

From SPS to RHIC:

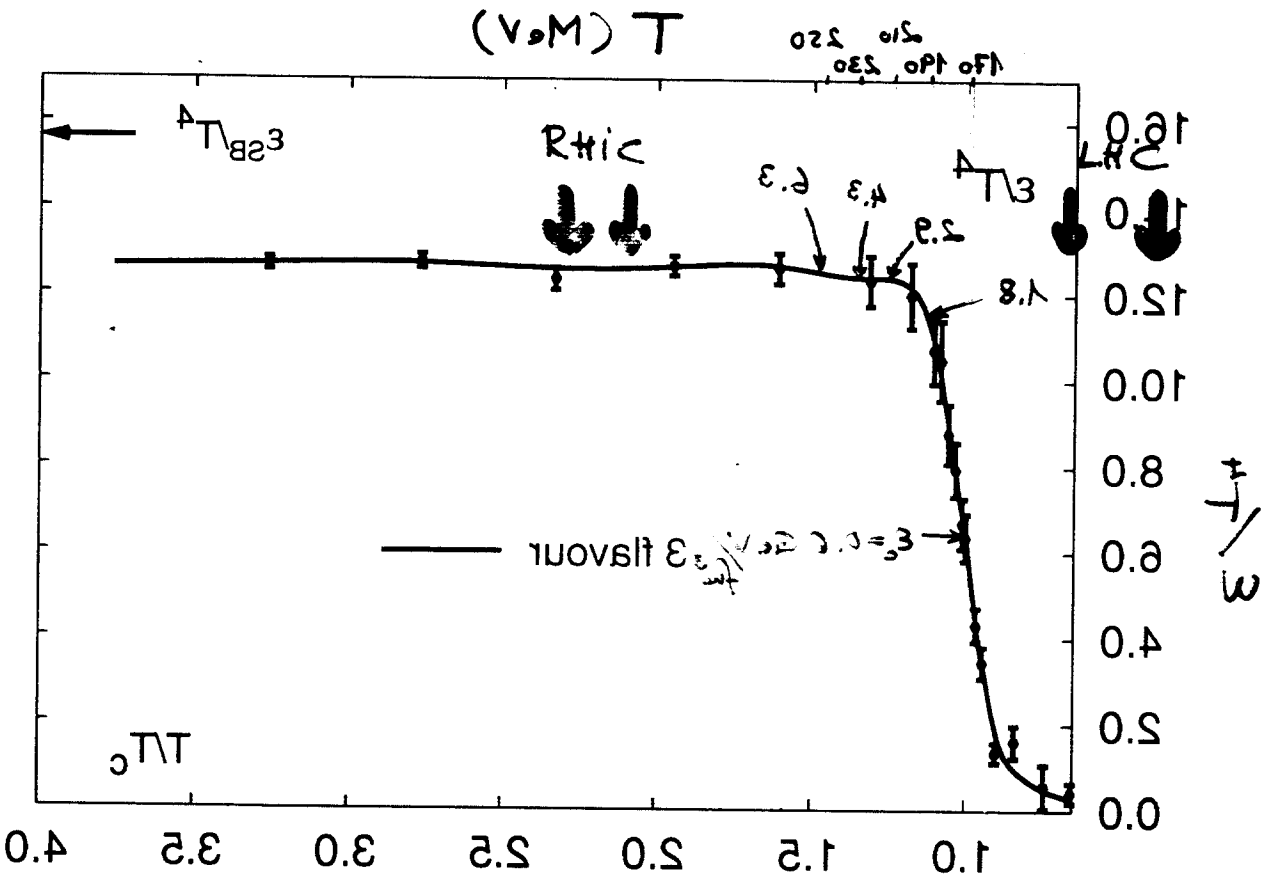
Breaking the Barrier to
the Quark-Gluon Plasma

Ulrich Heinz
(Ohio State University)

Lattice QCD with 3 flavours

light flavour

(2 masses $m_1 + m_2$ + 1 strange flavour: 3 operators $\approx 12\%$)



(Karsch, Hasenpflug, Perlmutter '99)

$T_c \approx 170$ MeV ($\pm 10\%$) (F. Karsch, hep-lat/9902008)

$T_c \approx 170$ MeV $\approx 3 \approx 1.6$ GeV f_{π^3}

$T_c \approx 250$ MeV $\approx 3 \approx 3.2$ GeV f_{π^3}

CHJ

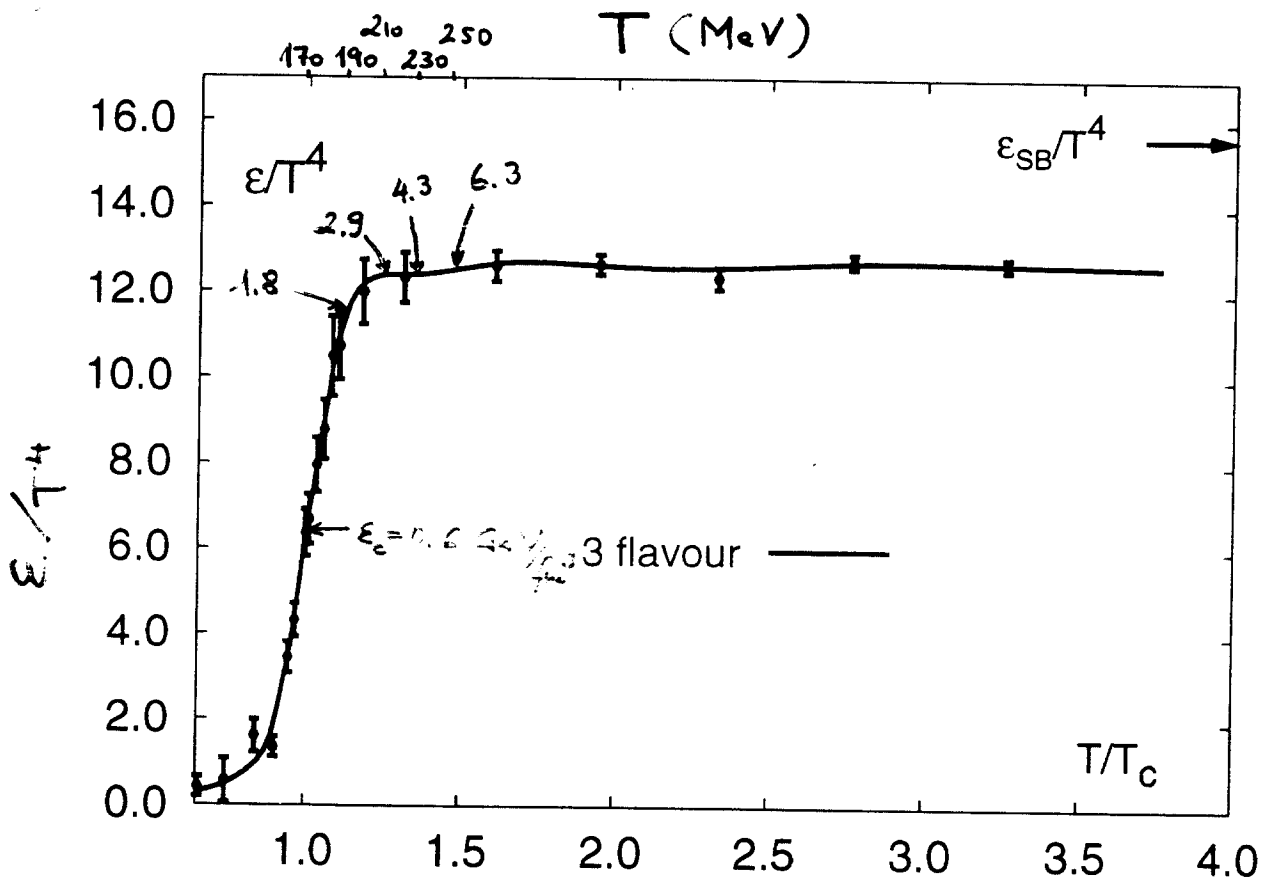


CHJ



Lattice QCD with 3 dynamical light flavors

(2 massless + 1 strange flavor: ϵ decreases by $\approx 15\%$)

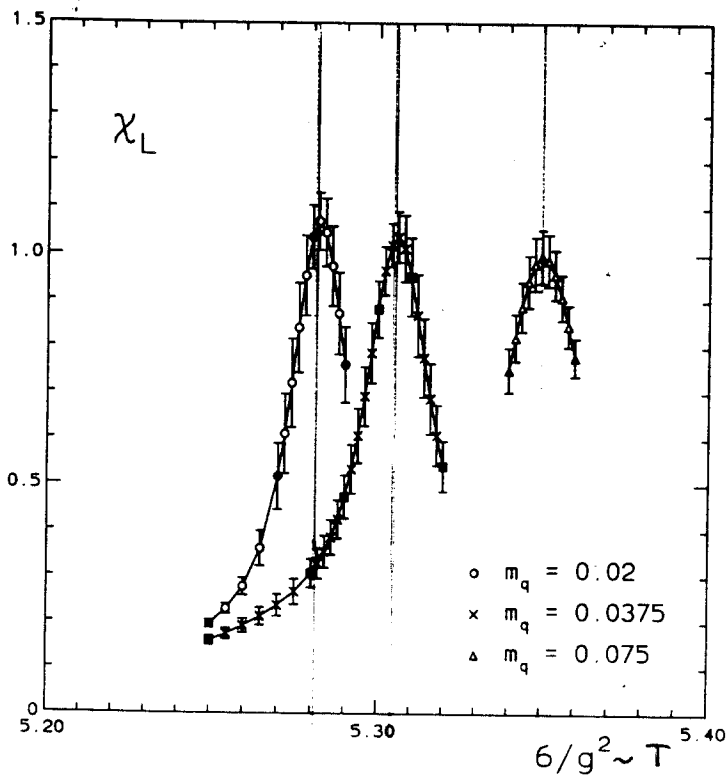


$T_c \approx 170 (\pm 10?) \text{ MeV}$ (F. Karsch, hep-lat/9509006)
 $\epsilon_c \approx 0.6 \text{ Ge}^4/\text{fm}^3$

- $T_c \approx 170 \text{ MeV} \quad \hat{=} \quad \epsilon_c \approx 0.6 \text{ Ge}^4/\text{fm}^3$
- $T_c \approx 220 \text{ MeV} \quad \hat{=} \quad \epsilon_c \approx 3.5 \text{ Ge}^4/\text{fm}^3$

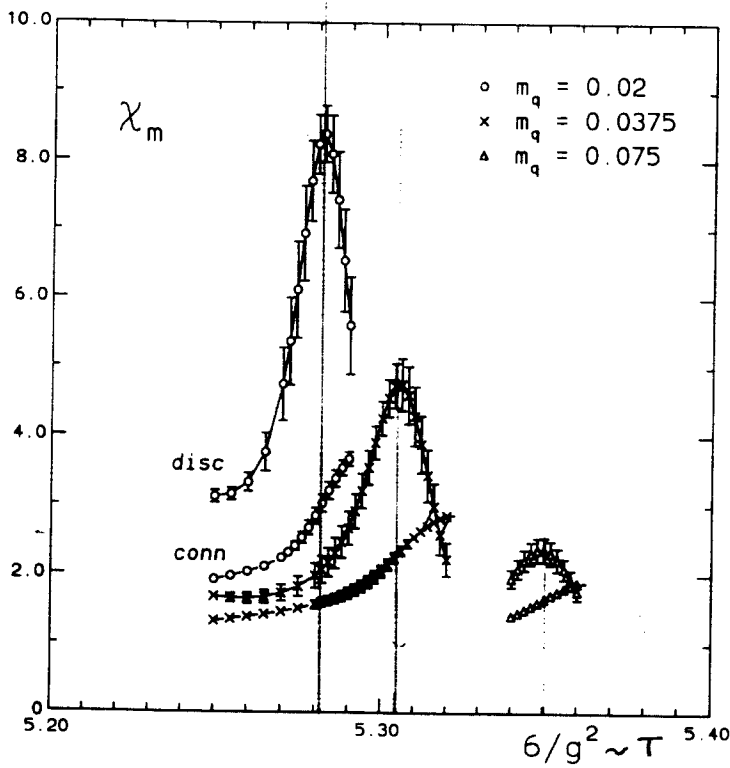
Chiral symmetry restoration and deconfinement

Polyakov
loop
response
function



deconfinement

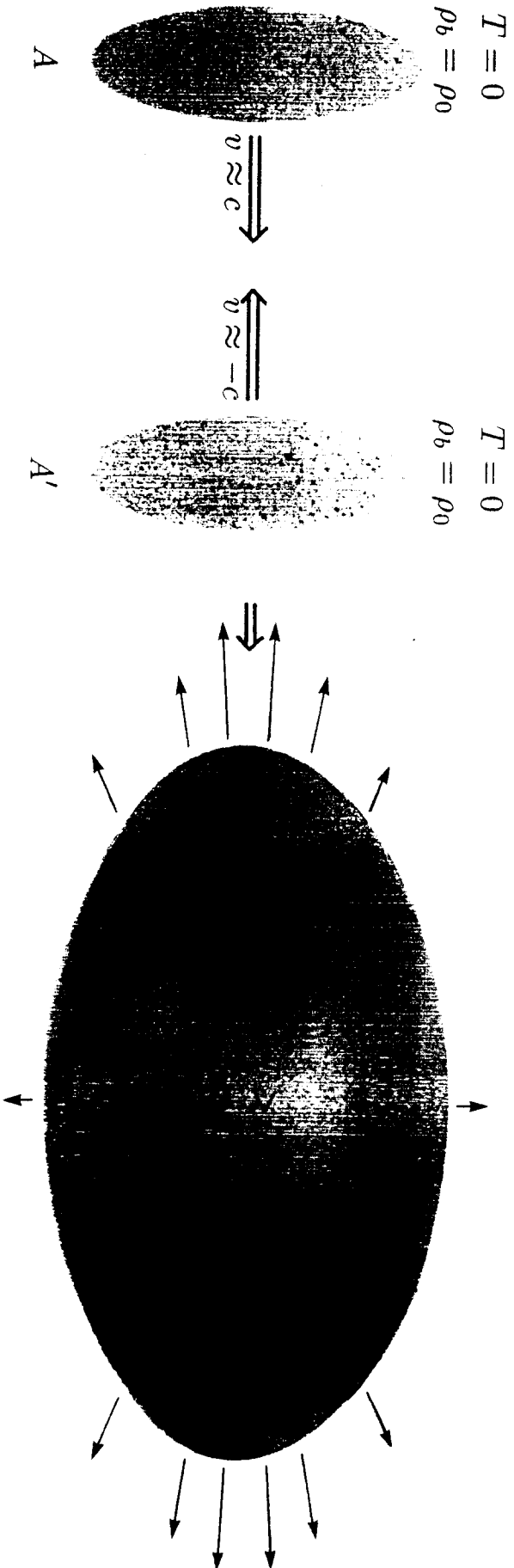
chiral
susceptibility



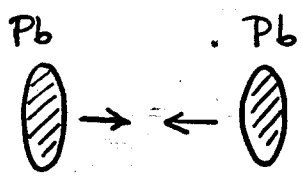
chiral symmetry
restoration

F. Karsch, E. Laermann, PRD50 (1994) 6954

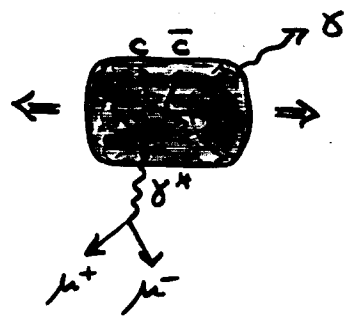
"THE LITTLE BANG"



