ハドロンの収量比
と
化学平衡

Chemistry of Hadrons

$$\rho_i = \gamma_s^{|s_i|} \frac{g_i}{2\pi^2} T^3 \left(\frac{m_i}{T}\right)^2 K_2\left(\frac{m_i}{T}\right) \lambda_q^{Q_i} \lambda_s^{S_i}$$

$$\lambda_q = \exp\left(\frac{\mu_Q}{T}\right), \quad \lambda_s = \exp\left(\frac{\mu_s}{T}\right)$$

Q_i : 1 for u d, -1 for $\bar{u}$ $\bar{d}$

S_i : 1 for s, -1 for $\bar{s}$

g_i : spin-isospin freedom

m_i : particle mass

Fitting parameters

T : Chemical freezeout temperature

μ_q : u,d chemical potential

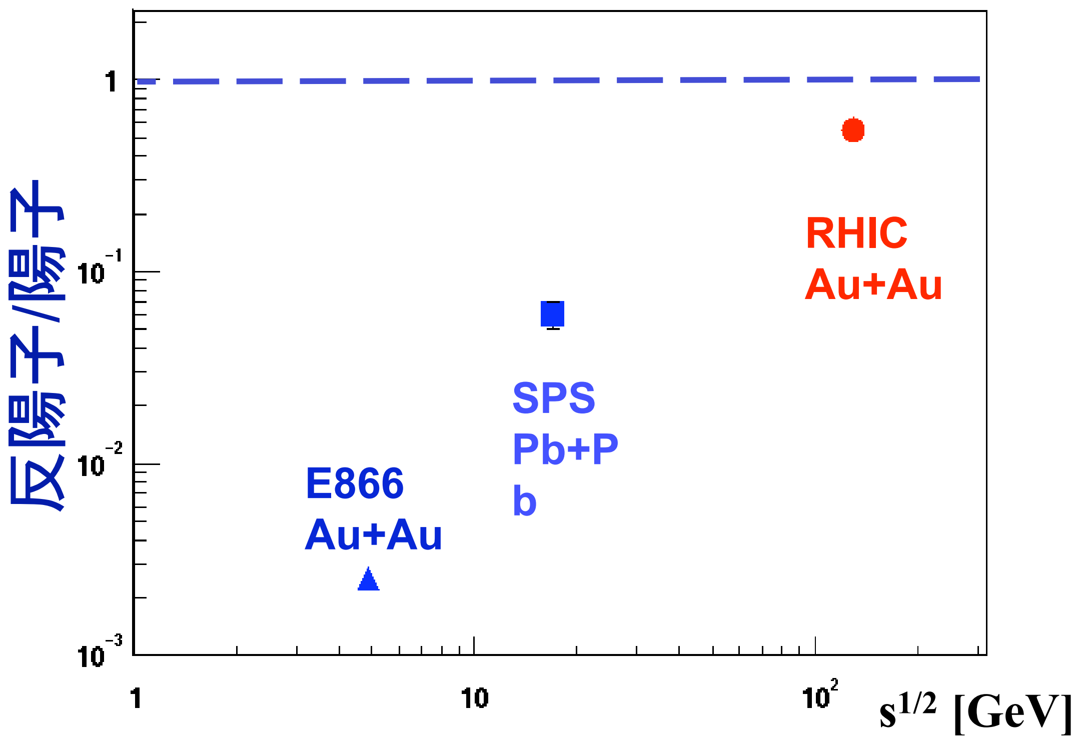
μ_q : strangeness chemical potential

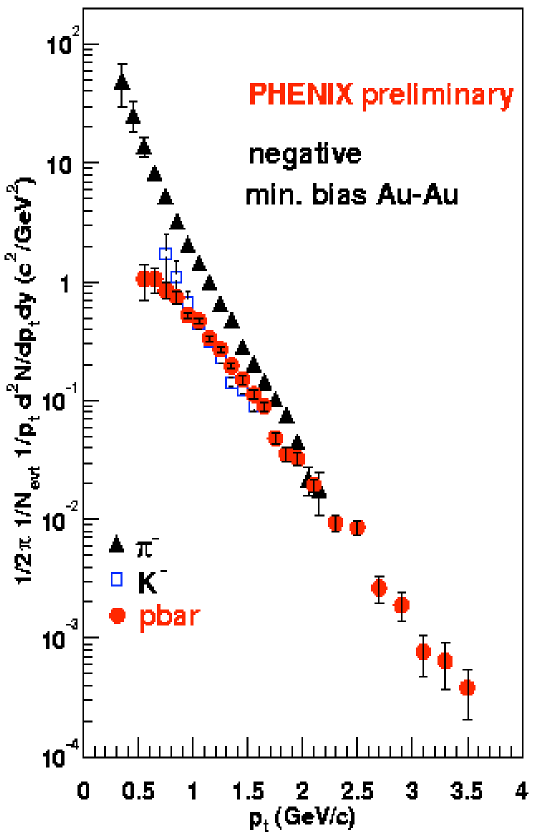
γ_s : strangeness saturation factor

反陽子／陽子

- 反陽子/陽子～0.6
  粒子・反粒子バランスが1に近い
  Big Bang に近い状態が実現

- 反陽子の収量が異常に多い
  高い運動量領域でパイオンを凌駕
  新しい対生成機構？
  軽い粒子生成の抑制機構？





粒子／反粒子の Chemistry

反粒子・粒子比

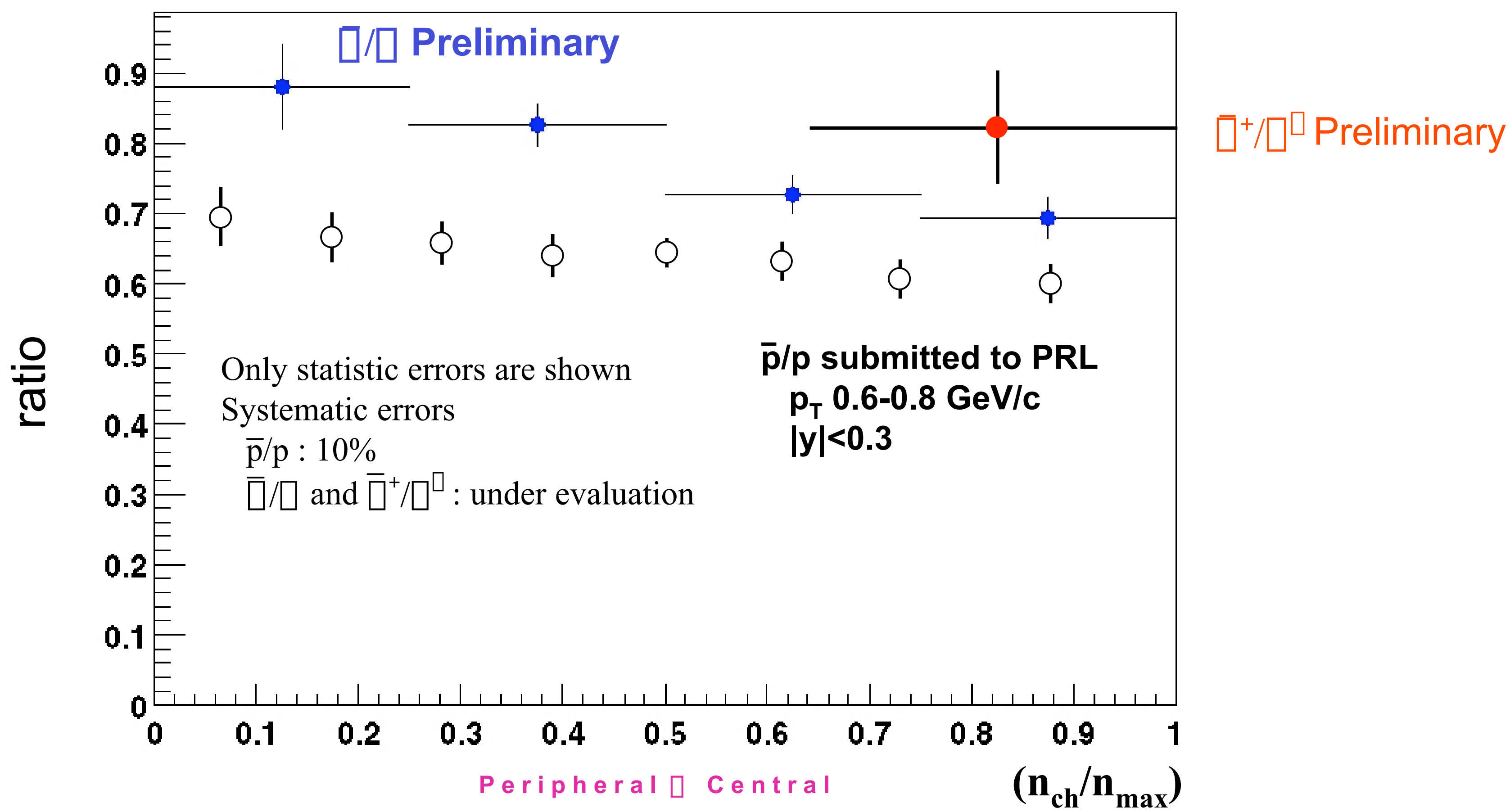
- Strangeness chemical potential $\mu_s \sim 0$ を仮定
- 反陽子／陽子比 → その他の反バリオン／バリオン比

  クォーク fugacity（逃散度）: z_q = $\exp(2\mu_q/T)$

	CAL.	EXP.
$\bar{p}/p(uud) = (z_q)^{-3}$		0.6(0.06)
$\bar{\Lambda}/\Lambda(uds) = (z_q)^{-2}$	0.72(0.05)	0.73(0.03)
$\bar{\Xi}/\Xi(uss) = (z_q)^{-1}$	0.84(0.03)	0.82(0.08)
$K^-/K^+(u\bar{s}) = (z_q)^{-1}$	0.84(0.03)	0.88(0.05)

- 単純な計算と良く合う

Multiplicity dependence of ratios



- 中心衝突で反粒子/粒子の比が下がる傾向
  - 反粒子の吸収？

Particle ratio

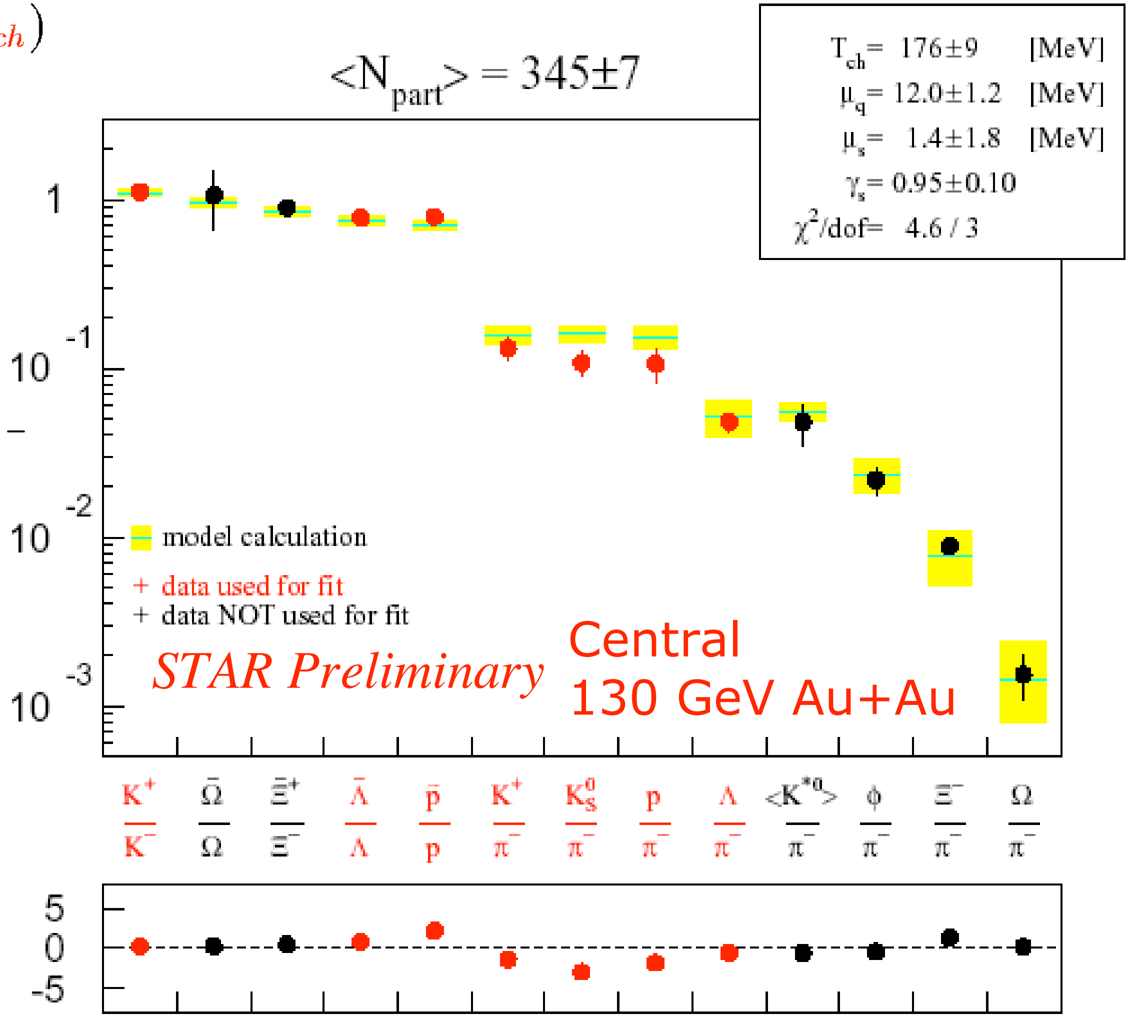
$$\rho_i = \gamma_s^{|s_i|} \frac{g_i}{2\pi^2} T_{ch}^{\ 3} \left(\frac{m_i}{T_{ch}}\right)^2 K_2(m_i/T_{ch})\ \lambda_q^{\ Q_i}\ \lambda_s^{\ s_i}$$

M. Kaneta and N. Xu, J. Phys. G**27** (2001) 589

$$\lambda_q = \exp(\mu_q/T_{ch}), \quad \lambda_s = \exp(\mu_s/T_{ch})$$

T_{ch} : Chemical freeze-out temperature
μ_q : light-quark chemical potential
μ_s : strangeness chemical potential
γ_s : strangeness saturation factor

Q_i : 1 for u and d, -1 for u and d
s_i : 1 for s, -1 for s
g_i : spin-isospin freedom
m_i : particle mass
K2 : the second-order modified Bessel function

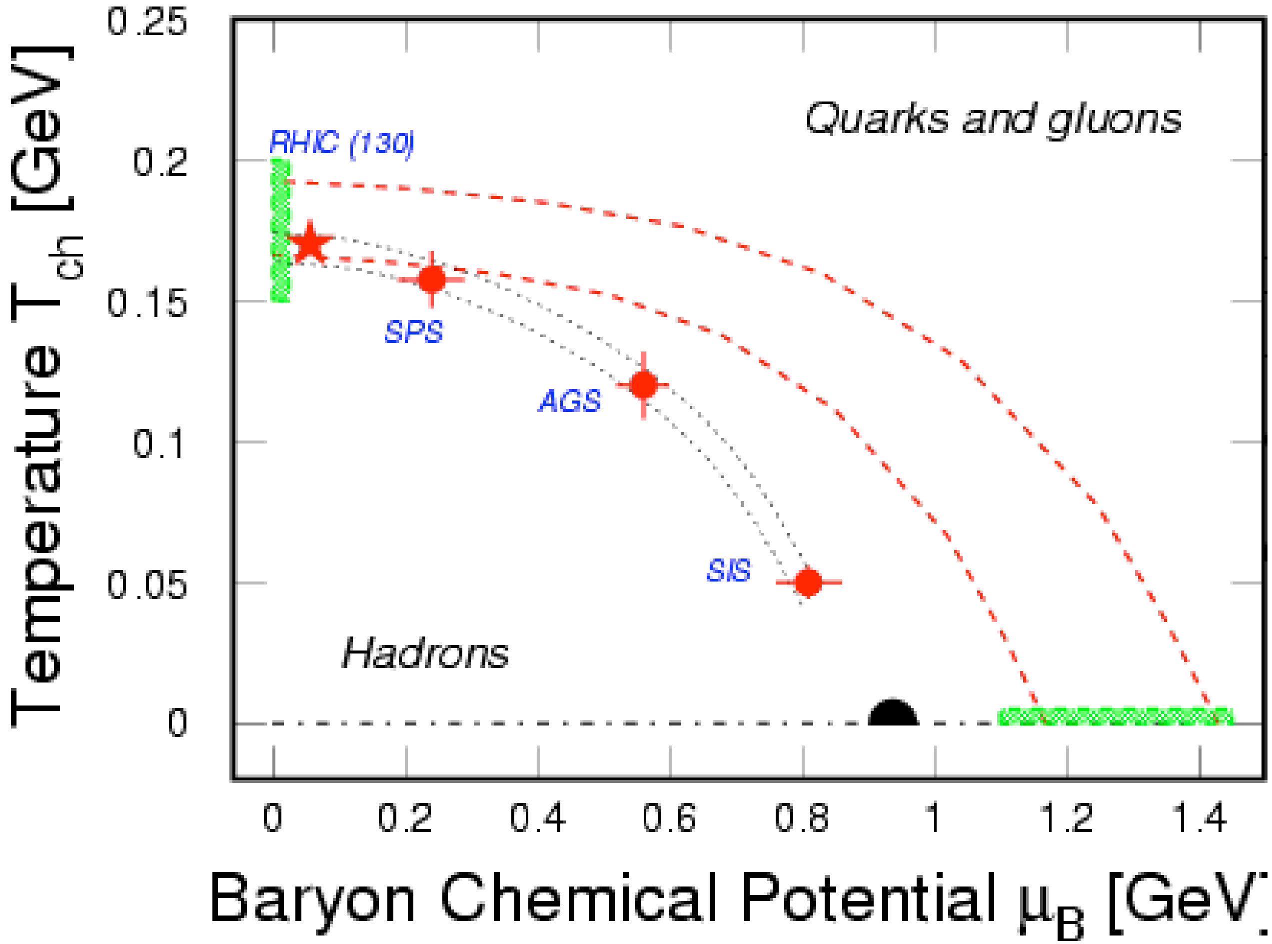


Simple chemical freeze-out model remarkably well agrees with data.

