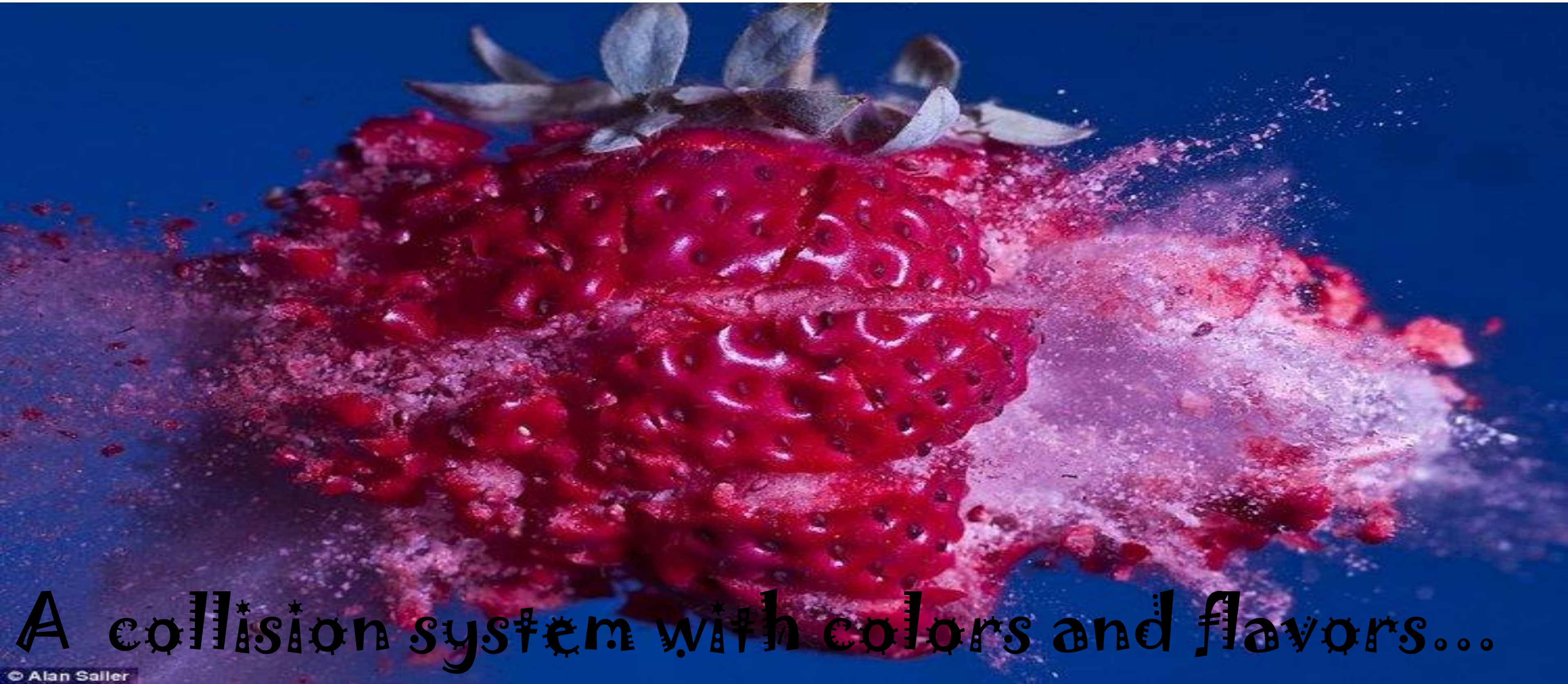
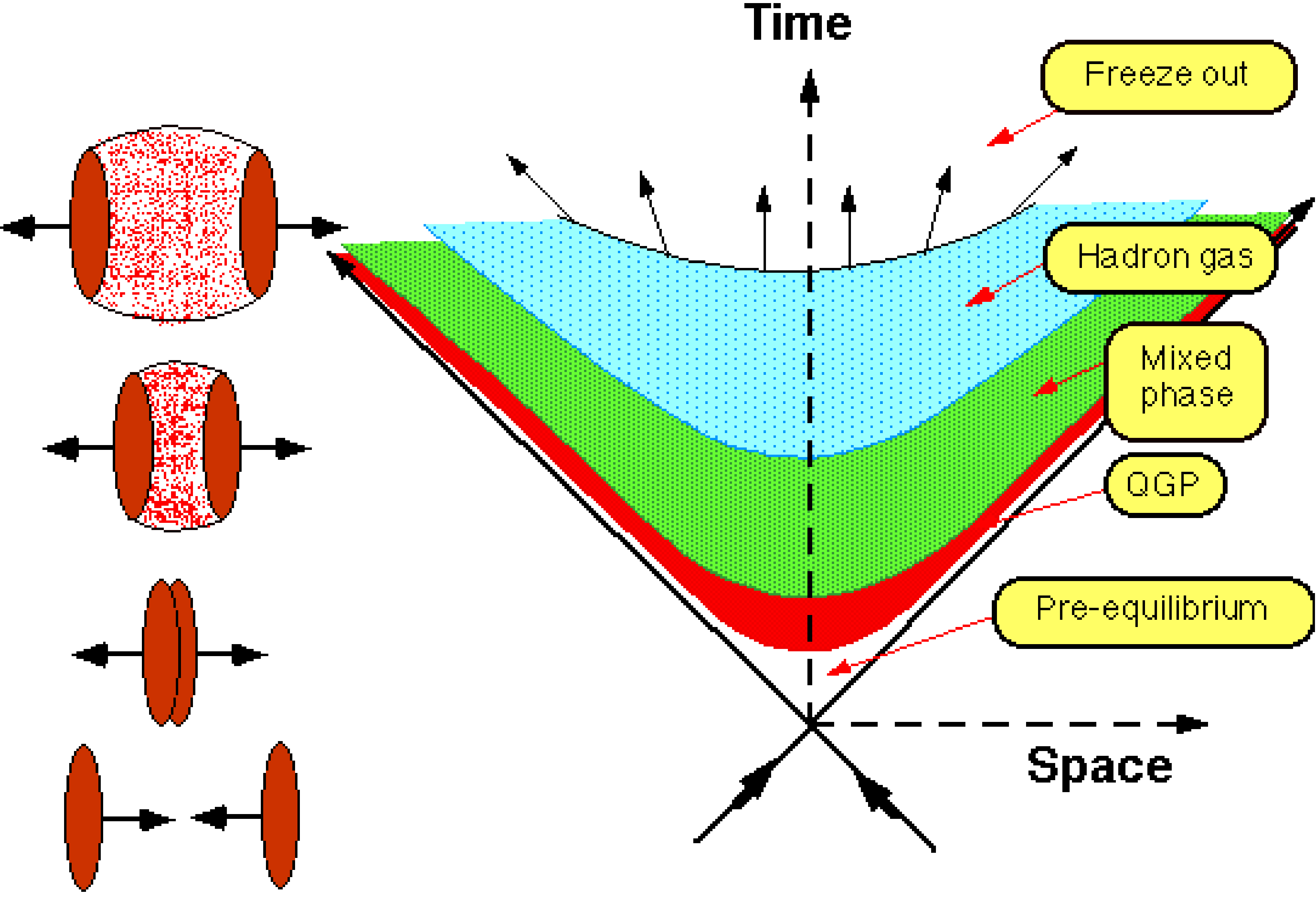
Matter flows in high-energy heavy-ion collisions

Gang Wang (UCLA)



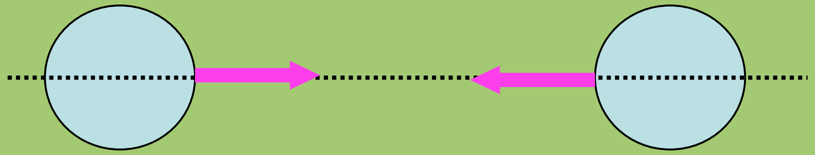

Time
Freeze out
Hadron gas
Mixed phase
QGP
Pre-equilibrium
Space

Impact parameter & Reaction plane

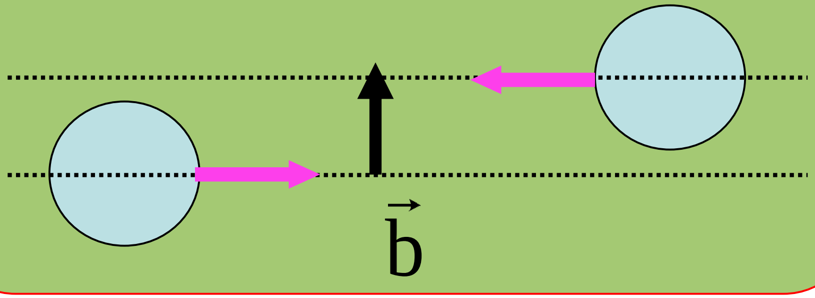
Impact parameter vector $\vec{b}$:

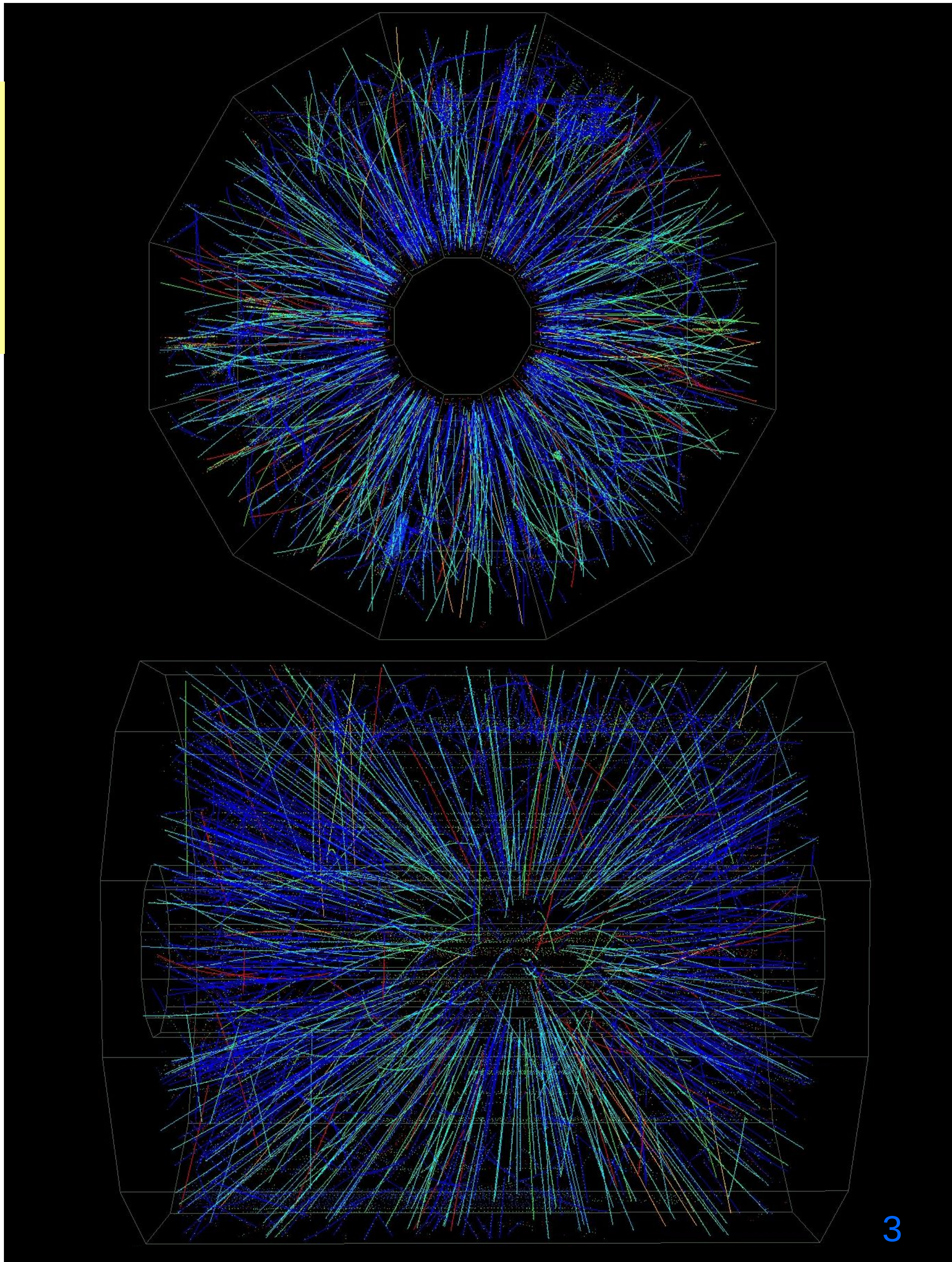
- $\perp$ beam direction
- connects centers of colliding nuclei

$b = 0 \leftrightarrow$ “central collision”
many particles produced



“peripheral collision”
fewer particles produced





Impact parameter & Reaction plane

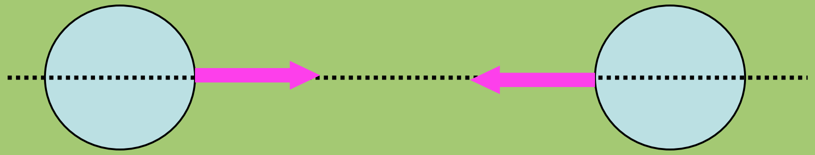
Impact parameter vector $\vec{b}$:

- $\perp$ beam direction
- connects centers of colliding nuclei

Reaction plane:

spanned by beam direction and $\vec{b}$

b = 0 ↔ “central collision”
many particles produced



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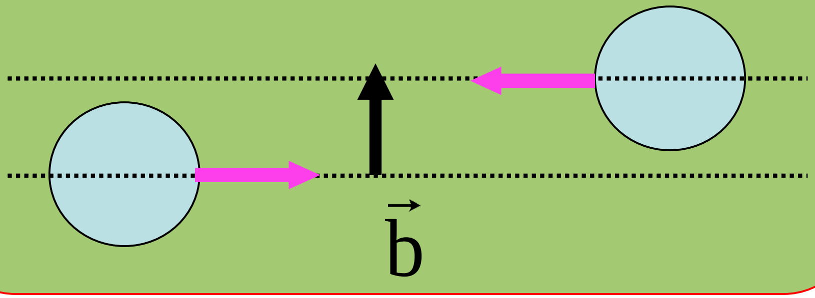
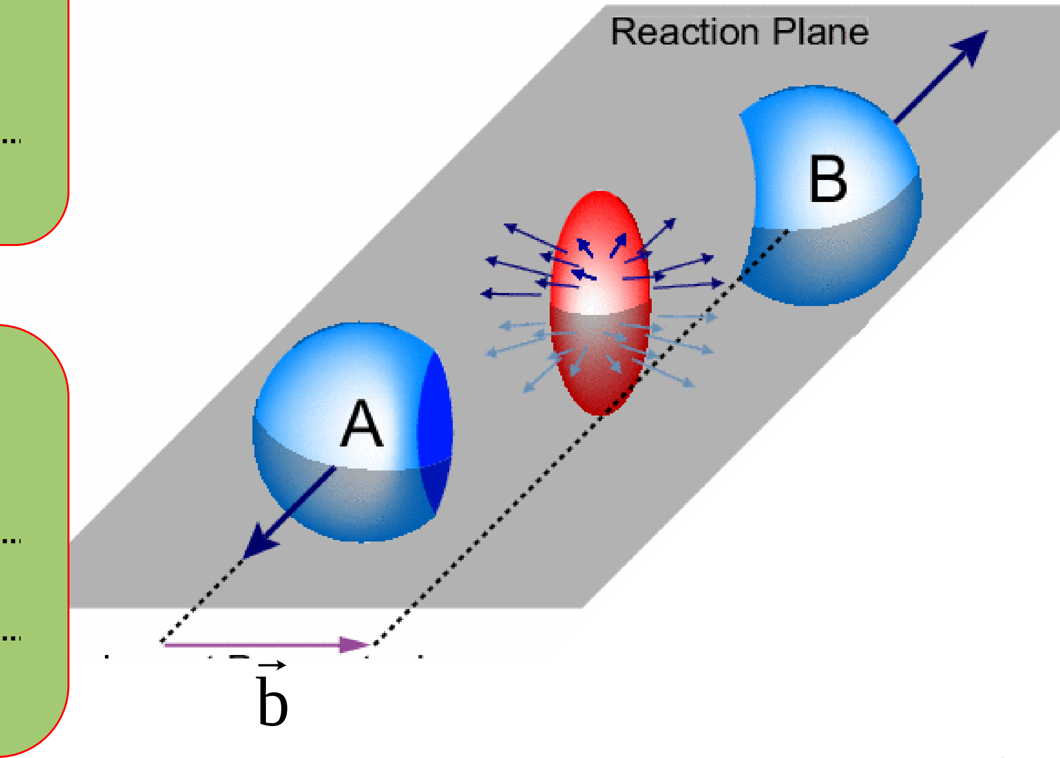
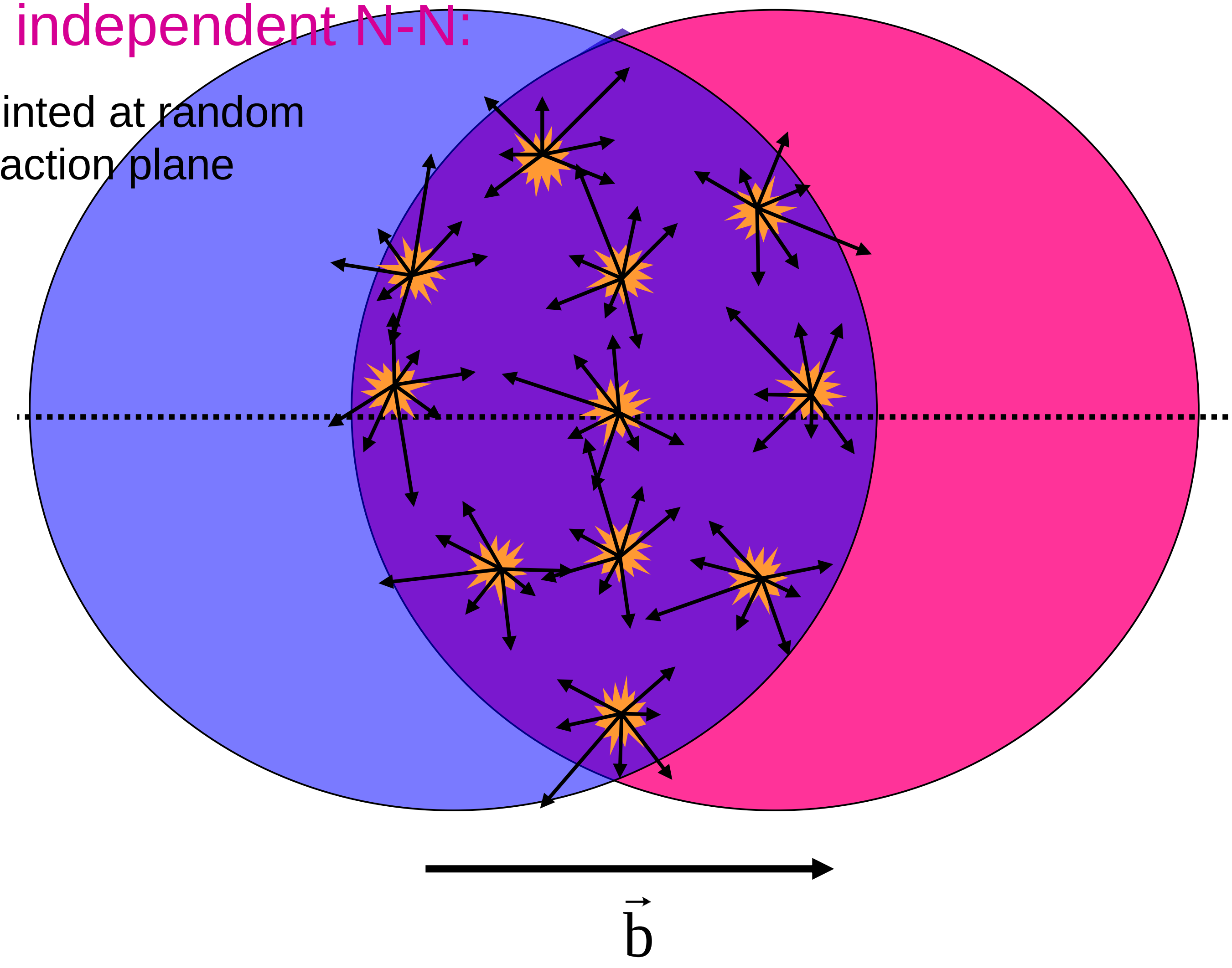




How do semi-central collisions evolve?

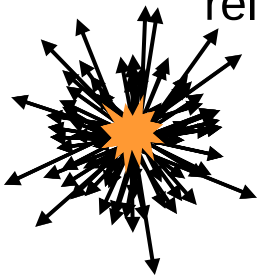
1) Superposition of independent N-N:

momenta pointed at random
relative to reaction plane



How do semi-central collisions evolve?

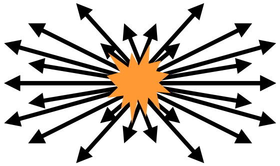
1) Superposition of independent p+p:



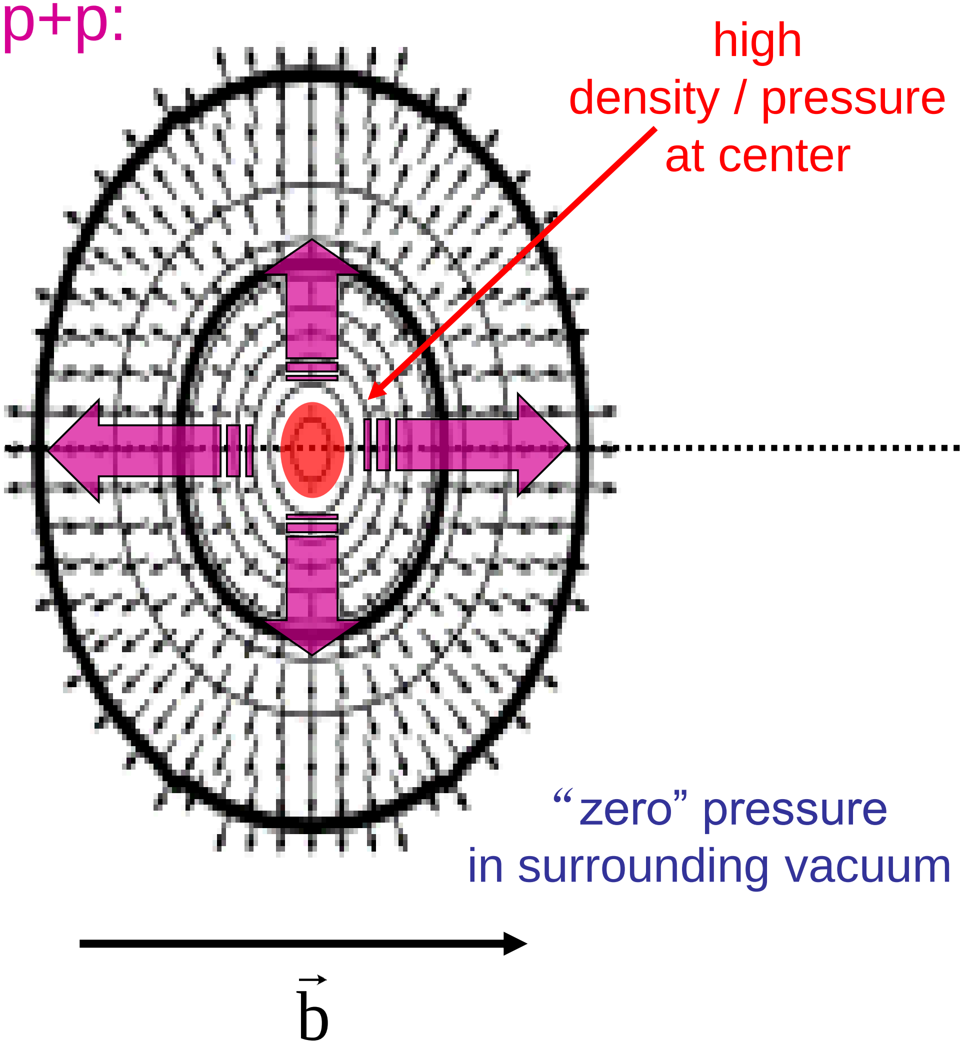
momenta pointed at random
relative to reaction plane

2) Evolution as a **bulk <u>system</u>**

Pressure gradients (larger in-plane)
push bulk “out” → “flow”



more, faster particles
seen in-plane



high
density / pressure
at center

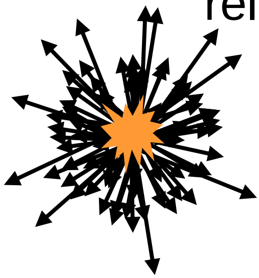
“zero” pressure
in surrounding vacuum

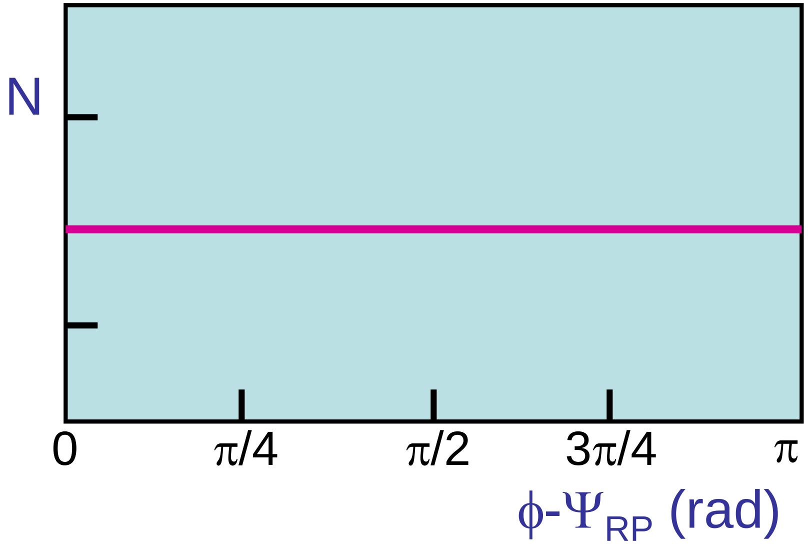
$\vec{b}$

How do semi-central collisions evolve?

1) Superposition of independent N-N:

momenta pointed at random
relative to reaction plane





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Pressure gradients (larger in-plane)
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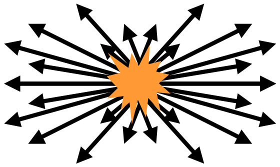

more, faster particles
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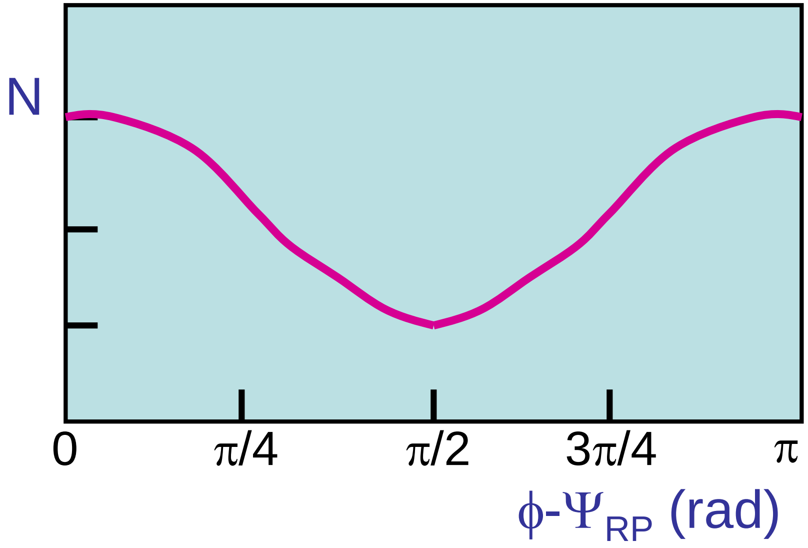
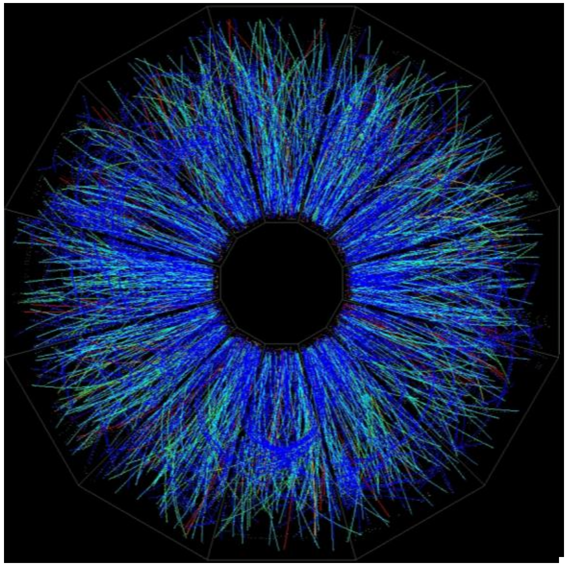


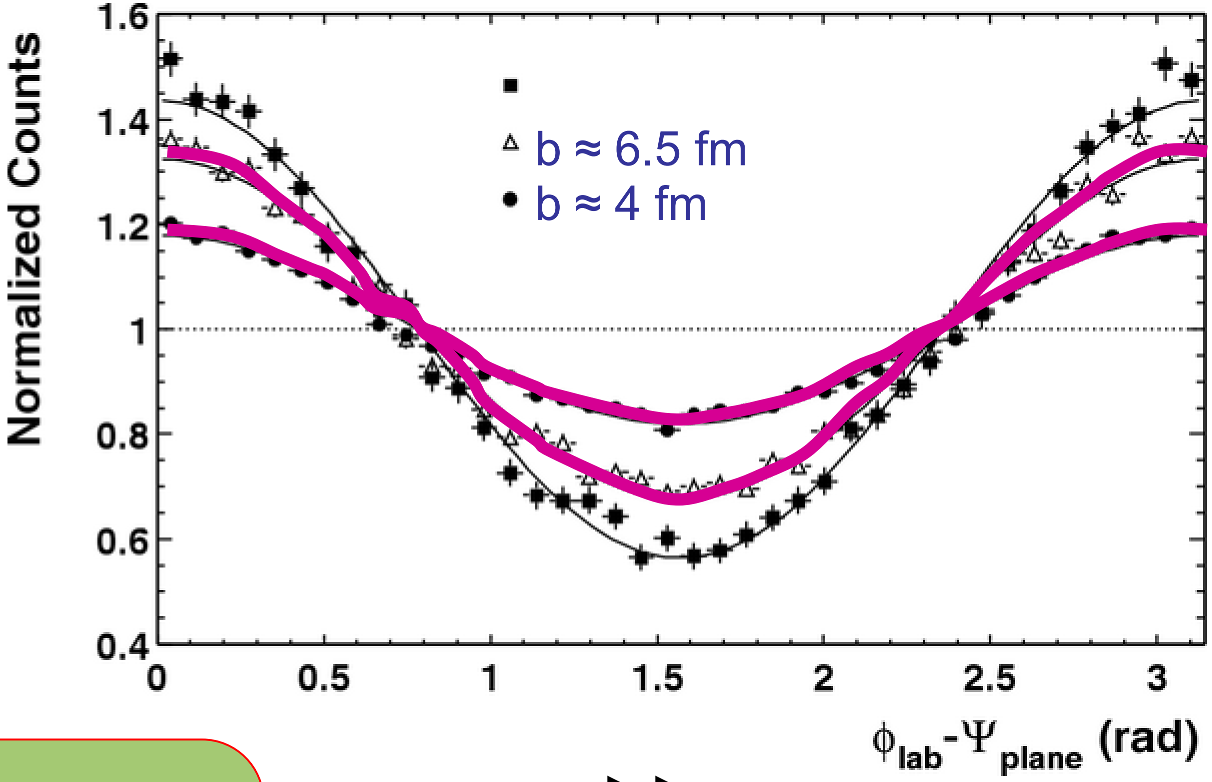
Azimuthal distributions

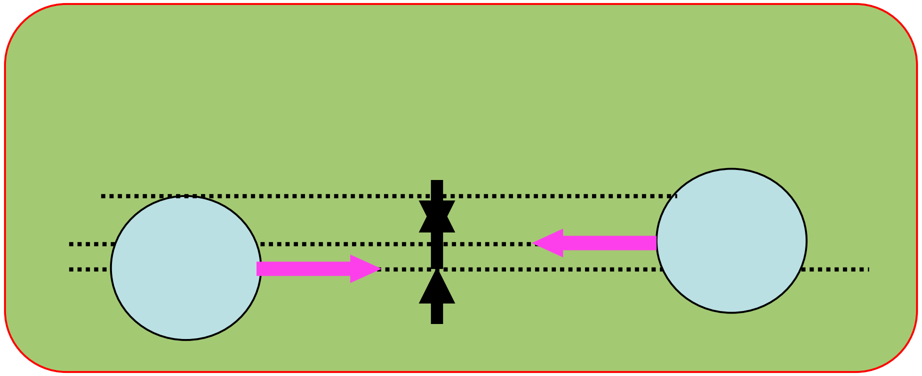


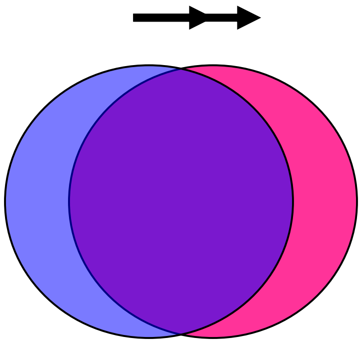
mid-central collisions

“central” collisions

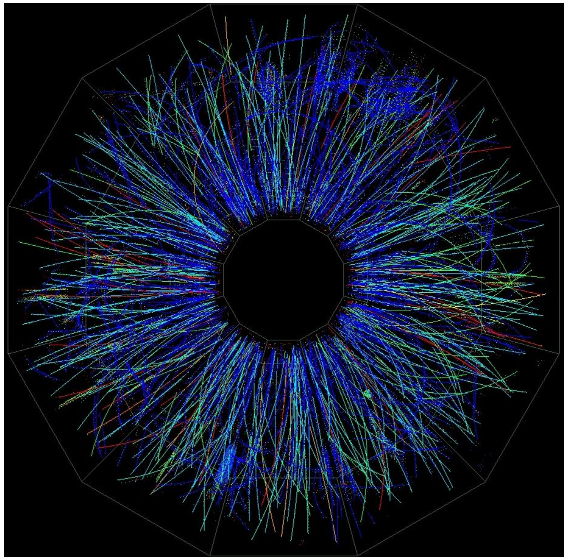
STAR, PRL**90** 032301 (2003)



