



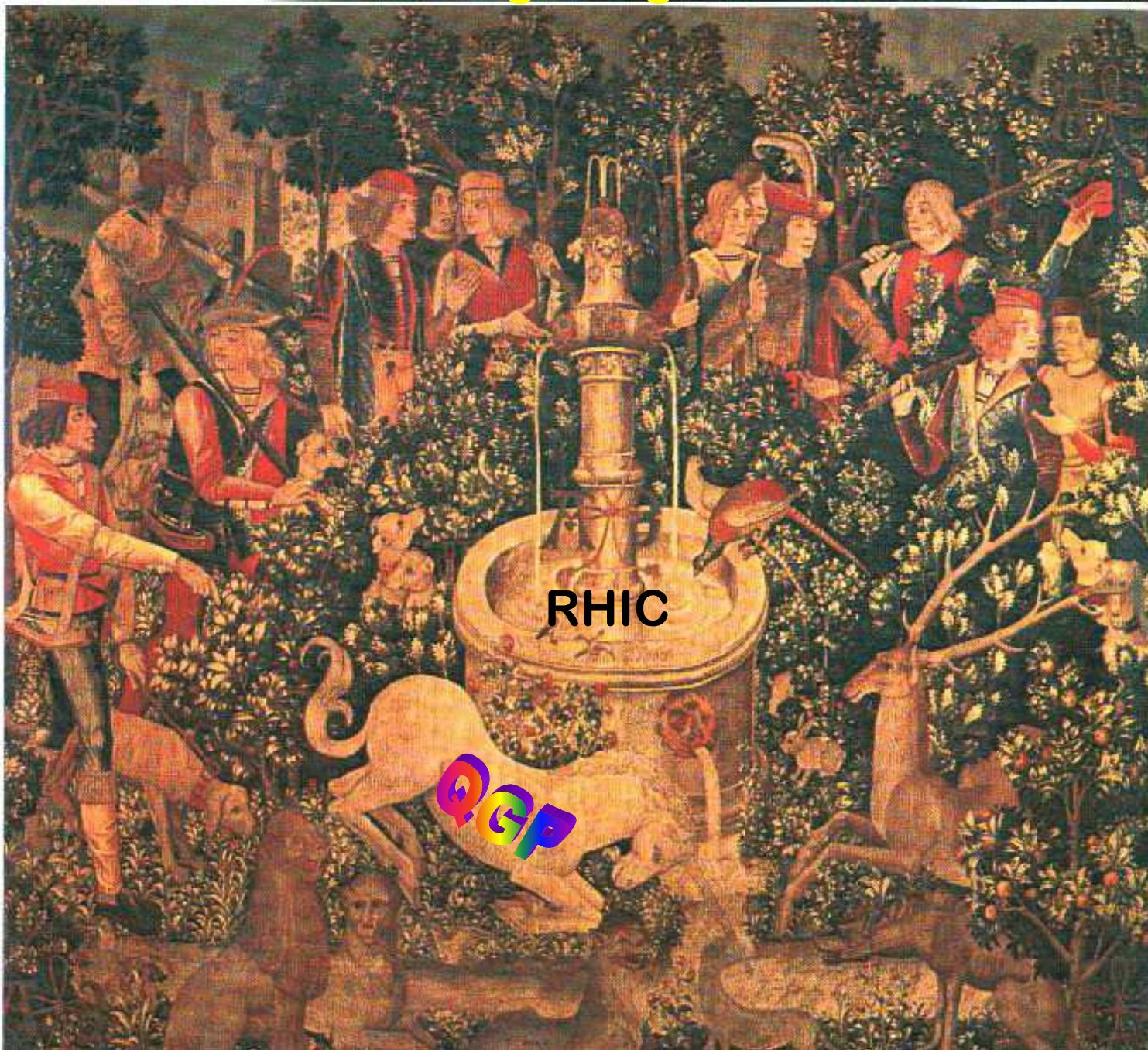

What Have We Learned So Far?

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.”



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

“The QM04 conference left me with contradictory impressions:

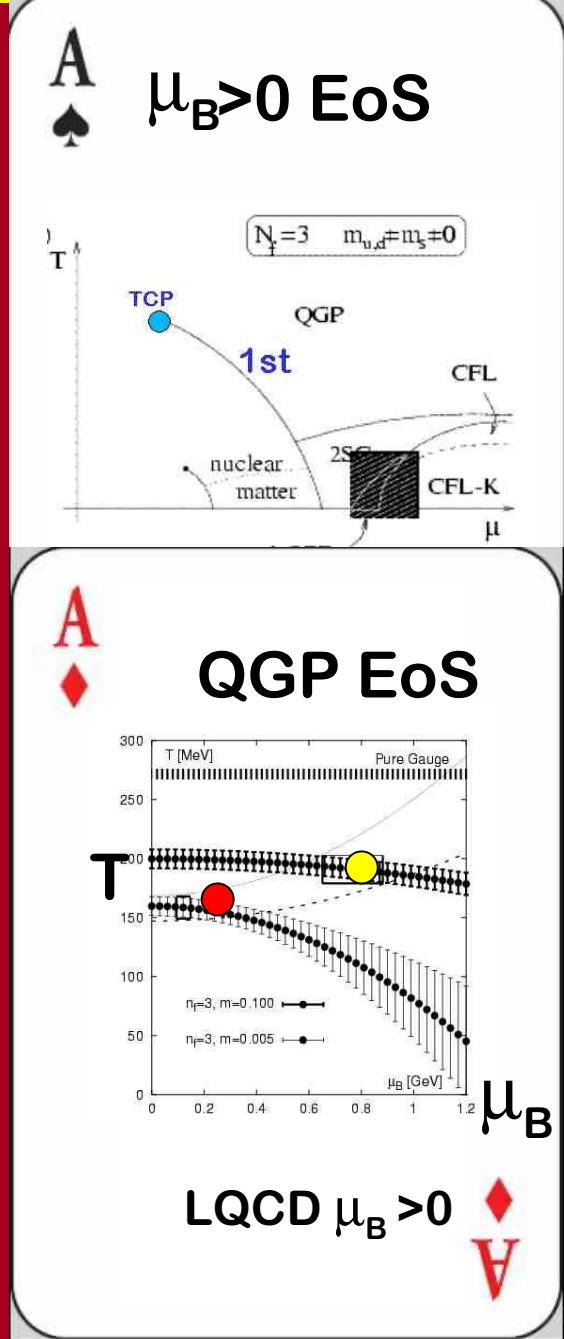
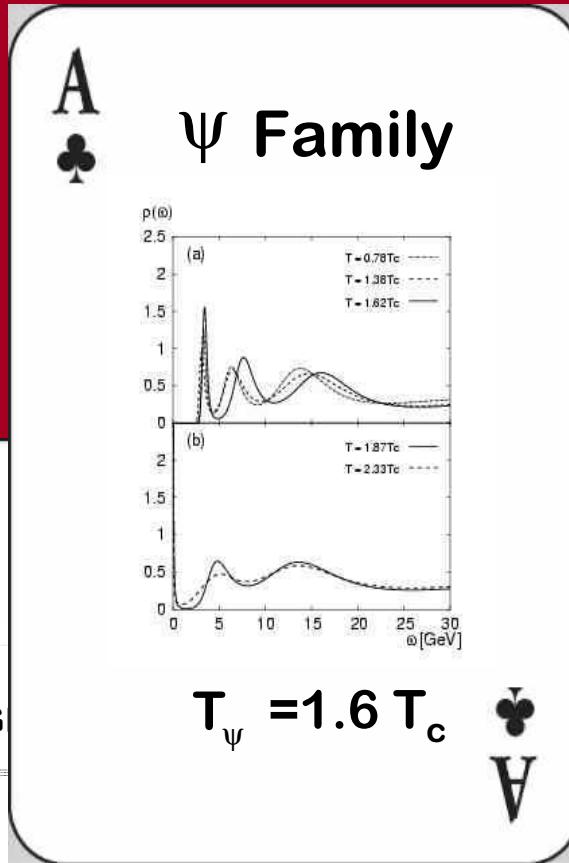
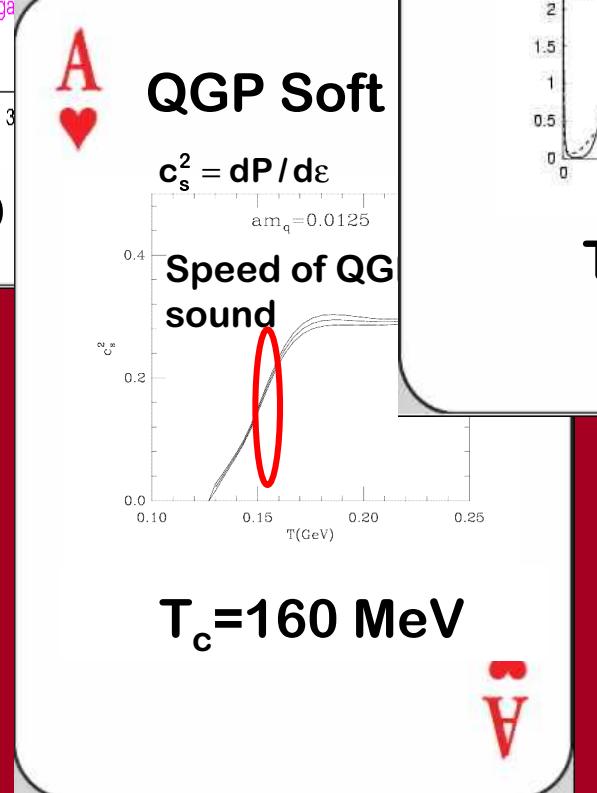
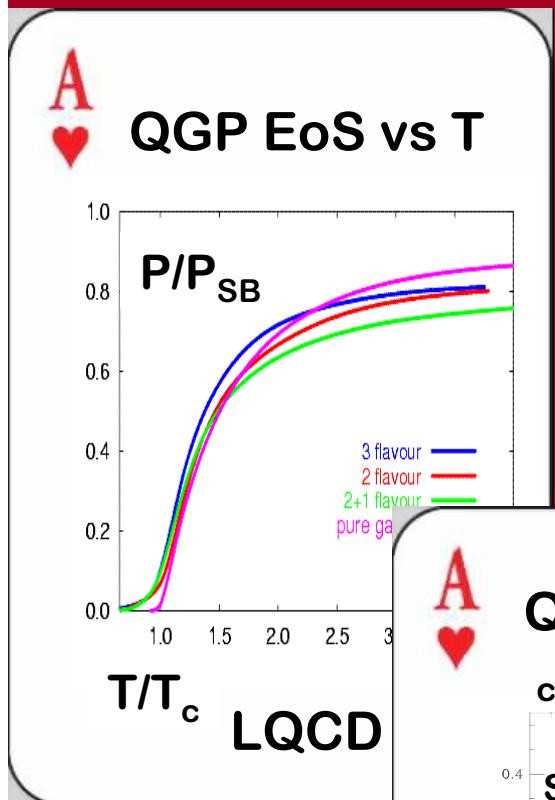
On the one hand, most scientists seem to think that we’re getting closer to identifying a quark-gluon plasma.

