Heavy-Ion Physics
– Hydrodynamic Approach

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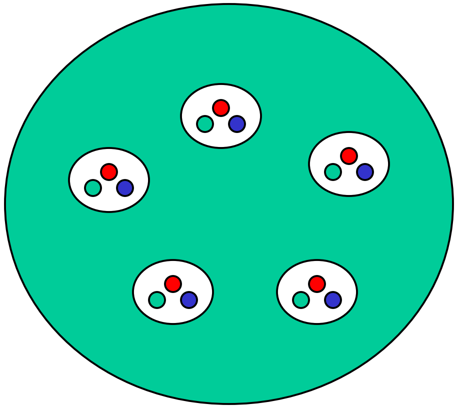
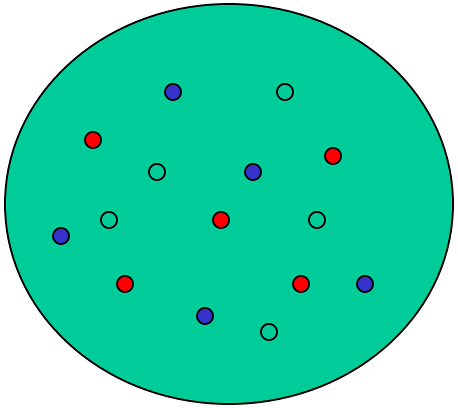
- Introduction
- Hydrodynamic aspect
- Observables explained
- Recombination model
- Summary

HIM 2008.11.14

Nuclear matter at high temperature/ density





Normal nucleus

Nucleus at high T
or baryon density

$$r = r_0 A^{1/3}$$

$$\rho = \rho_0$$

Strong interaction

QCD – color
– confinement
– asymptotic freedom
– gluon

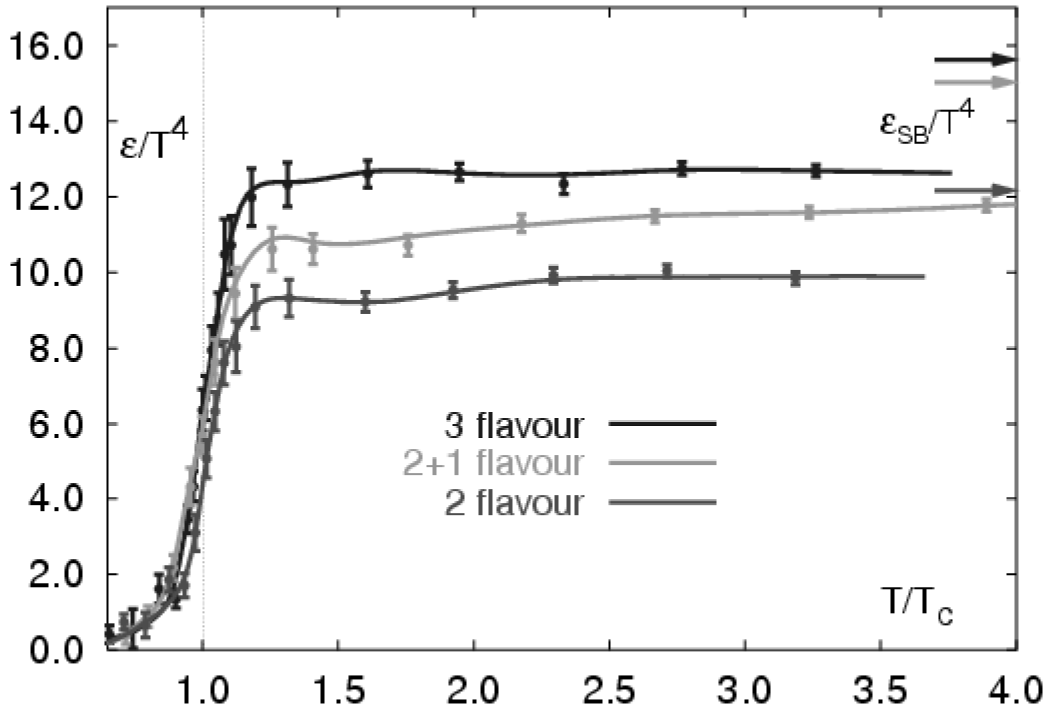
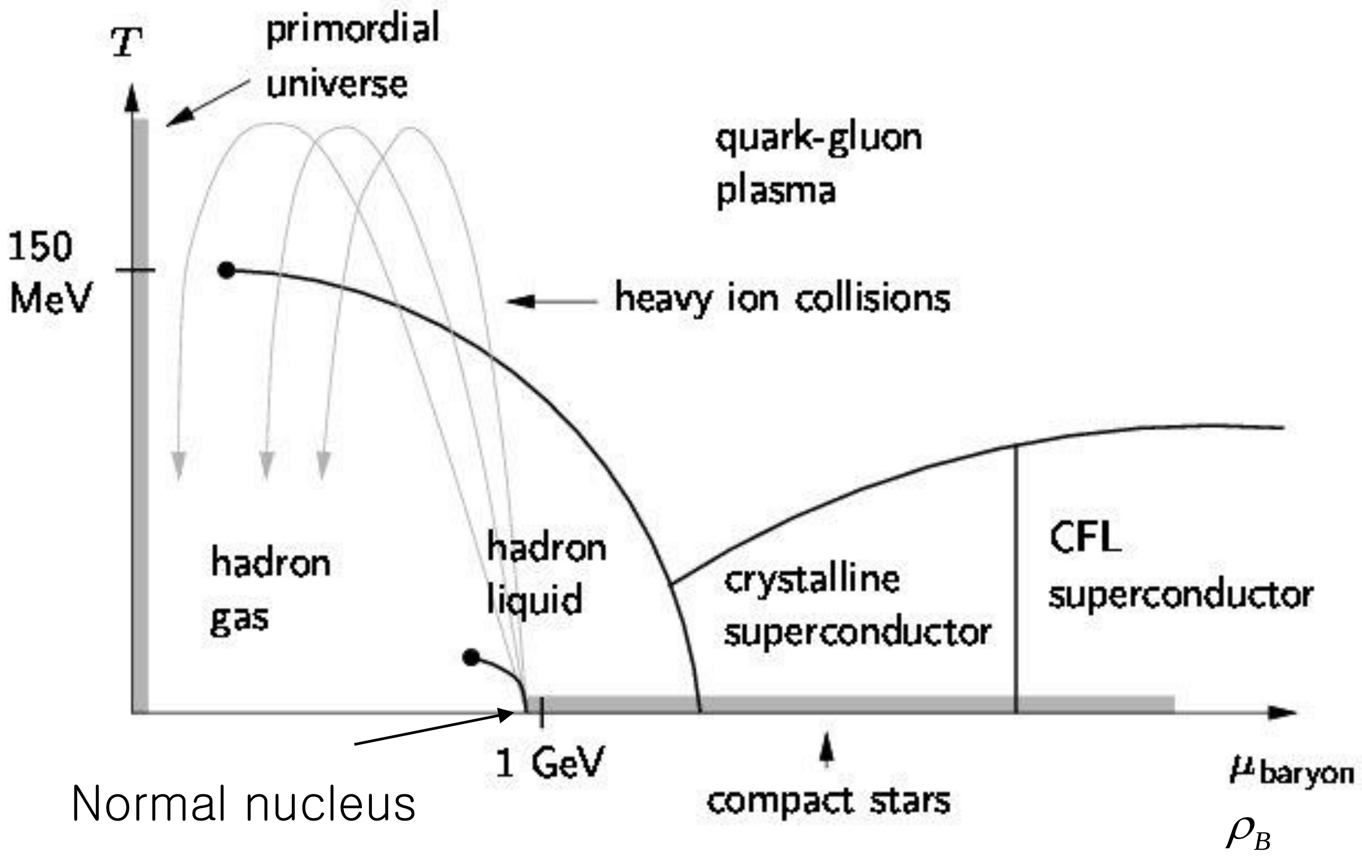
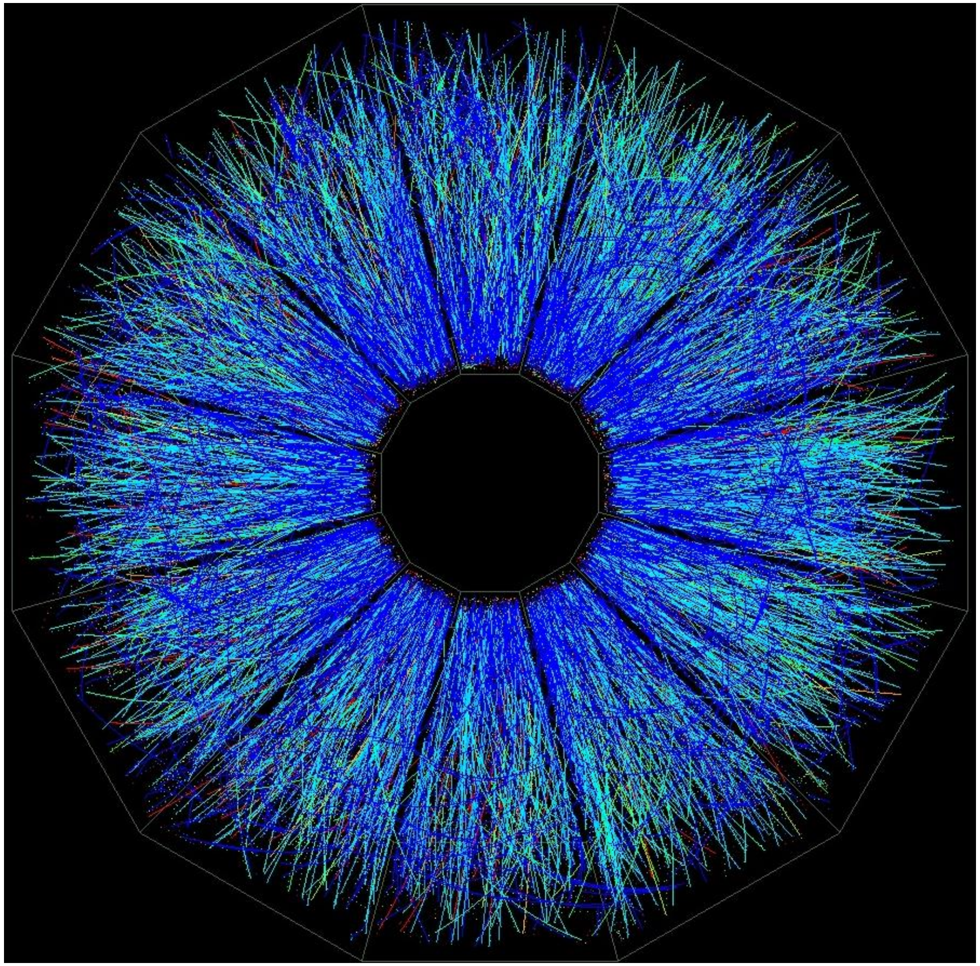