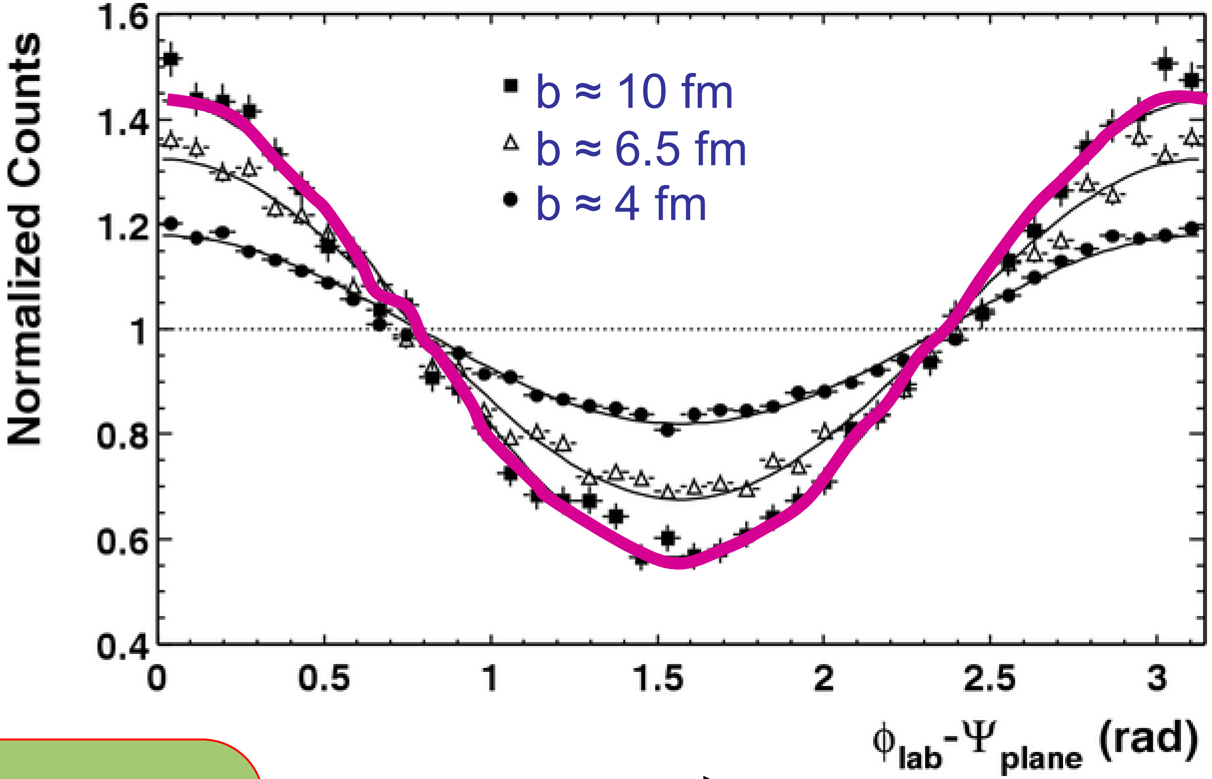




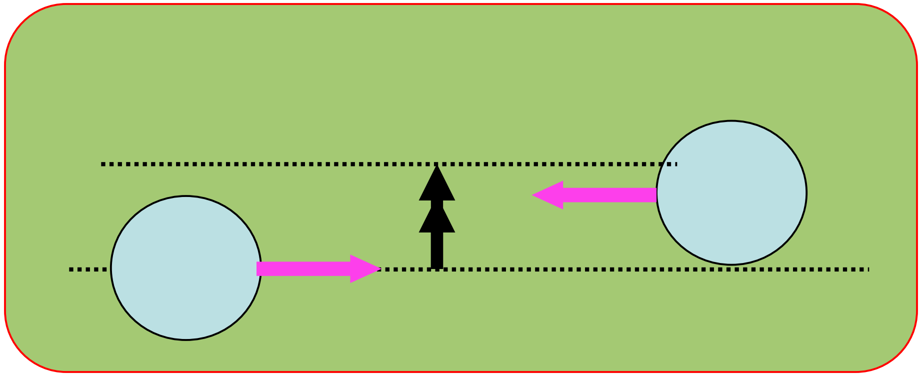
Azimuthal distributions

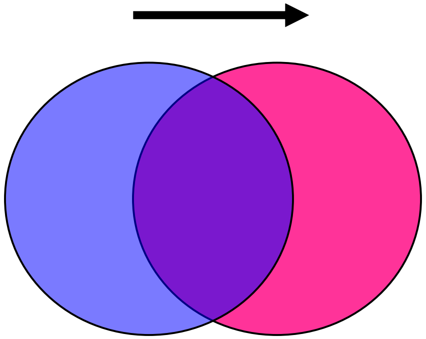


STAR, PRL**90** 032301 (2003)



peripheral collisions

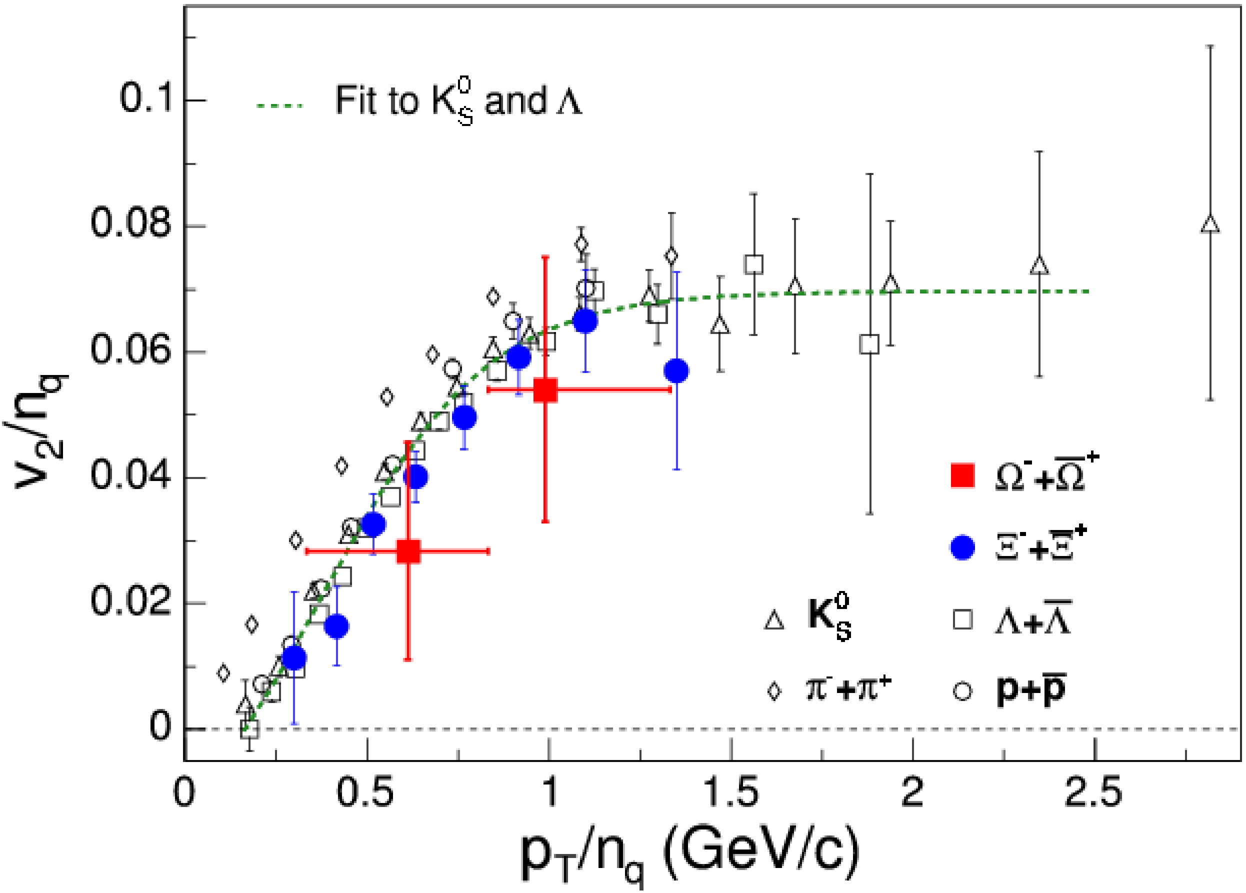




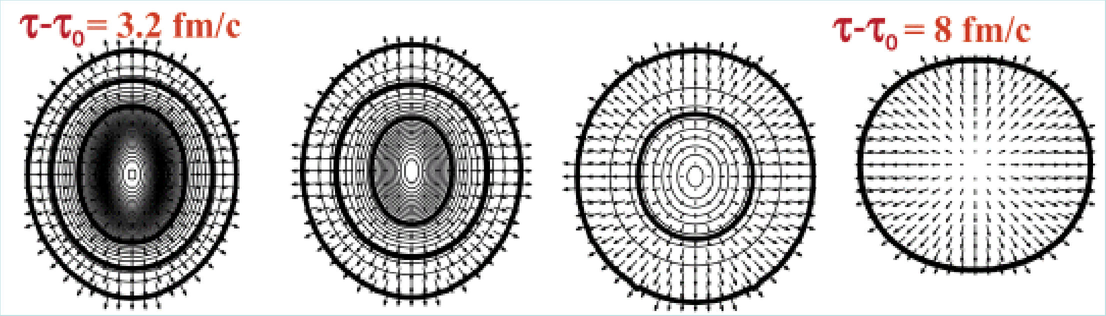
Elliptic flow: collectivity&sensitivy to early stage

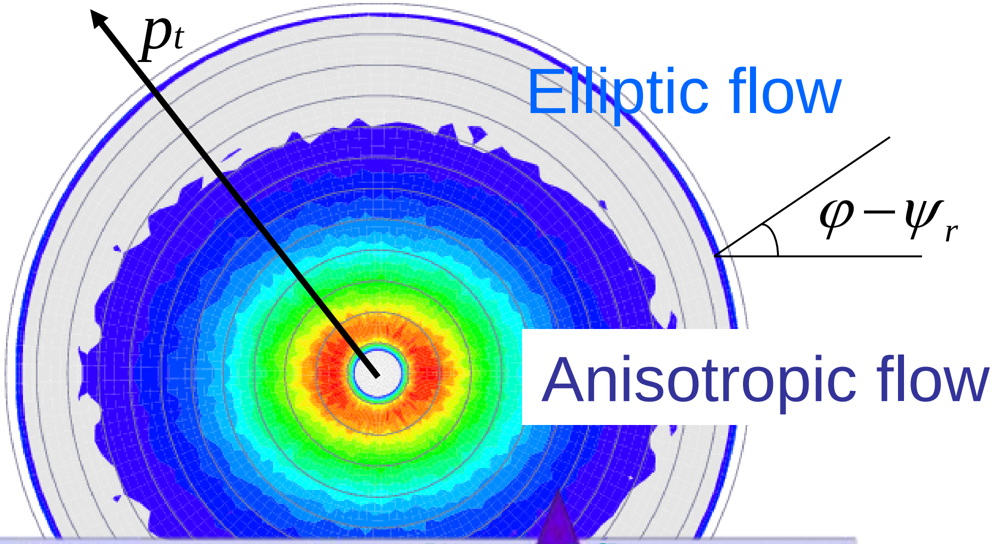
"Elliptic flow"

- evidence of *collective* motion
- quantified by v_2
- geometrical anisotropy → momentum anisotropy
- sensitive to *early* pressure
- evidence for
  - early thermalization
  - QGP in early stage



Hydrodynamic calculation of *system evolution*



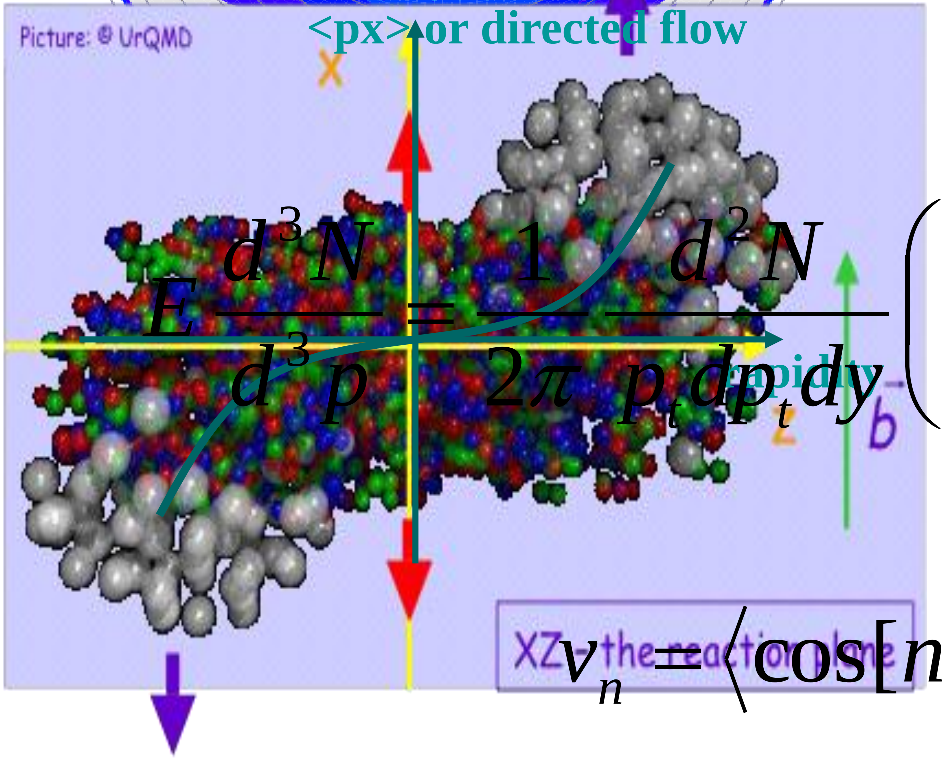


Elliptic flow

Anisotropic flow

Directed flow

Higher harmonics

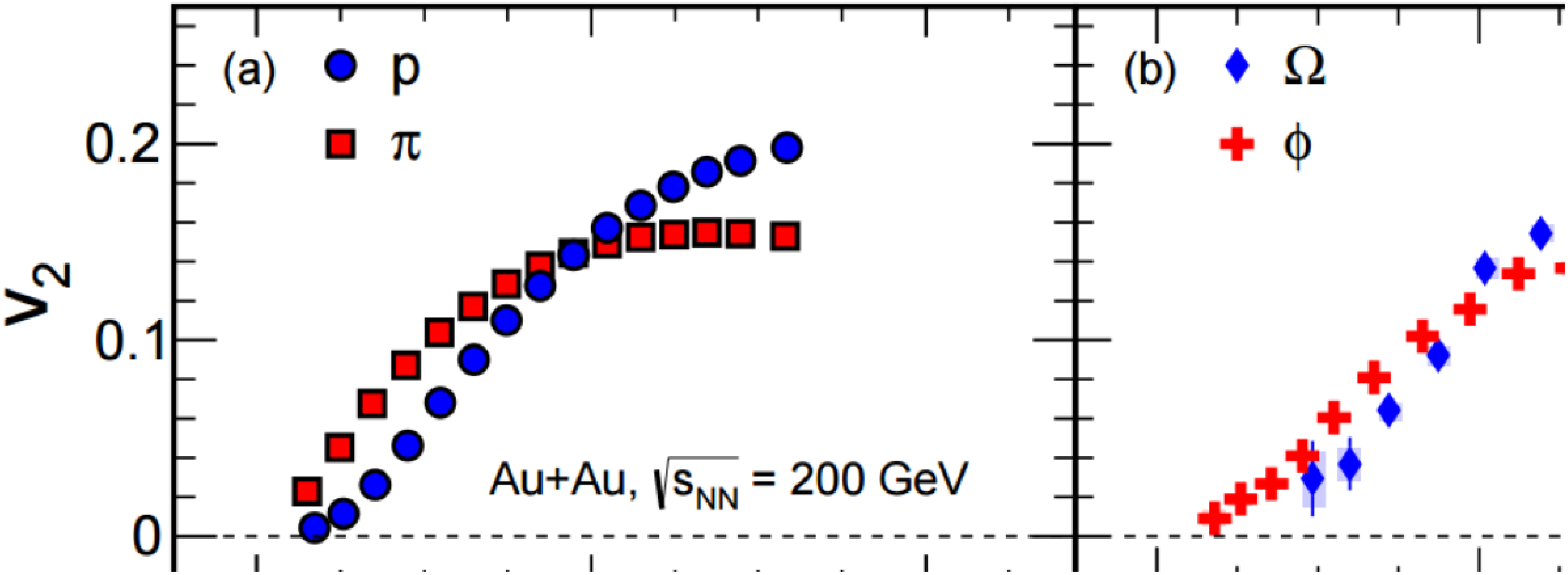


$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t\,dp_t\,dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\varphi-\psi_r)]\right)$$