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

Outline of My Talk:

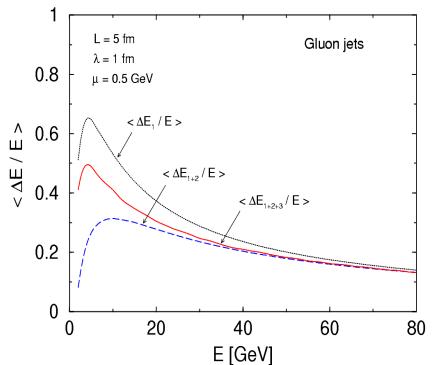
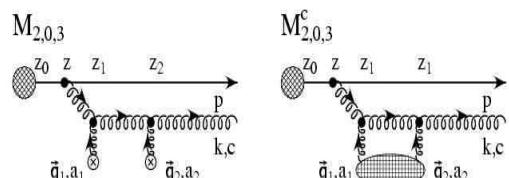
- 1) QCD Theory definition of QGP**
- 2) Operational definition of QGP**
- 3) Evidence for QGP as of QM04**
- 4) First hints of CGC**

P_{QCD} theory definition of a QGP

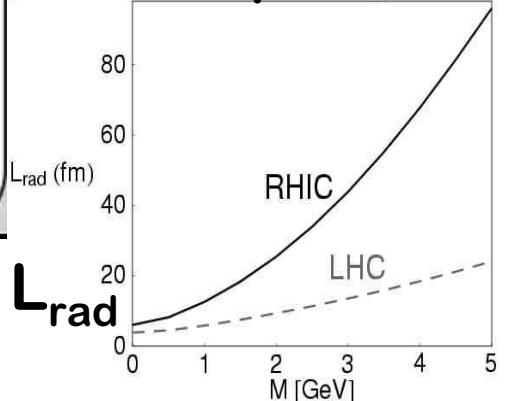


pQCD theory definition of a QGP

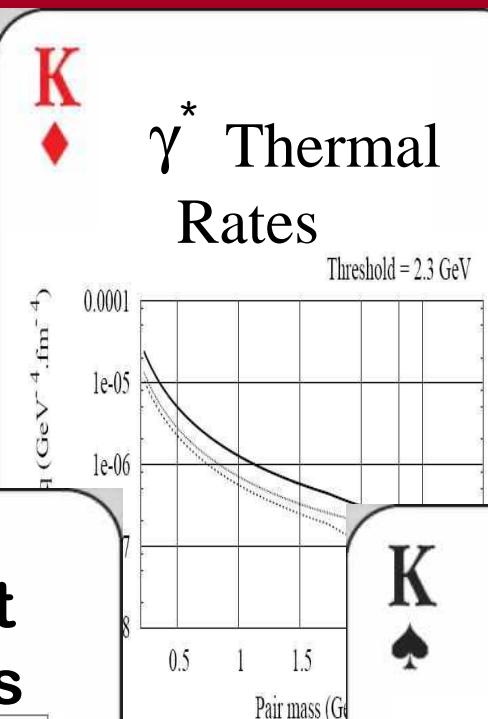
K Energy Loss
♣ $\Delta E(p_T, M, \rho, L)$



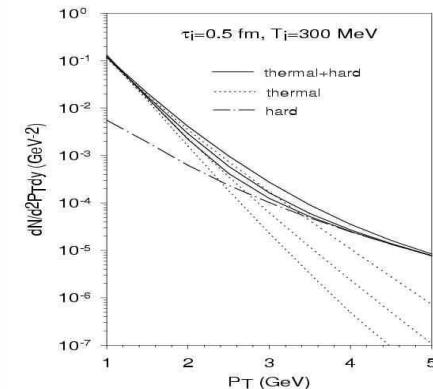
K
Transport Properties



K
 γ^* Thermal Rates

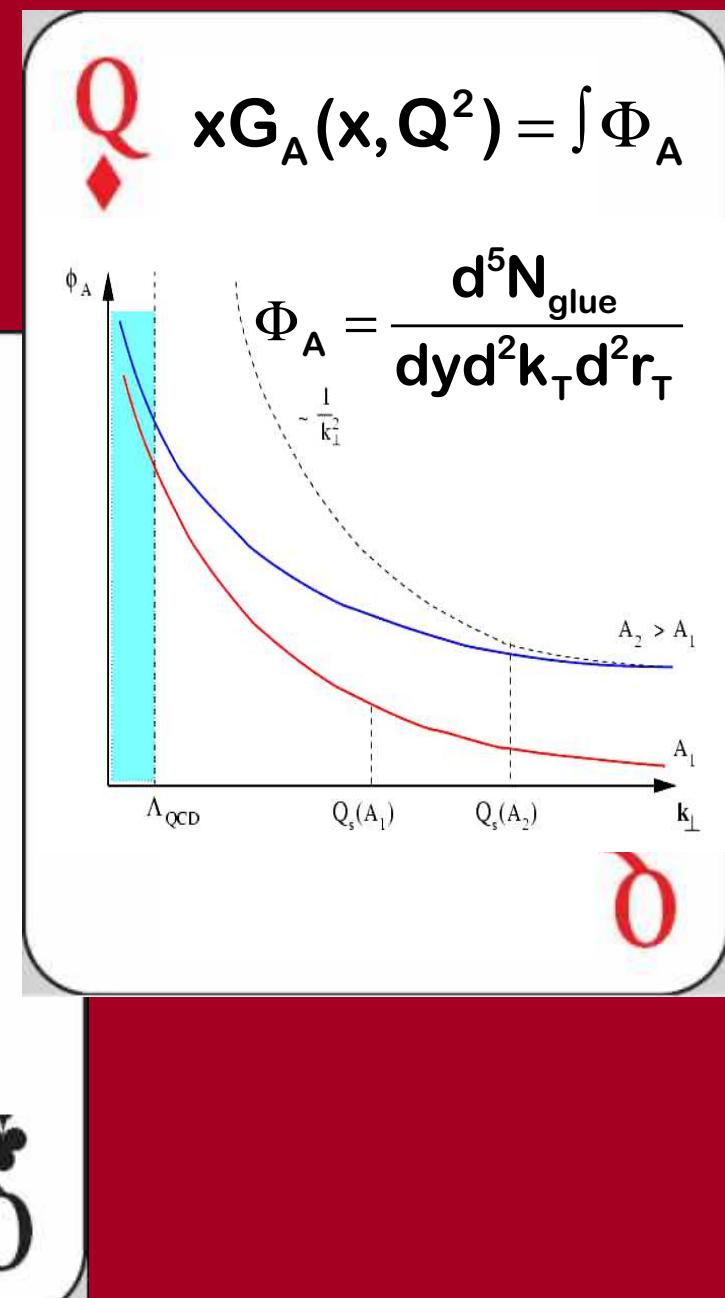
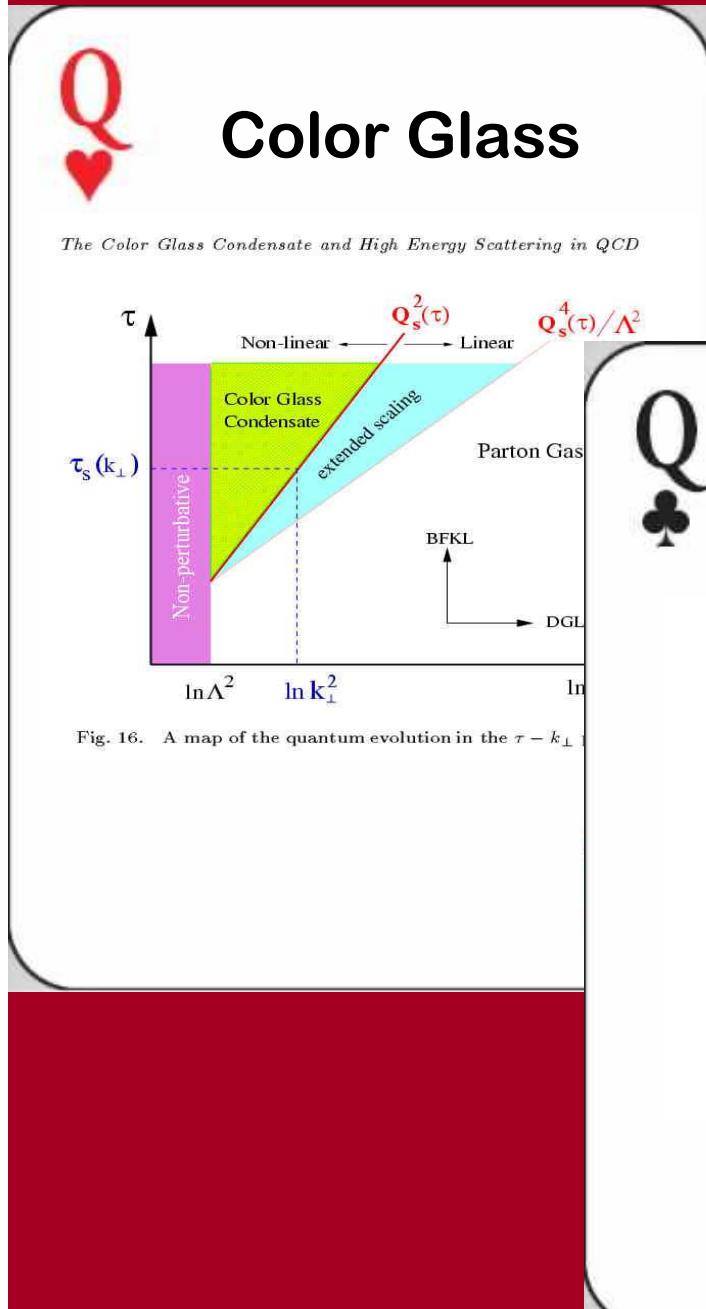


