System size, energy and centrality dependence of strange hadron elliptic flow at STAR

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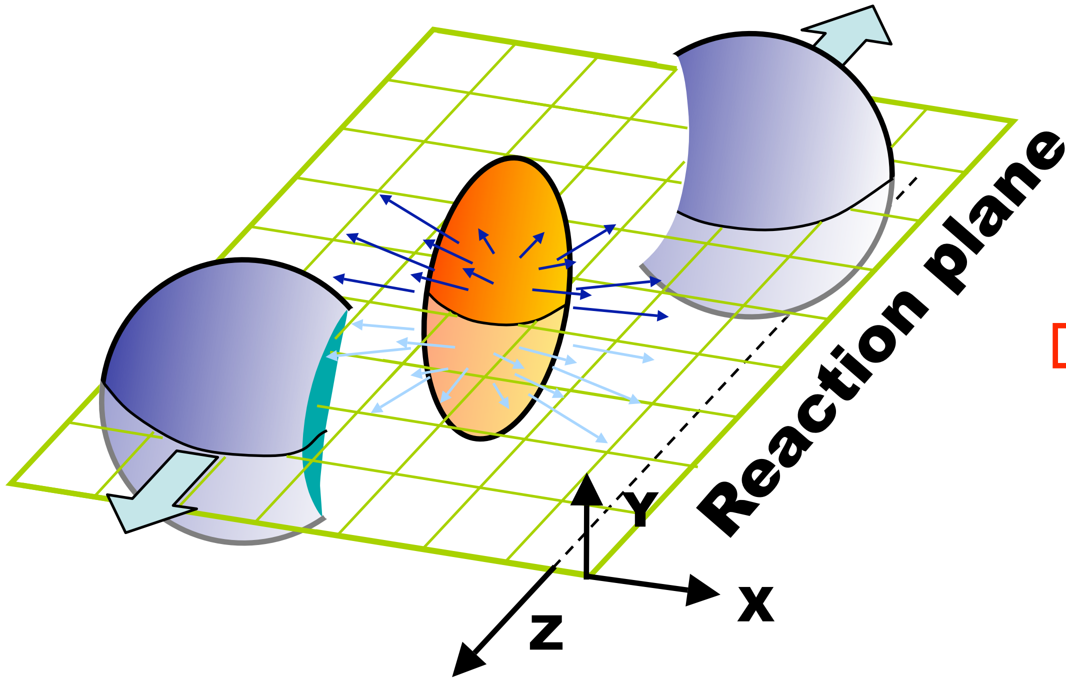
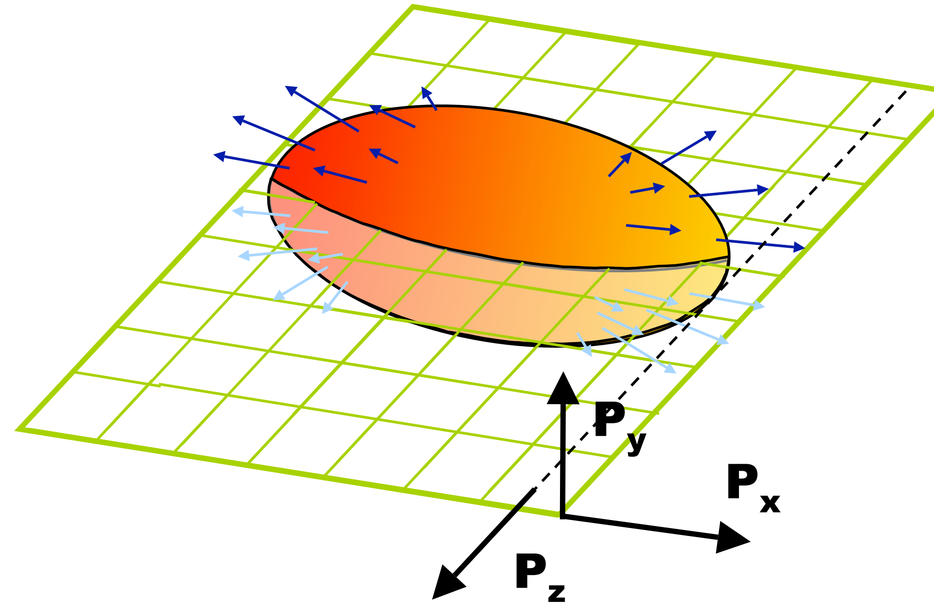
Outline

- Introduction and motivation
- STAR experiment
- Results
  - ✓ Partonic collectivity
    - Differential v_2 measurement, $v_2(p_T)$ and $v_2(m_T$ - mass) in Cu + Cu collisions at 200 GeV
  - ✓ Does RHIC v_2 reach ideal hydrodynamical limit ?
    - Centrality dependence of $\langle v_2 \rangle$ in Au + Au & Cu + Cu collisions at 200 GeV
- Summary

Elliptic flow (v_2); early probe





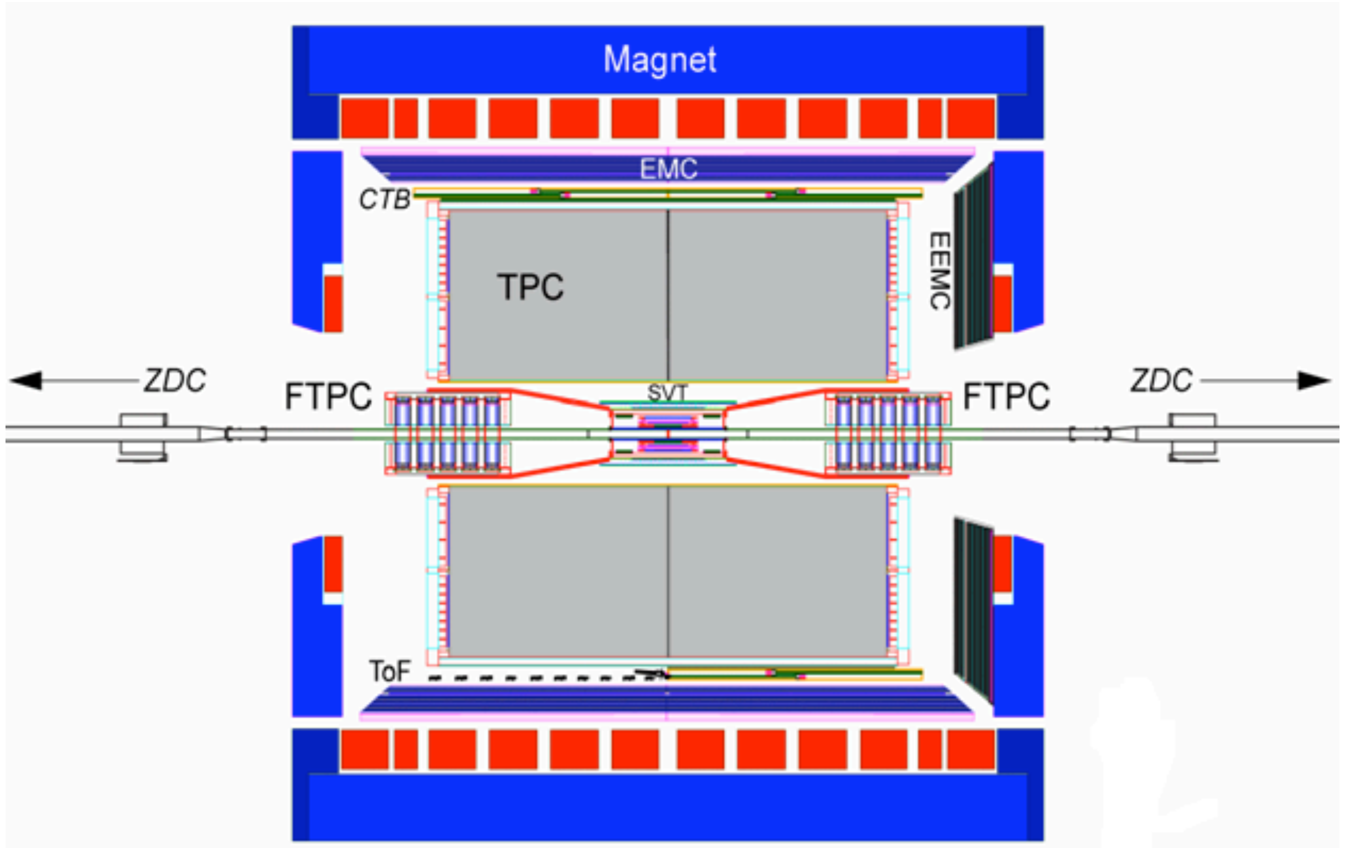
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

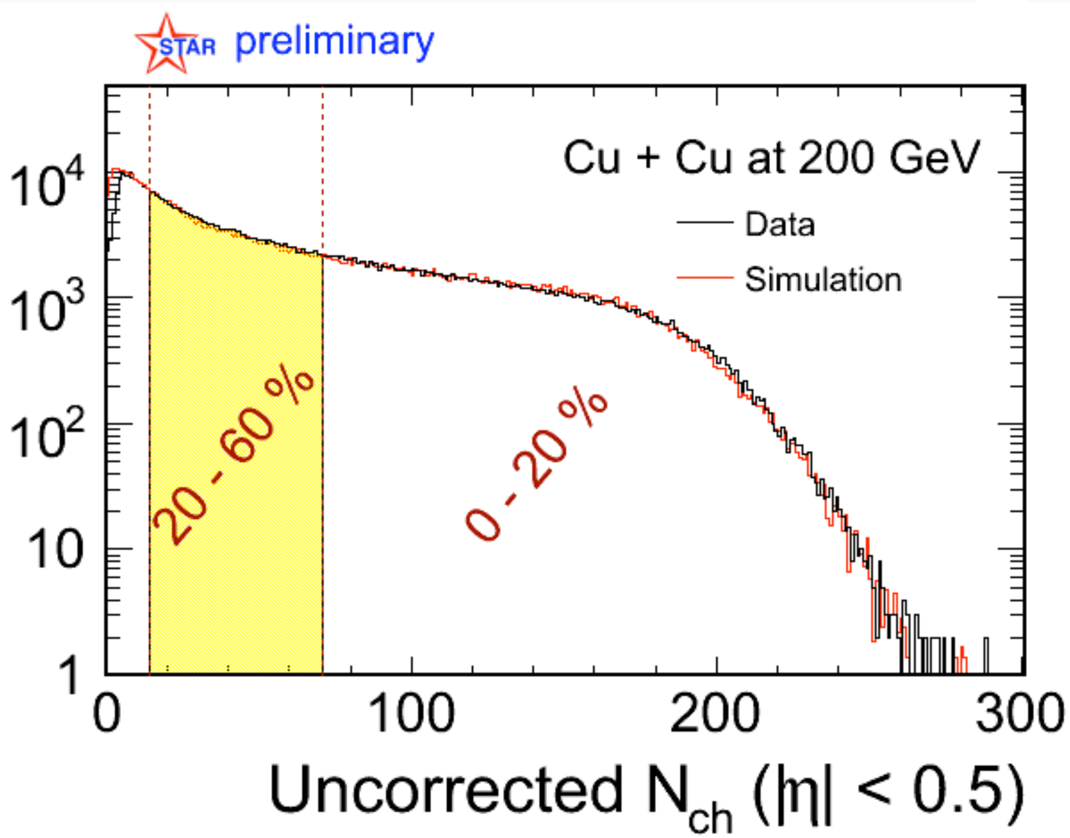
$$v_2 = \langle \cos(2\phi') \rangle$$

ϕ' : azimuthal angle of particles with respect to the reaction plane

- Elliptic flow (v_2); Second harmonic coefficient of Fourier expansion
- Sensitive to early "partonic "stage of heavy ion collisions
  - ✓ Initial spatial anisotropy (ε) → final momentum anisotropy (v_2)
  - ✓ Sensitive to bulk properties; speed of sound, shear viscosity

