Hard-scattering and Jets from RHIC to LHC: a critical review

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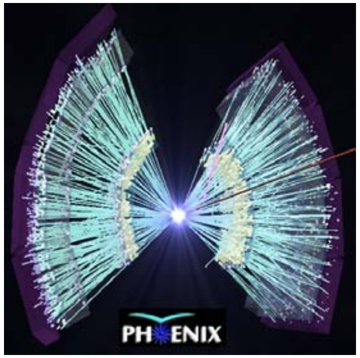


High p_T physics at LHC
University of Jyväskylä, Finland
March 23-27 , 2007

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

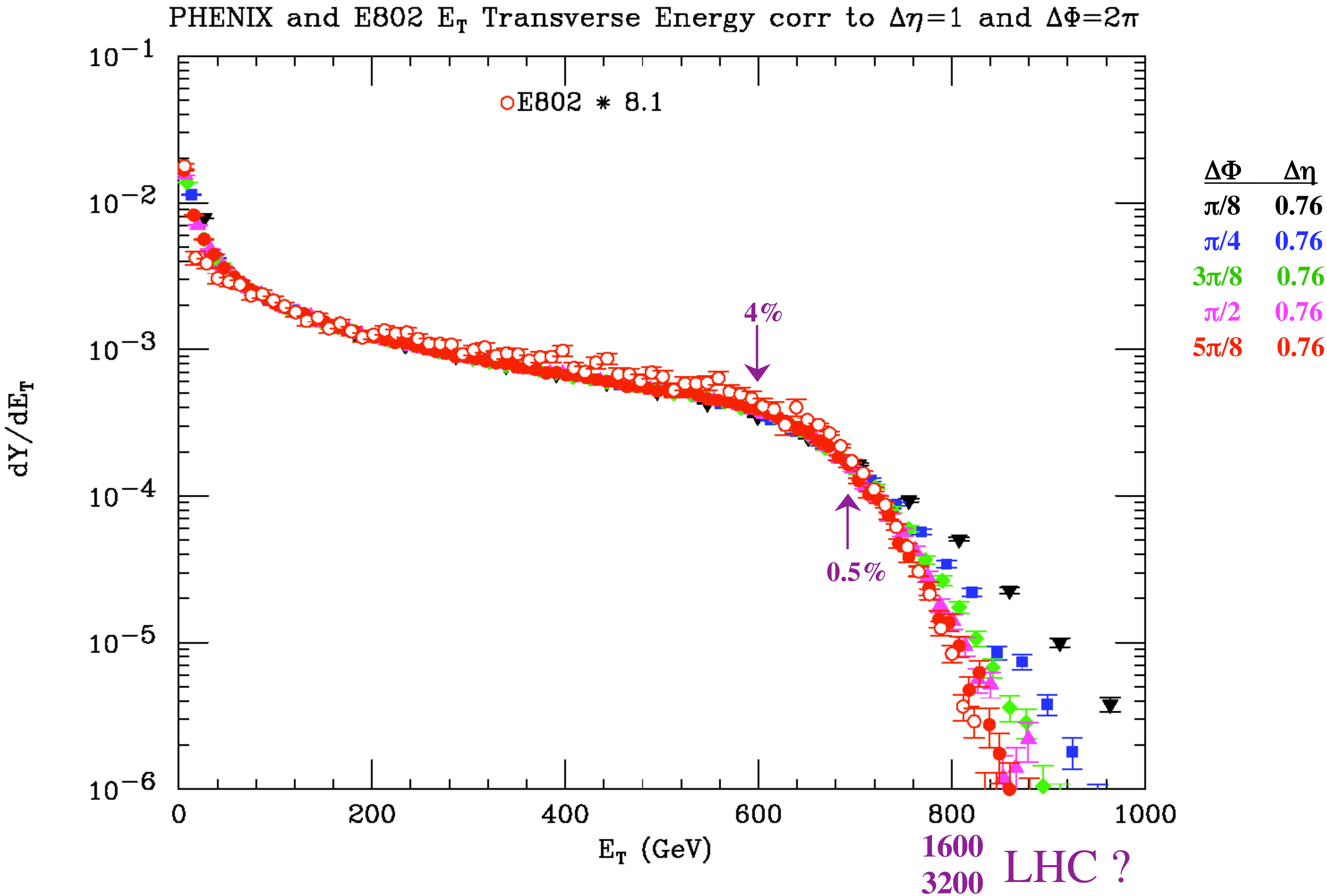
BDMPS 1997-1998

- 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.

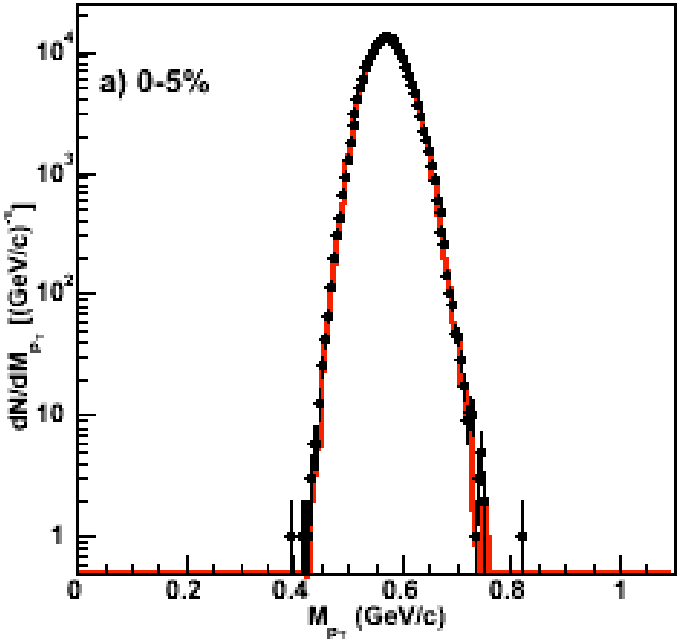
- As the expected energy in a typical jet cone $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is $\pi R^2 \times 1/2\pi \times dE_T/d\eta = R^2/2 \times dE_T/d\eta \sim 300$ GeV for R=1 at $\sqrt{s_{NN}}=200$ GeV where the maximum Jet energy is 100 GeV, Jets can not be reconstructed in Au+Au central collisions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

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

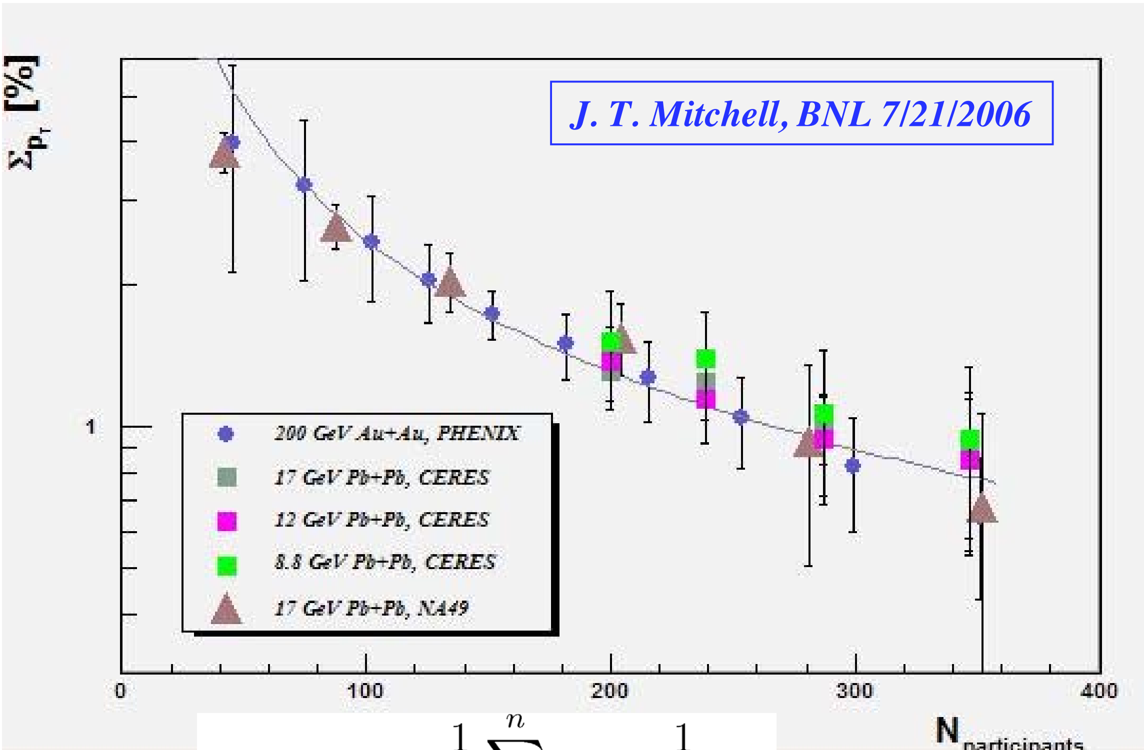


Non-Random Fluctuations of E_T measured in PHENIX (a nice jet cone) ~1% ~ 15 GeV LHC



compare Data to Mixed events

Random Fluctuations:
~5-8%~75-120 GeV



$$M_{p_T} = \overline{p_T} = \frac{1}{n}\sum_{i=1}^{n} p_{T_i} = \frac{1}{n} E_{Tc}$$

$$\Sigma_{p_T}^2 = \frac{\sigma_{M_{p_T}}^2}{\mu^2} - \frac{1}{n}\frac{\sigma_{p_T}^2}{\mu^2} \approx \frac{\sigma_T^2}{\langle T\rangle^2}$$

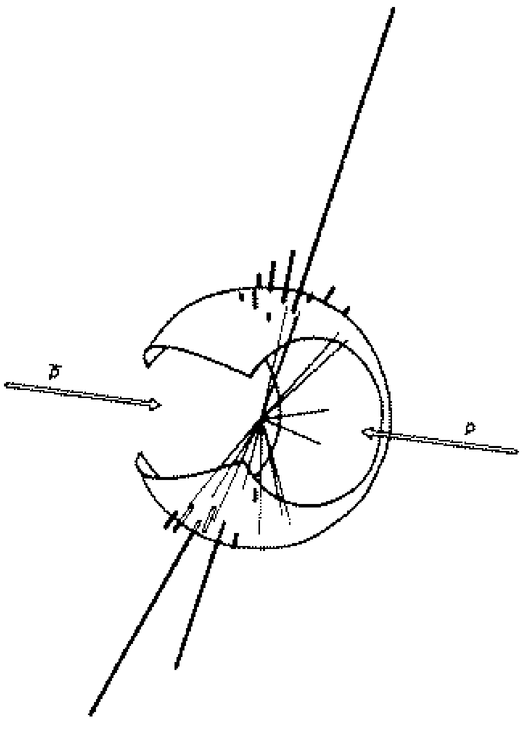
Are the fluctuations identical in adjacent patches of R=1 ?

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

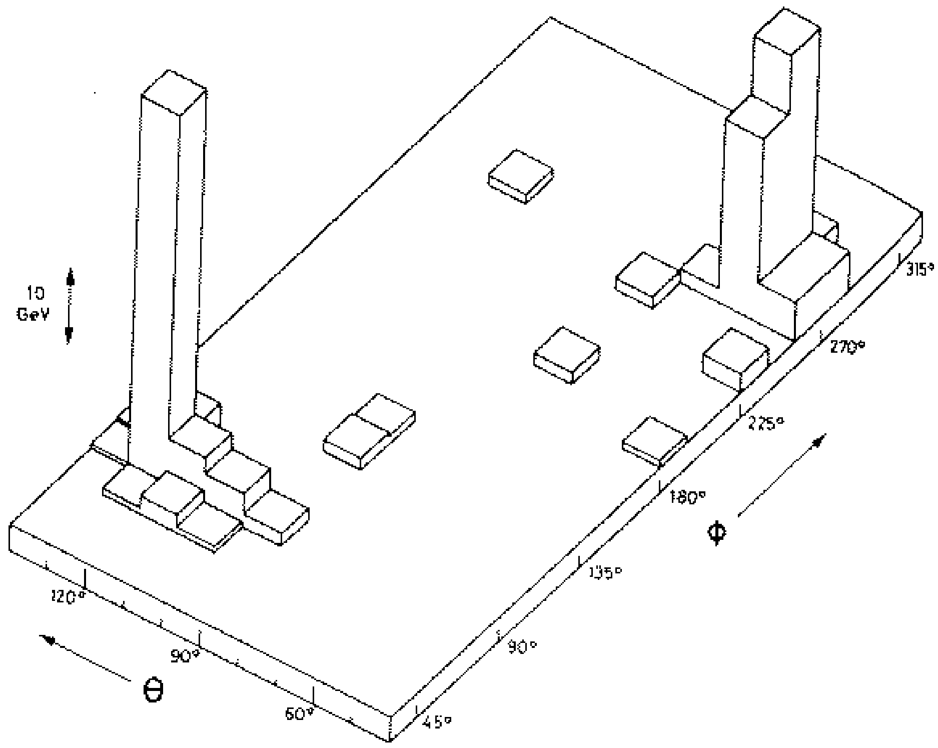
e.g. see M. D. Corcoran, Phys. Rev. D**32** (1985)592-603
or my colloquium here Friday, March 23, 2007

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.

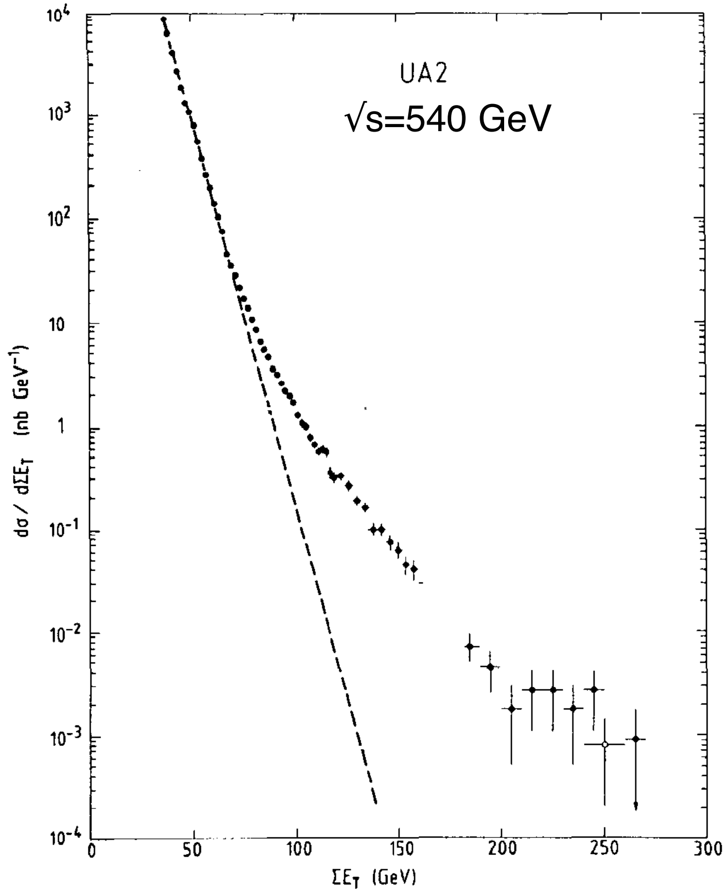


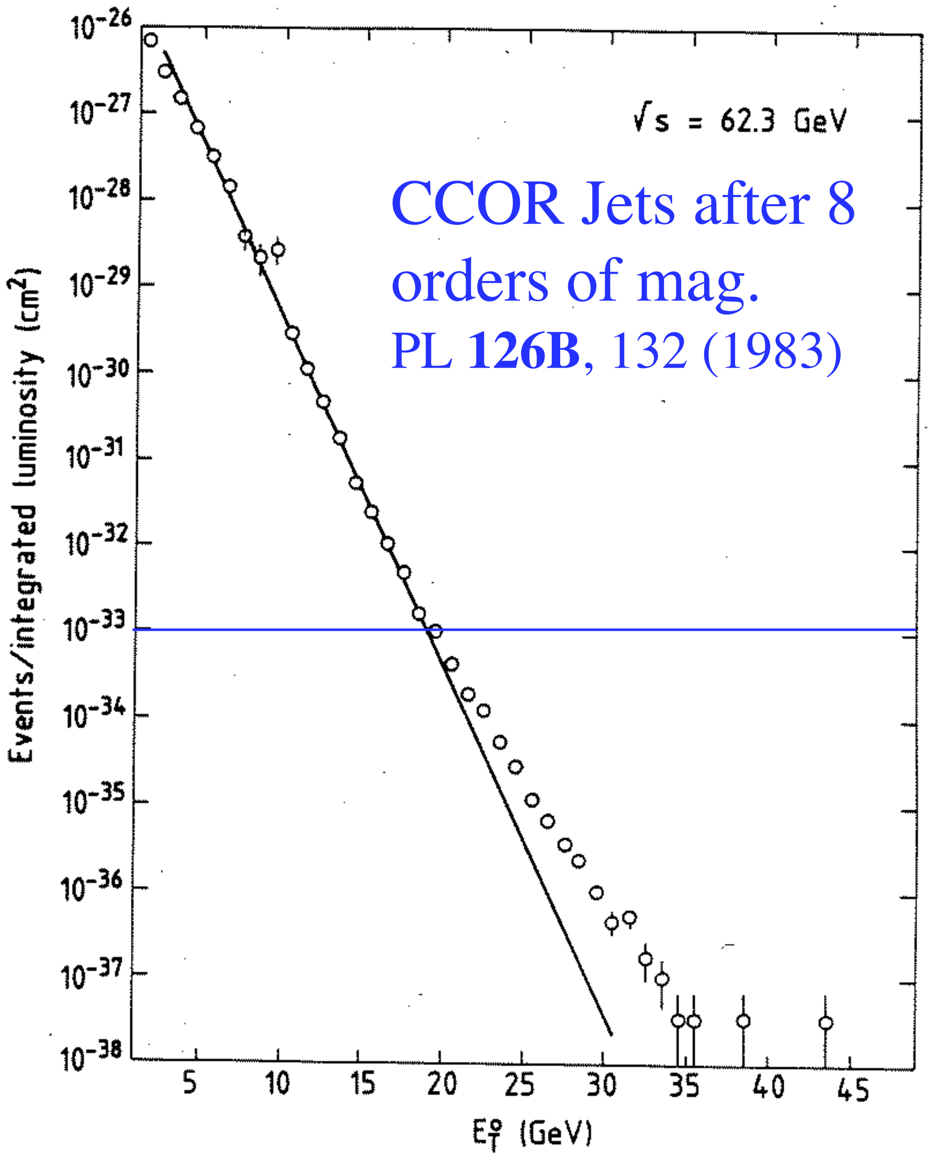
(a)



(b)

Jets not apparent in E_T distributions





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

UA2-Jets after 5-6 orders of magnitude PLB 138, 430 (1984)

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

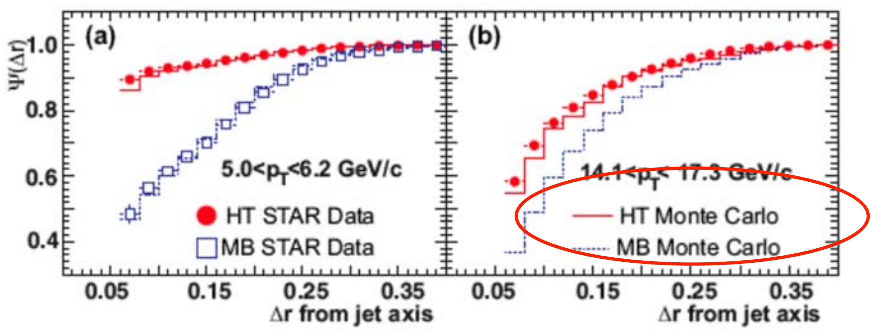


FIG. 1: Jet profile $\Psi(\Delta r, r_{\rm cone}, p_T)$ versus inner cone size Δr at $r_{\rm cone} = 0.4$ for MB (open squares) and HT (filled circles) data compared with STAR Monte Carlo simulation in two jet p_T bins (a) $5.0 < p_T < 6.2$ and (b) $14.1 < p_T < 17.3\,\mathrm{GeV/c}$. The MB jet yield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

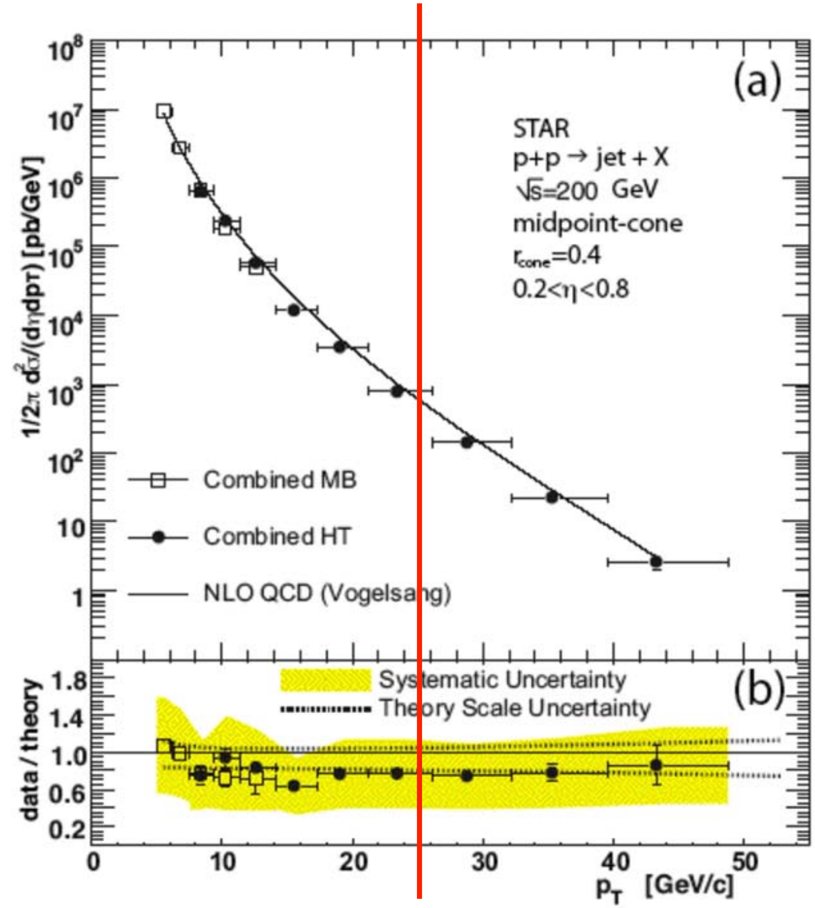
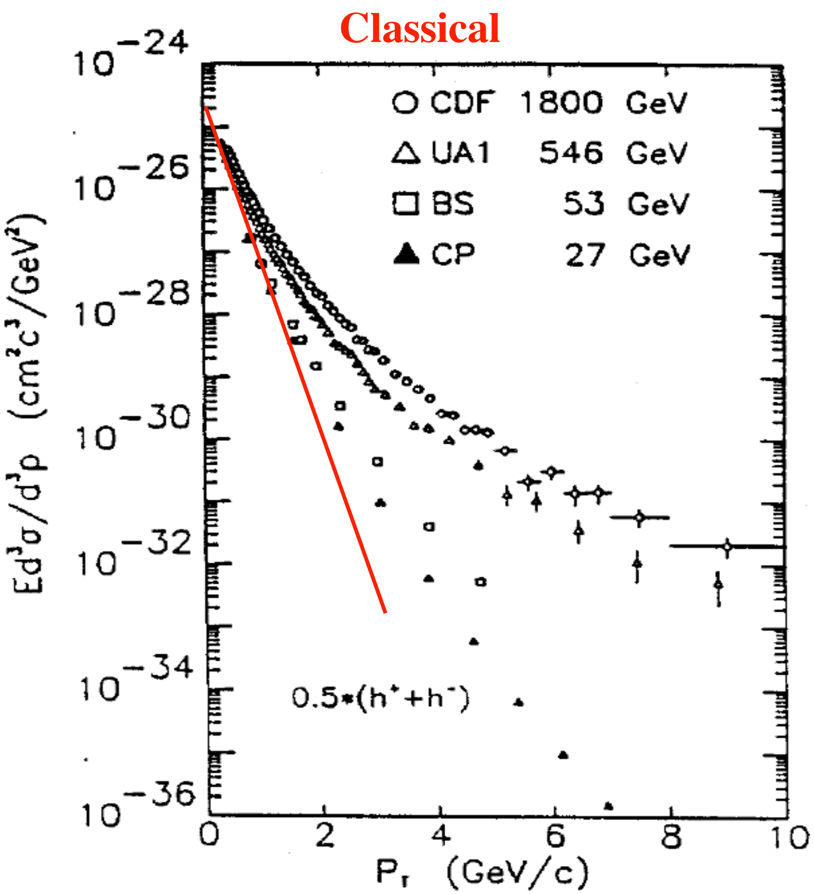


FIG. 2 ... p → jet+ ... ius of 0.4.

