Experimental evidences of hydrodynamic flow in high-energy heavy-ion collisions

Univ. of Tsukuba

CiRfSE

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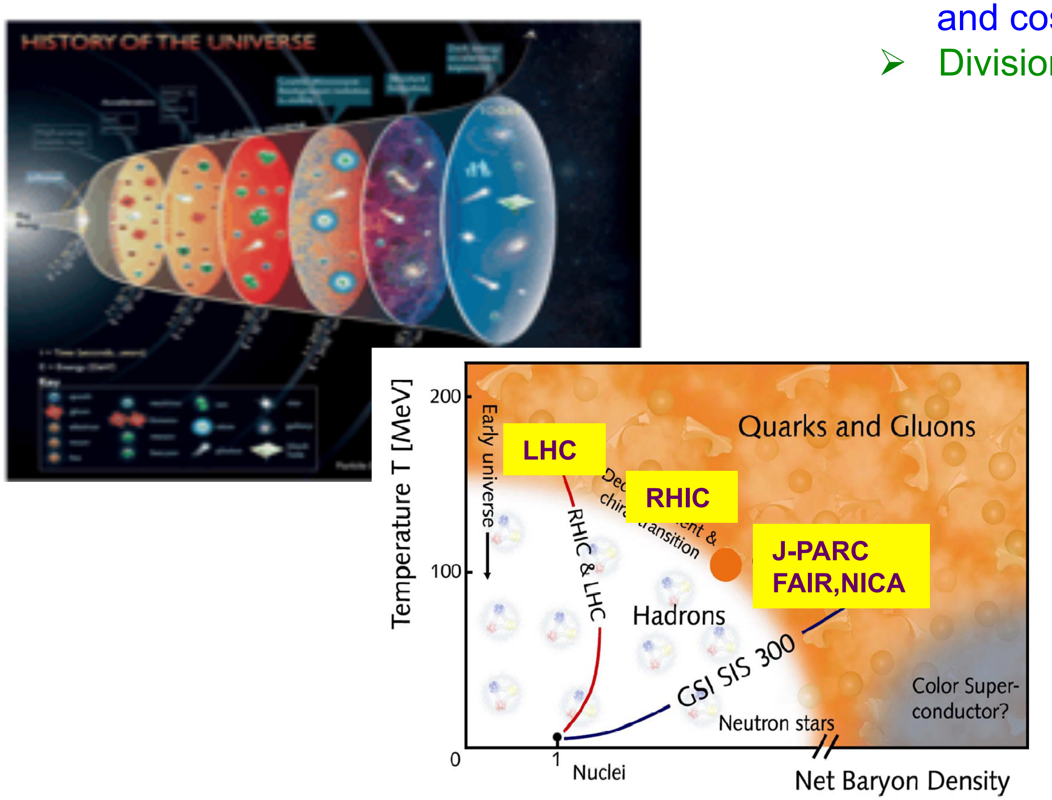
- Center for Integrated Research in Fundamental Science and Engineering (CiRfSE)
- Research Core for the History of the Universe (experimental elementary particle, nuclear physics and cosmology groups)
- Division of Quark Nuclear Matters

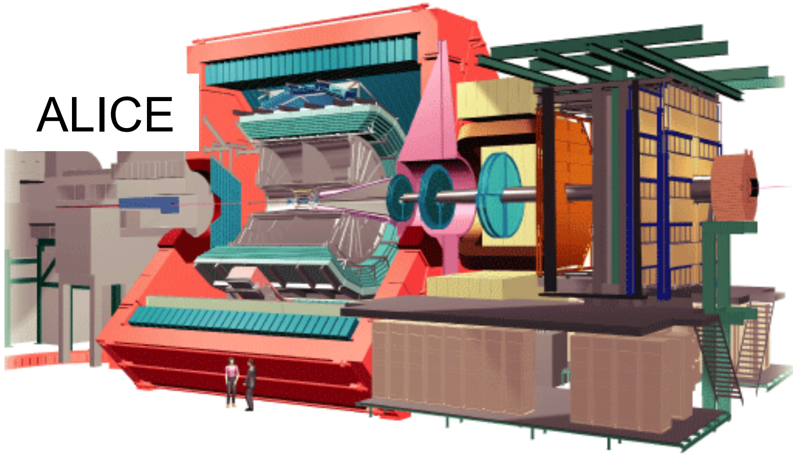


Contents

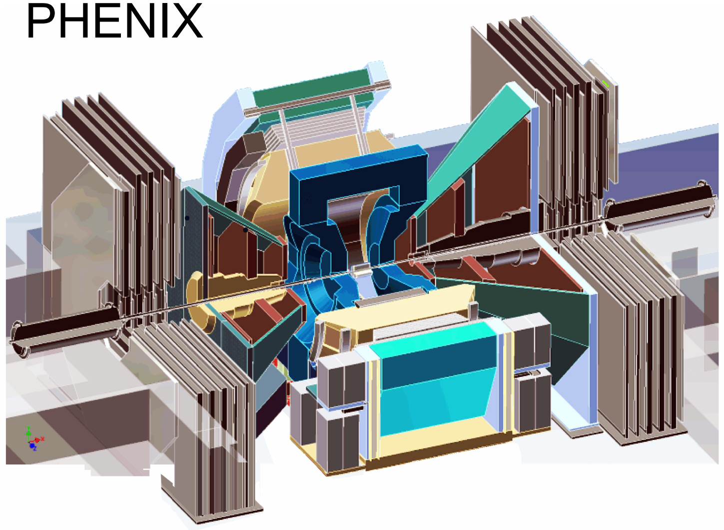
- connection between radial and elliptic flows
- from partonic to hadronic system
- possible flow in small and high-dense system
- relation to the critical point

