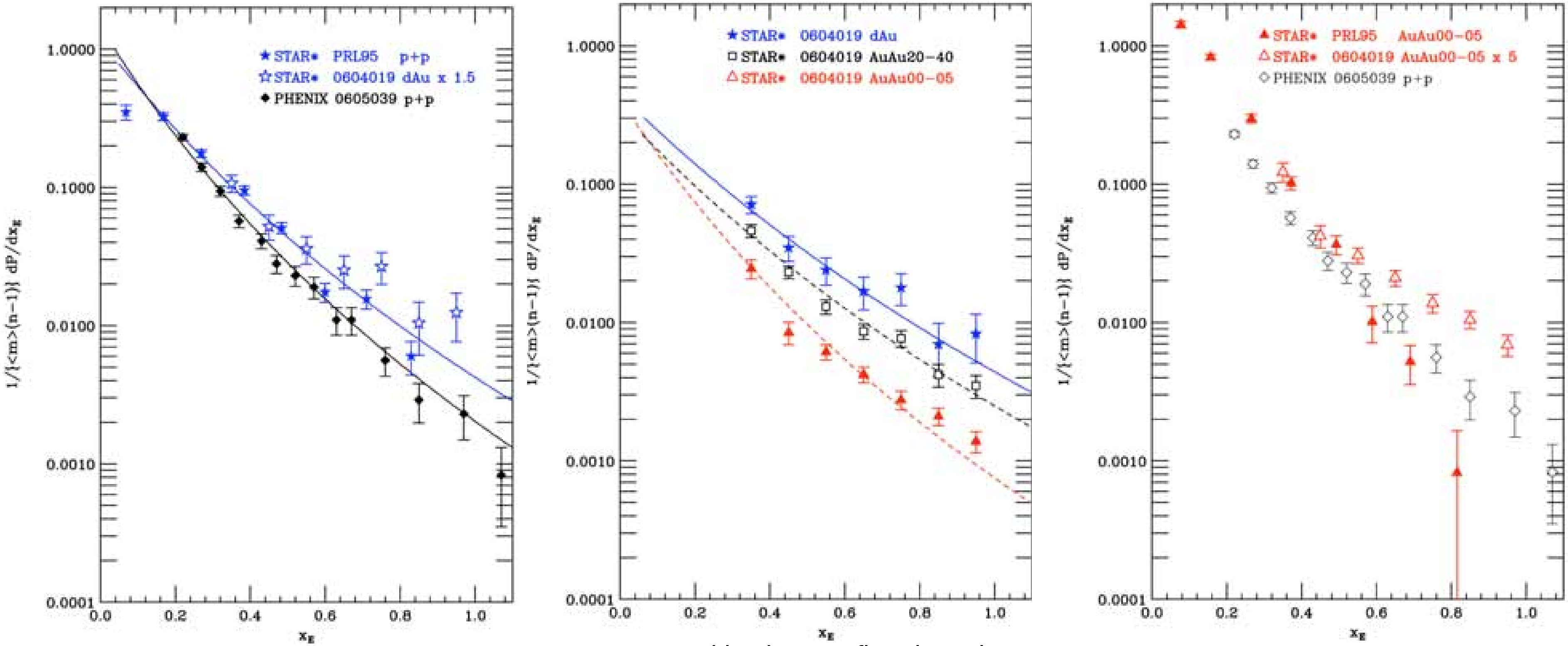
STAR nucl-ex/0604018

- away-side widths similar for central and peripheral
- Away-side width INCREASES with increasing p_{Ta}??!!!

