The Quark-Gluon-Plasma Is Found at RHIC

(but experimentalists have *Yet* to recognize it)

Miklos Gyulassy
Columbia University

Three major discoveries at RHIC

1) Conclusive evidence for Bulk P_{QCD} collective flow of 5000 □, K, p
2) Conclusive evidence for pQCD jet quenching in Au+Au at RHIC
3) Conclusive evidence of jet *un*quenching in d+Au: Null Control

All 3 are explained by QCD dynamics

1) My Conclusion: **1+2+3=QGP** $E/V(\tau \sim 0.2\ fm/c) \sim 100\,\varepsilon_0$

Au+Au at 200 AGeV made Bulk QGP Matter

Outline

1. Overview of 3 convergent lines of evidence

2. Bulk Collective Flow and the QCD Equation of State

3. Parton Diagnostics: Jet Quenching

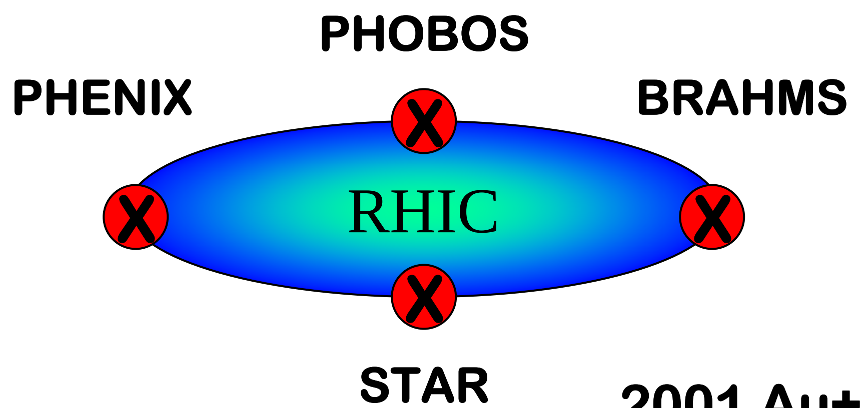
4. The D+Au Null Control

5. Conclusion: The QGP is found

Theoretical Prediction 1975-...

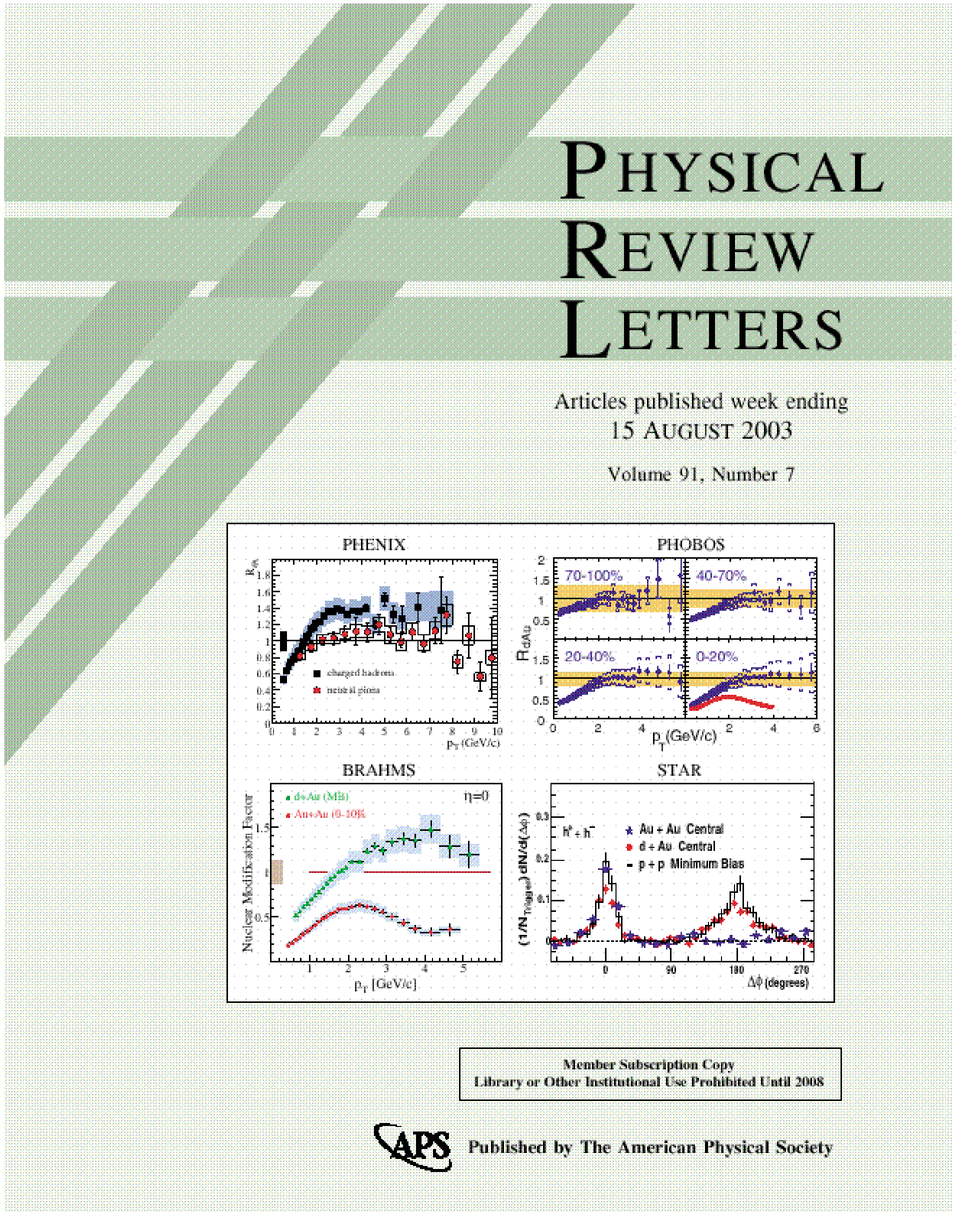
Asymptotic Freedom
Deconfinement
Chiral Symmetry

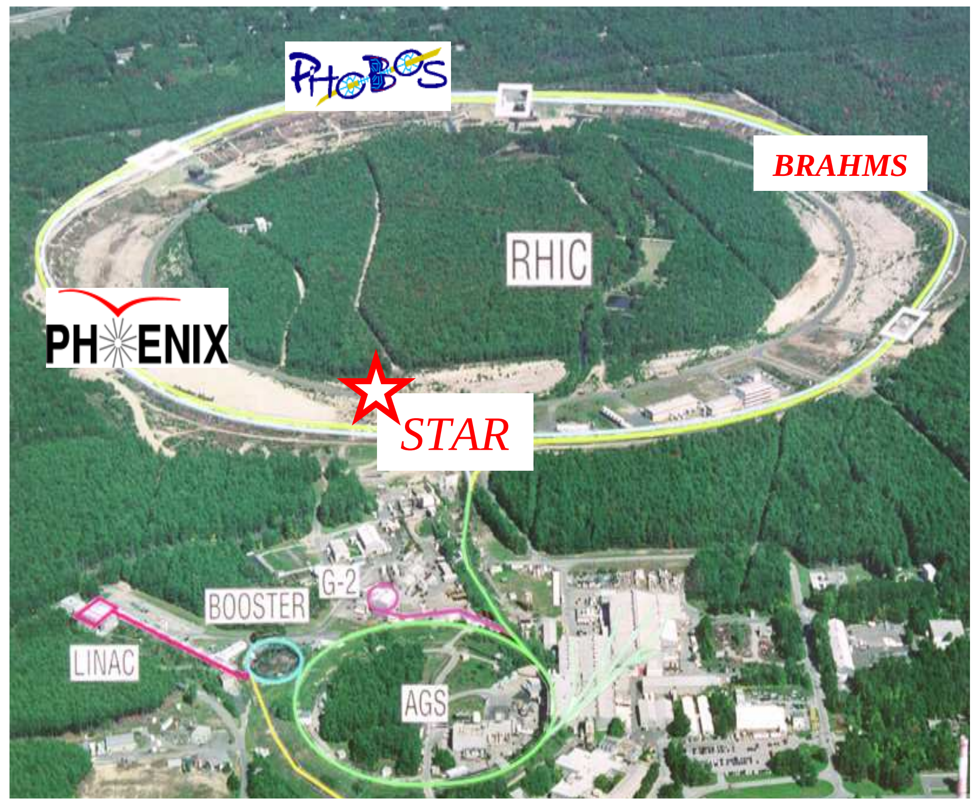
Experimental Tools 2000-...



2001	Au+Au	130 AGeV
2002	Au+Au, p+p	200 AGeV
2003	D+Au	200 AGeV

3rd RHIC Milestone





Kemer 9/26/03

VOLUME 68, NUMBER 10 PHYSICAL REVIEW LETTERS XN Wang, MG 9 MARCH 1992

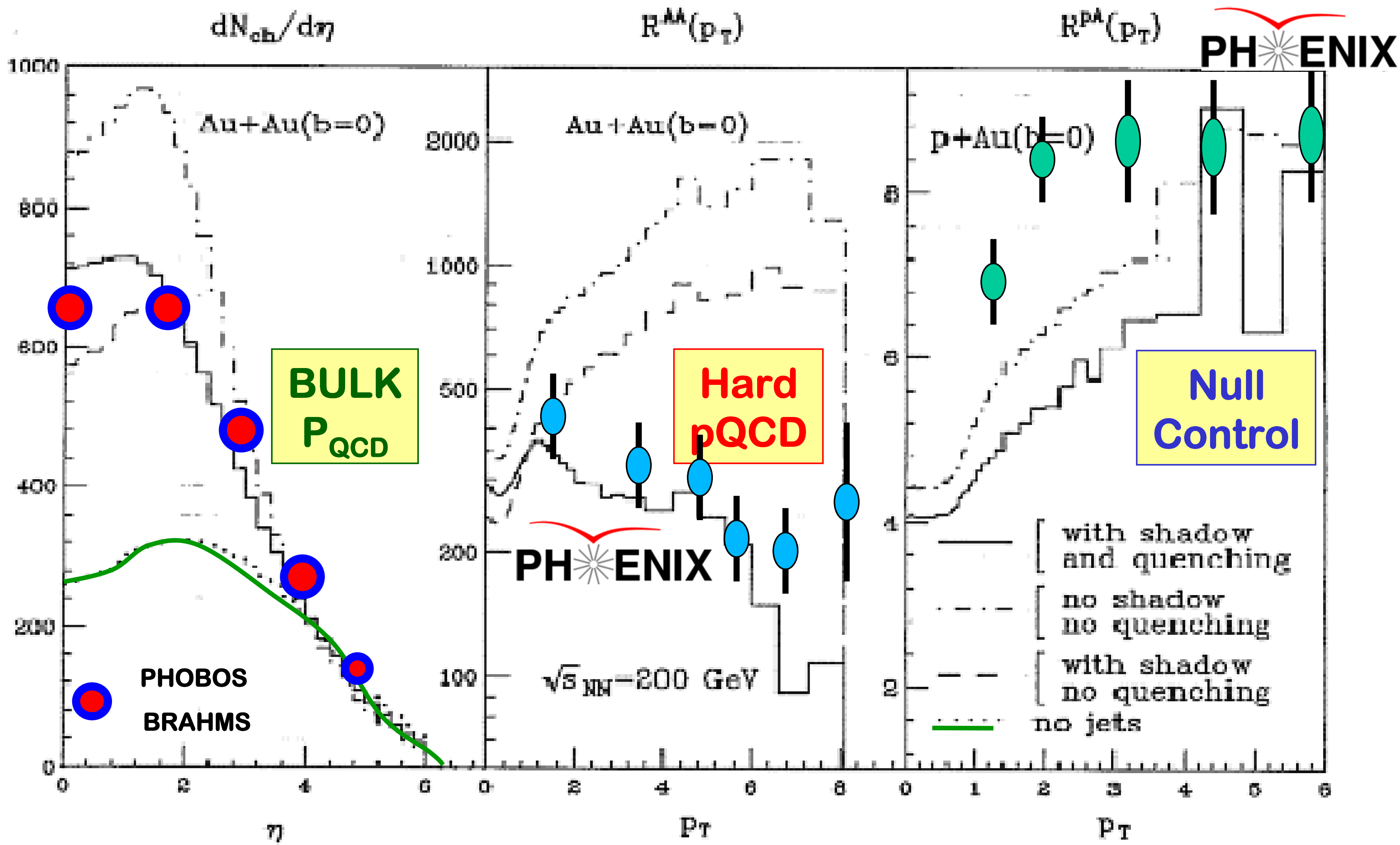
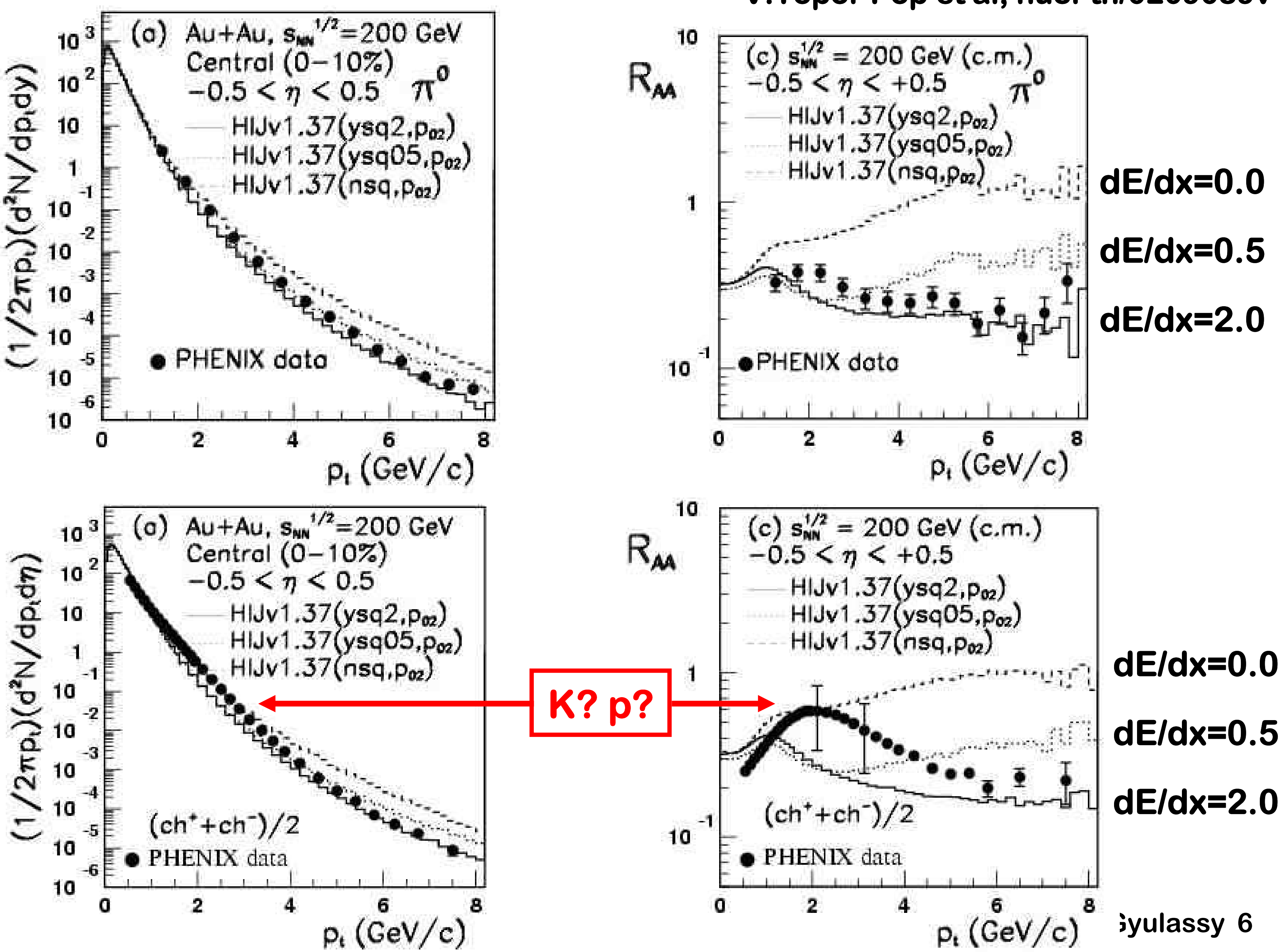


FIG. 1. Results of HIJING on the dependence of the inclusive charged-hadron spectra in central Au+Au and p+Au collisions on minijet production (dash-dotted line), gluon shadowing (dashed line), and jet quenching (solid line) assuming that gluon shadowing is identical to that of quarks and $dE/dl = 2$ GeV/fm with $\lambda_s = 1$ fm. $R^{AB}(p_T)$ is the ratio of the inclusive p_T spectrum of charged hadrons in $A+B$ collisions to that of $p+p$.

Mini-Jet quenching and the Baryon anomaly

V.Topor Pop et al, nucl-th/0209089v4



What is a Quark Gluon Plasma?

How will we recognize it in the lab

if we don't know what it looks like?

We need an operational QGP definition !

My 3 Part Definition of a QGP

1. A form of matter (many body dynamical system) with a unique set of Bulk (collective) phenomena and partonic diagnostics

2. which are calculable in the deconfined (Colored) quark-gluon basis of QCD

3. And which can be turned on or off via Control experiments

Examples of *NON*-QGP systems in QCD

1.	e+e- -> q q g	2 ok but not 1
2.	p+p -> pi, K, p	2 ok but not 1
3.	e+A -> jets	2 ok but not 1
4.	Nucleus A	1 ok but not 2
5.	SIS,AGS res. gas	1 ok but not 2
6.	SPS A+A	1 ok but 2~OK but not 3!

SPS AA discovered important QGP *PRE*-requisites

1. Statistical (microcanonical) phase space hadronization
   - Final Hadron degrees of freedom equilibrated (NA49)
   - Even hyperons (WA97) T_{chem}~170 MeV~T_c

2. Bulk Radial Flow v_T~0.6 c transverse Doppler shift (NA49)
   - Pion wind blows for a long time; Baryons windsurf
   - Conclusive evidence for Hadronic FSI

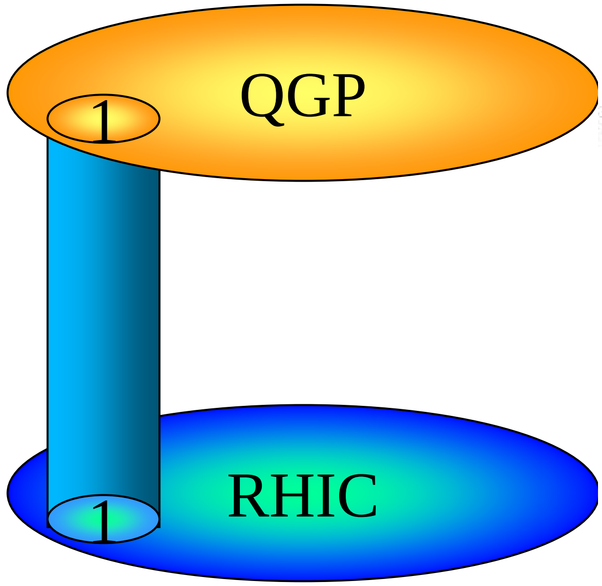
3. QCD probe $c\underline{c}$ ->J/Psi found strongly suppressed (NA50)
   - BUT phenomenon *Failed* to turn off in p+A, S+A Control !