The LITTLE BANG

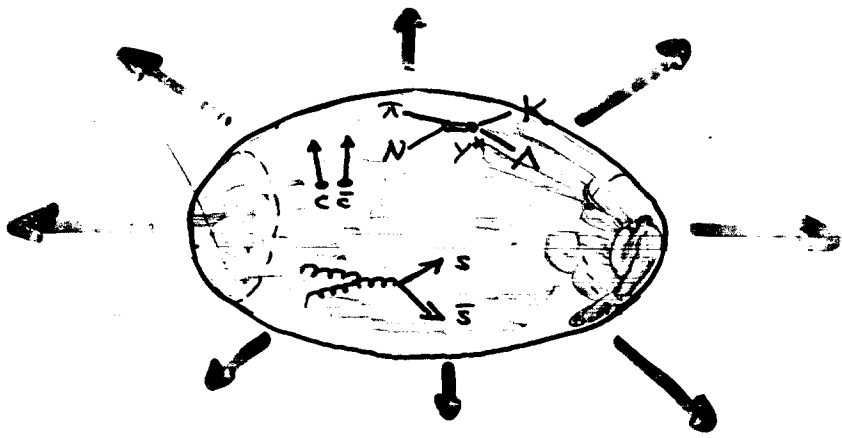


$\tau < 0$



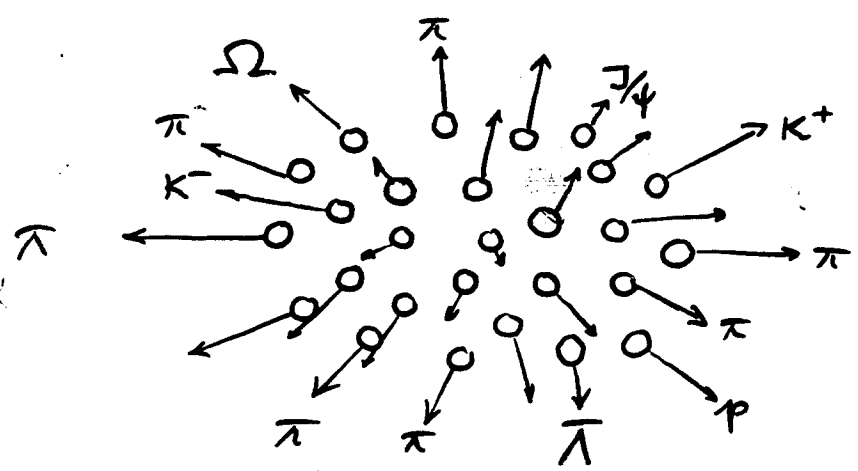
$0 < \tau \lesssim 1 \text{ fm}/c$

"hard scattering"



$1 \text{ fm}/c \lesssim \tau \lesssim 15 \text{ fm}/c$

"expansion"



$\tau \gtrsim 10-15 \text{ fm}/c$

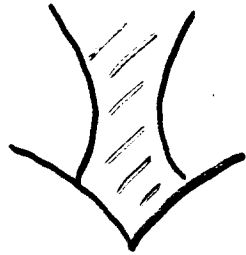
"freeze-out"

$1 \text{ fm}/c = 3 \times 10^{-24} \text{ sec}$

QGP



Thermalized
system of
quarks + gluons



PRESSURE



Collective expansion
&
Flow

Alu + Au @ 40 + 40 A Gel

13 June 2000

2 classes of observables:

Early and late signatures



direct,
but rare



indirect,
but very abundant

Strategy:

Reconstruct the LITTLE BANG from the late signals; check consistency with early signals.

BIG BANG:

- Late signatures:
- Hubble expansion (today)
 - Cosmic microwave background of thermal photons (300 000 yrs)
 - Primordial nucleosynthesis (3 mins.)
- Early signature(s):
- Baryon # asymmetry (?)

Initial energy density ϵ_0 in Pb+Pb @SPS:

(1) From measured E_T and Bjorken's formula:

$$\bar{\epsilon}_{Bj}(\tau_0) = \underbrace{\frac{1}{\pi R_{Pb}^2}}_{\substack{\text{overlap} \\ \text{area}}} \underbrace{\frac{1}{\tau_0} \frac{dE_T}{dy}}_{\substack{\text{length of} \\ \text{fireball at } \tau_0}} \quad \left(\text{assumes } \eta = y \right)$$

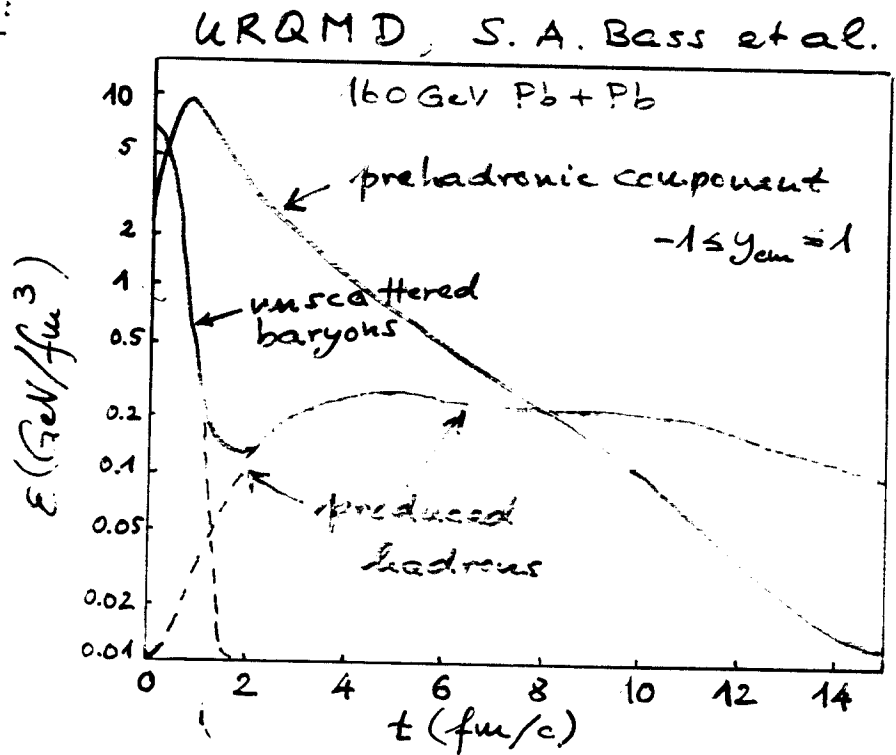
\uparrow 12.5 fm^2 \uparrow 1 fm \uparrow 400 GeV (with $\sqrt{s_{NN}} = 17.3 \text{ GeV}$)
 \uparrow 10% more in "very central" colls.



$$\bar{\epsilon}_{Bj}^{Pb+Pb} (1 \text{ fm}/c) = 3.2 \pm 0.3 \text{ GeV}/\text{fm}^3$$

(2) From HBT analysis of final state and back-extrapolation: Very similar values

(3) From simulations:



Late Signatures:

- hadrons made out of u, d, s quarks and antiquarks which are created throughout collision history
- decouple late (large cross sections), via "dynamical freeze-out"
($T_{\text{scattering}} > T_{\text{expansion}}$)

I. Hadron momentum spectra \leftrightarrow
thermalization & collective expansion

Collective flow \leftrightarrow pressure \leftrightarrow equation of state

\rightarrow "Hubble constant" of the LITTLE BANG

II. Hadronic abundances \leftrightarrow

chemical equilibration

\rightarrow "primordial hadrosynthesis"

Strangeness: $\tau_{s\bar{s}} \sim \tau_{\text{fireball}}$

\rightarrow Strangeness yields sensitive to "new physics" which reduces $\tau_{s\bar{s}}$

The freeze-out stage: an exploding thermal fireball

Separating temperature & flow:

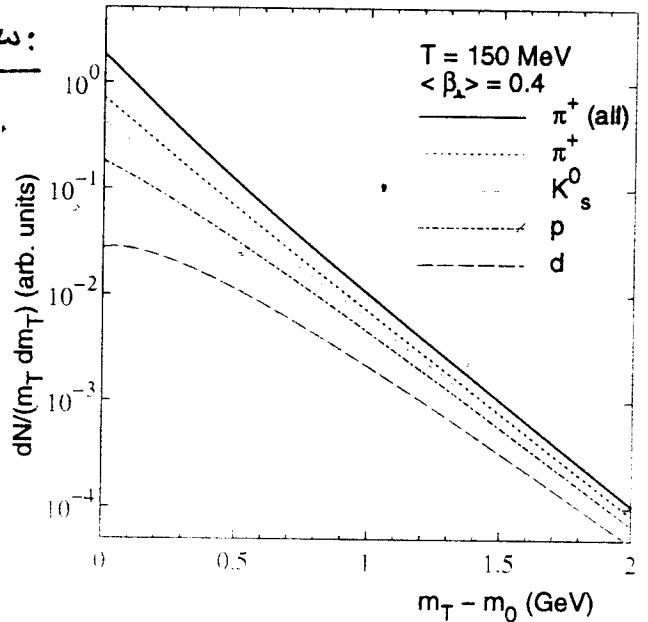
(1) Mass dependence of slope:

$$T_{\text{slope}} \approx T_f + \frac{1}{2} m_0 \langle v_{\perp} \rangle^2$$

($m_{\perp} \lesssim 2m_0$)

$$T_{\text{slope}} \approx T_f \sqrt{\frac{1 + \langle v_{\perp} \rangle}{1 - \langle v_{\perp} \rangle}}$$

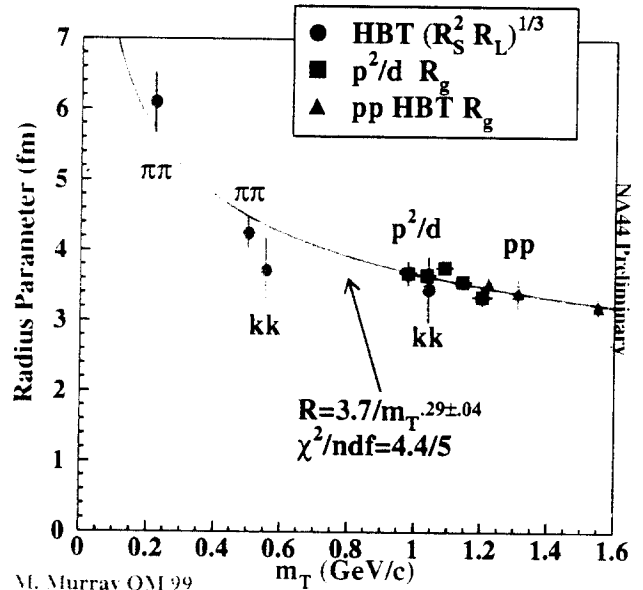
($m_{\perp} > 2m_0$)



(2) M_T -dependence of HBT correlation function and deuteron coalescence probability:

$$R_{\perp}^2 \approx \frac{R^2}{1 + 3 \frac{M_T}{T_f} \langle v_{\perp}^2 \rangle}$$

PbPb Radii versus Transverse Mass



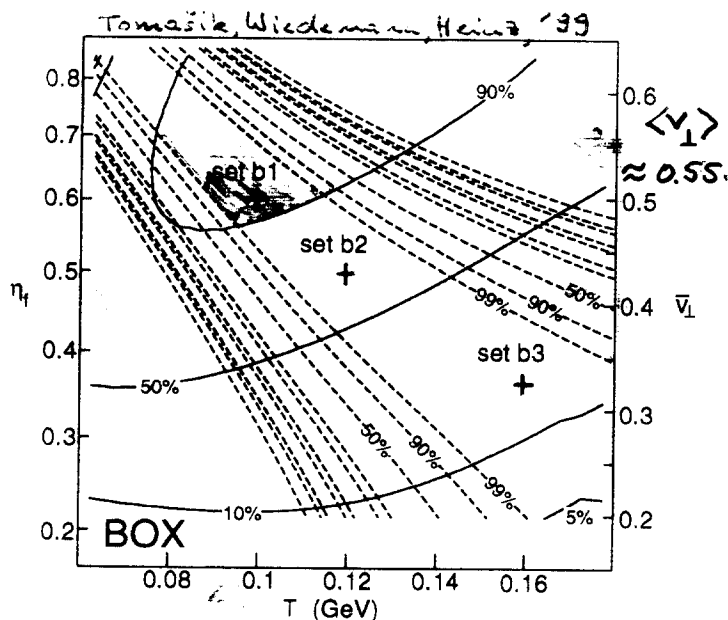
see also NA52 NA49

(3) Correlate π^- slope and $\pi^-\pi^-$ Bose-Einstein correlations:

(NA44 correlations - et al., EPJ 1999)

$$\rightarrow E_f \approx 0.05 \text{ GeV}/\text{fm}^3$$

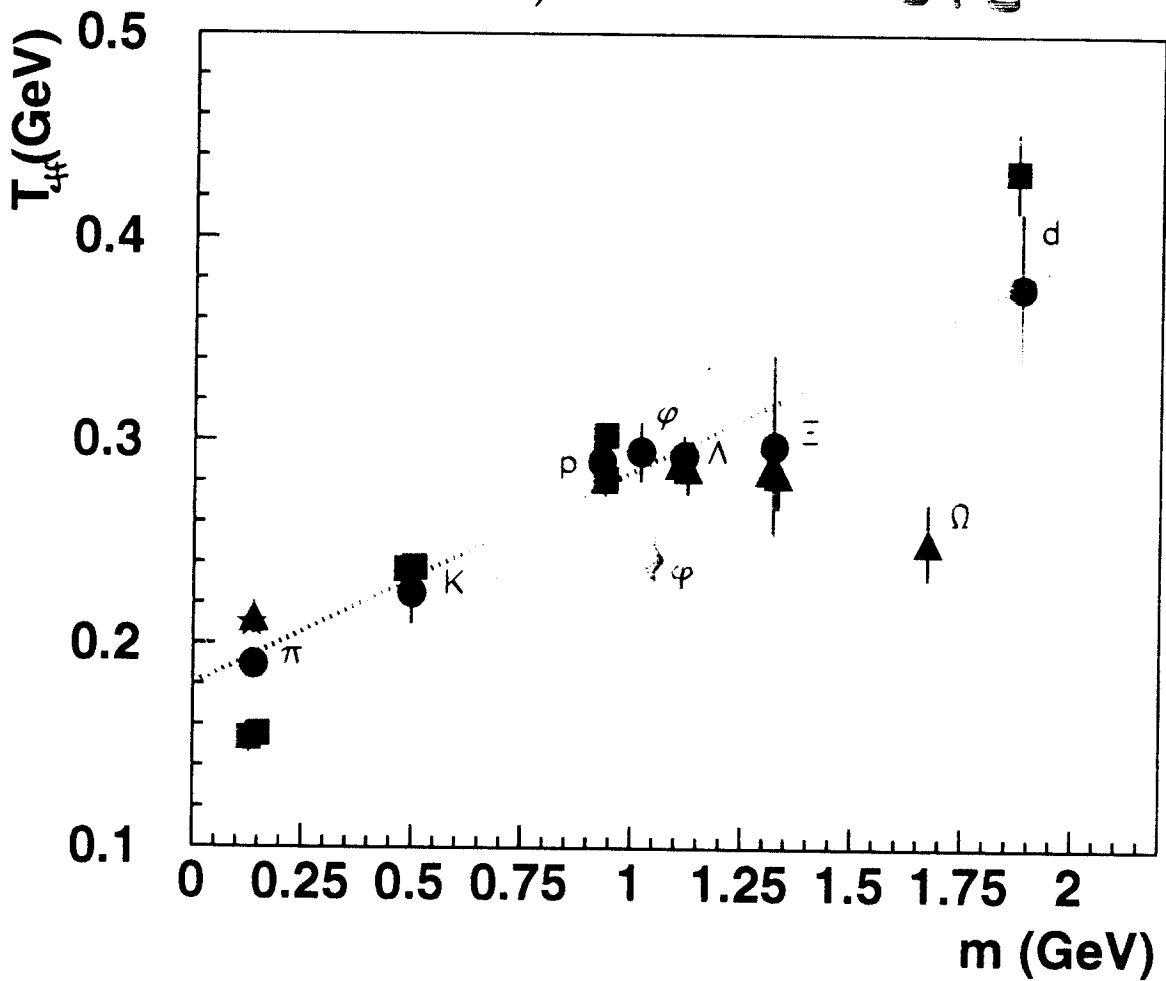
$$T_f \approx 100 \text{ MeV}, \langle v_{\perp} \rangle \approx 0.55c$$



$$T_f \approx 100 \text{ MeV}$$

mass dependence of inverse slopes

158 A GeV/c Pb + Pb SPS

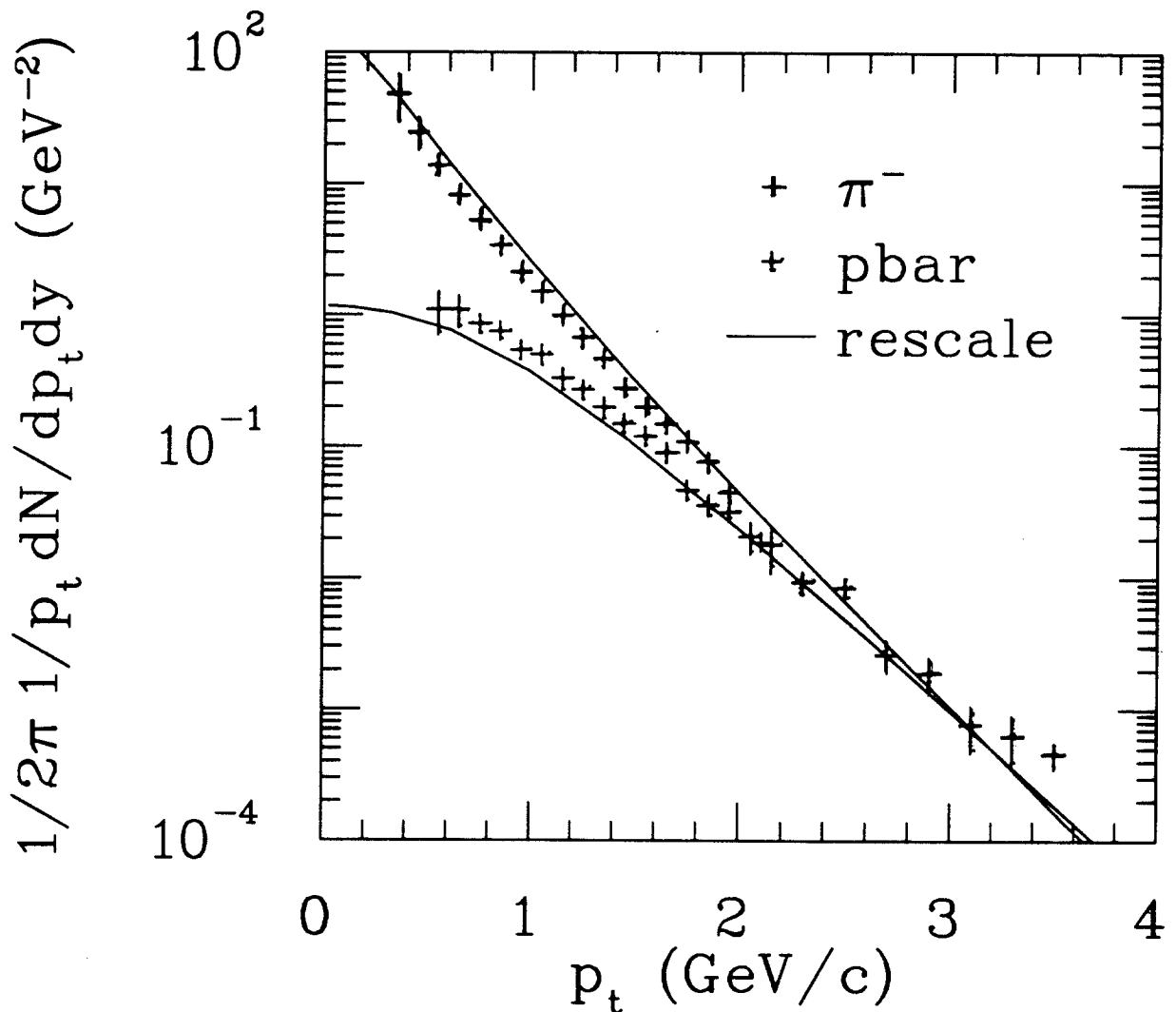


- NA49
- ▲ WA97
- ◆ NASO
- NA44
- ★ WA98

P_t spectra, minimum bias

negative

RHIC, Au+Au @ 130 A GeV



Data: Phenix, preliminary QM'01

curves: hydrodynamics

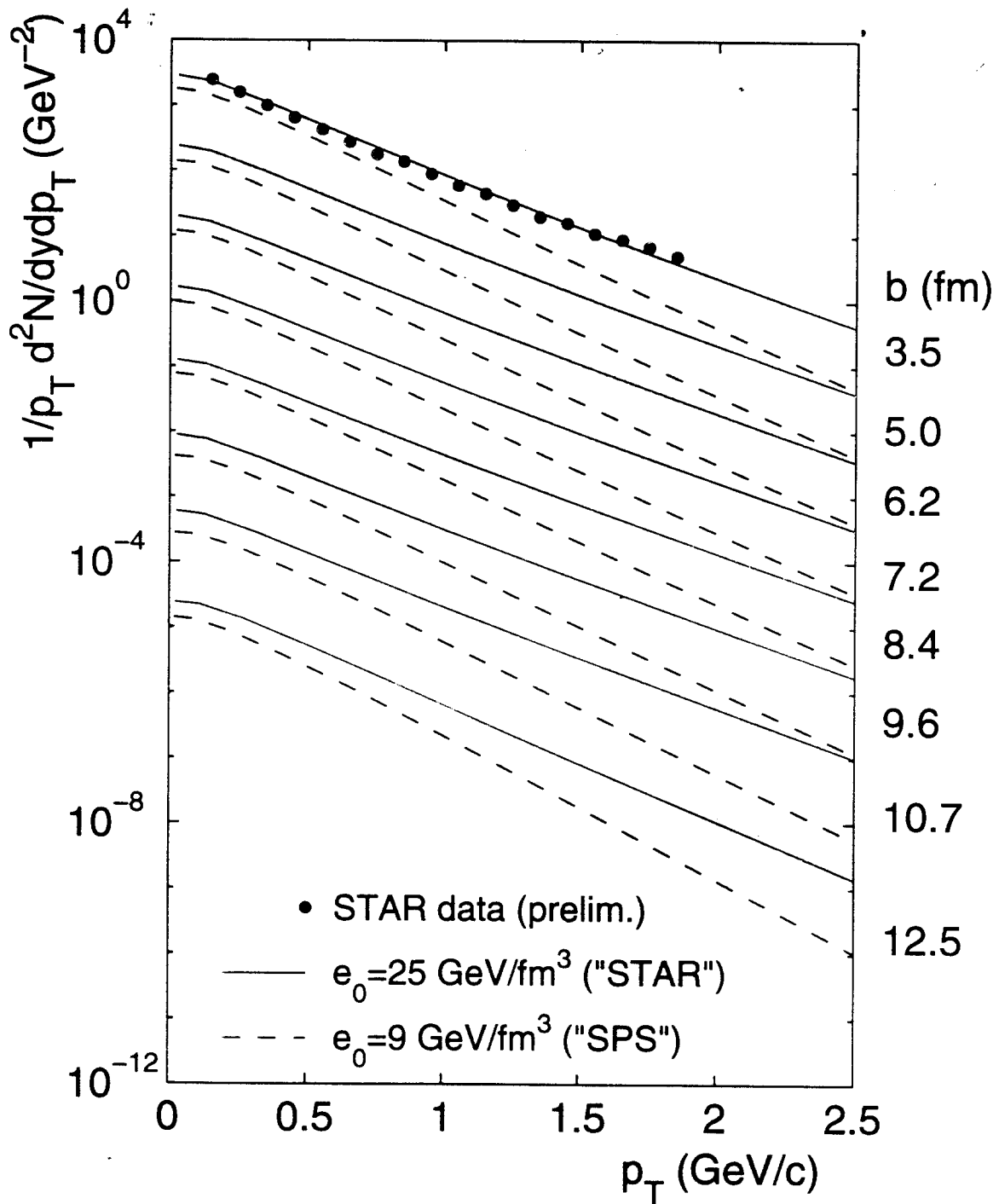
P. Huovinen, P. Kolb et al., PLB503(2001)58

$$T_{f.o.} = 135 \text{ MeV}, \quad \langle v_{\perp} \rangle = 0.45 c \quad (\approx 1.2 \times \text{SPS})$$

$$\bar{\epsilon} (1 \text{ fm}^3) = 5.7 \text{ GeV/fm}^3 \quad (\approx 1.8 \times \text{SPS})$$

