RHIC

?CGC?

QGP

What Have We Learned So Far?

A Theoretical Perspective

Miklos Gyulassy
Columbia University

January 16, 2004

Quark Matter 2004, Oakland CA

NSAC Long Range Plan 1983

R.Stock QM04: "Unicorn Captured"

"He is tethered to a tree and constrained by a fence, but the chain is not secure and the fence is low enough to leap over.

The unicorn could escape if he wished. Clearly, however, his confinement is a happy one, to which the ripe, seed-laden pomegranates in the tree testify."

http://www.medieval-tapestry-wallhangings.com/unincap1.html

QM04 Dilemma: J.K. Davidson, Science Writer, S.F.Chron.

“The QM04 conference left me with contradictory impressions:

On the one hand, most scientists seem to think that we’re getting closer to identifying a quark-gluon plasma.

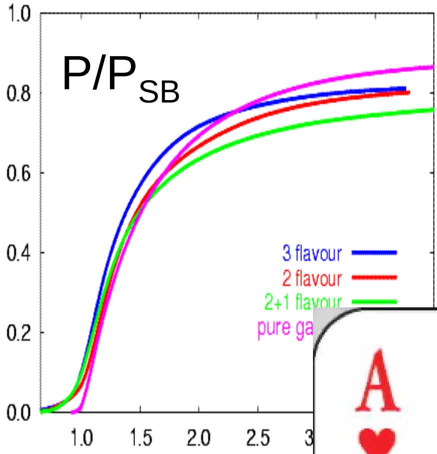
On the other hand, there seemed to be significant disagreement on what a quark-gluon plasma IS! “

Outline of My Talk:

1) QCD Theory definition of QGP
2) Operational definition of QGP
3) Evidence for QGP as of QM04
4) First hints of CGC