Experiments at RHIC and LHC

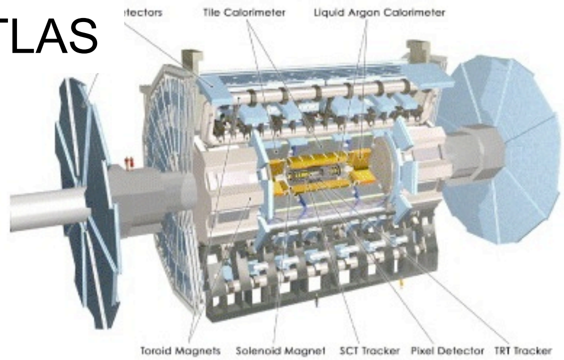
ALICE

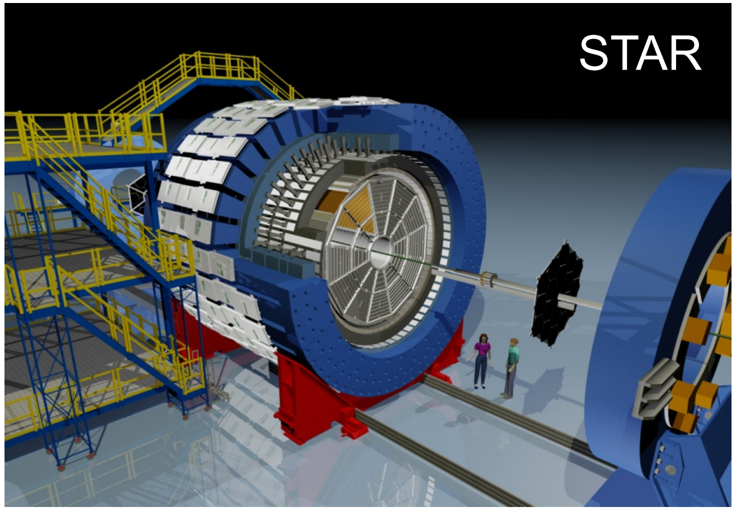


PHENIX

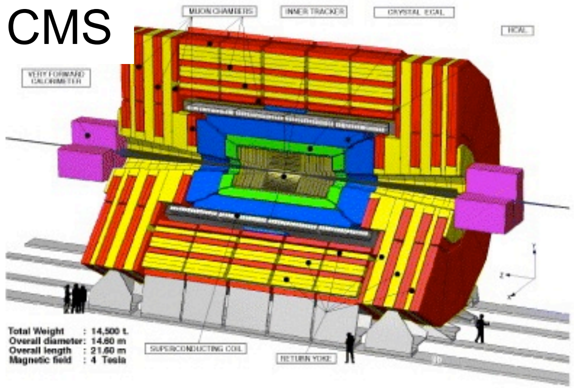


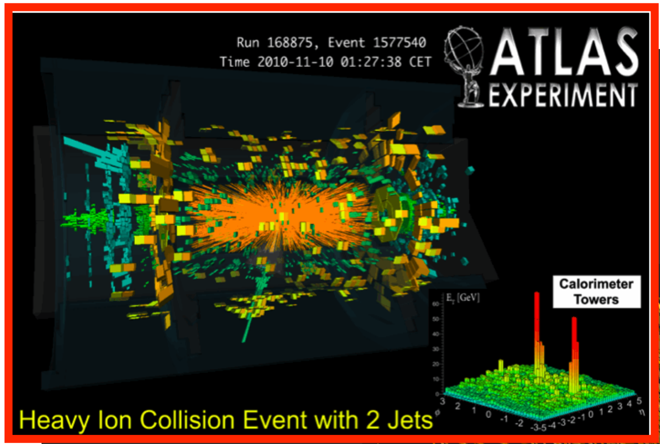
ATLAS

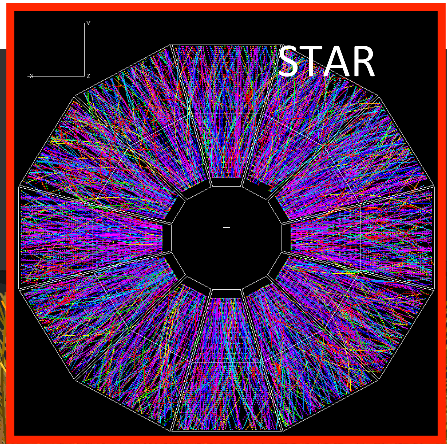


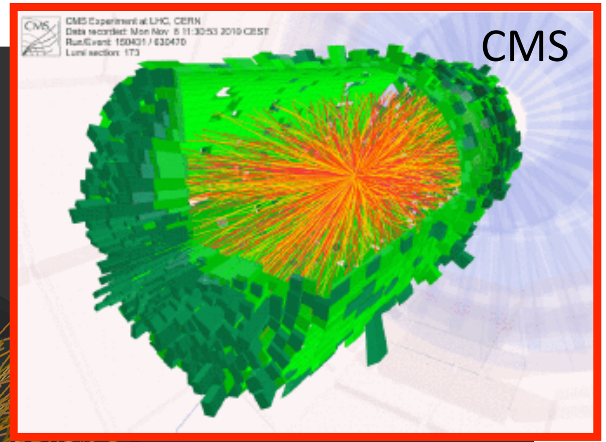


CMS



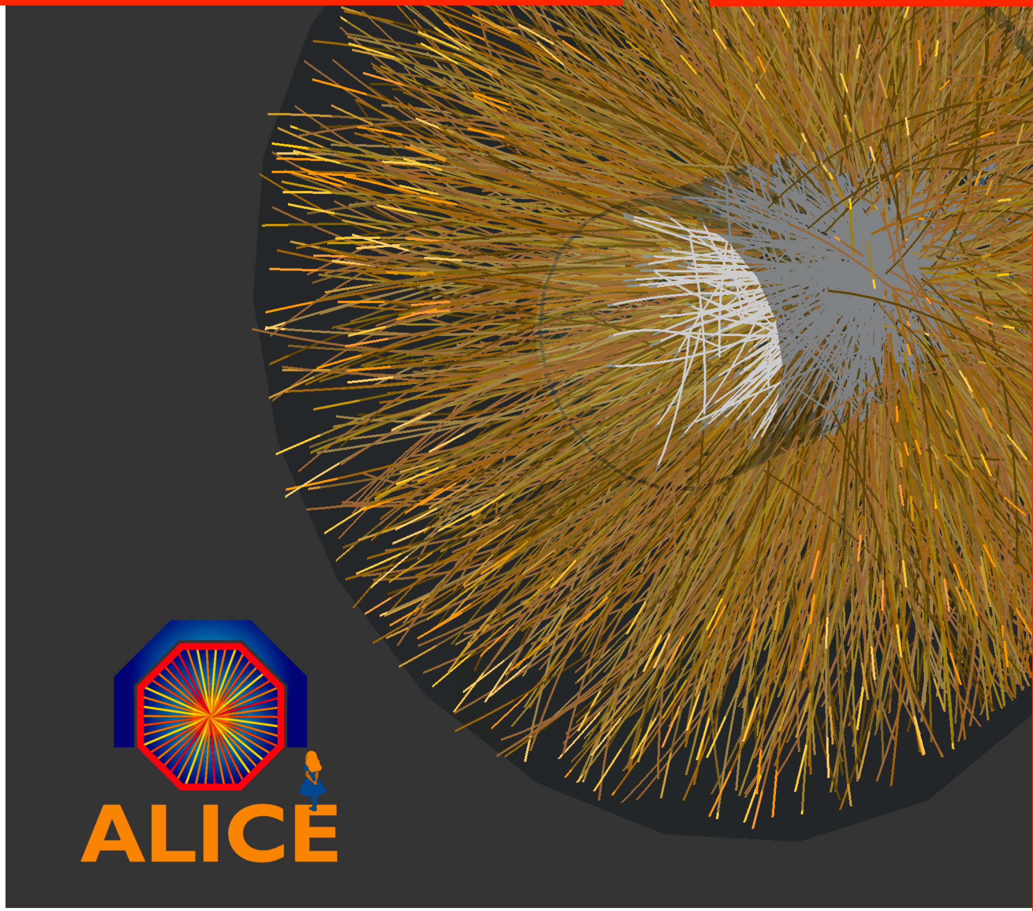


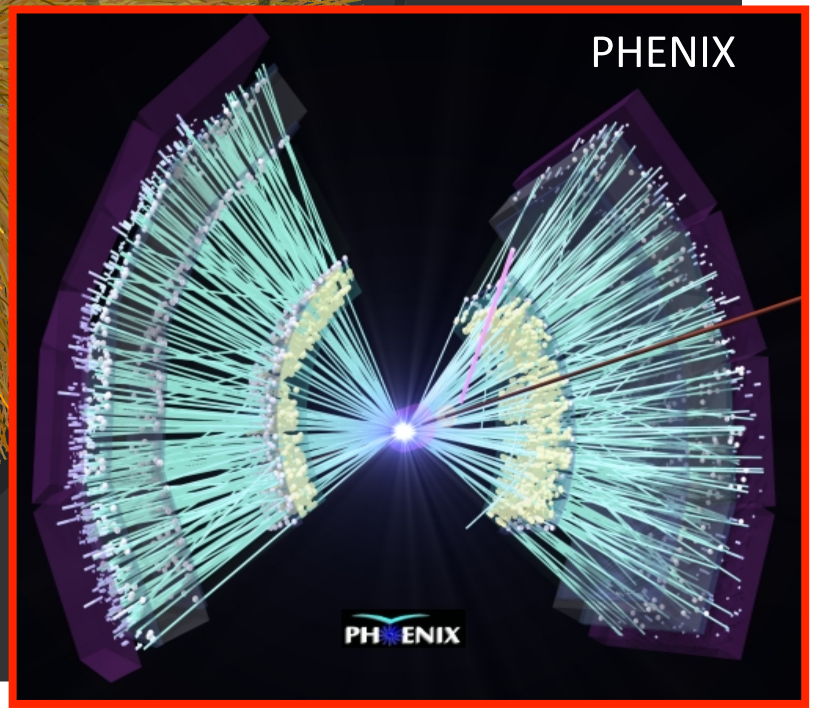




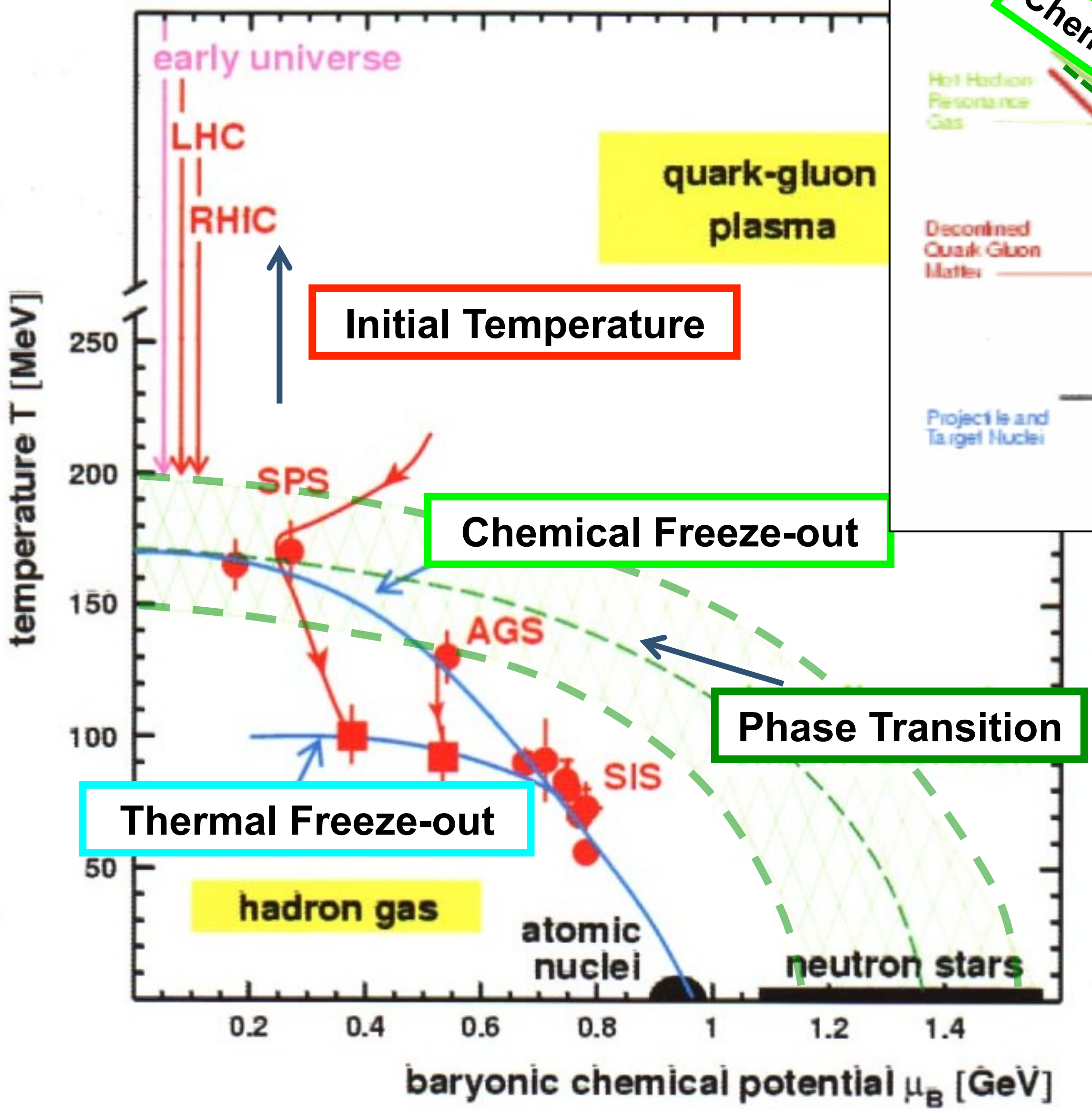
A+A central collision

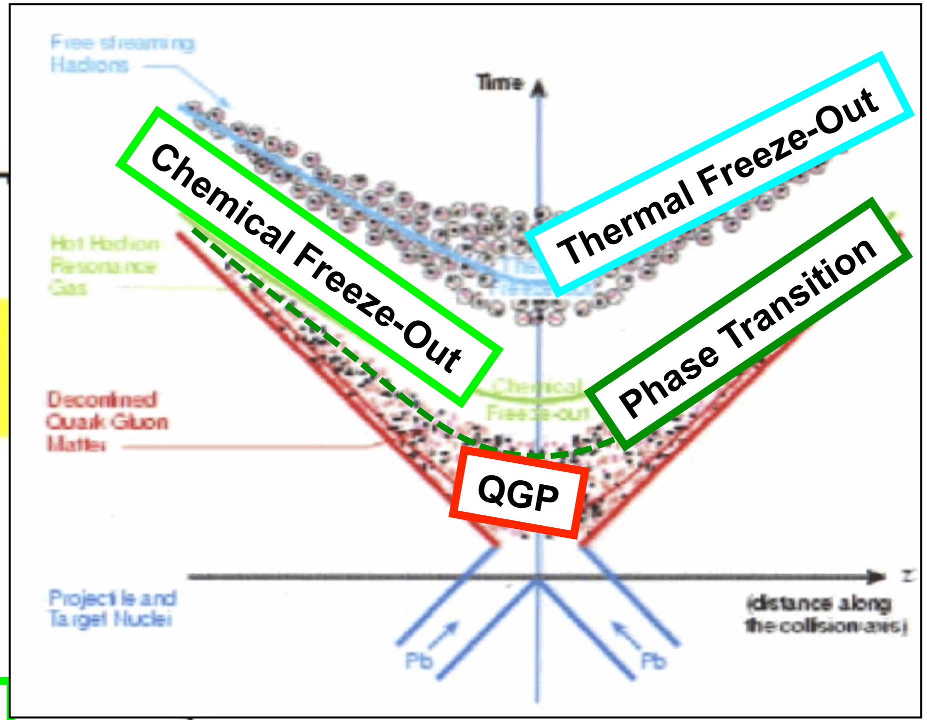
A few – 10k particles in an event





History of Temperature

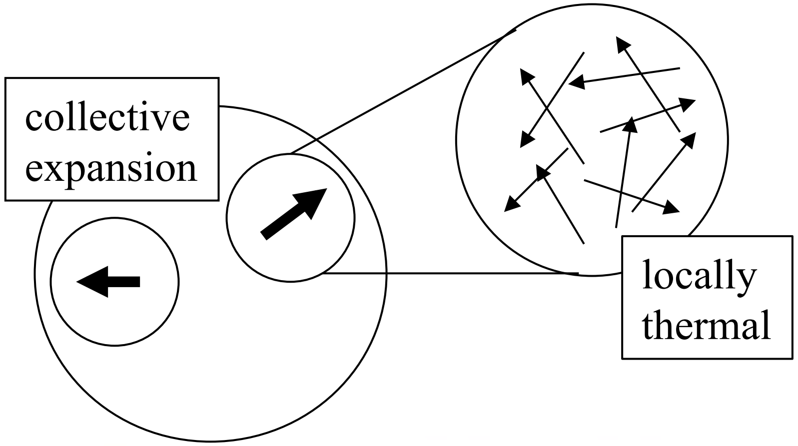


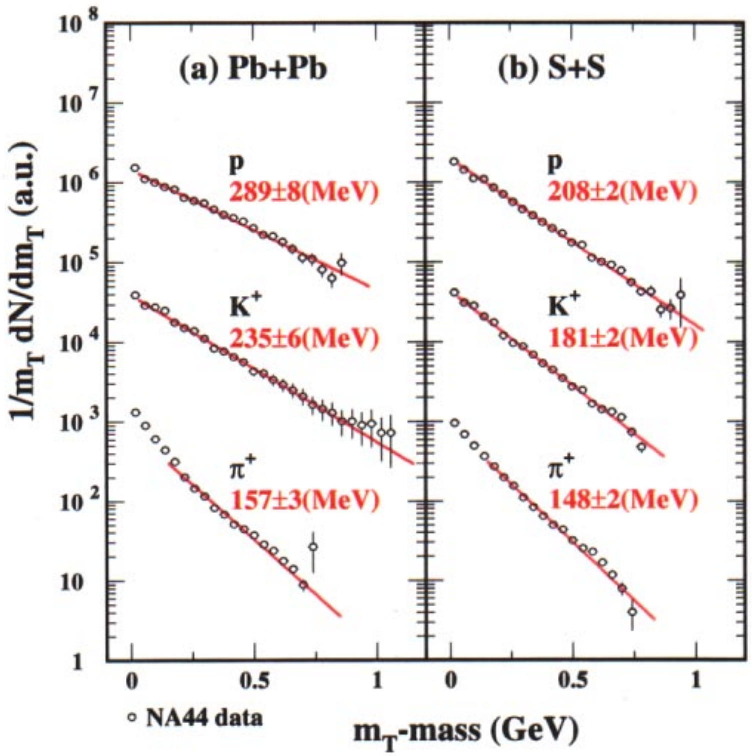


Thermal Freeze-out

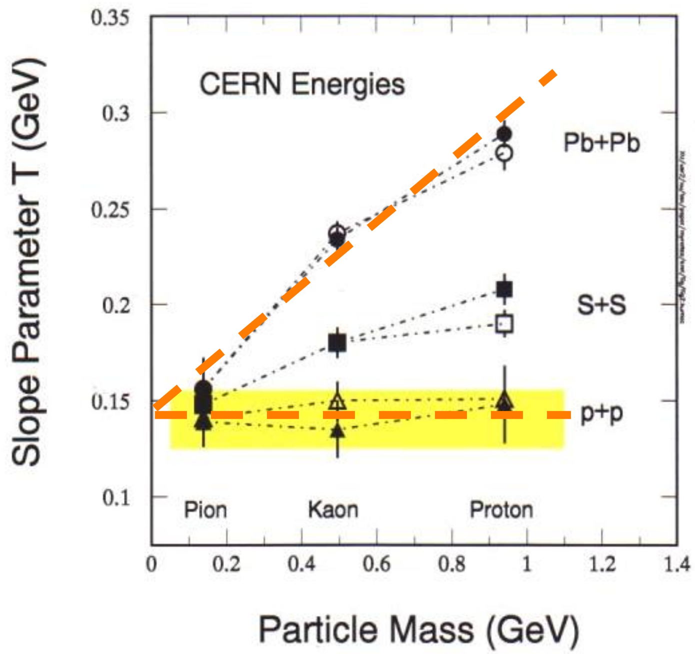
[at the end of elastic collisions]

Momentum distributions are determined with freeze-out temperature T_{fo} and collective radial expansion $<b_T>$





transverse mass distribution

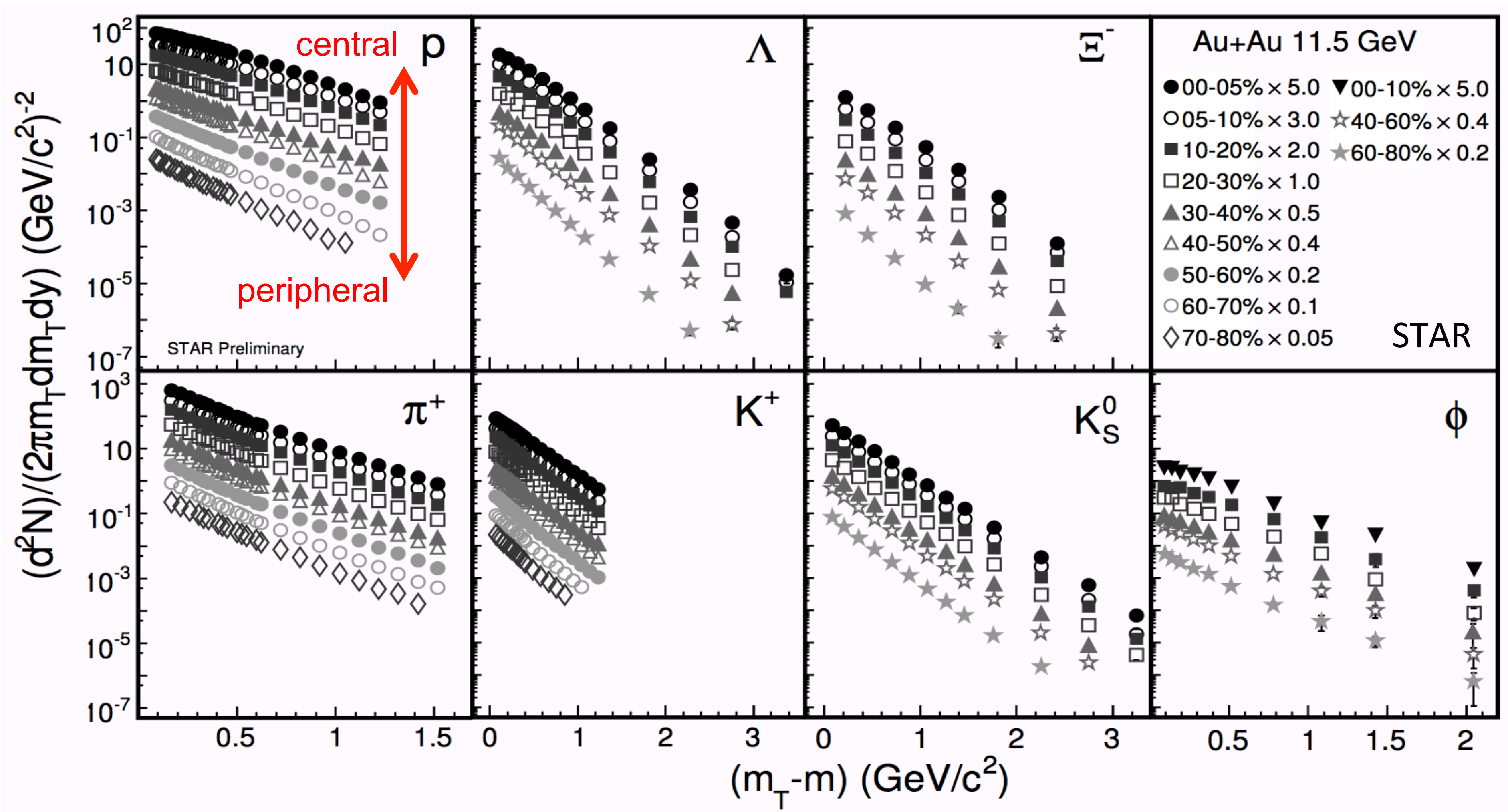


E = Ethermal + Ecollective

$$T_{eff} = T_{fo} + 0.5\, m \langle v_{\perp} \rangle^2$$

~140 MeV

Hadron spectra at sqrt(s_{NN})=11.5 GeV

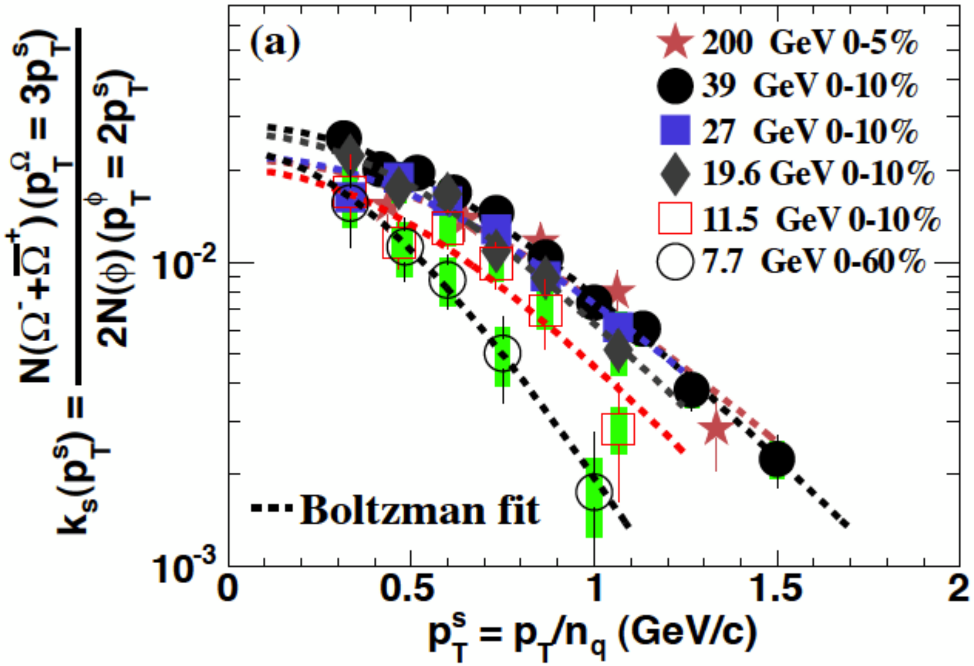


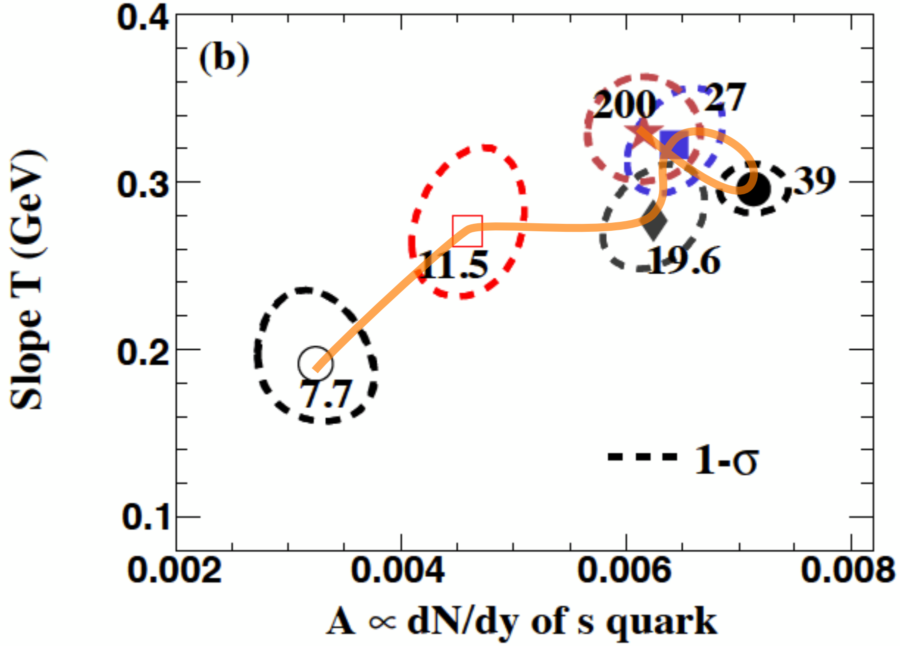
Strangeness Quark p_T distribution

based on Quark Coalescence picture

$\Omega(sss)$ / $\phi(ss)$ ~ s quark yield

arXiv:1506.07605, STAR





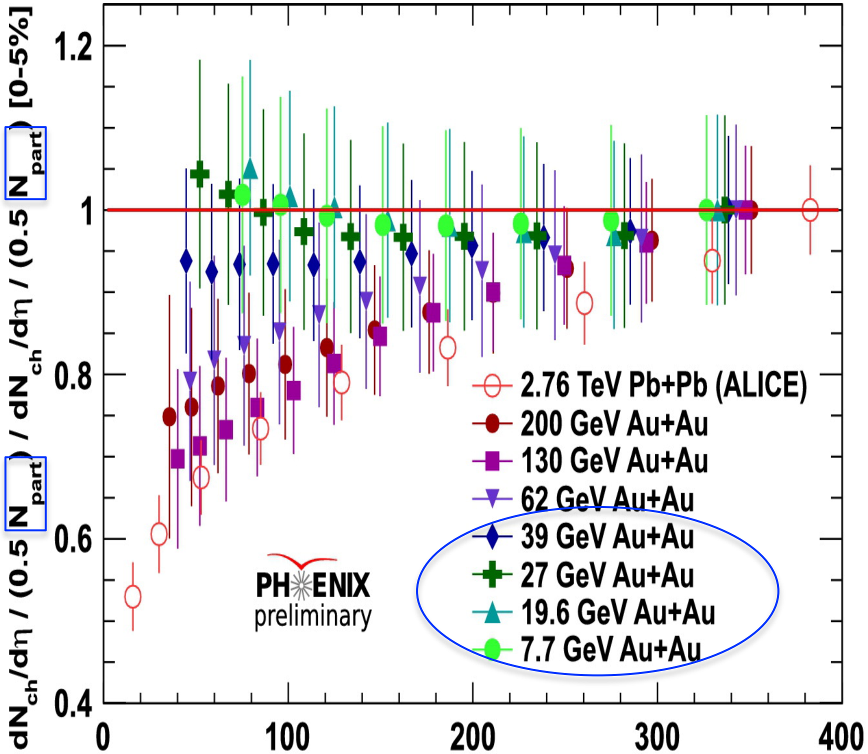
Charged particle multiplicity (Y = $dN_{ch}/d\eta$)

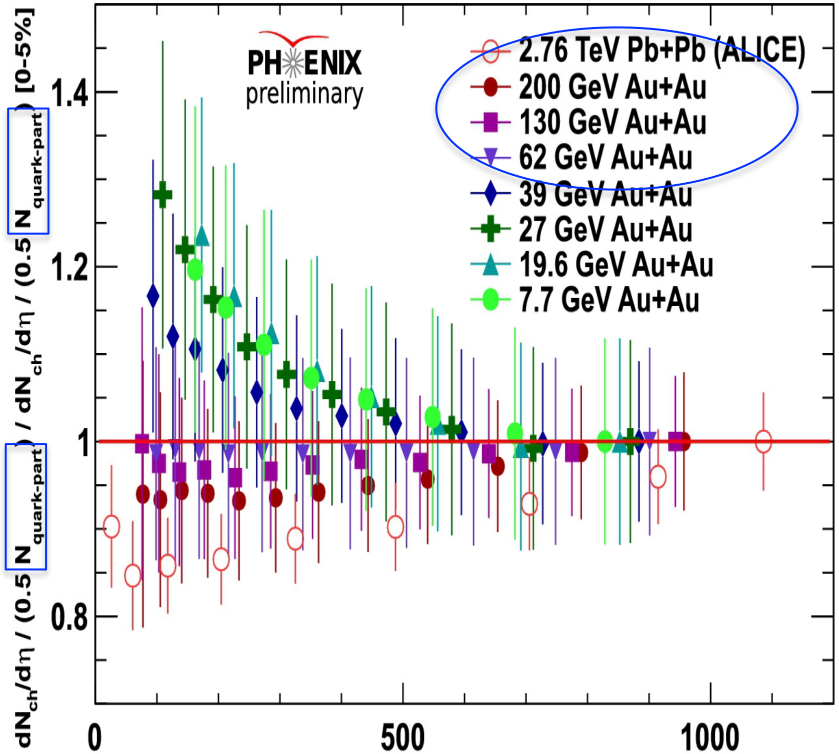
Npart + Ncoll explanation

nucleon or quark participant?

