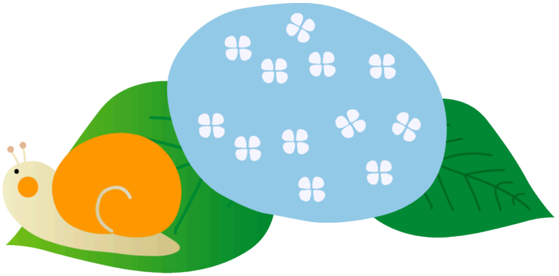
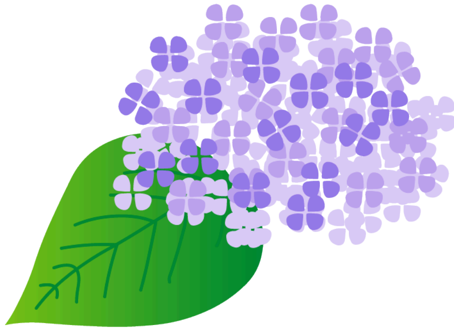
生成粒子の集団運動流（フロー）からみる高エネルギー原子核衝突

名古屋大学
野中　千穂



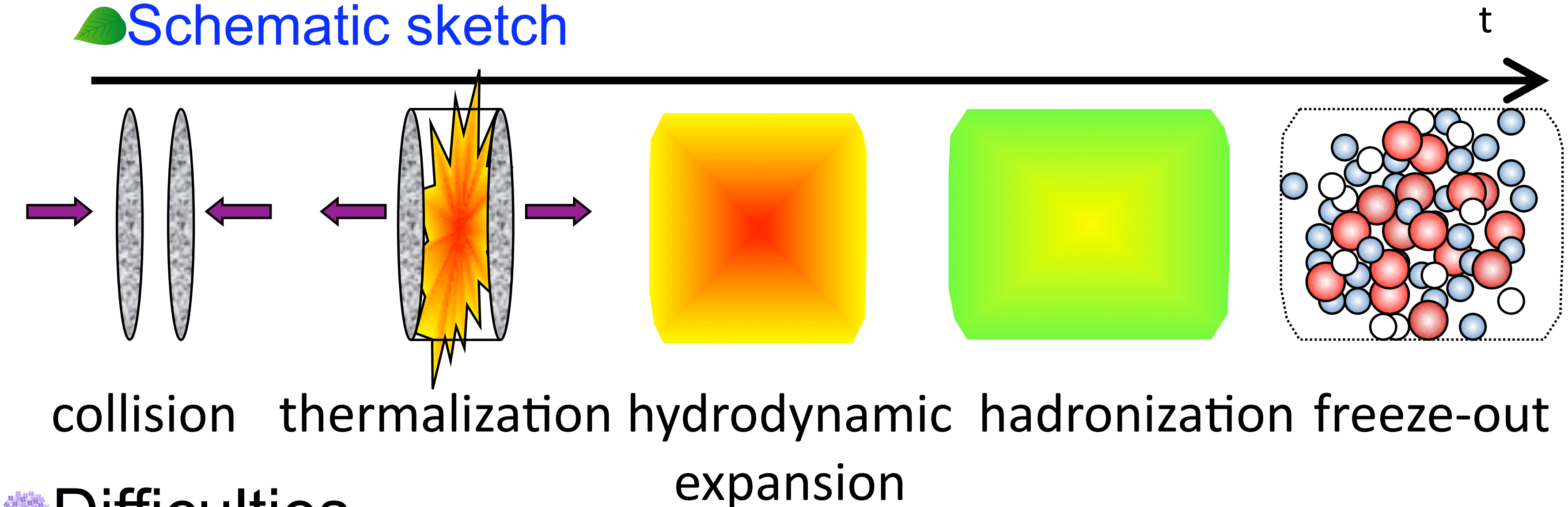
2008年6月16日＠第3回Heavy Ion Pub、名古屋

Introduction



How to find the QGP

- Relativistic Heavy Ion Collision
  - Schematic sketch



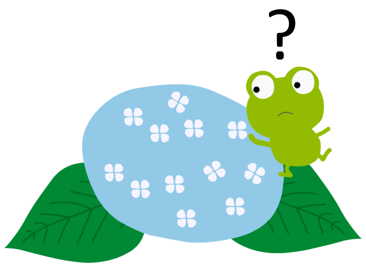
- Difficulties

•Complicated process

initial state
hydrodynamic expansion
hadronization
freeze-out

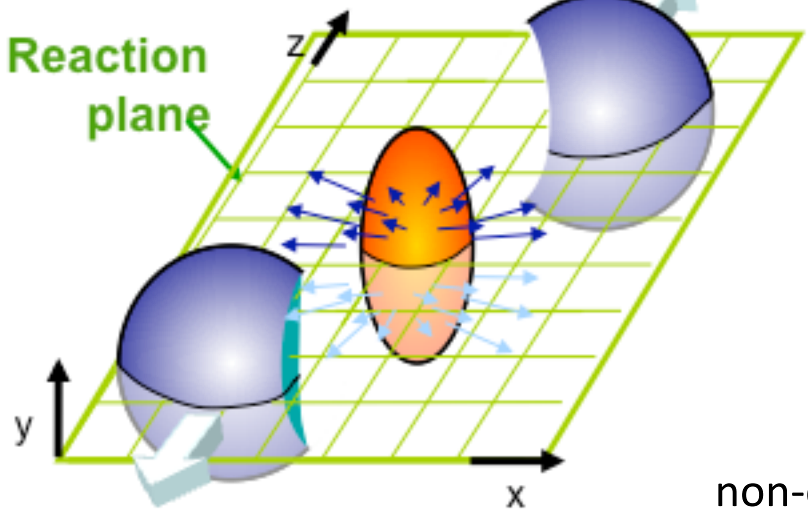
•QGP signature ?

hadron spectra
two particle correlations
flow (radial, elliptic, direct)
fluctuation (charge, multiplicity)
electromagnetic probes…..

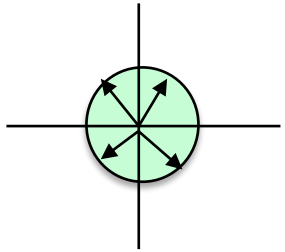


Collective Flow

collision axis



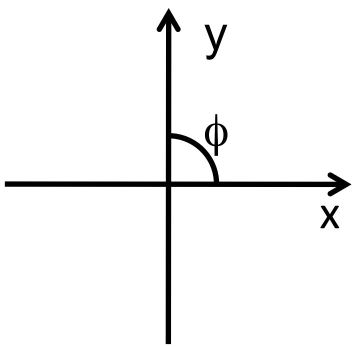
central collision

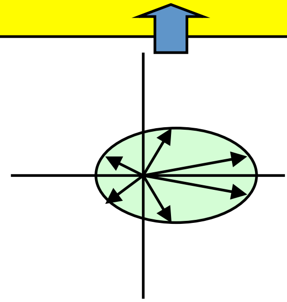


radial

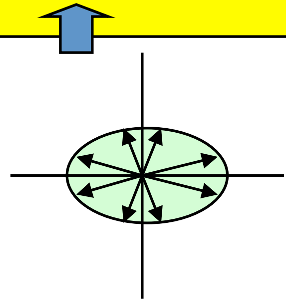
non-central collision

$$\frac{dN_i}{dyd\phi}\left(\frac{dN_i}{dyd\phi d^2P_T}\right) = N_{i0}\left(1 + 2v_1\cos(\phi - \phi_0\right) + 2v_2\cos 2(\phi - \phi_0) + \ldots)$$



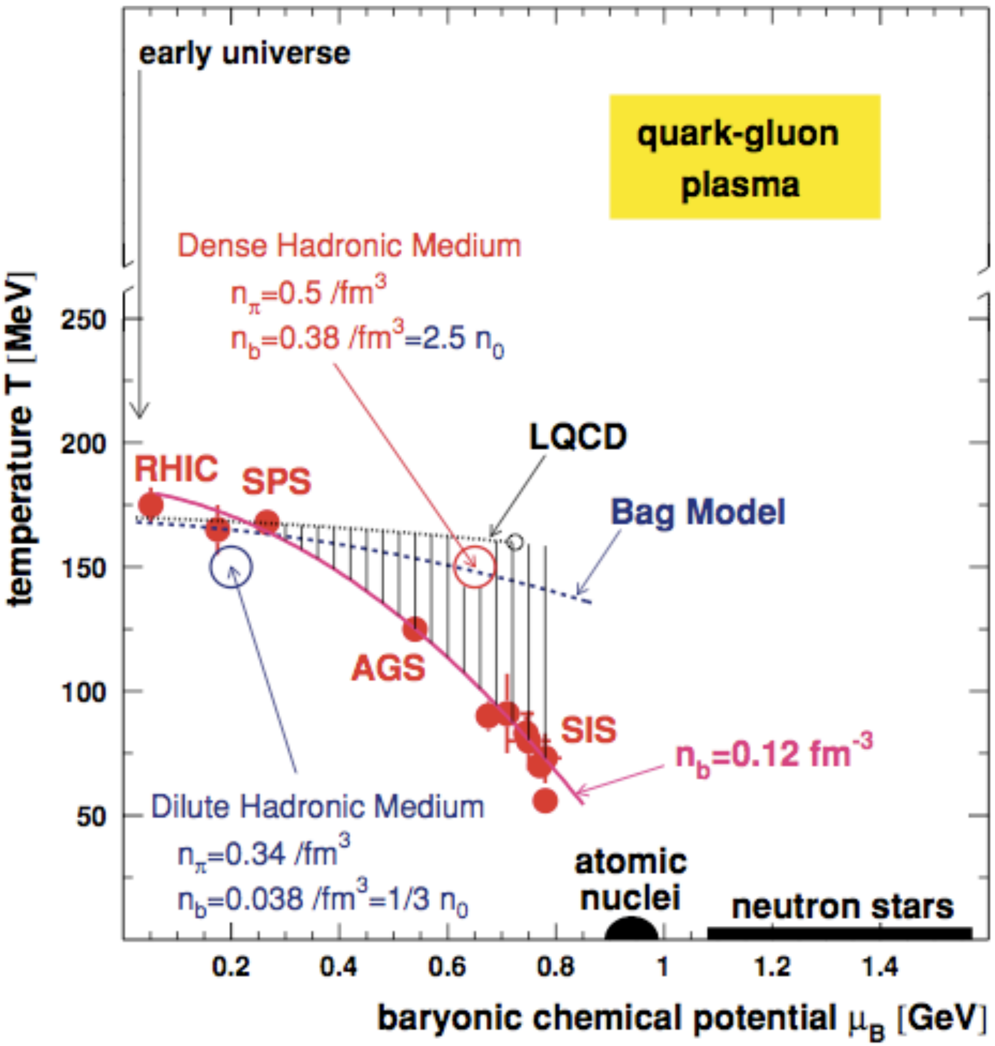


directed



elliptic

QGP on the Earth



Relativistic Heavy Ion Collision

			$\sqrt{s_{NN}}$ GeV
1987	BNL-AGS	Si	5
1987	CERN-SPS	S	20
1992	BNL-AGS	Au	4
1994	CERN-SPS	Pb	17
2000	BNL-RHIC	Au +Au	200
2010	CERN-LHC	Pb +Pb	5600

RHIC: Energy Frontier

RHIC Run History

run	year	species	$\sqrt{s_{NN}}$ GeV
1	2000	Au+Au	130
2	2001/02	Au+Au	200
		p+p	200
3	2002/03	d+Au	200
		p+p	200
4	2003/04	Au+Au	200
		Au+Au	62
		p+p	200
5	2004/05	Cu+Cu	200,62,22
		p+p	200
6	2006	p+p	62
7	2006/07	Au+Au	200
8	2007/08	d+Au	200

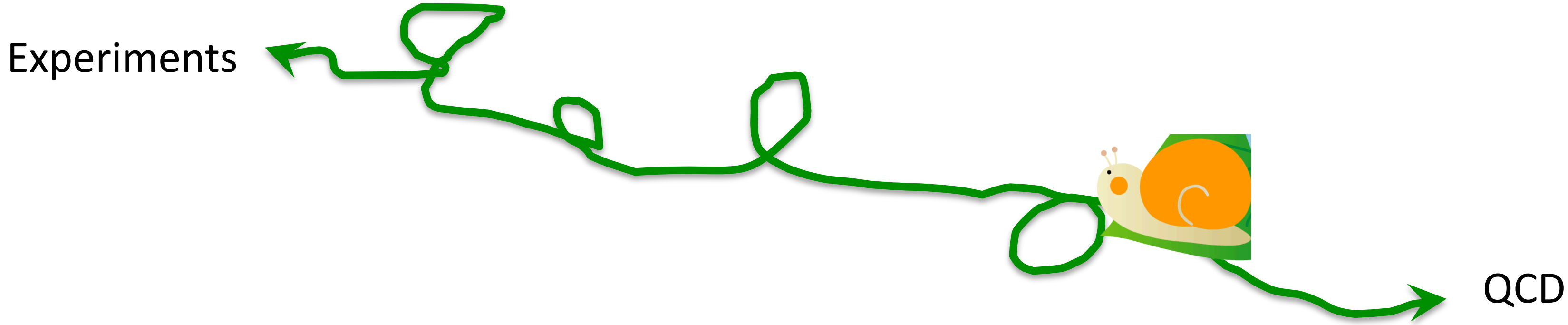
http://www.agsrhichome.bnl.gov/RHIC/Runs/

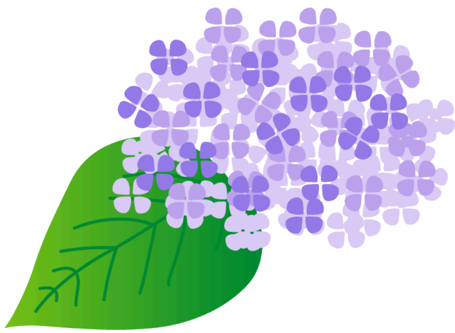
heavy ion collision

- **energy frontier**
- p+p : baseline
- d+Au: initial vs. final
- Cu+Cu: system size
- Energy dependence

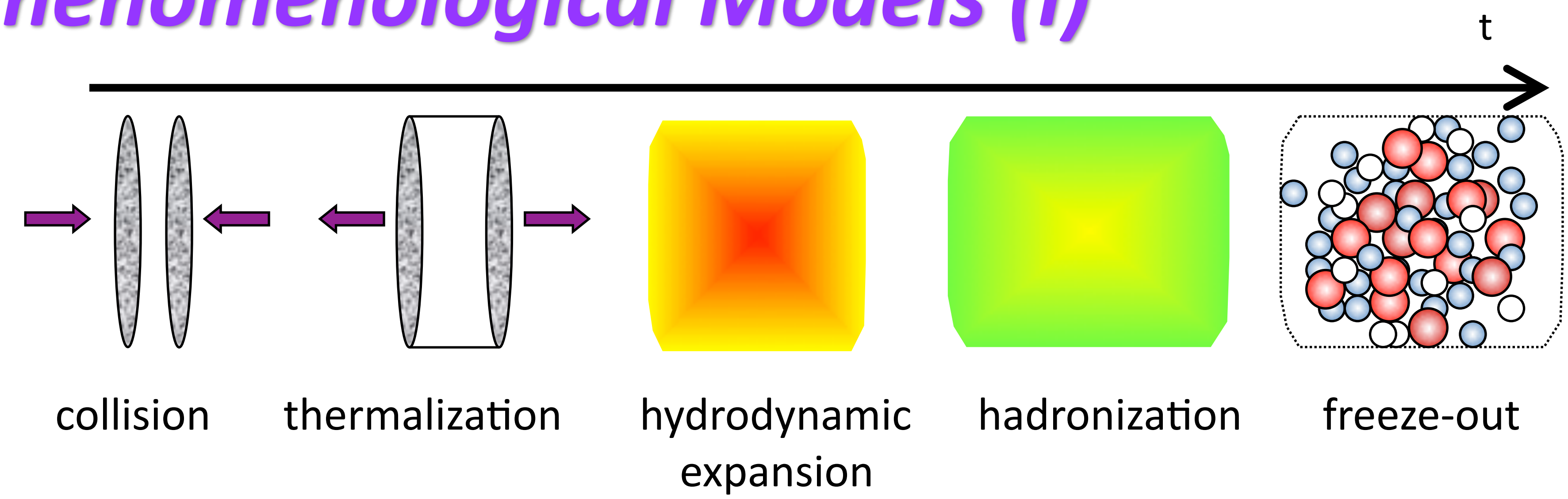
PHENIX, STAR, PHOBOS, BRAHMS

Phenomenological Analyses





Phenomenological Models (I)



Color Glass Condensate

Hydrodynamic Model

Cascade Model

Parton base

Hadron base

dynamical

static

Thermal ・Statistical Model

Phenomenological Models (II)

low P_T — intermediate P_T — high P_T → P_T

<2 GeV — $2 < P_T < 4\sim6$ GeV — $4\sim6 < P_T$ GeV

Hydrodynamic Model

Thermal・Statistical Model

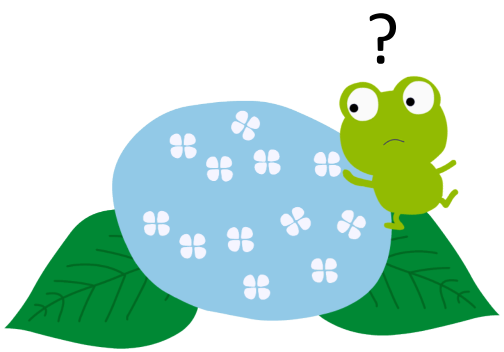
- Particle spectra
- Hadron ratios
- Collective flow

Recombination Model

- Particle spectra
- Hadron ratios
- Collective flow
- Nuclear modification factors

Perturbative QCD

- Nuclear modification factors
- Jets in medium



Collective Flow at RHIC

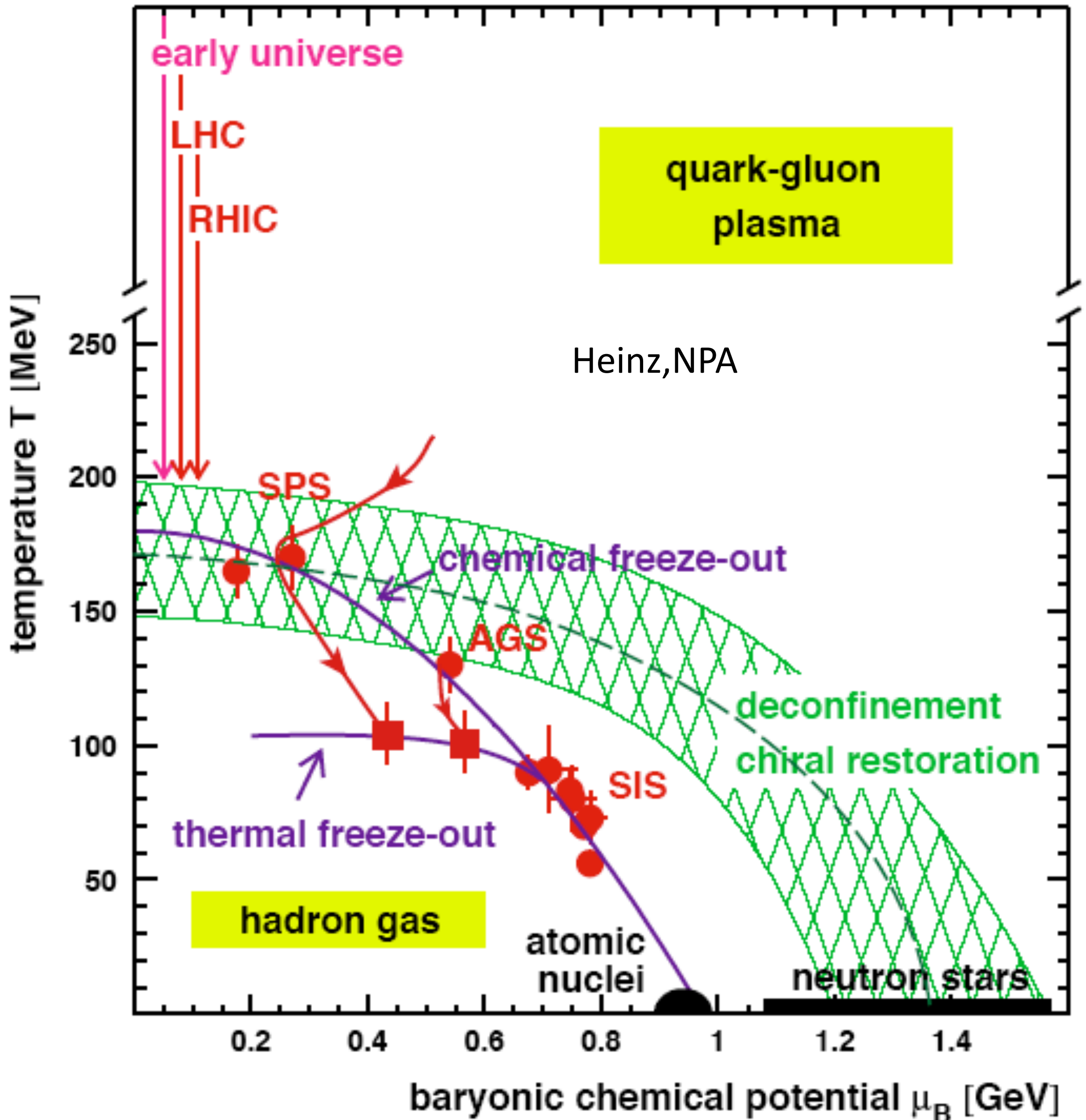
- Radial flow
- Elliptic flow
- Higher harmonics, $v_{4,}$ v_6
- Directed flow

Collective Flow at RHIC

- Radial flow
- Elliptic flow
- Higher harmonics, v_4, v_6
- Directed flow

- Data
  P_T spectra, m_T spectra
- Models
  - Hydro inspired model
    ex. blast wave model
  - Hydrodynamic model
  - Recombination model
- Physics
  - Kinetic freezeout temperature
  - Hadronization mechanism

