KE_T and Quark Number Scaling of v_2

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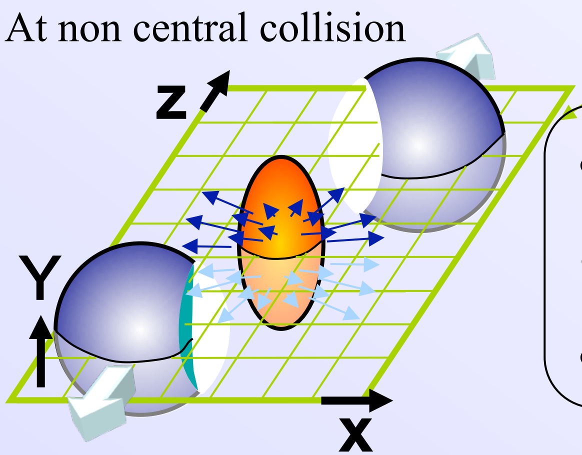
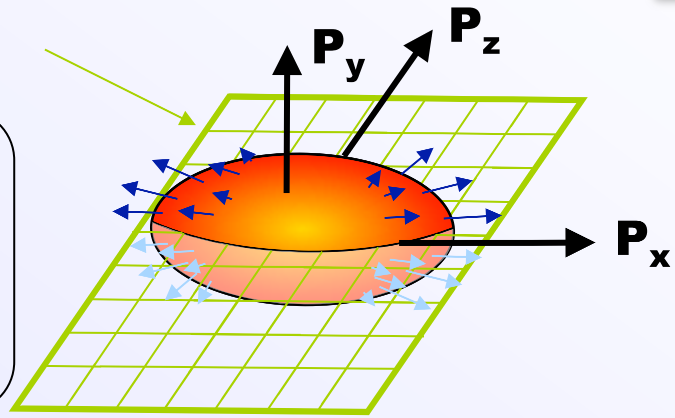
Elliptic Flow (v_2)



Geometrical anisotropy

- *Small mean free path*
- *Thermalization*
- *Pressure gradient*

Elliptic flow



Momentum anisotropy

Momentum anisotropy reflects the hot dense matter.

Fourier expansion of the distribution of produced particle angle (ϕ) to reaction plane (Ψ)

$$N(\phi) = N_0\{1 + 2v_1\cos(\phi - \Psi) + 2v_2\cos[2(\phi - \Psi)] + \ldots\}$$

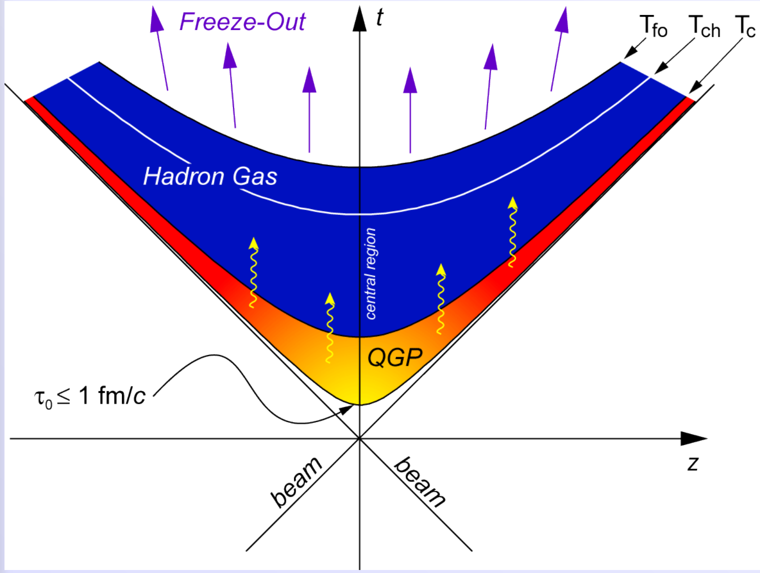
$$v_n = \langle \cos[n(\phi - \Psi)] \rangle$$

v_2 is the coefficient of the second term → indicates ellipticity

v_2 measurement has been considered as a powerful probe for investigating the property of the QGP.

Time Evolution

The matter produced in the high energy heavy ion collision is expected to undergo several stages from the initial hard scattering to the final hadron emission.



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Hadron gas	Kinematical freeze-out
	Chemical freeze-out
Mixed phase	Hadronization Expansion & Cooling
QGP	Thermalization
pre-equilibrium	
Collision	Hard scatterings

When the matter is thermalized, we expect

Hydro-dynamical behavior at quark level .

Note whenever the matter interacts each other, v_2 could change.

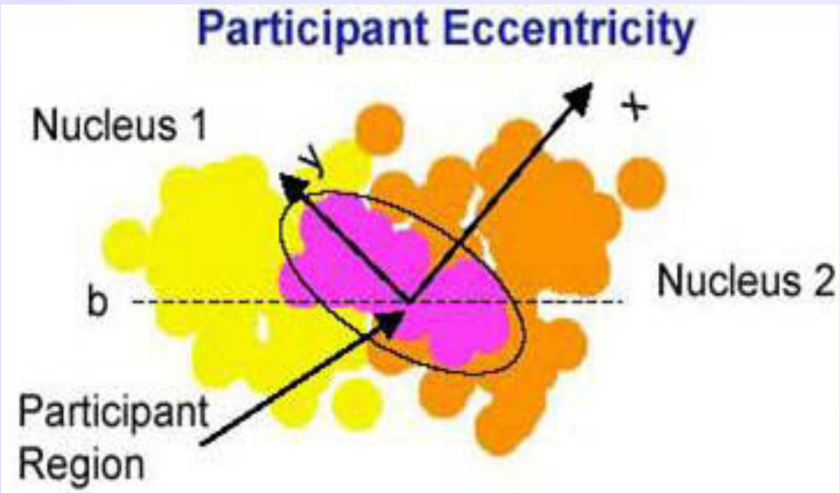
Need a comprehensive understanding from thermalization through hadronization to freeze-out.

Words

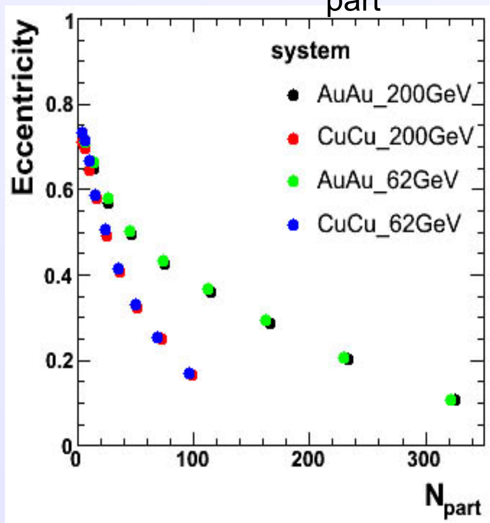
N_{part} --- Number of nucleons participating the collision
Eccentricity (ε) --- geometrical eccentricity of participant nucleons

- Monte-Carlo simulation with Glauber model
- Nucleus formed by wood-Saxon shape
- Participant eccentricity which is calculated with long and short axis determined by distribution of participants at each collision.

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



ε vs. N_{part}

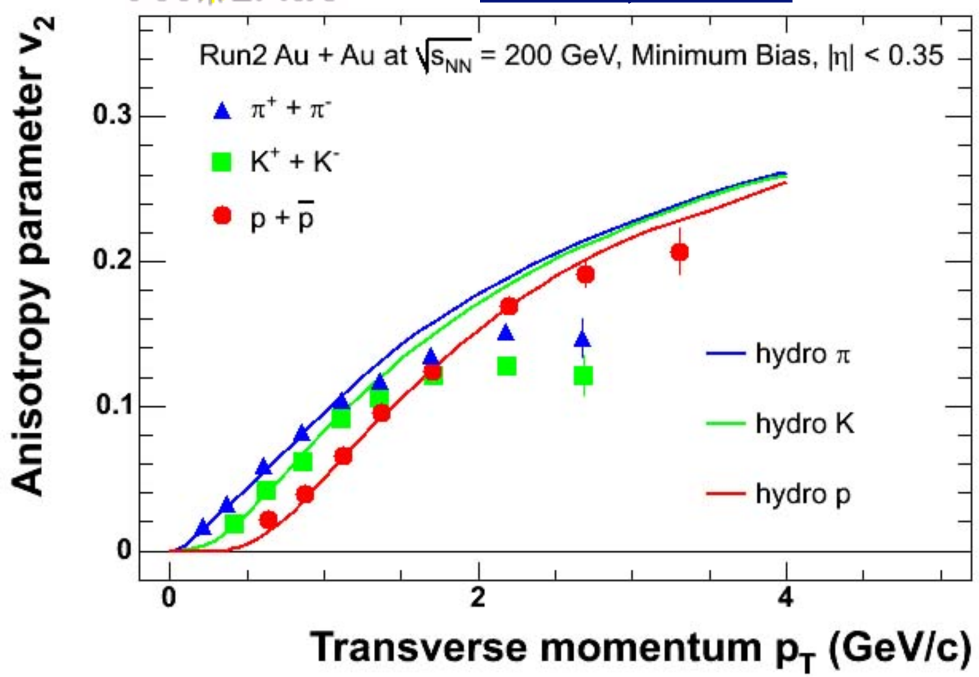


Fundamental Findings of v_2 at RHIC

- Hydro-dynamical behavior
- KE_T scaling
- Quark number scaling

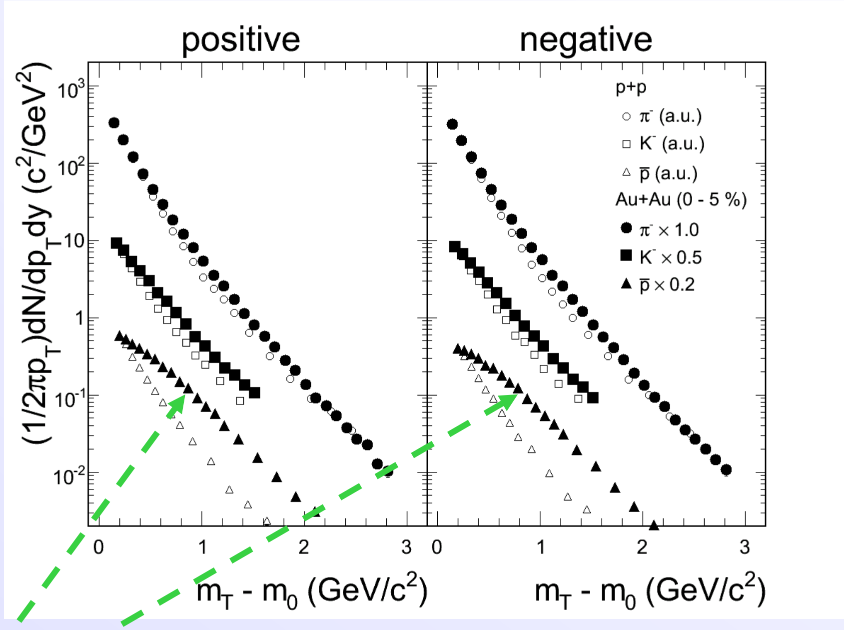
v_2 explained by hydro model

PHENIX **PRL 91, 182301**



v_2 at low p_T (<~2 GeV/c) can be explained by a hydro-dynamical model assuming:

→ Early thermalization(~0.6 fm/c)



Mass Ordering: **v2(π)>v2(K)>v2(p)**

→Existence of radial flow.

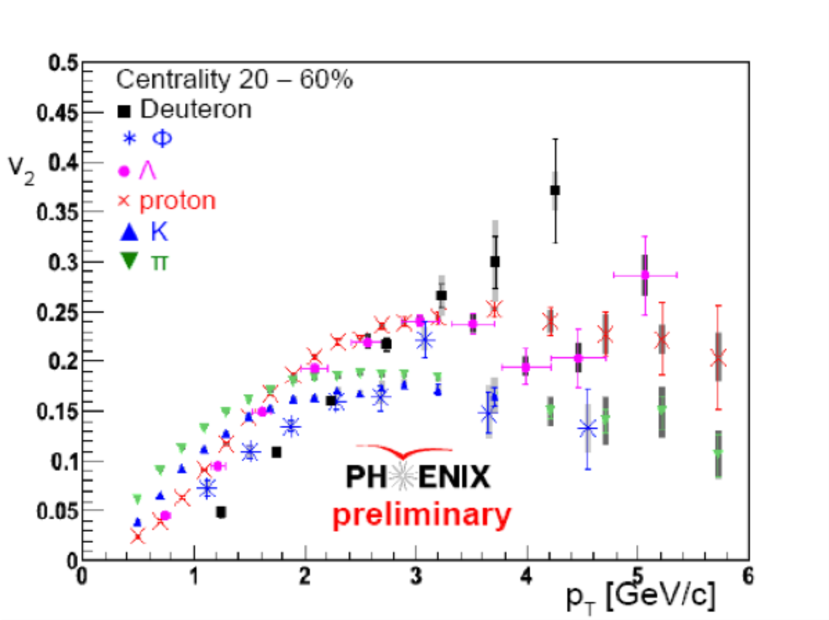
Single particle spectra also indicates radial flow.

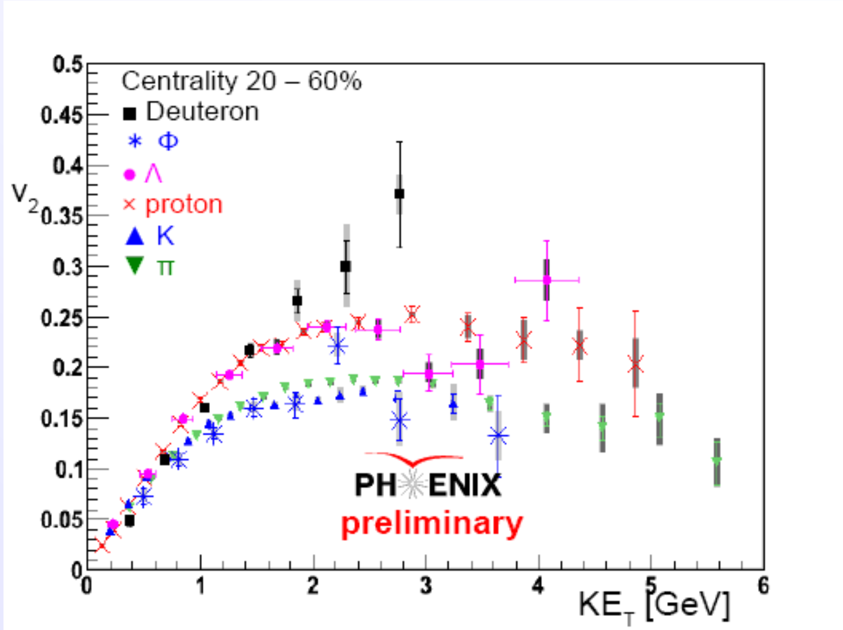
convex shape due to radial flow.