$R = (Y/N_{Part}) / (Y/N_{Part})^{central}$

$R = (Y/N_{Quark\text{-}Part}) / (Y/N_{Quark\text{-}Part})^{central}$

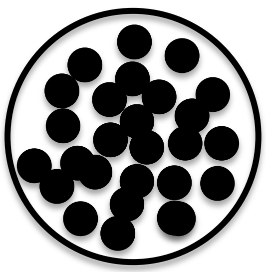




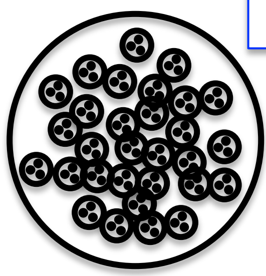
N_{Part}

$N_{Quark\text{-}Part}$

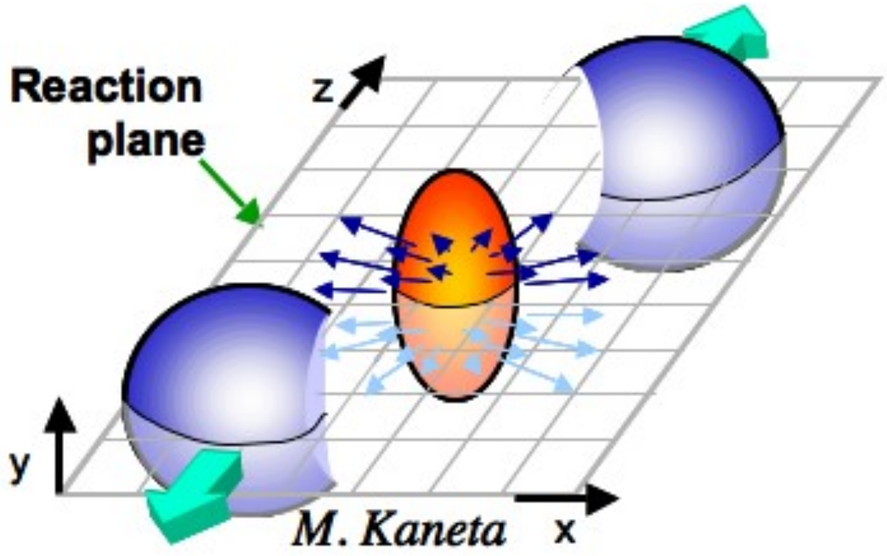
QM14, PHENIX

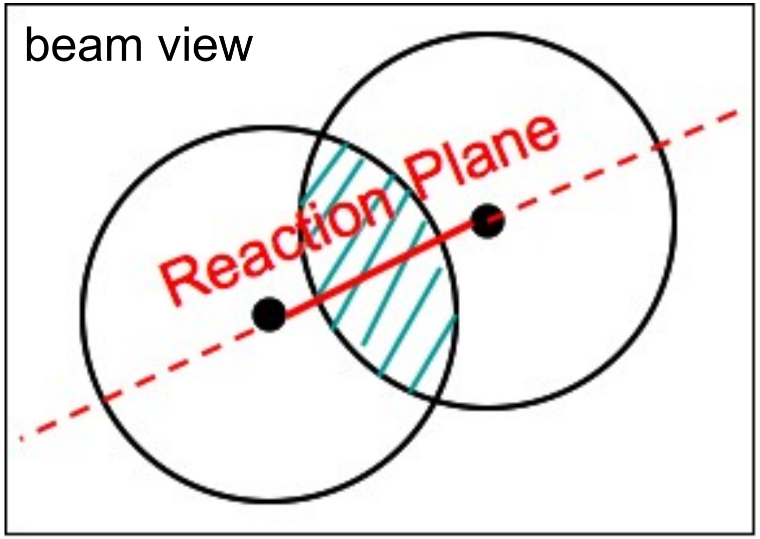


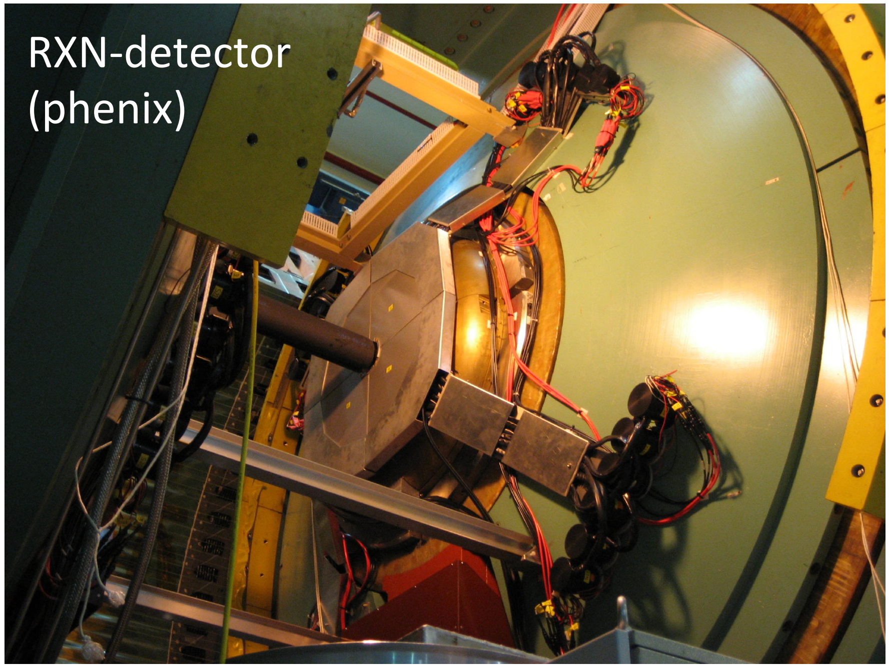
Nucleon picture ⟷ Quark picture

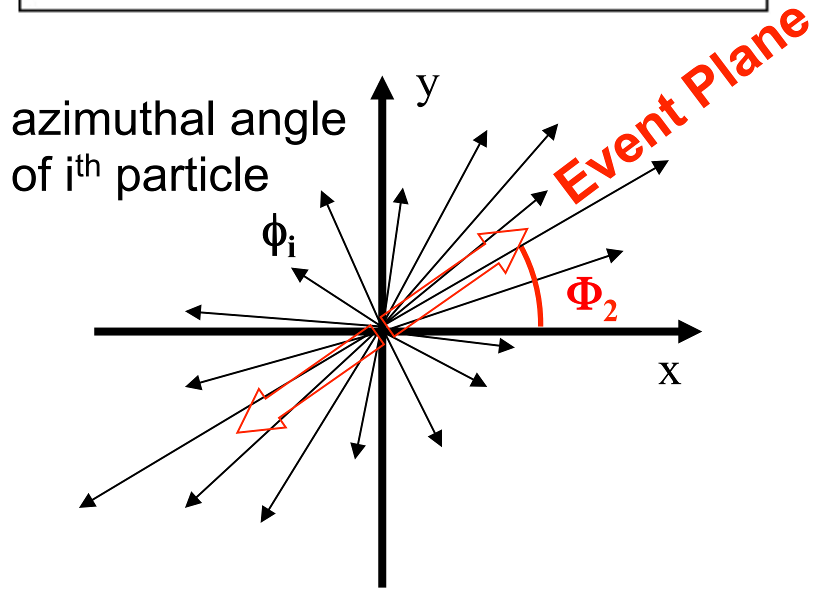


Reaction Plane : Event Plane

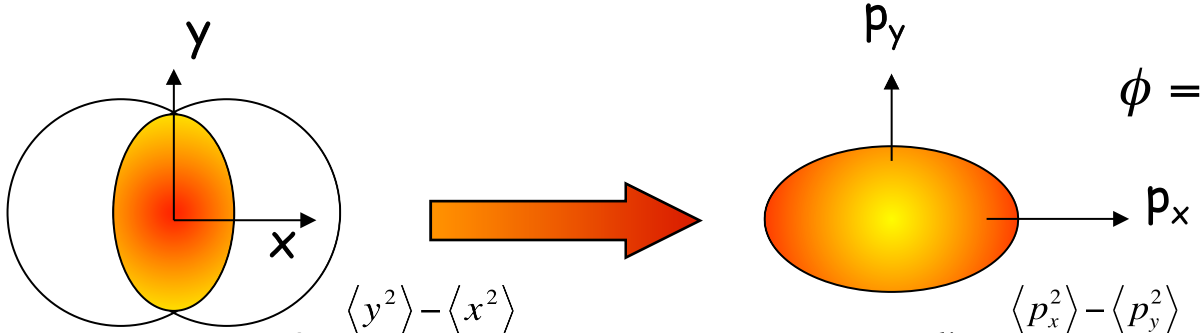








2^{nd} order event anisotropy v_2 (Elliptic flow, Elliptic emission)

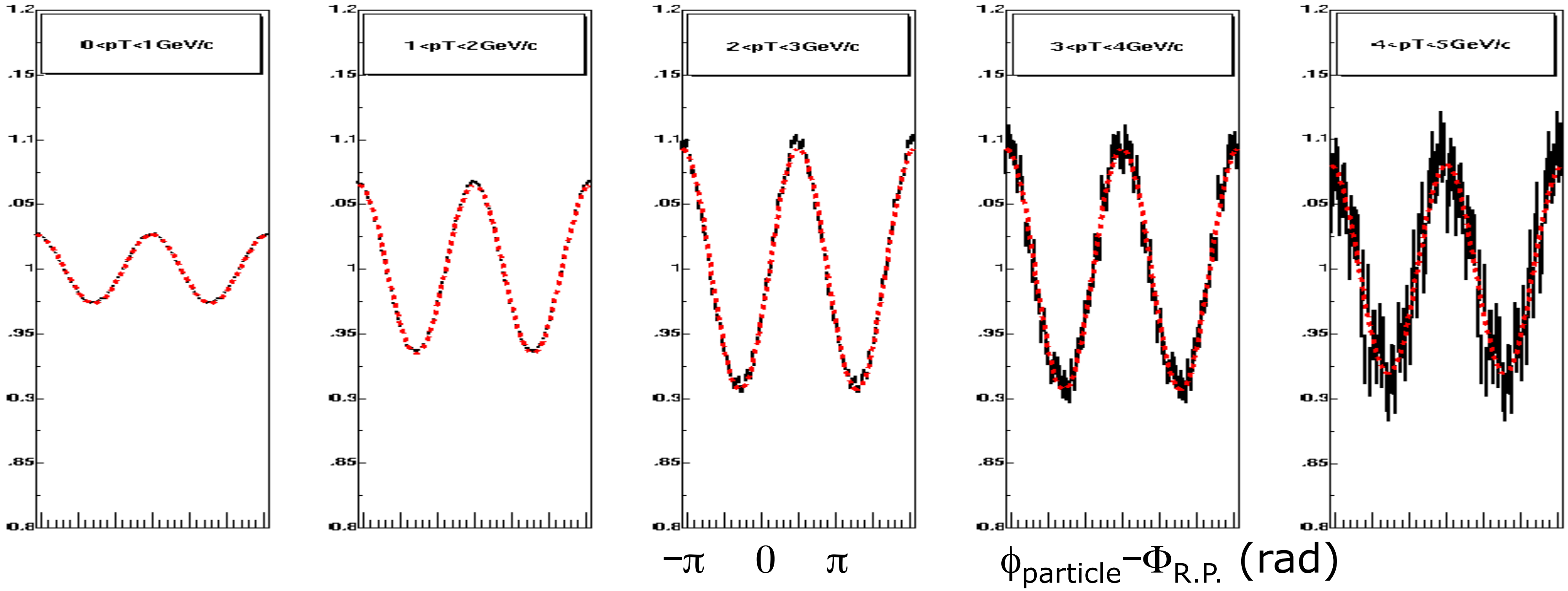


$$\phi = \text{atan}\frac{p_y}{p_x}$$

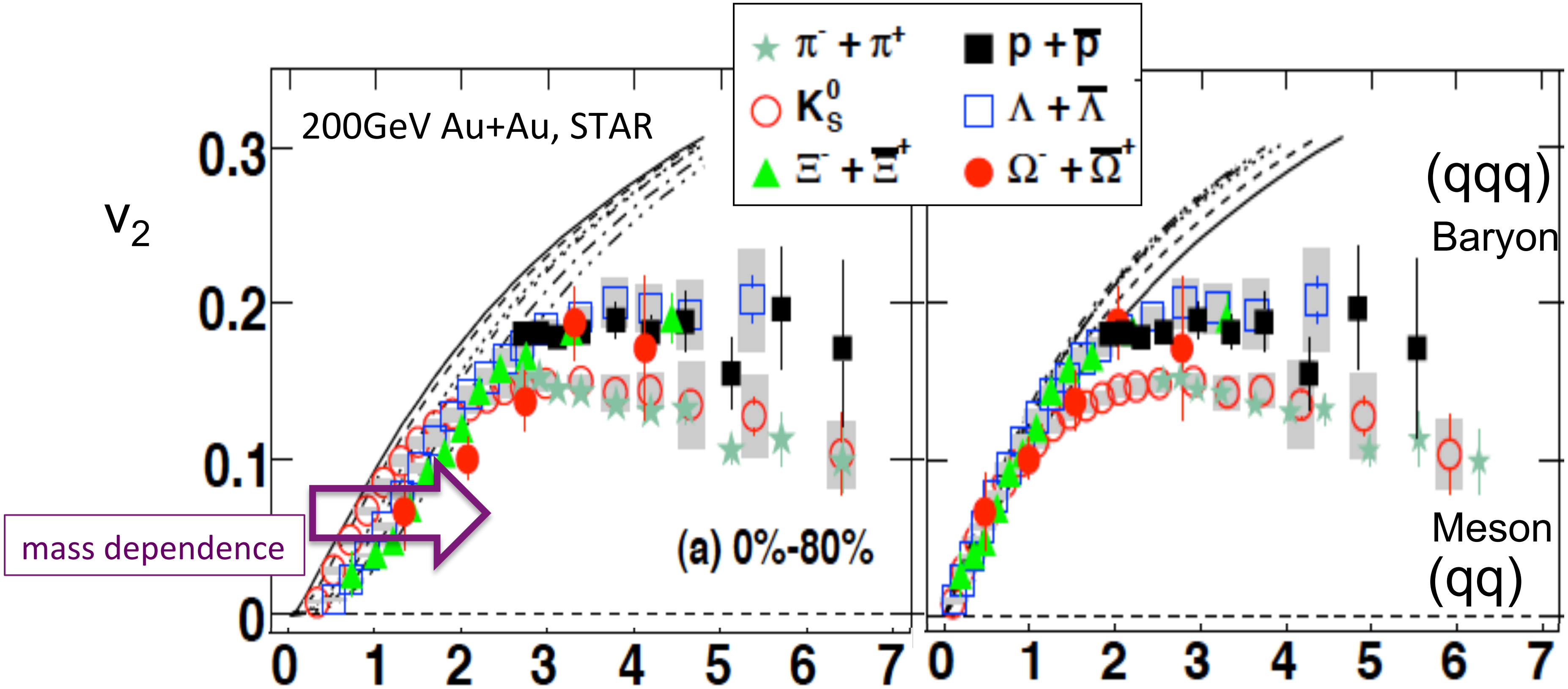
$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

Geometrical anisotropy **Momentum anisotropy**



p_T and particle mass dependence of v_2

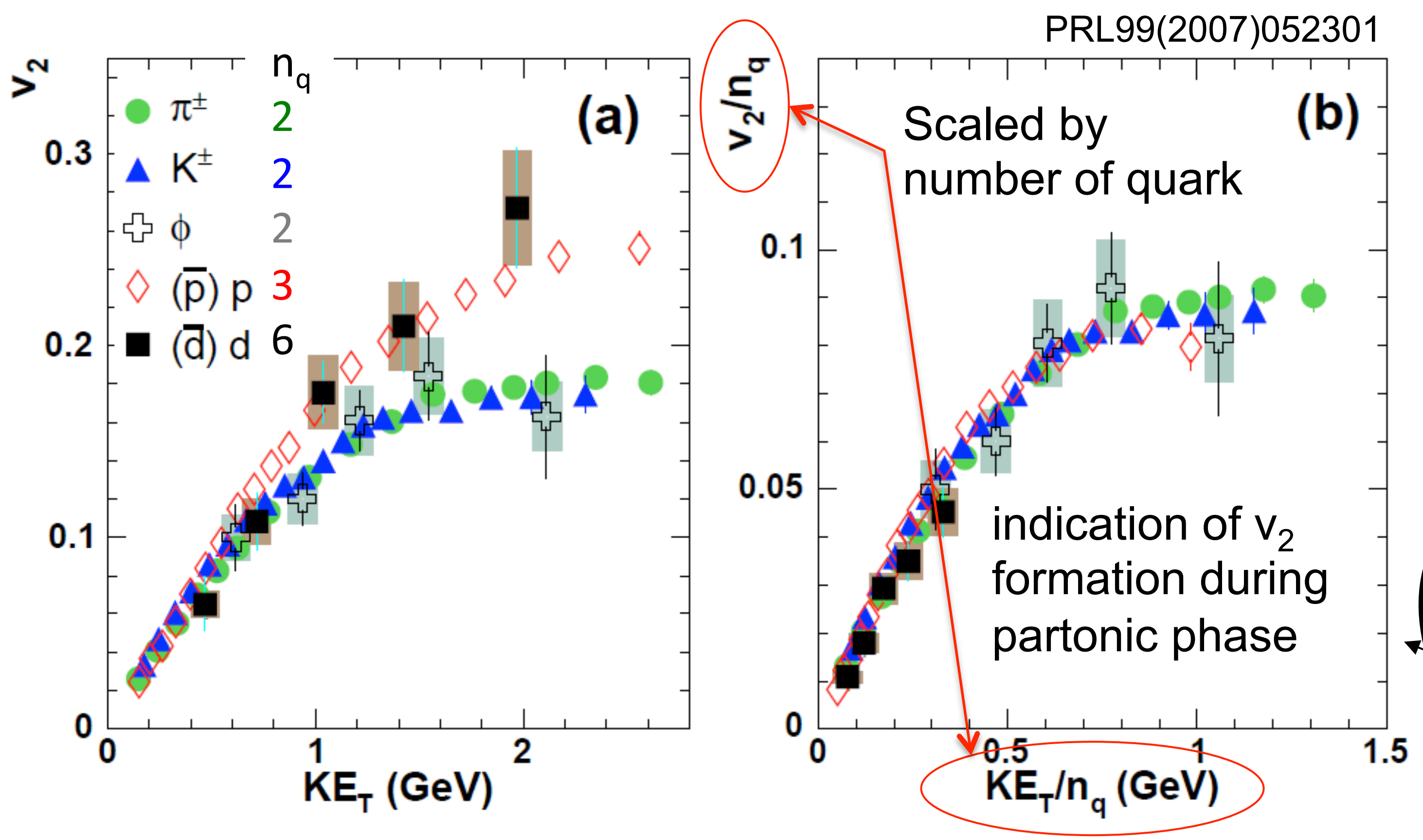


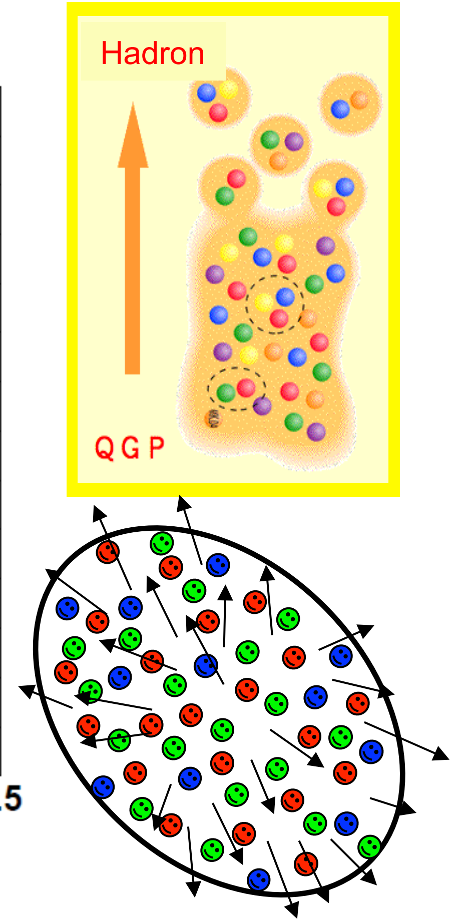
lines :
Hydrodynamic model calculation for various mass particles

p_T (GeV/c)