Chemical Equilibrium

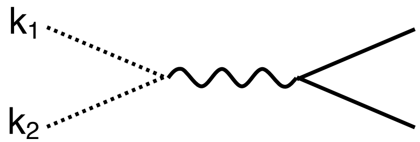
Particle ratio →

Chemical equilibration at high temperature (at QGP?)



Strangeness Production in QGP Phase

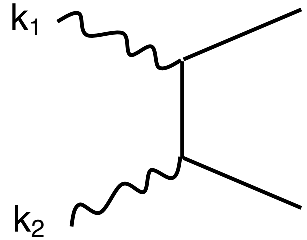
- $q\bar{q}$ annihilation : $\sigma(q\bar{q}) = \frac{8\pi\alpha_s^2}{27s}\left(1 + \frac{2M^2}{s}\right)w(s)$

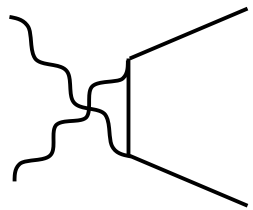


- two gluon collision :

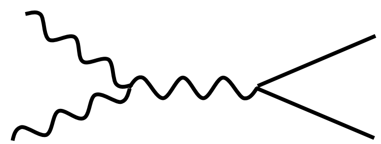
$$\sigma(gg) = \frac{2\pi\alpha_s^2}{3s}\left[\left(1 + \frac{4M^2}{s} + \frac{M^4}{s^2}\right)\tanh^{-1} w(s) - \frac{7s + 31M}{8s} w(s)\right]$$

$$s = (k_1 + k_2)^2 \qquad w(s) = \left(1 - \frac{4M^2}{s}\right)^{1/2}$$





- $\alpha_s \sim 0.6$
- M(strange quark) = 150 MeV
- $\sigma(q\bar{q}) \sim \sigma(gg) \sim 0.1$mb at $\sqrt{s} \approx 0.4 \sim 1$GeV



- meson & hyperons

  coalescence with u, d quarks

  in the hadronization stage

$$R = \frac{dN}{dtdx^3} = \frac{8}{\pi^4}\int_{4M^2} ds\, s\,\sigma(gg)\left[\int\int dk_1 dk_2\, \delta(4k_1k_2 - s) f_g(k_1) f_g(k_2)\right]$$

$$+ \frac{9}{4\pi^4}\int_{4M^2} ds\, s\,\sigma(q\bar{q})\left[\int\int dk_1 dk_2\, \delta(4k_1k_2 - s) f_q(k_1) f_{\bar{q}}(k_2)\right]$$

8 : 9/4 = 256 : 64 = 8^2 x 2^2 : 3^2 x 2^2 x 2 ==> Gluon interaction dominates

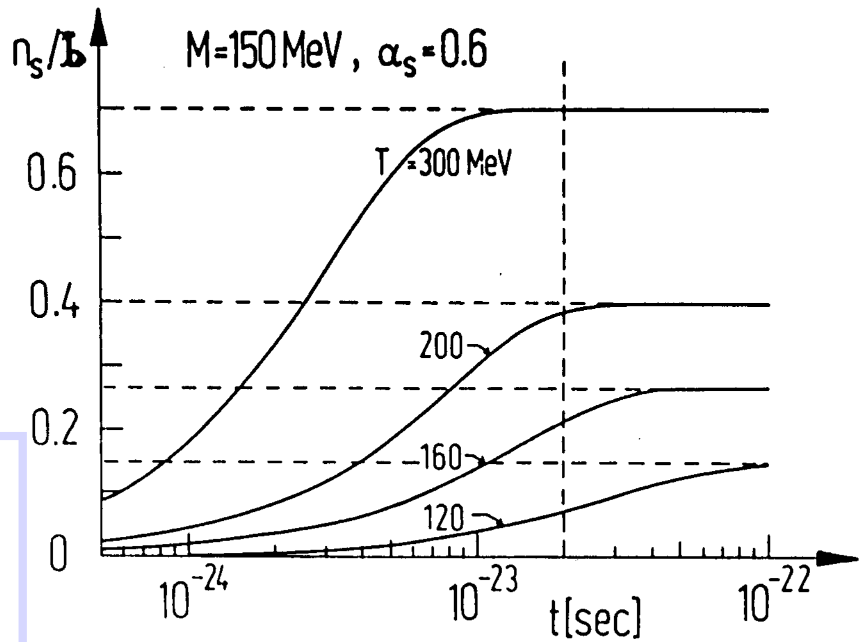
N_g N_e N_q N_s N_f

$$R \sim \frac{7}{3\pi^2}\alpha_s^2 M T^3 e^{-2M/T}\left(1 + \frac{51}{14}\frac{T}{M} + \ldots\right)$$

$$\frac{dn_s}{dt} = R\left[1 - \left(\frac{n_s(t)}{n_s(\infty)}\right)^2\right]$$

$$n_s(0) = 0$$

$$n_s(t) = n_s(\infty)\tanh(t/\tau)\ ; \quad \tau = \frac{n_s(\infty)}{R}$$



$n_s(t)$ saturation(= chemical equilibrium) :

achieved within 6 fm (2x 10^{-23} sec)

for T > 160 MeV

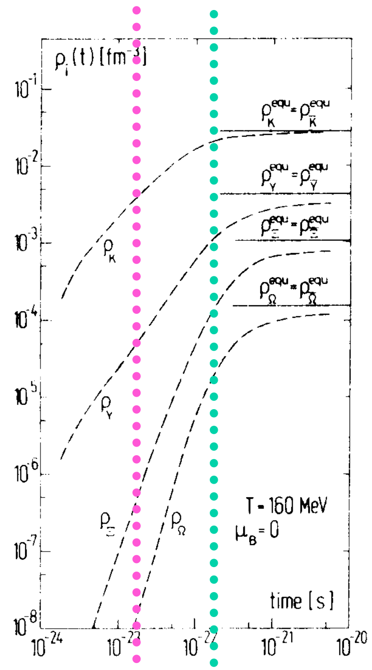
Strange Particles in Hot Hadron Gas

elaborate calculation:

P. Koch, B. Mueller, J. Rafelski,: Phys. Rep. 142 (1986) 167

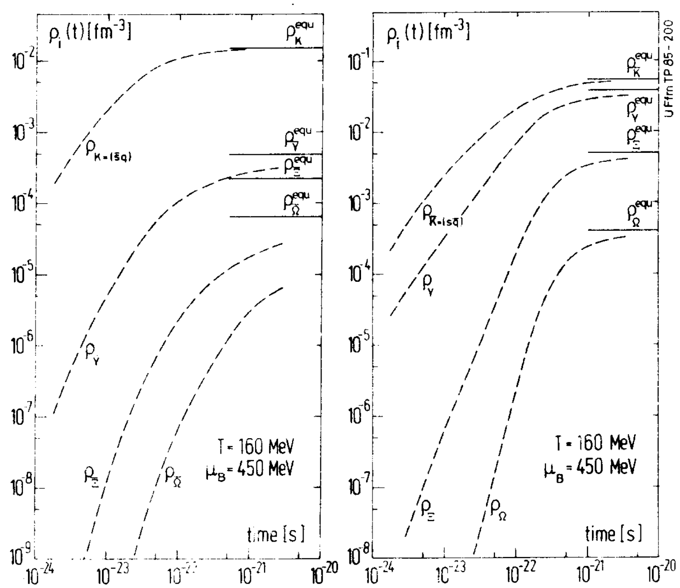
(□, K; N, □, □, □, □ and antiparticles)

- strangeness production: □N → KY
  □ ~ 0.1 mb or less: sharply rise with temperature
- strangenss exchange: KN → □Y
  □ ~ 0.2 - 0.5 mb: temperature indenpendent
- baryon annihilation: NN → n□
  □ ~ 100 mb at low T; fall with temperature



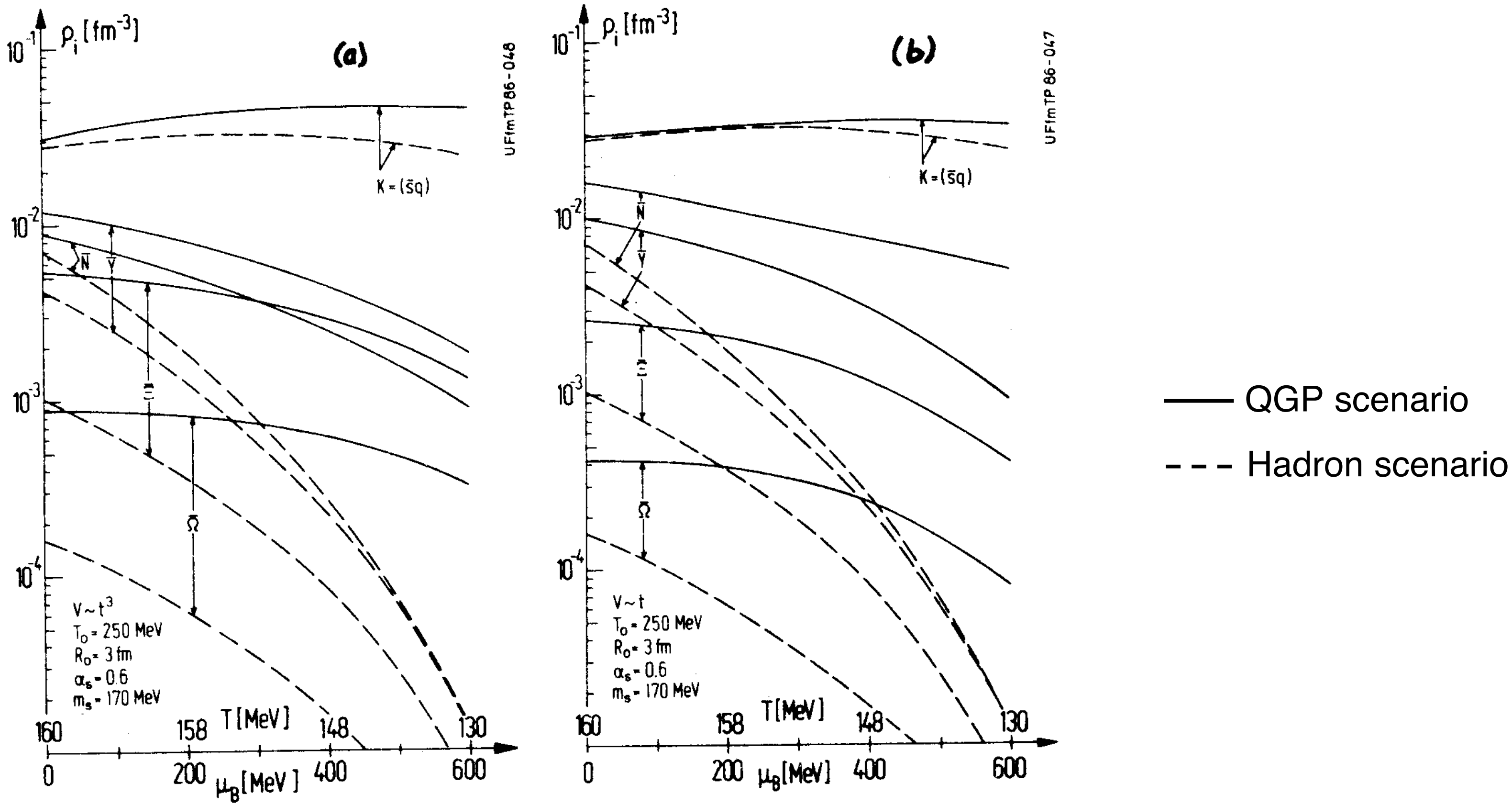
- Long equilibration time, compared to QGP case
- (Anti-)baryons takes longer than Kaons

  small cross section for strangeness production
  small cross section for baryon pair production



Results in case of Full Evolution

- Kaon yield is not different much
- large difference for anti-particles; □, □, □

