What We Have Learned from the Measurement of Azimuthal Anisotropy of Identified Particles in Relativistic Heavy Ion Collisions

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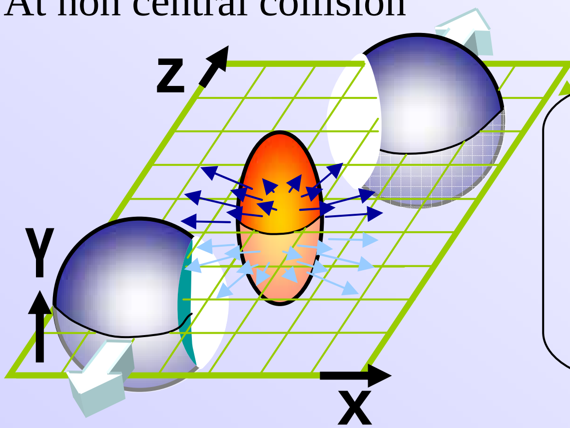
Contents

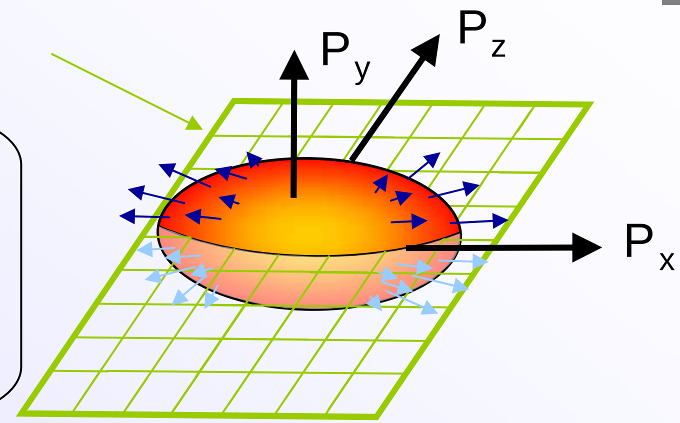
Azimuthal Anisotropy, Elliptic Flow (v_2)

At non central collision



Reaction plane (Ψ)

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



Geometrical anisotropy → 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)

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

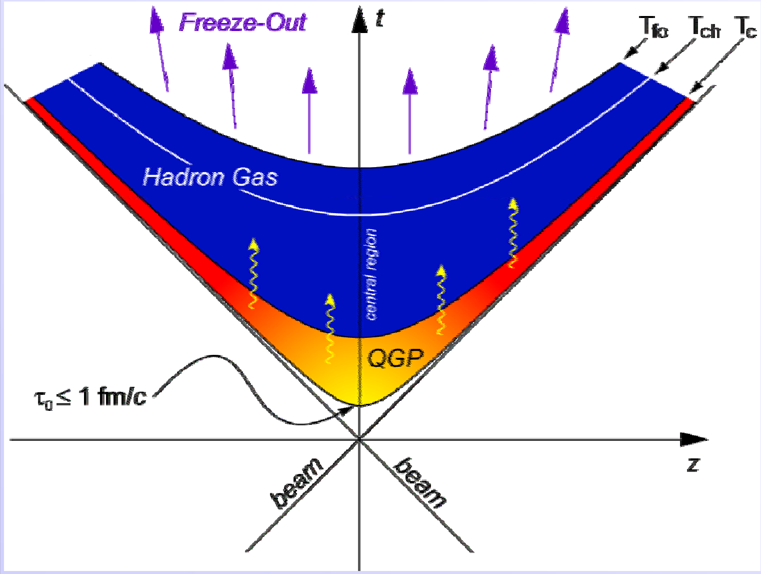
$$v_n = \langle\cos[n(\phi-\Psi)]\rangle$$

v_2 is the coefficient of the second term $\rightarrow$ 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.

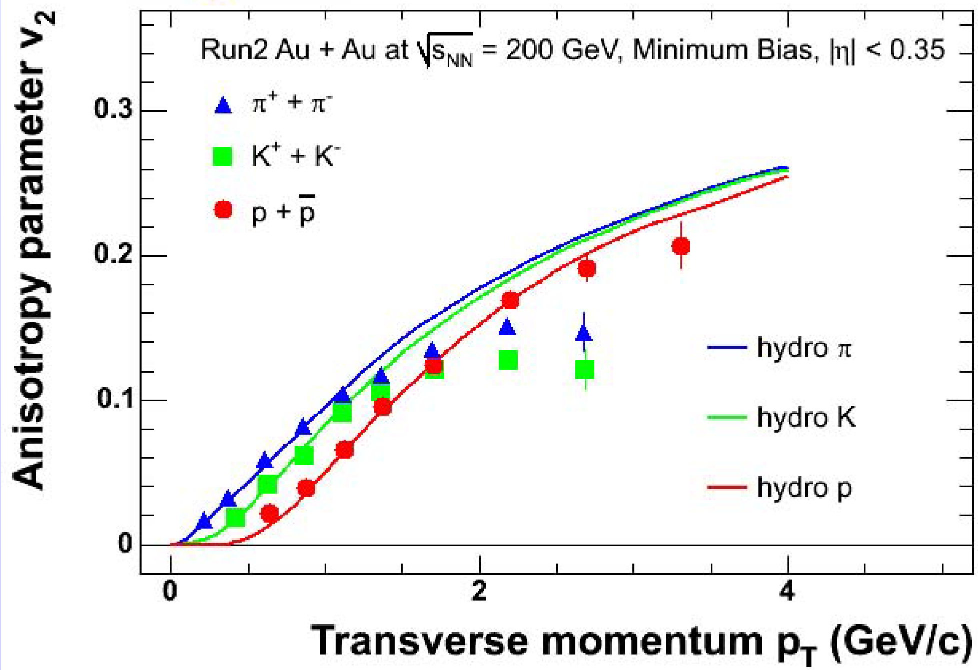
Need a comprehensive understanding from thermalization through hadronization to freeze-out.

Fundamental Findings of v_2 at RHIC

- Hydro-dynamical behavior
- Quark recombination

v_2 explained by hydro model

PRL 91, 182301



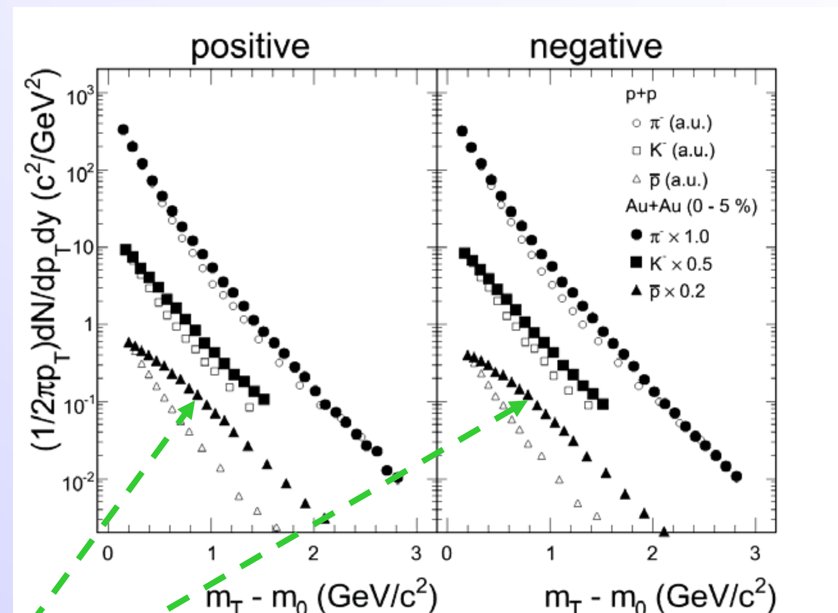
Mass Ordering: **v2(π)>v2(K)>v2(p)**

→Existence of radial flow.

Single particle spectra also indicates radial flow.

