Elliptic and triangular collective flow of identified charged hadrons in Au+Au at $\sqrt{s_{NN}}$=200 GeV

Petr Parfenov
for the STAR Collaboration

National Research Nuclear University MEPhI

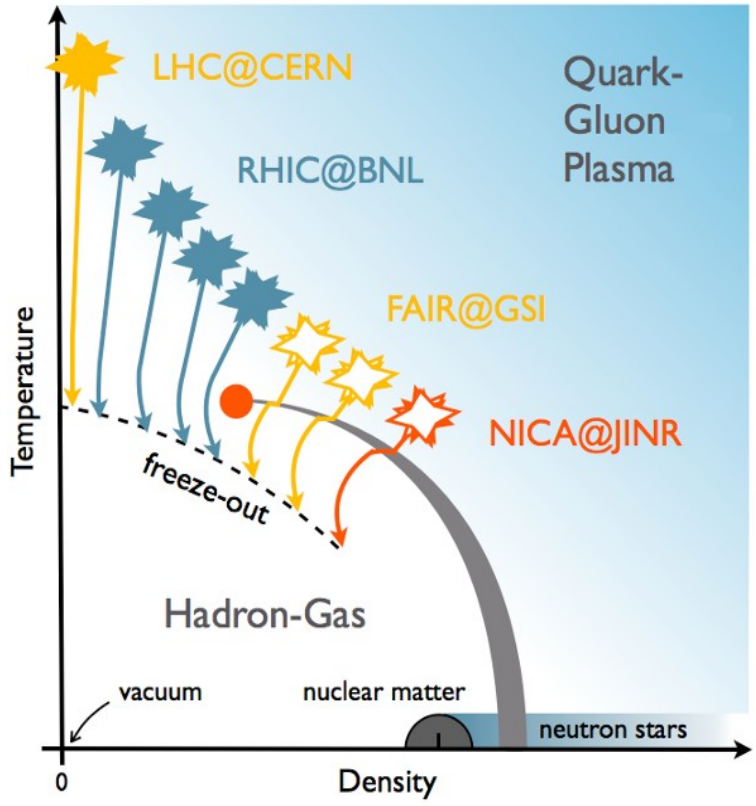
ICNFP 2020 – 9th International Conference on New Frontiers in Physics

Kolymbari, Crete (Greece), Sep. 4-11, 2020

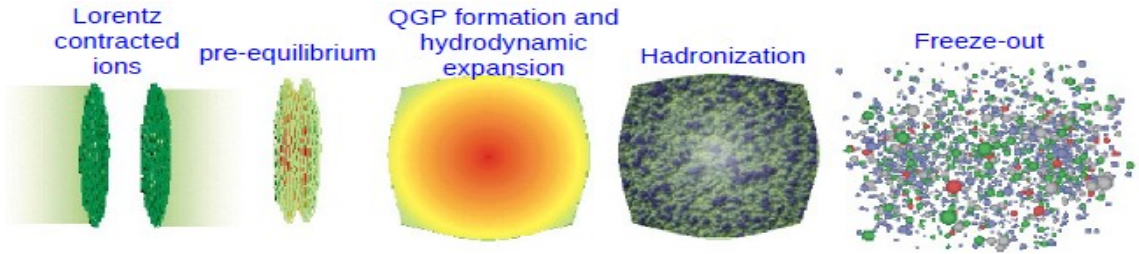
Outline

- Motivation
- Anisotropic flow at RHIC and LHC
- The STAR detector at RHIC
- Analysis methods
- Results
- Summary and Outlook

Phase Diagram of the Strongly-Interacting Matter



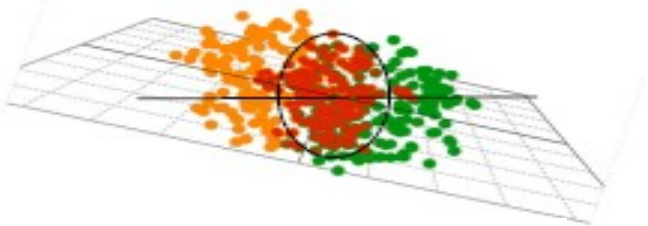
Top RHIC/LHC: validation of the cross over transition leading to the sQGP

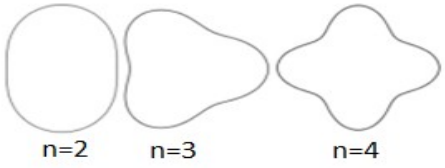


- ***Top RHIC energy /LHC - access to high T and small μ_B***
- ***RHIC-BES/SPS/NICA/FAIR - access to different systems and a broad domain of the (μ_B,T)-plane***

$$\frac{\eta}{s}(T,\mu),\ \frac{\zeta}{s}(T,\mu),\ c_s(T),\ \hat{q}(T),\ \alpha_s(T),\ \text{etc}$$

Anisotropic Collective Flow at RHIC/LHC

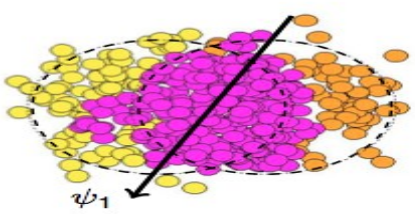


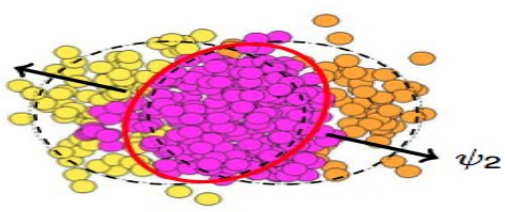


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$

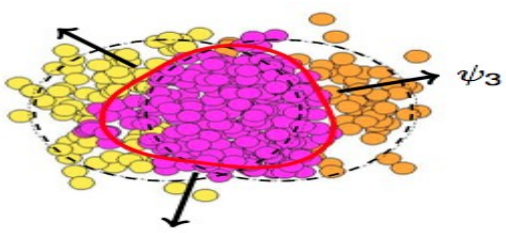
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n(\phi - \Psi_n)\right]\right)$$

Initial eccentricity (and its attendant fluctuations), ε_n, drives momentum anisotropy, v_n, with specific viscous modulation