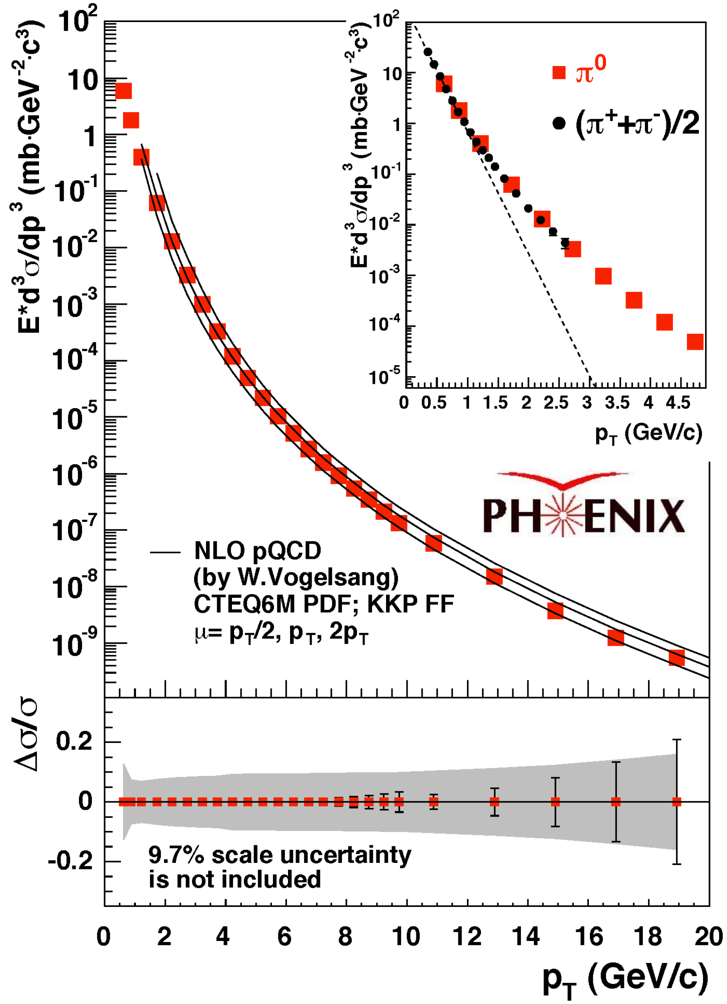
I guess that they missed my colloquium and the period 1978-82 or I have to read the fine print more carefully-triggered by cluster not unbiased?

cf. Single particle inclusive p_T spectrum

Classical



New



Hard scattering evident after only 3-4 orders of magnitude p_T>2 GeV/c

NLO-pQCD precison agreement
Strattmann Vogelsang hep-ph/0702083

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

$$a + b \to c + d$$

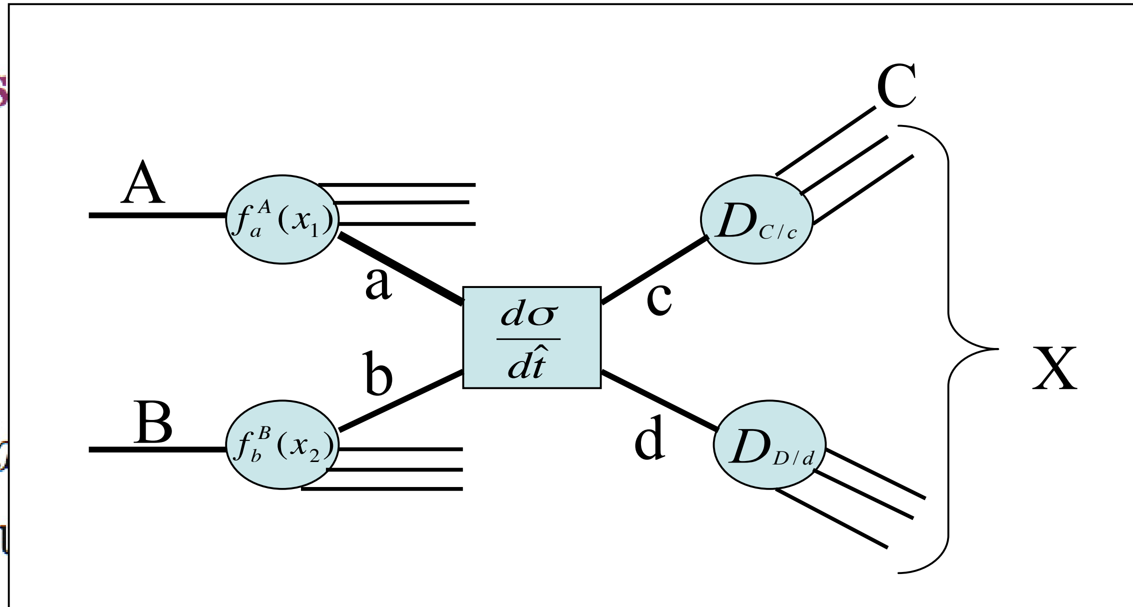
$f_a^A(x_1)$, $f_b^B(x_2)$, are structure functions, the differential probabilities for constituents a and b to carry momentum fractions x_1 and x_2 of their respective protons, e.g. $u(x_1)$,

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

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

for constitu … x_1 and x_2

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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

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

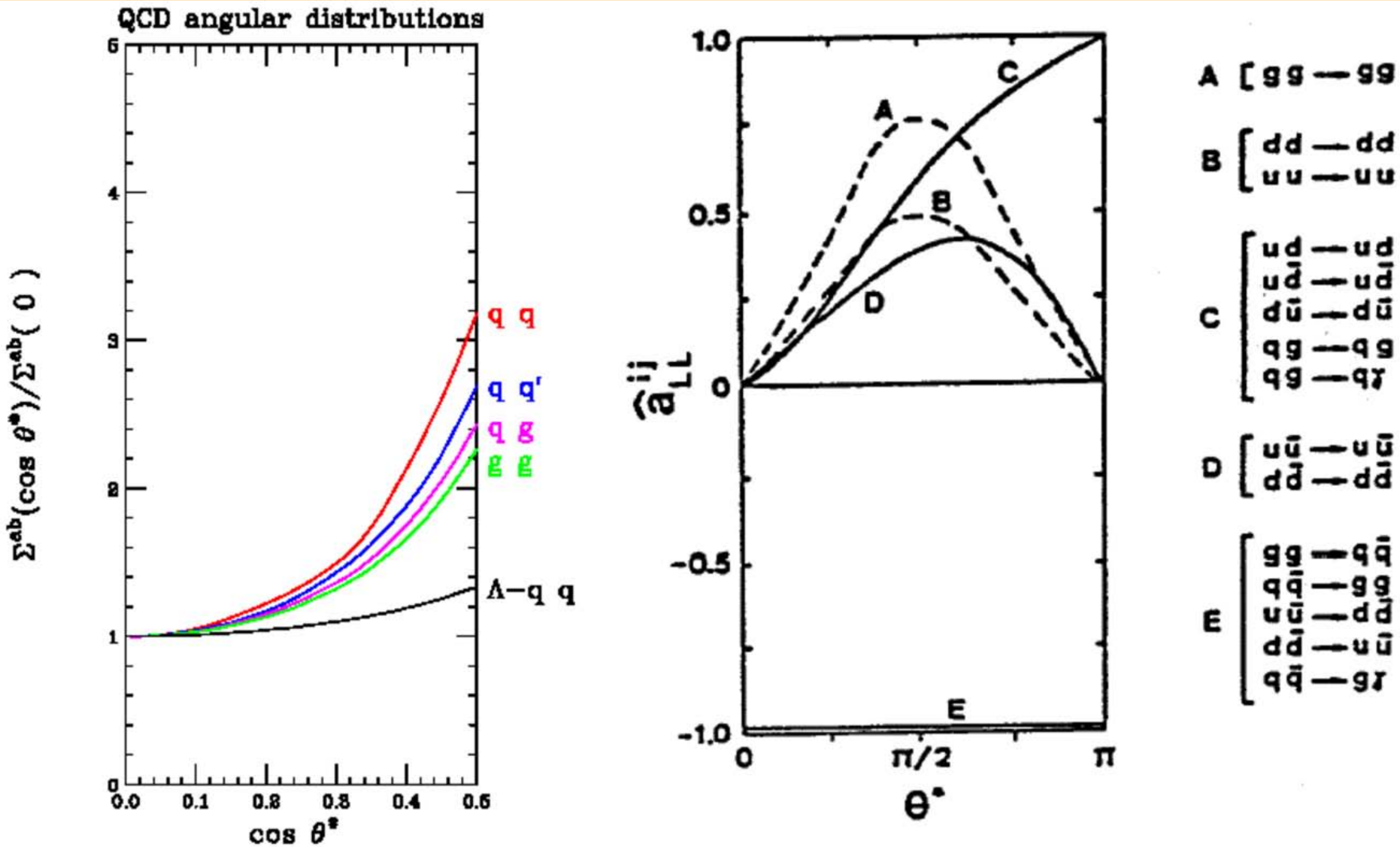


Fig. 2. Characteristic QCD Subprocess angular distributions: (a) scattering; (b) spin asymmetry

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.

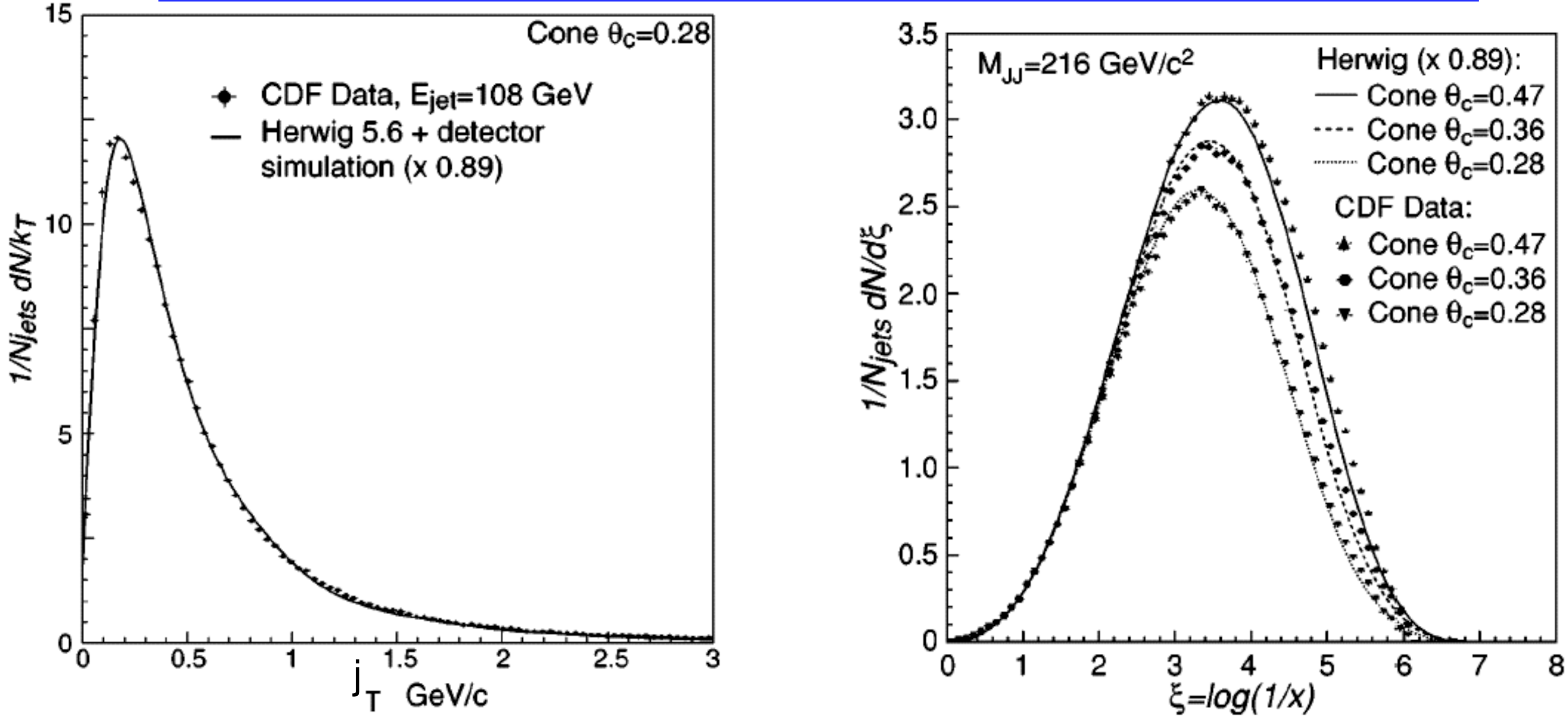
- Also jets will be produced by many different subprocesses:

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

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

CDF jet measurement in p-p collisions 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

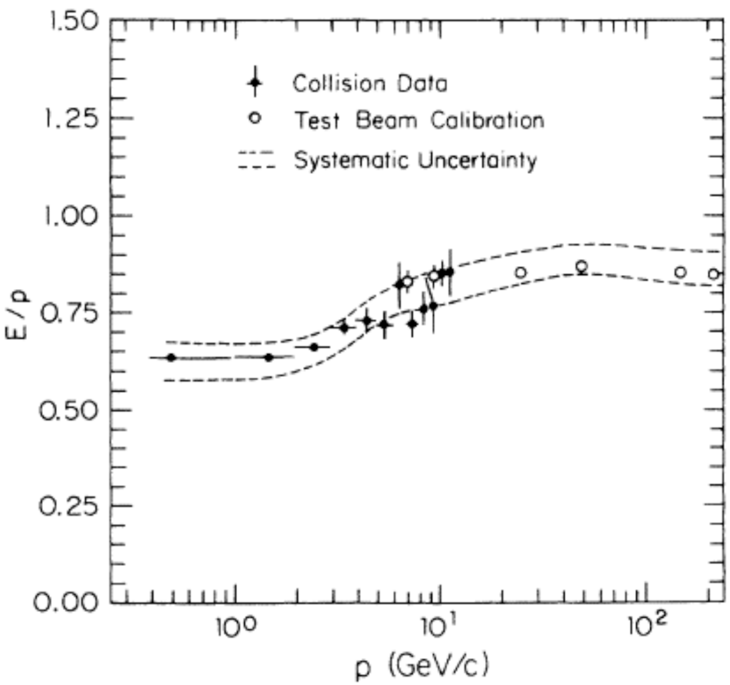


FIG. 6. CDF central calorimeter response (E/p) to pions as a function of incident momentum. The high-energy data come from test beam measurements, and the low-energy data (≤ 12 GeV) comes from isolated tracks in minimum-bias events.

D. Uncertainties in energy scale

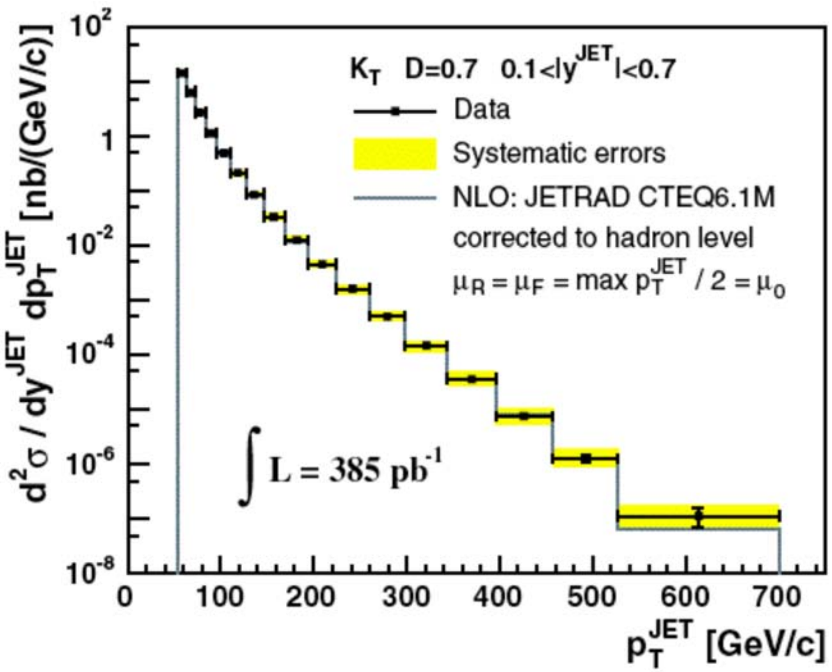
The dominant systematic uncertainty in the central jet energy scale results from the uncertainty in the single-pion response when convoluted with the jet fragmentation function [15]. The uncertainty in single-pion response is indicated by the dashed lines in Fig. 6. The uncertainty in the central energy 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 (≈ 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.

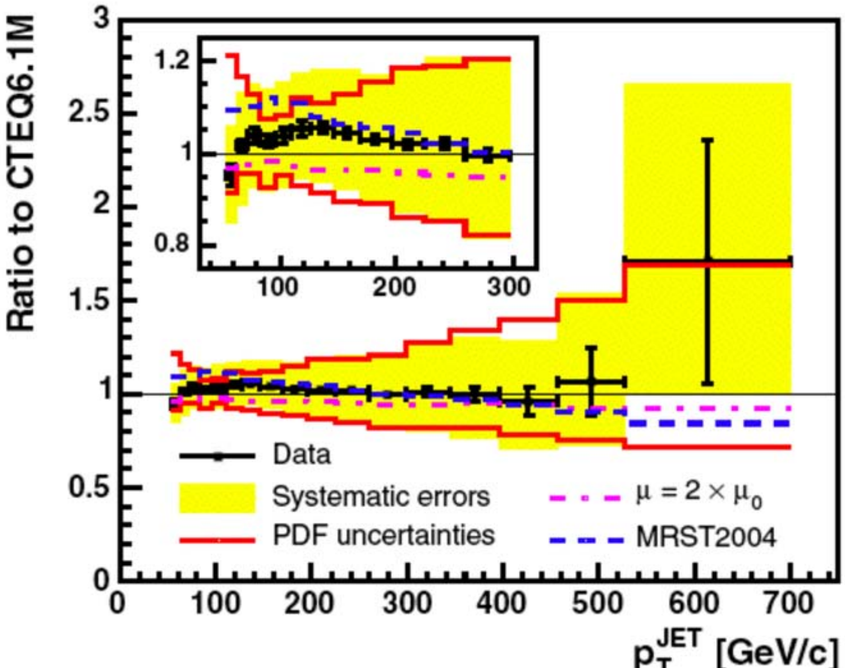
C. Underlying event and clustering corrections

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



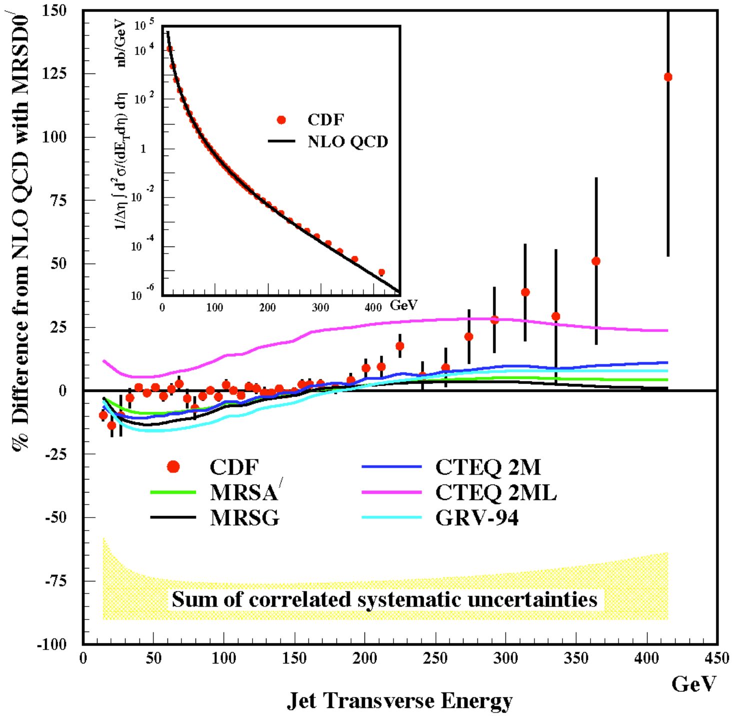


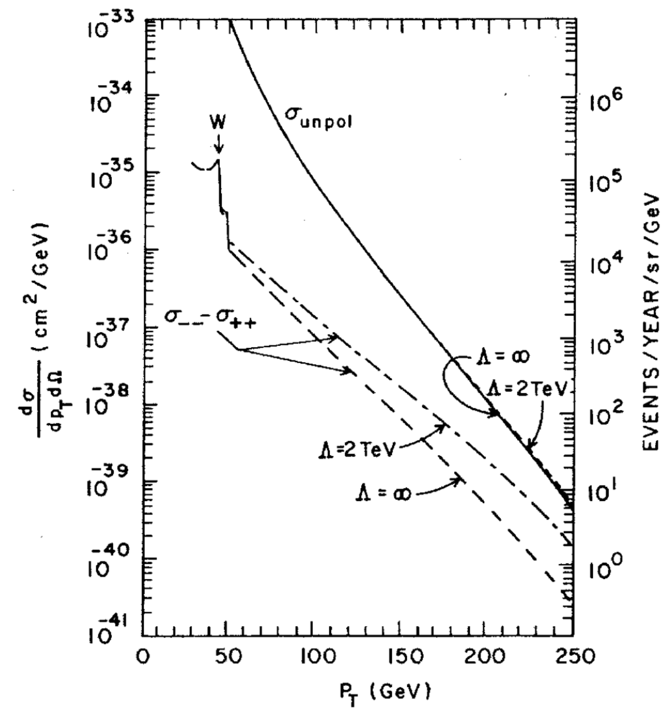
The measured crosssection is in agreement with NLO pQCD predictions after the necessary nonperturbative parton-to-hadron corrections are taken into account.