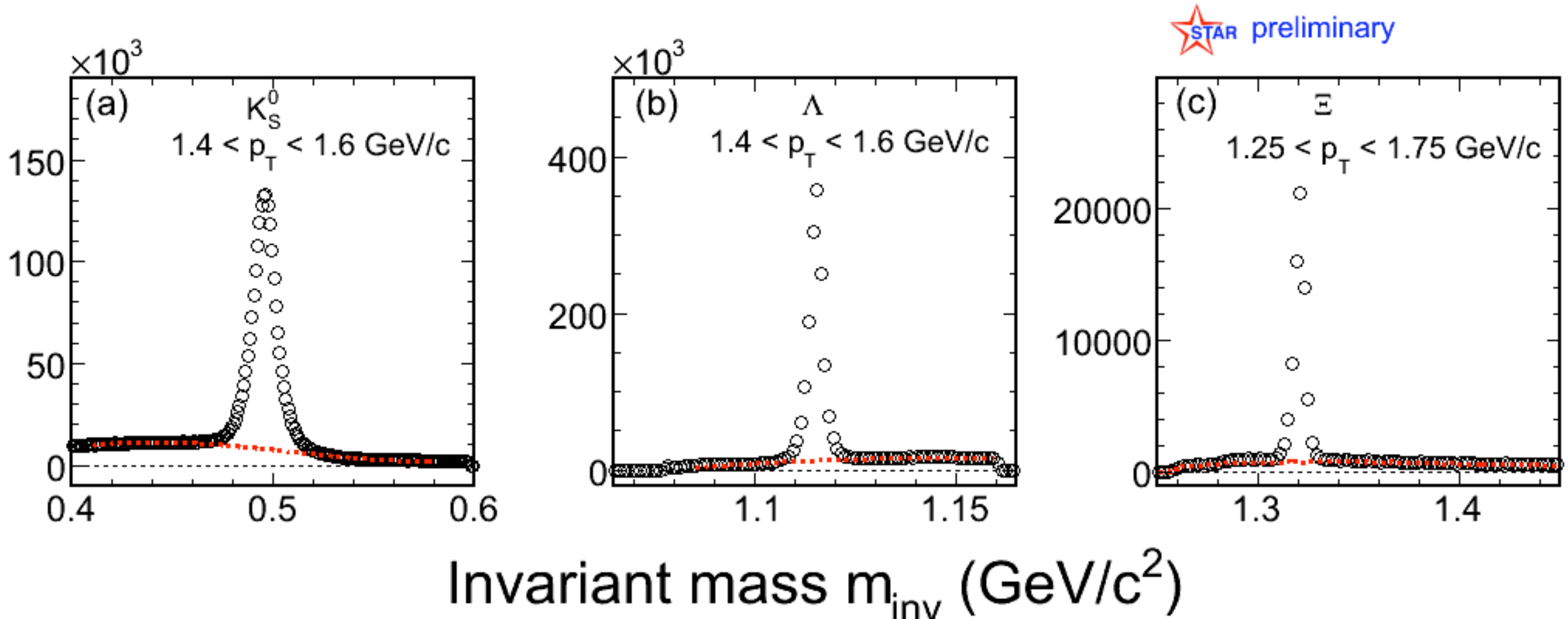
STAR experiment





- **Large acceptance**
  - ✓ Main TPC; $|\eta| < 1$, full azimuth
  - ✓ K^0_S, Λ, Ξ; $0.2 < p_T < 4$ GeV/c
- **Cu + Cu at 200 GeV**
  - ✓ ~ 24 M events
- **Centrality; 0 - 60 %**
  - ✓ 0 - 20 and 20 - 60 %
- **Event plane**
  - ✓ Forward TPC, $2.5 < |\eta| < 4$
    - Rapidity gap could reduce “non-flow” effects, which are correlations not originated from the reaction plane

Particle identification

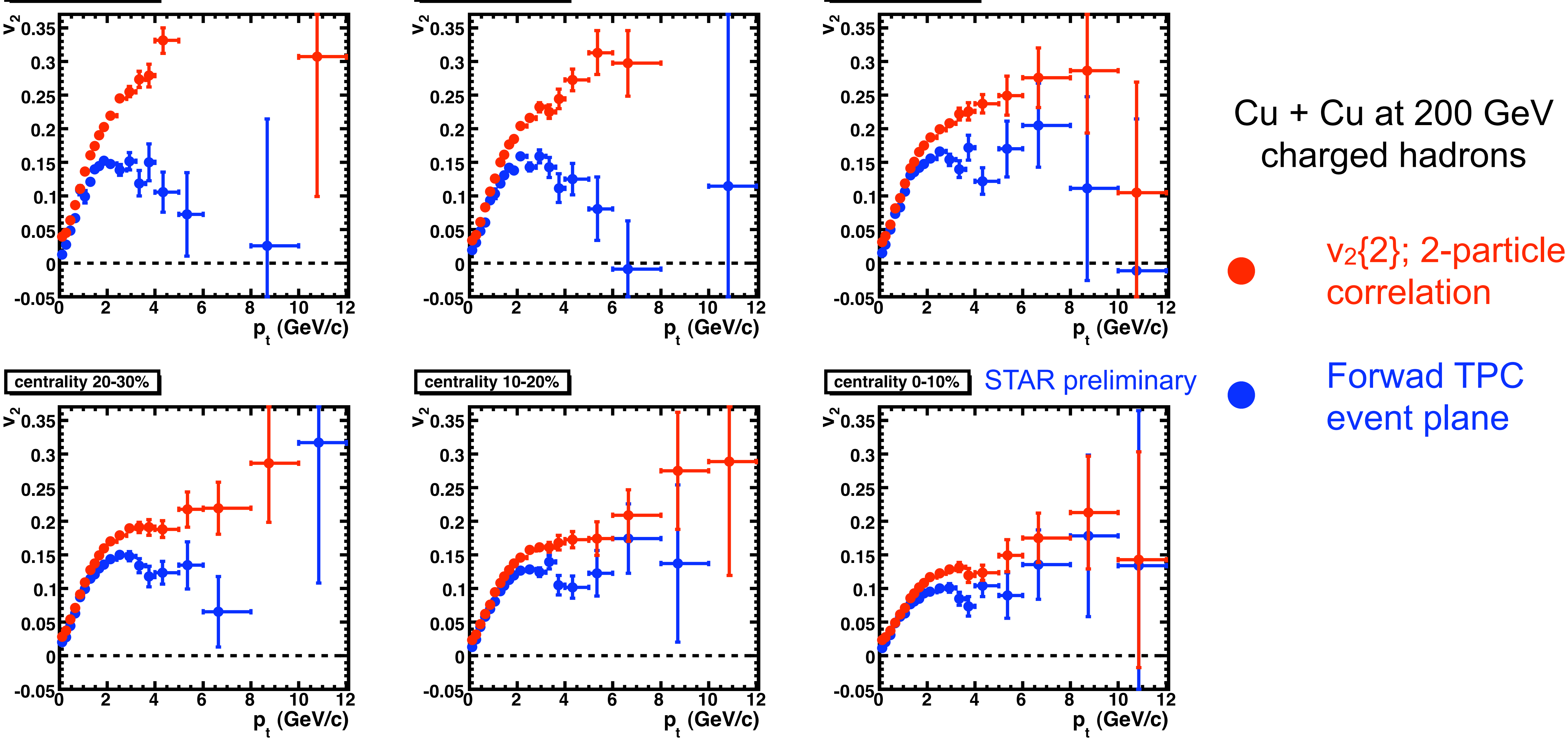


$$K_S^0 \rightarrow \pi^+ + \pi^- \qquad \Lambda \rightarrow p + \pi^- \qquad \Xi \rightarrow \Lambda + \pi^-$$

- Reconstructed by weak decay topology
  - ✓ Daughter hadrons are identified by dE/dx in TPC
- Signal to background ratio ~ 3 - 20