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

→ Early thermalization(~0.6 fm/c)

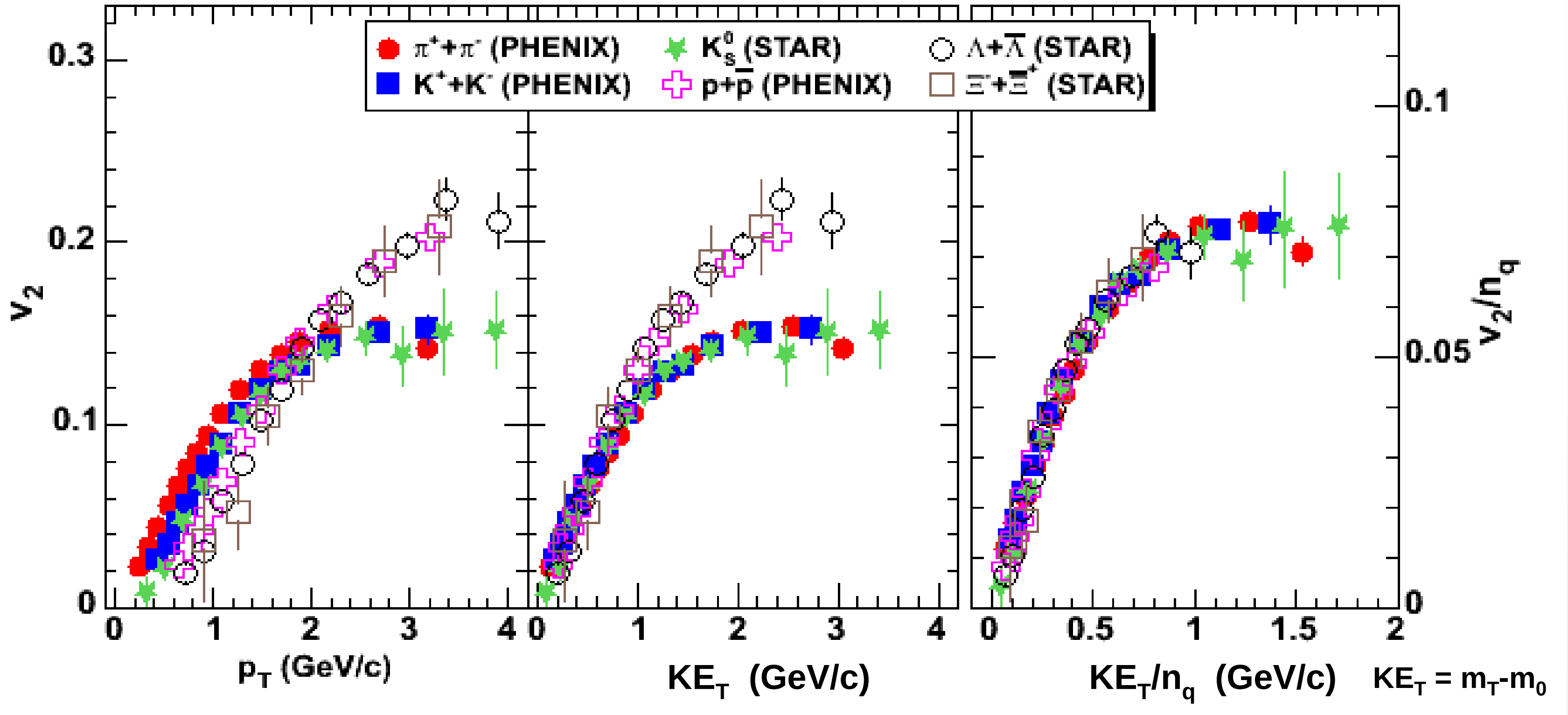


convex shape due to radial flow.

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

Quark recombination (quark number scaling)

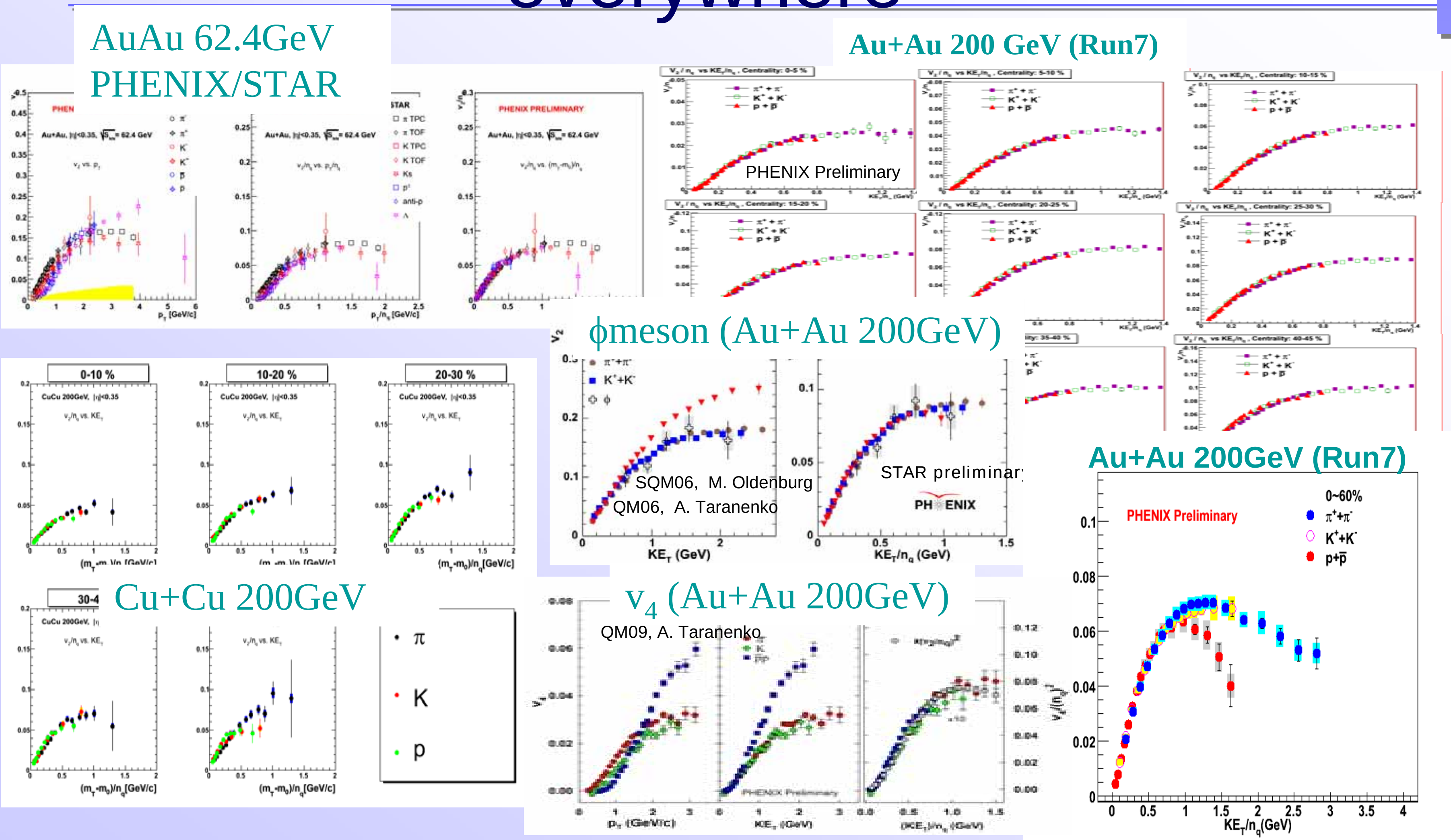
PHENIX **PRL. 98, 162301 (2007)** Au+Au, $\sqrt{s_{NN}}$ = 200GeV