Freezeout Temperature

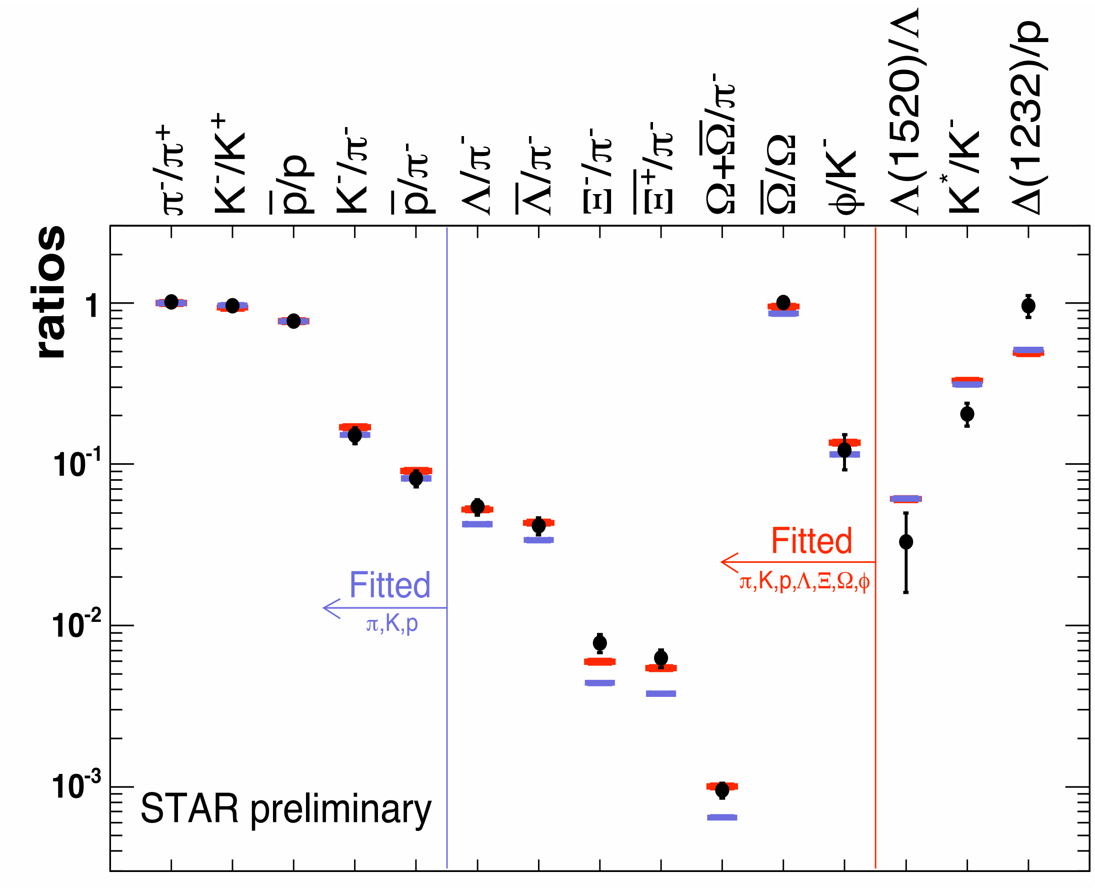


Statistical-Thermal Model

ex.Cleymans et al. , PRC71,054901(2005)

$$N_i^{\rm prim} = Vg_i \int \frac{d^3p}{(2\pi)^3} dm_i \left[\gamma_s^{-|S_i|} e^{\frac{E_i - \mu_i Q_i}{T}} \pm 1 \right]^{-1} BW(m_i)$$

$$N_i = N_i^{\rm prim} + \sum_j {\rm Br}^{i \to j} N_j^{\rm prim}$$



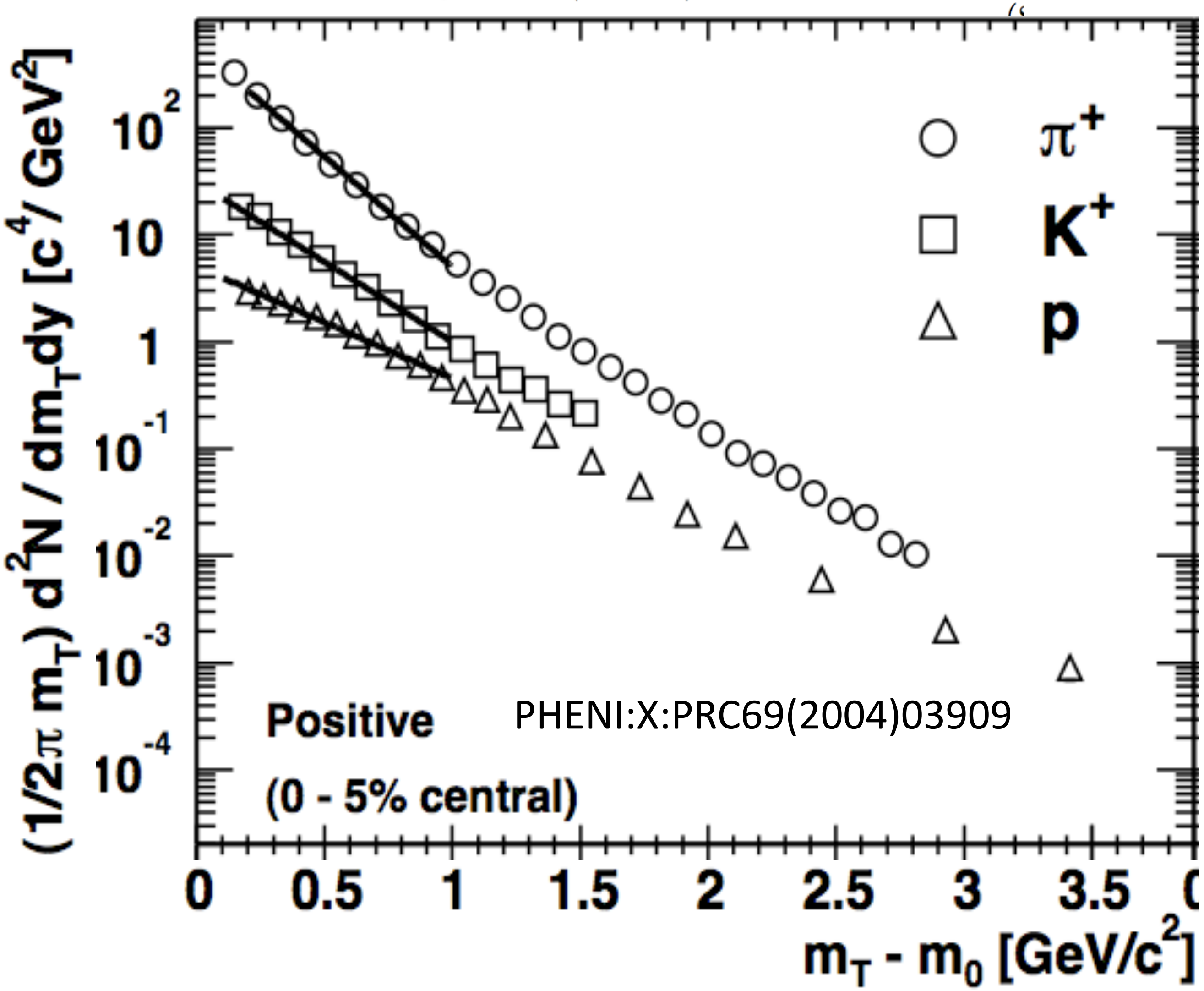
parameter fit:

T, μ_B, μ_s, γ_s

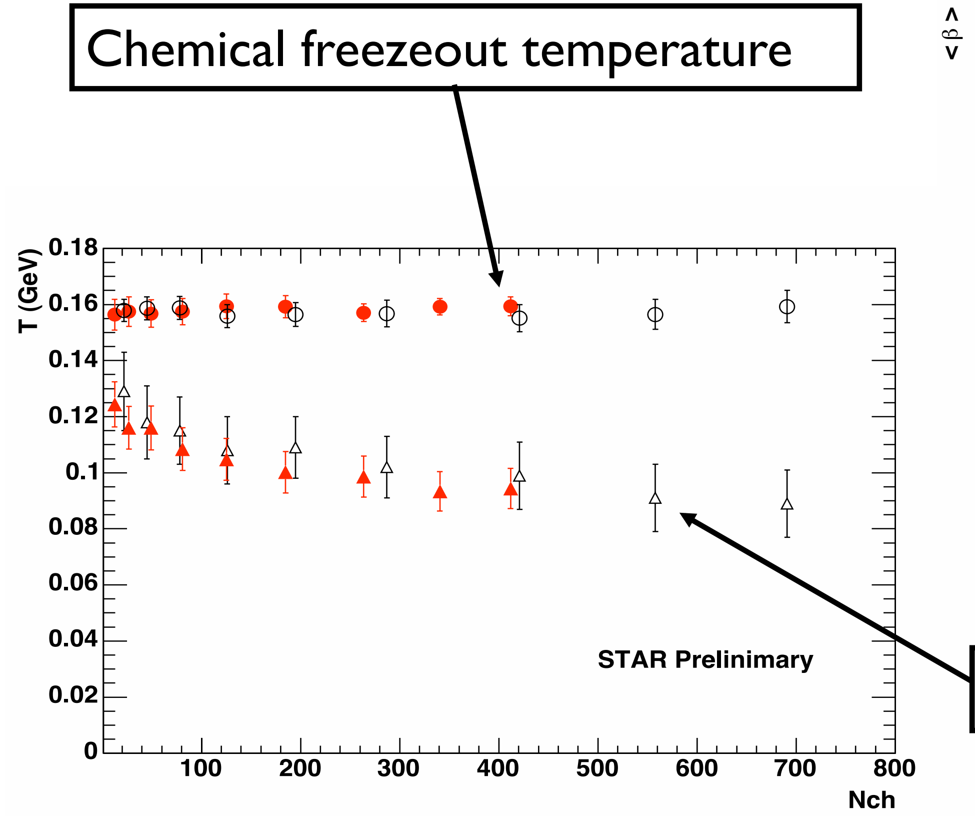
Chemical freezeout

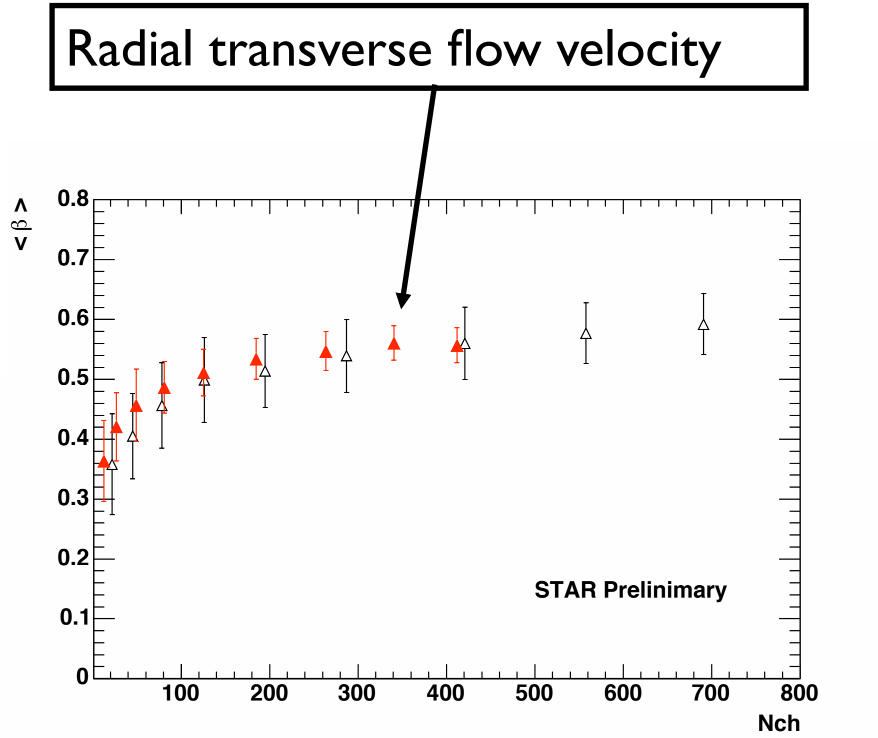
m_T Distributions

$$\frac{d^2N}{2\pi m_T dm_T dy} = \frac{1}{2\pi T(T+m_0)} \cdot A \cdot \exp\left(-\frac{m_T - m_0}{T}\right),$$

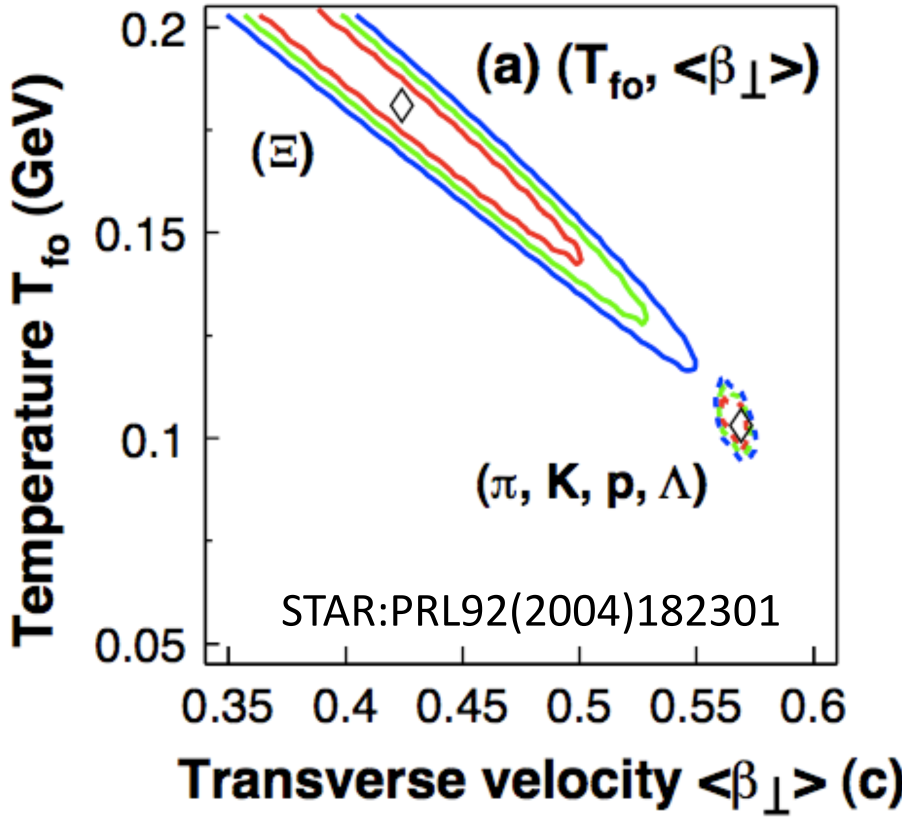


$T_{chem} \neq T_{kin}$





Multi Strange Particles



- π,K,p,Λ
  T_{chem}=160~170 MeV
  T_{kin}~100 MeV
- Multi strange particles
  T_{kin}~170 MeV
  Small cross section
  Information just after phase transition

- Parameterization by a simple model
  Detailed analyses: ex. Relativistic hydrodynamic model

Collective Flow at RHIC

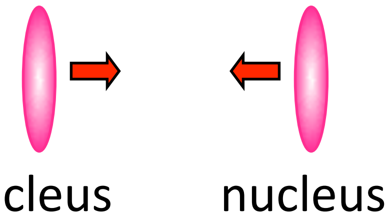
- Radial flow
- Elliptic flow
- Higher harmonics, v_4, v_6
- Directed flow

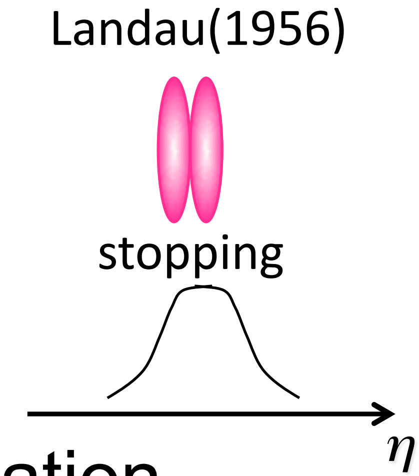
sQGP

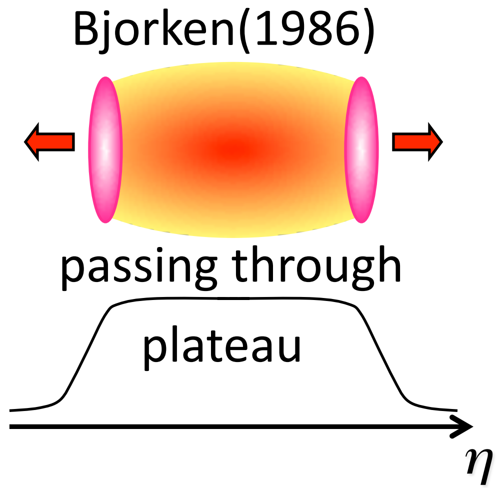
- Data
  - elliptic flow
    vs. P_T, rapidity, multiplicity
    system size, collision energy
  - fluctuations
- Models
  - Hydrodynamic model
  - Recombination model

Hydrodynamic Models

- Assumptions (for multiple particle production)
  - Local thermalization
  - Mean free path ~ 0







- Relativistic

  Hydrodynamic Equation

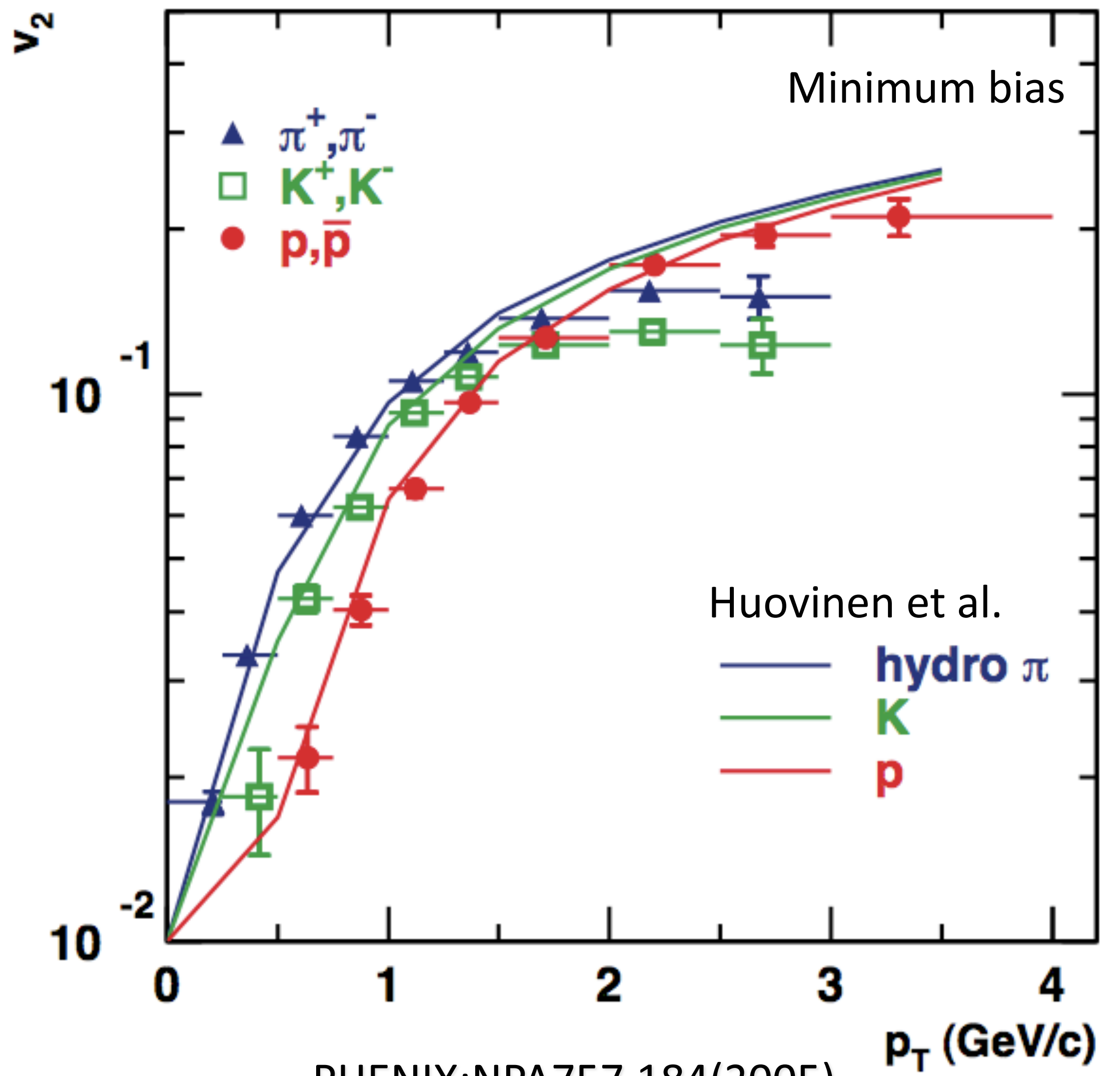
$$\partial_\mu T^{\mu\nu} = 0$$

$T^{\mu\nu}$: energy momentum tensor

- Equation of State
  - Advantage: Phase transition

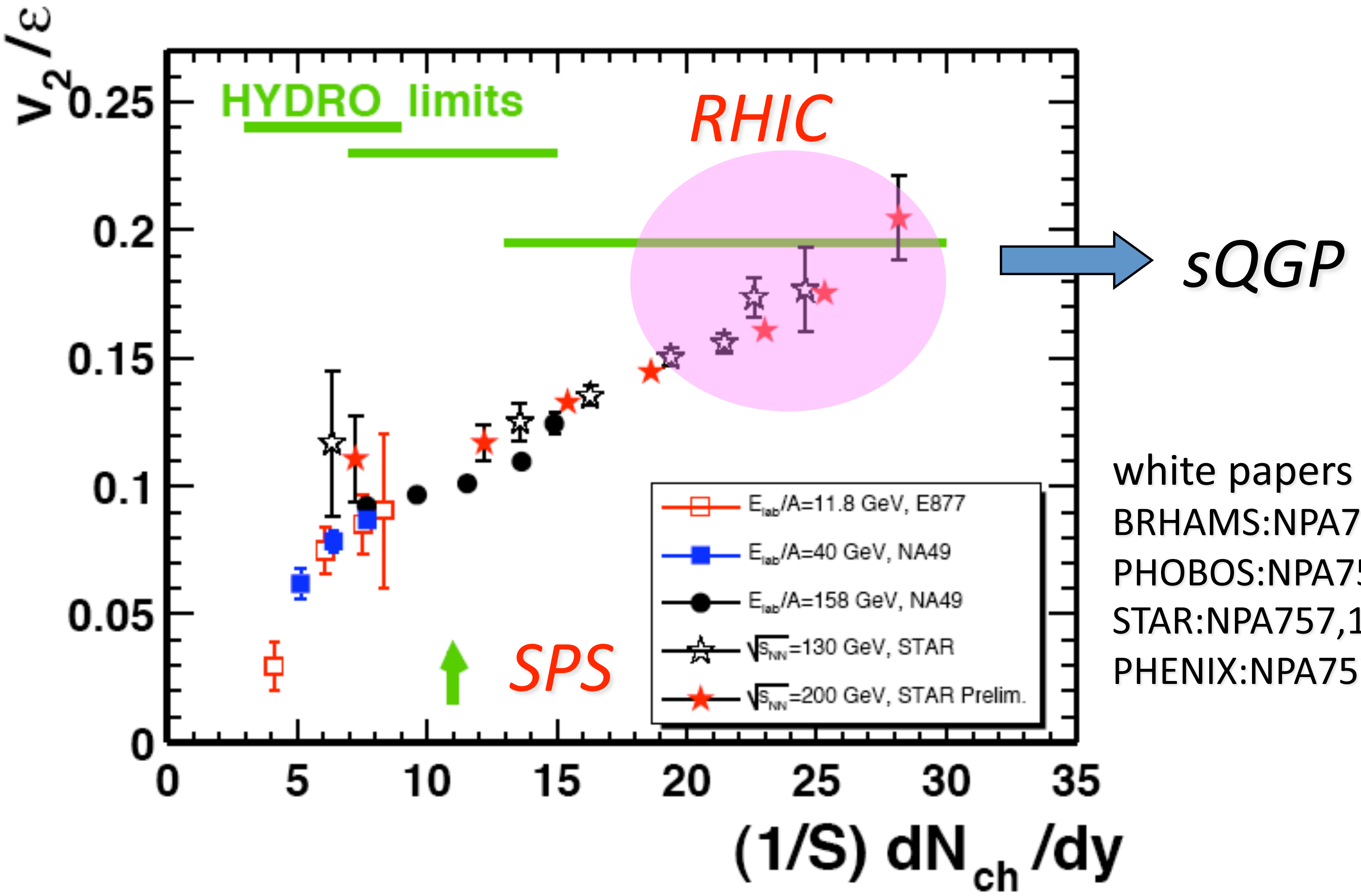
    QGP phase ⟺ Hadron phase

Success of Hydro at RHIC



PHENIX:NPA757,184(2005)

V2 vs multiplicity



white papers
BRHAMS:NPA757,1(2005)
PHOBOS:NPA757,28(2005)
STAR:NPA757,102(2005)
PHENIX:NPA757,184(2005)