Forward TPC event plane

S. Voloshin, QM2006

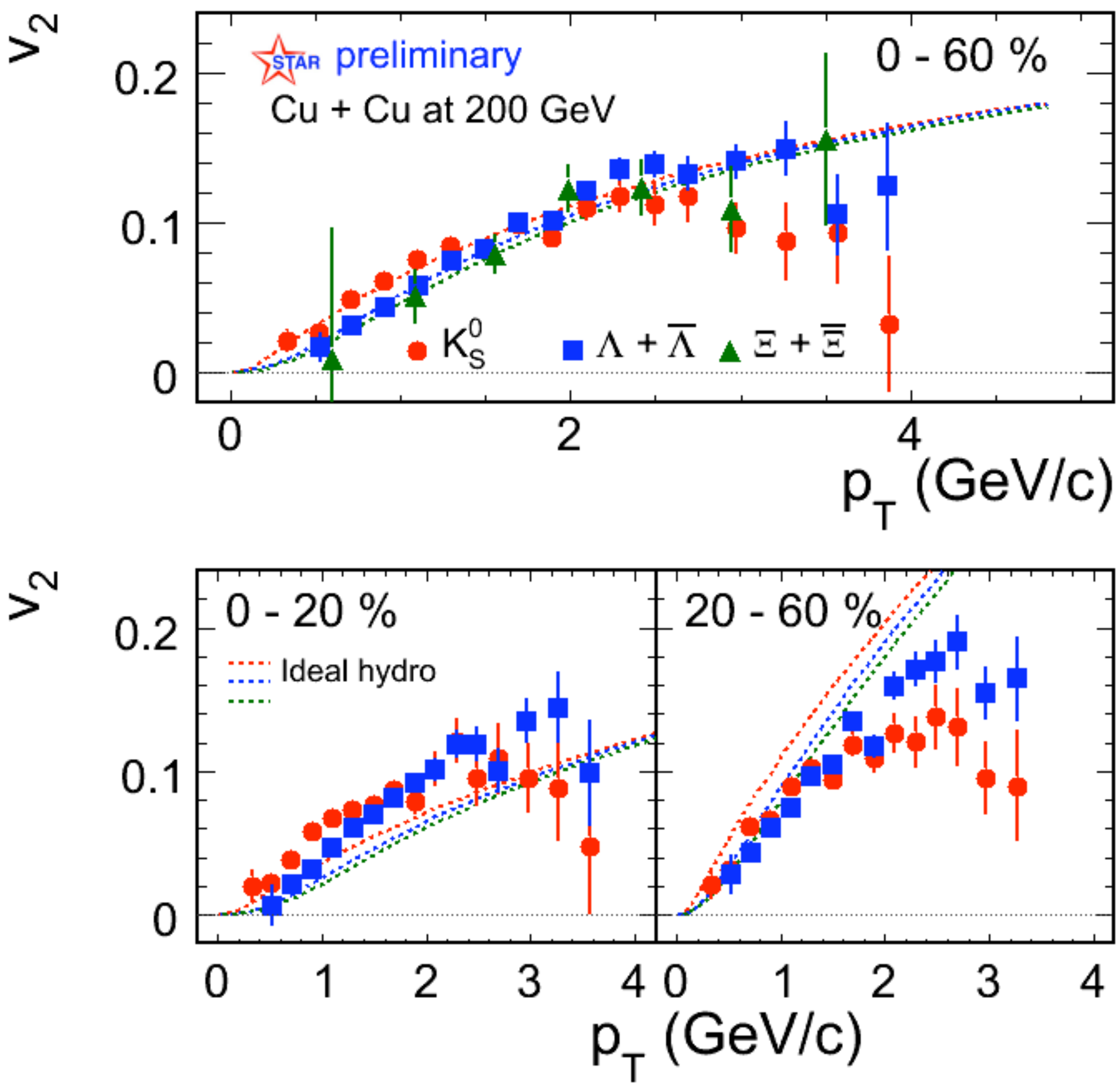


- Non-flow effects can be reduced by Forward TPC (FTPC) event plane

➡ Measure v_2 with respect to the FTPC event plane !

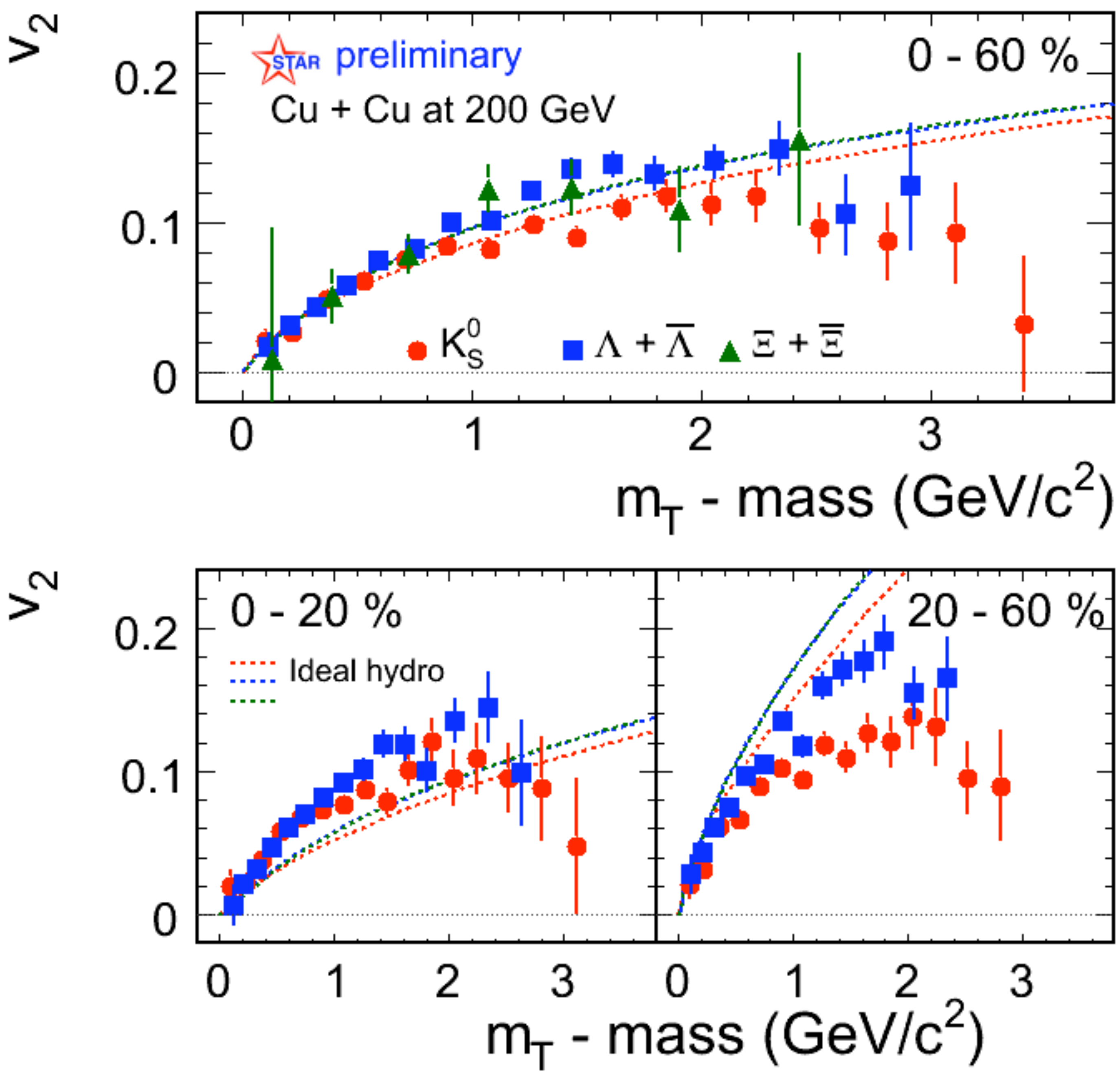
$v_2(p_T)$: K^0_S, Λ , Ξ

Ideal hydro from Pasi Huovinen, private communication;
T_c = 170 MeV, T_f = 125 MeV, first order phase transition, EOS Q



- Smaller v_2 for heavier hadrons in p_T < 2 GeV/c
- p_T > 2 GeV/c
  - ✓ $v_2(\Lambda) > v_2(K^0_S)$
  - ✓ Sizable $v_2(\Xi)$
- Ideal hydro fails to reproduce centrality dependence of $v_2(p_T)$
  - ✓ Fluctuation of eccentricity ?
  - ✓ Finite viscosity ?
  - ✓ Incomplete thermalization ?