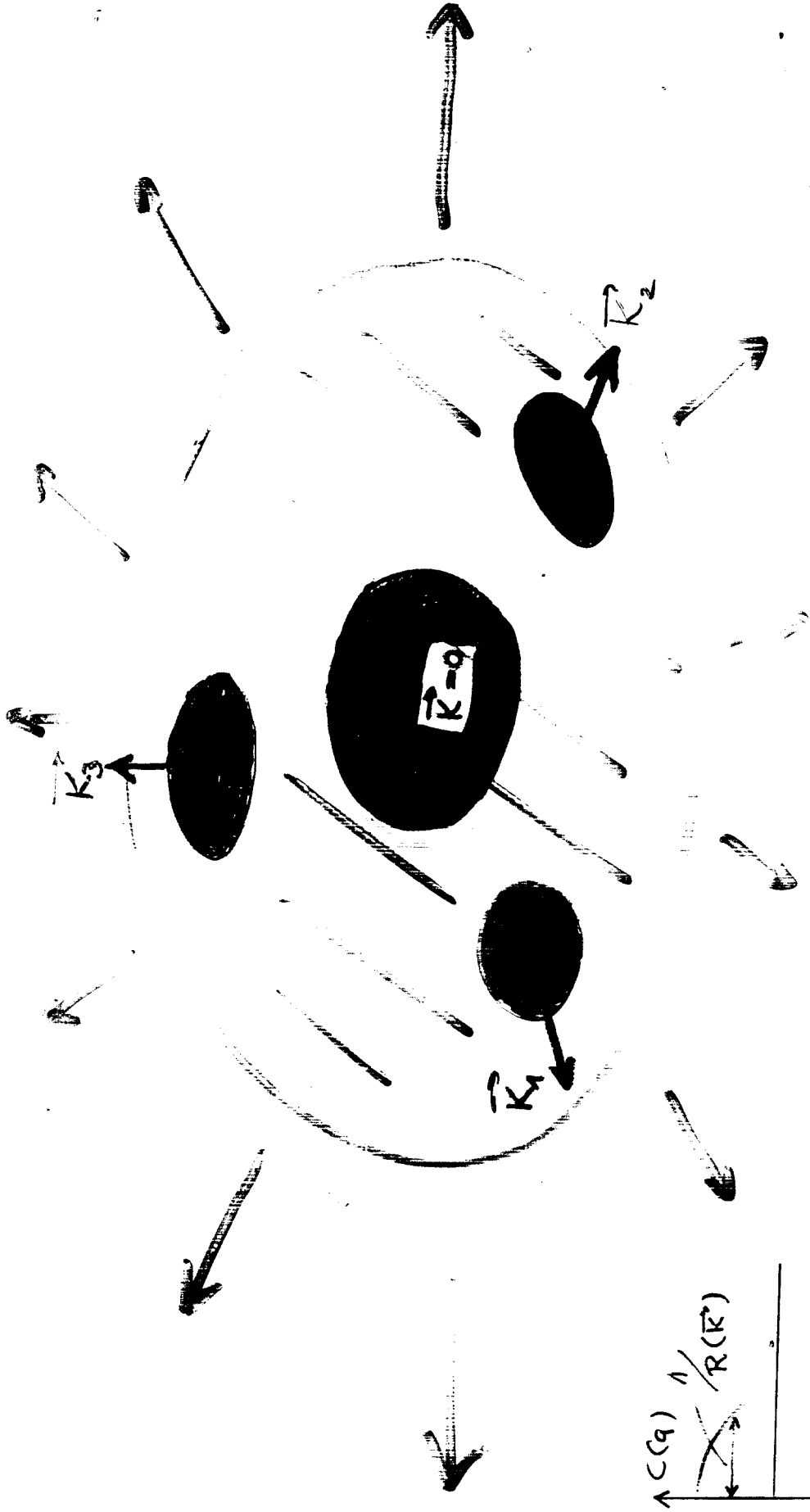
Parameter free prediction!

† STAR, DNP 2000



P. Huovinen, P. Kolb et al., PLB 503 (2001)

2-particle Bose-Einstein interferometry



measures "homogeneity regions" $\hat{=}$ Hubble volumes

- What happened from $\Sigma_0 \approx 3 \text{ GeV}/\text{fm}^3$ down to $\Sigma_f \approx 50 \text{ MeV}/\text{fm}^3$?

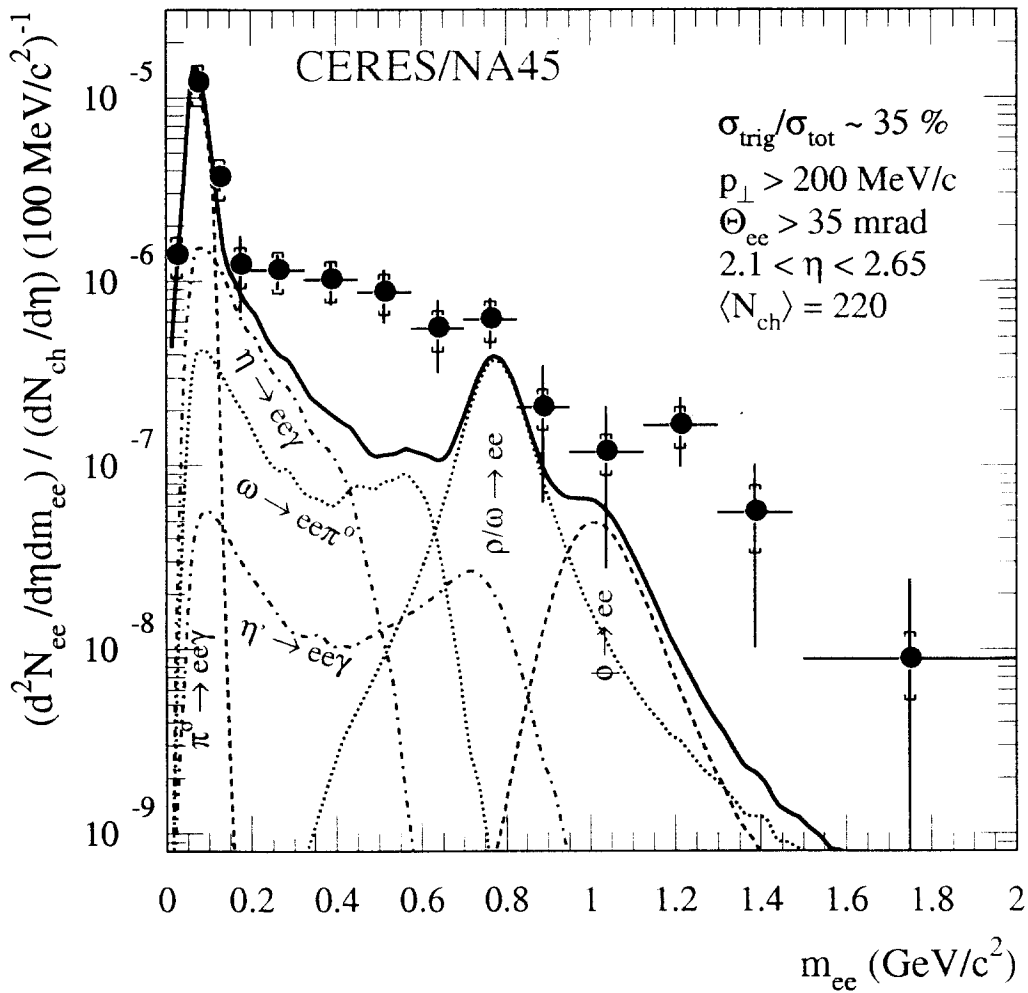
In particular:

- What can we learn about the behaviour of the matter in the very dense initial stages?

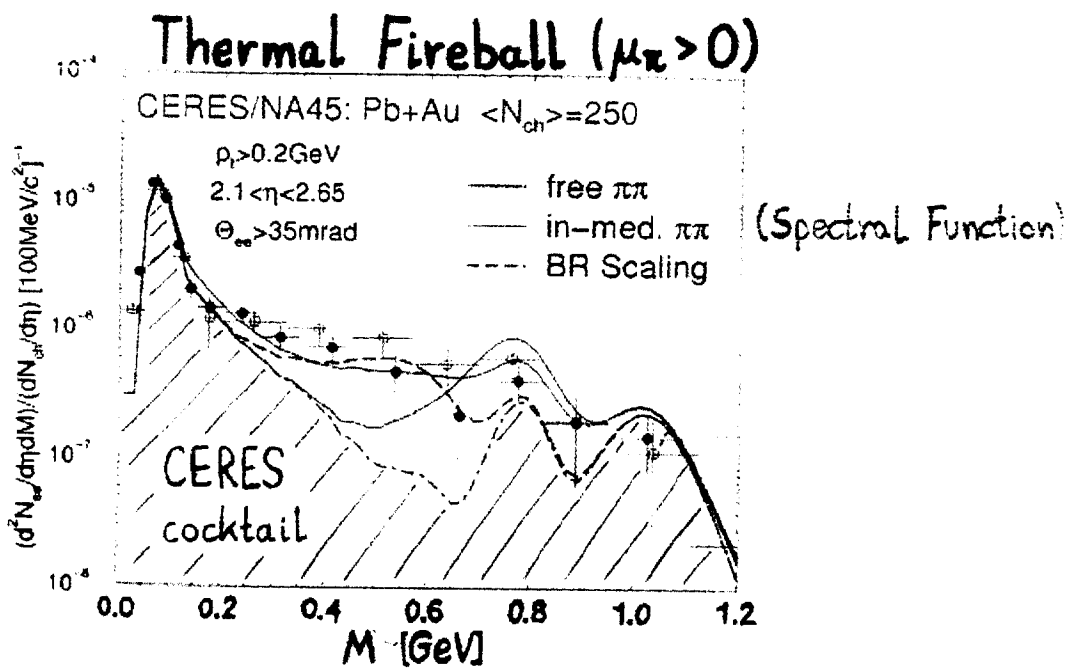
"The disappearing ρ "

Thermalization in action

Pb-Au 160 GeV/nucleon



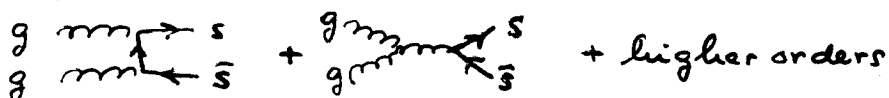
$$\begin{aligned}
 \text{enhancement factor} &= \frac{\text{integral of data}}{\text{integral of sources}} (m > 0.2 \text{ GeV}/c^2) \\
 &= 2.7 \pm 0.3(\text{stat}) \pm 0.5(\text{syst})
 \end{aligned}$$



Ralf Rapp, Quark Matter '99

Key QGP predictions:

- ✓ Strangeness enhancement and chemical equilibration due to shorter time scale for $s\bar{s}$ production: (Rafelski + Müller '82)



↔ gluon deconfinement + chiral symmetry restoration
(high gluon density + low mass thresholds)

Hadronic background: associated production + strangeness exchange

Multi-strange (anti) baryon production inhibited by low densities and high mass thresholds in hadron gas.

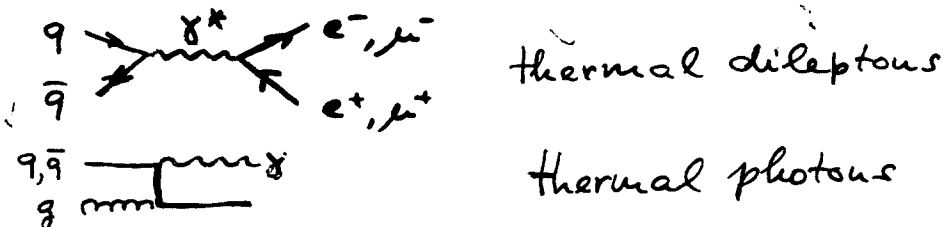
- ✓ $J/\psi, \chi_c, \psi'$ suppression due to color screening

↔ color deconfinement + high gluon density

Hadronic background: hadronic FSI with incoming nucleus and comoving produced hadrons

Comover scattering unable to reproduce observed $\psi', \chi_c, J/\psi$ suppression pattern.

- Thermal electromagnetic radiation: (Shuryak, Kharzeev, Ruvinskyan...?)



backgrounds: Drell-Yan, $D \rightarrow K\pi \rightarrow \mu^+\mu^-$, bremsstrahlung from charged hadrons; $\pi^0, \eta, \dots \rightarrow \gamma\gamma$

Marginal S/B @ SPS, but more hope at RHIC and LHC (thermal rate $\sim T^4$)

Strangeness enhancement & chemical equilibration

(1) Hadron yields compatible with chemical equilibrium at

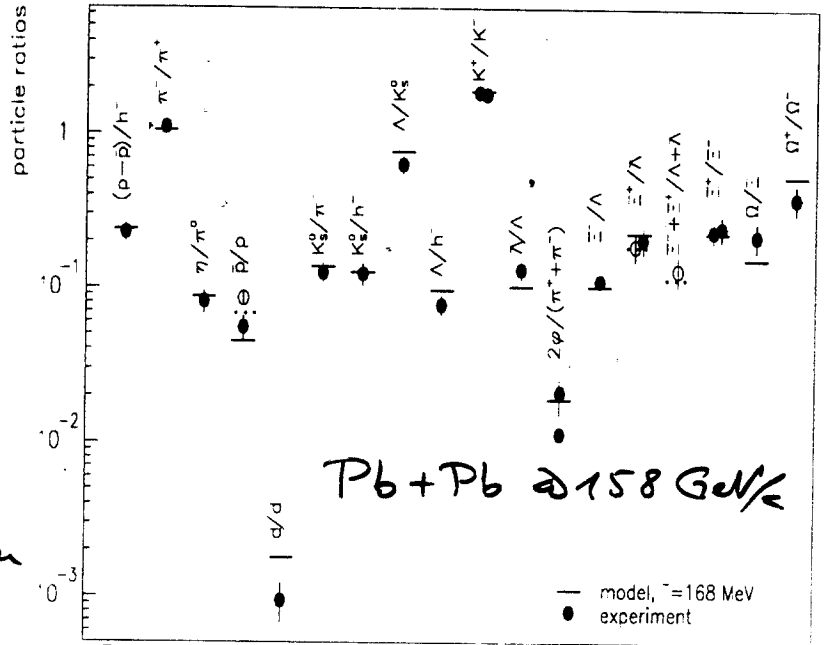
$$T_{chem} = 168 \text{ MeV} \approx T_{had}$$

"pre-established chemical equilibrium"



statistical hadronization of quarks & gluons

(U.H., 6M97; R. Stock, P.3456, 27)