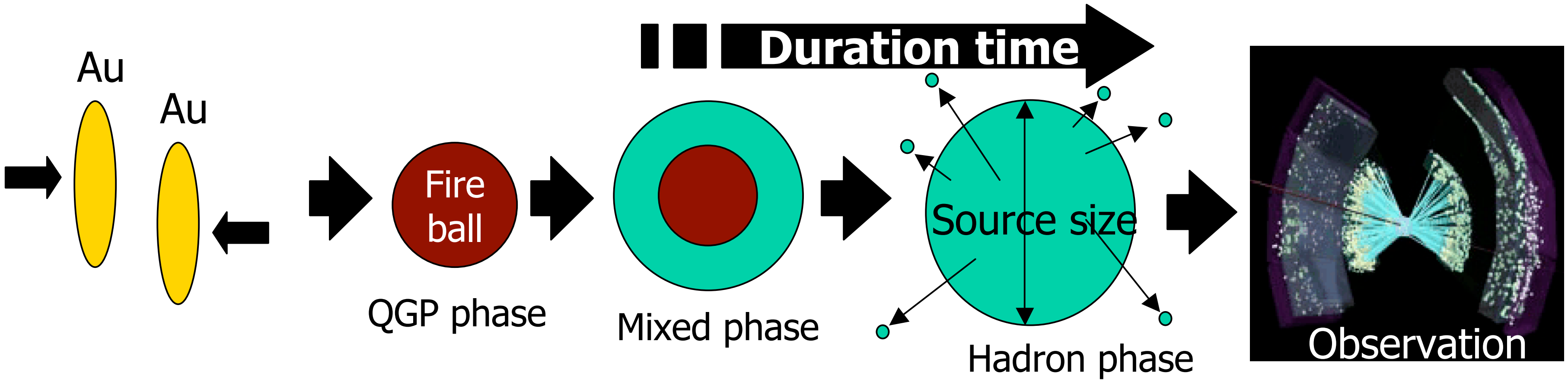


volume (3D) expansion

longitudinal expansion

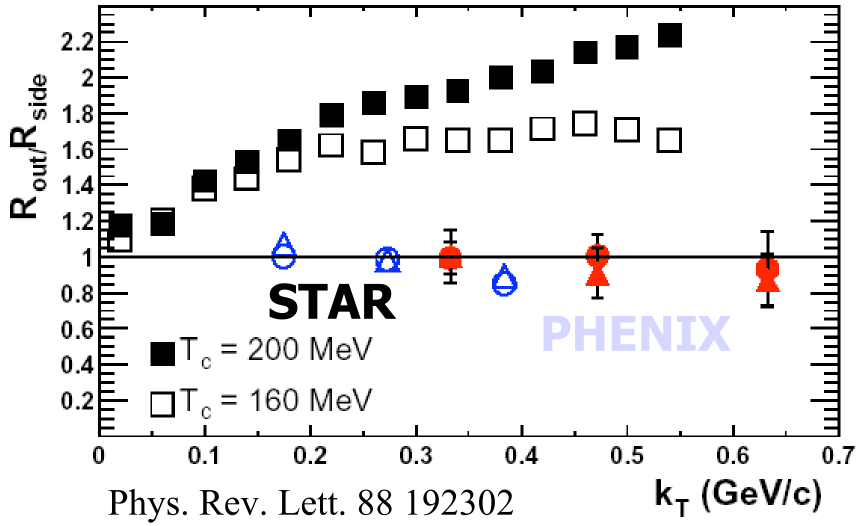
HBT

Physics motivation

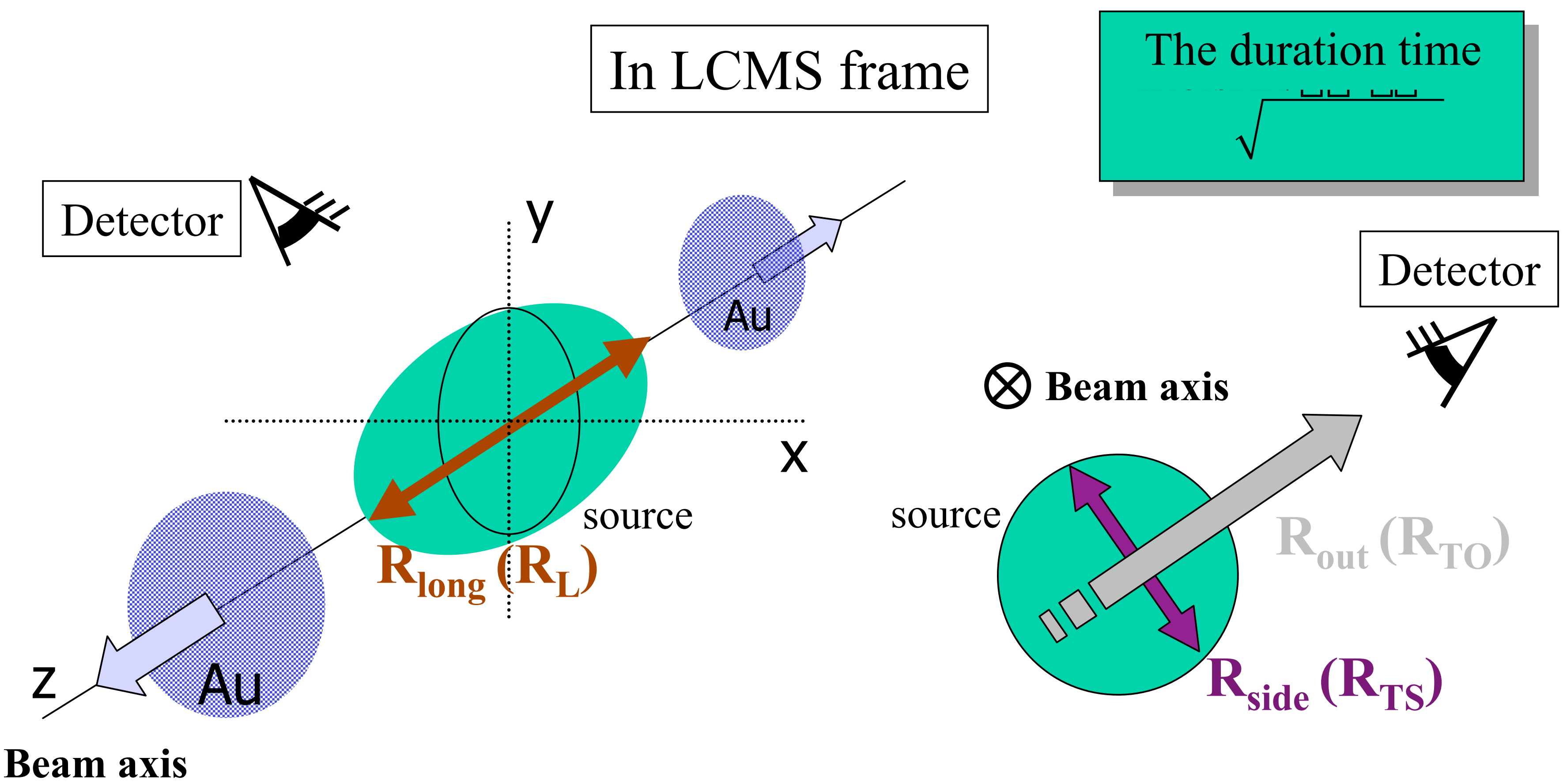


Some models predict that the source size will become bigger and duration time become longer via QGP phase

PHENIX and STAR results show that source radii don't increase and no duration time at sqrt(s_{NN})=130GeV

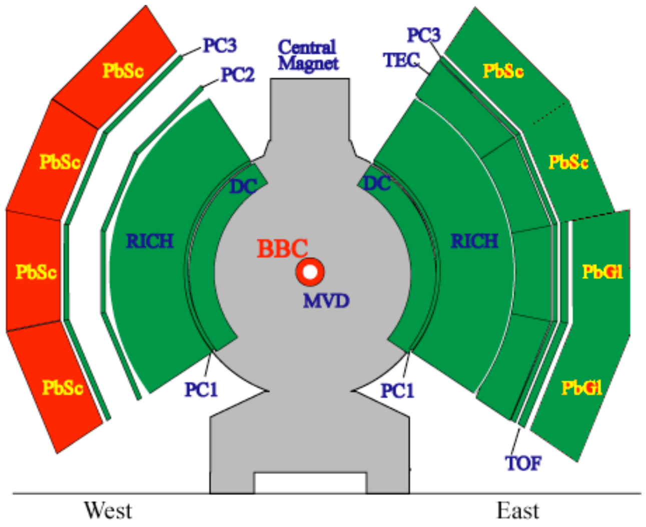


Bertsch-Pratt source radii

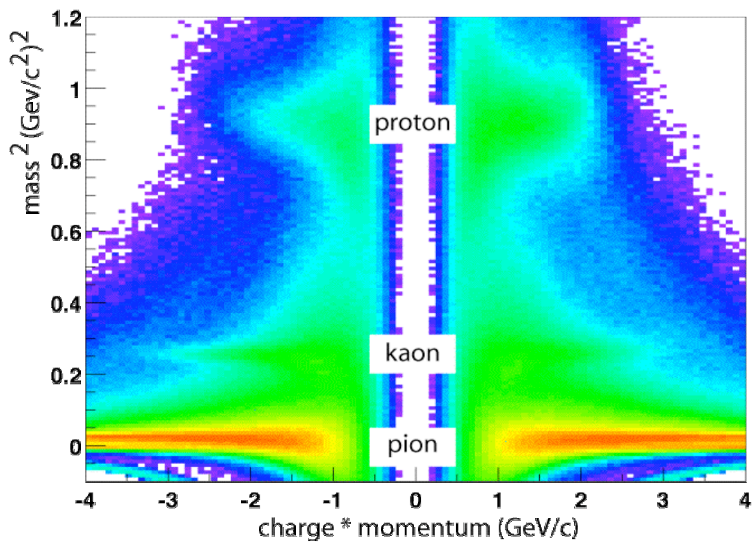


Data statistics from PHENIX Run2

- About 50M minimum bias event.
  - Z-vertex < 30 cm
  - p_T>0.2GeV/c
- Charged pi, K PID by EMCal
  - 1.5σ within pi mass,
    (and 2.0σ away from K mass)
  - 1.5σ within K mass,
    (and 2.5σ away from p, pi mass)

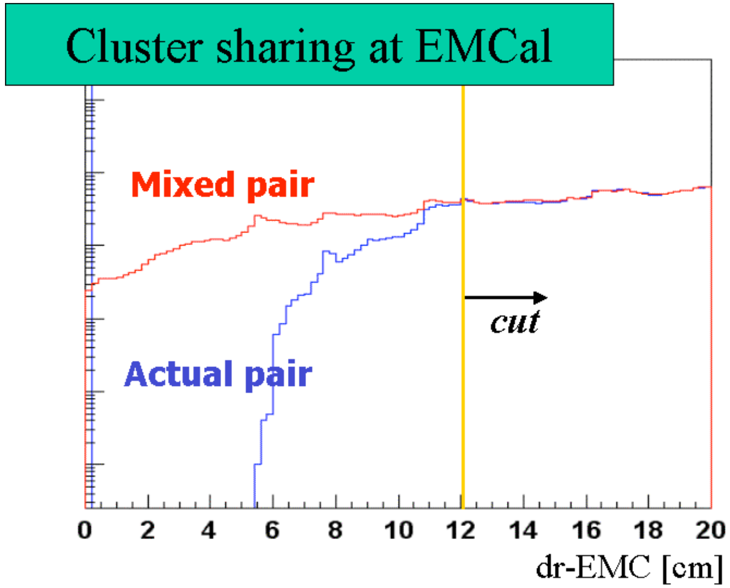


	Run2 data	Run1 data
pi+ pair	164M	4.2M
pi- pair	157M	4.6M
K+ pair	1.2M	0.023M
K- pair	1.1M	0.029M



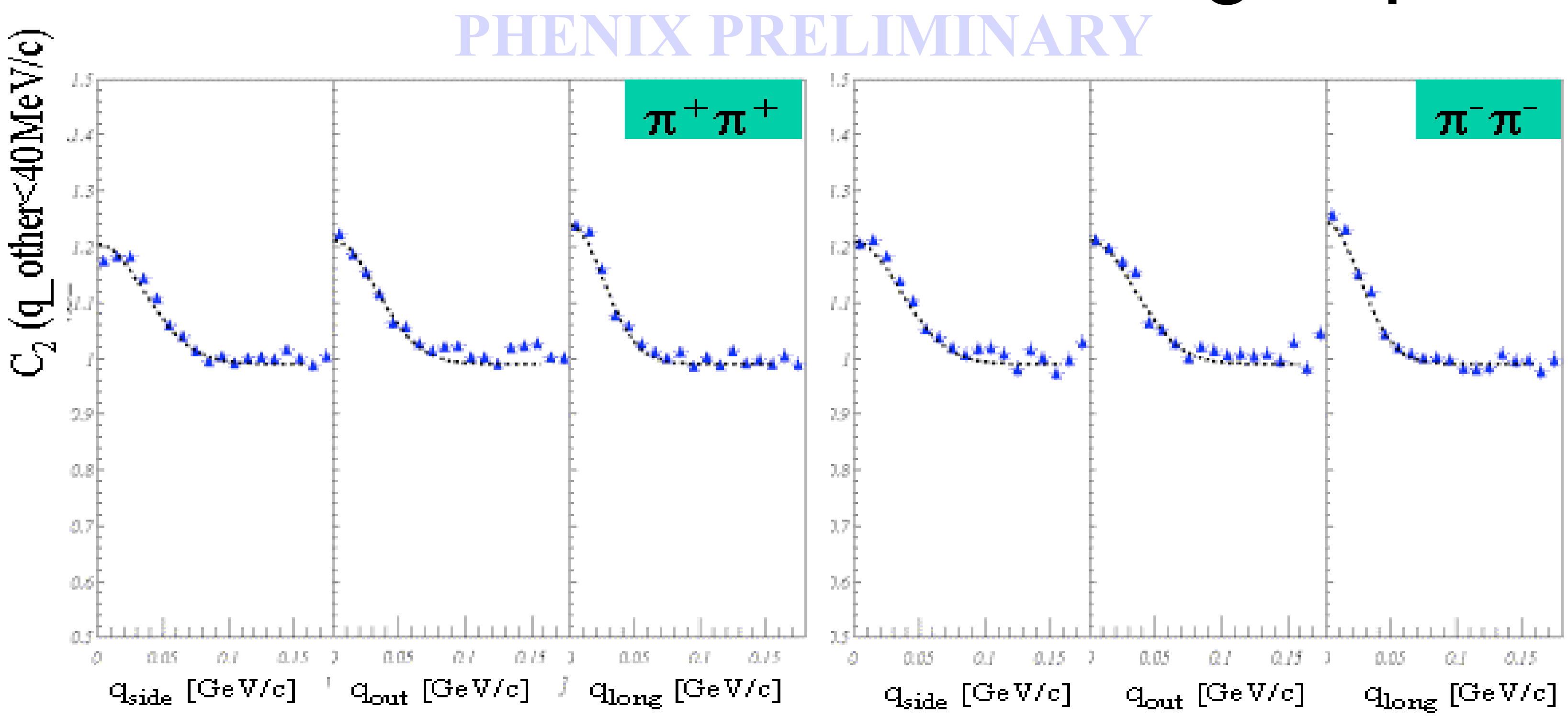
Corrections & systematic errors

- Pair cuts
  - Tracking inefficiency cut
  - Ghost track cut
  - Cluster sharing cut
- Coulomb correction
  - The Coulomb effect is corrected by full coulomb correction with momentum smearing.