FIG. 2: Scaled energy density ϵ/T^4 for thermal lattice-QCD with two and three light quark flavors and for two light and one heavier flavor (from Karsch [43]).

Phase structure of QCD



Relativistic heavy-ion collisions



- Brookhaven AGS
  S+Au 15GeV A

- CERN SPS
  Pb+Pb 158GeV A

- RHIC
  Au+Au 200 Gev A

- LHC : ALICE, CMS
  -under construction

Landau Hydrodynamics

Landau, Izv. Akad. Nauk SSSR 17,51(1953)
Nuovo Ciment, Suppl. 3, 11115(1956)

pp collision
Initial condition – initial entropy of the system
adiabatic hydrodynamic motion
constant total entropy – constant number of particles
longitudinal expansion followed by transverse expansion

has successfully explained

1. total number of produced charged particles
2. rapidity distribution dN / dy

Hydrodynamic equations

$$\partial_\mu T^{\mu\nu} = J^\nu$$

Energy momentum tensor

$$T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - Pg^{\mu\nu}$$

Longitudinal expansion

$$\frac{\partial T^{00}}{\partial t} + \frac{\partial T^{01}}{\partial z} = 0$$

$$\frac{\partial T^{01}}{\partial t} + \frac{\partial T^{11}}{\partial z} = 0$$

Transverse expansion

$$\frac{\partial T^{02}}{\partial t} + \frac{\partial T^{22}}{\partial x} = 0$$

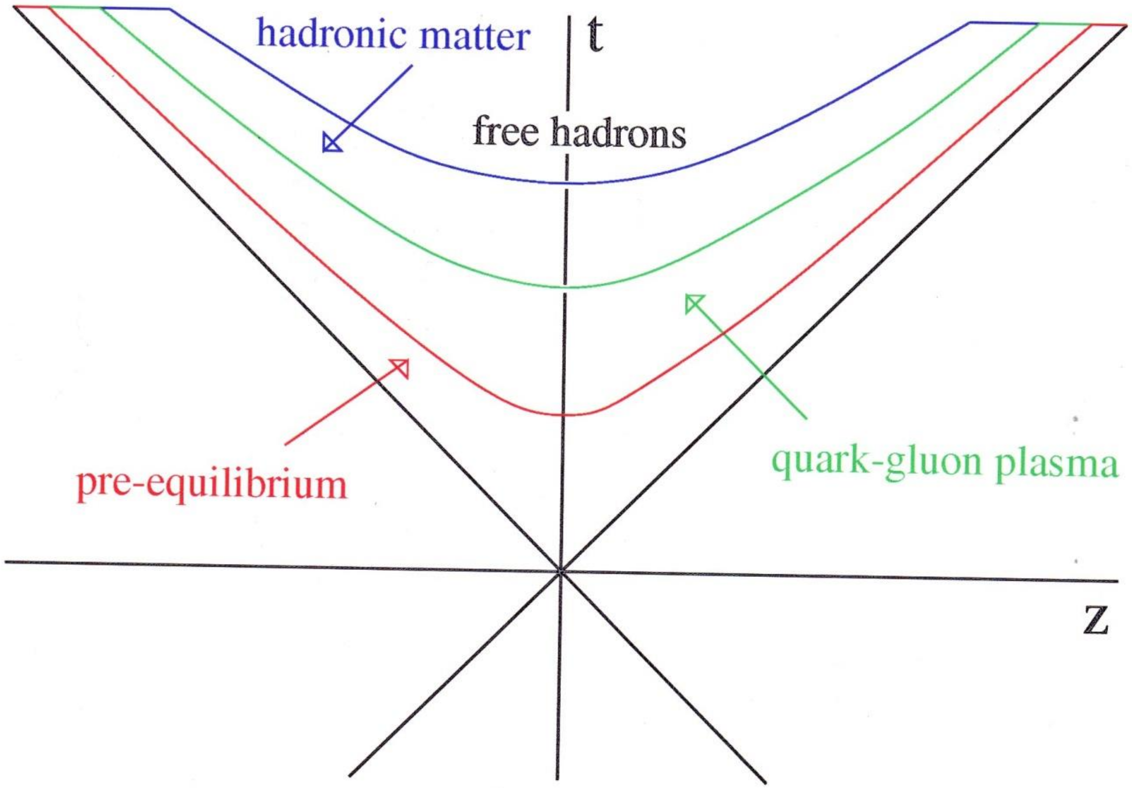
Equation of state

$$P = P(\varepsilon)$$

$$P = \varepsilon / 3$$

for relativistic massless gas

Schematic view of heavy-ion collisions



fireball model

Cooper–Frye formula for produced hadrons

$$E\frac{d^3N}{dp^3} = \int p_\mu d\sigma_\mu \frac{1}{e^{-p_\mu u_\mu / T} \pm 1}$$