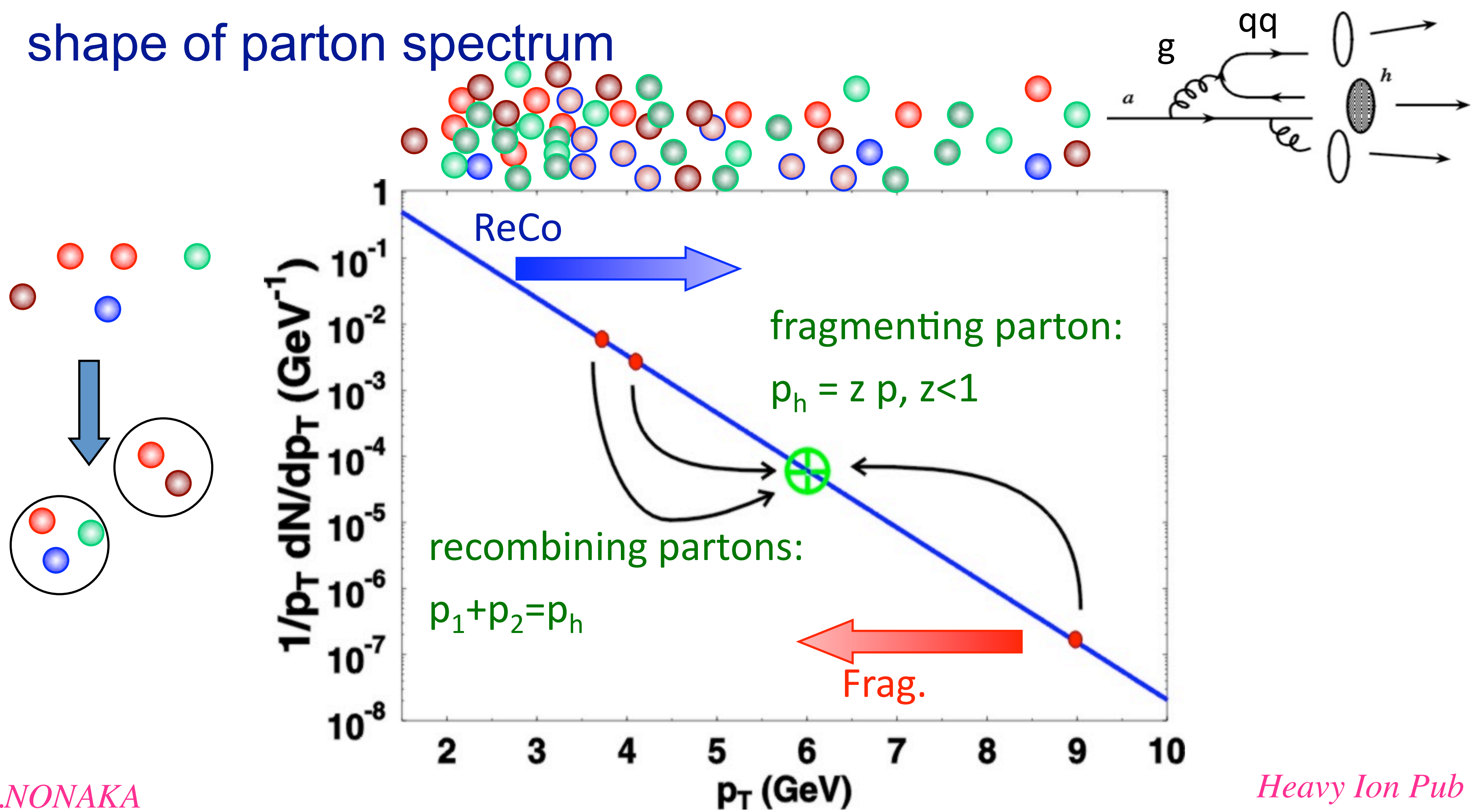
NA49:PRC68,034903(2003)

ReCo+Fragmentation Model

Duke-Minnesota-Osaka

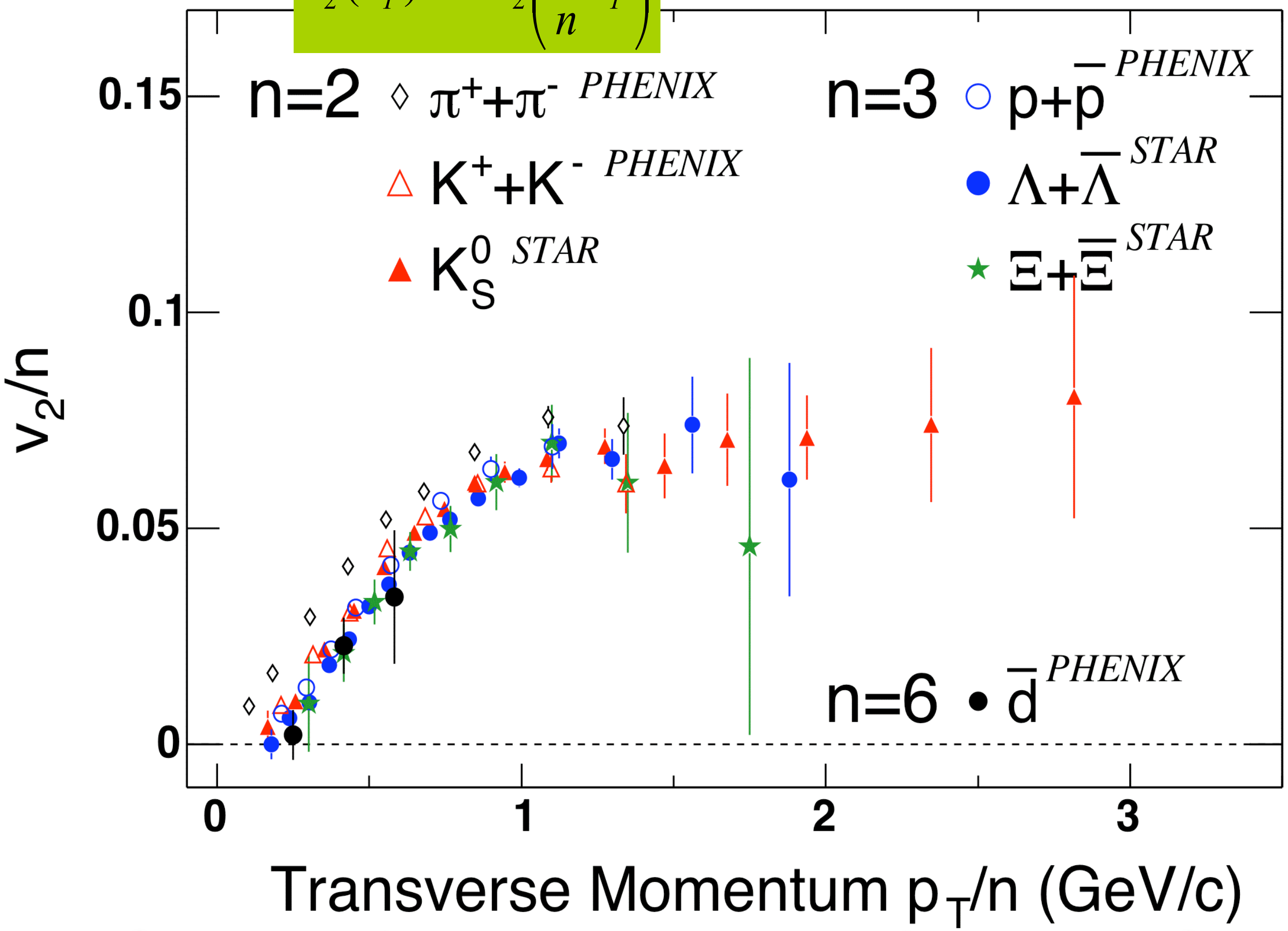
ReCo vs. Fragmentation

- phase space density of partons
- shape of parton spectrum



Quark Number Scaling

- Elliptic flow $v_2^h(P_T) \approx n v_2\left(\frac{1}{n}P_T\right)$



ReCo (Recombination or Coalescence) Models

New Discoveries at RHIC, April 2005

Strongly Interacting (coupled) Quark-Gluon Plasma: sQGP

- From Theory
  - Nuclear Physics A 750 (2005) : Quark-Gluon Plasma
  - New Discoveries at RHIC:
    - T.D.Lee, M.Gyulassy, L.McLerran, E.Shuryak, B.Mueller, X-N.Wang, H.Stocker,J.-P.Blaizot and F.Gelis, N.P.Samios
  - Color Glass Condensate
  - Hydrodynamic flow
  - Jet quenching
  - Recombination model
  - Viscosity
- From experiment
  - Nuclear Physics A 757 (2005)
  - First three year of operation of RHIC
  - PHENIX, STAR, BRAHMS, PHOBOS

Collective Flow at RHIC

- Radial flow
- Elliptic flow
- Higher harmonics, $v_{4,}$ v_6
- Directed flow

sQGP

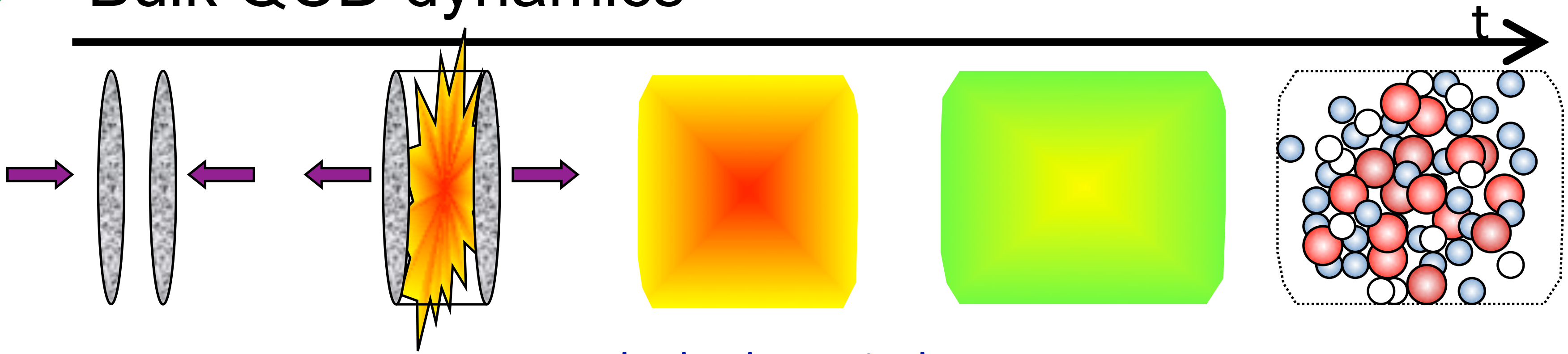
- Data
  - elliptic flow

    vs. P_T, rapidity, multiplicity

    system size, collision energy
  - fluctuations
- Models
  - Hydrodynamic model
  - Recombination model
- Physics
  - Early time thermalization
  - Equation of states
  - Initial conditions
  - Viscosity effect
  - Resonances, hadron structure

Hydrodynamic Model

- Bulk QCD dynamics



collision thermalization hydrodynamical expansion hadronization freeze-out

phase transition

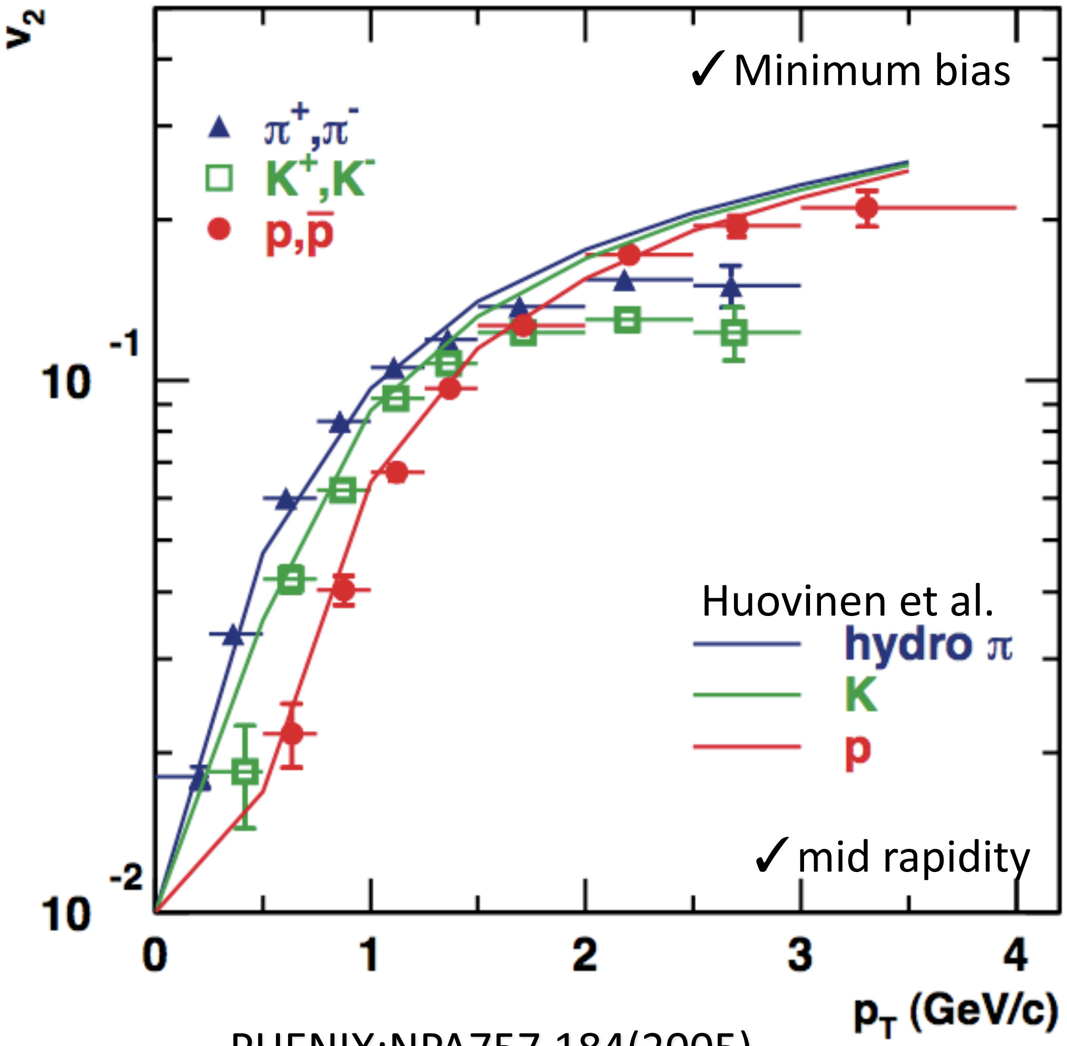
QGP phase Hadron phase

initial conditions
- Parametrization
  Glauber type
- Color Glass Condensate
- pQCD
- Cascade model

equation of states
- Bag model

freezeout process
- Viscosity effect of
  hadron phase
- Final state interactions

Success of Hydro at RHIC



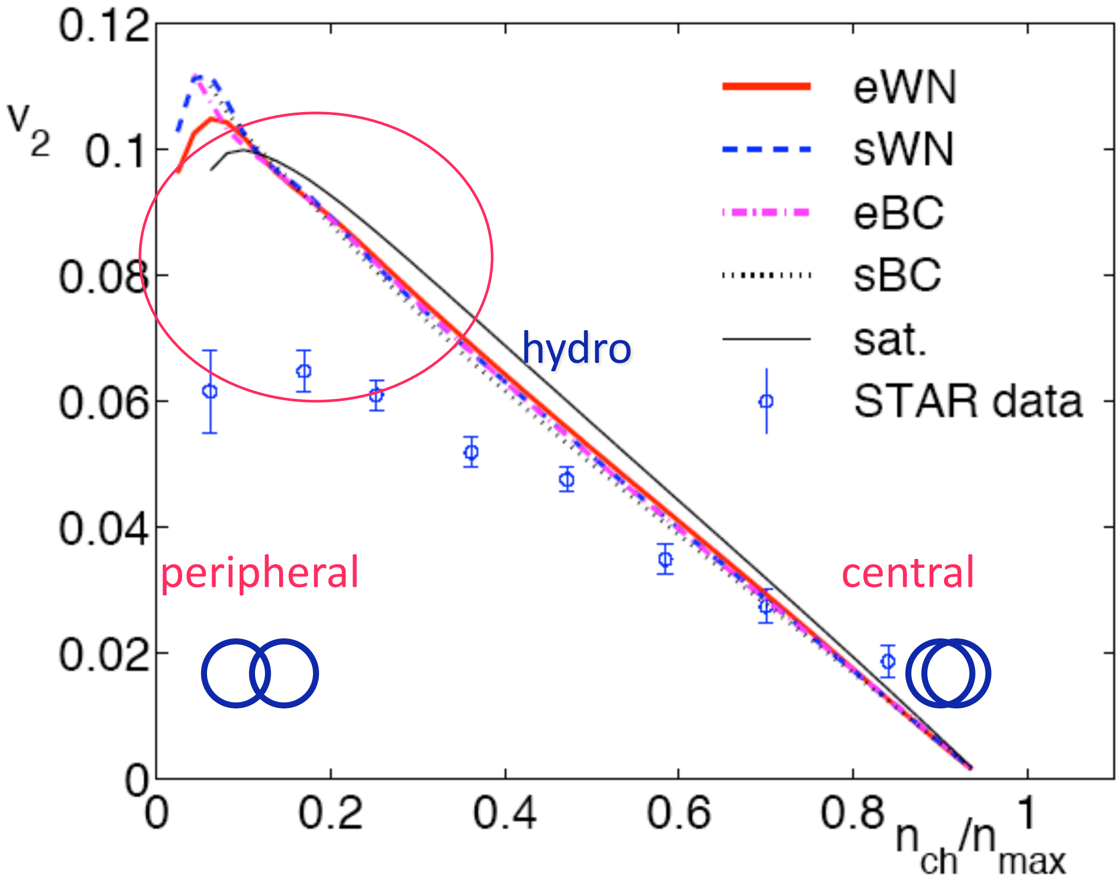
PHENIX:NPA757,184(2005)

Initial time
τ=0.6 fm

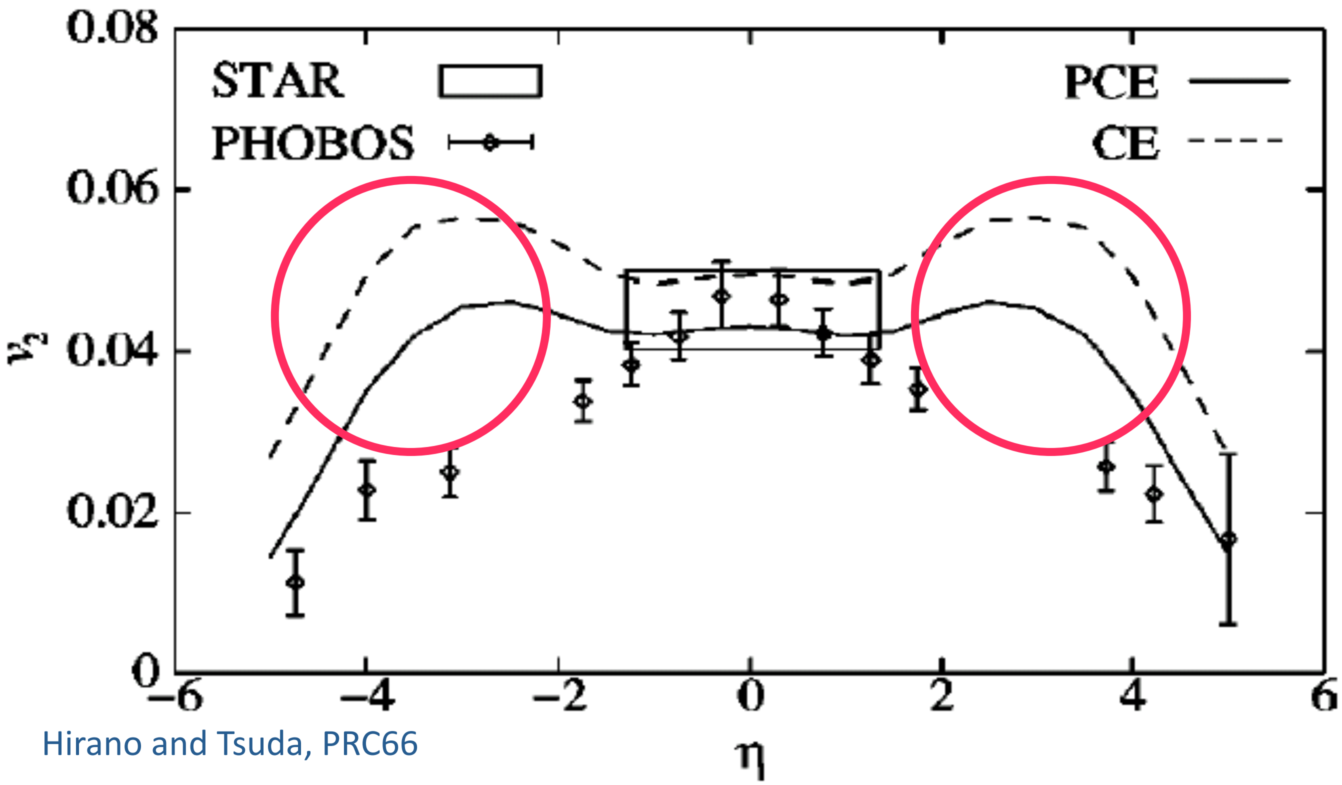
Early time thermalization

2-D Hydrodynamics
Initial conditions
Glauber type:

Centrality Dependence



Rapidity Dependence

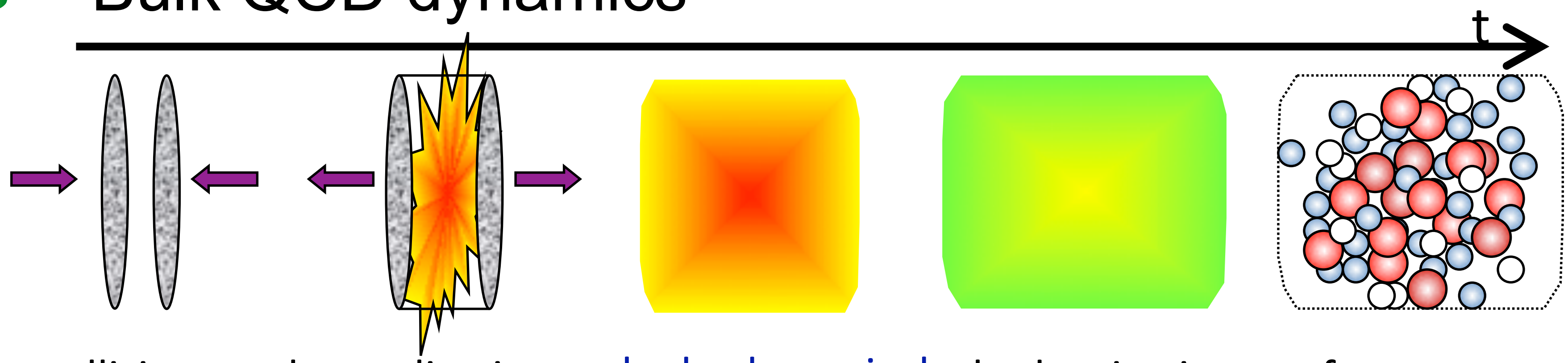


Hirano and Tsuda, PRC66

Forward/backward rapidity

Freezeout & Final State Interactions

- Bulk QCD dynamics



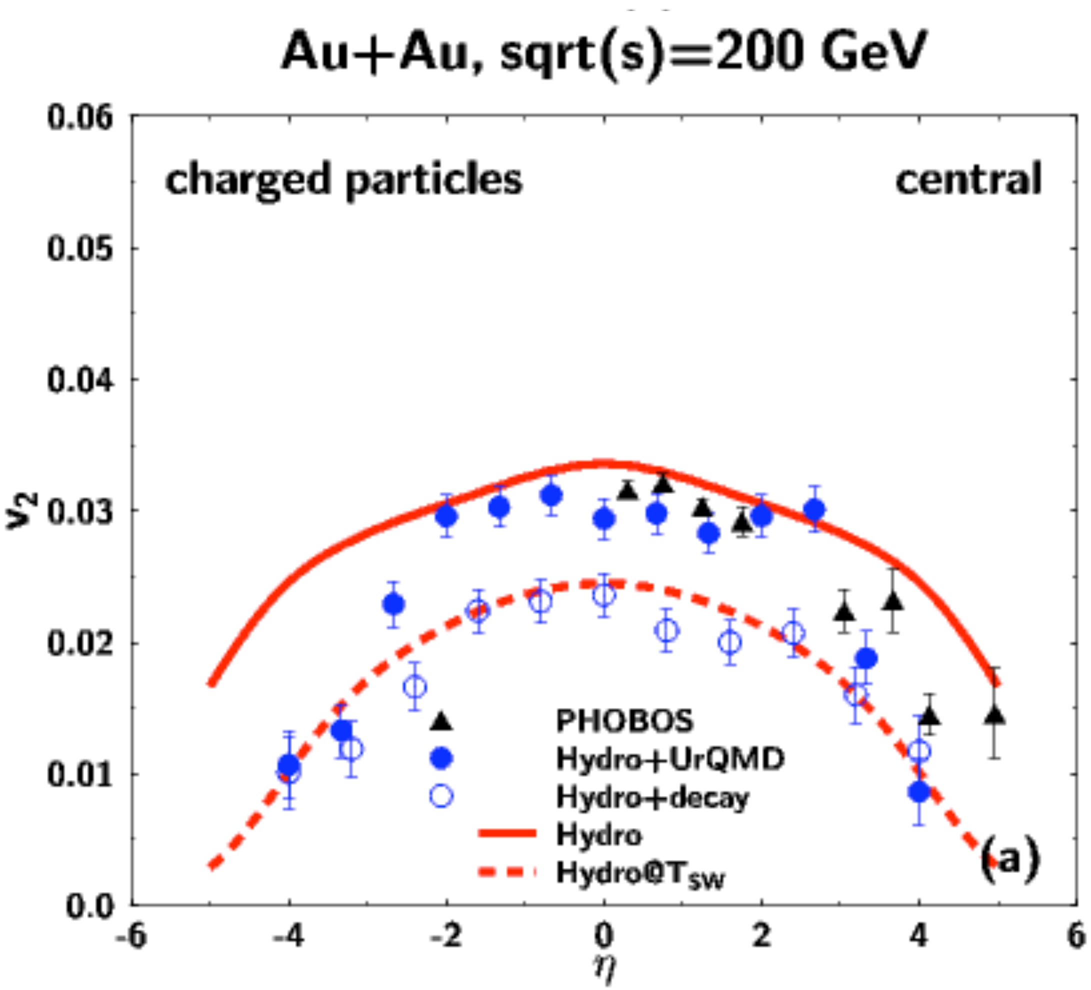
phase transition

QGP phase　　Hadron phase

Hydro　+　Cascade Model

Bass,Dumitru, Shuryak, Teaney, Hirano, Nara, Nonaka….