Sytematic errors (%)	lambda	Rside	Rout	Rlong	Rout/Rside
Cluster share cut	11.7	4.9	5.7	4.4	1.1
Tracking inefficiency cut	5.9	2.6	6.4	2.5	2.4
Ghost track cut	2.8	0.8	3.4	1.3	4.2
Coulomb	3.1	2.4	3.7	2.2	2.9
Total (%)	13.9	6.4	10.1	6	5.7

3-D correlation result of charged pions

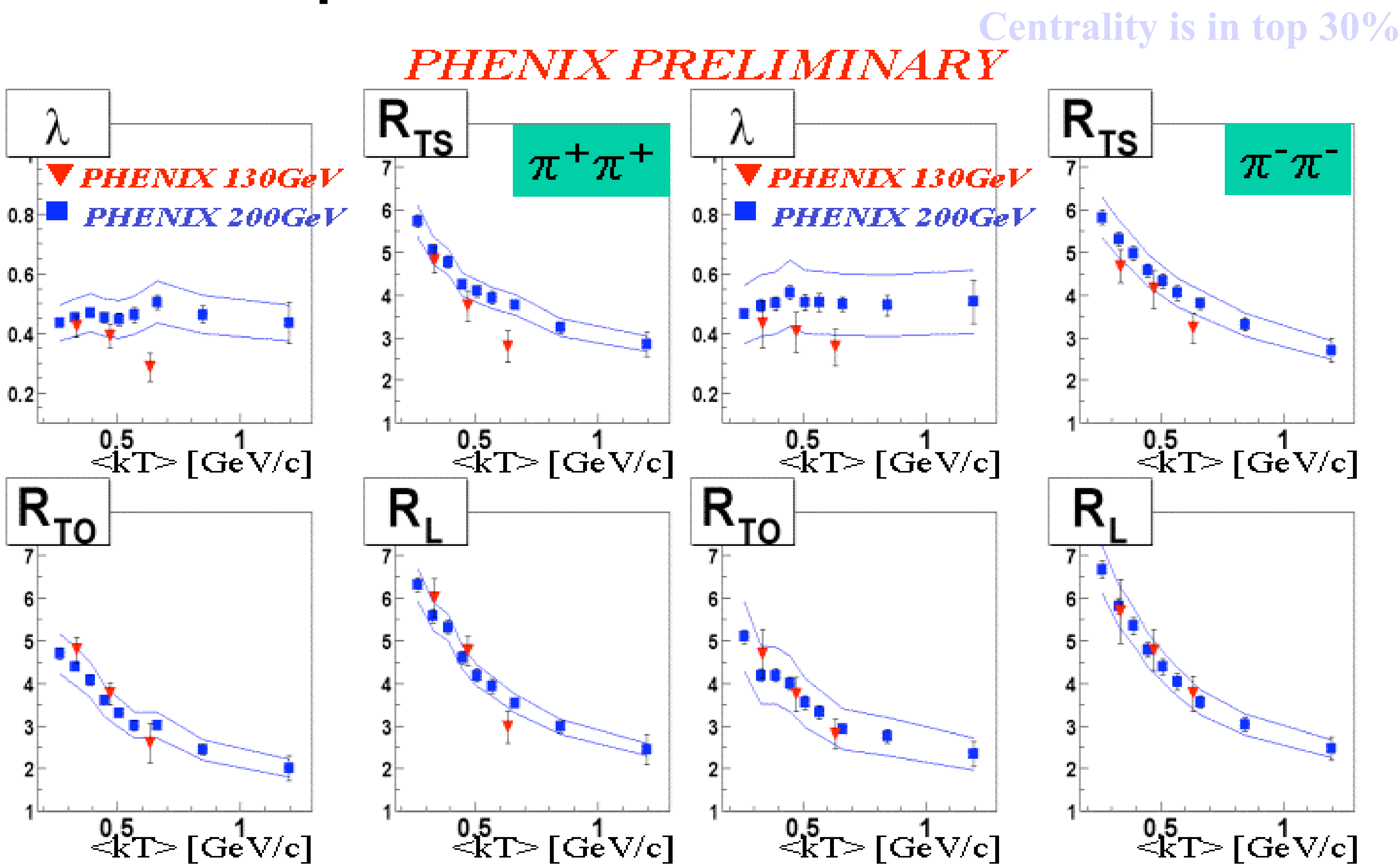


200 GeV Au+Au、Top 30% Centrality, 0.2<kT<2.0GeV/c, <kT>=0.46GeV/c

$\_ = 0.397 \pm 0.015$
$R_{side} = 4.40 \pm 0.12$
$R_{out} = 3.73 \pm 0.12$ [fm]
$R_{long} = 4.82 \pm 0.15$

$\_ = 0.434 \pm 0.018$
$R_{side} = 4.58 \pm 0.14$
$R_{out} = 3.88 \pm 0.14$ [fm]
$R_{long} = 5.24 \pm 0.18$

kT dependence of source radii



Comparison with hydrodynamic model

Recent hydrodynamic calculation by U.Heinz and P. F. Kolb (hep-ph/0204061)

Hydro w/o FS

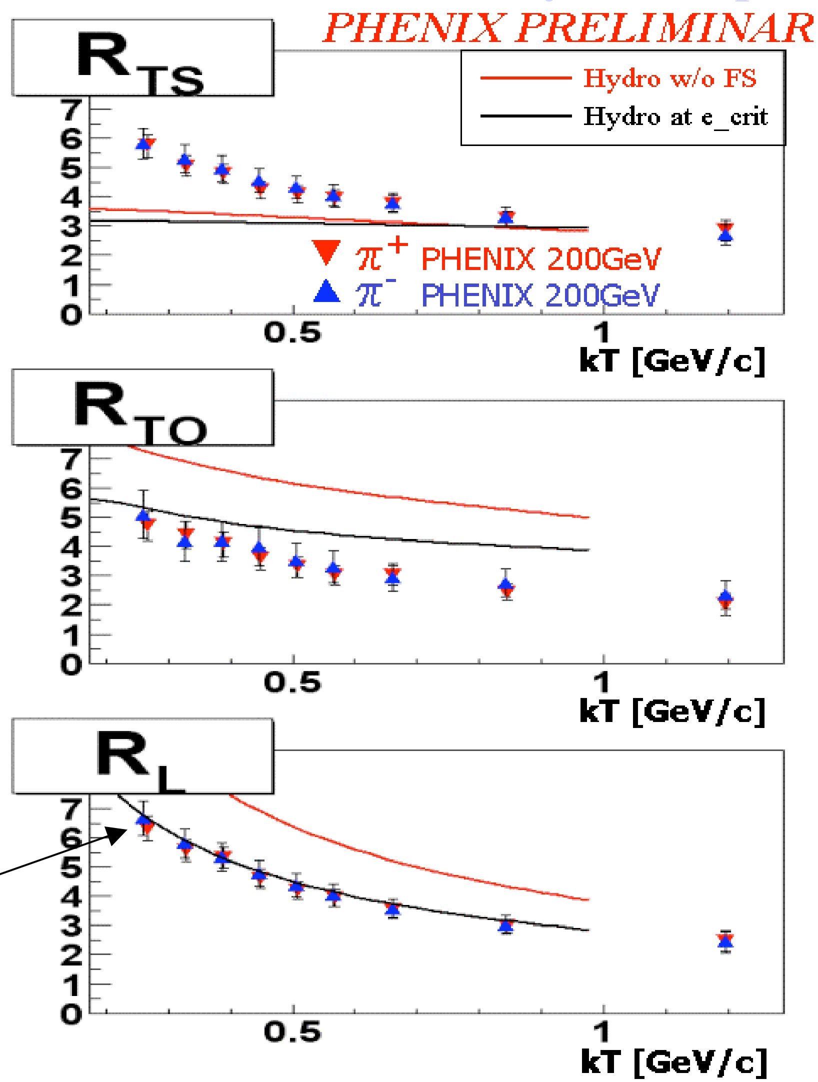
• Standard initialization and freeze out which reproduce single particle spectra.

Hydro at e_{crit}

• Assuming freeze out directly at the hadronization point. ($e_{dec} = e_{crit}$)

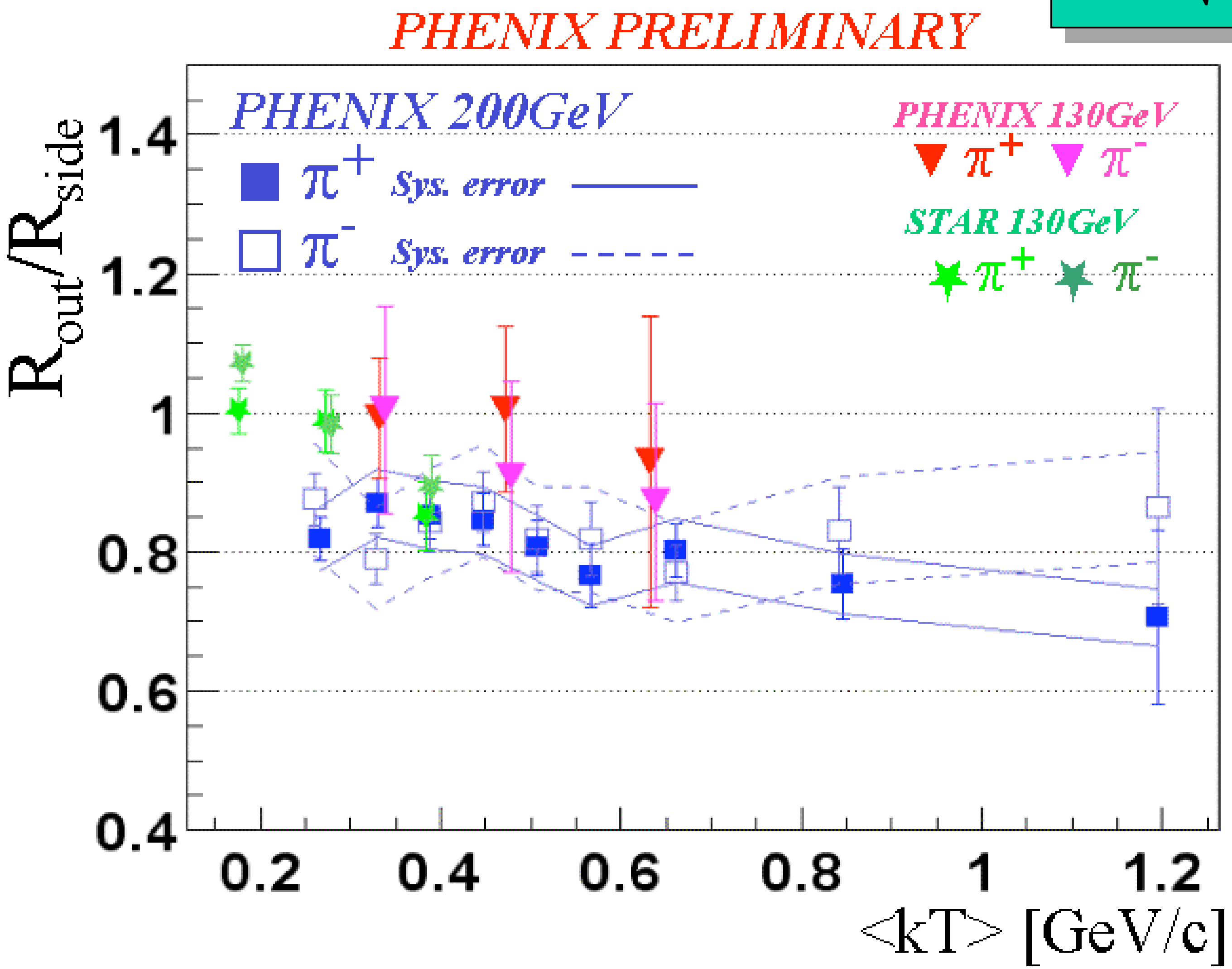
kT dependence of R_{long} indicates the early freeze-out?