$d\sigma_\mu$: freeze-out hypersurface

Particle Ratios

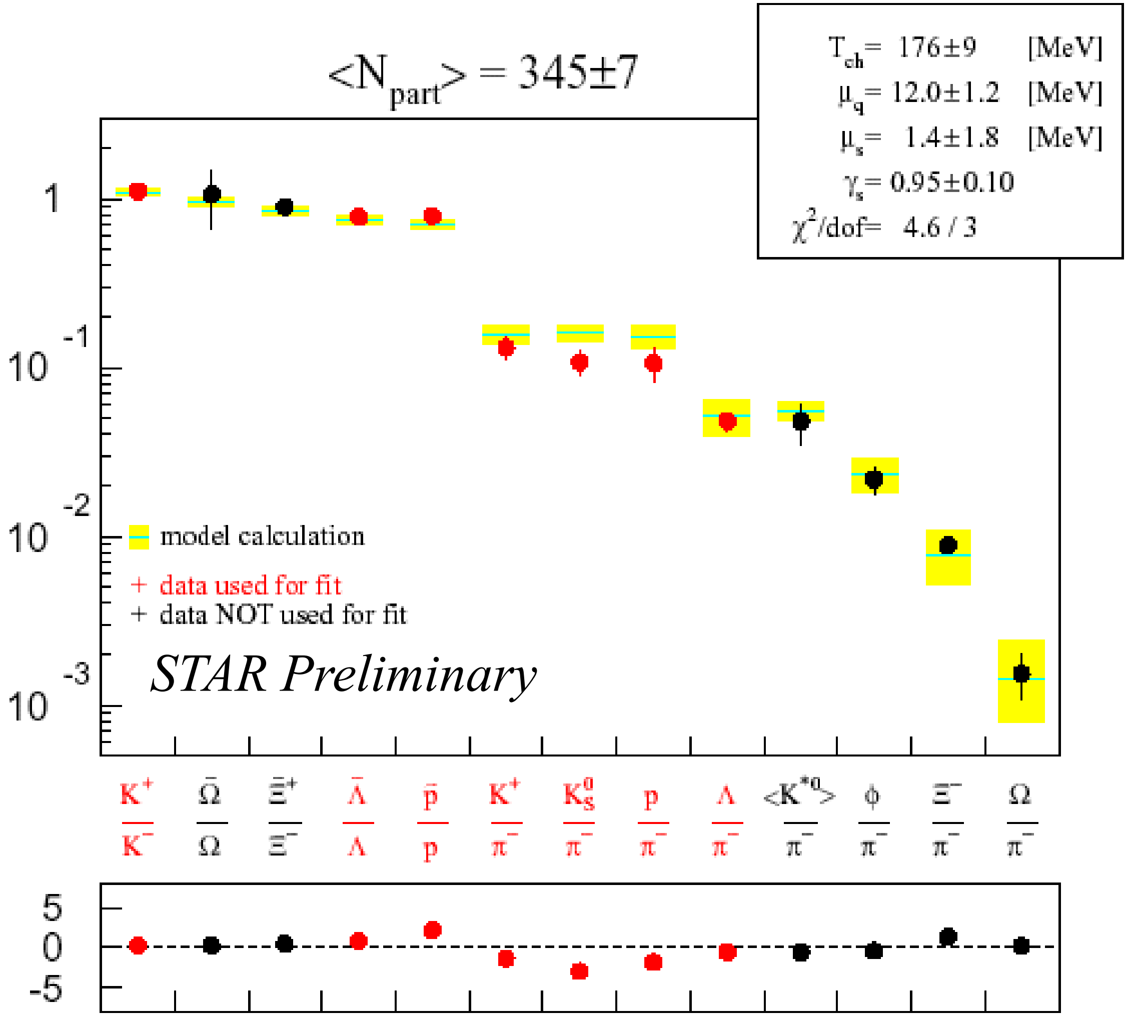
Central
130 GeV Au+Au

$$R = e^{-(\mu_i - \mu_j)/T}$$

Agreement between model and data is very good!

fit parameters :