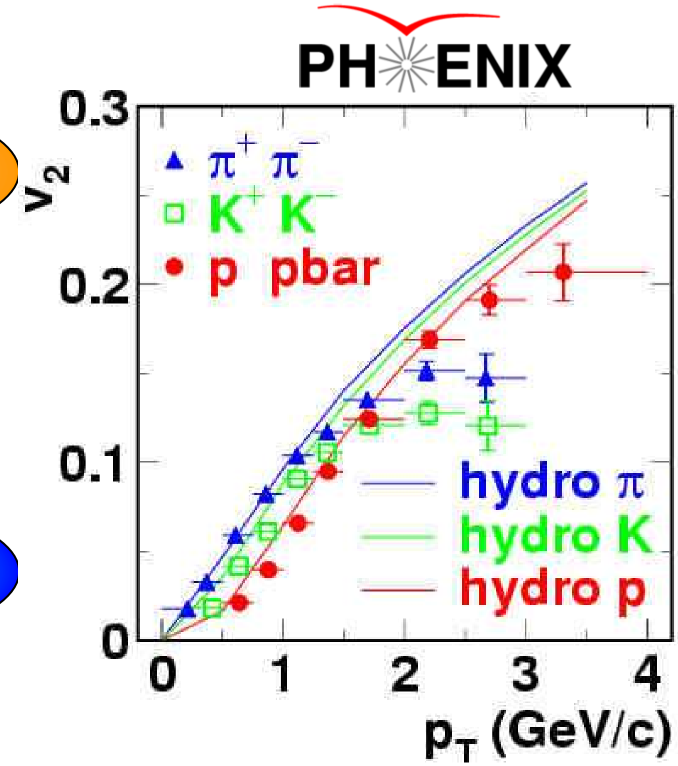
4. High p_T pQCD $\square^0$ probe *Failed* to quench due to initial state (Cronin) physics !

QCD parton probes at SPS failed the Null Control test of QGP

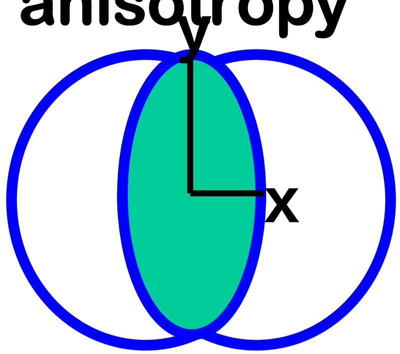
First Line of Evidence for QGP at RHIC

Bulk *Elliptic*
Collective
Flow
P_{QCD} EOS





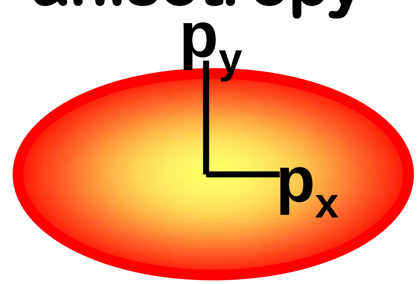
Initial *spatial* anisotropy



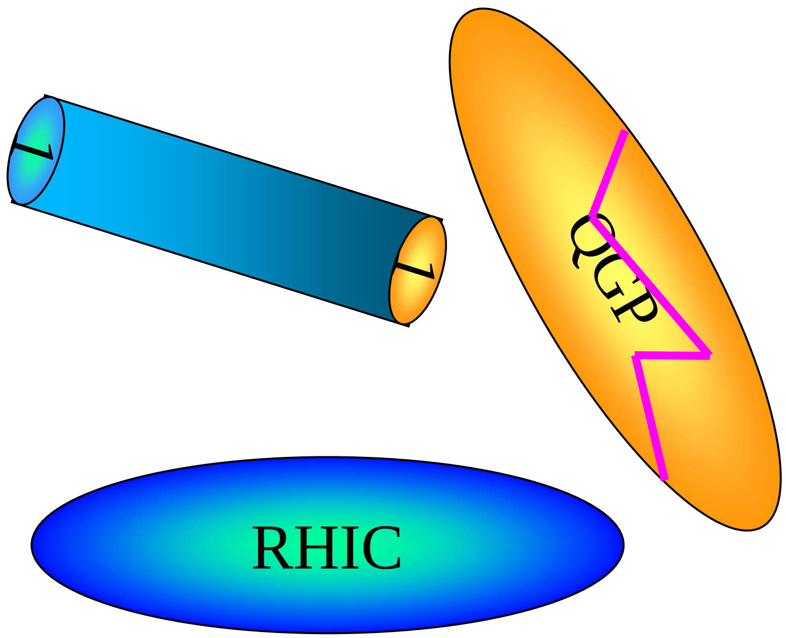
$\Rightarrow$

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

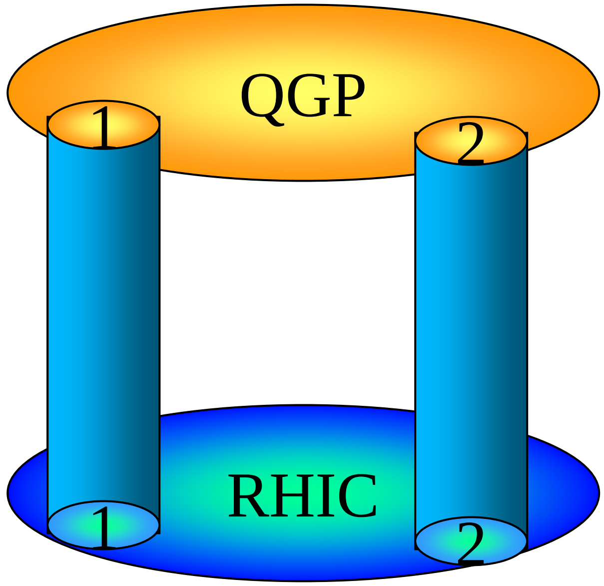
Final *momentum* anisotropy



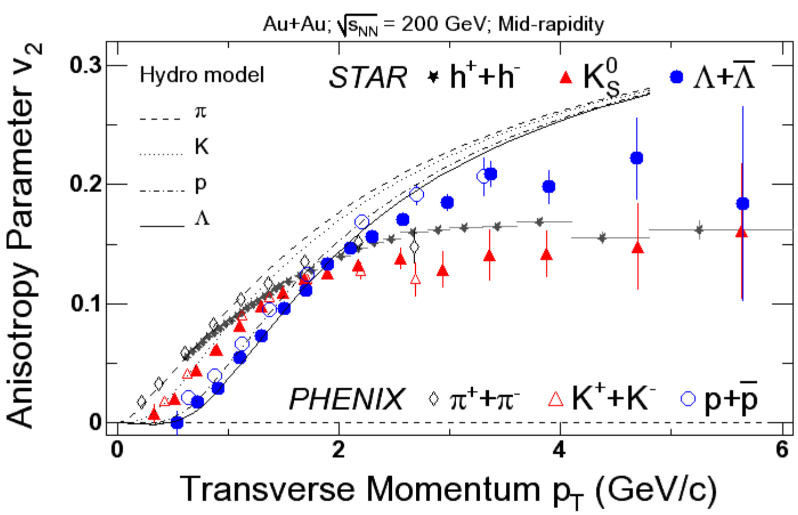
Unfortunately One Leg Tables Are Unstable!



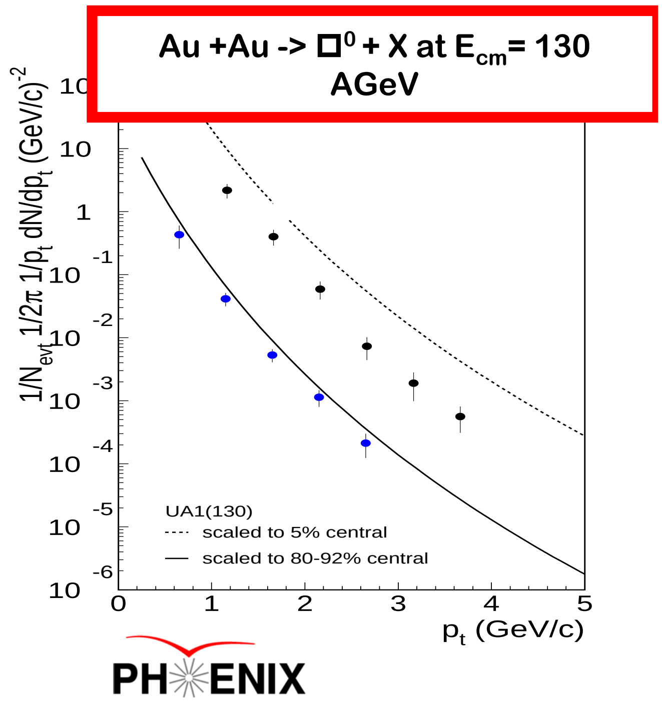
Second Line of Evidence for QGP at RHIC



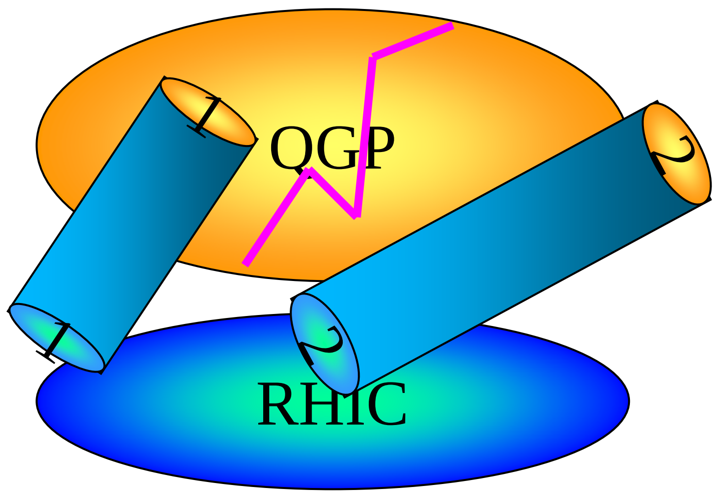
Bulk Elliptic Flow



Jet Quenching

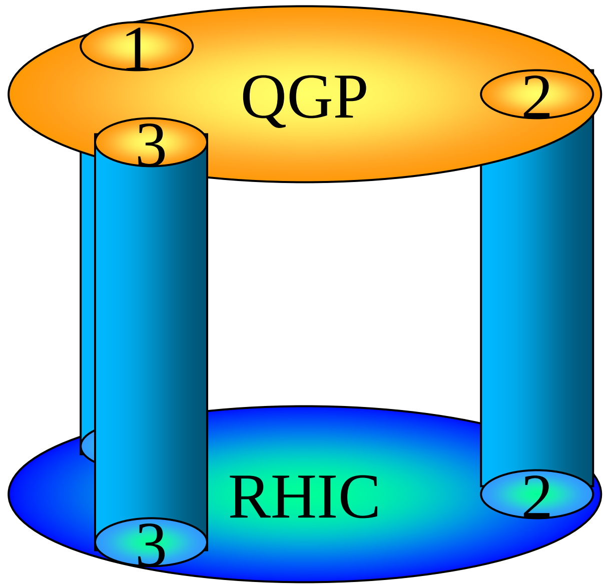


BUT
Two Legged
Tables are
STILL
Unstable!



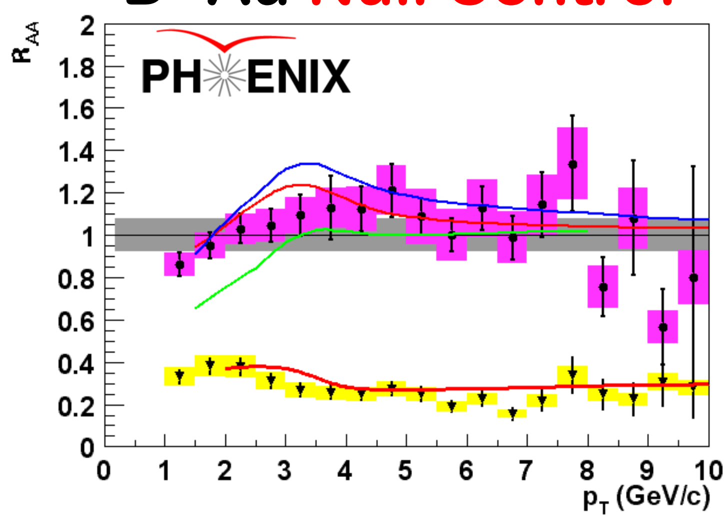
Third Line of Evidence for QGP at RHIC

Bulk
P_{QCD}



Parton
pQCD

D+Au Null Control + pp Calibration



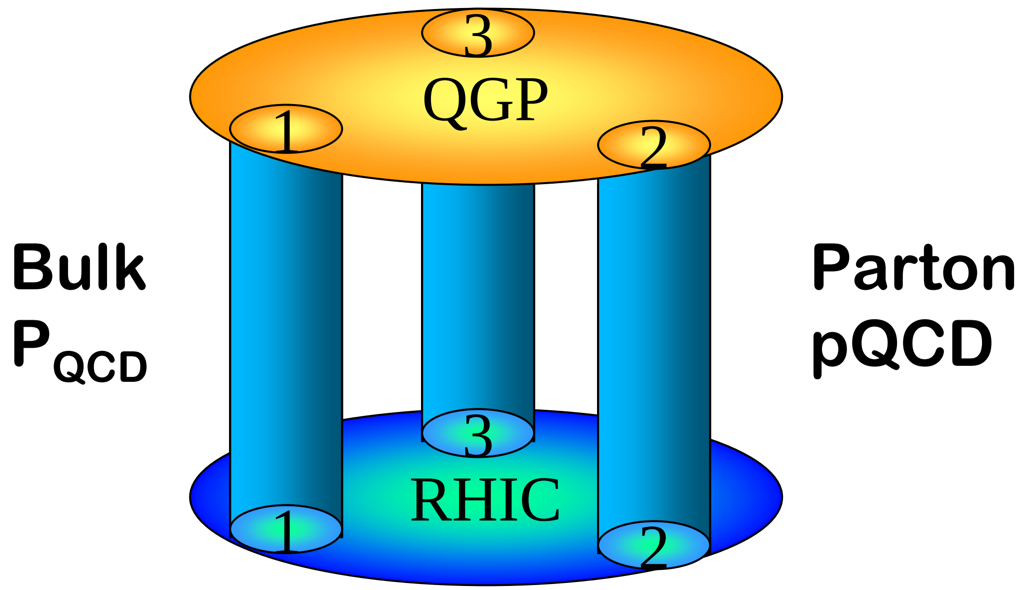
No Quench D+A !

Strong Quench A+A

Three Lines Converge to QGP at RHIC

Null Control

Three Legs
Stable Even
If Unequal



1. Bulk P_{QCD} Collective Elliptic Flow
2. Parton pQCD Jet dynamics
3. p+p Calibration and d+A Null Control

$$QGP = P_{QCD} + pQCD + dA = v_2 + (R_{AA}+I_{AA}) + R_{dA}$$

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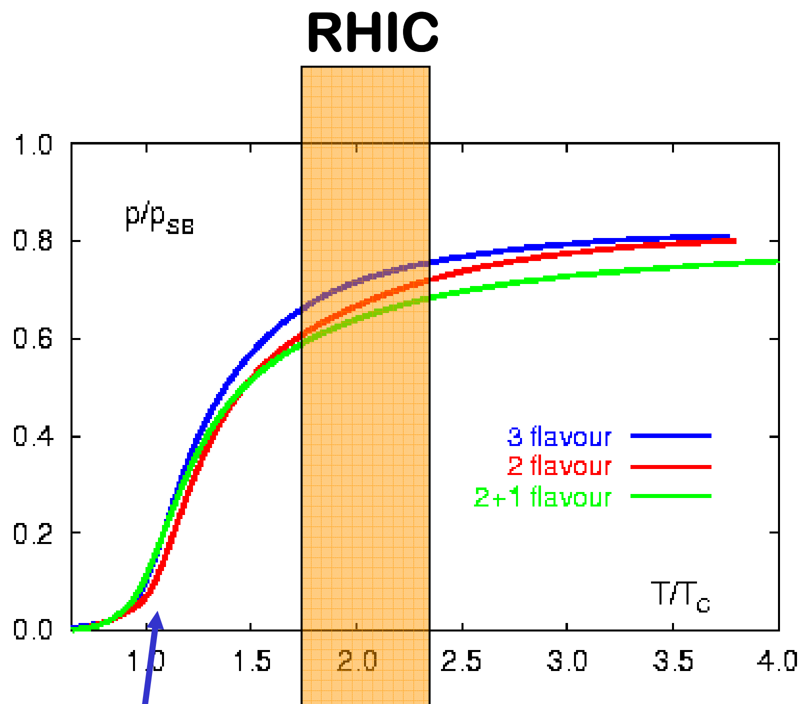
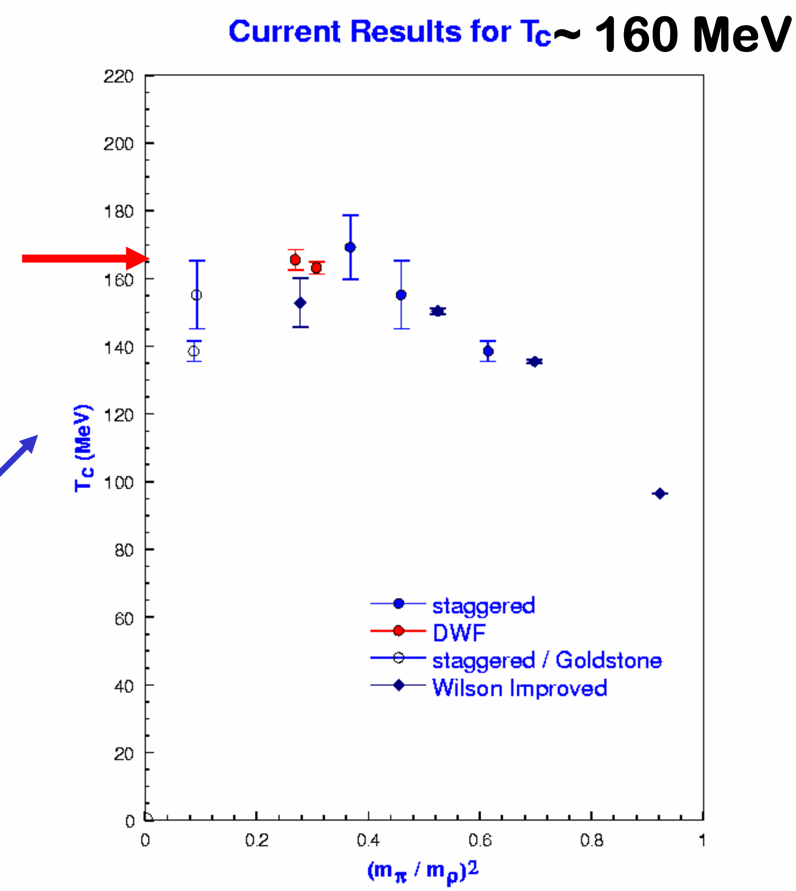
The QGP Equation of State from LQCD

$$P_{QCD} \approx \frac{1}{3} K_{QCD} T^4 - B_{vac}$$

$$\varepsilon_{QCD} \approx K_{QCD} T^4 + B_{vac}$$



F. Karsch et al



N. Christ et al

Goal is to test this unique prediction of QCD :