Normalized data with PRL95 curve



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

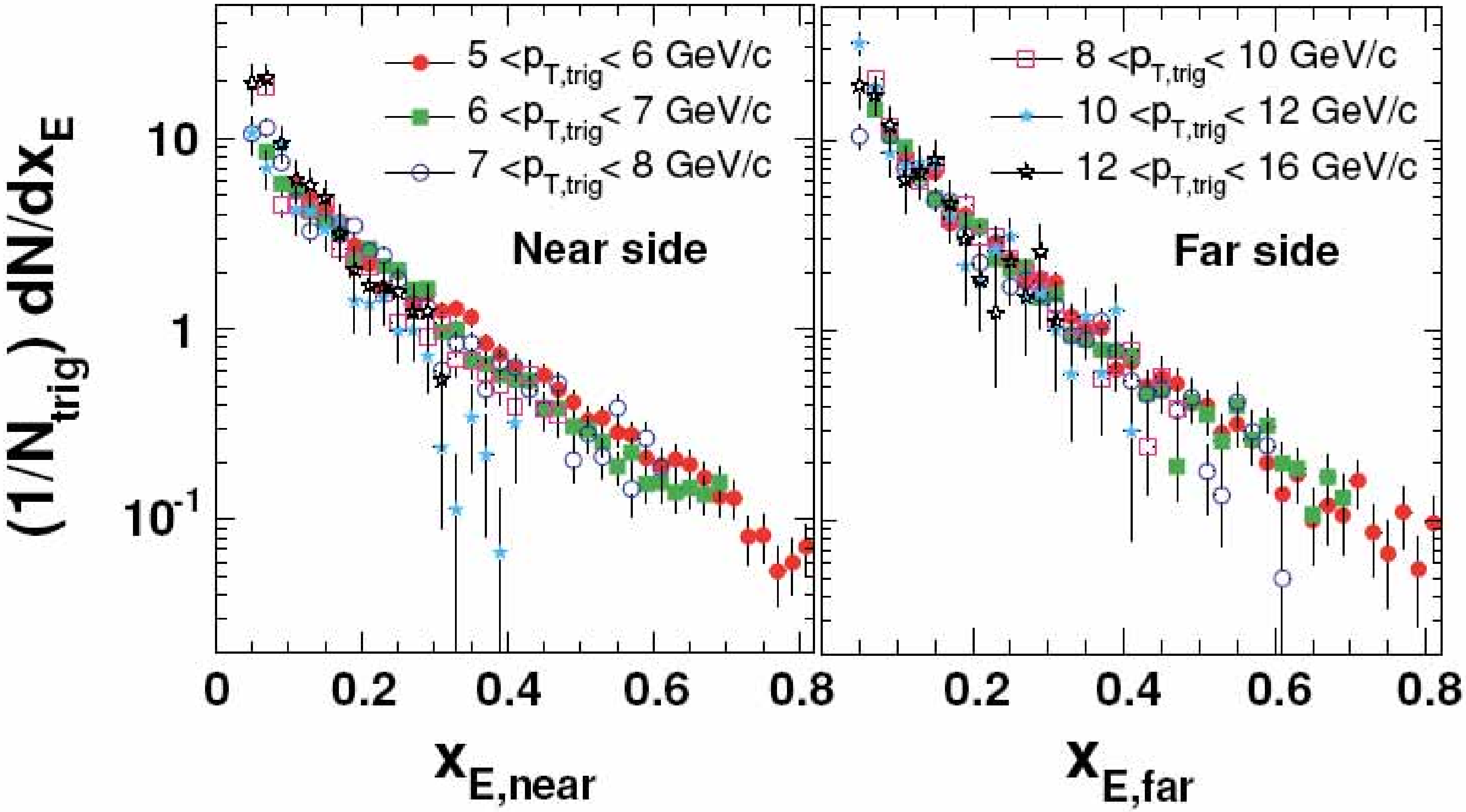


Norm (data)	Norm fit	hatx_h
Data*0.6	Fit*0.500	1.300
Data*0.6	Fit*0.350	1.200
Data*0.6	Fit*0.300	0.850

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

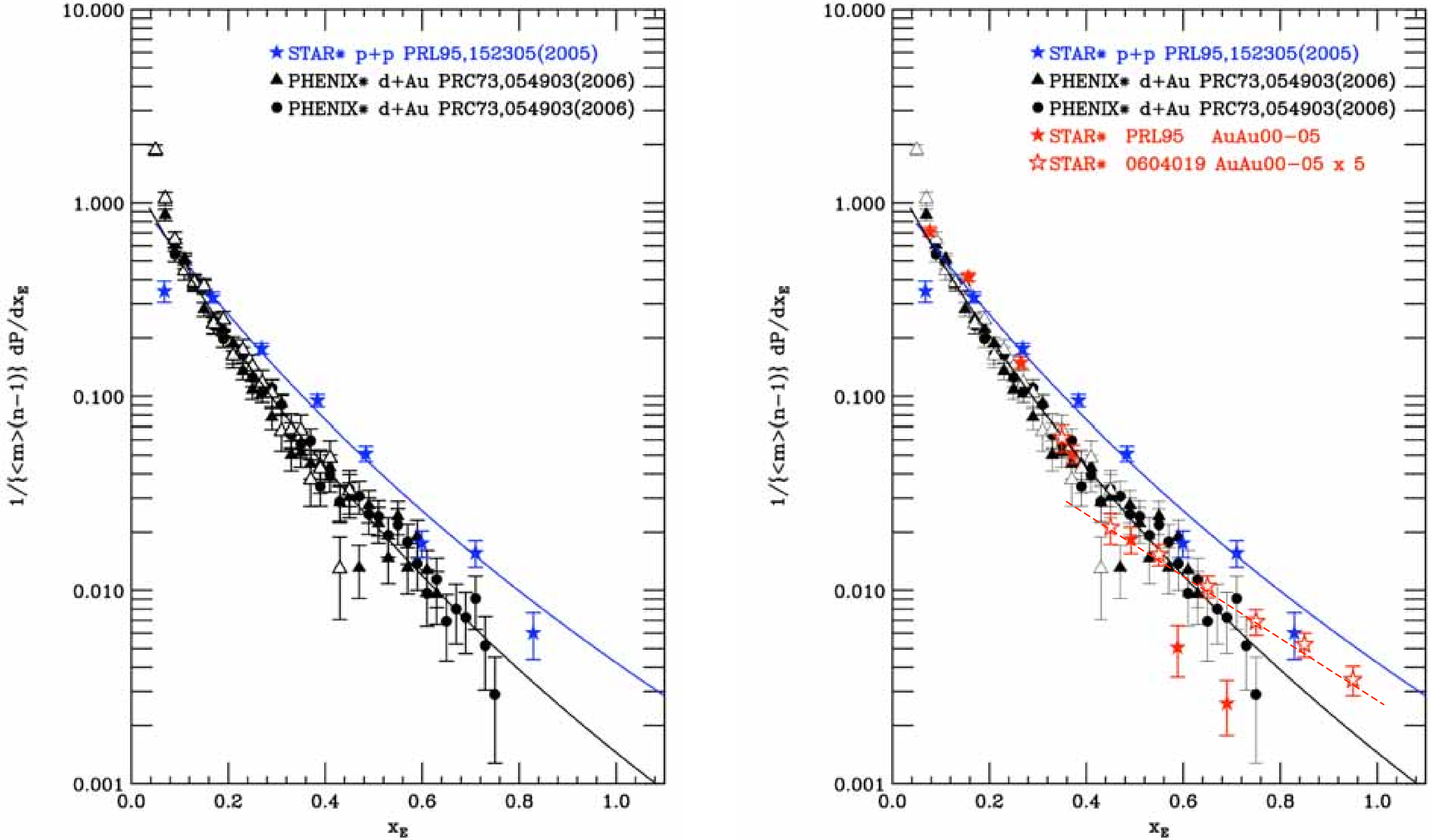
PHENIX d+Au results

PHENIX, PRC 73, 054903 (2006)



- Beautiful p+p and dAu results with pTt in STAR punchthrough range.