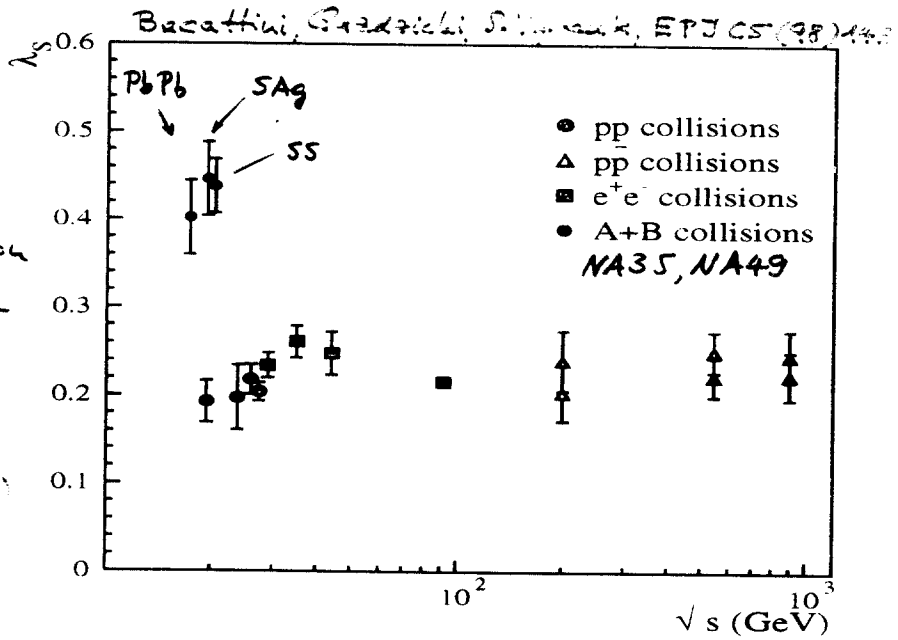
Braun-Kunzinger, Heppner, Kniehl, P.3465 (99)15

(2) Global strangeness enhancement by factor 2



rapid strangeness production before or during hadronization

(K. Redlich & S. Schenke, P.3456, 27)
 Z. Phys. C 54 (1992) 667
 Phys. Rev. Lett. 69 (1992) 1840

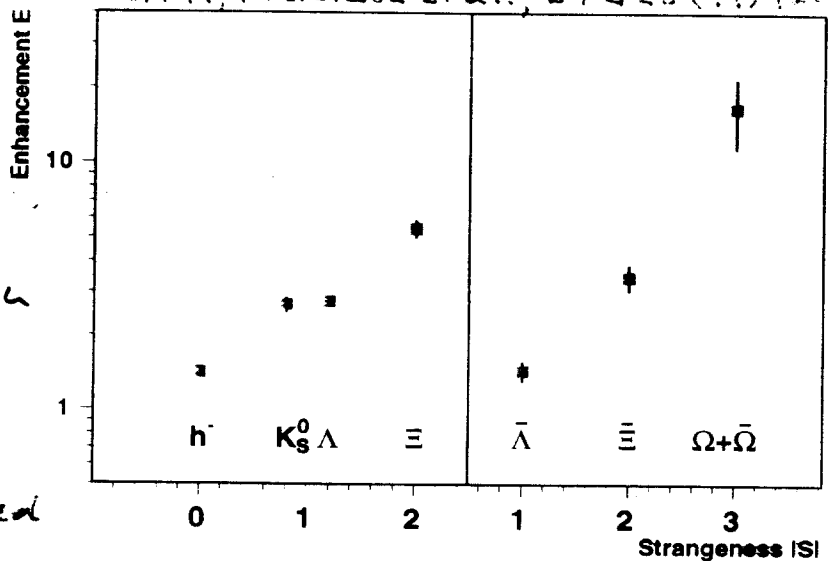


W. A. Barz, R. Lietava et al., JPG 25 (79) 46

(3) Large specific enhancement factors at y_{cm} (PbPb vs. pBe) for multistrange hadrons



statistical hadronization

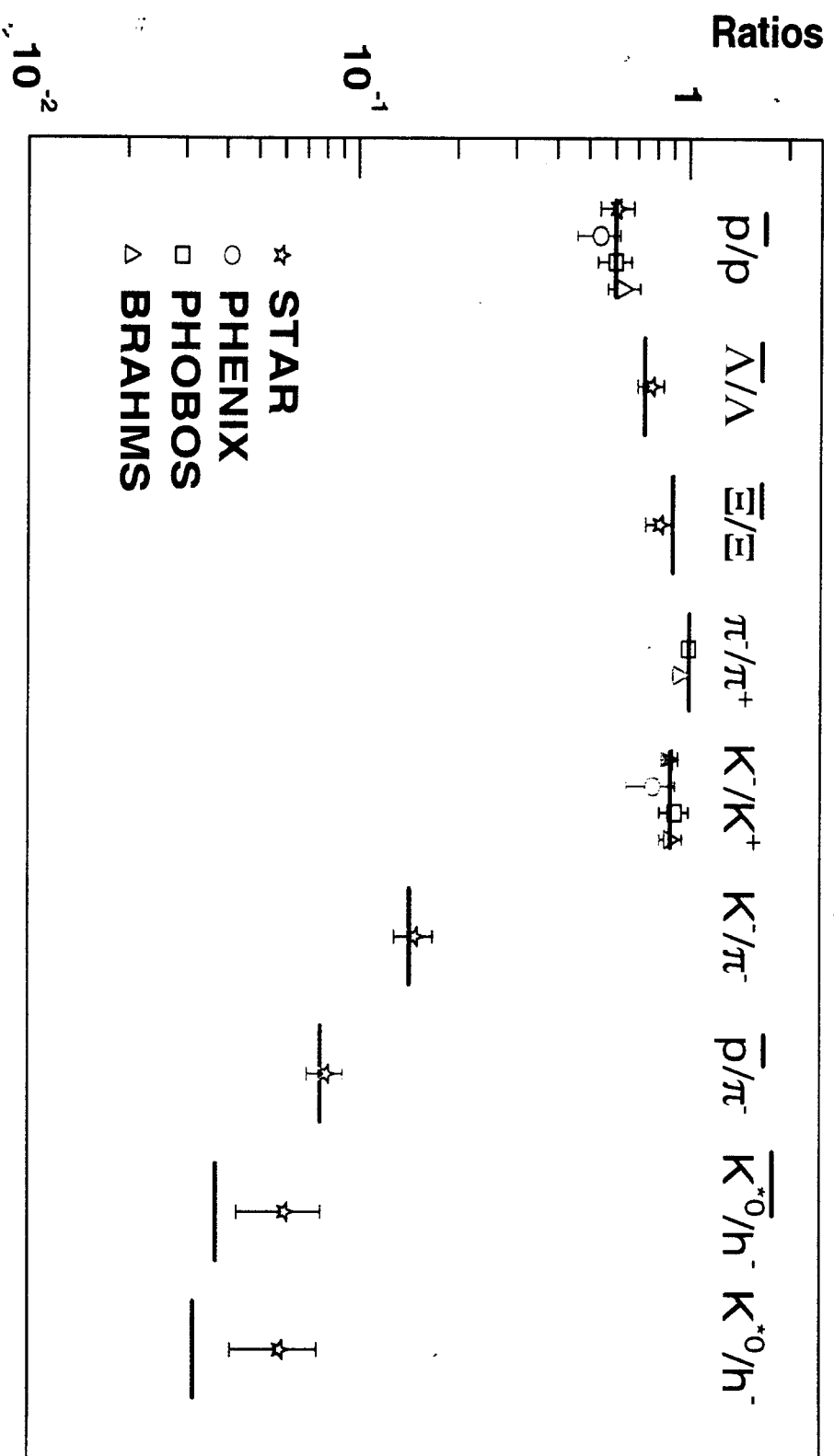


(1)-(3) cannot be explained by hadronic FSI!

Statistical description of RHIC data

P. Braun-Munzinger, D. Magestro, J. Stachel, K. Redlich

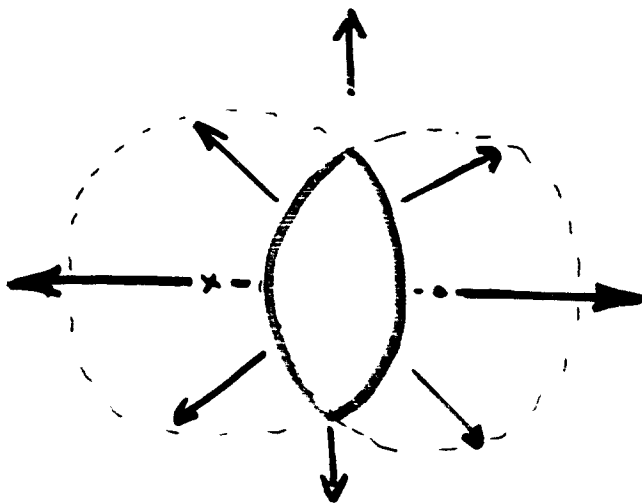
$T \approx 170 \text{ MeV}$, $\mu_0 \approx 45 \text{ MeV}$



$Au + Au @ 130 \text{ A GeV}$

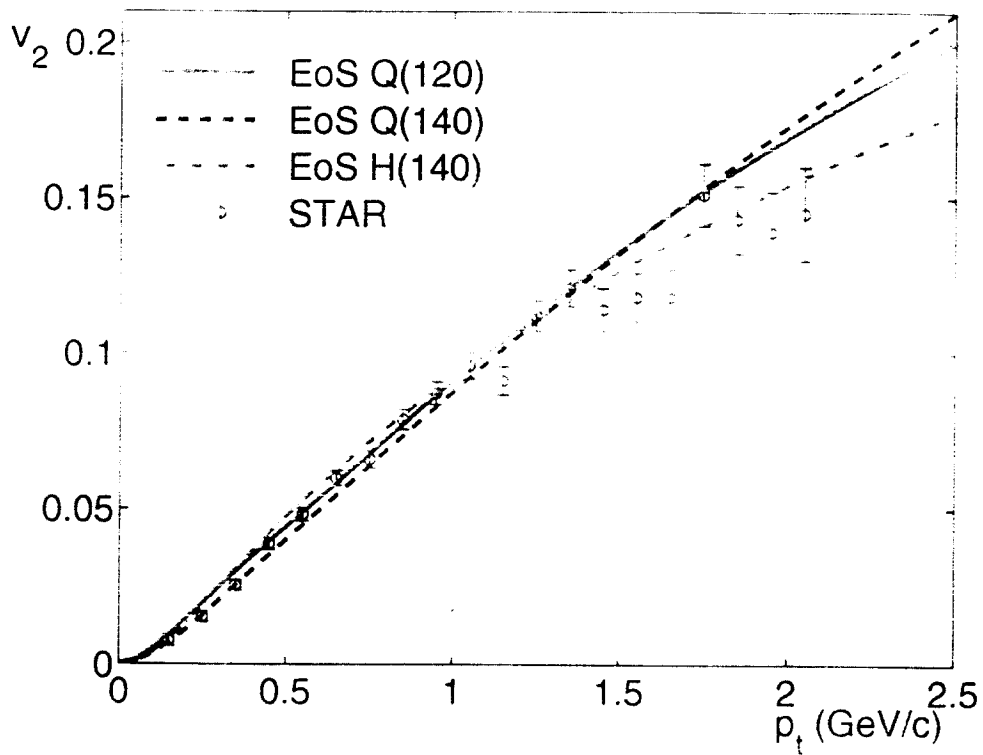
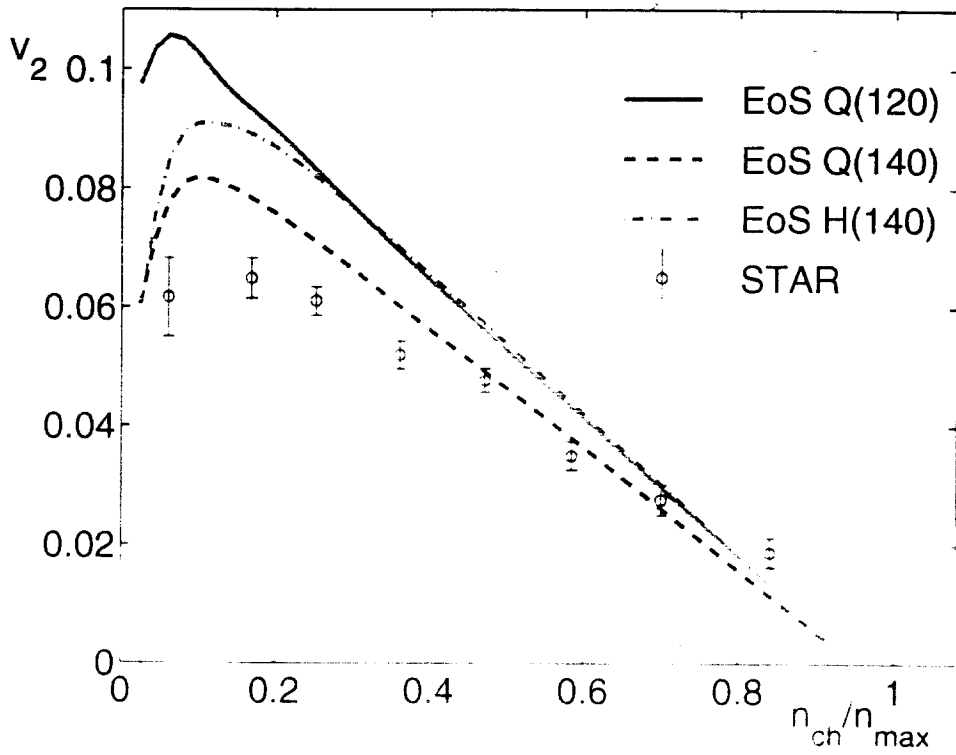
Elliptic Flow

an early hadronic signal



$$\frac{dN}{p_{\perp} dp_{\perp} dy d\phi} = \frac{dN}{2\pi p_{\perp} dp_{\perp} dy} \left(1 + 2 \underbrace{v_2(p_{\perp}, y)}_{\uparrow} \cos(2\phi) + \dots \right)$$

