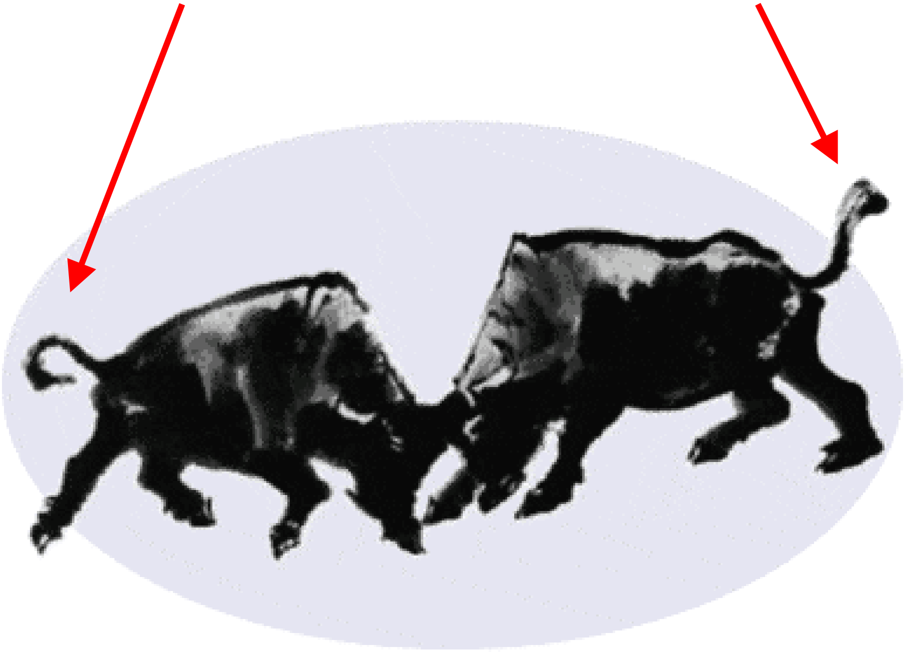
The pQCD tails provide indicators of What the Bulk is doing

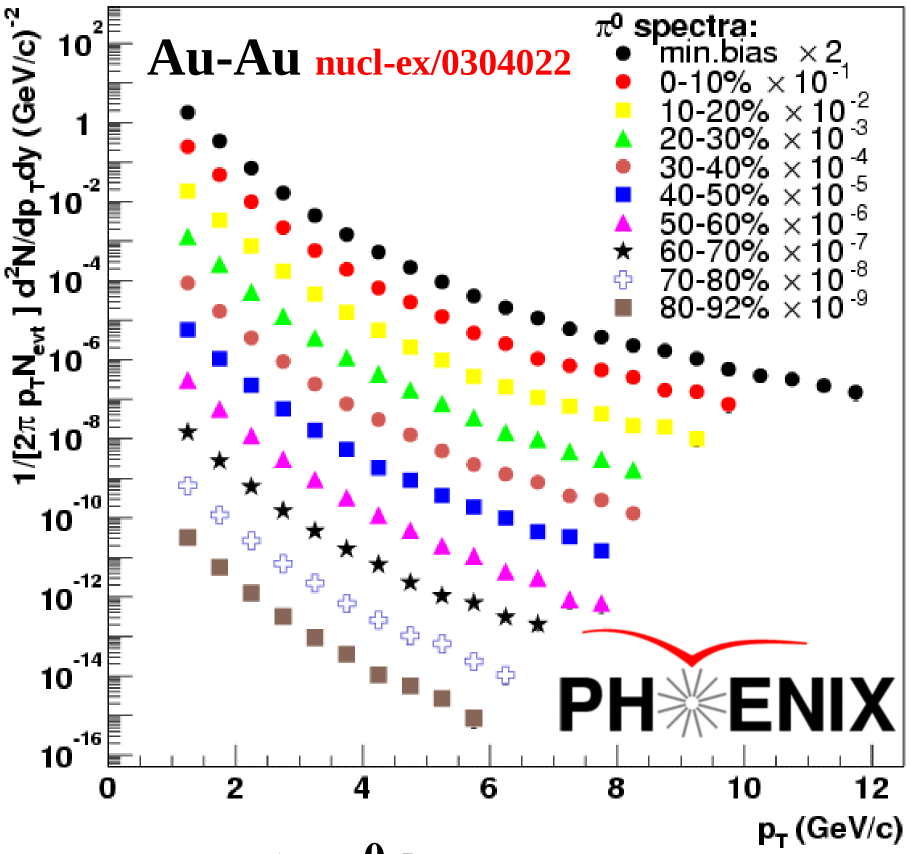


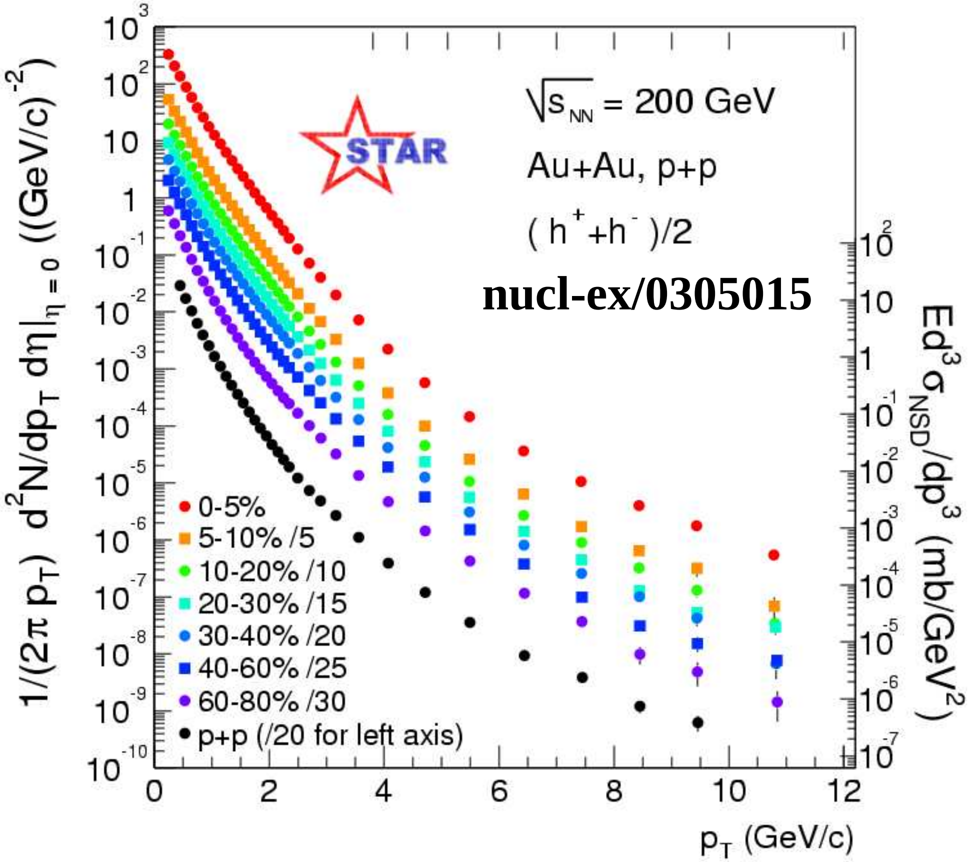
核子重如牛

對撞生新態

Nuclei as heavy as bulls
Through collision
Generate new states of matter

The high p_T window at RHIC is wide open





p+p-> π^0 hep-ex/0304038

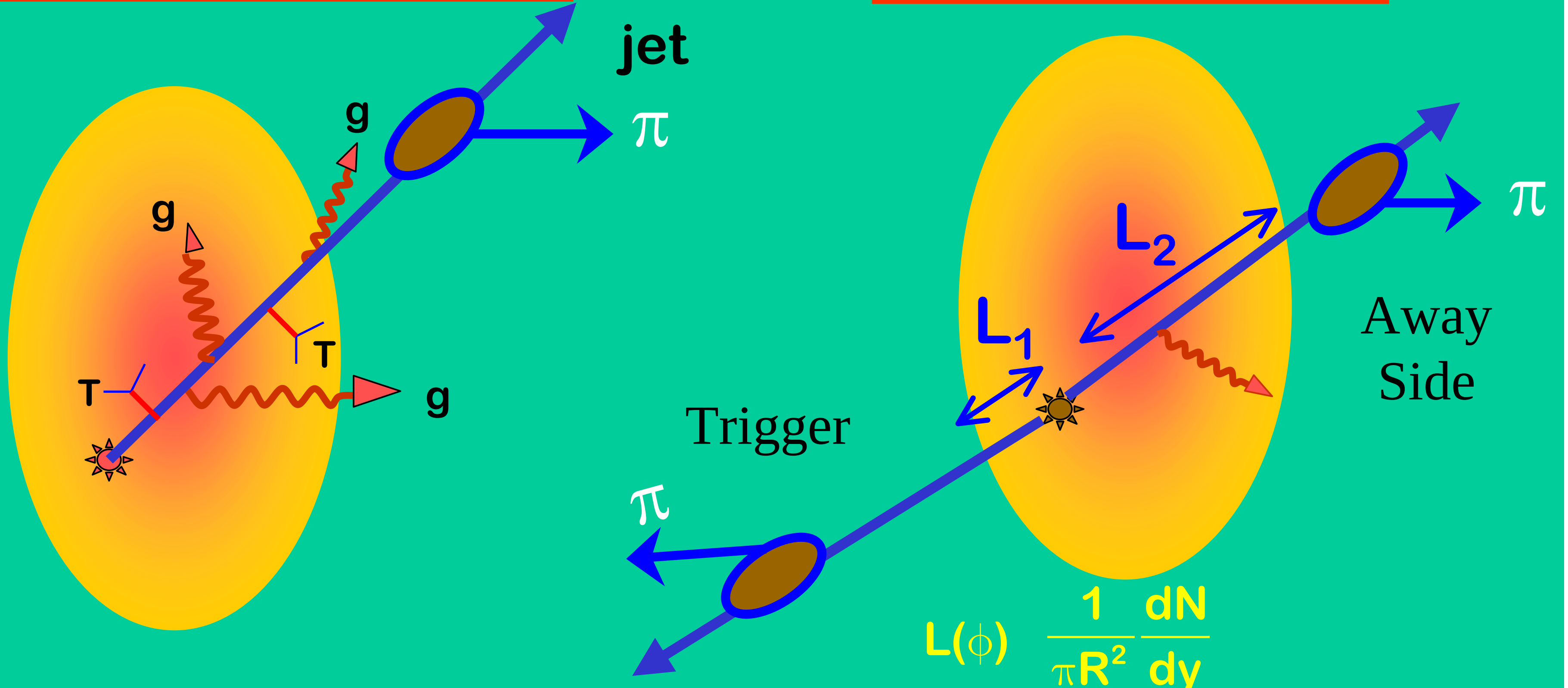
STAR PRL 89, 202301

High pT Tomography of the QGP

MG, I.Vitev, P. Levai; X.N. Wang, E.Wang, B.W.Zhang
Review nucl-th/0302077

Single Hadron Tomography

Di-Hadron Tomography

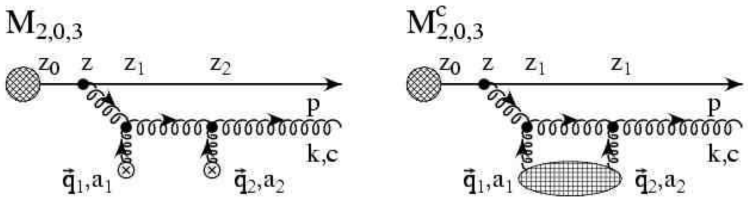


$$\Delta E_{GLV} \sim C_{Jet} C_T \alpha_s^3 \ \ell n \frac{p_T}{\mu^2 L} \overbrace{\int d\tau\, \tau\, \rho\big(\tau, r(\tau)\big)}^{L(\phi)\ \frac{1}{\pi R^2}\frac{dN}{dy}}$$

GLV Opacity Induced Radiation generalized to finite M

GLV: Nucl.Phys.B594(01)

M. Djordjevic, MG (03)



+ …

$$x\frac{dN^{(n)}}{dx\,d^2\mathbf{k}} = \frac{C_R\alpha_s}{\pi^2}\frac{1}{n!}\int\prod_{i=1}^{n}\left(d^2\mathbf{q}_i\,\frac{L}{\lambda_g(i)}\left[\bar{v}_i^2(\mathbf{q}_i)-\delta^2(\mathbf{q}_i)\right]\right)\times$$

$$\times\left(-2\,\tilde{\mathrm{C}}_{(1,\cdots,n)}\cdot\sum_{m=1}^{n}\tilde{\mathrm{B}}_{(m+1,\cdots,n)(m,\cdots,n)}\left[\cos\left(\sum_{k=2}^{m}\Omega_{(k,\cdots,n)}\Delta z_k\right)-\cos\left(\sum_{k=1}^{m}\Omega_{(k,\cdots,n)}\Delta z_k\right)\right]\right)$$

Hard, Gunion-Bertsch, and Cascade ampl. in GLV generalized to finite M

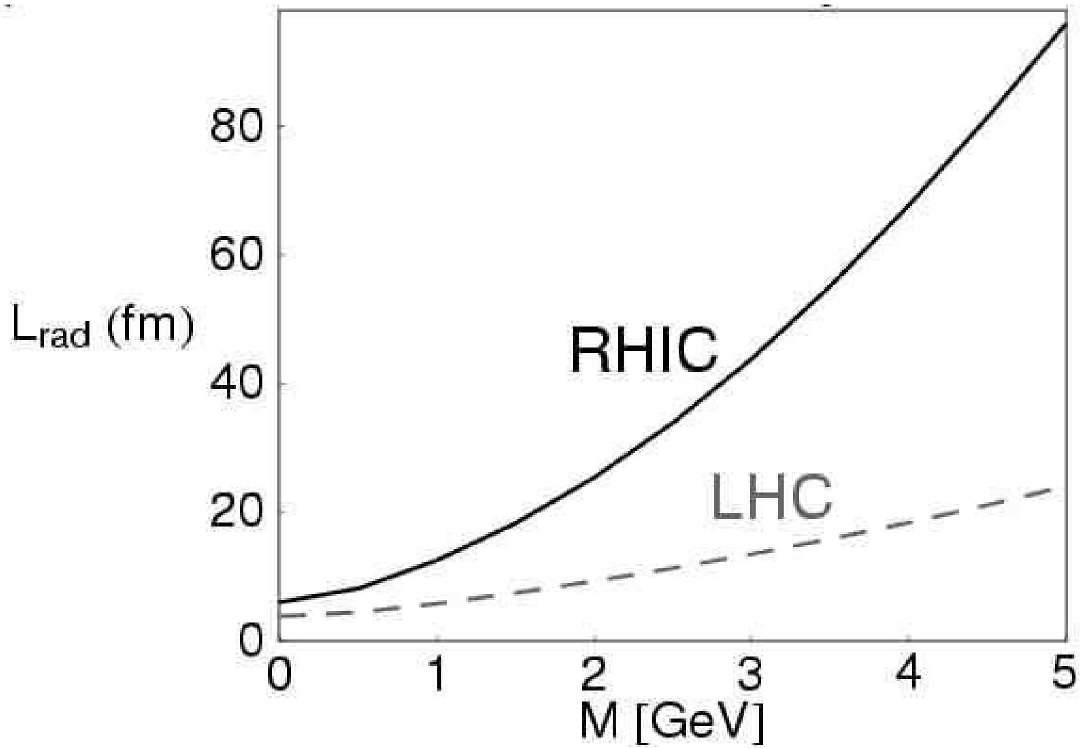
$$\tilde{\mathrm{H}} = \frac{\mathbf{k}}{\mathbf{k}^2+m_g^2+M^2x^2}\,, \qquad \tilde{\mathrm{C}}_{(i_1i_2\cdots i_m)} = \frac{(\mathbf{k}-\mathbf{q}_{i_1}-\mathbf{q}_{i_2}-\cdots-\mathbf{q}_{i_m})}{(\mathbf{k}-\mathbf{q}_{i_1}-\mathbf{q}_{i_2}-\cdots-\mathbf{q}_{i_m})^2+m_g^2+M^2x^2}$$

$$\tilde{\mathrm{B}}_i = \tilde{\mathrm{H}}-\tilde{\mathrm{C}}_i\,, \qquad \tilde{\mathrm{B}}_{(i_1i_2\cdots i_m)(j_1j_2\cdots i_n)} = \tilde{\mathrm{C}}_{(i_1i_2\cdots j_m)}-\tilde{\mathrm{C}}_{(j_1j_2\cdots j_n)}\,.$$

$$\omega_{(m,\cdots,n)} = \frac{(\mathbf{k}-\mathbf{q}_m-\cdots-\mathbf{q}_n)^2}{2xE} \to \Omega_{(m,\cdots,n)} \equiv \omega_{(m,\cdots,n)} + \frac{m_g^2+M^2x^2}{2xE}$$