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

Part of the learning curve CDF 1996

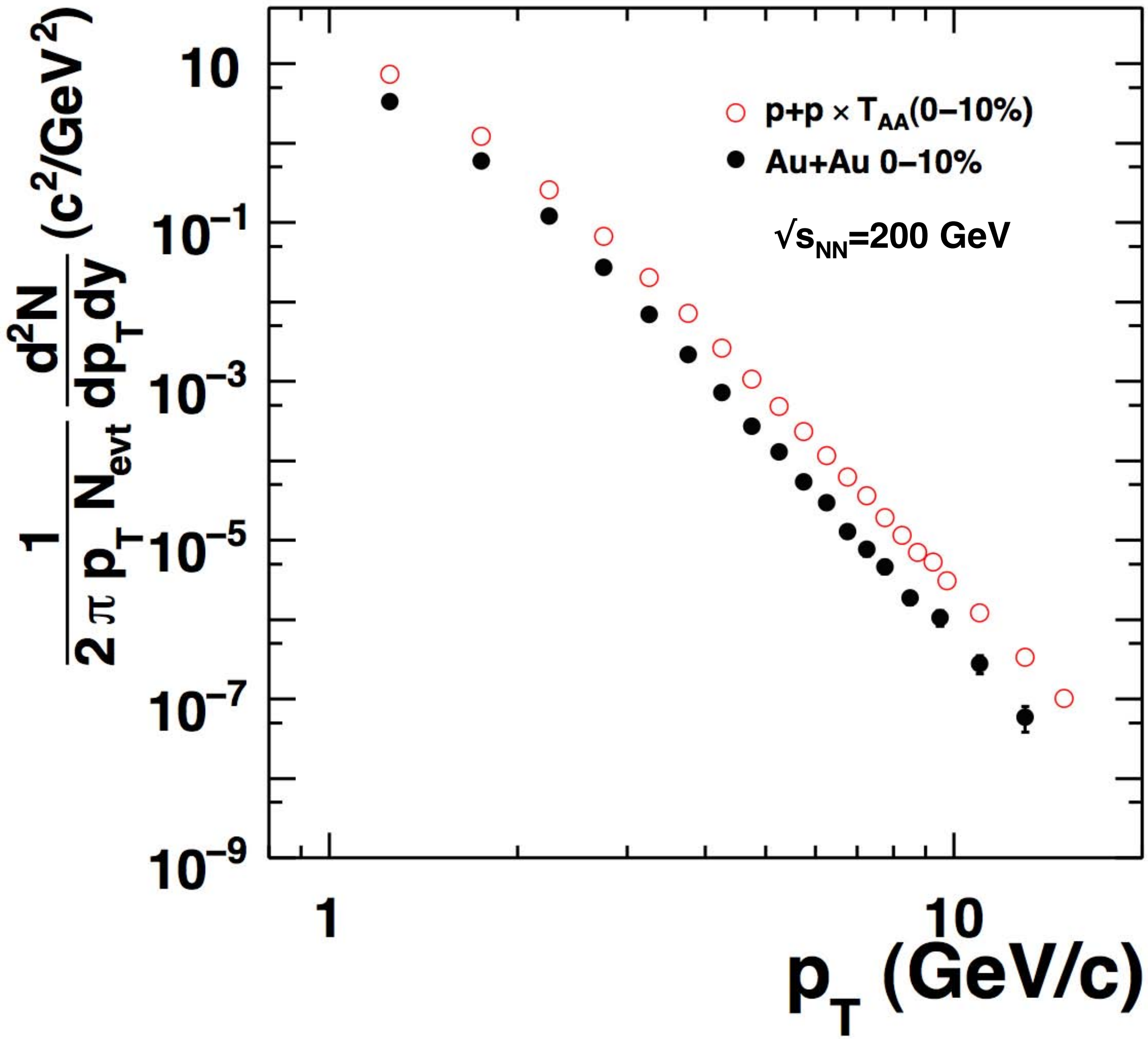




In PRL **77**, 438 (1996) CDF reported that Jet cross section deviates from QCD at large p_T. Figure looks exactly like 1983 Figure of Paige and Tannenbaum (BNL-33119, 1983) proposing to detect quark substructure via parity violation following [Eichten,Lane, Peskin, PRL **50**, 811 (1983)]. PV would be a clear signature of new physics! CDF deviation from QCD was explained by invoking an even better than new Gluon structure function CTEQ4HJ [Huston, et al, PRL 77, 444 (1996)]

Do you believe this? Needs to be checked with direct γ measurements with $x>0.25$

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

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

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

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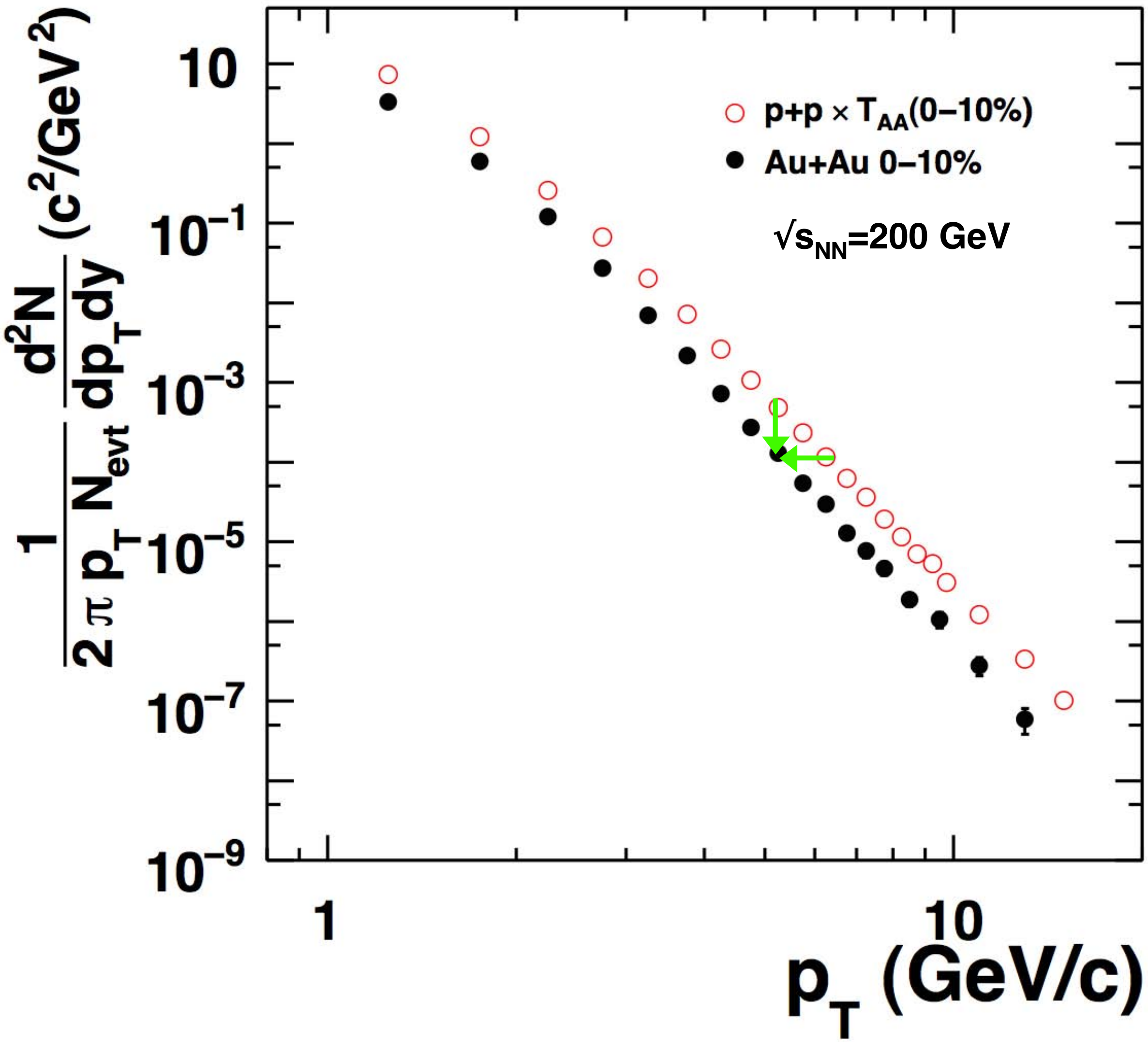

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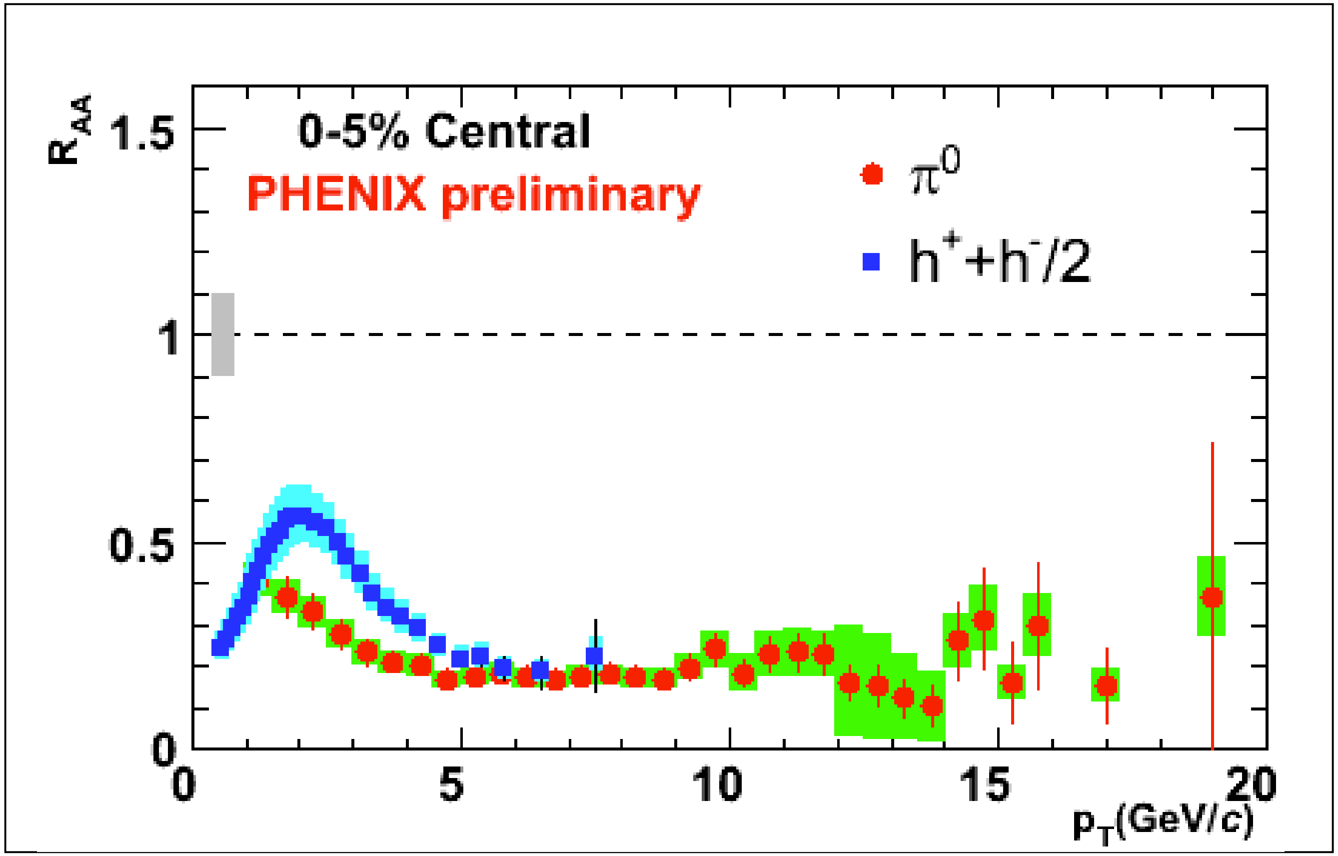
$$R_{BA} = \frac{\left[d^2N^{\pi}_{BA}/dp_T dy dN^{inel}_{BA}\right]}{\langle N_{coll}\rangle / \sigma^{inel}_{pp} \times \left[d^2\sigma^{\pi}_{pp}/dp_T dy\right]}$$

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)

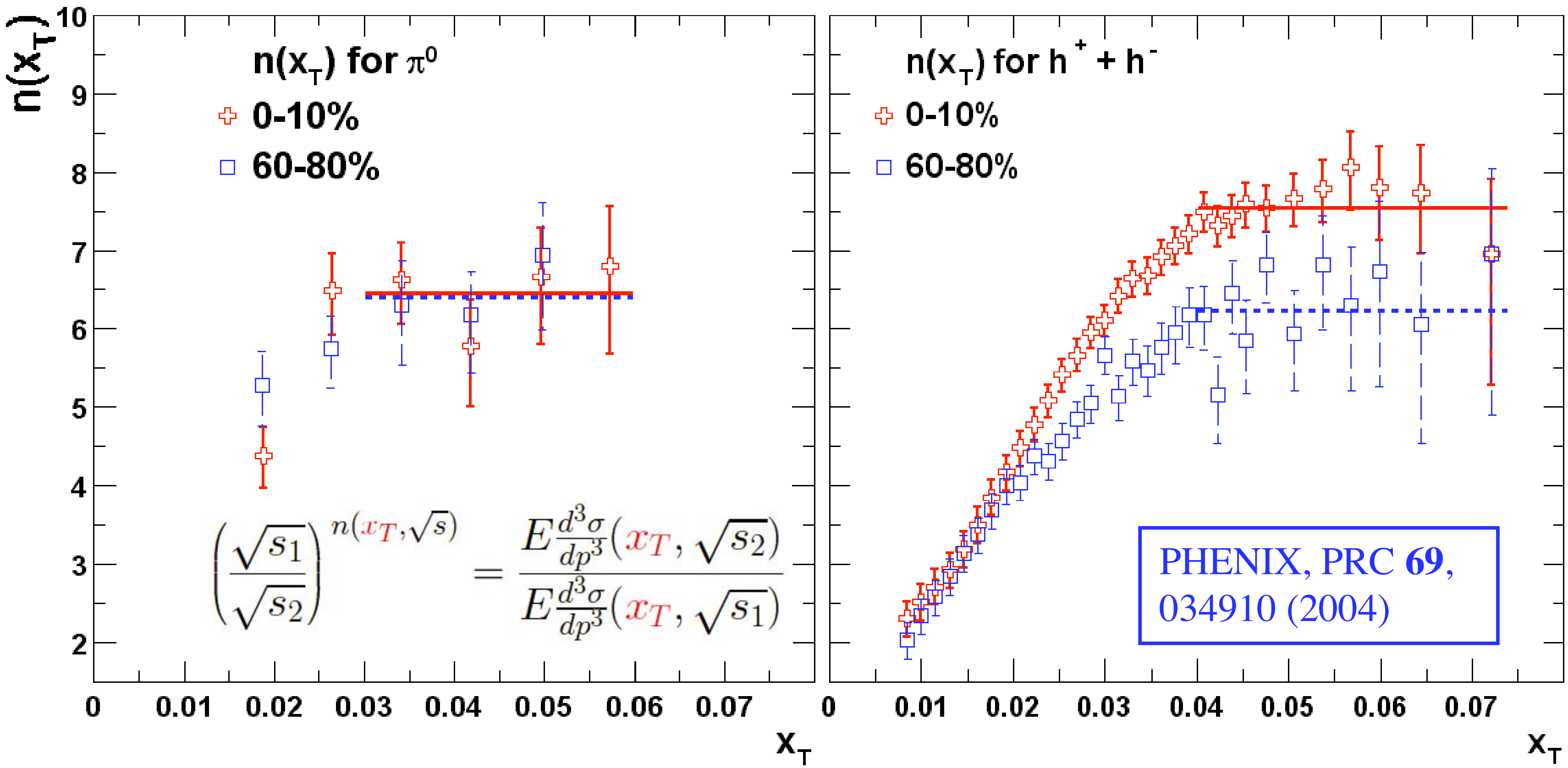
R_{AA}: π^0 and non-identified charged are different for p_T <6 GeV/c, dubbed "Intermediate p_T"

Au Au $\sqrt{s_{NN}}$=200 Gev-run 4



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

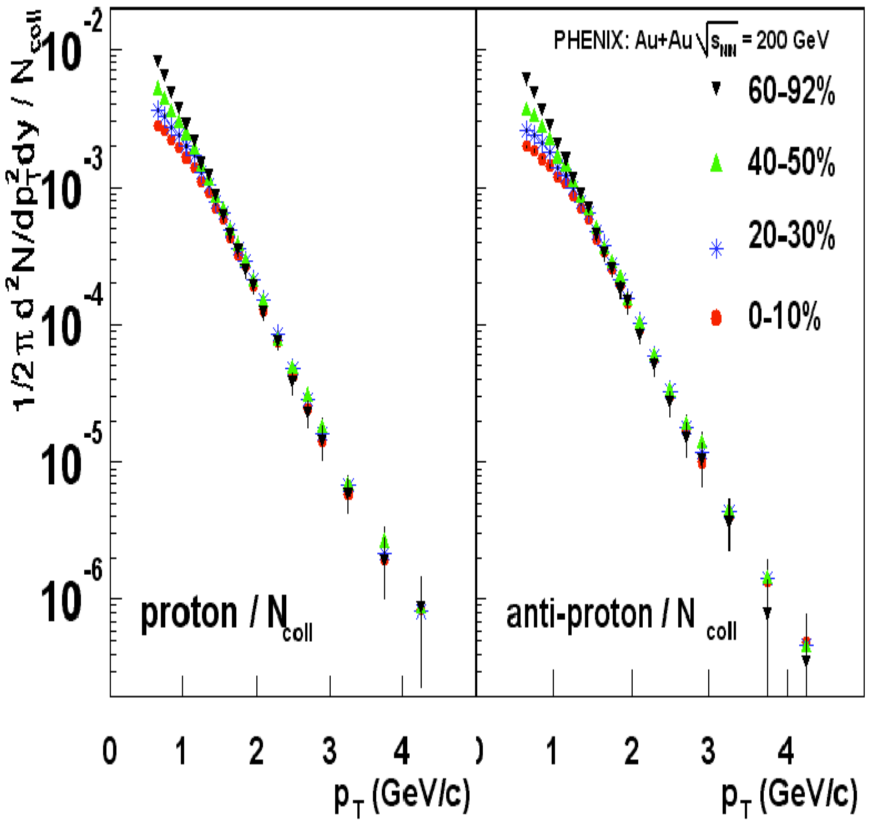


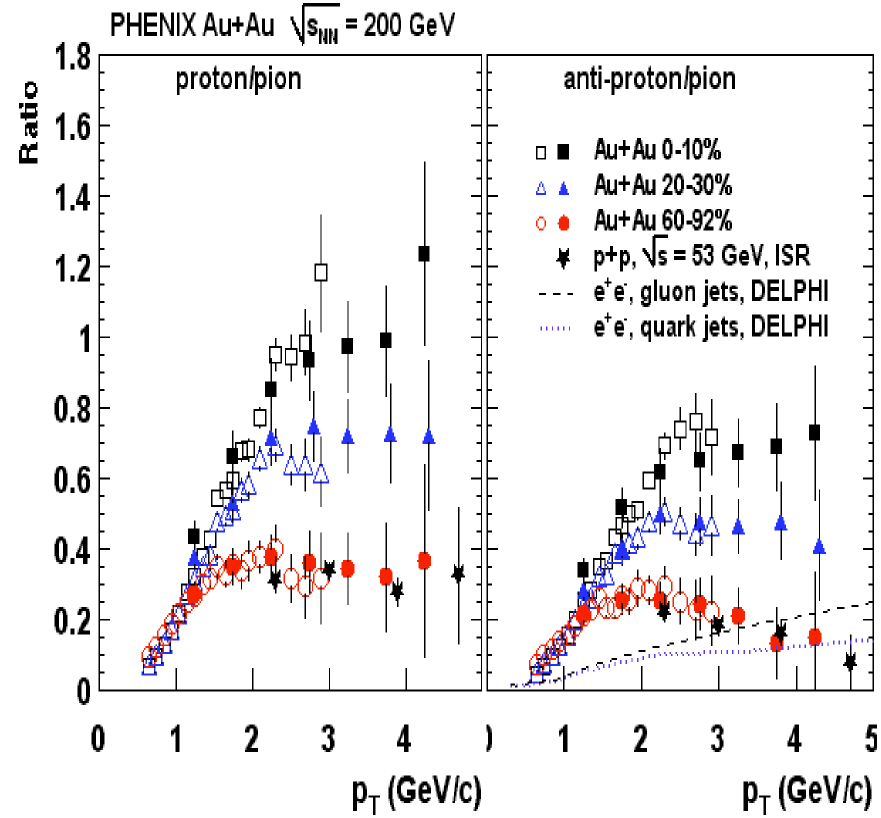
• π^0 x_T scales in both peripheral and central Au+Au with same value of n=6.3 as in p-p. Indicates that structure and fragmentation fns. (including any energy loss) *scale* in AuAu i.e. energy loss is fractional. Note: a constant fractional energy loss and a power law spectrum implies that R_{AA}=constant as observed!