$$T, \mu_B, \mu_S$$



STAR QM Poster: M. Kaneta

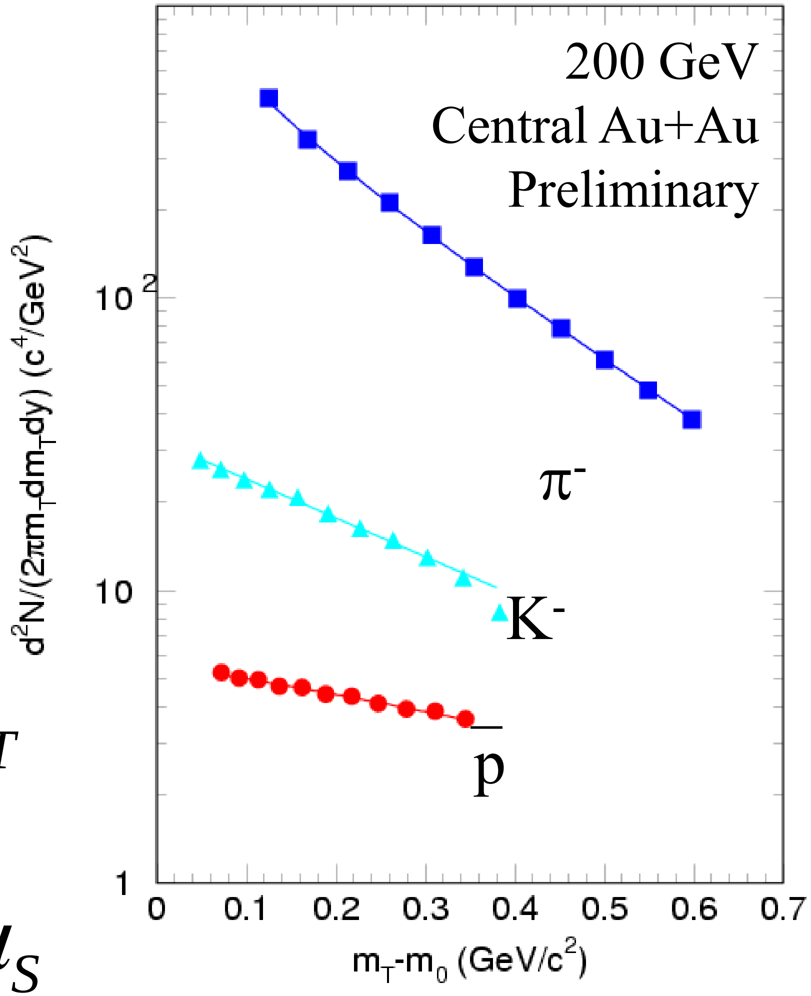
transverse momentun spectra

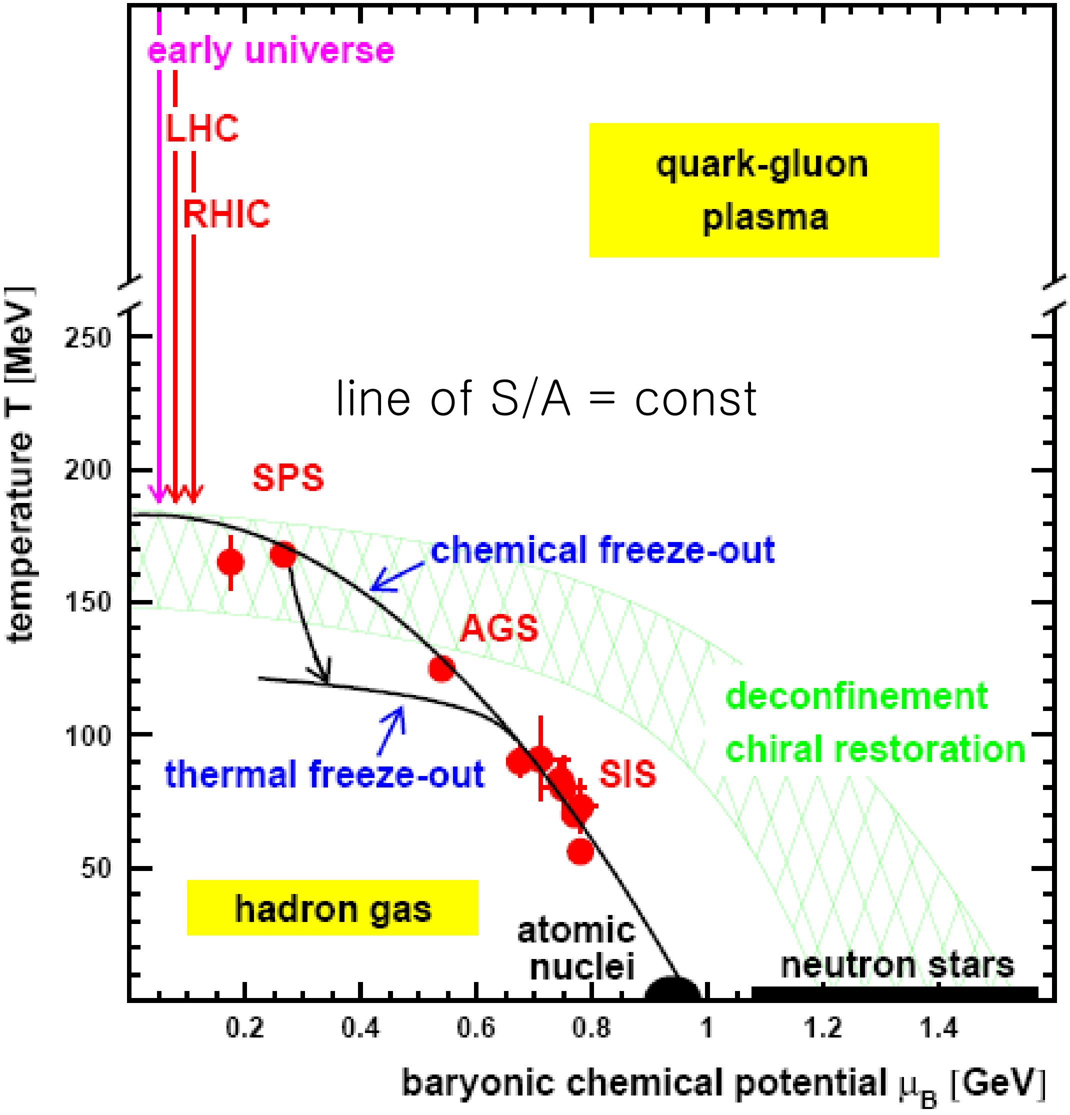
- Exponential shape
- Higher the mass, flatter the slope
- Fits all the different slopes simultaneouly

$$dN / p_T dp_T \propto e^{-p_\mu u_\mu / T}$$

$$\approx e^{-\gamma(E-\beta P_L)/T}$$

fit parameters T, β, μ_B, μ_S





line of S/A = const

Early chemical freeze-out followed by later thermal freeze-out

- Particle numbers fixed after chem. f.o. until thermal f.o.
  - need many chem. pot.

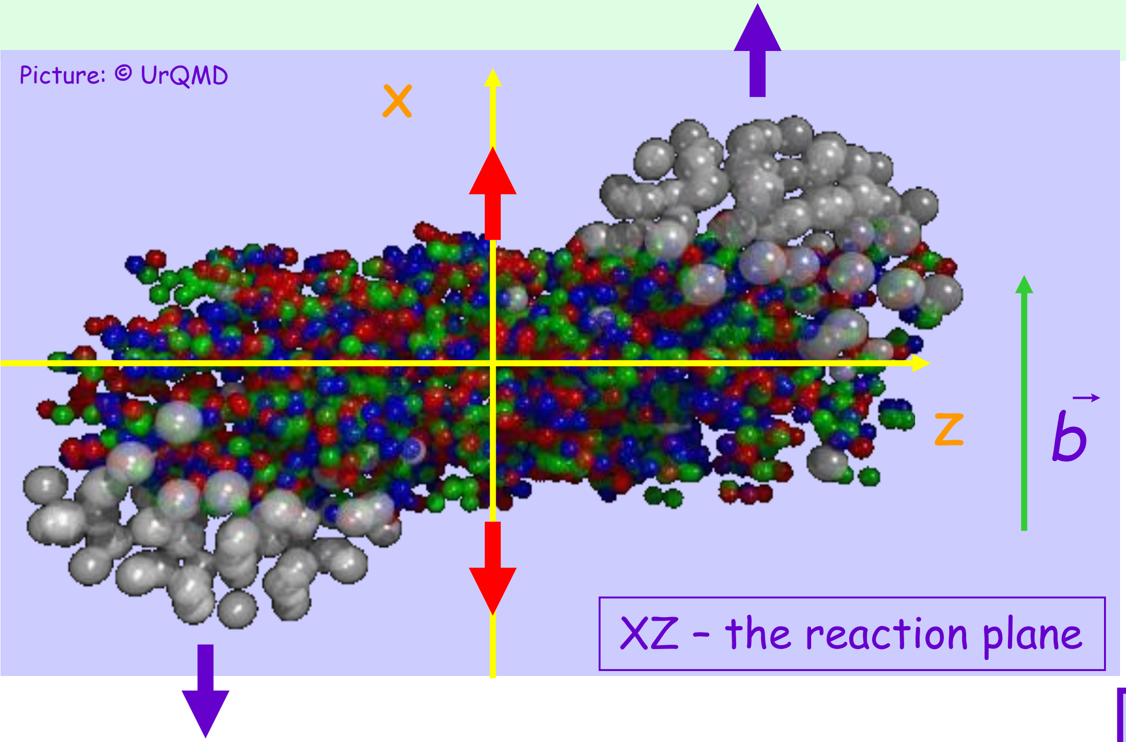
Teaney , Hirano

- Chem. f.o. + hadron cascade

Nonaka, Bass

Sudden hadronization ?