$$v_n=\langle\cos[n(\varphi-\psi_r)]\rangle$$

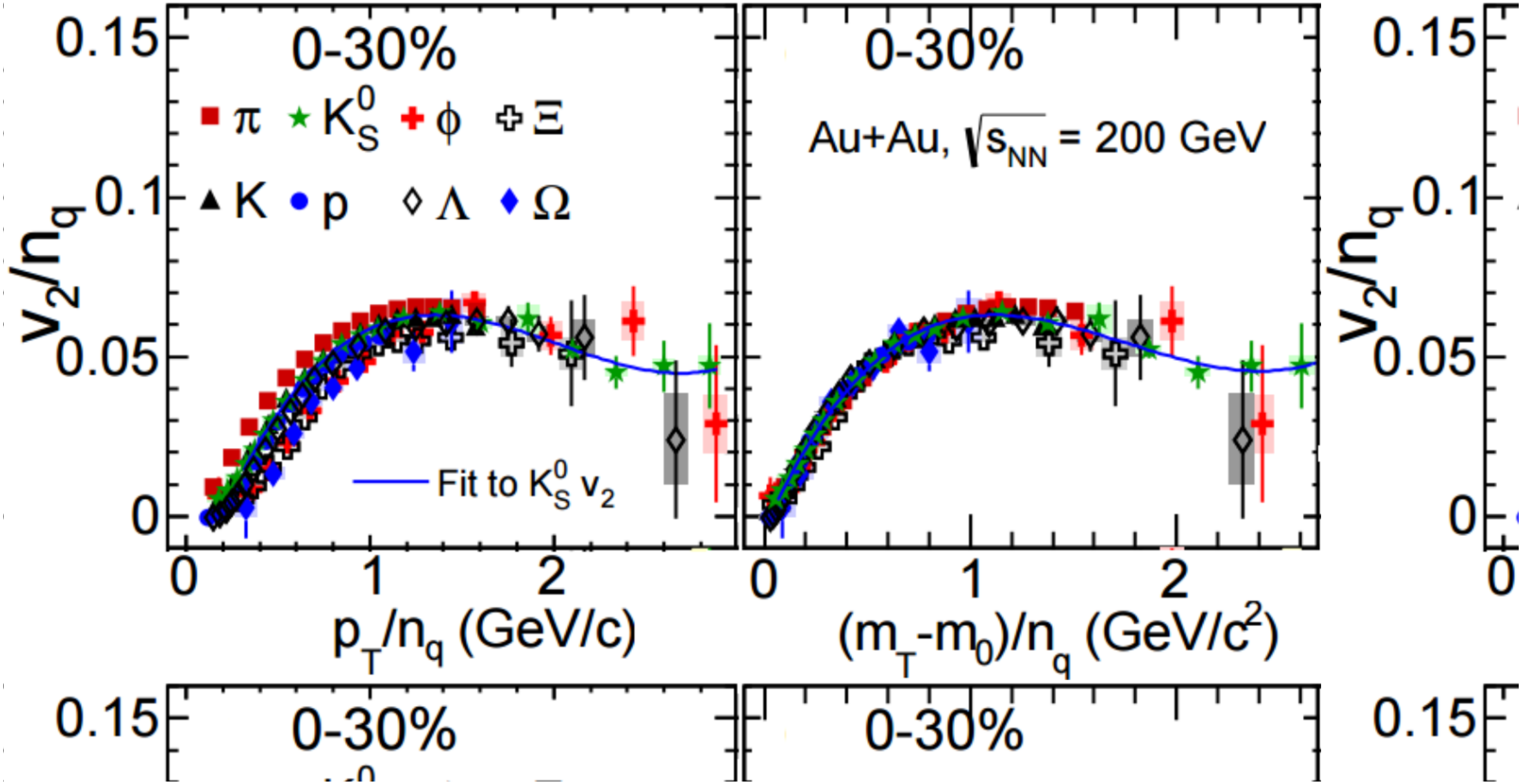
v_2 vs p_T

- v_2 increases with p_T
- Mass ordering at low p_T
- Meson/baryon splitting at intermediate p_T



STAR, PRL 116, 062301 (2016)

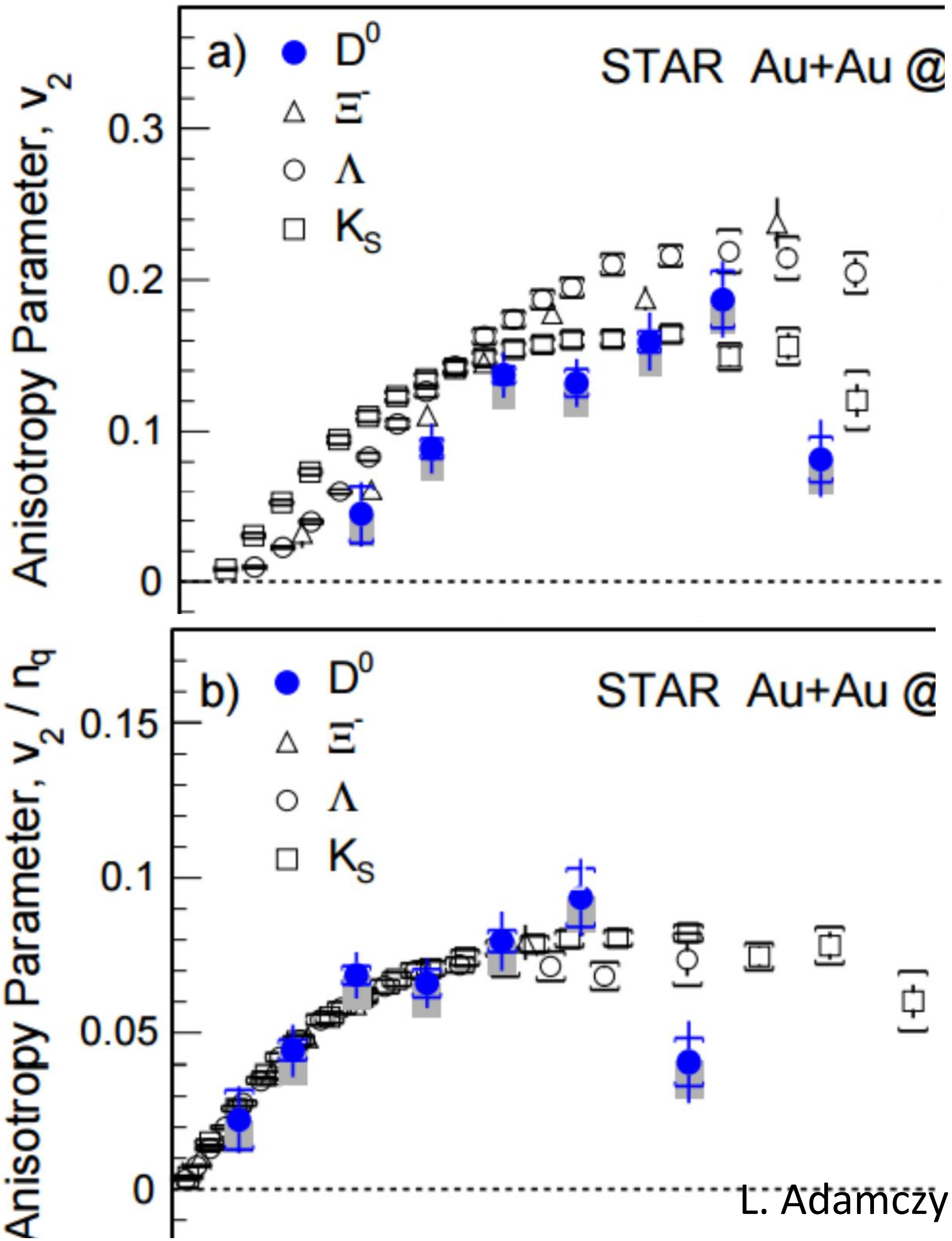
Intermidiate p_T: N_{cq} scaling



Partonic collectivity picture is supported for u, d, s.
What about heavier quarks?

$$m_T = \sqrt{p_T^2 + m_0^2}$$

D^0 v_2



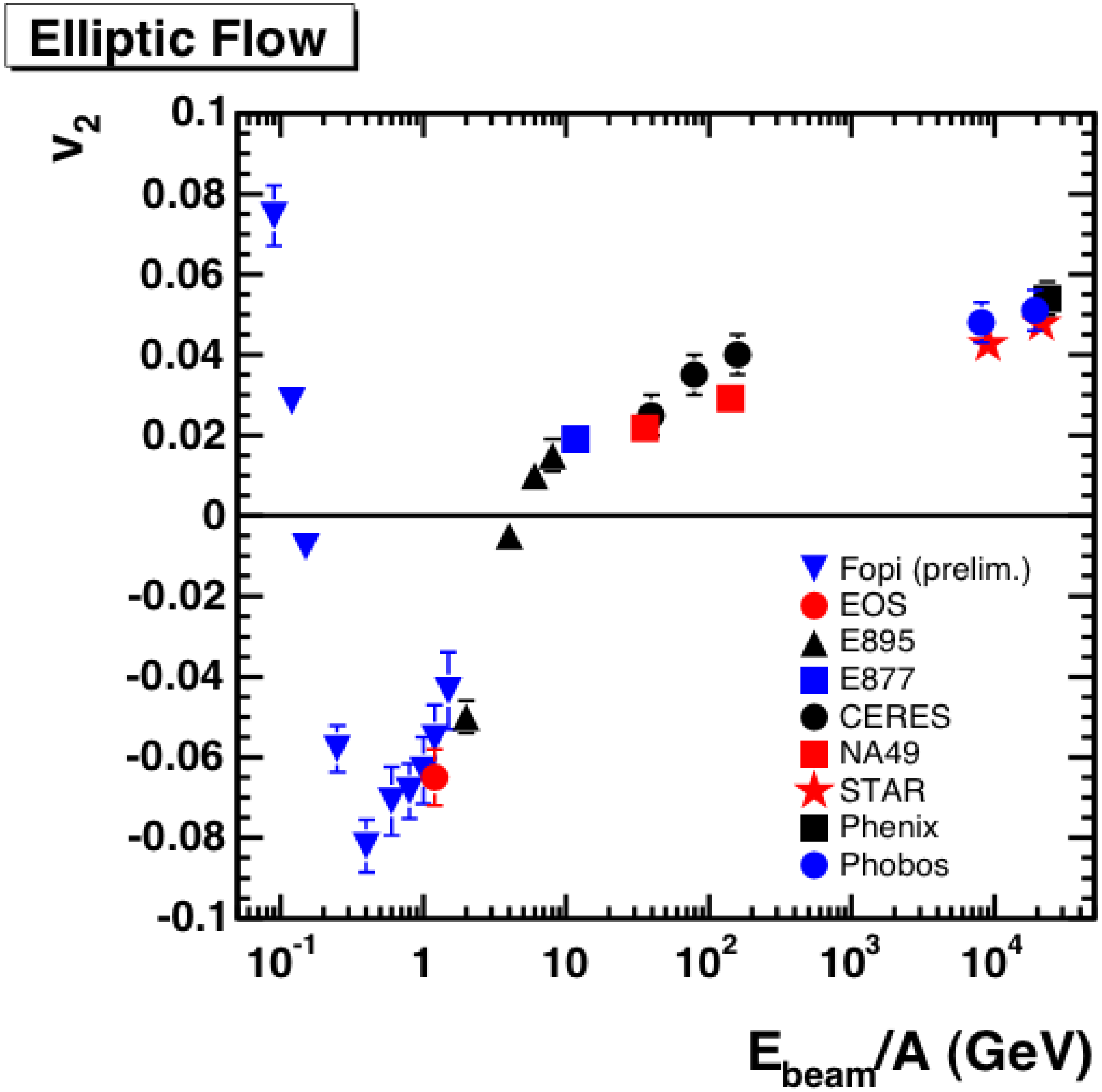
$c\bar{u}$ and $\bar{c}u$

Charm quarks seem to flow as much as light quarks.

$$m_T = \sqrt{p_T^2 + m_0^2}$$

L. Adamczyk et al. (STAR), arXiv:1701.06060

v_2 vs beam energy



Rich structure:

Transition from in-plane to out-of-plane and back to in-plane emission:

Low beam energies: rotational behavior

Mid beam energies: squeeze-out

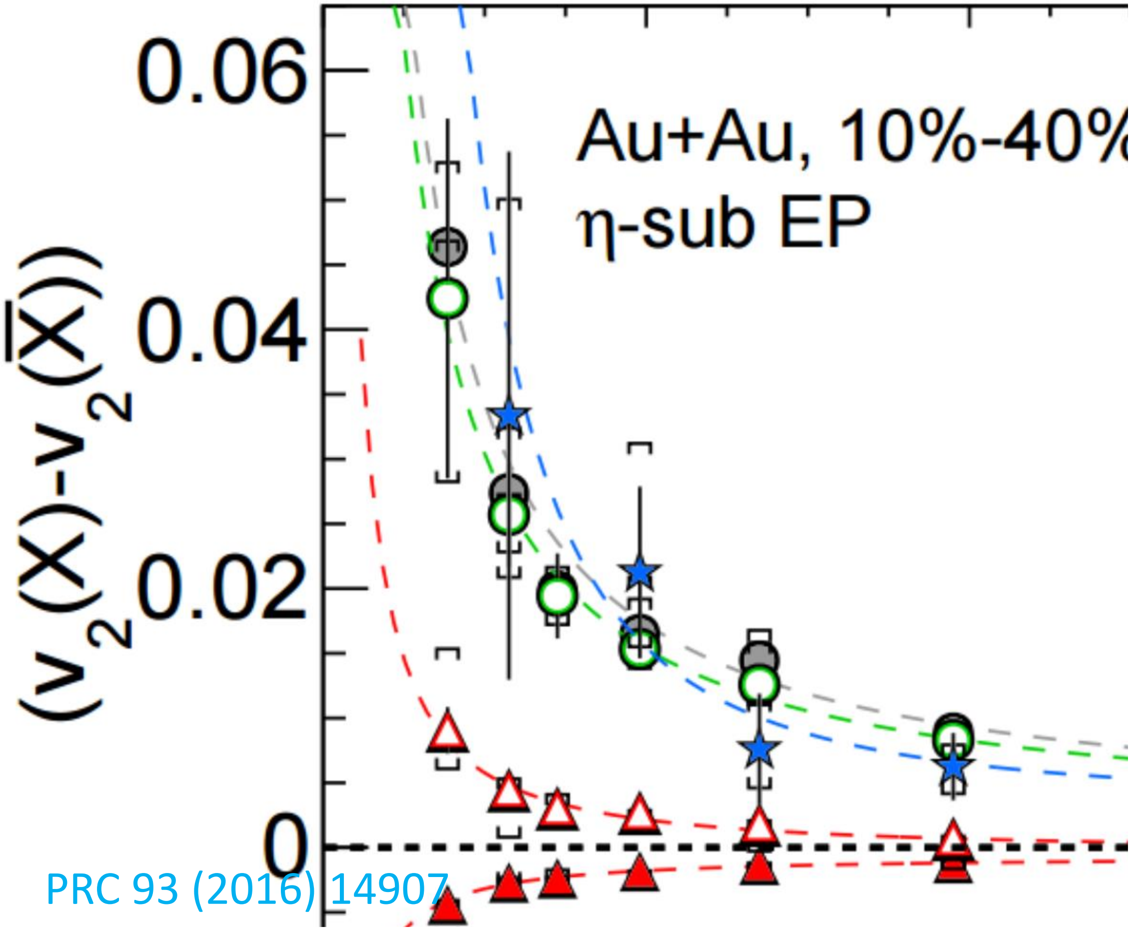
High beam energies: pressure-induced in-plane emission

v_2: particle vs anti-particle

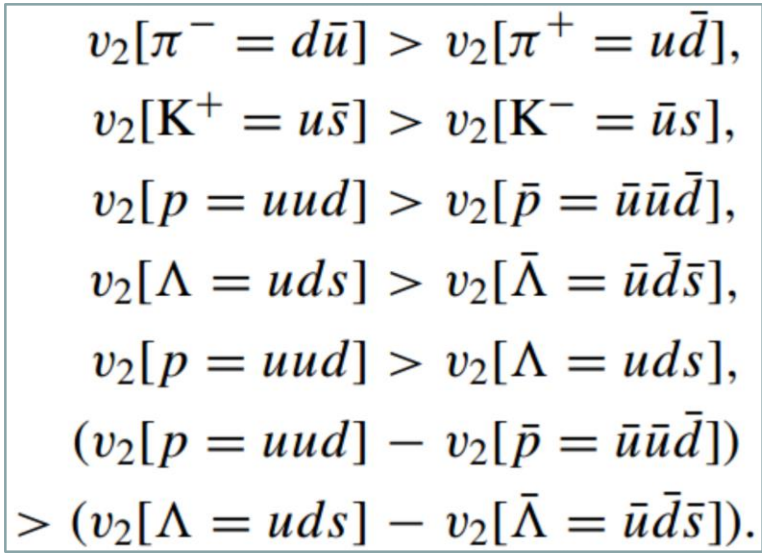
v_2 splitting between X and anti-X:
- disappearance of QGP?
- effect due to finite μ_B?
  - everything can be explained...

2 assumptions:
- coalescence
- more scattering for transport quarks

J. C. Dunlop, M. A. Lisa and P. Sorensen, PRC84 044914 (2011)



PRC 93 (2016) 14907

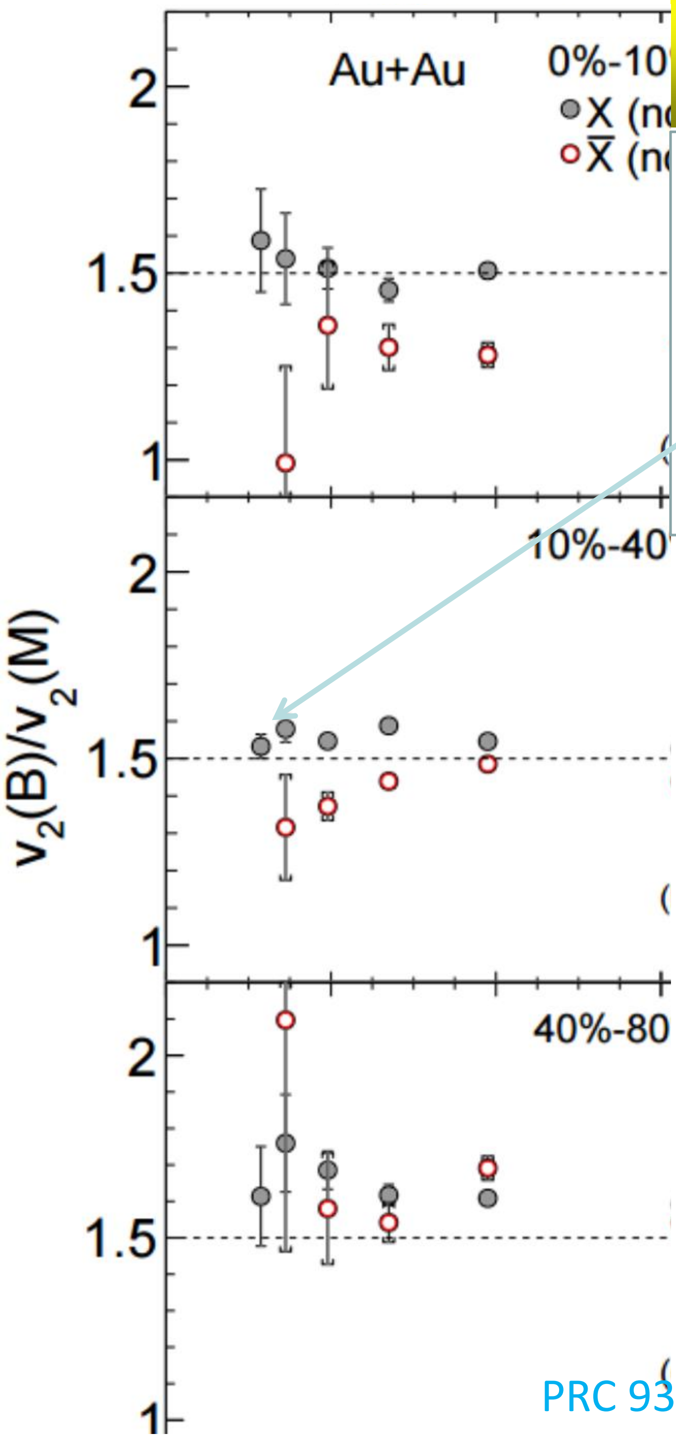


$$
\begin{aligned}
v_2[\pi^- = d\bar{u}] &> v_2[\pi^+ = u\bar{d}],\\
v_2[\mathrm{K}^+ = u\bar{s}] &> v_2[\mathrm{K}^- = \bar{u}s],\\
v_2[p = uud] &> v_2[\bar{p} = \bar{u}\bar{u}\bar{d}],\\
v_2[\Lambda = uds] &> v_2[\bar{\Lambda} = \bar{u}\bar{d}\bar{s}],\\
v_2[p = uud] &> v_2[\Lambda = uds],\\
(v_2[p = uud] &- v_2[\bar{p} = \bar{u}\bar{u}\bar{d}])\\
> (v_2[\Lambda = uds] &- v_2[\bar{\Lambda} = \bar{u}\bar{d}\bar{s}]).
\end{aligned}
$$

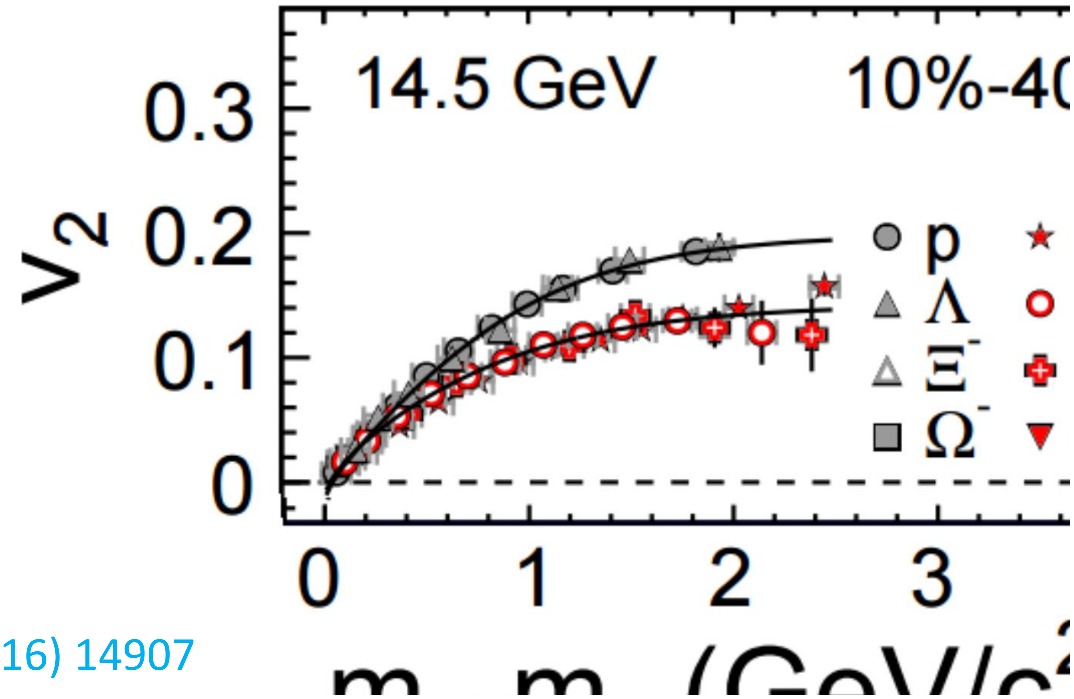
v_2: N_{cq}-scaling

v_2 splitting between B and M:

- fit the baryons and mesons separately
- perfect NCQ scaling → $v_2(B)/v_2(M)=1.5$
- a promising drop for anti-X in 10-40%
- future high statistics: anti-proton and K^-

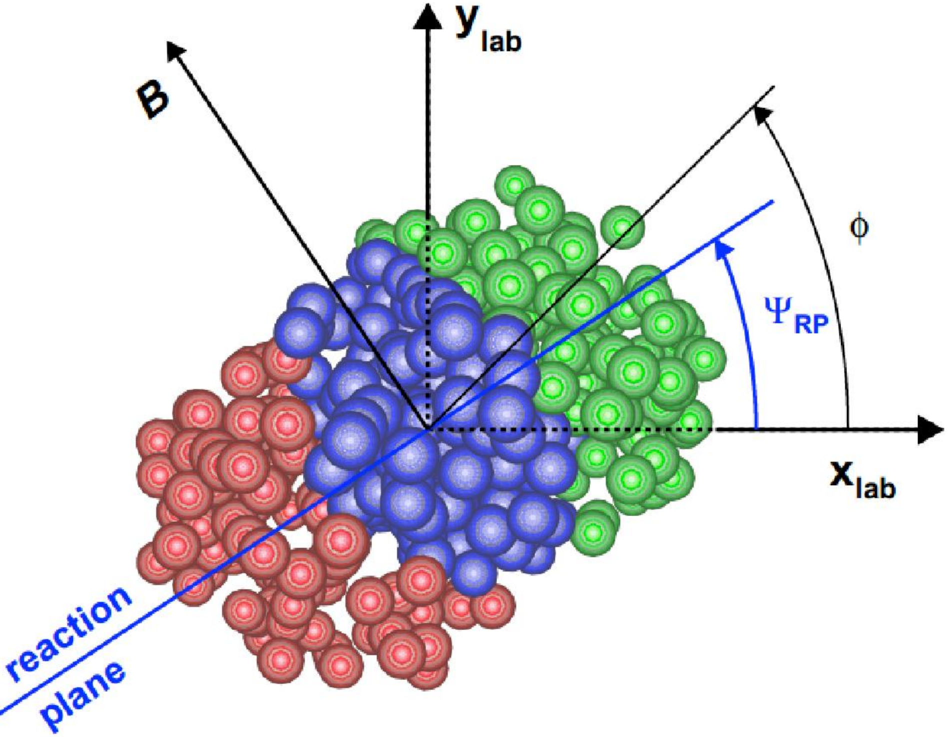


$$f_{v_2}(p_T, n) = \frac{an}{1+e^{-(p_T/n-b)/c}} - dn$$



PRC 93 (2016) 14907

Event plane

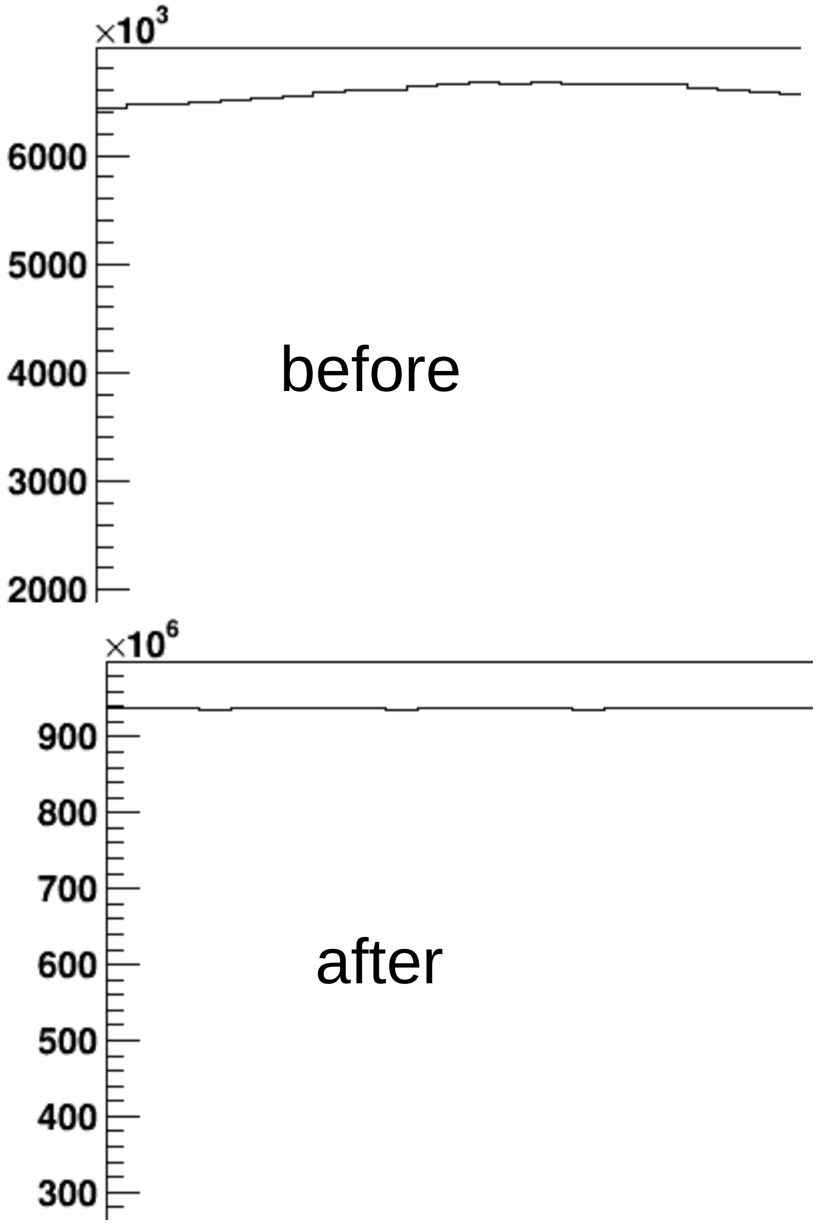


The estimated reaction plane is called the event plane.