• $(h^+ + h^-)/2$ 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



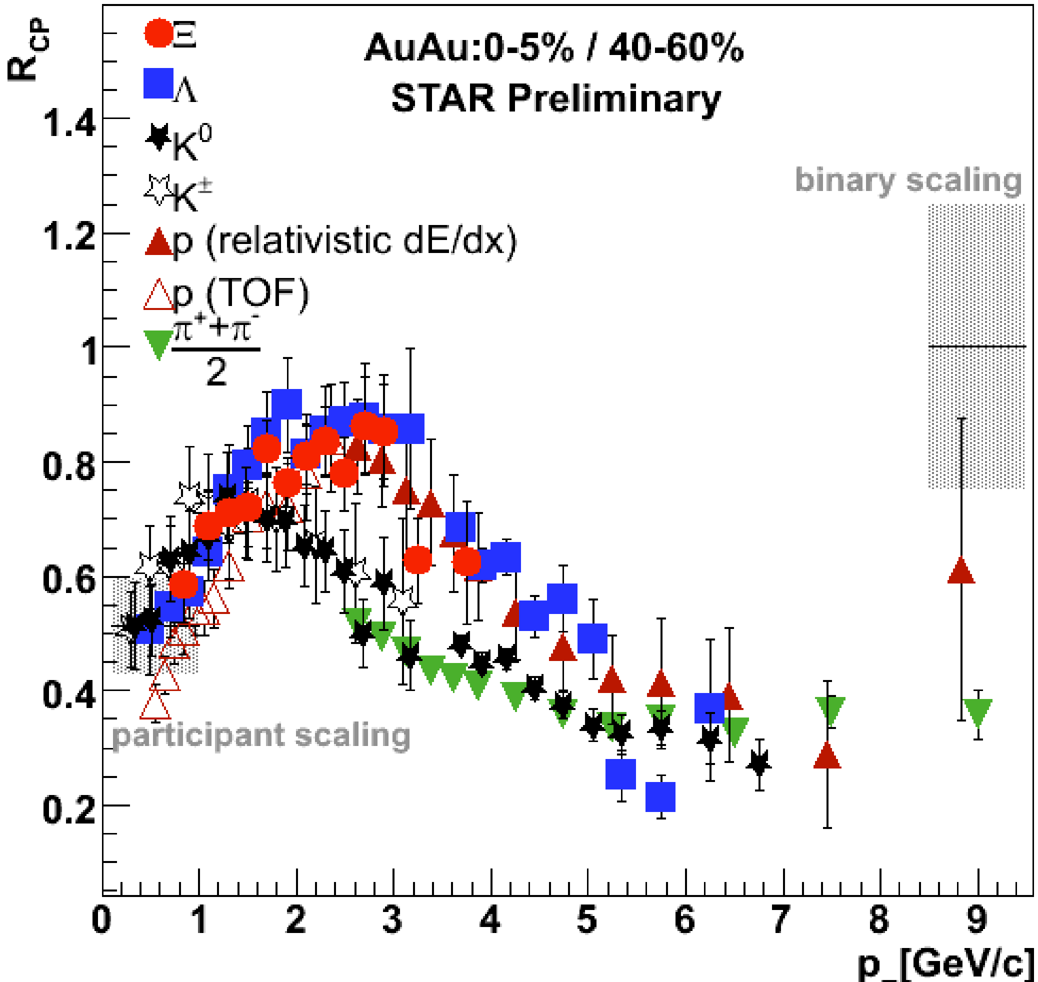


p± are not suppressed

p±/π± 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



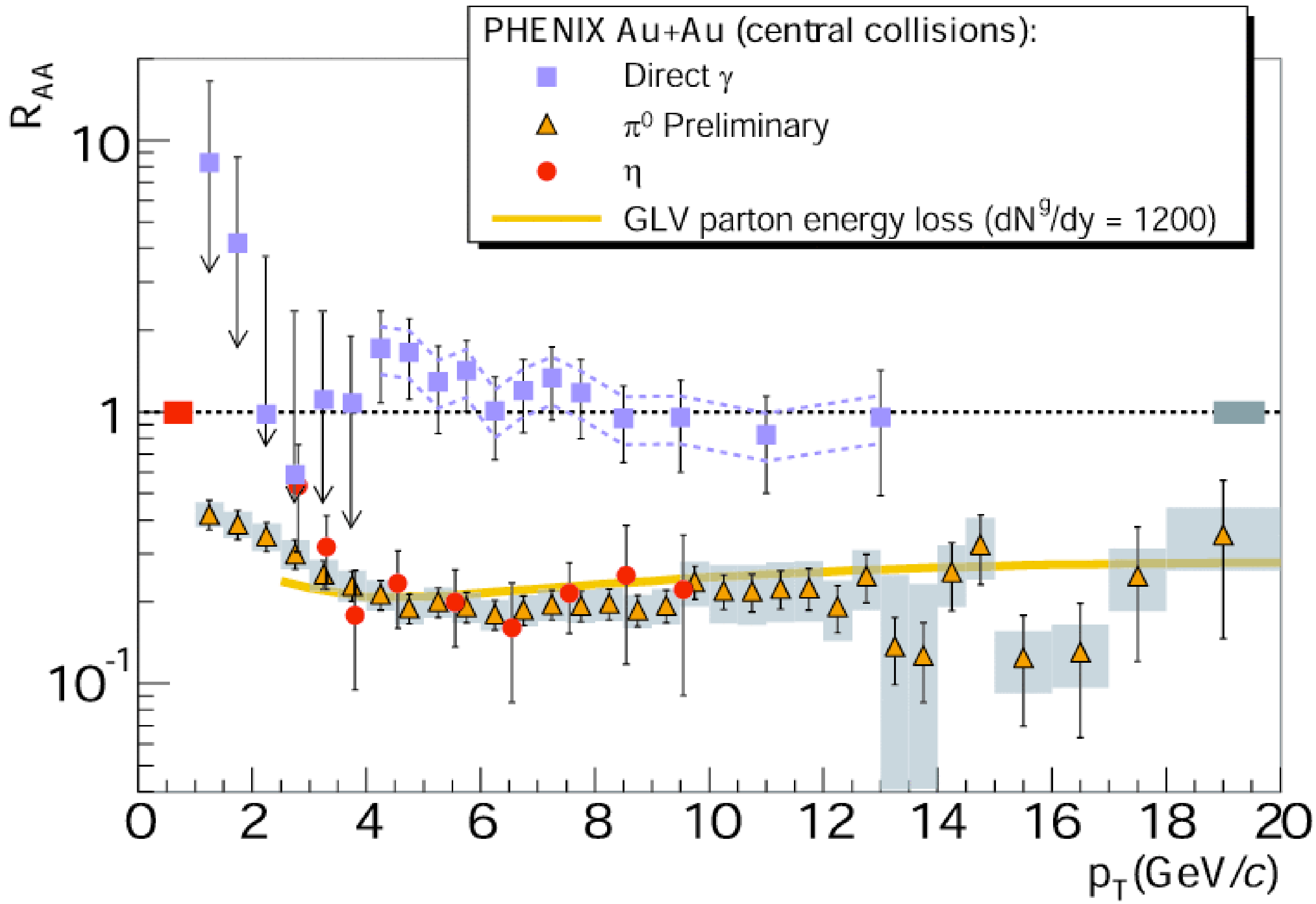
STAR-Jana Bielcikova Hard Probes 2006

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

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

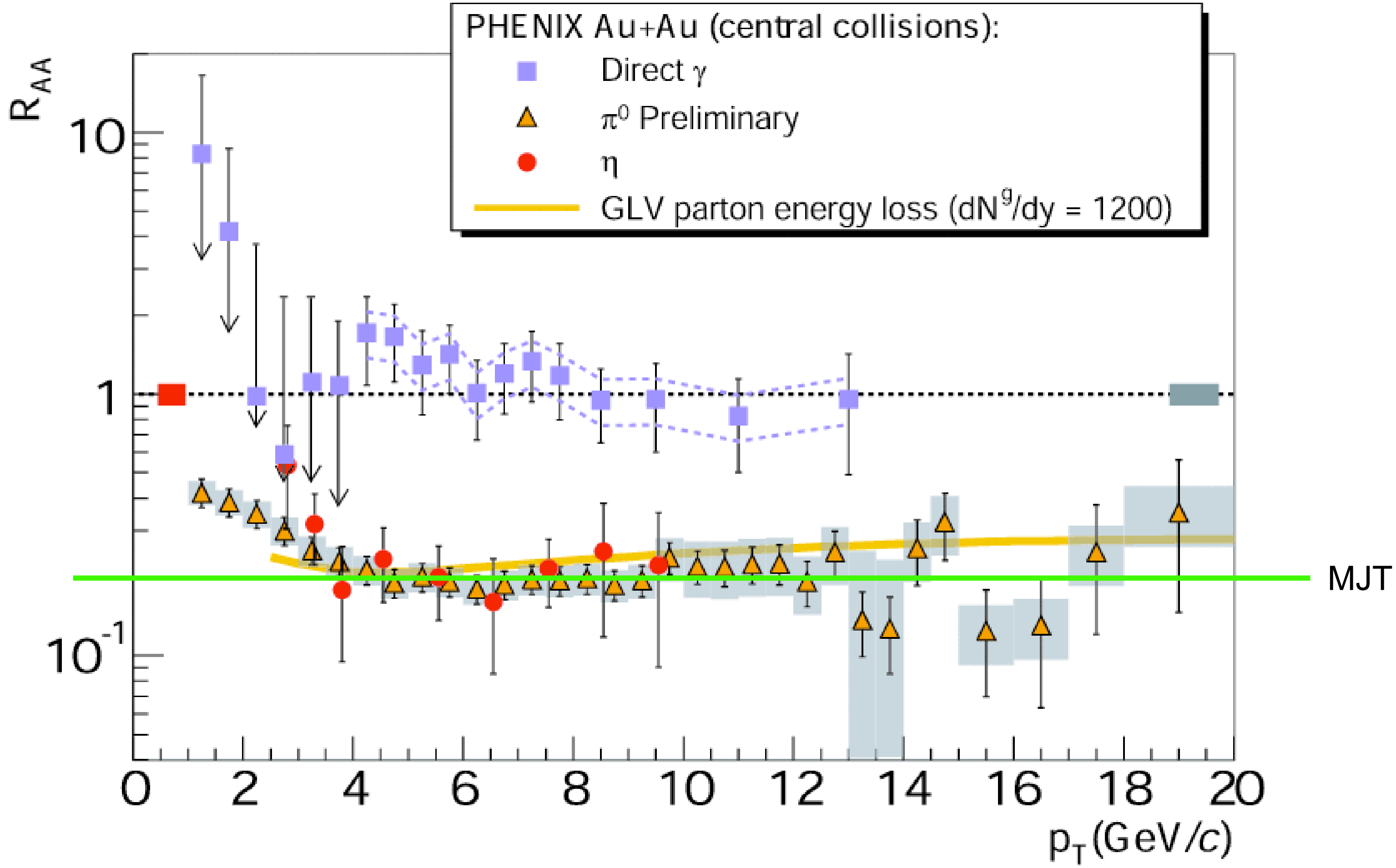
- Very important to measure at LHC--needs pid over a large p_T range

Status of R_{AA} in AuAu at $\sqrt{s_{NN}}$=200 GeV QM05



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?

Status of R_{AA} in AuAu at $\sqrt{s_{NN}}$=200 GeV QM05



Direct γ are not suppressed. π^0 and η suppressed even at high p_T
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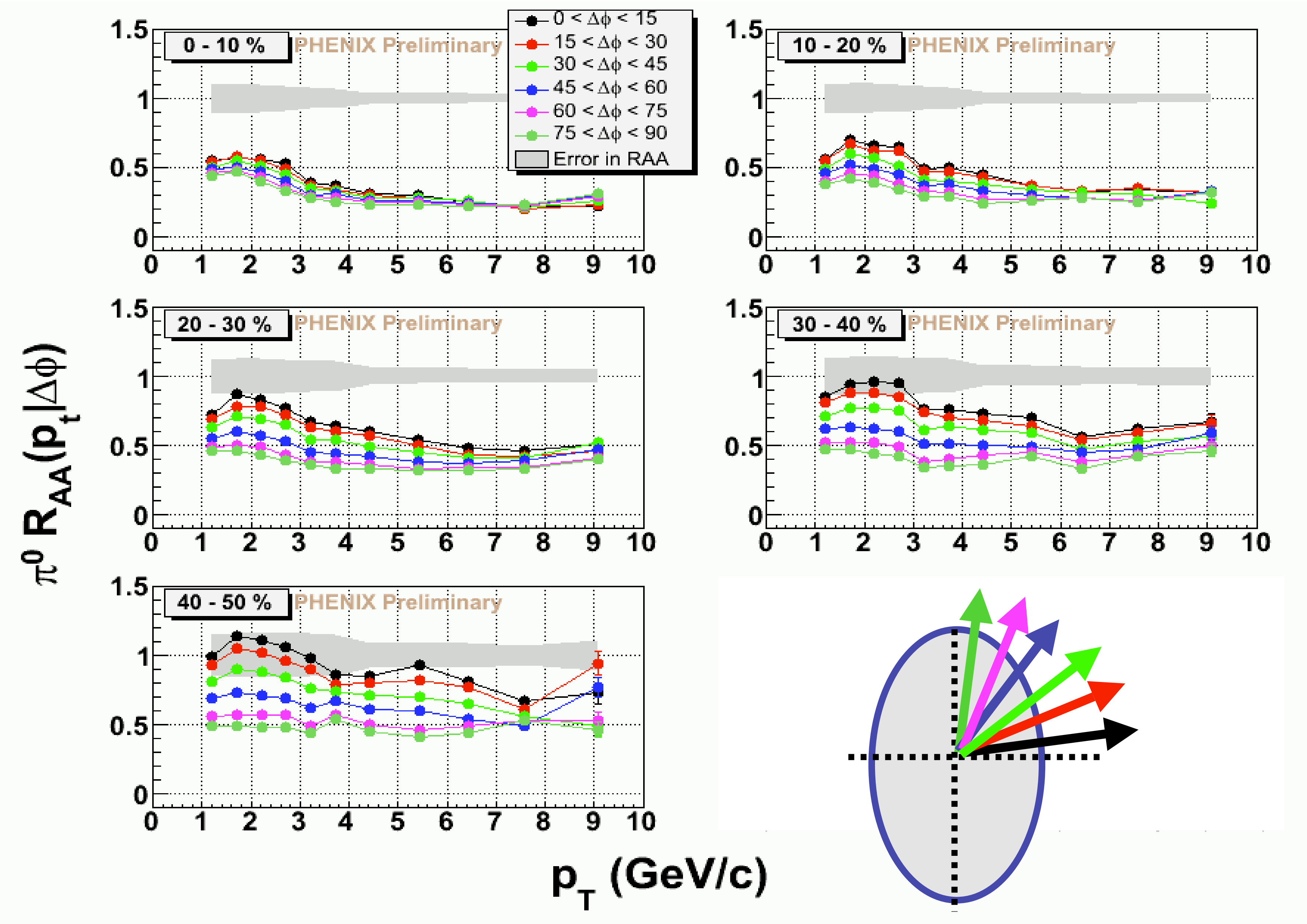
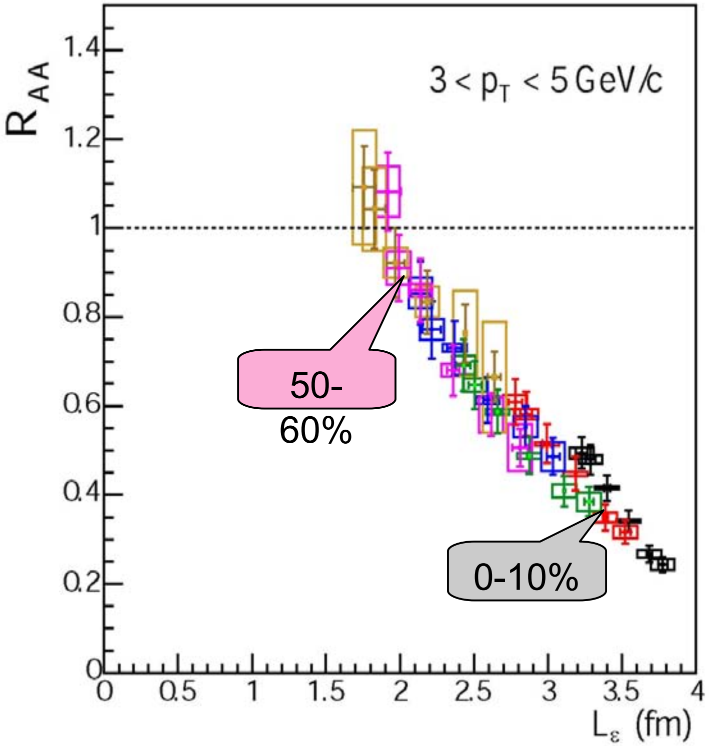
To test details of Theory⇒$R_{AA}(\Delta\phi, p_T)$-π^0

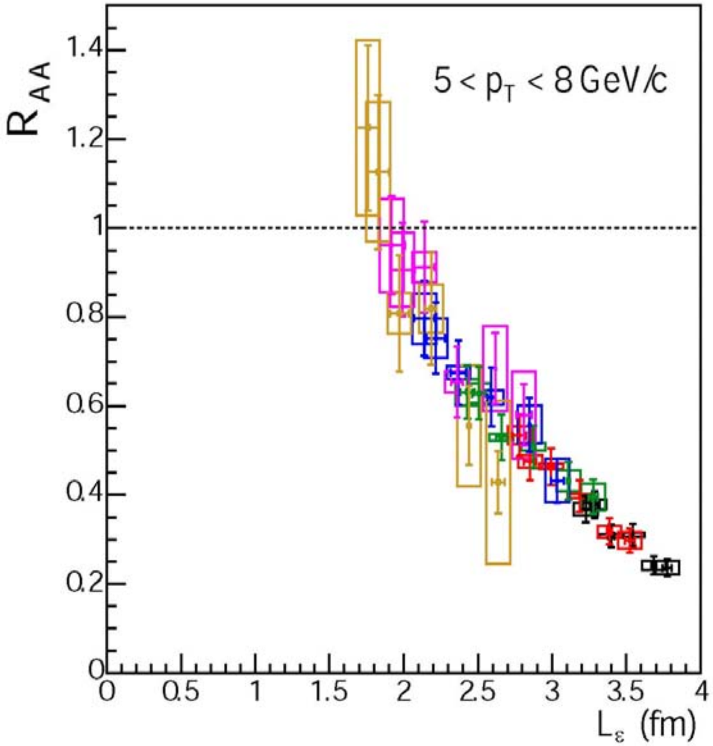


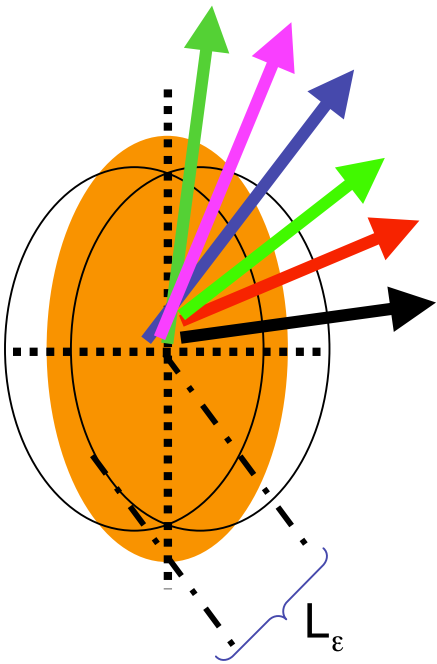
R_{AA} π^0 vs. Reaction Plane-learn something new!

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

The biggest result at QM2006??!

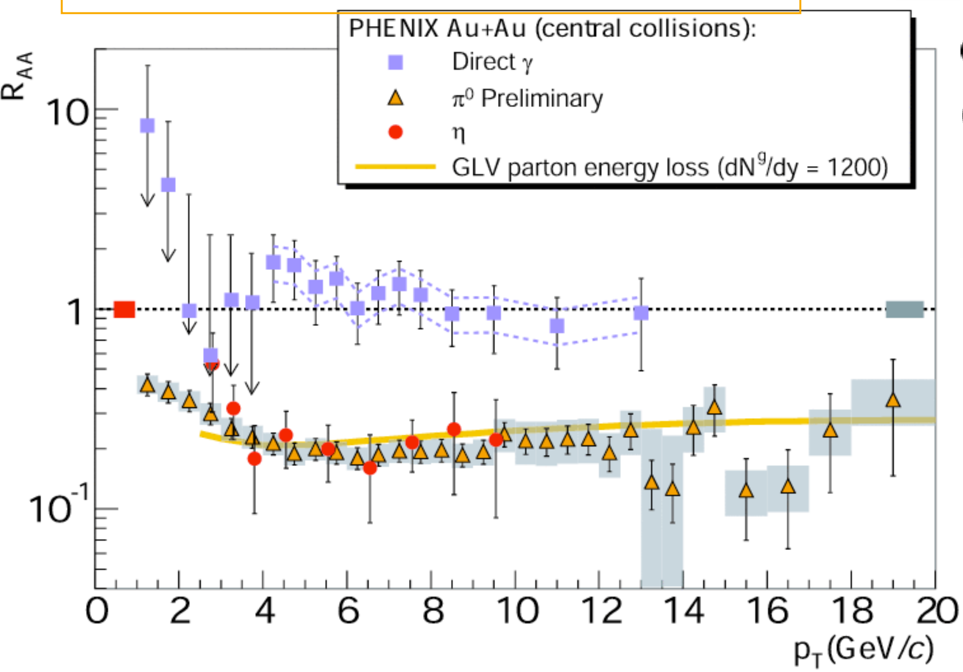
$$R_{AA}(p_T) = \frac{d^2Y^{AA}/dp_T dy}{\langle T_{AA}\rangle d^2\sigma^{NN}/dp_T dy}$$

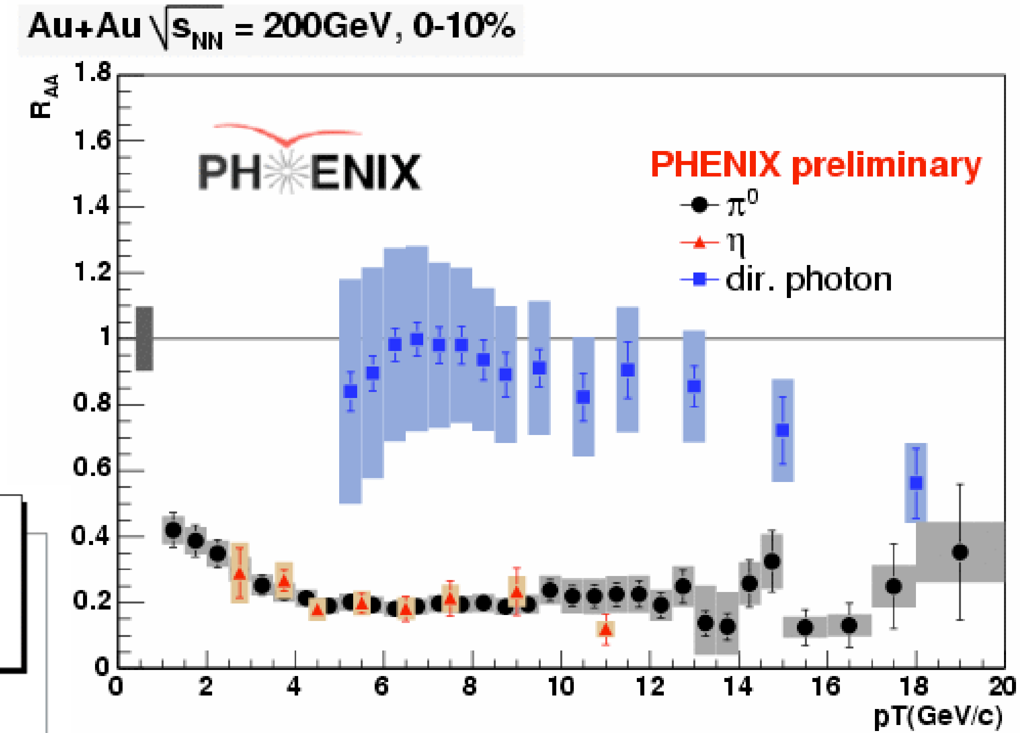
$$T_{AA} = \langle N_{coll}\rangle / \sigma_{inel.}$$

QM2005

-I wanted to make a T-shirt

pp dir γ reference is pQCD



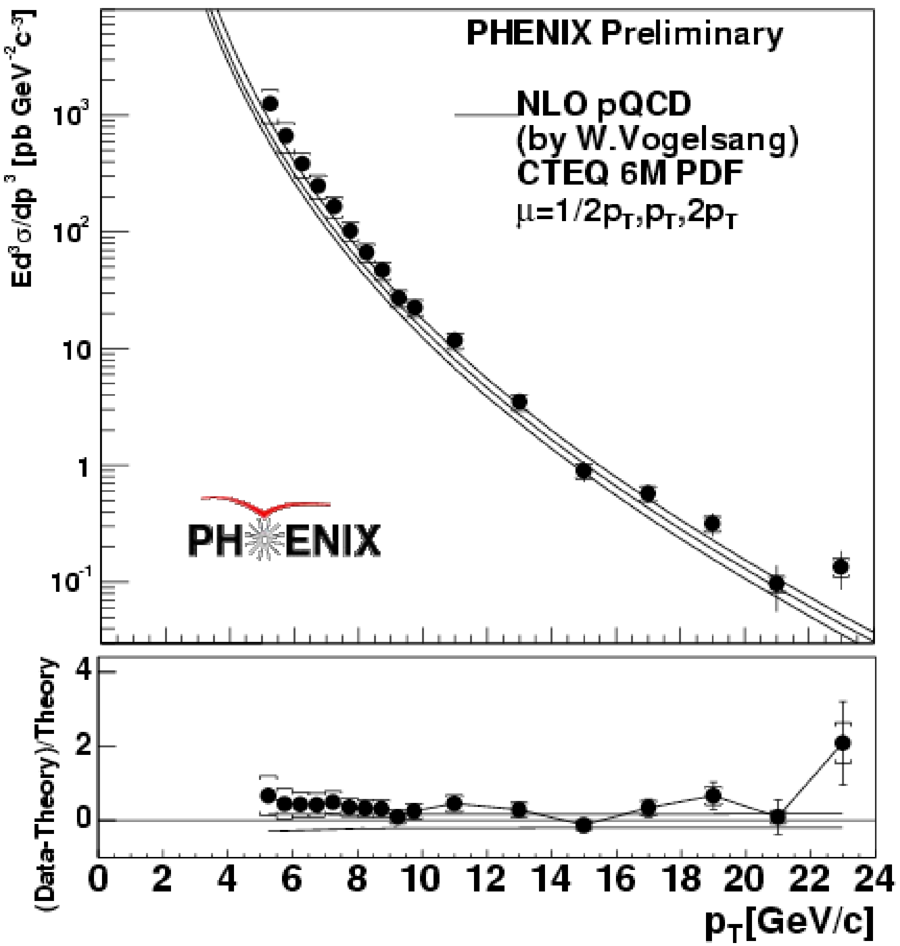


QM2006-

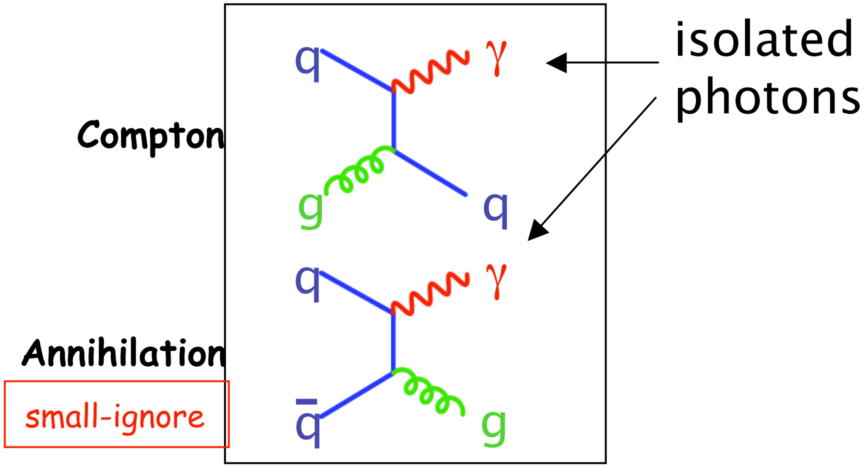
pp dir γ reference is run 5 msmt

If $R^{\pi}_{AA} = R^{\gamma}_{AA}$ the whole concept of energy loss changes: perhaps no effect for p_T>20 GeV

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.