K
Thermal γ



p_T

Weak coupling QCD theory of CGC seed of QGP



My Operational definition of QGP

$$\begin{aligned} \text{QGP} &= \text{Bulk Collective} + \text{Parton Dynamic} + \text{Discriminator} \\ &= P_{\text{QCD}} + p\text{QCD} + dA \\ &= v_n(p_T, m) + (R+I)_{AA} + (R+I)_{DA} \end{aligned}$$

1 2 3

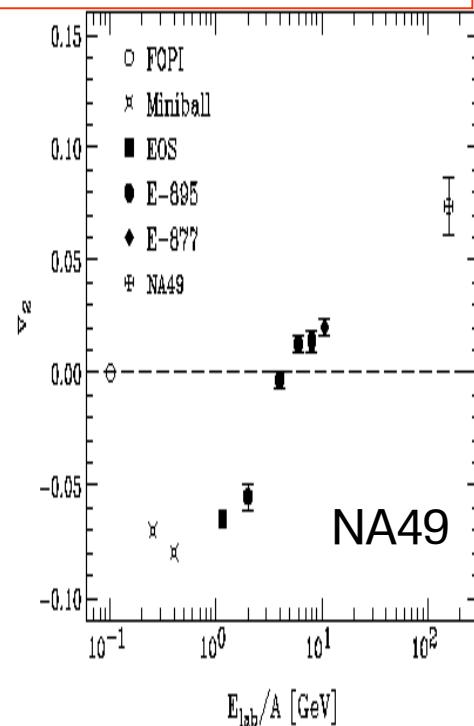
- 1) Evidence for P_{QCD} via v_n bulk collective flow of $10^4 \pi, p, K, \Lambda, \Xi, \Omega$
- 2) Evidence for pQCD jet quenching in Au+Au at RHIC
- 3) Evidence jet *un*-quenching in D+Au = Null Control

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

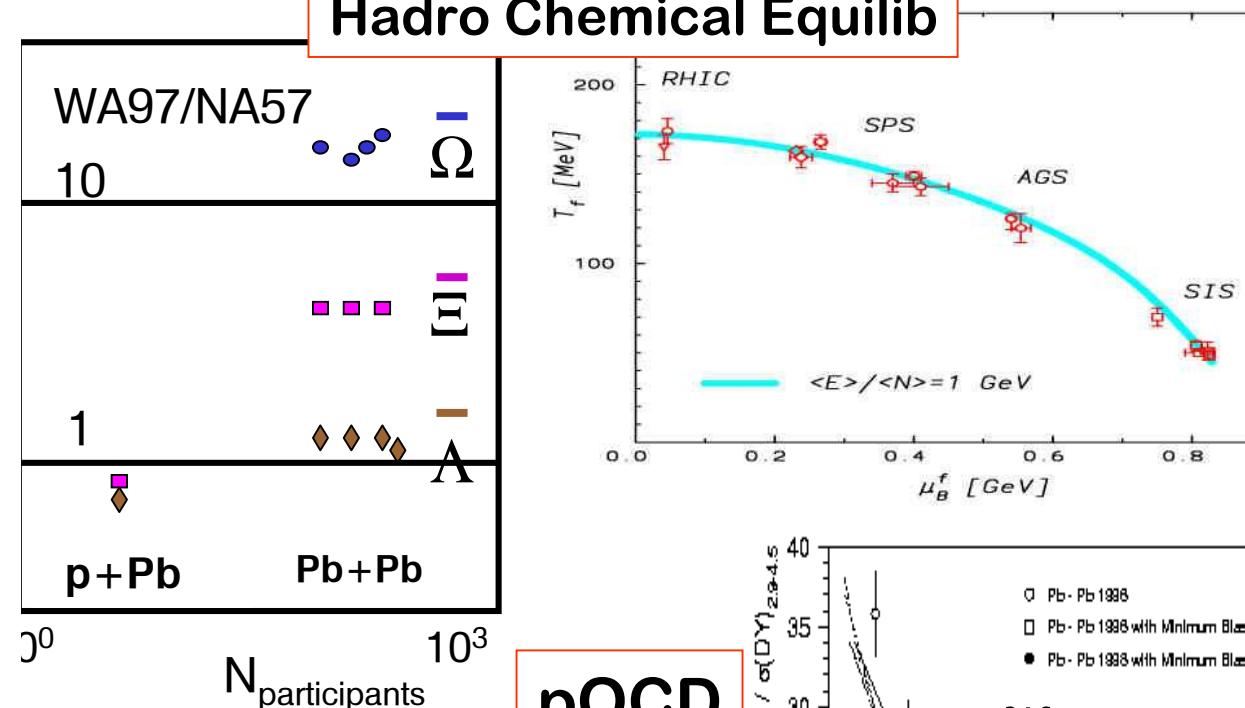
**My conclusion: “overwhelming evidence” at QM04
that QGP Bulk Matter is made in AuAu at 200 AGeV**