The softenning of P_{QCD}

$c_s \sim 0$ Near $T_c \sim 160$ MeV

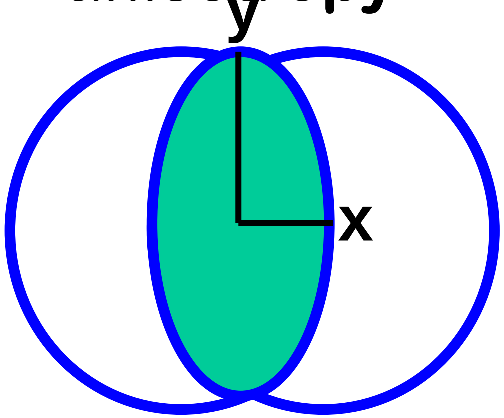
Bulk Collective Flow of QCD matter

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

QCD EOS

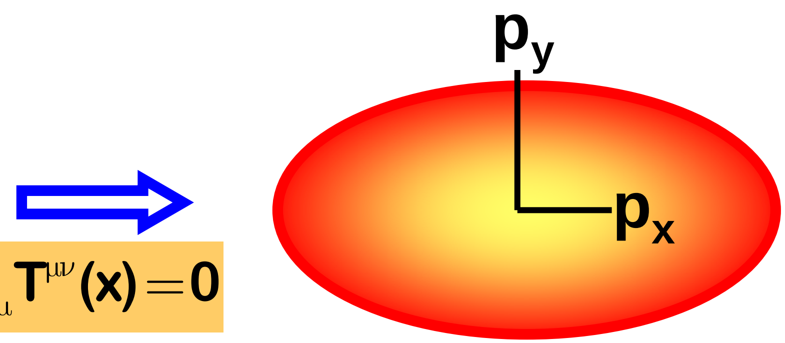
H. Stocker, W. Greiner (1980)
P.Kolb, U. Heinz et al
D.Teany, E. Shuryak et al
T. Hirano, Y. Nara

Initial *spatial* anisotropy



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

Final *momentum* anisotropy



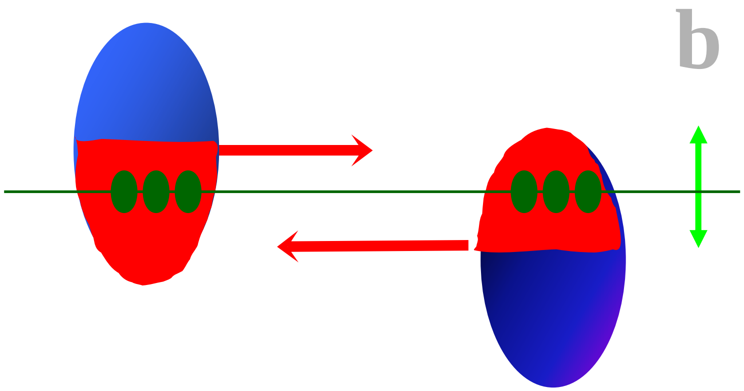
Elliptic Flow

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

The Nuclear Geometry Experimental Knob

Initial Geometry

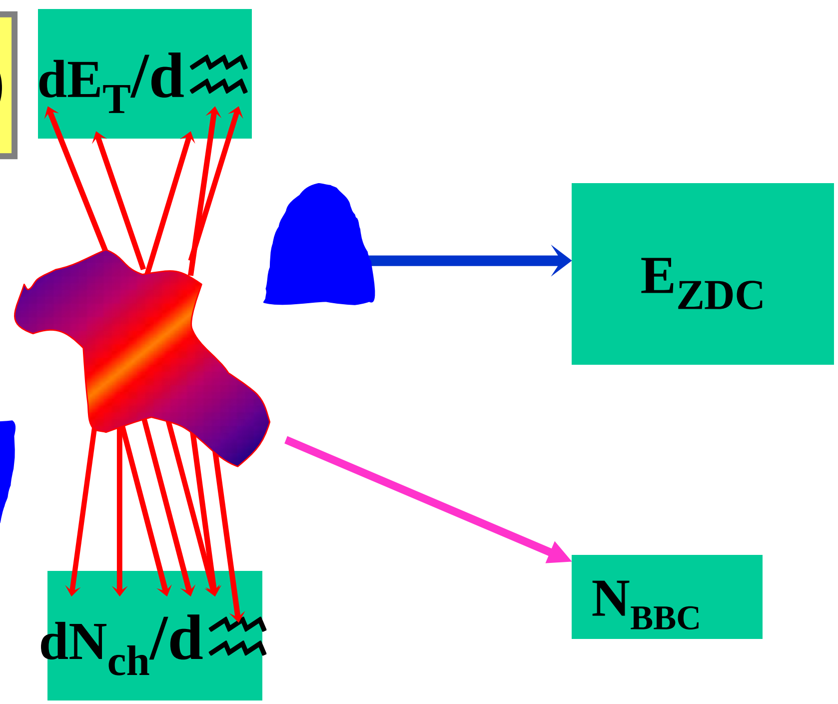
$$N_{part}(b) = 2\int d^2s\, T_A(s+\tfrac{b}{2})(1-e^{-\sigma T_A(s-\frac{b}{2})})$$



$$T_A(b) = \int dz\ \rho_A(z,b) \approx 2\rho_0\sqrt{R^2-b^2}$$

$$T_{AB}(b) = \int d^2s\, T_A(s+\tfrac{b}{2})T_B(s-\tfrac{b}{2})$$

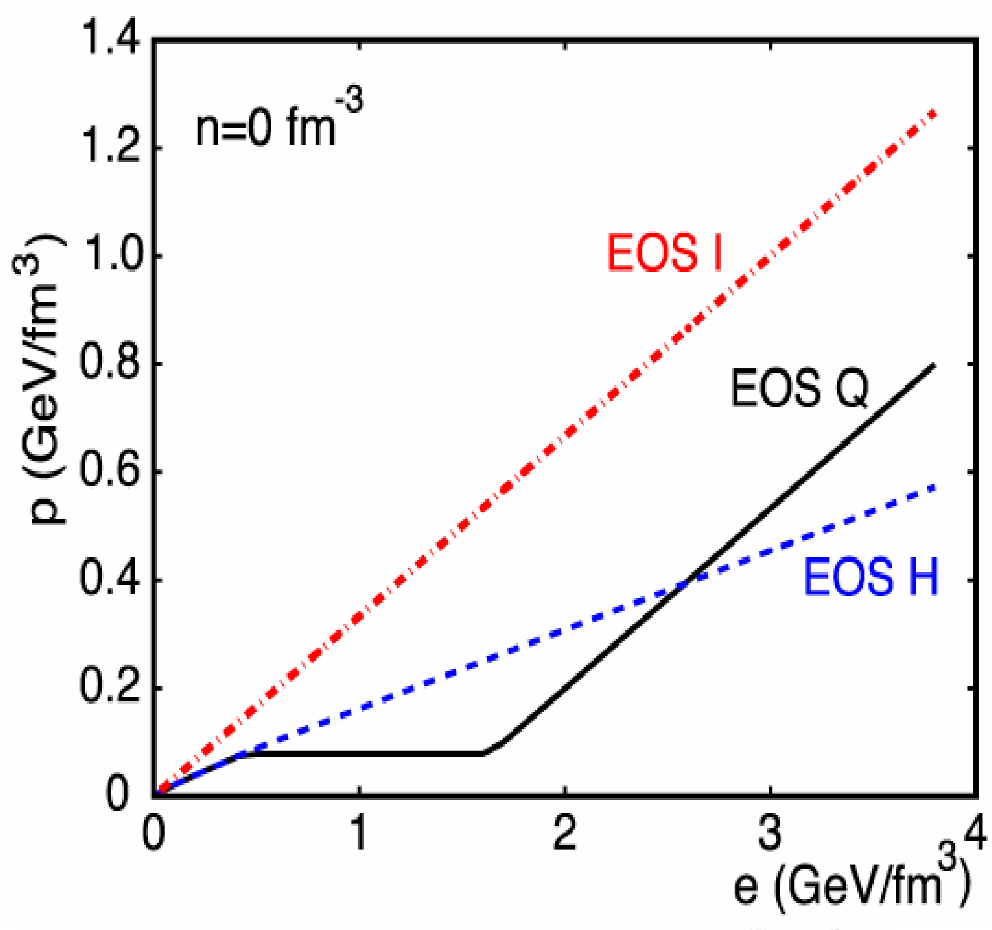
Experimental Handles



$$N_{coll}(b) = \sigma T_{AA}(b) \lesssim \frac{\sigma A^2}{\pi R^2} \sim A^{4/3} \sim 1100$$

Time evolution of ☞ asymmetry in non-central collisions

P.F.Kolb, J. Sollfrank and U. Heinz, PRC 62 (2000) 054909

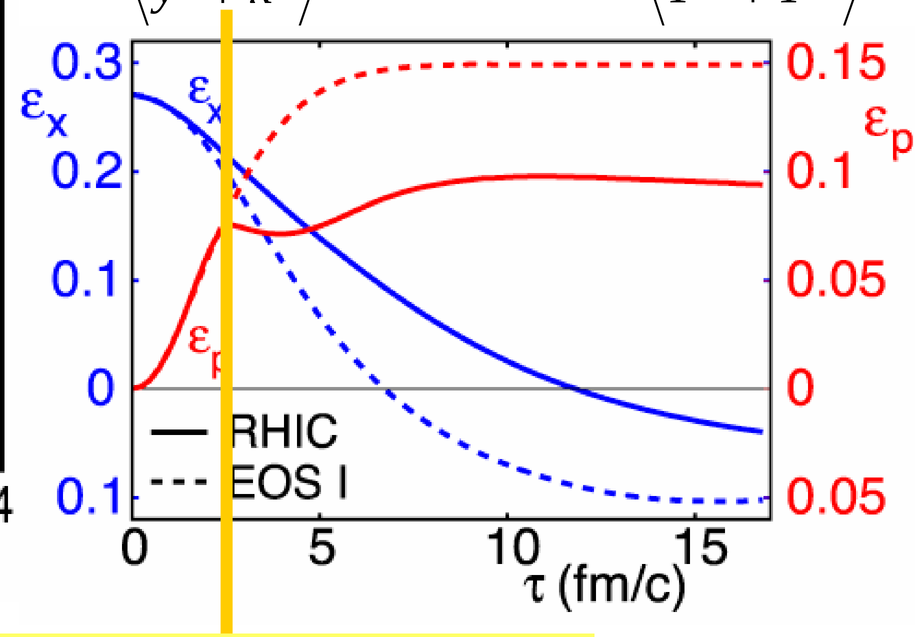


Spatial eccentricity

$$\varepsilon_x = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Momentum anisotropy

$$\varepsilon_p = \frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$



Elliptic flow generated t<3 fm/c!

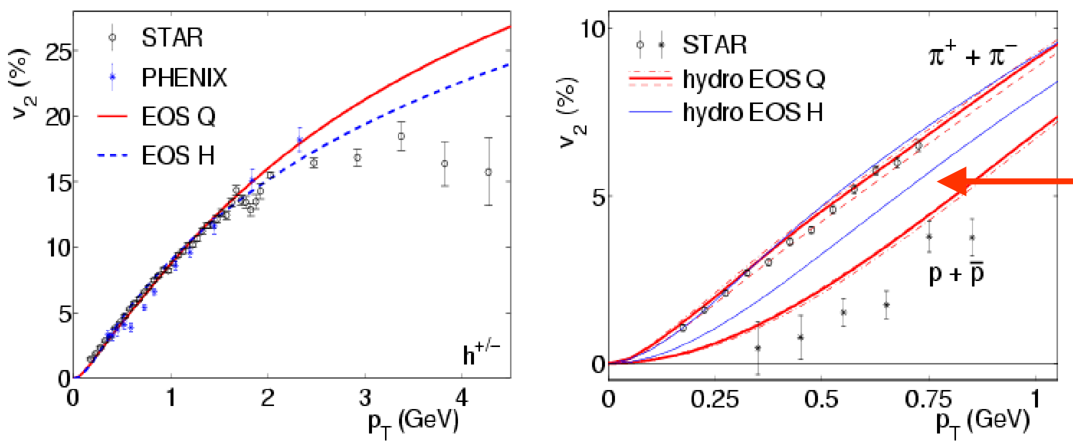
Zhang, Molnar

Observed Elliptic Flow at RHIC saturates hydro limit

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

P.Kolb U. Heinz, et al,
D.Teany, E. Shuryak et al
T. Hirano, Y. Nara

strong elliptic flow v_2, $v_2(p_\perp \leq 2\ \mathrm{GeV})$ exhausts hydrodynamic prediction

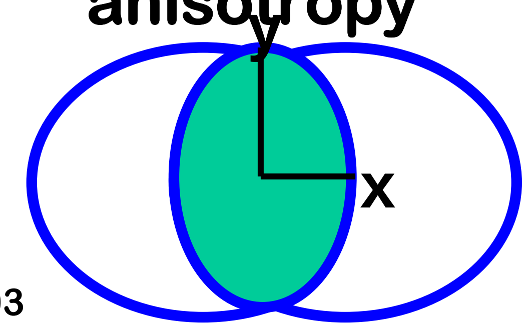


The most sensitive Barometric probe of the QCD Equation of State P(T)

M_h dependent $v_2(p_T)$

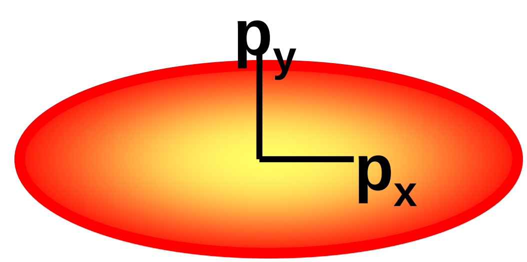
STAR Coll., PRL 86 (2001) 402; 87 (2001) 182301; PHENIX Coll., nucl-ex/020400512 and QM 2001

Initial *spatial* anisotropy



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

Final *momentum* anisotropy



STAR **Identified Particle Elliptic Flow in Au+Au Collisions at sqrt(s_{nn}) = 130 GeV**

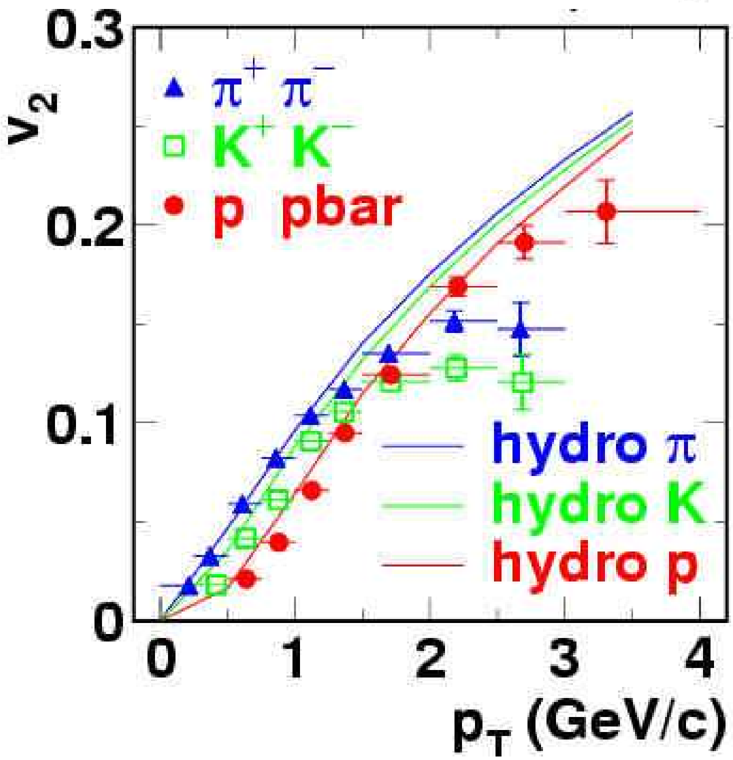
C. Adler *et al.* Phys. Rev. Lett. **87**, 182301 (2001).

nucl-ex/0306007

PHENIX

Elliptic Flow of Identified Hadrons in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV

nucl-ex/0305013 v1 16 May 2003



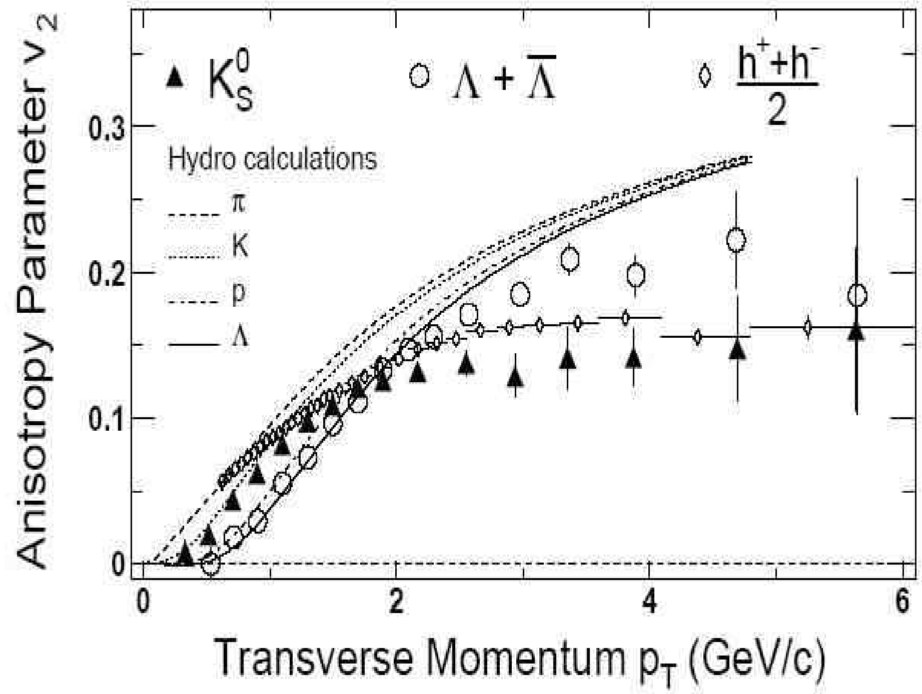
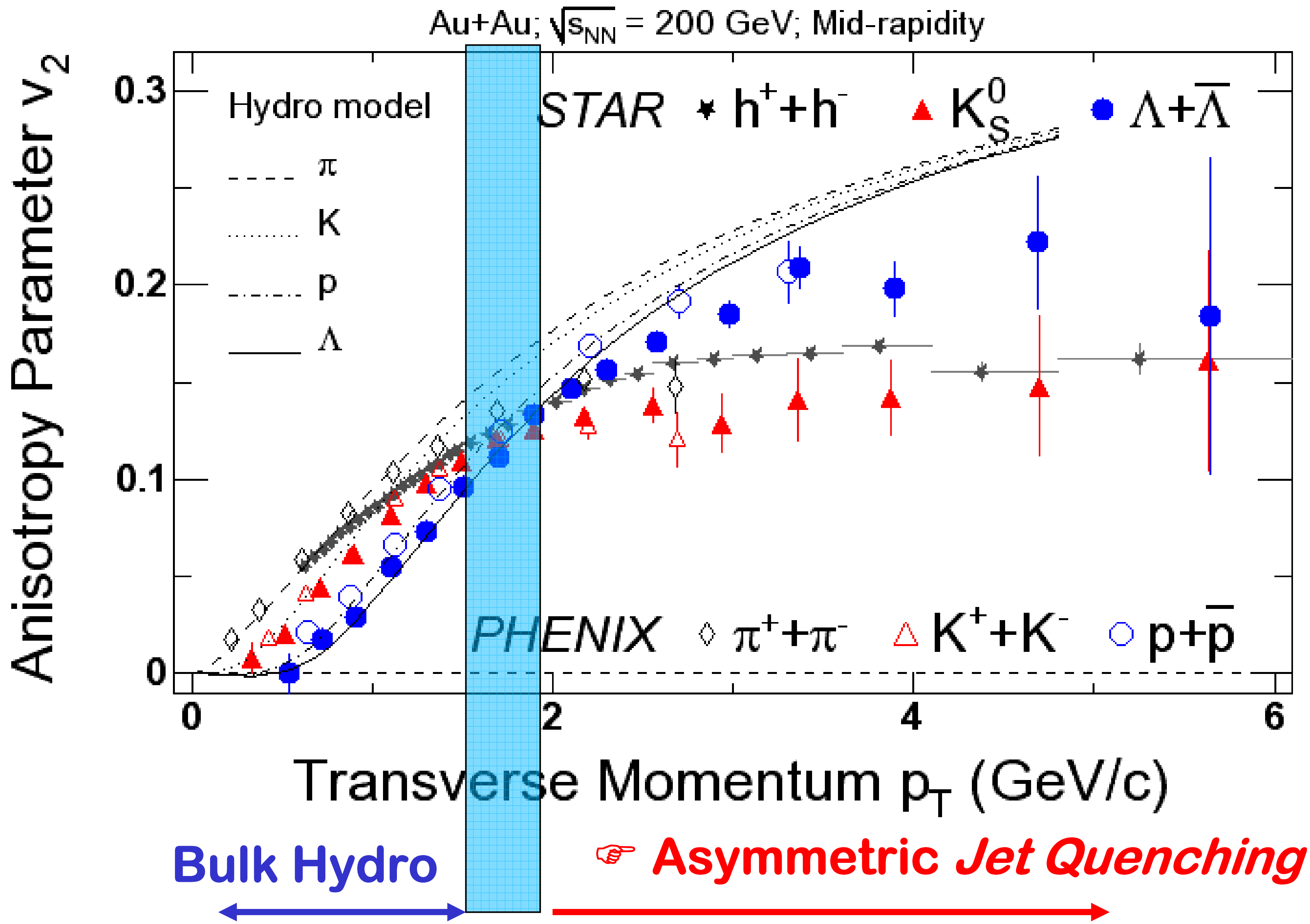


FIG. 1: The minimum-bias (0–80% of the collision cross section) $v_2(p_T)$ for K^0_S, $\Lambda+\overline{\Lambda}$ and $h^{\pm}$. The error bars shown are statistical only. Hydrodynamical calculations of v_2 for pions, kaons, protons and lambdas are also plotted [10].