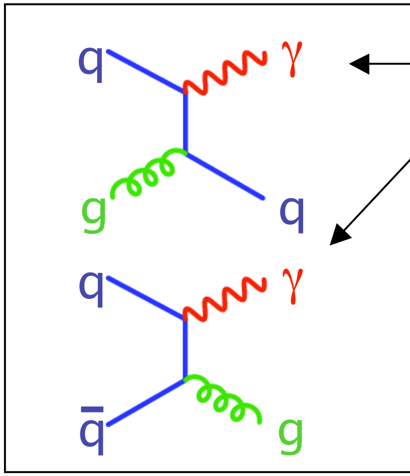
Direct photon production-simple theory hard experiment

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

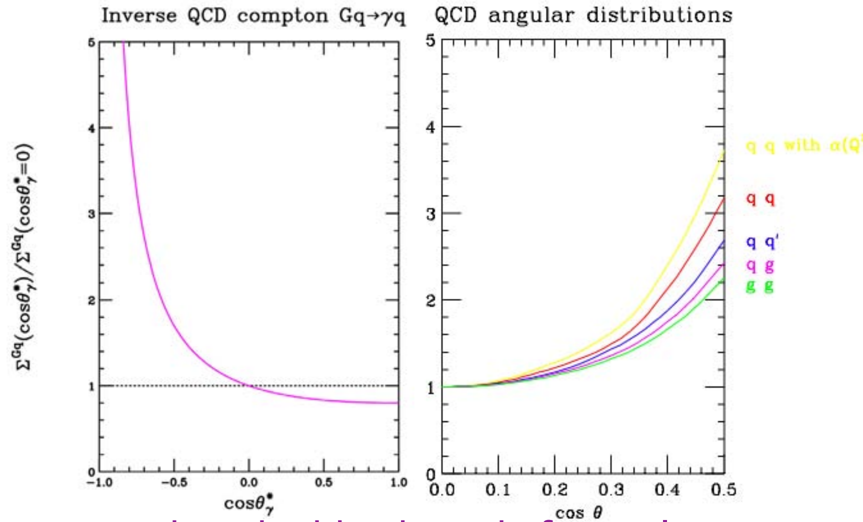
Compton

Annihilation

small-ignore



isolated photons



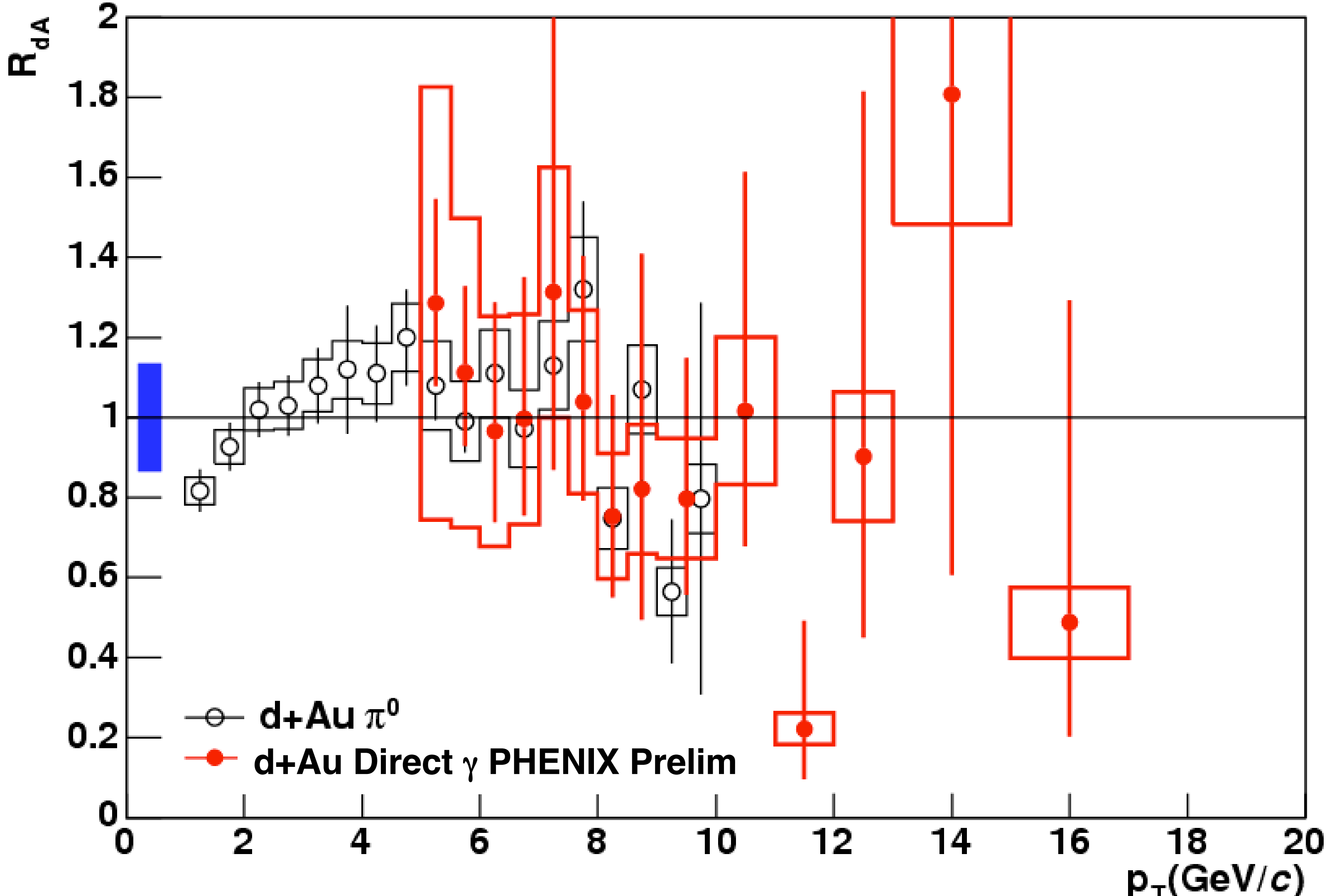
Compton distribution is much flatter than scattering and peaked backwards from gluon

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

Substitution and Jacobean gives:

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

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

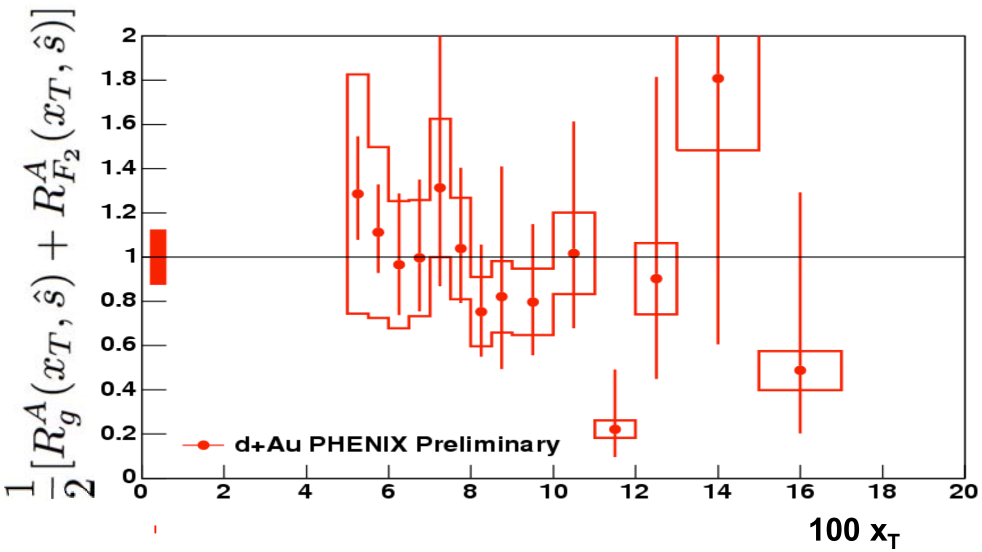
Nuclear Modification Factor-Min Bias

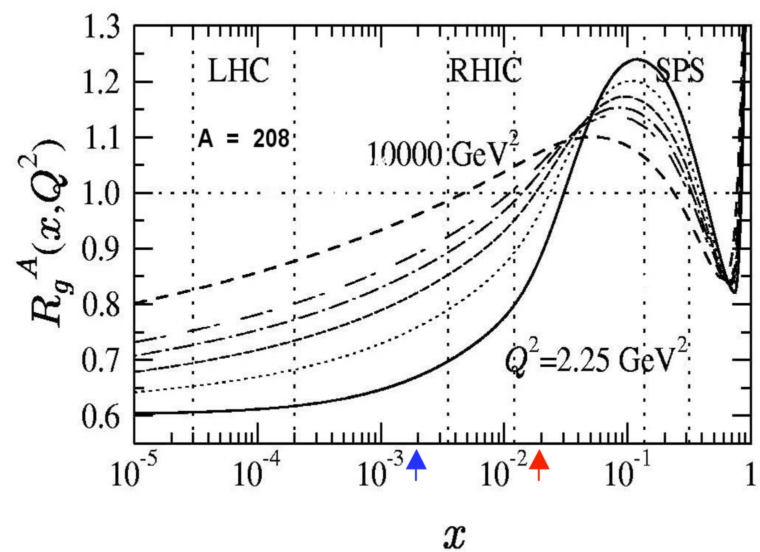
$$R_{dA} = \frac{d\sigma_\gamma^{dA}(p_T)/dp_T}{(2\times A)\times d\sigma_\gamma^{pp}(p_T)/dp_T}$$

$$\boxed{R_{dA} \approx \frac{1}{2}\left(\frac{F_{2A}(x_T)}{AF_{2p}(x_T)} + \frac{g_A(x_T)}{Ag_p(x_T)}\right)}$$

$$= R_g^A(x,Q^2)$$

Eskola, Kolhinen, Vogt hep-ph/0104124





Consistent with 1 ➔ No modification within the error

This is first measurement of 'EMC effect' for gluons

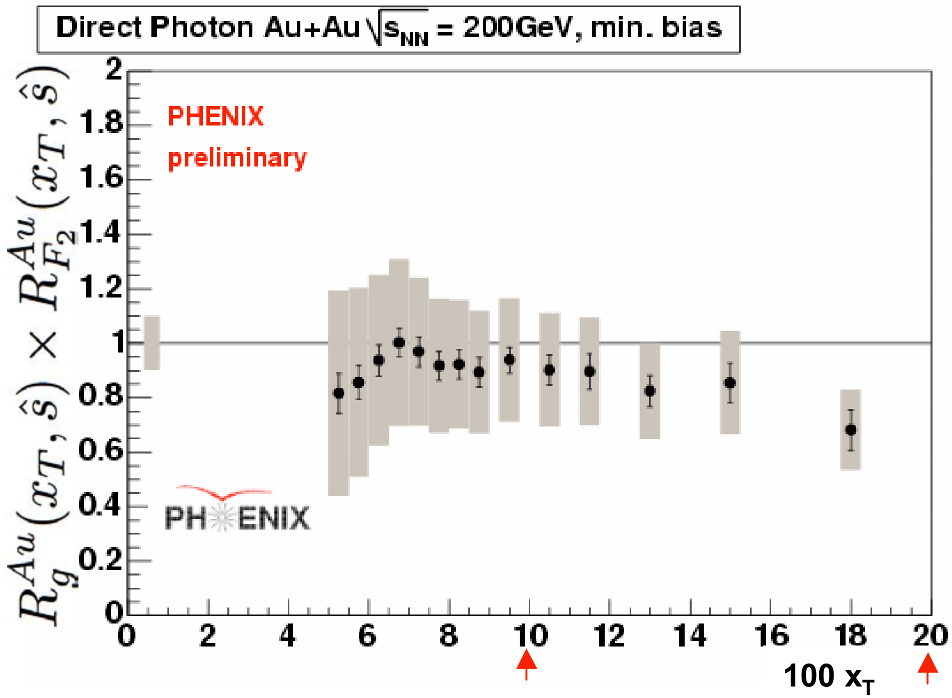
x	p_T(RHIC)	p_T (LHC)
0.02	2 GeV/c	60 GeV/c
0.002	0.2 GeV/c	6 GeV/c

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



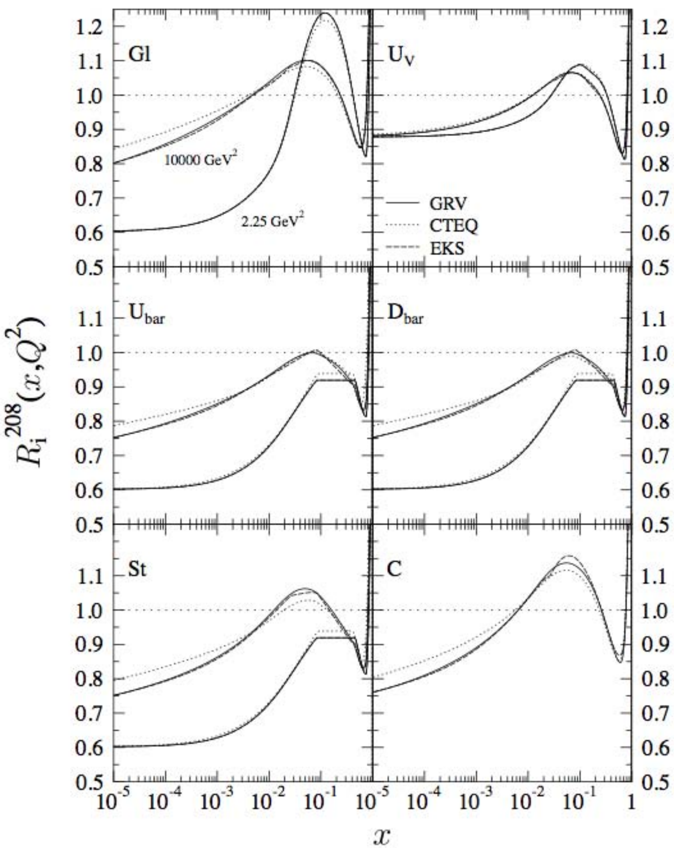


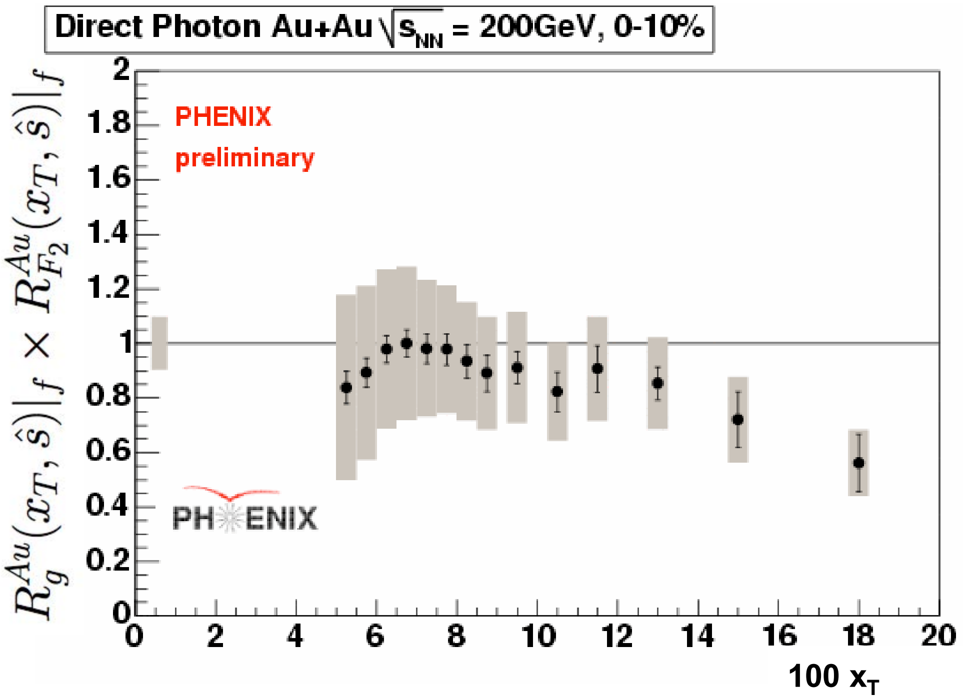
Fig. 1. The nuclear ratios $R_i^A(x,Q^2)$ for individual parton flavours $i = g, u_V, \bar{u}, \bar{d}, s, c$ of a lead nucleus $A = 208$ as functions of x at fixed values of $Q^2 = Q_0^2 = 2.25$ GeV^2 and $Q^2 = 10000$ GeV^2 as obtained by using the GRV-LO [25] distri-

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

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



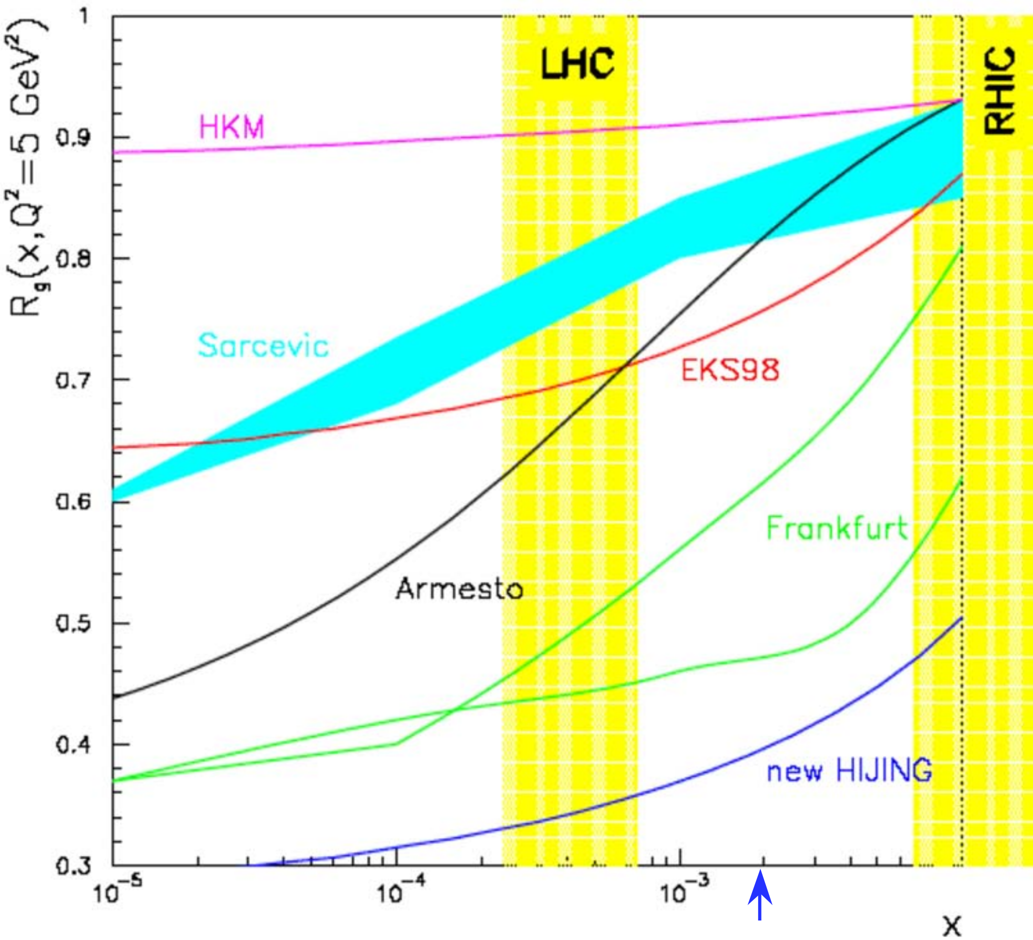
Theorists, HELP!

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!!!

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



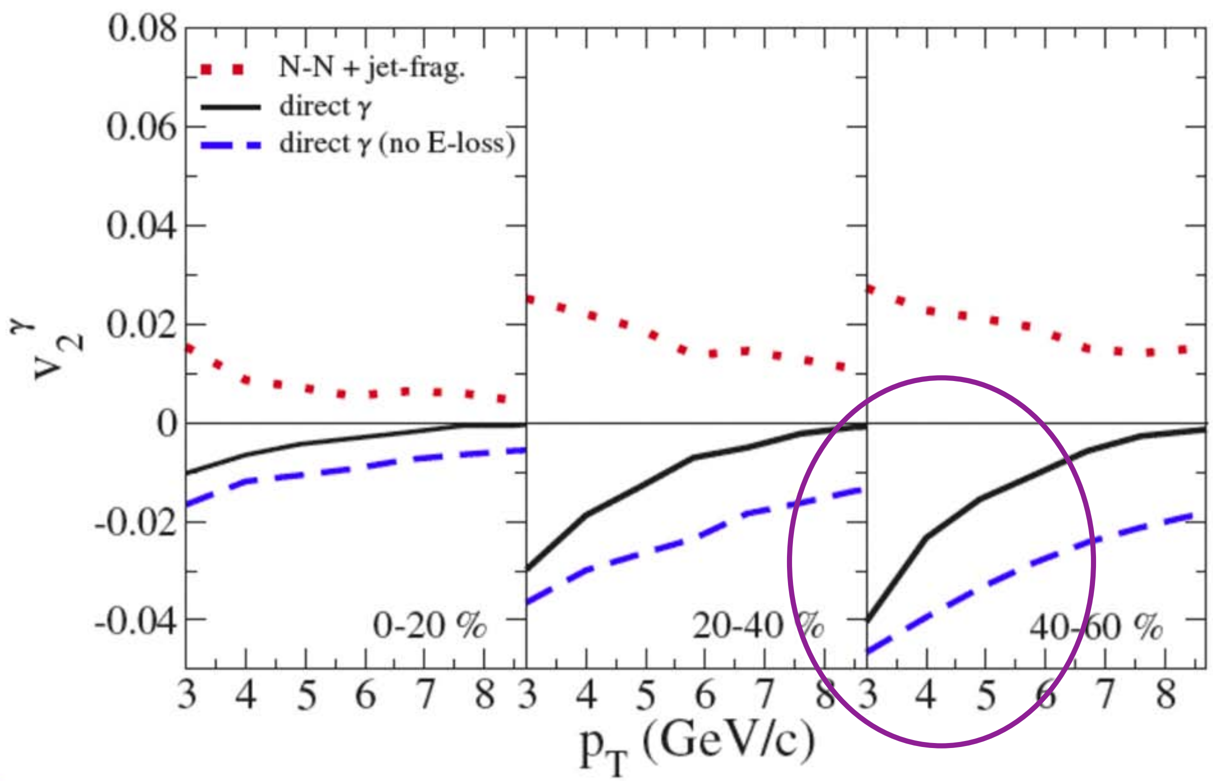
Predictions from CERN-Yellow-report-hep-ph/0308248

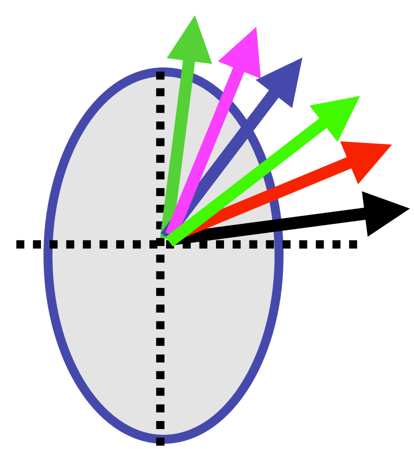
- For pp make sure to run at 900 GeV and 14000 GeV. Interpolation +QCD might be adequate to believe 5500 GeV
- LHC could be the CGC factory. $R_g(x,Q^2)$ not known for any A or any x or Q^2. Forward d+Au measurements at RHIC will be useful.