Elliptic coefficient v2

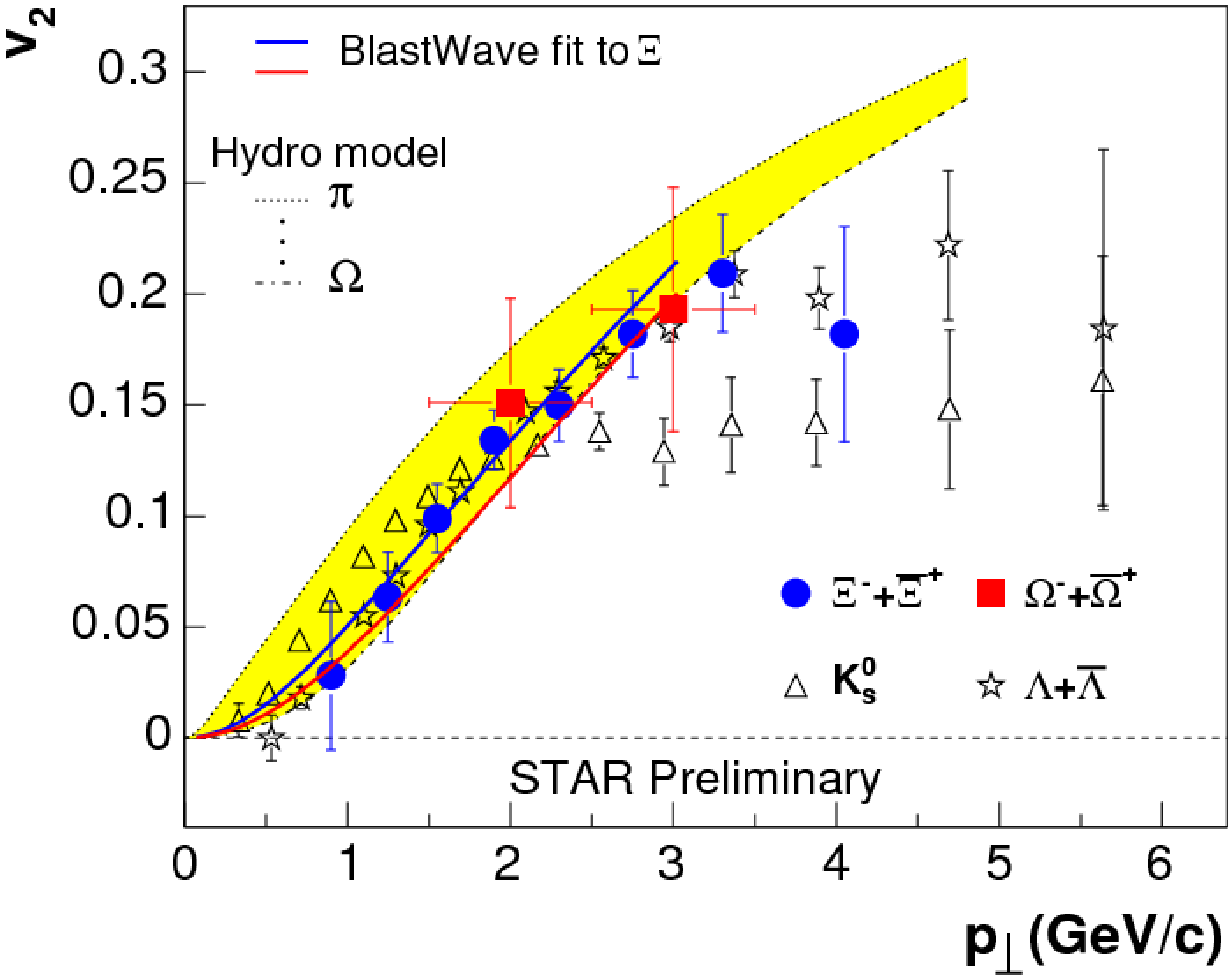


Anisotropic flow ≡ correlations with respect to the reaction plane

$$\frac{d^3N}{dp_t\,dy\,d\varphi} = \frac{d^2N}{dp_t\,dy}\,\frac{1}{2\pi}\left(1+2v_1\cos(\varphi)+2v_2\cos(2\varphi)+\ldots\right)$$

Directed flow

Elliptic flow


v₂
BlastWave fit to Ξ
Hydro model
π
Ω
Ξ⁻+Ξ̄⁺
Ω⁻+Ω̄⁺
K⁰ₛ
Λ+Λ̄
STAR Preliminary
0
0.05
0.1
0.15
0.2
0.25
0.3
0
1
2
3
4
5
6
p⊥(GeV/c)

Elliptic coefficients agree with those from the hydrodynamic calculation for the **perfect fluid**

- should be system of quarks and gluons but not of hadrons

Son : There exists **lower limit** of η / S , where η is bulk viscosity.

Ads/CFT

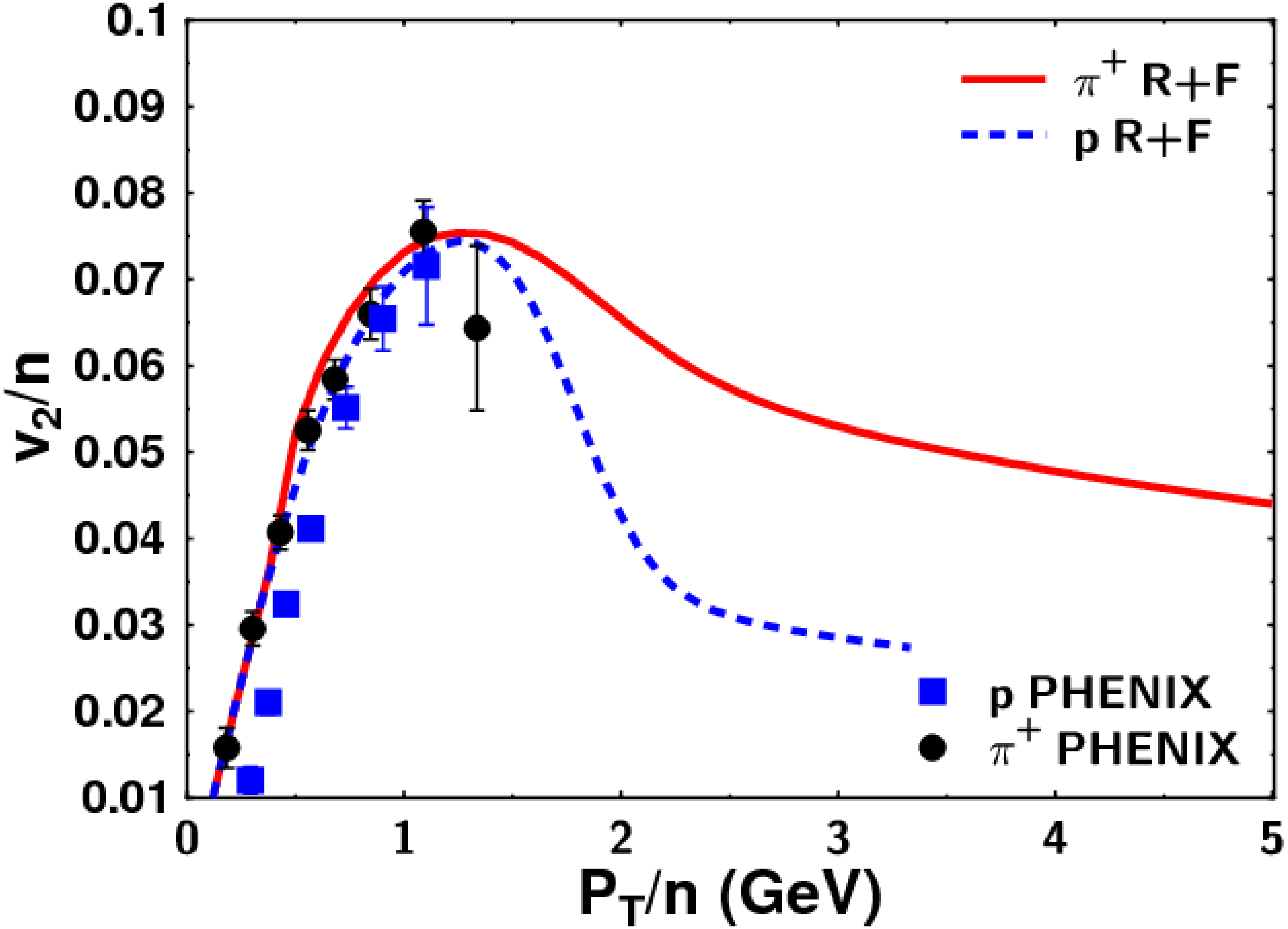
How can this contradiction reconciled?

- viscous relativistic hydrodynamics is being actively studied.
- problem of causality : Israel-Stewart formulation