$$Q_n \cos(n\Psi_n) = Q_x = \sum_i w_i \cos(n\phi_i)$$

$$Q_n \sin(n\Psi_n) = Q_y = \sum_i w_i \sin(n\phi_i)$$

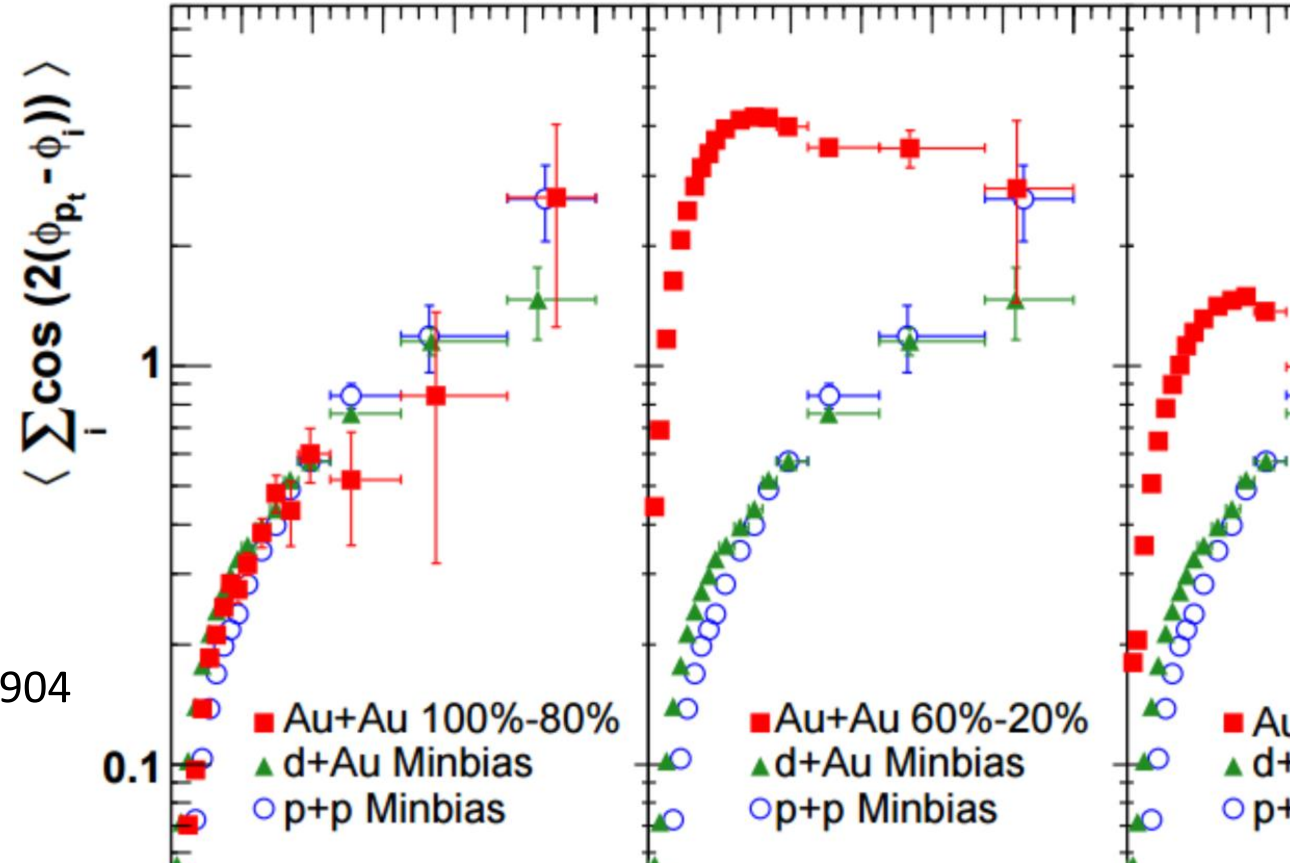
$$\Psi_n = \left(\tan^{-1}\frac{Q_y}{Q_x}\right)/n$$



E877, Phys. Rev. C 56 (1997) 3254

Collectivity vs non-flow

Collectivity is a global effect: multiple particles correlated across rapidity due to a common source



STAR, Phys. Rev. C 72 (2005) 14904

- Note 1: collectivity does not imply a specific physical interpretation (i.e. collectivity ≠ hydro)
- Note 2: correlations not related to the reaction plane (jets, resonance decays, momentum conservation, HBT and so on) are commonly called "non-flow"...

Cumulants

- $c_2\{k\}$ measures correlations from groupings of k particles, explicitly subtracts correlations from $< k$ particles

$$
\begin{aligned}
c_n\{2\} &= \langle\langle 2\rangle\rangle = \langle\langle\cos n(\varphi_1 - \varphi_2)\rangle\rangle \\
c_n\{4\} &= \langle\langle 4\rangle\rangle - 2\,\langle\langle 2\rangle\rangle^2 \\
c_n\{6\} &= \langle\langle 6\rangle\rangle - 9\,\langle\langle 4\rangle\rangle\,\langle\langle 2\rangle\rangle + 12\,\langle\langle 2\rangle\rangle^3
\end{aligned}
$$

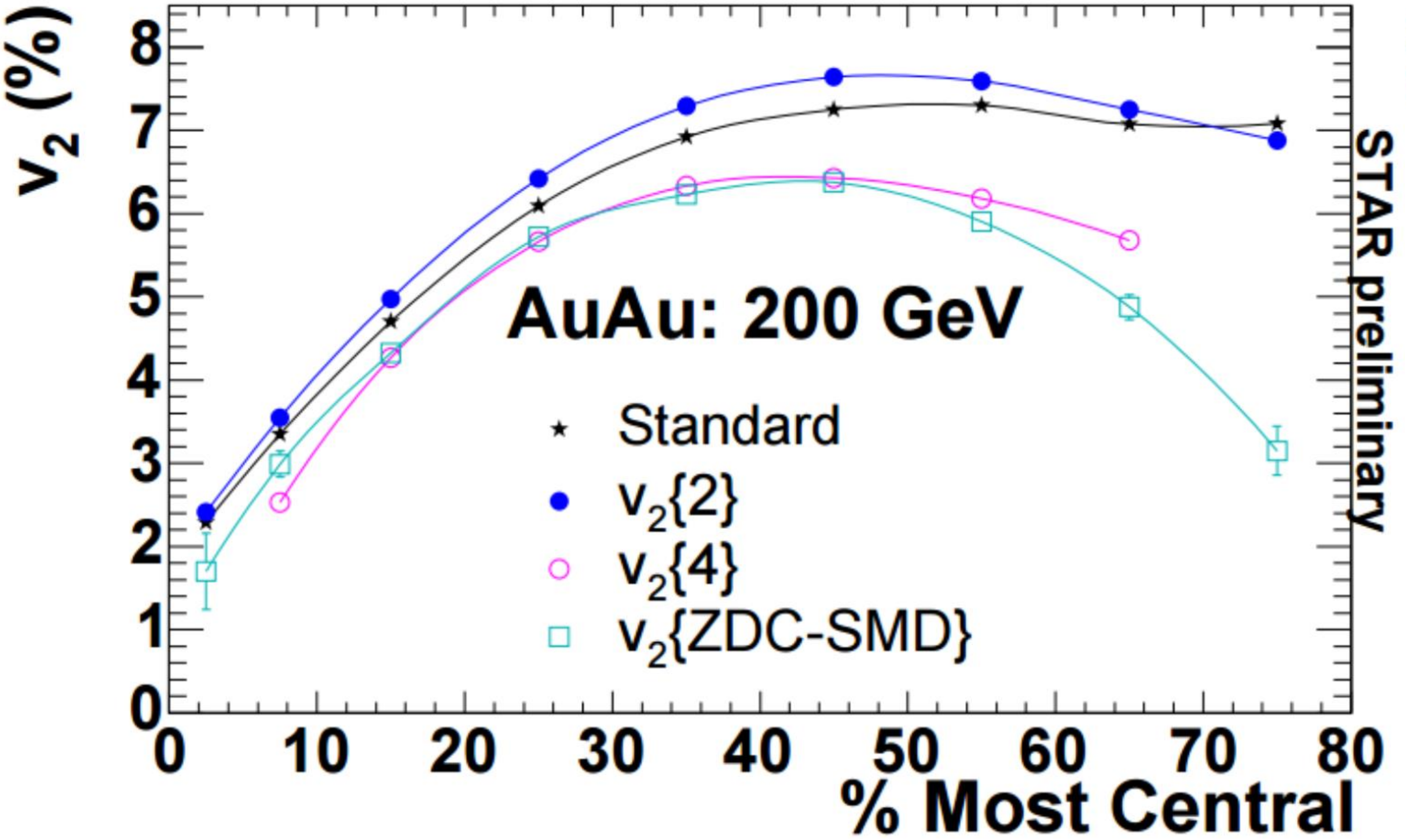
- $c_2\{k\}$ are related to $v_2\{k\}$

$$v_n\{2\} = \sqrt{c_n\{2\}},\ v_n\{4\} = \sqrt[4]{-c_n\{4\}},\ v_n\{6\} = \sqrt[6]{c_n\{}$$

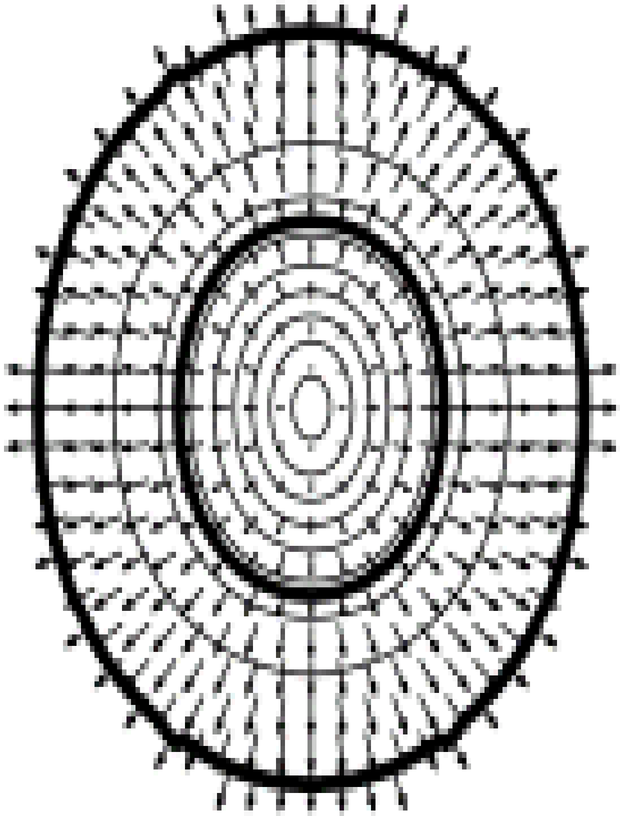
- $v_2\{\mathrm{LYZ}\}$ – removes all lower-order correlations

Different approaches, different results

- Several approaches give different v_2 values.
- Different centrality dependence.
- Non-flow and flow fluctuation.

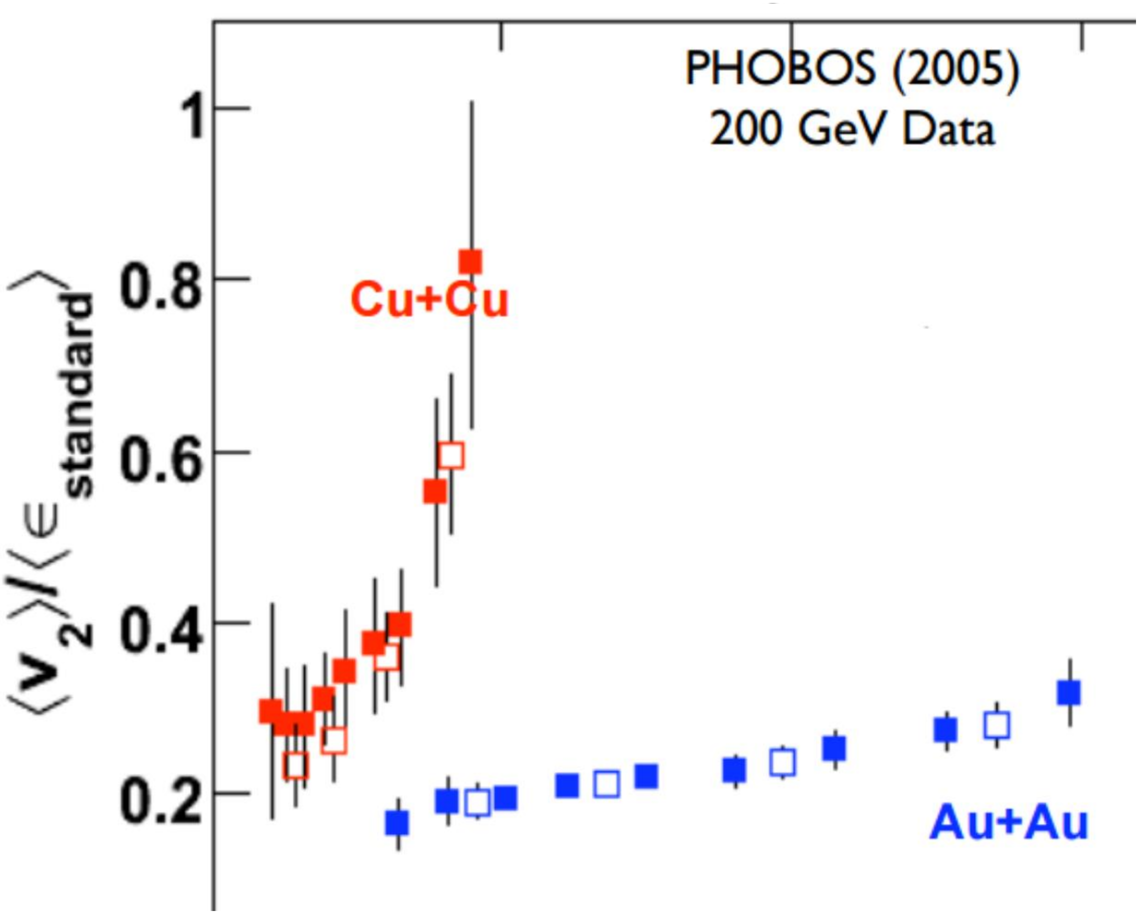


Eccentricity



Elliptic flow v_2 is supposed to be proportional to the initial spatial eccentricity, ε: (Optical Glauber)

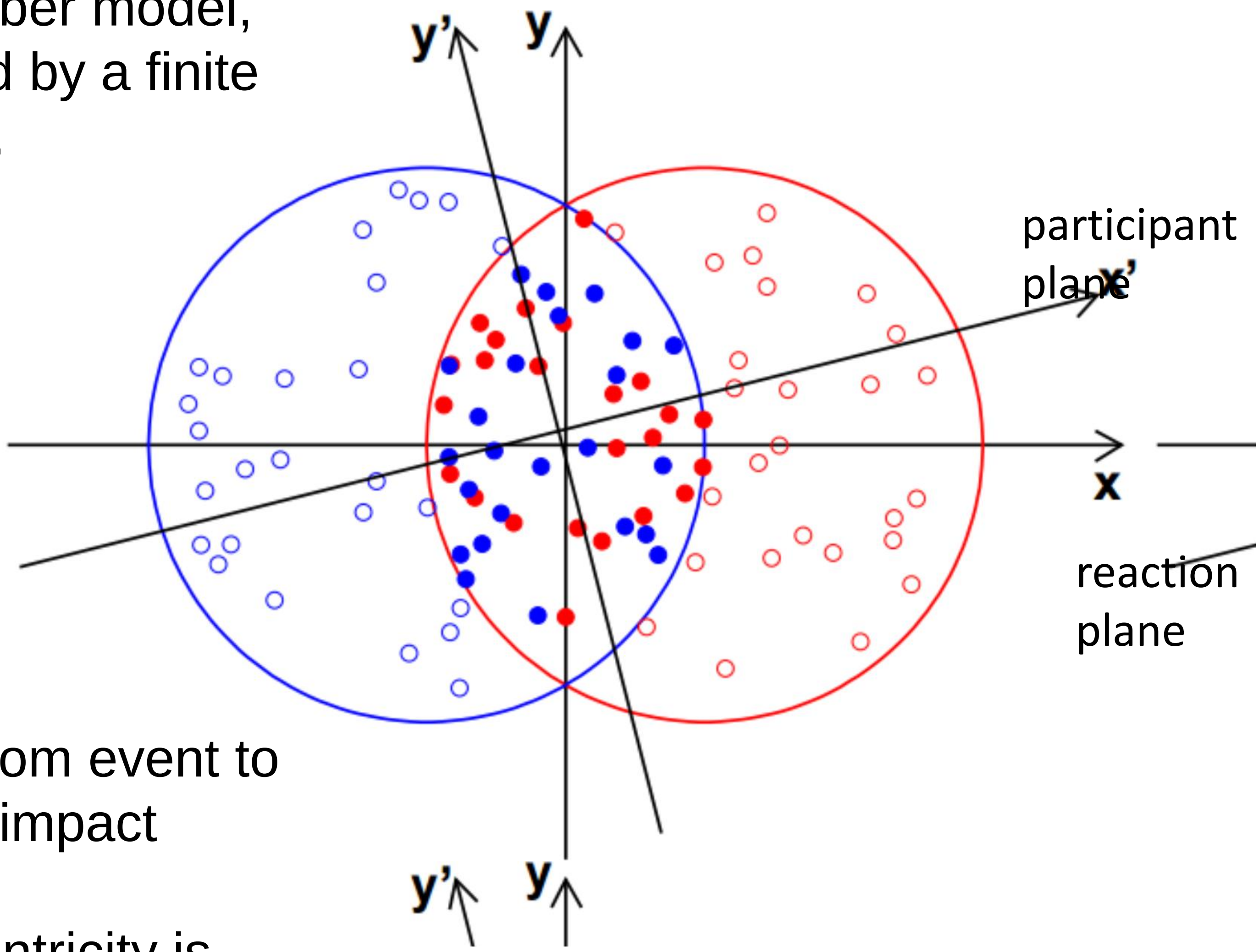
$$\varepsilon_{\mathrm{std}} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$



For same N_{part} (~ same initial density), $v_2/\varepsilon_{\mathrm{std}}$ is much larger in Cu+Cu than in Au+Au collisions

Participant plane

In Monte Carlo Glauber model, geometry is sampled by a finite number of nucleons.