Necessary QGP *Precursors* at SPS 2000

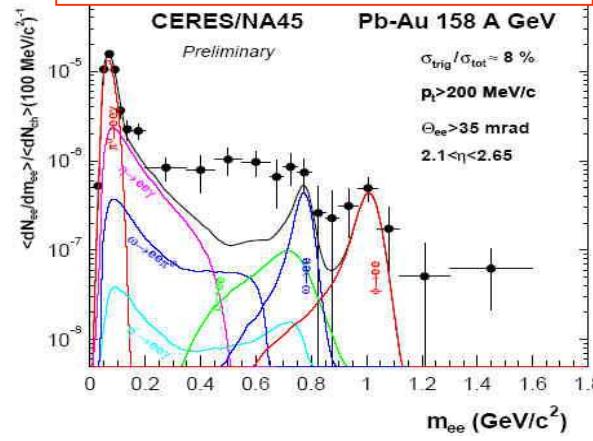
Collective Flow



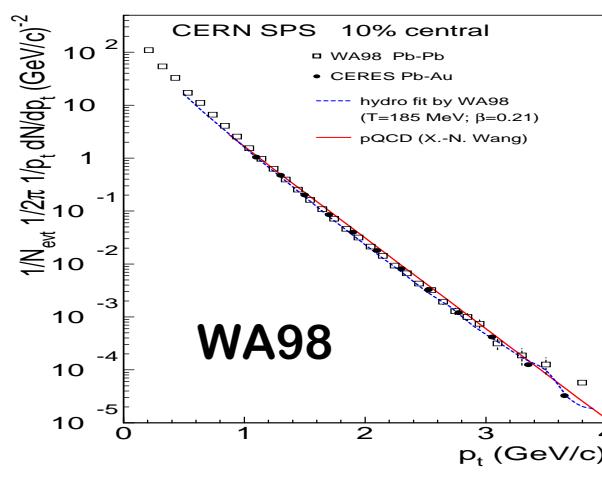
Hadro Chemical Equilib



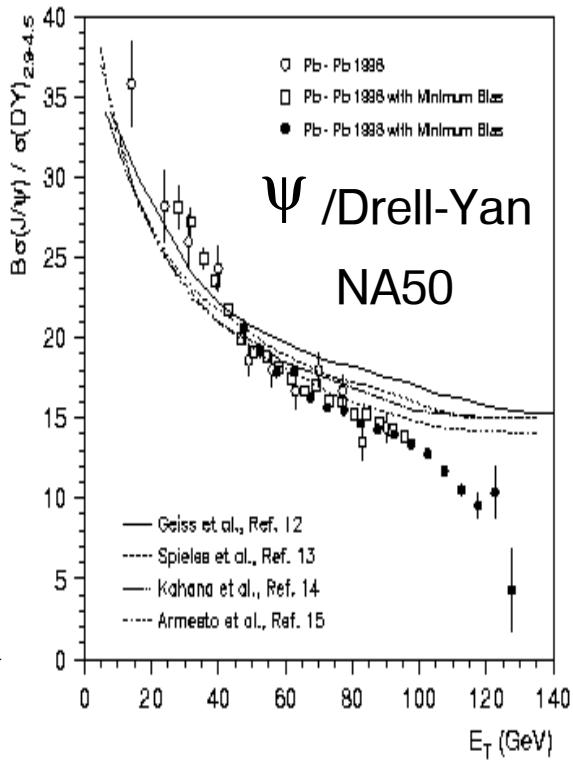
Medium Dispersion



pQCD

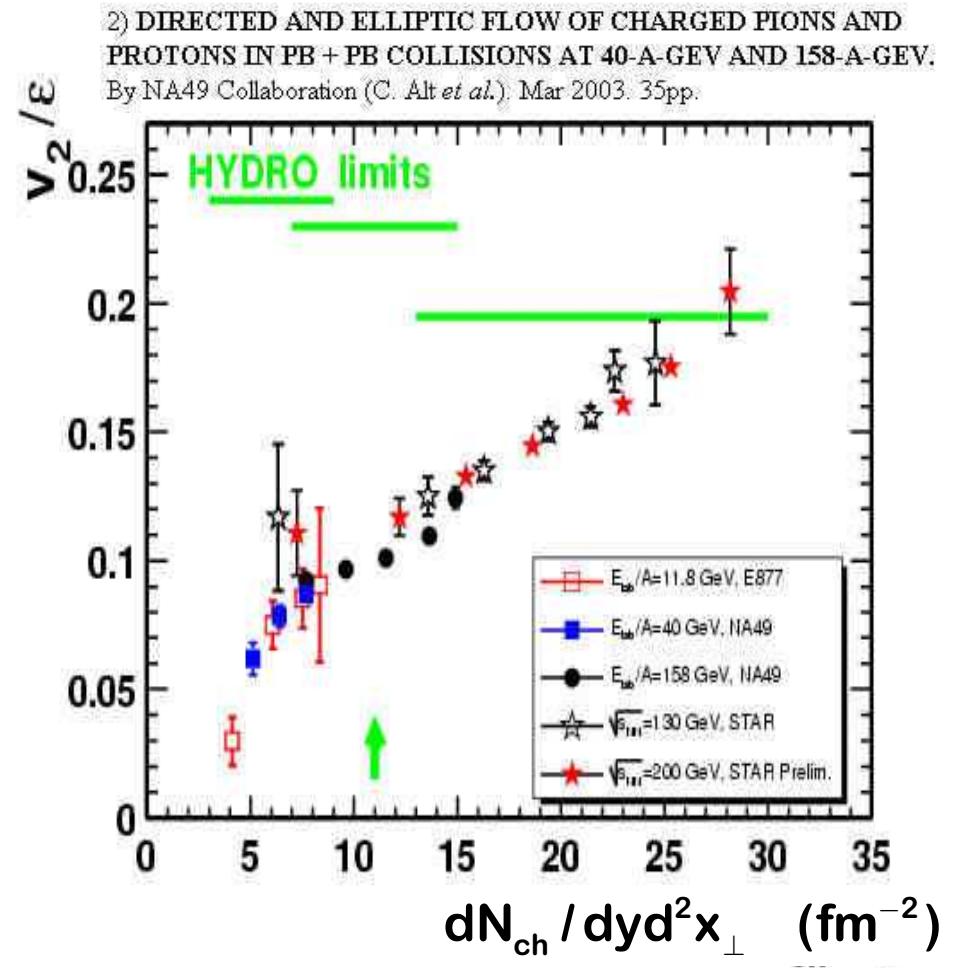
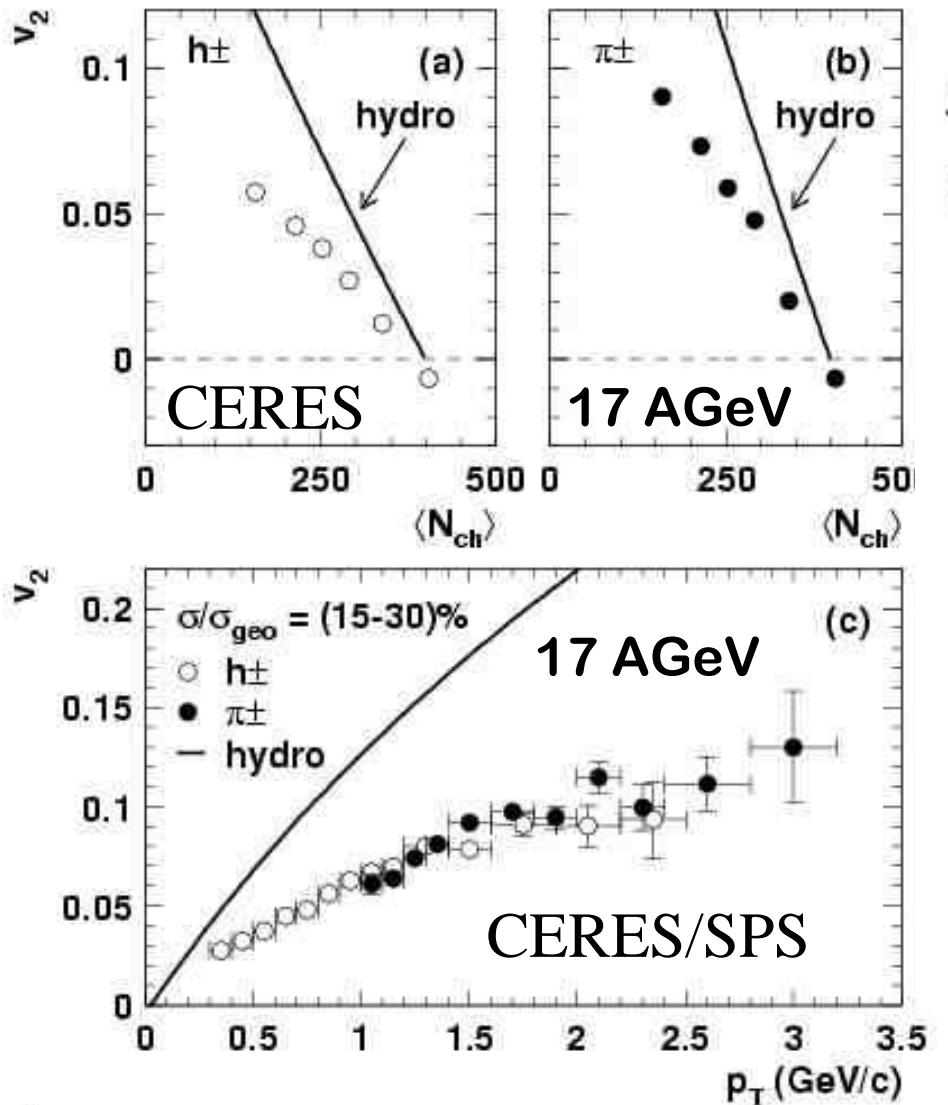