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

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

the quark number scaling everywhere

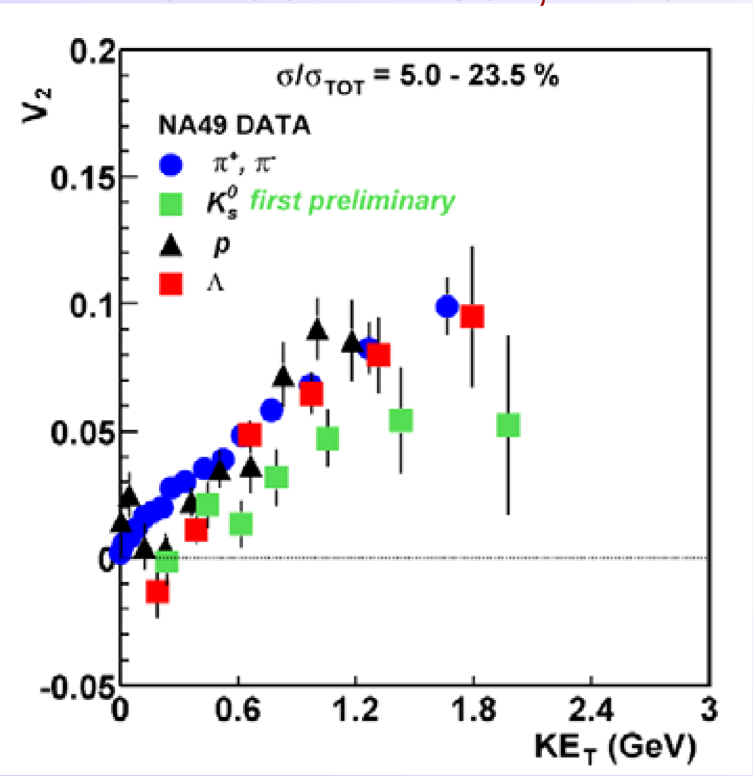


Quark number scaling work out up to K_{ET} ~1GeV/c.

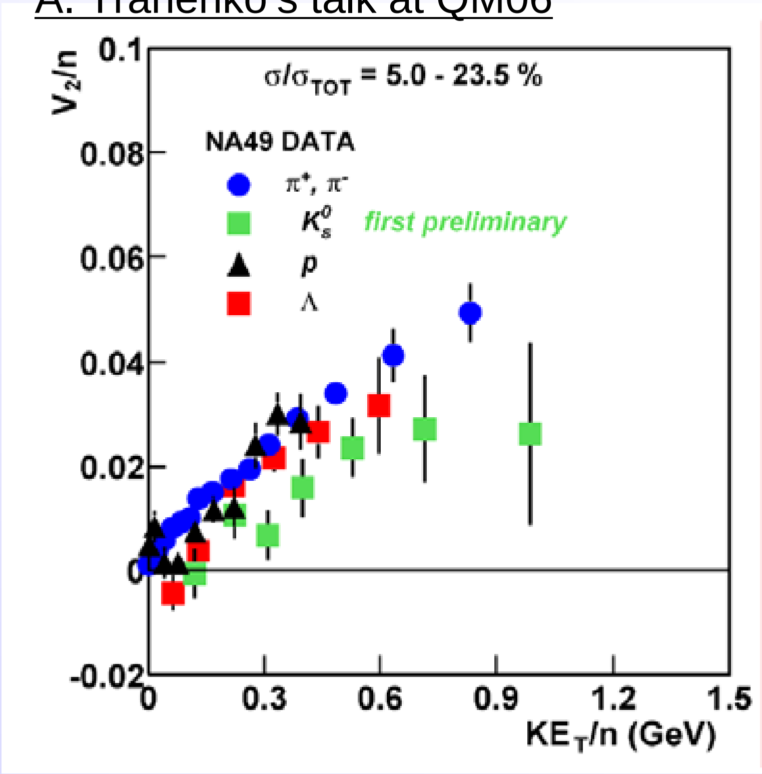
quark number scaling at SPS

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



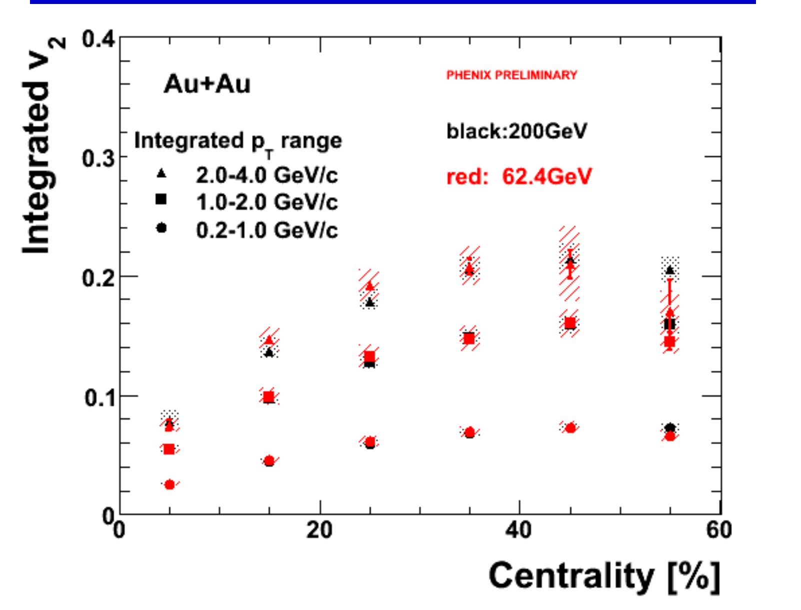
- Quark number + K_{ET} scaling doesn't seem to work out at SPS.
- No flow at quark level due to nonexistence of QGP ?

Systematic study of v_2

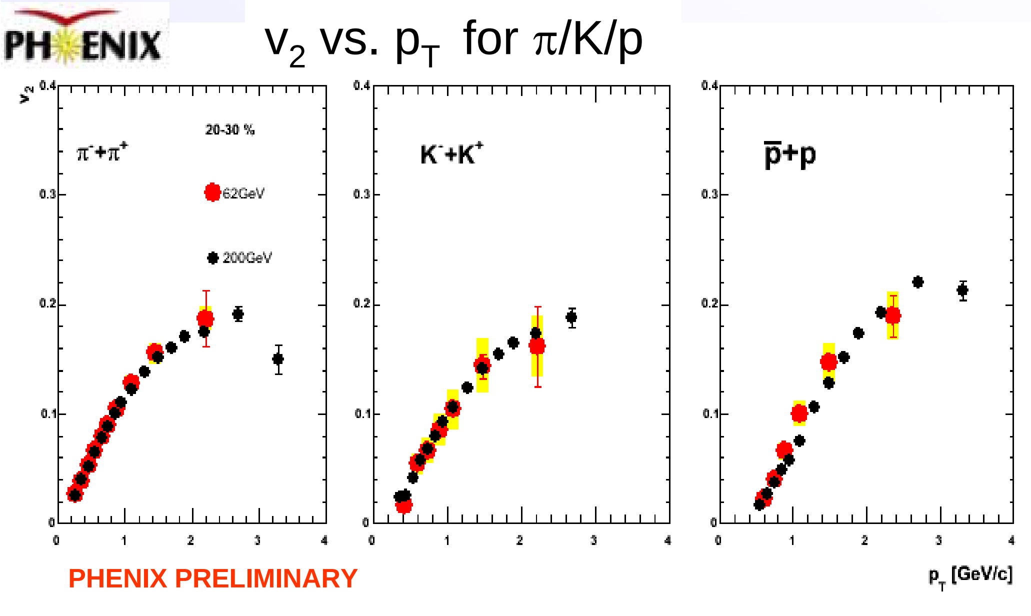
- Energy dependence
- System size dependece
  - –Au+Au vs. Cu+Cu
  - –Centrality dependence