v_2 vs m_T - mass

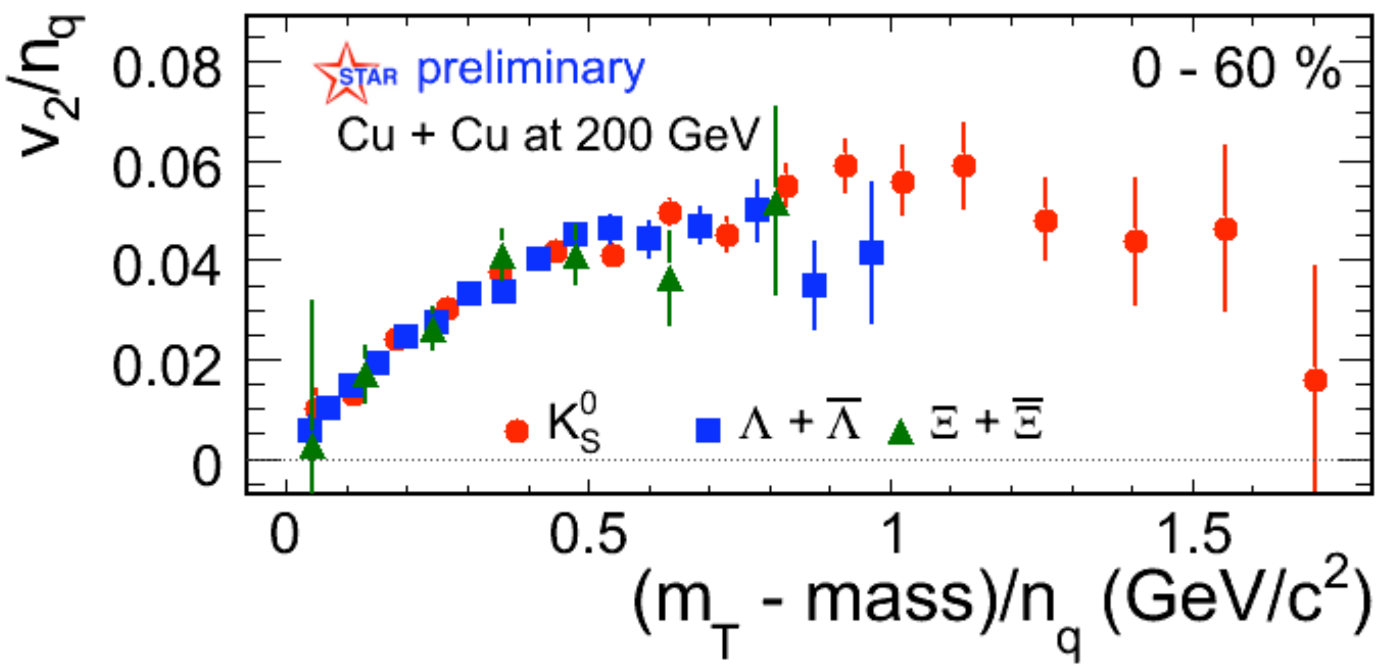


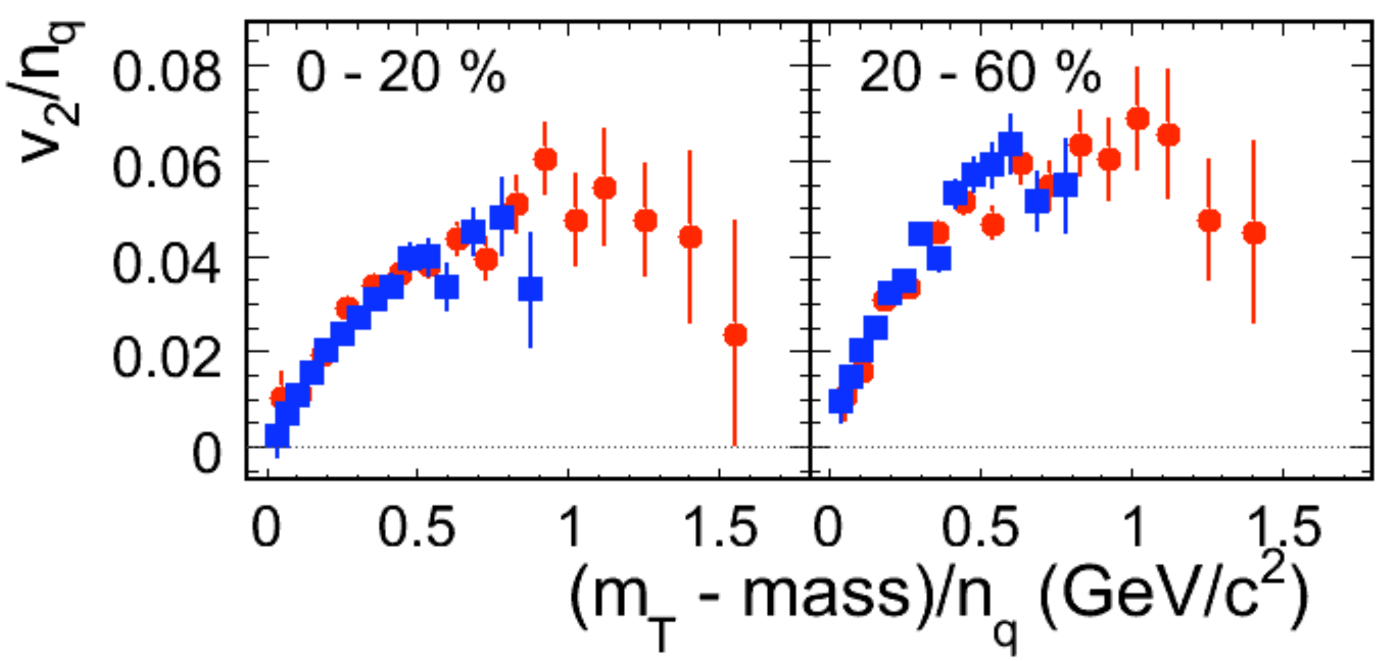
- m_T - mass < 1 GeV/c^2
  - ✓ v_2 seems to scale by m_T - mass
  - ✓ Ideal hydro calculation does not show m_T - mass scaling
- m_T - mass > 1 GeV/c^2
  - ✓ Clear baryon & meson effect for higher p_T

➡ Partonic flow ?

➡ Test Number of Quark (NQ) scaling of v_2

Number of Quark scaling of v_2





$$\frac{v_2^h(p_T)}{n_q} \approx v_2^q(p_T/n_q)$$

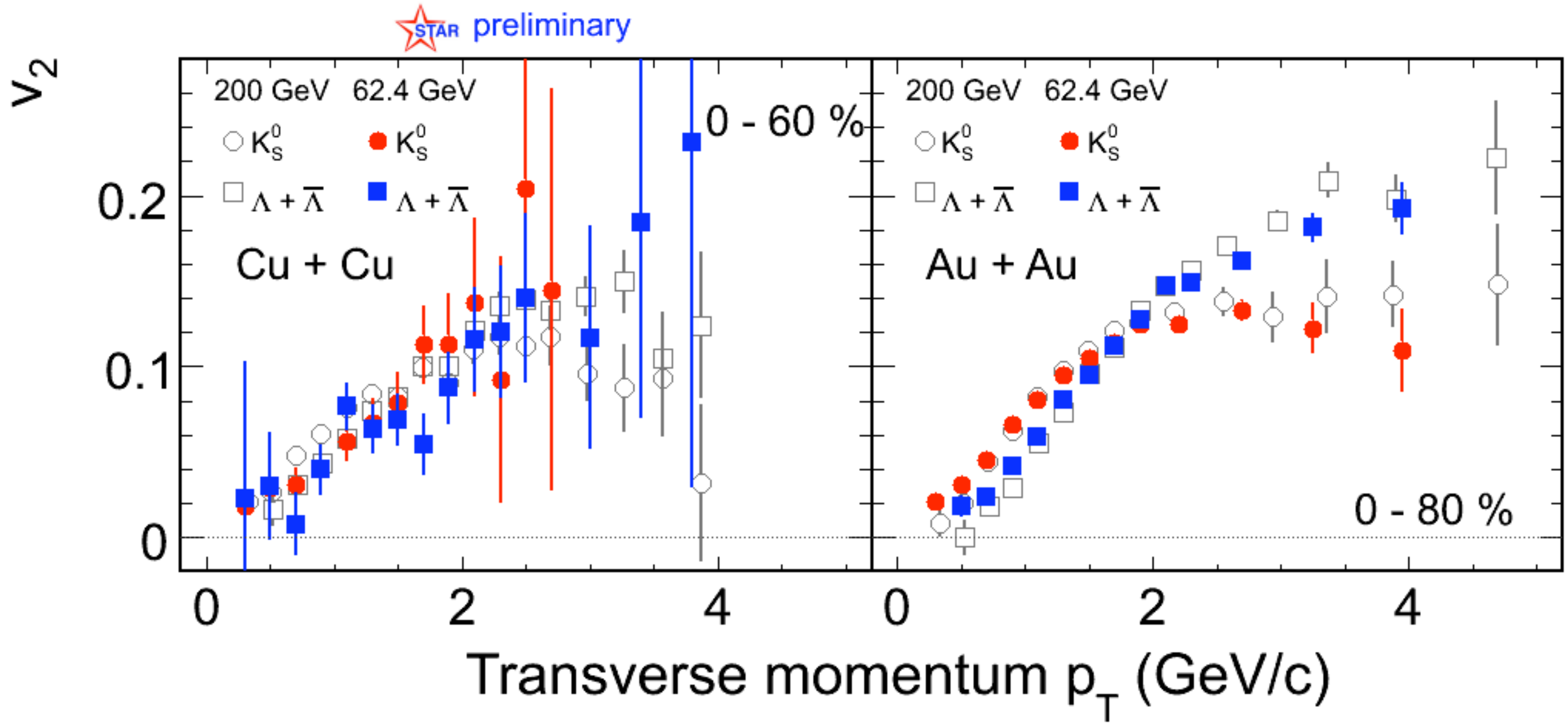
$$n_q = 2, 3$$

- NQ scaling of v_2
  - ✓ works well for measured strange hadrons in all centrality bins
  - ✓ from low to intermediate m_T - mass

➡ Partonic flow !

D. Molnar and S. Voloshin, PR**L91**, 092301 (2003)
R. J. Fries et. al., PR**C68**, 044902 (2003)
V. Greco et. al, PR**C68**, 034904 (2003)
J. Jia and C. Zhang, PR**C75**, 031901(R) (2007)
....

Cu + Cu 200 GeV vs 62.4 GeV

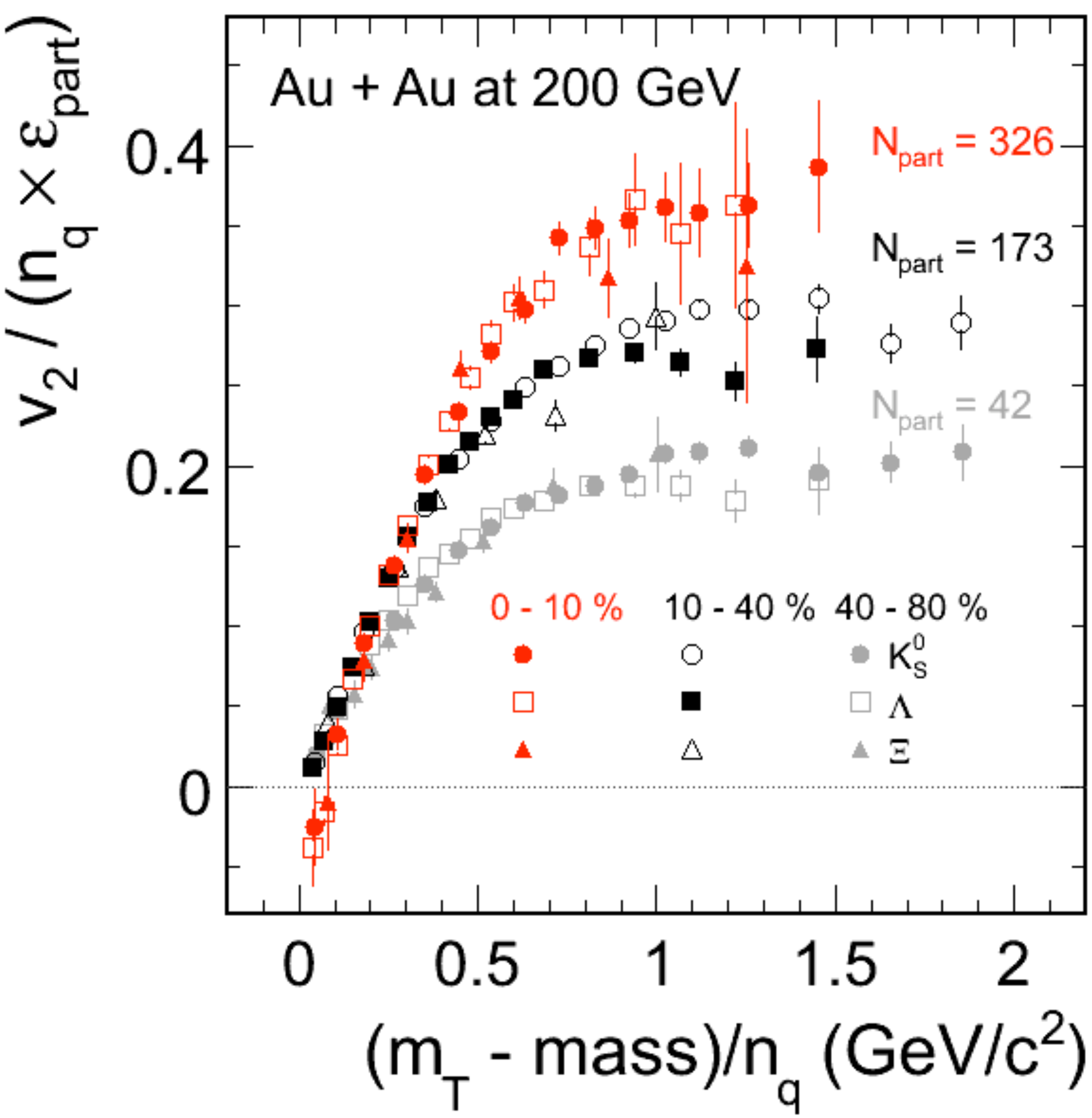


- v_2 in Cu + Cu at 200 and 62.4 GeV are consistent within statistical errors

STAR Au + Au 200 GeV : PR**C77**, 054901 (2008)
Au + Au 62.4 GeV : PR**C75**, 054906 (2007)

v_2 at Cu + Cu 62.4 GeV ~ 12.5 M events
- Same procedure used for 200 GeV. - Event plane resolution is 0.088 ± 0.004 in 0 - 60 %, about a factor of 2 smaller than that in 200 GeV due to lower multiplicity.