$m_T - m$ (GeV/c^2)

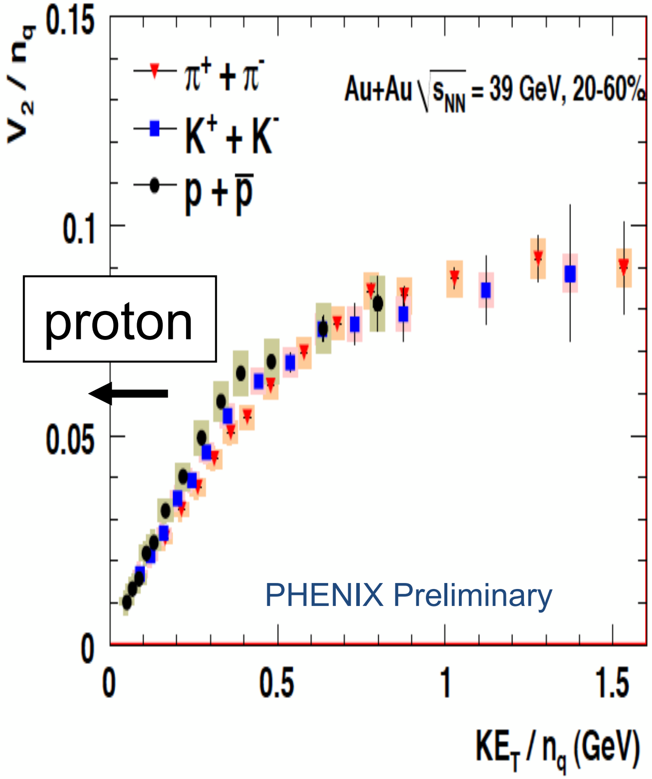
Constituent Quark Number Scaling in v_2



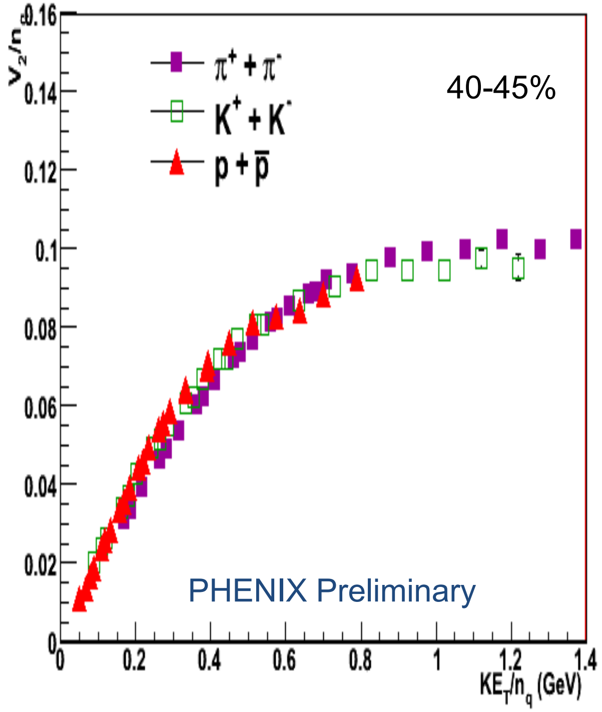


Deviation from (Quark Number) m_T Scaling --- radial expansion ---

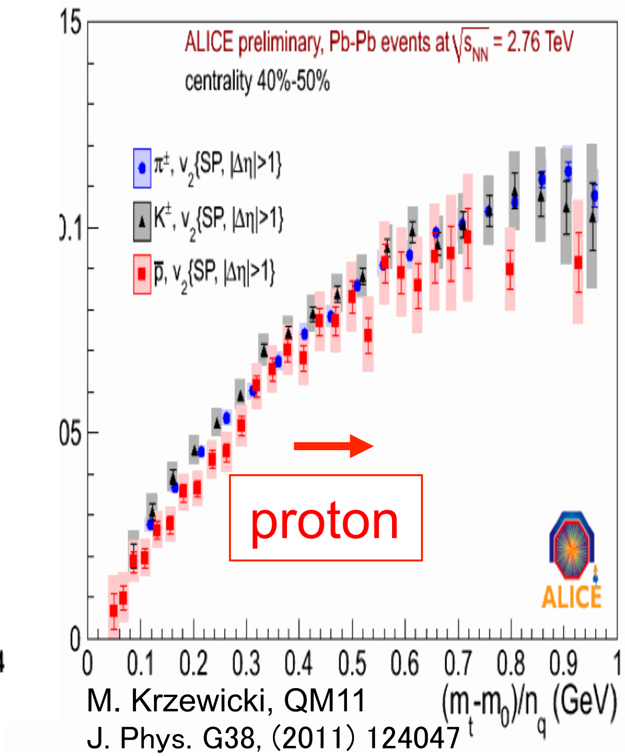
Au+Au 39GeV



Au+Au 200GeV



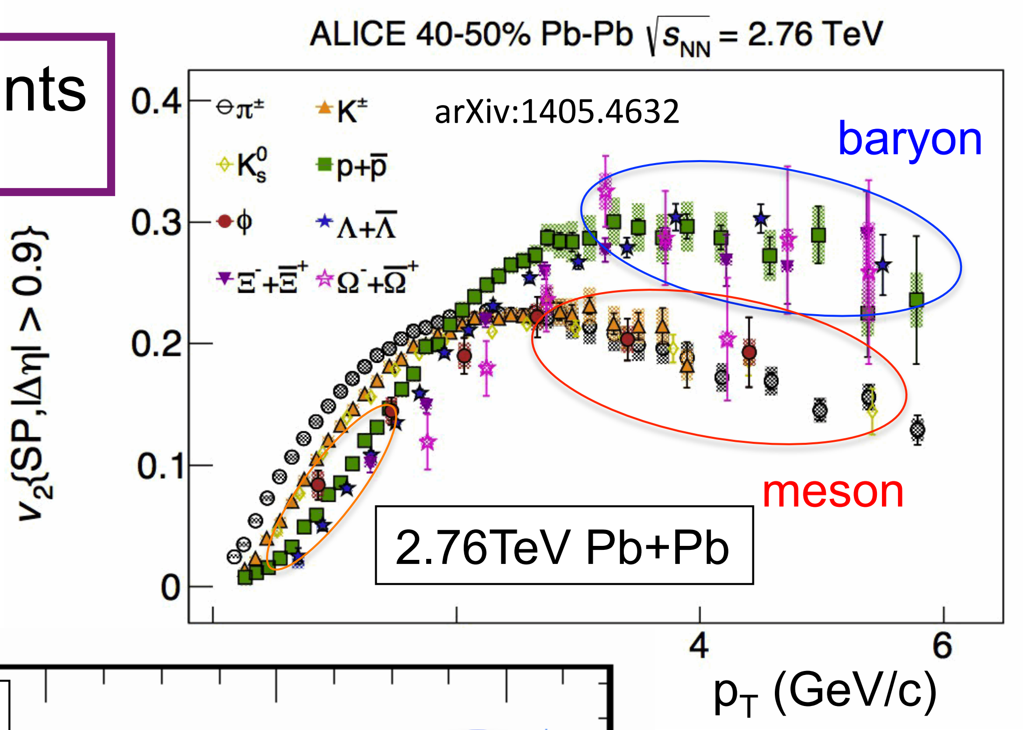
Pb+Pb 2.76TeV

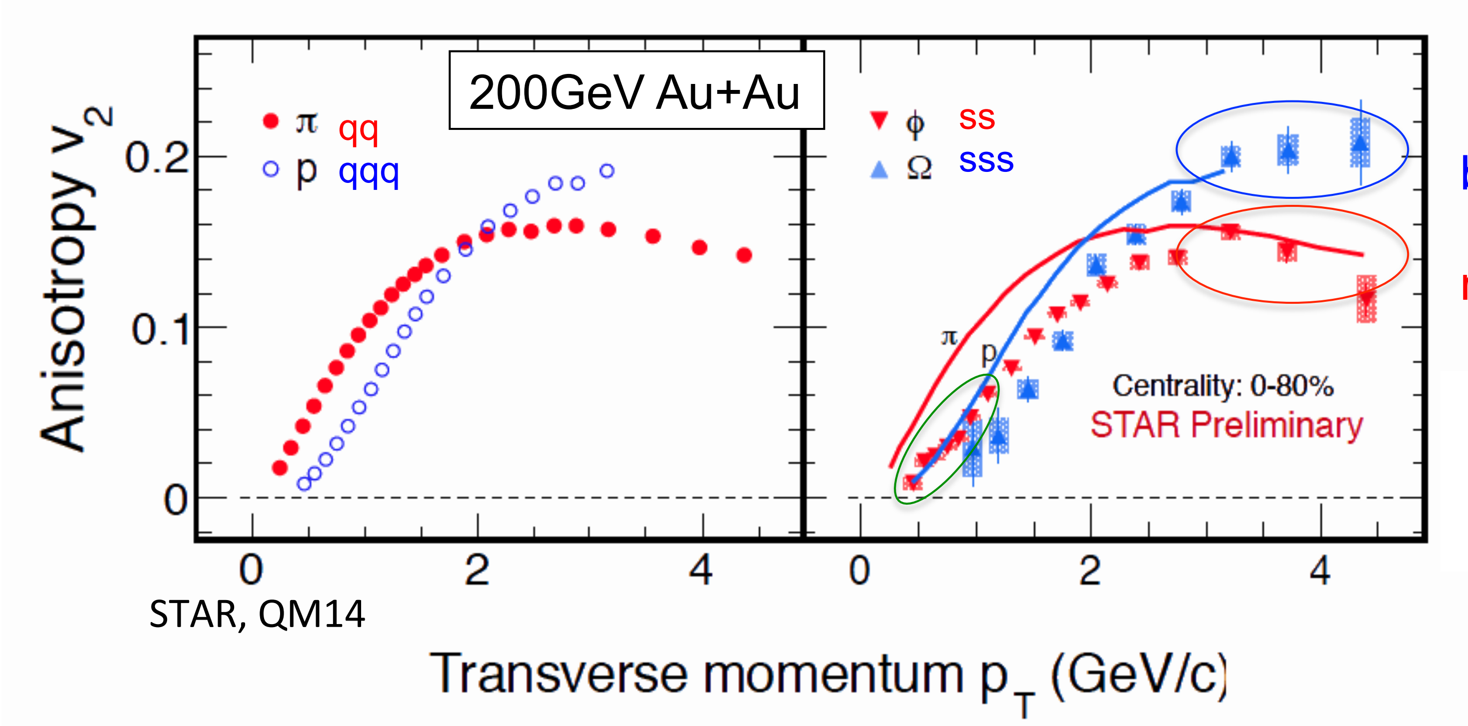


roughly $(m_T-m_0)/n_q$ scaled for all energies
larger p_T shift for heavier particles
radial flow increases with energy
elliptic and radial flows develop in different time scale

High precision v_2 measurements
at RHIC and LHC

- High statistics measurements allow a precise comparison of $v_2(p)$ and $v_2(\phi)$.
- Some small deviation from hydro-like mass dependence of v_2 at low p_T, that is expected by small hadronic cross section of ϕ-meson than that of proton.



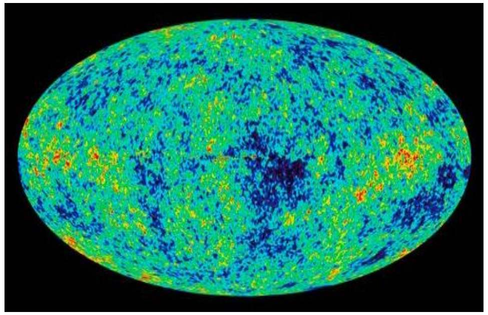


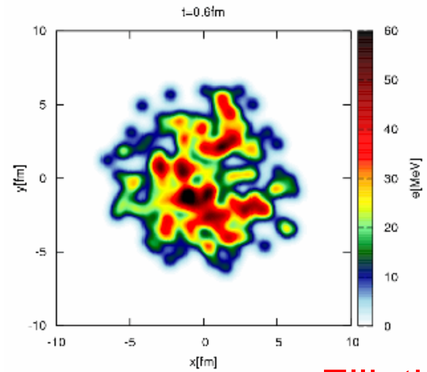
baryon

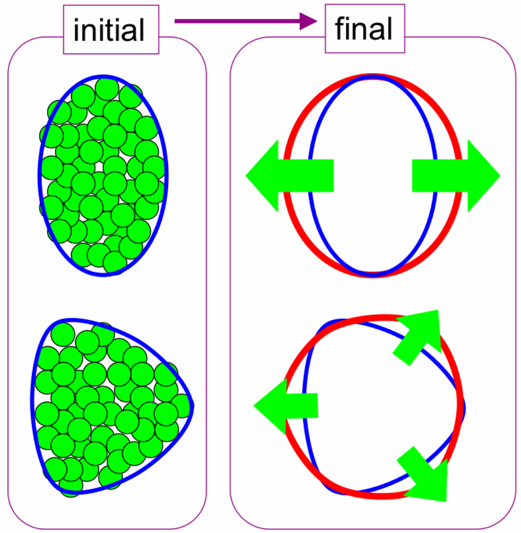
meson

Number of quark scaling as a signal of partonic phase

Triangular expansion / geometry

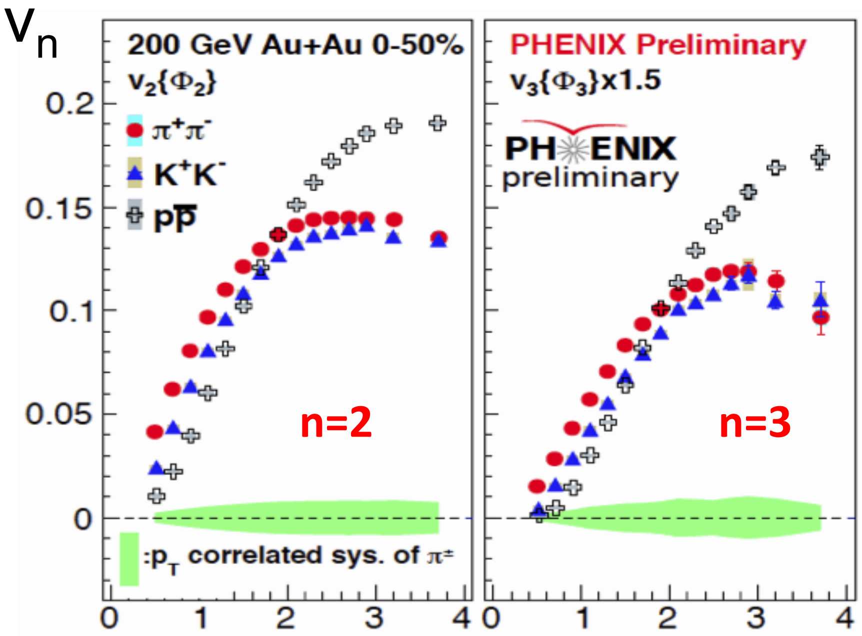


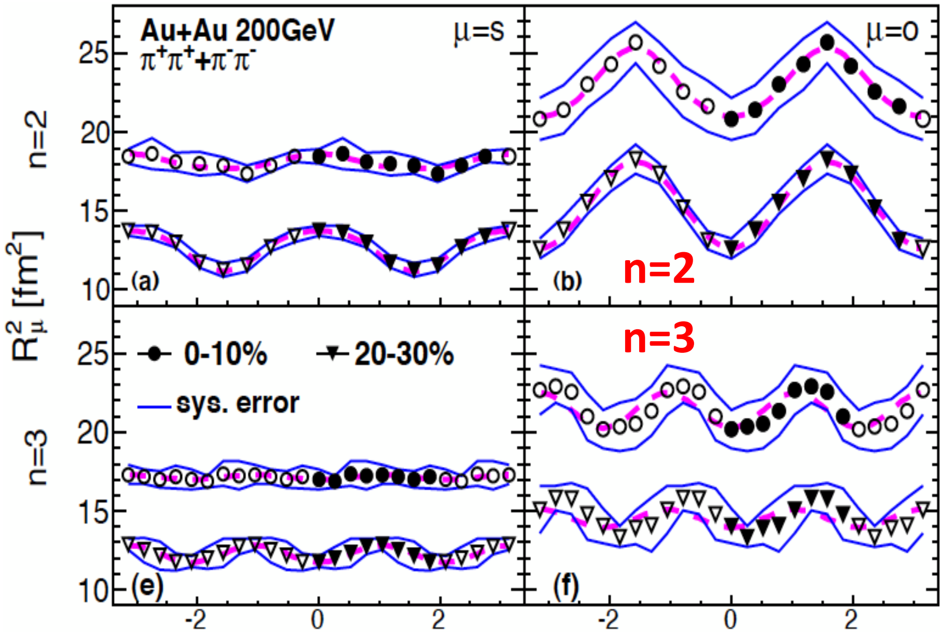




Elliptic and Triangular expansion : v_2, v_3

Elliptic and Triangular shape : $R^{HBT}{}_{\Phi 2}$, $R^{HBT}{}_{\Phi 3}$





PHENIX, QM12

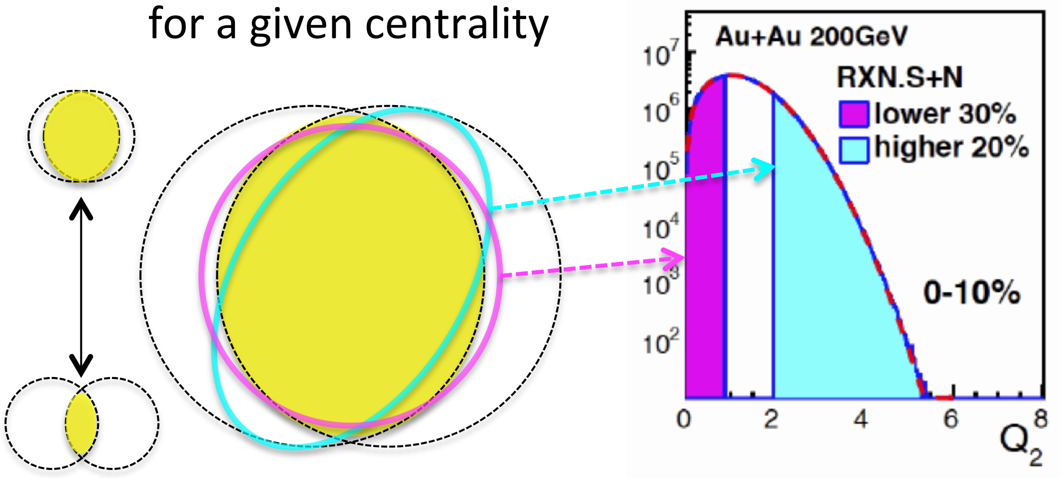
p_T [GeV/c]

PRL112 (2014) 222301

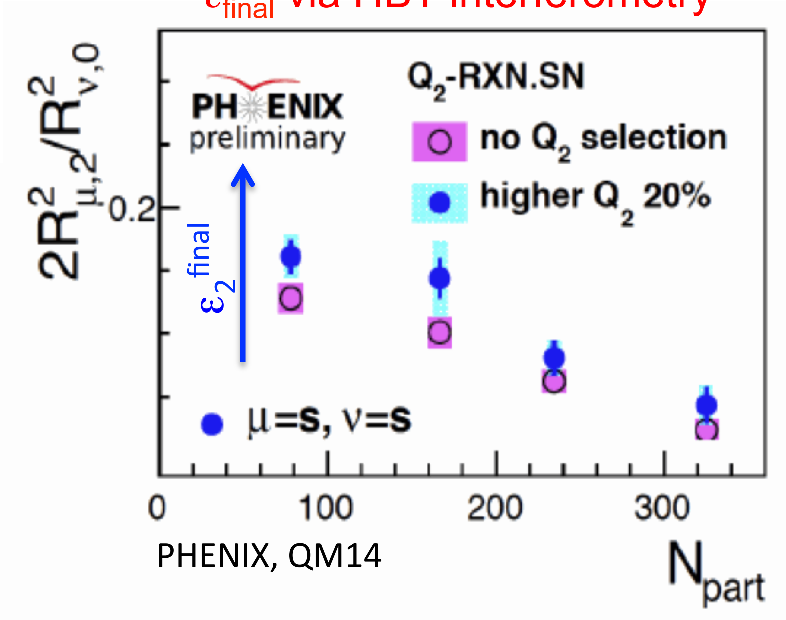
$\phi - \Psi_n$ [rad]