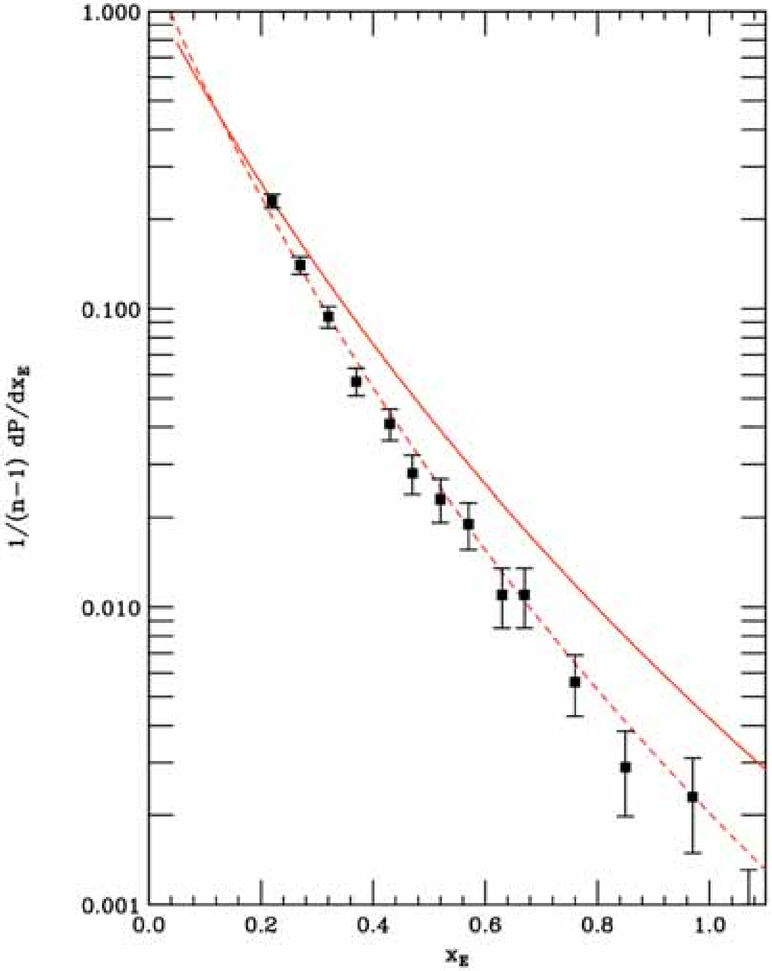
PHENIX d+Au PRC73

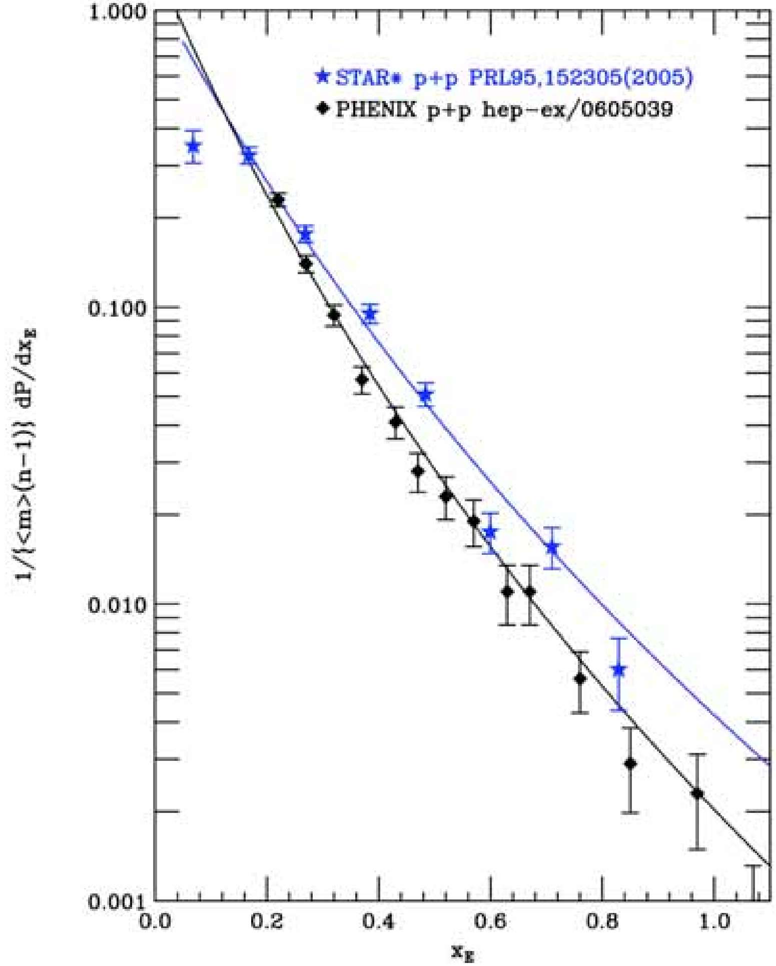


$\hat{x}_h = 0.75$ $\hat{x}_h = 1.0$

- STAR 0604018 AuAu0-5 flatter than all published p+p and d+Au data ????

It works for STAR p+p and:





a) * means data normalized w.r. to hep-ex/0605039

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

Conclusions

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

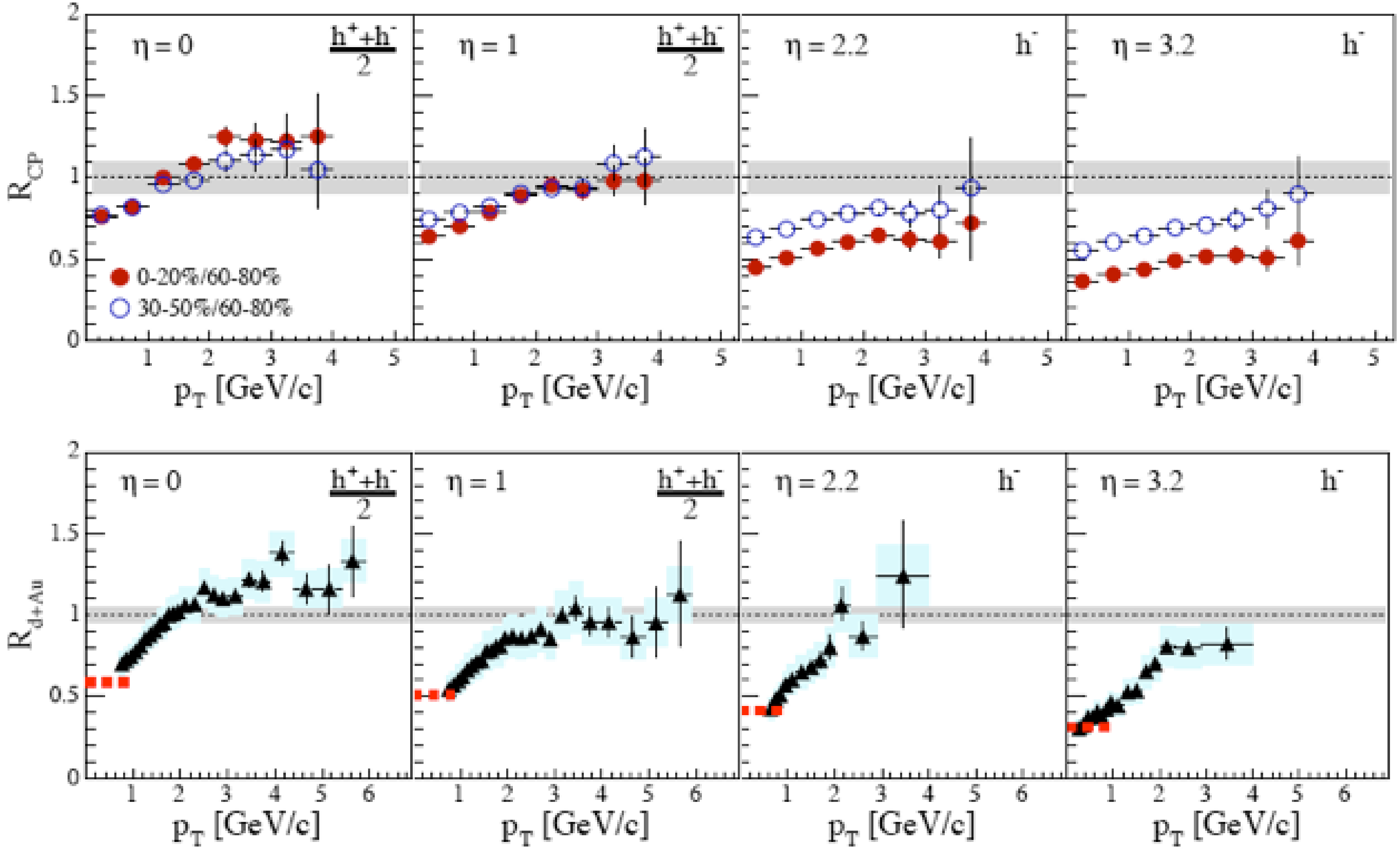
- Both STAR Au+Au measurements show a decrease in the ratio of the transverse momentum of the away jet relative to the trigger jet with increasing centrality. For both data sets $\hat{x}_h$ decreases by a factor of ~2 from p+p (dAu) to Au+Au central collisions. Much more info than I_{AA}.