System size dependence



Au + Au : STAR PRC**77**, 054901 (2008)
Event plane is determined at the Main TPC

$$\varepsilon_{part} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$

$$\sigma_x^2 = \{x^2\} - \{x\}^2, \quad \sigma_y^2 = \{y^2\} - \{y\}^2,$$

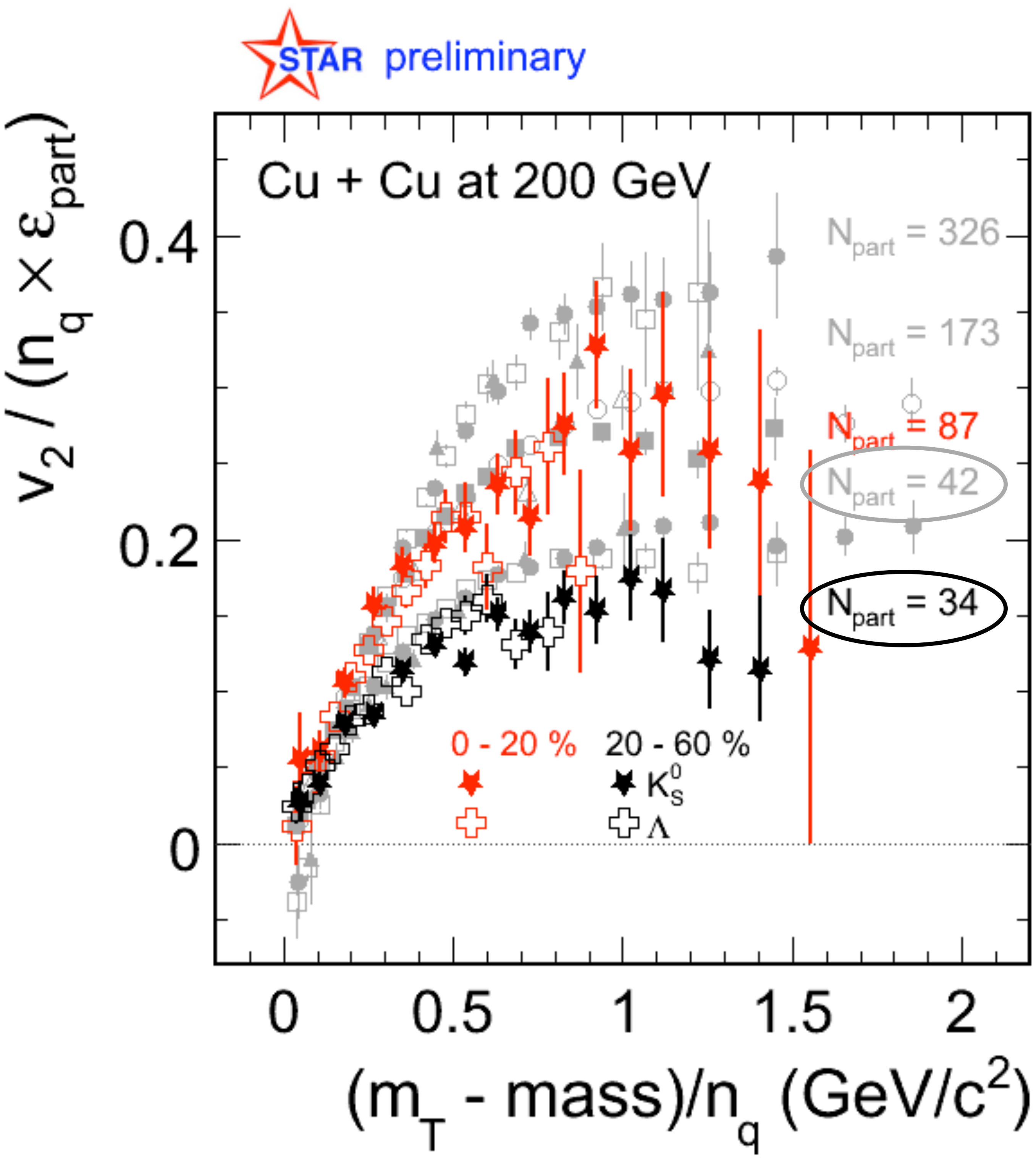
$$\sigma_{xy} = \{xy\} - \{x\}\{y\}$$

- FTPC & TPC event plane
  - ✓ sensitive to participant eccentricity
- Stronger collective flow in more central collisions

➡ **$v_2 \propto f(\varepsilon, N_{part})$**

➡ Does v_2 reach ideal hydrodynamical limit ?

System size dependence



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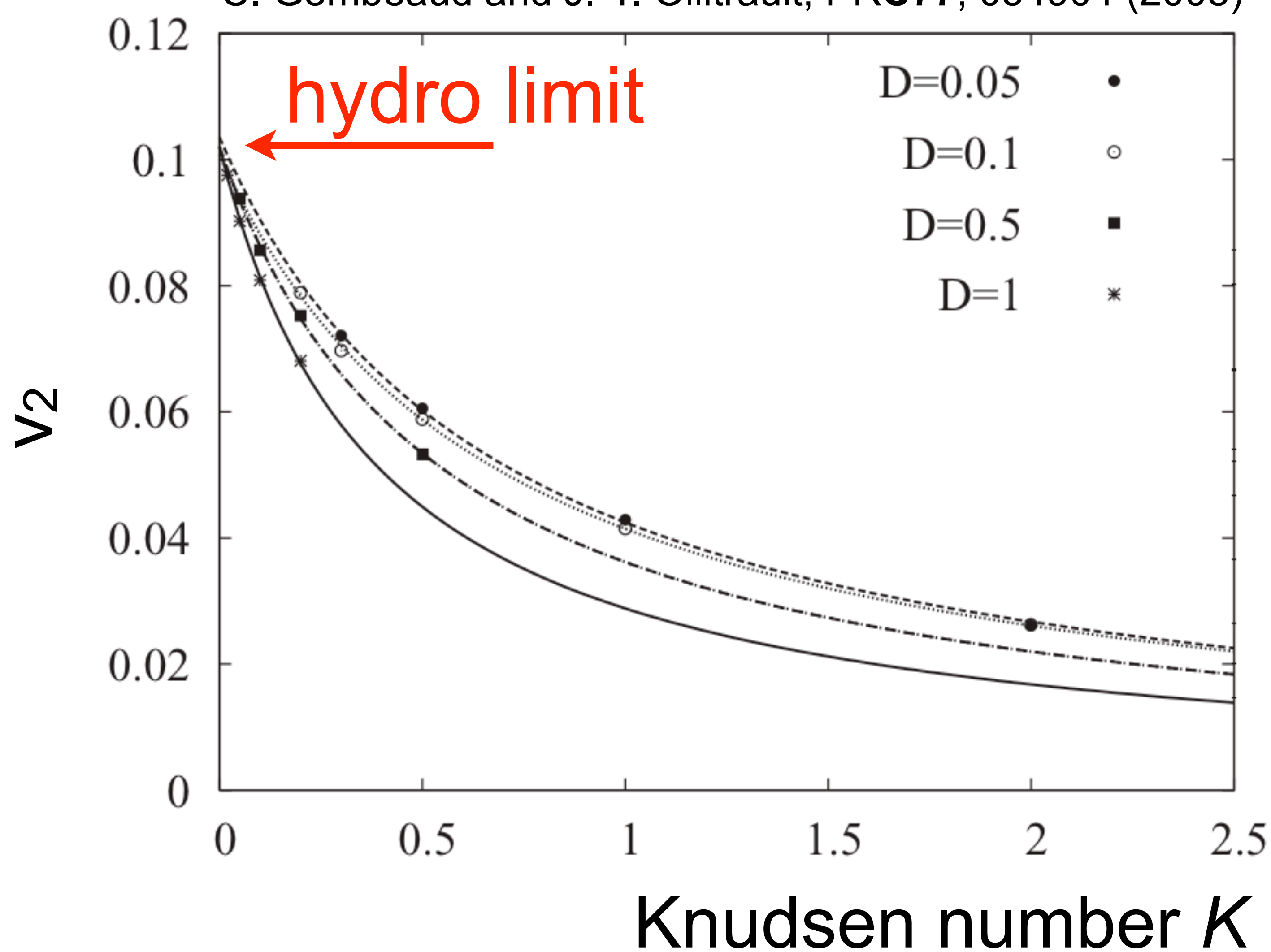
Transport model approach

C. Gombeaud and J.-Y. Ollitrault, PR**C77**, 054904 (2008)



- Knudsen number
  - ✓ degrees of equilibration
  - ✓ Reach hydro limit when $K \rightarrow 0$
- Transport model results (symbols) can be reproduced by the formula below
  - ✓ $K_0 = 0.7$, $c_s^2 = 1/3$

$$\frac{v_2}{\varepsilon} = h \text{ (Hydro limit)}, \qquad \frac{v_2}{\varepsilon} \propto \frac{1}{S}\frac{dN}{dy} \text{ (Low density limit)}$$

$$\rightarrow \frac{v_2}{\varepsilon} = \frac{h}{1+K/K_0} \text{ (from low density to hydro limit)}, \quad \text{where } \frac{1}{K} = \frac{\sigma c_s}{S}\frac{dN}{dy}$$

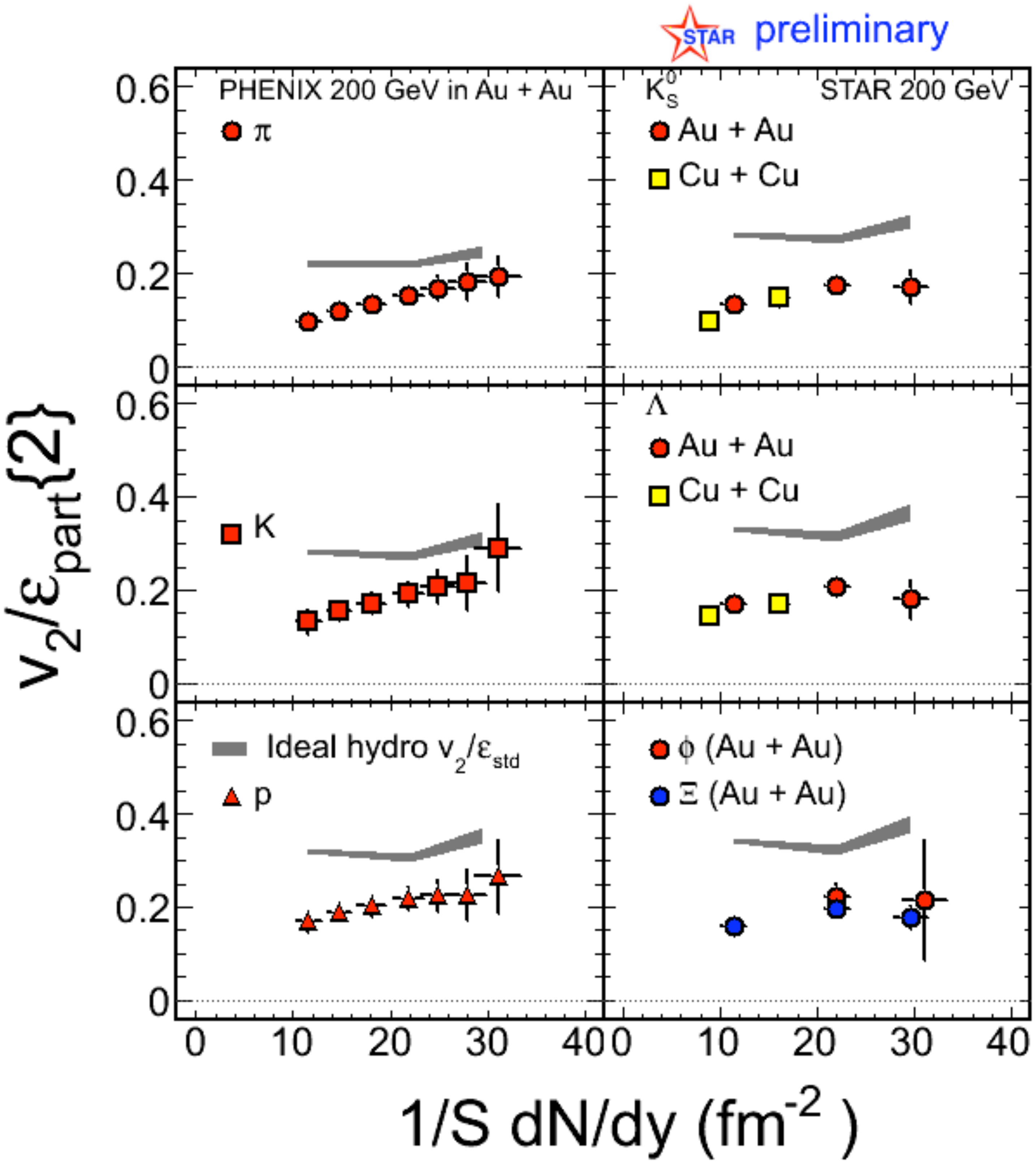
$$= \begin{cases} h & (K \rightarrow 0, \text{ Hydro limit}) \\ h \times (K_0 \sigma c_s)(1/S)dN/dy & (K \gg 1, \text{ Low density limit}) \end{cases}$$