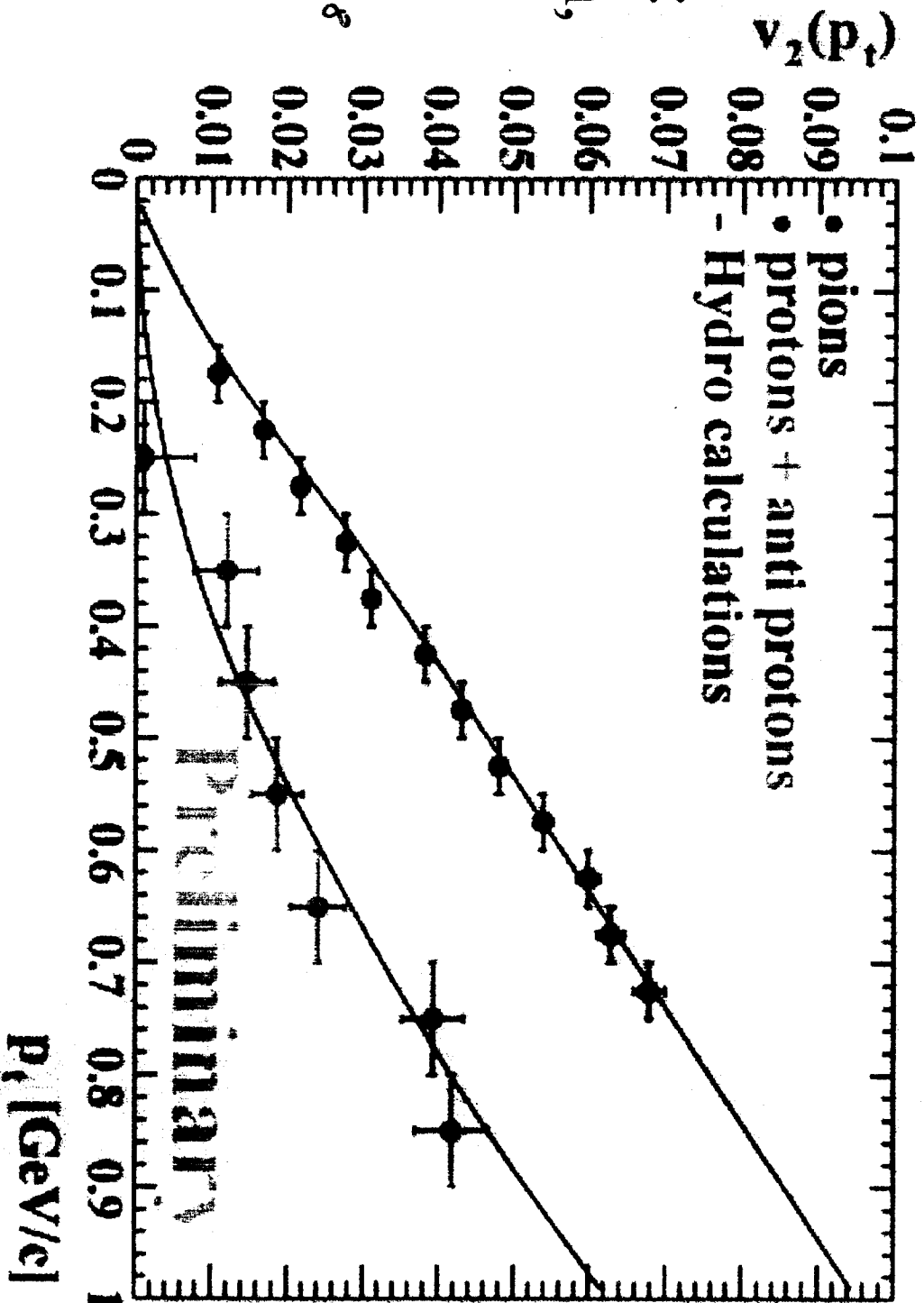
elliptic flow coefficient





A Hydro view of the world

- Hydro calculations:
 - P. Huovinen,
 - P. Kolb and
 - U. Heinz
- PLB 503 (2001) 58

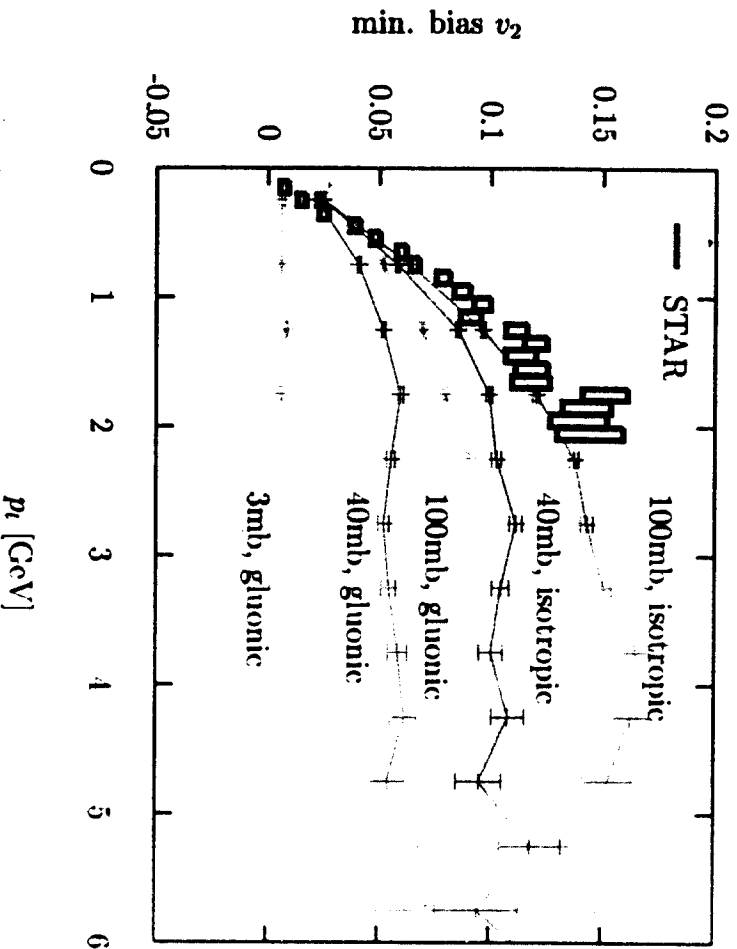


In fact, a lot of research is going on

~ 30% of each
~ 10 times of each

Minimum bias v_2

MPC Au+Au, $dN/d\eta_{cent} = 210$ (HIJING, 130A GeV)

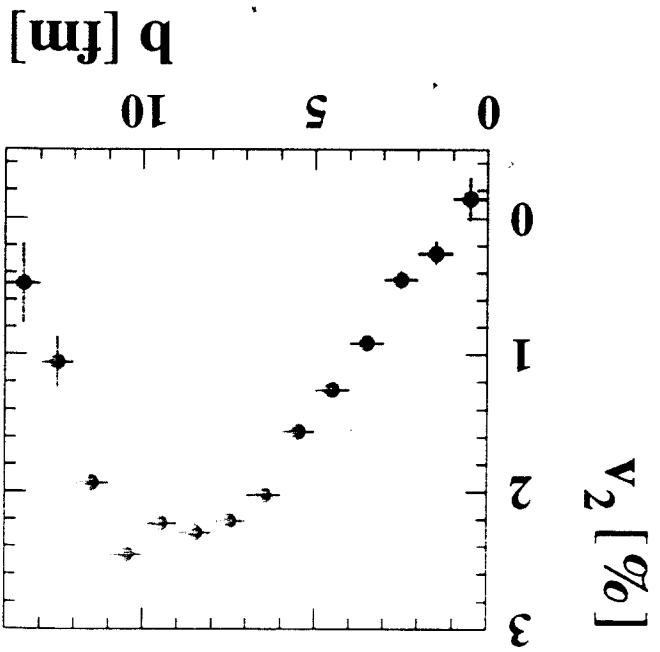


Simple estimate:

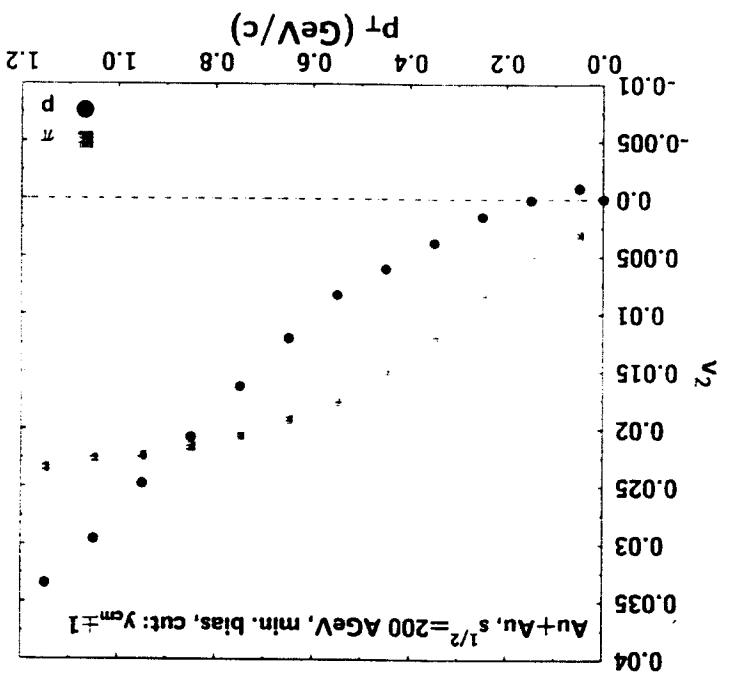
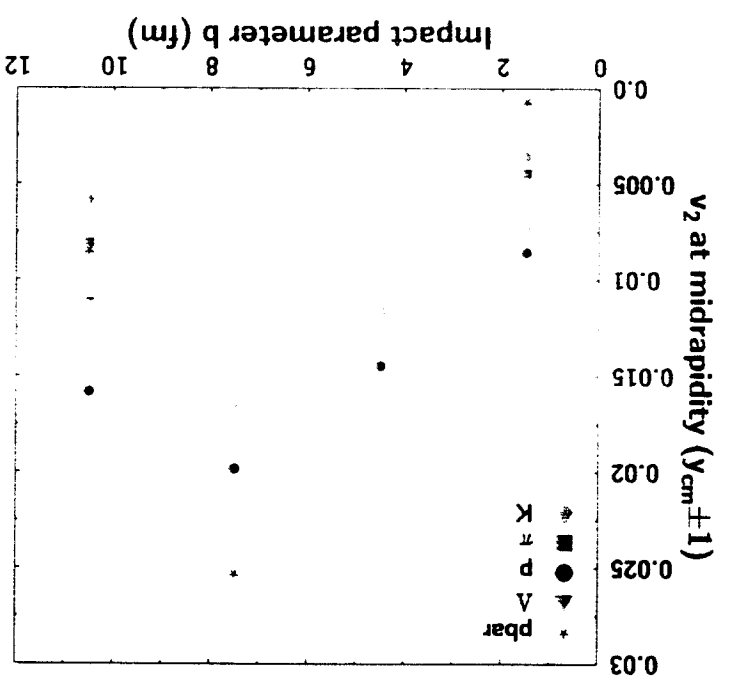
$$v_2^{minbias} = \frac{2\pi}{\pi b_{max}^2} \int_0^{b_{max}} v_2(b) b db$$

b_{max} not known \rightarrow take 12fm

- v_2 grows with p_t until $\sim 2 - 3\text{GeV}$, then saturates
 - data supports: HIJING $dN/d\eta_{cent} = 210$, $\sigma = 100\text{mb}$ isotropic,
or EKRT $dN/d\eta_{cent} = 1000$, 21mb isotropic
 - also possible with gluonic but needs higher cross sections or densities
- NOTE: 3mb gluonic requires $dN/d\eta \sim 7000$ (!)**



• RQMDv2.4
 [Snellings, Poskanzer, Voloshin, nucl-ex/9904003]
 $\sqrt{s} = 200 A \text{ GeV}$