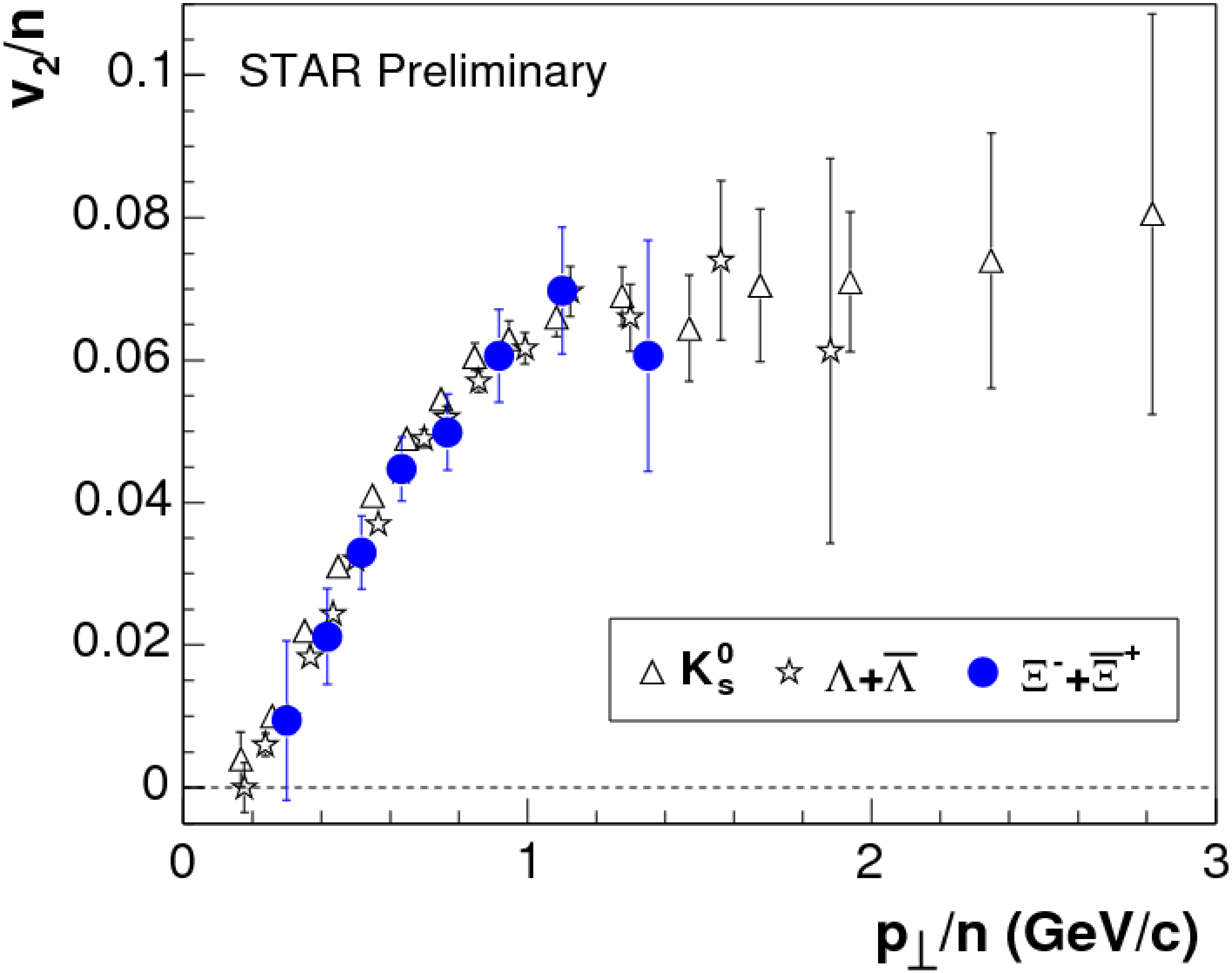
- **Son's prediction may be wrong.**

V2 and pT per number of constituent quarks scales.

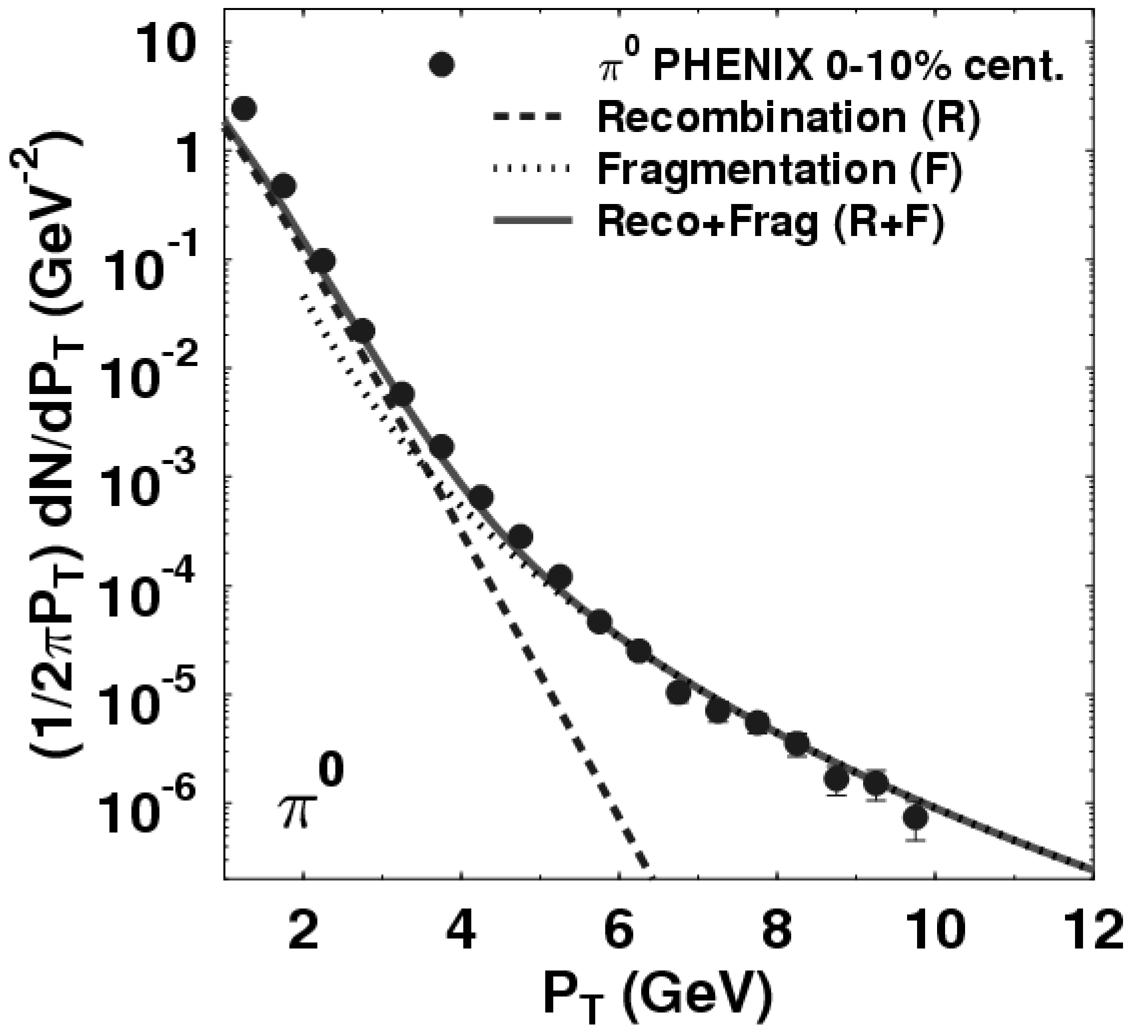
- quarks show collective behavior.



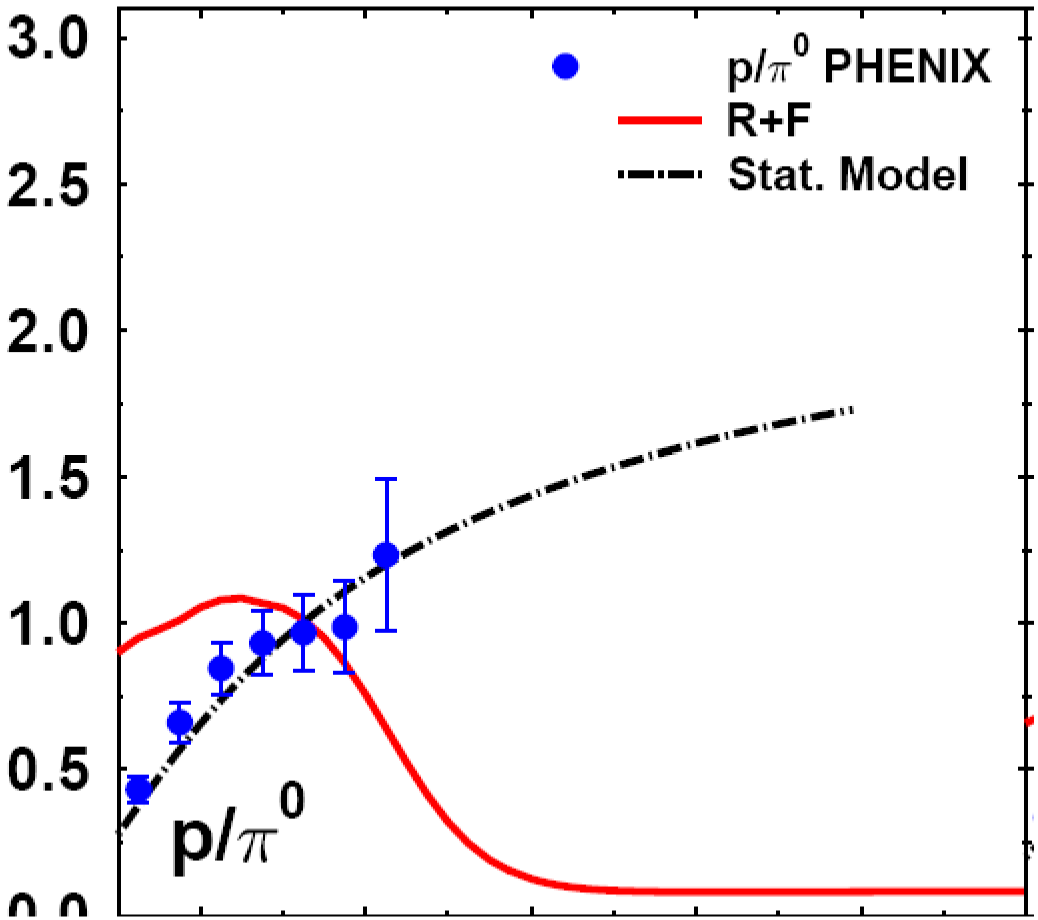
Constituent quark number scaling
– quarks show collective flow