PHENIX: Au+Au: PRC **63**, 034909 (2004);
p+p: PRC**74**, 024904 (2006)

KE_T Scaling

Presented by Yoshimasa IKEDA at spring JPS 2010 Au+Au, $\sqrt{s_{NN}}$ = 200GeV (RUN7)





$$KE_T = m_T - m_0 = \sqrt{(m_0^2 + p_T^2)} - m_0$$

Λ v_2 is similar to proton v_2 .

Φ v_2 is near to meson (π or K) rather than baryon (p or Λ) at mid- p_T (= 2 – 5 GeV).

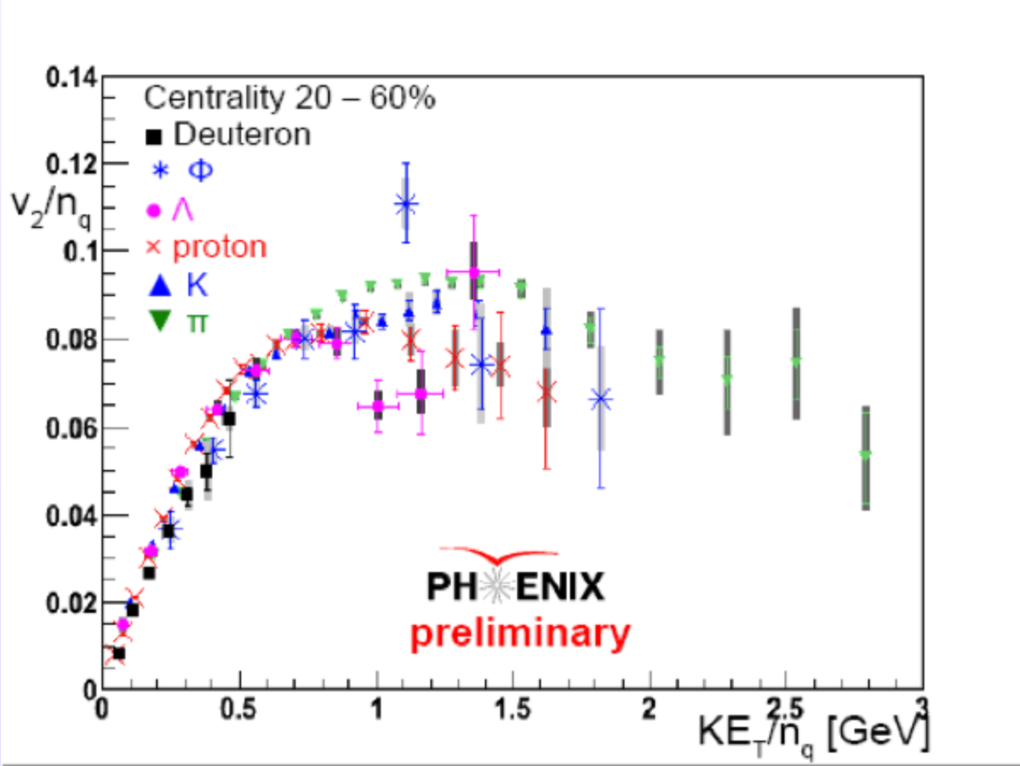
Mass ordering can be seen at low p_T. → scaled by KE_T

Clearly different between meson and baryon v_2.

Quark number scaling

Presented by Yoshimasa IKEDA at spring JPS 2010

Au+Au, $\sqrt{s_{NN}}$ = 200GeV (RUN7)

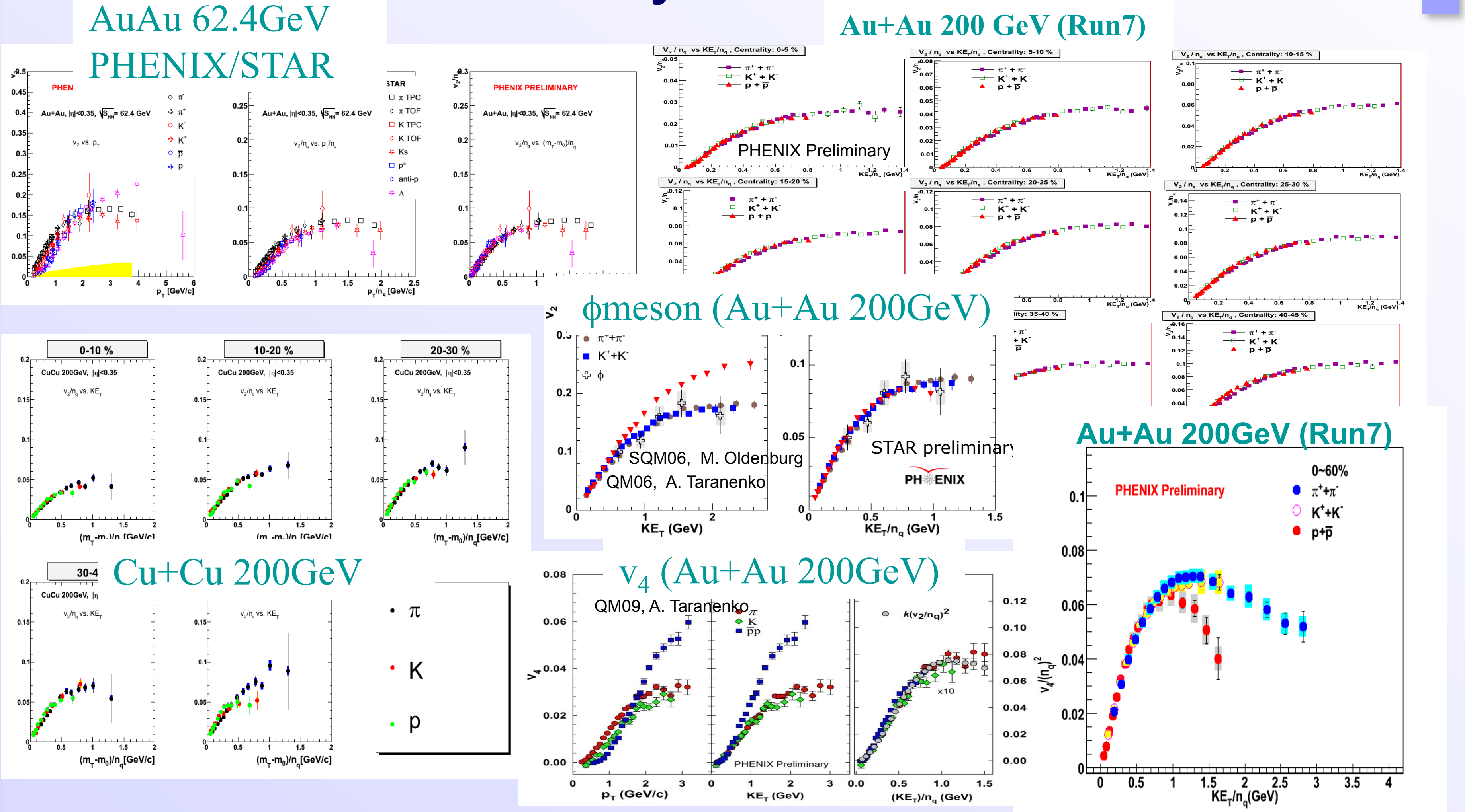


$v_2(p_T)$ /n_{quark} vs. KE_T/n_{quark} becomes one curve independent of particle species.

Significant part of elliptic flow at RHIC develops at quark level.

→ QGP phase

the quark number scaling everywhere

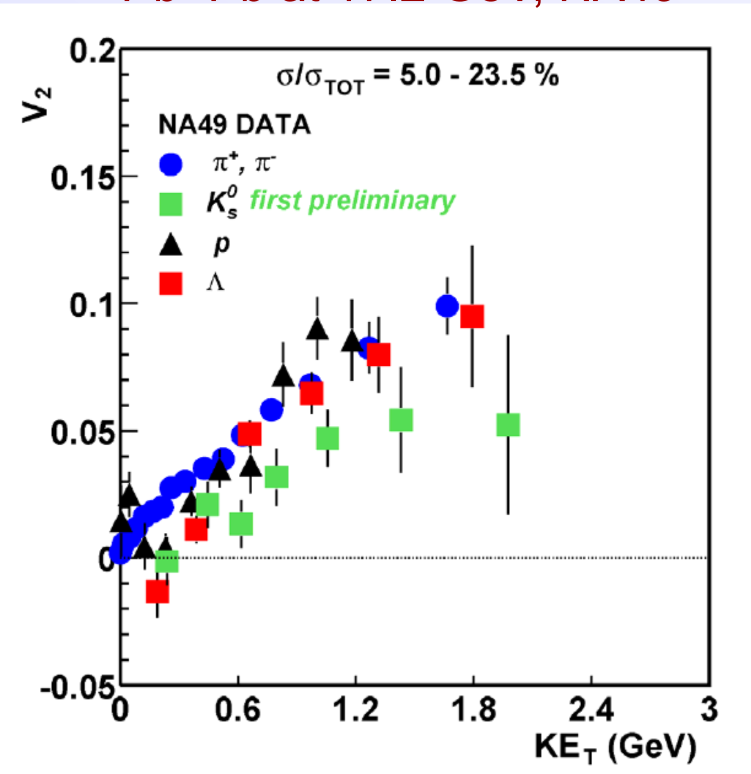


Quark number scaling work out up to K_{ET} ~1GeV.

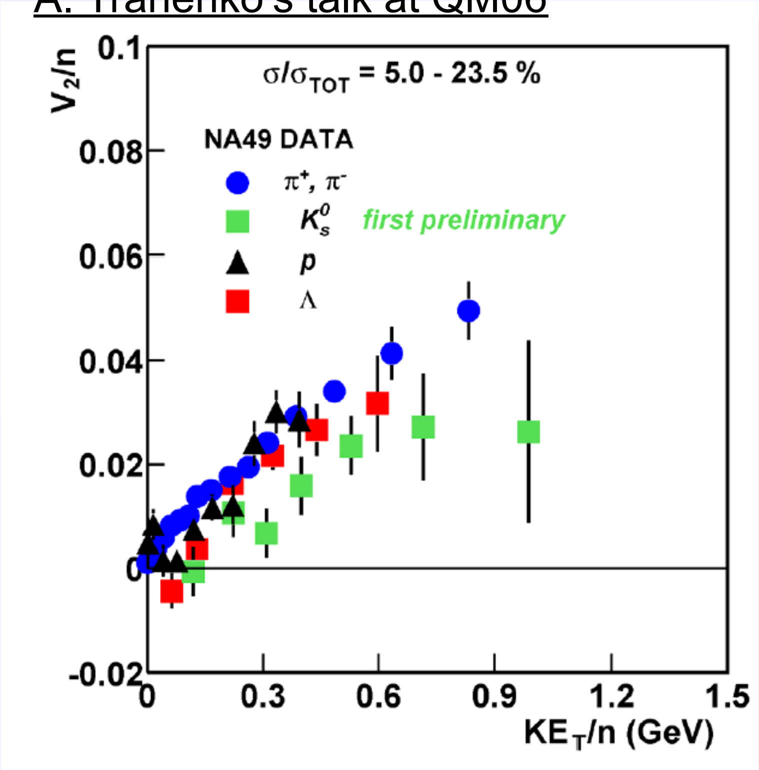
quark number scaling at SPS

v_2 of p, π, Λ - C. Alt et al (NA49 collaboration) nucl-ex/0606026 submitted to PRL
v_2 of K^0 (preliminary) - G. Stefanek for NA49 collaboration (nucl-ex/0611003)

Pb+Pb at 17.2 GeV, NA49



A. Tranenko's talk at QM06



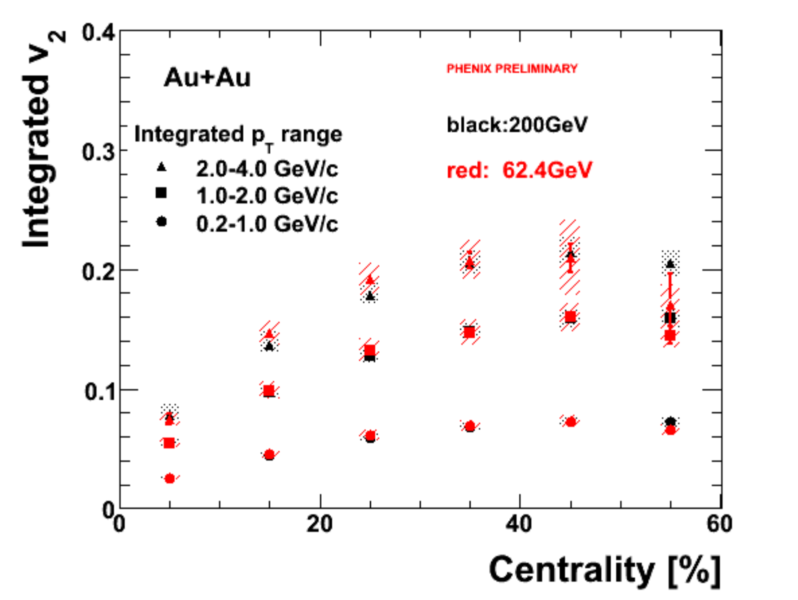
- Quark number + K_{ET} scaling doesn't seem to work out at SPS.
- No flow at quark level due to nonexistence of QGP ?