σ : parton cross section
c_s : speed of sound

S : transverse area (obtained by Glauber MC)

STAR

Centrality dependence of $\langle v_2 \rangle$

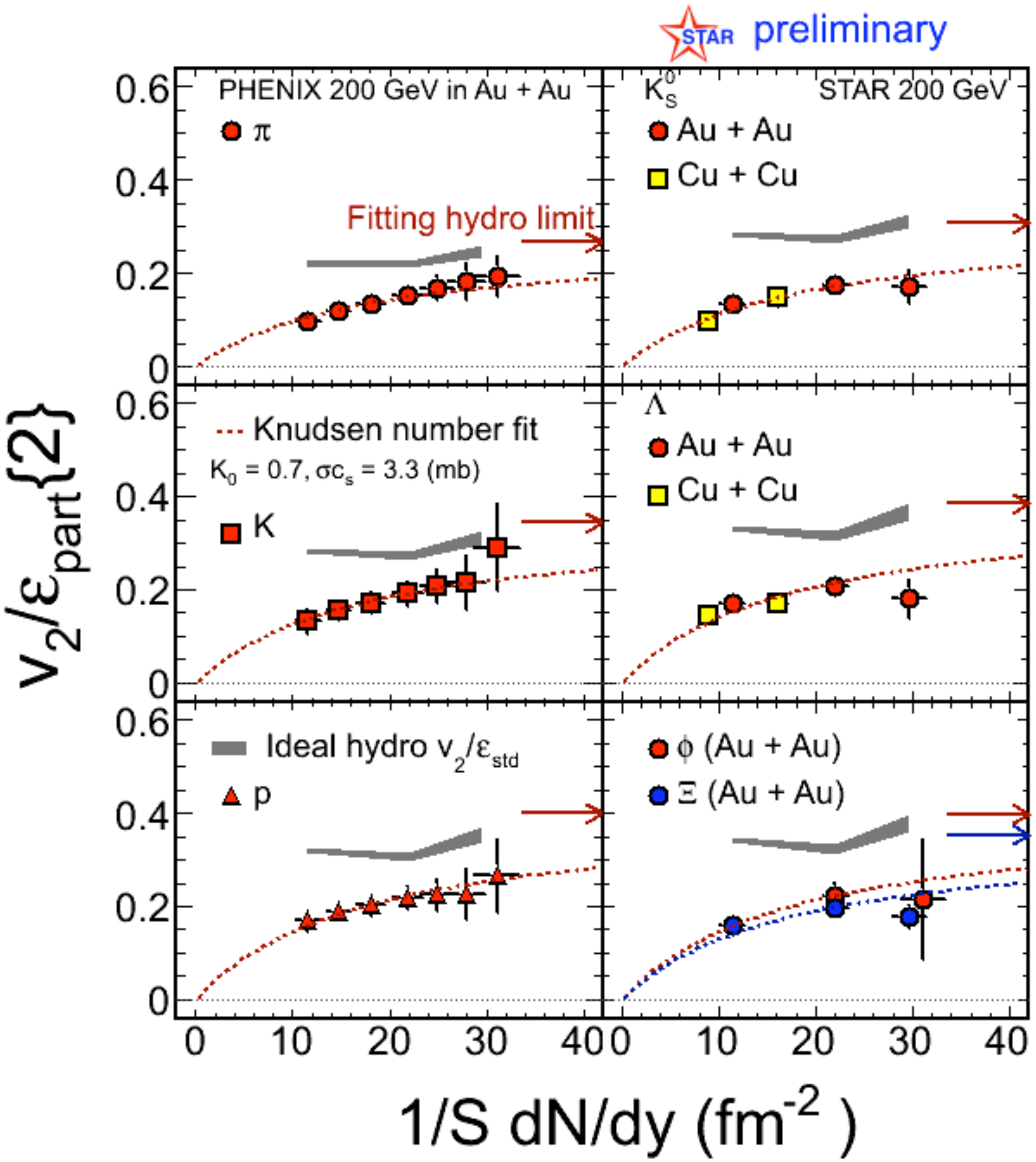


- Ideal hydro > data
- Simultaneous fit
  - ✓ well describe the data
    - assuming σ is same for all hadrons
- "Fitting" hydro limits increase as a function of mass
  - ✓ qualitatively consistent with ideal hydrodynamics

PHENIX π, K and p: preliminary, nucl-ex/0604011v1
STAR K^0_S, Λ, Ξ : Phys. Rev. **C77**, 054901 (2008)
STAR φ : Phys. Rev. Lett. **99**, 112301 (2007)
Ideal Hydro. : P. Huovinen and P. V. Ruuskanen, Annu. Rev. Nucl. Part. Sci. **56**, 163 (2006) and private communication

Note: Fit $v_2\{4\}$ and $v_2\{ZDC\text{-}SMD\}$ for charged hadrons as well but not plotted here

Centrality dependence of $\langle v_2 \rangle$



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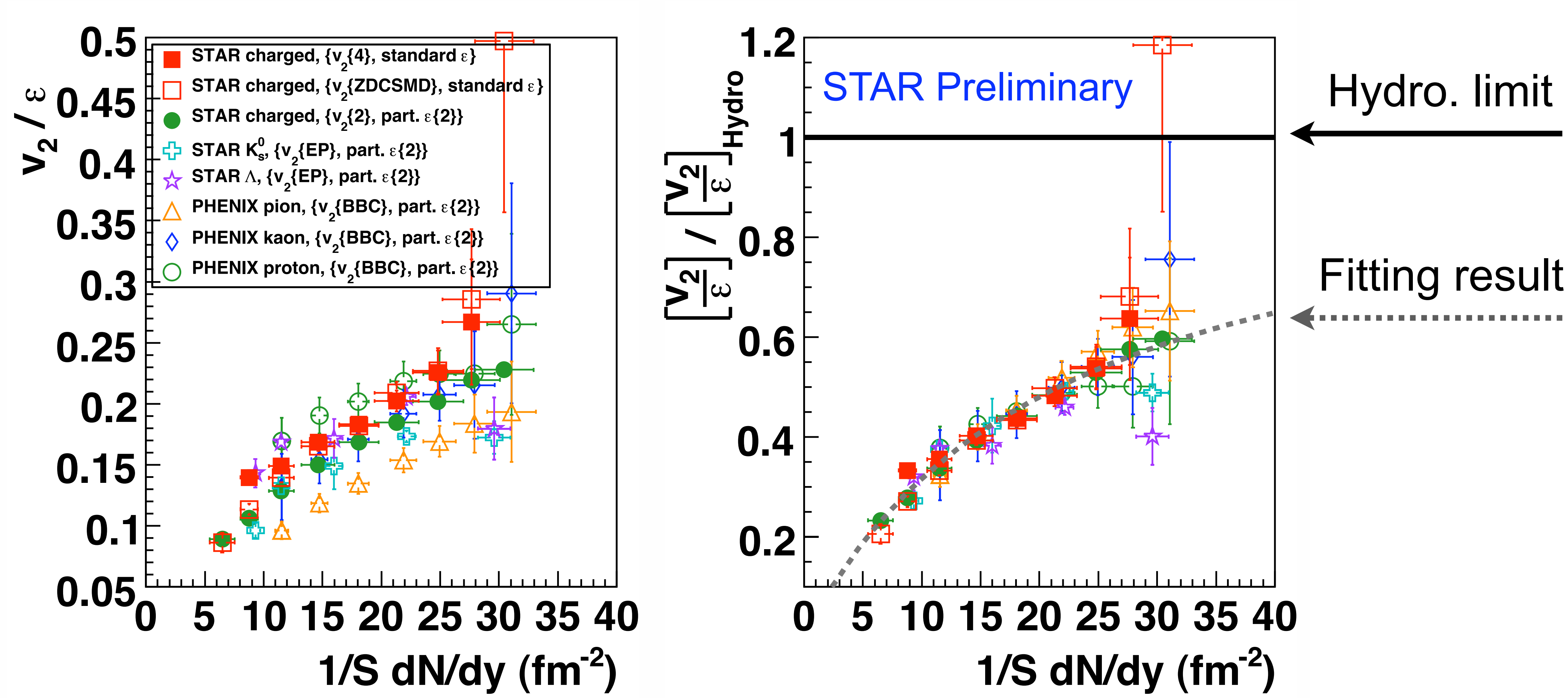
Hydrodynamical limit ?



- Universal curve for different particles, methods, systems and experiments

  ✓ assumption; σ = const. for all hadrons

➡ Hydro limit has not been reached at RHIC within the transport model approach

Hydrodynamical limit ?