Energy dependence
Au+Au   200 vs. 62 GeV

Centrality dependence



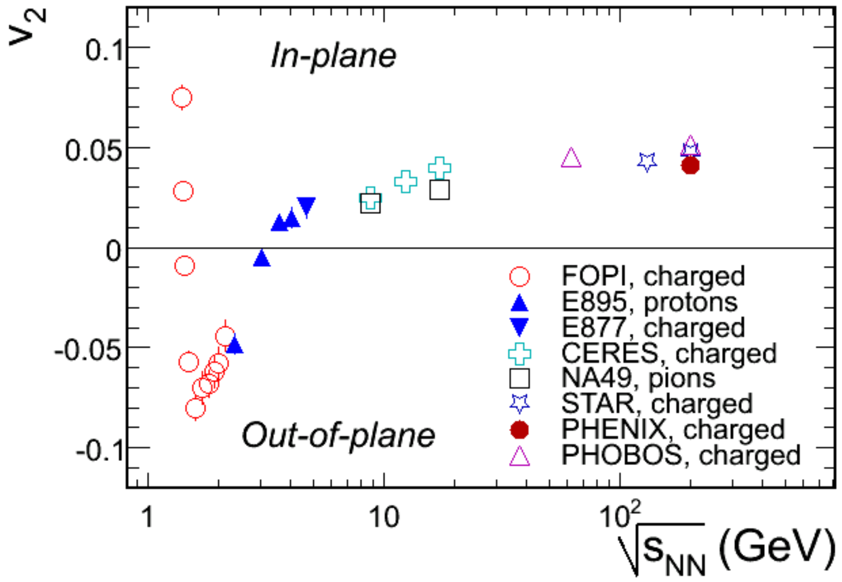
Identified particles



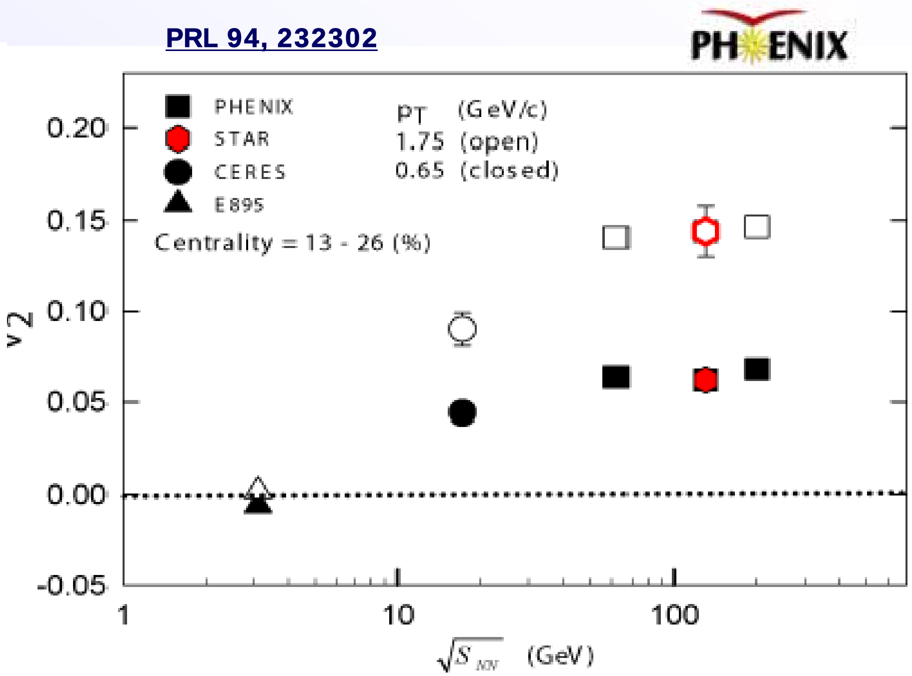
No significant difference between 200 and 62 GeV.

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



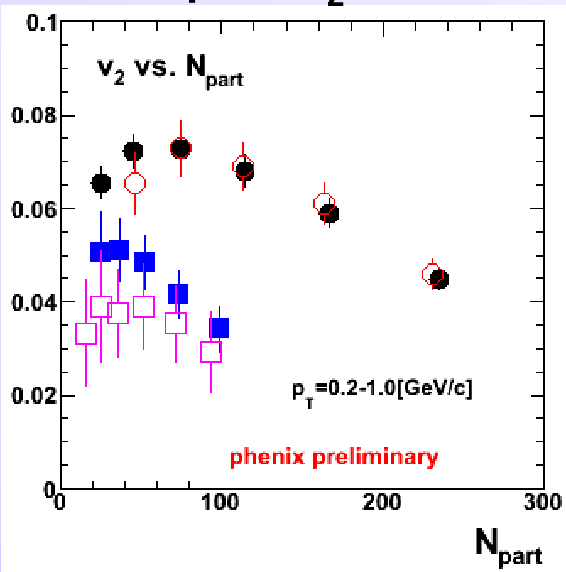
~ 50% increase from SPS to RHIC.

Above 62.4 GeV, v_2 seems to be saturated.

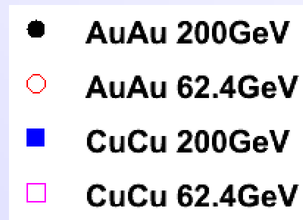
→ The matter reaches thermal equilibrium state at RHIC.

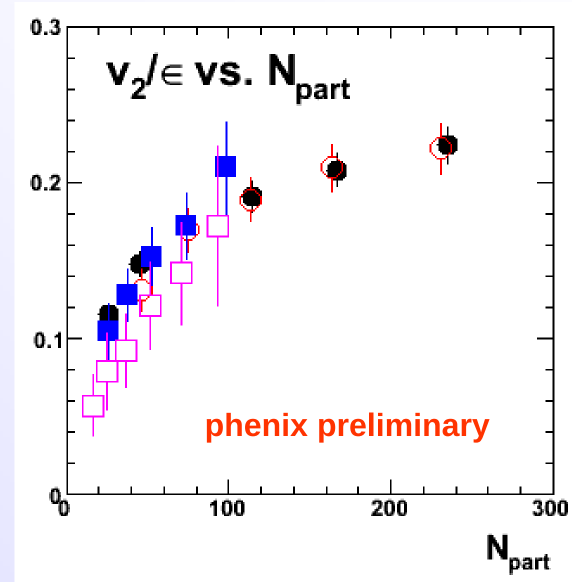
Au+Au vs. Cu+Cu

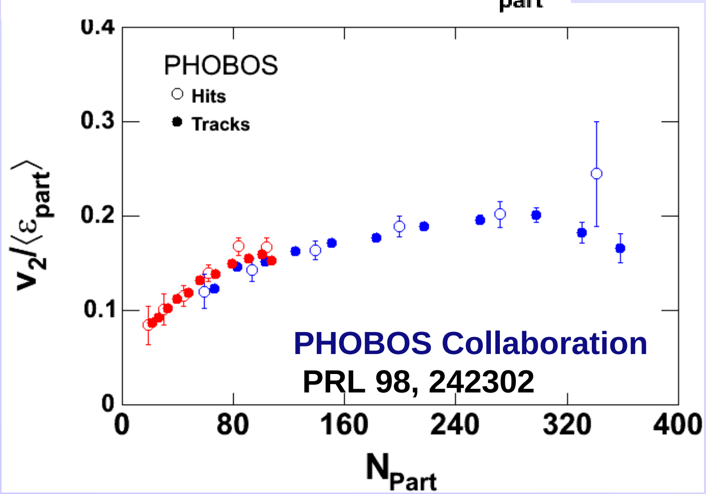
Compare v_2 normalized by eccentricity (ε) in collisions of different size.



0.2<p_T<1.0 [GeV/c]







Eccentricity scaling suggests early thermalization.