Centrality is in top 30%

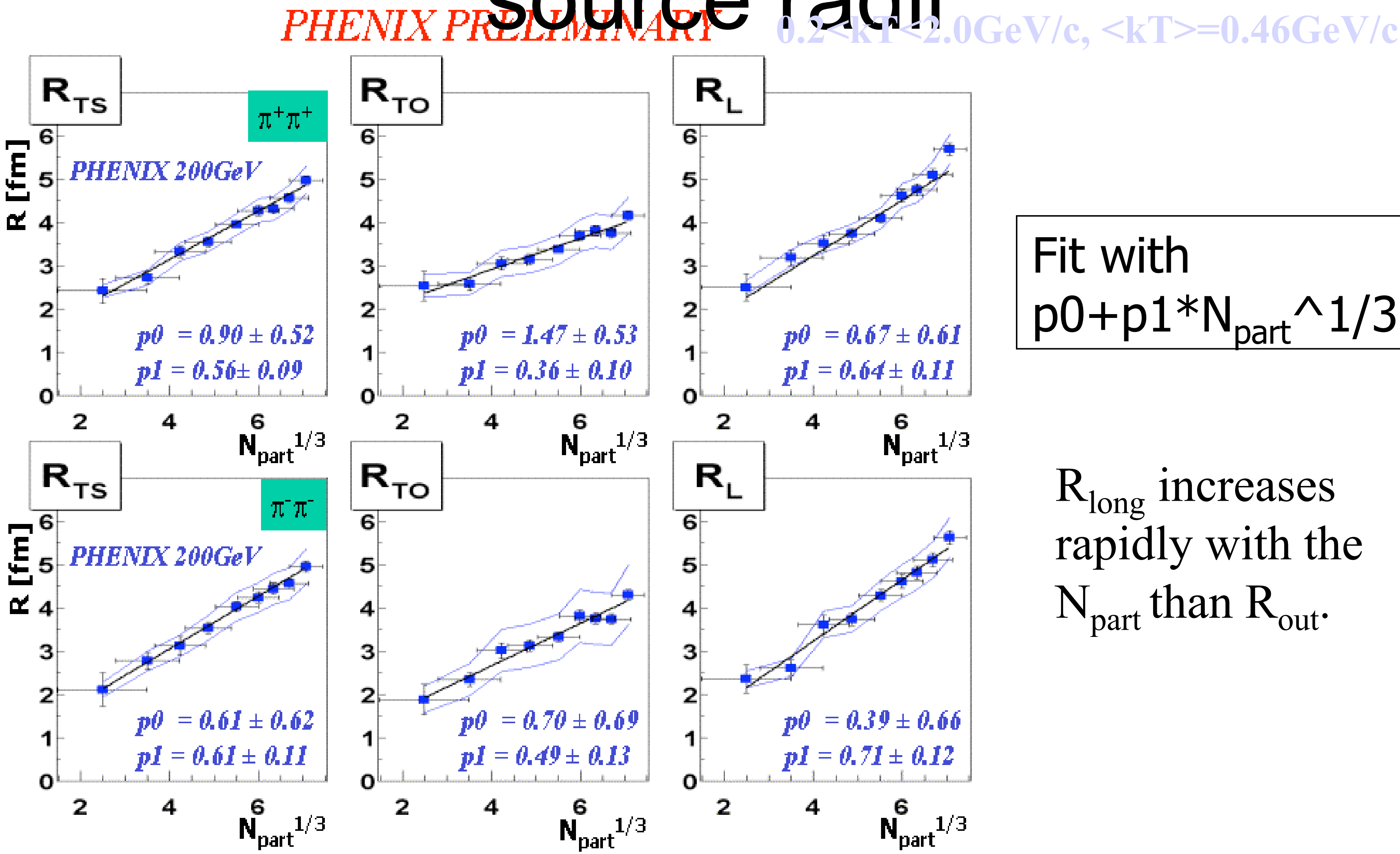


kT dependence of R_{out}/R_{side}

The duration time



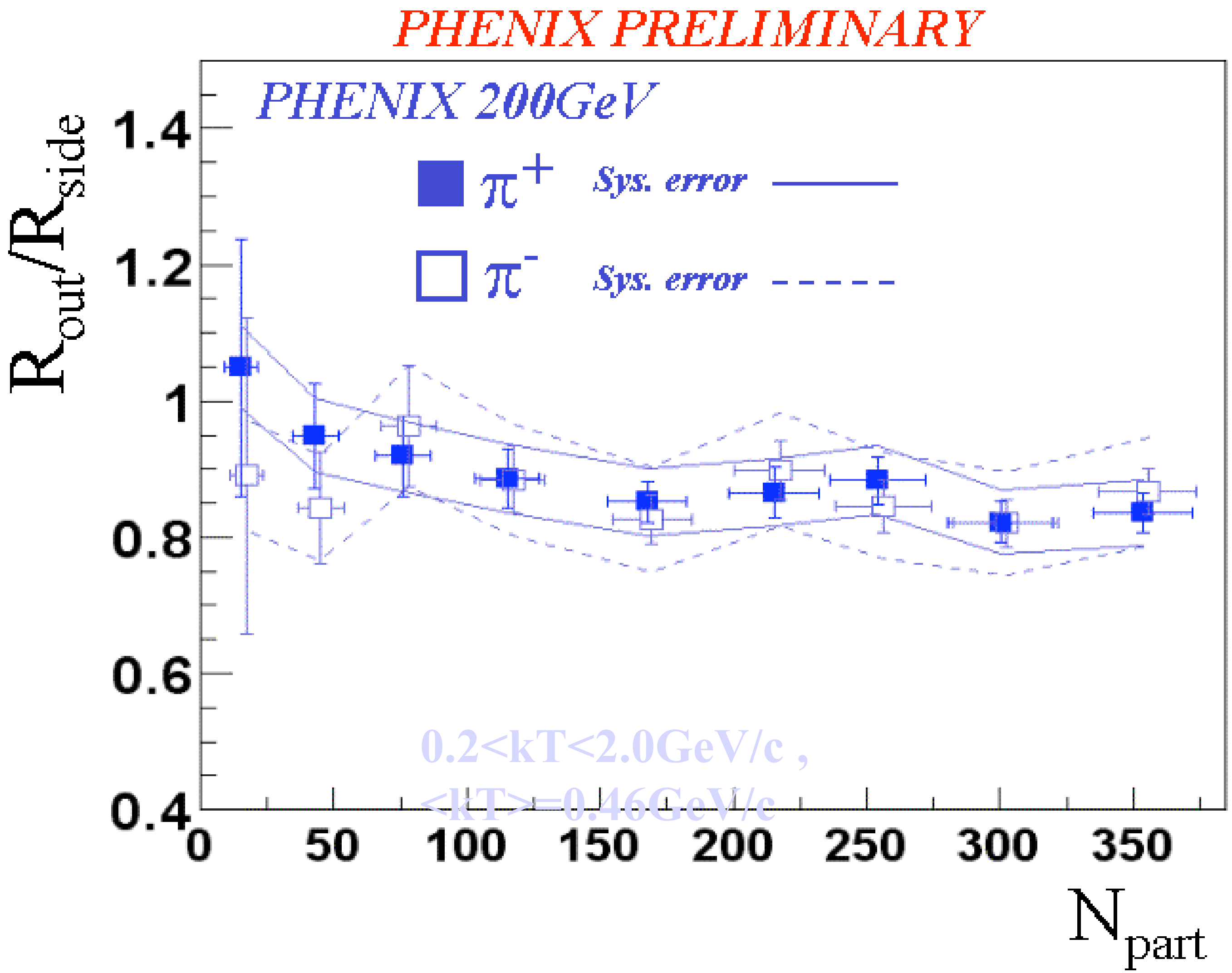
Centrality dependence of source radii



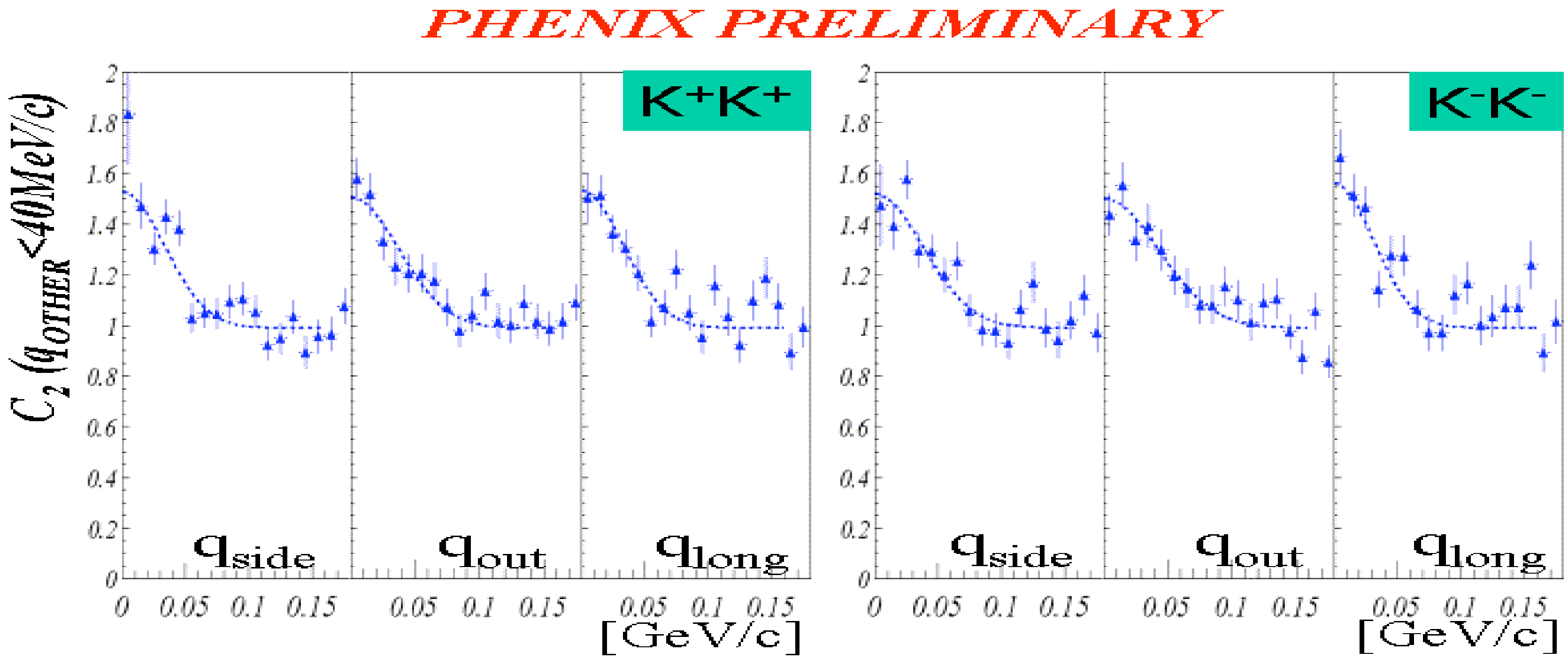
Fit with $p0+p1*N_{part}$^1/3

R_{long} increases rapidly with the N_{part} than R_{out}.

Centrality dependence of R_{out}/R_{side}



3-D correlation results of charged kaons

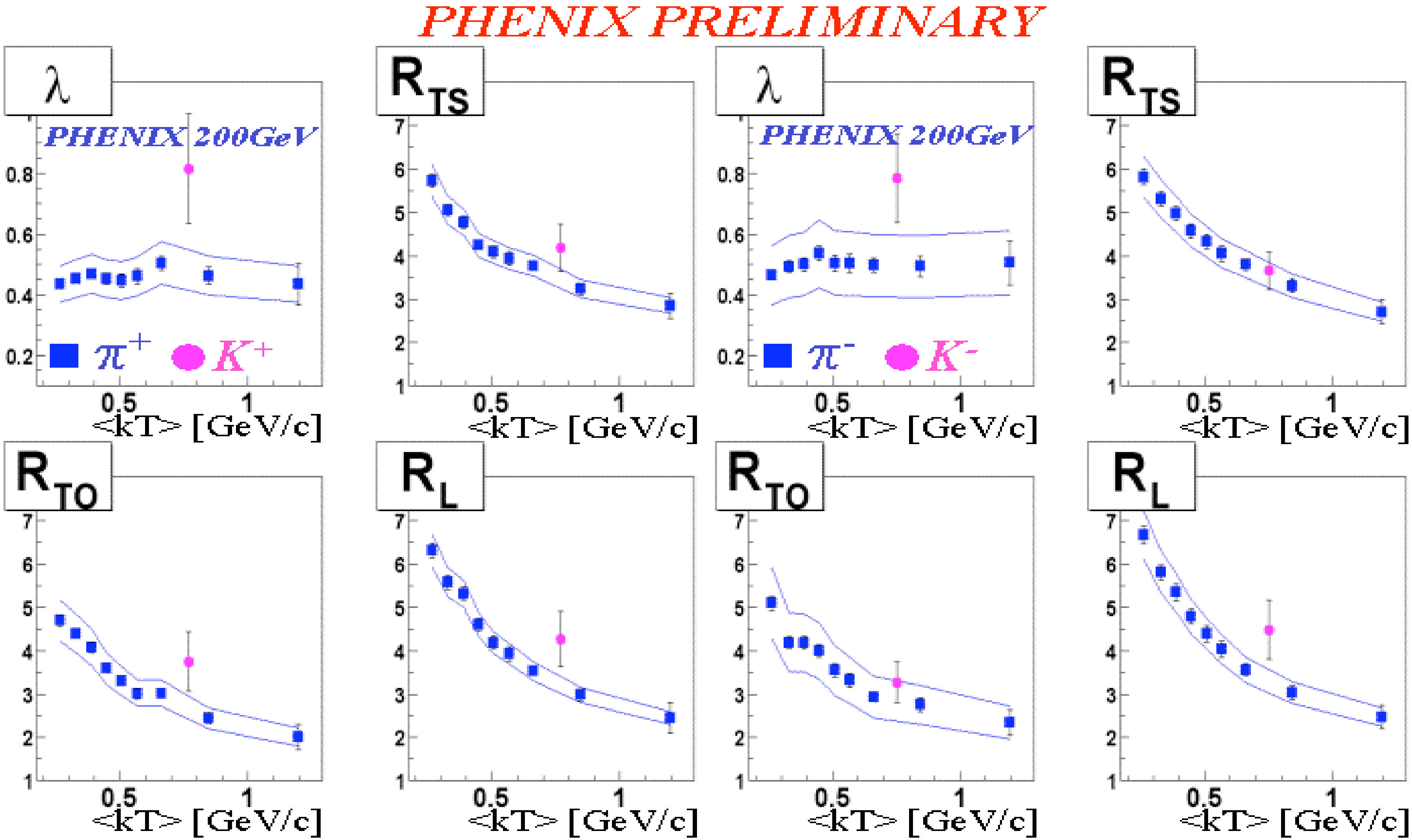


200 GeV Au+Au、Top 30% Centrality, 0.2<kT<2.0GeV/c, <kT>=0.76GeV/c

_ = 0.815 ± 0.181	_ = 0.785 ± 0.181
$R_{side} = 4.18 \pm 0.54$	$R_{side} = 3.65 \pm 0.43$
$R_{out} = 3.72 \pm 0.69$ [fm]	$R_{out} = 3.23 \pm 0.47$ [fm]
$R_{long} = 4.27 \pm 0.65$	$R_{long} = 4.48 \pm 0.68$