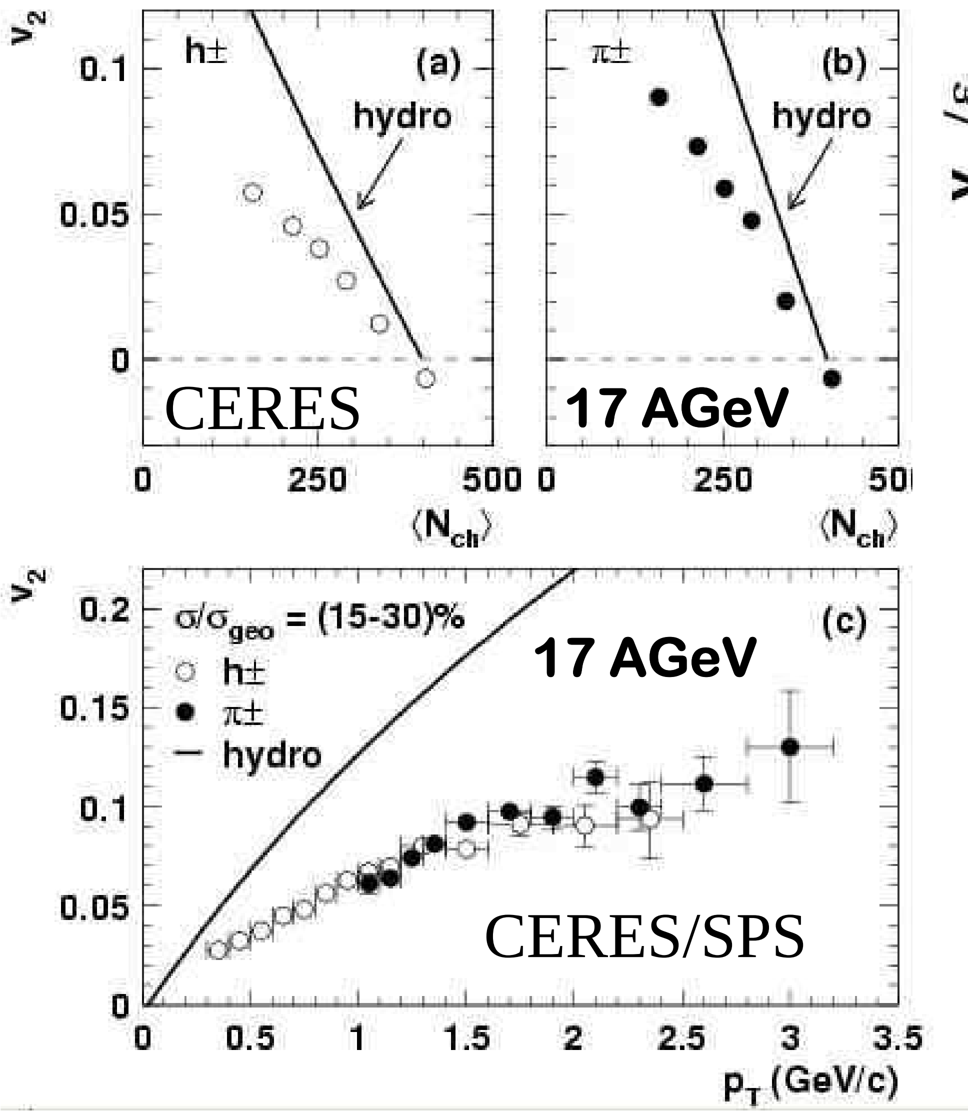
Hydro: P. Huovinen, P.F. Kolb, U.W. Heinz, P.V. Ruuskanen and S.A. Voloshin, Phys. Lett. **B503**, 58 (2001).

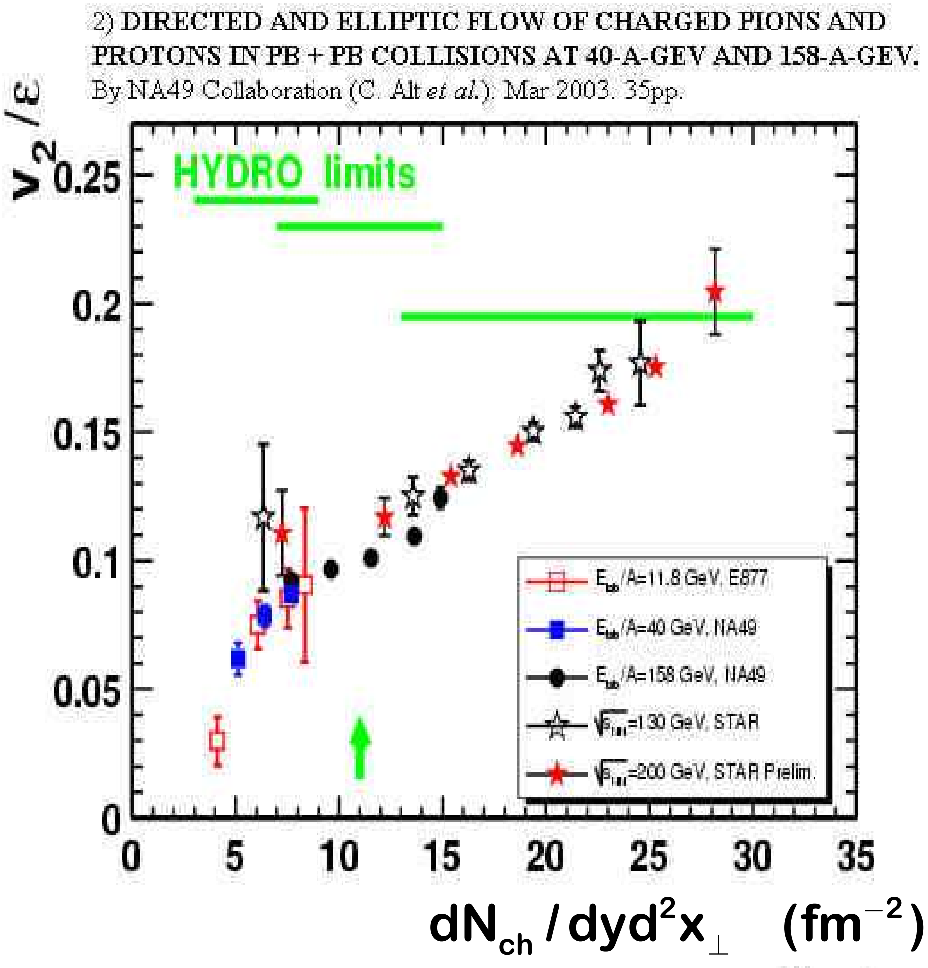


Au+Au; √sNN = 200 GeV; Mid-rapidity
Anisotropy Parameter v2
Hydro model
π
K
p
Λ
STAR
h++h-
K0S
Λ+Λ̄
PHENIX
π++π-
K++K-
p+p̄
0.3
0.2
0.1
0
0
2
4
6
Transverse Momentum pT (GeV/c)
Bulk Hydro
☞ Asymmetric Jet Quenching

<u>Below</u> RHIC energies, QCD hydro over-predicts elliptic flow!

$v_2(E_{cm})$ → QGP hydro for the *FIRST* time at RHIC!





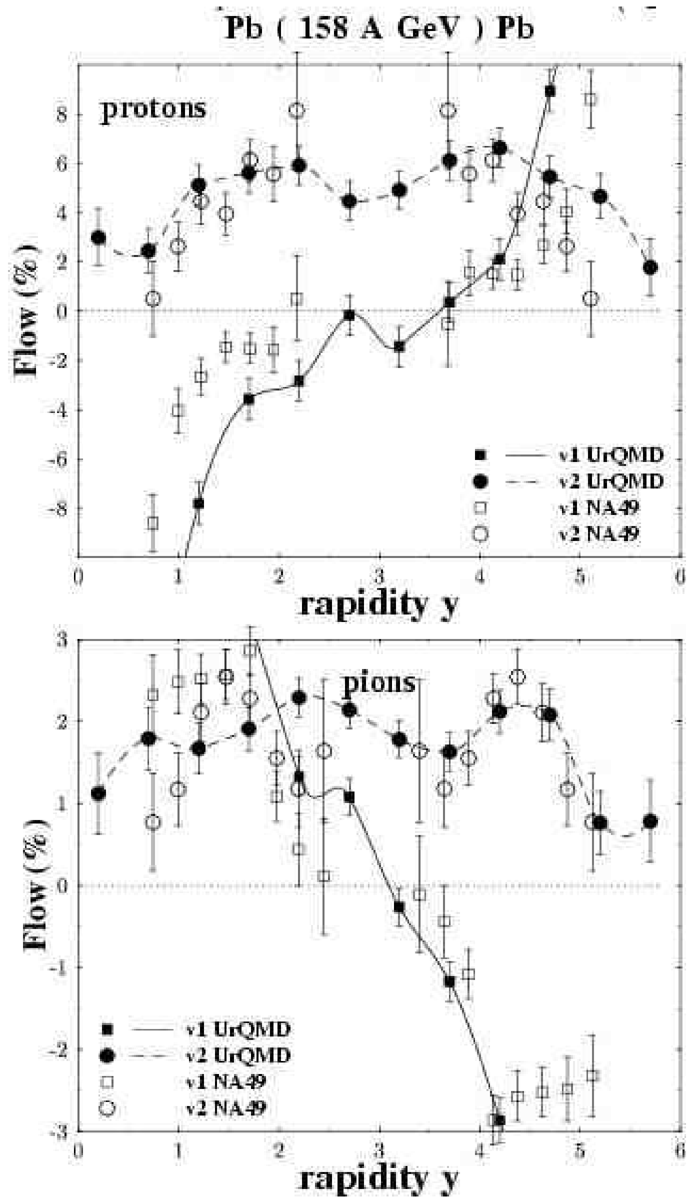
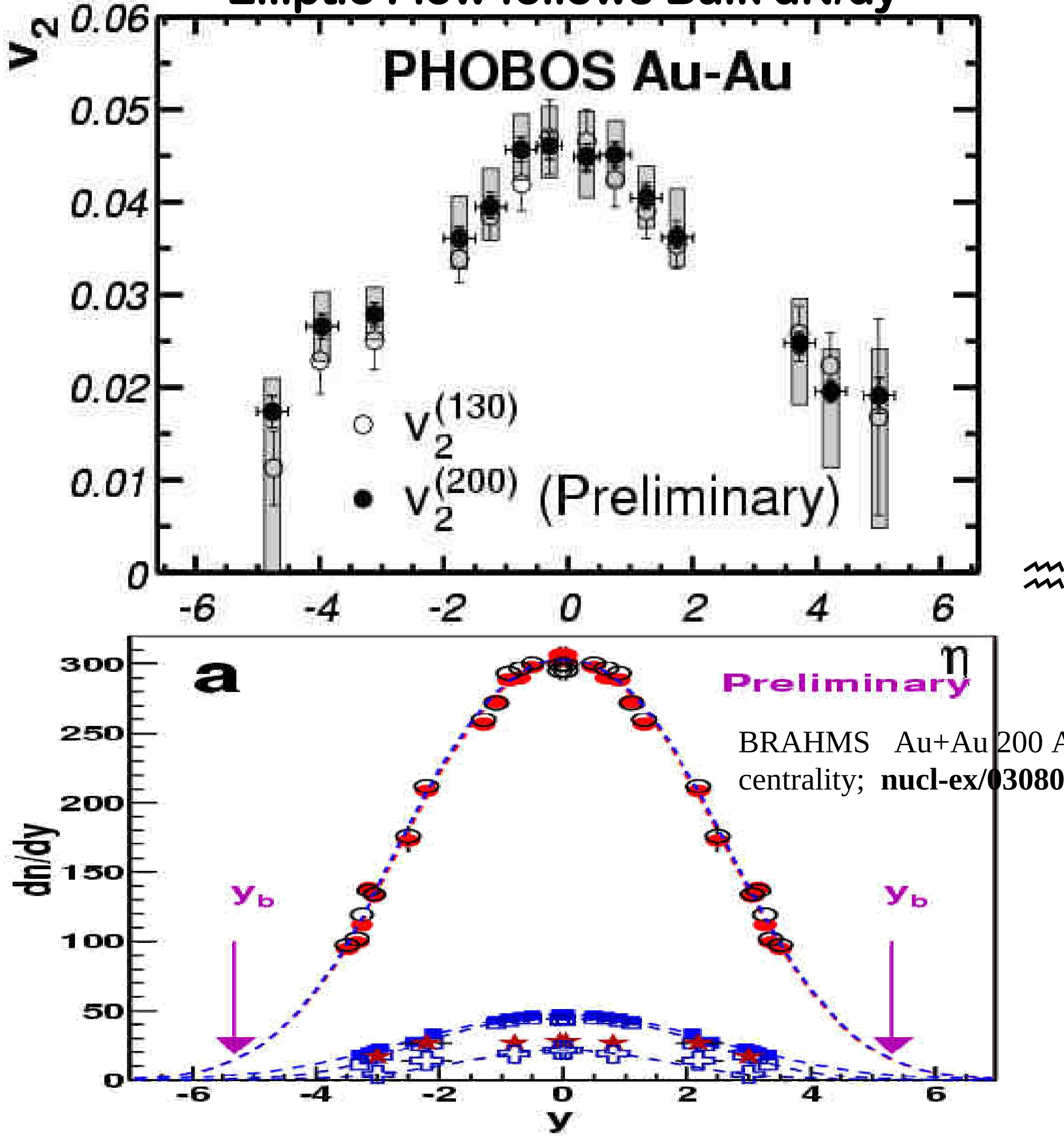


FIG. 2. Flow parameters v_1 and v_2 as a function of rapidity for protons (upper diagram) and charged pions (lower diagram). Open symbols are data and full symbols display the UrQMD results

S.Soff, S.A. Bass, M. Bleicher, H.Stoecker, Walter Greiner
nucl-th/9903061

Resonance/String Transport
UrQMD explains SPS
***Sub*-Hydro Flows v1 and v2**

Elliptic Flow follows Bulk dN/dy



BRAHMS Au+Au 200 AGeV 5% centrality; **nucl-ex/0308004**

Summary Part I:

1) BULK Elliptic azimuthal flow of 1000's of pions in non-central A+A is found at all energies, AGS, SPS, RHIC

2) However, only above 130 AGeV does the collective flow reach the hydrodynamic limit ($dN_{ch}/dyd^2r > 25/fm^2$)

3) The hadron flavor dependence of $v_2(p_T)$ requires soft QCD equation of state $c_s \sim 0$ for $T \sim T_c \sim 160$ MeV

Is this the evidence for the production of equilibrated QGP?

How can we know if quark gluon degrees of freedom are relevant?