Simultaneous fit for measured hadrons gives a constraint on shear viscosity

See Yuting Bai's talk

Parallel session IV: Particle production, 14:20 - 14:40, Today

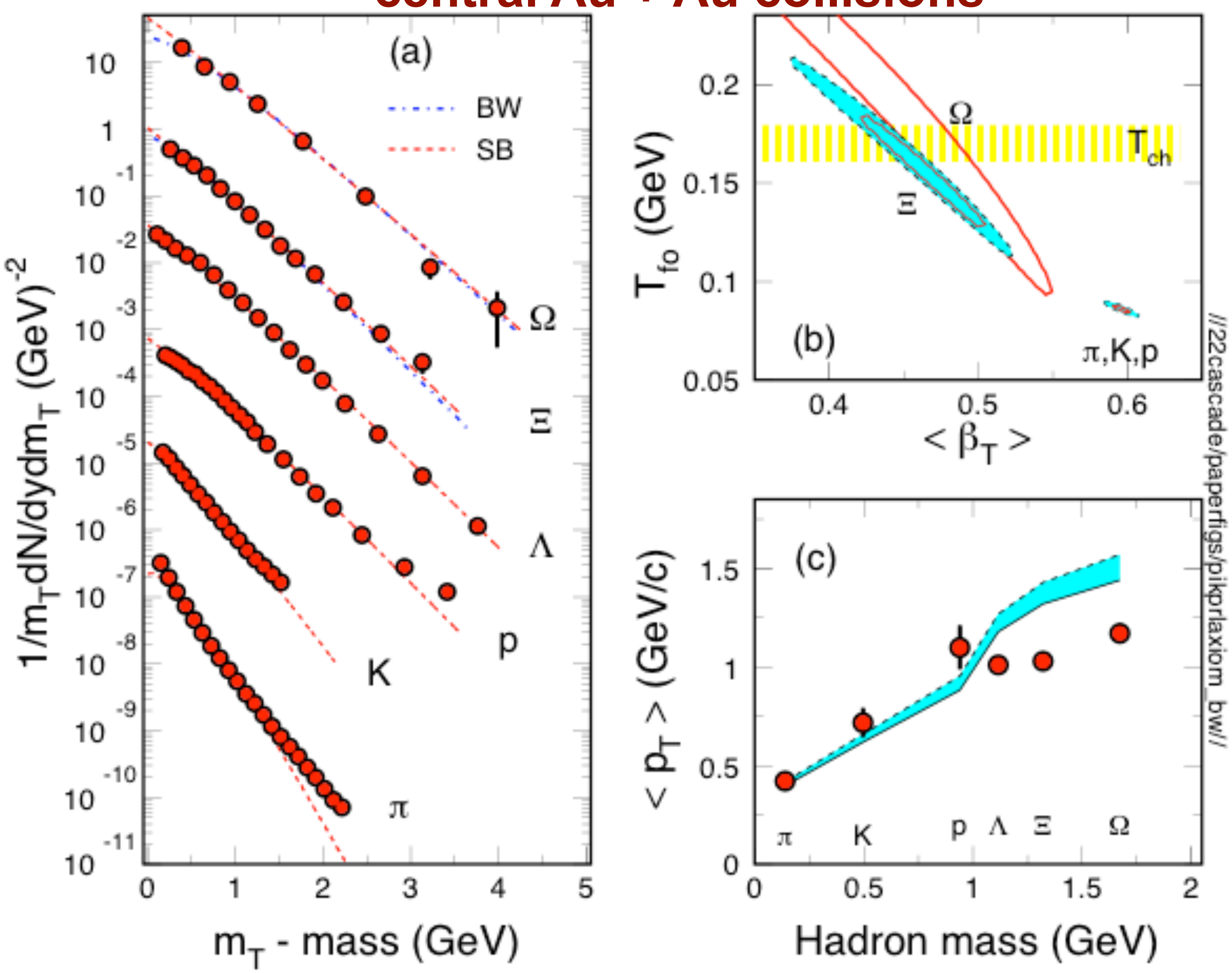
Conclusions

- Elliptic flow (v_2) for K^0_s, Λ and Ξ have been measured in Cu + Cu 200 GeV at STAR
  - ✓ Heavier hadrons have smaller v_2 in $p_T < 2$ GeV/c
  - ✓ Baryon/meson effect in $p_T > 2$ GeV/c ; $v_2(K^0_S) < v_2(\Lambda)$, sizable $v_2(\Xi)$
  - ✓ Ideal hydro failed to reproduce centrality and m_T - mass dependence of v_2
  - ✓ v_2 at 62.4 GeV is consistent with that at 200 GeV in Cu + Cu collisions
- Number of Quark (NQ) scaling of v_2 in Cu + Cu collisions
  - ✓ Strange hadrons follow the NQ scaling → **Partonic flow**
- Centrality dependence of $\langle v_2 \rangle$ at 200 GeV
  - ✓ Stronger collective flow for more central collisions, **$v_2 \propto f(\varepsilon, N_{part})$**
  - ✓ Transport model fit with finite Knudsen number
  - ➡ **Ideal hydrodynamical limit has not been reached at RHIC**
    Simultaneous fit for measured hadrons gives a constraint on shear viscosity (see Yuting Bai's talk)

Extra slides

Why strange hadrons ?

central Au + Au collisions



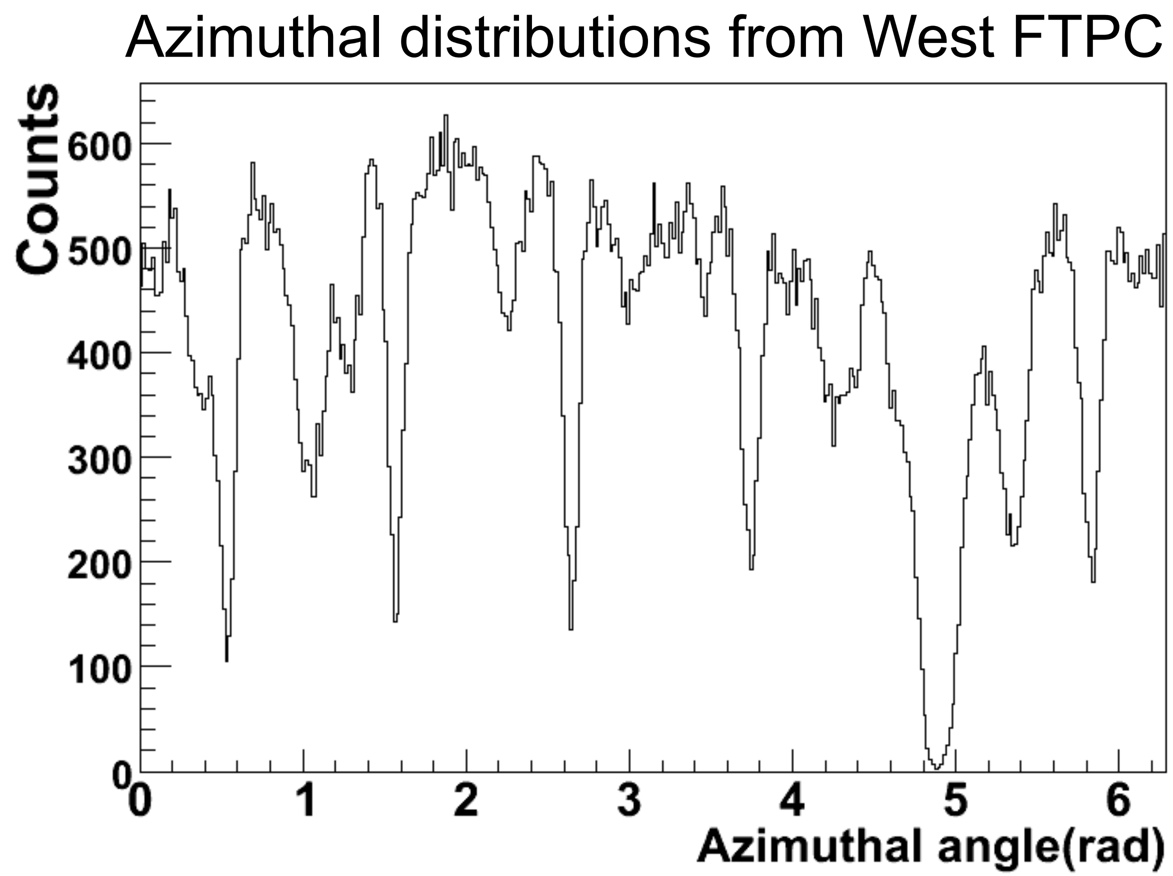
π, K, p; PHENIX, PR**C69**, 034909 (2004): 200 GeV
STAR, PRL**92**, 112301 (2004): 200 GeV
Λ, Ξ, Ω; STAR, PRL**92**, 182301 (2004): 130 GeV
Hydro.; P. Kolb et al., PR**C67**, 044903 (2003)

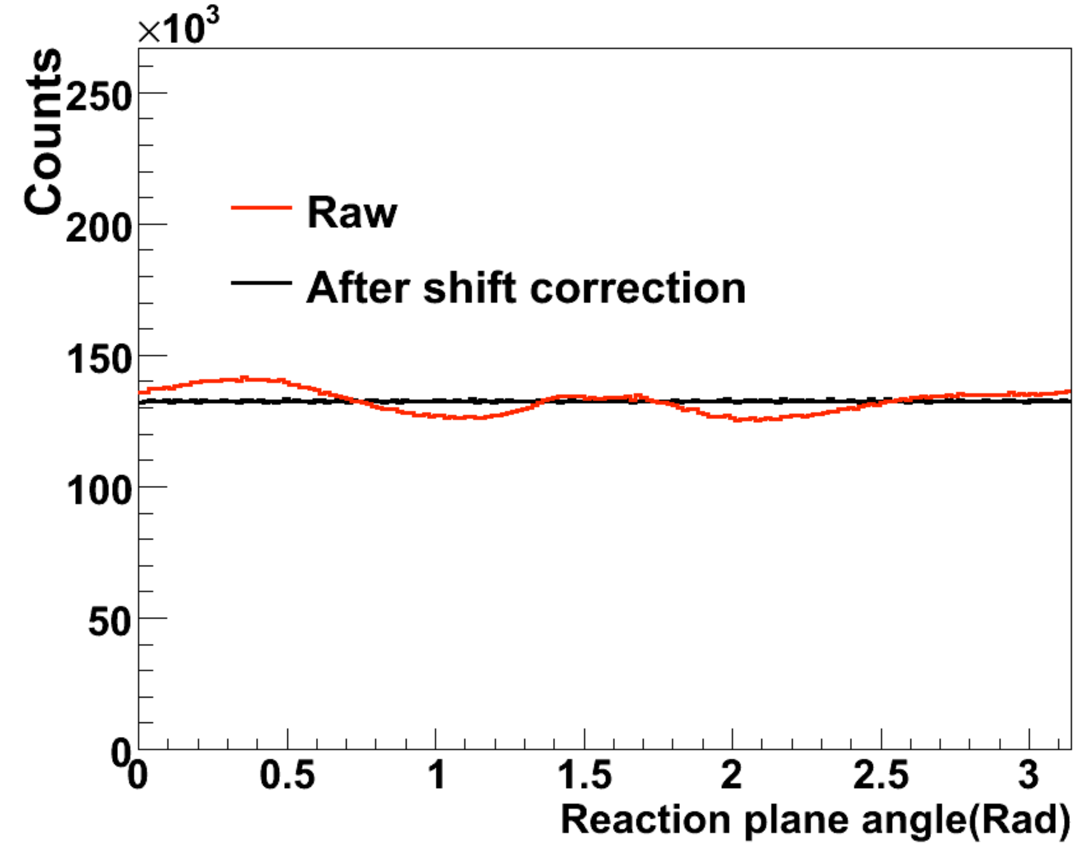
- (Multi-)strange hadrons seem to freeze-out earlier than light hadrons
  - ✓ Lower $\langle\beta_T\rangle$ and higher kinetic freeze-out temperature T_{fo} than π, K and p
  - ✓ $T_{fo} \sim T_{ch}$

➡ Sensitive to "partonic" stage

➡ How about v_2 ?