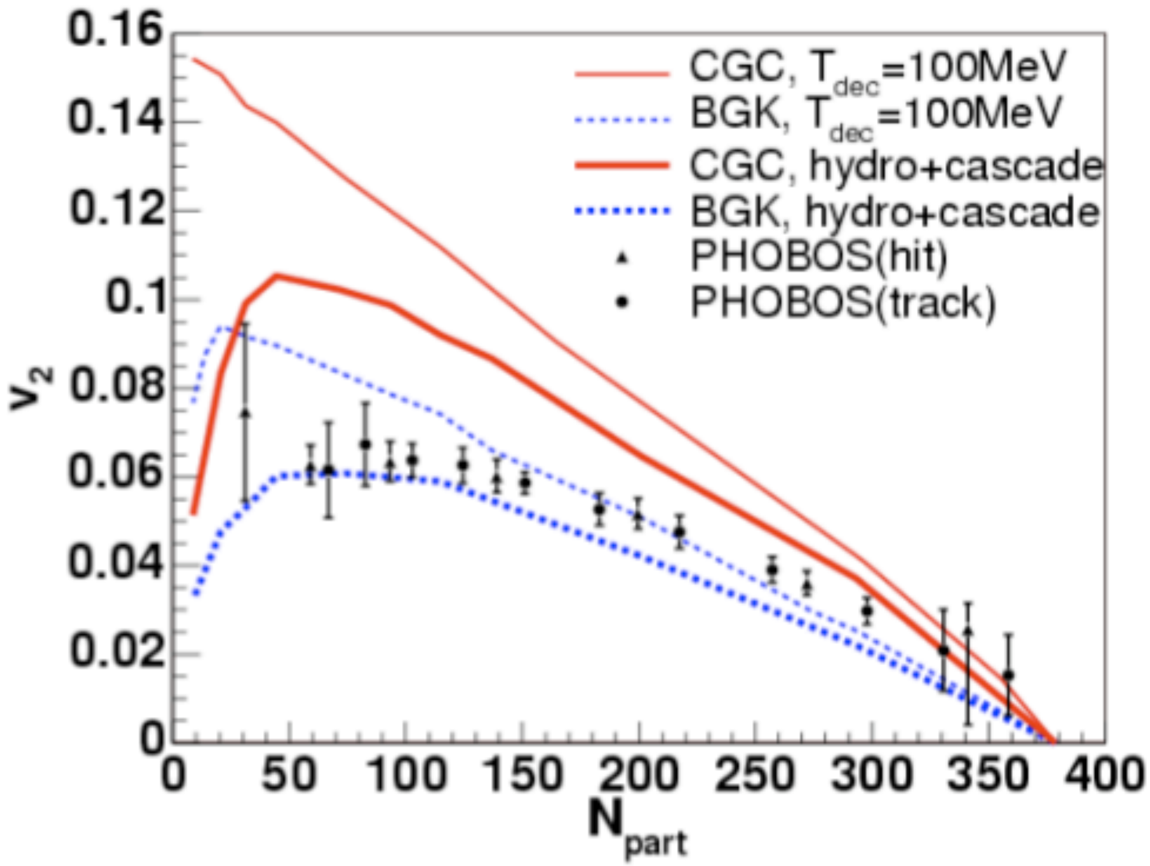
Rapidity Dependence



- Hydro+decay ~ Hydro@T_{SW}
- v_2 grows in hadron phase a bit.
- v_2 builds up in QGP phase.

Centrality Dependence

T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, Phys. Lett. B636(2006),299



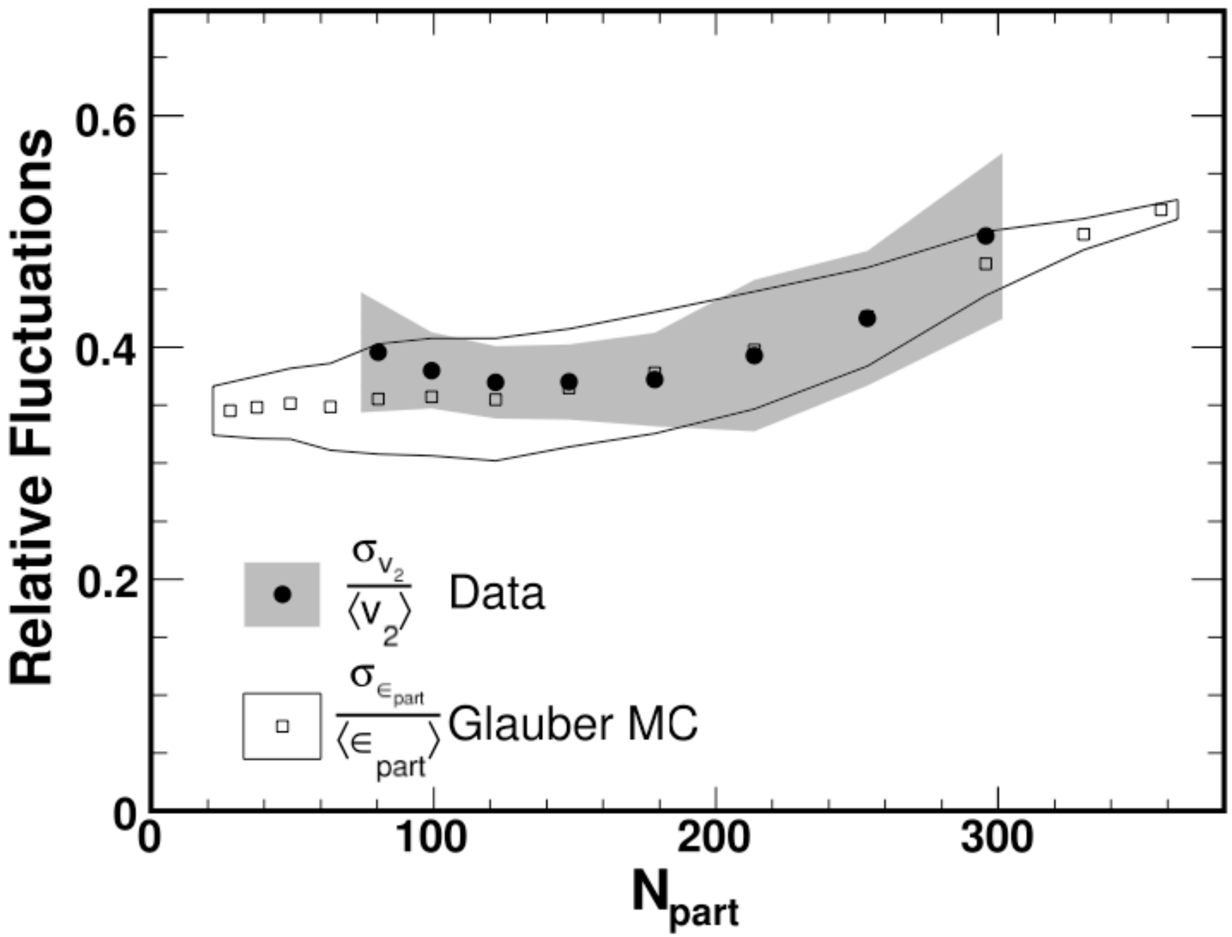
Viscosity Effect even in QGP phase?

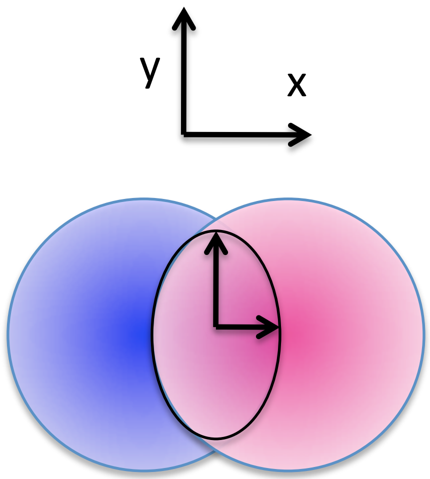
→ Viscous relativistic hydrodynamic models

Incomplete equilibration: Bhalerao et al. PLB627(2005)

Fluctuations

- Au+Au 200 AGeV PHOBOS



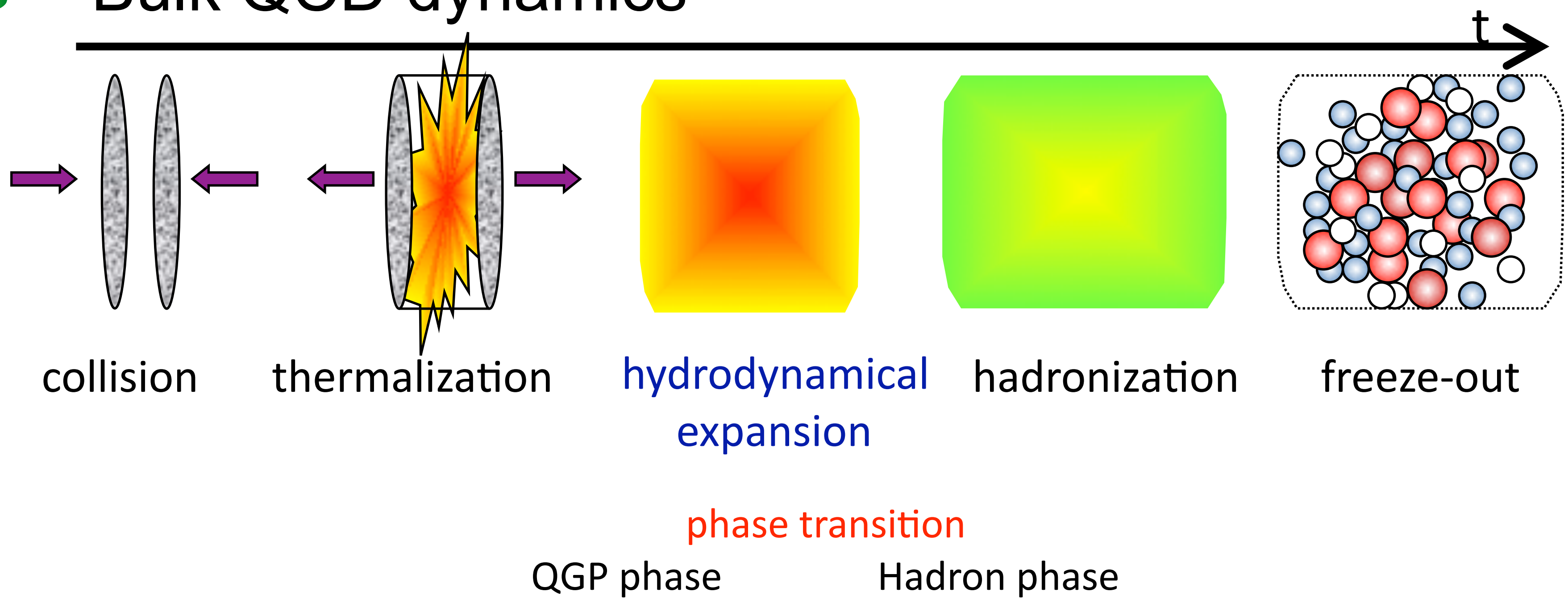


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

- Elliptic flow
  pressure gradient

Perfect Fluid at RHIC?

- Bulk QCD dynamics

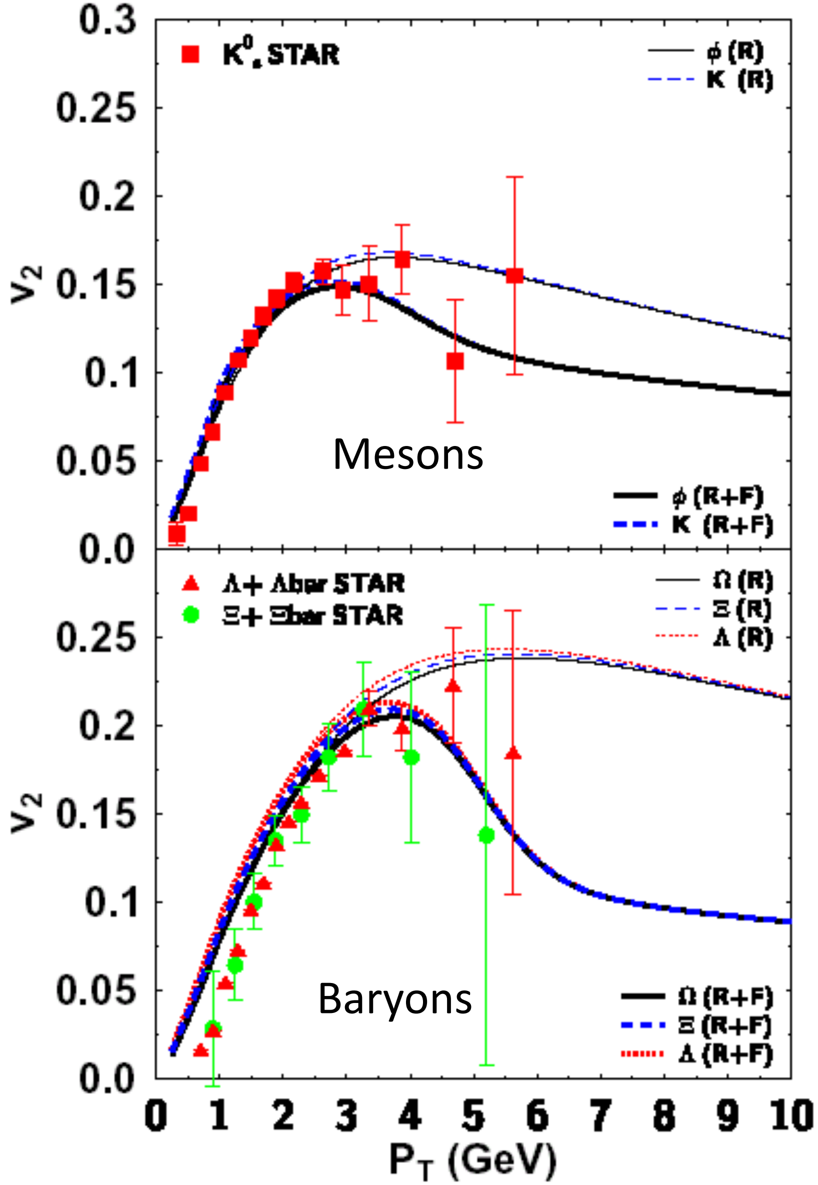


initial conditions
- Parametrization Glauber type
- Color Glass Condensate
- pQCD
- Cascade model

equation of states
- Bag model
- Quasi particle model
- Lattice QCD

freezeout process
- Viscosity effect of hadron phase
- Final state interactions

Quark Number Scaling



$$v_2(P_T) = \langle \cos 2\Phi \rangle = \frac{\int d\Phi \cos 2\Phi d^2N/d^2P_T}{\int d\Phi d^2N/d^2P_T}$$

- v_2^{baryon} saturates at higher P_T
- at high P_T: fragmentation
  $\longrightarrow$ $v_2^{\text{baryon}} \sim v_2^{\text{meson}}$

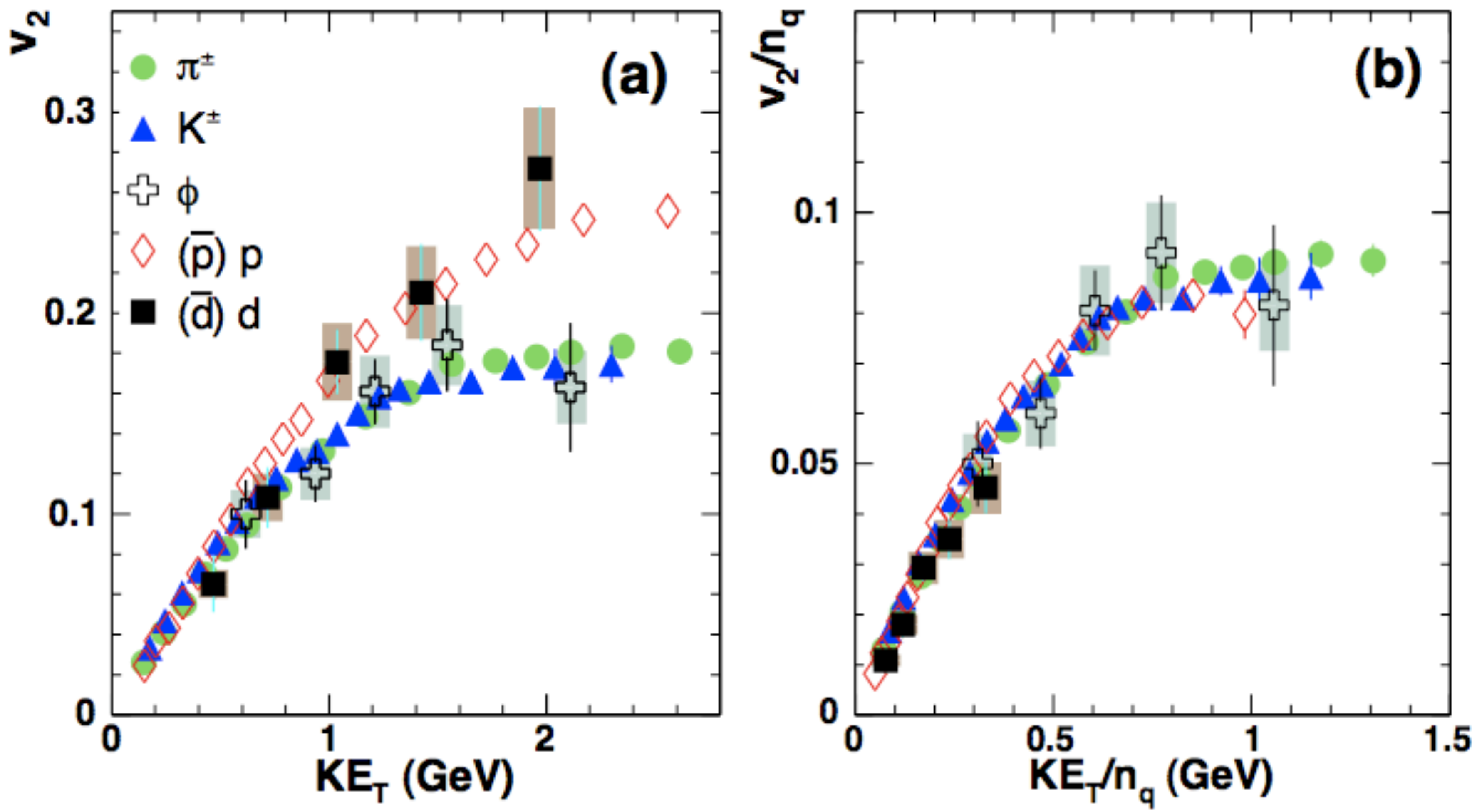
ϕ meson

- mass effect ?
  Hydrodynamical model
  $m_\phi \approx m_\Lambda \longrightarrow v_2^\phi \approx v_2^\Lambda$
- # of constituent quarks ?
  $v_2^\phi \sim v_2^K$

PLB587,73(2004)