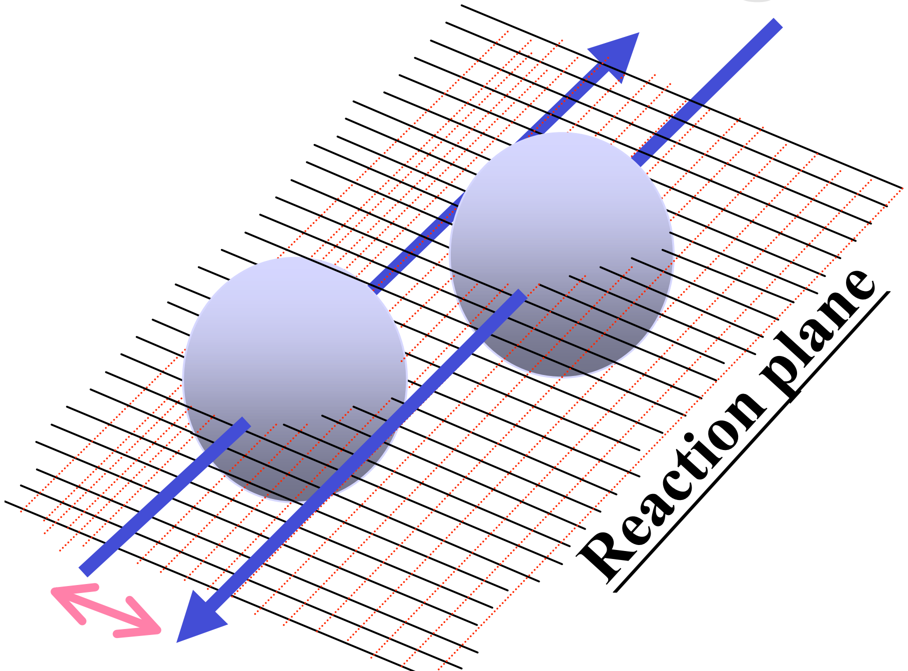
Comparison of kaon to pion

In the most 30% central

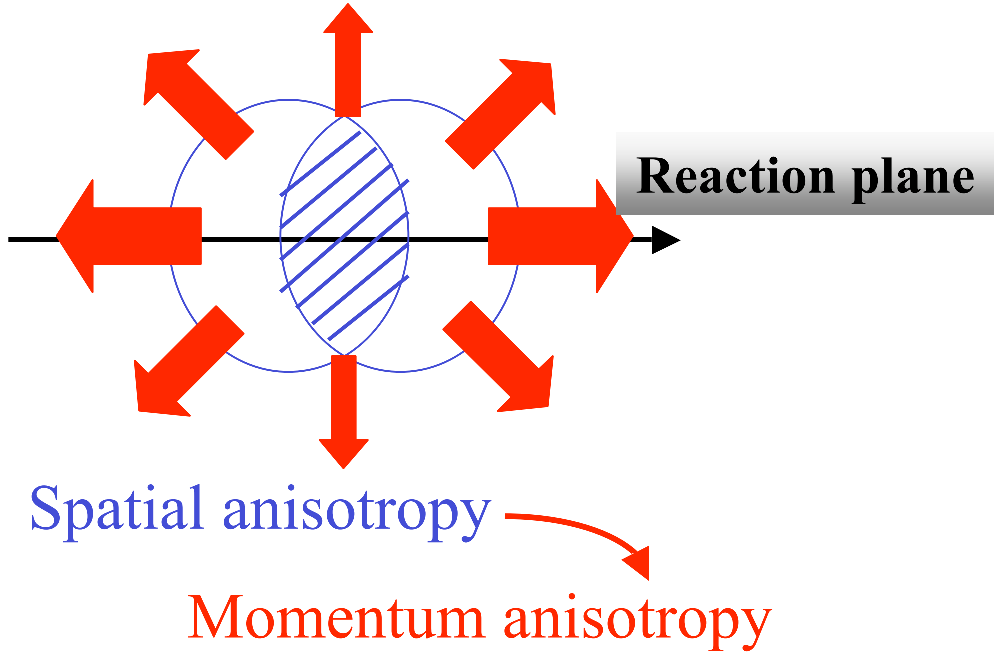


Elliptic Anisotropy

Early thermalization ?
- Strong elliptic flow v_2-



b : Impact parameter

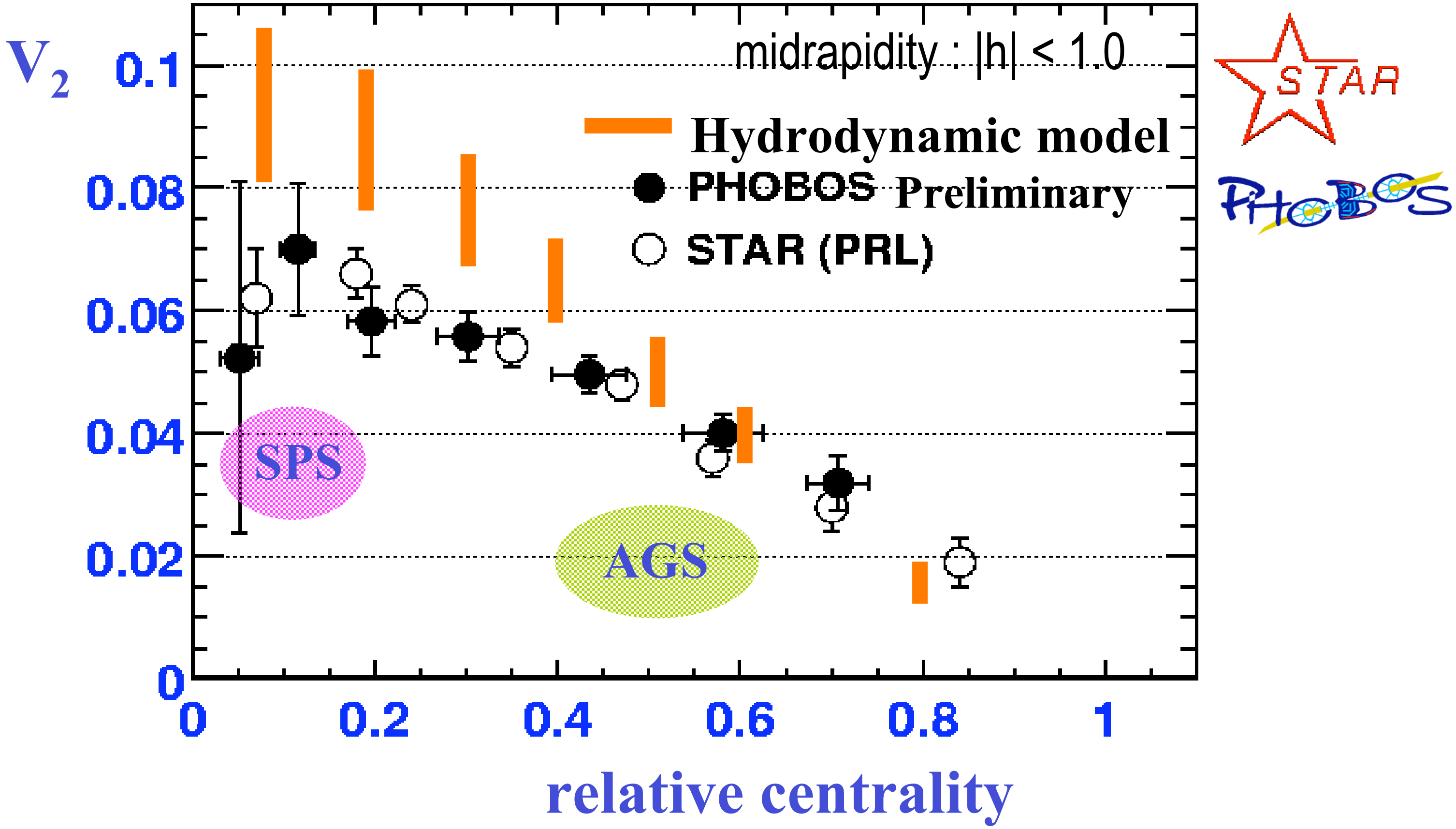


$$dN/d\phi = N [1 + \Sigma 2v_n \cos(n\phi)]$$

ϕ : azimuthal angle for measured particles from a reaction plane

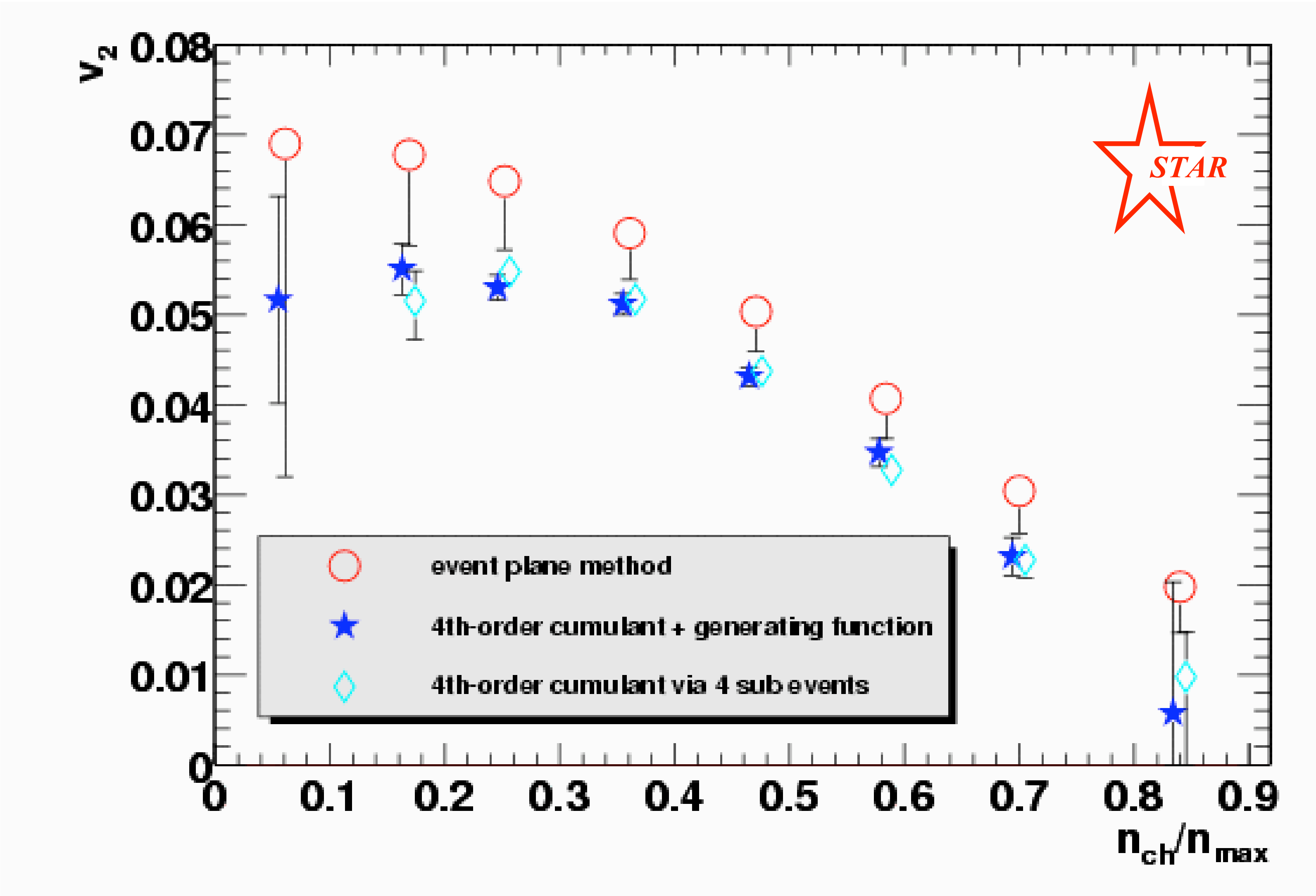
v_n : anisotropy parameter

Centrality Dependence of Elliptic Flow

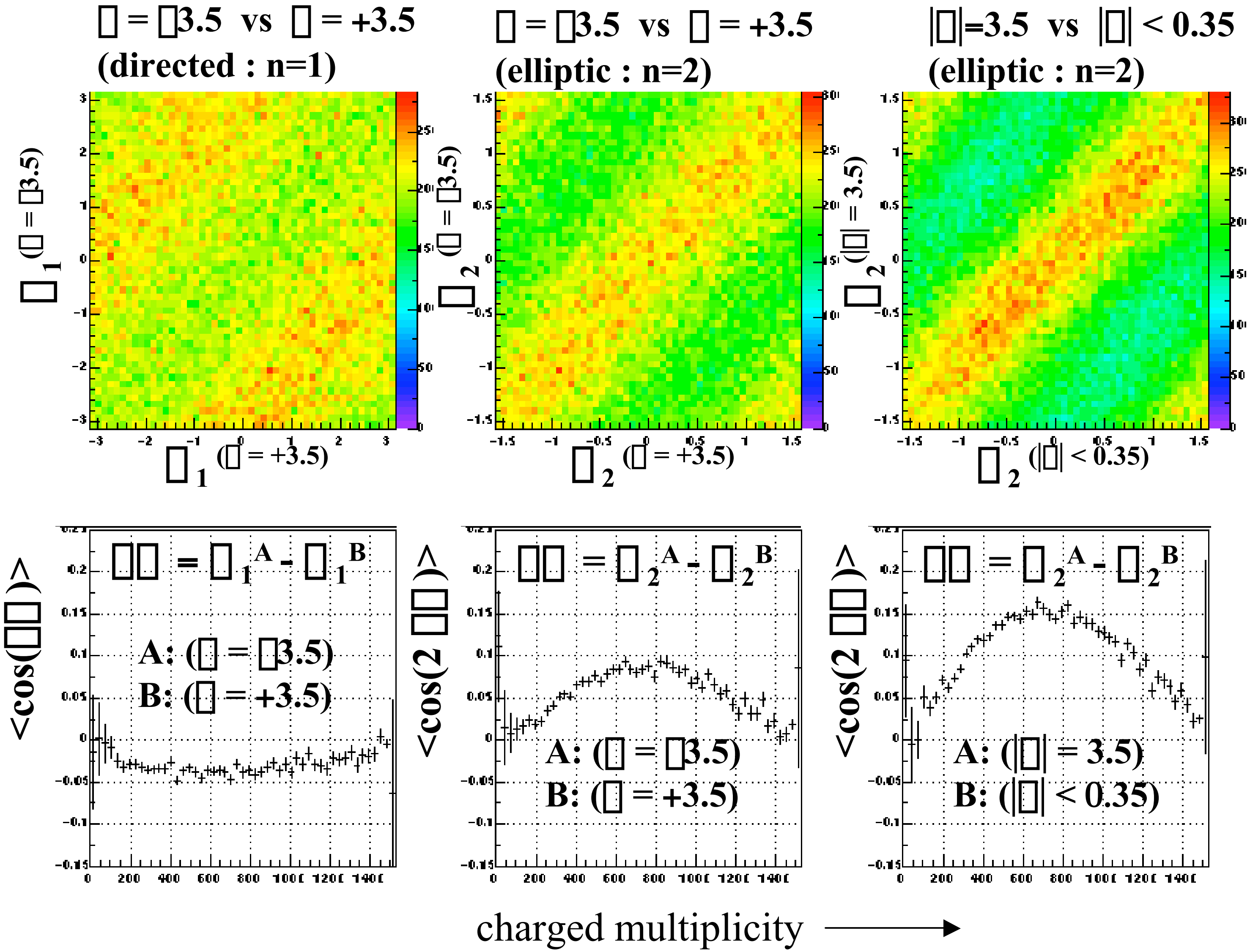


surprise: （１）フローが非常に強い
（２）model の予想と comparable

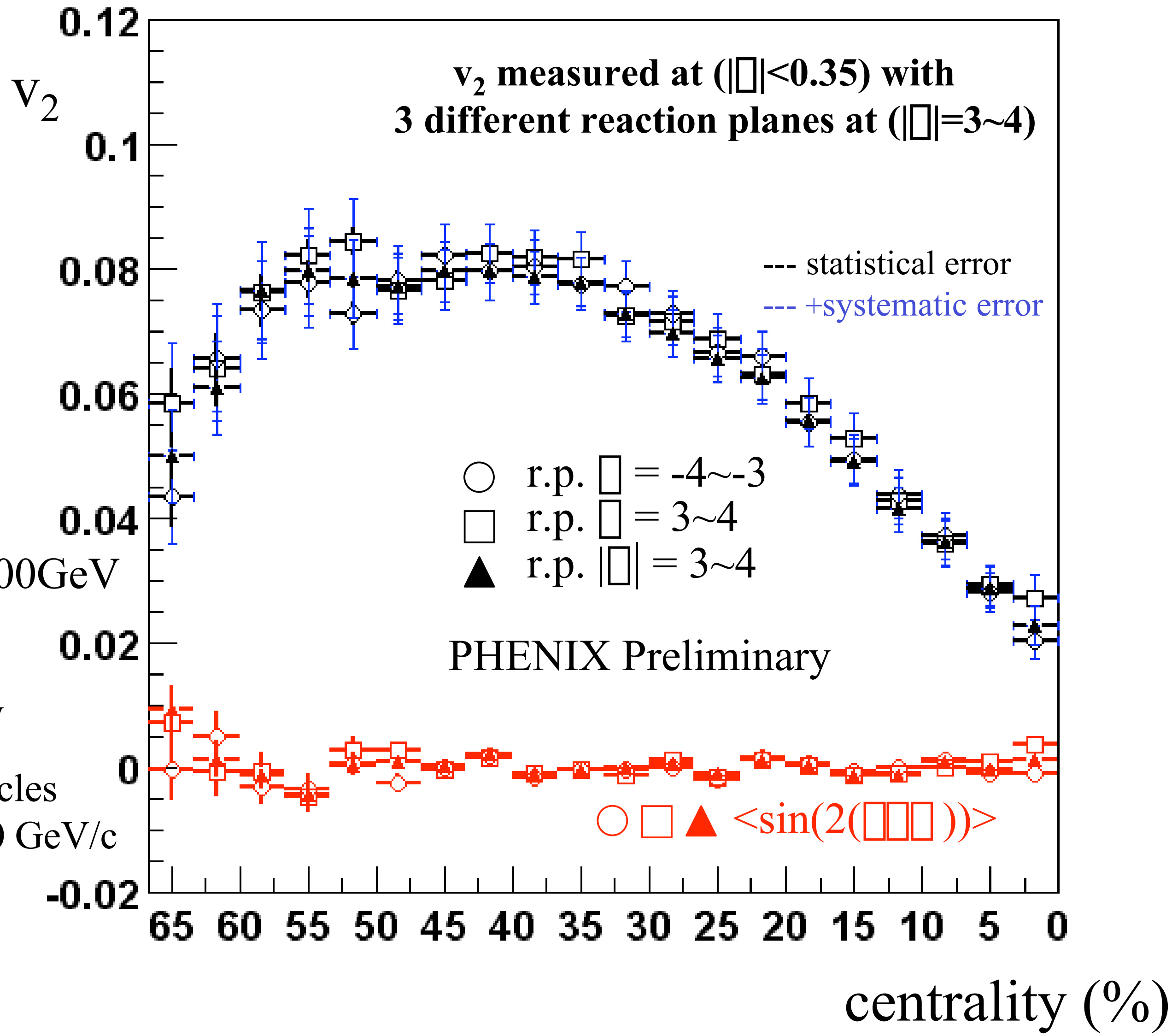
flow and non-flow contributions



Reaction plane determination in PHENIX