- 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 $z_T \geq 0.5$

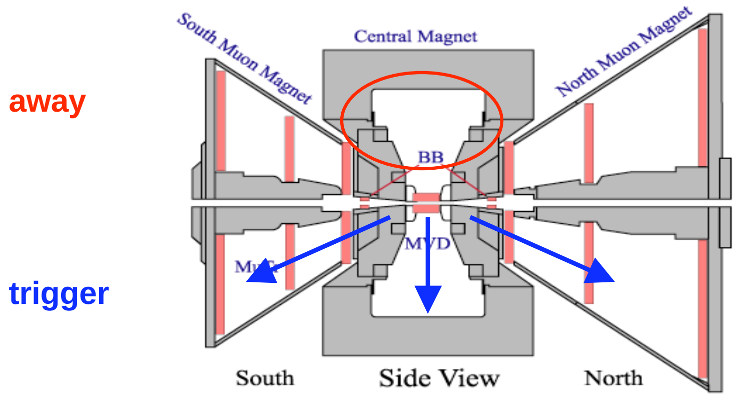
CGC?
'Monojets' in d+Au?

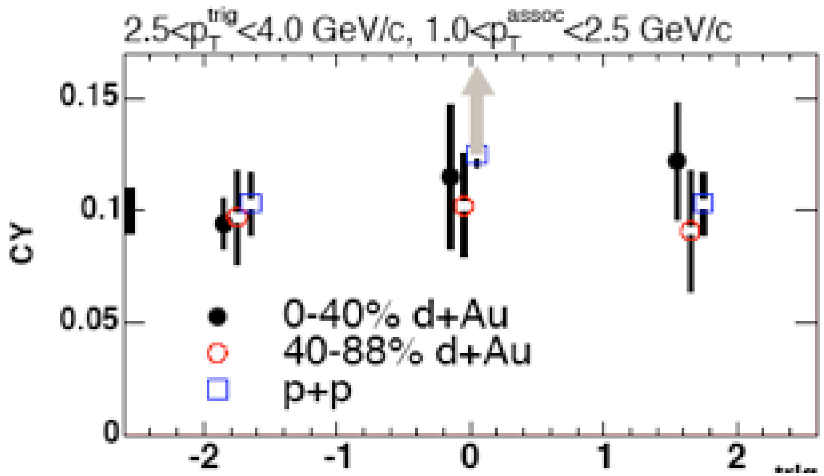
Brahms R_{dAu}, R_{CP} in d+Au vs rapidity

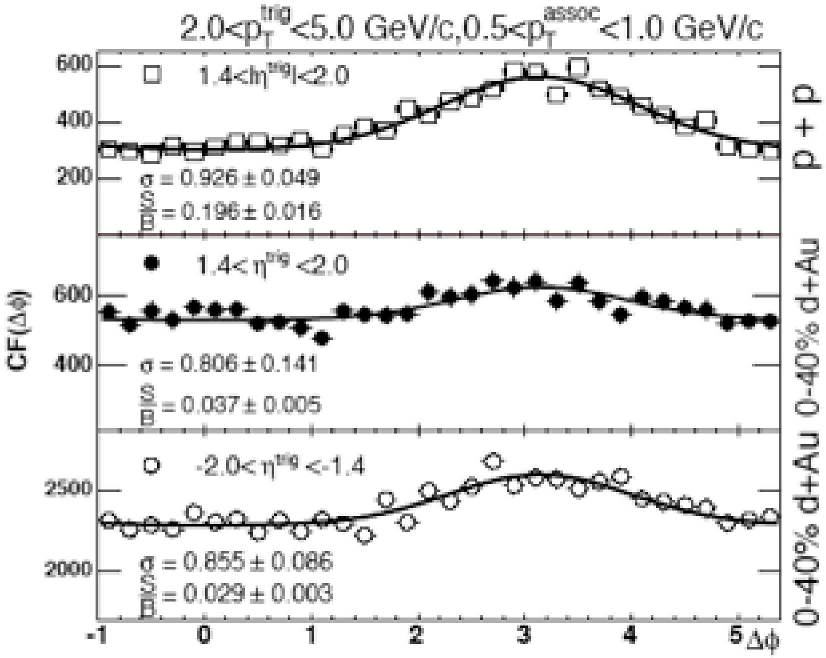


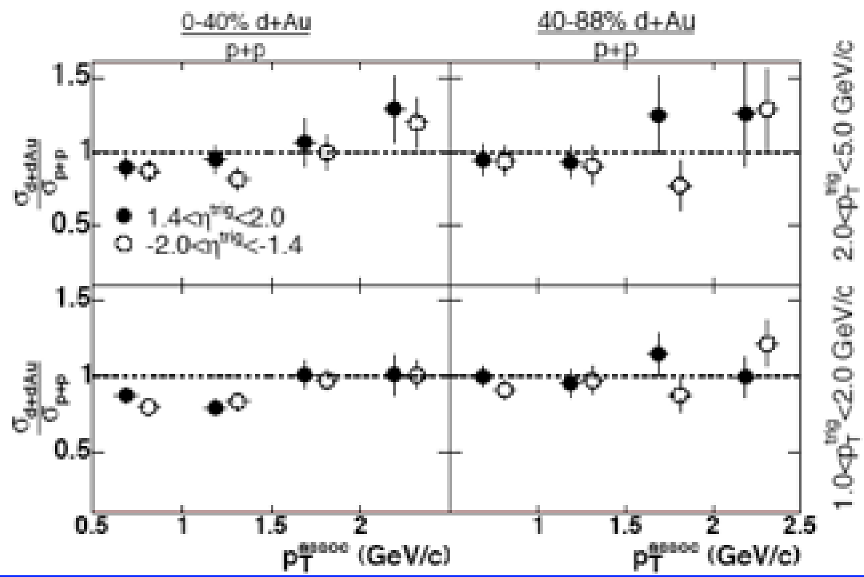
BIG effect in RCP; some tendency in RdAu. BRAHMS PRL**93** 242303