Quark Number Scaling

PHENIXPRL99(2007)052301



v_2 for Resonance Particles

- QGP resonances:

  hadronizing QGP, no rescattering

  K_0^* $d,\bar{s}$ quarks n=2 scaling

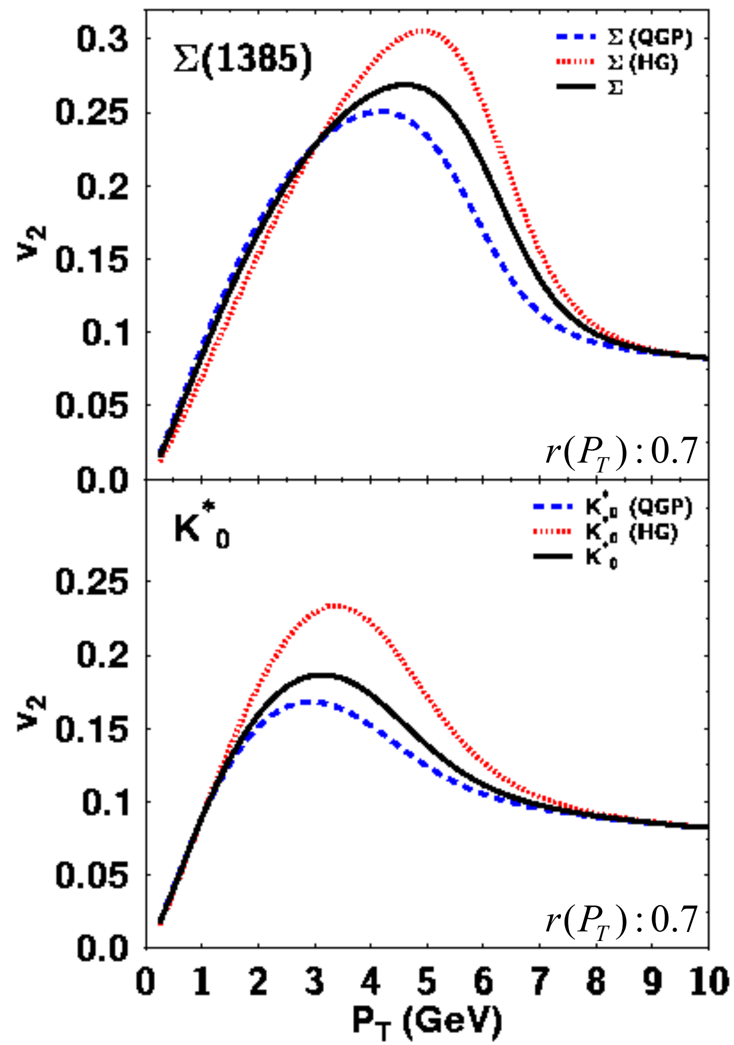
- HG resonances:

  hadron final stage, h-h rescattering

  K_0^* $K^+ + \pi^- \to K_0^*$ n=4 scaling

$$v_2^h(P_T) \approx n v_2\left(\frac{1}{n}P_T\right)$$

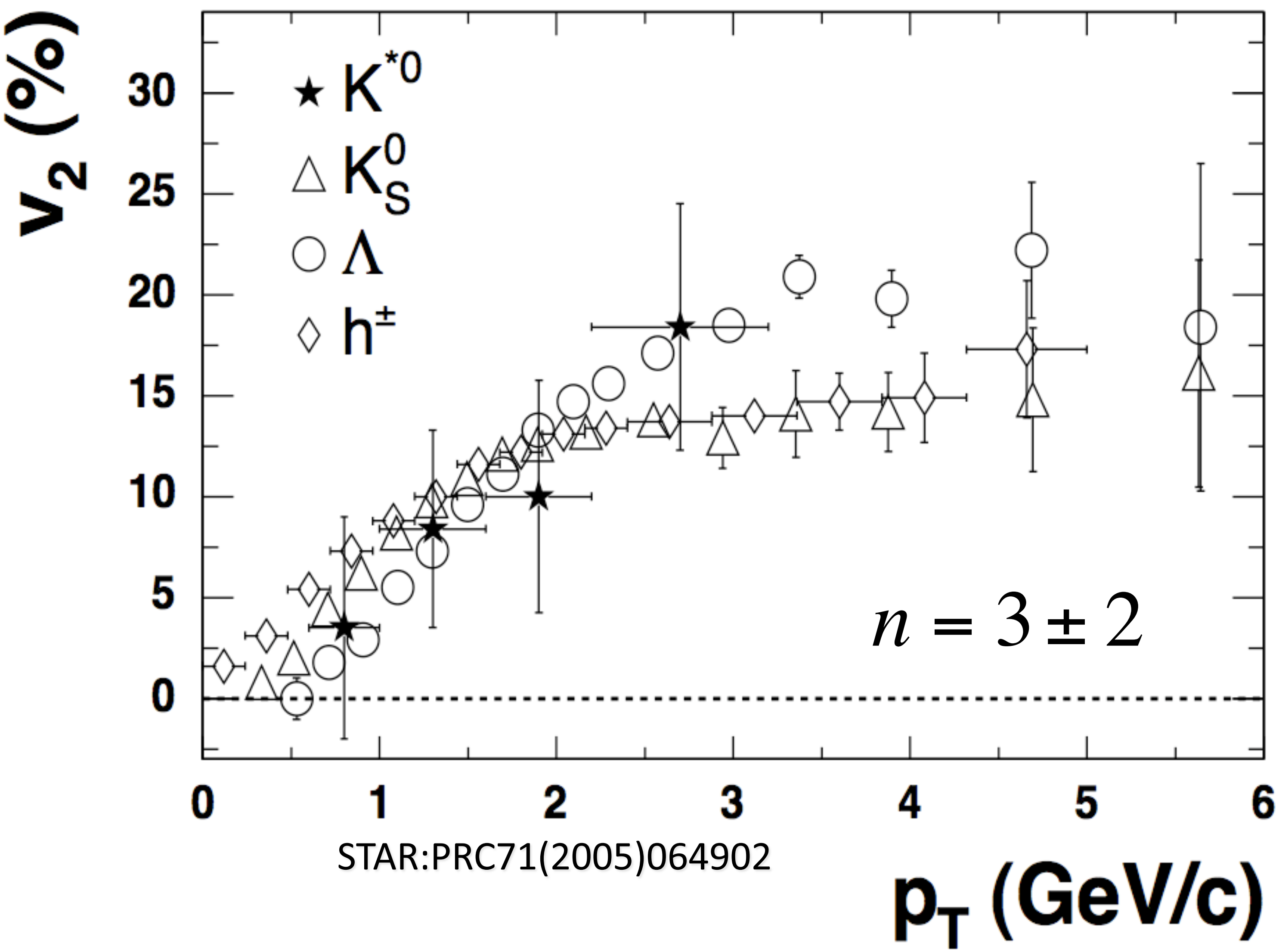
Key: v_2 is additive for composite particles



Total

$$v_2^{\text{full}} = r(P_T)v_2^{\text{QGP}} + (1-r(P_T))v_2^{\text{HG}}$$

$r(P_T)$ is determined by experiments and related to width of particles and cross section in the hadronic medium.



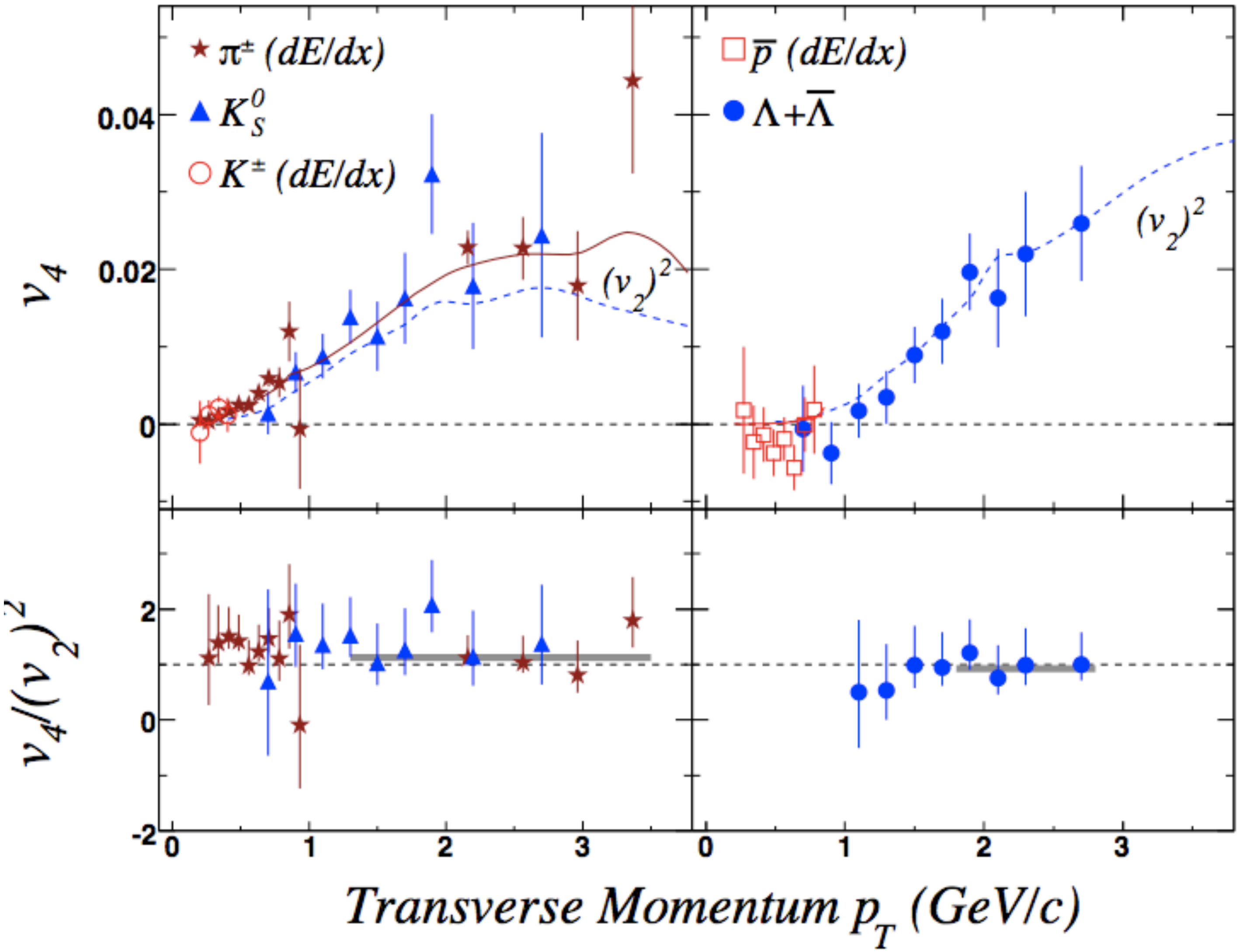
STAR:PRC71(2005)064902

Collective Flow at RHIC

- Radial flow
- Elliptic flow
- Higher harmonics, v_4, v_6
- Directed flow

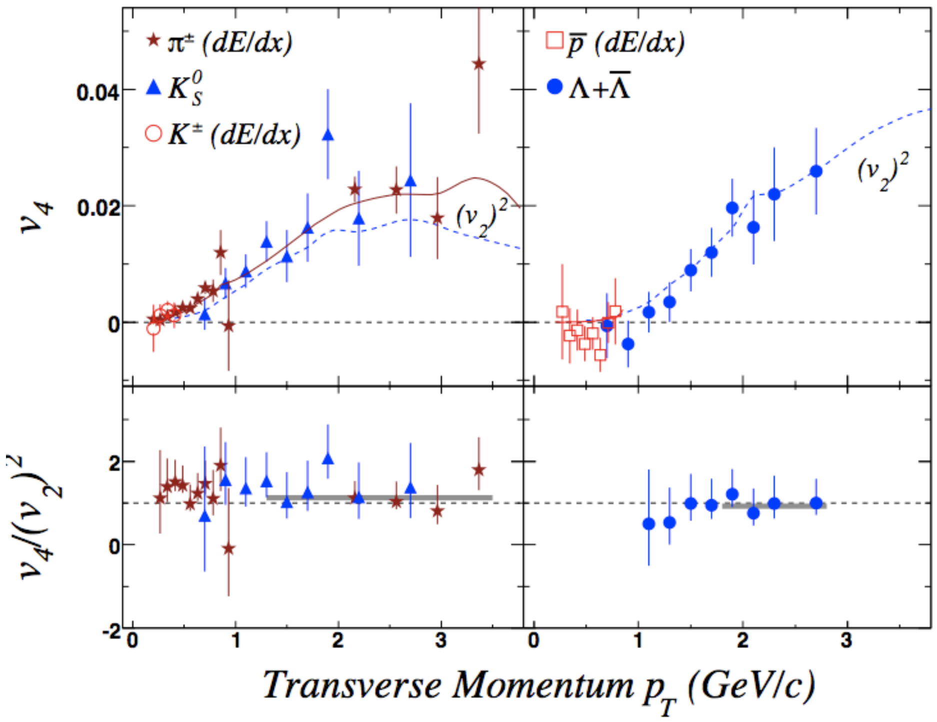
- Data
  - v_4 *vs.* P_T, centrality
- Models
  - Hydrodynamic model
  - Recombination model
- Physics
  - Equilibrium
  - Quark number scaling

V_4 as a function of P_T



STAR:PRC75(2007)54906

Equilibration, Recombination



STAR:PRC75(2007)54906

- Initial conditions
  Kolb, PRC68(2003) 031902
- Equilibration
  (deviation from ideal hydro)
  Borghini, Ollitrault:PLB 642(2006)227

$[v_4/v_2^2]$ > 0.5

- Recombination
  Texas group
  Phys. Rev. C 69, 031901 (2004)

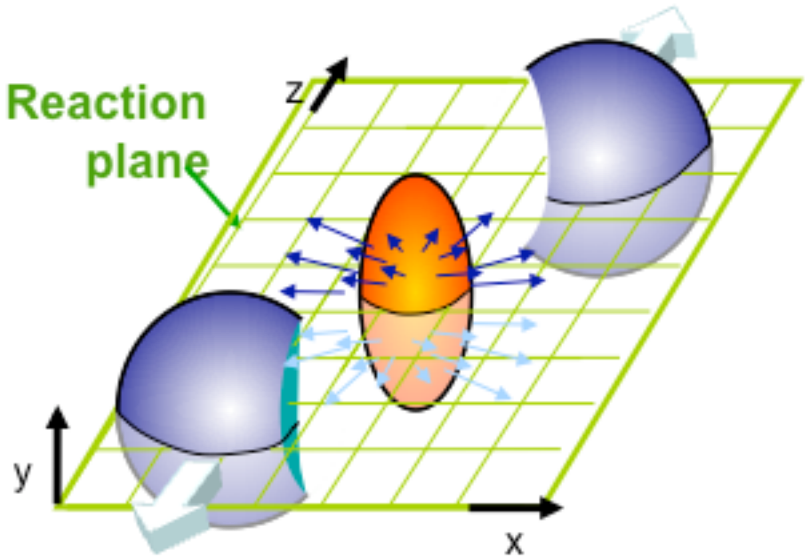
$$[v_4/v_2^2]^{\text{Meson}}_{2p_T} \approx 1/4 + (1/2)\,[v_4/v_2^2]^{\text{Quark}}_{p_T}$$

$$[v_4/v_2^2]^{\text{Baryon}}_{3p_T} \approx 1/3 + (1/3)\,[v_4/v_2^2]^{\text{Quark}}_{p_T}$$

$$[v_4/v_2^2]^{\text{Baryon}}_{3p_T} \approx 1/6 + (2/3)\,[v_4/v_2^2]^{\text{Meson}}_{2p_T}$$

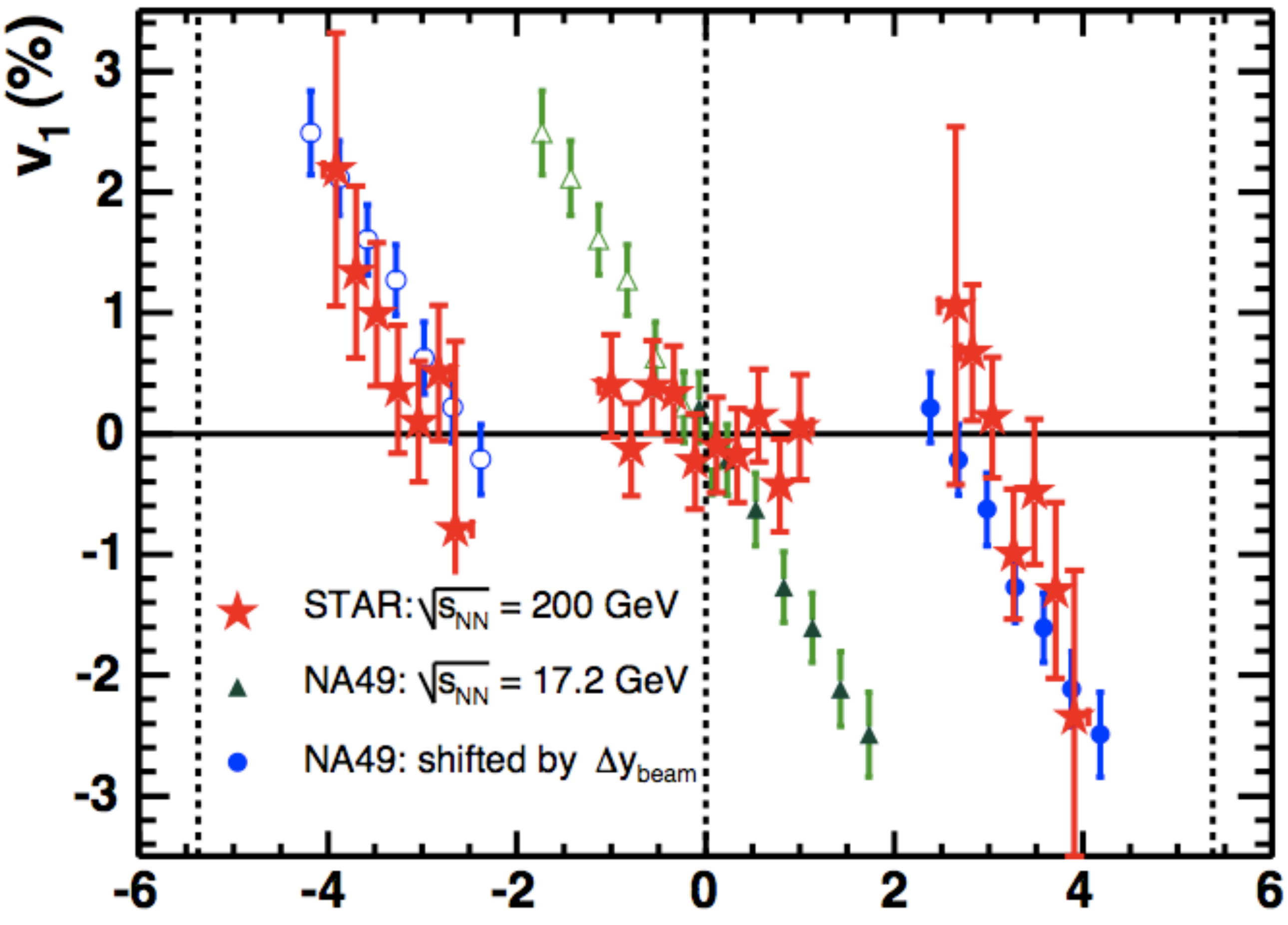
Collective Flow at RHIC

- Radial flow
- Elliptic flow
- Higher harmonics, $v_{4,}$ v_6
- Directed flow



- Data
  - Directed flow *vs.* rapidity, collision energy
- Models
  - Transport model
  - Hydrodynamic model
- Physics
  - Stopping
  - Matter compressibility

Directed Flow



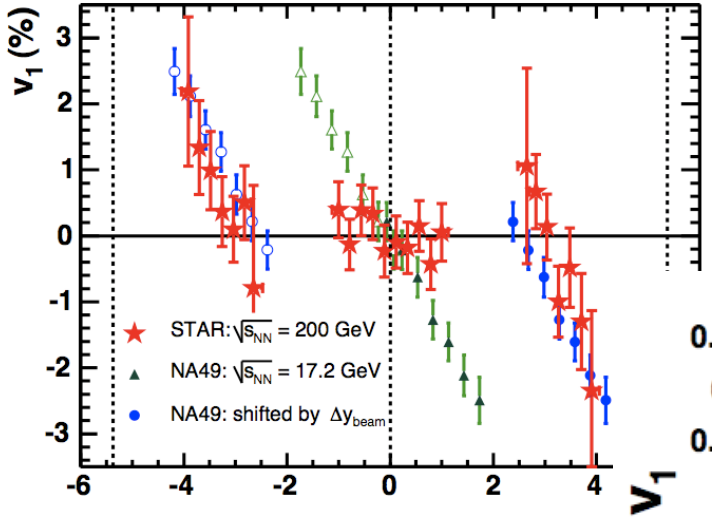
STAR:PRL92(2004)062301,PRC72(2005)014904

charged hadrons

- RHIC
  10~70% centrality
- Midrapidity
  $v_1 \sim 0$

Forward/Backward η?

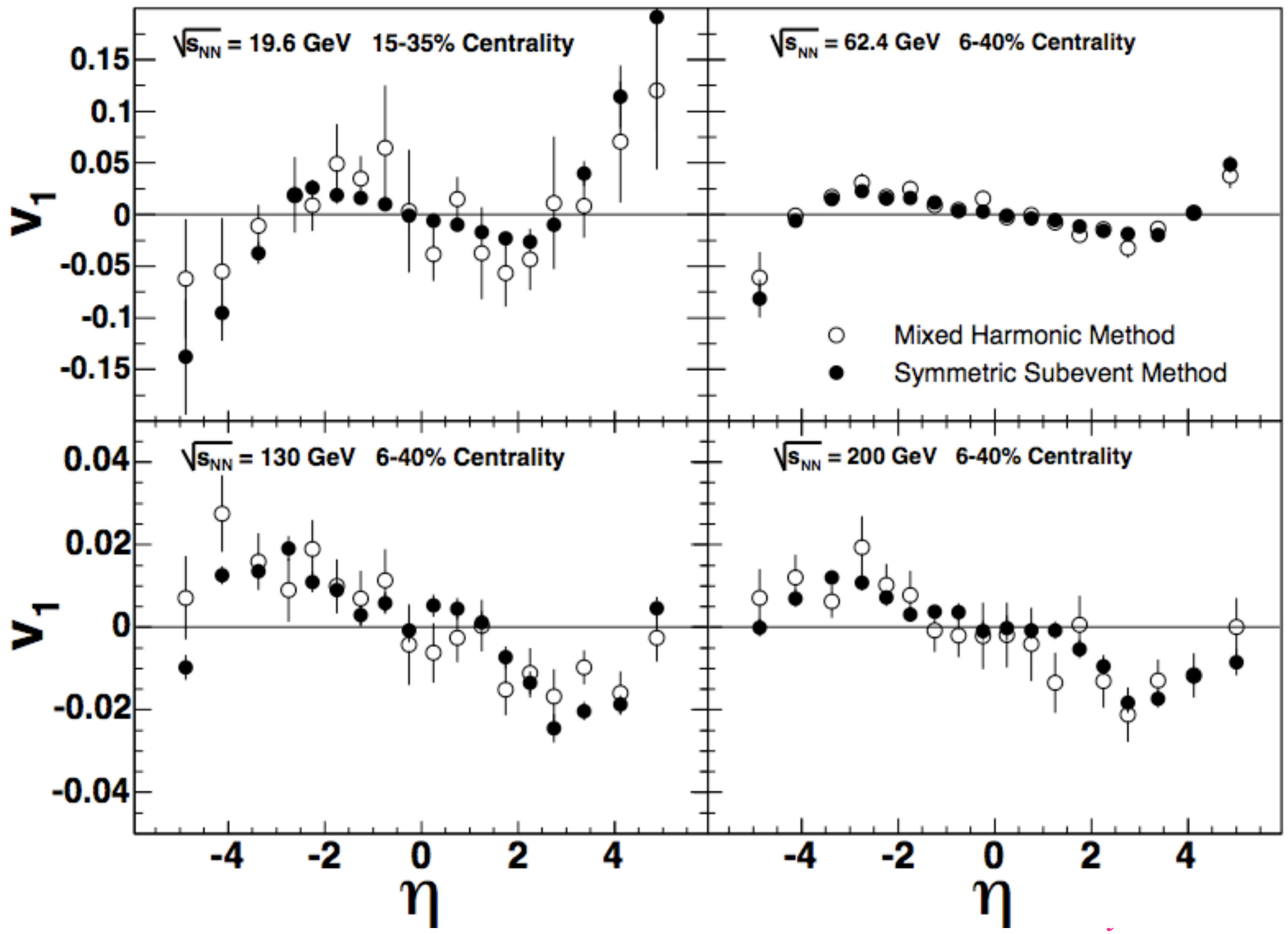
charged hadrons



- RHIC STAR
  10~70% centrality

- Midrapidity
  v_1~0

PHOBOS:PRL97(206)01231



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Background in Other Physical observables

- HBT
- Jet structure

Summary

- Success of
  (ideal) hydrodynamic model and recombination model
  - Strongly coupled (interacting) QGP
- Perfect fluid at RHIC?
  - Thermalization, viscosity….