Other scaling of v_2

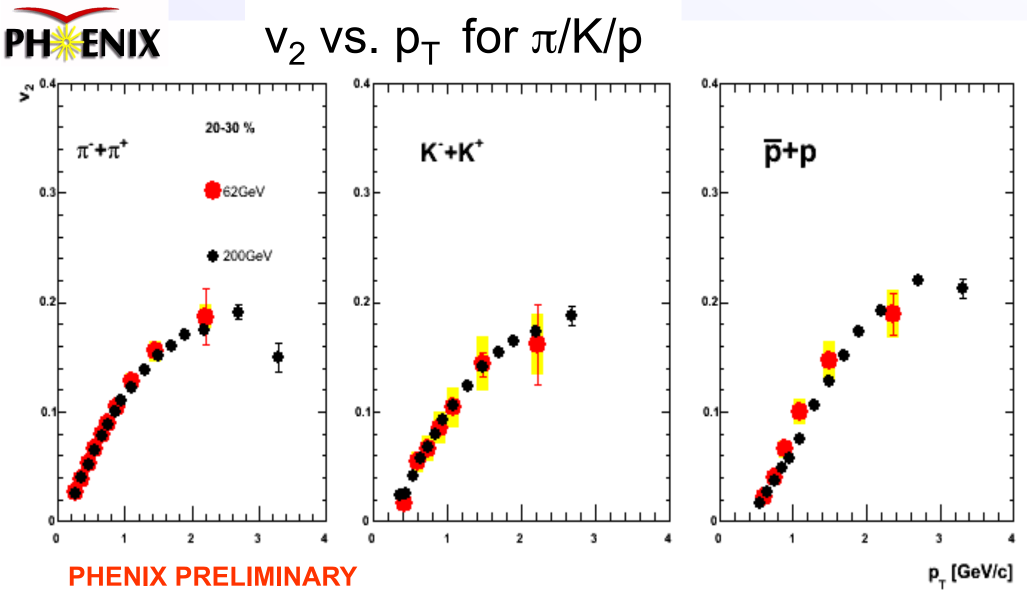
- Energy dependence
- Eccentricity scaling
- Npart scaling

Energy dependence
Au+Au   200 vs. 62 GeV

Centrality dependence



Identified particles

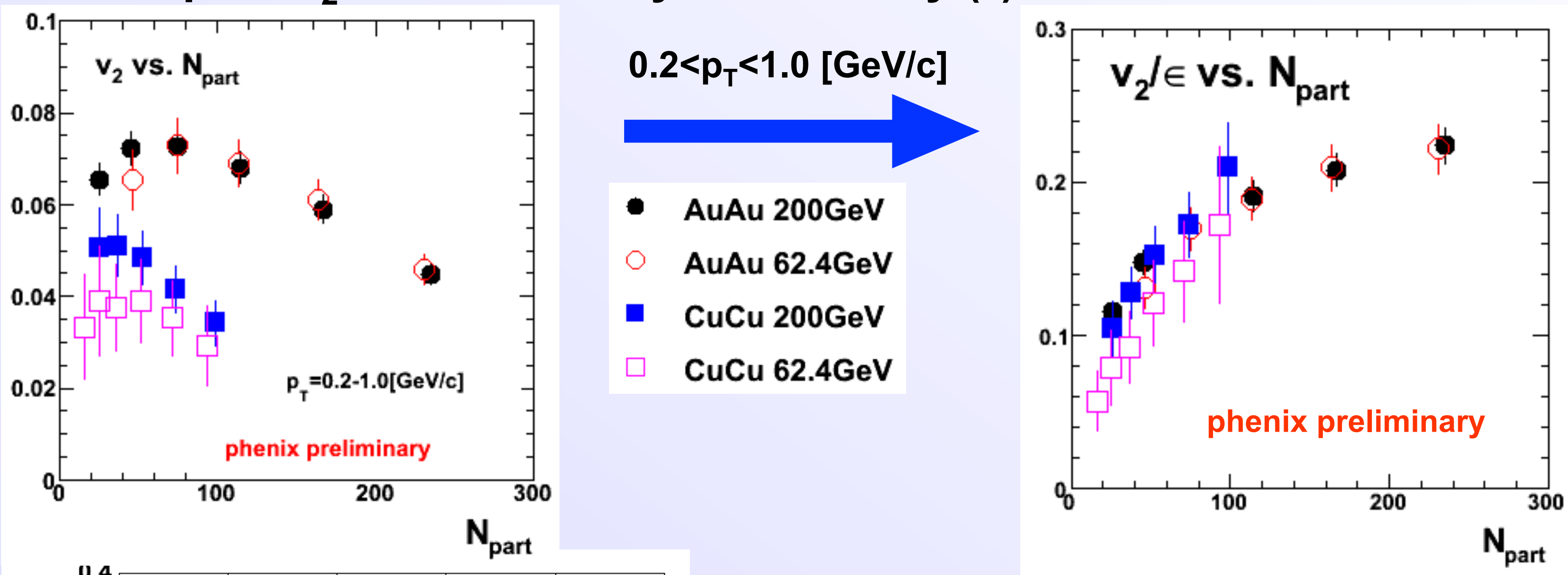


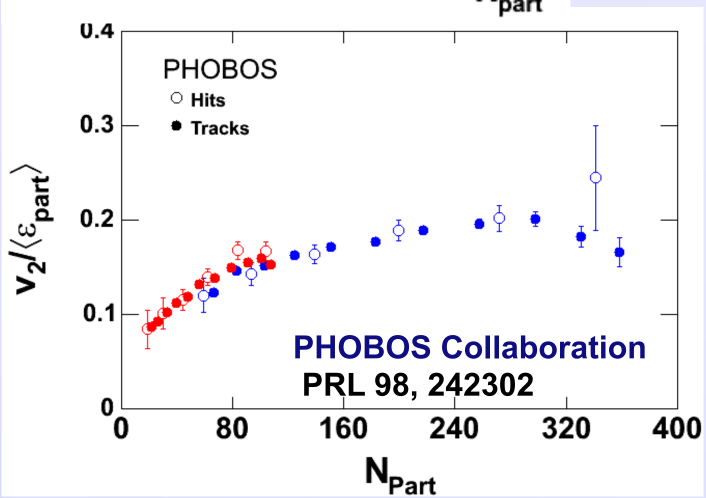
No significant difference between 200 and 62 GeV.

Eccentricity scaling

Au+Au vs. Cu+Cu

Compare v_2 normalized by eccentricity (ε) in collisions of different size.





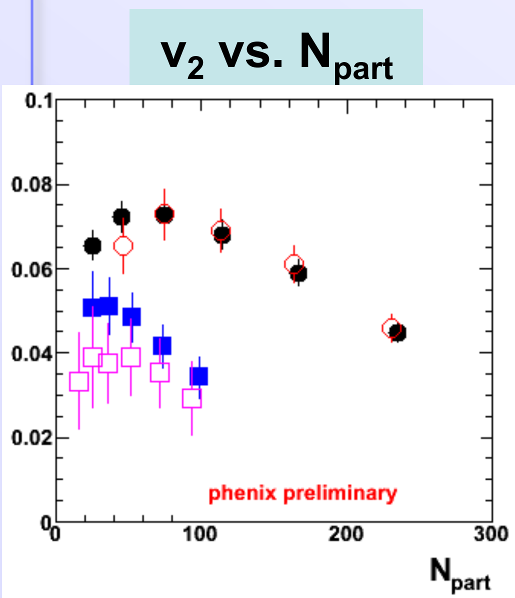
Eccentricity scaling suggests early thermalization.

There is a strong N_{part} dependence.

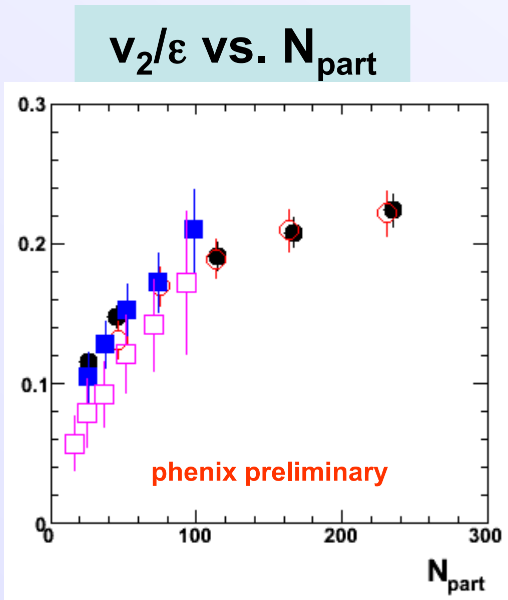
N_{part} Scaling

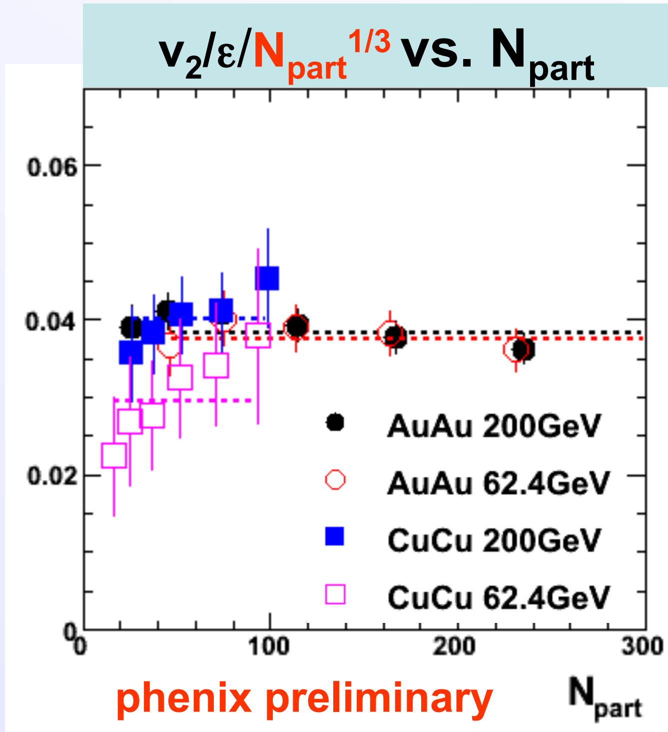
The dependence can be normalized by $N_{part}^{1/3}$.

Dividing by $N_{part}^{1/3}$



0.2<p_T<1.0 [GeV/c]



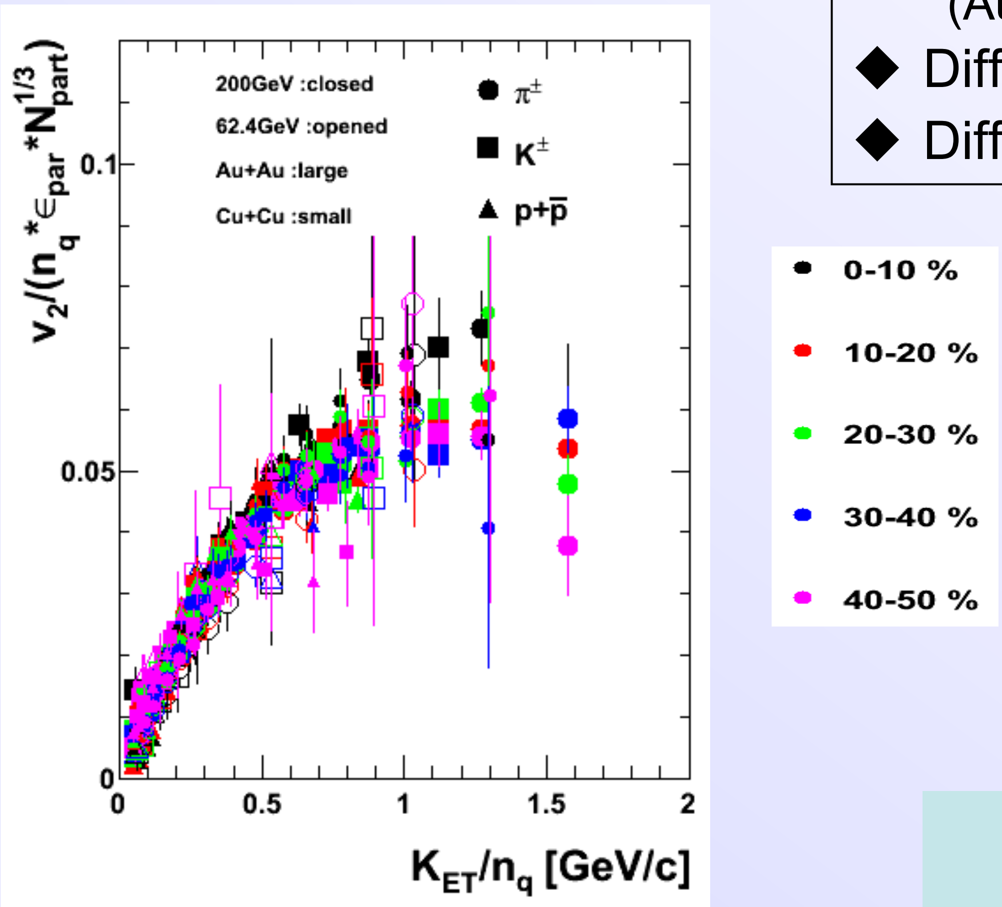


v_2/eccentricity/$N_{part}^{1/3}$ scaling works for all collision systems except small N_{part} at 62 GeV.

- This exception may indicate non-sufficient thermalization region.

Universal v_2 for identified charged hadrons

Taking all scaling together,



- Different Energy and System (AuAu200, CuCu200, AuAu62)
- Different Centrality (0-50%)
- Different particles (π/ K /p)

45 curves

$$\frac{v_2(K_{ET}/n_q)}{n_q \times \varepsilon \times N_{part}^{1/3}}$$

Scale to one curve.

χ2/ndf = 2.1 (with systematic errors)

Then, we have a question .

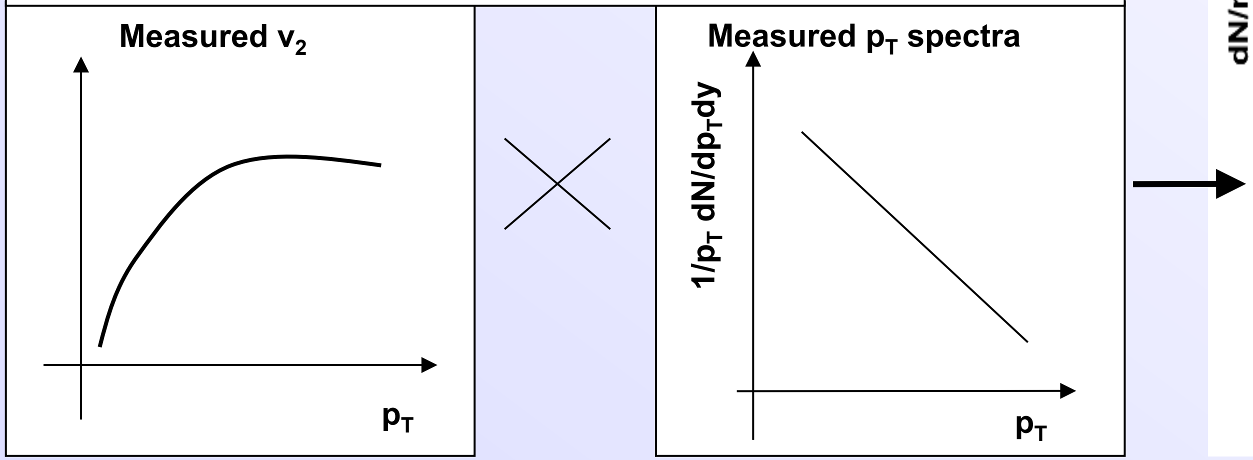
If the matter is thermalized and the pressure gradient produce the flow, what is the reason for N_{part} dependence and KE_T scaling of v_2?