Ψ /Drell-Yan

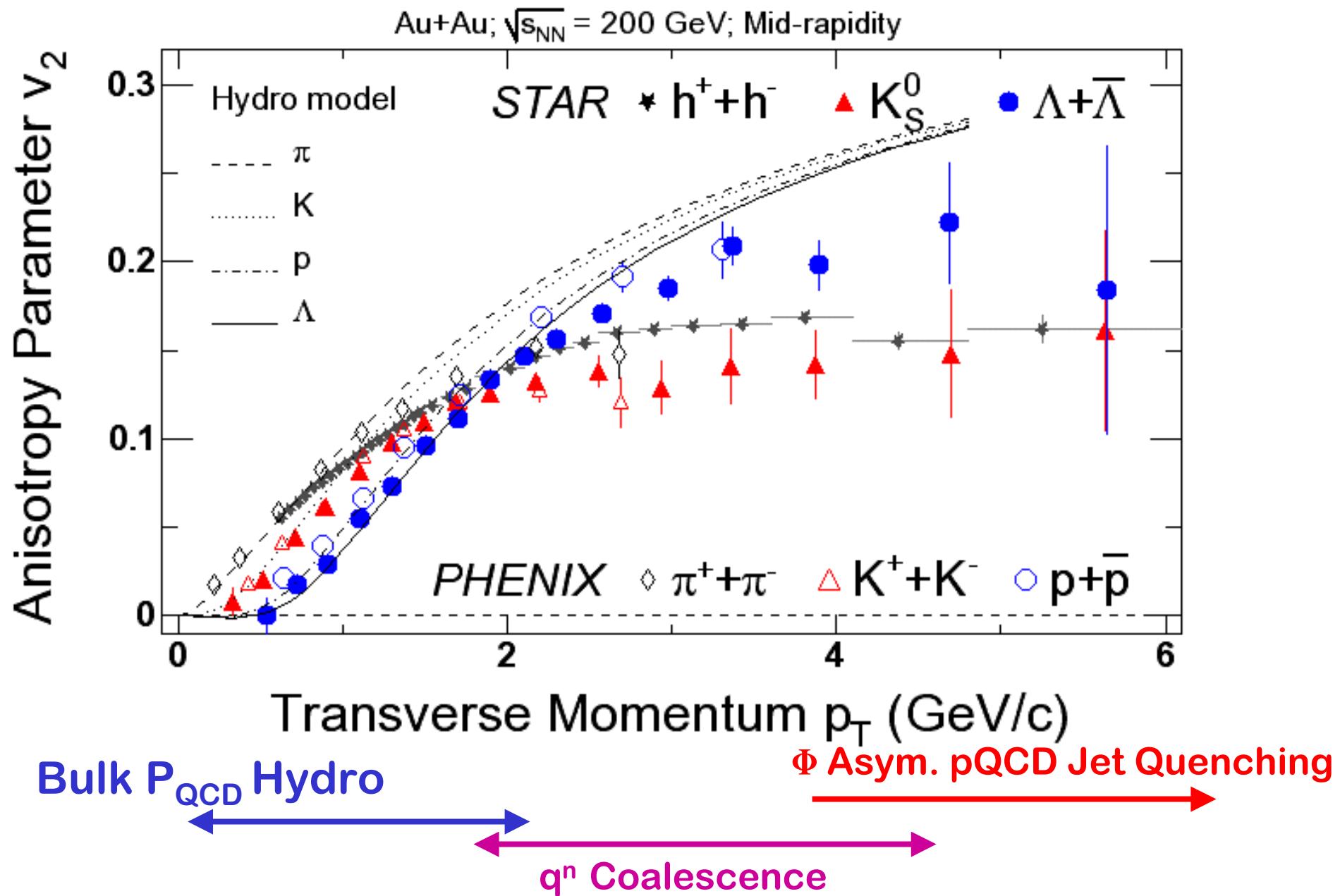


But Critical Missing Signature of the QGP at SPS

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



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



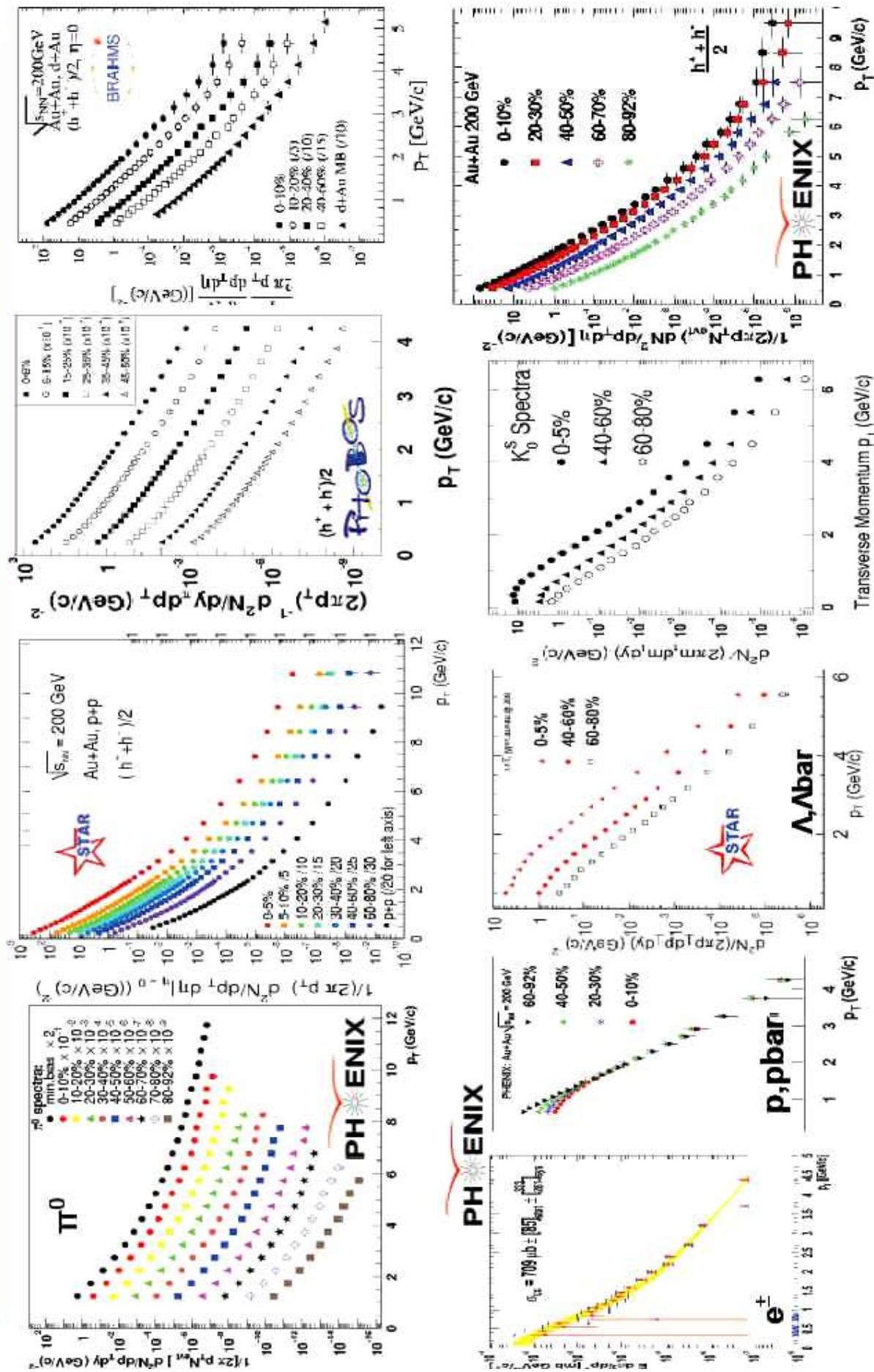
2nd and 3rd Lines of Evidence for QGP

Jet Quenching

pQCD Parton Dynamics

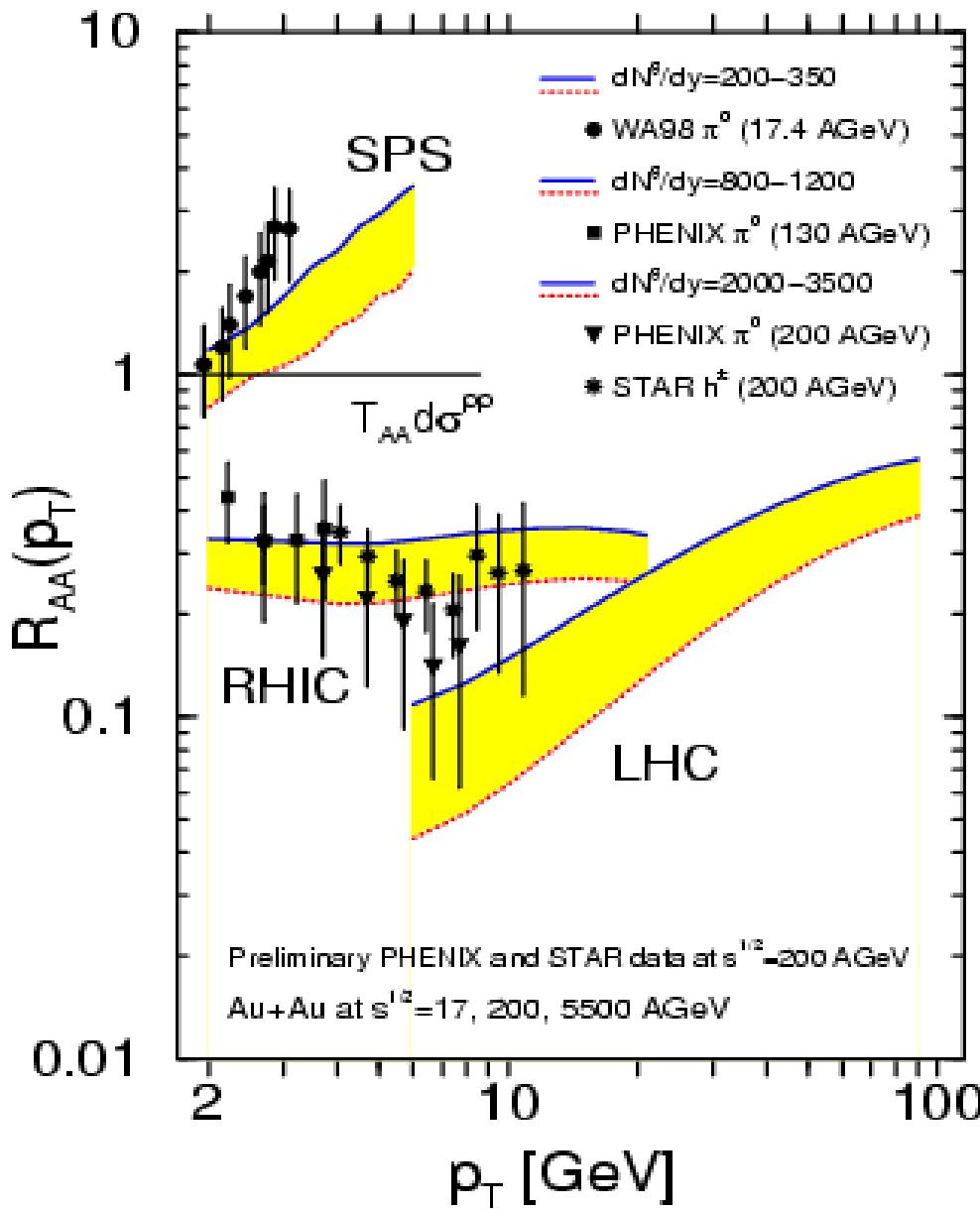
Jet Tomography

High p_T spectra in Au+Au @ 200 GeV



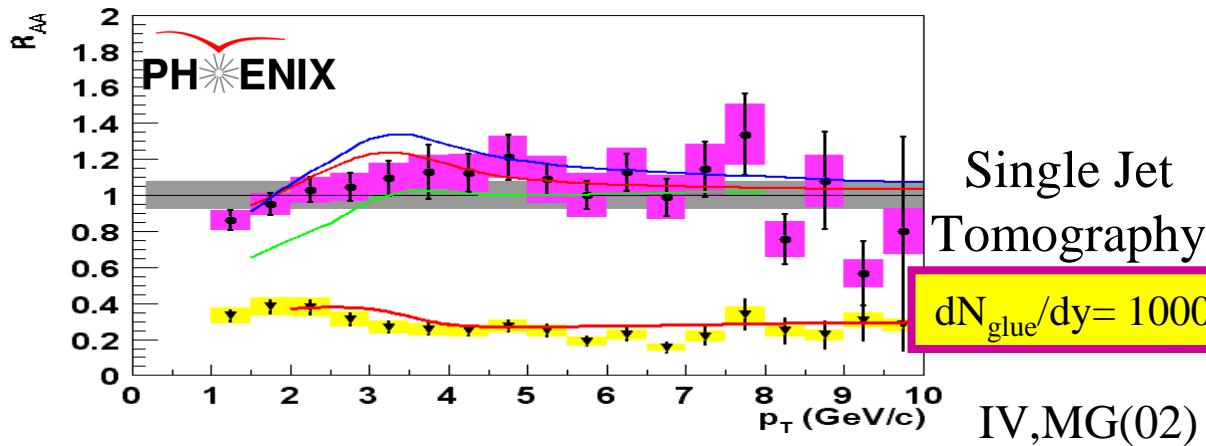
Single Hadron Tomography from SPS, RHIC, LHC