P_{QCD} theory definition of a QGP

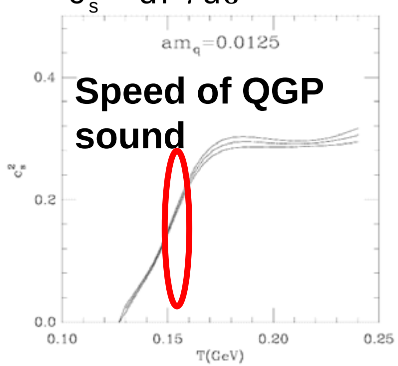
QGP EoS vs T



T/T_c LQCD

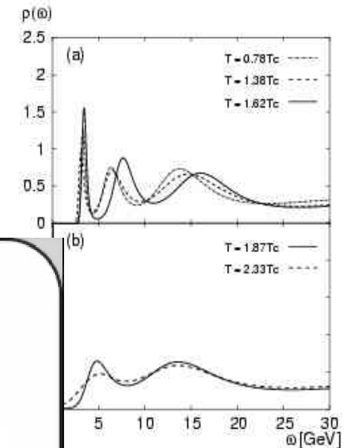
QGP Soft point

$c_s^2 = dP/d\varepsilon$



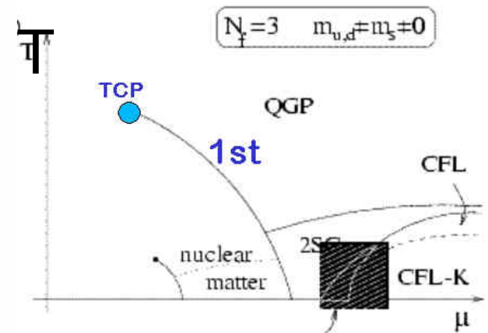
T_c=160 MeV

✡ Family

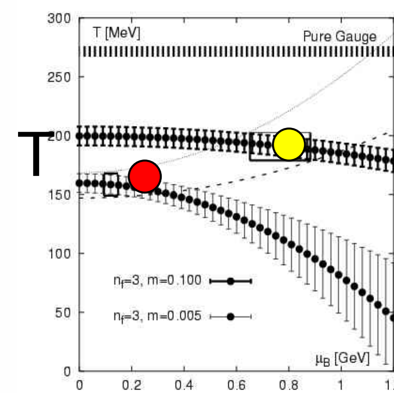


$T_{\square}$=1.6 T_c

❍$_B$>0 EoS

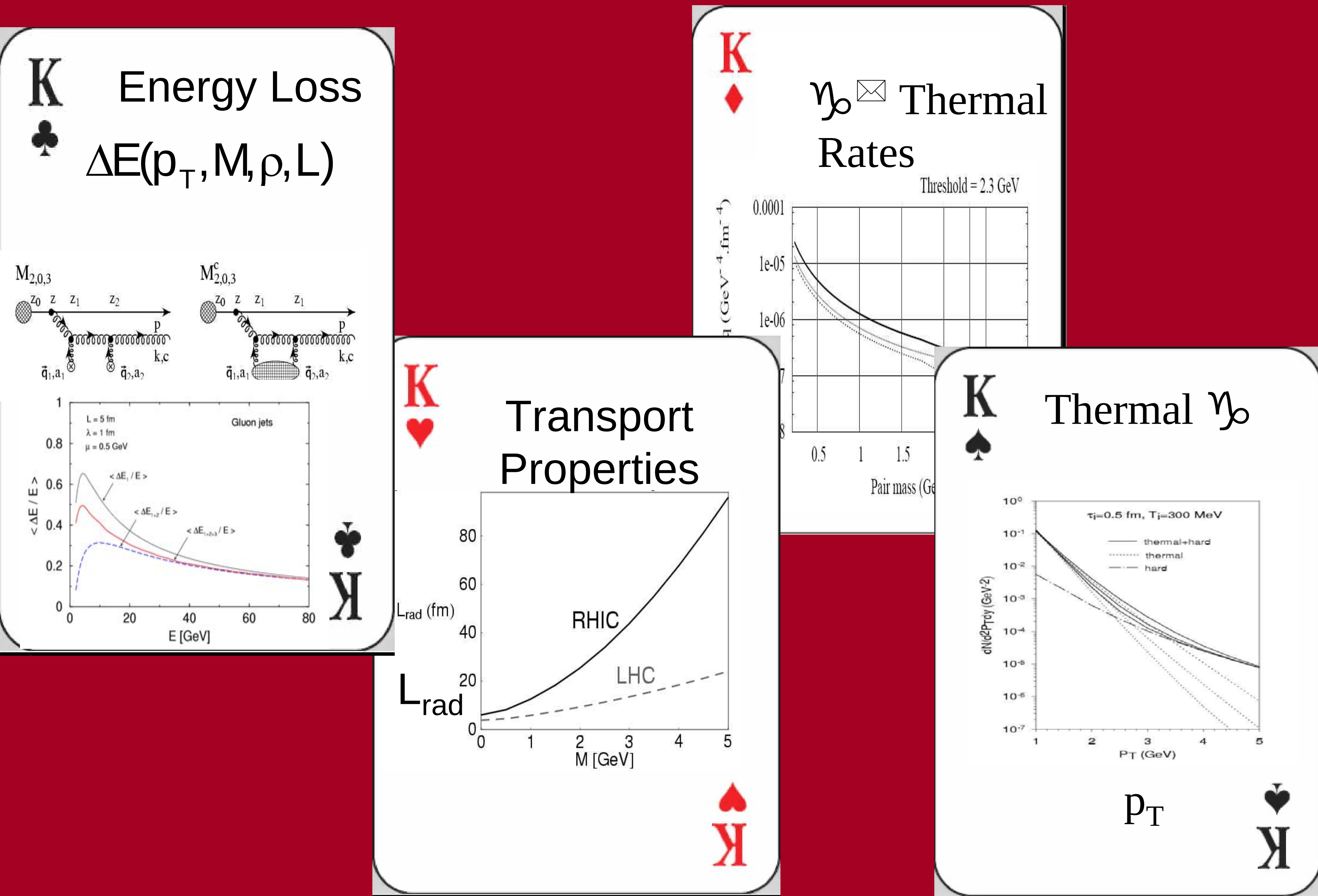


QGP EoS

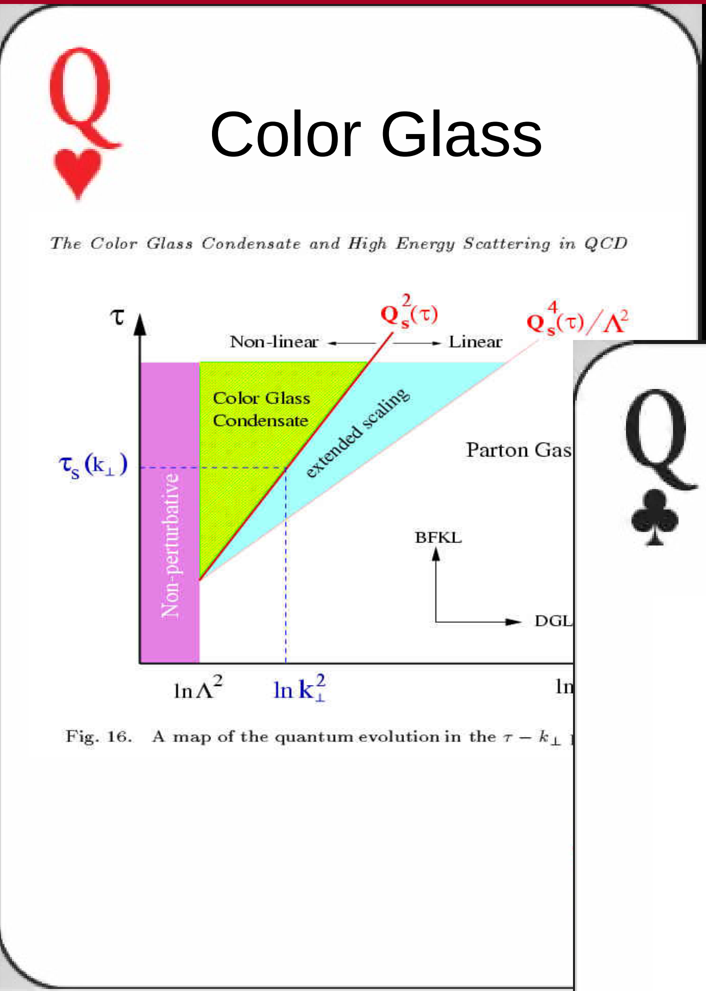


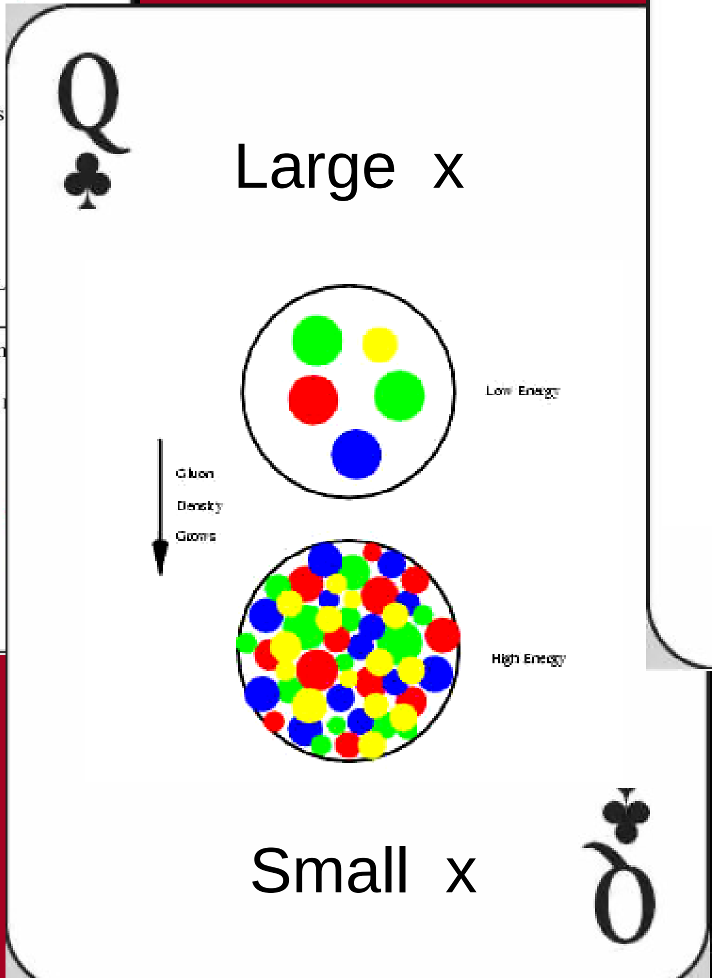
LQCD ❍$_B$>0

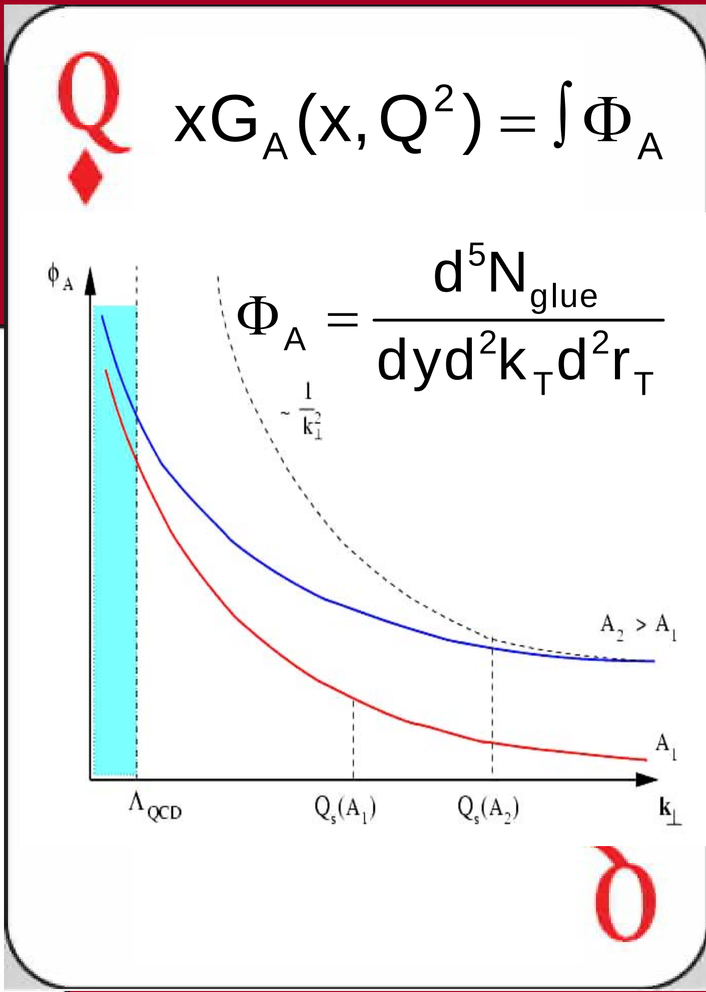
pQCD theory definition of a QGP



Weak coupling QCD theory of CGC seed of QGP







My Operational definition of QGP

QGP = Bulk Collective + Parton Dynamic + Discriminator

= P_{QCD} + pQCD + dA

= $v_n(p_T,m)$ + $(R+I)_{AA}$ + $(R+I)_{DA}$

1 2 3

1) Evidence for P_{QCD} via v_n bulk collective flow of 10^4 □, K,p,☹📭

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

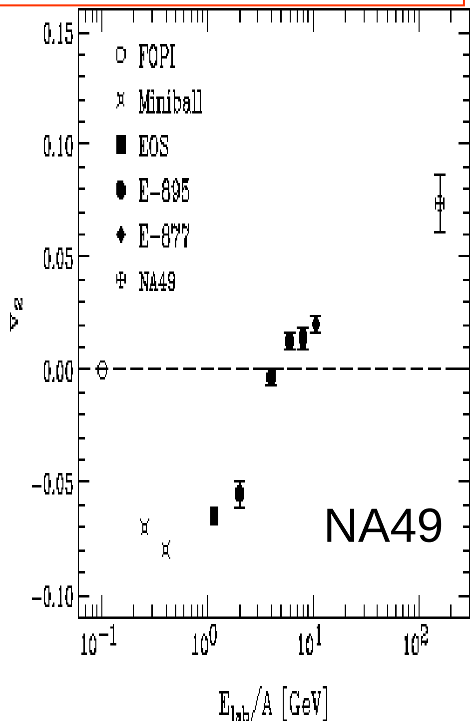
3) Evidence jet *un*-quenching in D+Au = Null Control

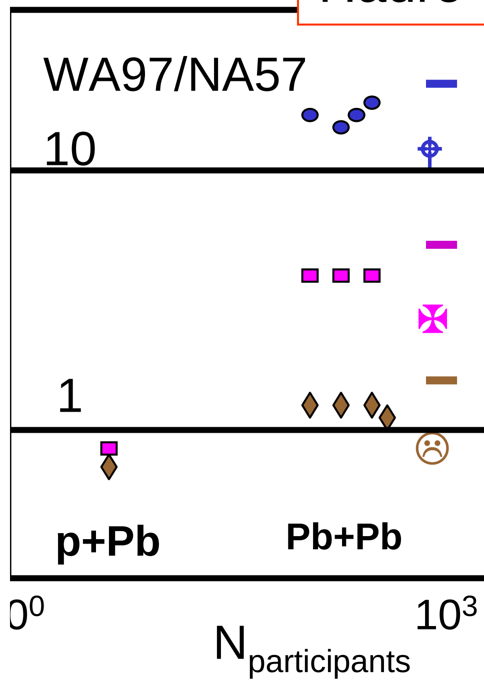
2+3 are necessary but 1 is critical for sufficiency !

My conclusion: “overwhelming evidence” at QM04 that QGP Bulk Matter is made in AuAu at 200 AGeV