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

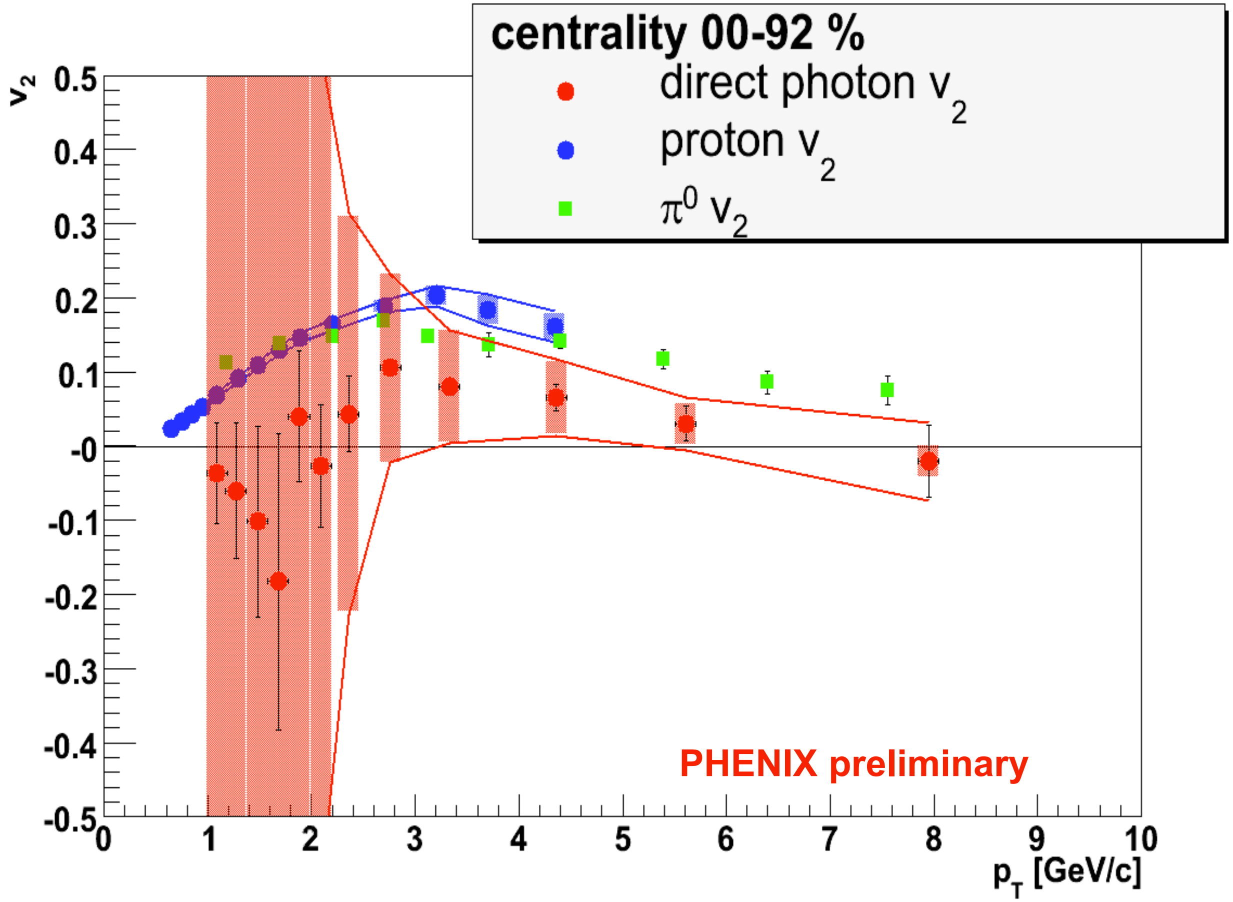
Direct γ with respect to the reaction plane

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



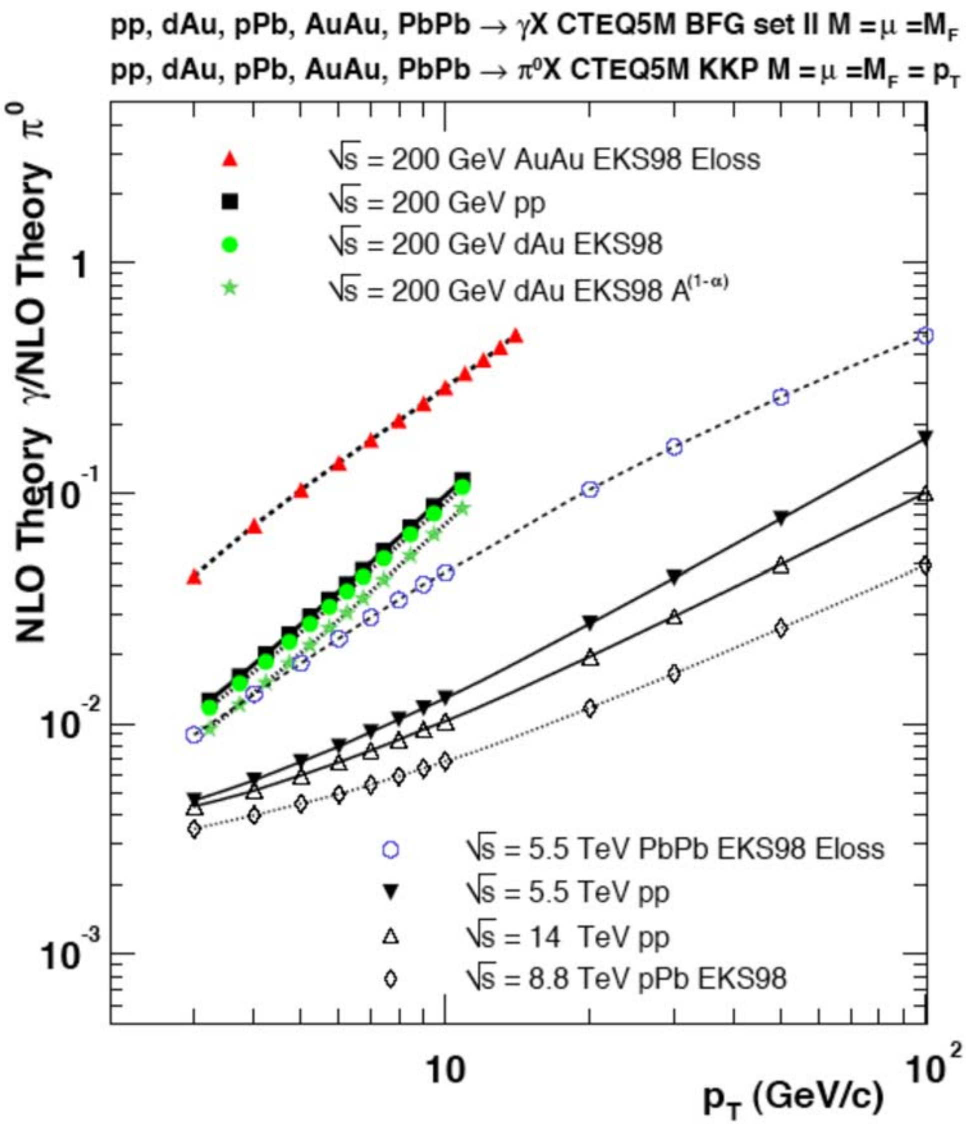


PHENIX direct-γ v_2 QM2006



Needs big improvement. We just have installed a new reaction plane detector for coming high luminosity Au+Au run7 for rare probe v2 measurement at PHENIX

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

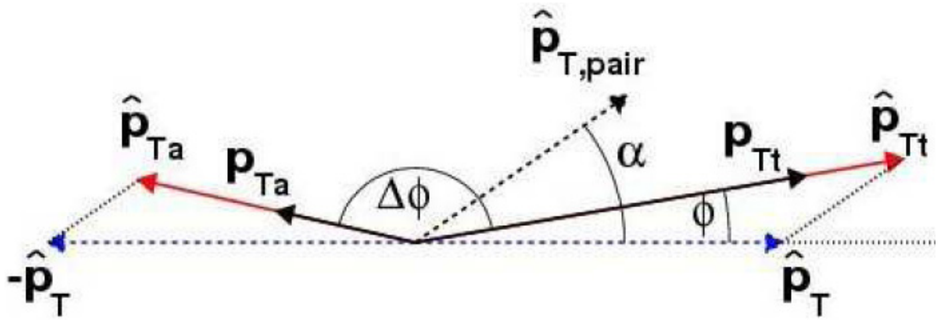
CERN Yellow Report-hep-ph/0311031

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

Correlations

A very interesting formula

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

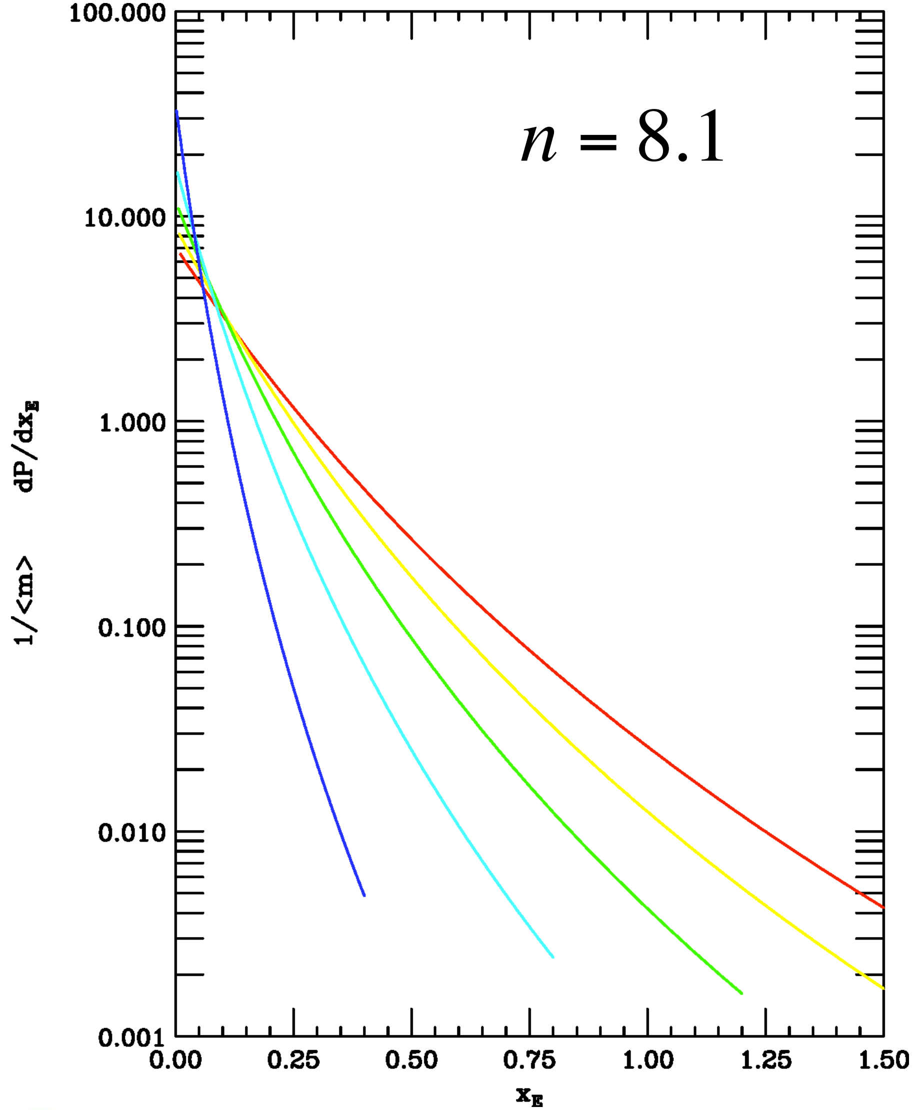


$$x_E = \frac{-p_{T_a}\cos\Delta\phi}{p_{T_t}} \simeq \frac{p_{T_a}}{p_{T_t}} \quad \longrightarrow \quad \hat{x}_h = \frac{\hat{p}_{T_a}}{\hat{p}_{T_t}}$$

measured

Ratio of jet transverse momenta

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



$\hat{x}_h$

1.0

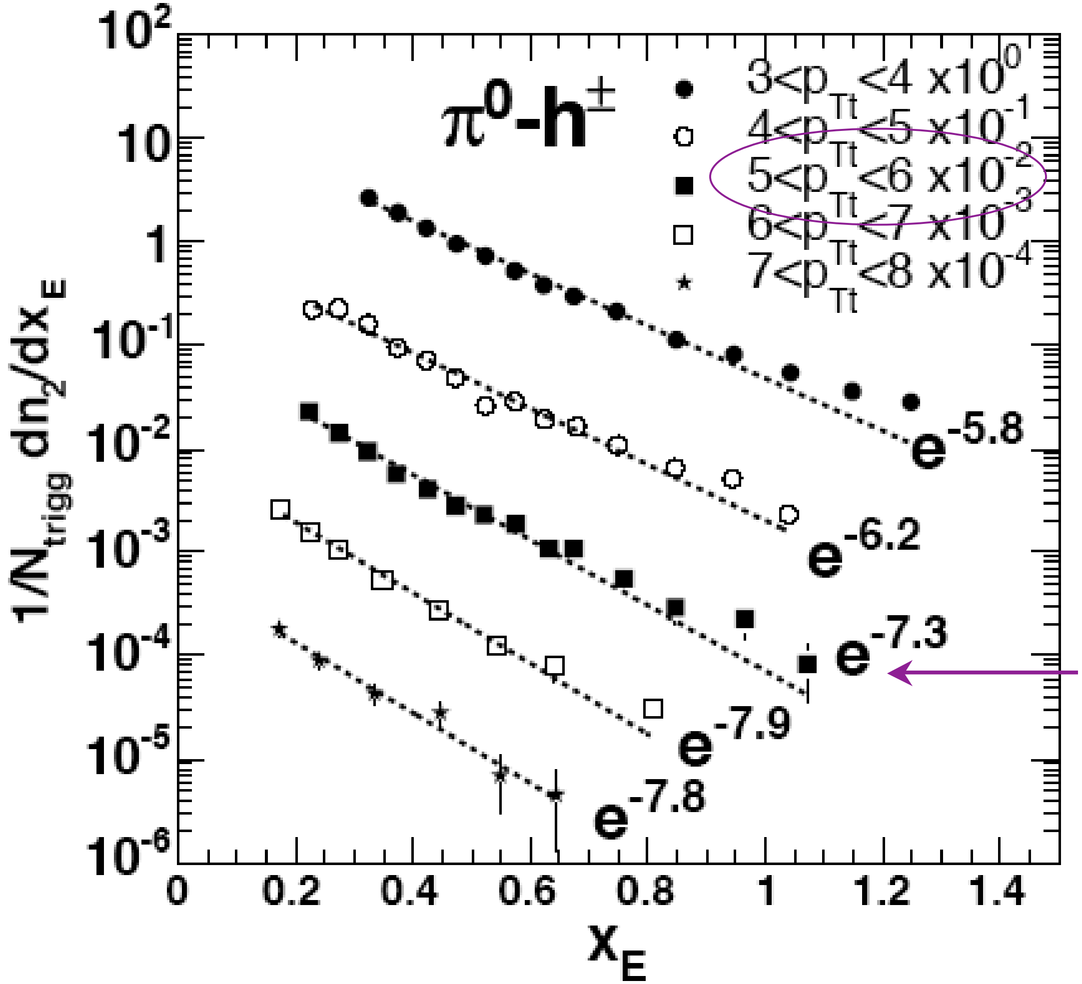
0.8

0.6

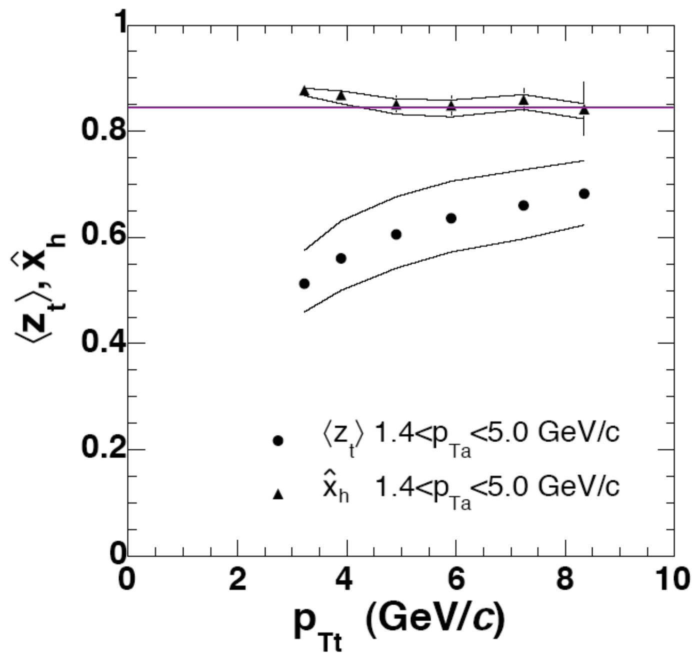
0.4

0.2

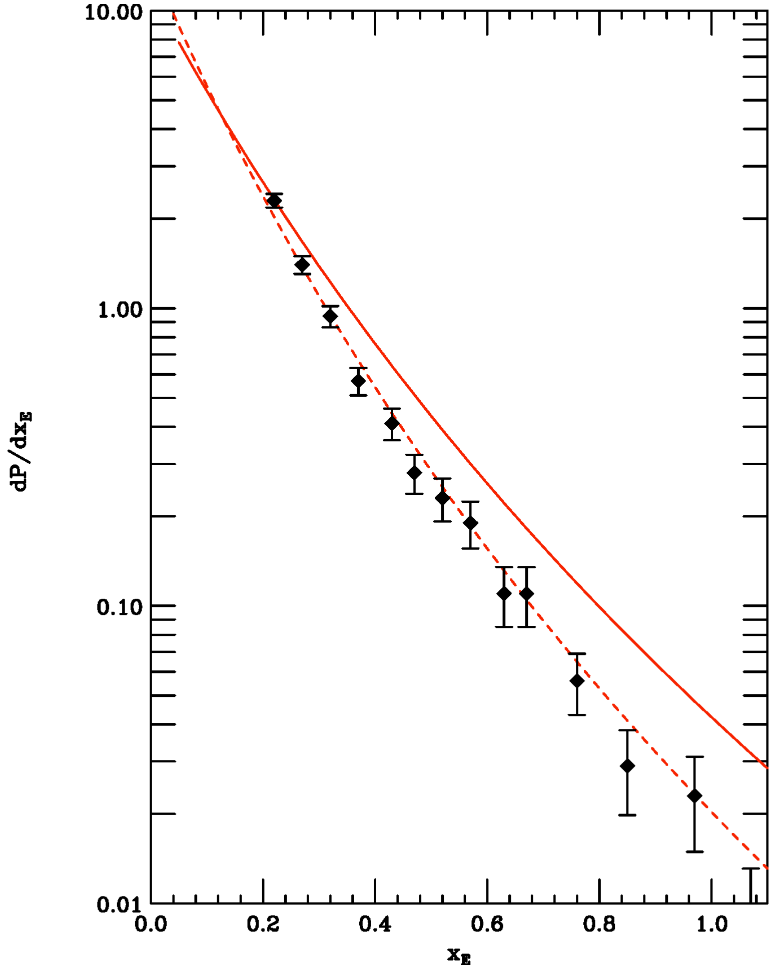
The formula works in p+p



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



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



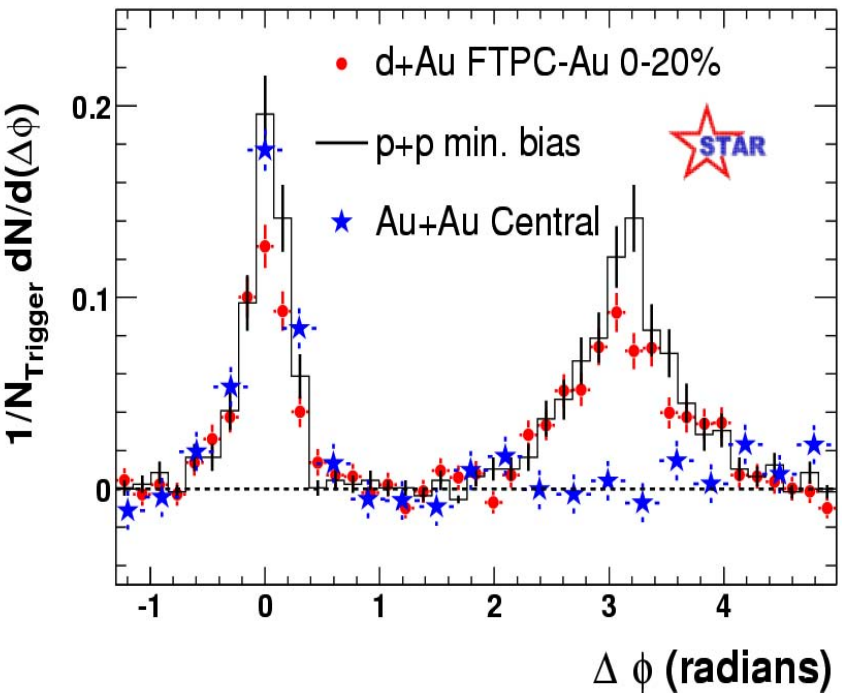
$$f(y) = 1.63 \times \frac{7.1}{(1+y)^{8.1}}$$

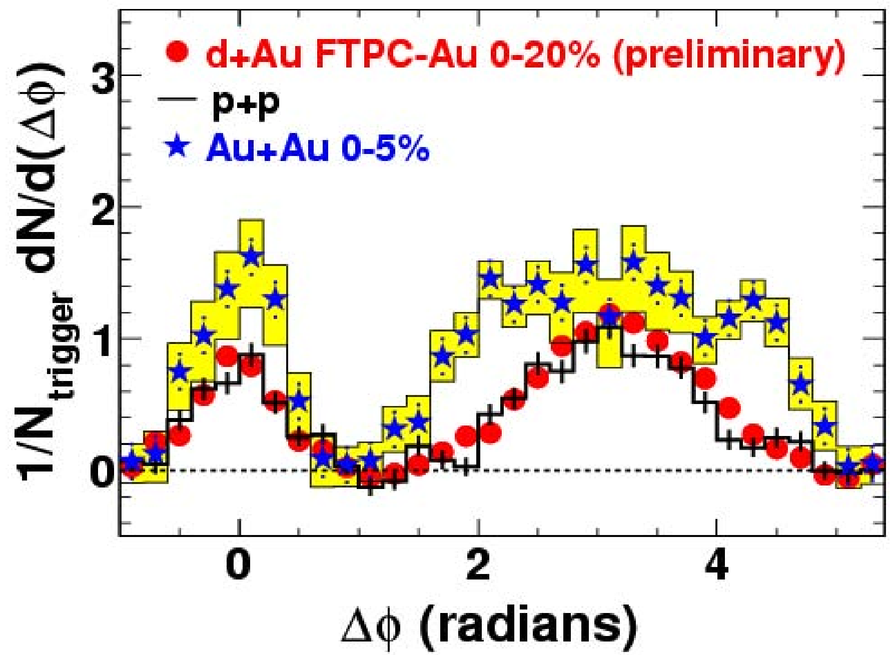
$x_E = y$

$x_E = \hat{x}_h\, y = 0.8\, y$

Application 2-particle correlations in Au+Au

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 $\boxed{2 < p_{Ta} < p_{Tt}}$