Radiation Length in QGP

$$\frac{d\Delta E}{dL} \equiv \frac{E}{L_{rad}(M, m_g, E, L)}$$



E_q=10 GeV, μ=0.5

E_q=30 GeV, μ=0.7

$$\mathbf{dN_{AB\to H} = T_{AB} \otimes \left(f_{a/A} \otimes f_{b/B}\right)^{shad}_{\Delta k_T} \otimes d\sigma_{ab\to c} \otimes P(\Delta E) \otimes D_{H/c}}$$

M. Djordjevic, MG nucl-th/0310076

3 Milestones passed at RHIC

$$\mathrm{QGP} = P_{QCD} + \mathrm{pQCD} + \mathrm{dA}$$

$$= \underbrace{v_2(p_T,m)}_{1} + \underbrace{(R+I)_{AA}}_{2} + \underbrace{(R+I)_{DA}}_{3}$$

1) Evidence for P_{QCD} via v_2 bulk collective flow of 10^4 π, K, p, Λ, Ξ

2) Evidence for pQCD jet quenching in Au+Au at RHIC

3) Evidence jet *un*-quenching in D+Au = Null Control

Conclusion: QGP Matter seen in AuAu at 200 AGeV

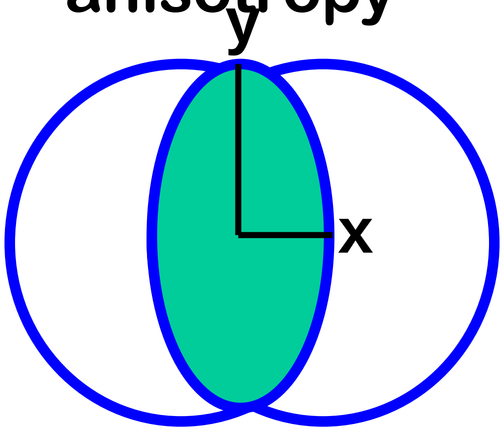
Bulk Collective Flow of QCD matter

$$\partial_\mu T^{\mu\nu} = \partial_\mu \left\{ u^\mu u^\nu (\varepsilon(T) + P(T)) - g^{\mu\nu} P(T) \right\} = 0$$

QCD EOS

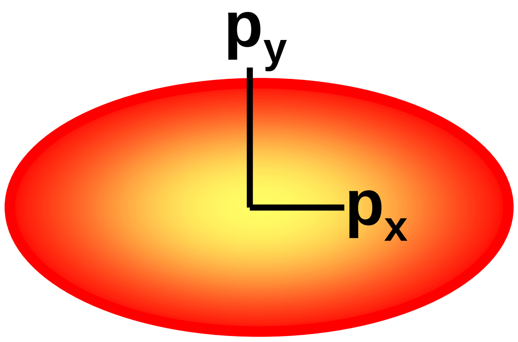
H. Stocker, W. Greiner (1980)
J. Ollitrault (1992)
P.Kolb, U. Heinz et al (2000)
D.Teany, E. Shuryak et al
T. Hirano, Y. Nara 3+1D

Initial *spatial* anisotropy



$$\partial_\mu T^{\mu\nu}(x) = 0$$

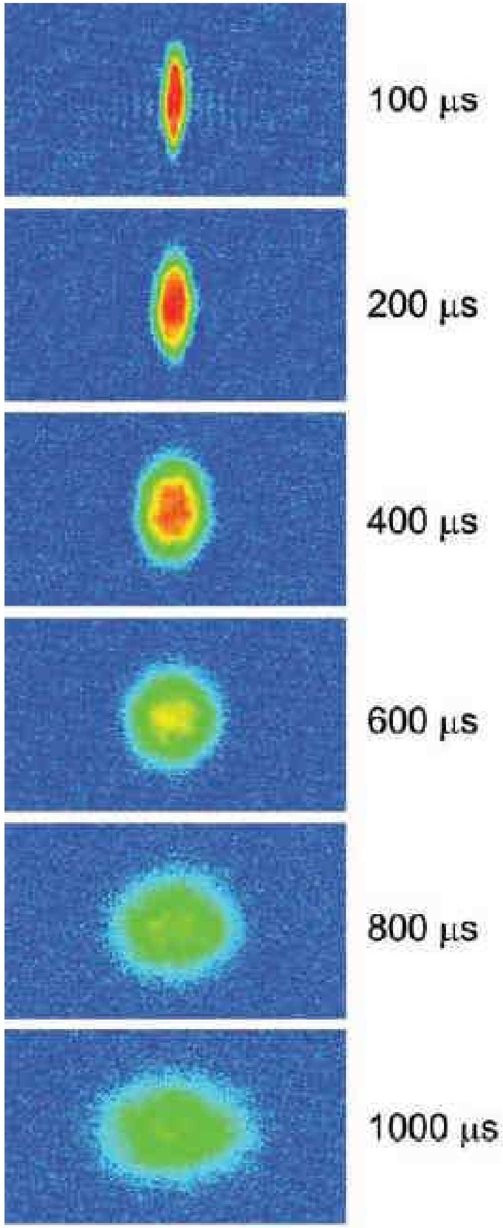
Final *momentum* anisotropy



Elliptic Flow

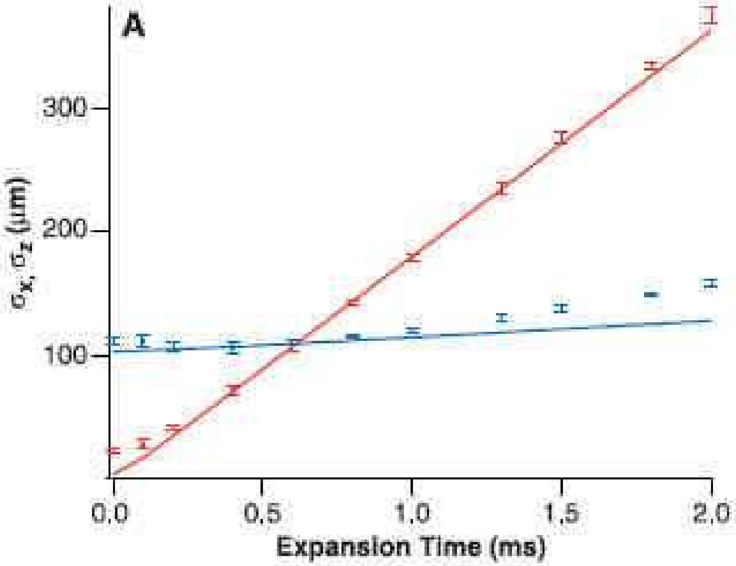
$$\frac{dN}{dy\,dp_T^2\,d\phi} = \rho(y, p_T)\left\{1 + 2 v_2(p_T)\cos(2\phi) + \cdots\right\}$$

Elliptic Flow of Ultracold Li_6 Atoms



K.M.O'Hara etal, Science 2002

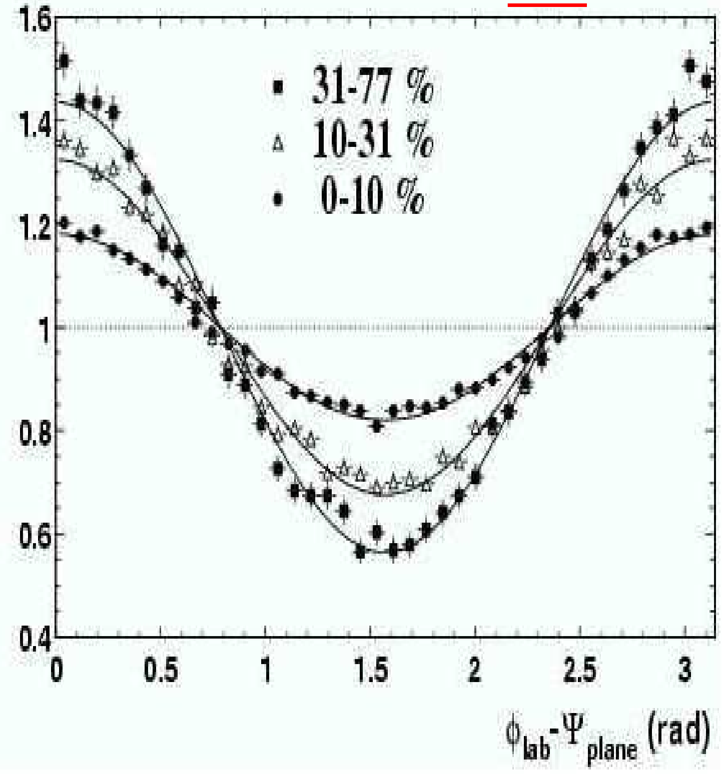
T~ 50 10^{-9} K

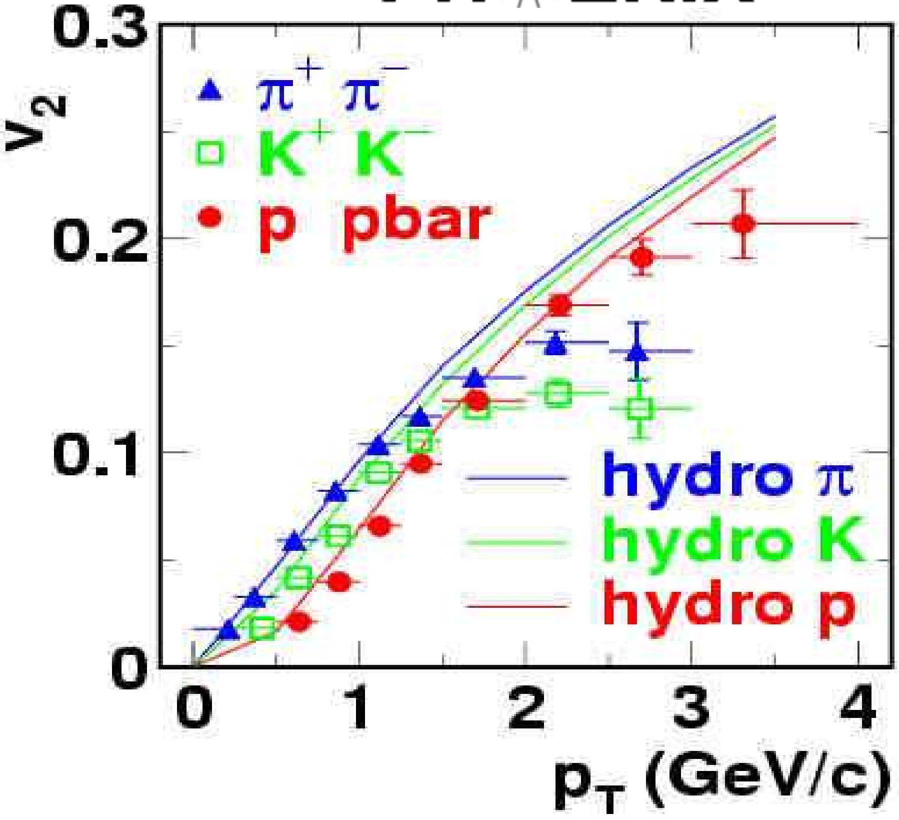


Observed Elliptic Flow of 10^{12}K QGP at RHIC

Hydro: P.Kolb et al, D.Teany et al
Exp: A. Poskanzer, S. Voloshin, ...