d+Au is it CGC?⇒`Monojets’? ⇒ correlations





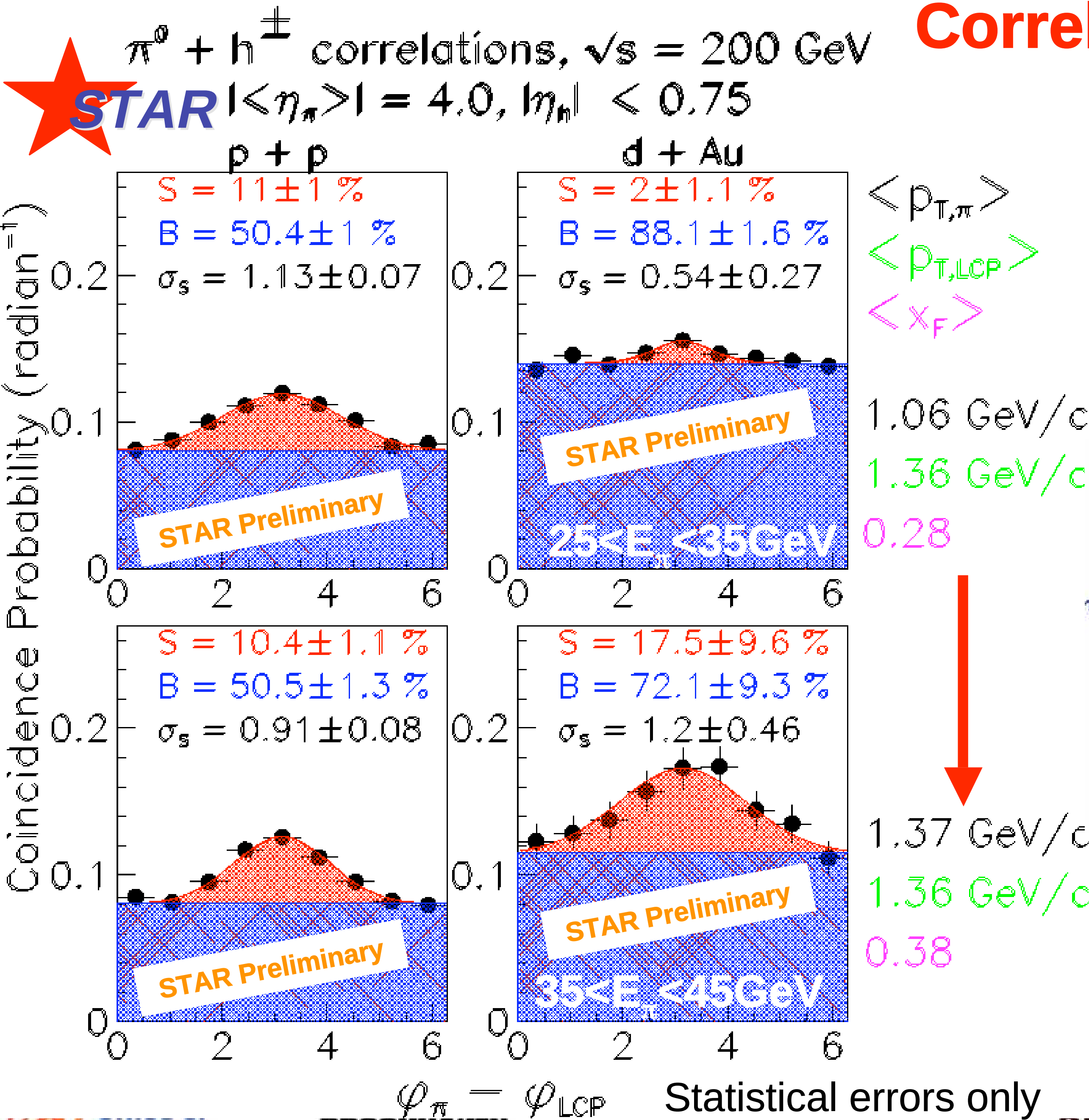




widths and conditional yields the same for triggers in all 3 spectrometers for pp and dAu