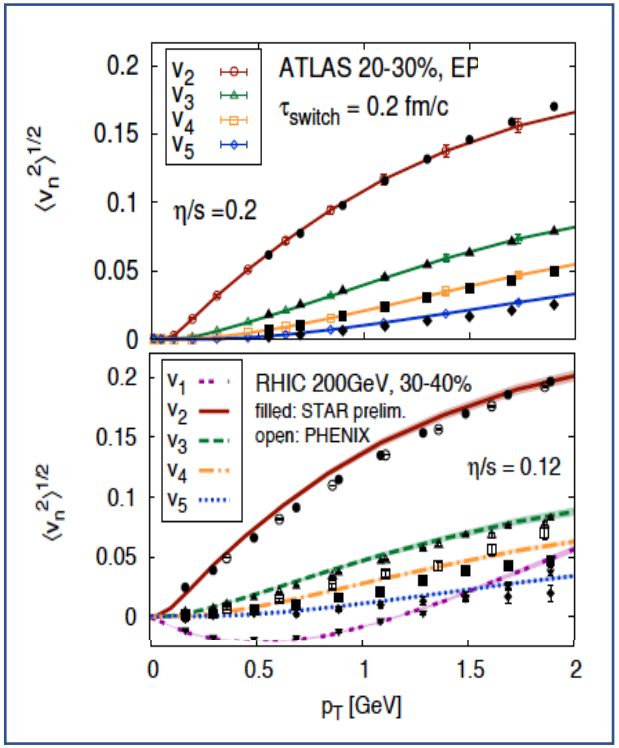


v_2 - elliptic flow

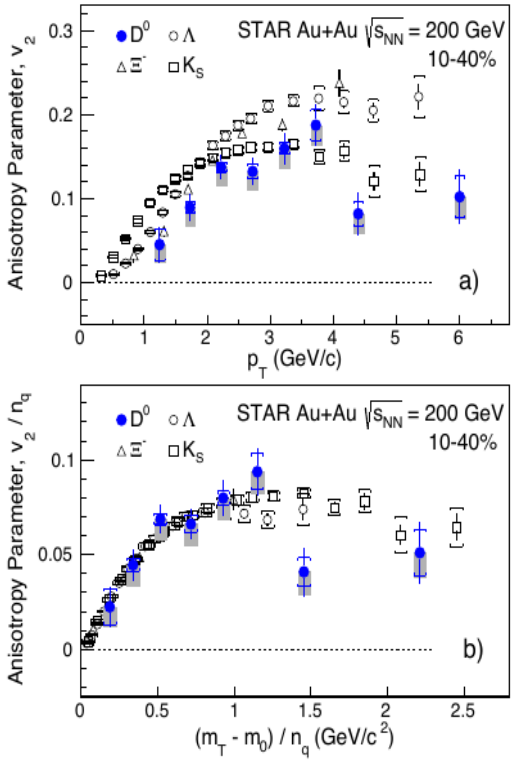


v_3 - triangular flow

Anisotropic Collective Flow at RHIC/LHC



Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302



STAR PRL118 (2017) 212301

v_n (p_T, centrality) - sensitive to the early stages of collision.
Important constraint for transport properties: EOS, η/s, ζ/s, etc.

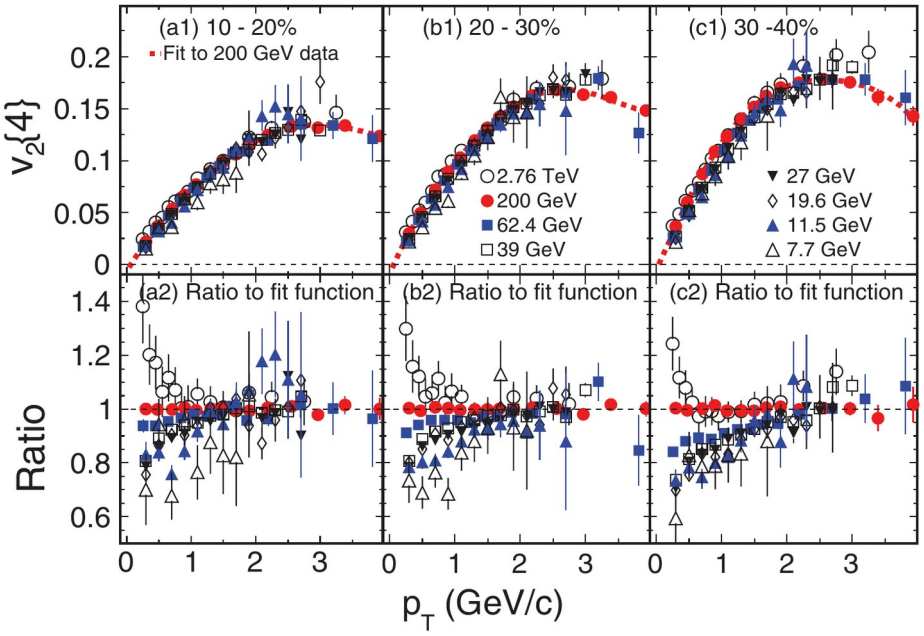
v_n of identified hadrons:

Mass ordering at p_T < 2 GeV/c
(hydrodynamic flow, hadron rescattering)

Baryon/meson grouping at p_T > 2 GeV/c
(recombination/coalescence),
Number of constituent quark (NCQ) scaling

Beam-Energy Dependence of Elliptic Flow (v_2)

STAR: Phys. Rev. C 86 (2012) 54908



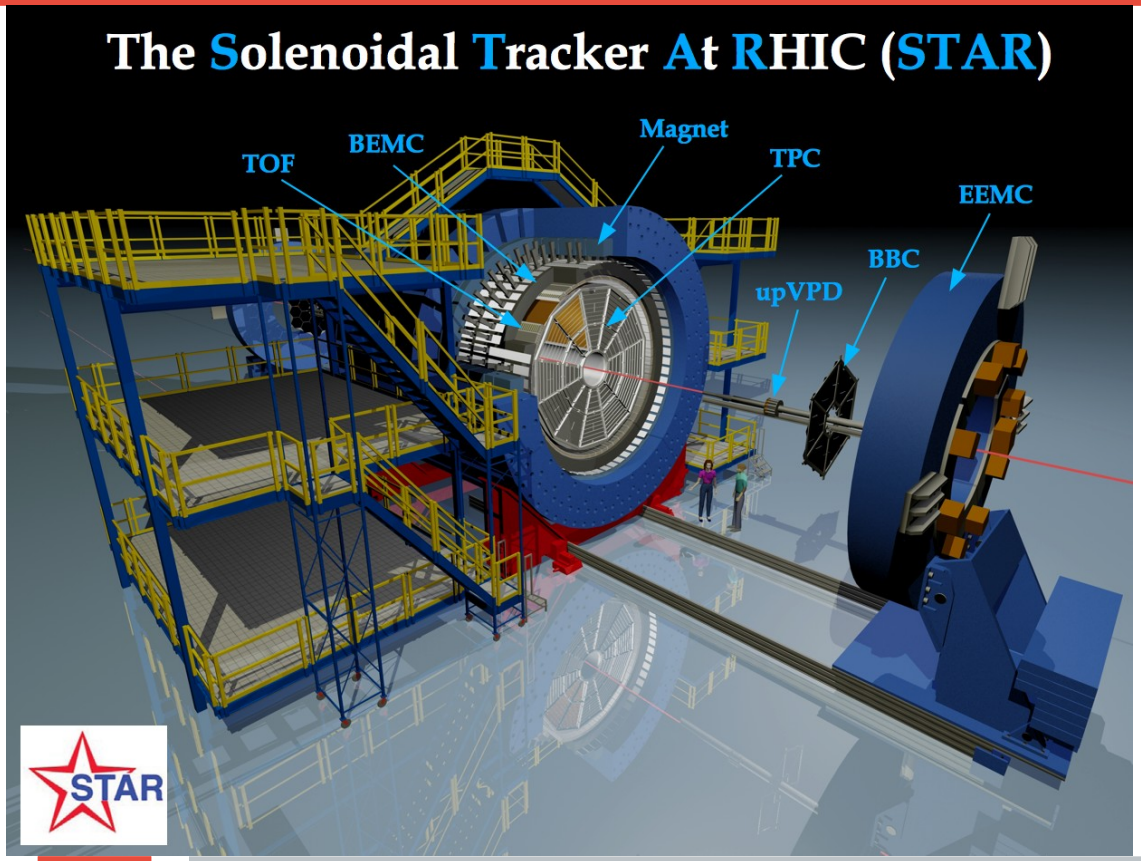
Small change in v_2 for inclusive charged hadrons as the collision energy changes by a factor ~400 (from 7.7 GeV to 2.76 TeV) and initial energy density changes by nearly a factor of 10.