$d^3N/dydp_T\,d\phi$

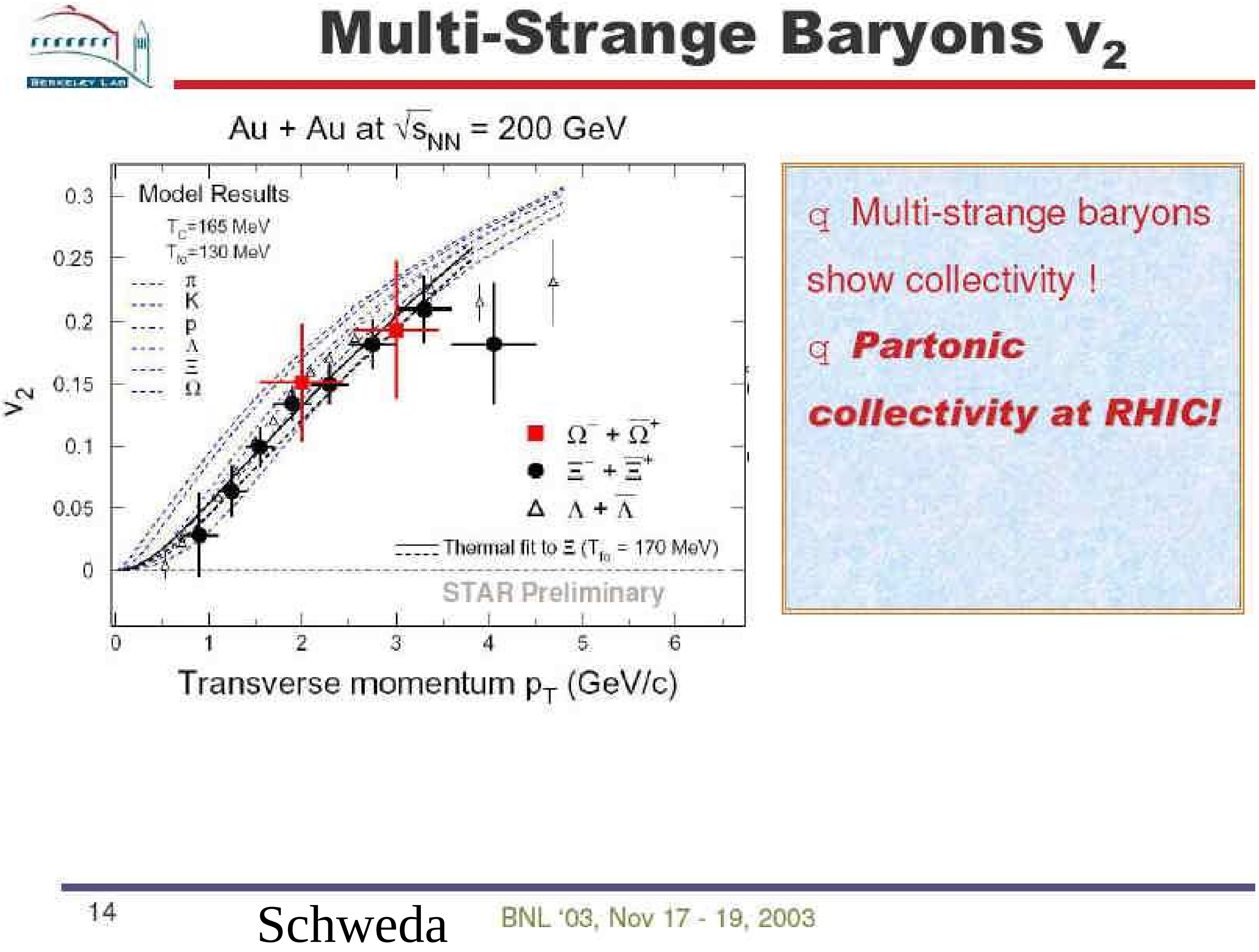




Azimuthal Fourier Expansion

$$\frac{dN}{dy\,dp_T^2\,d\phi} = \rho(y,p_T)\left\{1+2\,v_1(p_T)\cos(\phi)+2\,v_2(p_T)\cos(2\phi)+\cdots\right\}$$

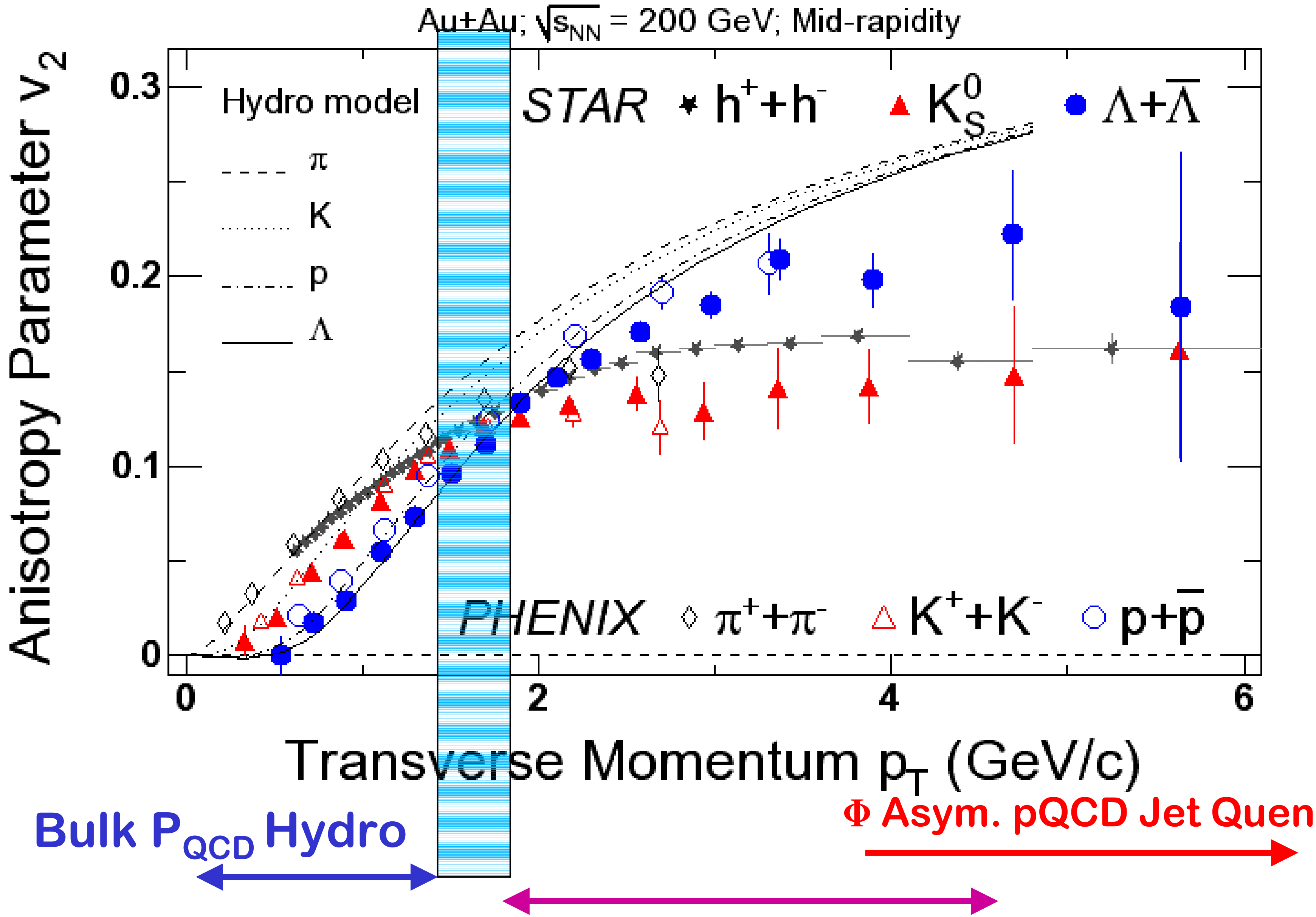
Even Ω(sss) marches in lock step with Ξ, Λ, p, K, π !



Multi-Strange Baryons v_2

- Multi-strange baryons show collectivity !
- ***Partonic collectivity at RHIC!***

14 Schweda BNL '03, Nov 17 - 19, 2003



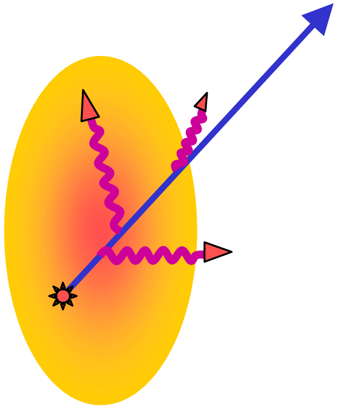
Bulk P_{QCD} Hydro

Φ Asym. pQCD Jet Quenching

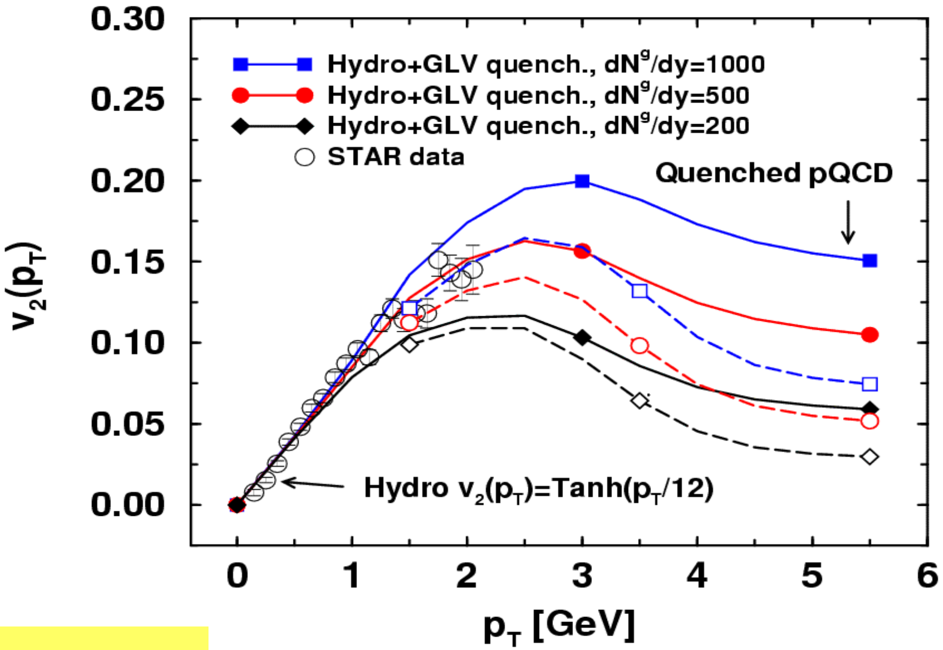
q^n Coalescence ?

Azimuthal $v_2(p_t)$ Tomography

$\rho_{QGP}(\tau, x_0 + \hat{\mathbf{n}}\tau)$



I. Vitev, X.N. Wang, MG, PRL86(01)



- - - Wood Saxon
—— Sharp Cylinder

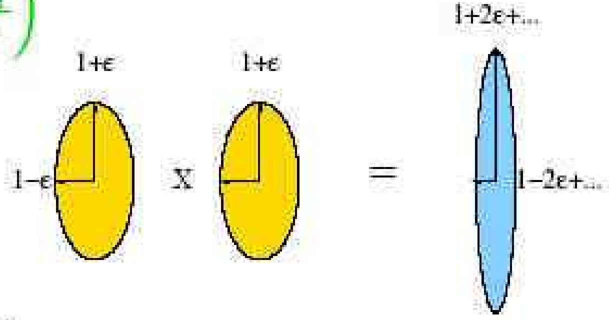
Energy Loss Asymmetry not enough with Wood-Saxon diffuse geometry

Need an asymmetry amplifier

Coalescence amplifies elliptic flow

D. Molnar and S. Voloshin, PRL 91 (03)

narrow wave fn. limit $(\vec{q}=0)$: $\frac{dN_M}{d\phi} \propto \left(\frac{dN_q}{d\phi}\right)^2$



$$\begin{aligned} v_2^M(p_\perp) &\approx v_2^a\left(\frac{p_\perp}{2}\right) + v_2^a\left(\frac{p_\perp}{2}\right) \\ v_2^B(p_\perp) &\approx v_2^a\left(\frac{p_\perp}{3}\right) + v_2^b\left(\frac{p_\perp}{3}\right) + v_2^c\left(\frac{p_\perp}{3}\right) \end{aligned}$$

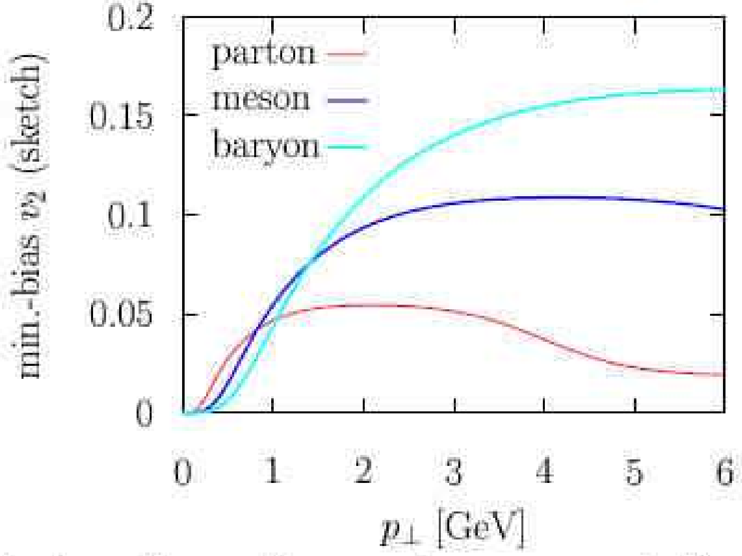
⇒ **hadron flow amplified at high $p_\perp$**

if all quarks have same v_2:

3× for baryons

2× for mesons

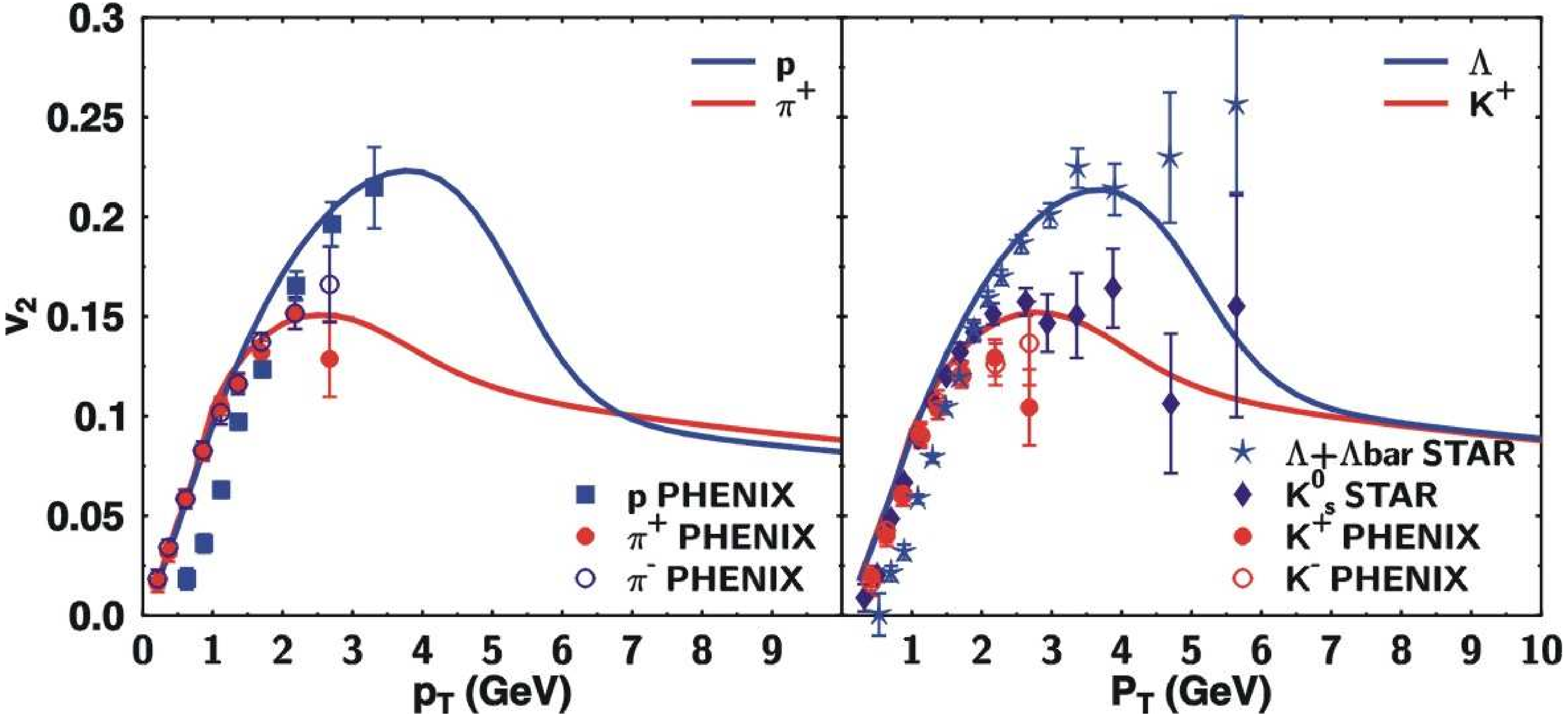
" $v_2^h(p_\perp) \approx n \times v_2^q(p_\perp/n)$ "