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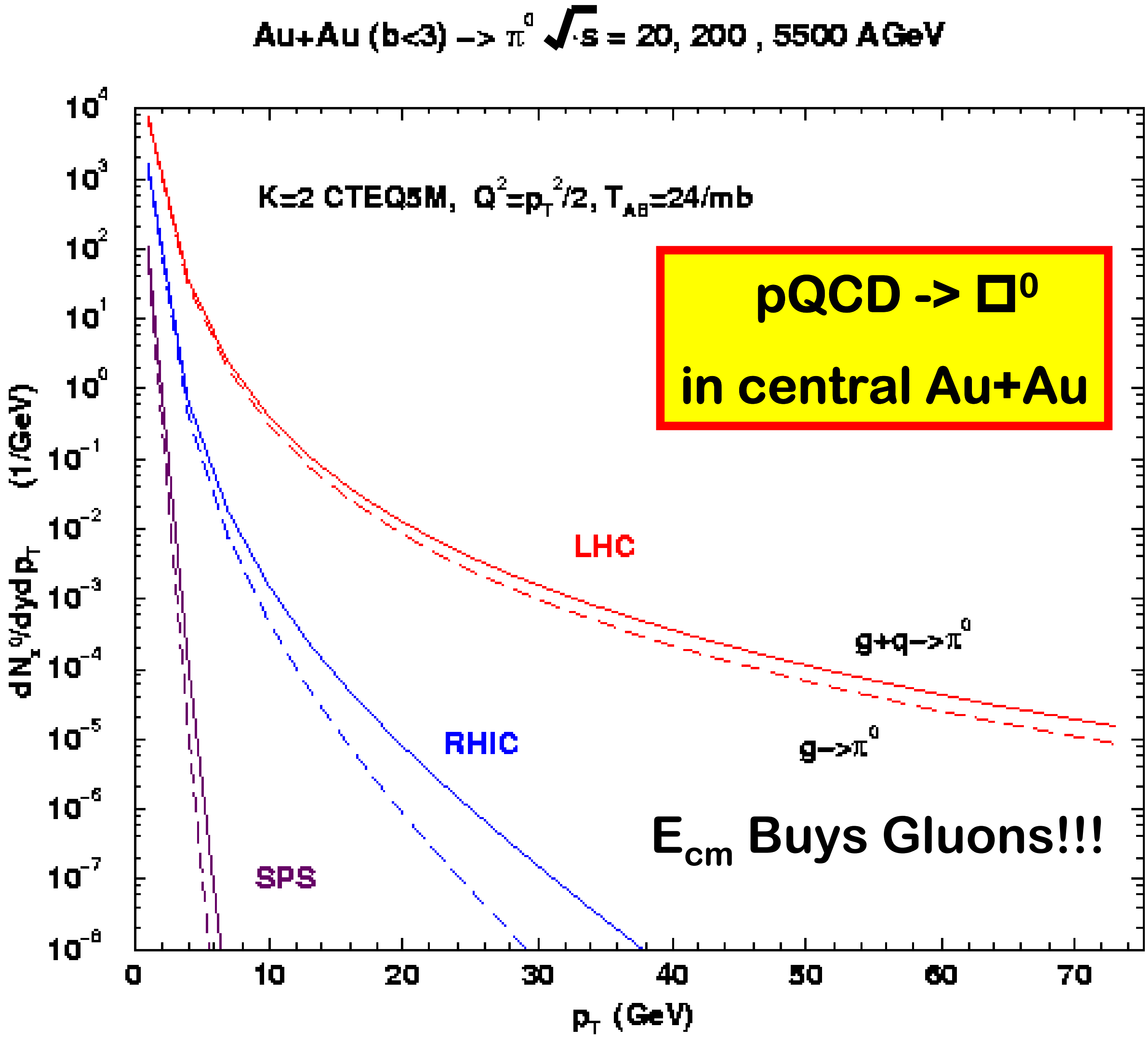
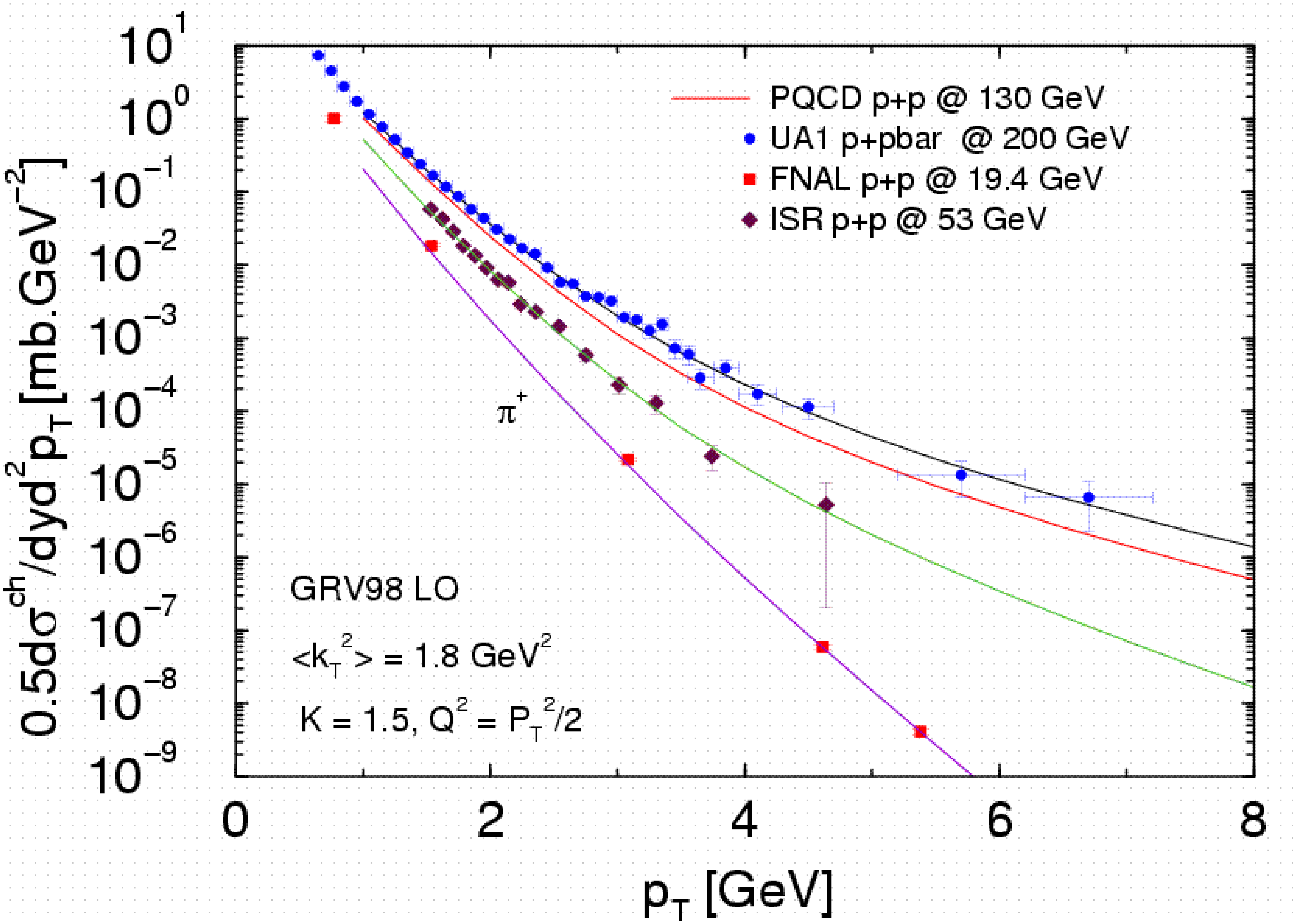
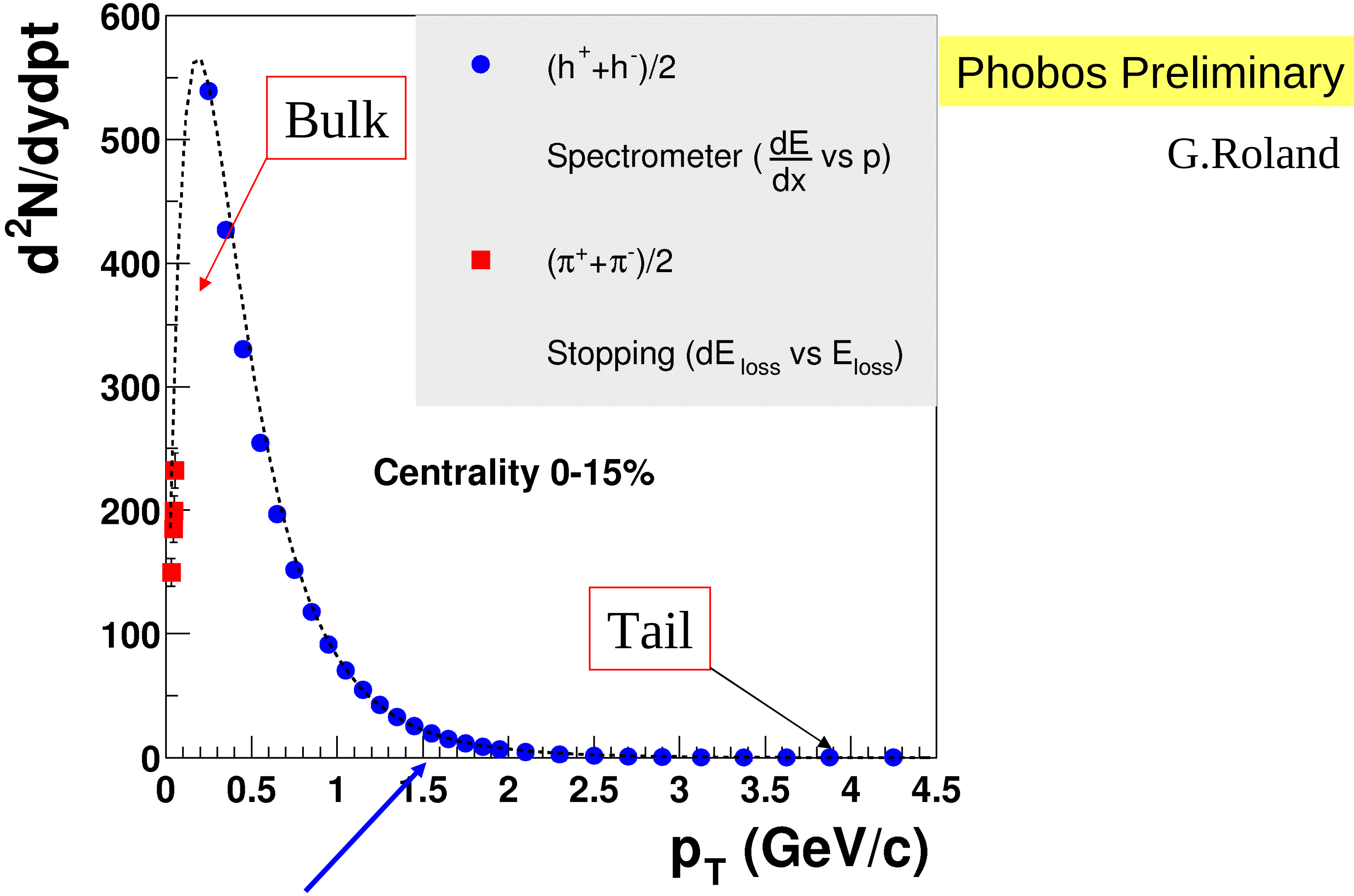

Au+Au (b<3) –> π0 √s = 20, 200 , 5500 AGeV
K=2 CTEQ5M, Q2=pT2/2, TAB=24/mb
pQCD -> □0
in central Au+Au
LHC
g+q–>π0
g–>π0
RHIC
SPS
Ecm Buys Gluons!!!
dNπ0/dydpT (1/GeV)
pT (GeV)
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
0
10
20
30
40
50
60
70

pQCD Calibration to p+p Baseline



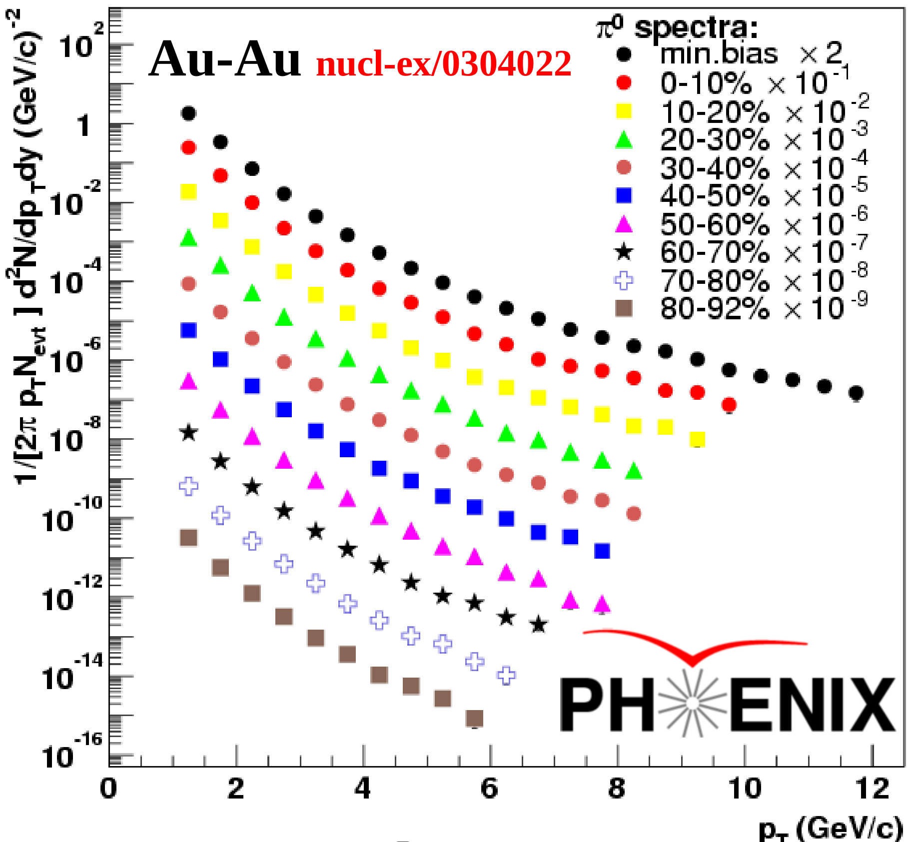
 MG, I Vitev, XN Wang, Phys.Rev.Lett.86:2537-2540,2001

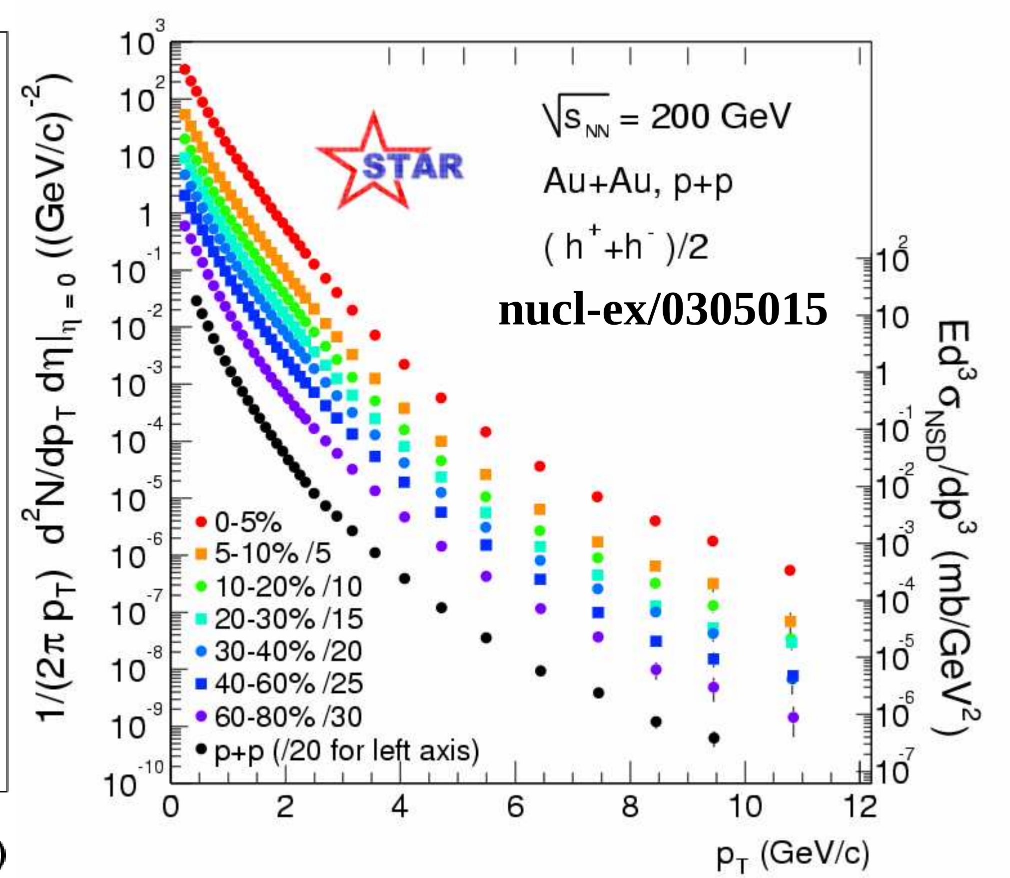
p_T Distribution of Charged Particles



We can use this tiny calibrated pQCD tail to probe the QGP Bulk!

The high p_T window at RHIC is now wide open





p+p-> □ □ hep-ex/0304038

STAR PRL 89, 202301

Pion Quenching at 200 AGeV

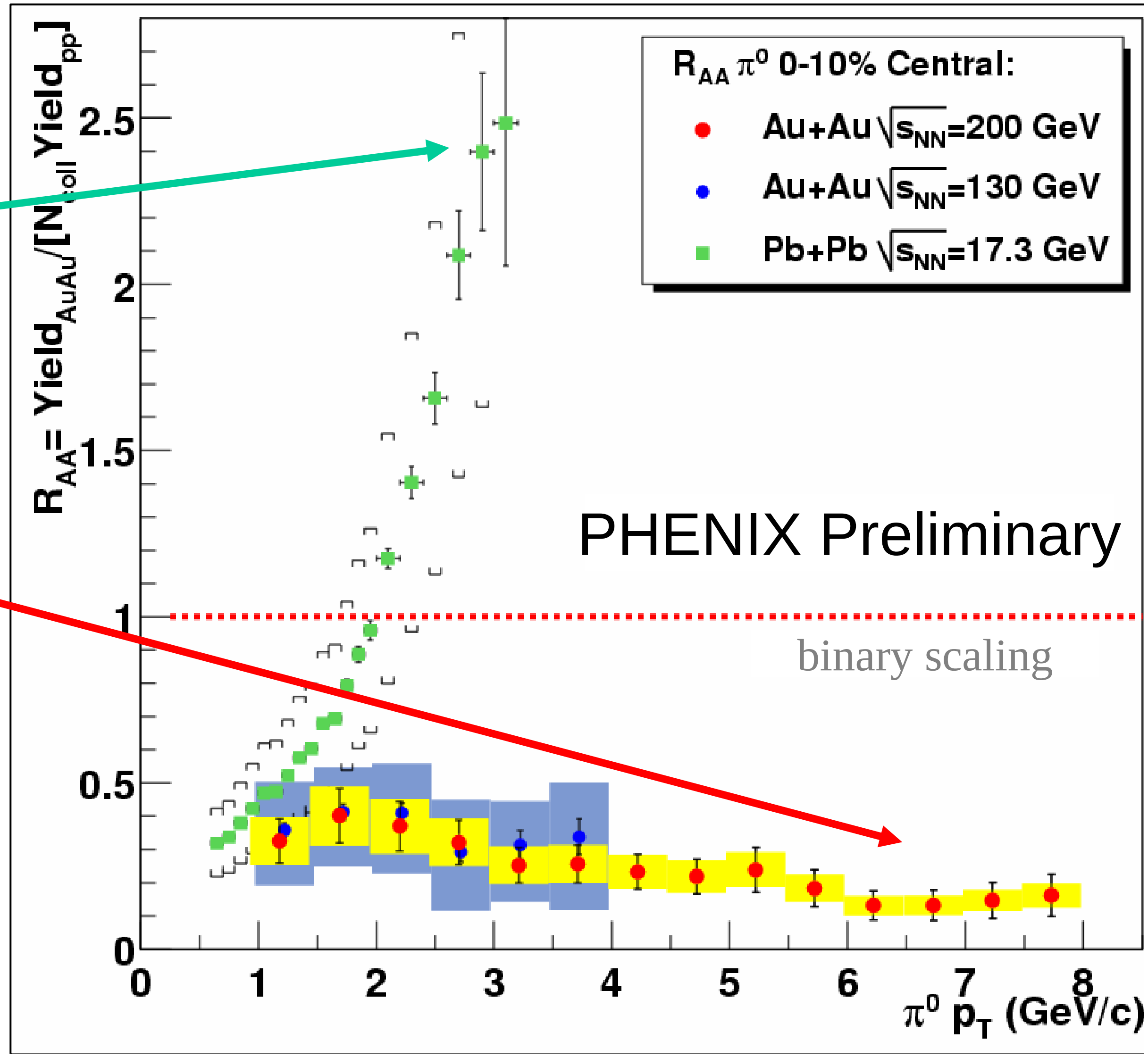
PHENIX

$$R_{AA}(p_T) = \frac{1/N^{events}\, d^2N_{AA}/dp_T d\eta}{\langle N^{binary}\rangle (d^2\sigma^{pp}/dp_T d\eta / \sigma_{pp}^{inelastic})} =$$

D. d'Enterria QM02

SPS – "Cronin" effect

RHIC – "Jet Quenching"