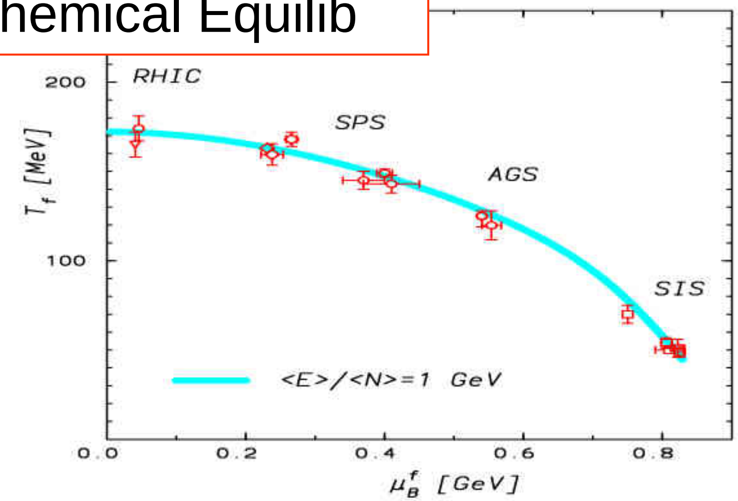
Necessary QGP *Precursors* at SPS 2000

Collective Flow

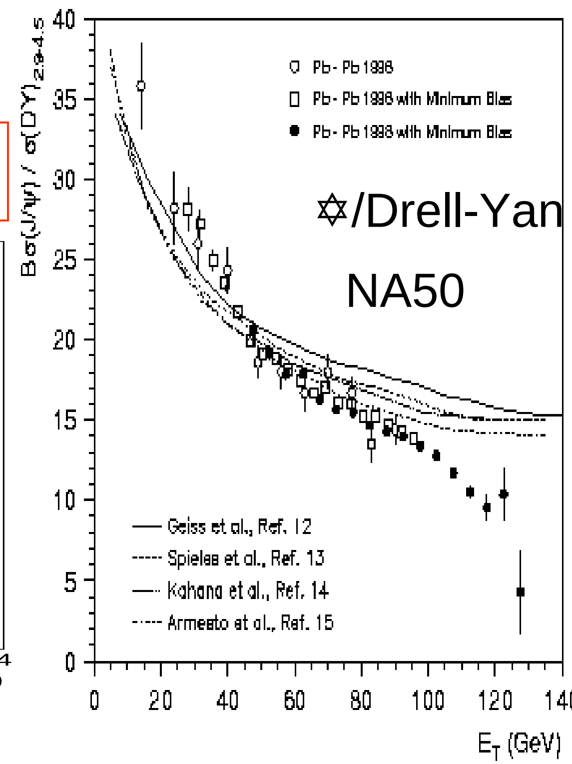




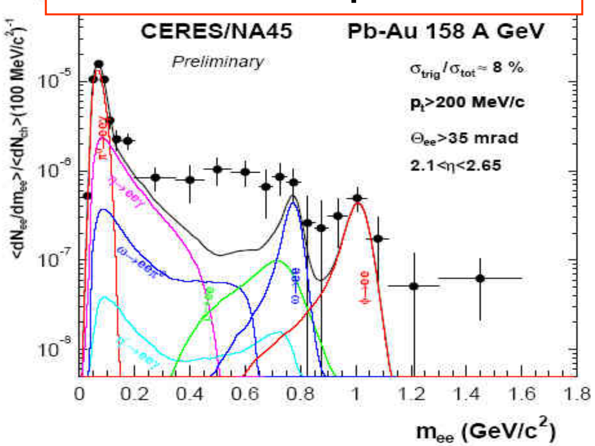
Hadro Chemical Equilib

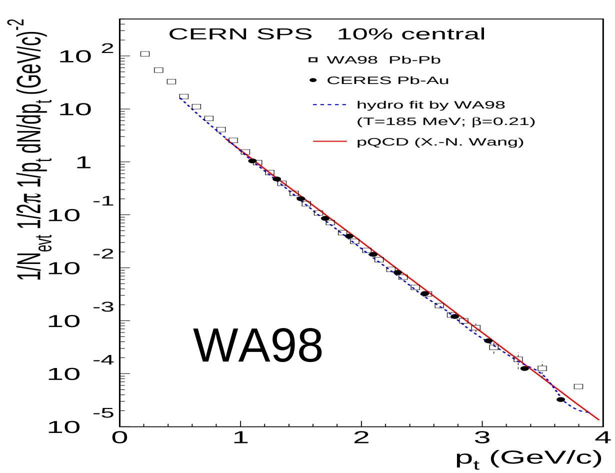


pQCD



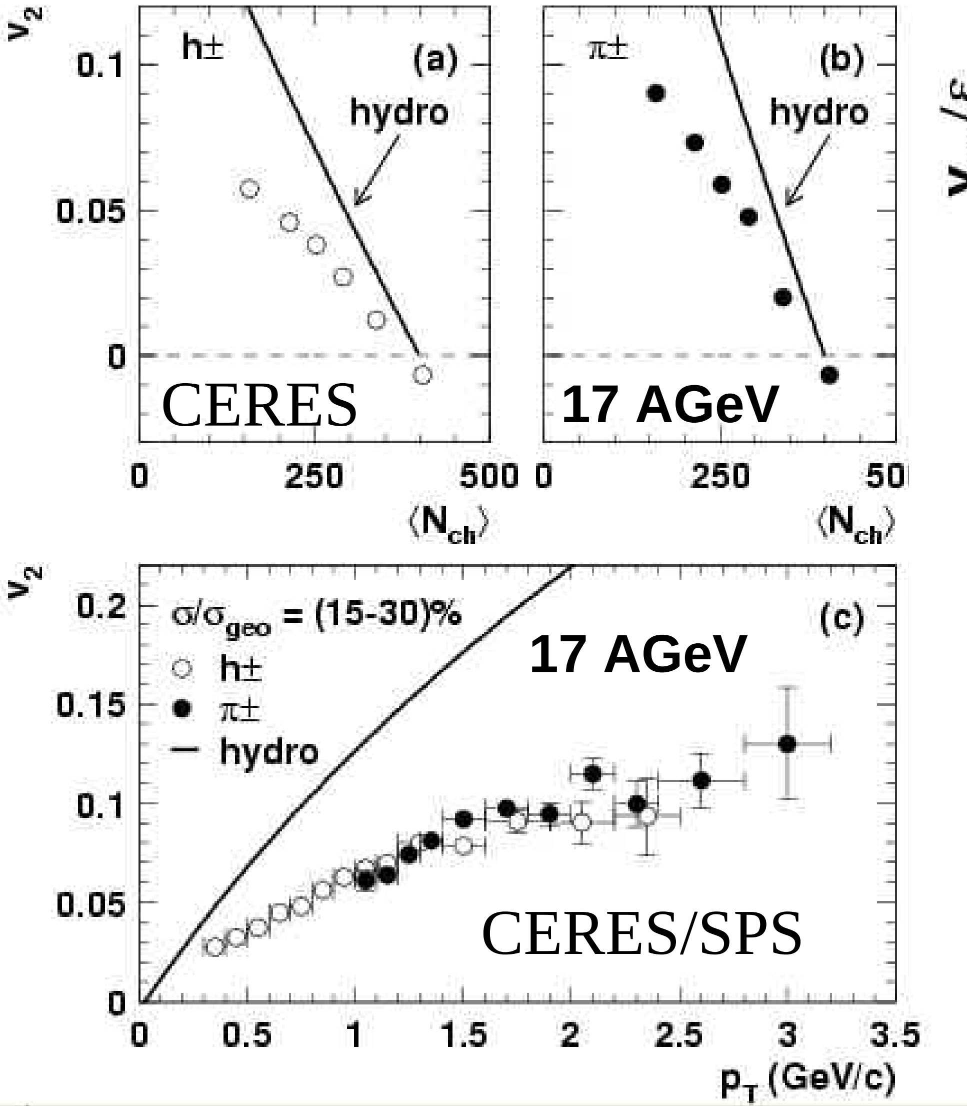
Medium Dispersion



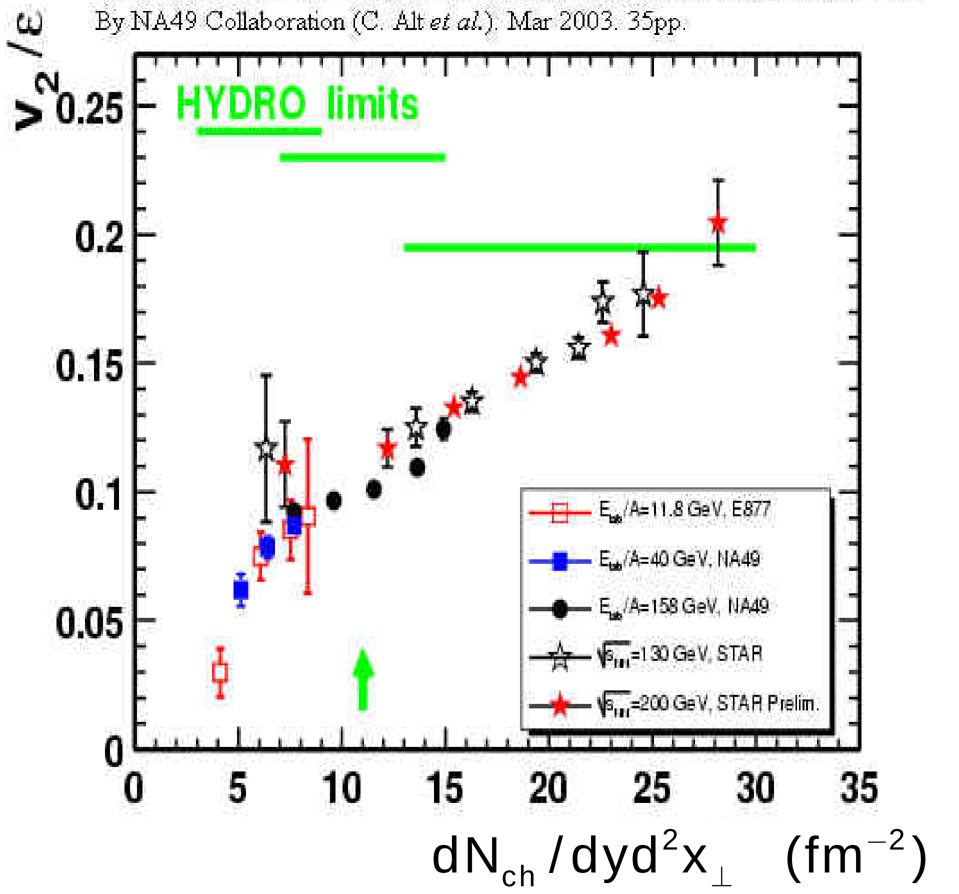


But Critical Missing Signature of the QGP at SPS

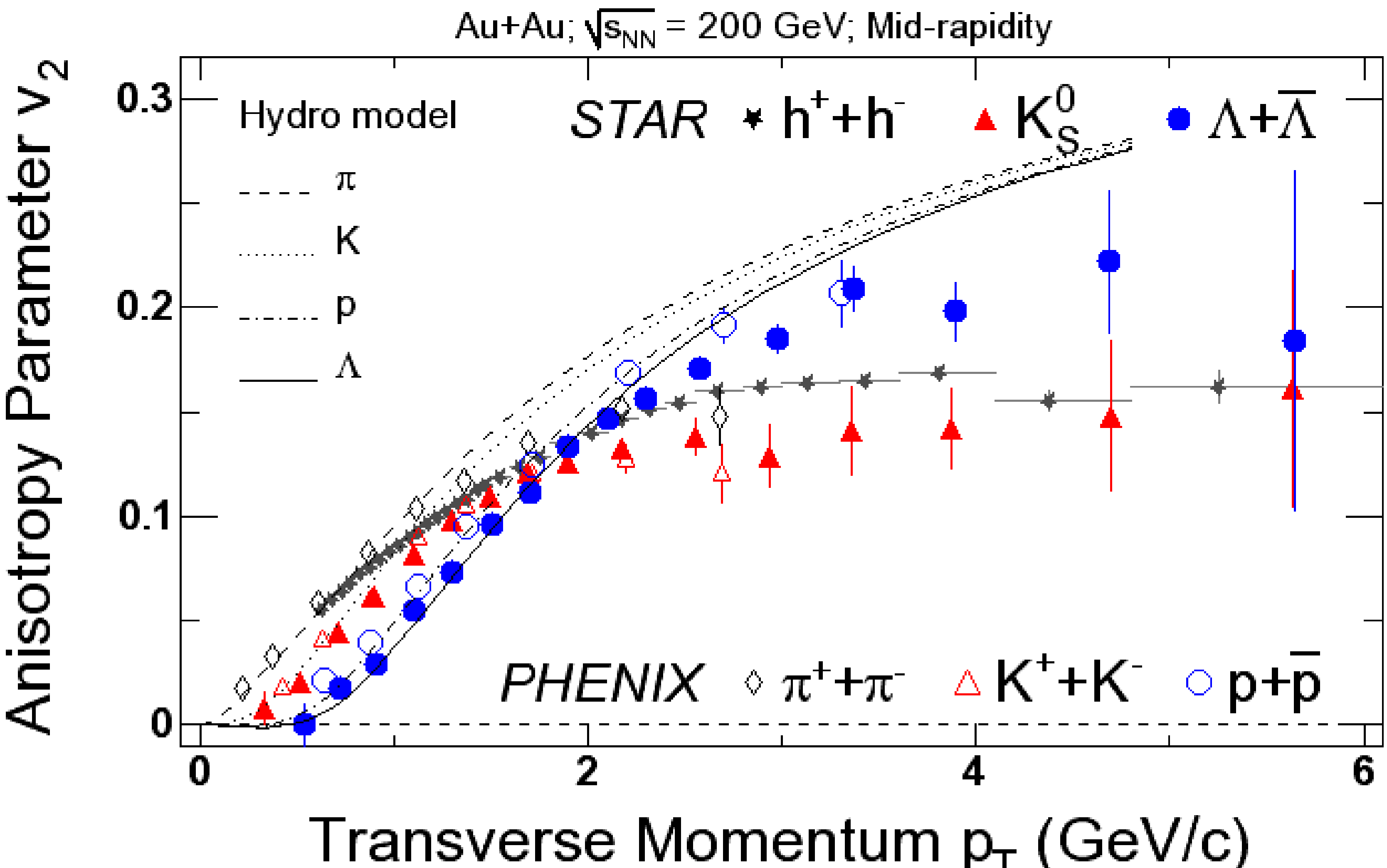
Below RHIC energies, Bulk Flow does not reach QGP hydro!



2) DIRECTED AND ELLIPTIC FLOW OF CHARGED PIONS AND PROTONS IN PB + PB COLLISIONS AT 40-A-GEV AND 158-A-GEV.
By NA49 Collaboration (C. Alt *et al.*). Mar 2003. 35pp.



The QGP Fingerprint at RHIC = Bulk collective flow $P_{QCD}(T)$



Bulk P_{QCD} Hydro

☞ Asym. pQCD Jet Quenching

q^n Coalescence

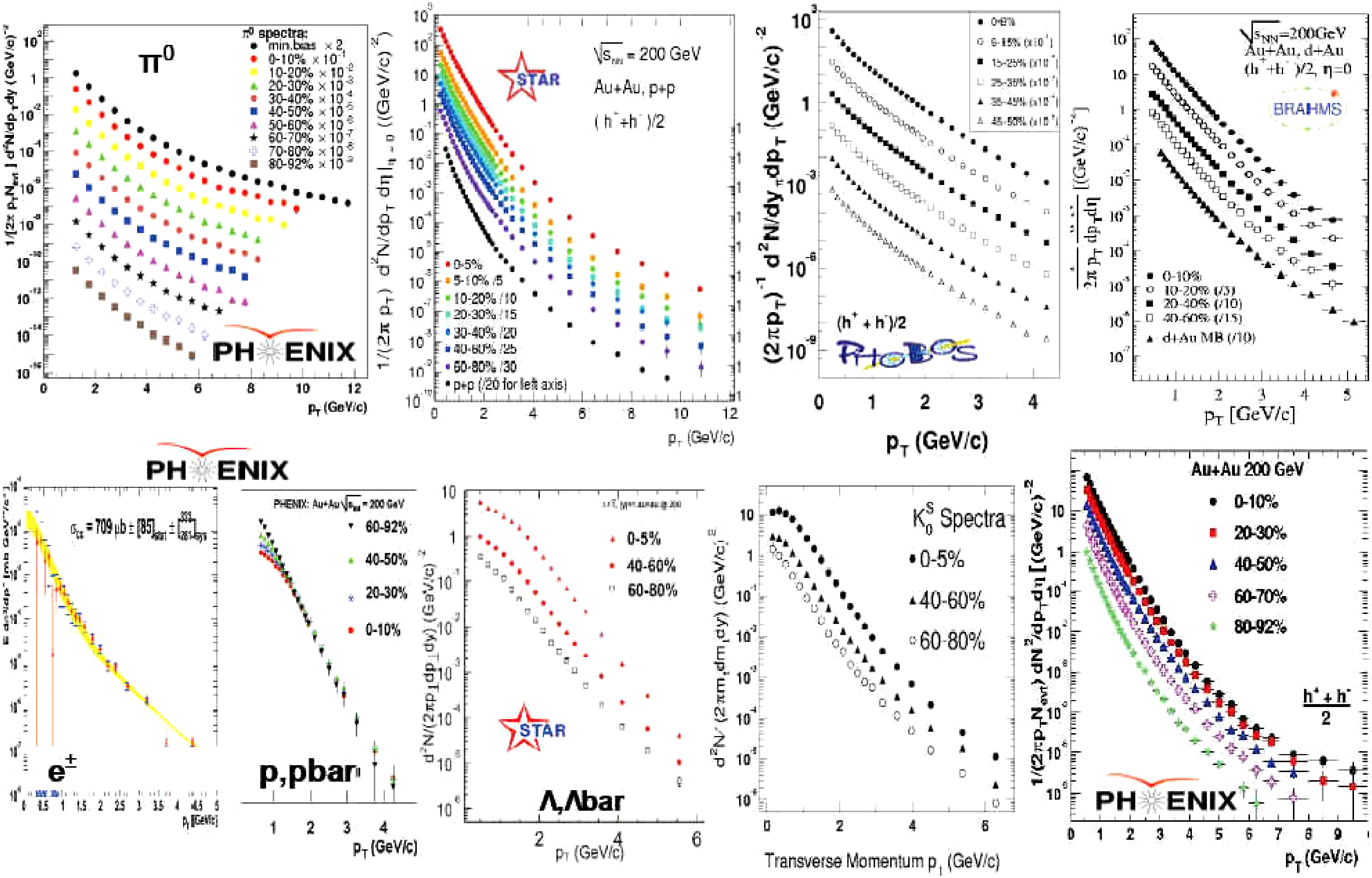
2nd and 3rd Lines of Evidence for QGP

Jet Quenching

pQCD Parton Dynamics

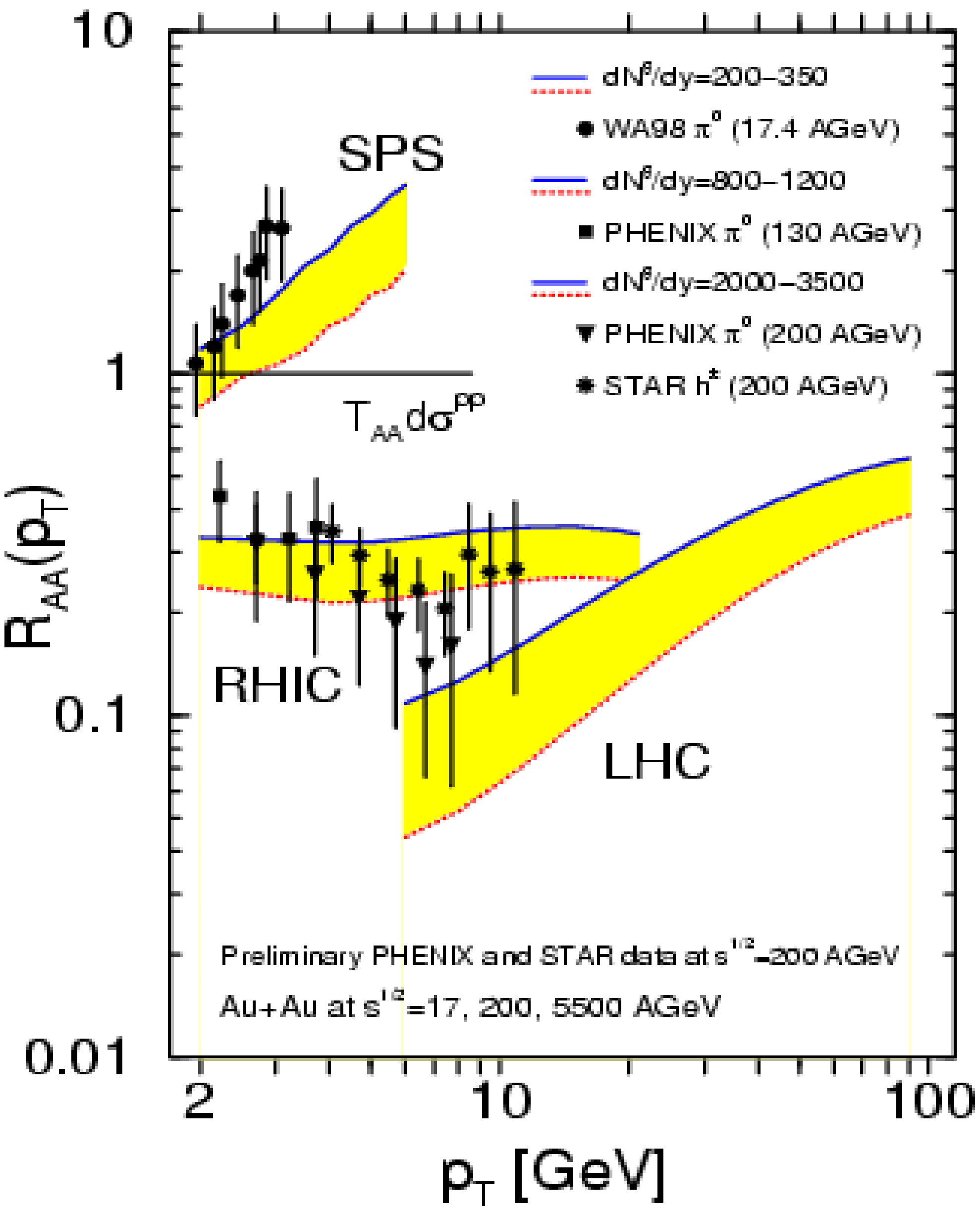
Jet Tomography

High p_T spectra in Au+Au @ 200 GeV



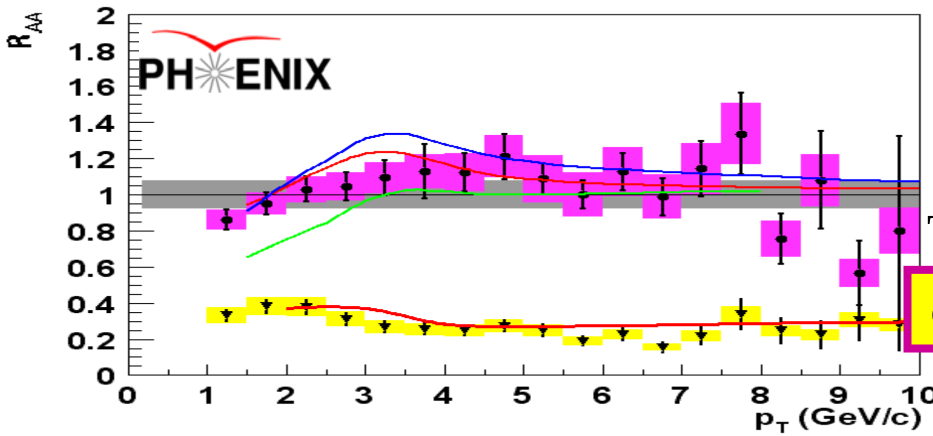
Single Hadron Tomography from SPS, RHIC, LHC