PHENIX nucl-ex/0603017

Correlations in d+Au

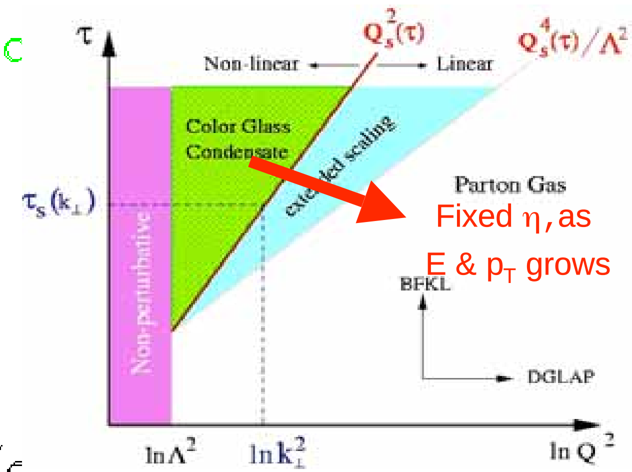


Statistical errors only

- are suppressed at small $\langle x_F\rangle$ and $\langle p_{T,\pi}\rangle$

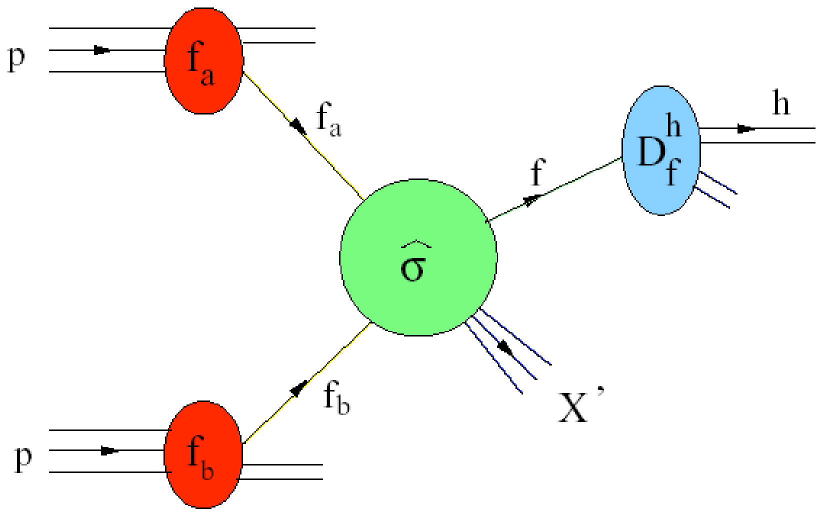
$S_{pp}-S_{dAu}$= (9.0 ± 1.5) %

consistent with CGC picture

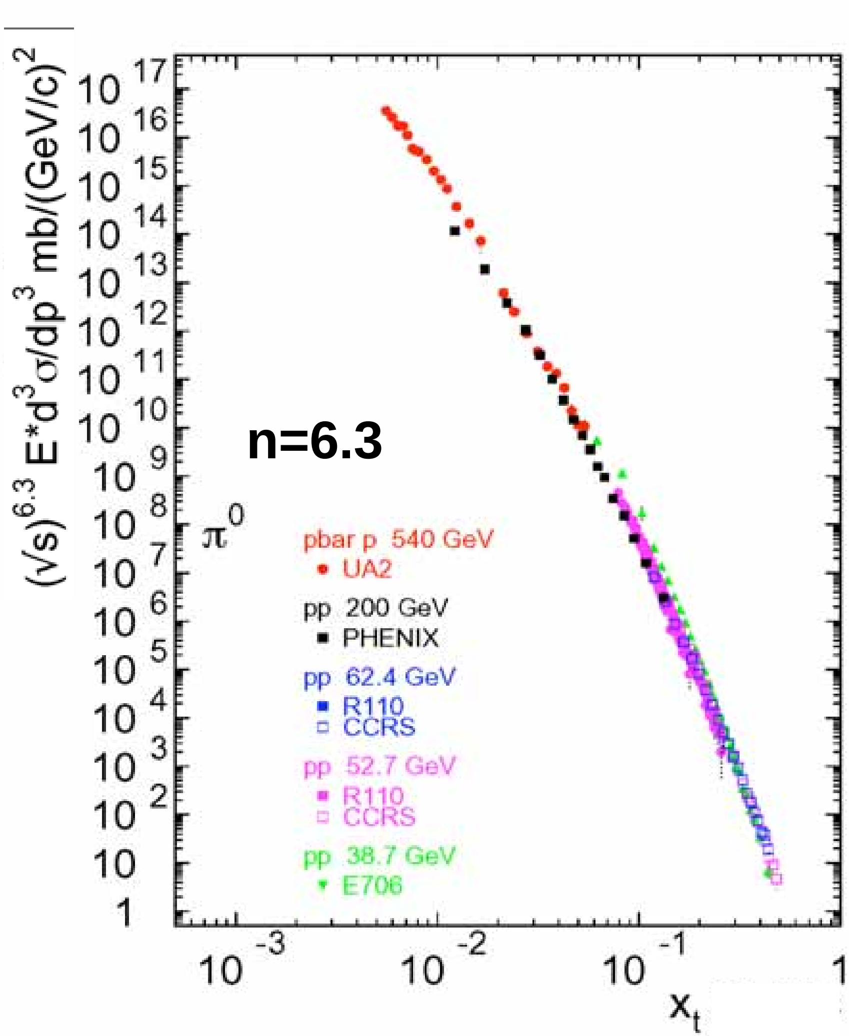


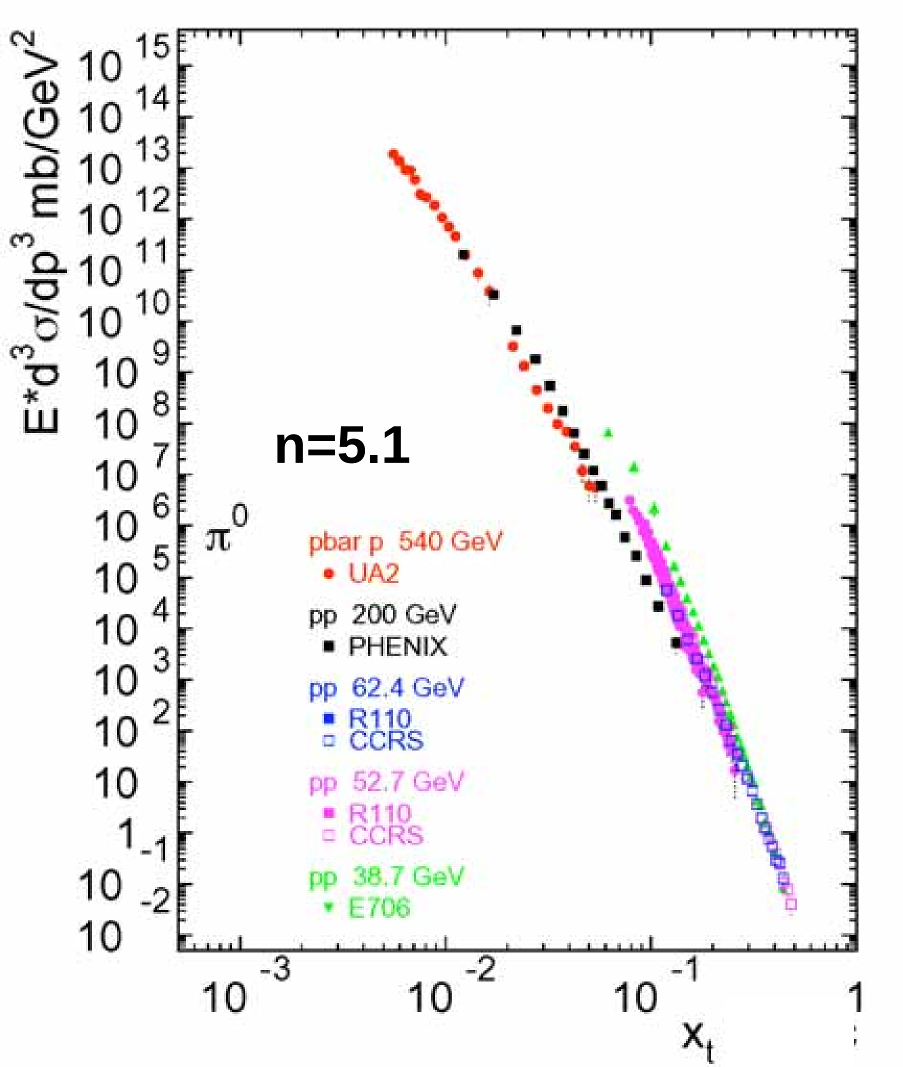
- are consistent in d+Au and p+p at larger $\langle x_F\rangle$ and $\langle p_{T,\pi}\rangle$