Different picture for identified hadrons?

Goal of this analysis:

1) Differential measurements of v_2 and v_3 for identified charged hadrons for Au+Au collisions at 200 GeV.
2) Detailed comparison between top RHIC and LHC energies.

The STAR detector at RHIC



Time Projection Chamber (TPC):

- Tracking of charged particles with ($|\eta| < 1$, 2π in φ)
- PID using dE/dx measurements

Time-Of-Flight (TOF):

- $|\eta| < 0.9$, 2π in φ
- PID using time-of-flight information

Event planes:

TPC ($|\eta| < 1$), BBC ($3.8 < |\eta| < 5.2$)

Data set:

Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

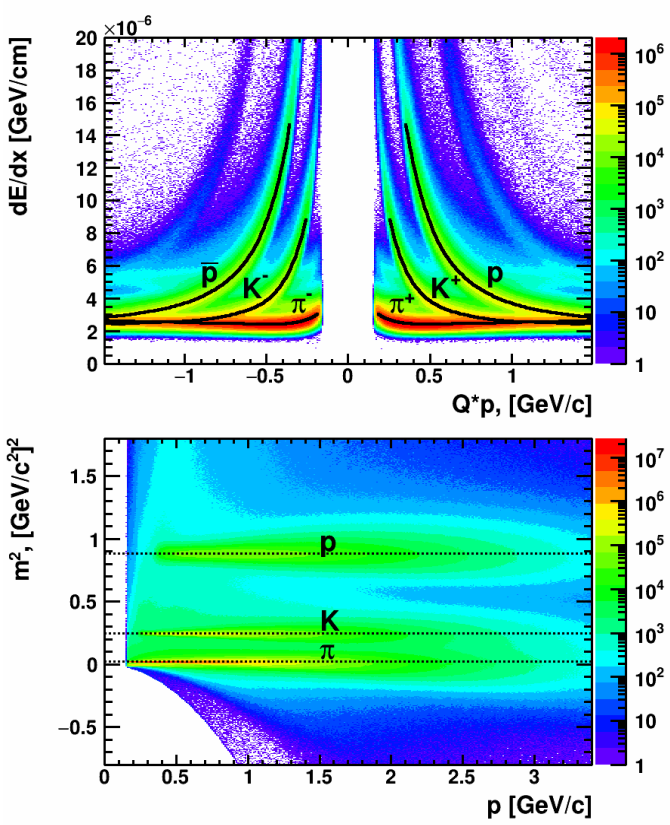
Particle identification

TPC

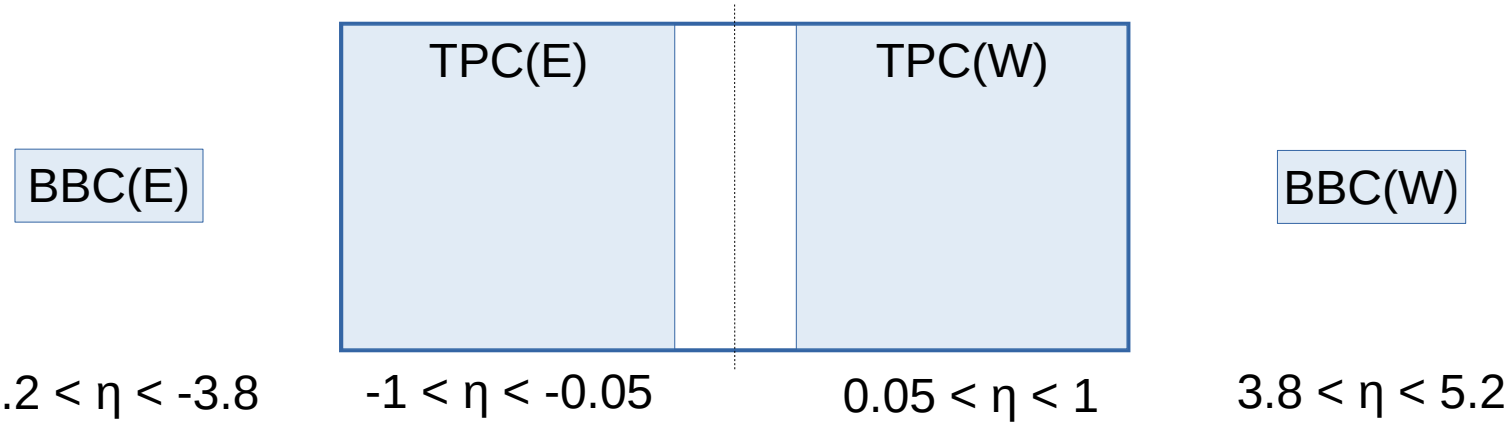
Particle identification via specific ionization energy loss (dE/dx).
Pion and kaon identification up to p~0.55 GeV/c.
Proton identification up to p~1.1 GeV/c.

TOF

Particle identification up to p=2.5 GeV/c
using time-of-flight information.



Analysis technique: Event Plane Method (EP)



East BBC/TPC half $(\eta<0) \rightarrow \eta_-$

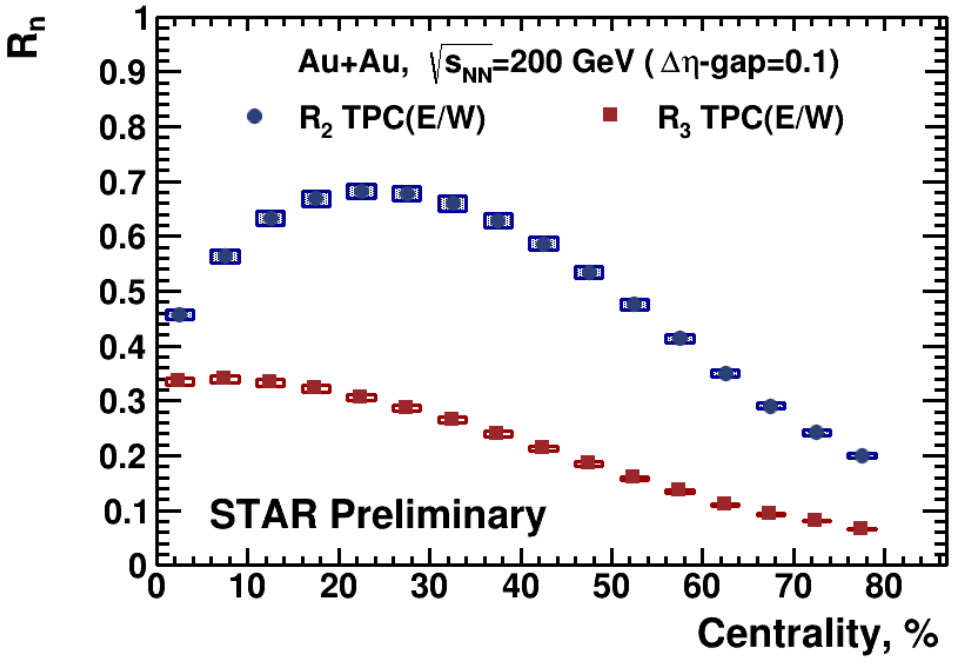
West BBC/TPC half $(\eta>0) \rightarrow \eta_+$