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



1. **Cronin dominates at SPS**
2. **Cronin+Quench+Shadow conspire to give ~ flat suppression out to highest pT at RHIC with $R \sim N_{part}/N_{bin}$**
3. **Predicts sub N_{part} quench, positive pT slope of R at LHC and $R_{LHC}(40) \sim R_{RHIC}(40)$**

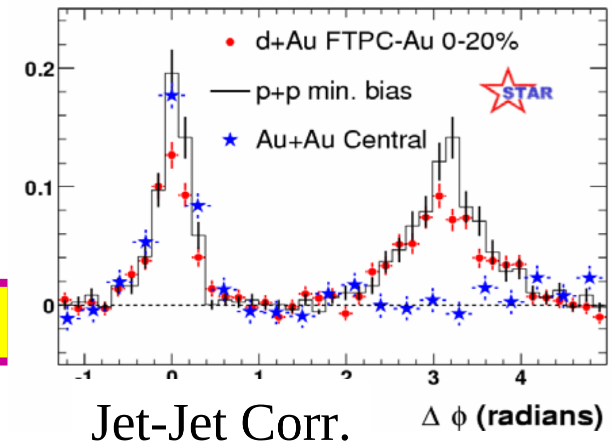
D+Au vs Au+Au @ 200 GeV:



Single Jet Tomography

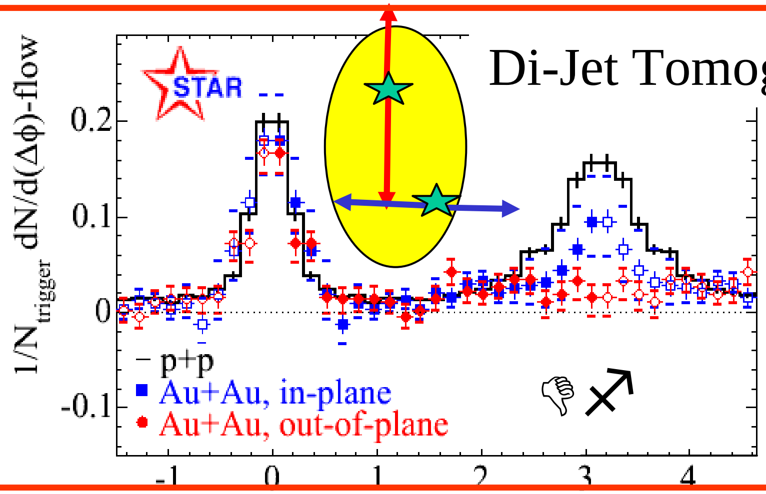
$dN_{glue}/dy= 1000$

IV,MG(02)

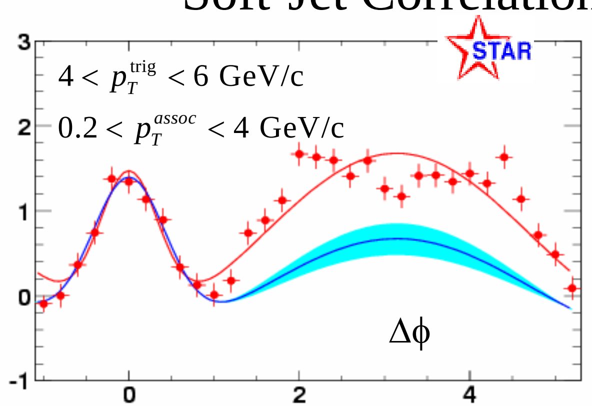


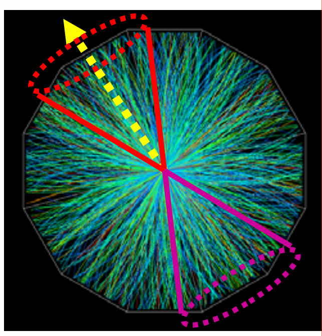
Jet-Jet Corr.

Di-Jet Tomography

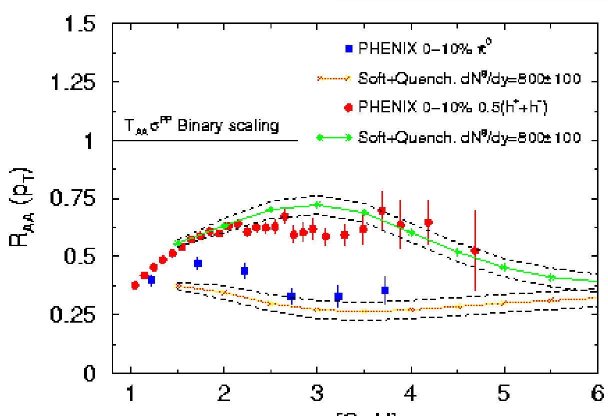


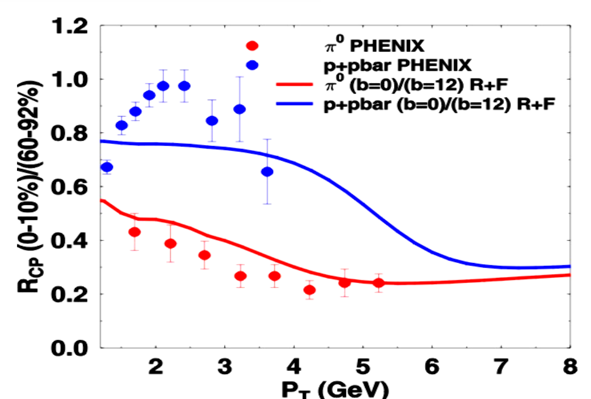
Soft-Jet Correlations





RHIC Baryon Anomaly





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
SW

4. Gluon saturation $p_T < Q_s$ predicted

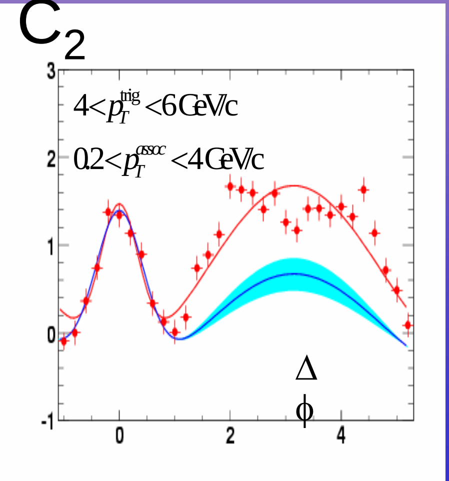
$dN_g/dy = 1000$ at $Q_{sat} = 1$ GeV at y=0

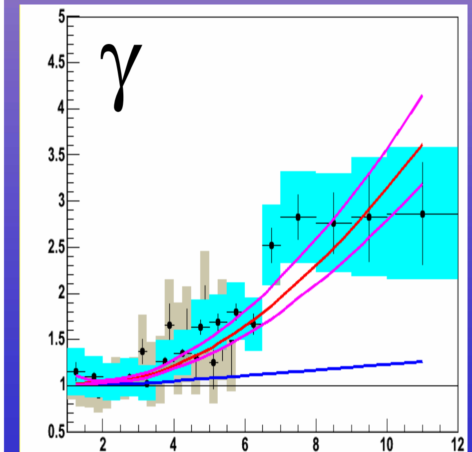
BM
McV
EKRT

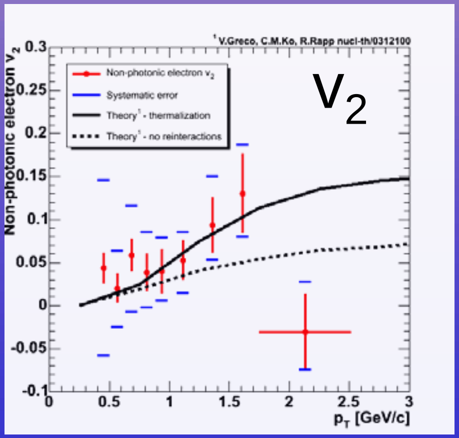
The END of searching for the QGP

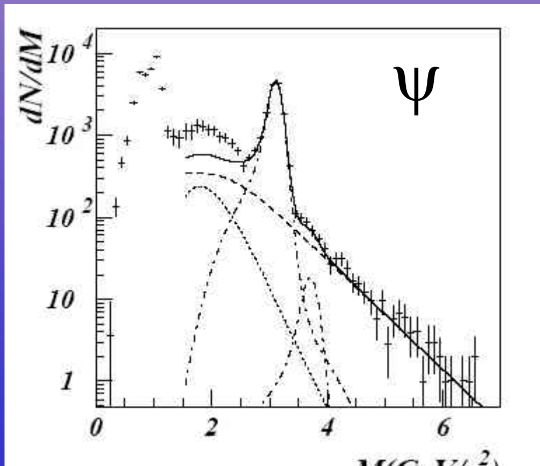
The BEGINNING of measuring its properties

- 12D Correlations
- Heavy Quarks
- Direct Photons
- Leptons
- and its relation to CGC







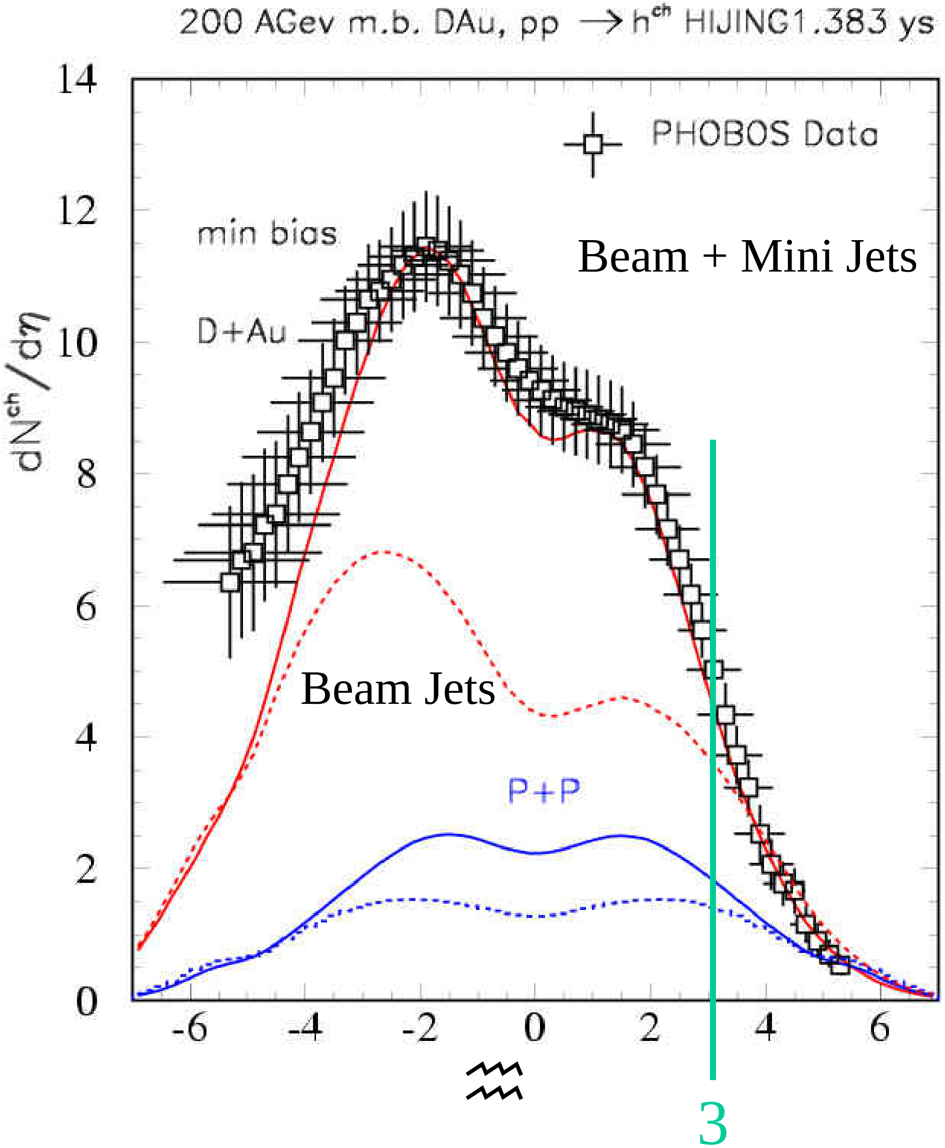


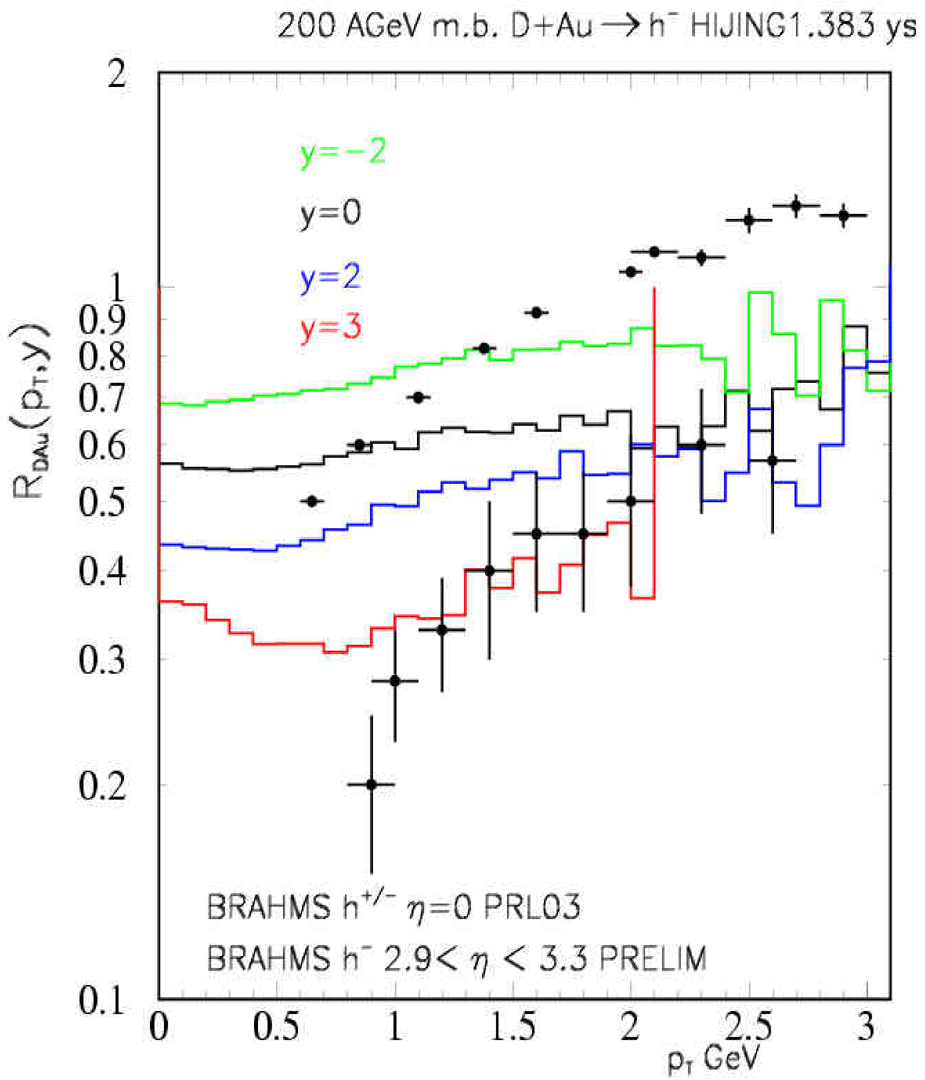
Has the CGC been seen at RHIC also?