Models:

- Relativistic hydrodynamic model
  - Initial conditions, equation of states, freezeout process
- Recombination model
  - Realistic parton distribution

LHC

low P_T — intermediate P_T — high P_T → P_T

	low P_T	intermediate P_T	high P_T
RHIC	<2 GeV	$2 < P_T < 4\sim6$ GeV	$4\sim6 < P_T$ GeV
LHC	$< 4\sim5$ GeV	$5 < P_T < 8\sim10$ GeV	$8\sim10 < P_T$

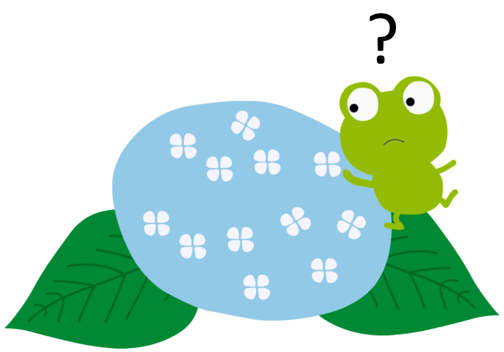
Hydrodynamic Model

Thermal・Statistical Model

Recombination Model

Perturbative QCD

Detailed analyses by hydrodynamic models and recombination models



RHIC

sQGP

LHC

wQGP

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Heavy Ion Pub

Back up

Quark Recombination Model

- Mesons

$$E\frac{d^3N_M}{d^3p} \propto \int_{\Sigma_f} p^\mu d\Sigma_\mu \int_0^1 dx w(r;xp_T)\overline{w}(r;(1-x)p_T)\left|\phi_M(x)\right|^2$$

- Baryons

$$E\frac{d^3N_B}{d^3p} \propto \int_{\Sigma_f} p^\mu d\Sigma_\mu \int_0^1 dx \int_0^{1-x} dx' w(r;xp_T)w(r;x'p_T)\overline{w}(r;(1-x-x')p_T)\left|\phi_B(x,x')\right|^2$$

ϕ_M,ϕ_B:light-cone wave function

- Equal momentum fraction(x=1/2,x=x'=1/3)

$$E\frac{d^3N_M}{d^3p} \cong C_M w^2(p_T/2), E\frac{d^3N_B}{d^3p} \cong C_B w^3(p_T/3)$$

C_M,C_B:coalescence probabilities

Elliptic Flow

- Hadrons <- Quarks

$$w \propto 1 + 2v_{2,q} \cos 2\phi$$

$v_{2,q}$:Elliptic flow of quarks

- Mesons

$$\frac{d^2 N_M}{d\phi dp_T p_T} \propto [1 + 2v_{2,q} \cos 2\phi]^2 \cong 1 + 4_{2,q} \cos 2\phi$$

$$\Rightarrow \quad v_{2,M}(p_T) \cong 2v_{2,q}(p_T/2), \quad v_{2,B}(p_T) \cong 3v_{2,q}(p_T/3)$$

Quark number scaling

3-D Hydrodynamic Model

- Relativistic hydrodynamic equation

$$\partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu} : \text{energy momentum tensor}$$

  - Baryon number conservation

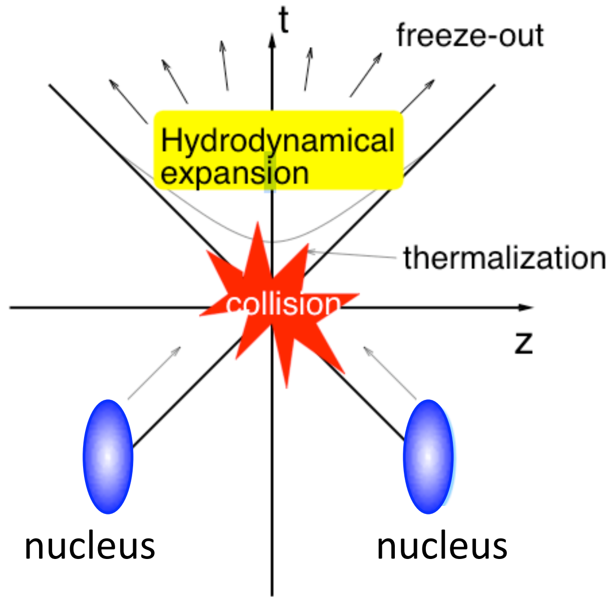
$$\partial_\mu (n_B(T,\mu)) = 0$$

- Coordinates

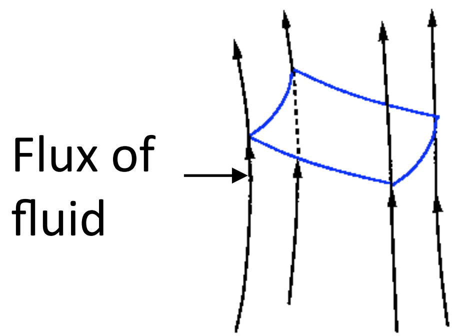
$$(\tau, x, y, \eta) : \tau = \sqrt{t^2 - z^2}, \eta = \tanh^{-1}\left(\frac{z}{t}\right)$$

- Lagrangian hydrodynamics
  - Tracing the adiabatic path of each volume element
  - Effects of phase transition on observables
  - Computational time
  - Easy application to LHC
- Algorithm
  - Focusing on the conservation law

$$\partial_\mu (s(T,\mu)u^\mu) = 0, \ \partial_\mu (n_B(T,\mu)u^\mu) = 0$$

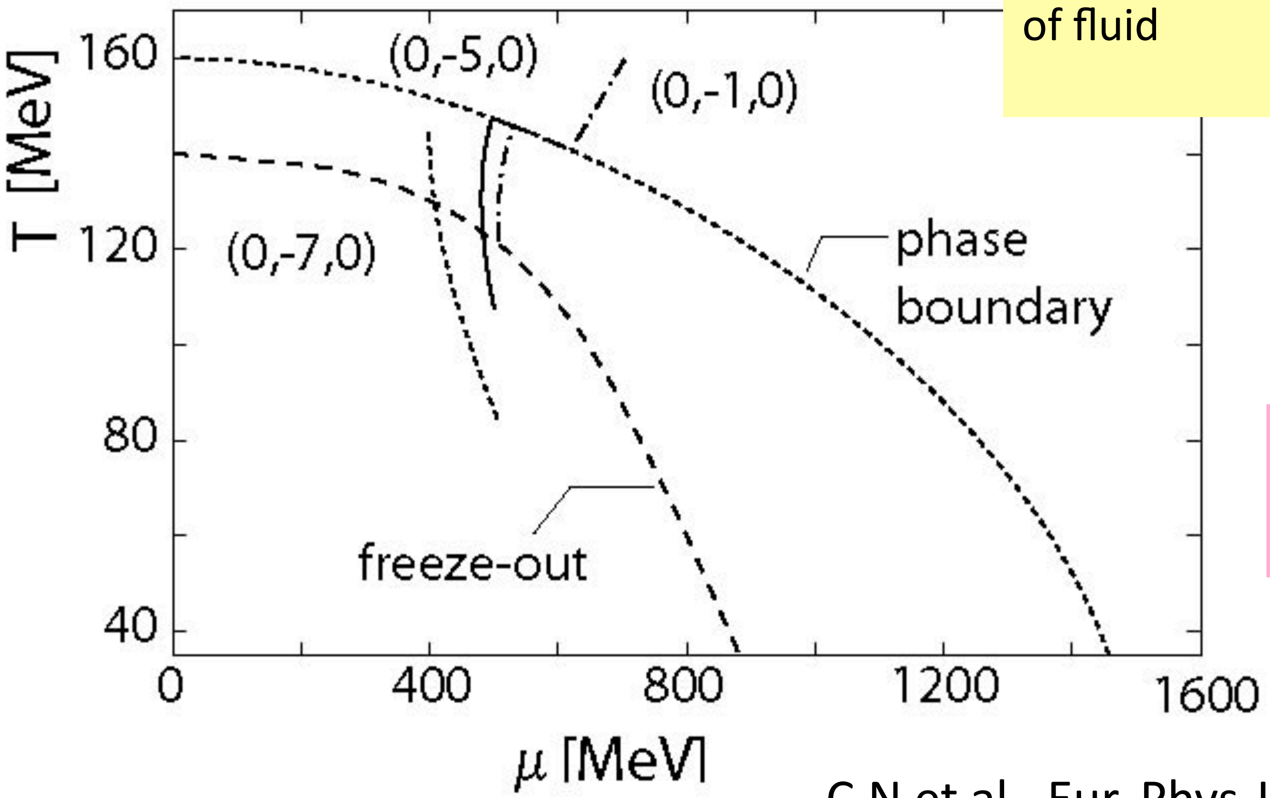


Lagrangian hydrodynamics



Trajectories on the phase diagram

- Lagrangian hydrodynamics

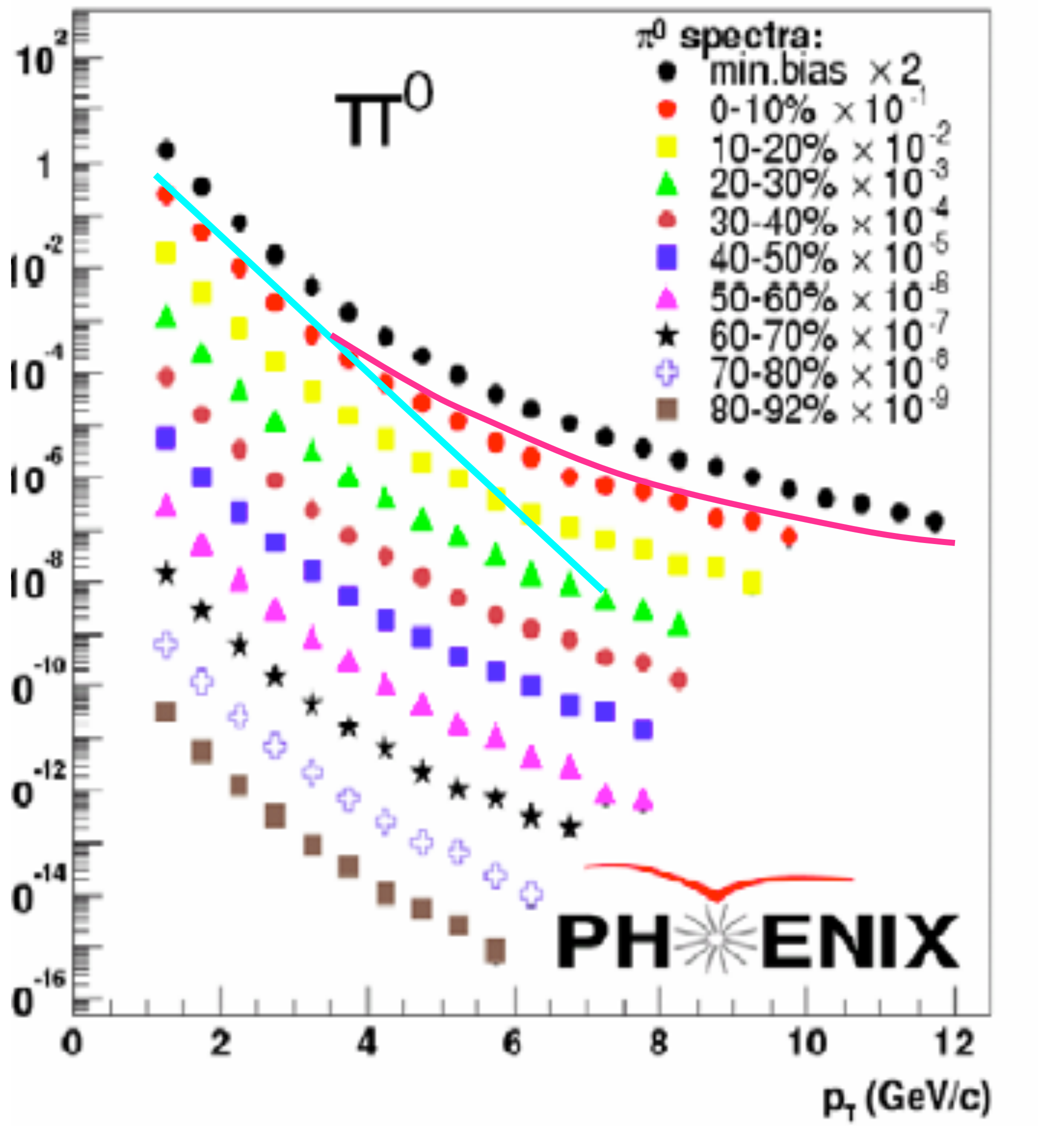


temperature and chemical potential of volume element of fluid

Effect of phase transition

C.N et al., Eur. Phys.J C17,663(2000)

P_T Distributions



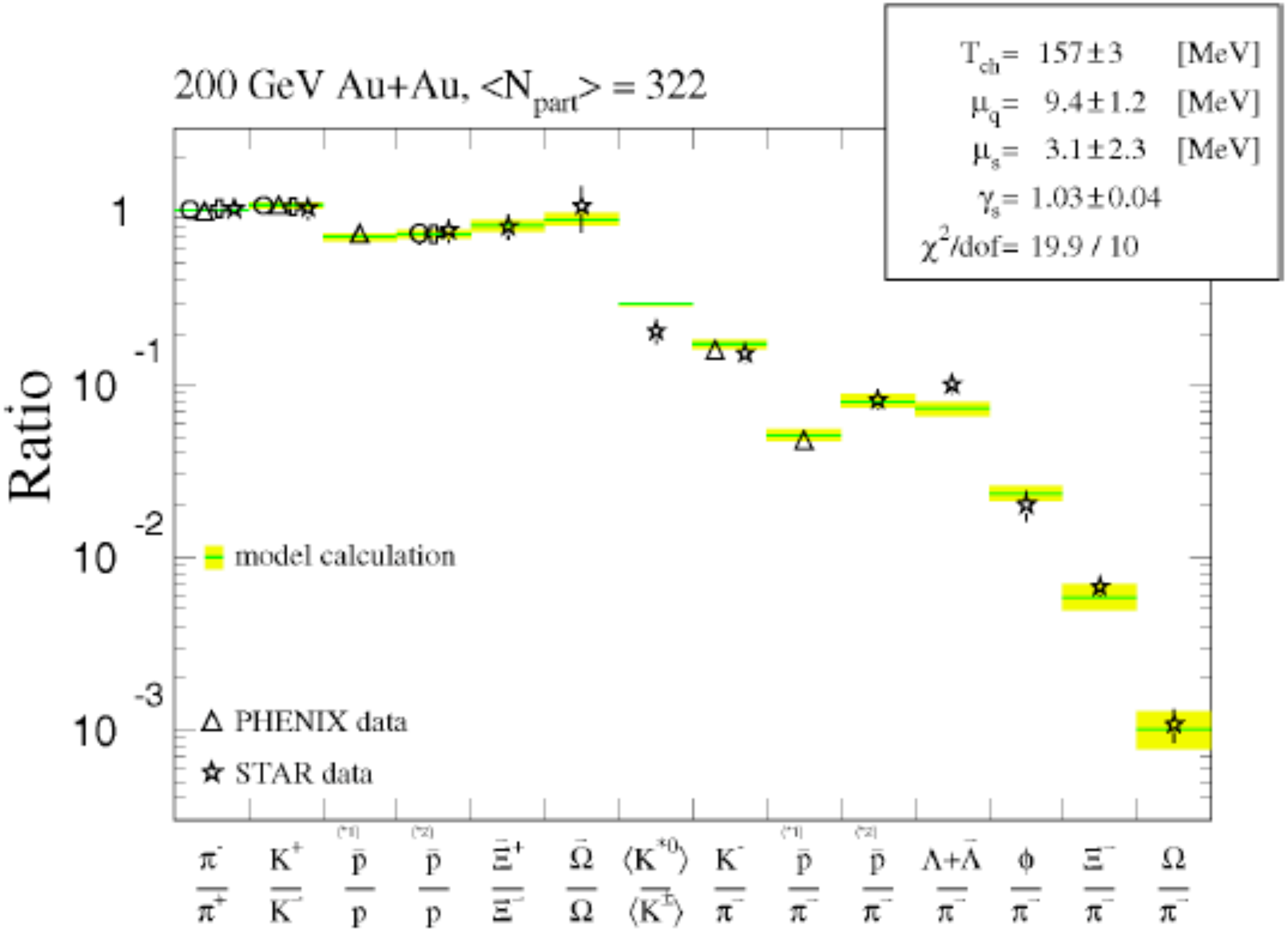
- Low P_T<2 GeV:thermal

$$\frac{1}{P_T}\frac{dN}{dP_T} \approx \exp(-P_T/T)$$

- High P_T>5~6 GeV
: pQCD

$$\frac{1}{P_T}\frac{dN}{dP_T} \approx P_T^{-n}$$

Hadron ratios



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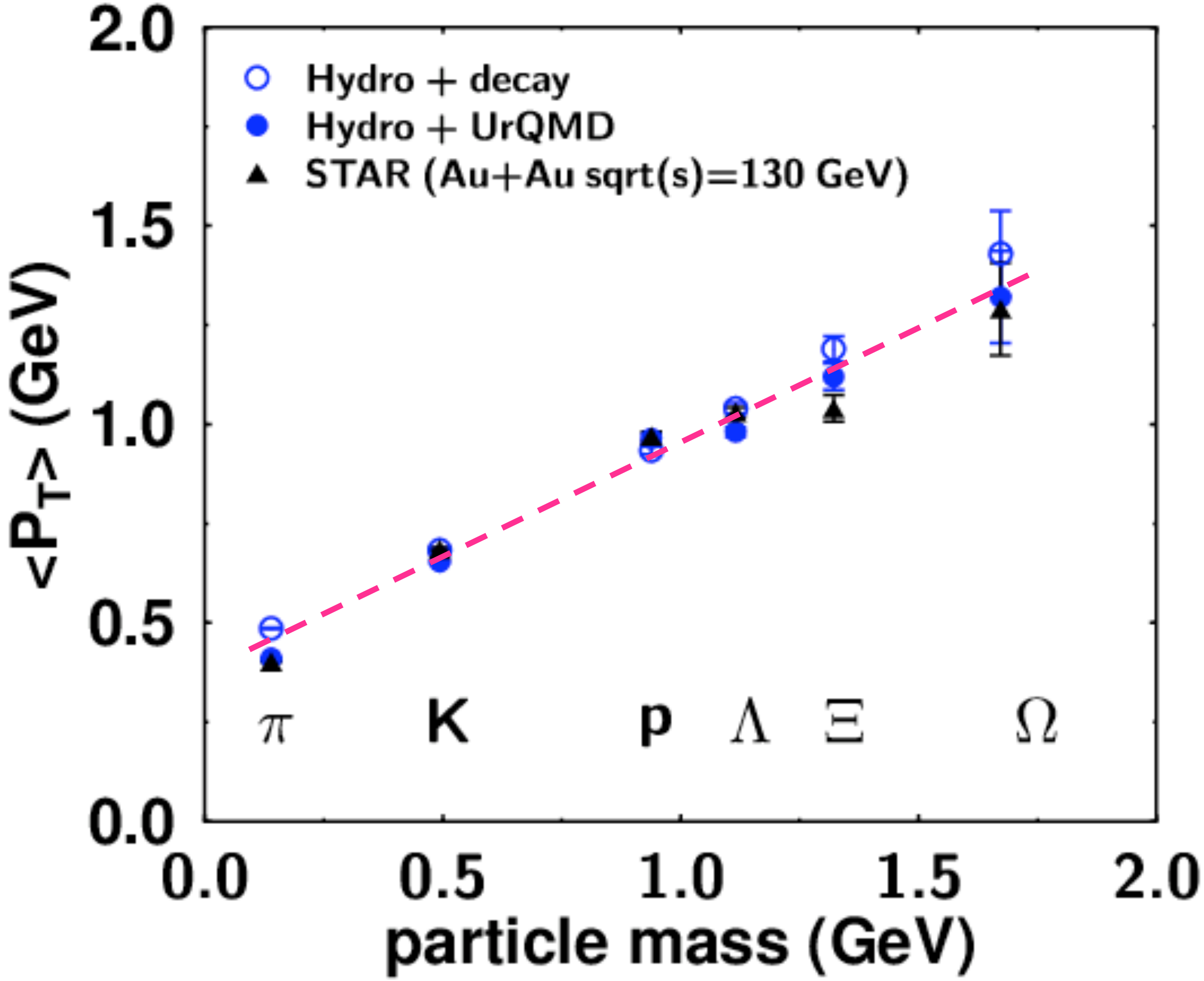
$\langle P_T \rangle$ vs mass



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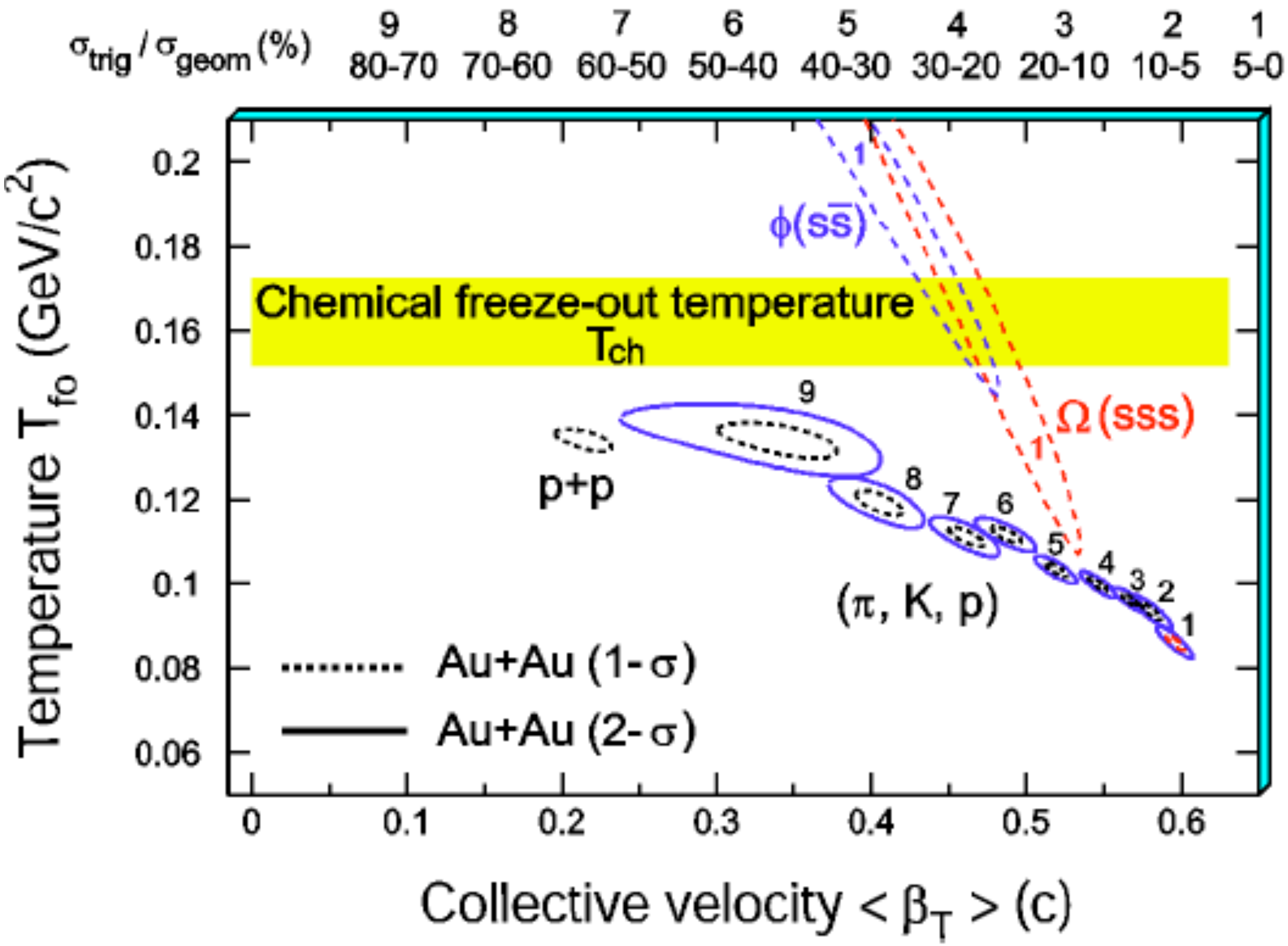
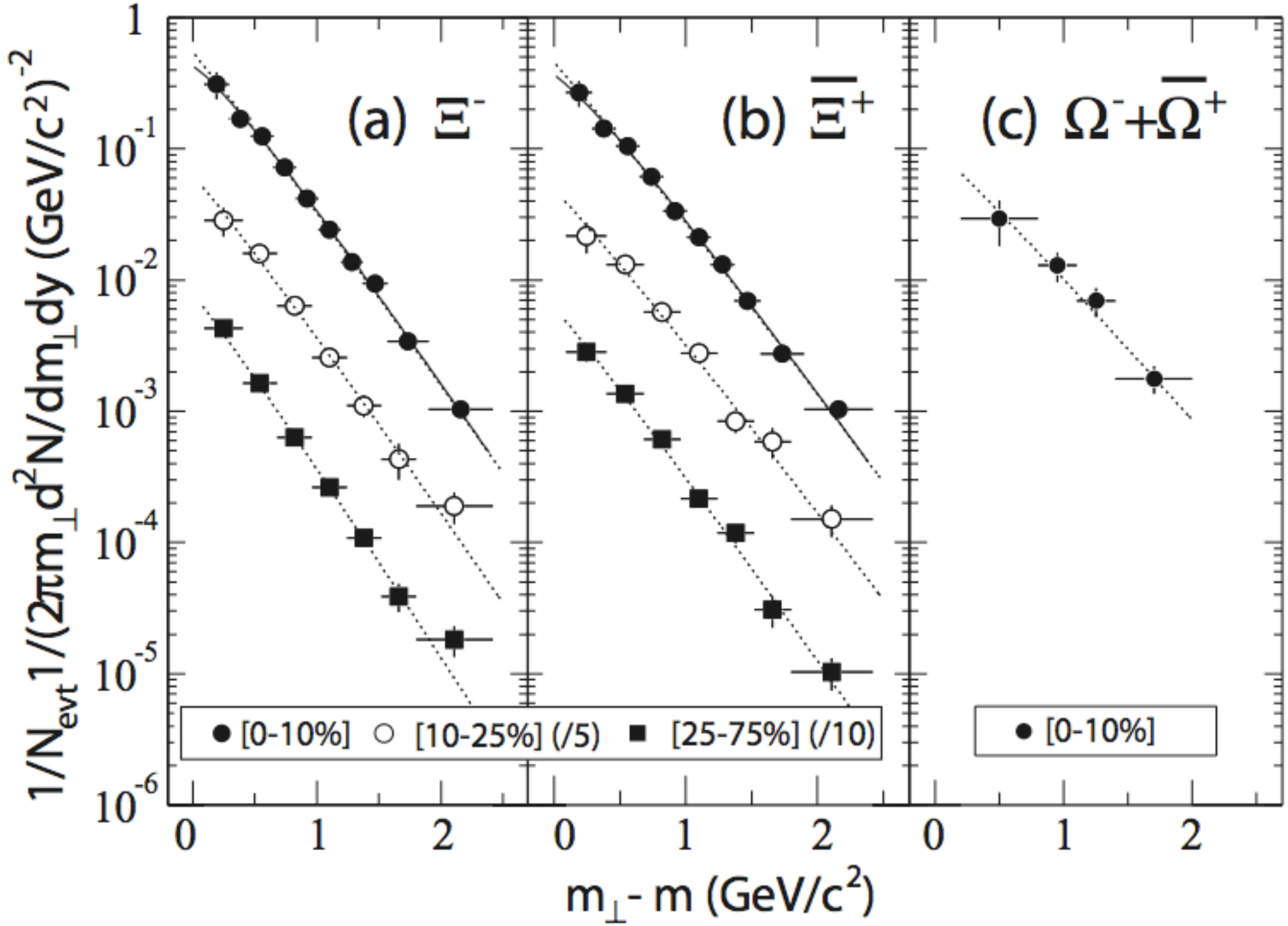
T_{fo} and β_T