Event Shape Engineering Q_2 (~v_2)

relation of $\varepsilon_2^{initial} - v_2 - \varepsilon_2^{final}$
for a given centrality

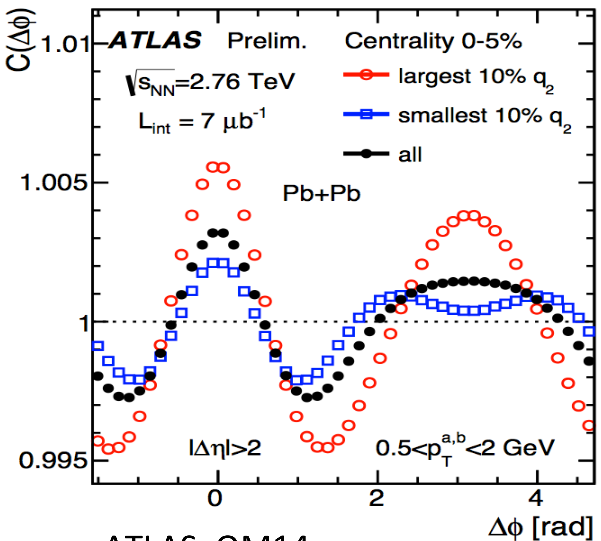


ε_{final} via HBT interferometry

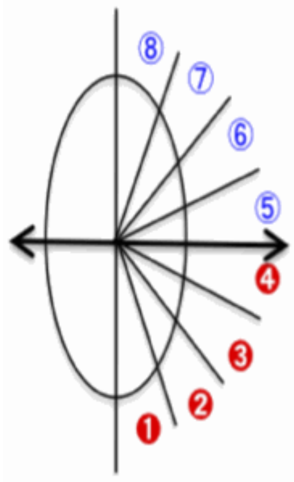


PHENIX, QM14

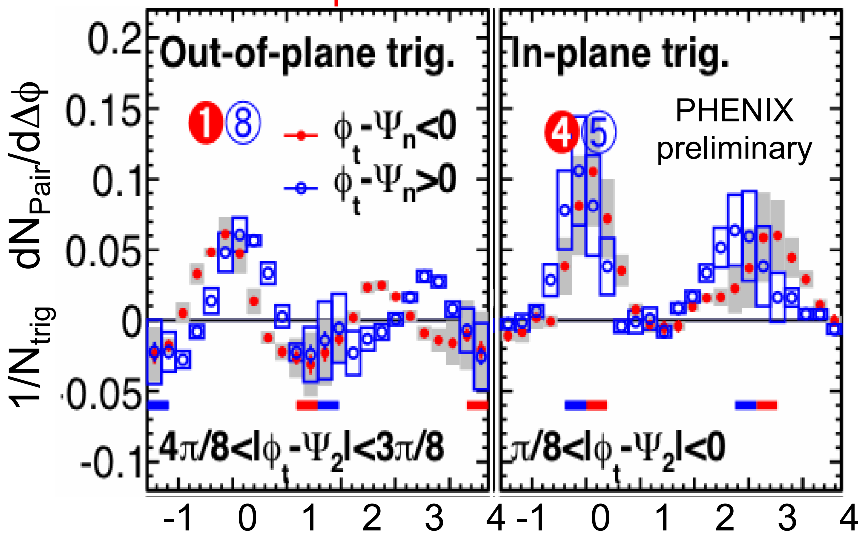
2-particle correlation



ATLAS, QM14



R.P. dependence of correlation

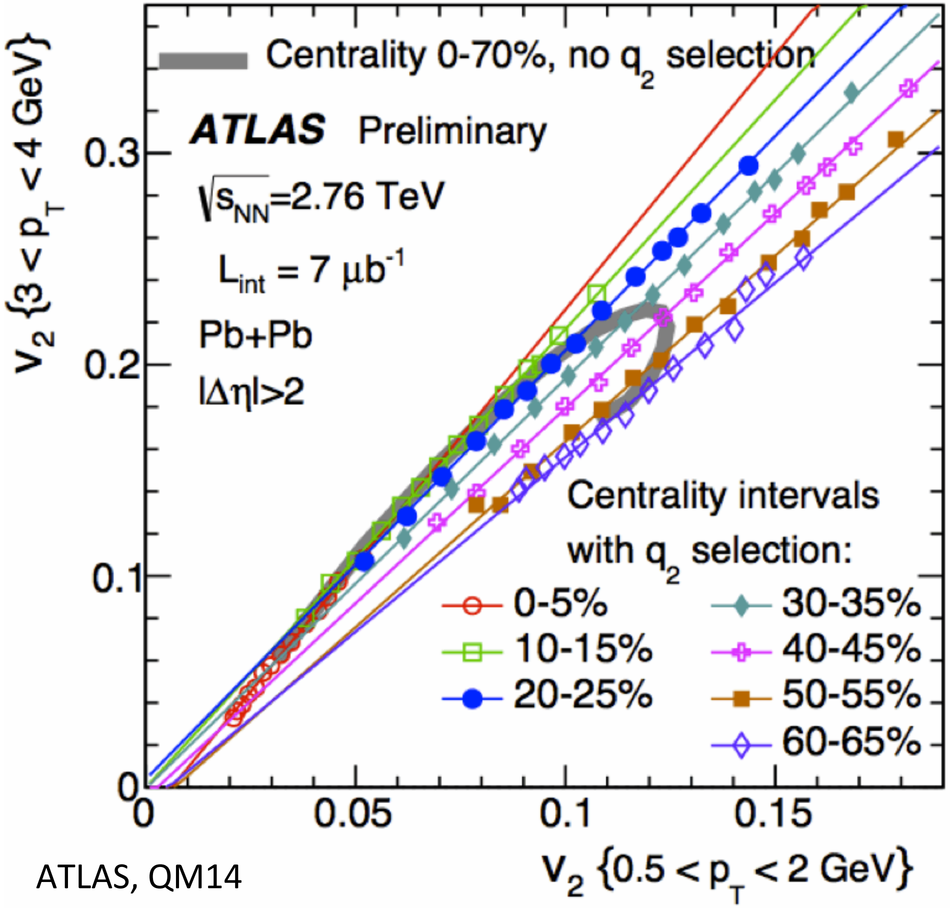


PHENIX, QM12

$\Delta\phi = \phi_{Asso.} - \phi_{Trig.}$

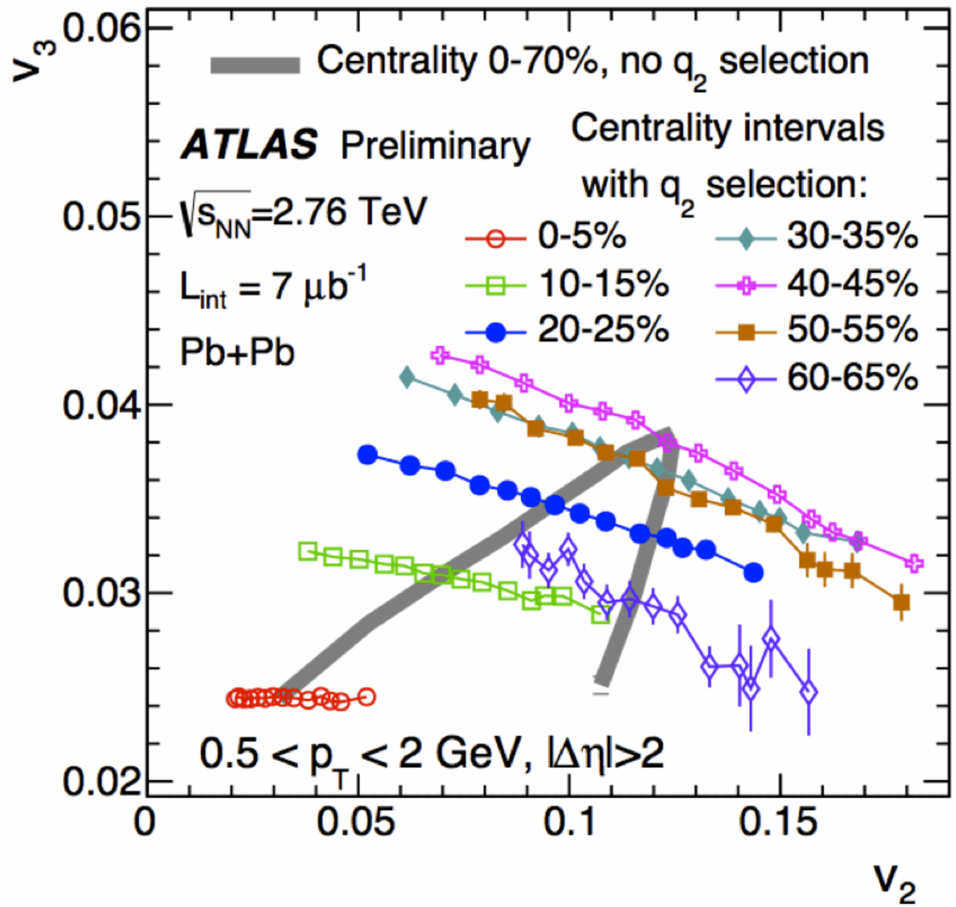
Cross harmonics correlation with Q_2 selection

$v_2^{(Low\ pT)}$ vs $v_2^{(high\ pT)}$



ATLAS, QM14

v_2 vs v_3



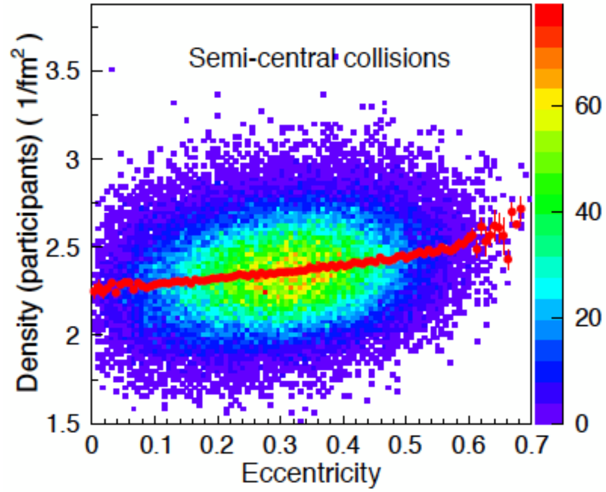
Event Shape Engineering
--- Test in ALICE experiment ---

(arXiv:1507.06194)

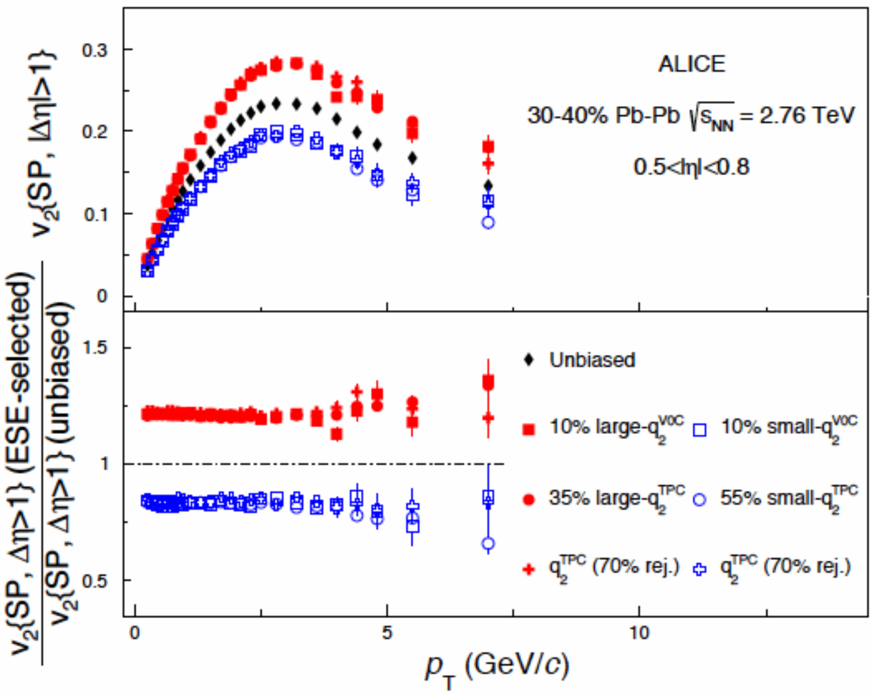
Glauber simulation
$\rho - \varepsilon$ correlation

↓

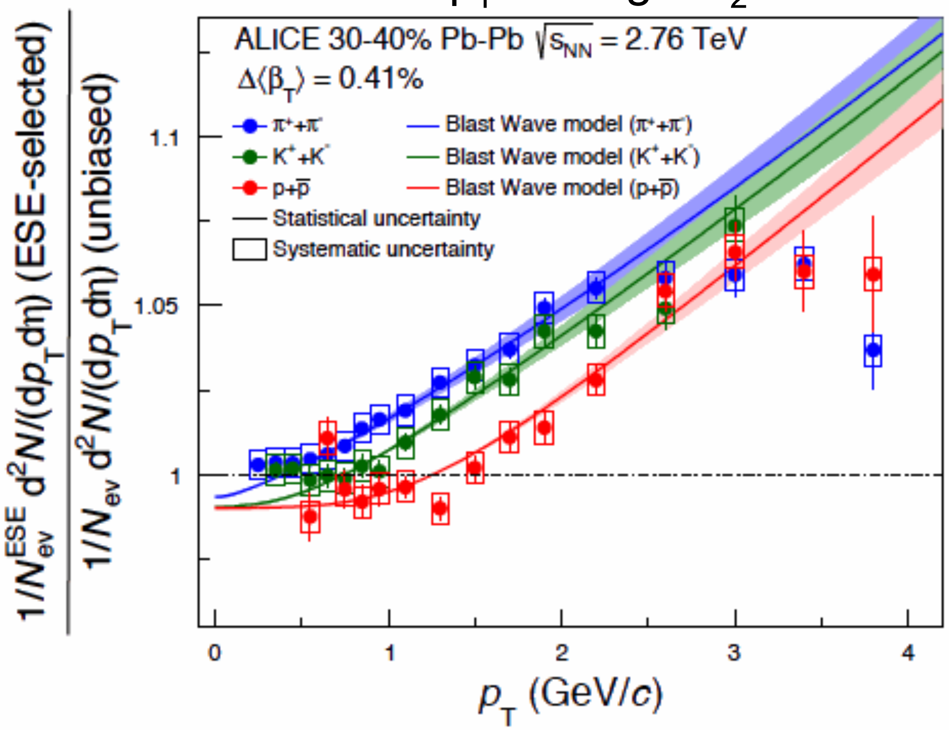
$\beta_T - v_2$ correlation



flat p_T dependence ~ 5GeV/c
confirmation of initial geometry selection

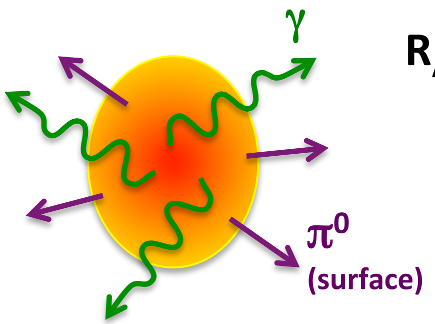


increased radial flow
+0.41% in β_T for large Q_2 event

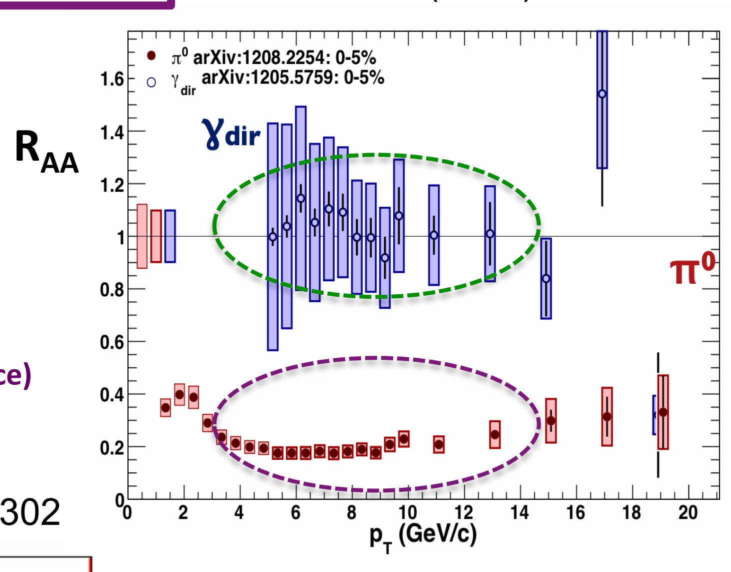


High p_T direct photon as penetrating probe

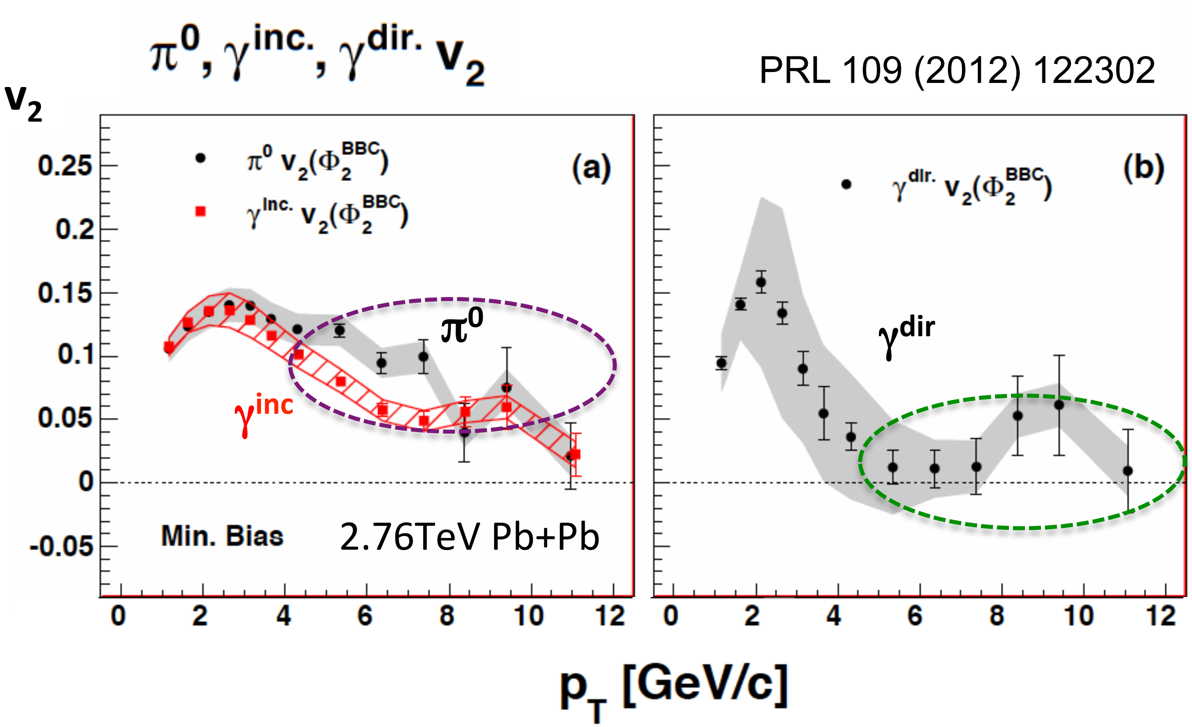
$p_T > 5$ GeV/c	hadron	γ^{dir}
R_{AA}	< 1	~ 1
v_2	> 0	~ 0