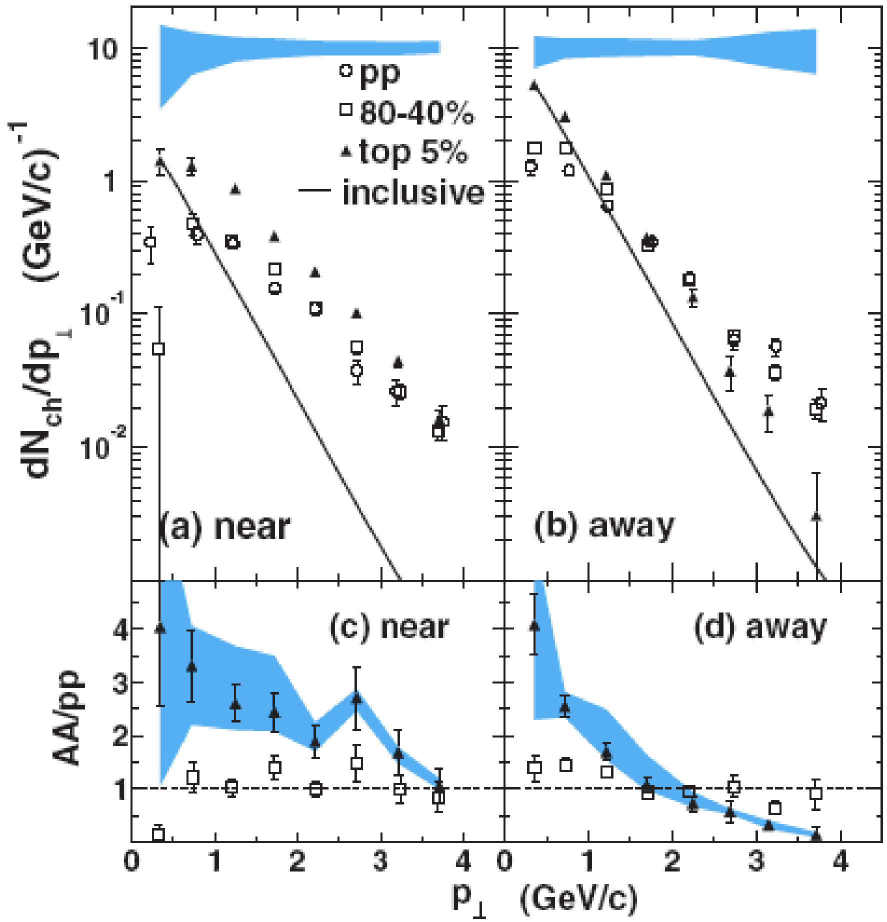
$x_h = p_{Ta}/p_{Tt} \sim 0.5$

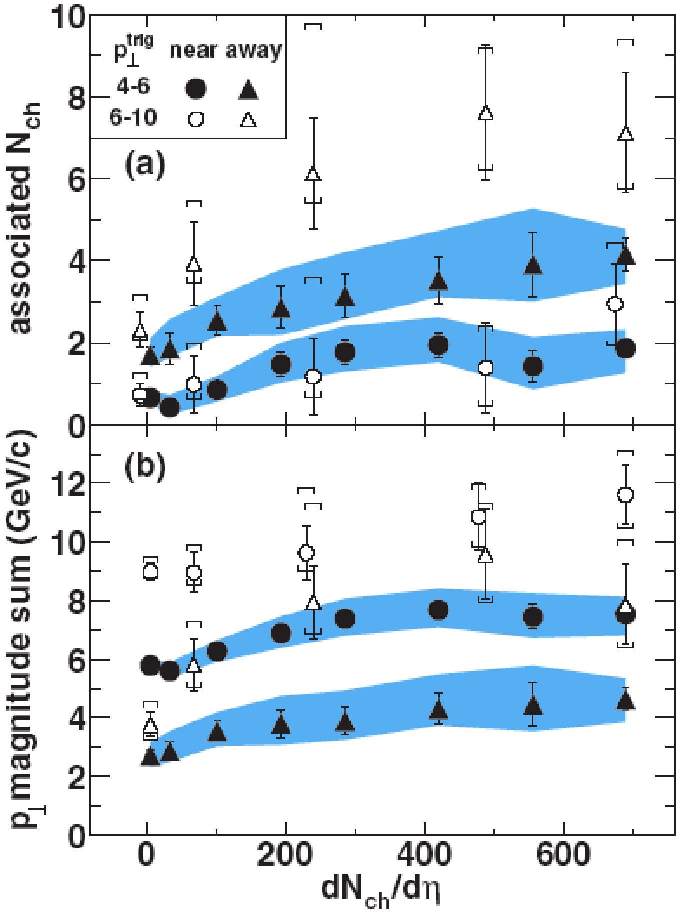
STAR-PRL**95**(2005)152301

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

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

I applied my x_E formula to STAR PRL 95 yields



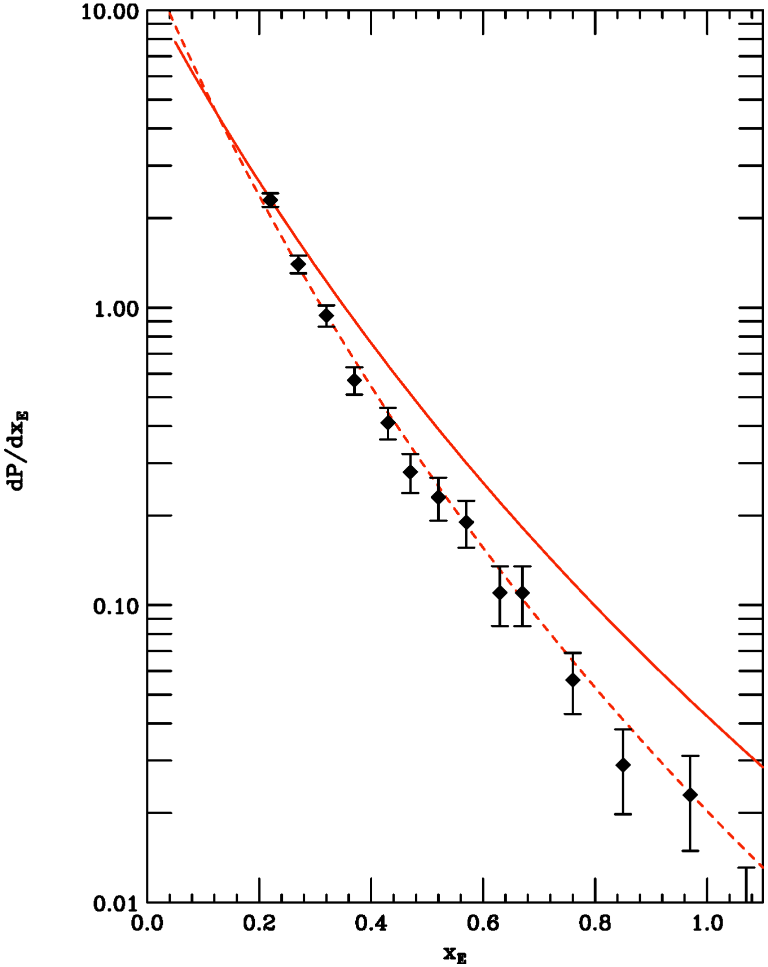


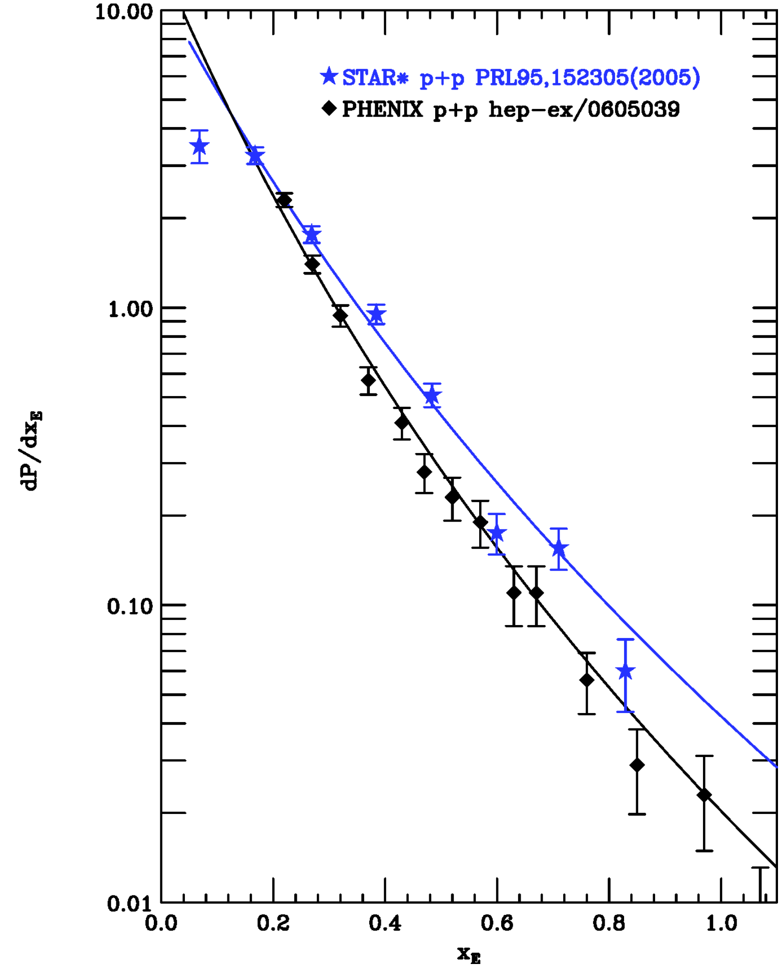
$4 < p_{Tt} < 6$ GeV/c $\langle p_{Tt}\rangle$=4.56 GeV/c

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

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

It works for STAR p+p and:

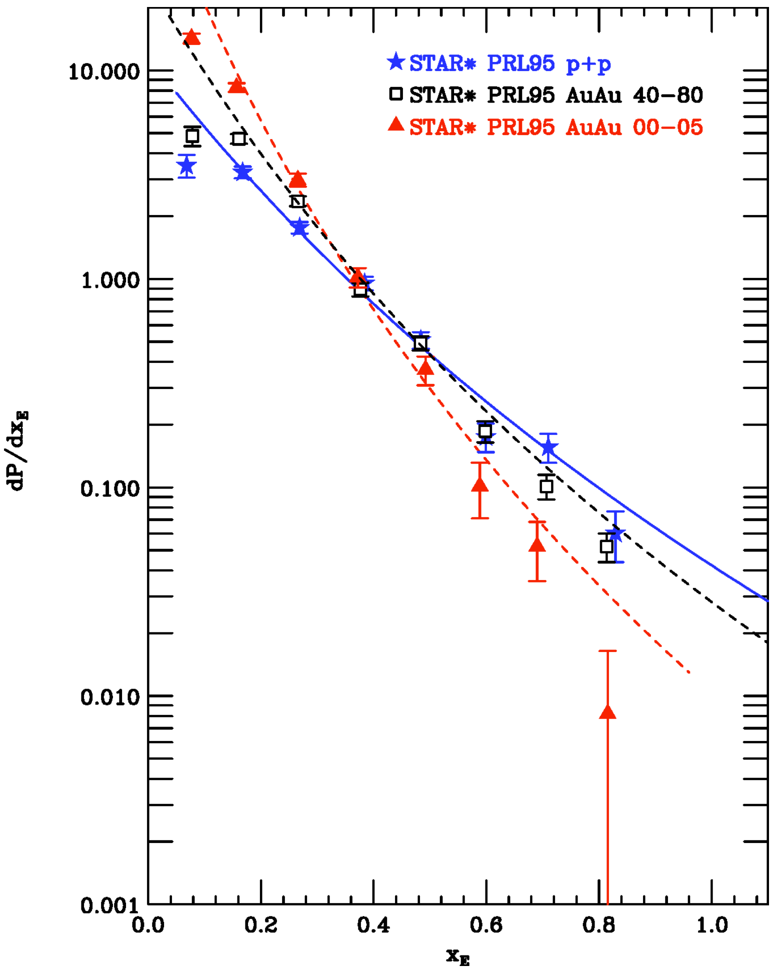




a) * means data normalized to agree with hep-ex/0605039-PRD **74**, 072002

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

STAR Au+Au--Clear $x_E / \hat{x}_h$ effect with centrality

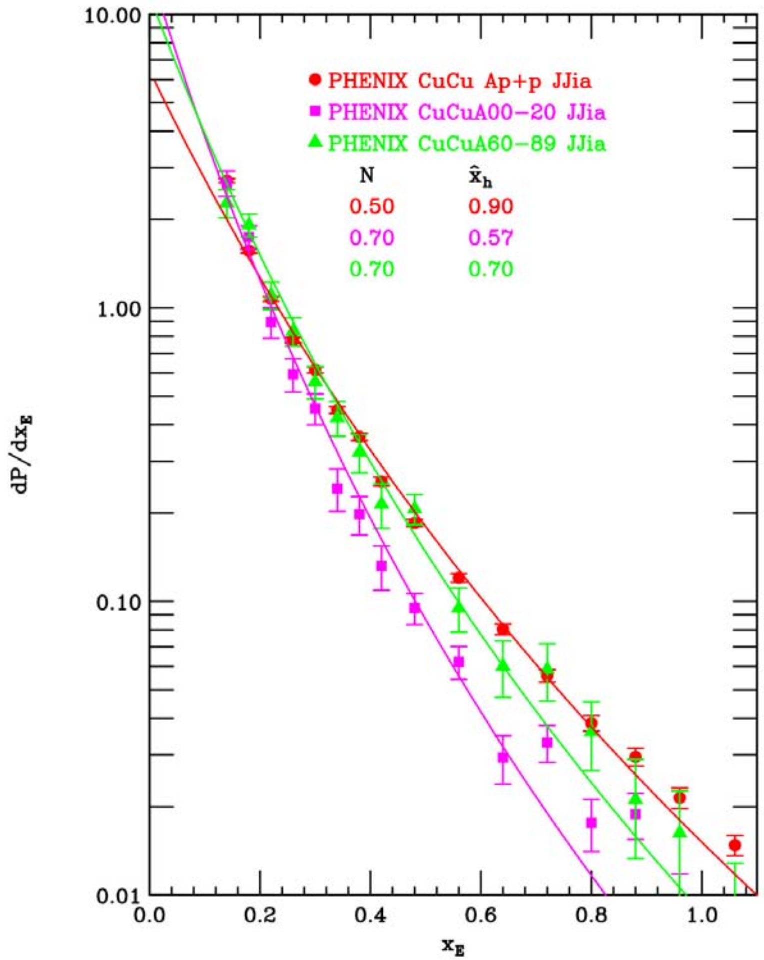


p+p	data*0.6	fit*1.0	$\hat{x}_h$ =1.0
AuAu40-80	data*0.6	fit*1.75	$\hat{x}_h$ =0.75
AuAu00-05	data*0.6	fit*4.0	$\hat{x}_h$ =0.48

- 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

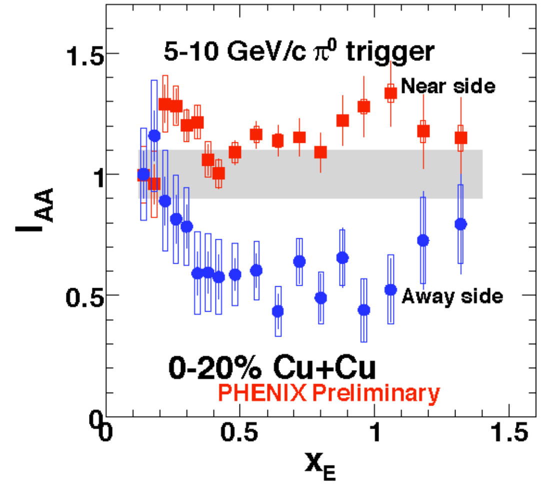
STAR, J. Adams, Fuqiang Wang, et al PRL **95**, 152301 (2005)

Also--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$^\pm$



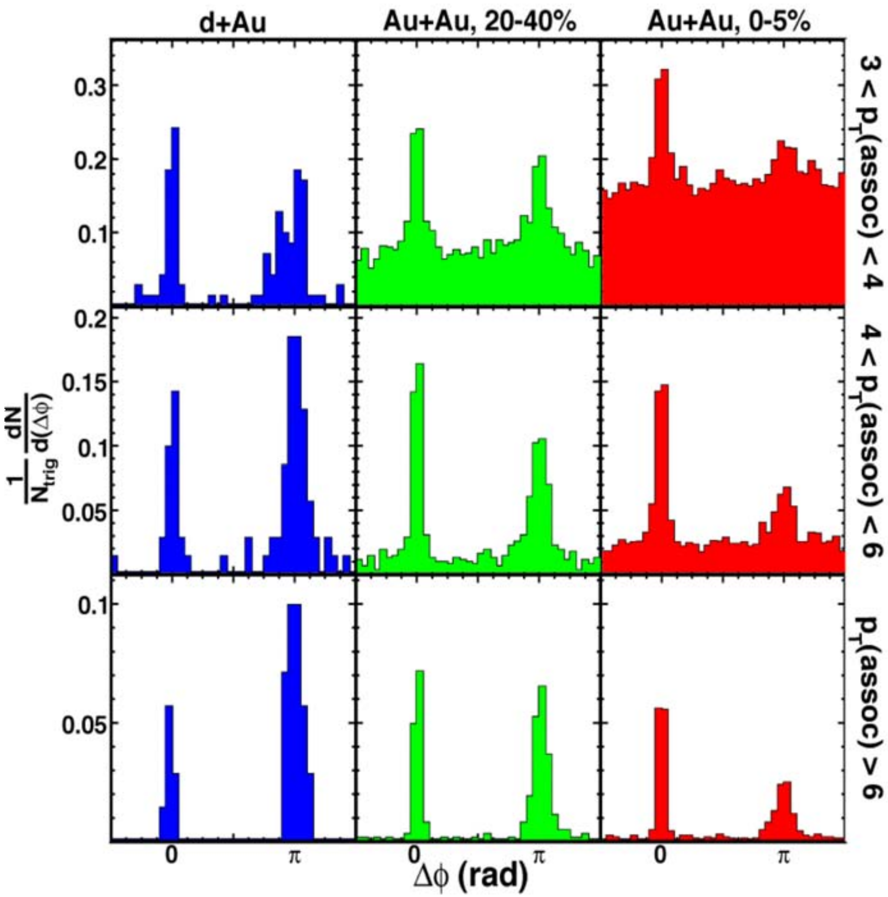
$\hat{x}_h$ Conclusions

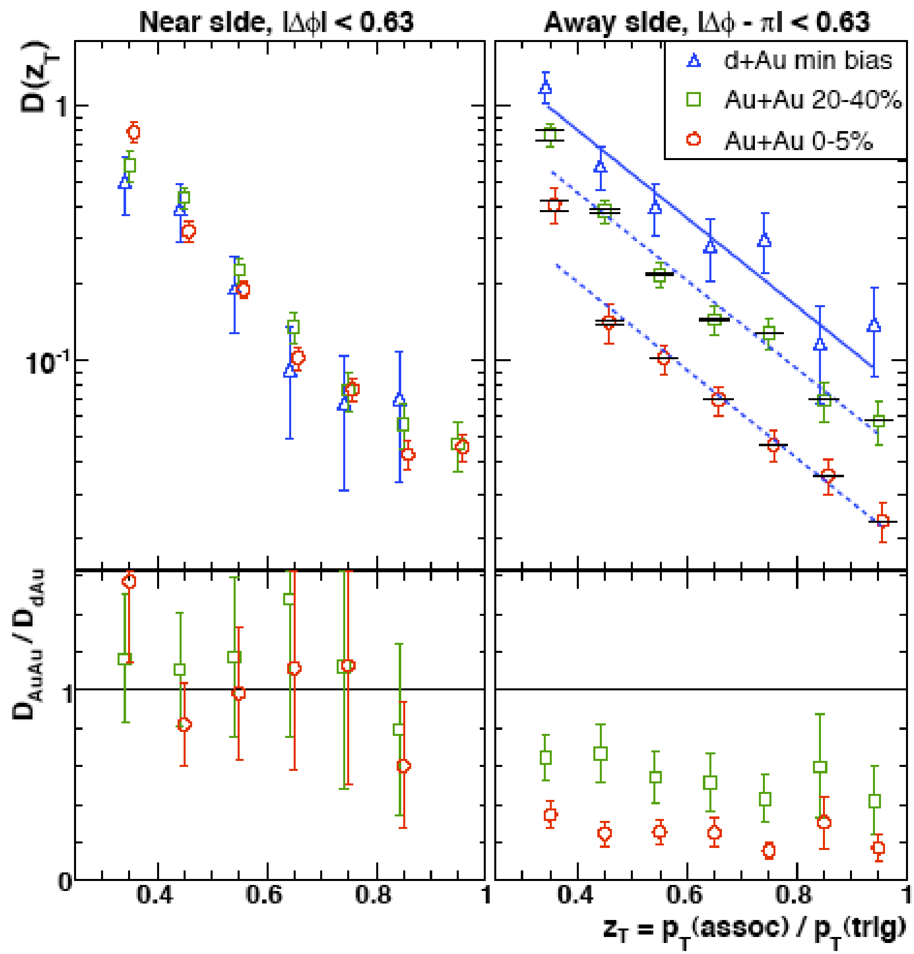
- Both the STAR data (FQ.Wang) and PHENIX QM2006 data nicely exhibit the $x_E/\hat{x}_h$ scaling in the range $0.2 < x_E < 0.6$ as the dominant feature. Thus, in my opinion, the simple scaling formula adjusted to fit the data in the range $0.2 < x_E < 0.6$ is a simple and elegant way to characterize 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.

Newer STAR data AuAu: nucl-ex/0604018



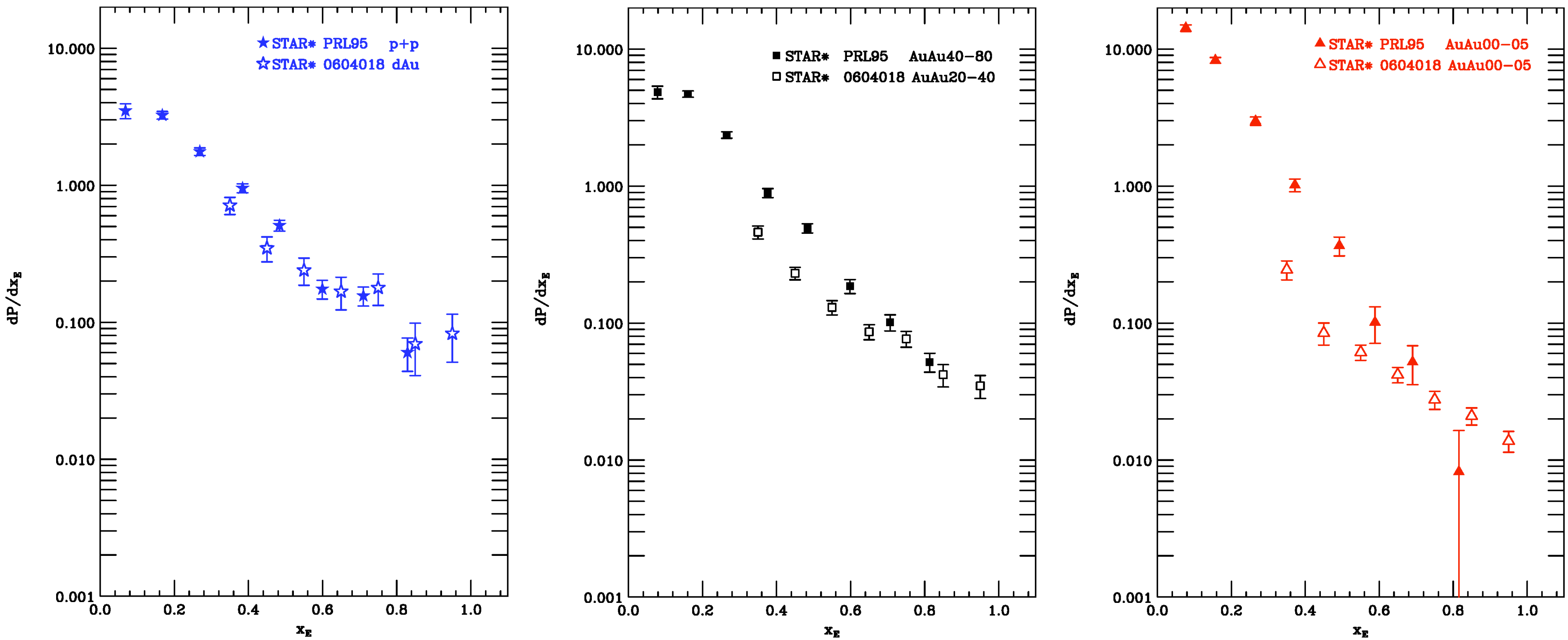


$8 < p_{Tt} < 15$ GeV/c $\langle p_{Tt}\rangle = 9.38$ GeV/c

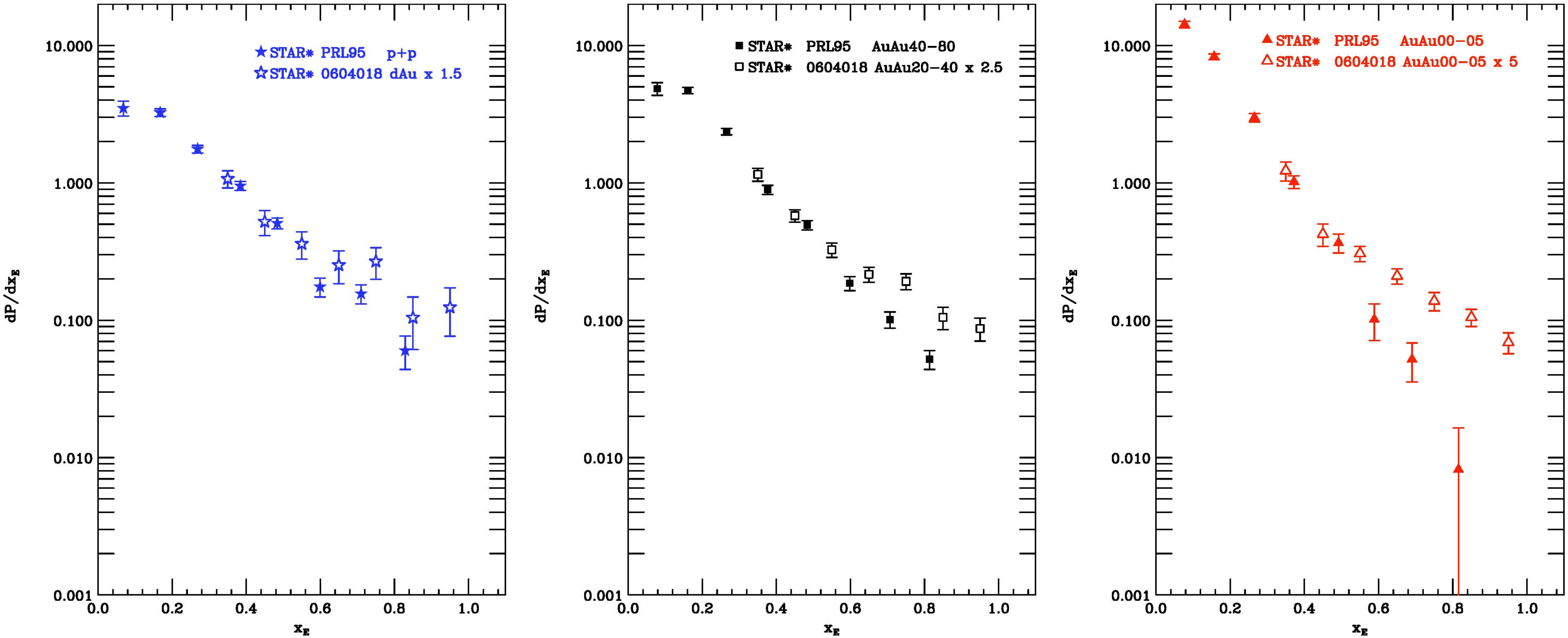
STAR, J. Adams, D. Magestro, et al PRL **97**, 162301 (2006)