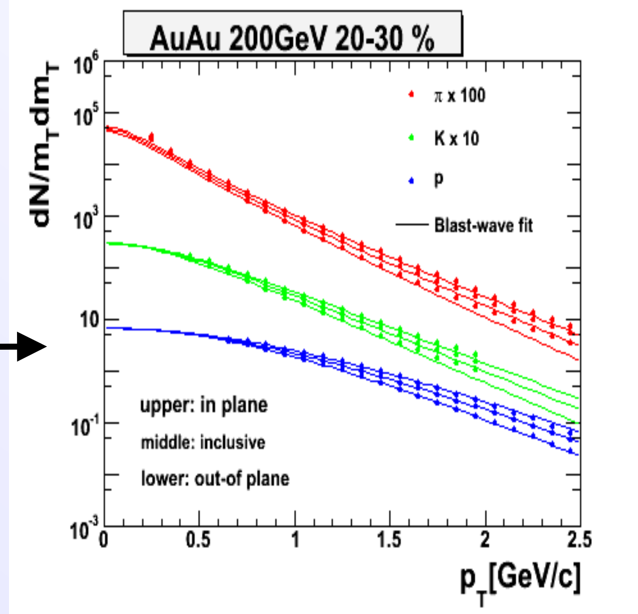
Blast Wave Model Fit

Blast Wave Fitting for v_2 and Spectra

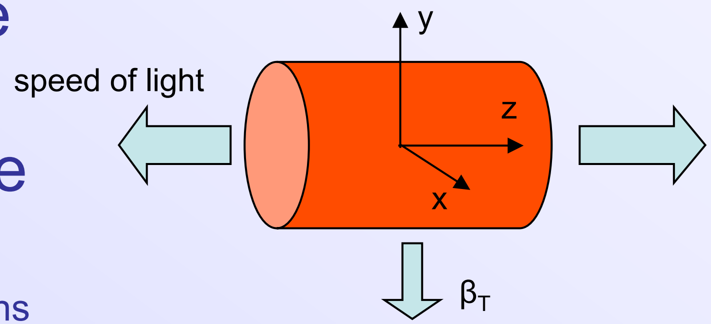
We use this well-known fitting technique to obtain the information of the flow velocity and temperature in and out-of plane **separately**.

Measured spectra weighted by ϕ distribution

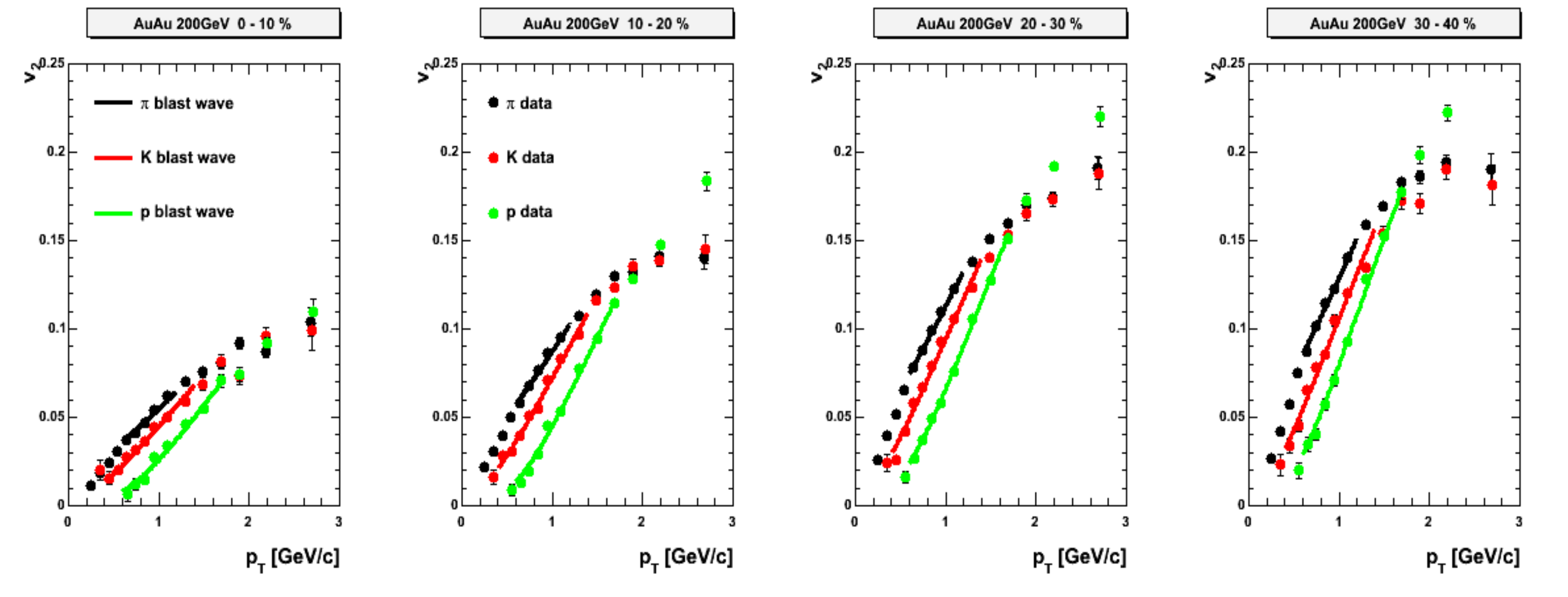




Fitting p_T distribution in and out-of plane ***separately*** for π/K/p simultaneously by blast wave, β_T and T_{fo} in and out-of plane are obtained ***separately***.

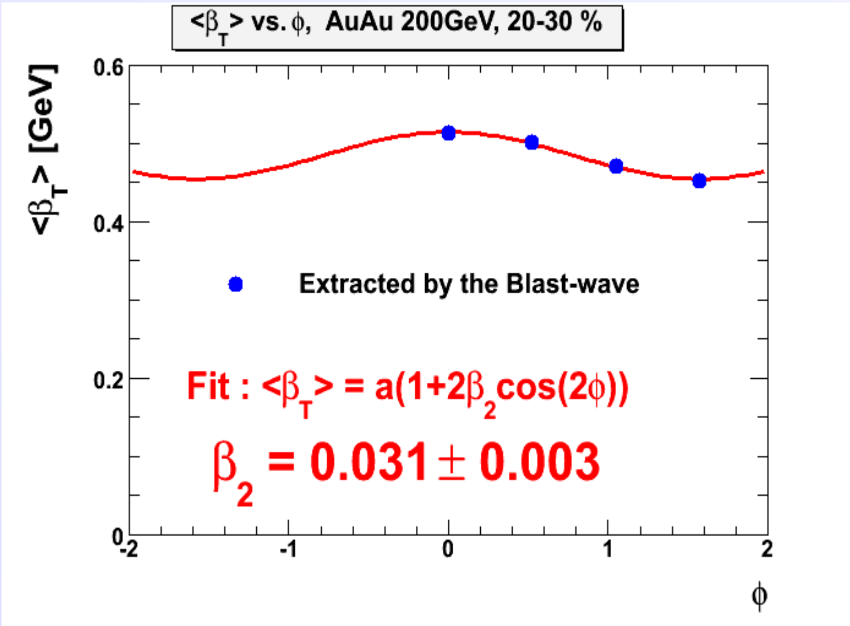


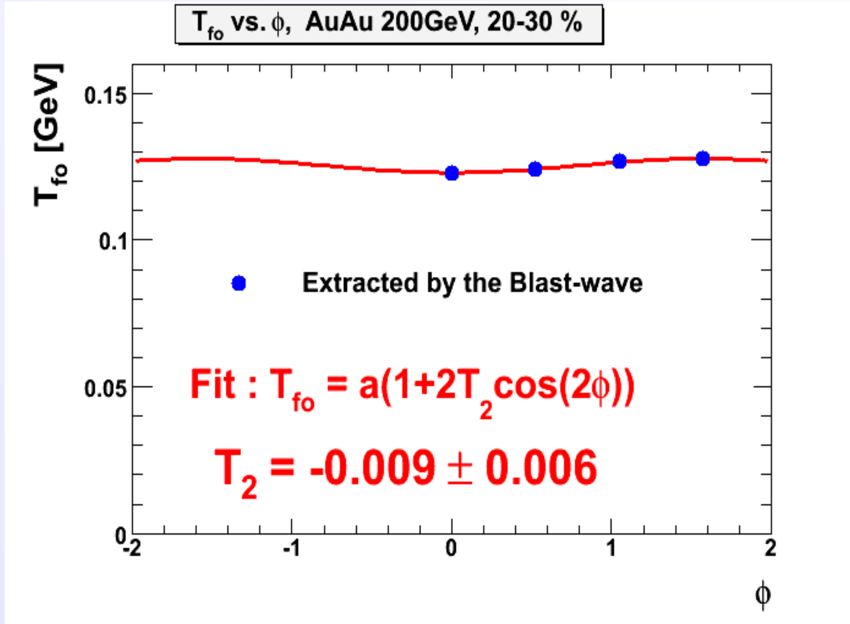
Radial flow and KE_T scaling



- Species dependence of v_2 can be reproduced by the Blast-wave model → Radial flow effect

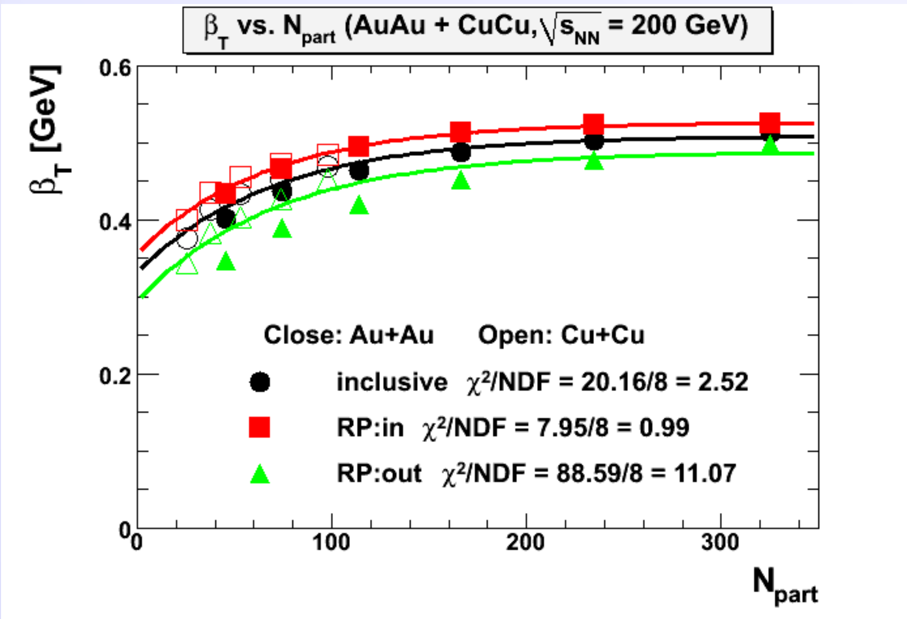
Azimuthal dependence of β_T and T_{fo}

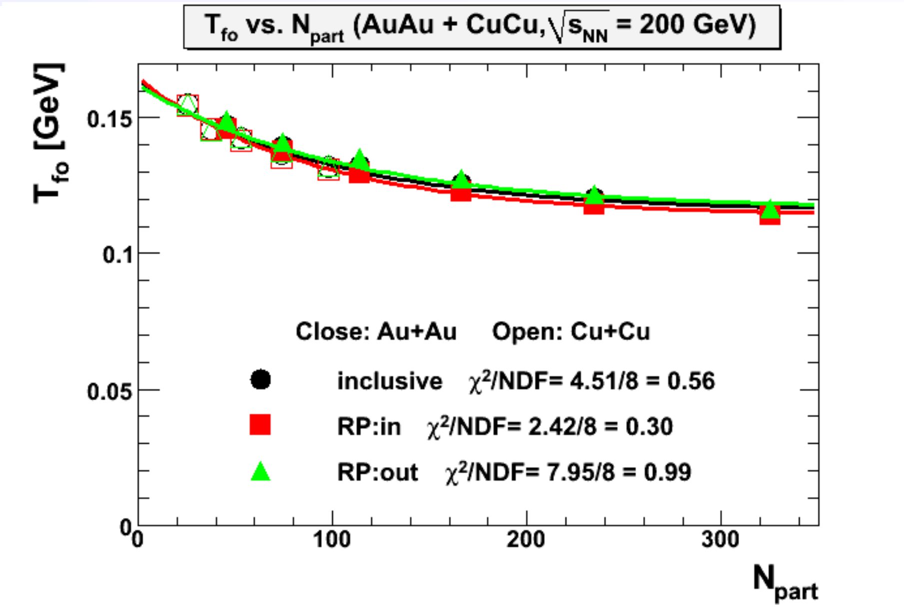




- β_T has clear azimuthal dependence.
  - **Larger velocity @ in-plane**
- T_{fo} has small azimuthal dependence.
  - **Lower temperature @ in-plane**

N_{part} Dependence of β_T and T_{fo}

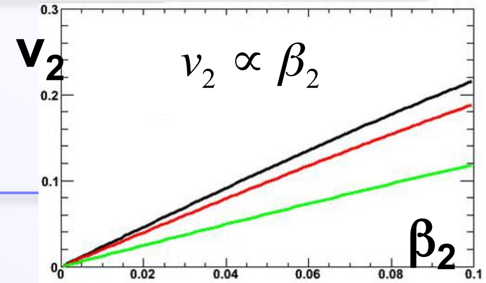




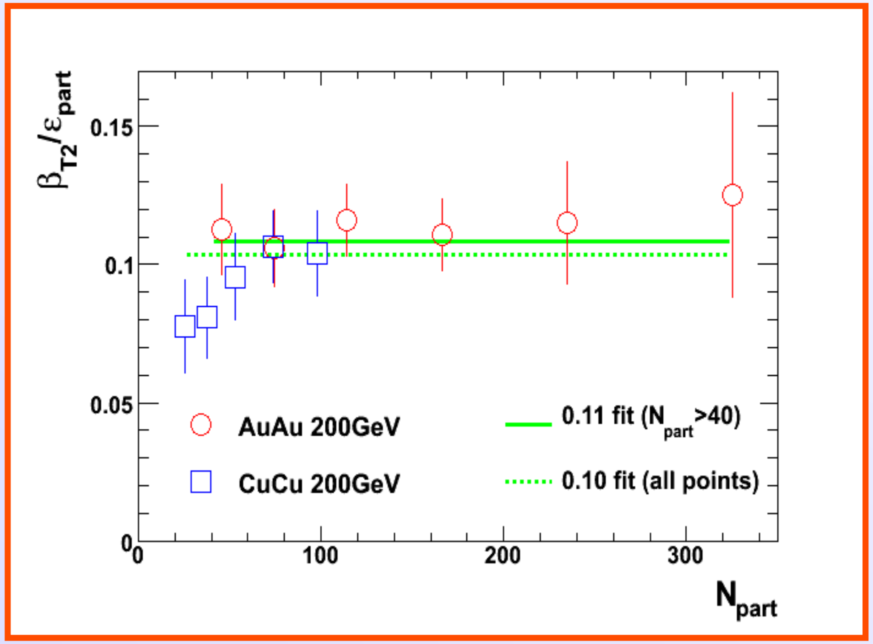
T_{fo} and β_T agree between Au+Au and Cu+Cu, especially for the in-plane.