Transverse momentum spectra in the large PT region



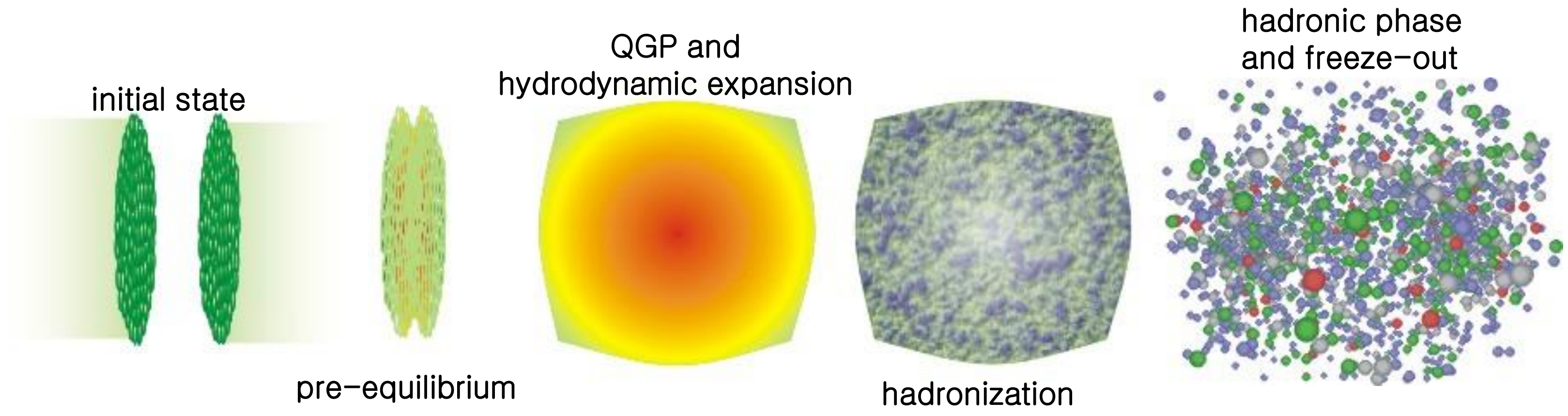
P/pion



Pt (GeV/c)

Recombination model

Dynamic recombination model



QGP

- hydrodynamic evolution - C. Nonaka
- reasonable for a perfect fluid

Hadronization via recombination

- recombination

Hadronic rescattering

- URQMD - S. Bass

mesons

$$E\frac{N_M}{d^3P} = C_M \int_{\Sigma} d\sigma_R \frac{P\cdot u(R)}{(2\pi)^3} \int_0^1 dx\, w_a(R; x\mathbf{P})\ \left|\phi_M(x)\right|^2\ w_b(R;(1-x)\mathbf{P})$$

baryons

meson wave function

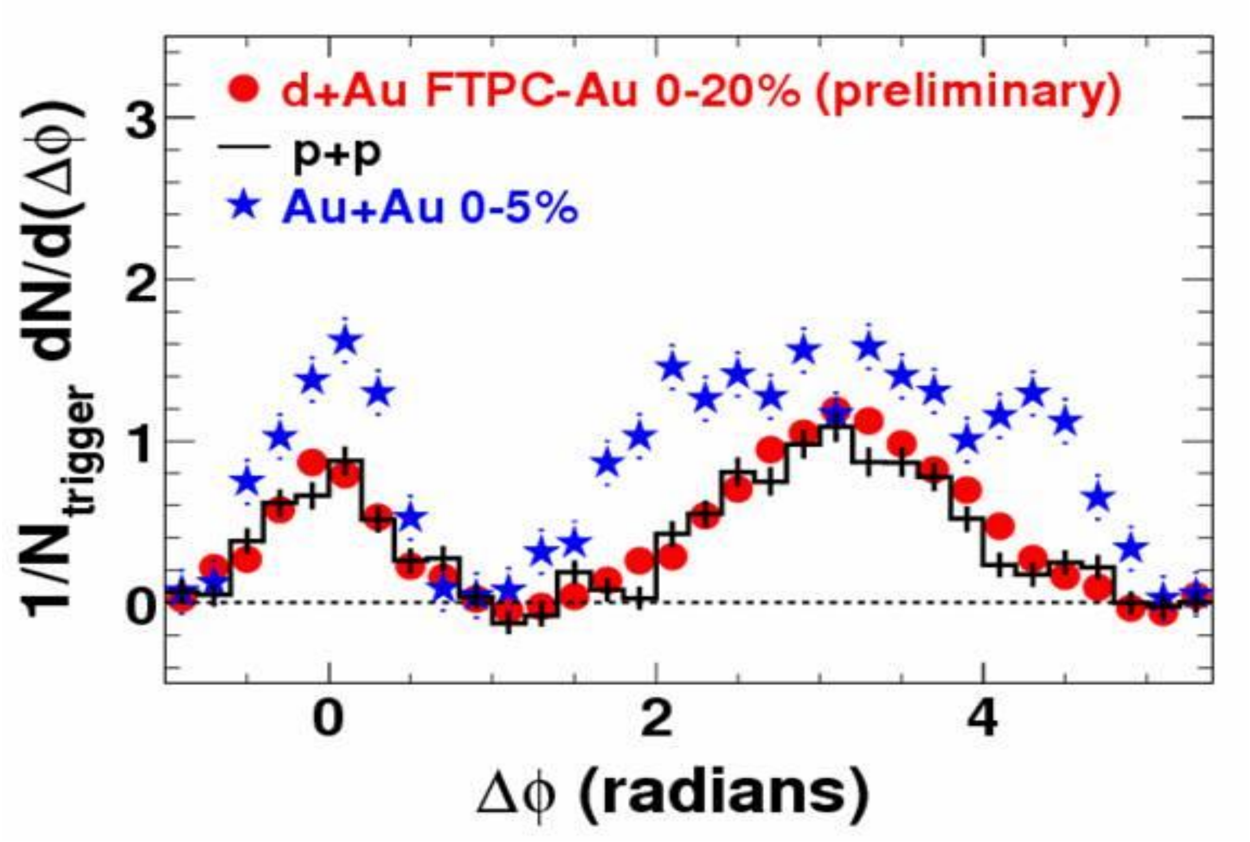
$$E\frac{N_B}{d^3P} = C_B \int d\sigma_R \frac{P\cdot u(R)}{(2\pi)^3} \int \mathcal{D}x_i\, w_a(R; x_1\mathbf{P}) w_b(R; x_2\mathbf{P}) w_c(R; x_3\mathbf{P})\ \left|\phi_B(x_1, x_2, x_3)\right|^2$$

quark distribution

$$w_a(R;p) = \gamma_a e^{-p\cdot v(R)/T} e^{-\eta^2/2\Delta^2} f(\rho,\phi)$$

Degeneracy factor C_M or C_B

Quenching or broadening of away-side jet?