v_2 measurement at PHENIX

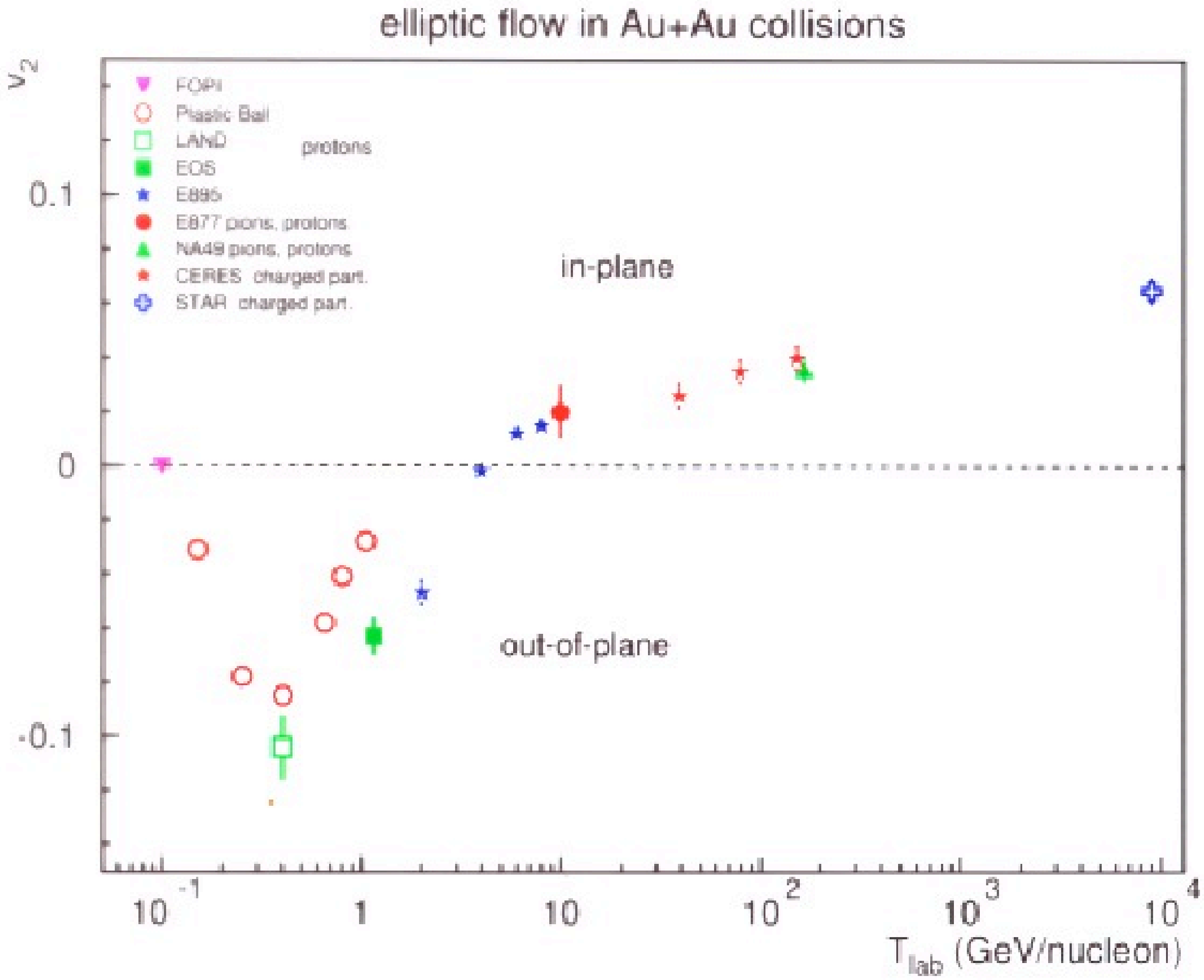


Au+Au at
$\mathrm{sqrt}(s_{NN})$=200GeV

v_2(|□|<0.35)
vs centrality

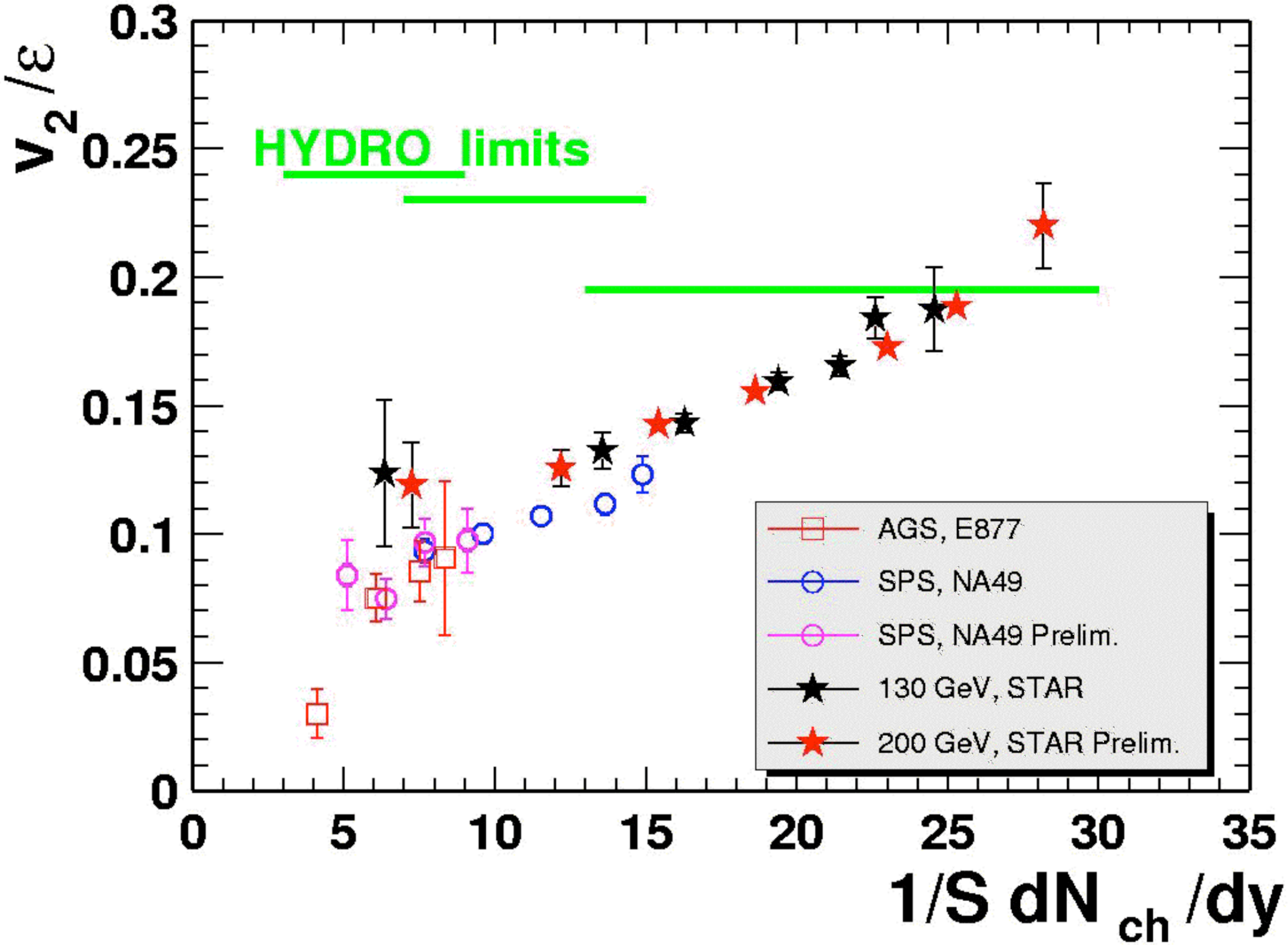
charged particles
0.2 < pT < 10 GeV/c

Elliptic Anisotropy のエネルギー依存性



非常に強い
非対称性

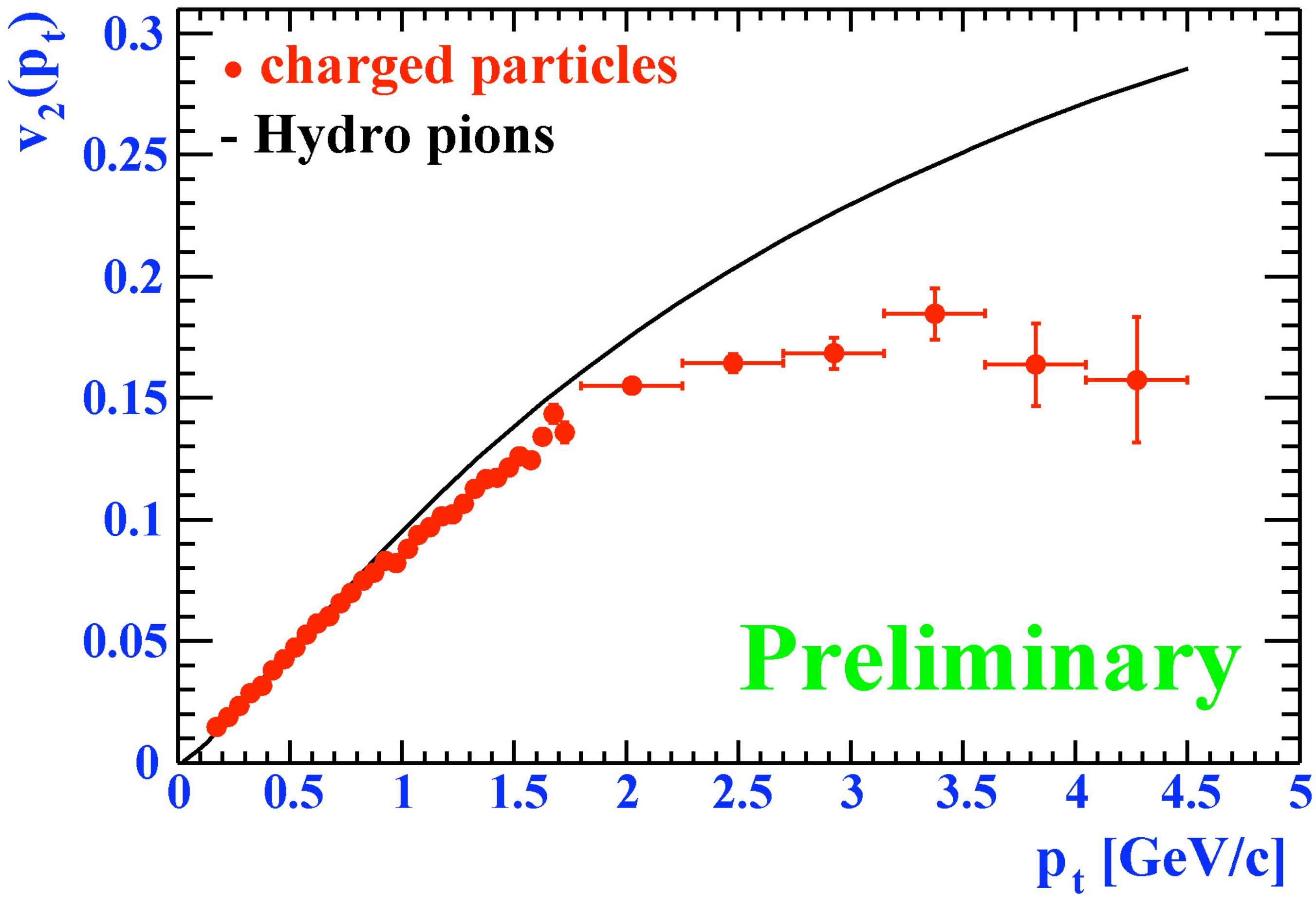
v2 scaling



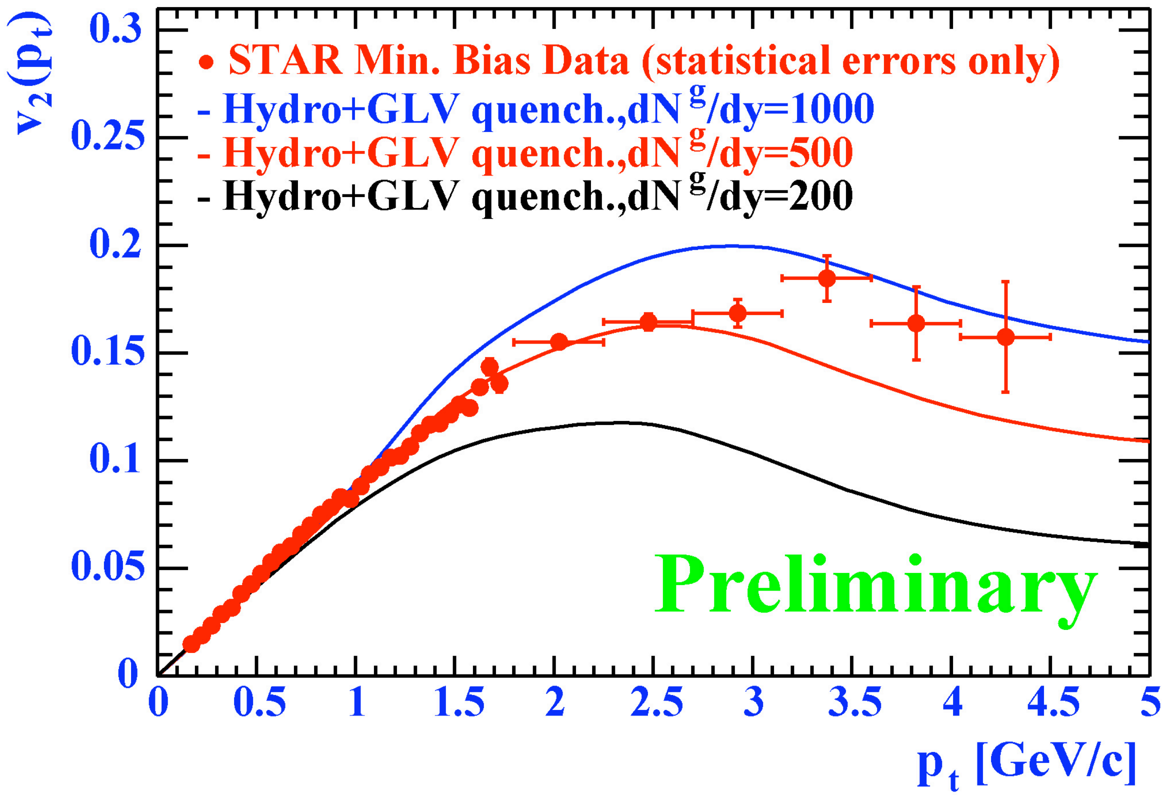
HYDRO limits
v_2/ε
$1/S \; dN_{ch}/dy$
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
AGS, E877
SPS, NA49
SPS, NA49 Prelim.
130 GeV, STAR
200 GeV, STAR Prelim.

Charged particle anisotropy $0<p_T<4.5$ GeV/c

- Minimum bias data
- Only statistical errors
- Systematic error 10% - 20% for p_t = 2 – 4.5 GeV/c