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 $R_{LHC}(40) \sim R_{RHIC}(40)$

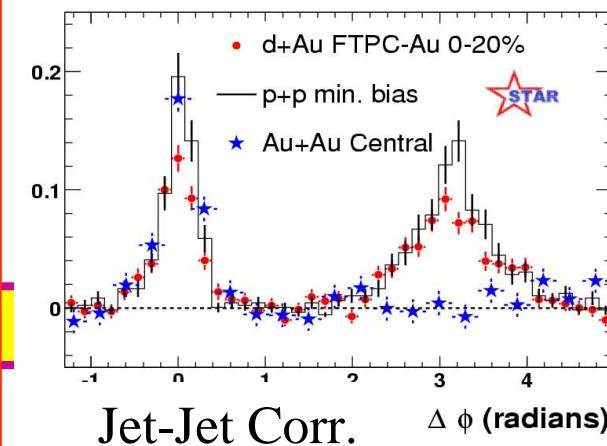
D+Au vs Au+Au @ 200 GeV:



Single Jet
Tomography

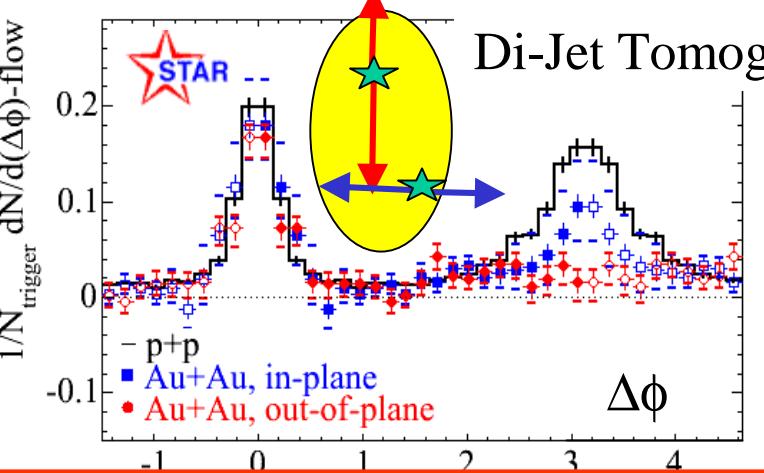
$dN_{glue}/dy = 1000$

IV, MG(02)

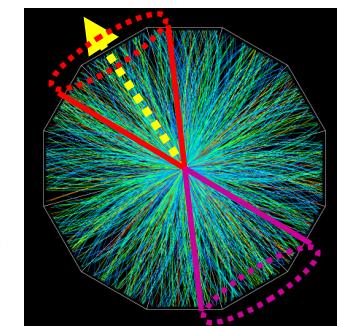
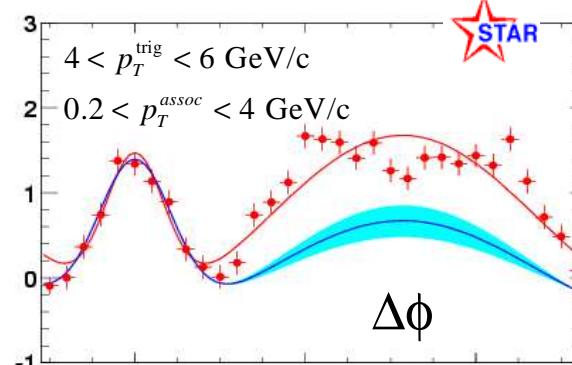


Jet-Jet Corr.

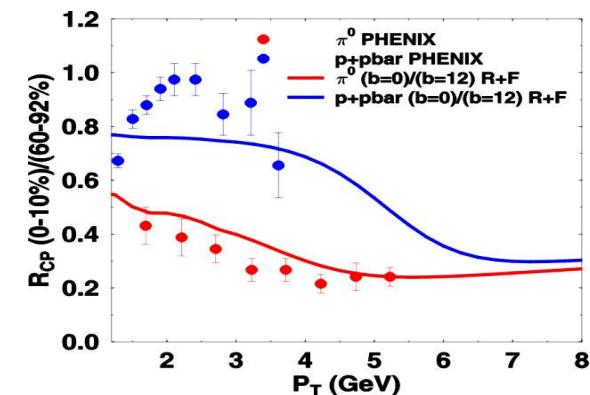
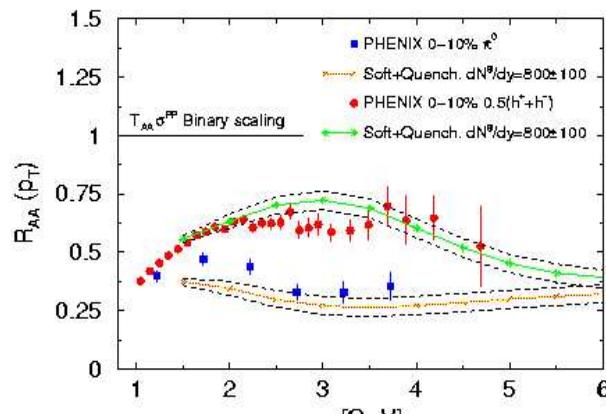
Di-Jet Tomography



Soft-Jet Correlations



RHIC Baryon
Anomaly



Four independent calibrations of Initial QGP density

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

1. Bjorken Backward extrapolation

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

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

$$\varepsilon_{\text{Hydro}} > 2 \varepsilon_{Bj} = 500 \text{ GeV}/30 \text{ fm}^3 = 100 \varepsilon_0$$

KHH
TS
HN

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

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

GLV
WW
SW

4. Gluon saturation $p_T < Q_s$ predicted $dN_g/dy = 1000$ at $Q_{\text{sat}} = 1 \text{ GeV}$ at $y=0$

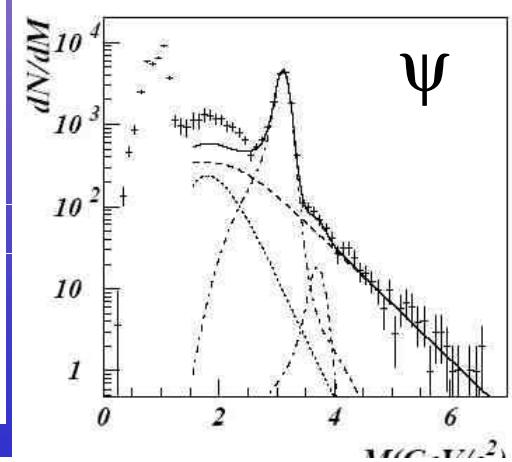
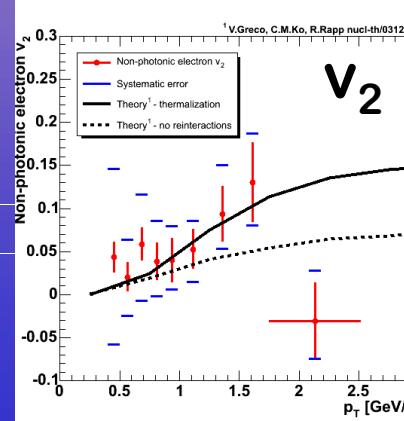
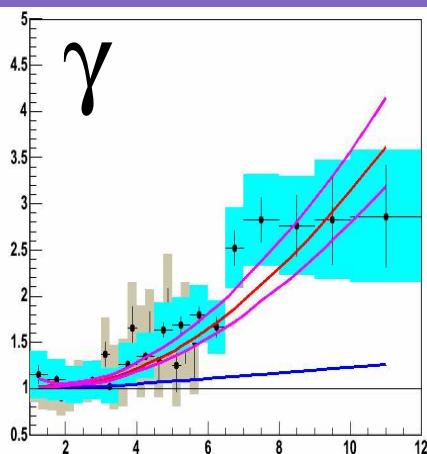
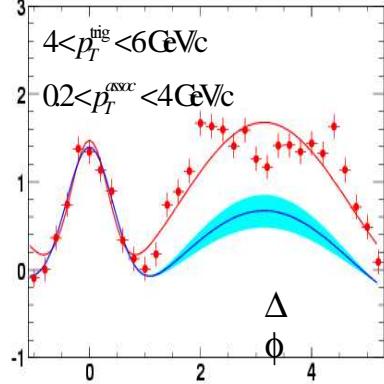
BM
McV
EKRT