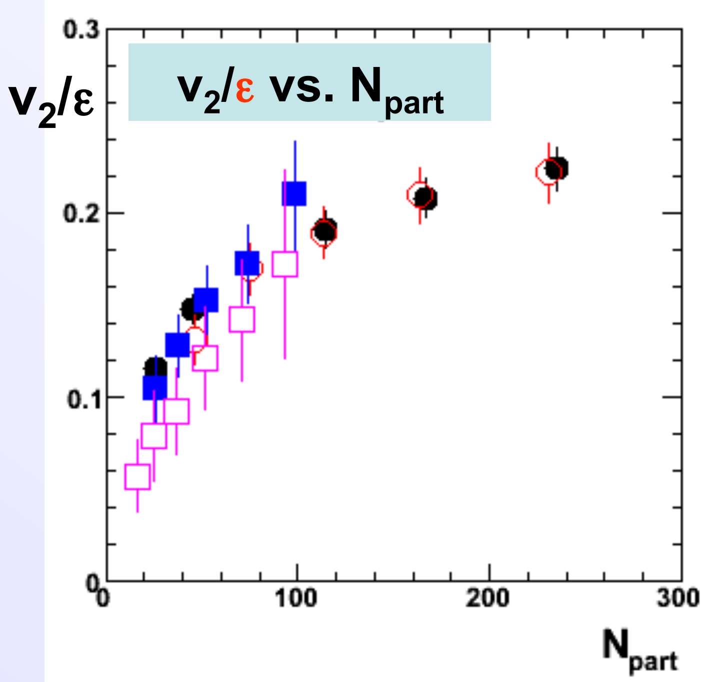
Since v_2 is produced by the difference between in and out-of plane, the modulation of β_T is expected to have important rule to make v_2.

Eccentricity scaling here !



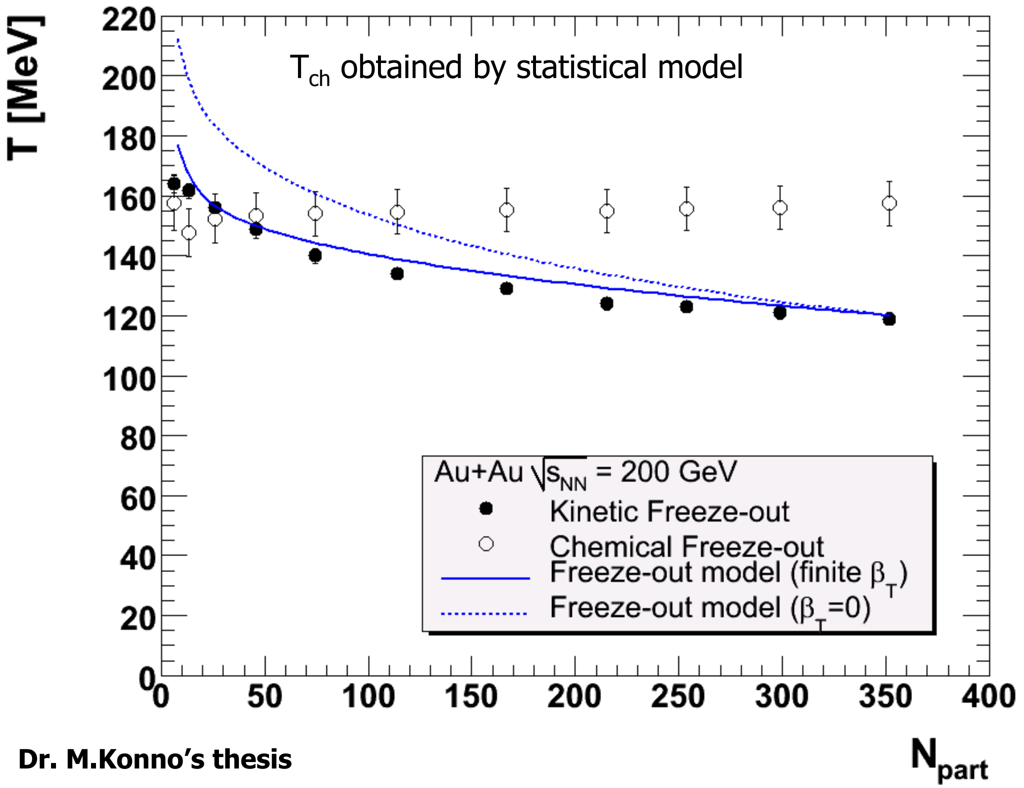
$\beta_{T2} = (\beta_T^{in} - \beta_T^{out}) / (\beta_T^{in} + \beta_T^{out}) / 2$





β_{T2} scaled by eccentricity agrees between Au+Au and Cu+Cu .
β_{T2}/eccentricity is flat at N_{part} > 40. → ε **drives** β_{T2} **!** . →Signal of Thermalization !?!?
v_2 is proportional to β_{T2} if other parameters are fixed.
BUT, v_2/ eccentricity is "not" flat → What courses N_{part} dep. of v_2 ??

Freeze-out Temperature and v_2

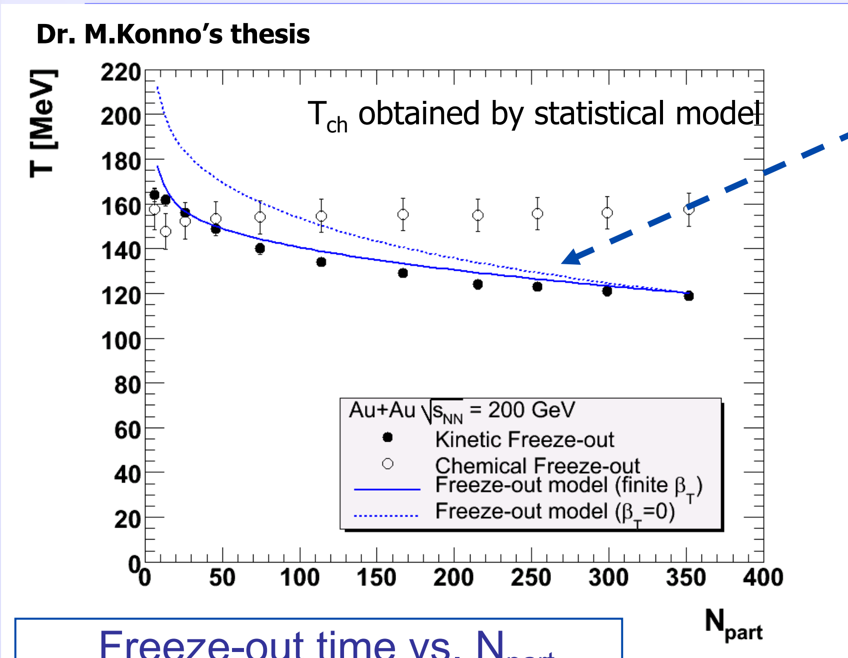


T_{fo} depends on N_{part} (while T_{ch} doesn't) !

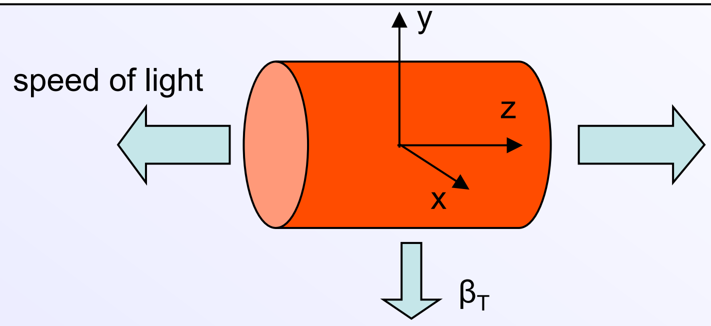
Larger system size → Lower T_{fo} → Steeper spectra → Larger v_2

Why does larger system have lower freeze out temperature ?

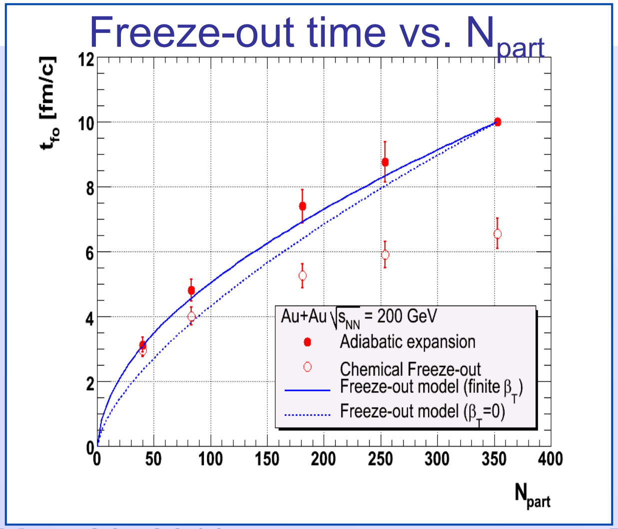
Freeze-out Temperature and Time



Simple adiabatic expansion model



[Assumption]
-Cylindrically expanding
-Freeze-out condition: $\lambda(t)=R(t)$



The model explains N_{part} dependence well !

The times until freeze-out can be calculated by this model. Larger system takes more time to freeze-out. →This makes lower T_{fo}

Summary

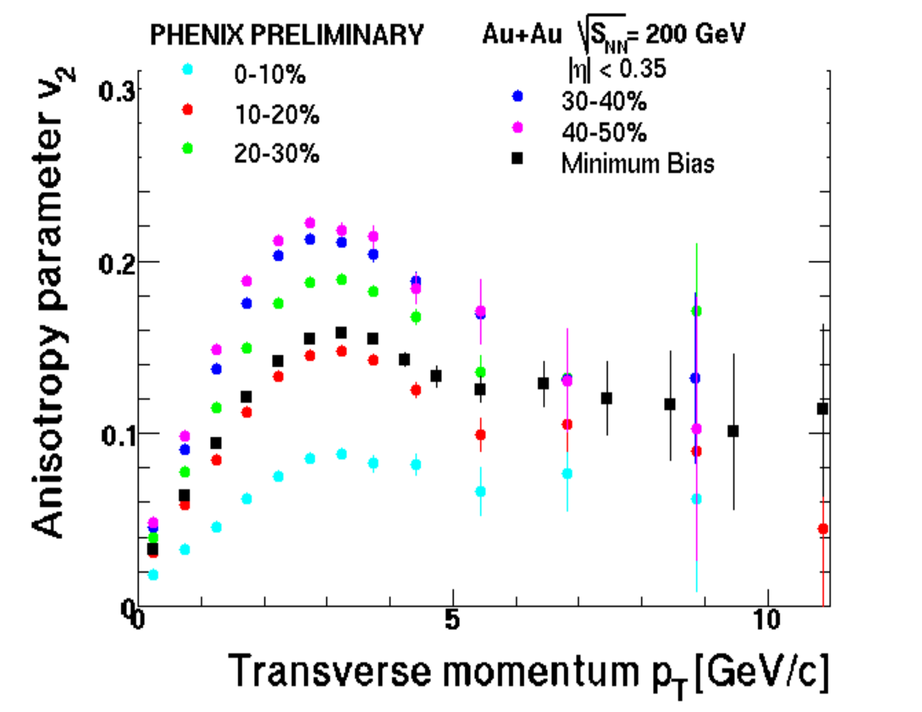
- Systematic study of v_2 have been done in Au+Au/Cu+Cu at $\sqrt{s_{NN}}$ = 62.4/200 GeV.
- v_2 values are saturated above 62.4 GeV in Au+Au.
  - Local thermalization
- $v_2(p_T)$ follows quark number + KE_T scaling in Au+Au (200,62GeV) and Cu+Cu (200GeV) .
  - Flow at quark level → QGP phase
- $v_2(N_{part})$ / ε are same between Au+Au and Cu+Cu at 200 GeV.
  - Eccentricity scaling → Early thermalization
- $v_2(p_T)$ /ε/$N_{part}^{1/3}$ scaling works except for small N_{part} at 62 GeV.
  - Existence of a universal v_2 scaling at RHIC
  - Exception may indicate non-sufficient thermalization region.

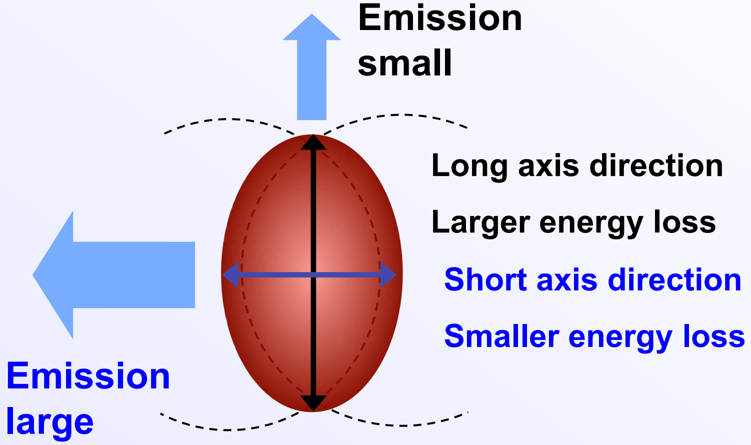
<From Blast-wave fit results with v_2 and spectra together>

- β_2/eccentricity is constant not depending on system size (N_{part}>40).
  - Early thermalization !
- Larger system freezes out later at lower temperature.
  - cause the N_{part} dependence of v_2/ ε .