PRL 109 (2012) 152302



PRL 109 (2012) 122302

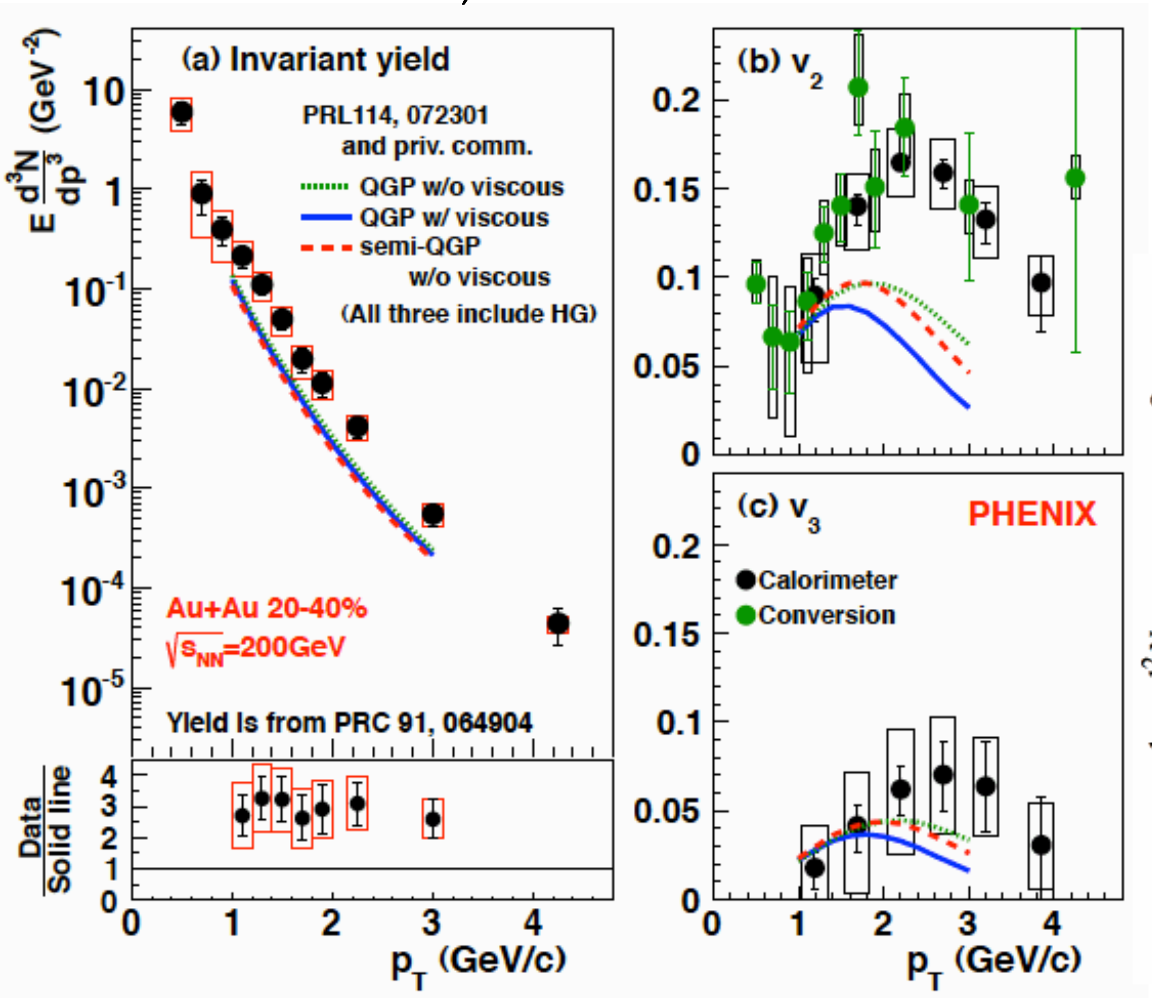


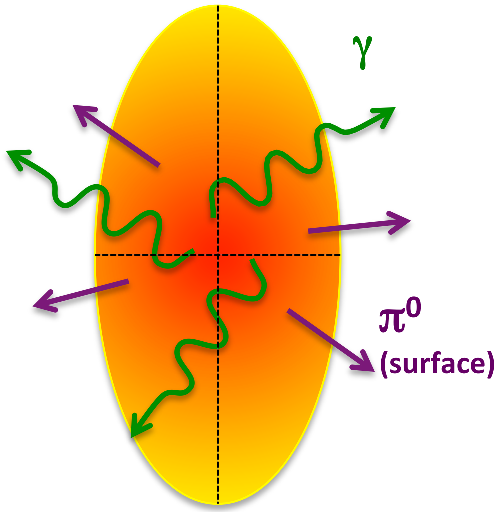
$$R_{AA} = \frac{N\,(A+A)}{N_{coll}\,N(p+p)}$$

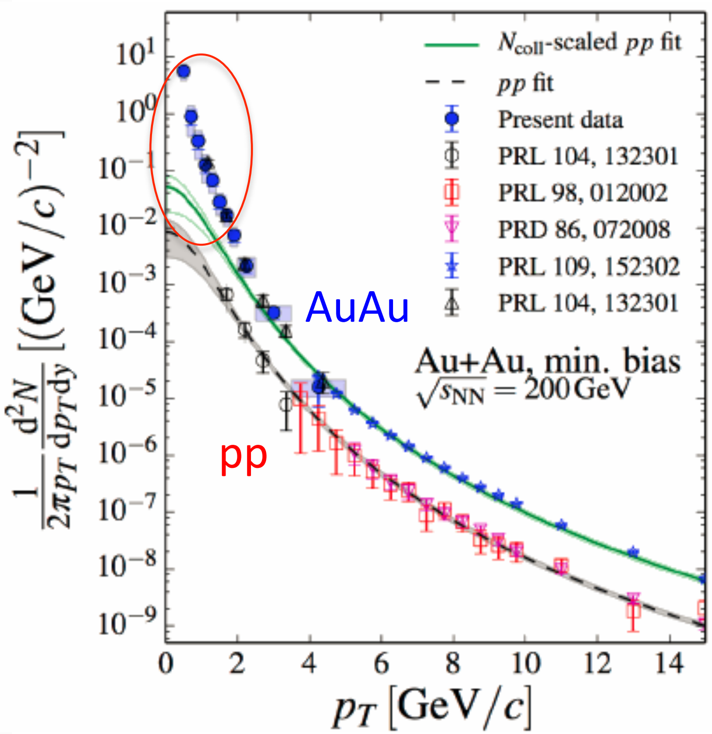
relative yield with respect to a simple independent superposition of pp data

Direct Thermal Photon

Direct (thermal) photon, 200GeV Au+Au,
RHIC-PHENIX, arXiv:1509.07758

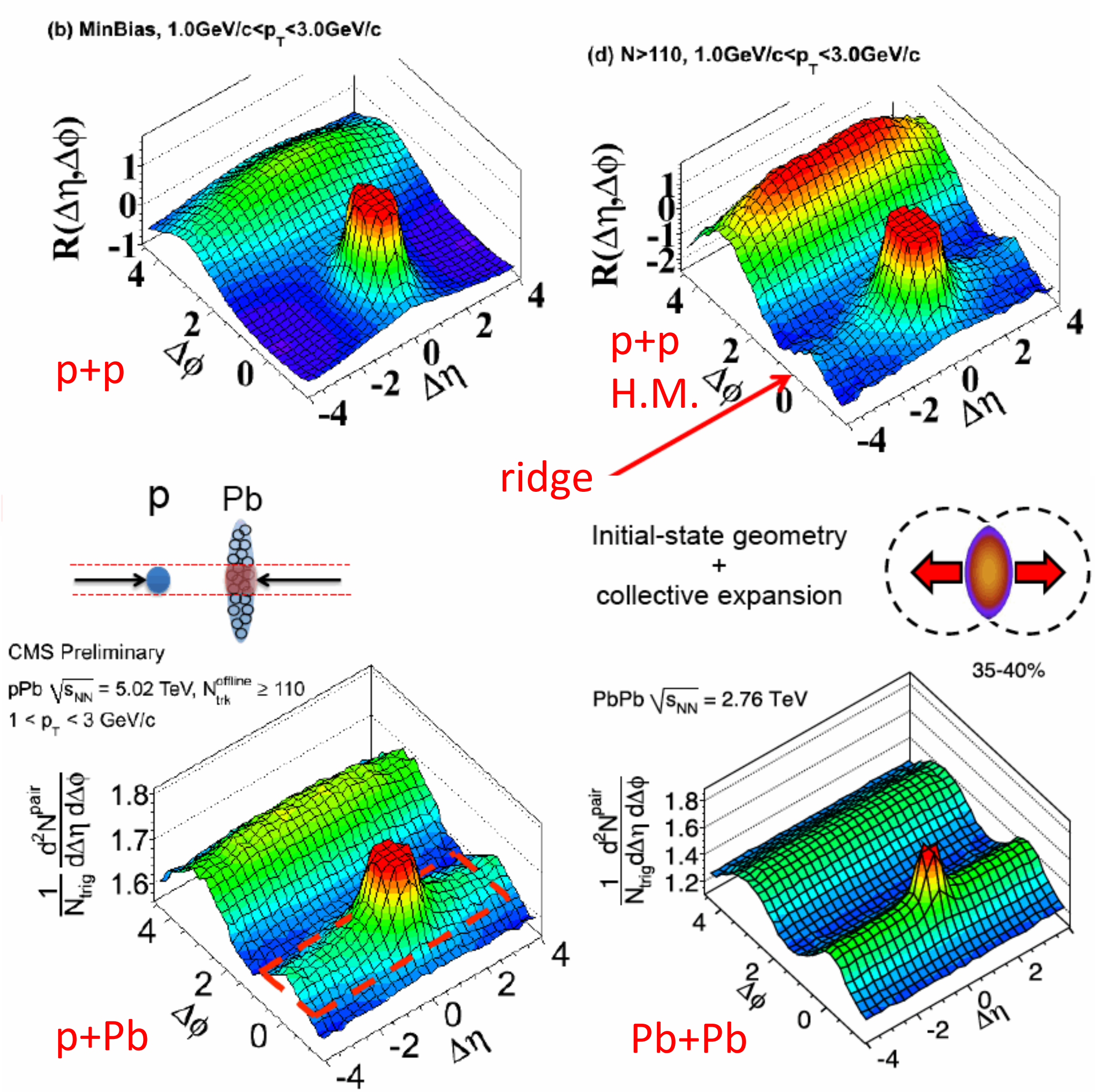


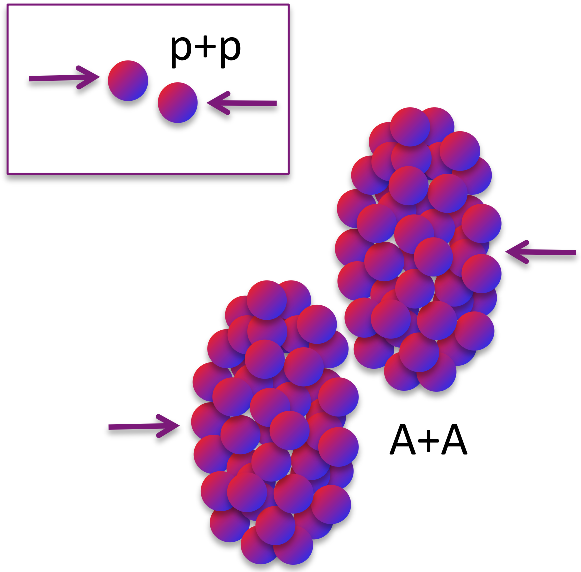


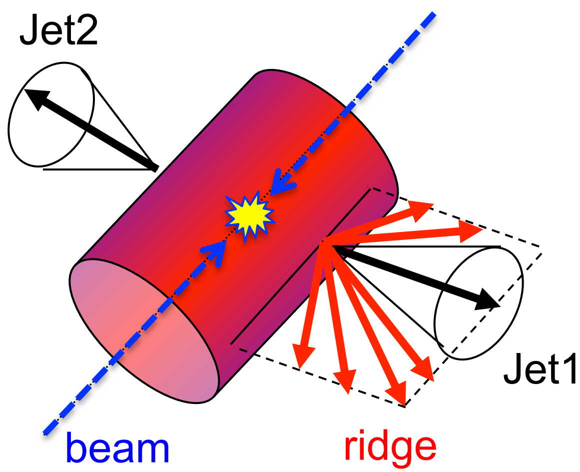


CMS

Small, but high density system



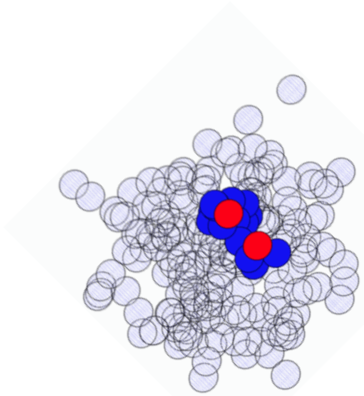




Hydrodynamic collectivity in small system?

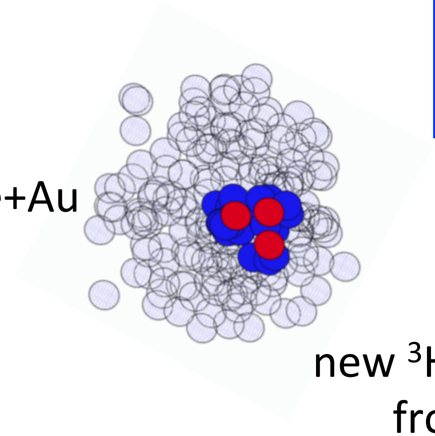
2nd half of RUN16 at RHIC
Energy scan with d+Au
at 20, 39, 62 and 200GeV

Glauber model



d+Au

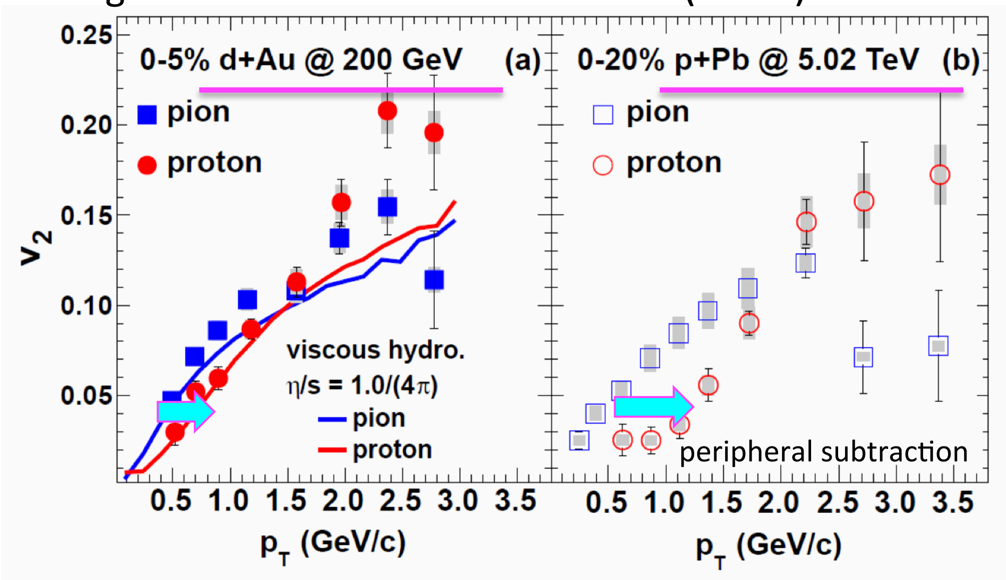
^{3}He+Au



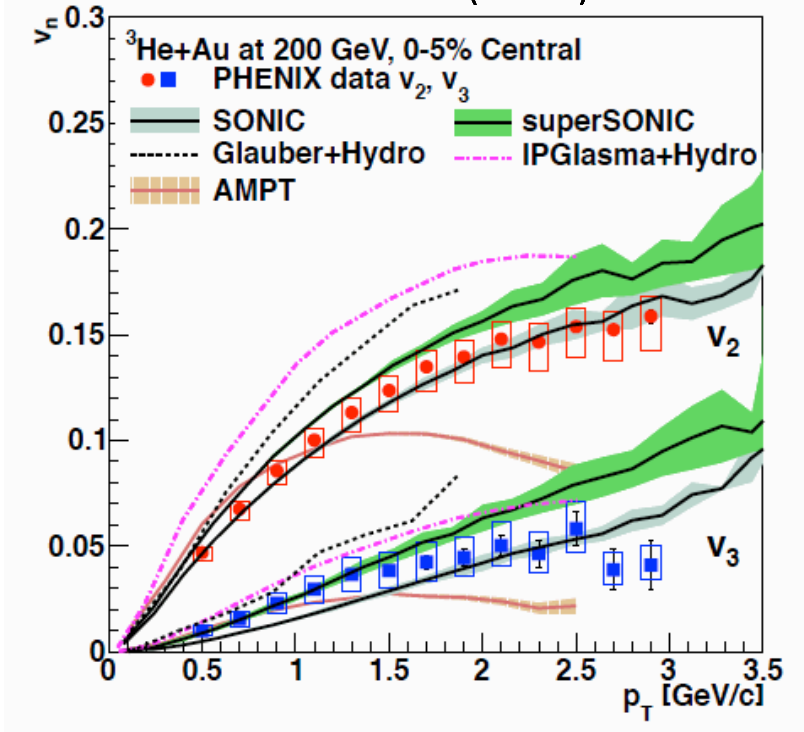
new ^{3}He+Au collision data from RHIC-RUN14