- this **KEY EFFECT** solves opacity puzzle (much smaller parton v_2 needed)

Flavor Dependence of v2 via Recombination

Rainer J. Fries: BNL Flow Workshop 11.19.03

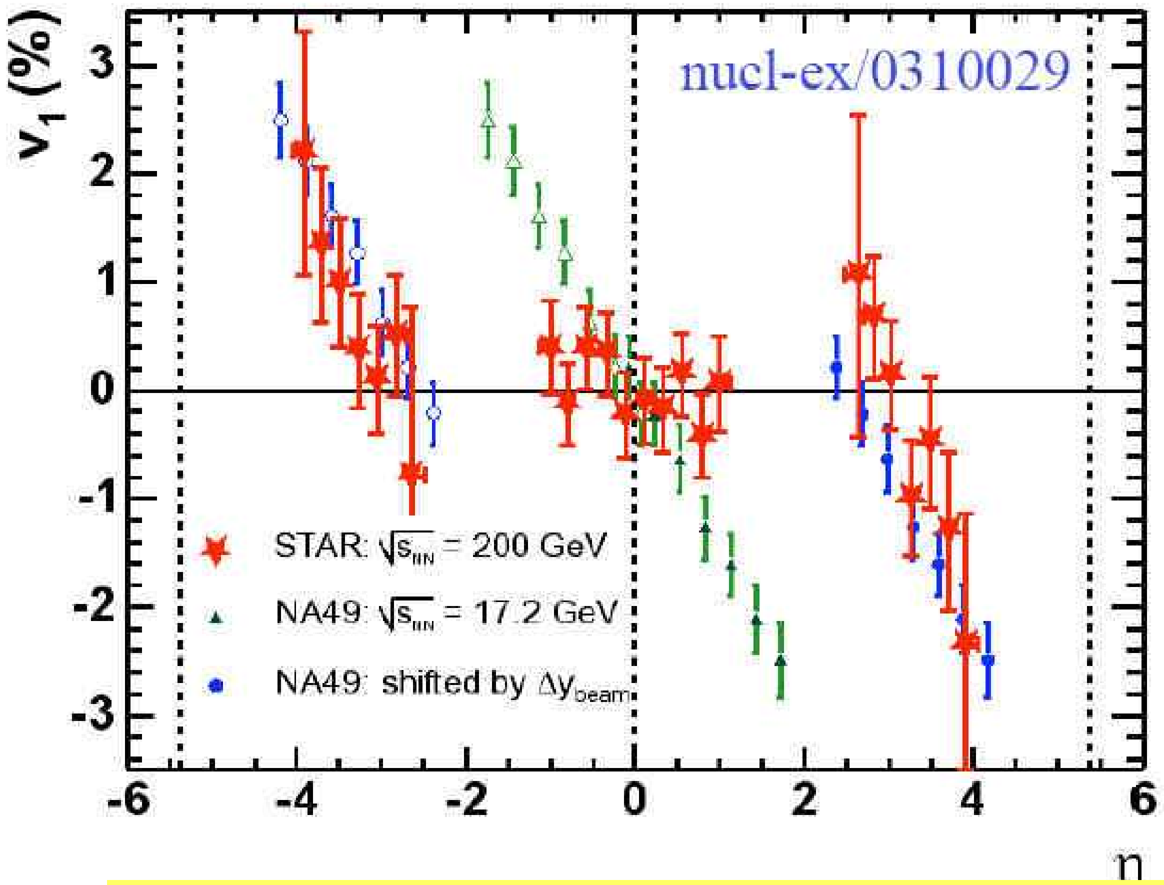


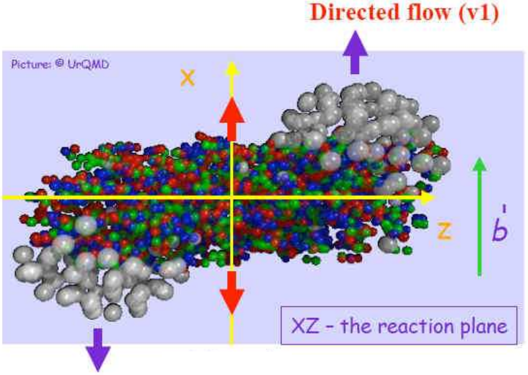
- Recombination describes measured flavor-dependence of v2!

Collectivity correlated over 8 units of rapidity !!

New!

Directed flow at RHIC





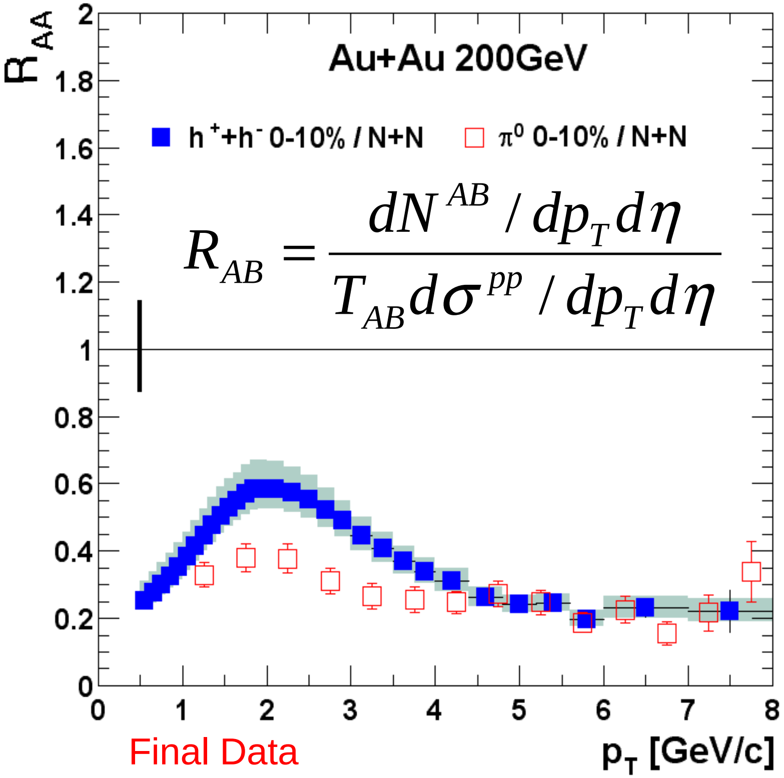
Limiting Frag
Pattern

v1(y=3) reaction plane Φ_R same as from v2(0) !

Aihong Tang, Flow workshop Nov. 2003
BNL

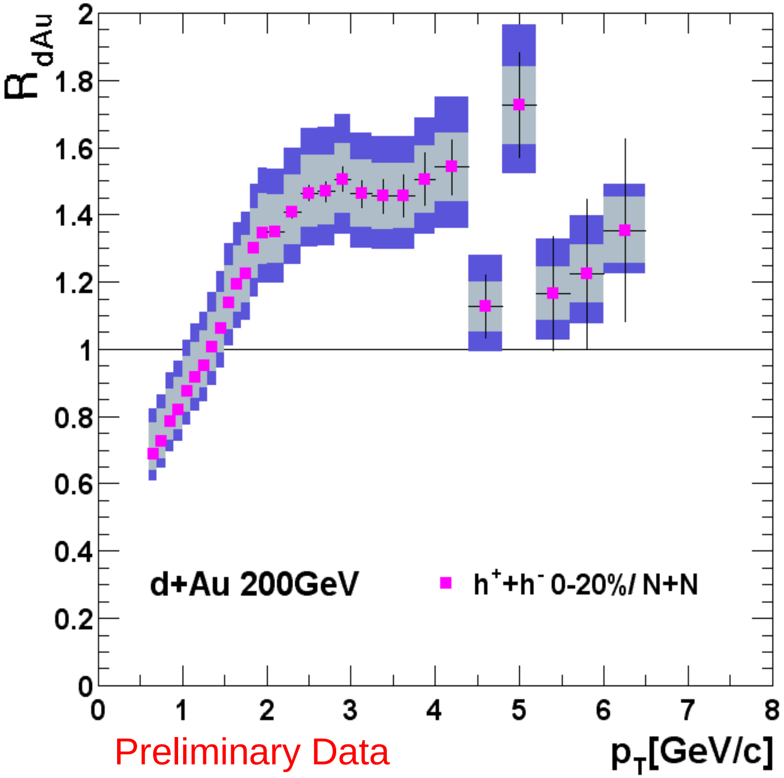
Centrality Dependence of High p_T A+B vs p+p

Au + Au Experiment



Final Data

d + Au Control Experiment



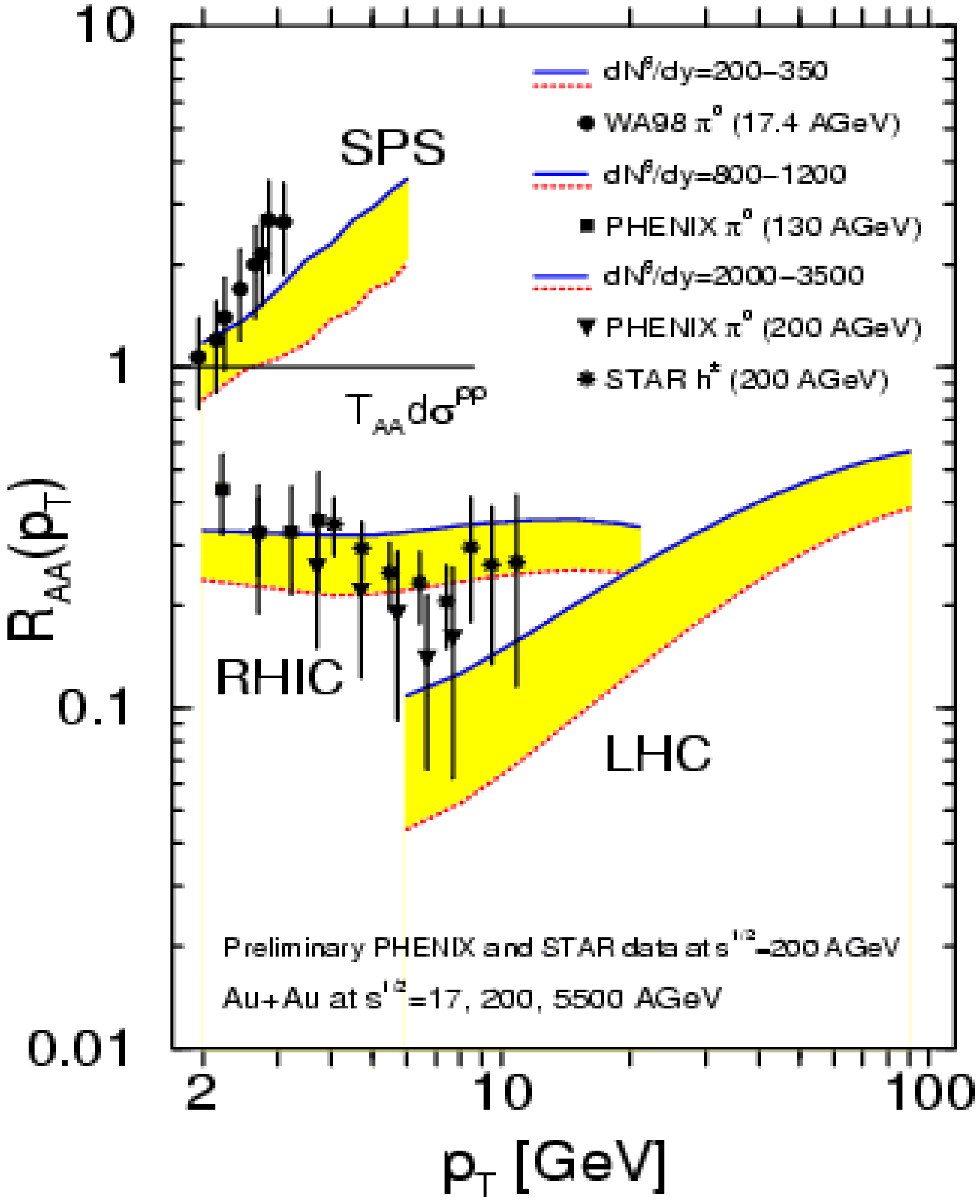
Preliminary Data

- Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.

T. Hemmick 6/18/03

Single Hadron Tomography from SPS, RHIC, LHC

Ivan Vitev and MG, Phys.Rev.Lett. 89 (2002)



1) Cronin *enhancement* dominates at SPS

2) Cronin+Quench+Shadow conspire to give ~ flat $R_{AA} \sim N_{part}/N_{bin}$ at RHIC

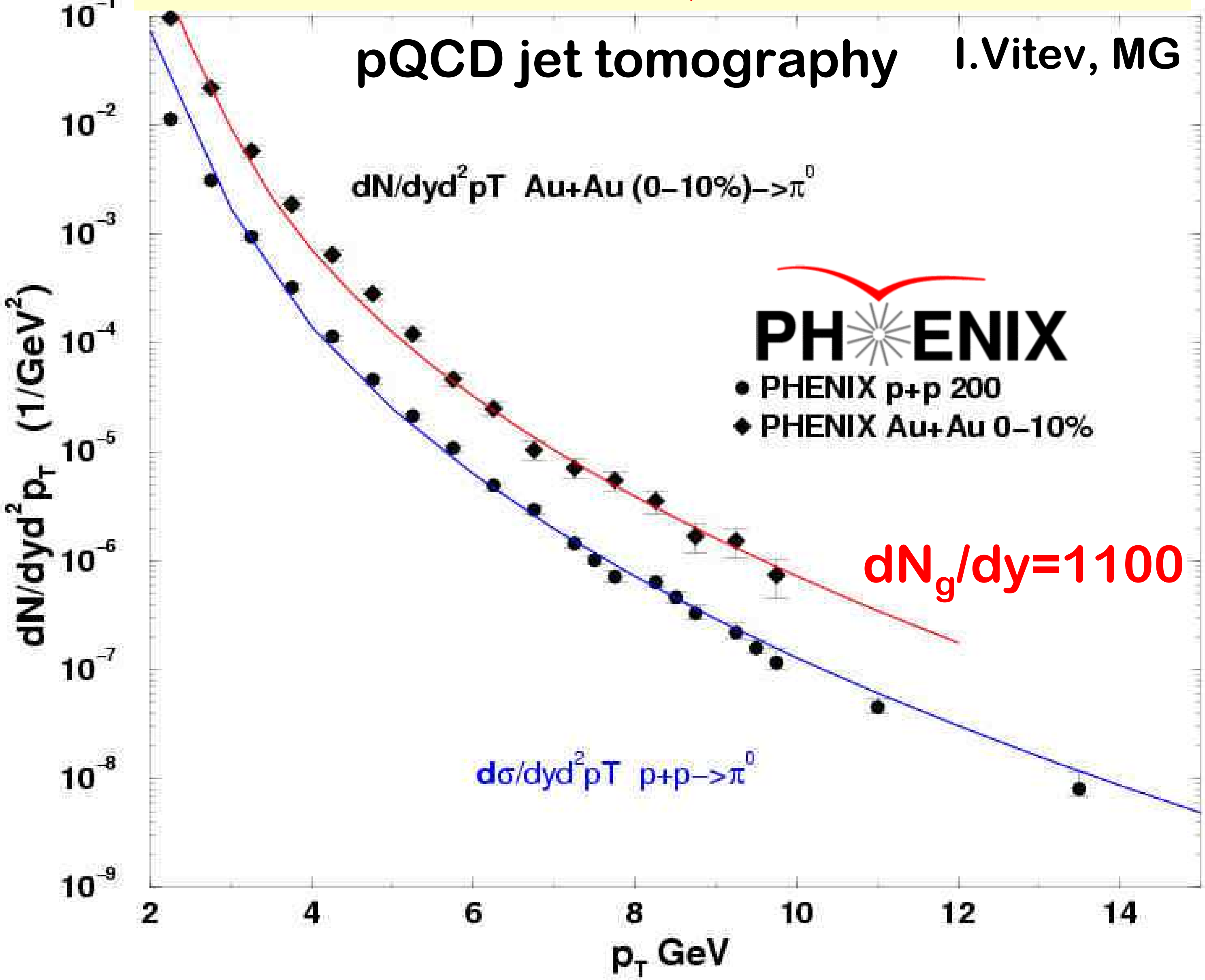
3) R_{AA} + I_{AA} data indicate $dN_g/dy \sim 1000$ -> $\rho_g \sim 100\ \rho_0$

$$dN_{AB\to\pi} = T_{AB} \otimes \left(f_{a/A} \otimes f_{b/B}\right)^{shad}_{\Delta k_T} \otimes d\sigma_{ab\to c} \otimes \underline{P(\Delta E)} \otimes D_{\pi/c}$$