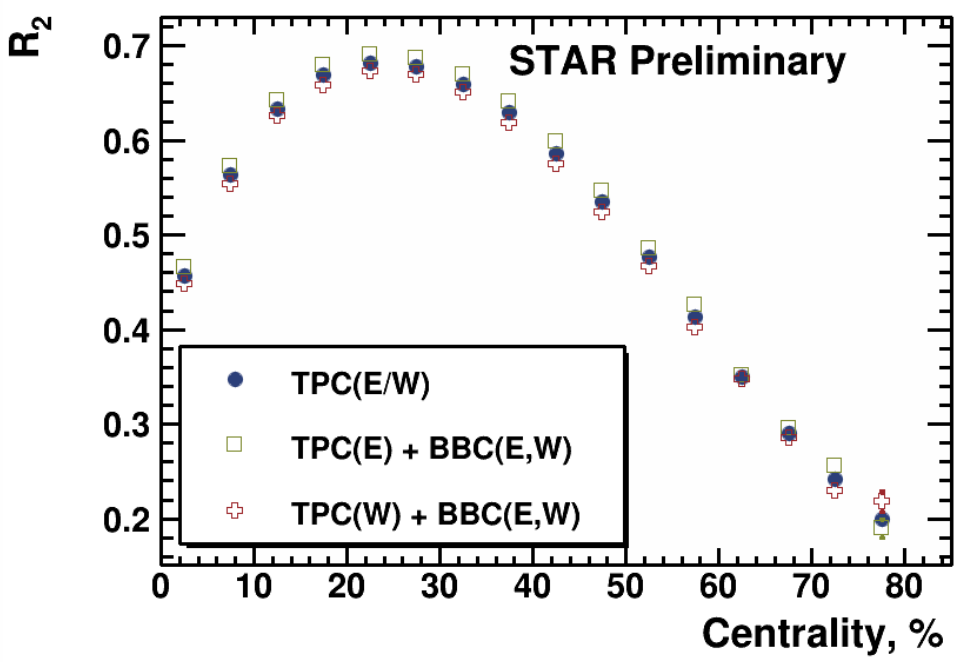
$$v_n = \frac{\left\langle \cos\left[n\left(\varphi_{\eta^\pm} - \Psi_{n,\eta^\mp} \right) \right] \right\rangle}{\sqrt{\left\langle \cos\left[n\left(\Psi_{n,\eta+} - \Psi_{n,\eta-} \right) \right] \right\rangle}}$$

Systematic uncertainty for v_n :

- EP resolution 2-sub vs. 3-sub event methods
- Difference between results for TPC and BBC EP
- Difference between the EP and Scalar Product (SP) methods