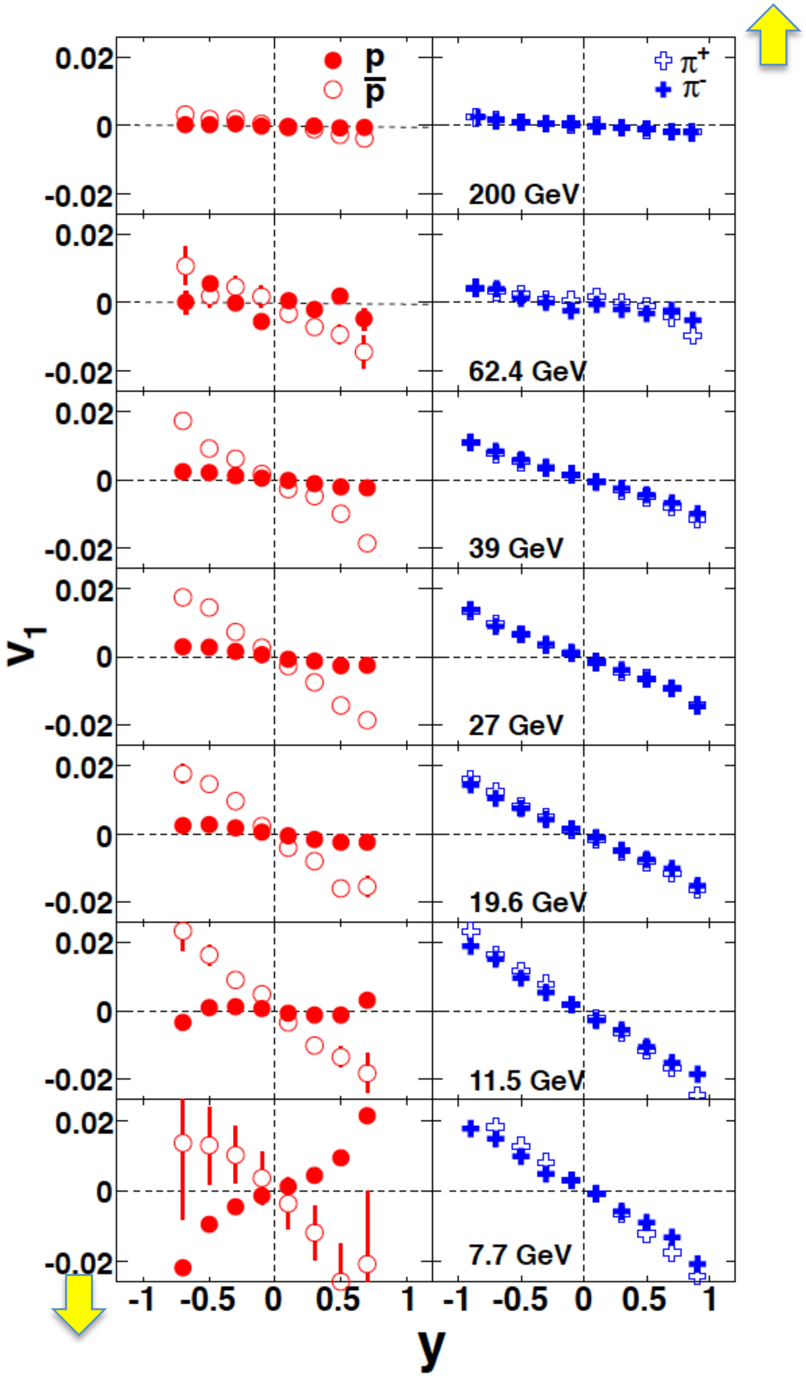
radial flow effect :
larger for heavier mass

PRL111(2013)212301

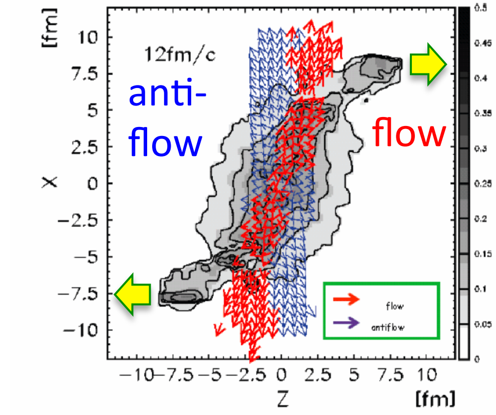


PRL115(2015)142301

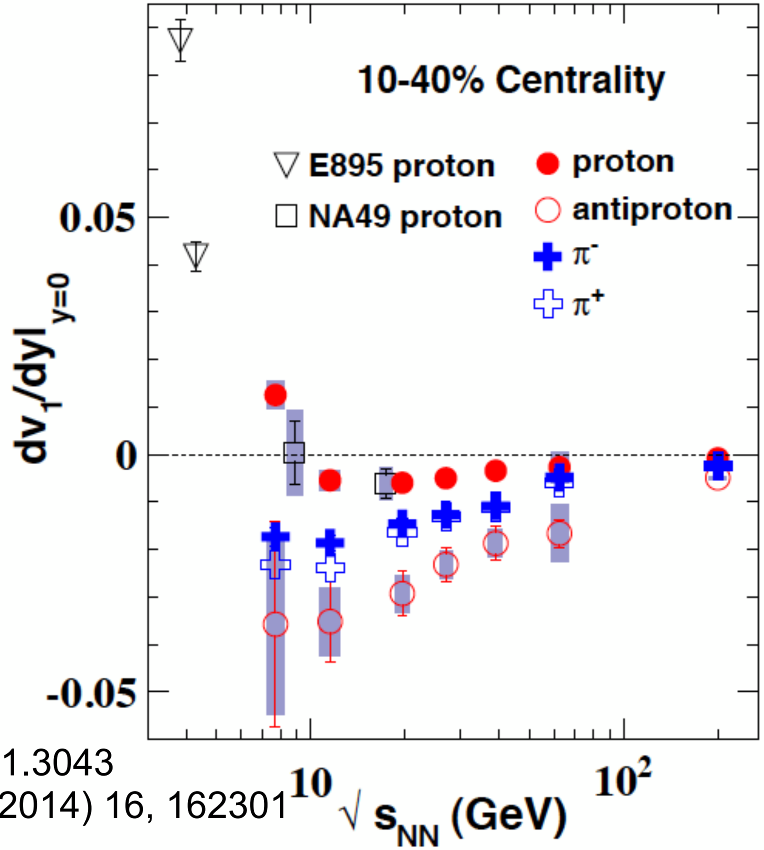




Directed Flow v_1



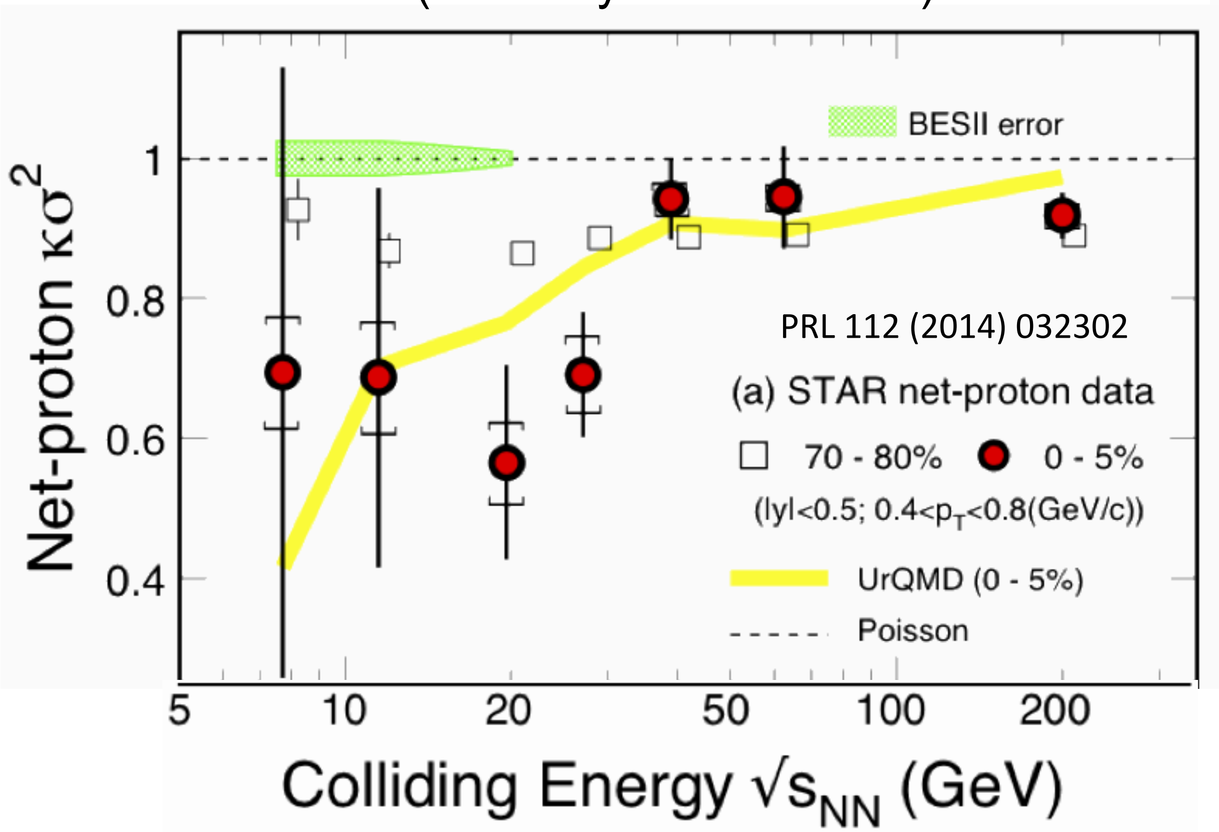
J. Brachmann et al., PRC 61, 24909 (2000).



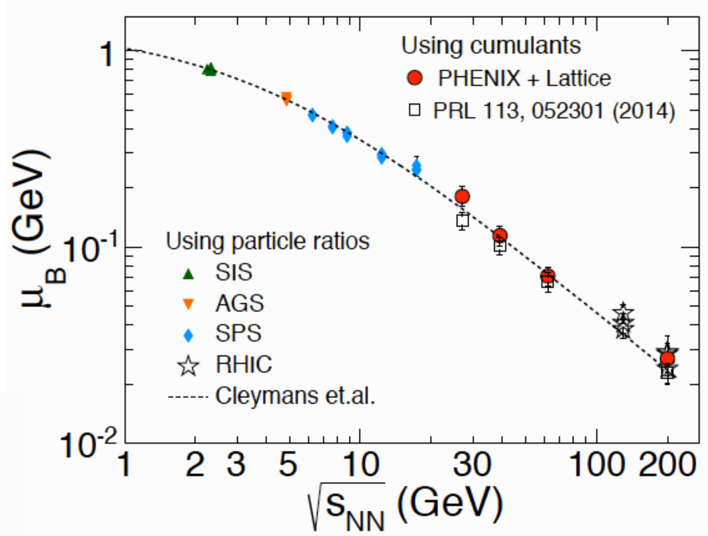
arXiv:1401.3043
PRL112 (2014) 16, 162301

Search for fluctuation originating from Critical Point

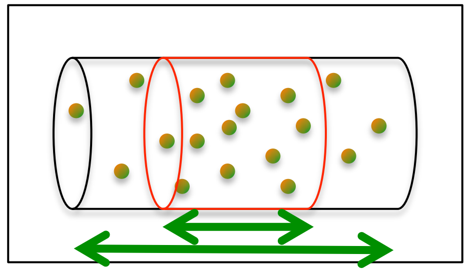
Higher moment of conserved quantity
(Net-Baryon distribution)



Correlation of this w.r.t. flow (e-by-e flow selection, larger sensitivity in "less flow" event?)



Baryon density from beam energy scan, 20-200GeV Au+Au, RHIC-STAR/PHENIX, arXiv:1506.07834



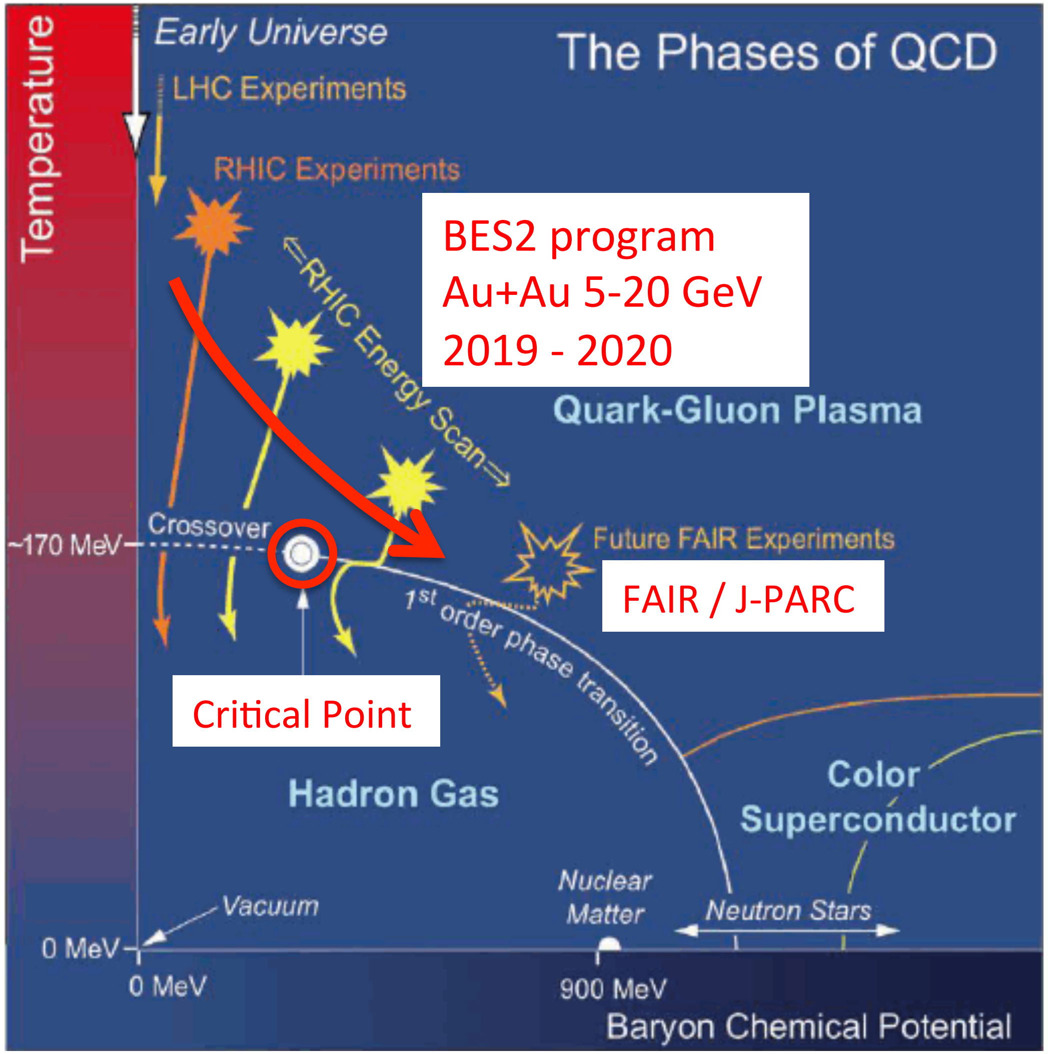
Change of correlation length at phase boundary close to the critical point

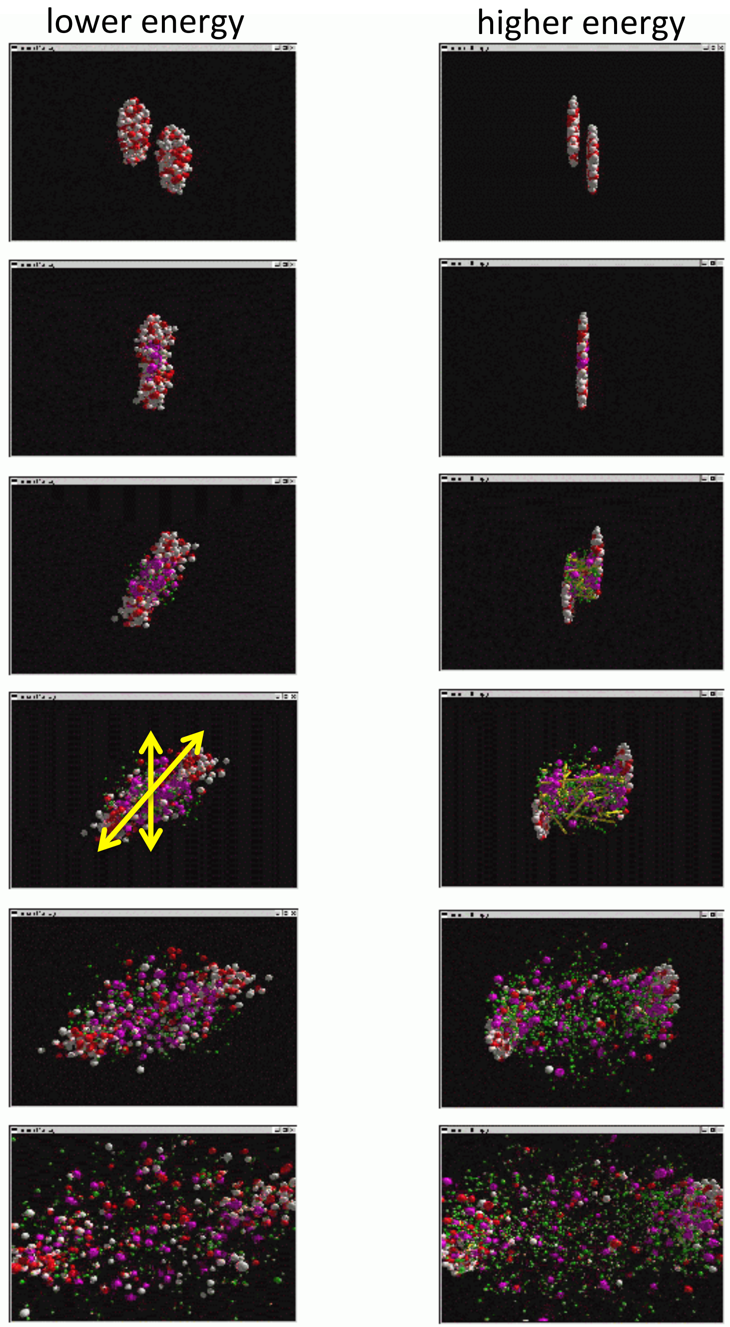
Summary

- connection between radial and elliptic flows
- from partonic to hadronic system
- possible flow in small and high-dense system
- relation to the critical point

Back-up slides follow…

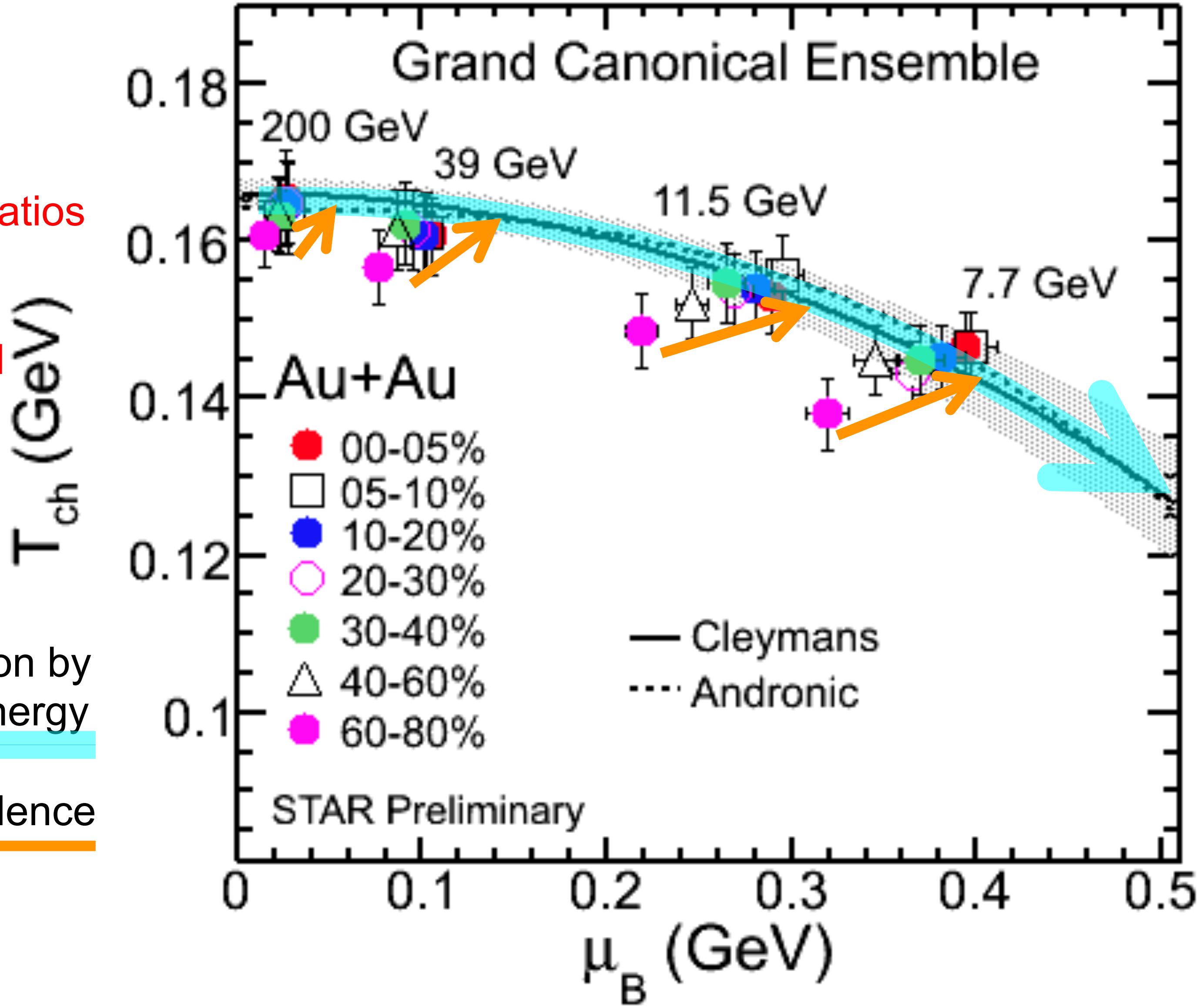
High-Temperature to High-Density with Beam Energy Scan 2 at STAR