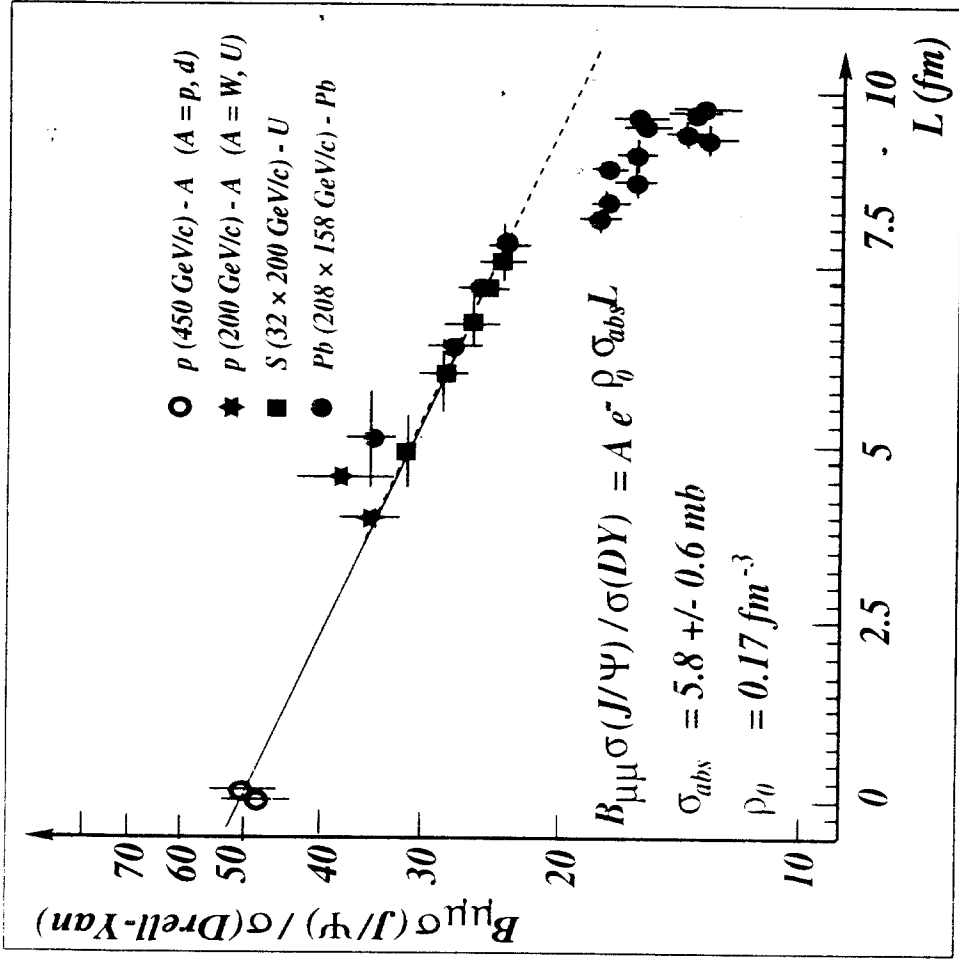
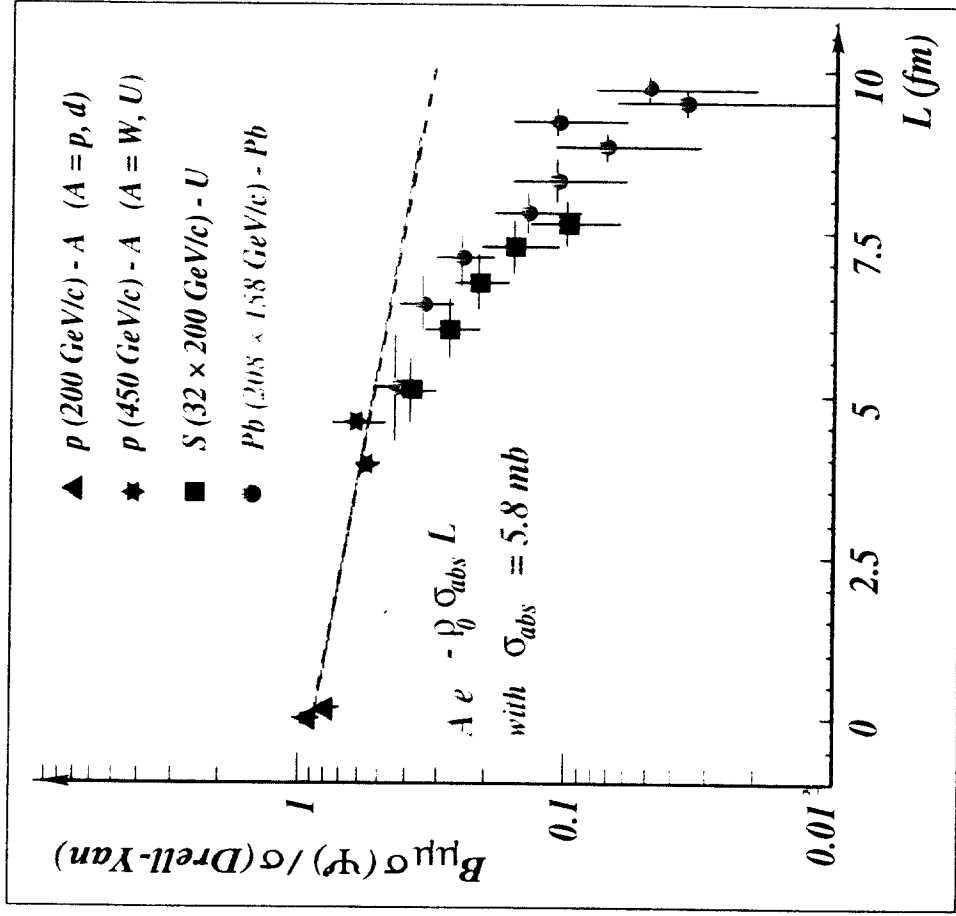


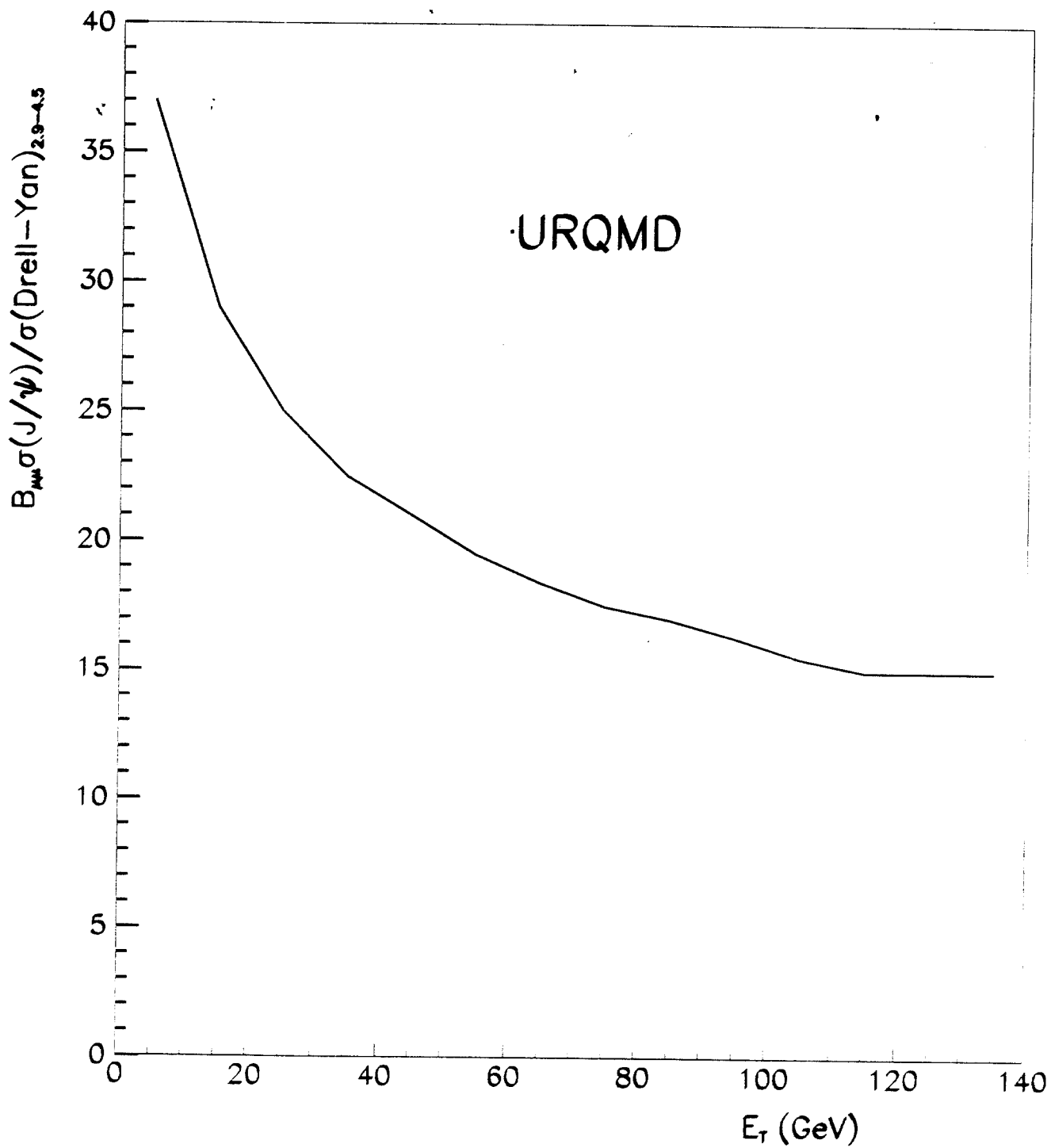
• URQMD [Bleicher, Stöcker, hep-ph/0006147]
 $\sqrt{s} = 200 A \text{ GeV}$
 Hadronic rescattering models fail badly, too

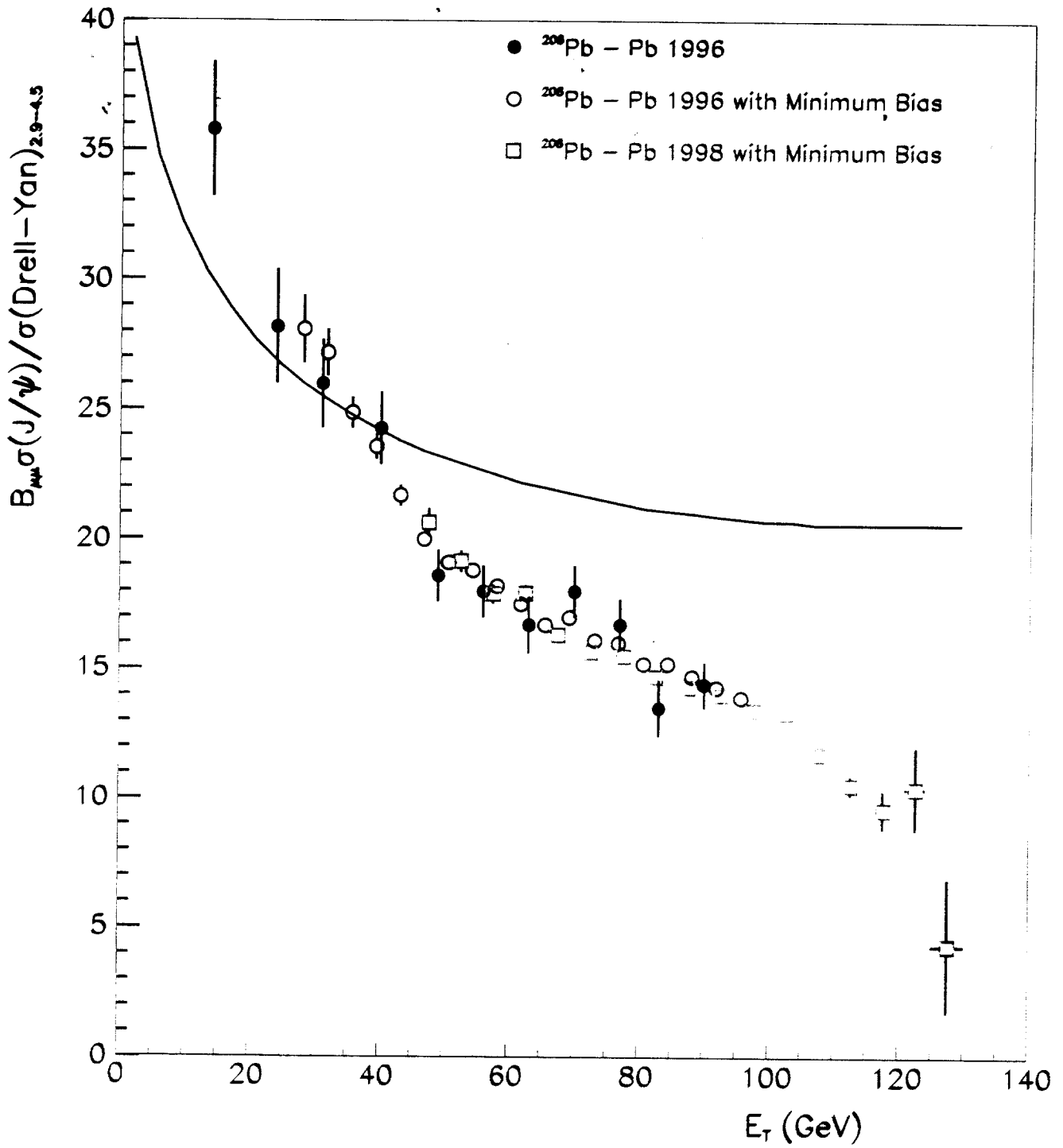
Anomalous suppression of J/ψ and ψ'

VASo, Quark Matter '97, Tishchenko

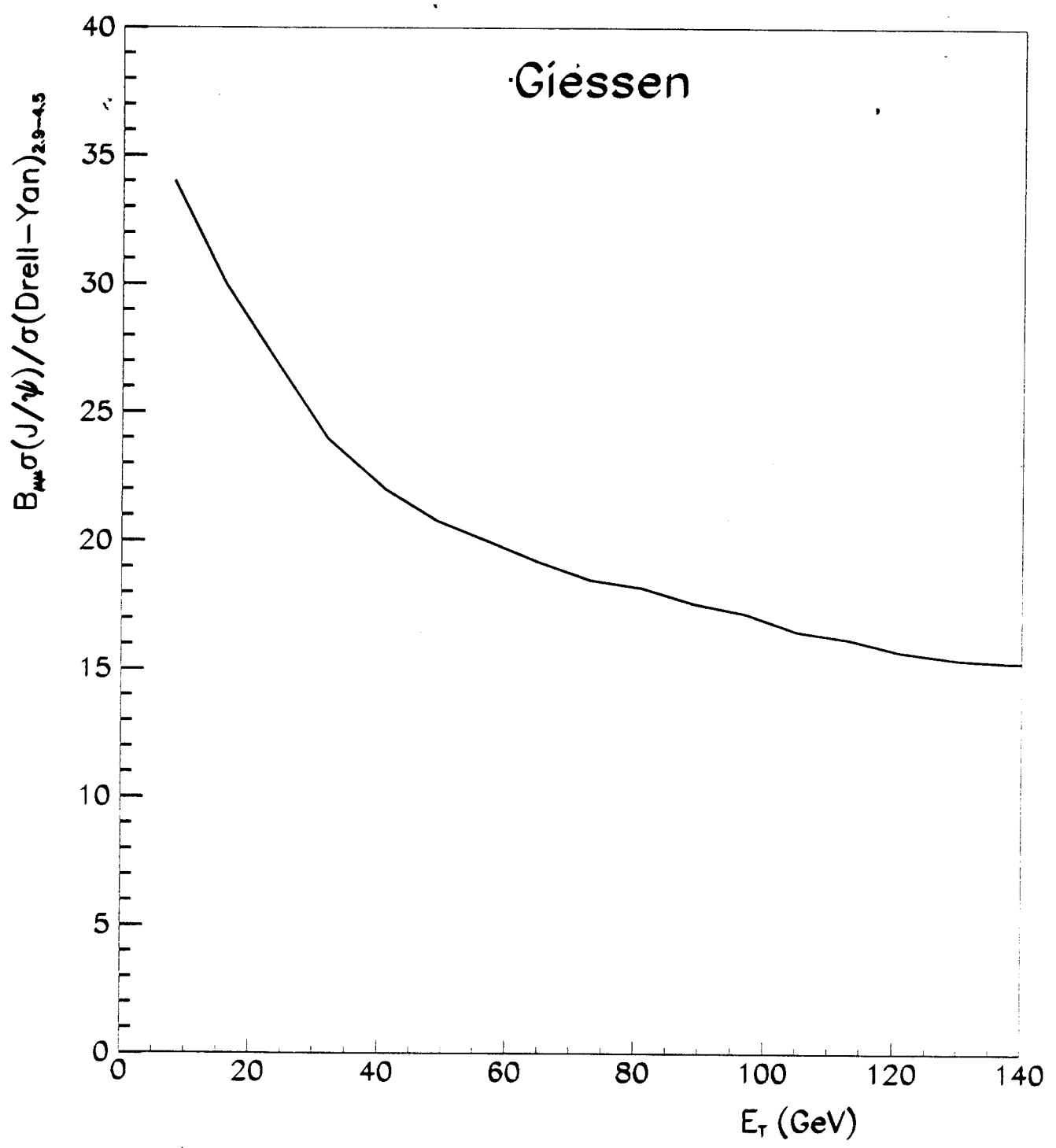
M. Alford et al. (NASo), PLB 450 (1999) 456