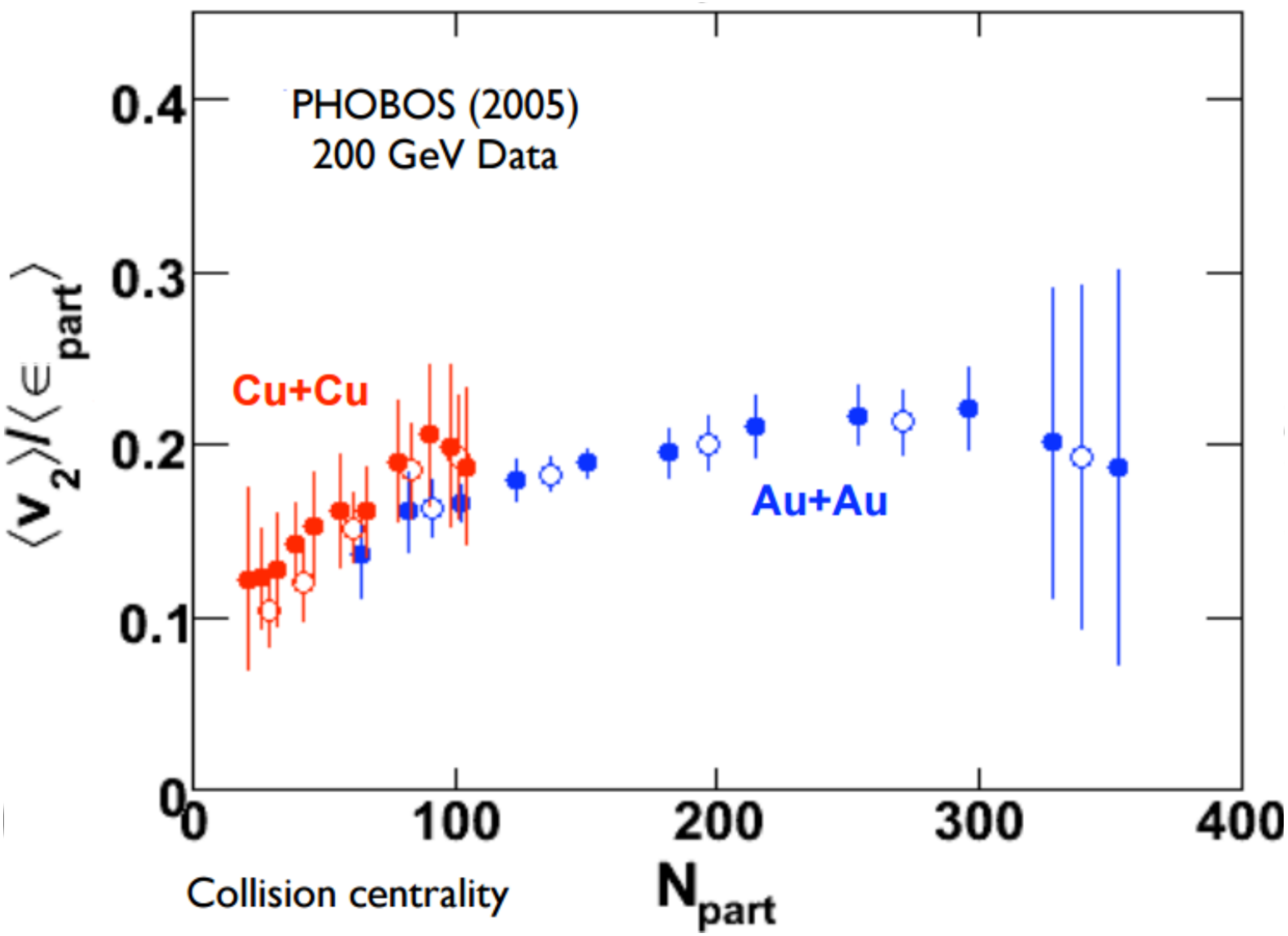
Eccentricity varies from event to event, even at fixed impact parameter.

The participant eccentricity is more relevant if flow is measured w.r.t the participant plane.

$$\varepsilon_{\mathrm{part}} = \frac{\sigma'^2_y - \sigma'^2_x}{\sigma'^2_y + \sigma'^2_x} = \frac{\sqrt{(\sigma^2_y - \sigma^2_x)^2 + 4(\sigma^2_{xy})^2}}{\sigma^2_y + \sigma^2_x}$$

System-size scaling

Re-interpretation with participant eccentricity yields v_2 scaling between Cu+Cu and Au+Au.



Flow and thermalization

What is thermalization ?

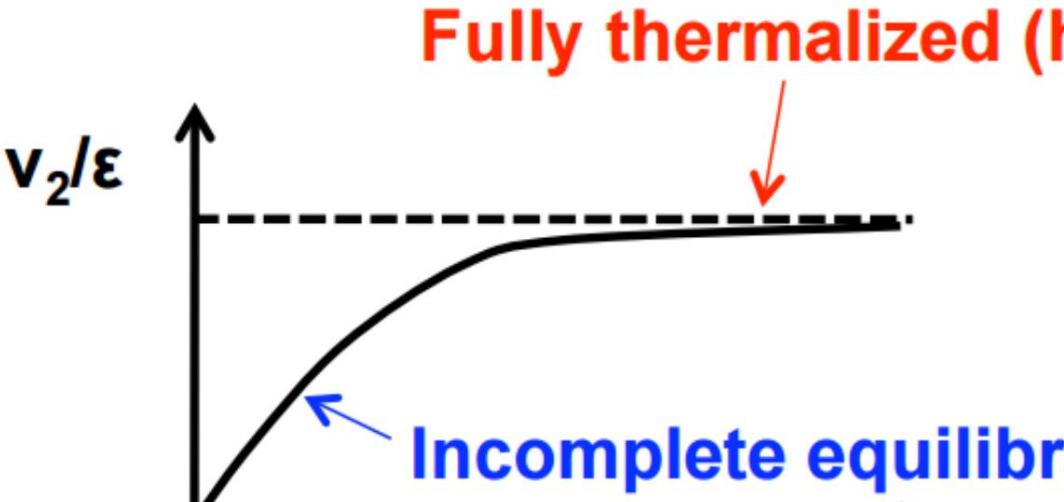
Equal partition of energy.

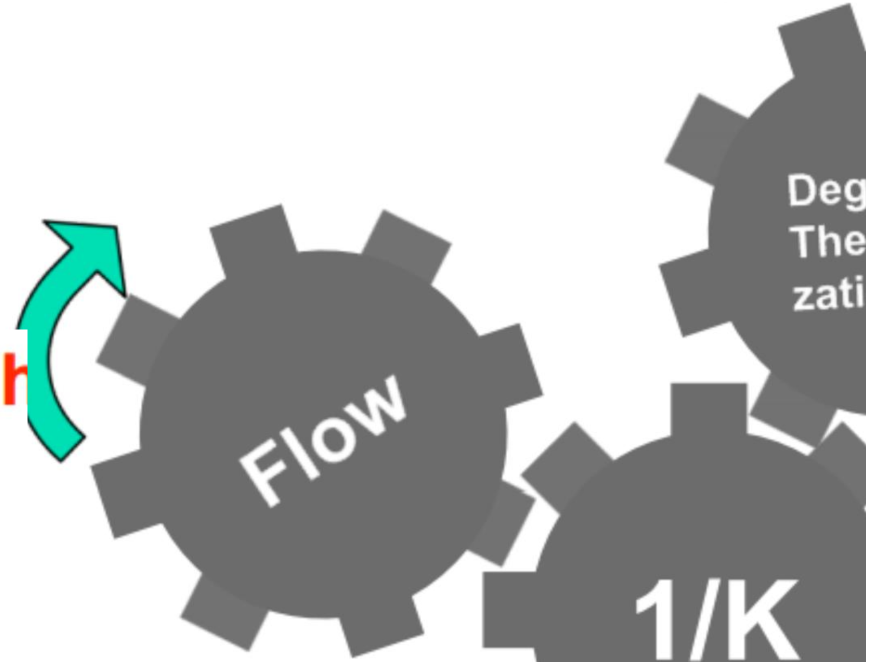
How is the thermalization achieved

Interactions !

How do we address the degree

Knudsen number (K=λ/R), 1/K





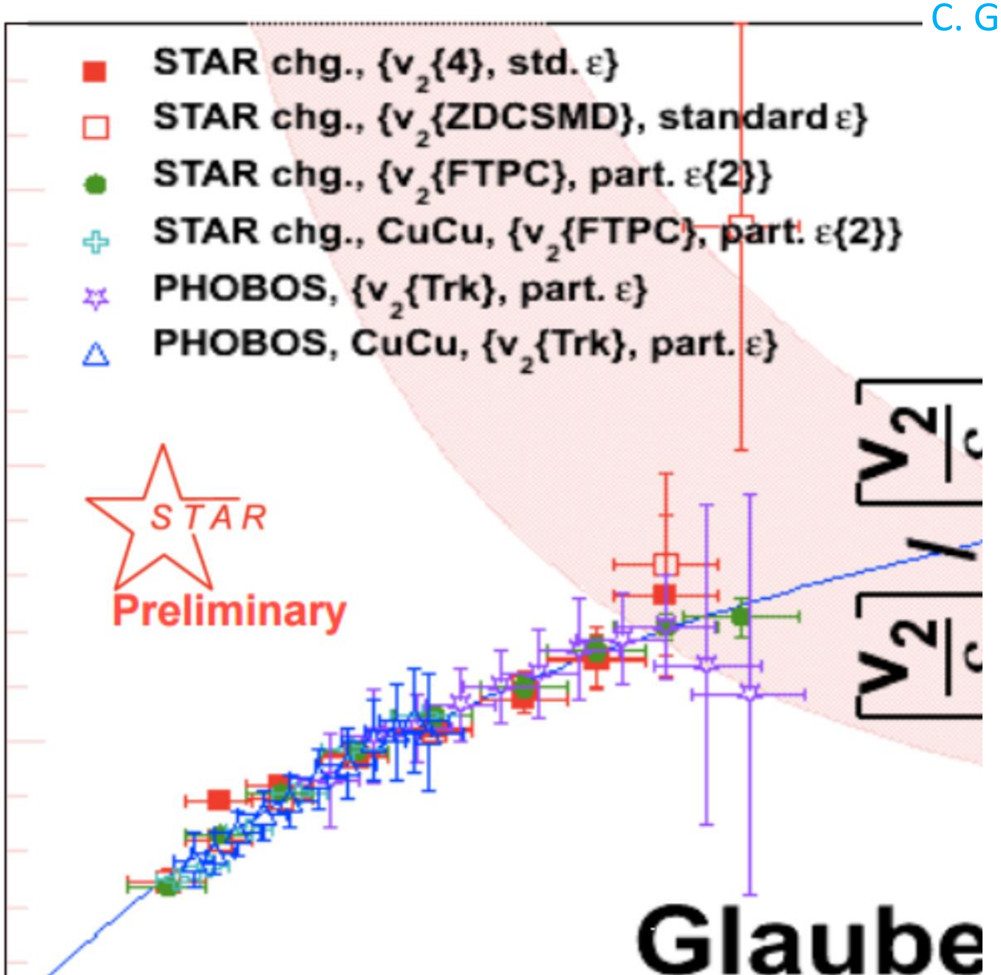
More scaling

$$\frac{v_2}{\varepsilon} = \left[\frac{v_2}{\varepsilon}\right]_{\mathrm{hydro}} \frac{1}{1+\mathrm{K}/\mathrm{K}_0}$$
$$= \left[\frac{v_2}{\varepsilon}\right]_{\mathrm{hydro}} \frac{1}{1+\left(\sigma c_s \frac{1}{S}\frac{dN}{dy}\right)^{-1}\frac{1}{\mathrm{K}_0}}$$

$$1-\left[\frac{v_2}{\varepsilon}\right] / \left[\frac{v_2}{\varepsilon}\right]_{hydro} \propto K$$ When K is small (Hydro Limit)

$$\left[\frac{v_2}{\varepsilon}\right] / \left[\frac{v_2}{\varepsilon}\right]_{hydro} \propto 1/K$$ When K is large (Low Density Limi

C. Gombeaud and J.-Y. Ollitrault, PRC**77** (2008)054904



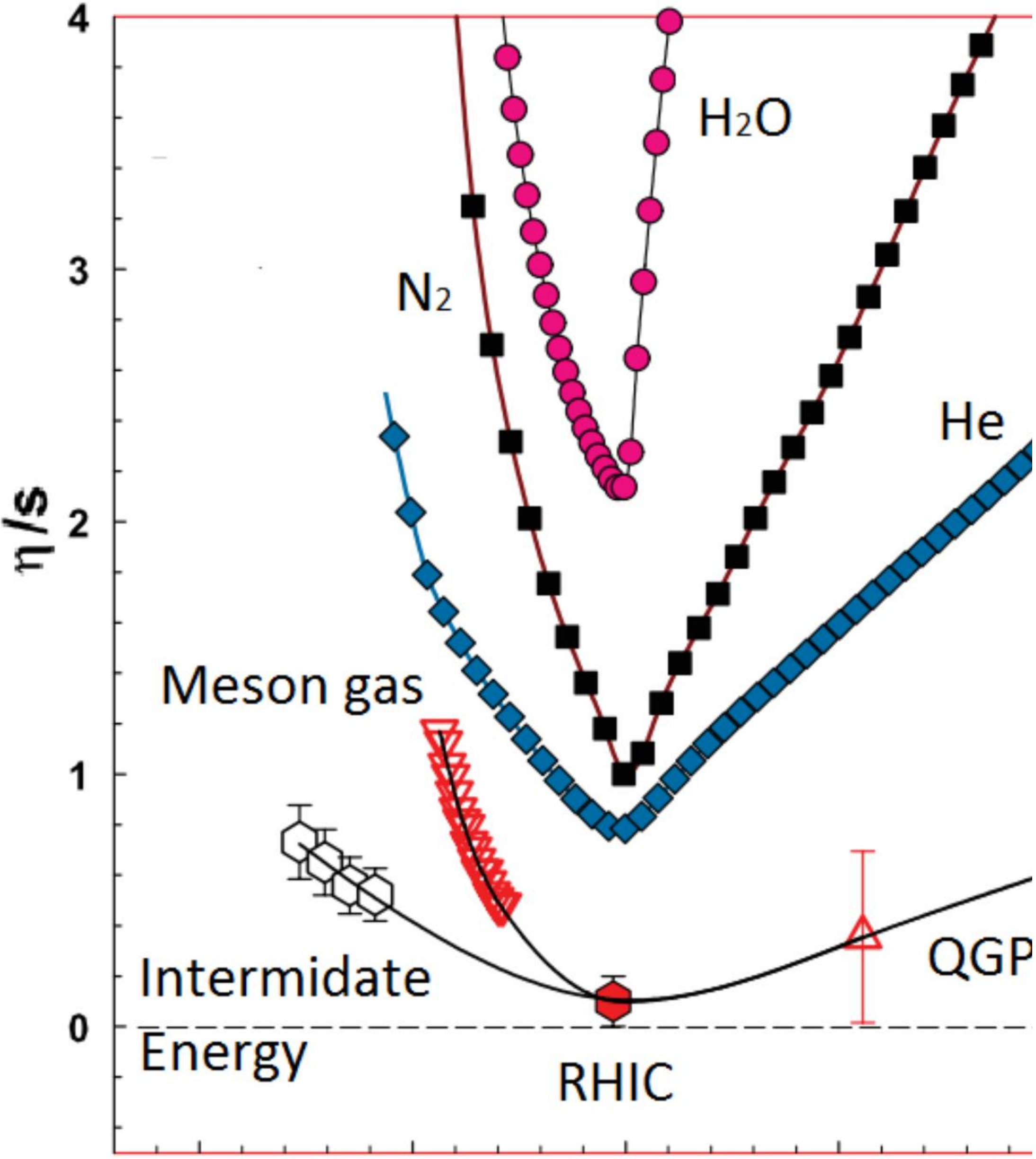
***K* : Knudsen number**
***σ* : parton X-section**
c_s : speed of sound
***S* : transverse area**

We may even extract viscosity (η/s) information from the scaling and fit:

$$\eta/s = 0.316\frac{T}{\sigma c_s}\frac{1/(S\bar{R})}{dN/dy}$$

Perfect liquid

R. Lacey et al., PRL 98, 092301(2007)

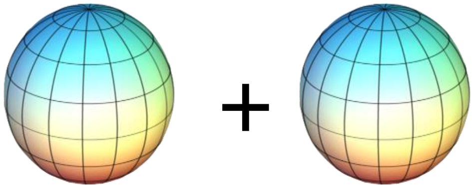


$$\eta / s < 2 \times \left(\frac{1}{4\pi} \right)$$

1/4π is the conjectured quantum limit.