Back Up

v_2 at high p_T

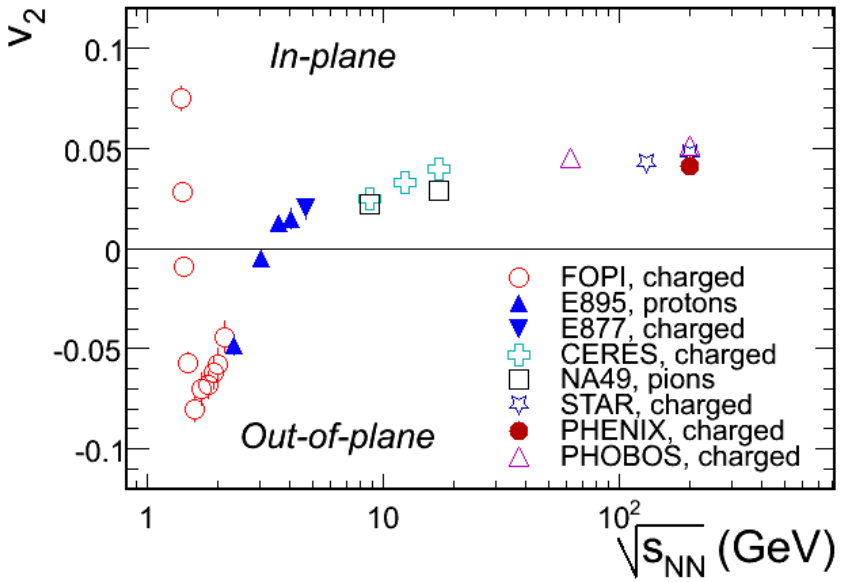




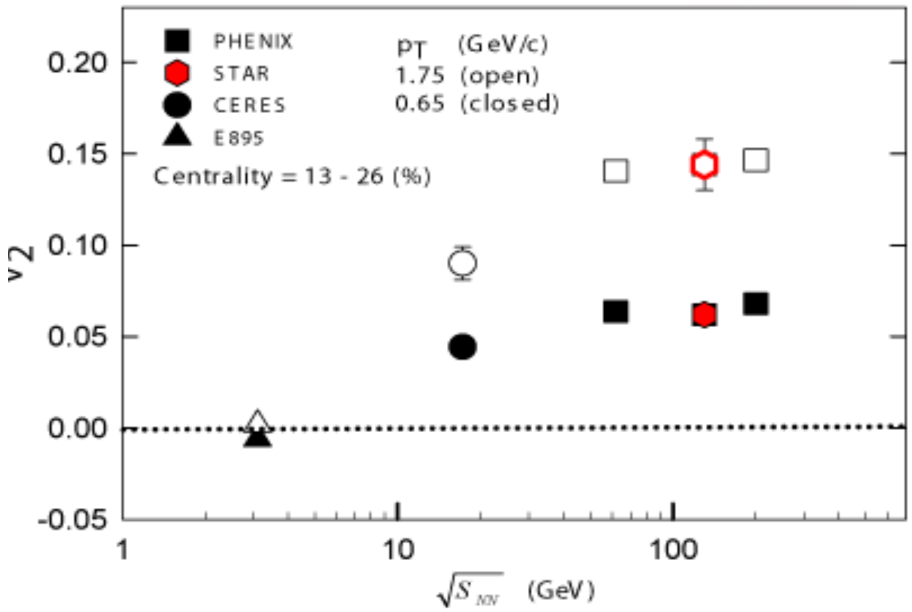
- Non-zero v_2 at high p_T
- Consistent to Jet suppression scenarios.

Energy dependence up to RHIC

FOPI : Phys. Lett. B612, 713 (2005). E895 : Phys. Rev. Lett. 83, 1295 (1999)
CERES : Nucl. Phys. A698, 253c (2002). NA49 : Phys. Rev. C68, 034903 (2003)
STAR : Nucl. Phys. A715, 45c, (2003). PHENIX : Preliminary.
PHOBOS : nucl-ex/0610037 (2006)



PRL 94, 232302



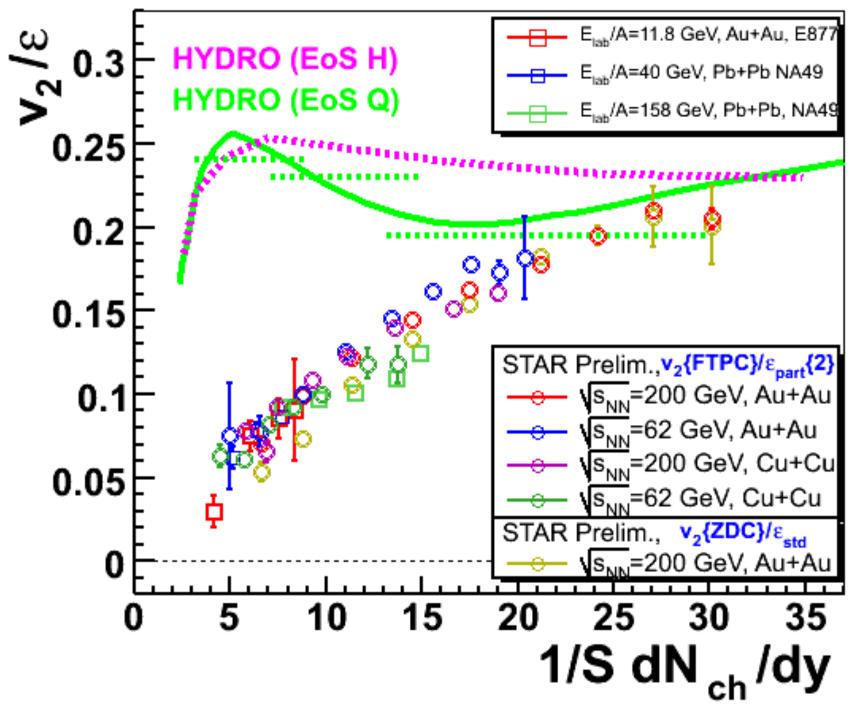
~ 50% increase from SPS to RHIC.

Above 62.4 GeV, v_2 seems to be saturated.

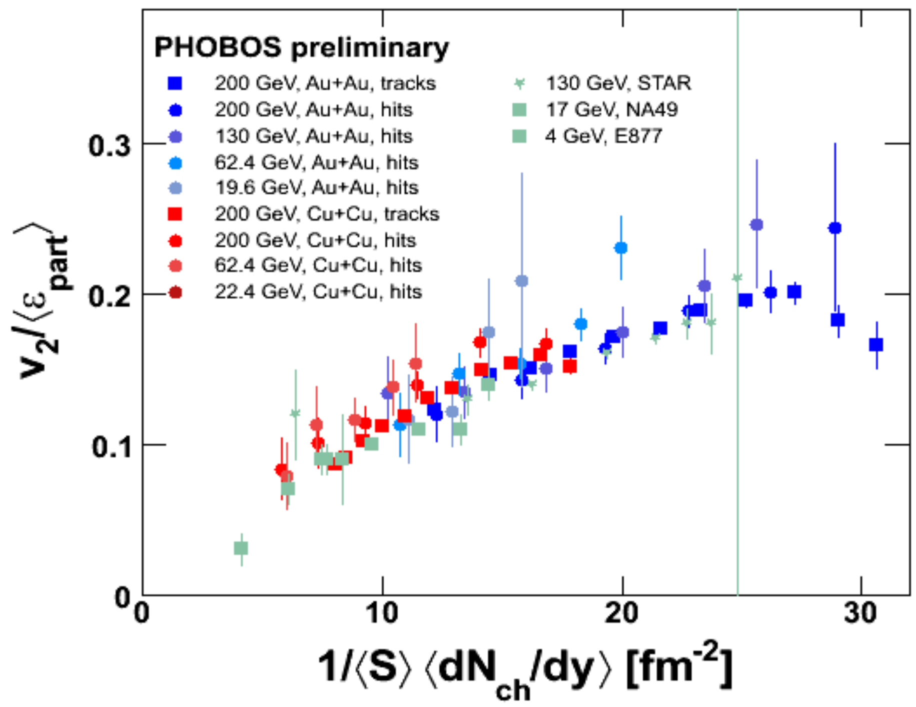
→ **The matter reaches thermal equilibrium state at RHIC.**

Scaling (others)

QM2006, S. A. Voloshin



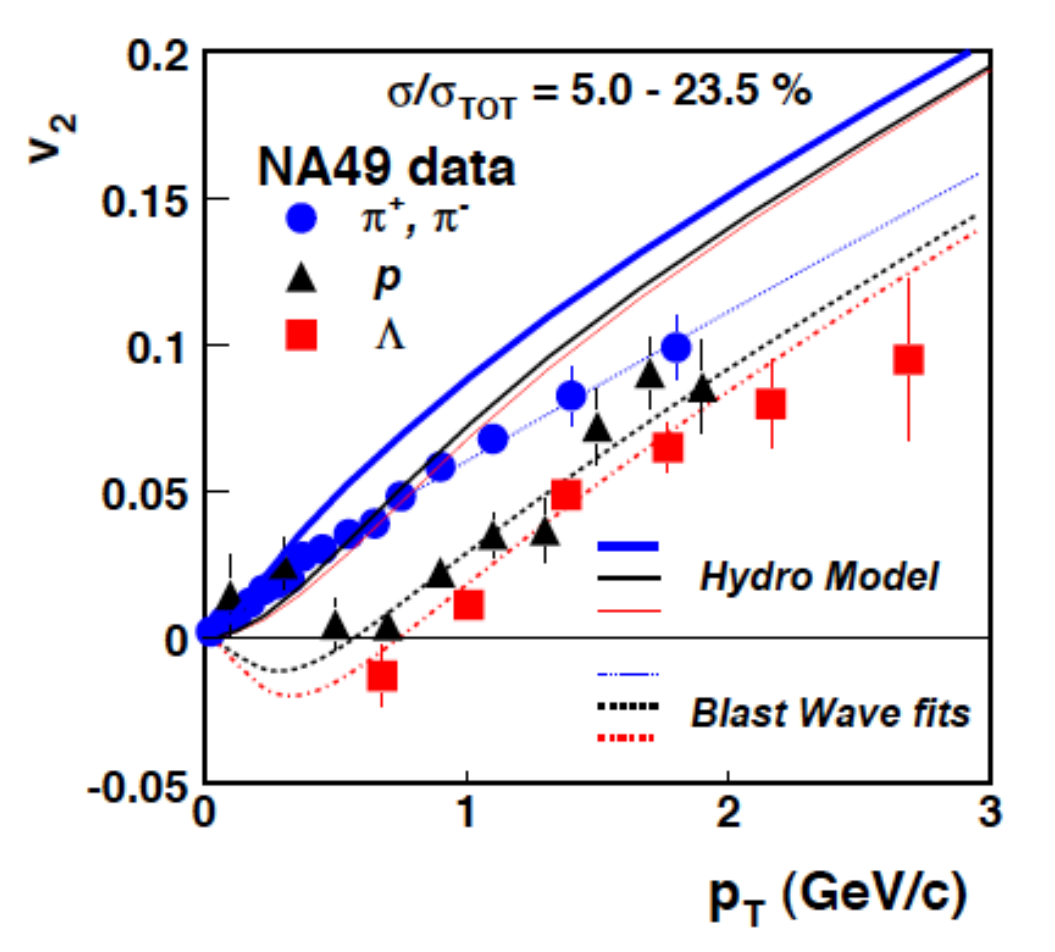
QM2006, R. Nouicer



- Straight line from SPS to RHIC energy.
- v_2 is reaching the hydro limit at central collision ?

LHC and low energy scan may have answer for this !?

v_2 compared with hydro model at SPS



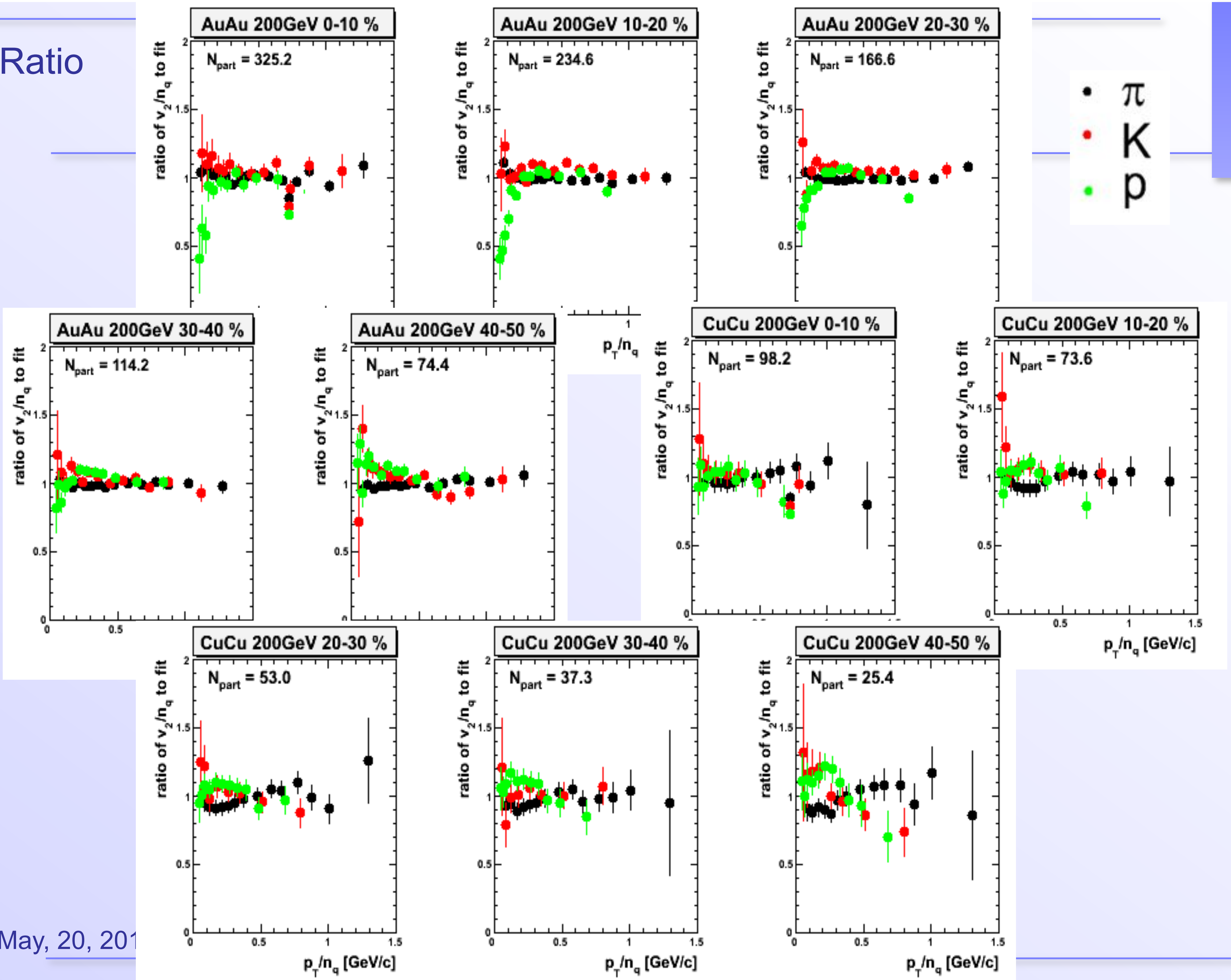
SPS ($\sqrt{s_{NN}}$ = 17 GeV)

NA49: nucl-ex/**0606026** (2007)