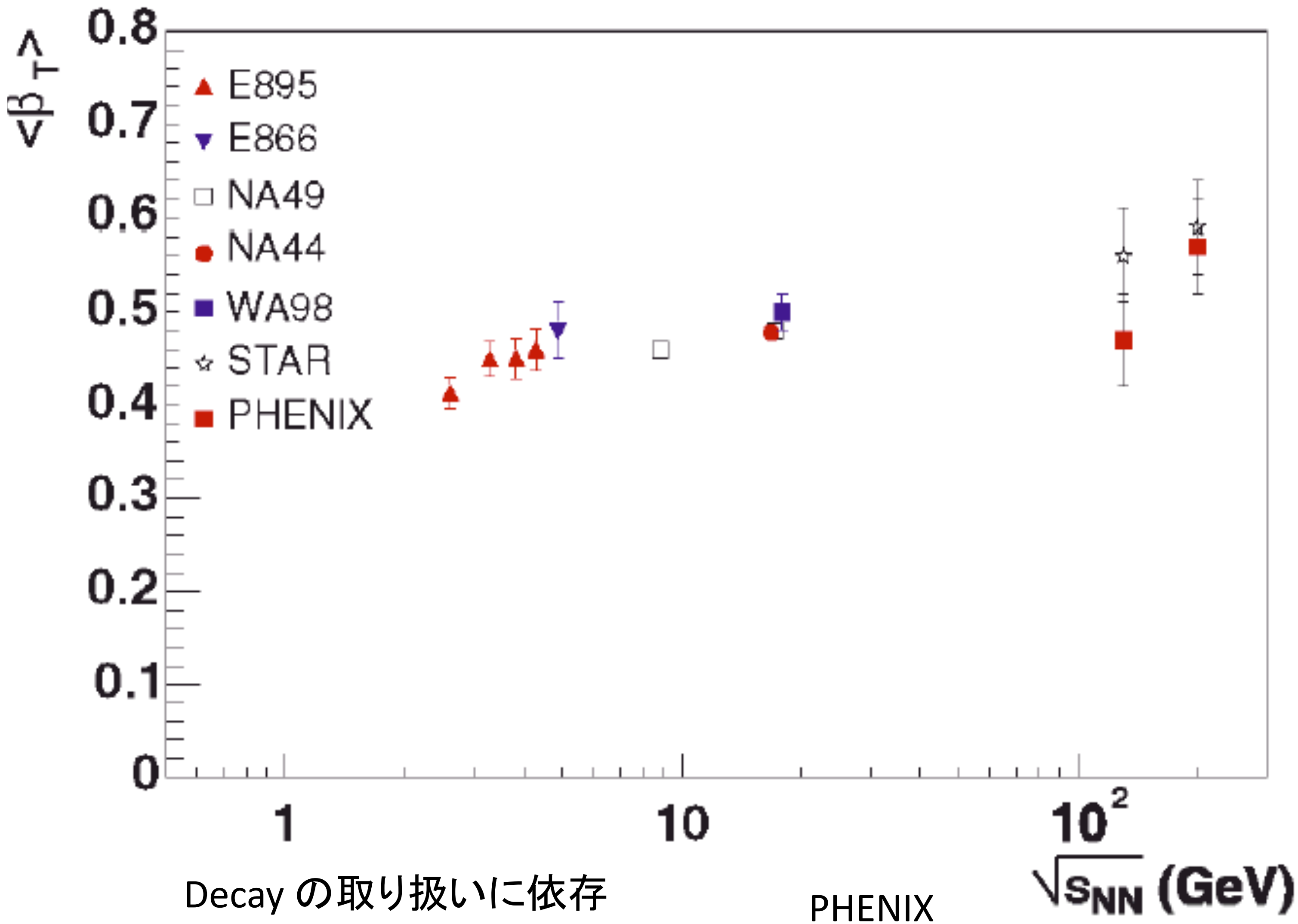
STAR

Different T_{fo} and β_T for Strange baryons ?



(a) Ξ⁻
(b) Ξ̄⁺
(c) Ω⁻+Ω̄⁺
1/N_evt 1/(2πm⊥d²N/dm⊥dy (GeV/c²)⁻²
m⊥- m (GeV/c²)
[0-10%] [10-25%] (/5) [25-75%] (/10)
[0-10%]

Transverse flow

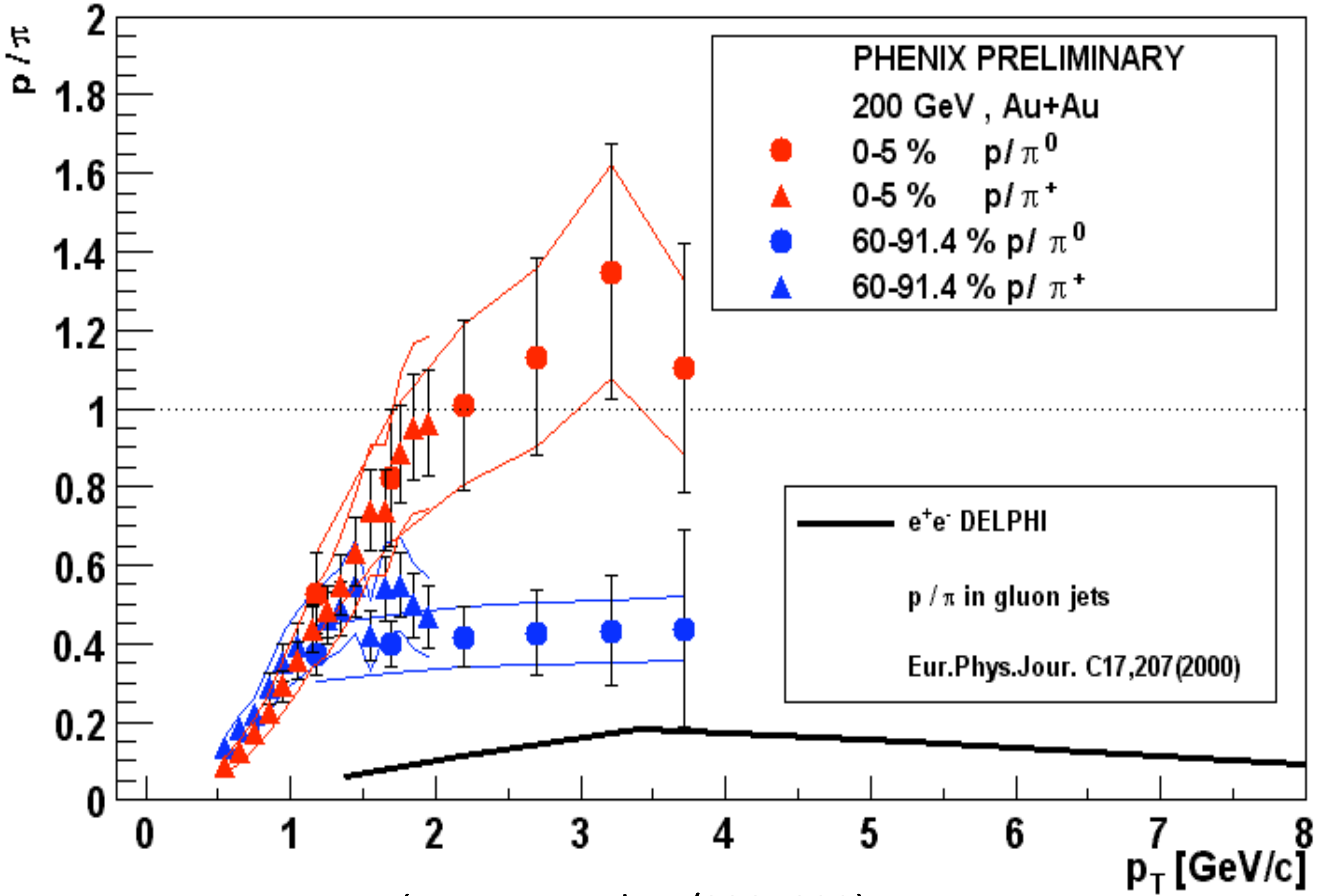


Decay の取り扱いに依存

PHENIX

Baryon Puzzle at RHIC 1

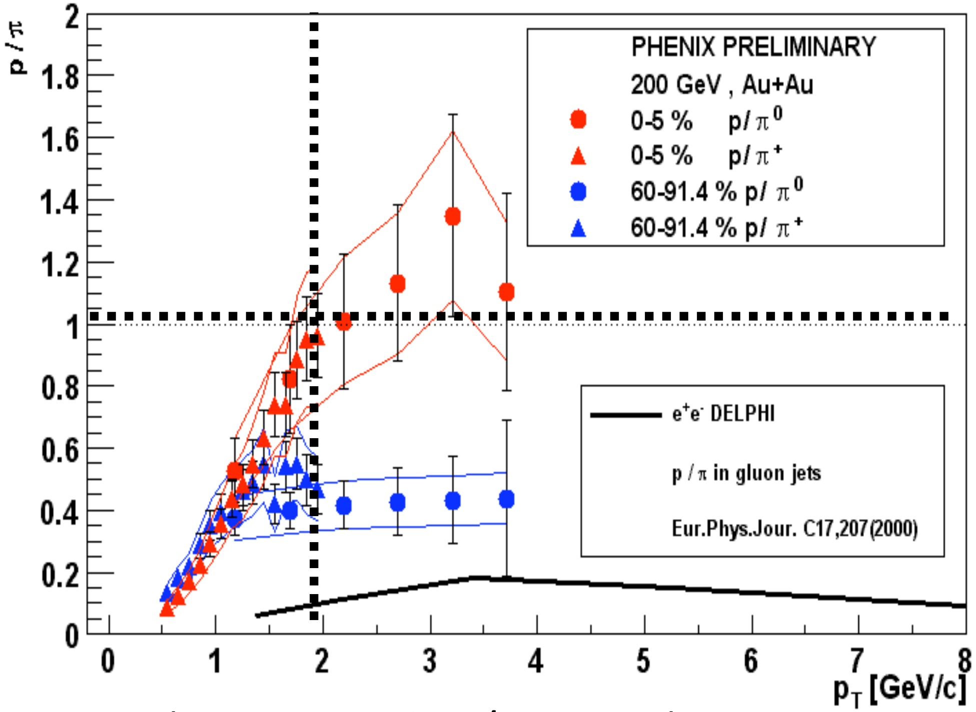
1. Large p/π ratio at high P_T



(PHENIX:nucl-ex/0307022)

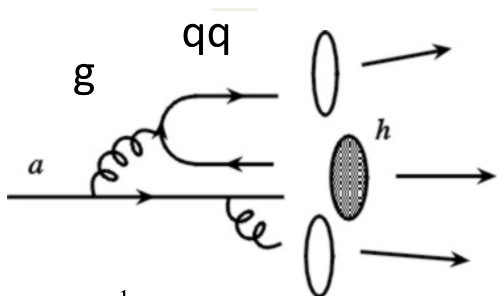
Baryon Puzzle at RHIC

1. Large p/π ratio at high P_T



(PHENIX:nucl-ex/0307022)

Fragmentation



$$E\frac{dN_h}{d^3P}=\int_0^1\frac{dz}{z^2}\frac{E}{z}\frac{dN_a}{d^3(P/z)}D_{\alpha\to h}(z)$$

$D_{a\to h}(z)$: fragmentation functions

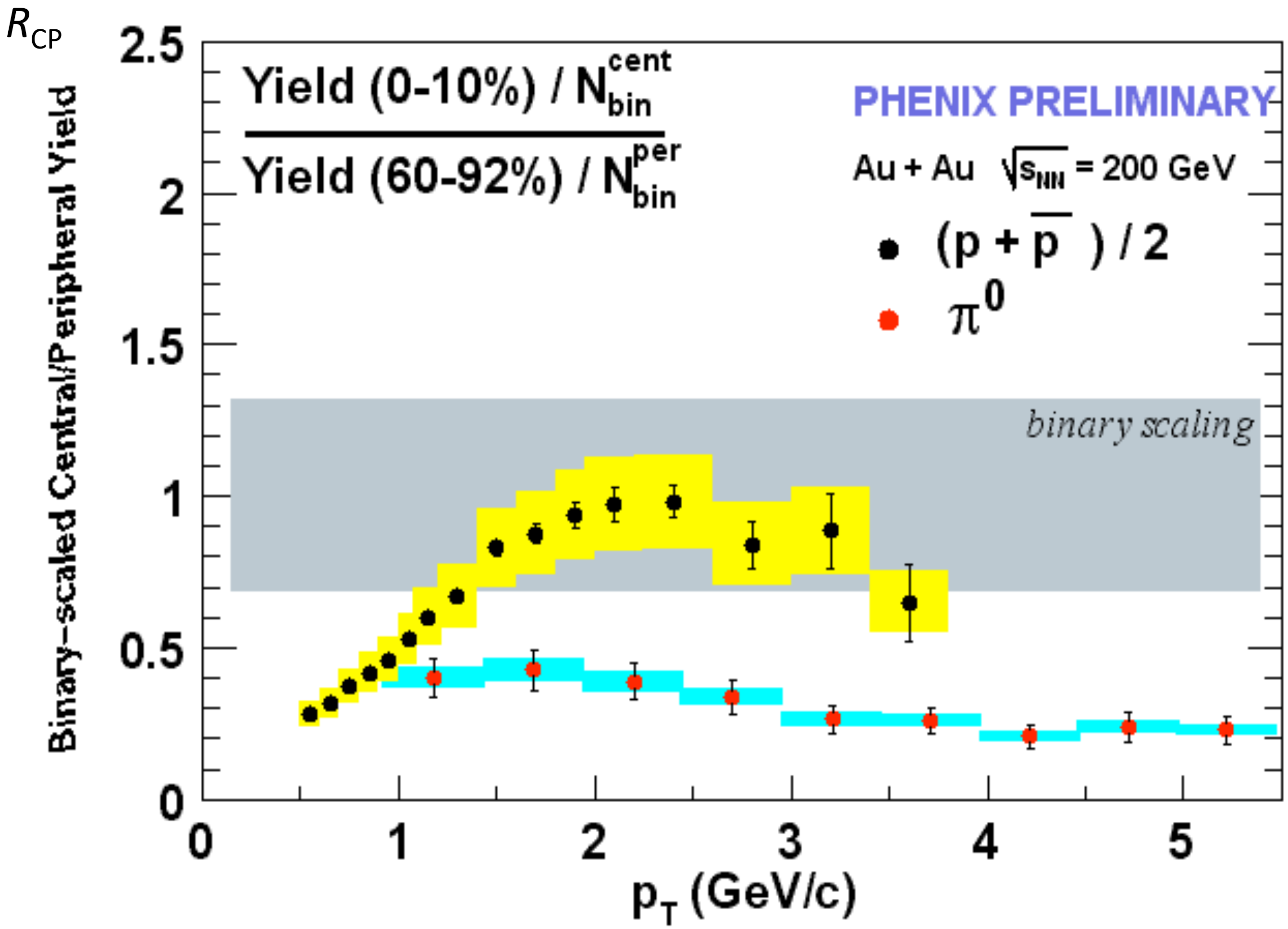
- p/π ratio ~ 1 (P_T>2 GeV) in central collisions

⟺

- p/π ratio << 1

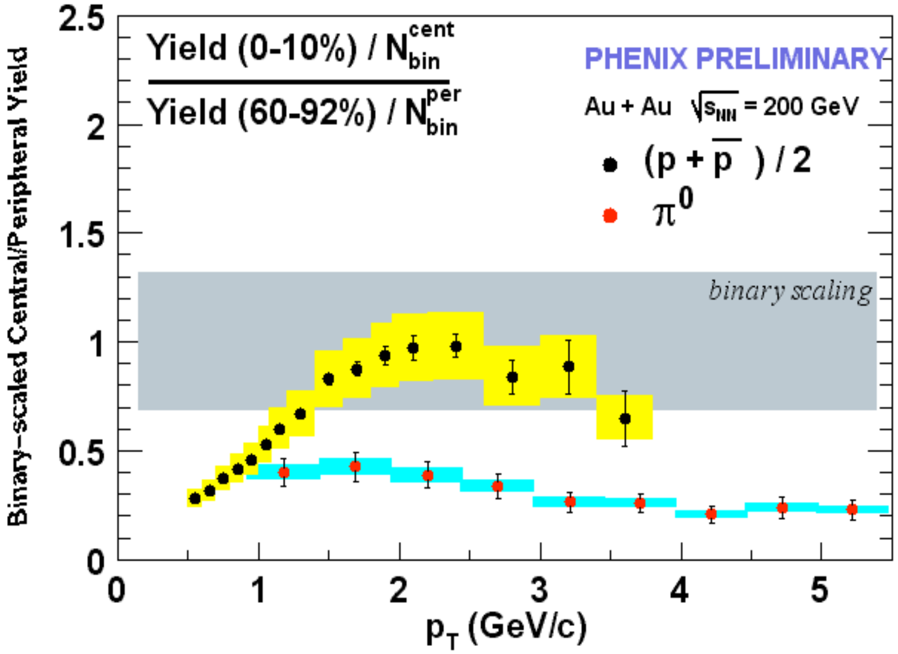
Baryon Puzzle at RHIC

2. Difference in baryon and meson jet-suppression



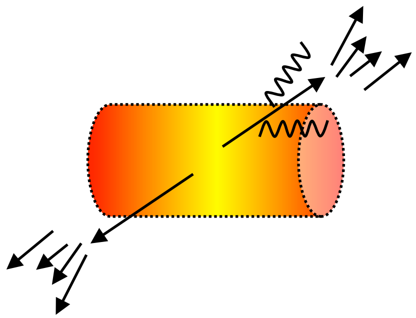
Baryon Puzzle at RHIC

2. Difference in baryon and meson jet-suppression



Fragmentation

- Parton energy loss at high P_T



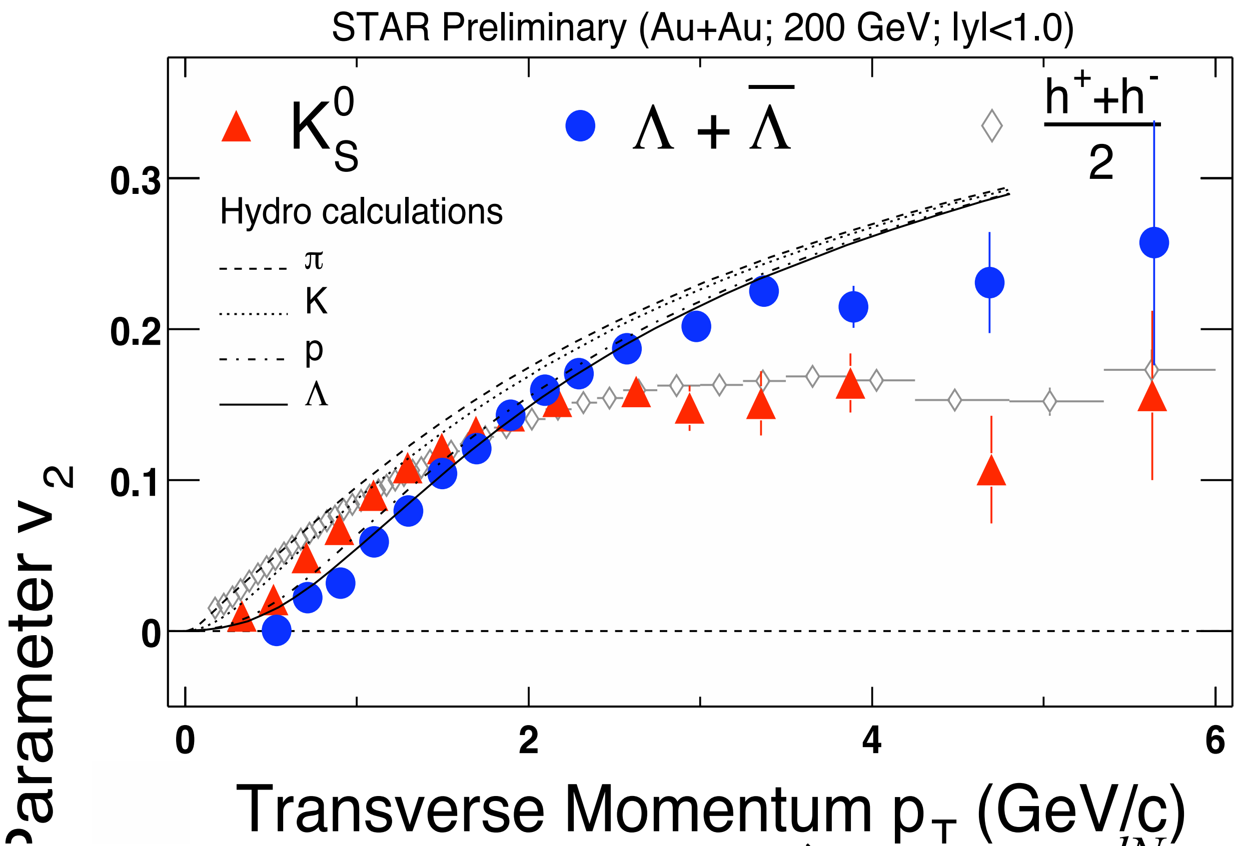
- hard scattering in medium
- jet quenching

- Suppression in R_{CP}^{baryon} occurs at higher P_T than R_{CP}^{meson}

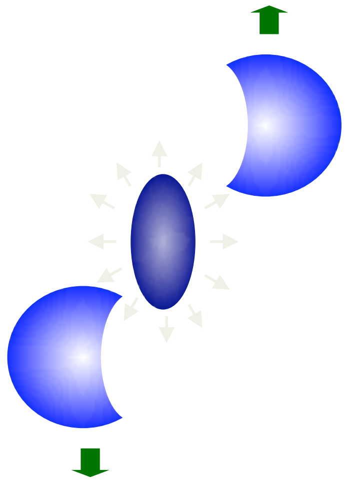
- R_{CP}^{baryon} should be the same as R_{CP}^{meson}.