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

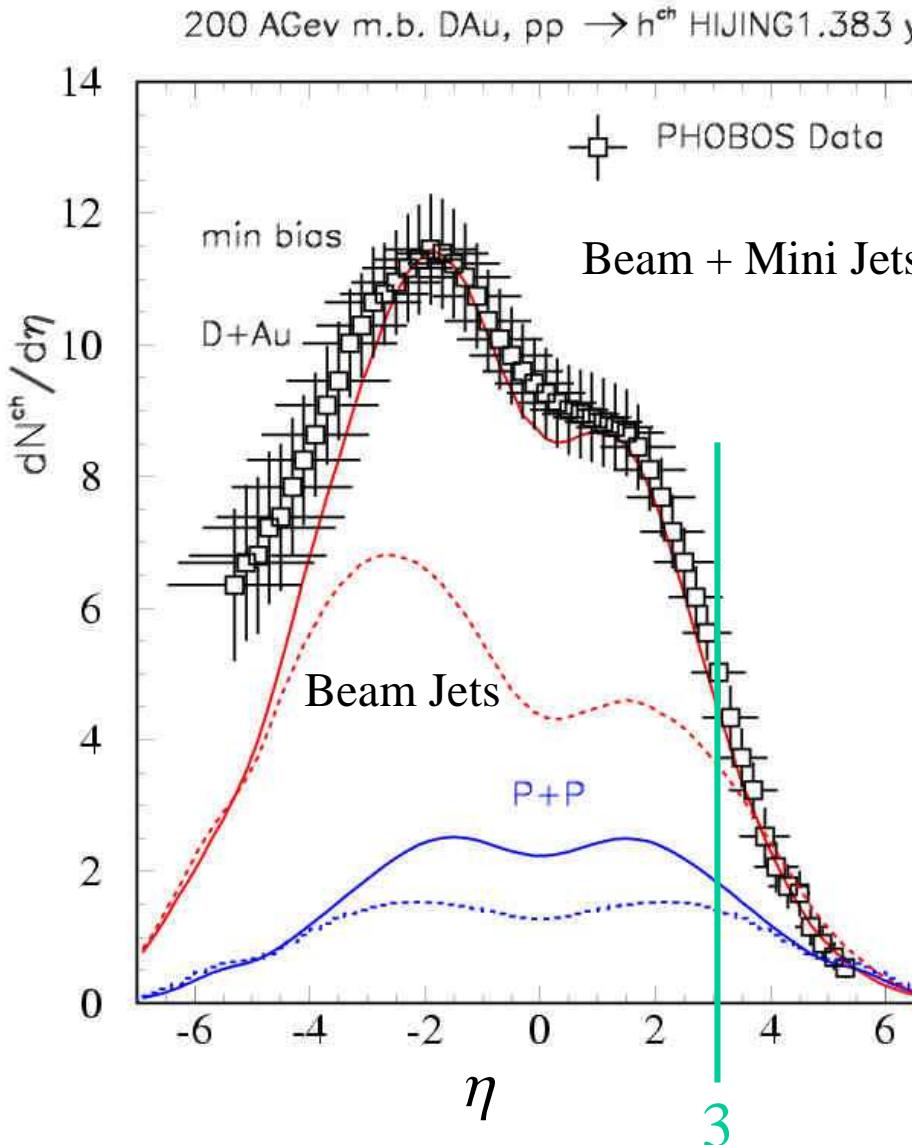
C_2



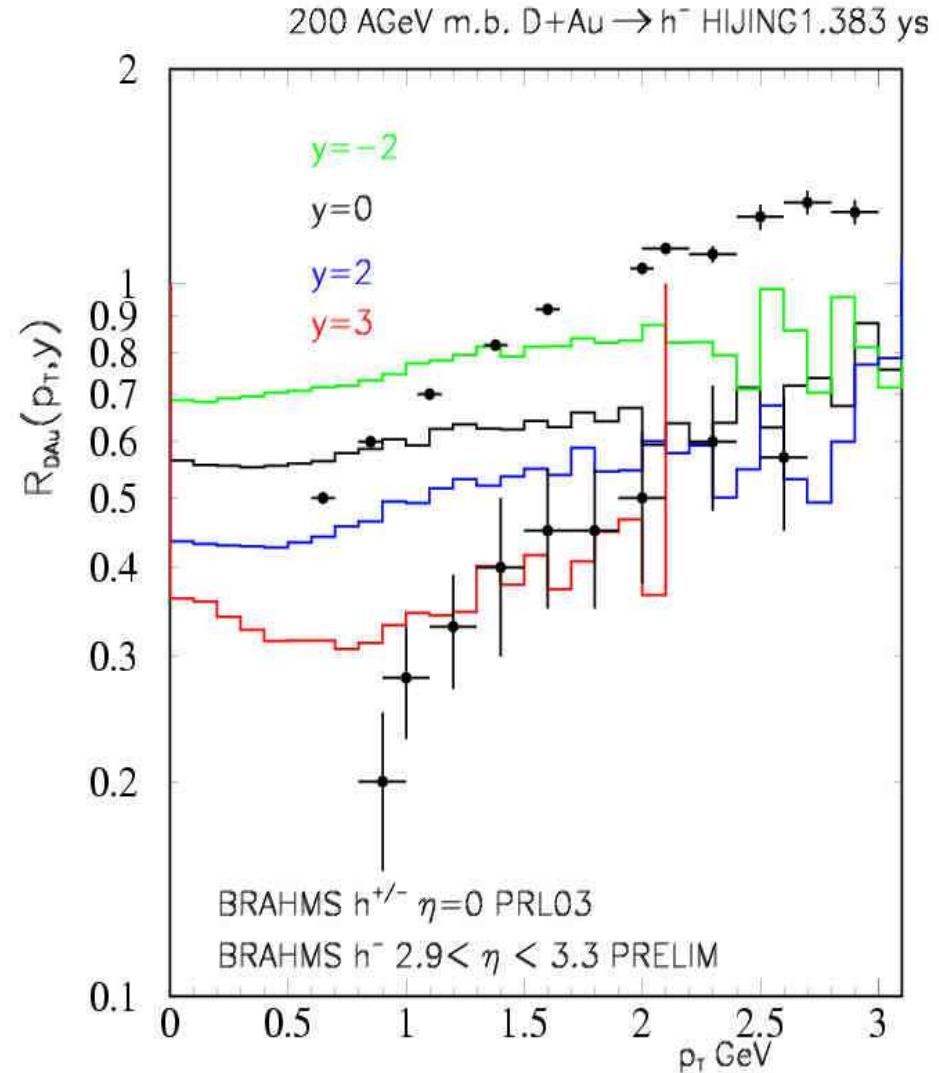
Has the CGC been seen at RHIC also?