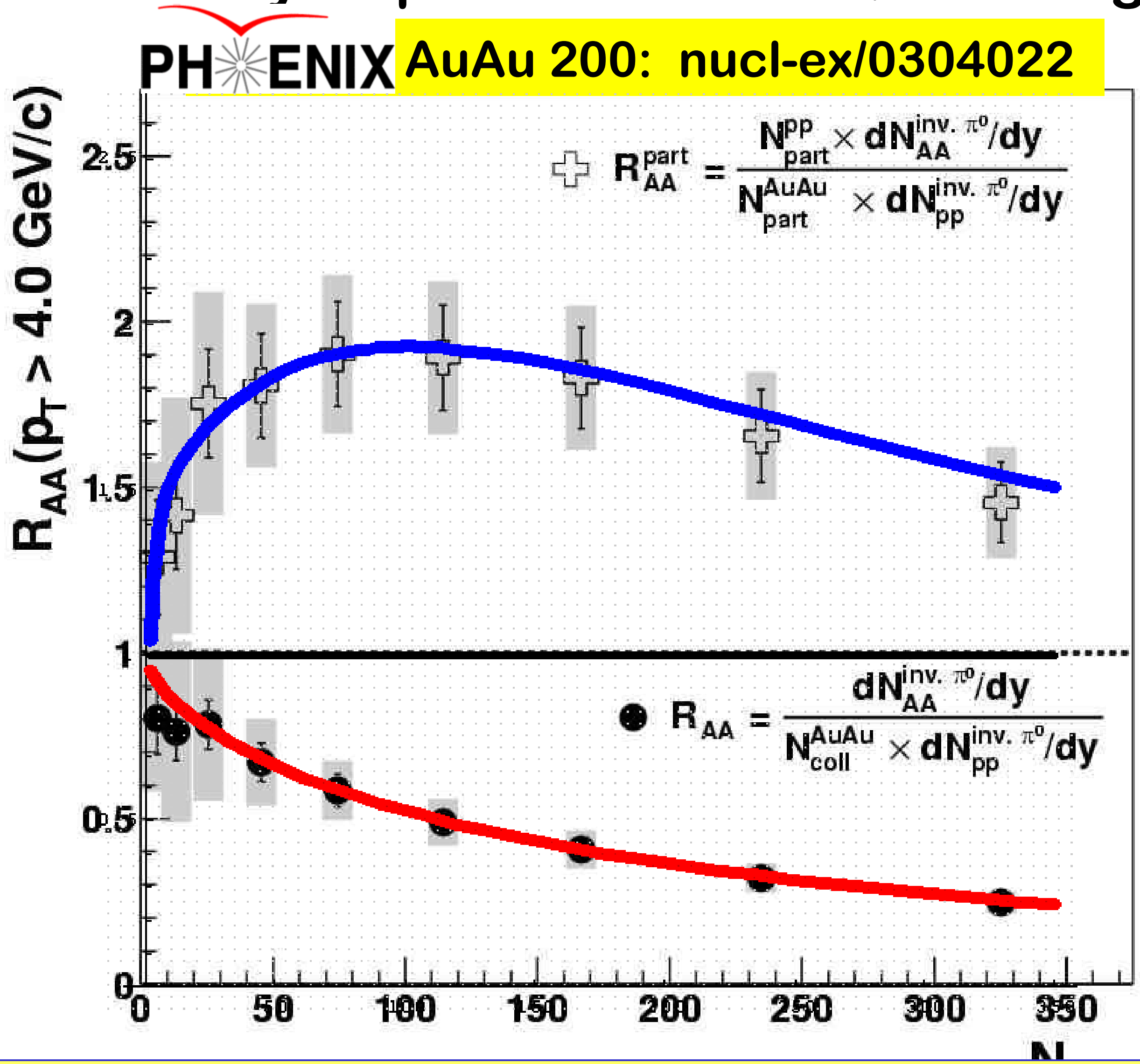
GRV
EKS
BKK
GLV

pQCD jet tomography

I.Vitev, MG



Centrality Dependence of π^0 Quenching

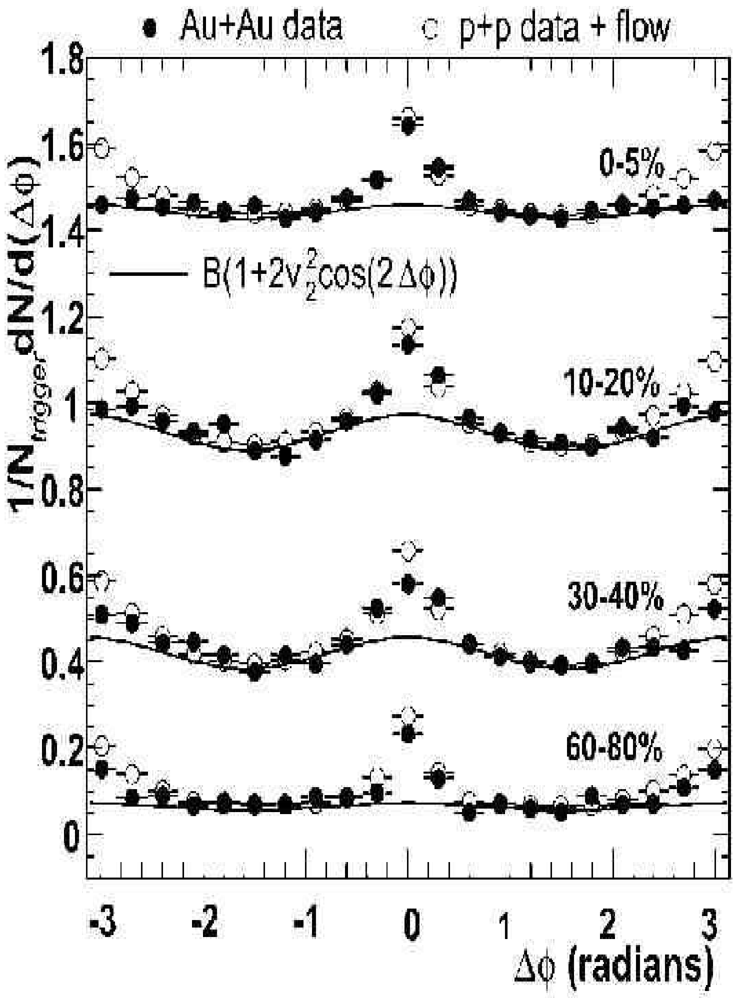

AuAu 200: nucl-ex/0304022

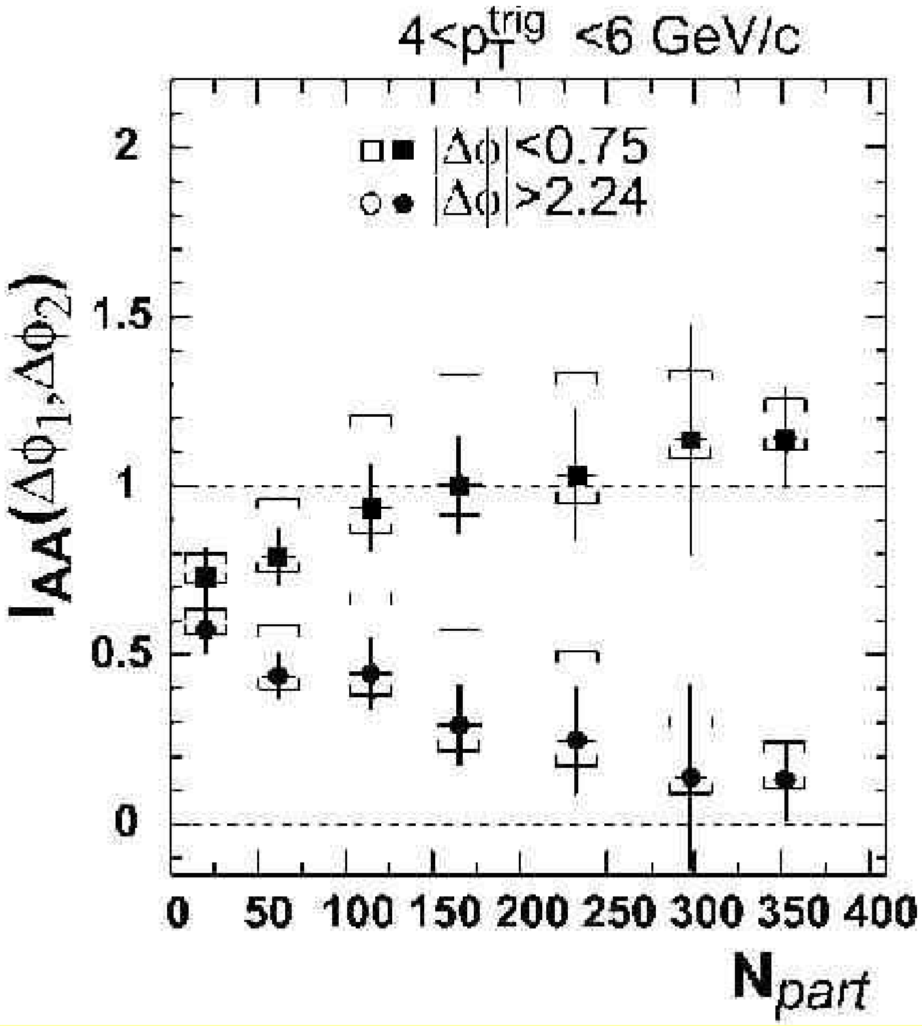
Consistent
With GLV
Formalism

$$\Delta E_{GLV} \propto \int d\tau\, \tau\, \rho\big(\tau, r(\tau)\big) \propto \frac{R}{\pi R^2}\frac{dN_g}{dy} \propto N_{part}^{2/3}$$

STAR: C. Adler et al. Phys. Rev. Lett. 90, 082302 (2003)

$$I_{AA}(\Delta\phi_1, \Delta\phi_2) = \frac{\int_{\Delta\phi_1}^{\Delta\phi_2} d(\Delta\phi)\{D^{\mathrm{AuAu}} - B[1 + 2v_2^2 \cos(2\Delta\phi)]\}}{\int_{\Delta\phi_1}^{\Delta\phi_2} d(\Delta\phi) D^{pp}}.$$



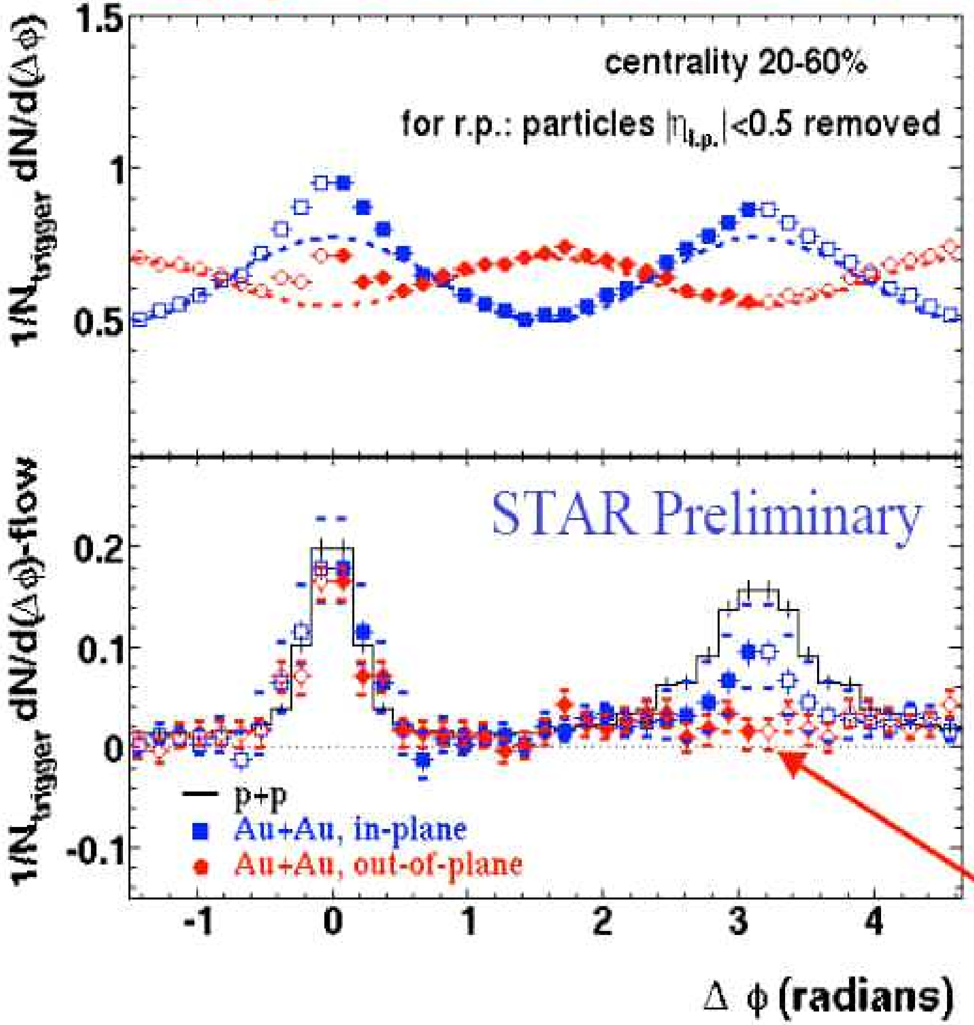


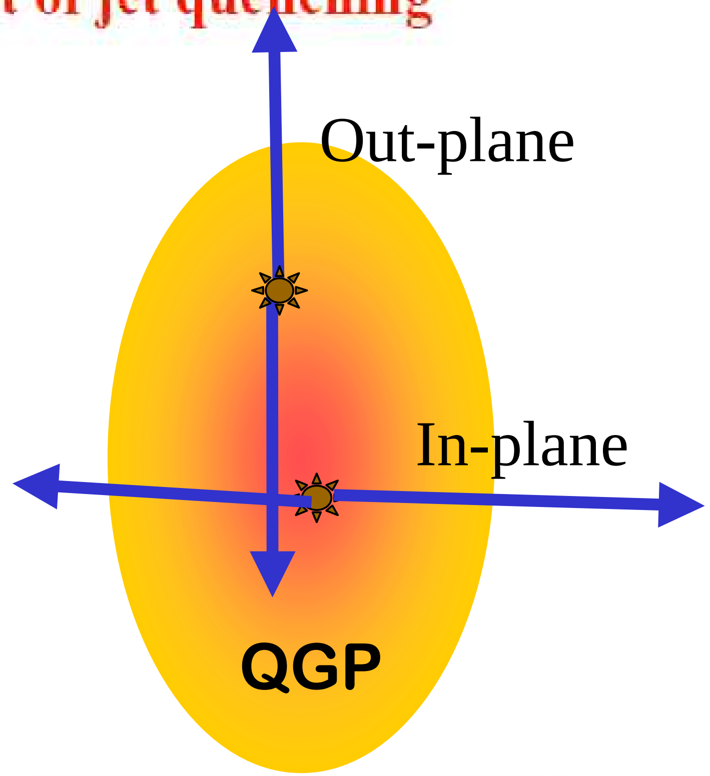
Correlation of Associated hadrons 2<pT<4 GeV with triggered 4<pT<6