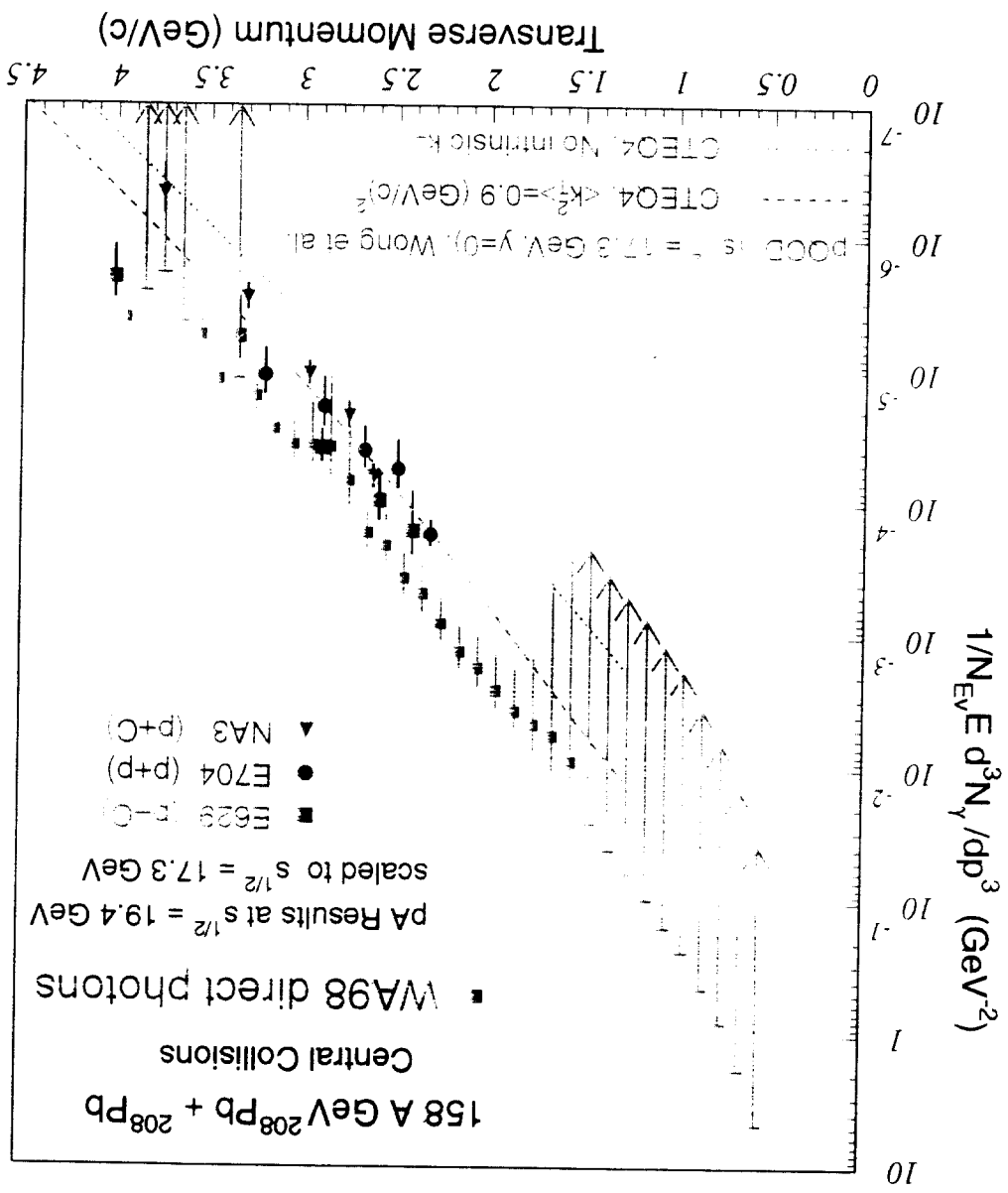






NA50 @ QM99





trip
-narrp
Spind



Negative Hadrons: Compare with \bar{pp}

p_T - distributions

UA1 $\sqrt{s} = 200$
 $\Rightarrow R (130/200)$

From power law scaling

$R = 0.92$ at 0.2 GeV/c

$R = 0.70$ at 2 GeV/c

"Hard" Scaling

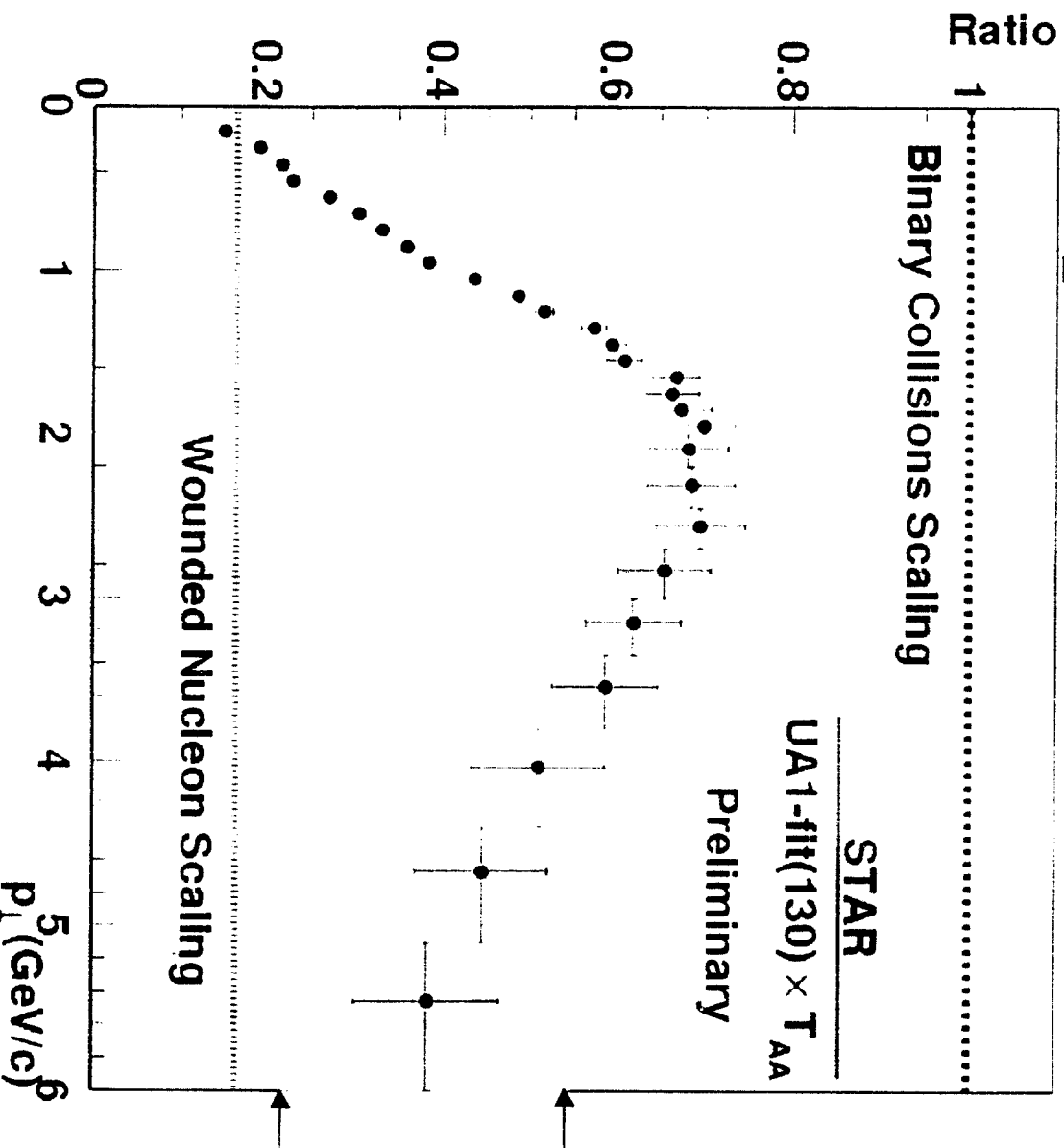
Nuclear Overlap Integral

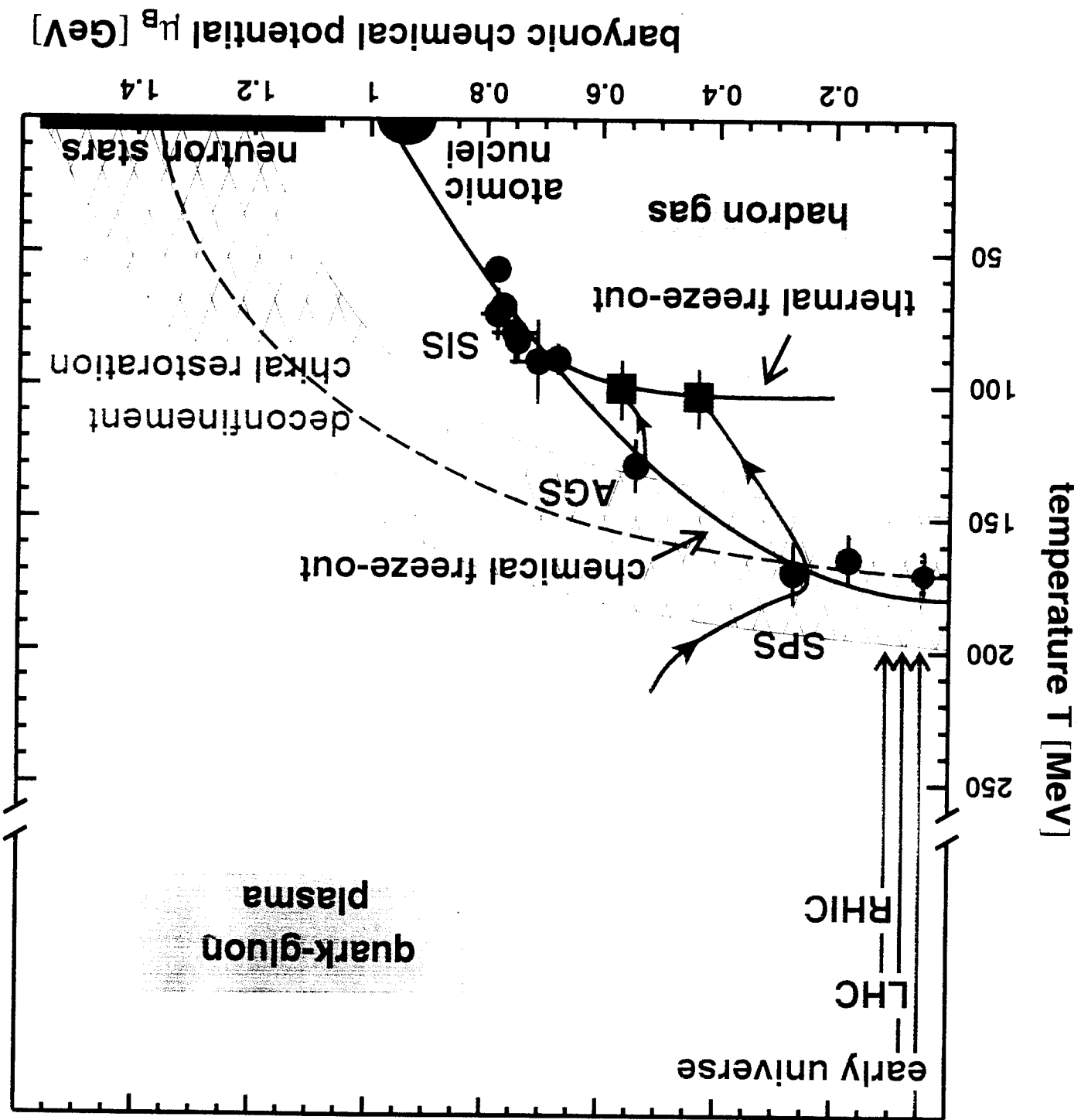
$T_{AA} = 26 \text{ mb}^{-1}$ for 5% most central

$N_{AA} / N_{pp} = N_{\text{bin coll}} = 1050$

"Soft" Scaling

$N_{AA} / N_{pp} = (344 / 2)$





→ The Little Bang

- Relativistic heavy ion collisions have taken us into unprecedented regions of energy density:
 - $\epsilon_0 \approx 3-4 \text{ GeV}/fm^3 \approx 20 \epsilon_{\text{nuclear matter}}$
 - $T_0 \approx 240-220 \text{ MeV}$ over large volume
- Strong evidence for large degree of thermalization and collective behavior.
 - Strangeness enhancement and χ, ψ suppression
 - patterns indicate initially dense, strongly interacting color-decoupled partonic phase ("QGP")
- "Primordial hadron synthesis": statistical hadronization of "QGP" into maximum entropy state of "pre-established classical equilibrium"
 - at $\epsilon_{\text{crit}} \approx 1 \text{ GeV}/fm^3$, $T_{\text{chem}} = T_{\text{had}} \approx 170 \text{ MeV}$
- "Thermal hadron radiation": momentum distribution decouple at $T_{\text{therm}} \approx 90-100 \text{ MeV}$
- "Hubble-like expansion": At decoupling strong radial expansion with $\langle v_T \rangle > 0.5c$

Summary