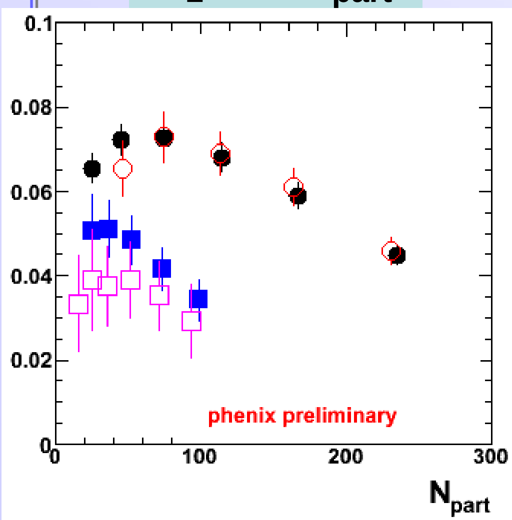
There is a strong N_{part} dependence.

N_{part} Scaling

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

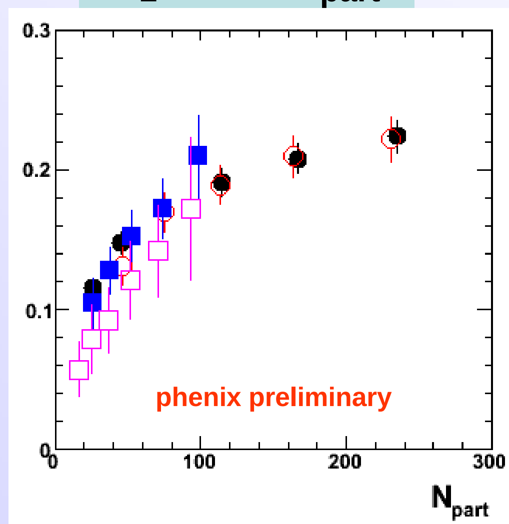
Dividing by $N_{part}^{1/3}$

v_2 vs. N_{part}

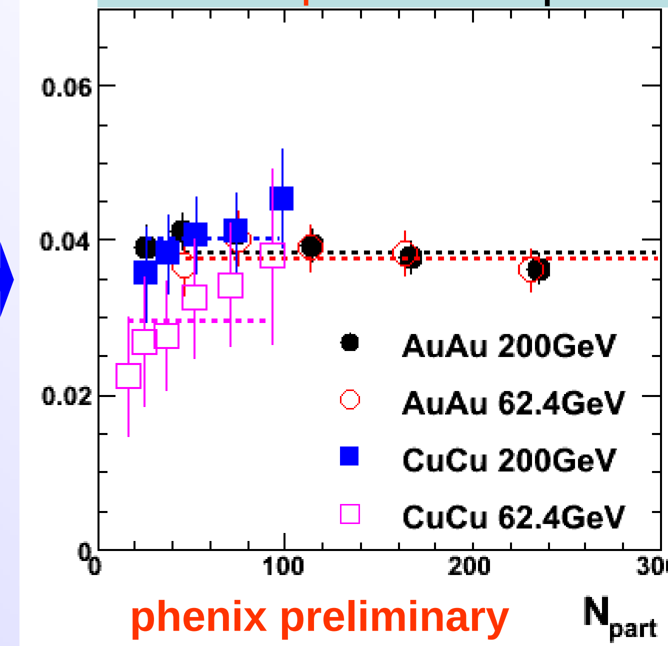


0.2<p_T<1.0 [GeV/c]

v_2/ε vs. N_{part}



$v_2/\varepsilon/N_{part}^{1/3}$ vs. N_{part}

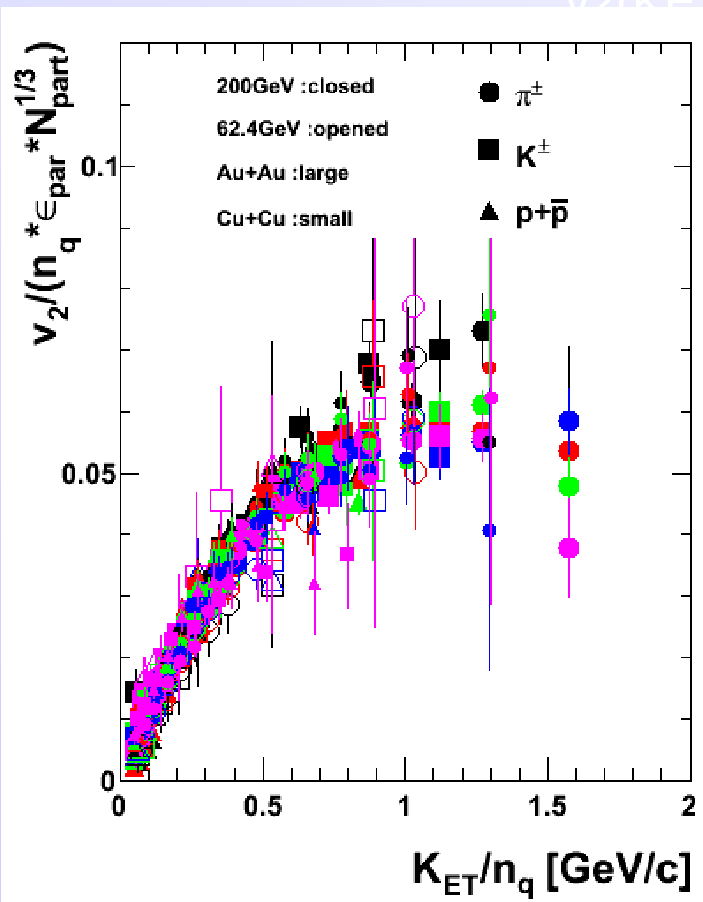


v_2/eccentricity/$N_{part}^{1/3}$ scaling works for all collision systems except small N_{part} at 62 GeV.

- This exception may indicate non-sufficient thermalization region.

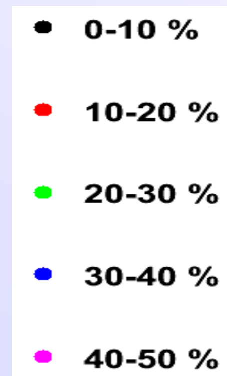
Universal v_2

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.

χ 2/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 of v_2?

Blast Wave Model Fit

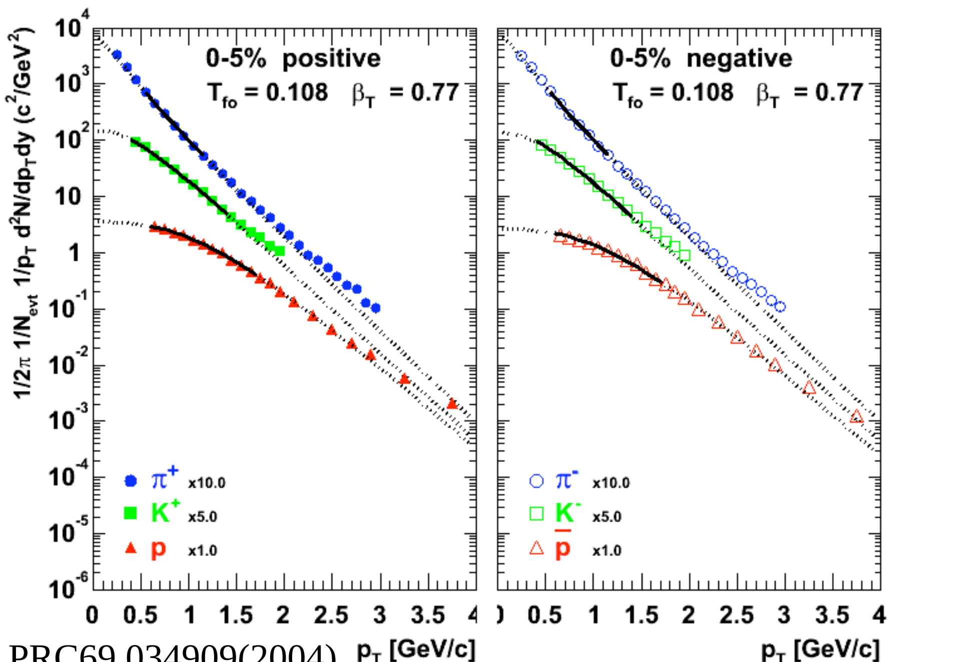
Blast-wave Model Fitting

Blast-wave model (local thermal equilibrium + collective transverse expansion) successfully describes the single particle spectra. * Ref: PRC48(1993)2462