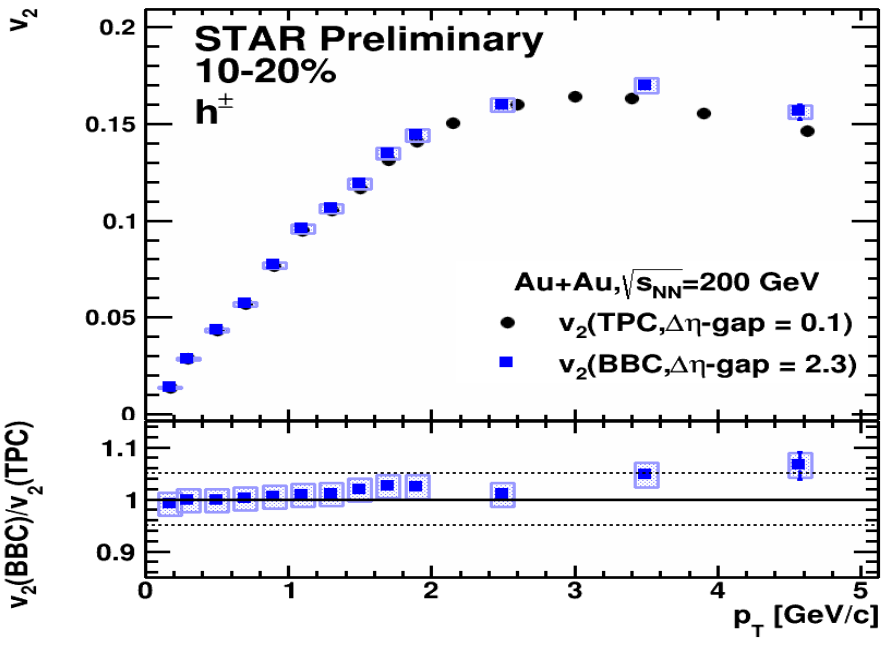
Event plane resolution

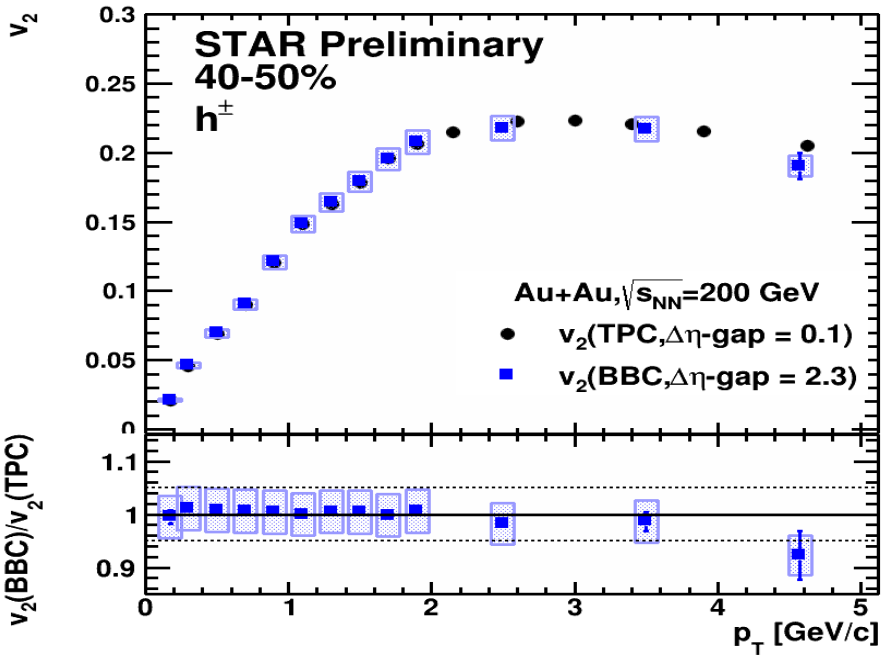




Good agreement between 2-sub & 3-sub event methods

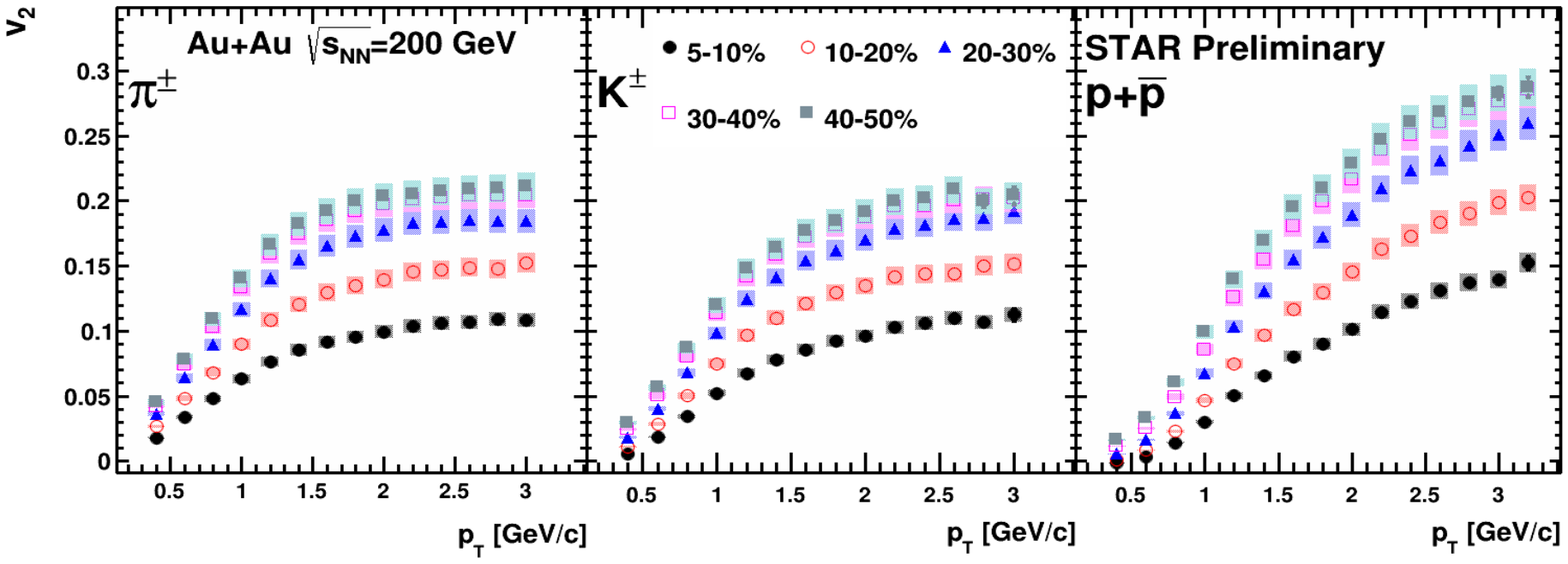
v_2 TPC vs. BBC event plane





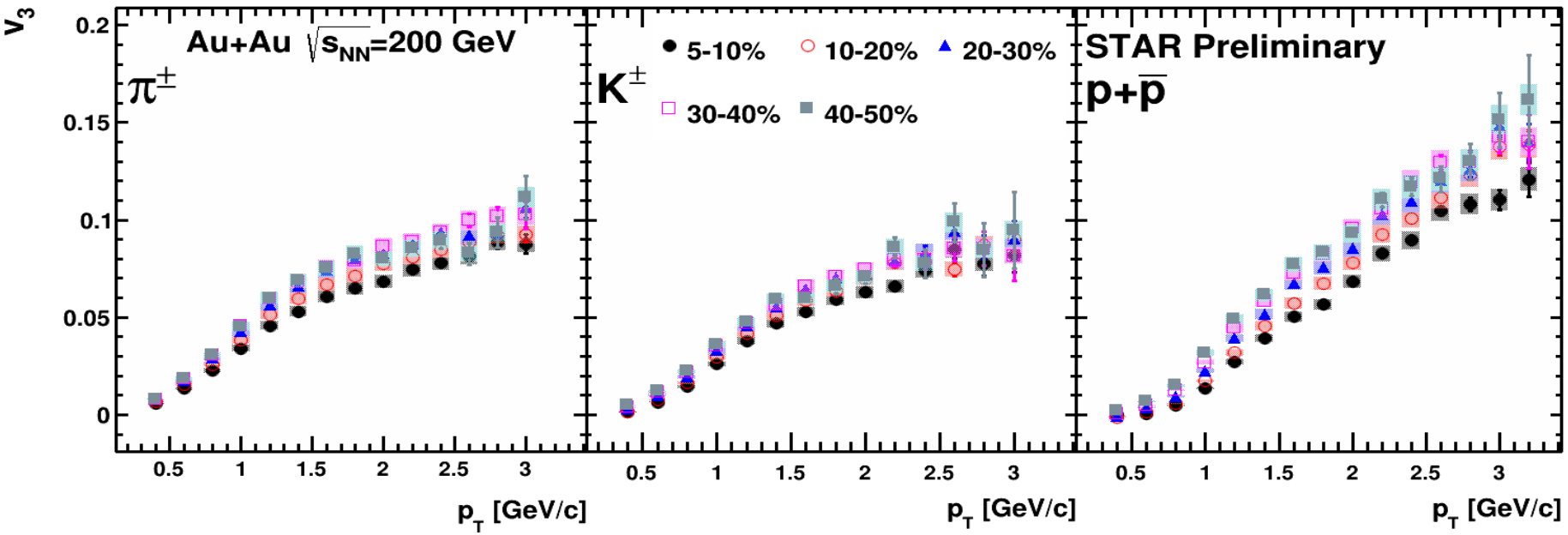
Good agreement for v_2 results obtained using EP from TPC and BBC.

$v_2(p_T)$ for identified hadrons



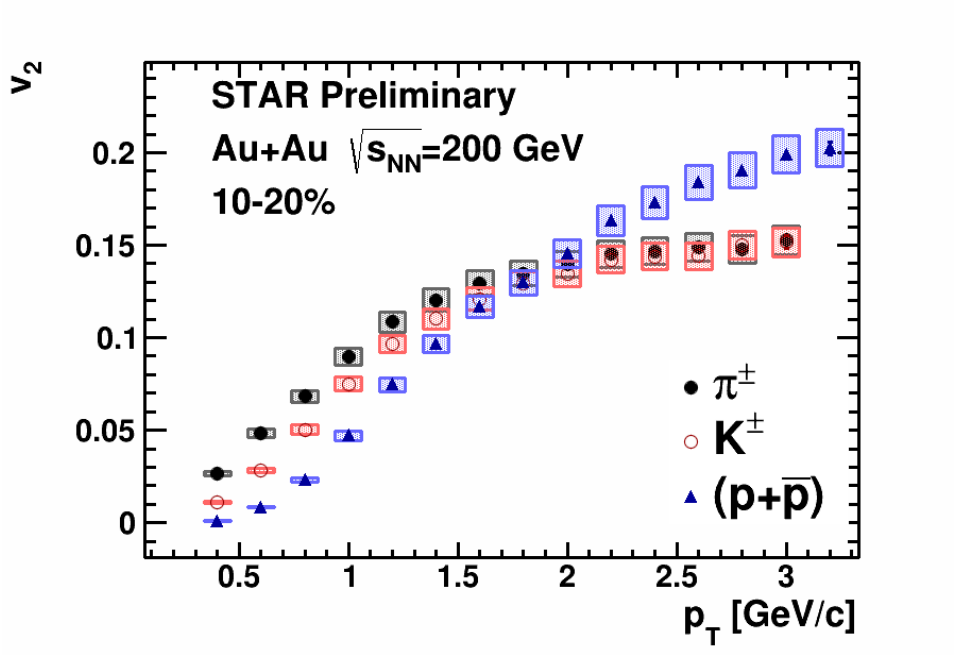
Strong centrality dependence of $v_2(p_T)$