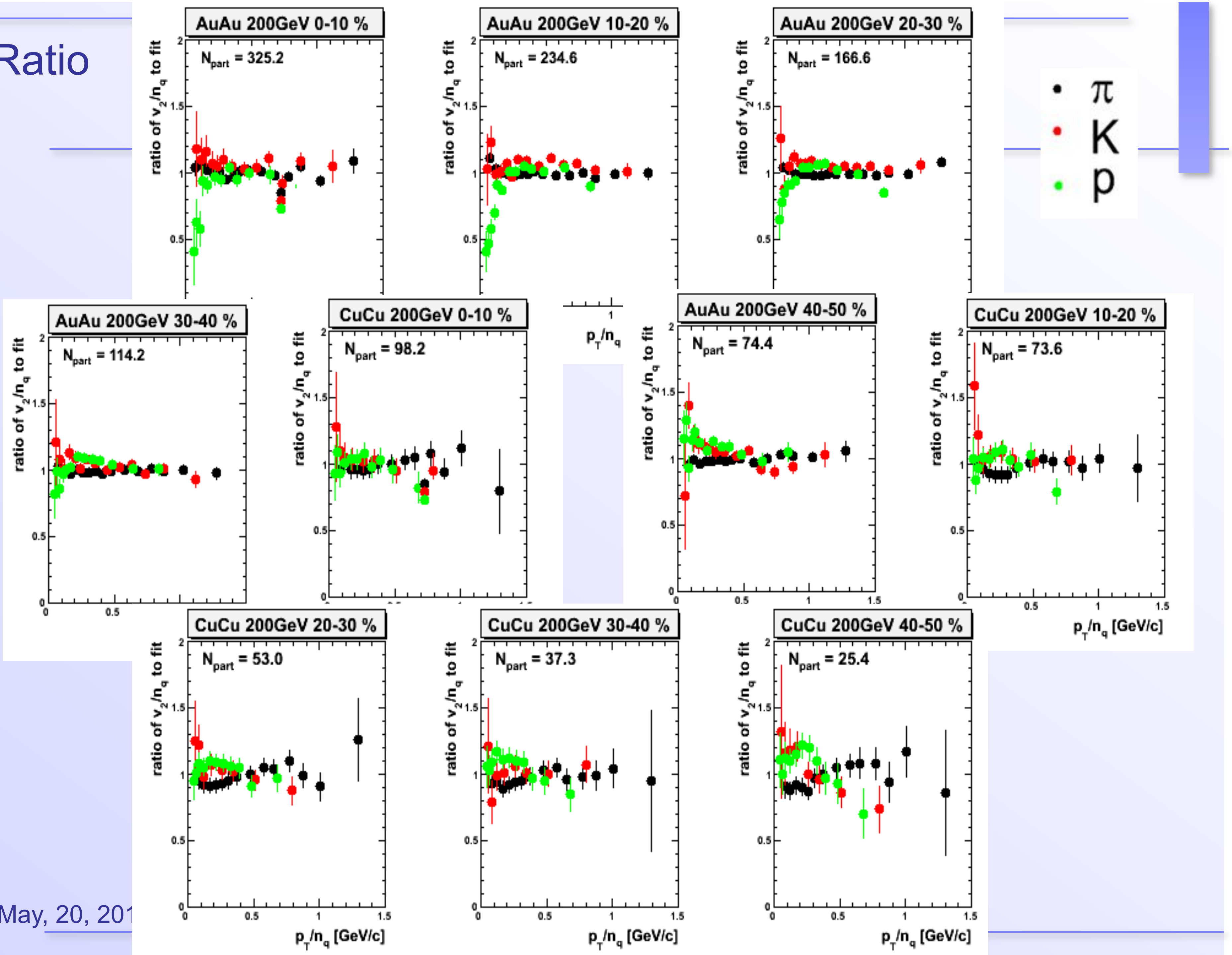
Hydro-dynamical model: 1st order phase transition, T_c=165 MeV, T_f=120 MeV, τ_0 = 0.8 fm/c

Hydro-dynamical model at SPS: Overestimate v_2

Ratio


AuAu 200GeV 0-10 %
N_{part} = 325.2
AuAu 200GeV 10-20 %
N_{part} = 234.6
AuAu 200GeV 20-30 %
N_{part} = 166.6
AuAu 200GeV 30-40 %
N_{part} = 114.2
AuAu 200GeV 40-50 %
N_{part} = 74.4
CuCu 200GeV 0-10 %
N_{part} = 98.2
CuCu 200GeV 10-20 %
N_{part} = 73.6
CuCu 200GeV 20-30 %
N_{part} = 53.0
CuCu 200GeV 30-40 %
N_{part} = 37.3
CuCu 200GeV 40-50 %
N_{part} = 25.4
ratio of v_2/n_q to fit
p_T/n_q [GeV/c]
π
K
p

Ratio



May, 20, 201

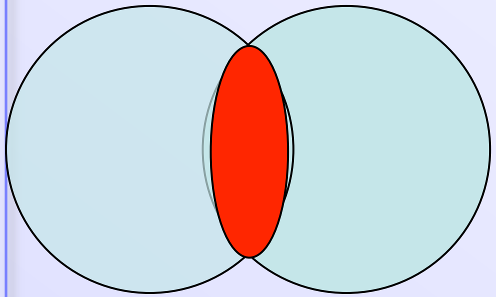
Back Up

Comparison with Hydro simulation

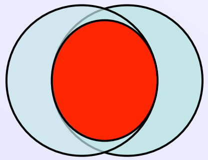
Differential v_2 in Au+Au and Cu+Cu Collisions

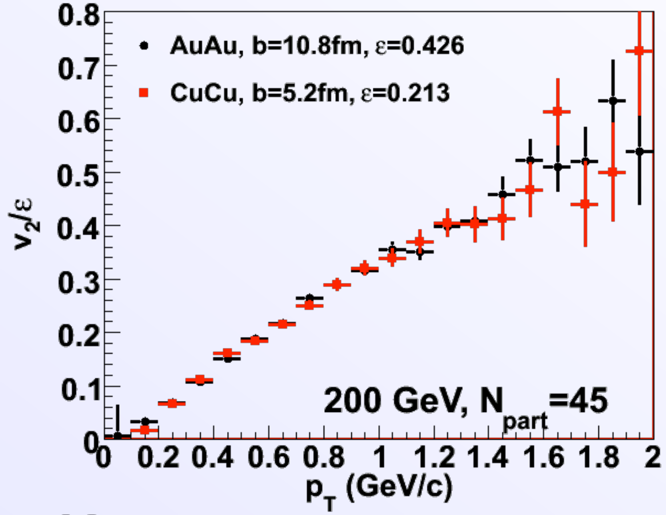
QGP fluid+hadron gas with Glauber I.C.

Au+Au



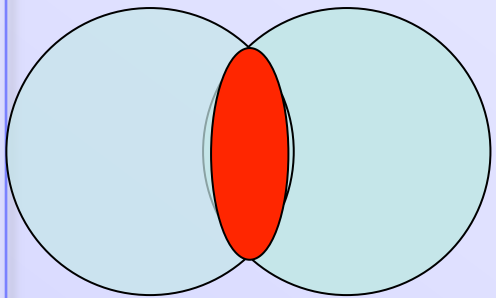
Cu+Cu



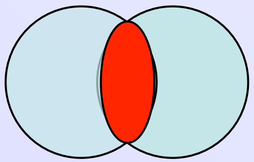


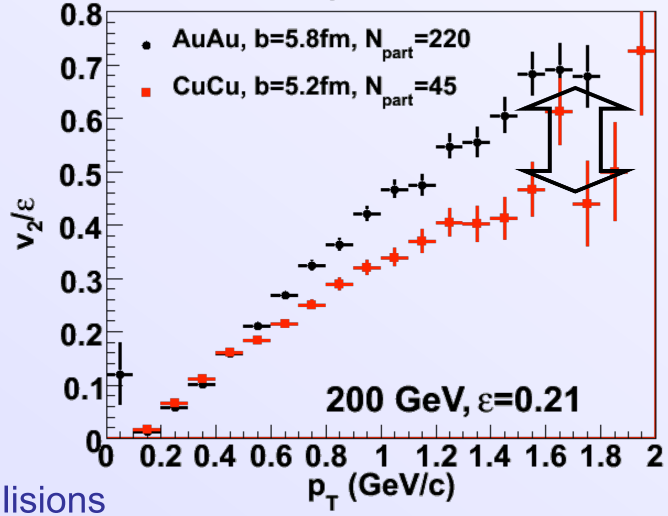
Same N_{part}, different eccentricity

Au+Au



Cu+Cu





Same eccentricity, different N_{part}

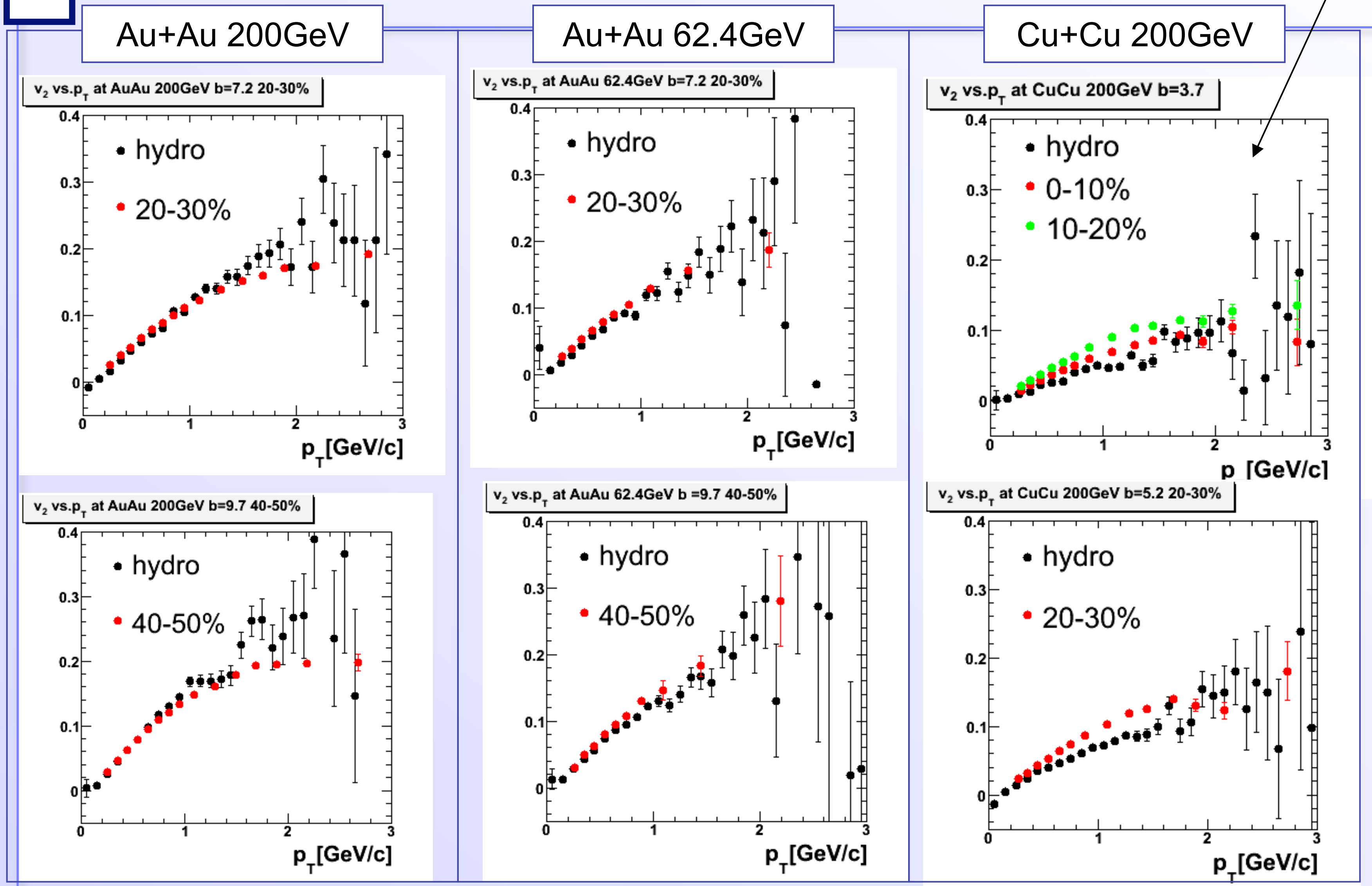
Comparison with hydro-simulation

Hydro calculations done by Prof. Hirano.

ref: arXiv:0710.5795 [nucl-th] and Phys. Lett.B 636, 299 (2006)

π

Hydro should be middle of two data.

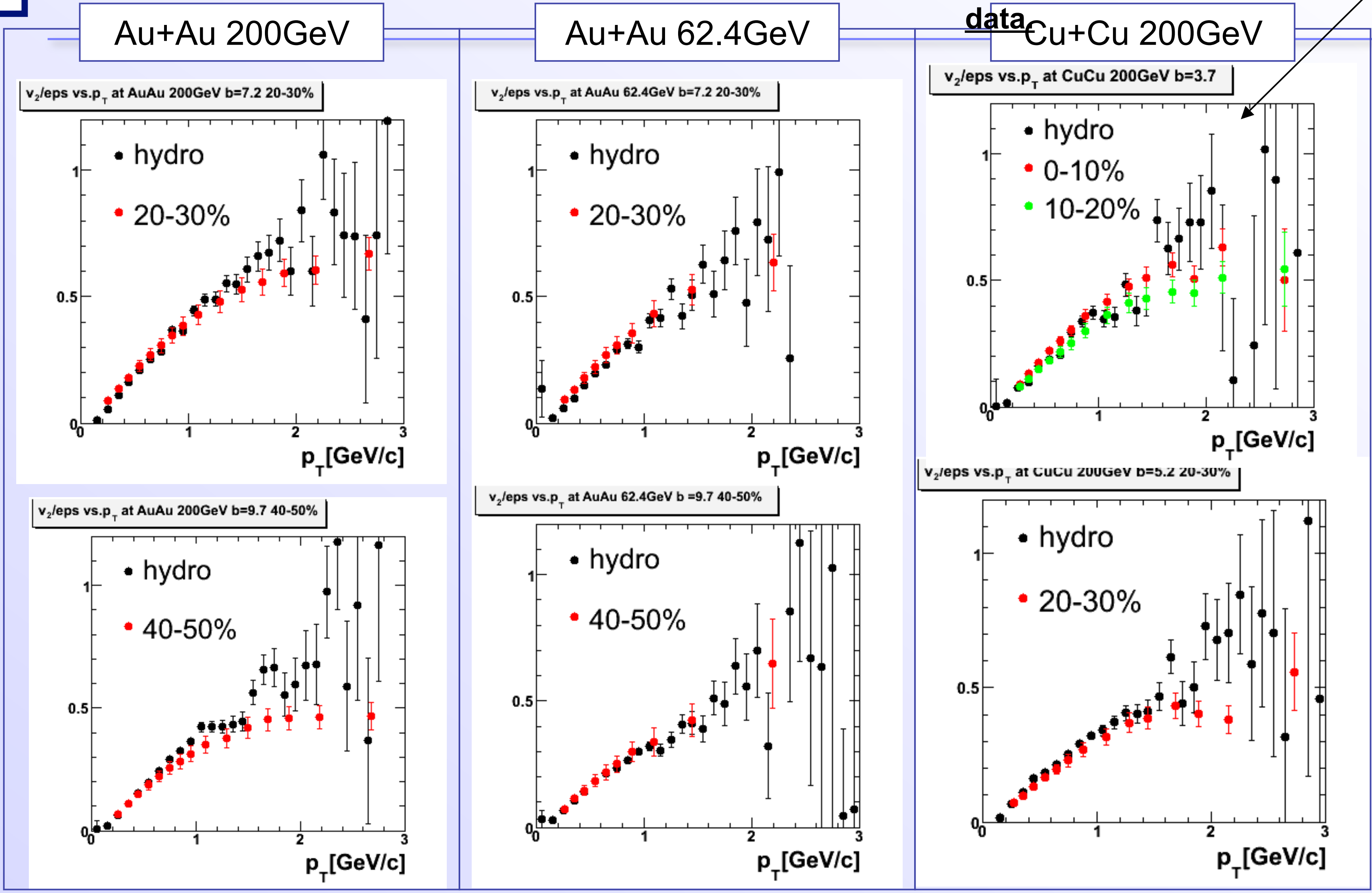


The Au+Au results agree well with hydro but Cu+Cu results don't.