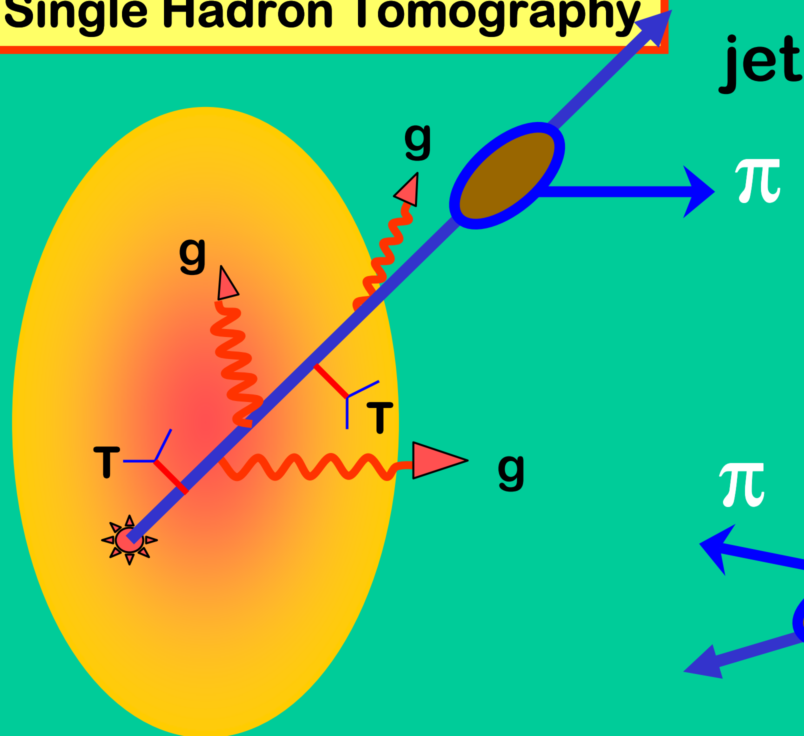


Jet Quenching and Tomography

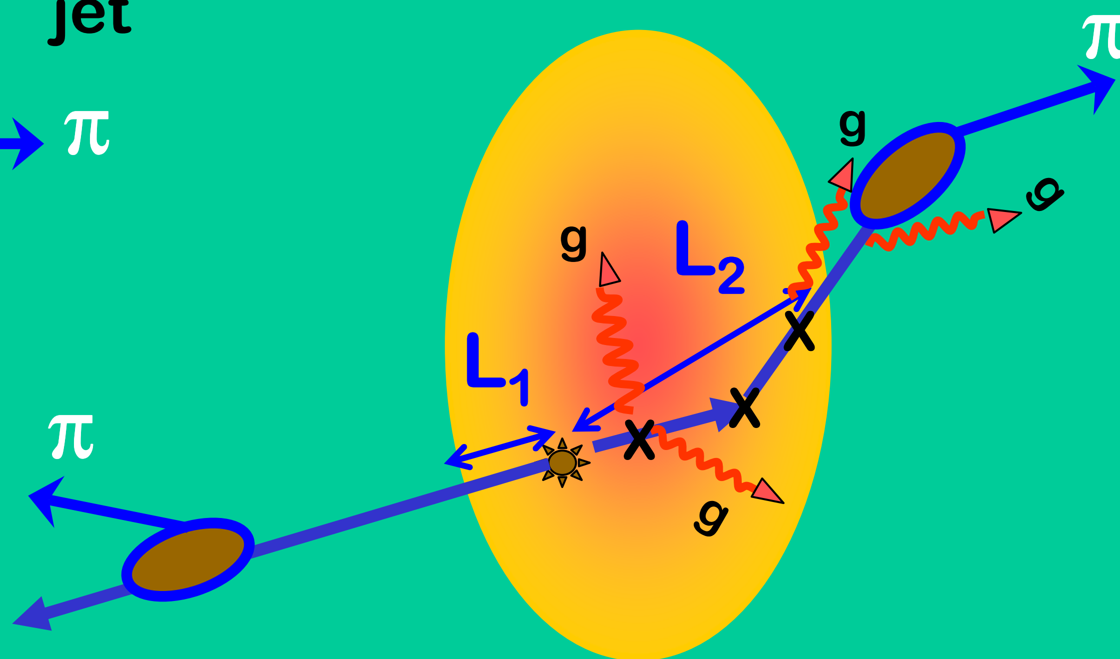
Ivan Vitev, Peter Levai, Xin-Nian Wang, MG

Reviewed in nucl-th/0302077

Single Hadron Tomography



Di-Hadron Tomography



$$L(\phi) \quad \frac{1}{\pi R^2}\frac{dN}{dy}$$

$$\Delta E_{GLV} \sim C_{Jet} C_T \alpha_s^3 \;\ell n \frac{p_T}{\mu^2 L} \int d\tau \, \tau \, \rho\big(\tau, r(\tau)\big)$$

Non-abelian Radiative Energy Loss

QCD Bethe-Heitler

QGP Multiple Collision

- G. Bertsch, F. Gunion, Phys. Rev. **D25** 746 (1982)
- M. Gyulassy, X.-N. Wang, Nucl. Phys. **B420** 583-614 (1994); Phys. Rev. **D51** 3436-3446 (1995)

"Thick" Plasma Limit

$$\Delta E = \alpha\sqrt{\omega_c E} \sim 10\,\mathrm{GeV}\left(\frac{L}{5\,\mathrm{fm}}\right)$$

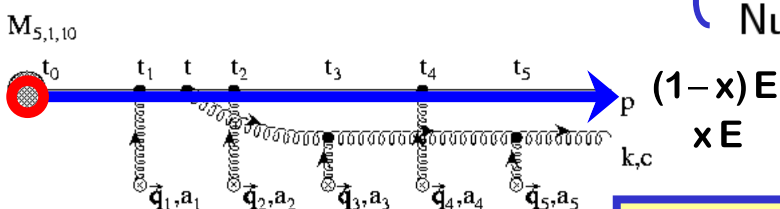
$$E < \omega_c = \left\langle \frac{q^2}{\lambda} \right\rangle \frac{L^2}{2} \approx 60\ \mathrm{GeV}$$

- R. Baier, Yu. Dokshitzer, A. Mueller, S. Peigne, D. Schiff, Nucl. Phys. **B483** 291-320 (1997); Phys. Rev. **C58** 1706-1713 (1998)
- B. Zakharov, JETP Lett. **65** 615-620 1997, JETP Lett. **73** 49-52 (2001)

"Thin" Plasma Limit

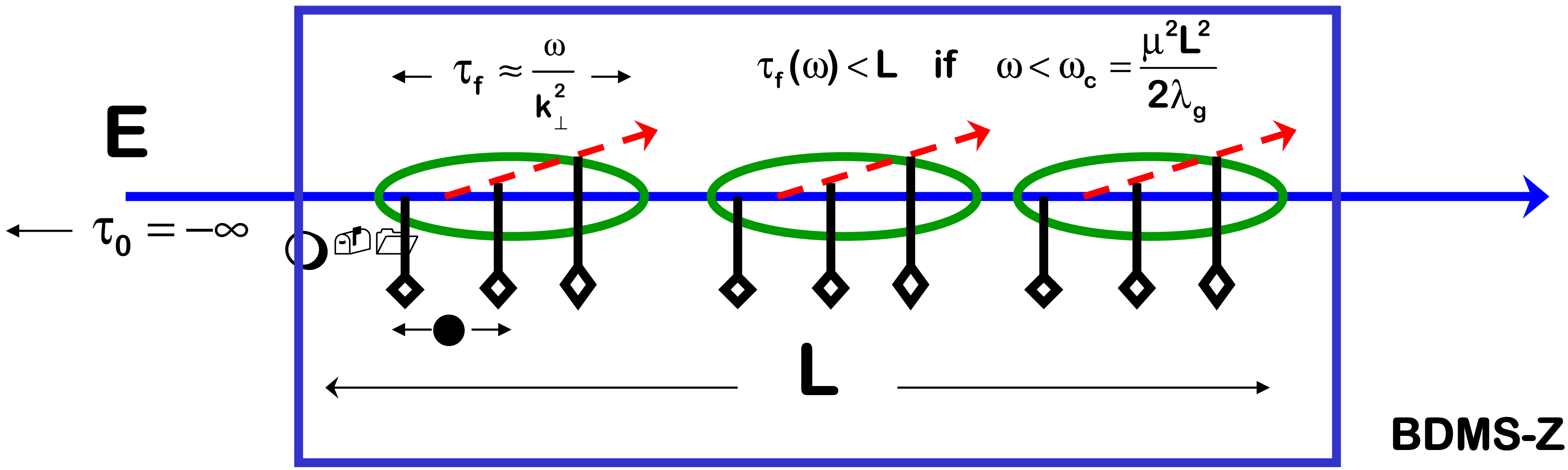
L/λ_g Opacity Expansion

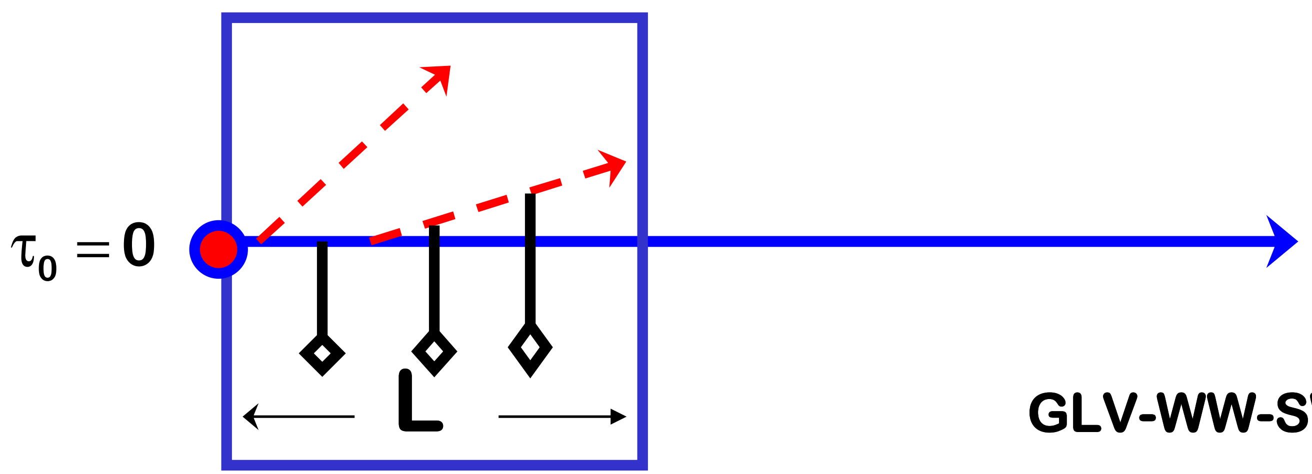
- M. Gyulassy, P. Levai, **Ivan Vitev NPB 595** 371-419 (2001); Phys. Rev. Lett. **85** 5535-5538 (2000) **Phys.Lett.B538:282-288,2002**
- U. Wiedemann, Nucl. Phys. **B588** 303-344 (2000), Nucl. Phys. **B582** 409-450 (2000)



$$\Delta E^{(1)} \approx \frac{9}{4}\alpha_s^3 \pi\, C_R \left(\frac{1}{\pi R^2}\frac{dN_g}{dy}\right)\left\{\mathrm{Log}\frac{2E}{\mu^2 L}\right\} L(\phi)$$

Thick vs Thin Plasma dE/dx





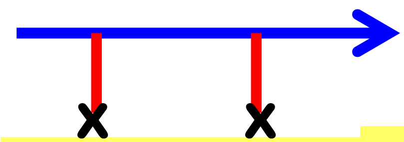
Gluon Double Differential Distributions to **All** Orders in Opacity

1. Add up all Direct and Virtual FSI at order $\left(\frac{L}{\lambda_g}\right)^n$
2. Use GLV Reaction Operator Formalism to solve recursion relations algebraically

Screened Yukawa

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

$$\left[-2\,\mathbf{C}_{(1,\cdots,n)}\cdot\sum_{j=1}^{n}\mathbf{B}_{(j+1,\cdots,n)(j,\cdots,n)}\left(\cos\left(\sum_{k=2}^{j}\omega_{(k,\cdots,n)}\Delta z_k\right) - \cos\left(\sum_{k=1}^{j}\omega_{(k,\cdots,n)}\Delta z_k\right)\right)\right]$$



$\Delta z_k = z_k - z_{k-1} \sim \frac{L}{n+1}$

LPM effect →

where

$$\omega_{(j,\cdots,n)} = \frac{(\mathbf{k}-\mathbf{q_j}-\cdots-\mathbf{q_n})^2}{2xE}$$

Inverse Formation Times

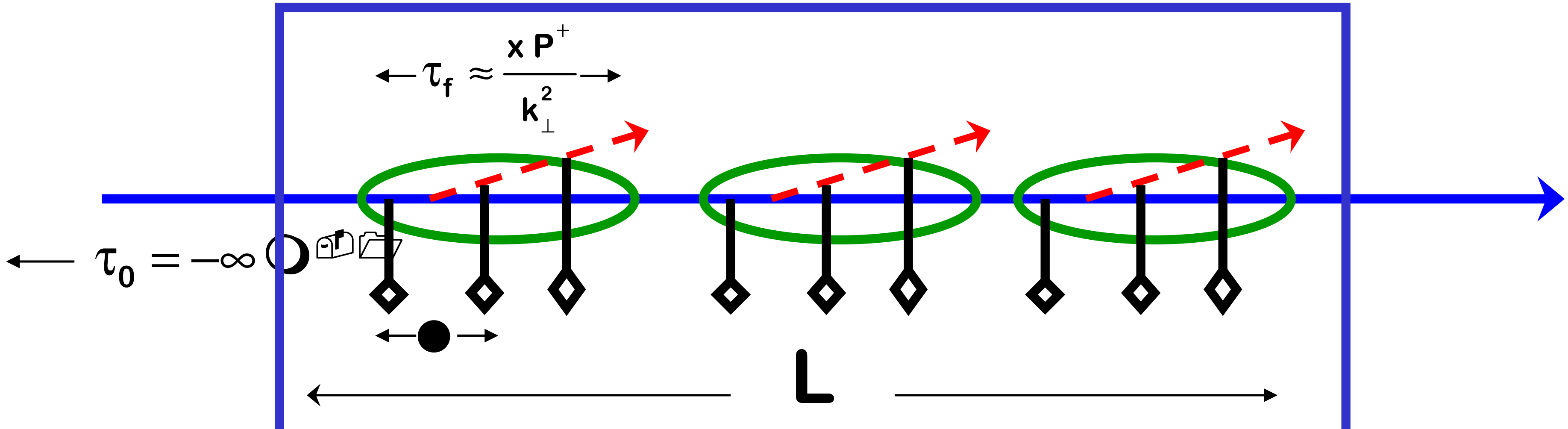
$$\mathbf{C}_{(j,\cdots,n)} = \frac{\mathbf{k}-\mathbf{q_j}-\cdots-\mathbf{q_n}}{(\mathbf{k}-\mathbf{q_j}-\cdots-\mathbf{q_n})^2}$$

Scatt amplitudes

$$\mathbf{B}_{(j+1,\cdots,n)(j,\cdots,n)} = \mathbf{C}_{(j+1,\cdots,n)} - \mathbf{C}_{(j,\cdots,n)}$$

GLV: Nucl.Phys.B594(2001)

BDMPS-Z Asymptotic Approach to dE/dx



$$\text{If } L \gg \tau_f \gg \lambda \gg \mu^{-1}, \text{ then } \langle k_\perp^2 \rangle \approx \mu^2 \frac{\tau_f}{\lambda_g}, \; \tau_f \approx \sqrt{x P^+ \lambda_g / \mu^2}$$

$$N_{coh} = \frac{L}{\tau_f}, \text{ and } x \frac{dN_g}{dx} \sim C_R \alpha_s N_{coh} \sim C_R \alpha_s \left(\frac{\mu^2/\lambda_g}{x P^+} \right)^{\frac{1}{2}} L$$

$$\text{If } \tau_f \gg L \gg \lambda \gg \mu^{-1}, \text{ then } \langle k_\perp^2 \rangle \approx \mu^2 \frac{L}{\lambda_g}, \; \tau_f \approx x P^+ \lambda_g / (\mu^2 L)$$

$$N_{coh} = 1, \text{ and } x \frac{dN_g}{dx} \sim C_R \alpha_s \quad \text{for } x > x_{fac} = \frac{\mu^2 L^2}{P^+ \lambda_g}$$

Initial Jet distribution $\rho_g(p) = \frac{dN_g}{dyd^2p} \sim \frac{c}{p^{n\sim 7}}$

No medium Pion distribution $\rho_\pi(p_\pi) = \int_{p_\pi}^{\infty} \frac{dp}{p_\pi} \rho_g(p) D_{\pi/g}(z = \frac{p_\pi}{p})$

In medium $p \to p - \Delta p(p) \approx p(1-\varepsilon)$

$D(z) \to D'(z) = \frac{\theta(1-\varepsilon-z)}{1-\varepsilon} D(z' = \frac{z}{1-\varepsilon})$

Quenched Pions $\rho_\pi(p_\pi, \varepsilon) = \int_{\frac{p_\pi}{(1-\varepsilon)}}^{\infty} \frac{dp}{p_\pi} \rho_g(p) \frac{1}{(1-\varepsilon)} D_{\pi/g}(z' = \frac{p_\pi}{p(1-\varepsilon)})$

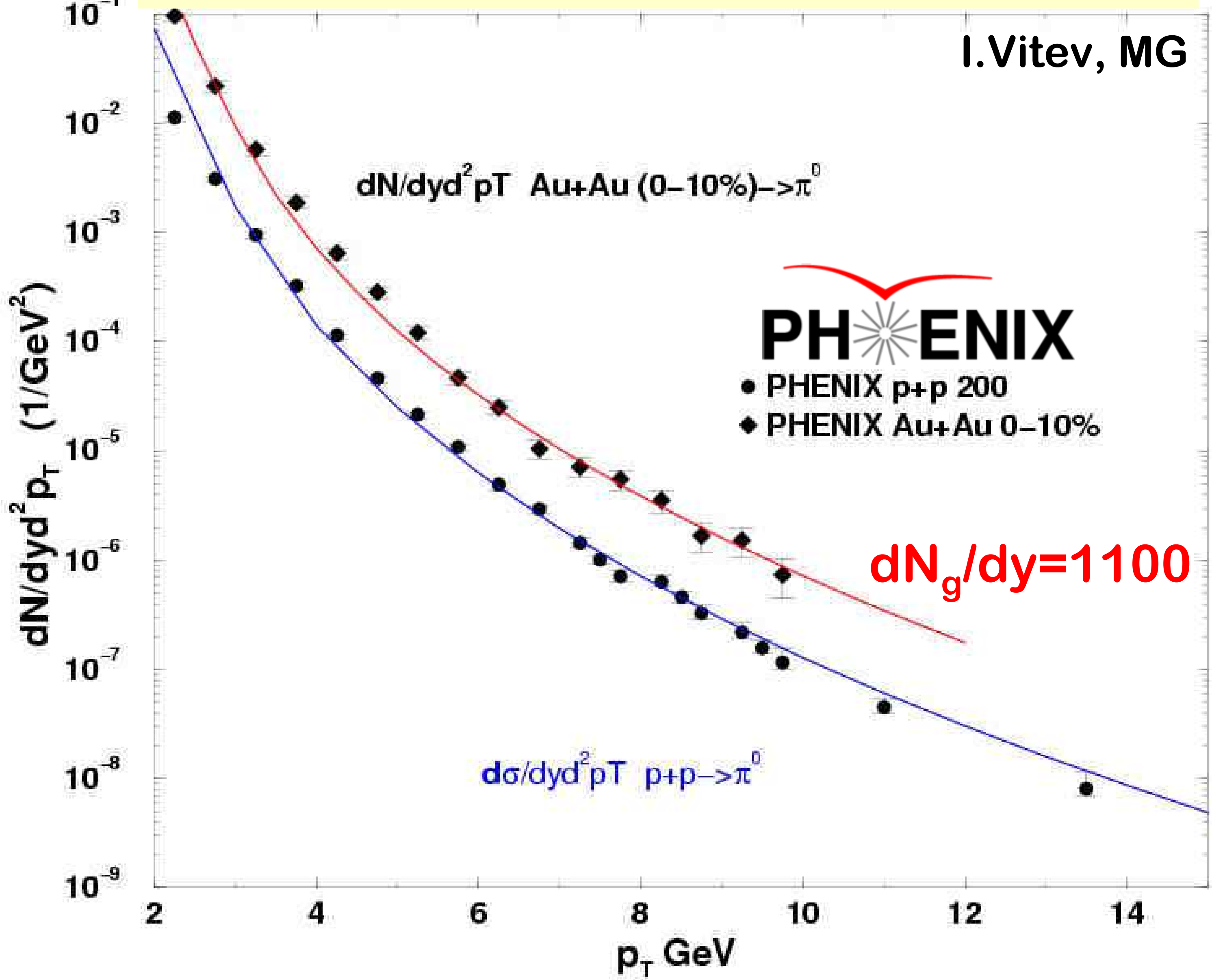
For $\rho_g(p) \propto 1/p^n$: $\rho_\pi^{quenched}(p_\pi) = \left\langle (1-\varepsilon)^{n-2} \right\rangle \rho_g(p_\pi)$