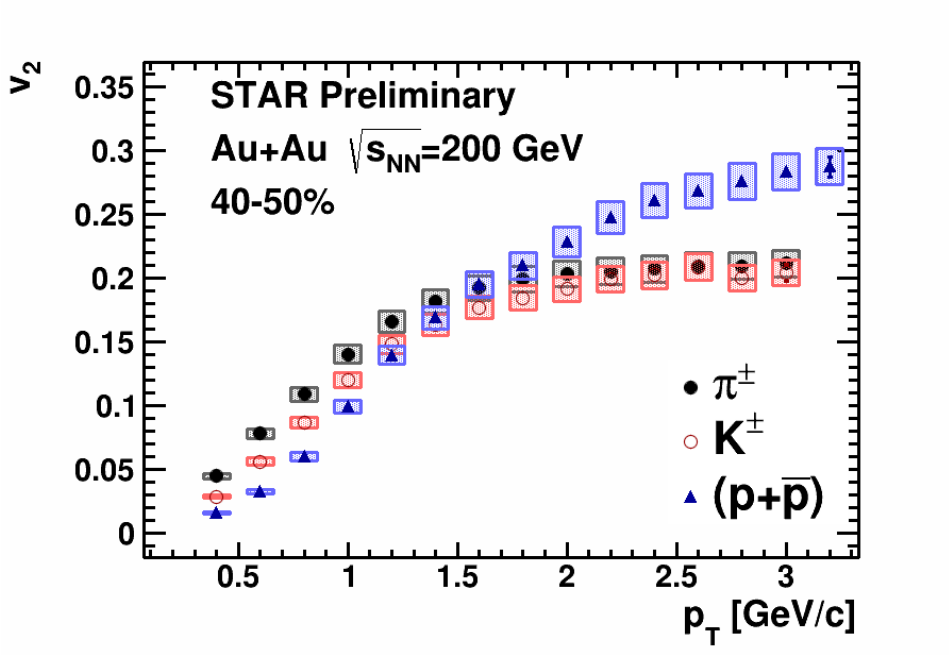
$v_3(p_T)$ for identified hadrons



Weak centrality dependence of $v_3(p_T)$

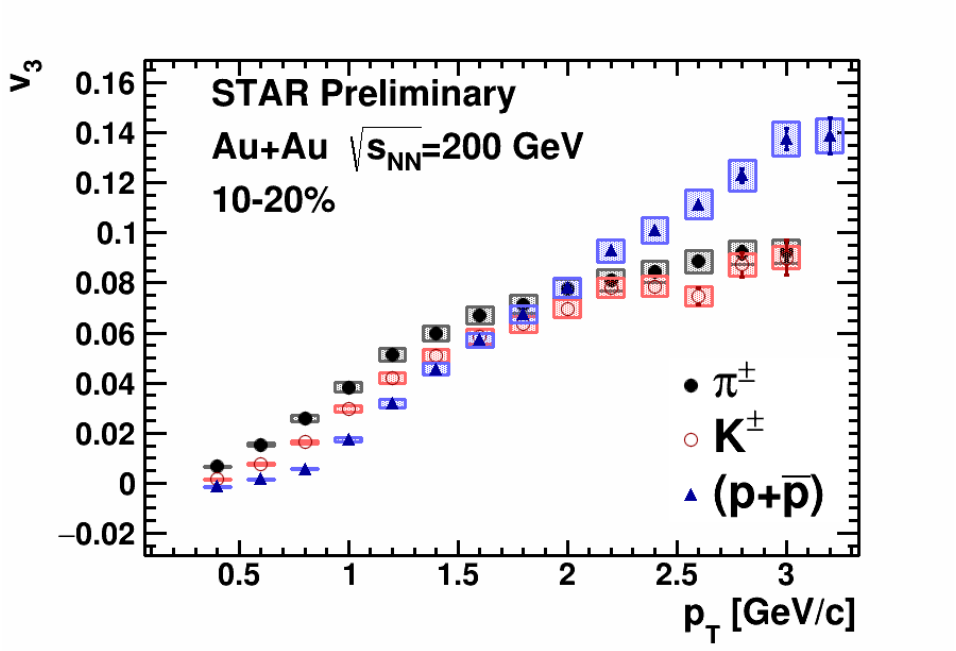
$v_2(p_T)$ for identified hadrons

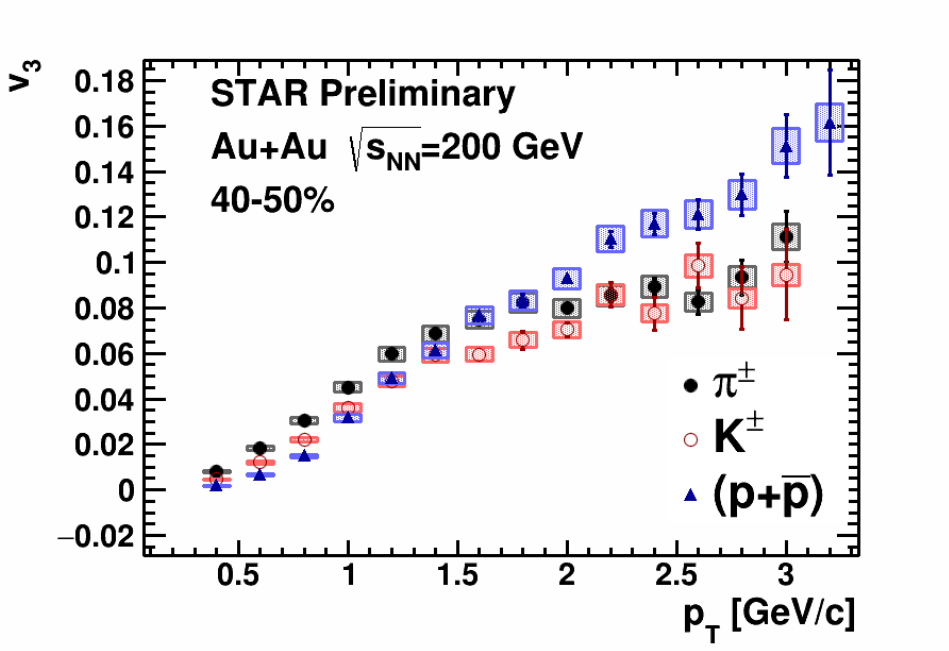




Mass ordering for p_T < 2 GeV/c and baryon/meson grouping for p_T > 2 GeV/c

$v_3(p_T)$ for identified hadrons