Baryon Puzzle at RHIC

3. Difference in baryon and meson elliptic flow



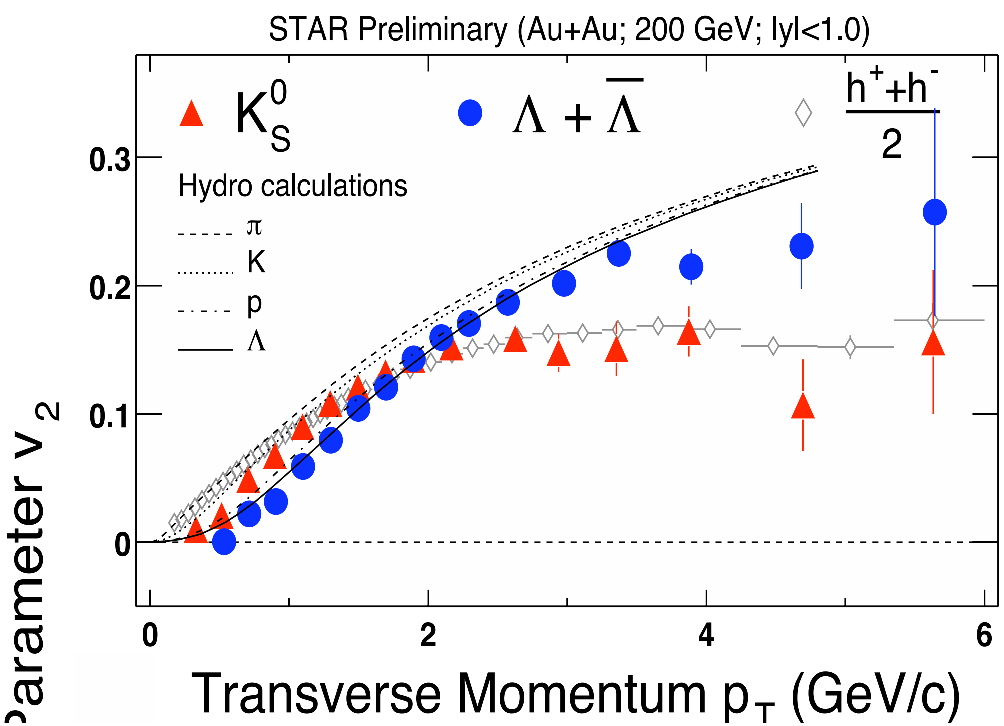
(STAR : PRL91 (2004) 052302)



$$\frac{dN}{d\varphi} \approx v_0(1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi))$$

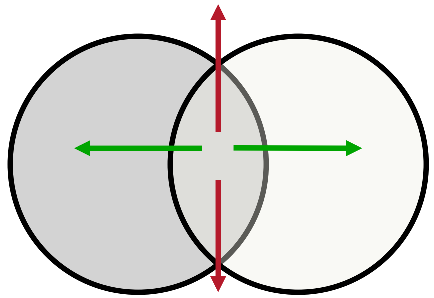
Baryon Puzzle at RHIC

3.Difference in baryon and meson elliptic flow



Fragmentation

$$v_2(P_T) = \langle \cos 2\Phi \rangle = \frac{\int d\Phi \cos 2\Phi d^2N/d^2P_T}{\int d\Phi d^2N/d^2P_T}$$

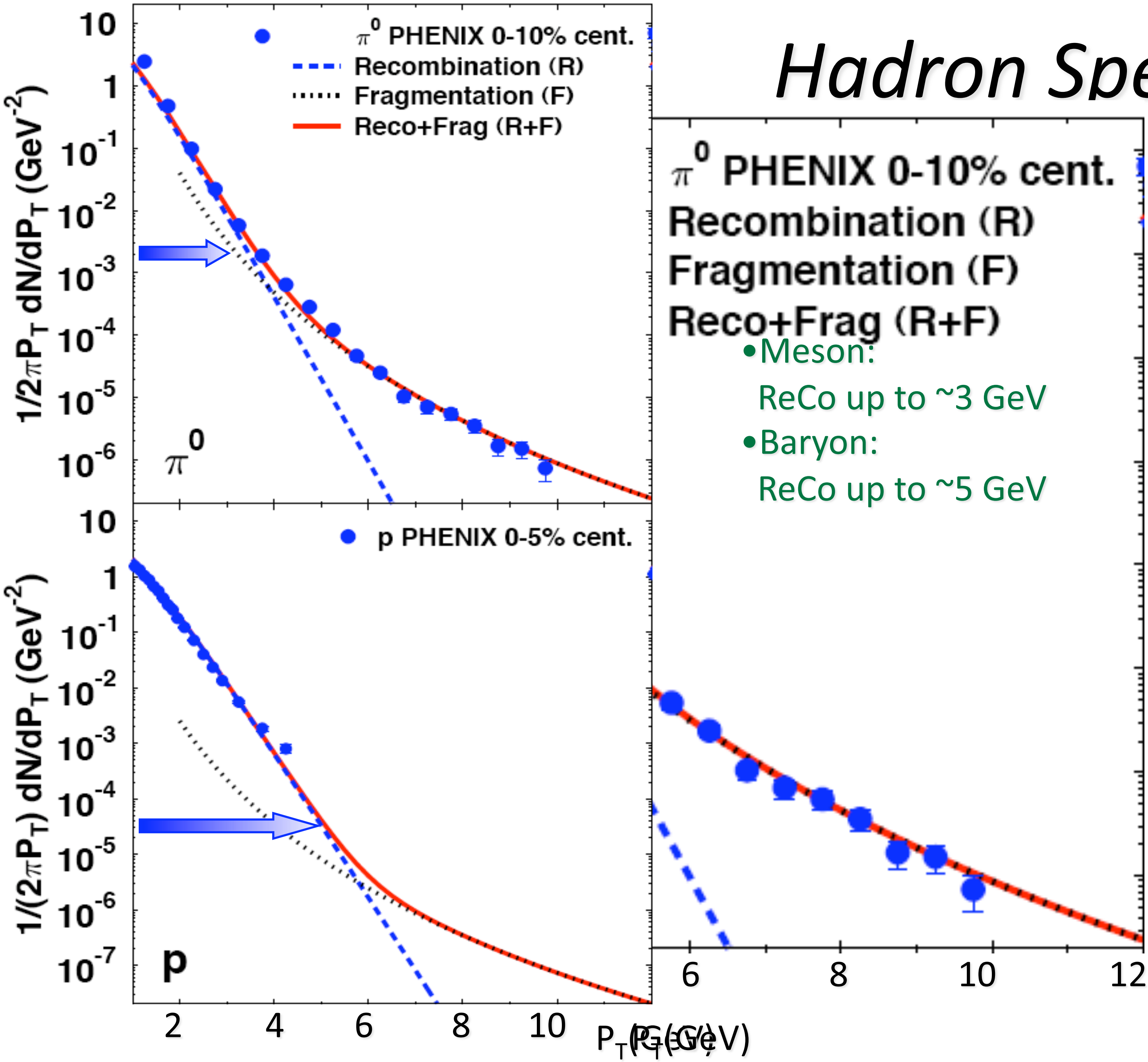


parton energy loss ∝

- Saturation in v_2^{baryon} occurs at higher P_T than v_2^{meson}.

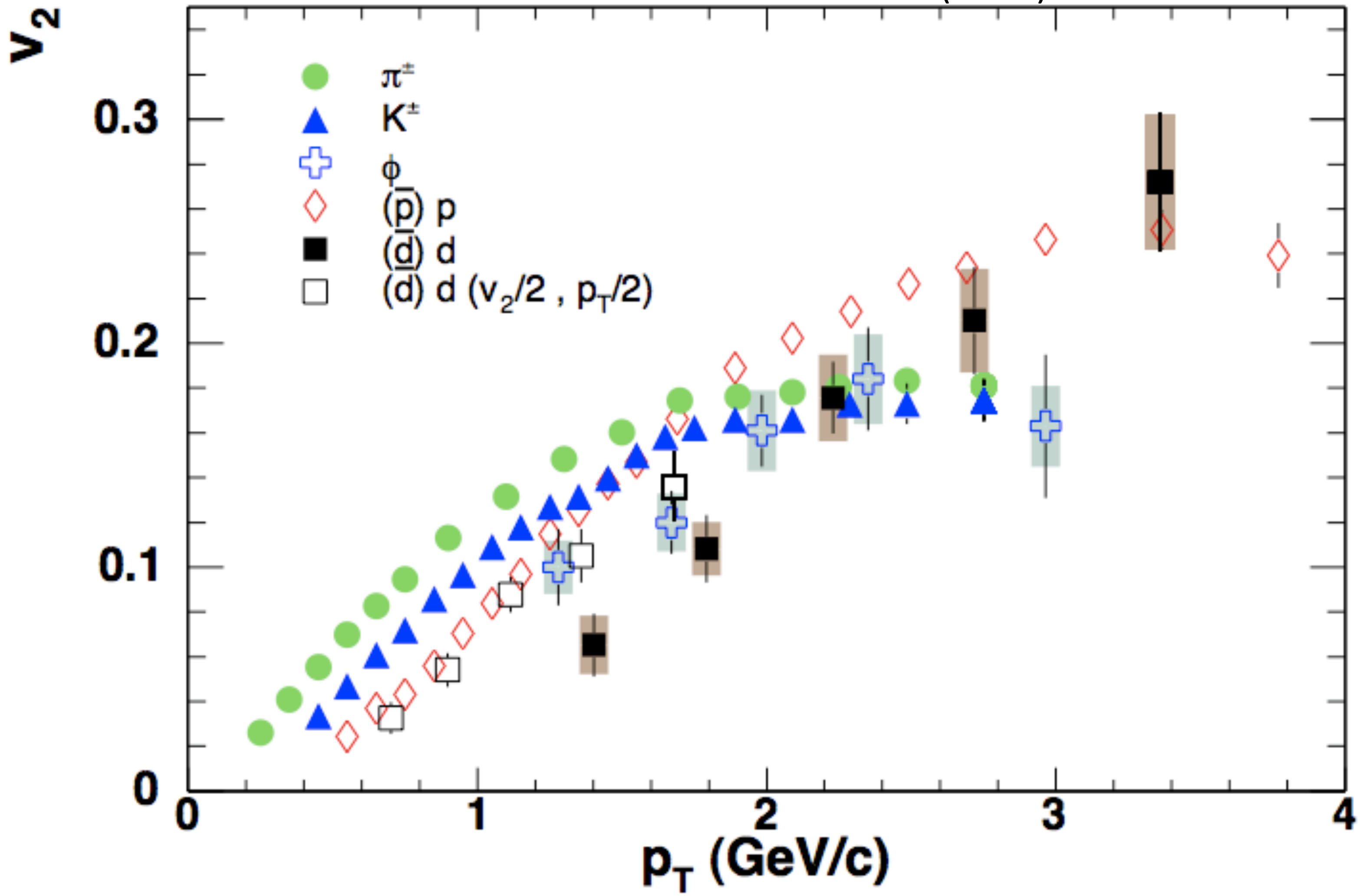
- v_2^{baryon} should be the same as v_2^{meson}.

Hadron Spectra

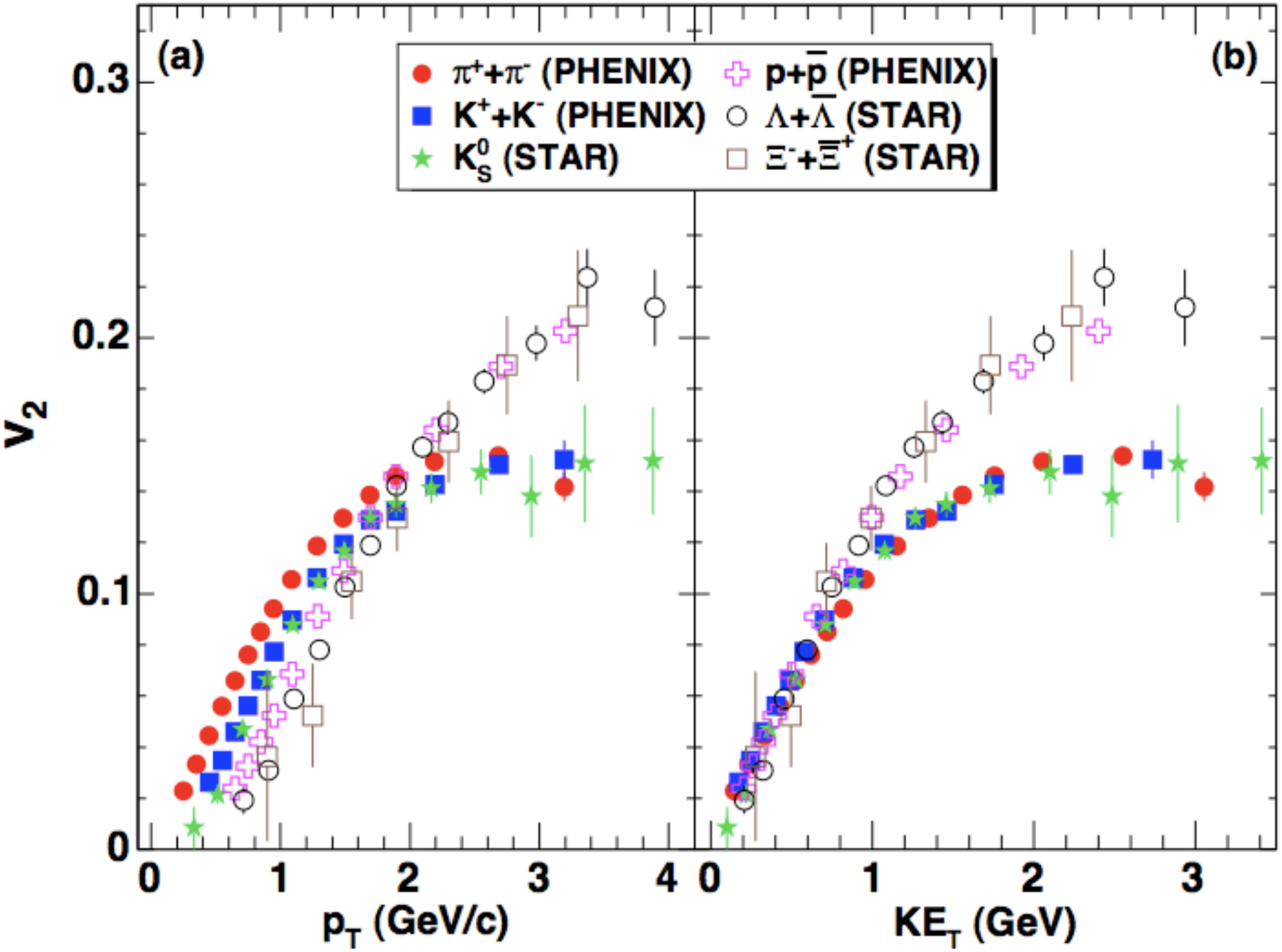


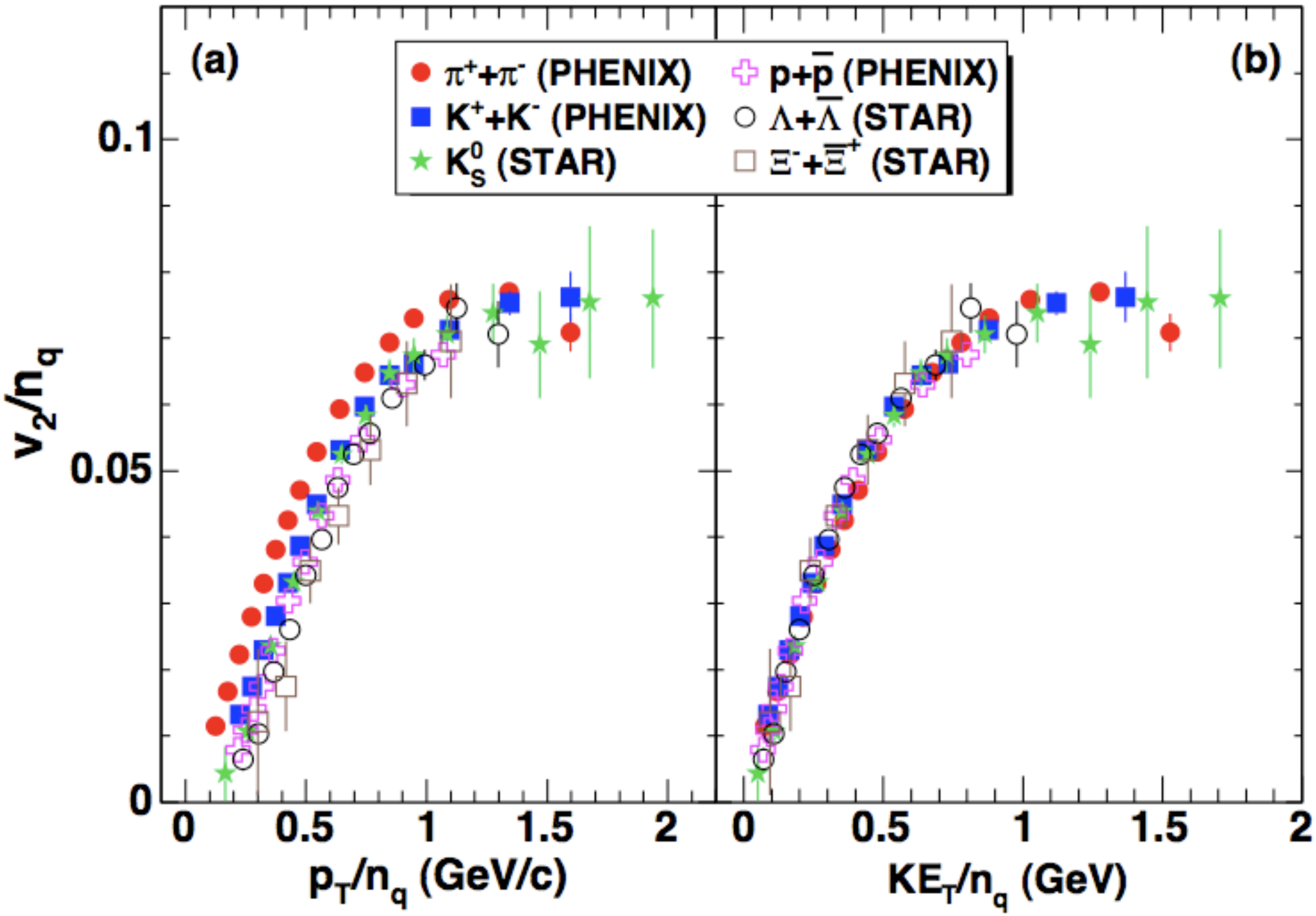
- Meson:
  ReCo up to ~3 GeV
- Baryon:
  ReCo up to ~5 GeV

PHENIXPRL99(2007)052301

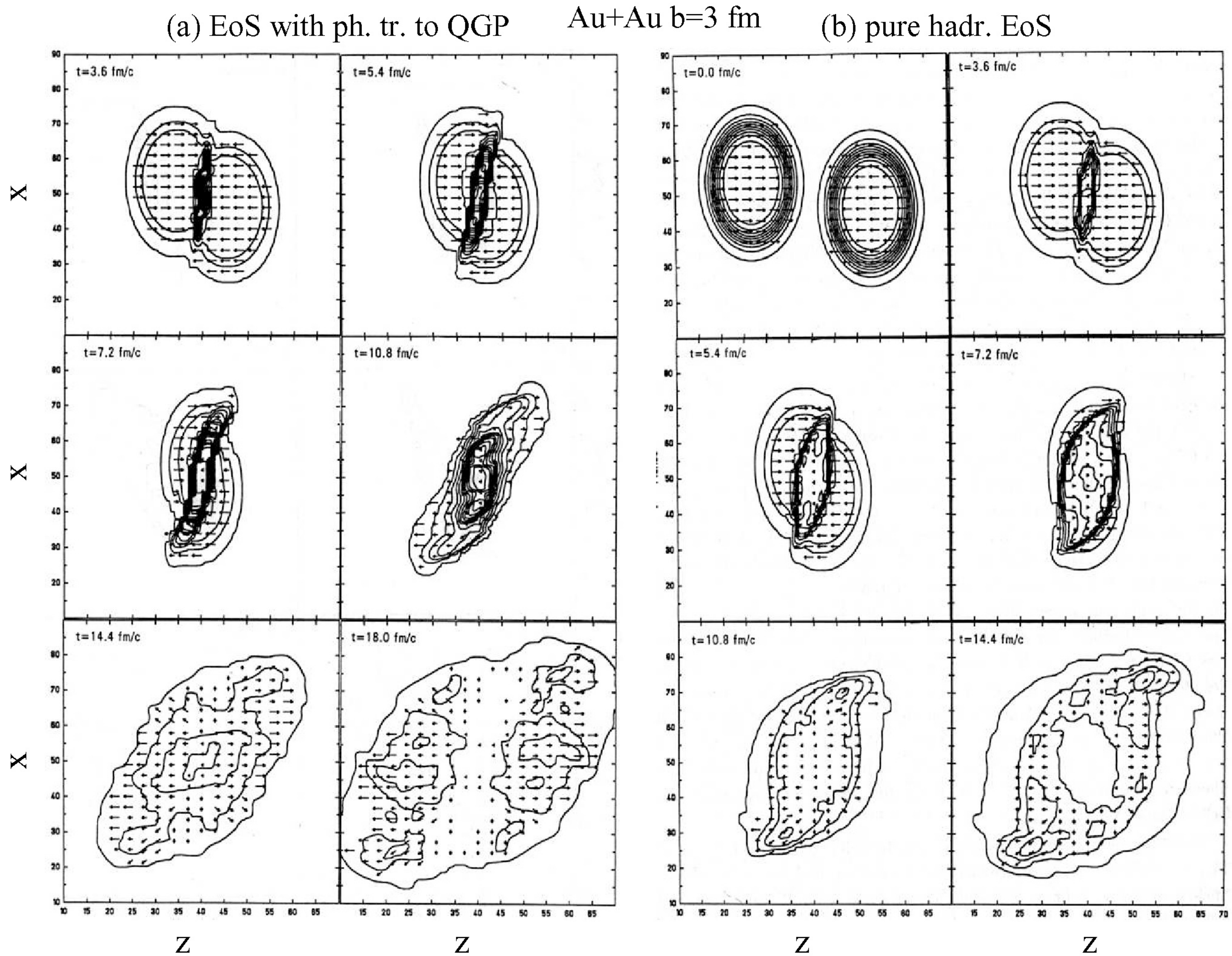


PHENIXPRL98(2007)162301




(a)
(b)
π⁺+π⁻ (PHENIX)
K⁺+K⁻ (PHENIX)
K⁰S (STAR)
p+p̄ (PHENIX)
Λ+Λ̄ (STAR)
Ξ⁻+Ξ̄⁺ (STAR)
v2/nq
0.1
0.05
0
0
0.5
1
1.5
2
pT/nq (GeV/c)
KET/nq (GeV)

Effect of Phase Transition



Rischke '95