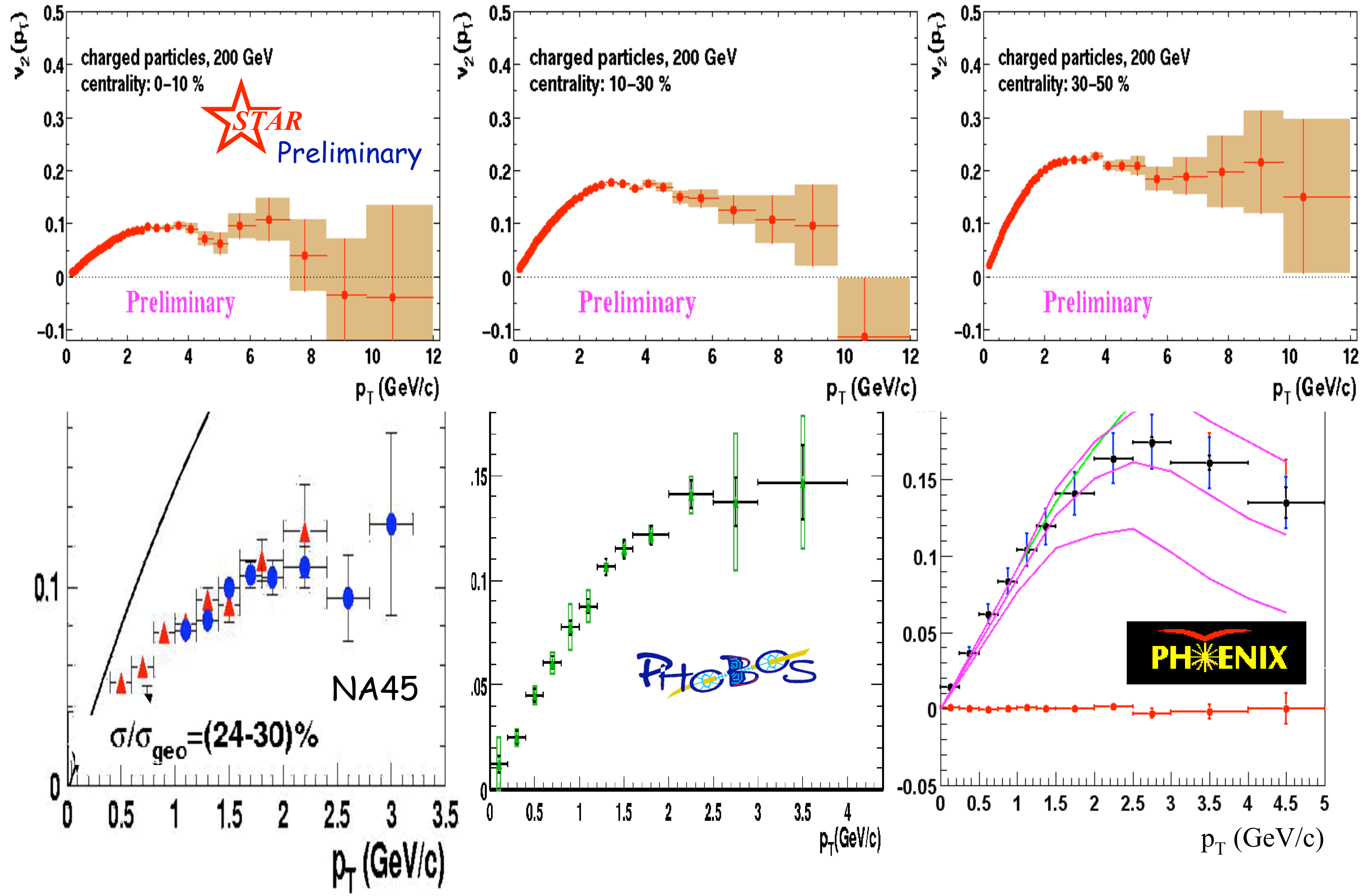
p_T dependence of flow



Hydro+GLV: M. Gyulassy, I. Vitev and X.N. Wang, nucl-th/00012092

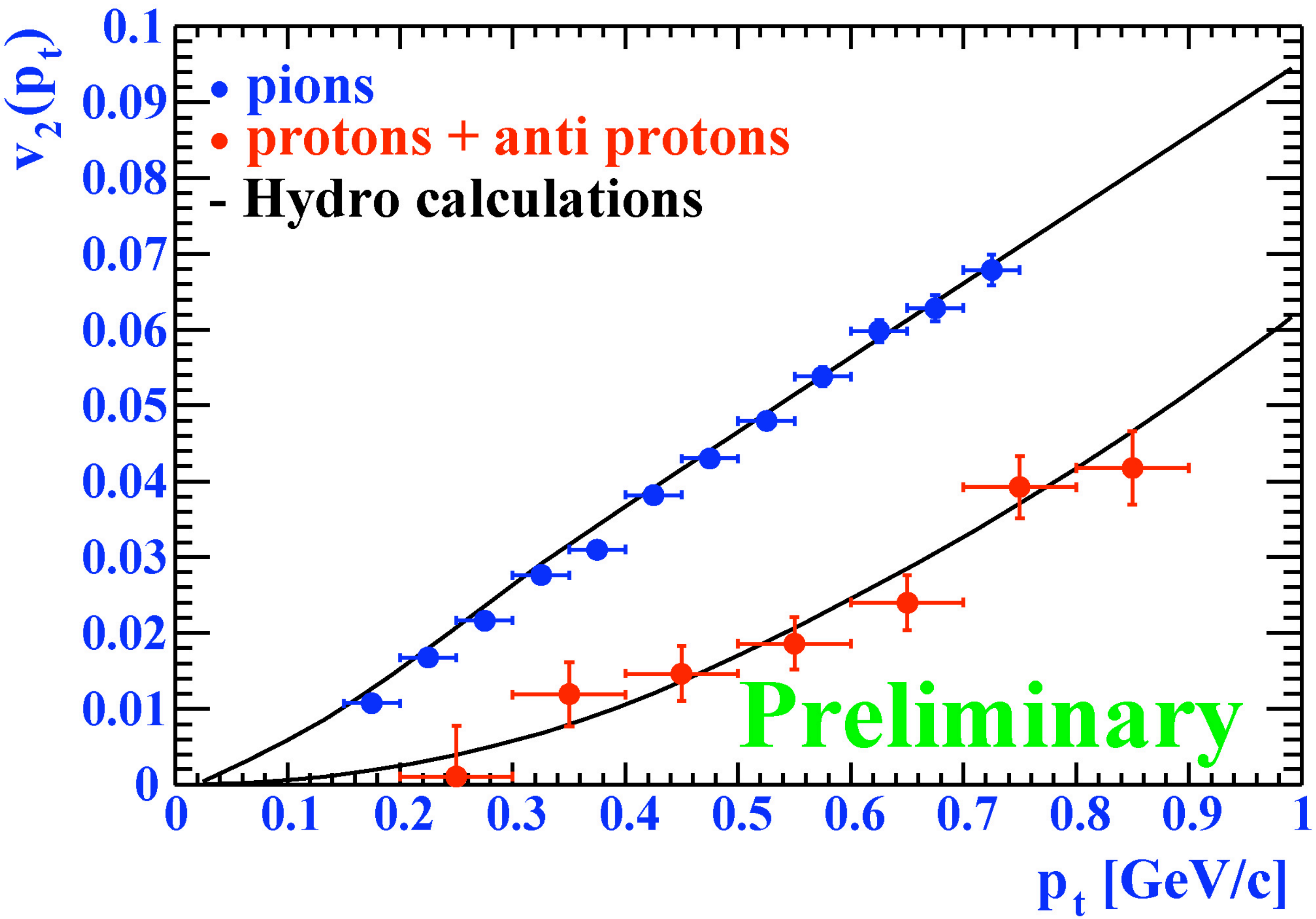
- flow starts to bend over at ~2 GeV/c
- matches well with models that incorporate jet quenching

v_2 saturates or drops at high p_T ?



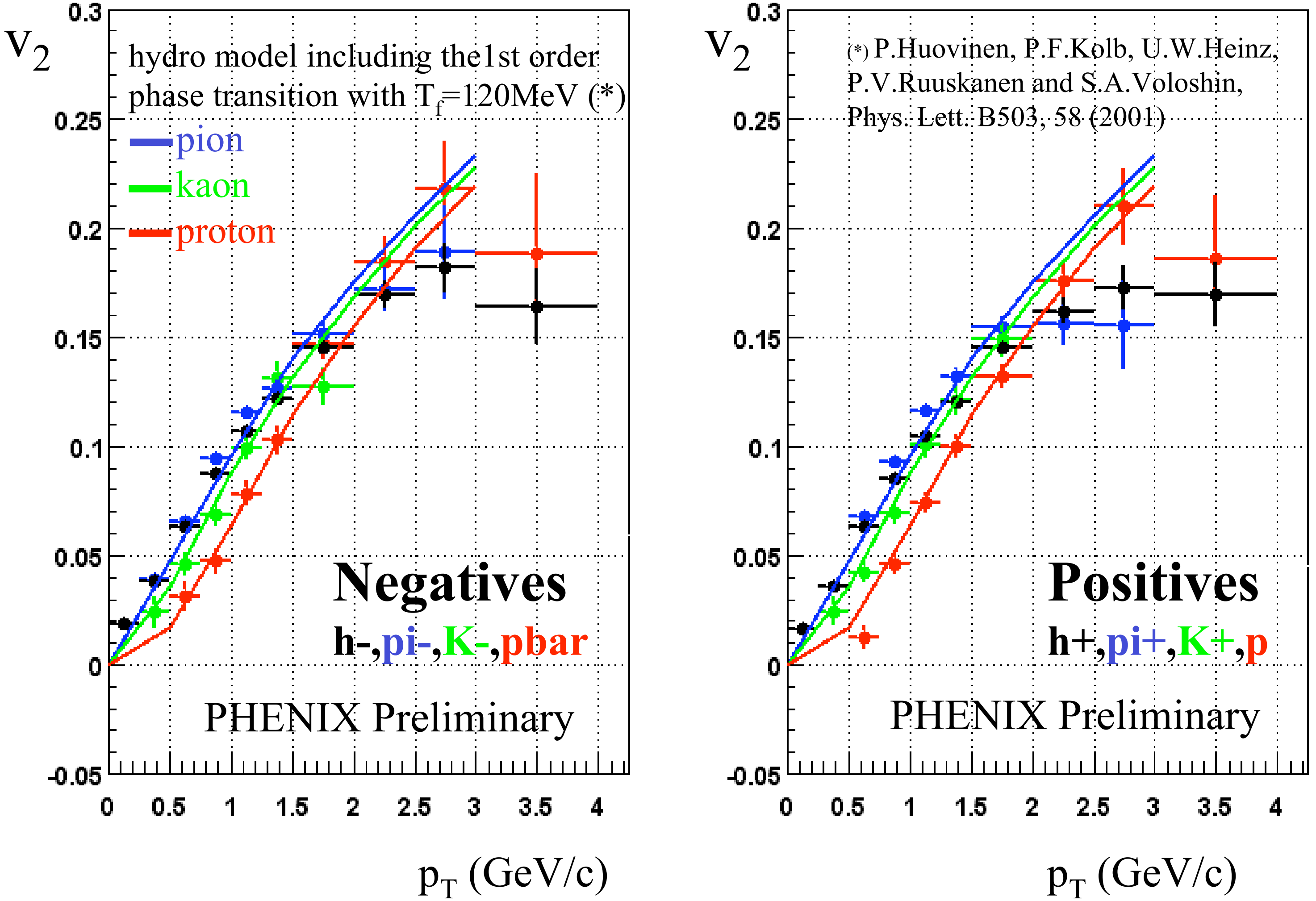
Comparison with a Hydrodynamical Model

- Hydrodynamical calculations: Huovinen, Kolb and Heinz

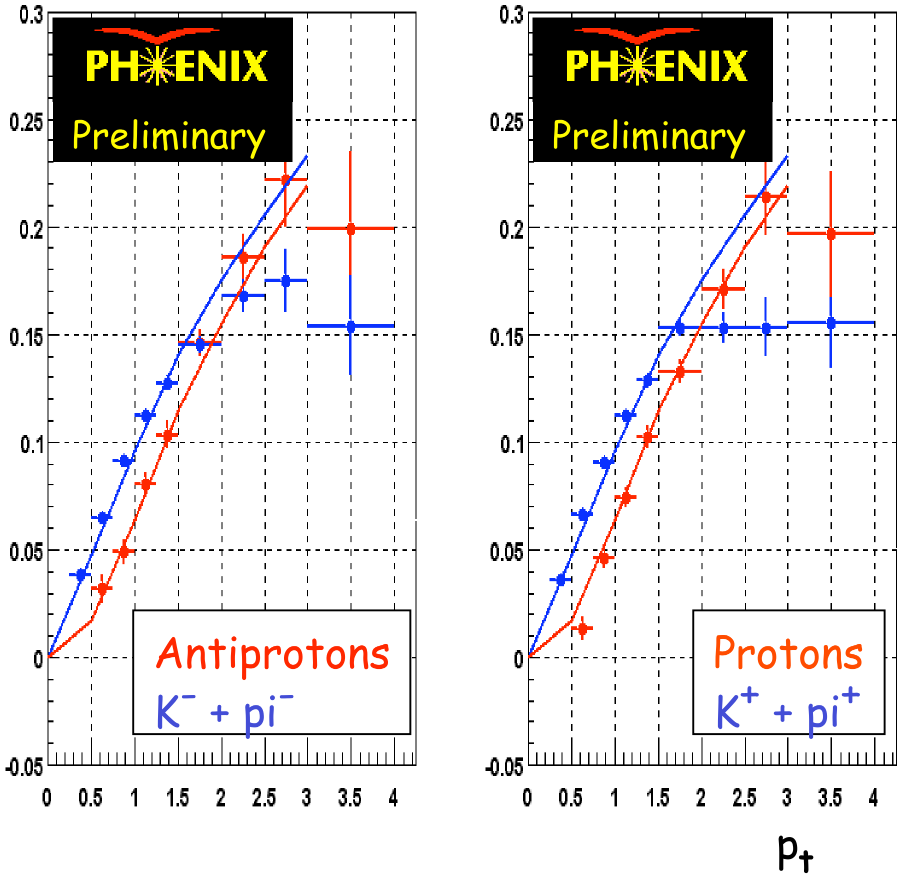


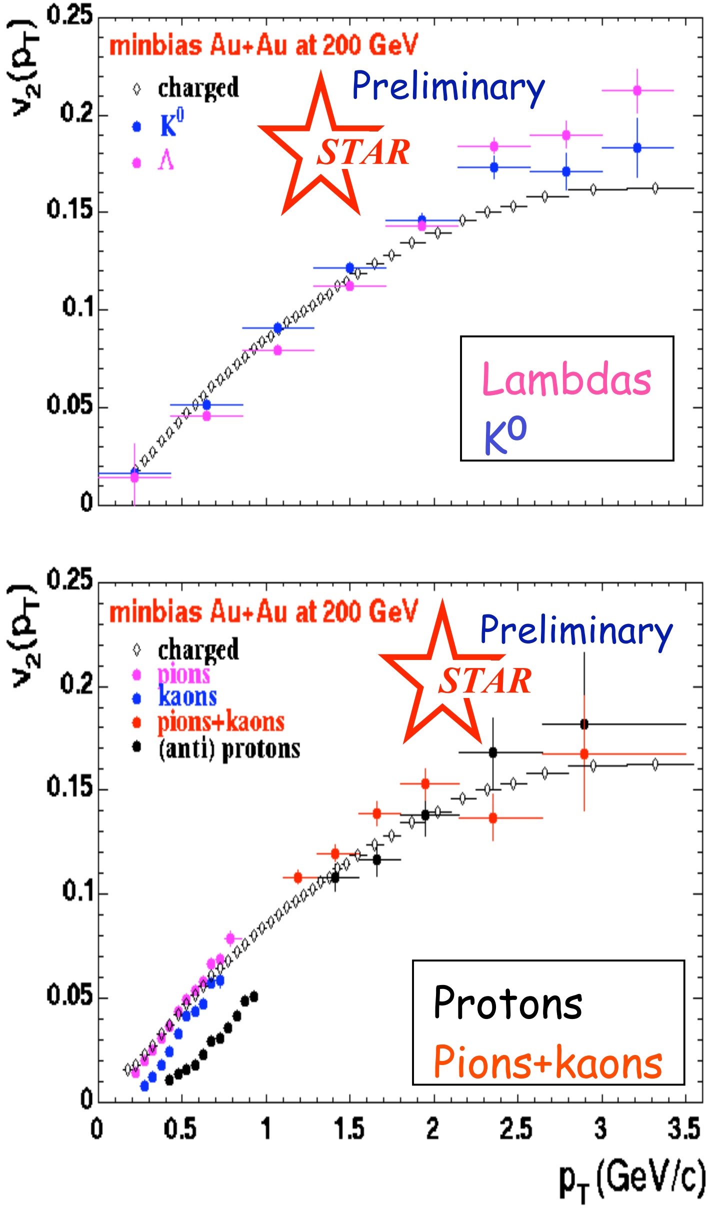
v_2 of identified hadrons

Au+Au at sqrt(s_{NN})=200GeV
min. bias r.p. |□|=3~4



reversed v_2 at p_T > 2GeV/c





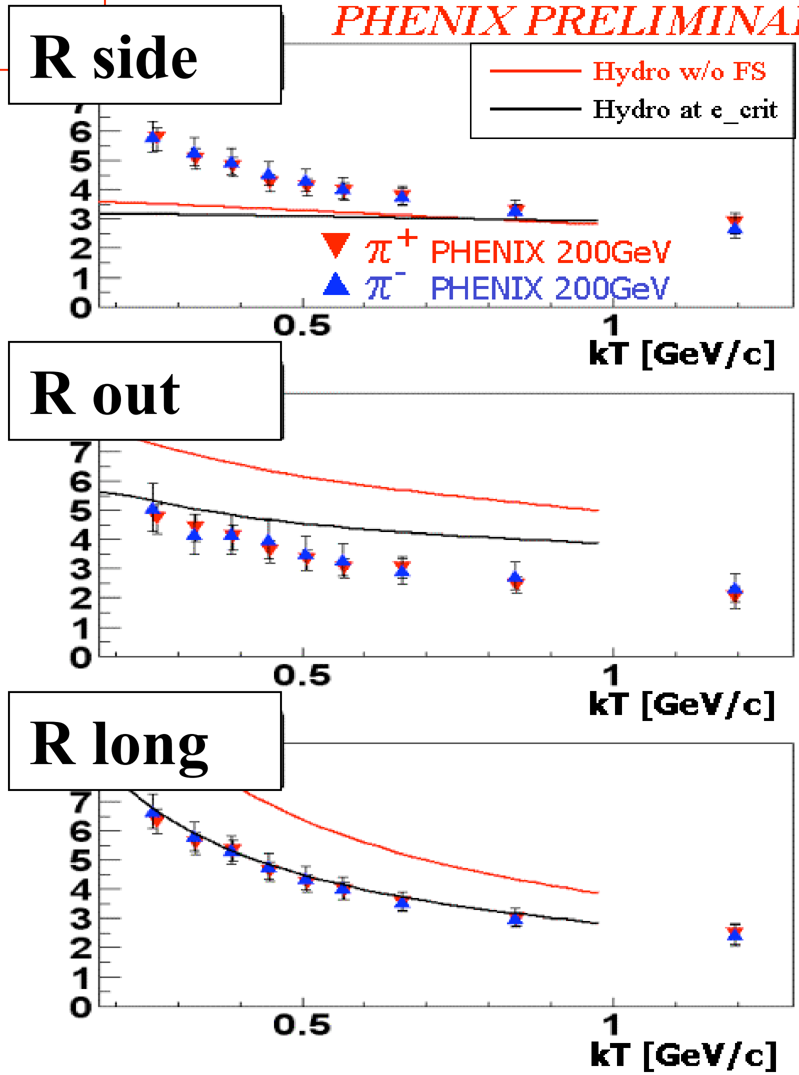
HBT puzzle

Akitomo Enokizono @ QM02

Centrality is in top 30%

PHENIX PRELIMINARY

Why duration time $\square = \mathrm{sqrt}(R_{out}^2 - R_{side}^2)/\square$ of the freeze-out is so short?



Hydro w/o Free Streaming

- Standard initialization and freeze out which reproduce single particle spectra.

Hydro at e_{crit}

- Assuming freeze out directly at the hadronization point. ($e_{dec} = e_{crit}$)

kT dependence of R_{long} indicates the early freeze-out?

Any initial conditions in hydro. can not solve the small Rside.

Recent hydrodynamic calculation by U.Heinz and P. F. Kolb (hep-ph/0204061)

k_T: average momentum of two particles