π

Comparison of $v_{2(data)}/\varepsilon_{participant}$ to $v_{2(hydro)}/\varepsilon_{standard}$

Hydro should be middle of two data



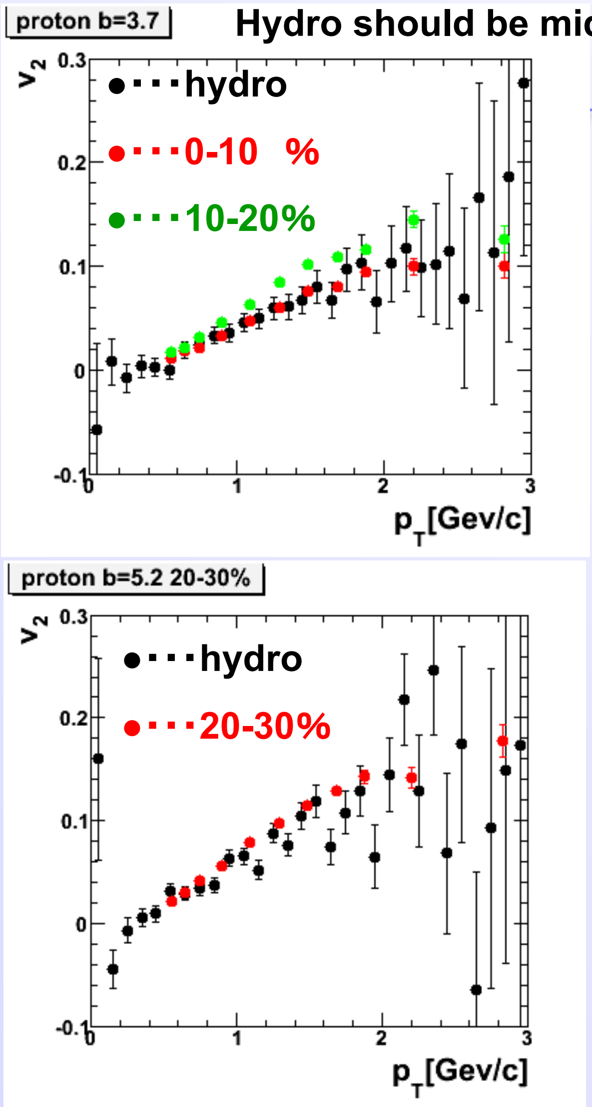
The Au+Au and Cu+Cu results agree well with hydro.

Comparison with hydro-simulation

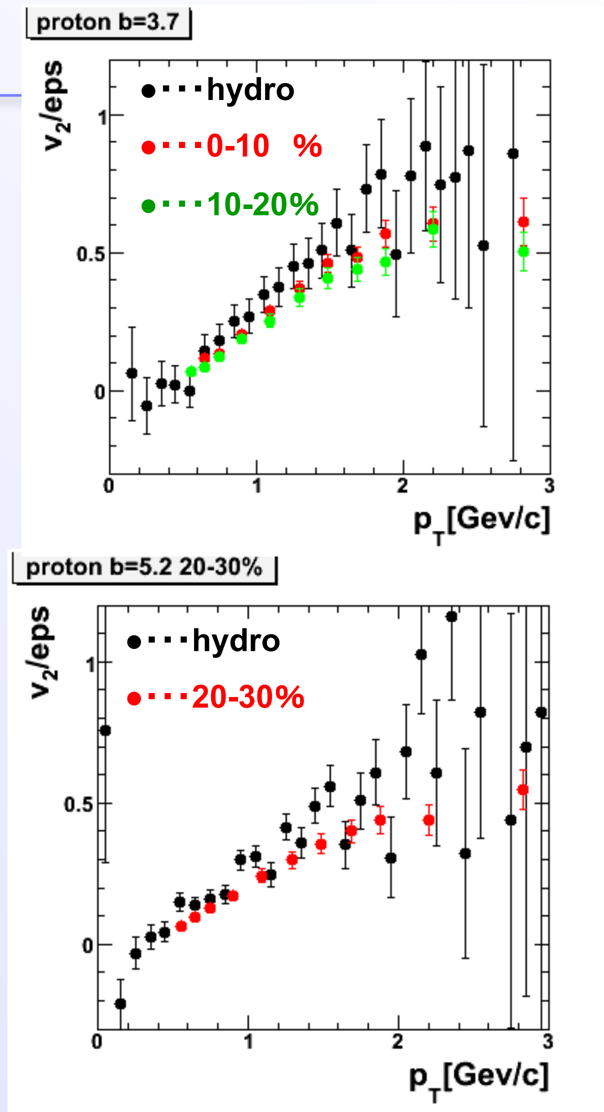
Cu+Cu 200GeV

p

Hydro should be middle of two data.

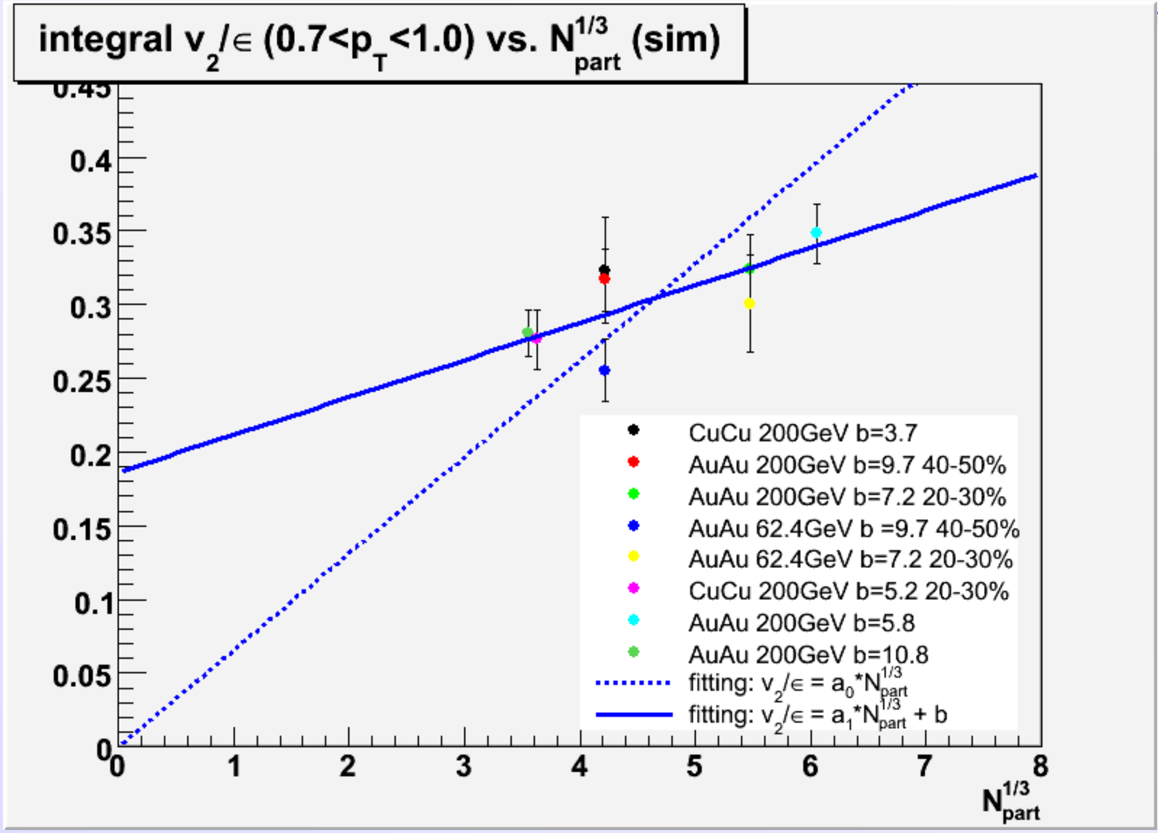


Normalized by eccentricities



v_2(data)/$\varepsilon_{participant}$ for proton doesn't agree with v_2(hydro)/$\varepsilon_{standard}$

Hydro v_2/ε vs. $N_{part}^{1/3}$

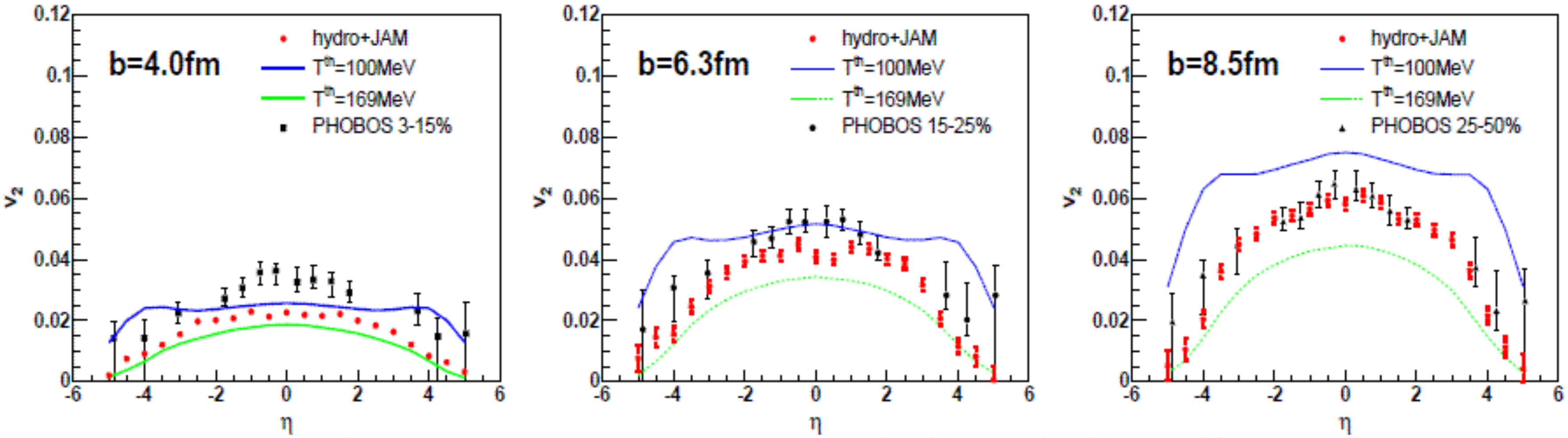


Fitting lines: dash line $v_2/\varepsilon = a{*}N_{part}^{1/3}$

solid line $v_2/\varepsilon = a{*}N_{part}^{1/3} + b$

Rapidity dependence

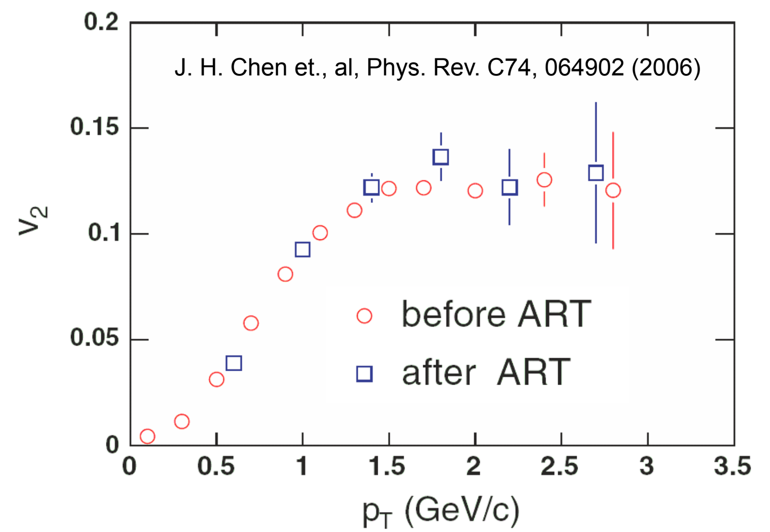
T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, PLB 636 (2006) 299

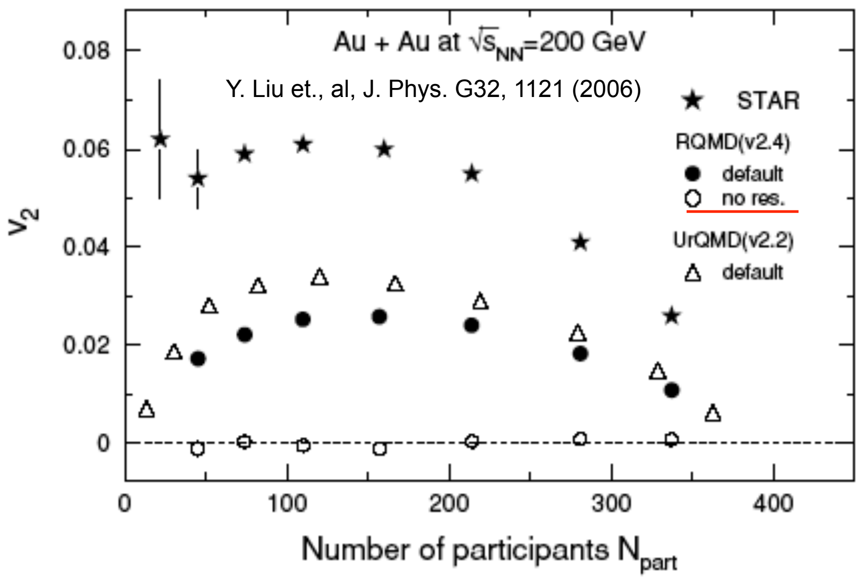


[Glauber model initial conditions (85% soft/15% hard)]

- To repoduce rapidity dependence of v2, need hadronic re-scattering as well as flow at QGP.

Multi-strange hadrons





- Why ?
  - ϕ and Ω are less affected by hadronic interactions
  - Hadronic interactions at a later stage do not produce enough v_2