- Indirectly, yes, as seed of QGP at y=0
- *Possible* Hints at y=3 (BRAHMS)
- But 30 year old soft beam physics
  Must be first subtracted !

Soft Beam Jets : dM/M Dominate Low pT at high y

D+Au HIJING





See: http://nt3.phys.columbia.edu/people/gyulassy/Talks/RBRC_120503/

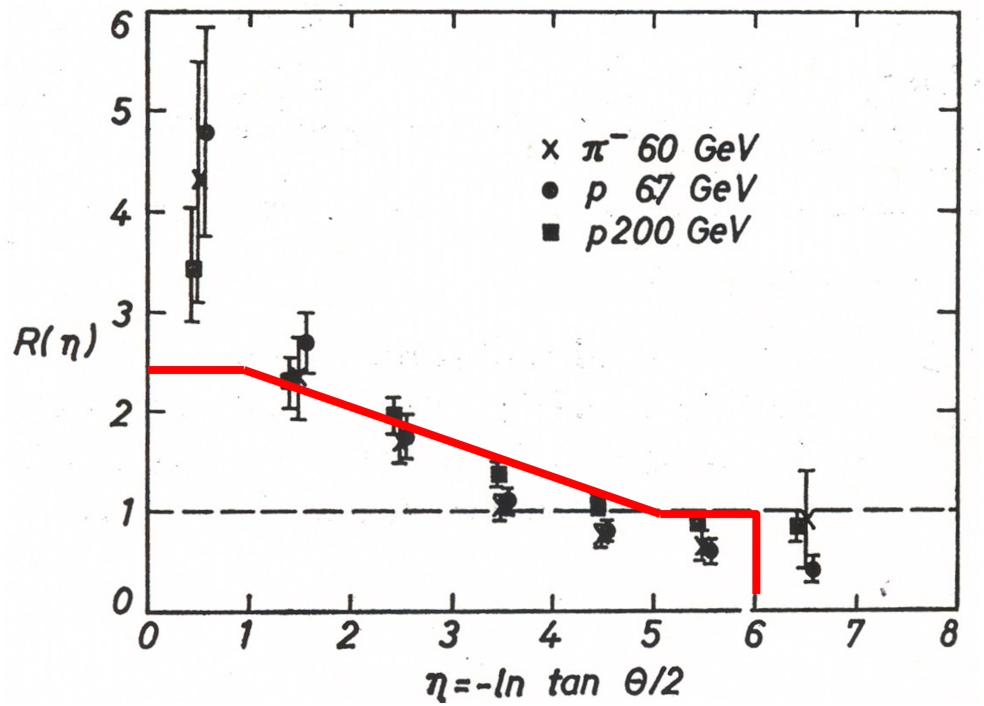
Proton+Emulsion data
W. Busza review 1976
(Acta Phys. Pol. B8, 333)

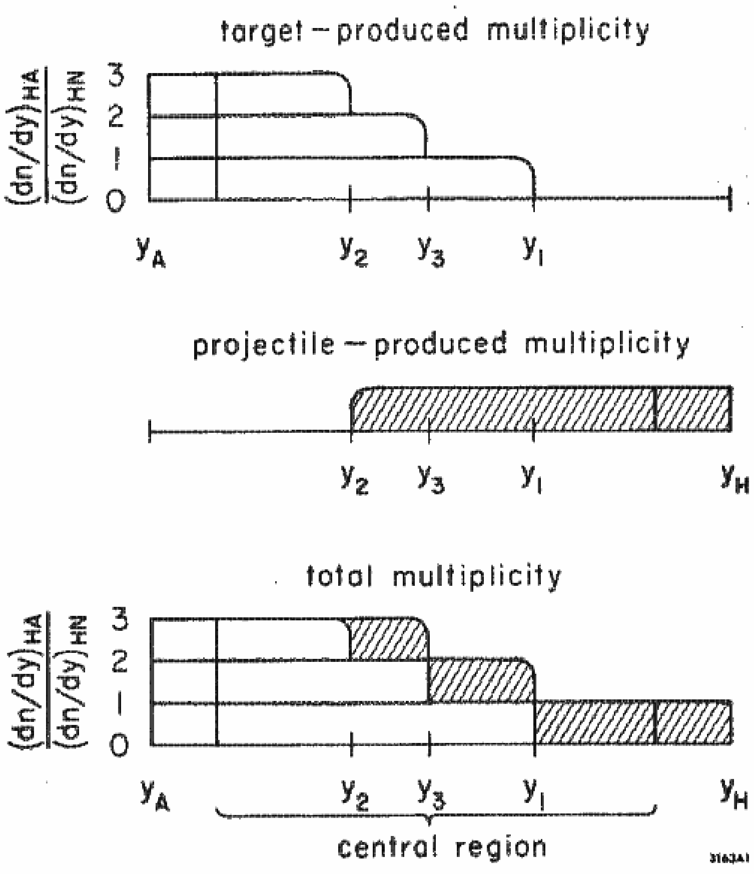
Brodsky, Gunion, Kuhn

PRL39(77)1120

Color Neutralization Model

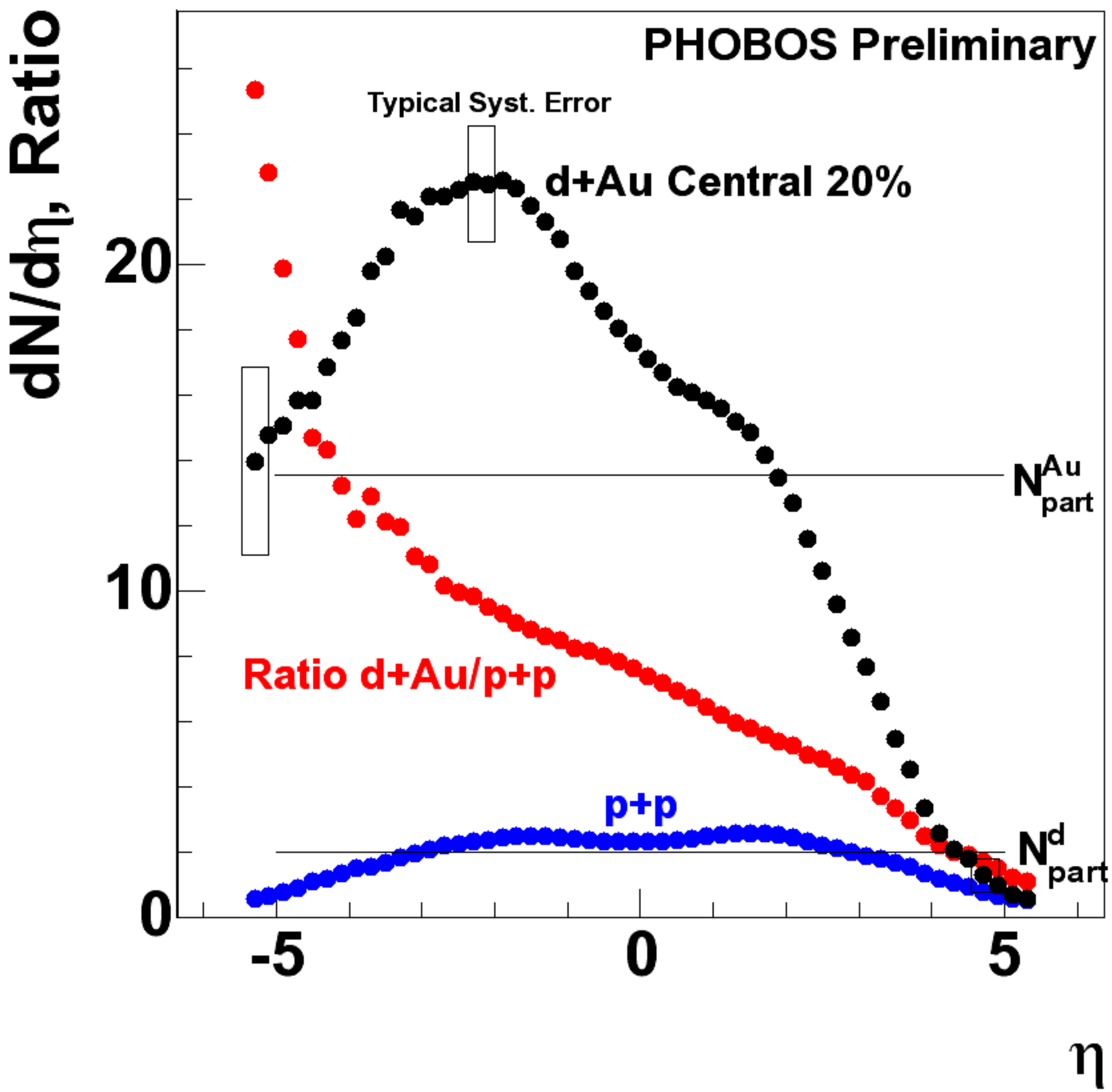
Feynman gas dy=dx/x= dM/M





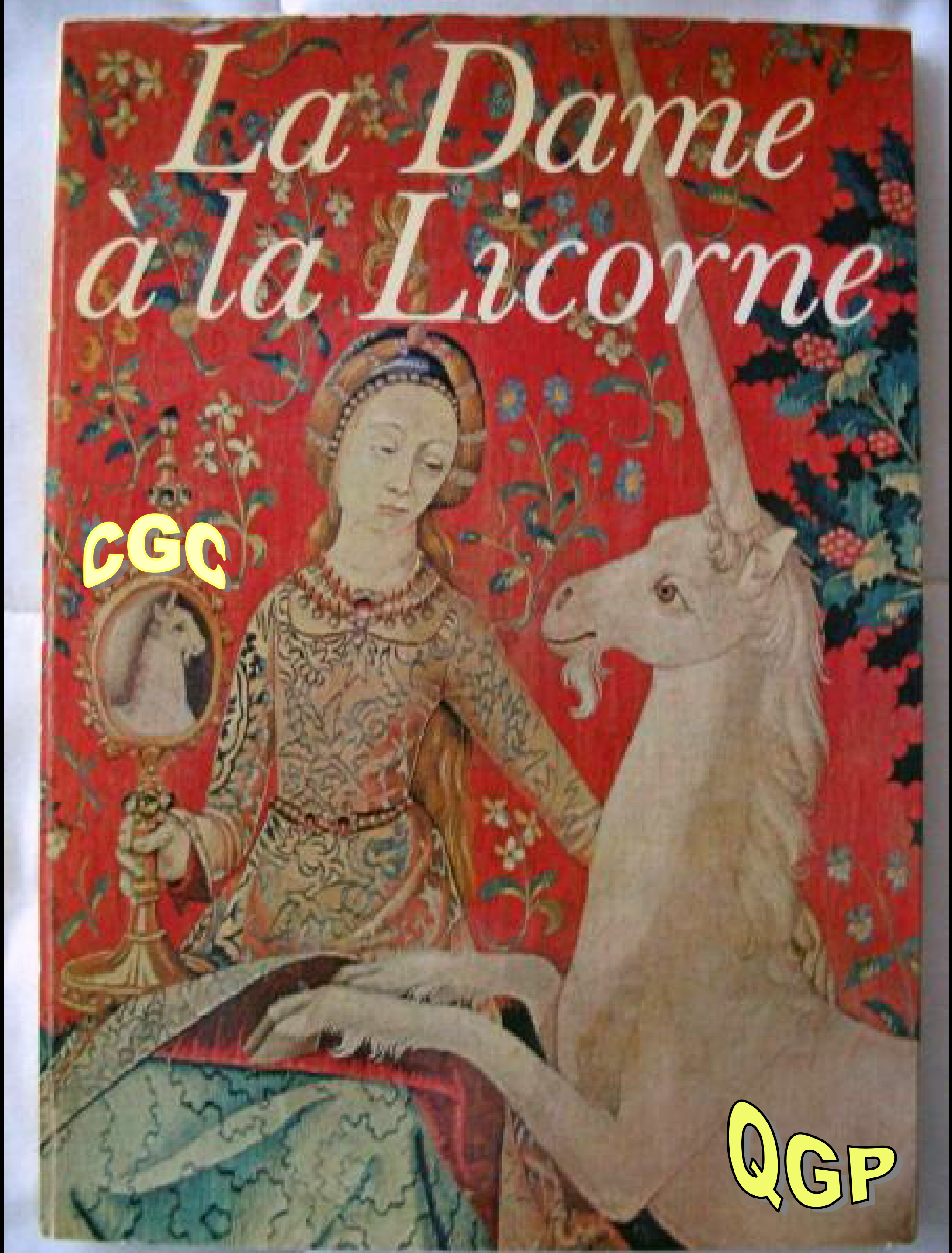
The low pT *Triangle*
Boundary Condition
Condition on $R_{pA}(y,p_T<1)$