- 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

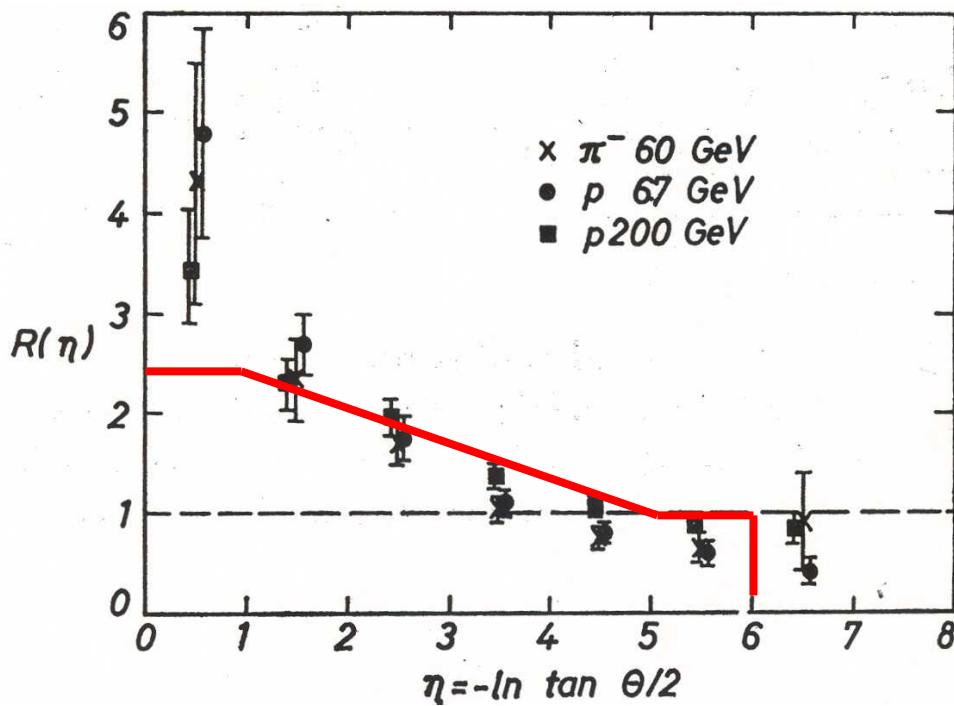


D+Au HIJING



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

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

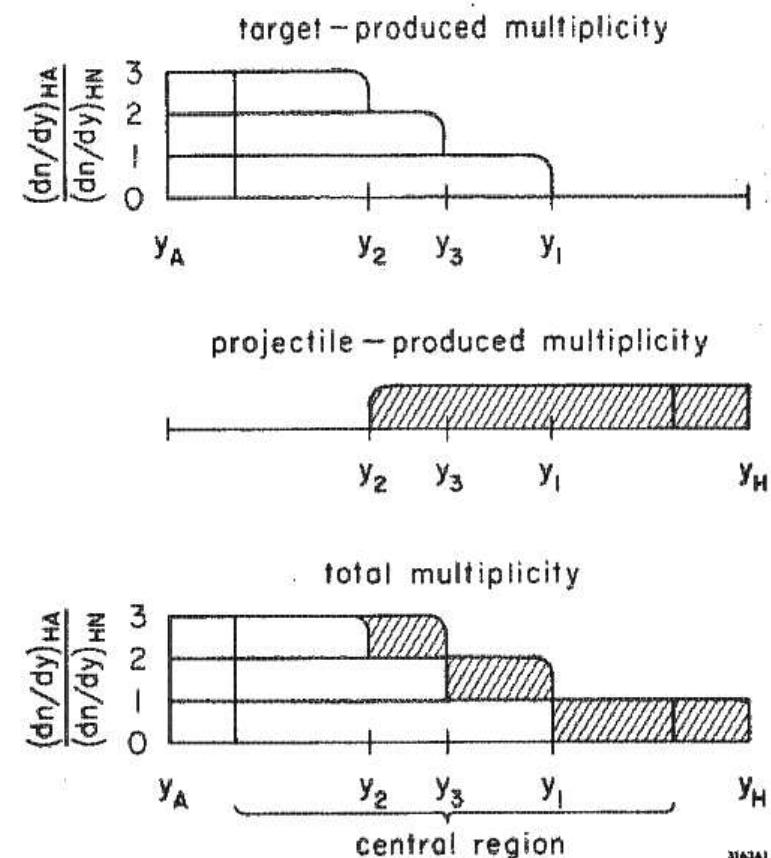


The low p_T *Triangle*
Boundary Condition
Condition on $R_{pA}(y, p_T < 1)$

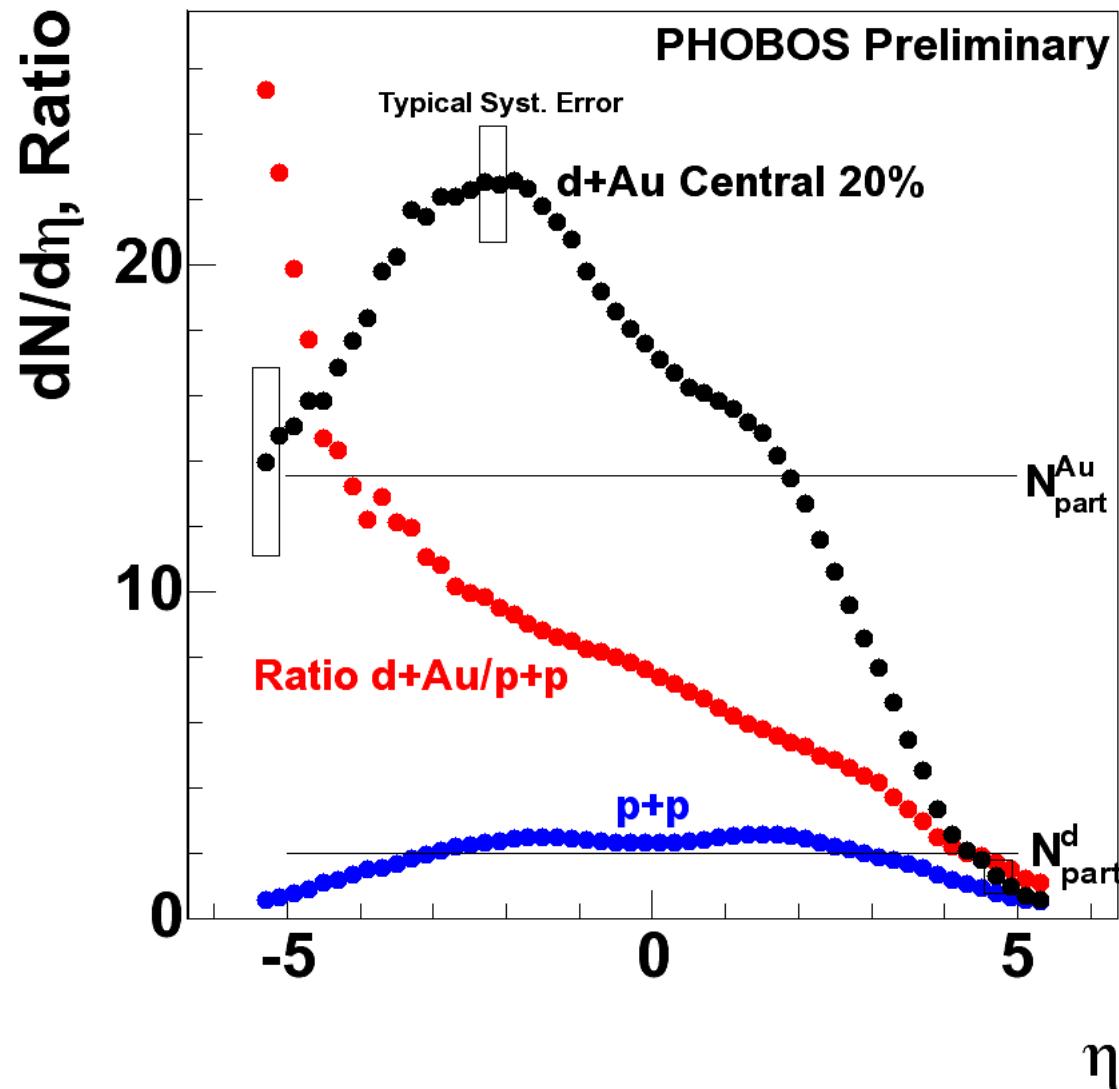
Brodsky, Gunion, Kuhn

PRL39(77)1120

Color Neutralization Model
Feynman gas $dy = dx/x = dM/M$

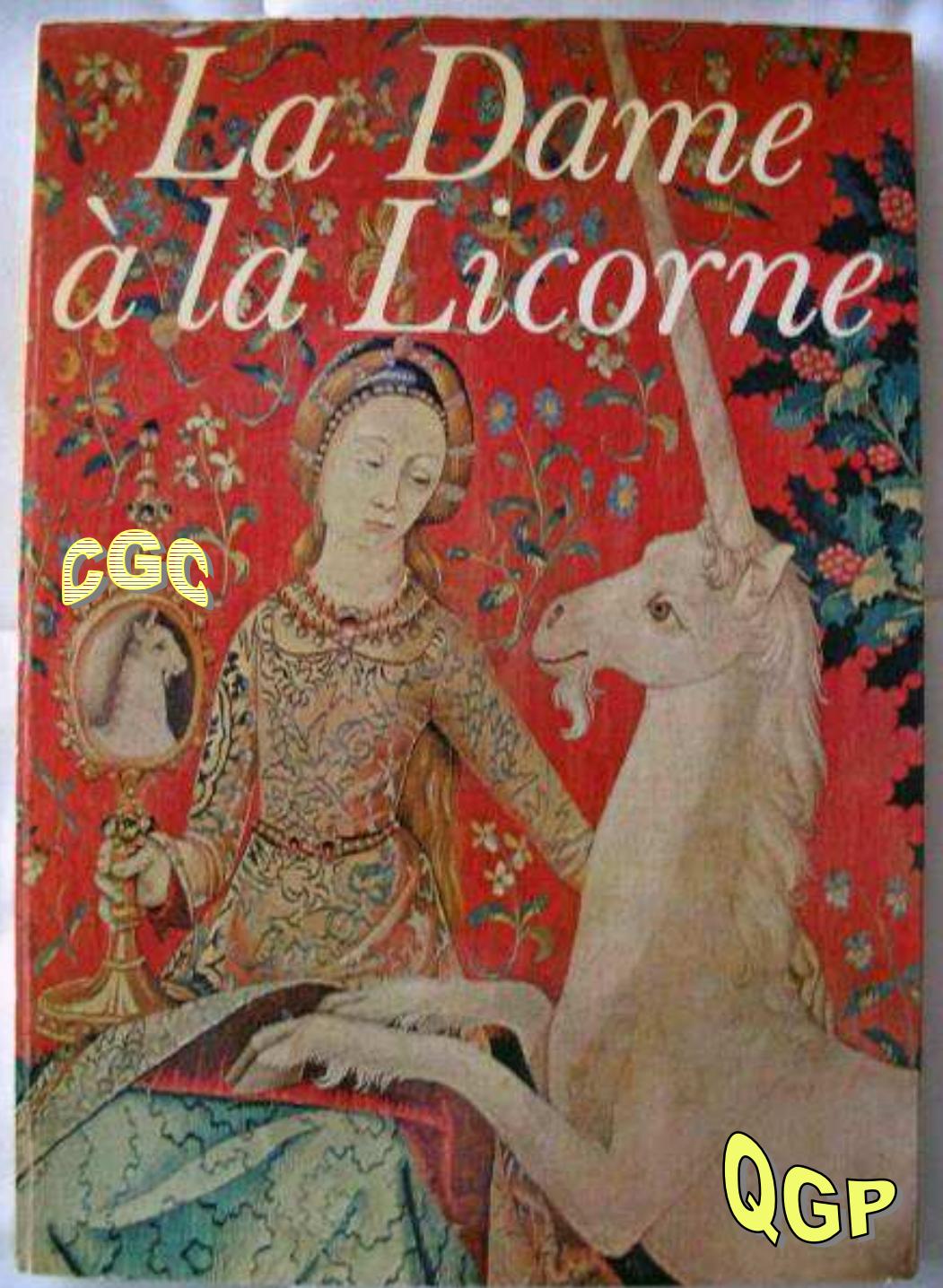


Preliminary: *Hot*-off-the-QM04-coffee-table



Addendum to Di Nezza, Steinberg talks

While
QGP
reflects
on
CGC



The
QGP
is
tamed