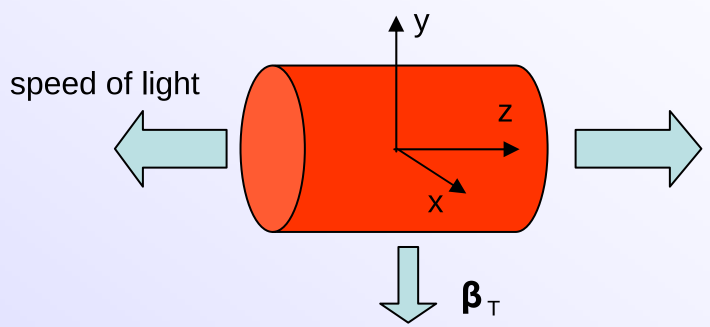
$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right) I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right)$$

$$\rho = \tanh^{-1}\beta_T$$

$$\beta_T = \beta_s\left(\frac{r}{R}\right)$$



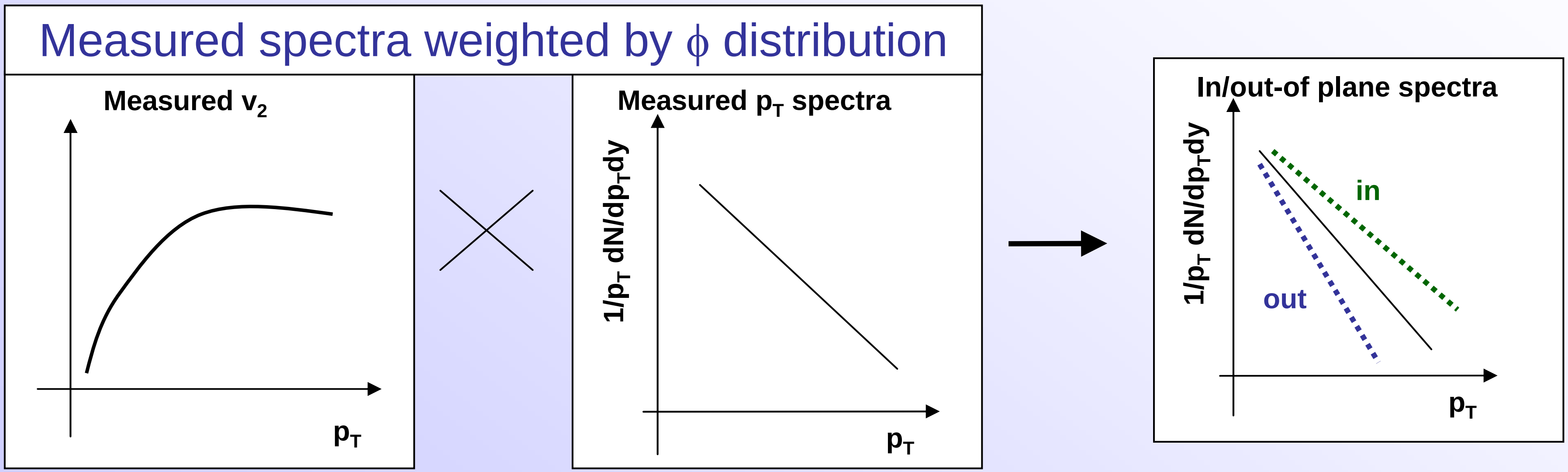
PRC69,034909(2004)



Thermal freeze-out temperature, T_{fo} and transverse velocity, β_T are extracted from this model fitting. (Normalization factor is also a free parameter)

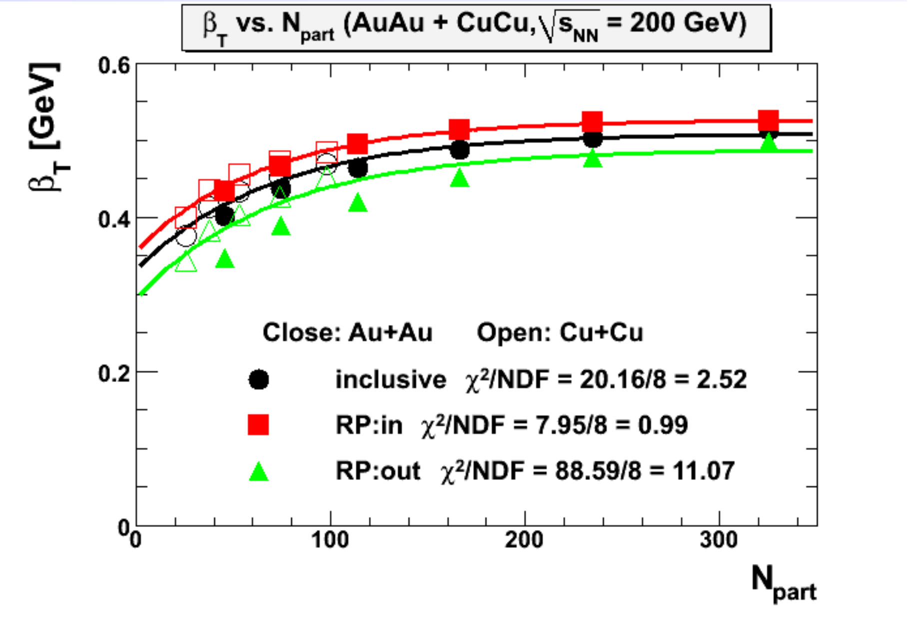
Blast Wave Fitting for v_2 and Spectra

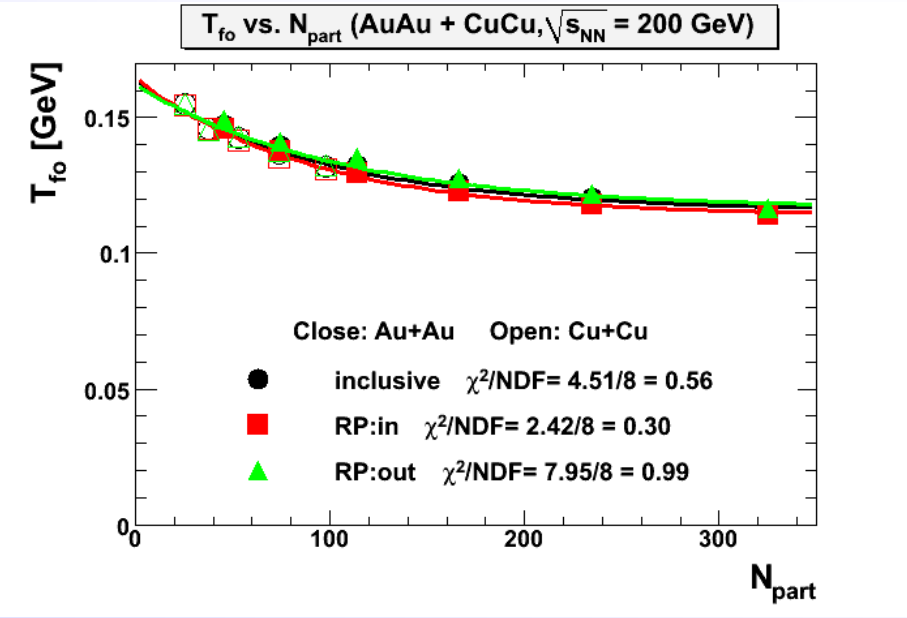
We use this well-known fitting technique to obtain the information of the flow velocity and temperature in and out-of plane **separately**.