Preliminary: *Hot*-off-the-QM04-coffee-table



Addendum to Di Nezza, Steinberg talks

While
QGP
reflects
on
CGC

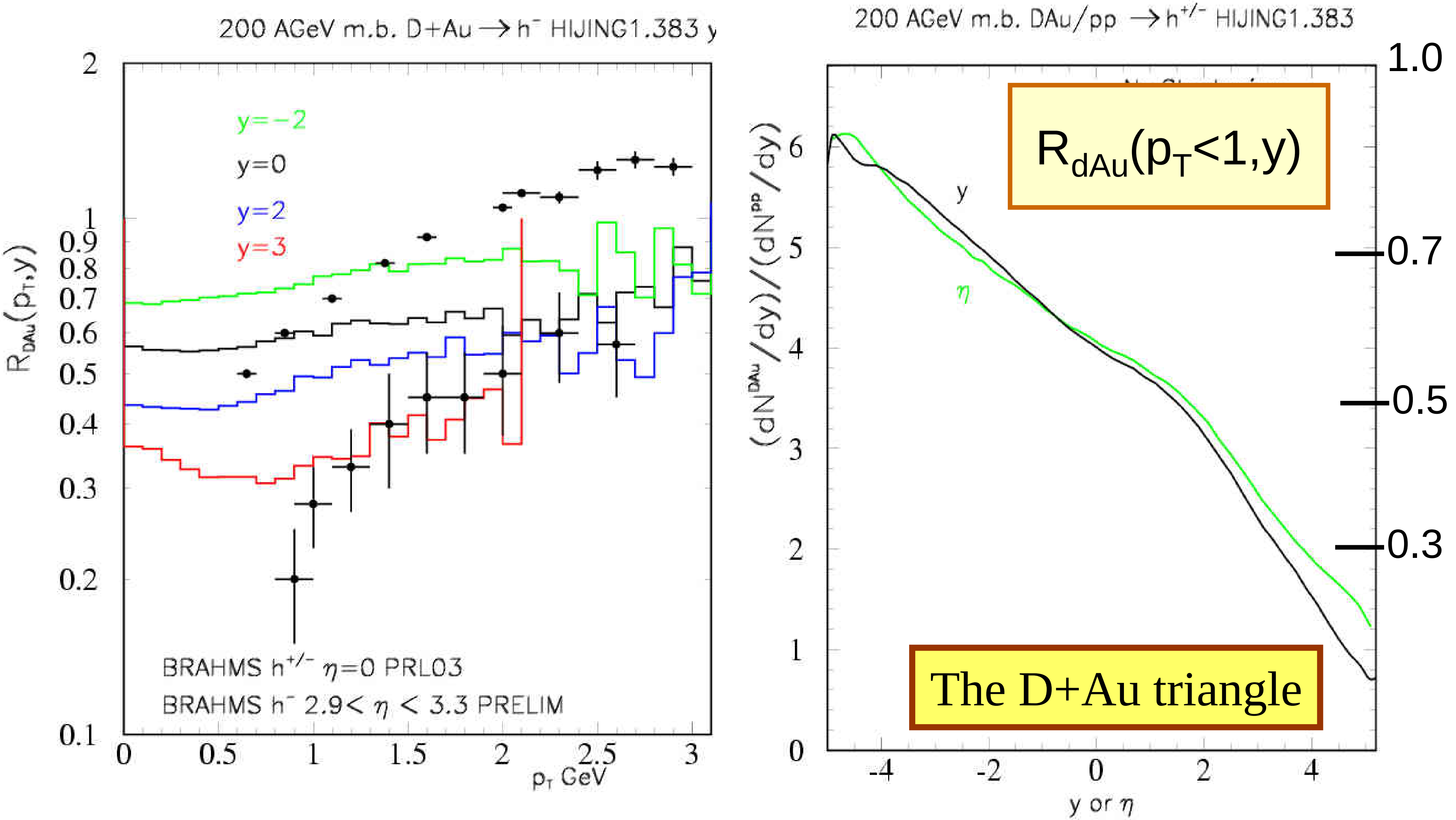


The
QGP
is
tamed

Appendix

A Low pT<0.5 *Triangle* boundary controls forward rapidity

R_{dA}" ■$_D$/■$_{Au}$



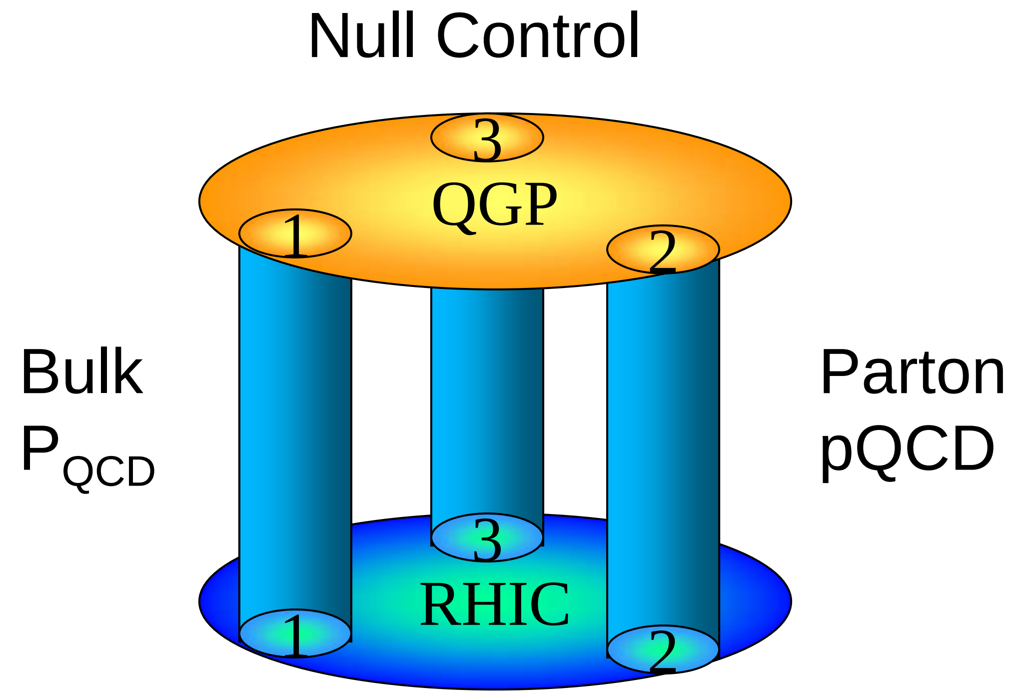
Experimental To Do List

- -5 < Y < 5 dAu to kinematic pT bounds CGC search
- $C_2(phi_1, phi_2, pt_1, pt_2, eta_1, eta_2, fl_1, fl_2$, Mult, A,B, Ecm)
- Heavy Quark tomography c and b, Hidden quarkonia
- Charm and Beauty Flow
- Direct Photons thermometry
- Tagged direct photon -quark jets!
- Excitation functions Ecm~50-100, A=1 - 200
- Pentaquark factory

Theory To Do List

- HBT source puzzle
- E_T/N E_{cm} invariance, N_{part} invariance
- v_n(pT, y, m) collective flow
- Transport properties of QGP
- Baryon transport dynamics
- Transient CGC -> QGP dynamics
- QGP at finite mu_B

Three Lines Converge to QGP at RHIC



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

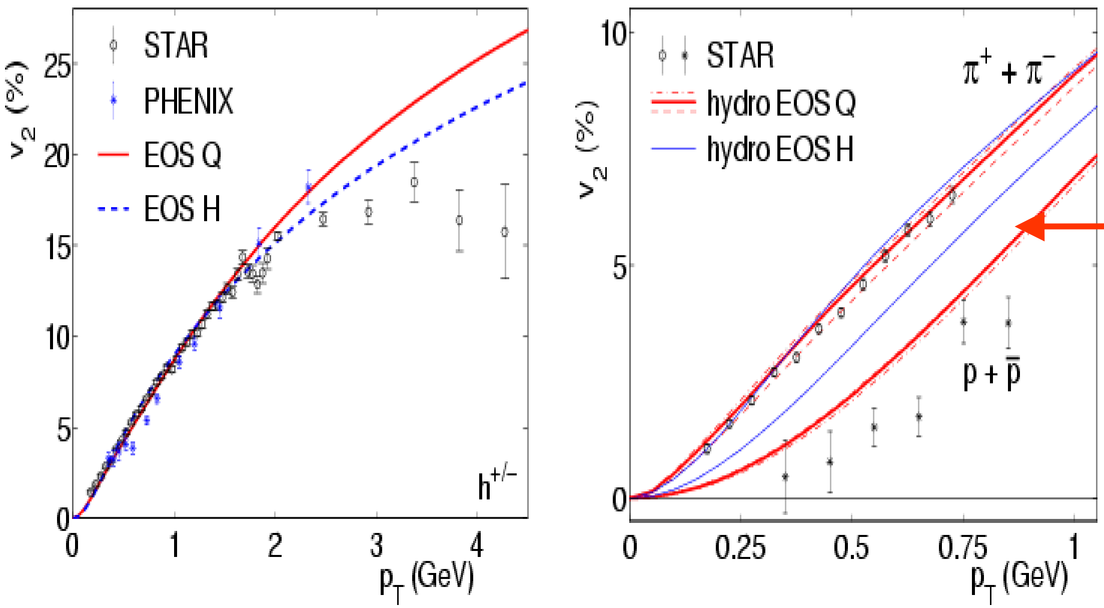
$QGP = P_{QCD} + pQCD + dA = v_2 + (R+I)_{AA} + (R+I)_{dA}$

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



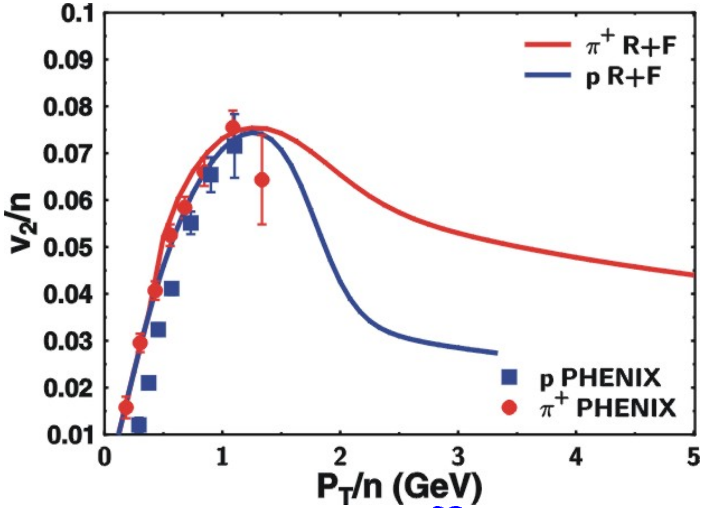
STAR Coll., PRL 86 (2001) 402; 87 (2001) 182301; PHENIX Coll., nucl-ex/020400512 and QM 2001

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

M_h dependent $v_2(p_T)$

Partonic Recombination + Fragmentation? vs QGP Hydro + Jets

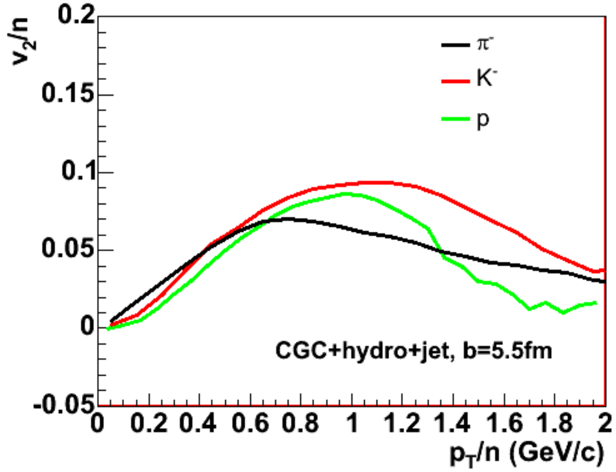
R.Fries, B. Muller, …



$$v_2^\pi/n \sim v_2^p/n$$

- Parameterized flow
- How to justify assumed $v_T \sim 0.55c$ at $T=T_c$?
- Idealized hard sphere geom

T.Hirano & Y.Nara



$$v_2^K/n \sim v_2^p/n$$

- Flow is dynamically calculated P_{QCD}
- Radial flow in hadron phase
  is also important.
  At $T=T_c$, $\langle v_T \rangle \sim 0.25c$
  T=100 MeV, $\langle v_T \rangle \sim 0.55c$