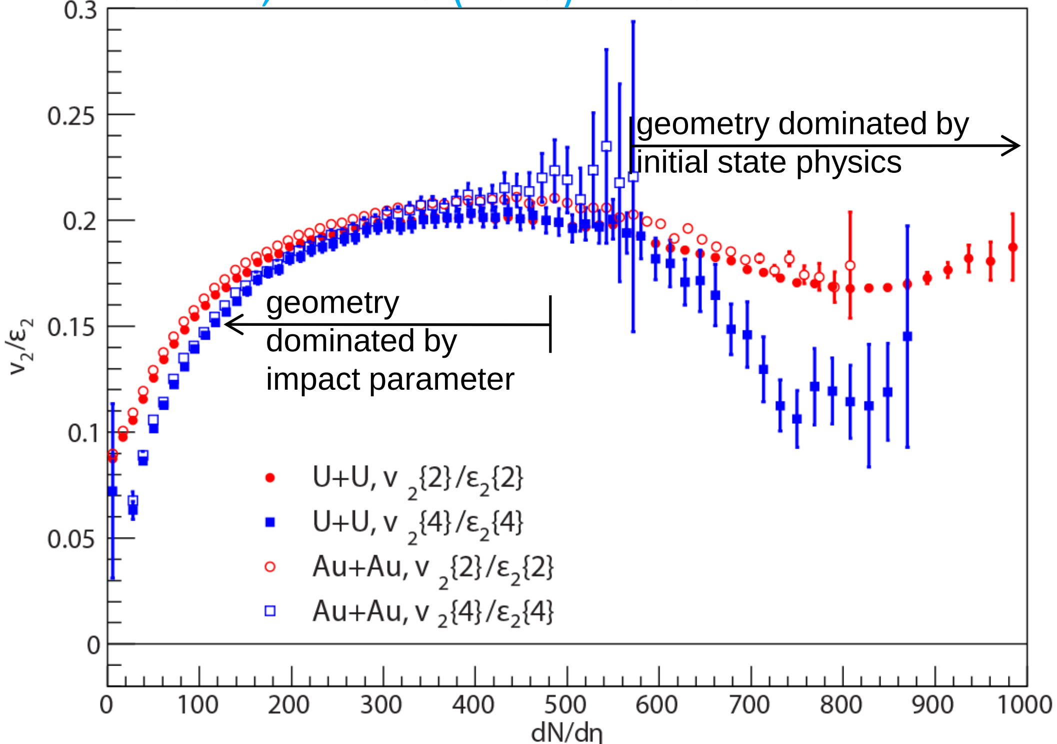
Breakdown of scaling?

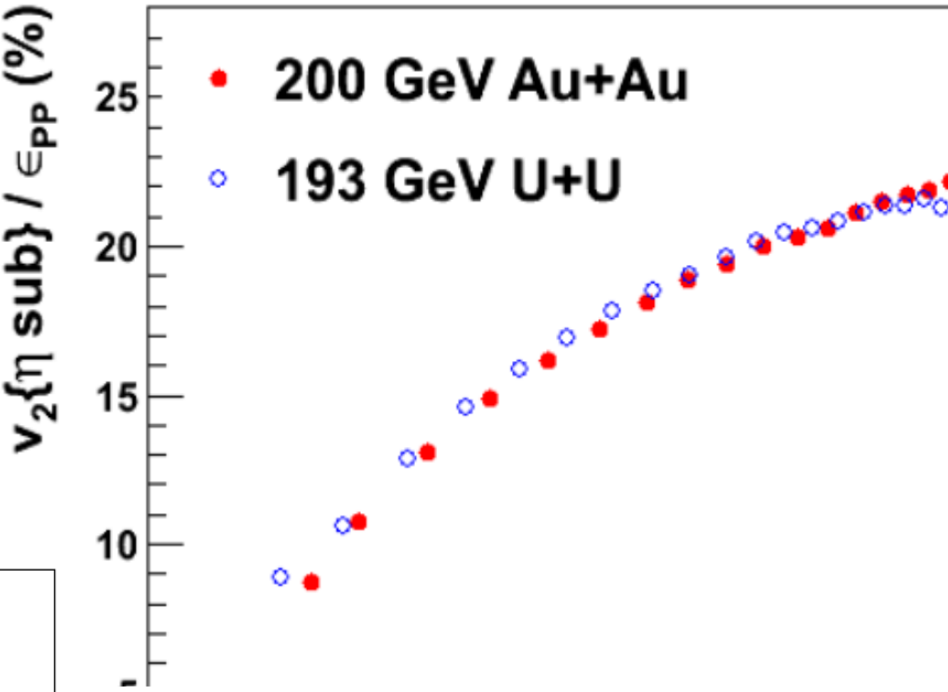
Au+Au Collisions



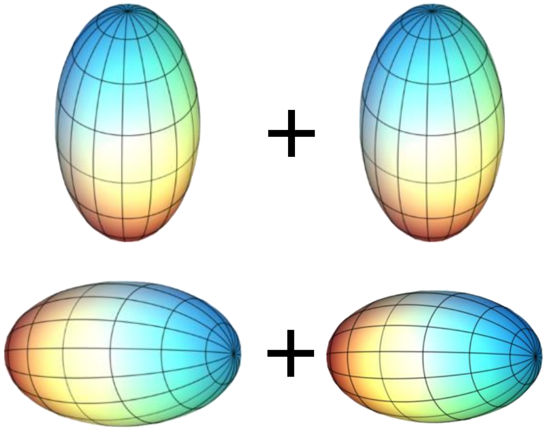
Oblate

STAR, PRL 115 (2015) 222301





U+U Collisions

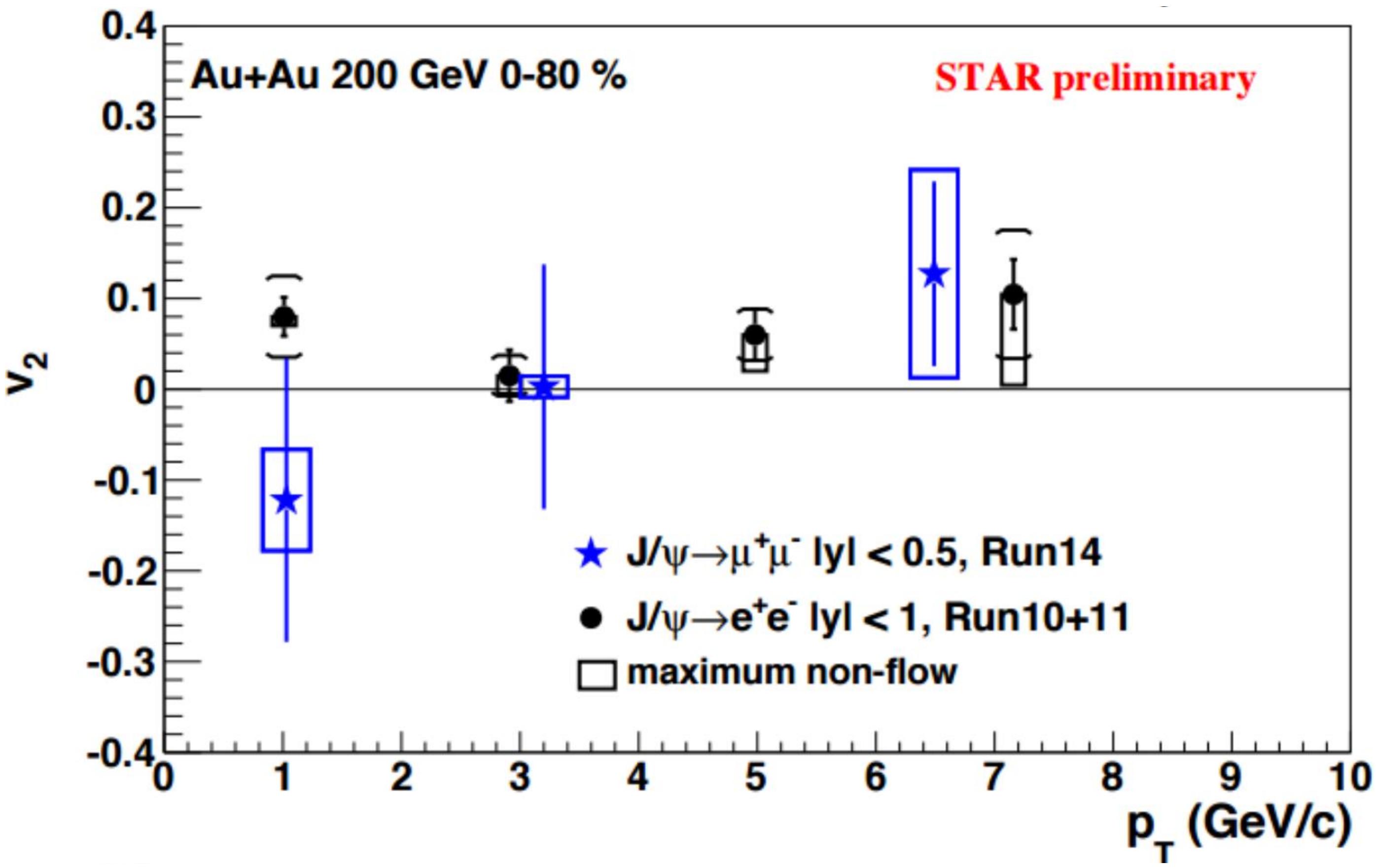


Prolate

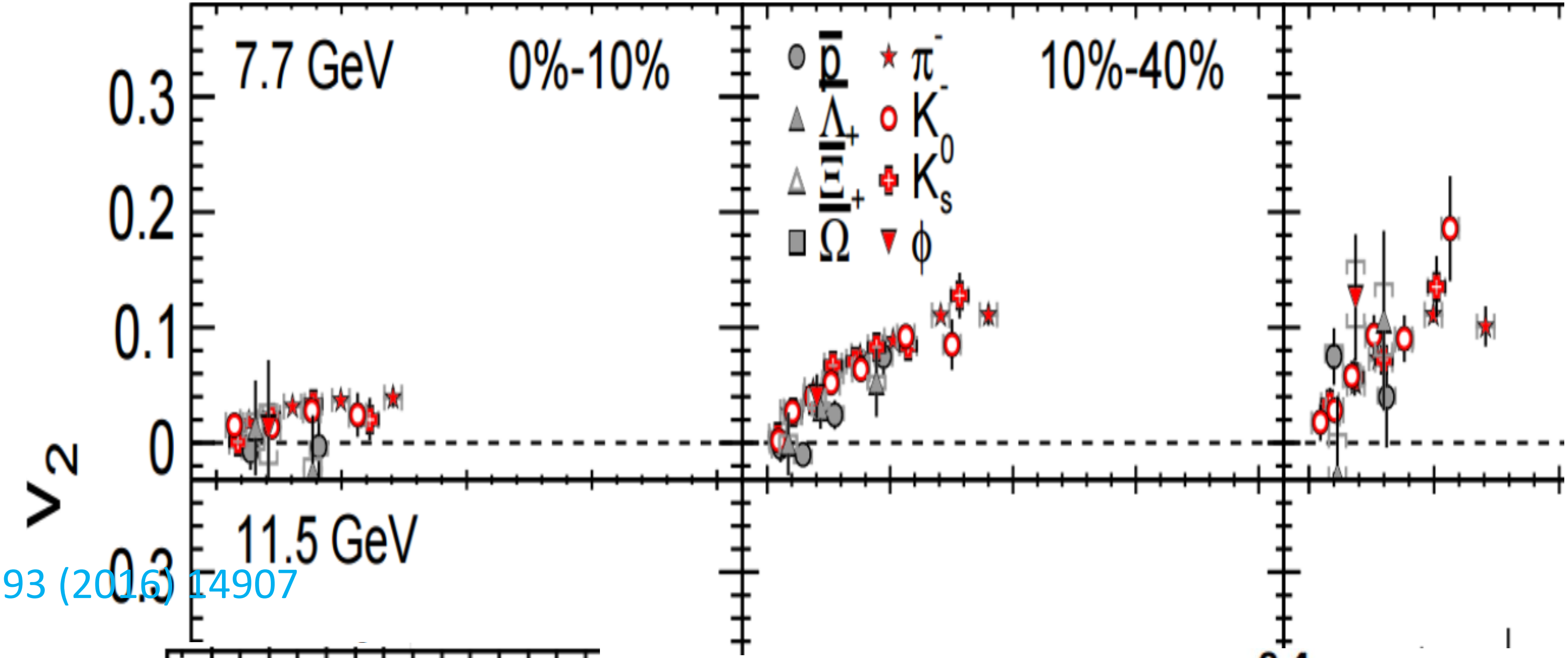
Back-up slides

J/ψ v_2

However, J/ψ doesn't seem to flow:
not enough flowing c quarks to regenerate J/ψ.



v_2: φ meson



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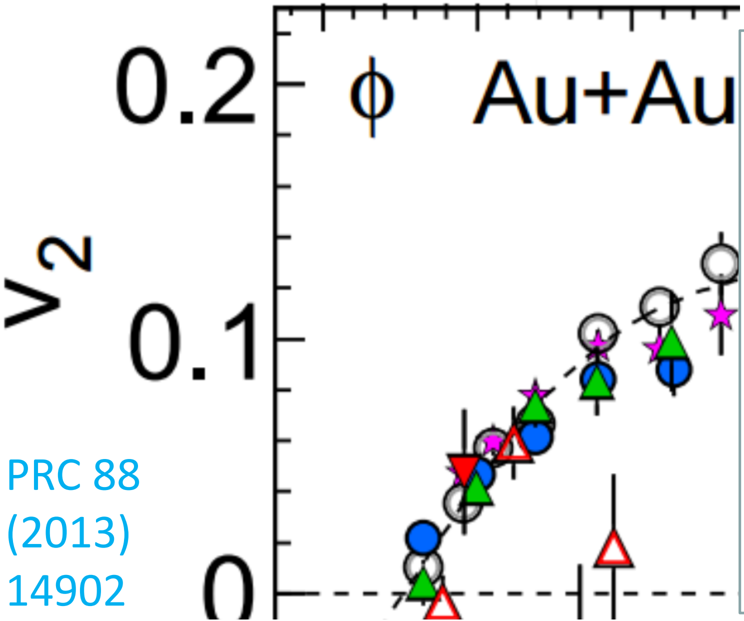

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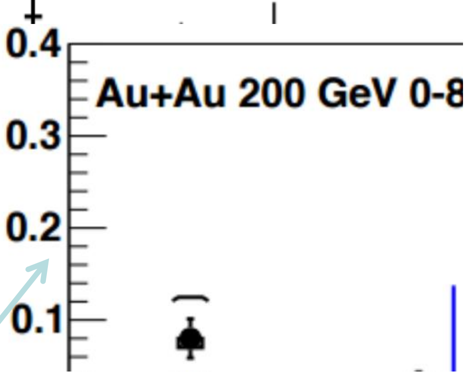
- φ meson v_2 may or may not disappear.
- Even if it does disappear, it may not mean that the QGP disappears.
- Remember J/ψ in



Regeneration is small, given finite v_2 of charm or strange quarks.