Quench Factor $S = \frac{\langle \rho_\pi(p,\varepsilon) \rangle}{\rho_\pi(p,0)} = \left\langle (1-\varepsilon)^{n-2} \right\rangle = (1 - Z\langle \varepsilon \rangle)^{n-2}$

Fluctuations reduce ΔE by factor $Z \sim 0.5$

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

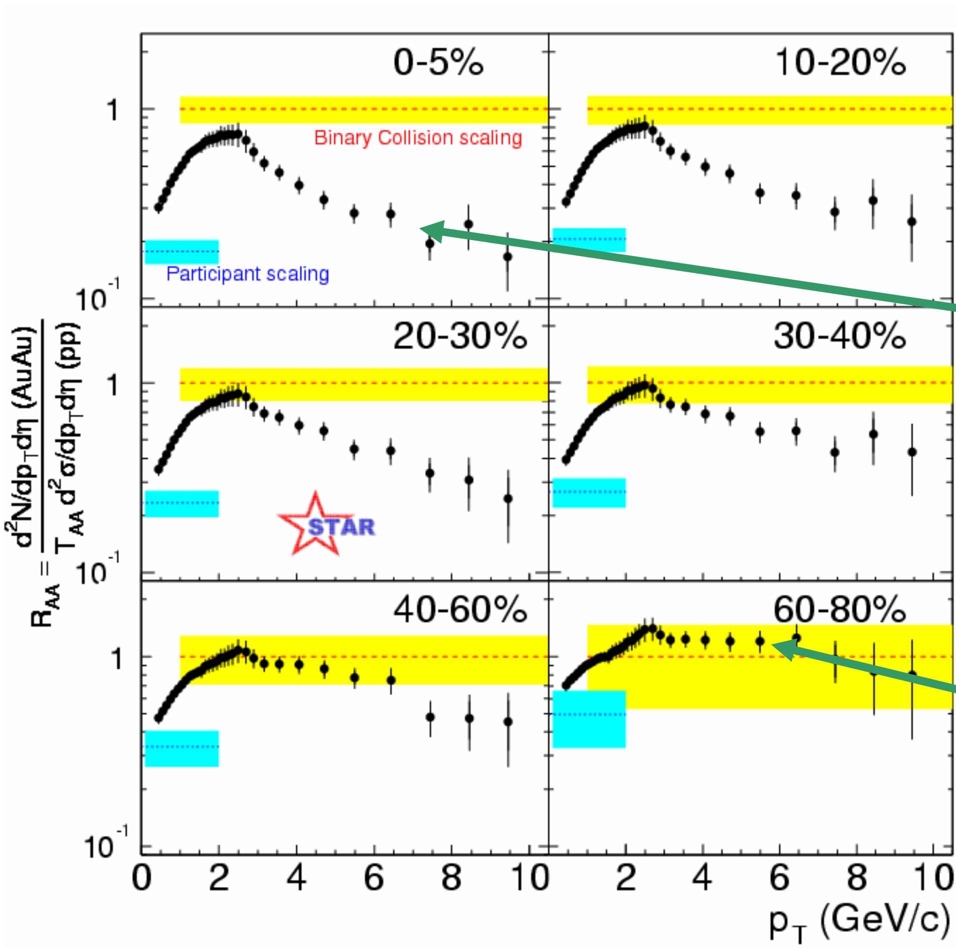
GRV
EKS
BKK
GLV

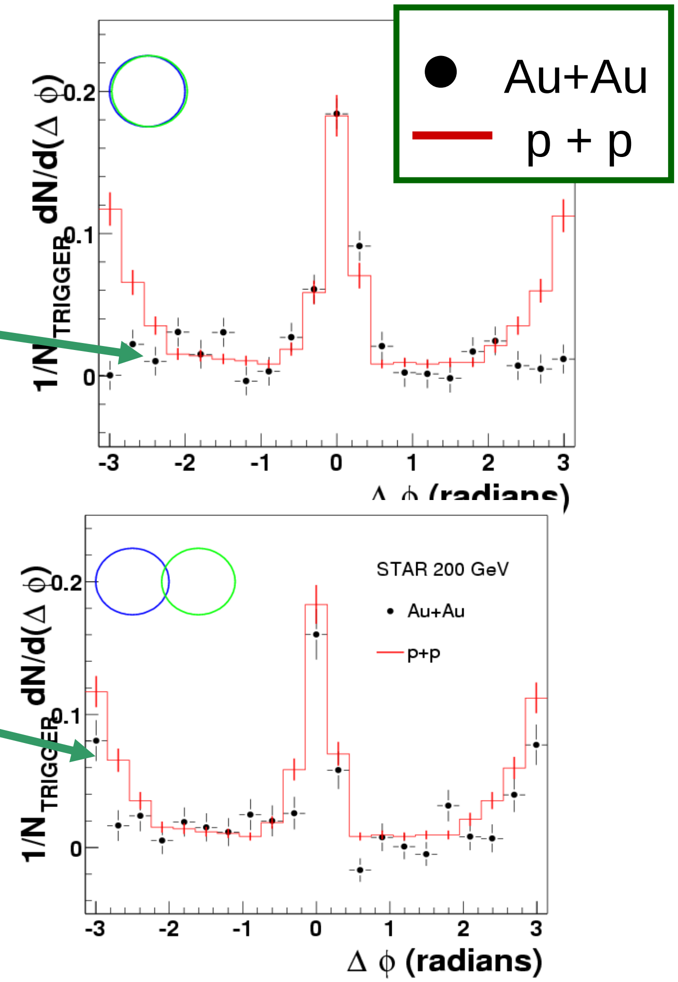


Absolute scale pQCD jet tomography

Quenching and *Mono-Jets*

STAR: 200 GeV Au+Au / p+p





Hadron suppression and disappearance of back-to-back 'jet' are correlated!
STAR PRL 90, 082302

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

Leading hadron fragments outside QGP

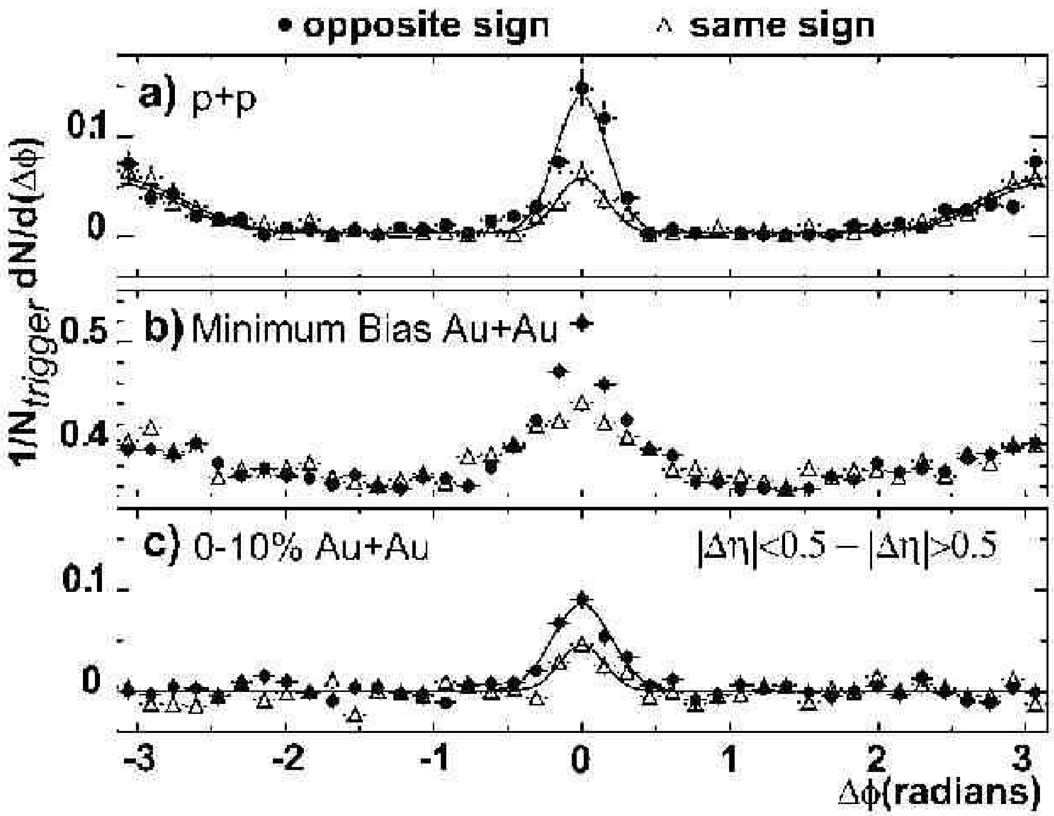
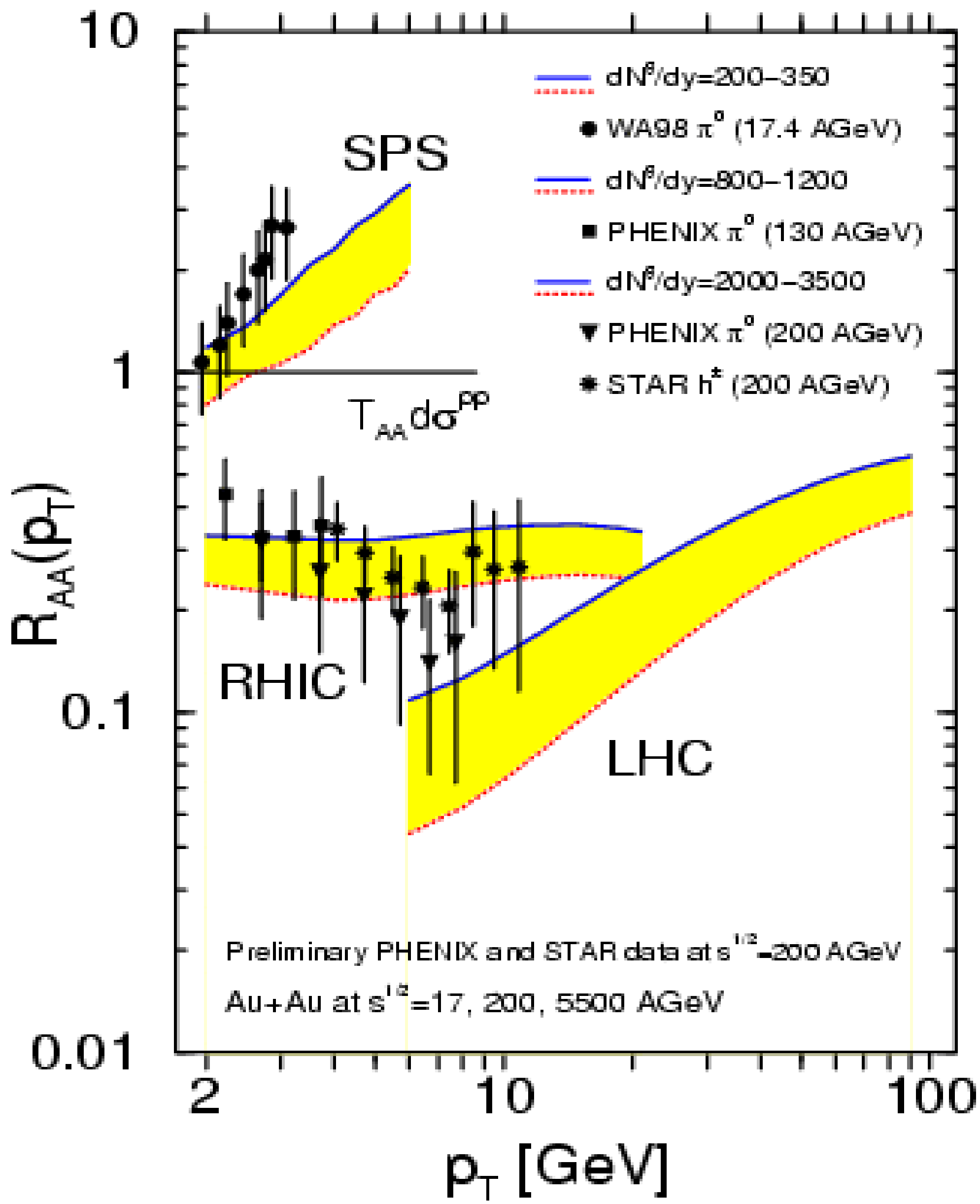


FIG. 1. Azimuthal distributions of same-sign and opposite-sign pairs for (a) $p + p$, (b) minimum bias Au + Au, and (c) background-subtracted central Au + Au collisions. All correlation functions require a trigger particle with $4 < p_T^{\mathrm{trig}} < 6\ \mathrm{GeV}/c$ and associated particles with $2\ \mathrm{GeV}/c < p_T < p_T^{\mathrm{trig}}$. The curves are one or two Gaussian fits.

Single Hadron Tomography from SPS, RHIC, LHC

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

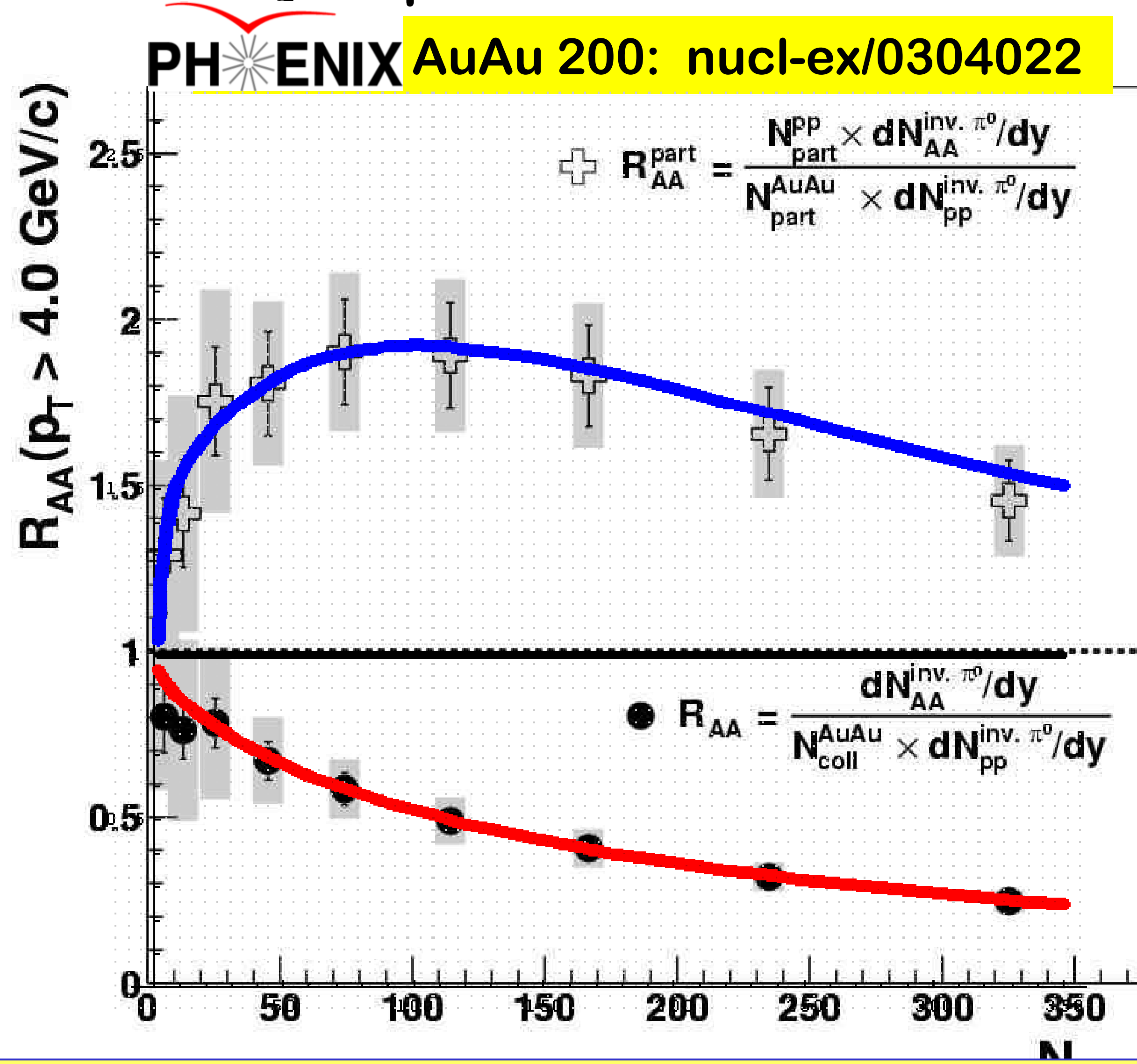


1) Cronin *enhancement* dominates at SPS

2) Cronin+Quench+Shadow conspire to give ~ flat R_{AA}~N_{part}/N_{bin} at RHIC dN_g/dy ~ 1000 -> ρ_g ~100 ρ_0