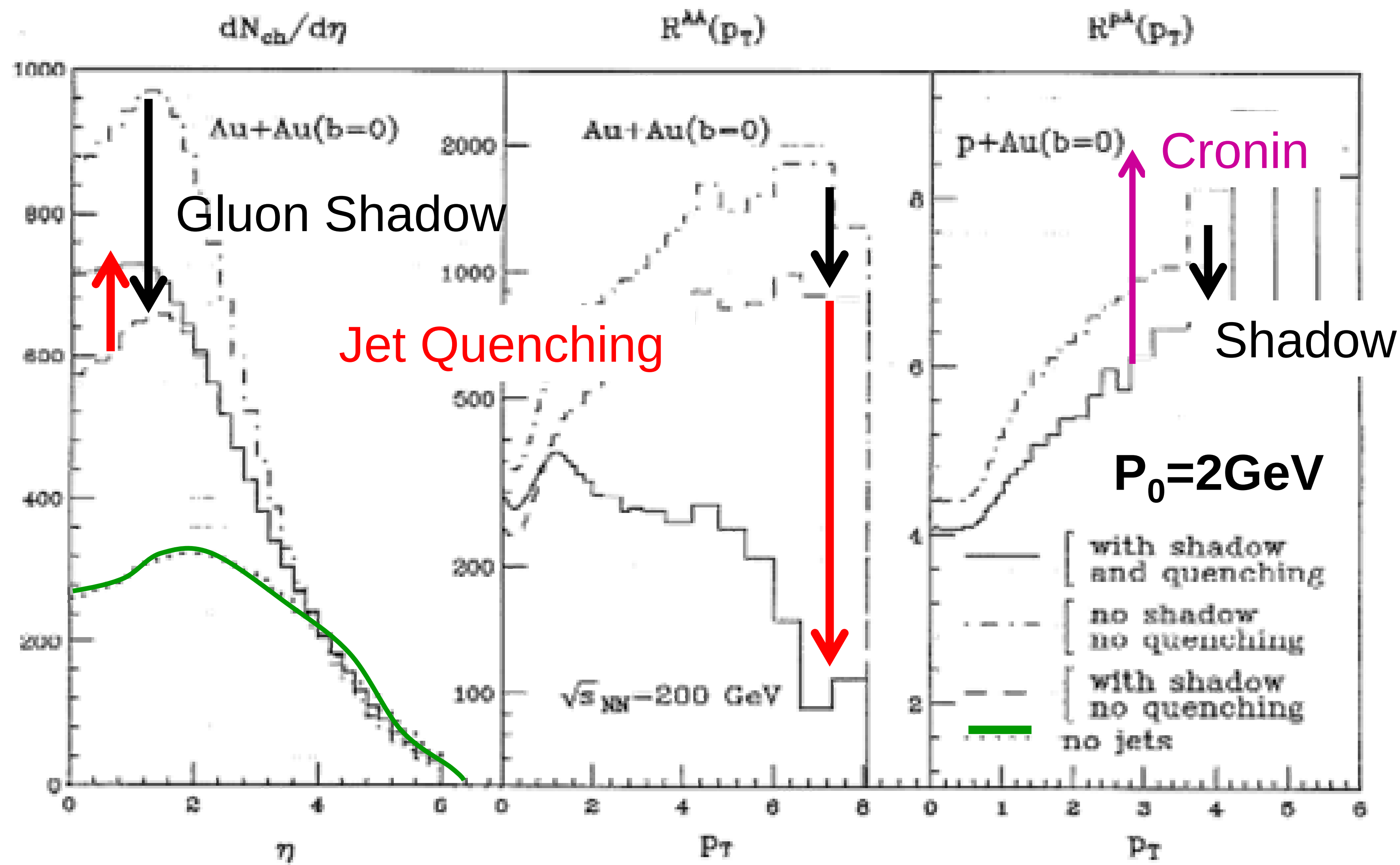


FIG. 1. Results of HIJING on the dependence of the inclusive charged-hadron spectra in central Au+Au and p+Au collisions on minijet production (dash-dotted line), gluon shadowing (dashed line), and jet quenching (solid line) assuming that gluon shadowing is identical to that of quarks and $dE/dl = 2$ 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 $p+p$.

Some Source Fits giving $R_{out}=R_{side}=R_K$

$$\frac{dN}{dx_{out}\,dt_f}$$

$$R_{out}^2 = \left\langle (x_{out} - v_K t_f)^2 \right\rangle - \left\langle (x_{out} - v_K t_f) \right\rangle^2 \approx \Delta(x_{out} - t_f)^2$$

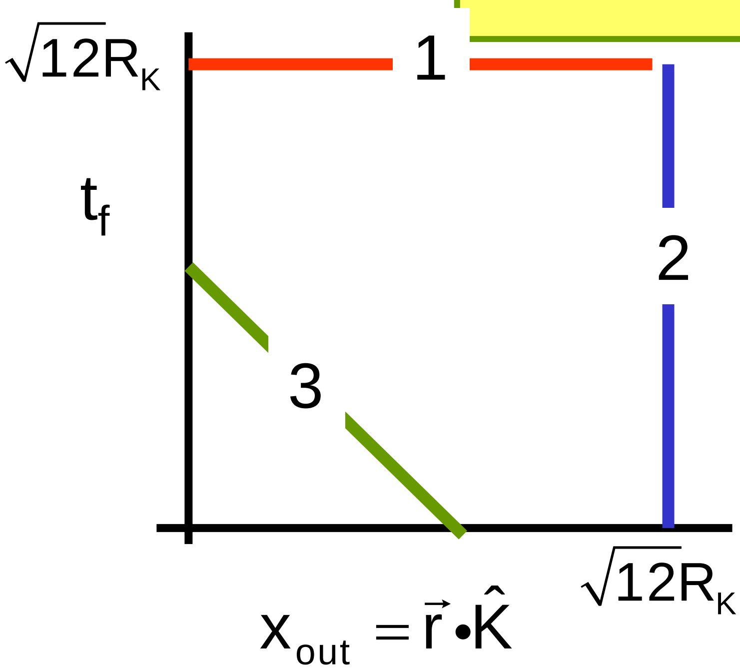
$\sqrt{3}\,R_K$

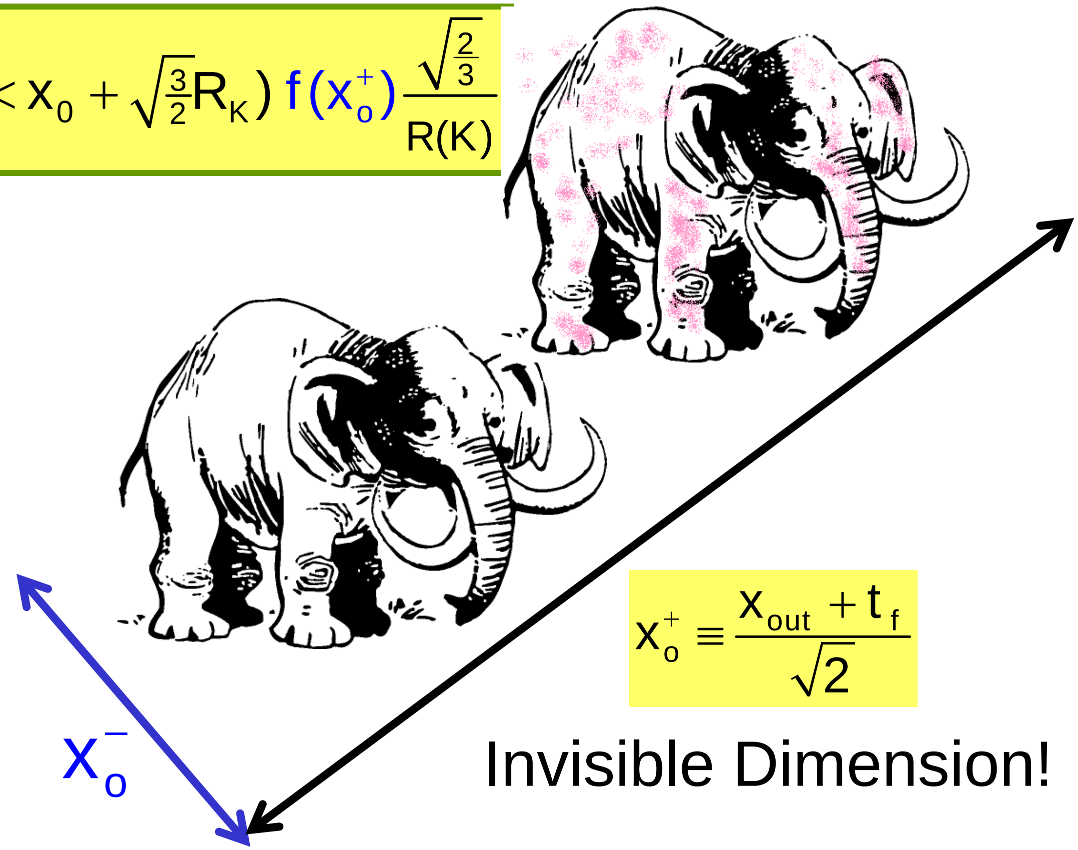
$$x_o^{\pm} \equiv \frac{x_{out} \pm t_f}{\sqrt{2}}$$

1) $\delta(t_f - \tau)\,\theta(x_0 < x_{out} < x_0 + \sqrt{12}\,R_K)\,\dfrac{1}{\sqrt{12R_K}}$

2) $\delta(x_{out} - x_0)\,\theta(\tau < t_f < \tau + \sqrt{12}R_K)\,\dfrac{1}{\sqrt{12R_K}}$

3) $\theta(x_0 < x_o^- < x_0 + \sqrt{\tfrac{3}{2}}R_K)\; f(x_o^+)\,\dfrac{\sqrt{\tfrac{2}{3}}}{R(K)}$





$$x_o^{+} \equiv \frac{x_{out} + t_f}{\sqrt{2}}$$

Invisible Dimension!

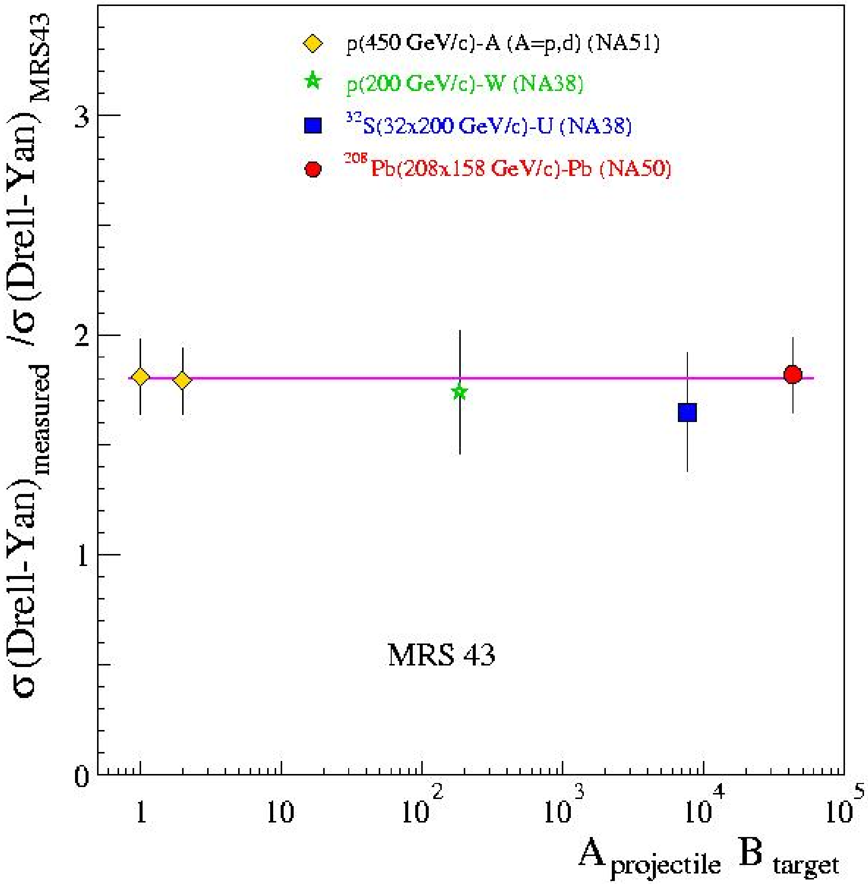
Drell-Yan and ✡ Production at CERN/SPS

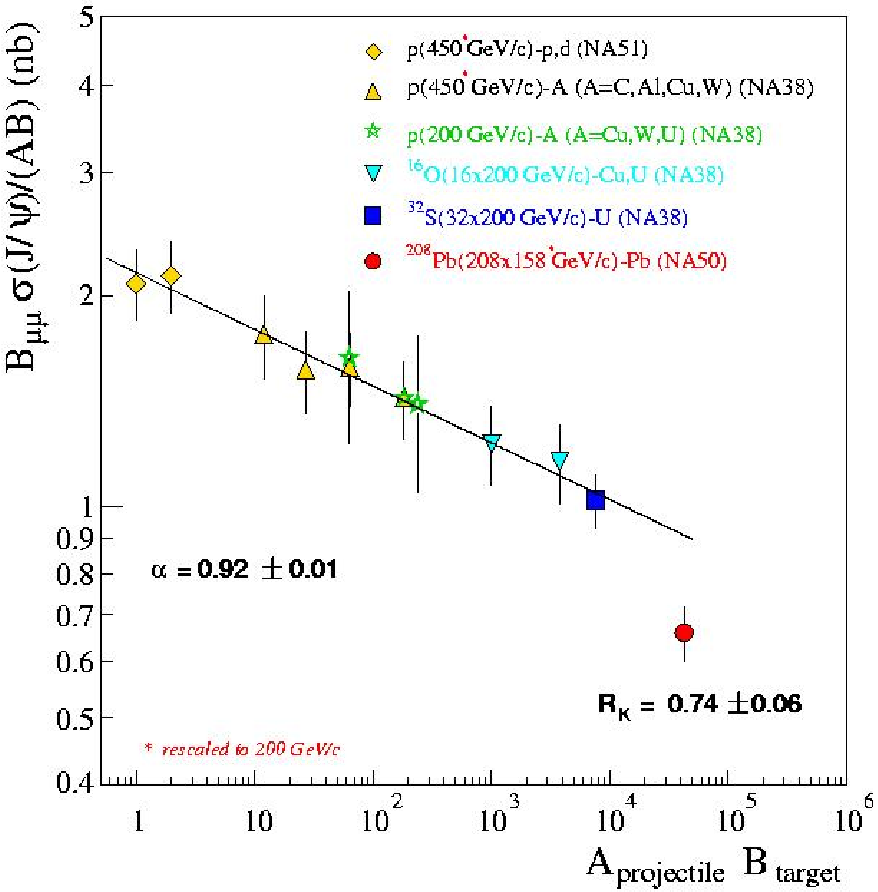
$$\sigma_{DY}(A+B \to q+\bar{q} \to \ell+\bar{\ell}) = AB\sigma_{DY}(pp)$$