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***.

N_{part} Dependence of β_T and T_{fo}





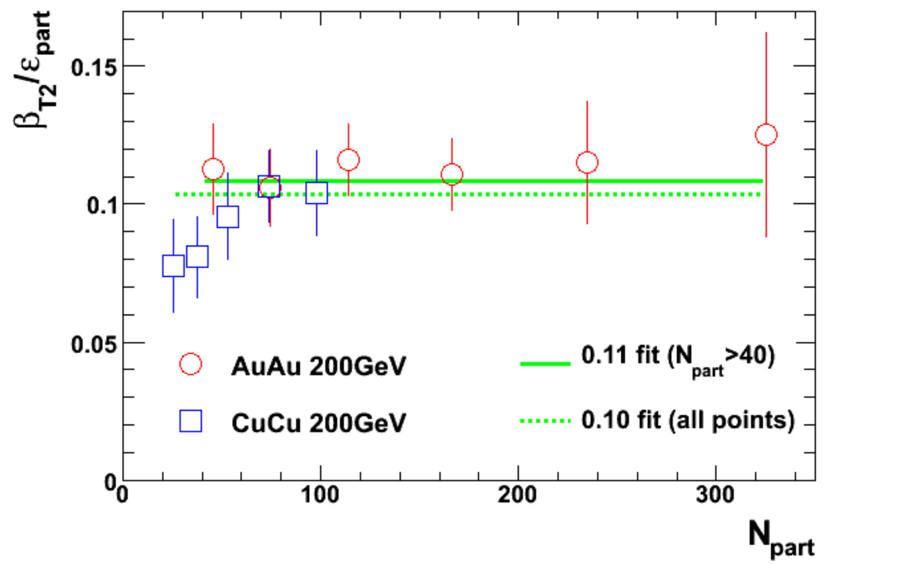
β_T is clearly different between in and out-of plane.
T_{fo} and β_T agree between Au+Au and Cu+Cu, especially for the in-plane.

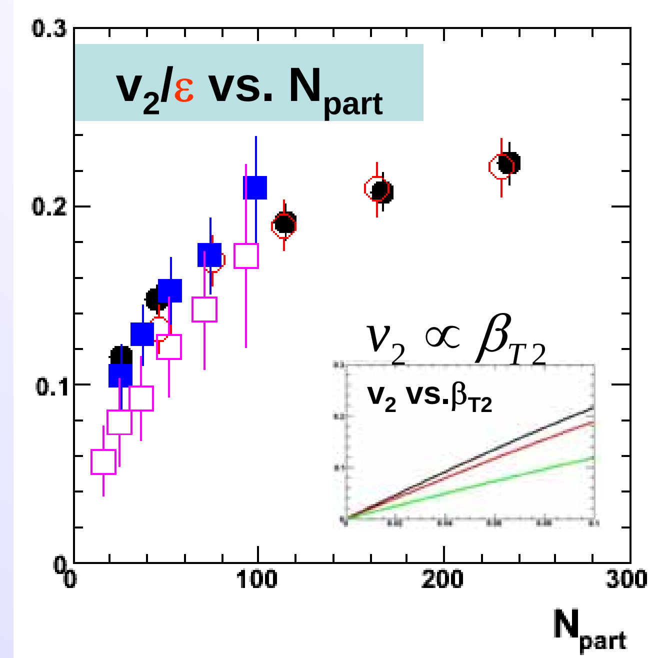
Since v_2 is produced by the difference between in and out-of plane, the modulation of β_T is expected to have important rule to make v_2.

Modulation of radial flow velocity

β_{T2} – Modulation amplitude of the second harmonic of the β_T

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





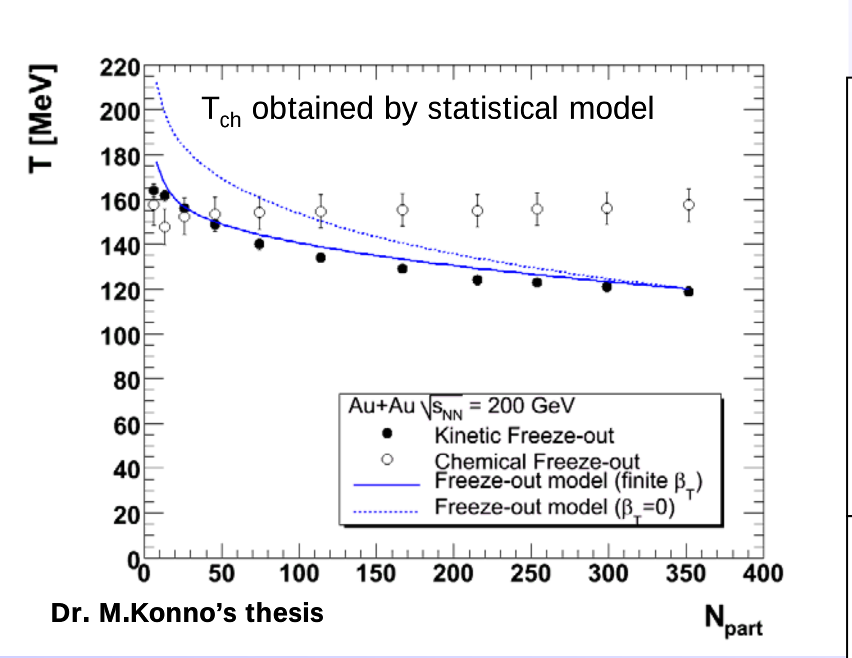
β_{T2} scaled by eccentricity agrees between Au+Au and Cu+Cu .

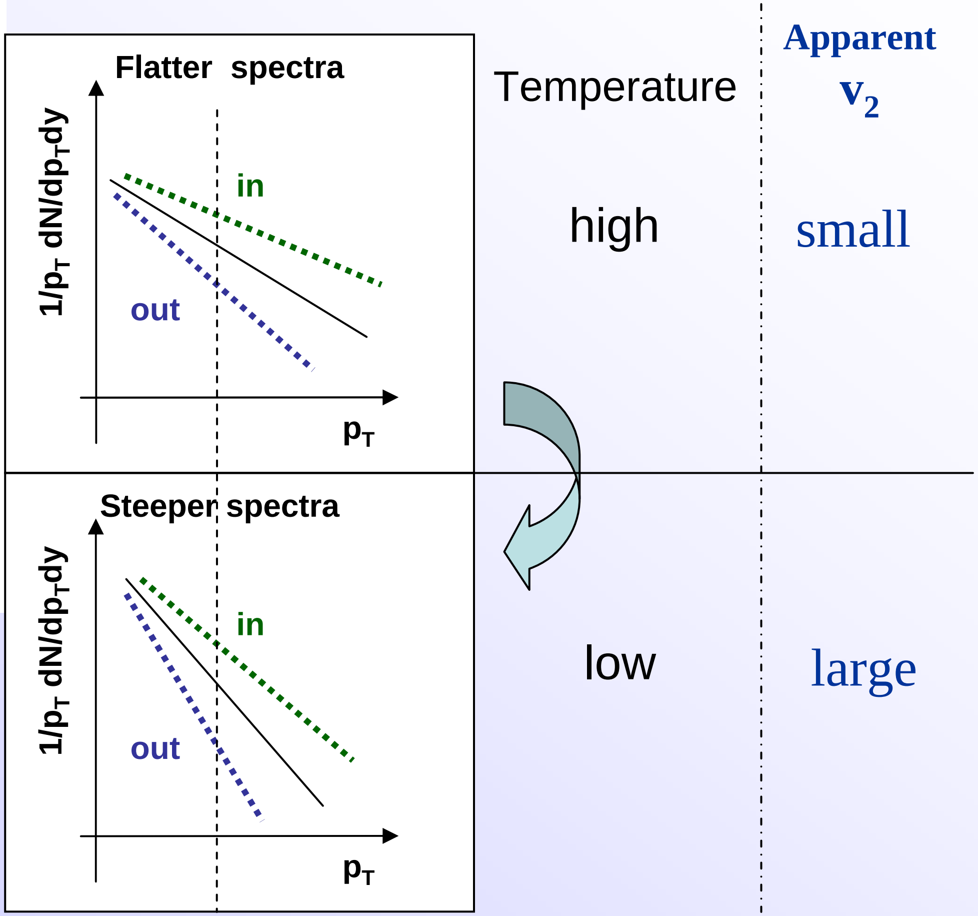
β_{T2}/eccentricity is flat at N_{part} > 40. → ε **drives β_{T2} !** . →Signal of Thermalization !?!?

v_2 is proportional to β_{T2} if other parameters are fixed.