Chemical Freeze-out via thermal model fitting

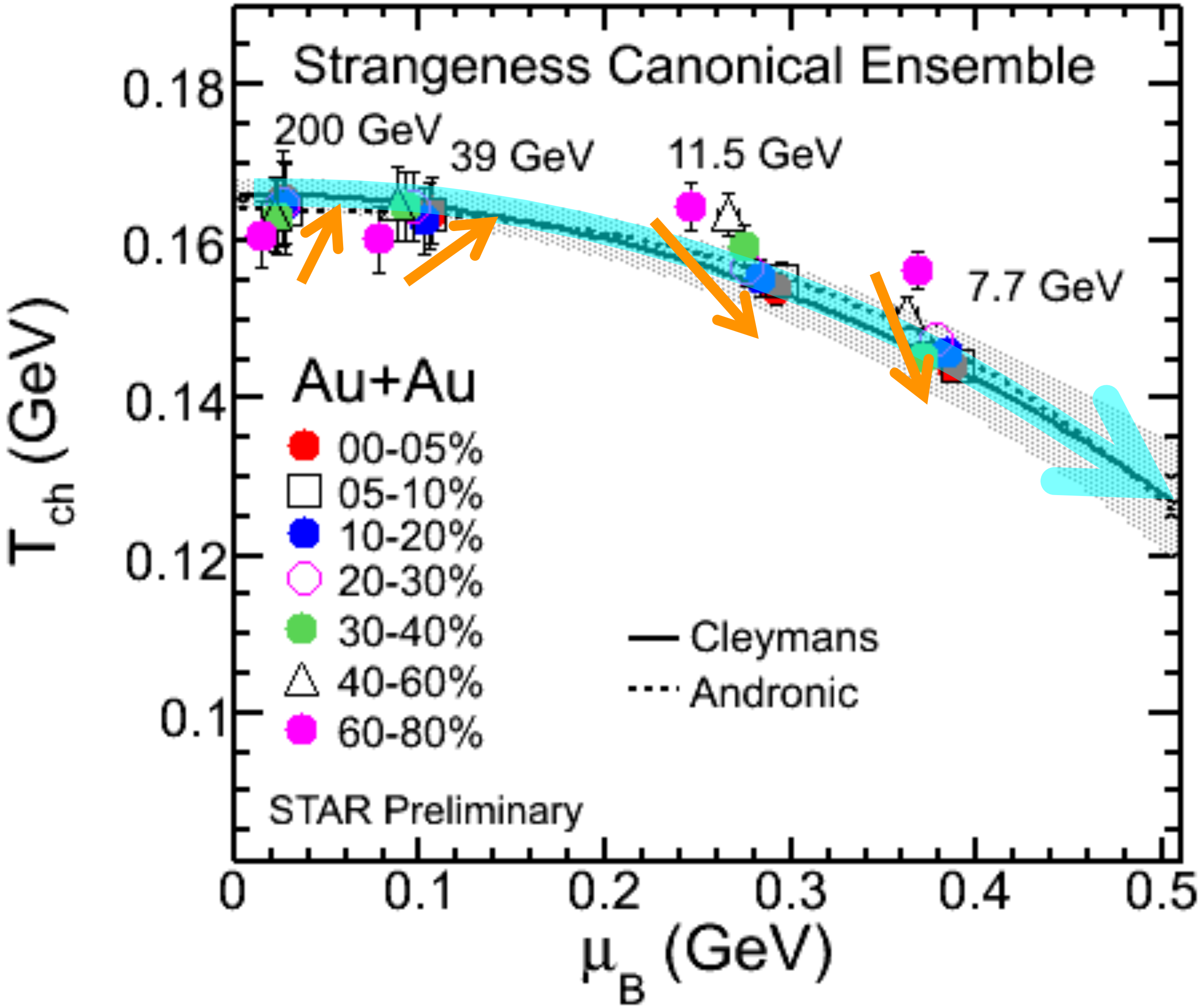
[at the end of inelastic collisions]
Particle yields and ratios are determined with chemical freeze-out temperature T_{ch} and Baryon chemical potential μ_B



High density region by lowering beam energy

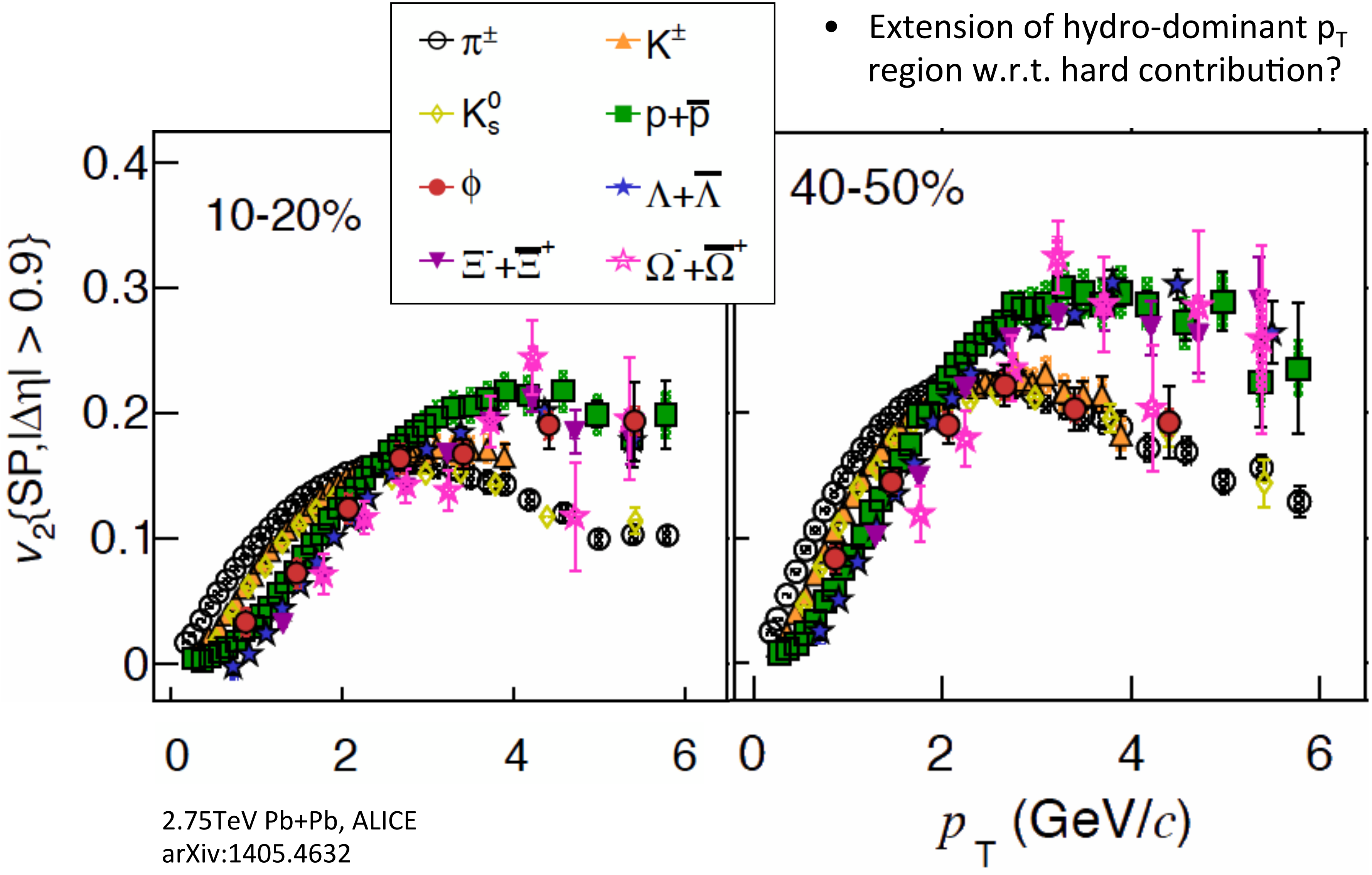
Centrality dependence

Chemical Freeze-out model fitting



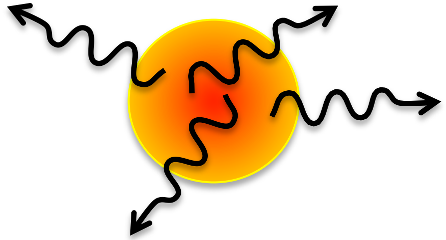
ϕ-meson v_2 --- a new puzzle ---

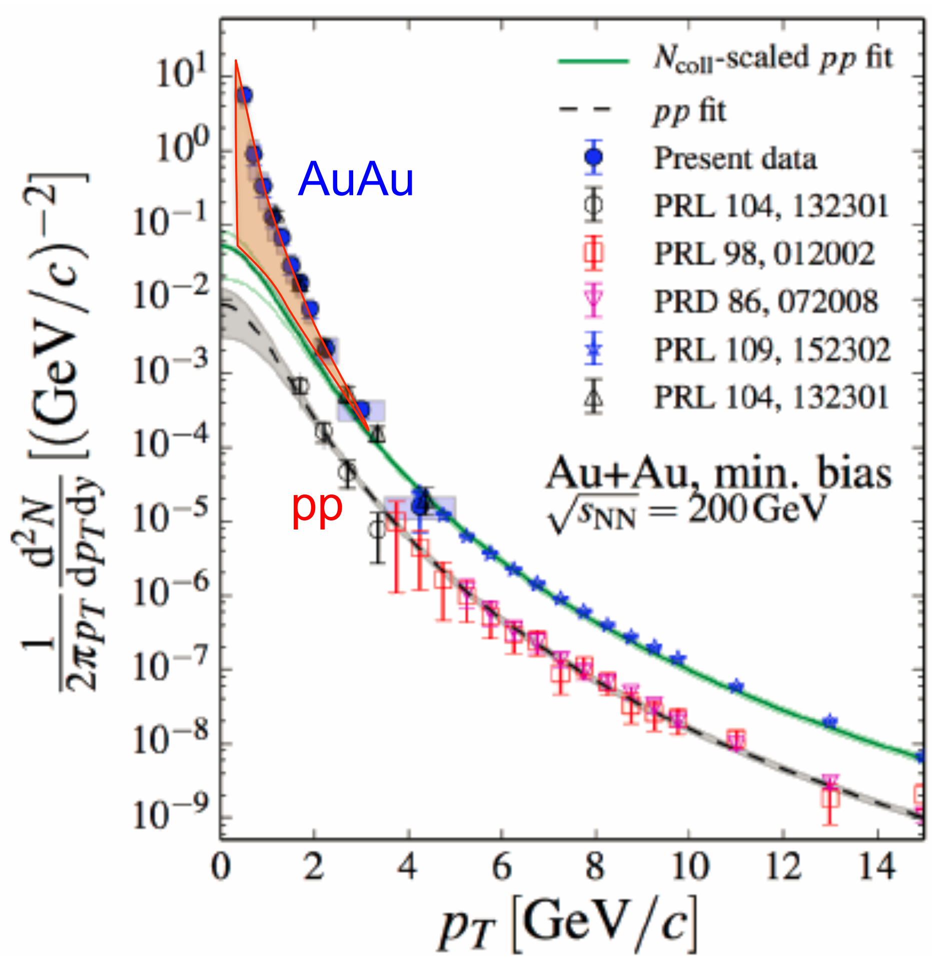
- ϕ puzzle between central and peripheral at LHC
- Extension of hydro-dominant p_T region w.r.t. hard contribution?



2.75TeV Pb+Pb, ALICE
arXiv:1405.4632

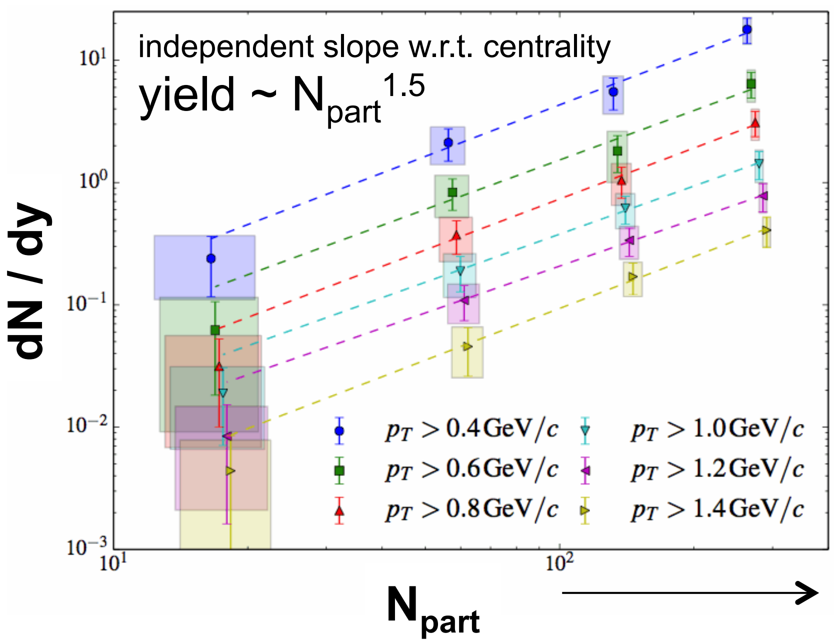
Temperature from Thermal Photon



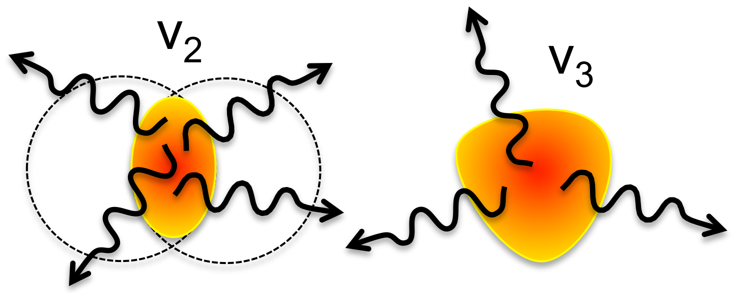


- Virtual and real photon measurements via internal and external conversion methods with electron pair measurements
- Real photon measurements with EMcal
- Initial temperature of 300~600MeV

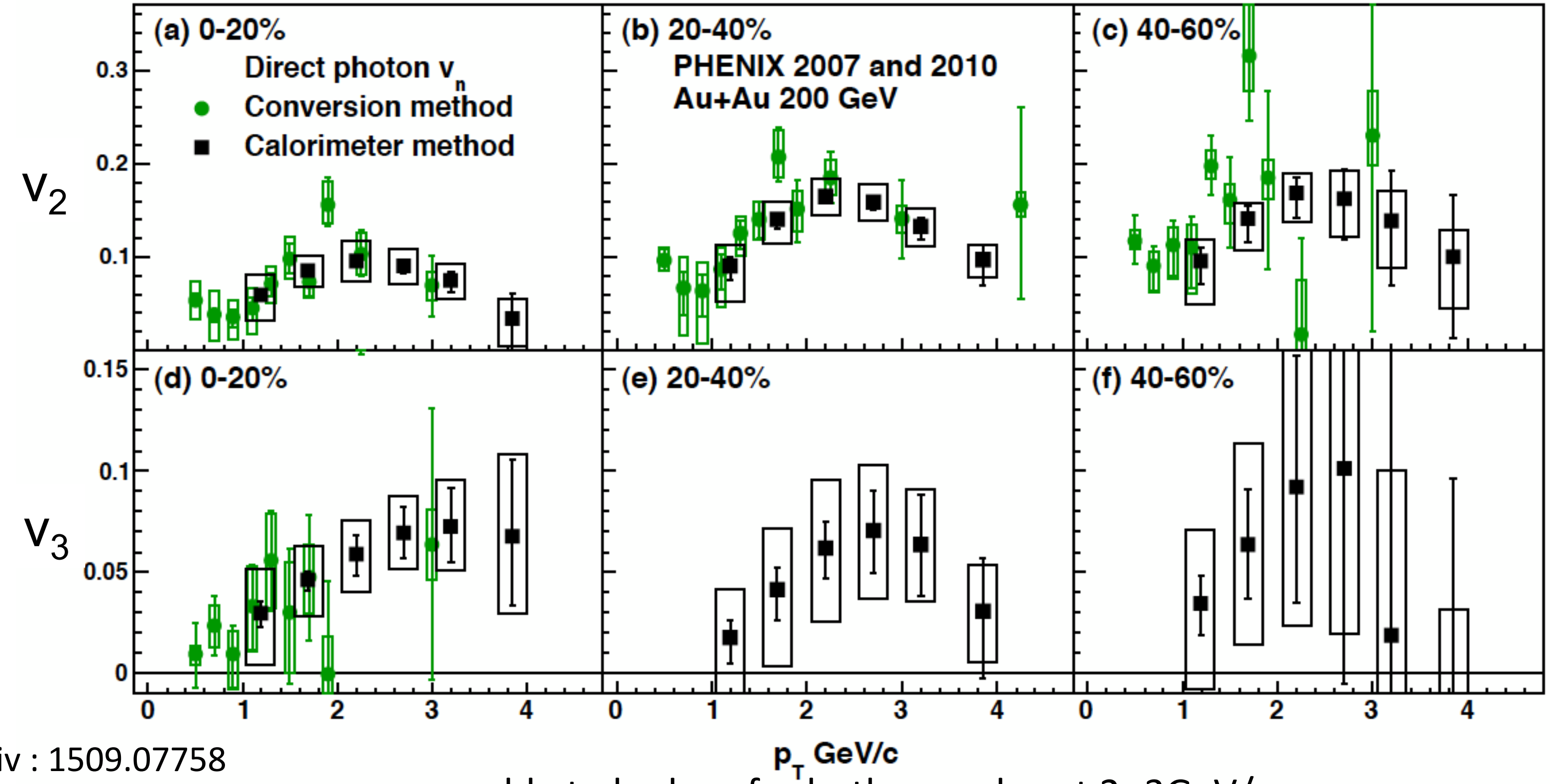
arXiv:1405.3940



Direct (thermal) photon v_2 and v_3



$v_n = \langle \cos n(\phi^{particle} - \Phi_n^{plane}) \rangle$
(n=2 : elliptic flow), (n=3 : triangular flow)



arXiv : 1509.07758

- comparable to hadron for both v_2 and v_3 at 2~3GeV/c
- significant contribution from photons from later stages (inconsistent with early photons from hotter period)
- flatter p_T dependence of v_2 at low p_T