$$\sigma_{\psi}(A+B \to c+\bar{c} \to \Psi) < AB\sigma(pp \to \Psi)!$$

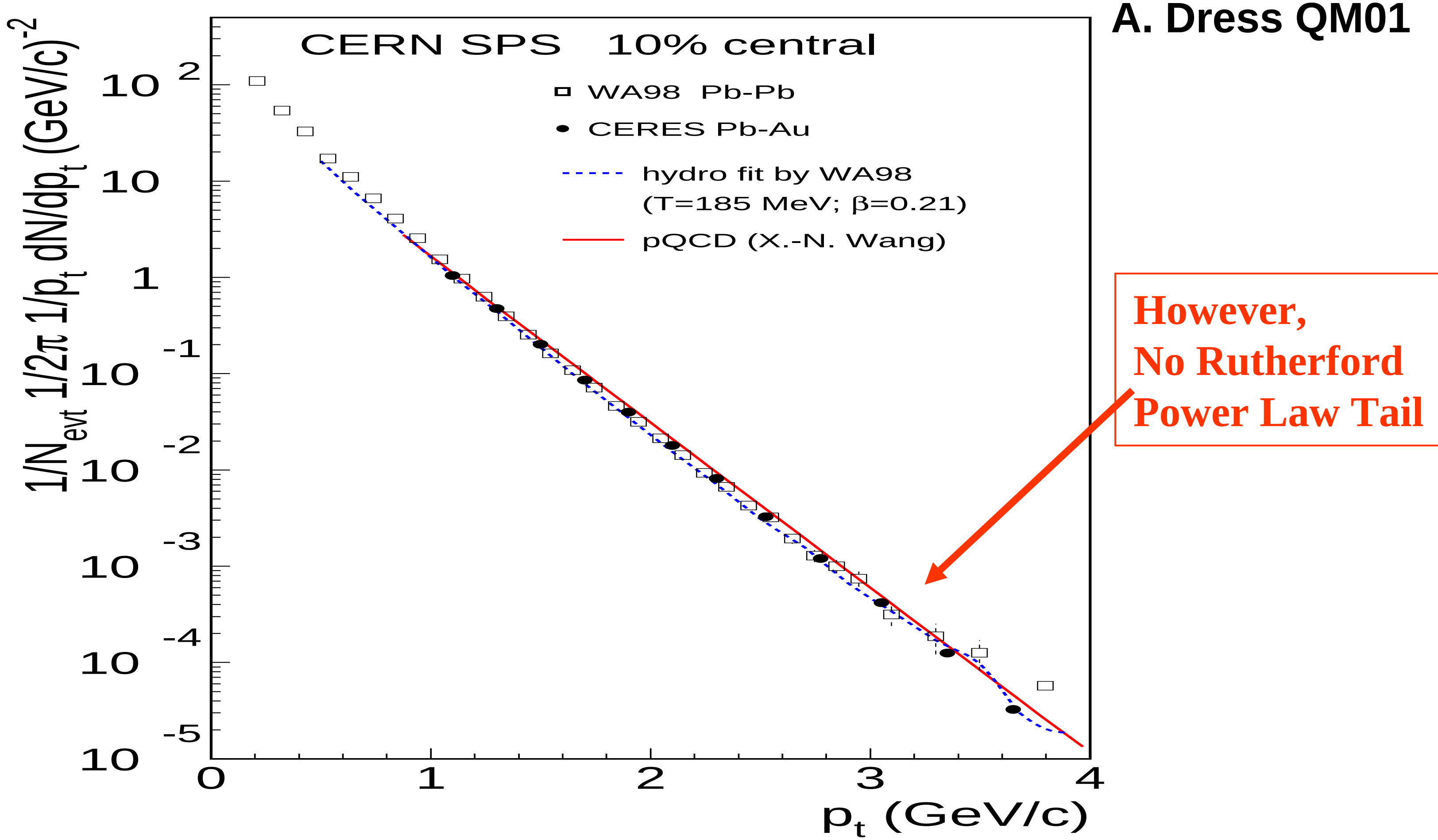
C. Lourenco NA50 QM01

Suppressed even in p+A !!



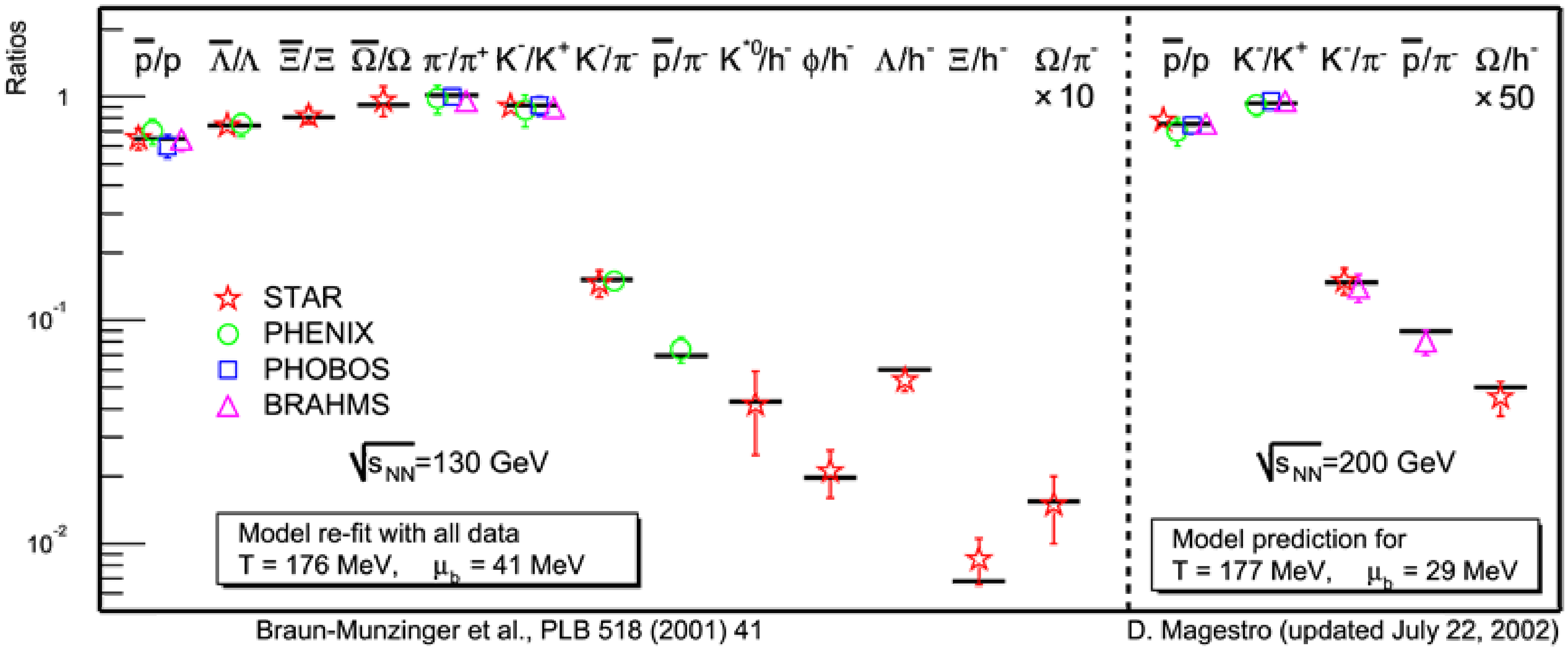


Results from the SPS



- data well described by pQCD + (intrinsic + initial) k_T (A,Q) broadenning
- data equally well described by hydrodynamic fit

Statistical Models Work Well at SPS *and* RHIC



Statistical Thermal Models

F. Becattini; P. Braun-Munzinger, J. Stachel, D. Magestro, J.Rafelski, J.Sollfrank et al. ***K.Redlich***

*** Works great, but there is not word of QCD in such analysis. Done entirely in color neutral Hadronic basis!**

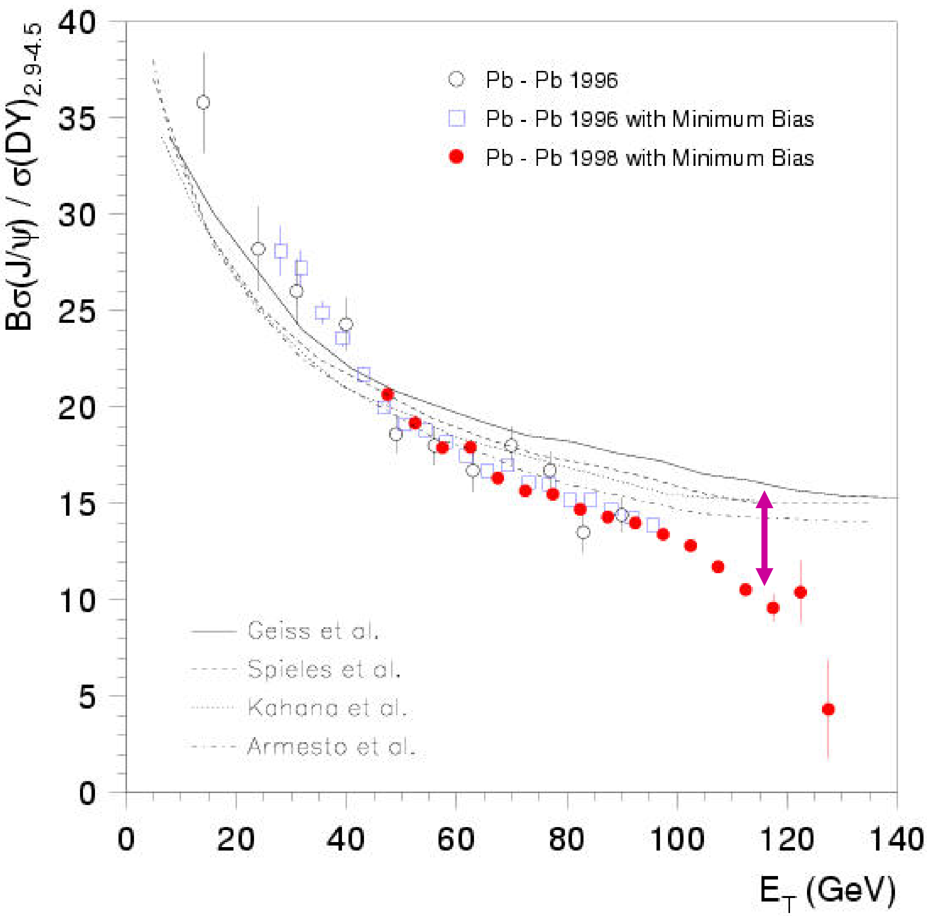
An equilibrated (Hagadorn) resonance gas was made

But shows no sign of a QGP !!

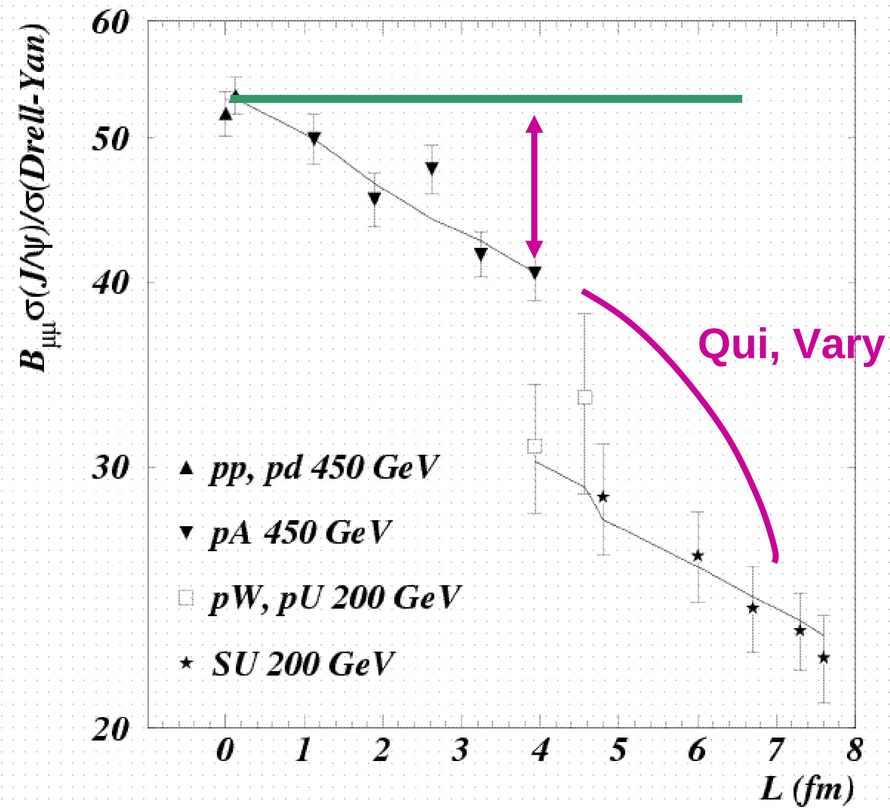
Partonic Diagnostics $\dfrac{c\bar{c} \rightarrow \psi}{q\bar{q} \rightarrow \ell\bar{\ell}}$

Effect does not turn off When medium is absent!

NA50 PbPb->J/Psi Suppression



P+A Control Experiment



Predicted Non-linear *Initial State* radiative energy loss in Cold A must be still tested via *Central* pA at both SPS and RHIC

A Low pT<0.5 *Triangle* boundary controls forward rapidity

R_{dA}" ■$_D$/■$_{Au}$