K. Filimonov: DNP 10.31.03

Di-Hadron Tomography

High pt v2 and correlation : the test of jet quenching





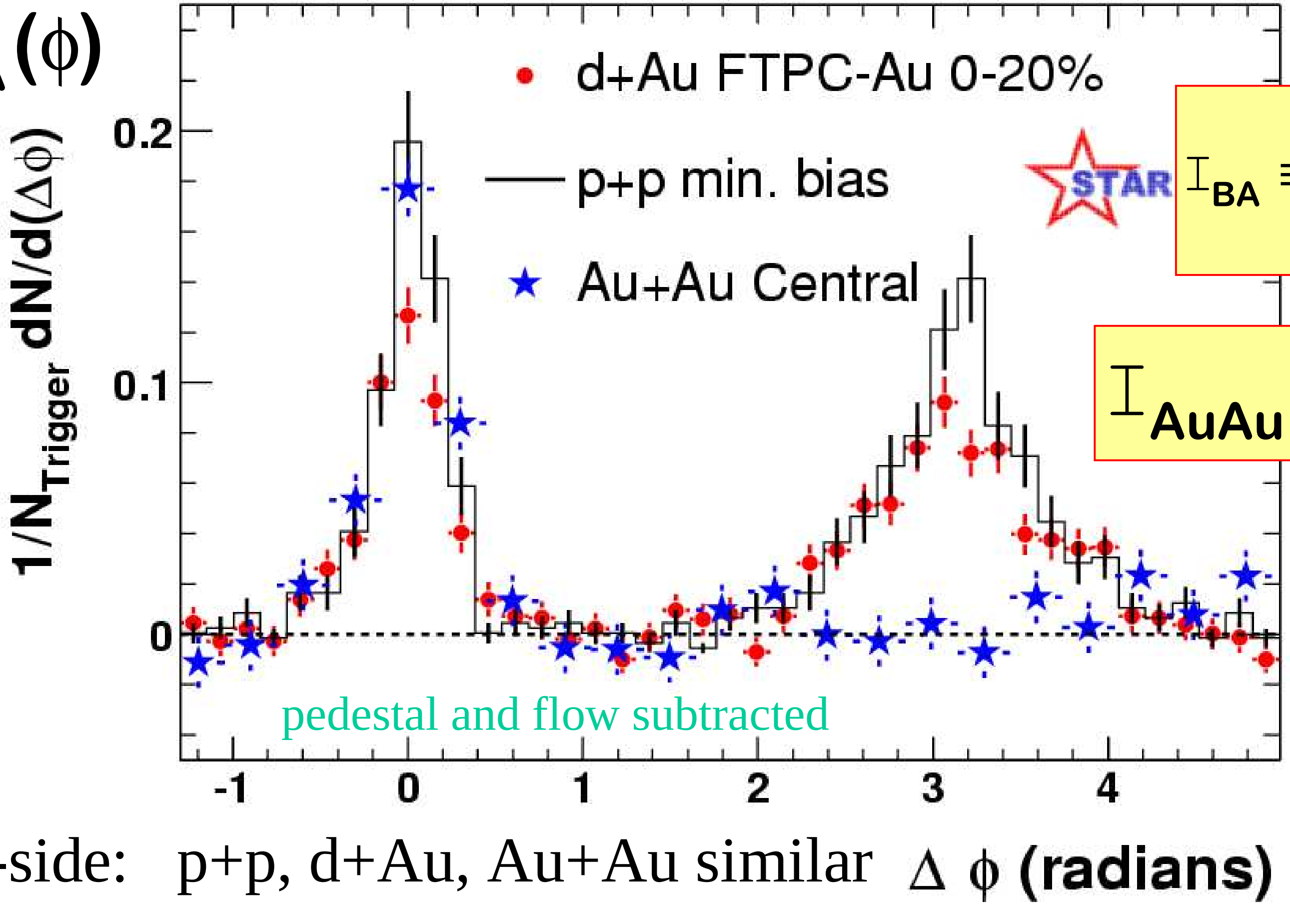
Back-to-back suppression is larger in the out-of-plane direction

A.Tang: BNL 11.18.03

13

“The Return of the Jeti” in D+Au

$C_{BA}(\phi)$



Away-Side

$$I_{BA} \equiv \frac{\int_{\pi/2}^{3\pi/2} d\phi\, C_{BA}(\phi)}{\int_{\pi/2}^{3\pi/2} d\phi\, C_{pp}(\phi)}$$

$$I_{AuAu} \ll I_{DAu} \approx 1$$

Near-side: p+p, d+Au, Au+Au similar

Away-side: Au+Au strongly suppressed relative to p+p and d+Au

Suppression of the back-to-back correlation
in central Au+Au is a final-state effect

P. Jacobs (STAR) 6/18/03

PHENIX

d-Au $\sqrt{s}$ =200 GeV:

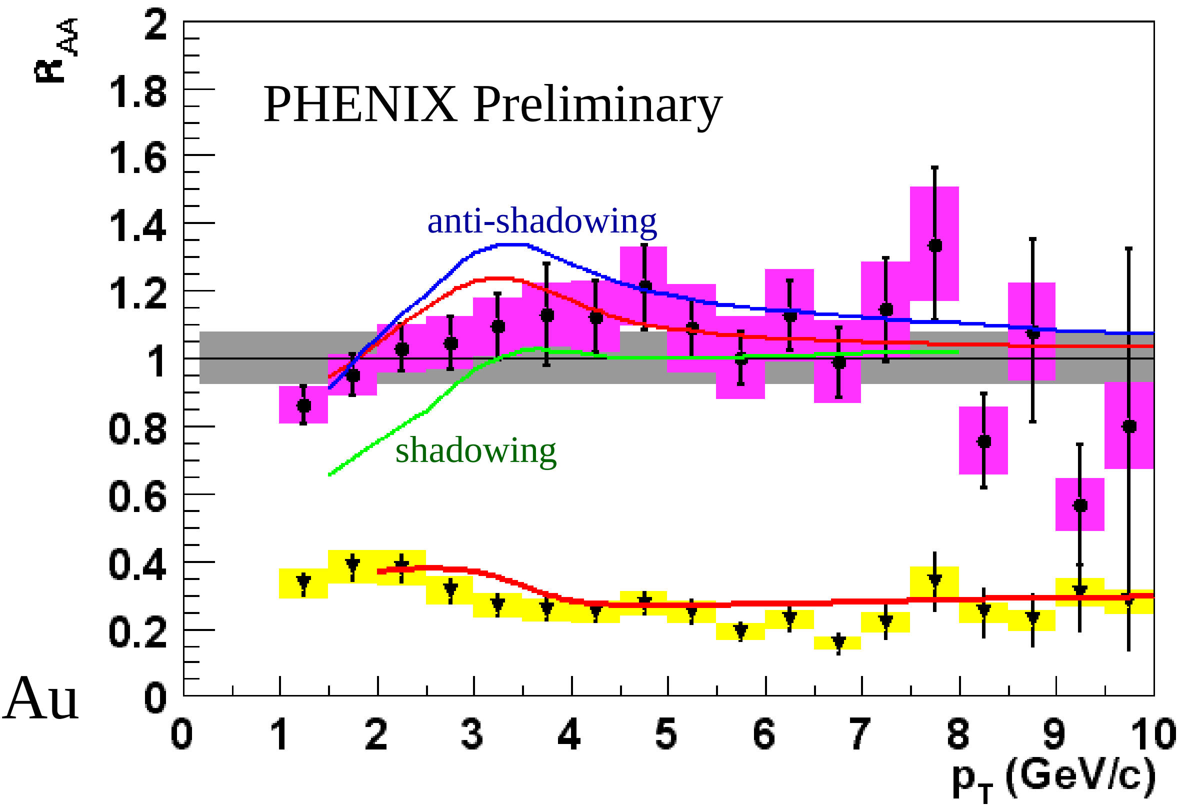
π^0 $R_{BA}(p_T)$ Predictions vs Experiment for central Au+Au and d+Au collisions

I. Vitev, nucl-th/0302002

I. Vitev and M. Gyulassy, PRL89 (2002) 252301

$$R_{AuAu} \ll R_{DAu} \sim 1$$

Consistent with QGP in AuAu

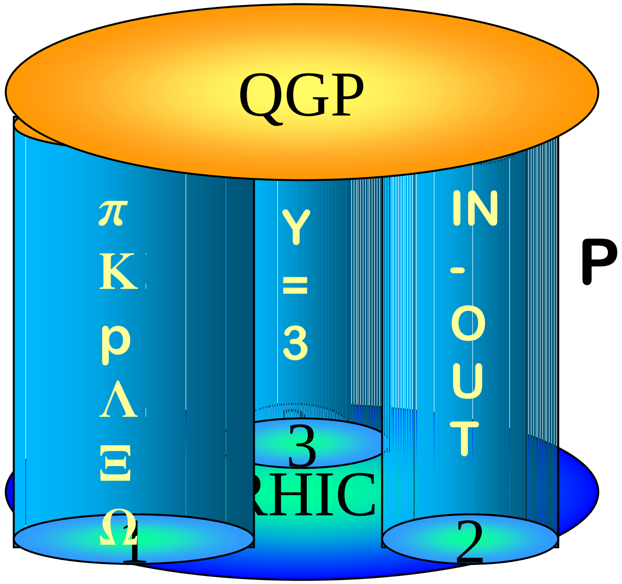


Converging Evidence to QGP at RHIC

Null Control D+Au

+ dA(y=3)

BulkCollectivity
P_{QCD}



Parton Quenching
pQCD

+ $v_1(y)$

+ $I_{AA}(\phi,\phi_R)$

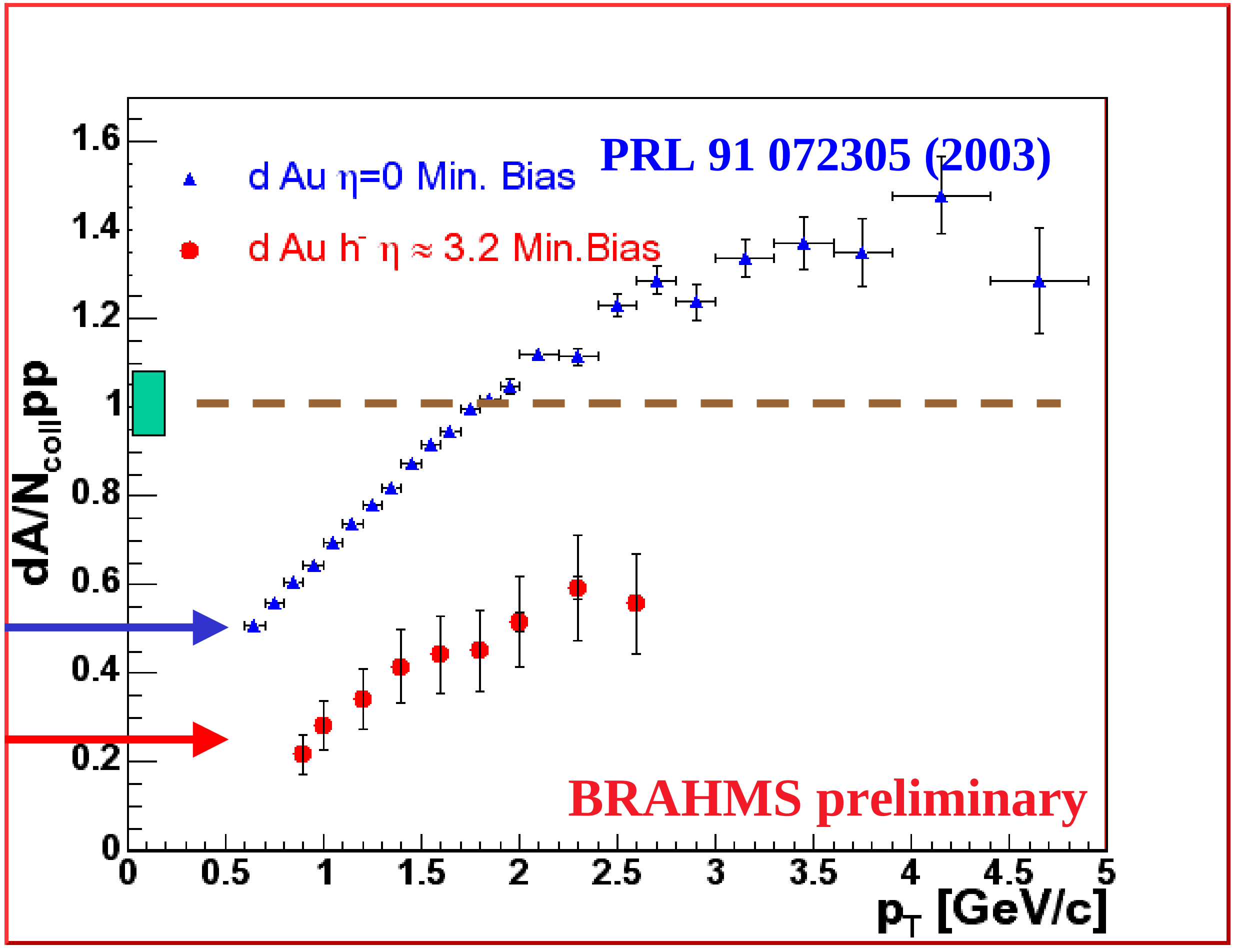
$$\boxed{QGP = P_{QCD} + pQCD + dA = v_2 + (R+I)_{AA} + (R+I)_{dA}}$$

$$+ v_1 + I_{AA}(\phi,\phi_R) + dA(y=3)$$

The preliminary D+AU data at y=3

Is this the CGC or Limiting Quark Fragmentation?