as expected by HIJING

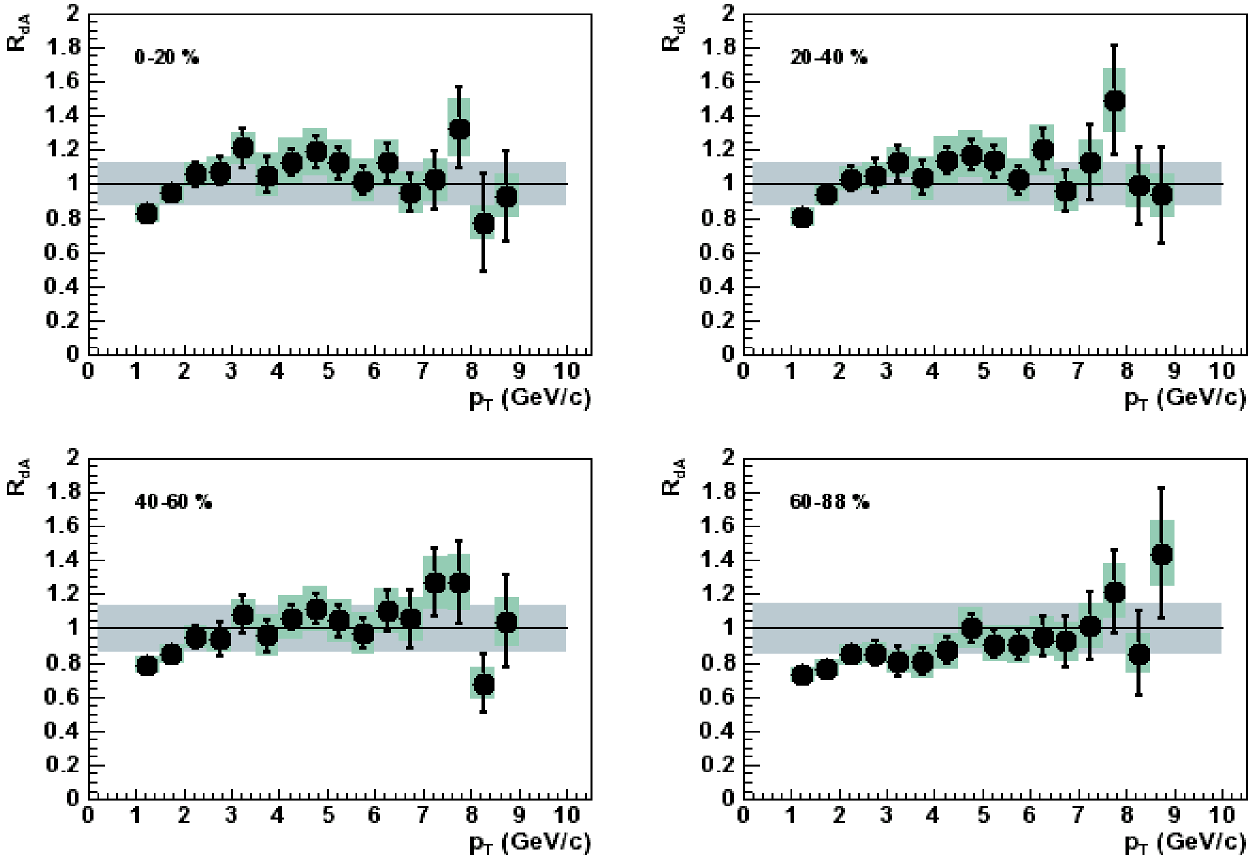

p
f_a
f_a
h
D_f^h
f
$\hat{\sigma}$
f_b
X'
p
f_b

Recall π^0: n=5.1 works better for x_T> 0.2



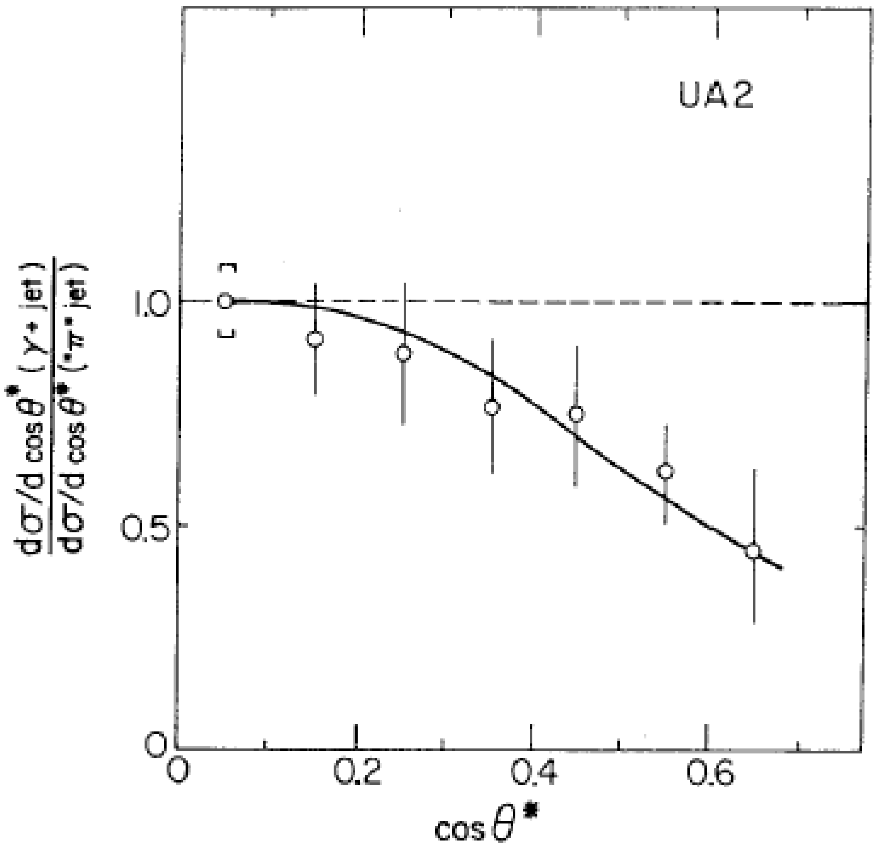


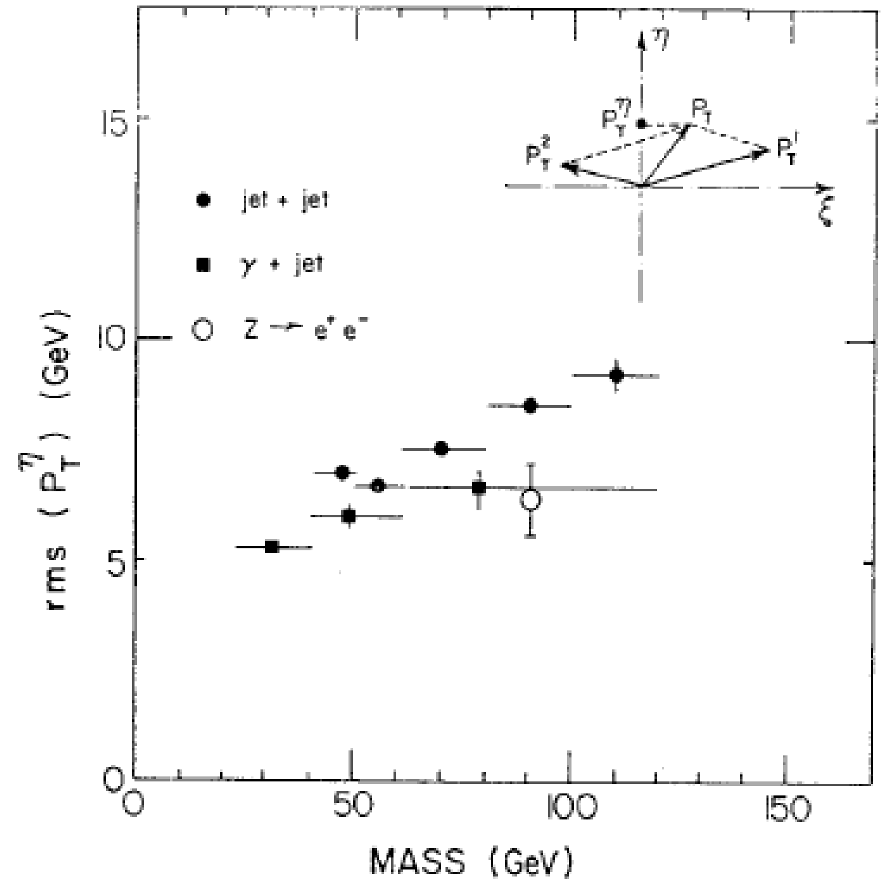
Cronin effect observed in d+Au at RHIC $\sqrt{s_{NN}}$=200 GeV



PHENIX preliminary π^0 d+Au vs centrality for DNP2003

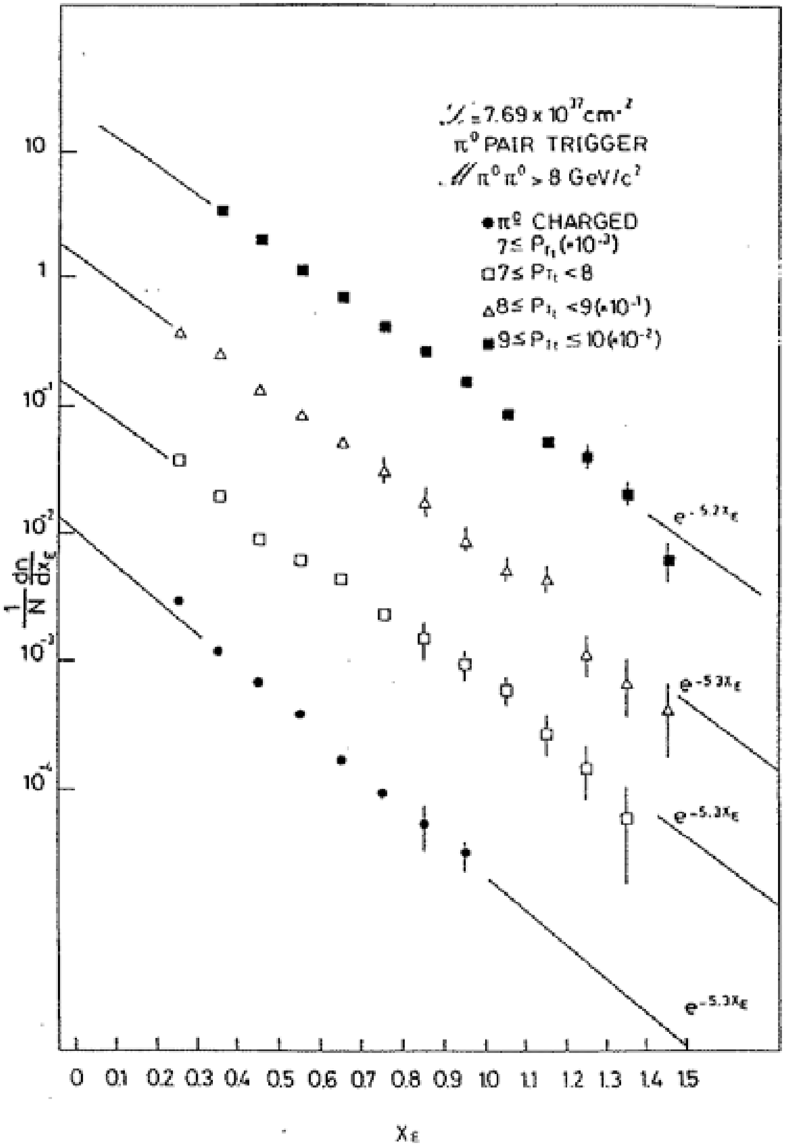
UA2 results on cosθ* and k_T in direct γ





R. Ansari, et al, UA2, ZPC **41**, 395 (1988)

x_E distribution measures fragmentation fn.



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

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

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

- independent of p_{Tt}

See M. Jacob's talk EPS 1979 Geneva

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).