3) Predict sub N_{part} quench, positive p_T slope of R at LHC

Centrality Dependence of □ Quenching

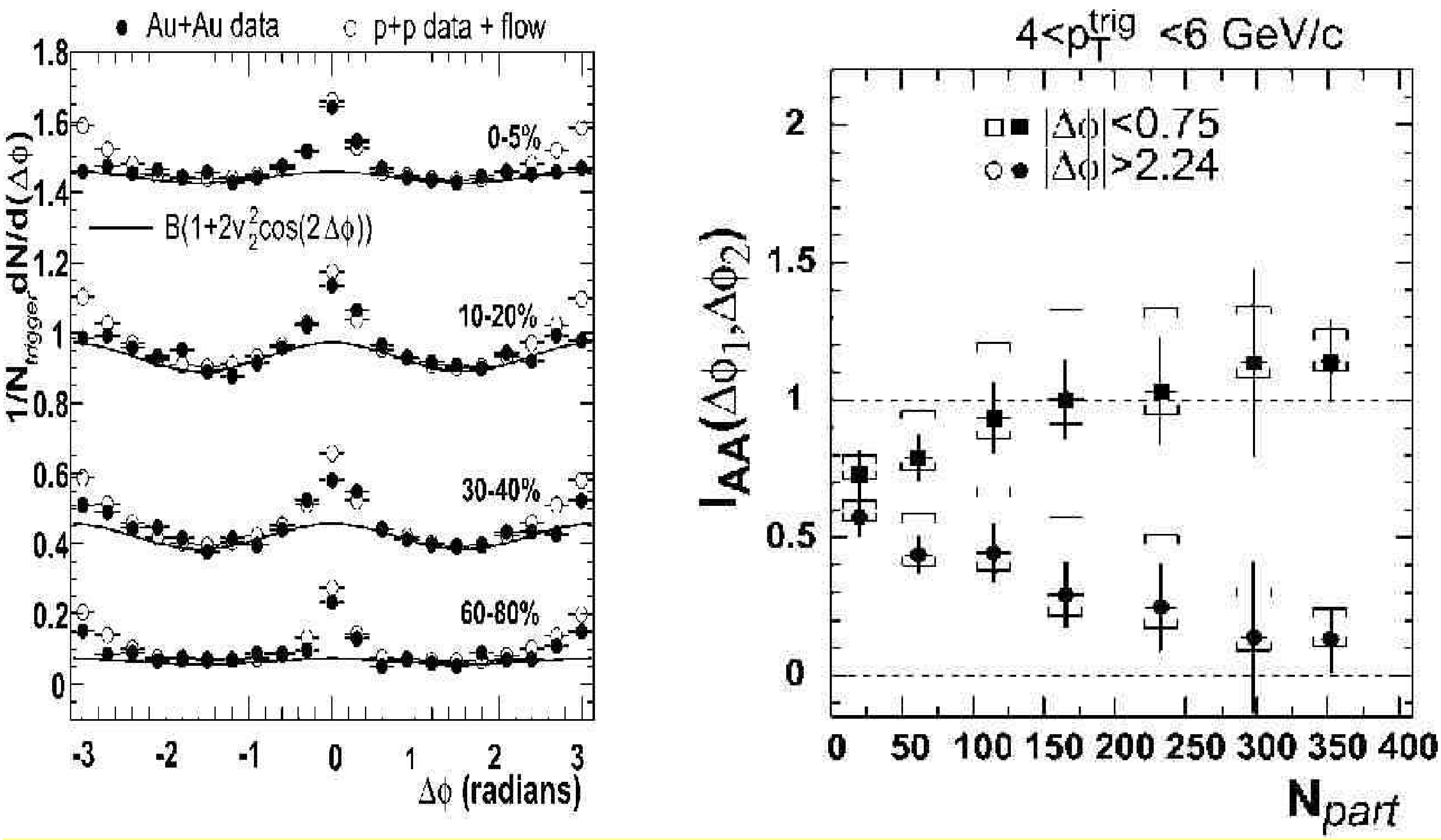


Consistent With GLV

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

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

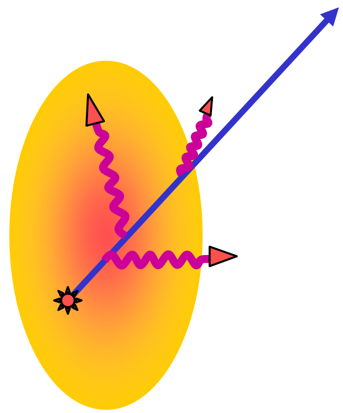
$$I_{AA}(\Delta\phi_1, \Delta\phi_2) = \frac{\int_{\Delta\phi_1}^{\Delta\phi_2} d(\Delta\phi)\{D^{\mathrm{AuAu}} - B[1 + 2v_2^2\cos(2\Delta\phi)]\}}{\int_{\Delta\phi_1}^{\Delta\phi_2} d(\Delta\phi) D^{pp}}.$$



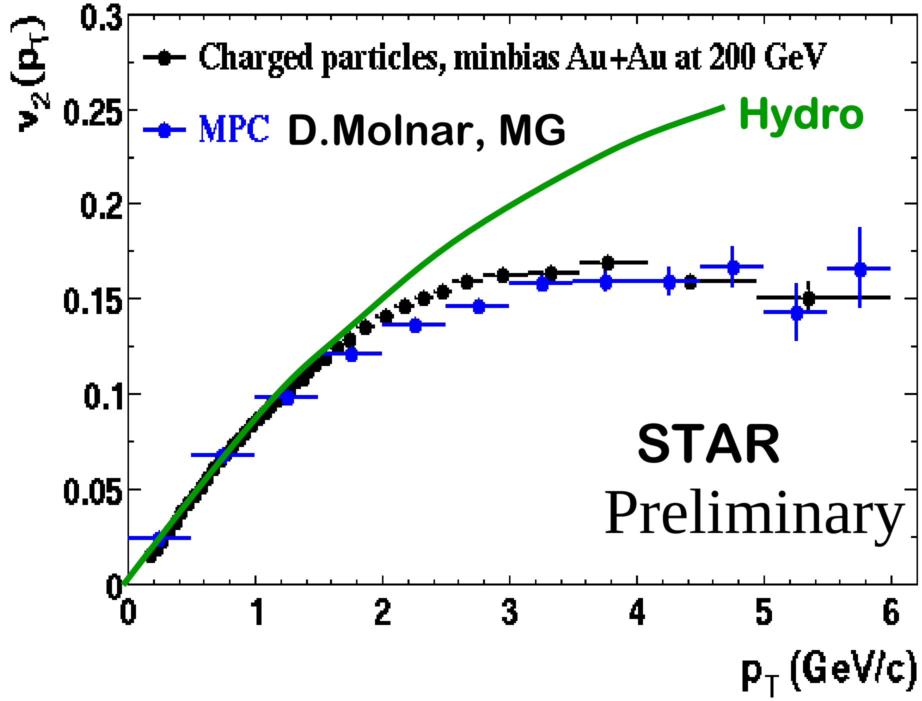
K **Correlation of Associated hadrons 2<pT<4 GeV with triggered 4<pT<6**

Azimuthal $v_2(p_t)$ Tomography

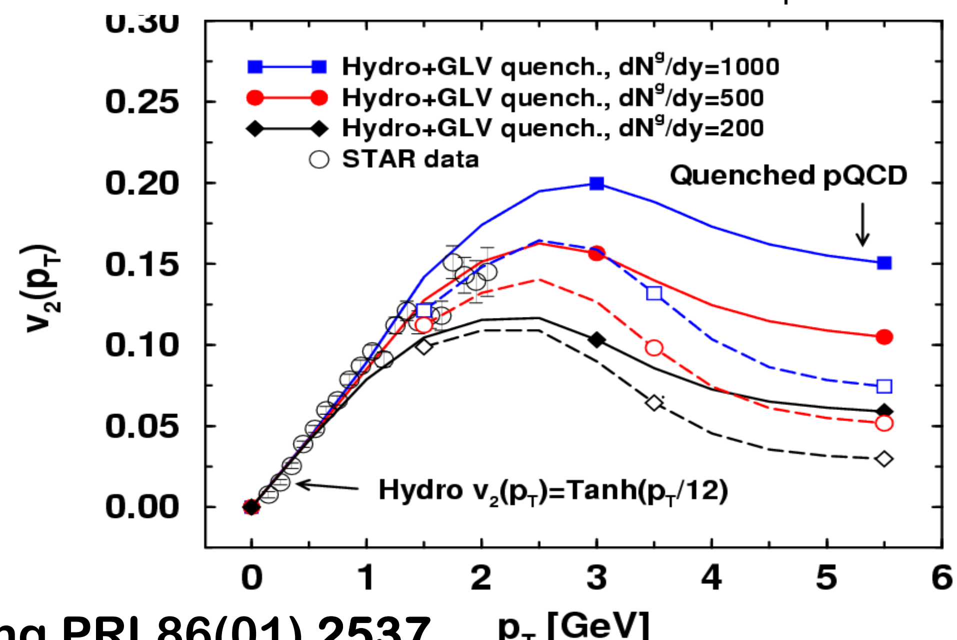
$$\rho_{QGP}(\tau, x_0 + \hat{n}\tau)$$



K.Filimonov QM02



Deviation from hydro above p_T> 2 GeV/c and approximate Saturation of v_2 explained by finite asymmetric energy loss of jets in noncentral AA



MG, I. Vitev, X.N. Wang PRL86(01) 2537

Summary Part II:

1) Strong suppression of $p_T > 4$GeV hadrons observed at RHIC as predicted due to jet quenching in opaque QCD matter

2) Jet tomographic analysis indicates that QGP matter has an initial energy density ~ 100 times nuclear matter

3) Centrality dependence of mono-jet production consistent with GLV radiative gluon energy loss $\propto \int d\tau\, \tau\, \rho(\tau, x(\tau)) \propto N_{part}^{2/3}$

Is this then the evidence for the production of a QGP?

We must still rule out strong initial state gluon shadowing!

[as suggested by Kharzeev, Levin, McLerran (CGC)]

Outline

1. Overview of 3 convergent lines of evidence

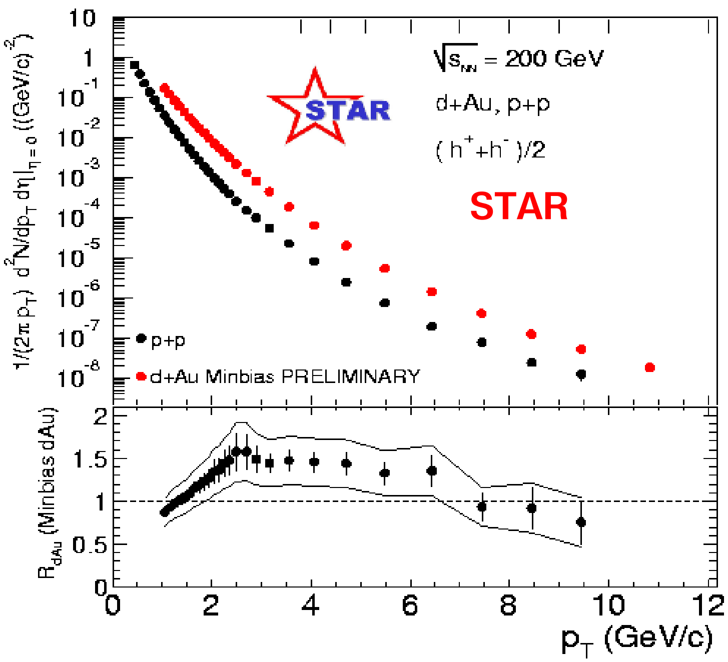
2. Bulk Collective Flow and the QCD Equation of State

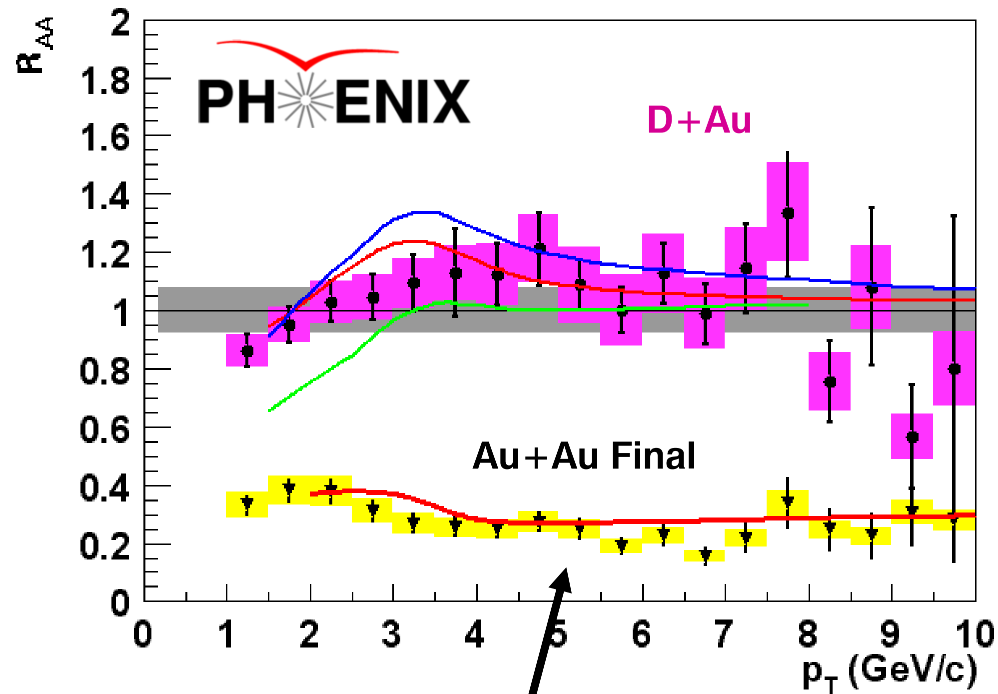
3. Parton Diagnostics: Jet Quenching

4. The D+Au Null Control

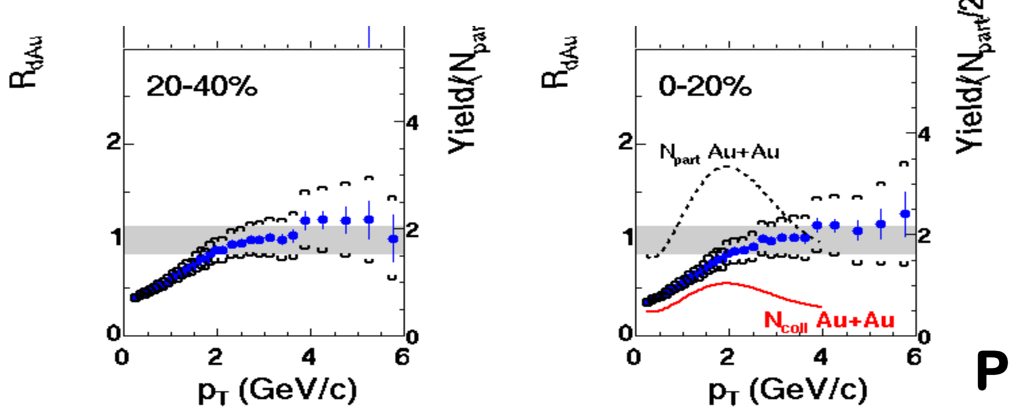
5. Conclusion: The QGP is found

The *UN*-Quenched Prediction for dA (for x>0.01) is confirmed !





PHOBOS



AA quench <u>must</u> be due to final state interactions: **Jet Quenching**

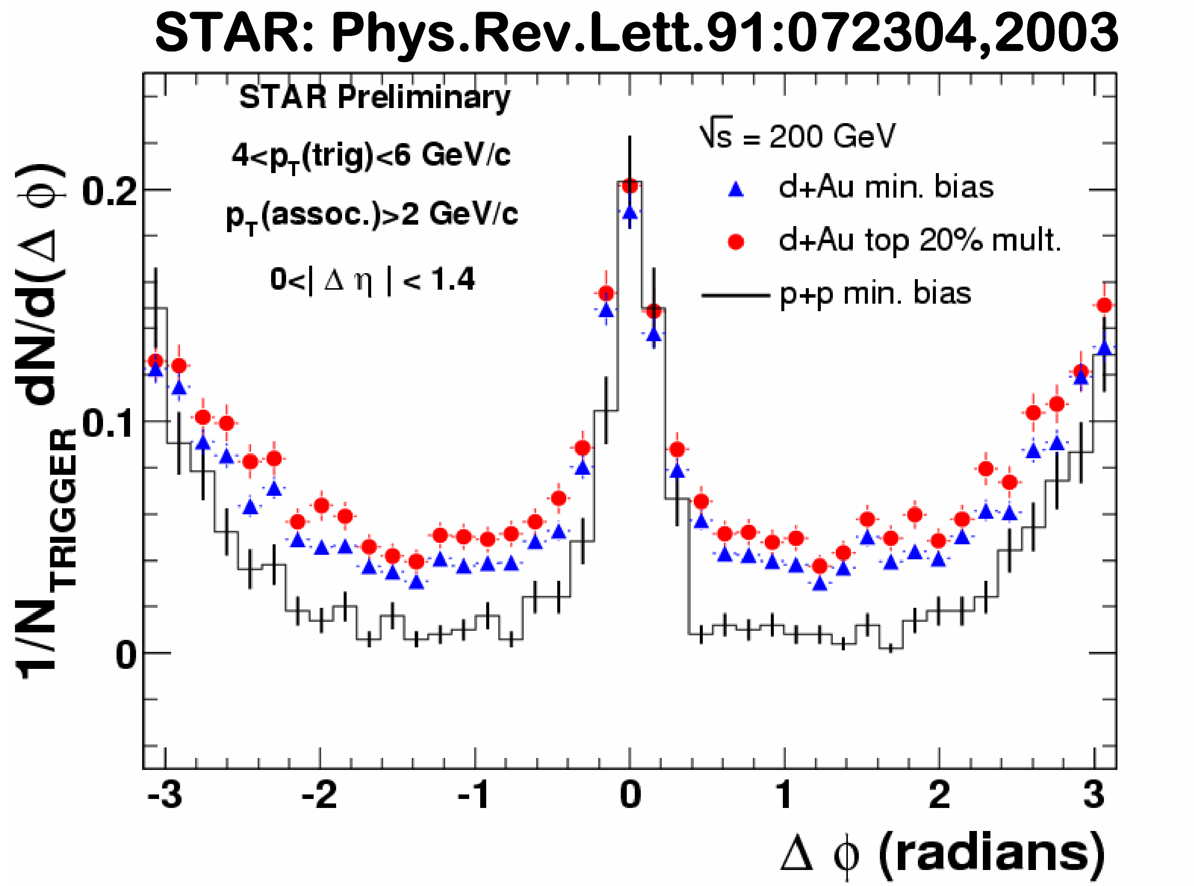
PHENIX, STAR, PHOBOS, BRAHMS
Phys.Rev.Lett.91 (2003)

CIPANP 5/21/03

d+Au: two-particle correlations

Check mate!

The NULL dA Quench prediction is seen in full strength back-to-back Correlations, as in p+p.



- underlying event grows: p+p < d+Au minbias < d+Au central
- near-side: correlation strength and width similar
- away-side: d+Au peak broadens but little centrality dependence

Unquenched back-to-back jets are observed in central d+Au!

Outline

1. Overview of 3 convergent lines of evidence

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4. The D+Au Null Control

5. Conclusion: The QGP is found

Four independent calibrations of Initial QGP density

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

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

My 3 Part Definition of a QGP is satisfied

1. A form of matter (many body dynamical system) with a unique set of Bulk (collective) phenomena and partonic diagnostics — Elliptic Flow, Jet Quenching

2. which are calculable in the deconfined (Colored) quark-gluon basis of QCD — LatticeQCD, pQCD

3. And which can be turned on or off via Control experiments — N_{part} and Au->D

Bonus: Softenning of the QGP EOS observed

The END of searching for QGP

The BEGINNING of measuring its properties

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

Experimental To Do List

•Y=+- 3 dAu to test if x=0.001 QGP->CGC ?

•$C_2(phi_1,phi_2, pt_1,pt_2, eta_1,eta_2, fl_1,fl_2, Mult, A,B, Ecm)$

•Heavy Quark tomography [Magdalena Djordjevic]

•Open Charm (enhancement?); J/Psi (suppression?)
• Charm Flow? [Sotiria Batsouli]

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

•Turn energy Ecm~50-100 and A=20-100 exp. knobs

Theory To Do List

- HBT source E_{cm} invariance?
- why No time-delay?
- E_T/N E_{cm} invariance, N_{part} invariance?
- Dissipative effects on $V_2(pT)$?
- $V_2(y)$ *NON* Bjorken boost invariant
- Baryon transport dynamics
- Thermalization, QGP Transport theory