Thanks to Dan Magestro for table of data points

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

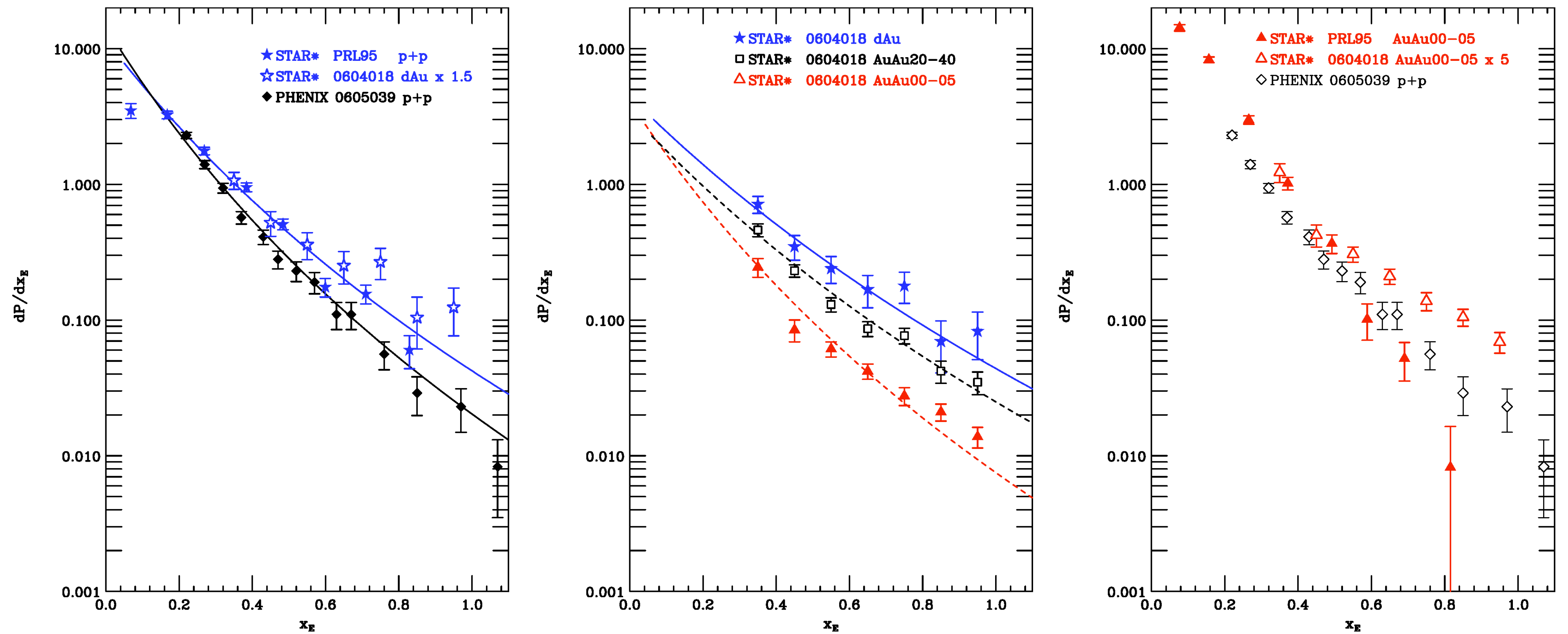


Normalize 064018 to PRL95 by eye



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

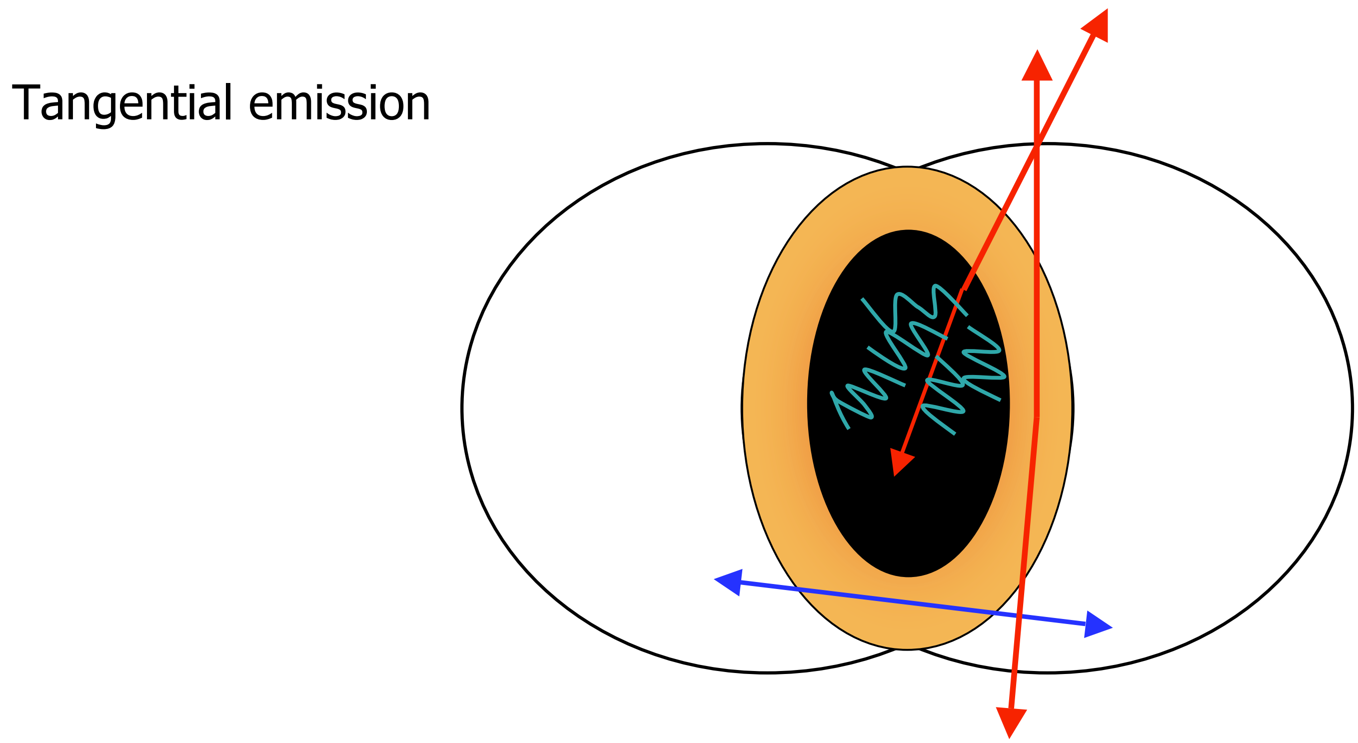
STAR 0604018 AuAu central flatter than PHENIX 0605039 p+p for x_E>0.5!



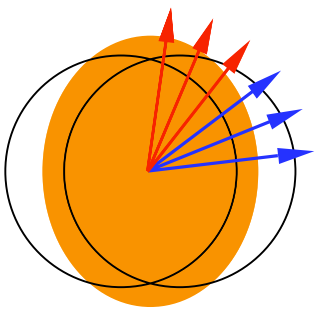
Norm (data)	Norm fit	hatx_h
Data*0.6	Fit*0.500	1.300
Data*0.6	Fit*0.350	1.200
Data*0.6	Fit*0.300	0.850

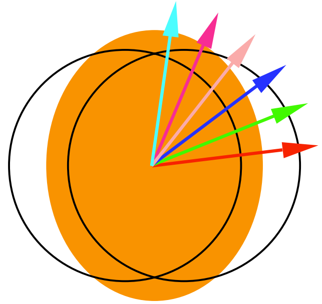
Can still fit, but curves too flat x_h>1, but still decreases with increasing centrality

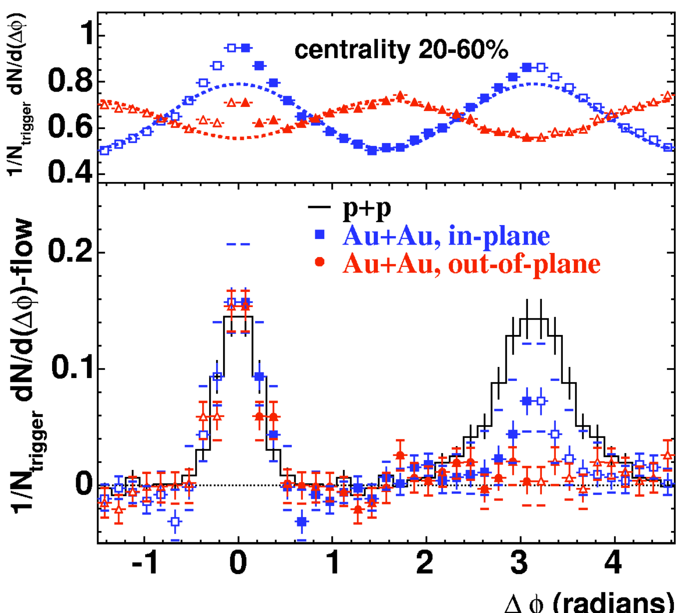
If this is punch-through due to tangential emission, why does it depend on p_T?



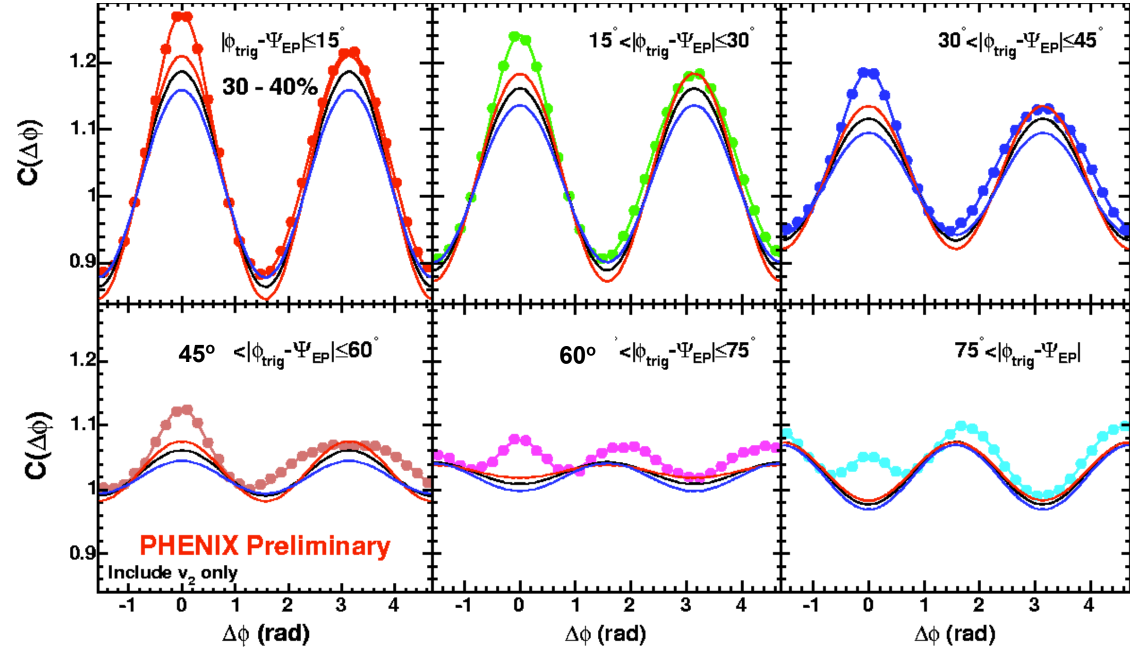
We must carefully map out how this effect depends on p_{Tt} and p_{Ta} and particle type and angle to the reaction plane...

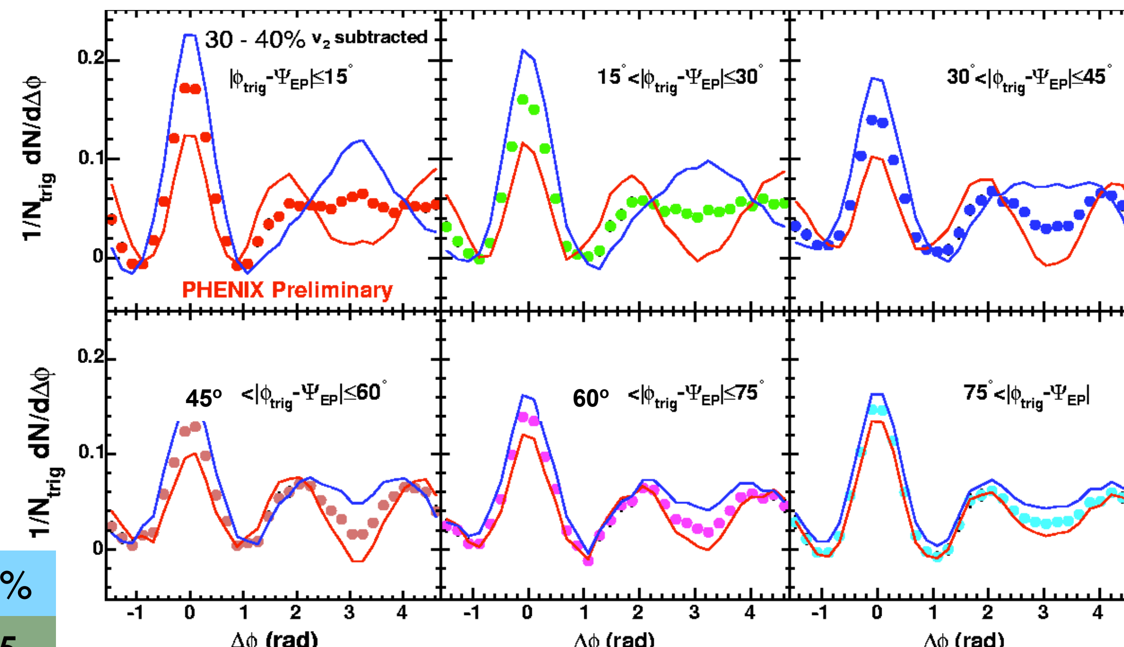






STAR PRL 91, 072304 (2003)





$h^\pm - h^\pm$

C: 20-60%

T: 4-6

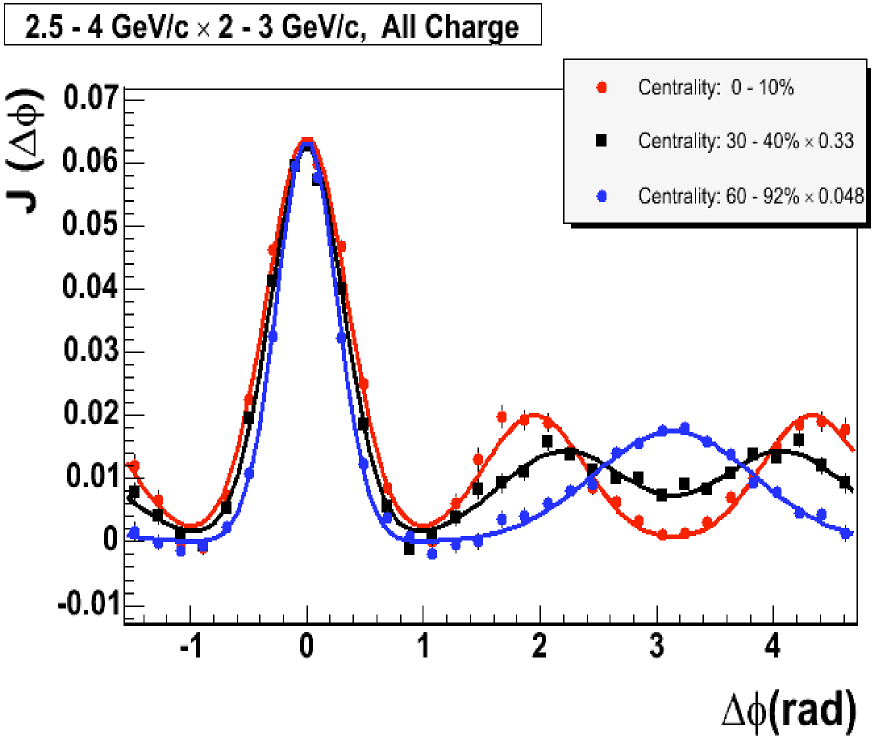
P: 2-$P_{T\ Trig}$

$h^\pm - h^\pm$ | C: 30-40%

T: 2.5 - 4 | P: 1 - 2.5

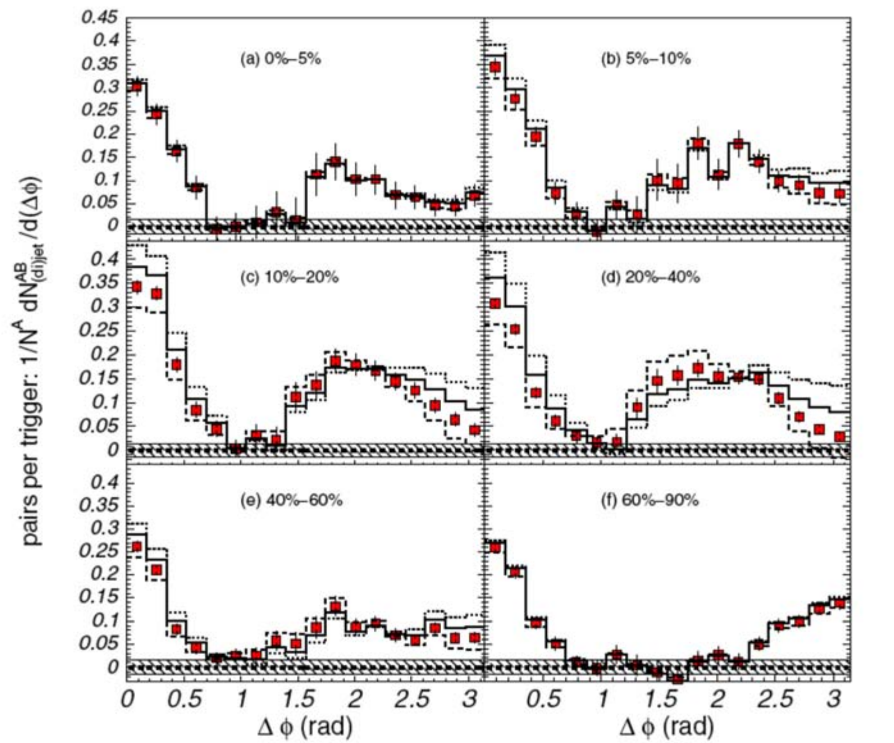
2-particle correlations AuAu at intermediate p_T

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

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

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

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.

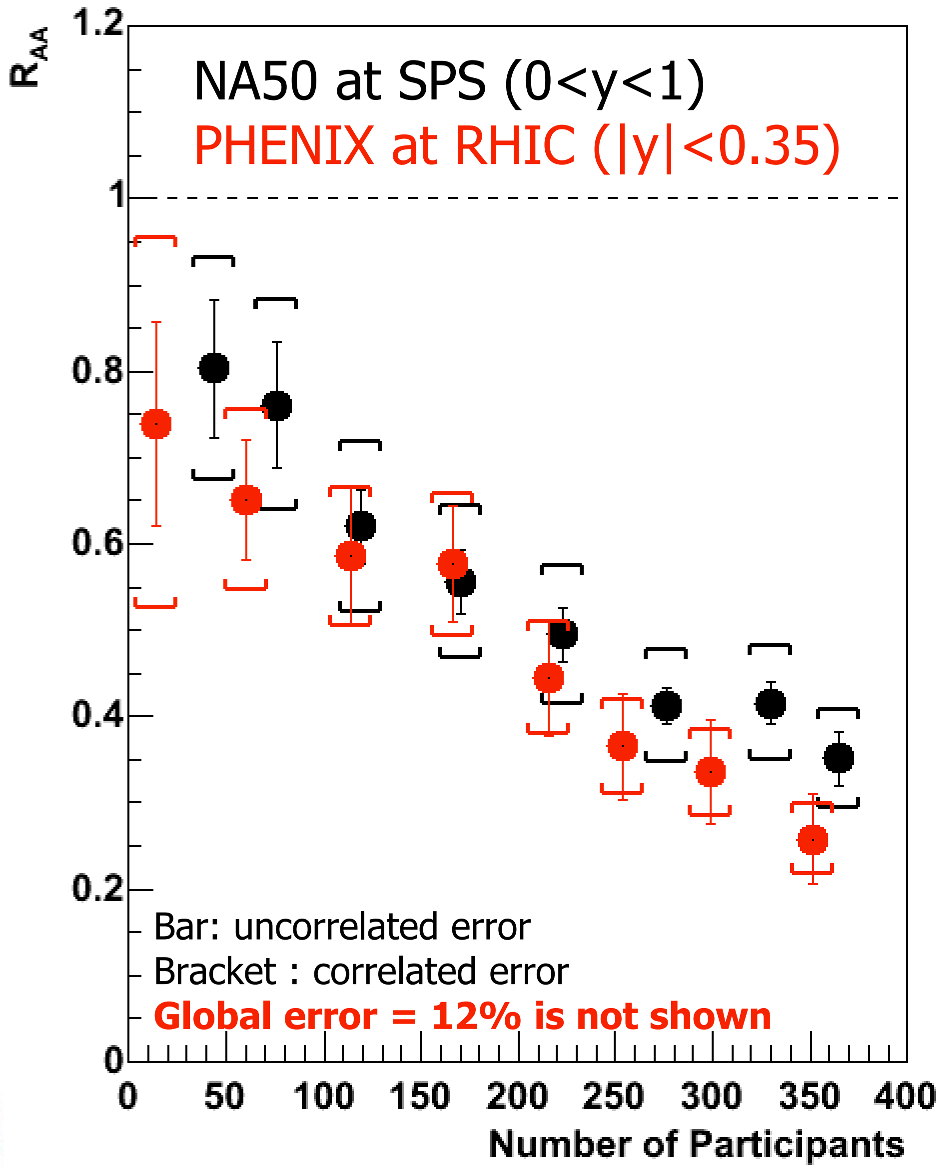
What I still don’t understand-II

- 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 ~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