- $4 < p_T^{trig} < 6$ GeV/c

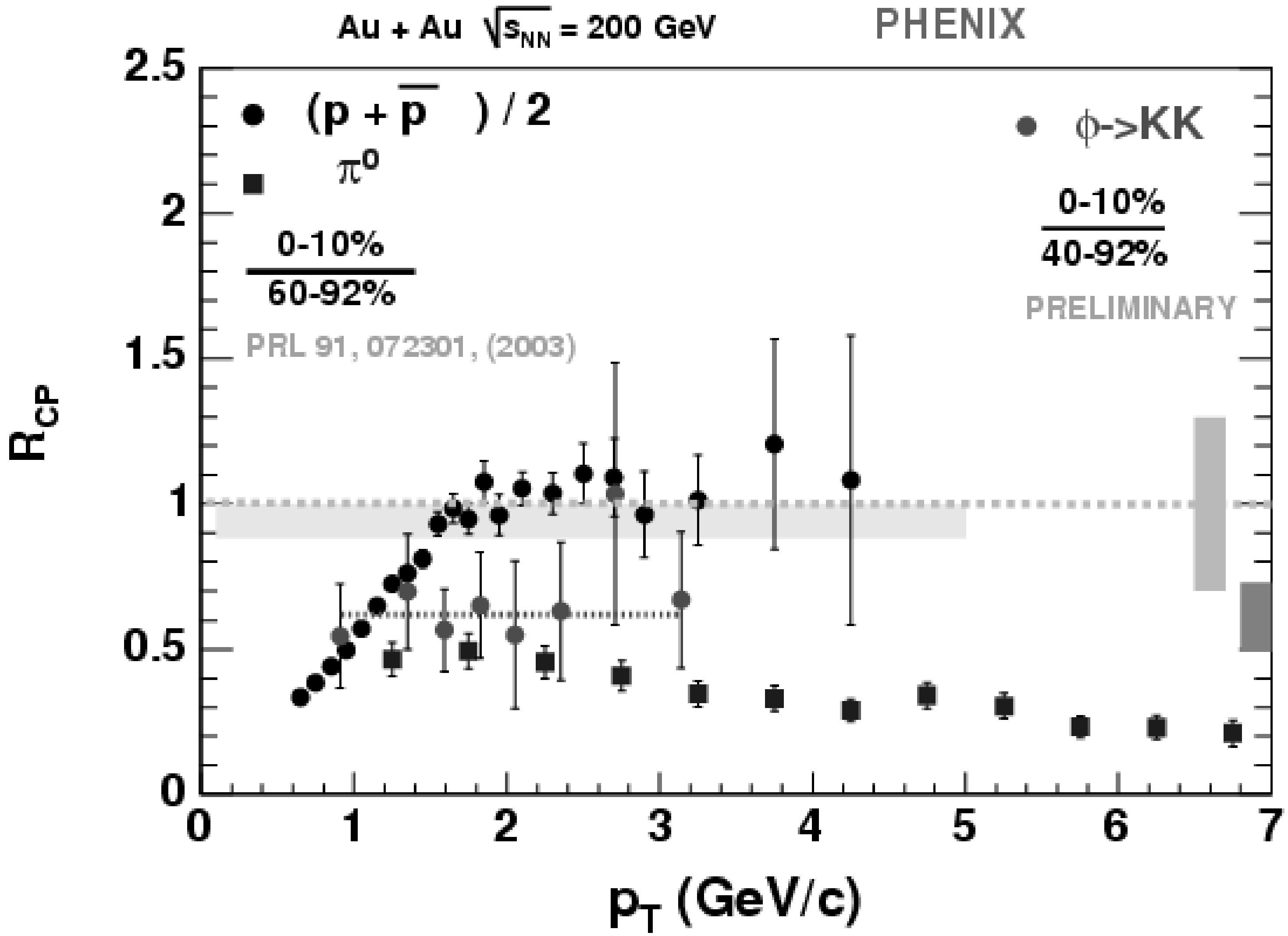
summary

- Hydrodynamic approach in heavy-ion collisions is quite successful in many of the observables.

- RHIC has revealed many new features
  - high pt suppression of hadrons
  - elliptic flow : strongly interacting perfect liquid vs. lower limit of η / S
  - viscous hydrodynamics
  - broadening of away-side jet : Mach cone?
  - ridge structure of near-side jet

- LHC is expected to show many interesting new Physics.

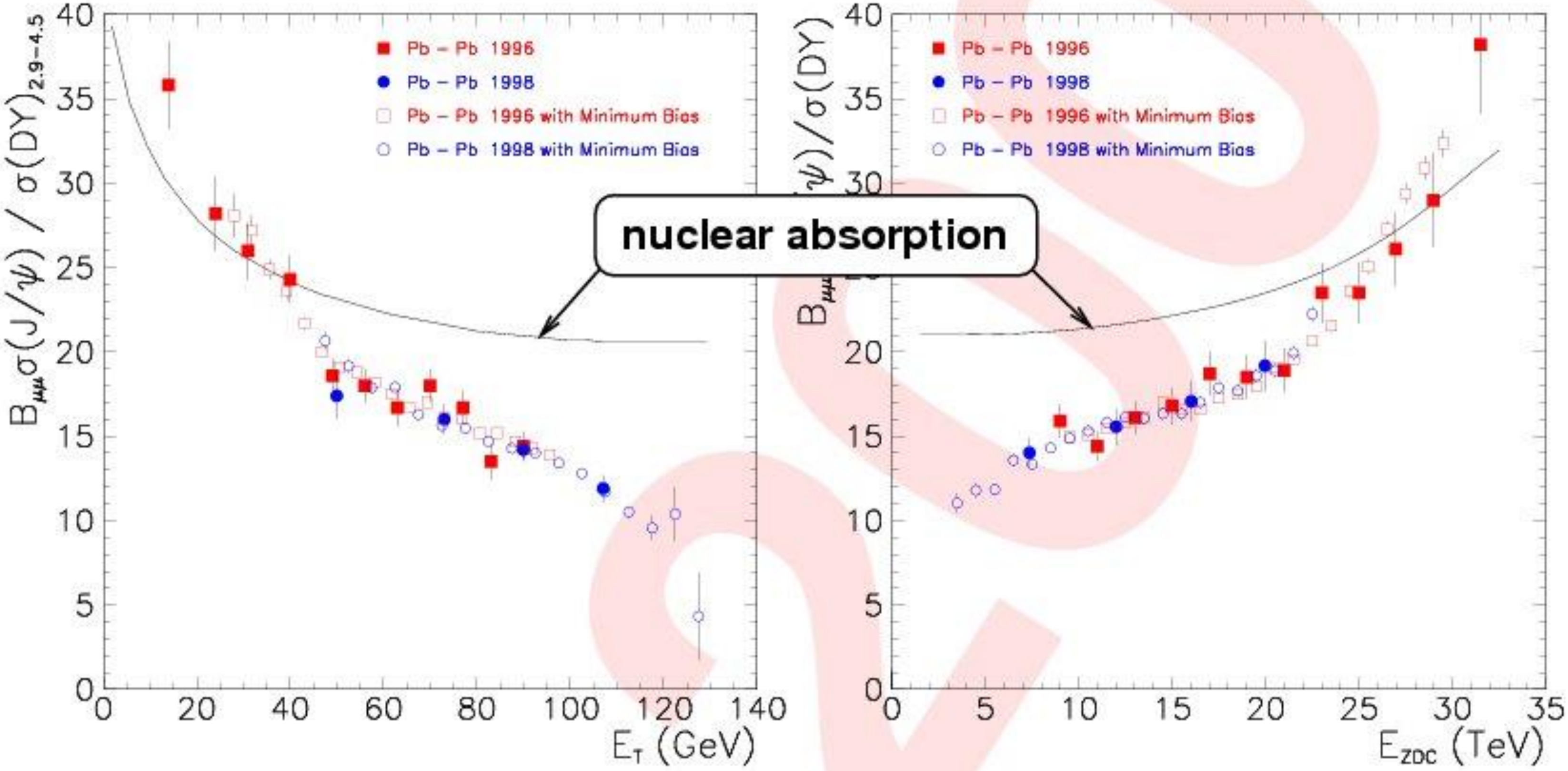
Suppression of high pt particles



J/ψ Anomalous Suppression

M.C. Abreu et al. Phys. Lett. B 477 (2000) 28, Phys. Lett. B 521 (2001) 195

(plots from F. Prino for NA50, Hirschegg 2002)



nuclear absorption