BRAHMS: d-Au Nuclear Modification factor at η ~3.2



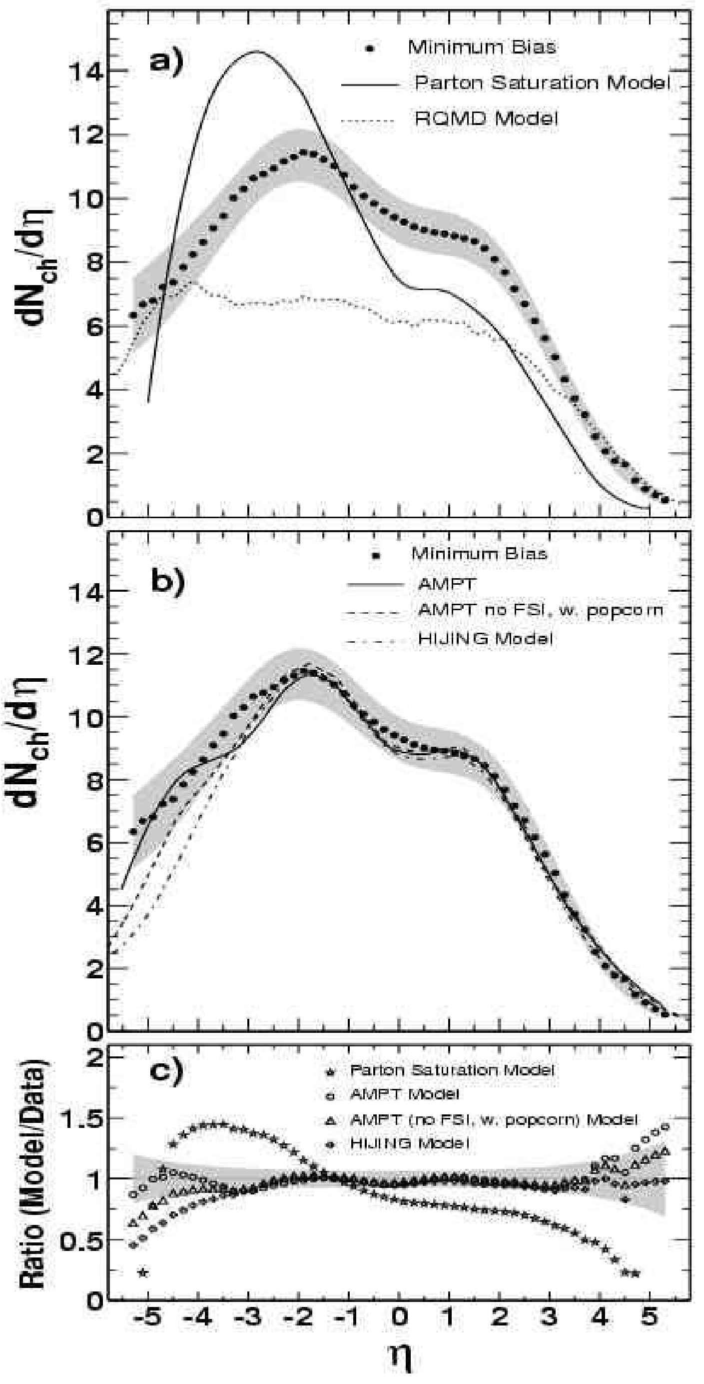
RdAu compares the yield of **negative particles** produced in dAu to the scaled number of particles with same sign in p-p

The scale is the number of binary collisions:

N_{coll}=7.2
(minimum biased)