Forward TPC event plane





Track selection at FTPC

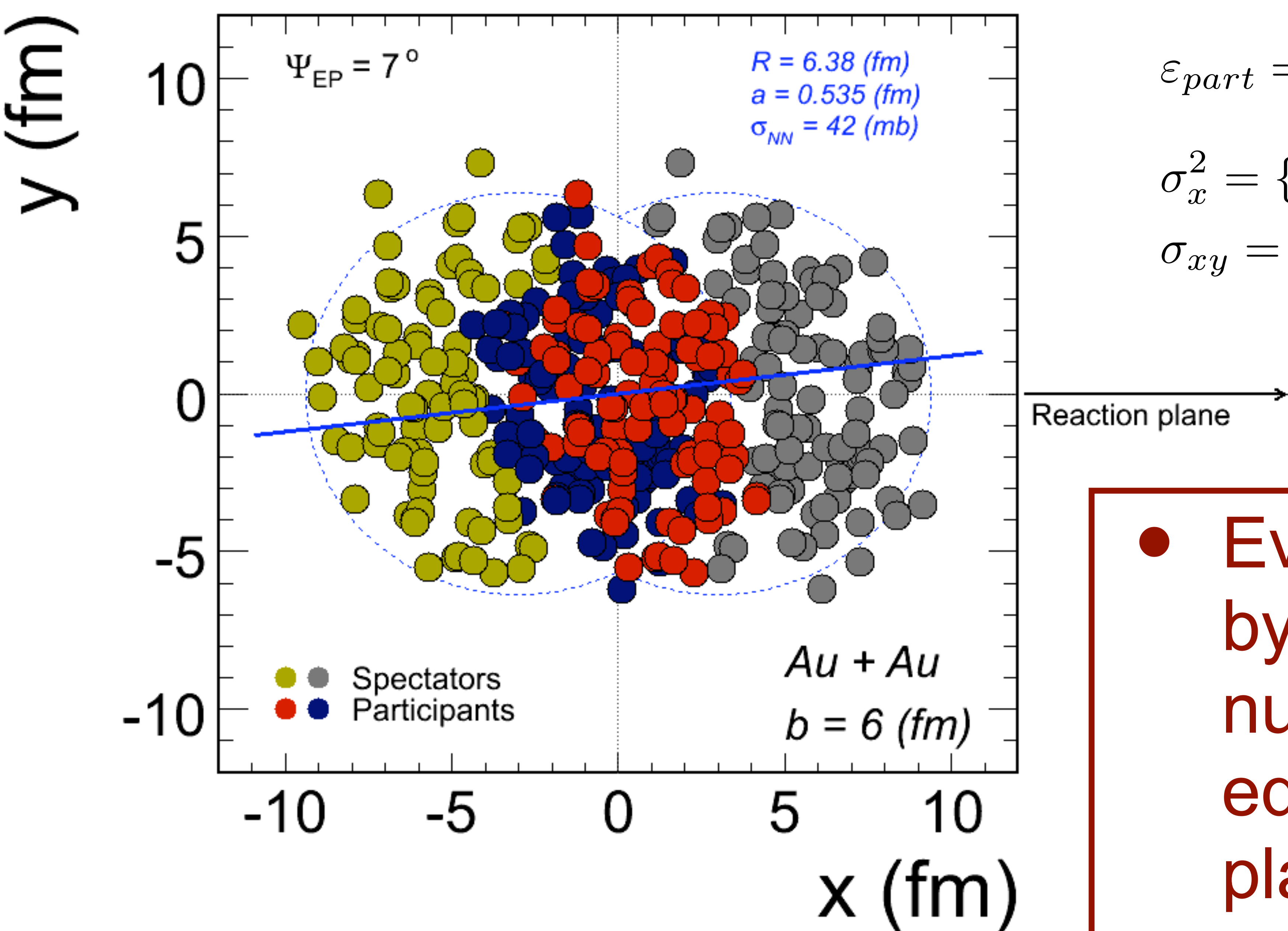
- ✓ 6 ≤ # of hit used in fit < 12
- ✓ $N_{fit}/N_{max} > 0.52$
- ✓ p_T = 0.1 - 2 GeV/c
- ✓ $|\eta|$ = 2.5 - 4

- Detector biases have been removed by
  - ✓ ϕ weight, inverse of ϕ distribution
  - ✓ Shift correction

$$n\Delta\Psi_n = \sum_{k=1}^{k_{max}} \frac{2}{k}\left[\langle\cos(kn\Psi_n)\rangle \sin(kn\Psi_n) - \langle\sin(kn\Psi_n)\rangle \cos(kn\Psi_n)\right]$$

Participant eccentricity

Au + Au at 200 GeV, Glauber MC simulation



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$$\sigma_x^2 = \{x^2\} - \{x\}^2, \quad \sigma_y^2 = \{y^2\} - \{y\}^2,$$

$$\sigma_{xy} = \{xy\} - \{x\}\{y\}$$

- Event plane defined by participant nucleons are not equal to true reaction plane
  - ✓ due to the event-by-event fluctuation of participants

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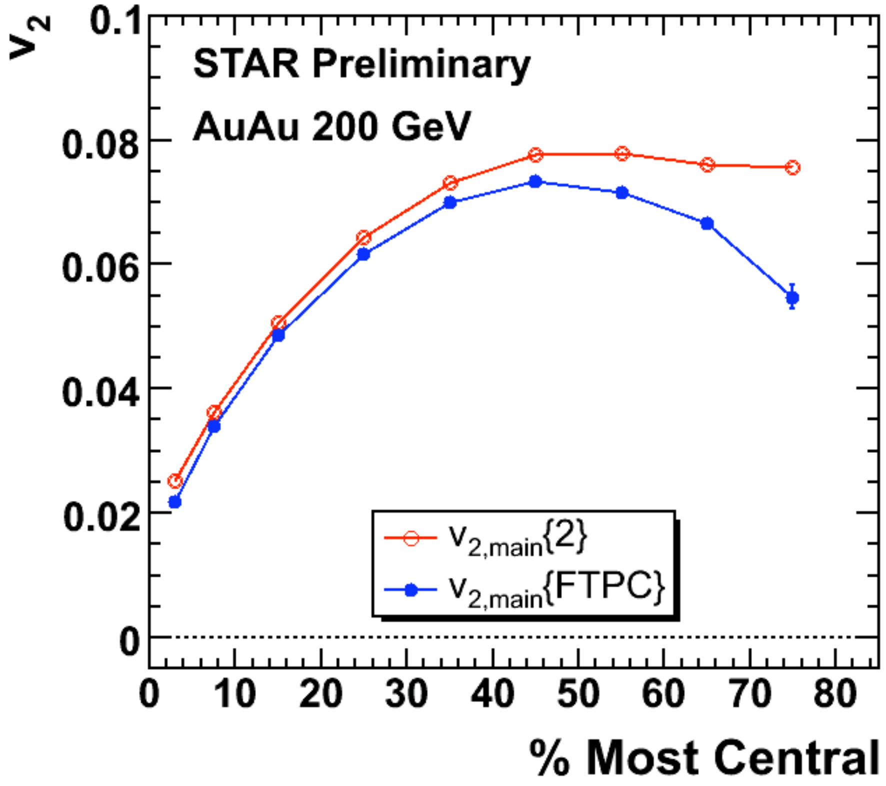
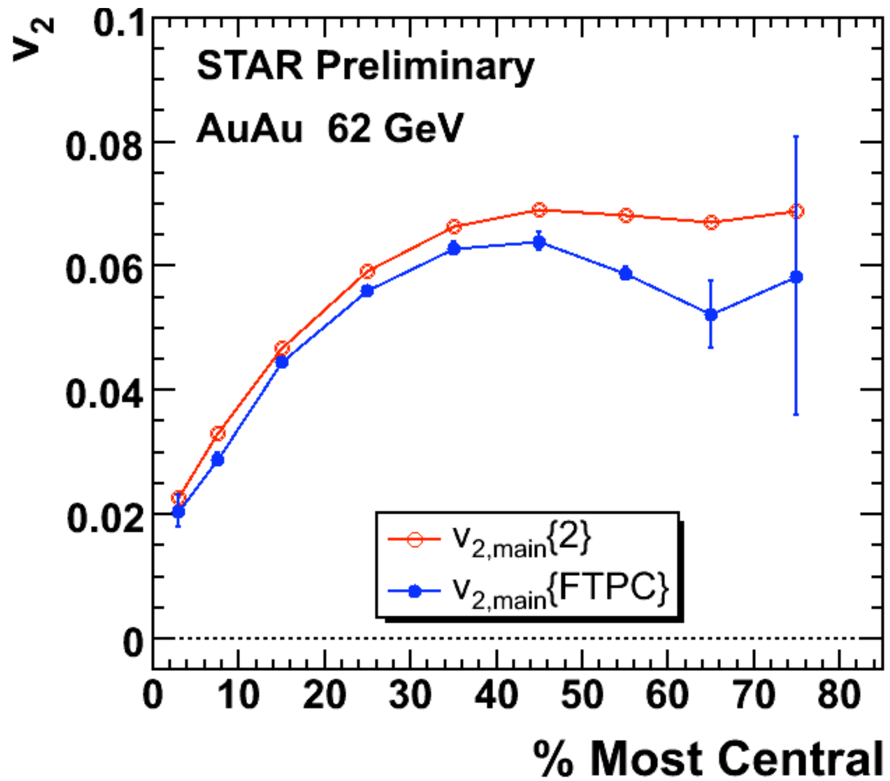
v_2\{FTPC\}

S. Voloshin, QM2006





Shown in **black** are results obtained by correlating two random particles from Main TPC. Non-flow contribution can be large and positive.

In **blue** are results for v_2 in the Main TPC region obtained from correlations (Forward*Main) and (East*West).
Relative systematic error at maximum flow
~< 3% (AuAu 200 GeV)
~< 5% (AuAu 62 GeV)
~< 12% (CuCu 200 GeV)
~< 20% (CuCu 62 GeV)

Note: significantly larger relative difference between black and blue points in Cu+Cu case compared to Au+Au

The difference (blue and red) is due to non-flow assuming that flow fluctuates coherently in the Main and Forward TPC regions