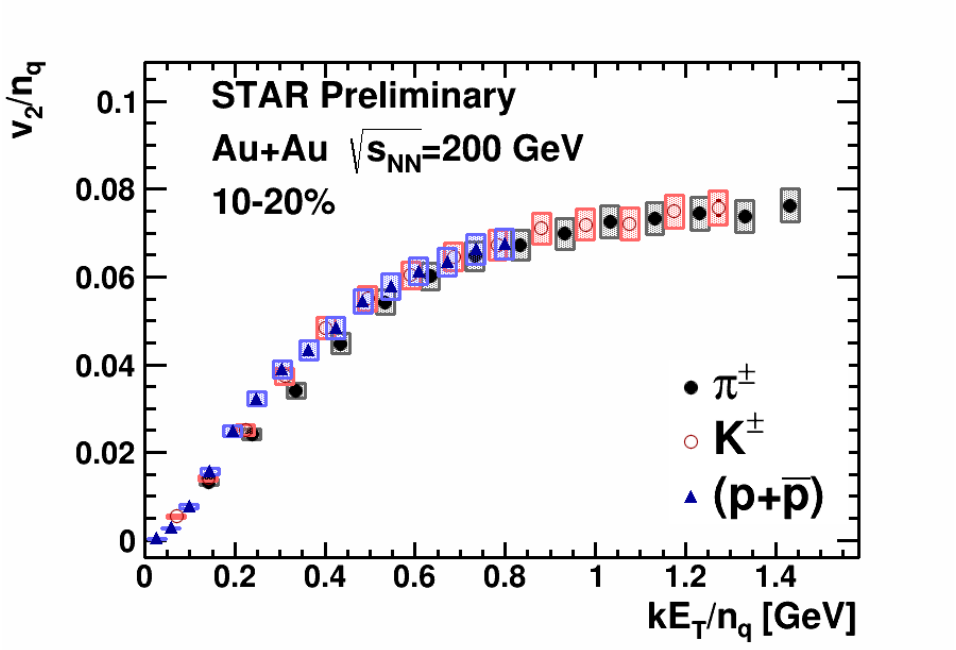


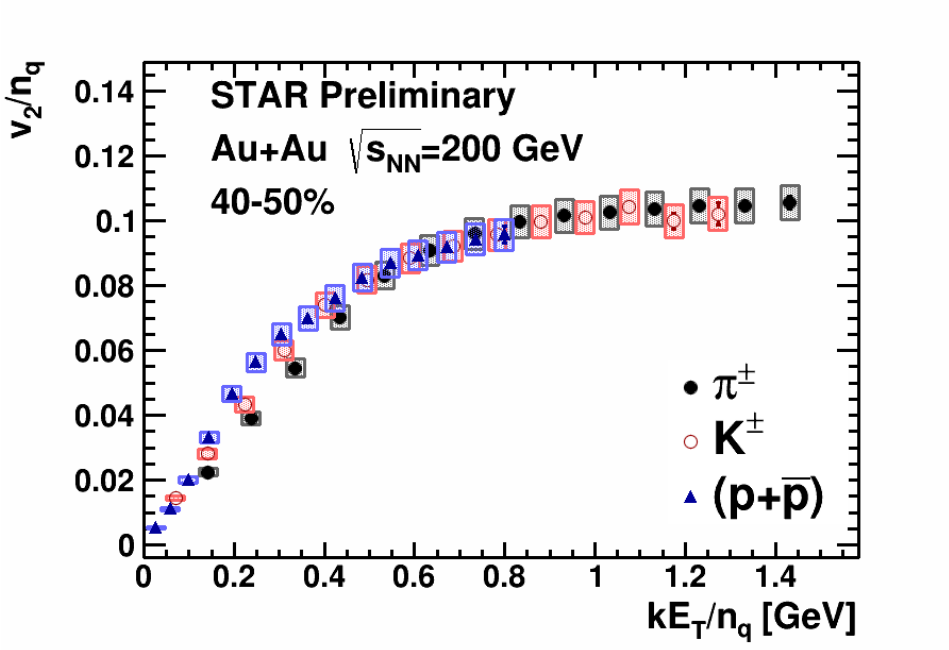


Mass ordering for p_T < 2 GeV/c and baryon/meson grouping for p_T > 2 GeV/c

v_2 quark number scaling

$k E_T \equiv m_T - m_0,\ m_T^2 = m_0^2 + p_T^2$

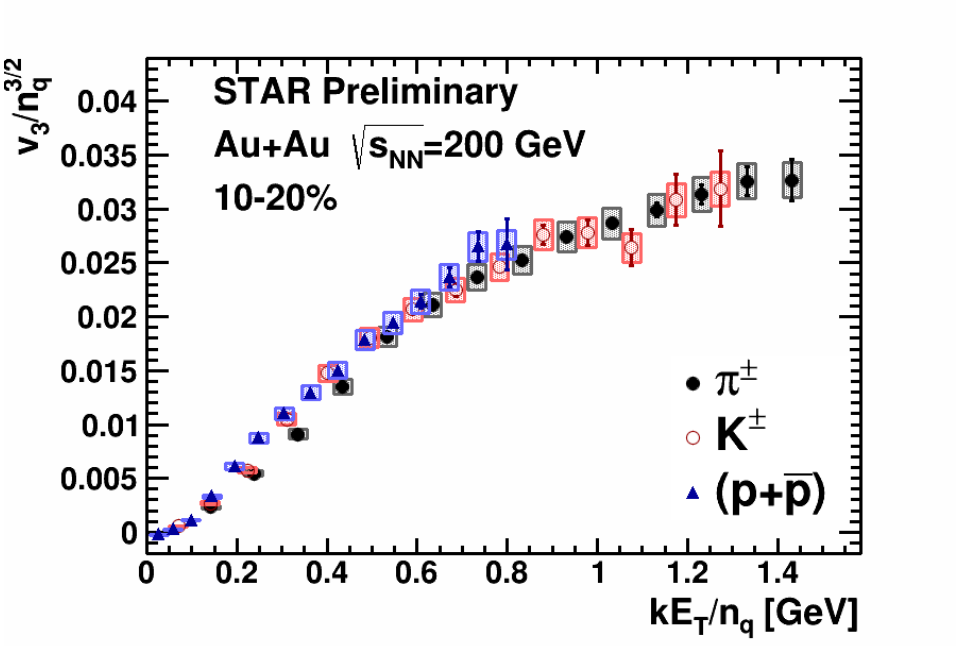


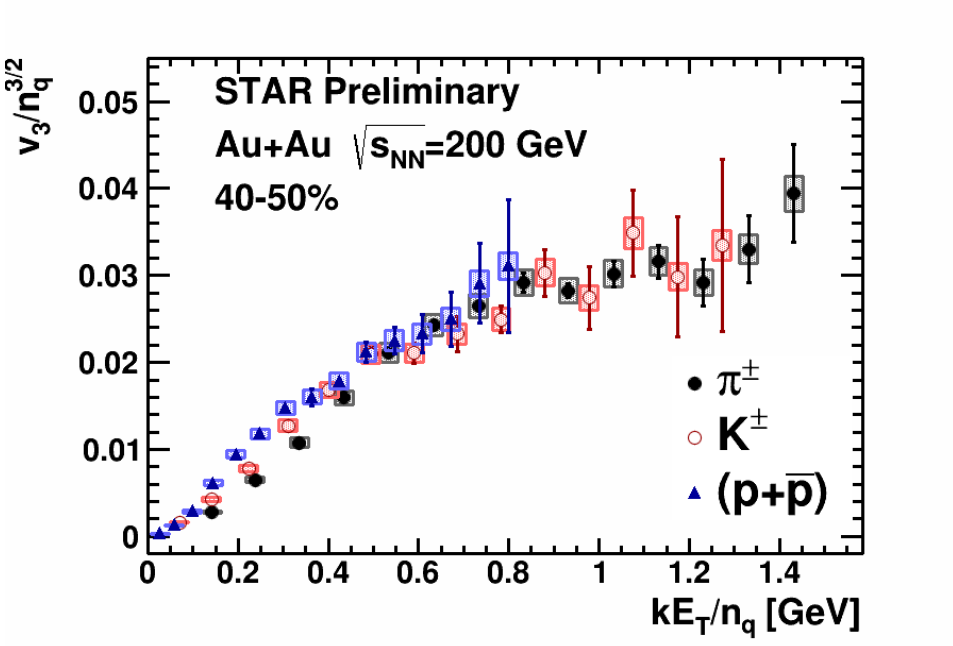


Expected scaling behavior for v_2 of identified hadrons