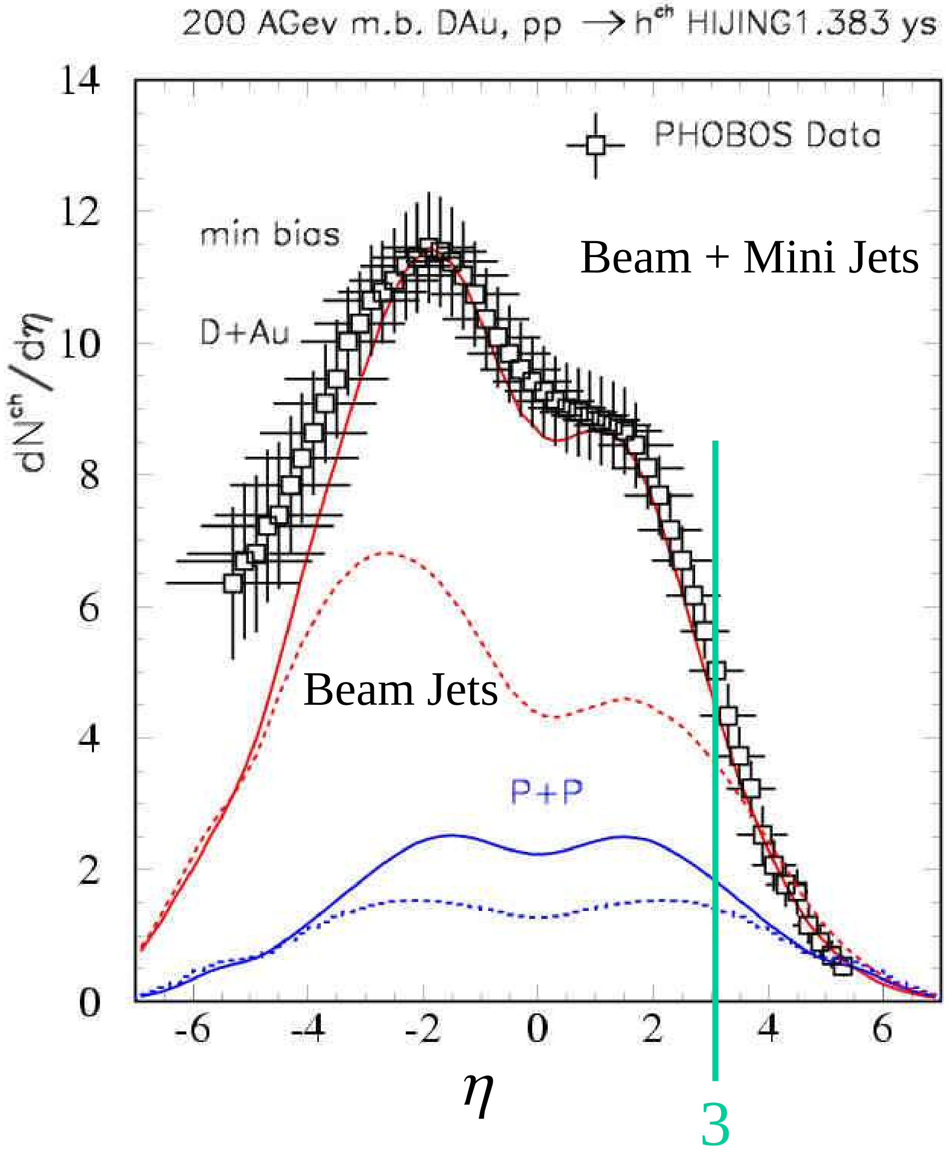
PHOBOS Global View
$dN/d\eta$ in D+Au

nucl-ex/0311009

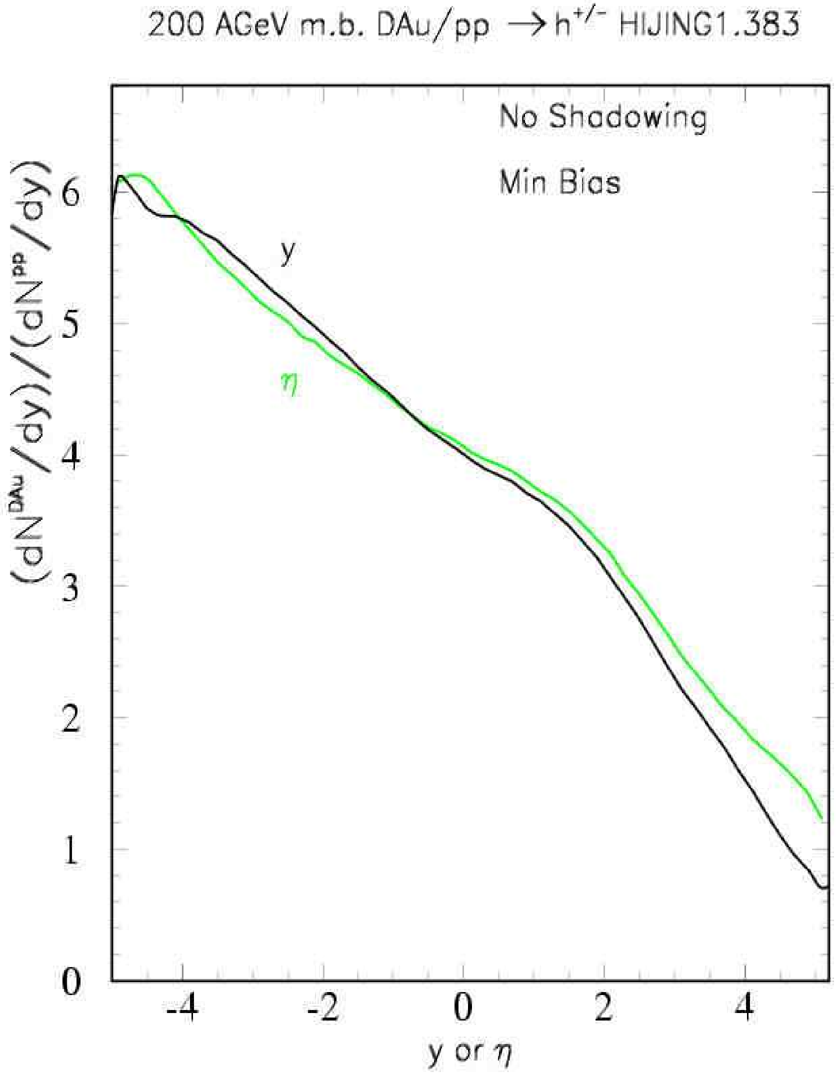


HIJING, AMPT
Predictions
account for D+Au

Beam Fragmentation Dominates y>3



The D+Au Triangle in HIJING



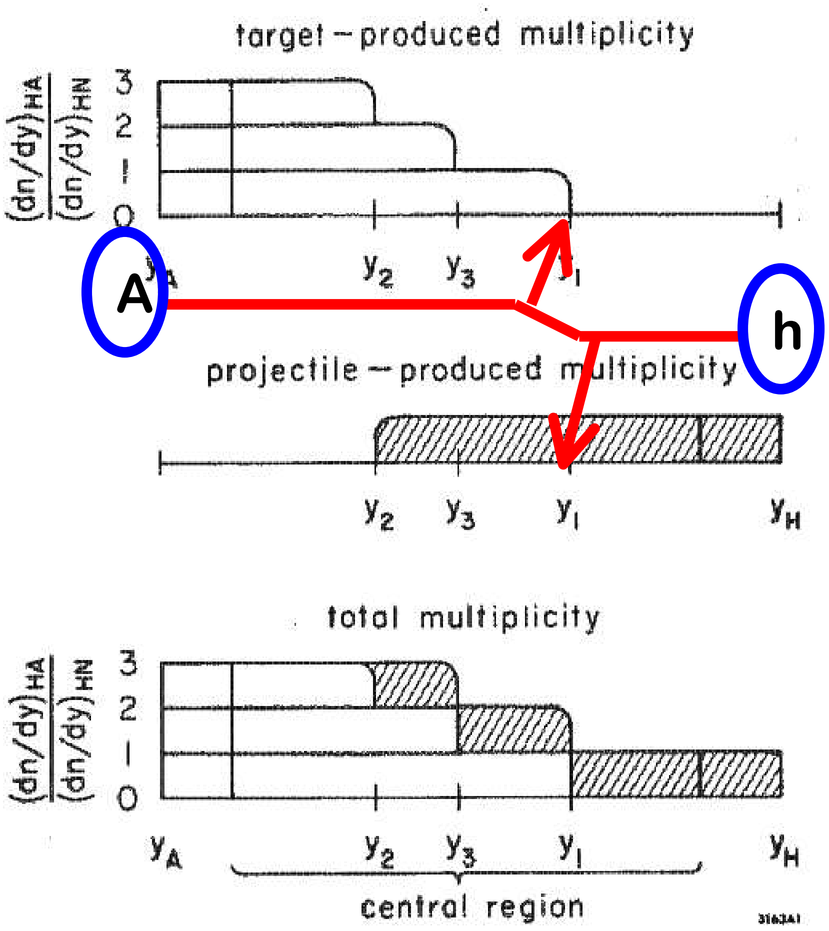
Brodsky, Gunion, Kuhn, PRL39(77)1120

Color Neutralization (Multi-Soft) Model

DPM: Capella et al

LUND: Anderson et al

HIJING: Wang , MG



Predicted Triangle pA distribution

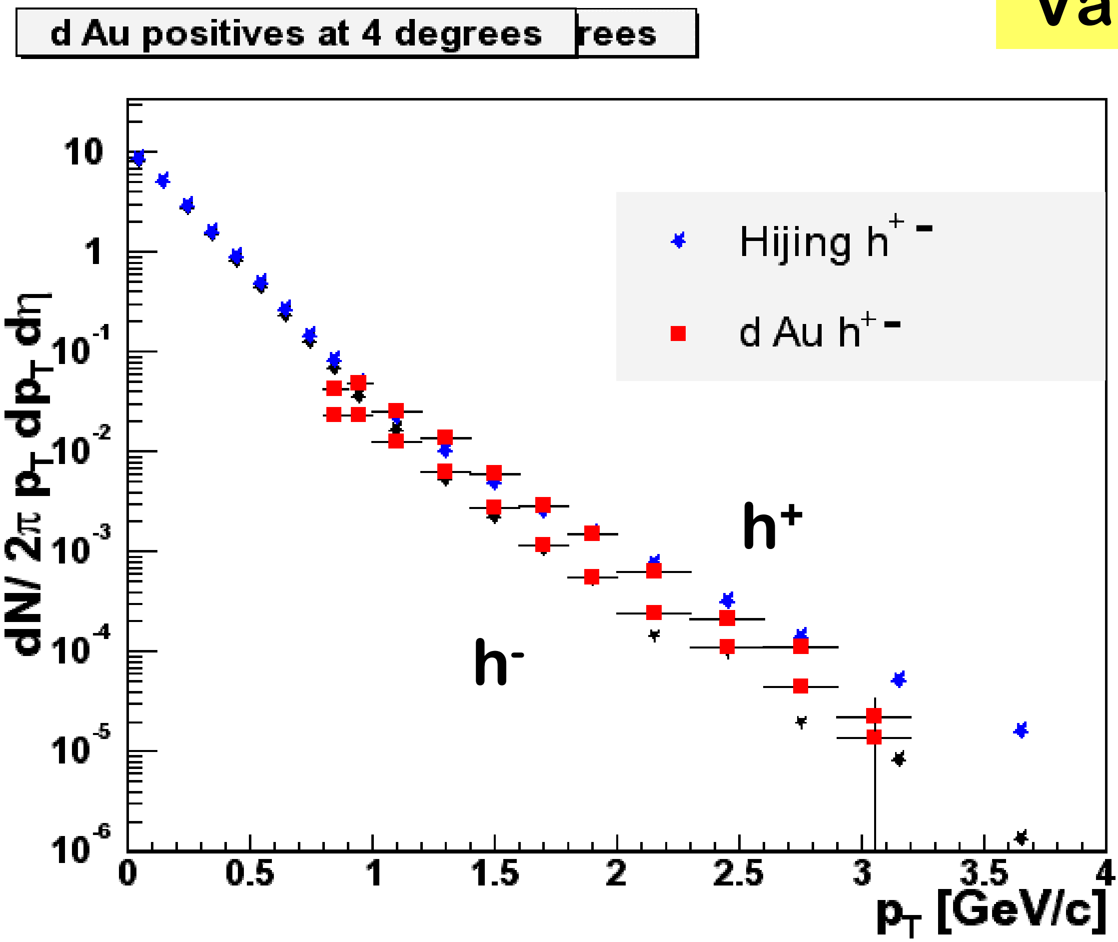
Triangle Distribution
Consequence of

1) Conservation of
Valence quarks, i.e. B

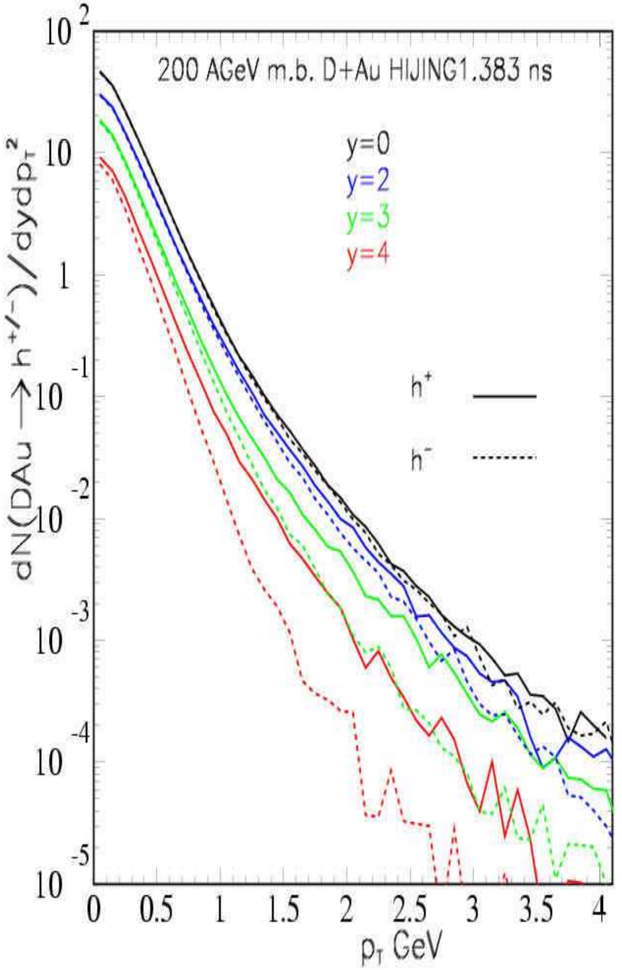
2) ~ 1/x Feynman Wee

Preliminary BRAHMS η=3

$h^+ > h^-$ Clear evidence of Valence quark fragmnt

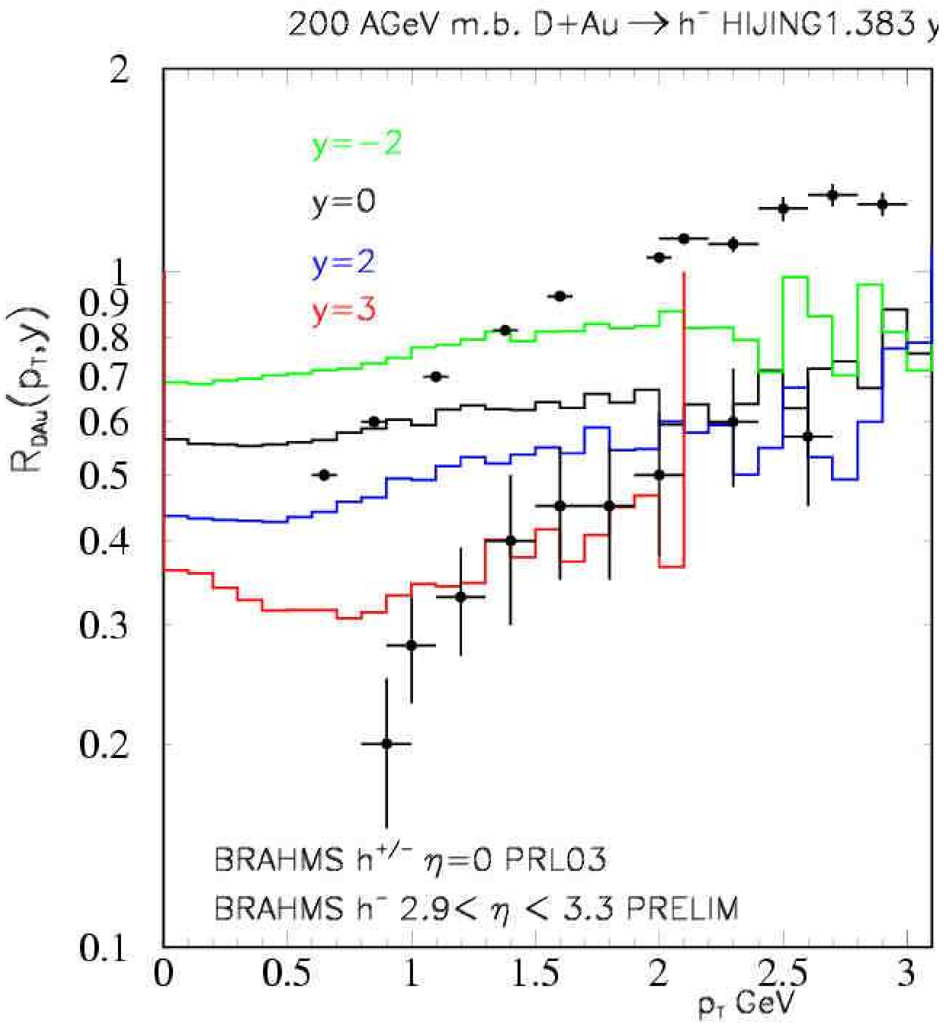


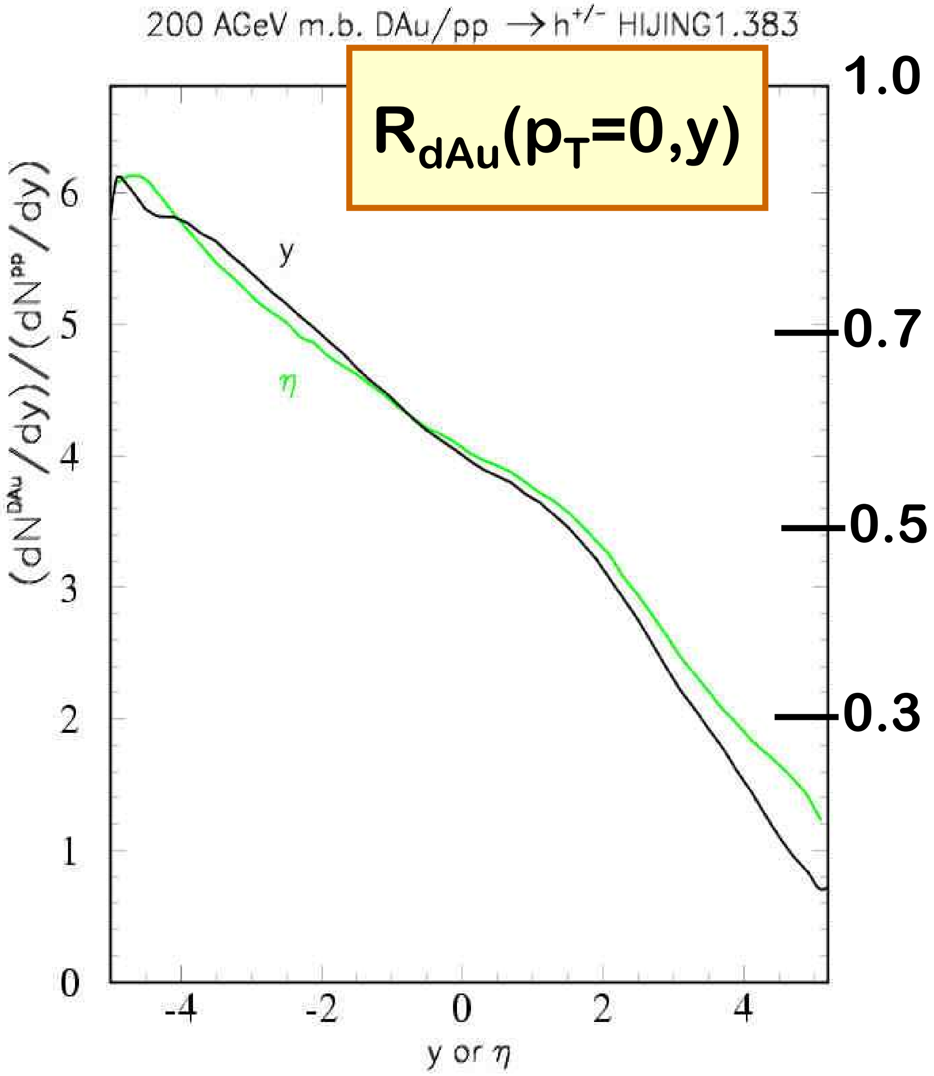
Debbe et al, DNP 10/31/2003



Low pT<0.5 *Triangle* boundary controls forward $R_{dA}(y_d) \sim 1/N_{coll}$!!

The D+Au triangle





http://www.thep.lu.se/Smallx/

THE SMALL X COLLABORATION @ LUND

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DGLAP, BFKL, CCFM ↔ CASCADE, LDCMC, ARIADNE

PYTHIA
HIJING

2 k_t-factorization versus higher order processes in collinear factorization

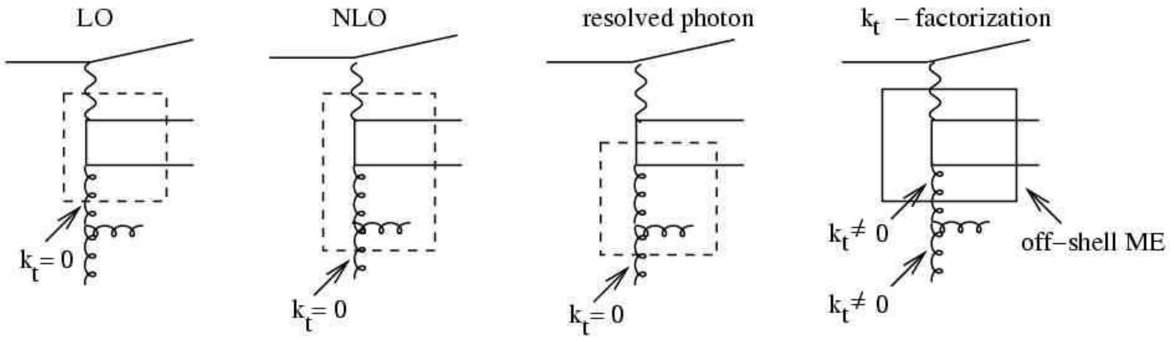

Figure 1. *Diagrammatic representation of LO, NLO and resolved photon processes in the collinear approach compared to the k_t-factorization approach.*

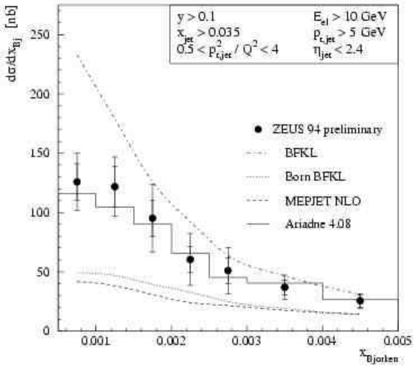

FIGURE 2. Forward jet cross section vs. x_{Bj}; a qualitative comparison between ZEUS data, QCD calculations and Ariadne Monte Carlo. Inner error bars are statistical errors only, the outer are the quadratic sum of statistical and systematic errors.

Wolfle DIS97

Four independent calibrations of Initial QGP density

$$\boxed{\varepsilon(\tau_0) \approx 100\, \varepsilon_0 = 15\ \mathrm{GeV/fm^3}}$$

1. Bjorken Backward extrapolation

$$E_T / N_\pi = 0.5\ \mathrm{GeV}, \quad dN_\pi / dy = 1000,$$
$$\tau_0 = 1/p_0 = 0.2\ \mathrm{fm/c}, \quad V = (0.2\ \mathrm{fm})\pi R^2 = 30\ \mathrm{fm^3}$$
$$\varepsilon_{Bj} = 500\ \mathrm{Gev}/30\ \mathrm{fm^3} = 100\, \varepsilon_0$$

2. Hydrodynamic initial condition needed for $v_2(p_T)$

$$\varepsilon_{Hydro} > 2\, \varepsilon_{Bj} = 500\ \mathrm{Gev}/30\ \mathrm{fm^3} = 100\, \varepsilon_0$$

KHH
TS
HN

3. Jet Tomography: $dN_g / dy = 1000$

$$\varepsilon_{Jets} \approx \varepsilon_{Bj} \approx 100\, \varepsilon_0$$

GLV
WW

4. Gluon saturation $p_T < Q_s$ predicted

$dN_g / dy = 1000$ at $Q_{sat} = 1$ GeV at $y=0$

MB
McV
EKRT

The END of searching for the QGP

The BEGINNING of measuring its properties

- 12D Correlations
- Heavy Quarks
- Direct Photons
- Leptons

Experimental To Do List

- Y=+- 4 dAu pt to kinematic bounds

- C_2(phi$_1$,phi$_2$, pt$_1$,pt$_2$, eta$_1$,eta$_2$, fl$_1$,fl$_2$, Mult, A,B, Ecm)

- Heavy Quark tomography

- Open Charm (enhancement?); J/Psi (suppression?)
- Charm Flow?

- Need Direct Photons thermometer
- and tagged direct photon -quark jets!

- Excitation function Ecm~50-100, A=20-100

Theory To Do List

- HBT source E_{cm} invariance?
  why No time-delay? Is Lin-Ko the answer?

- E_T/N E_{cm} invariance, N_{part} invariance?

- V_2(pT>2, m) source of Flat High pt saturation

- V_2(y)   ***NON*** Bjorken boost invariant 3+1 D

- Baryon transport dynamics

- Thermalization, QGP Transport theory