BUT, v_2/ eccentricity is "not" flat → What does course N_{part} dep. of v_2 ??

Freeze-out Temperature and v_2





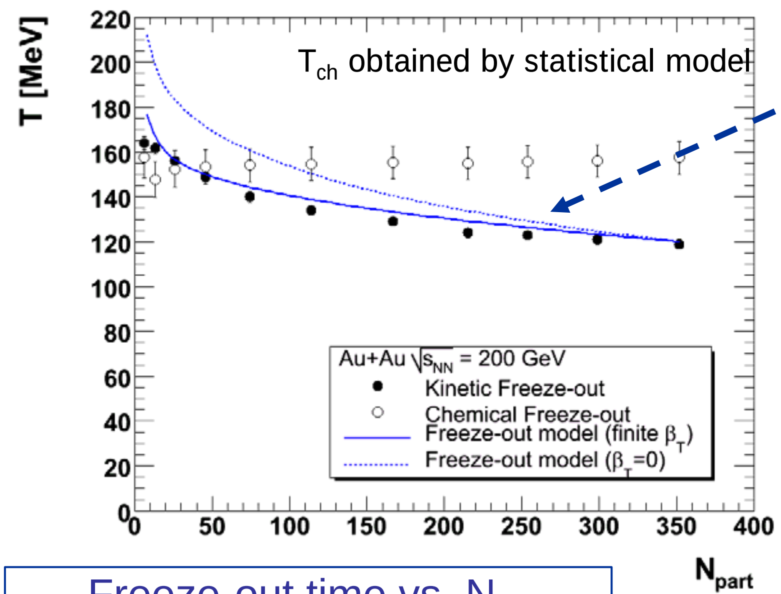
T_{fo} depends on N_{part} (while T_{ch} doesn't) !

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

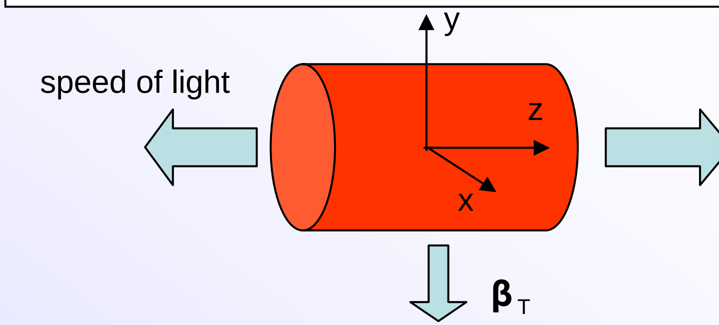
Why does larger system have lower freeze out temperature ?

Freeze-out Temperature and Time

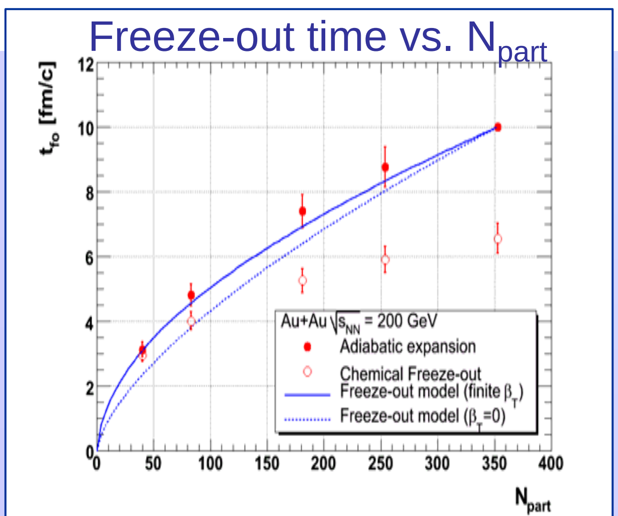
Dr. M.Konno's thesis



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.

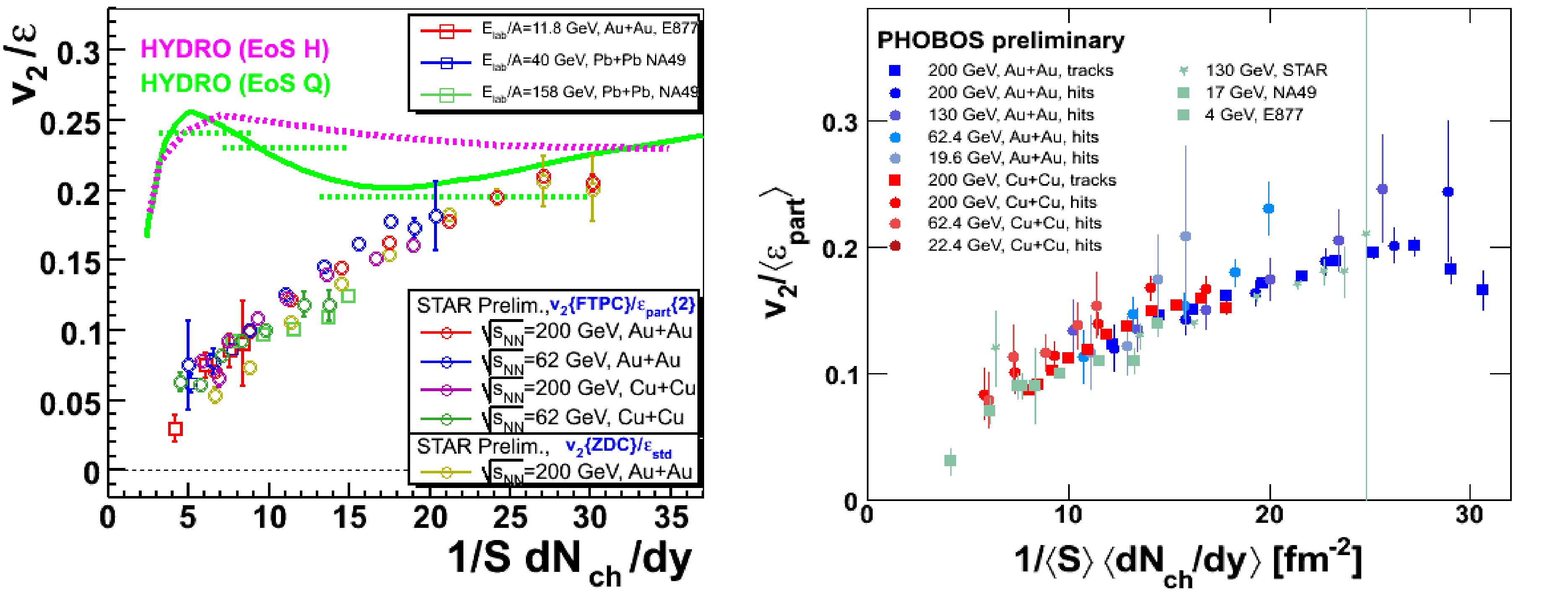
<From Blast-wave fit results with v_2 and spectra together>

- 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 .

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 may have answer for this !