v_3 quark number scaling

$k E_T \equiv m_T - m_0, \; m_T^2 = m_0^2 + p_T^2$

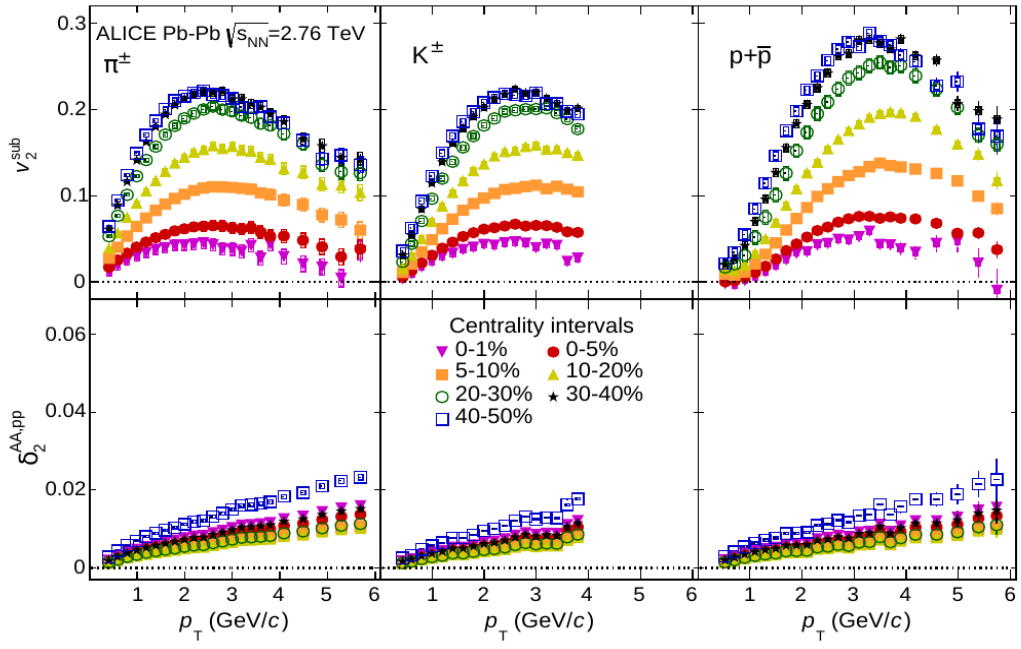


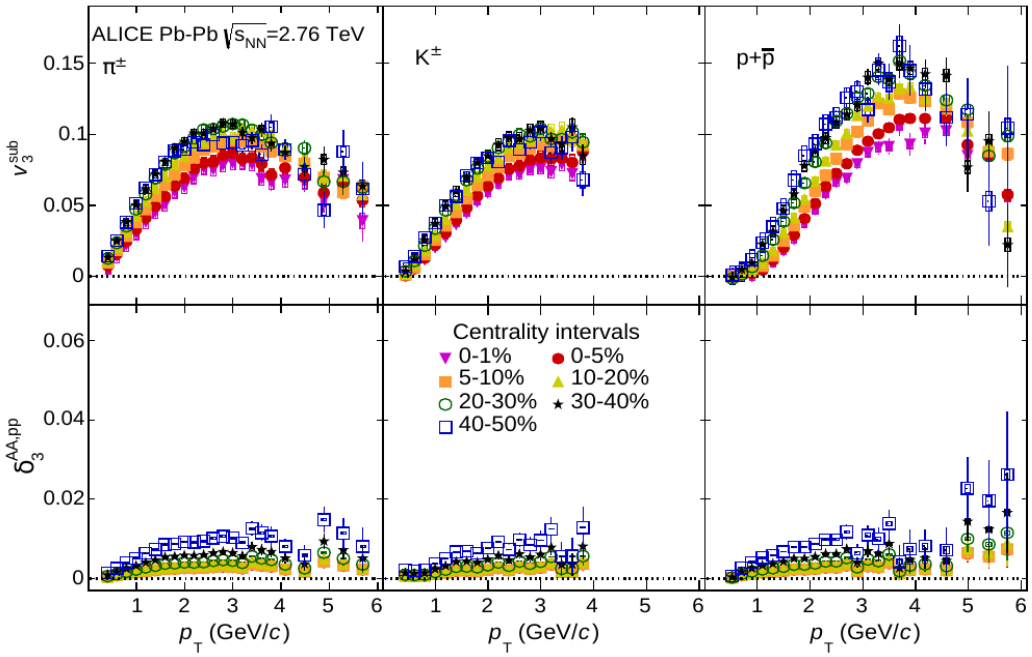


Expected scaling behavior for v_3 of identified hadrons

v_2, v_3 of identified hadrons for Pb+Pb at $\sqrt{s_{NN}}$=2.76 TeV (ALICE)

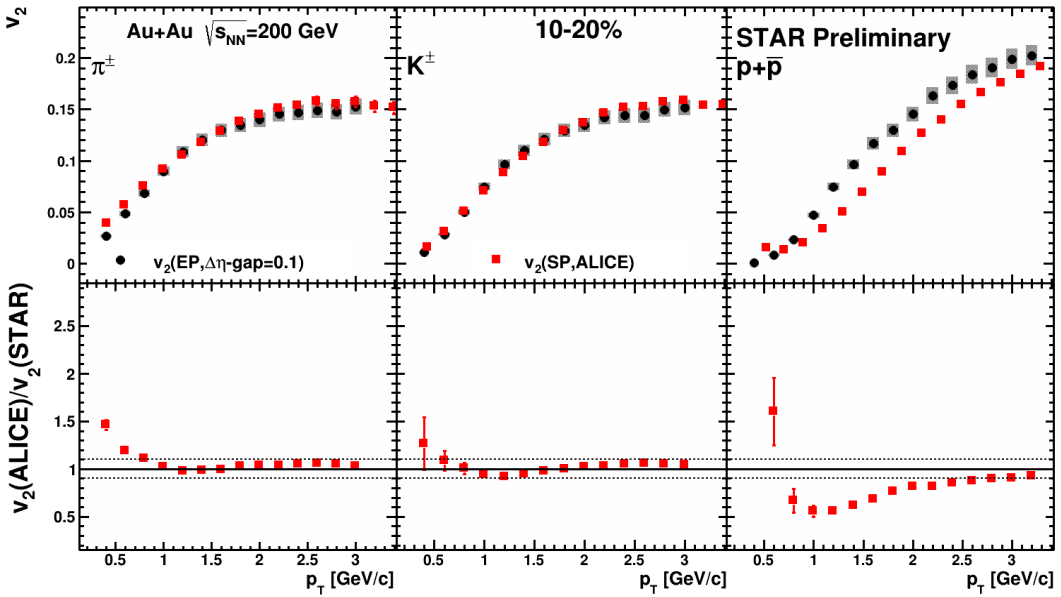
v_2 ALICE, JHEP 1609 (2016) 164 v_3

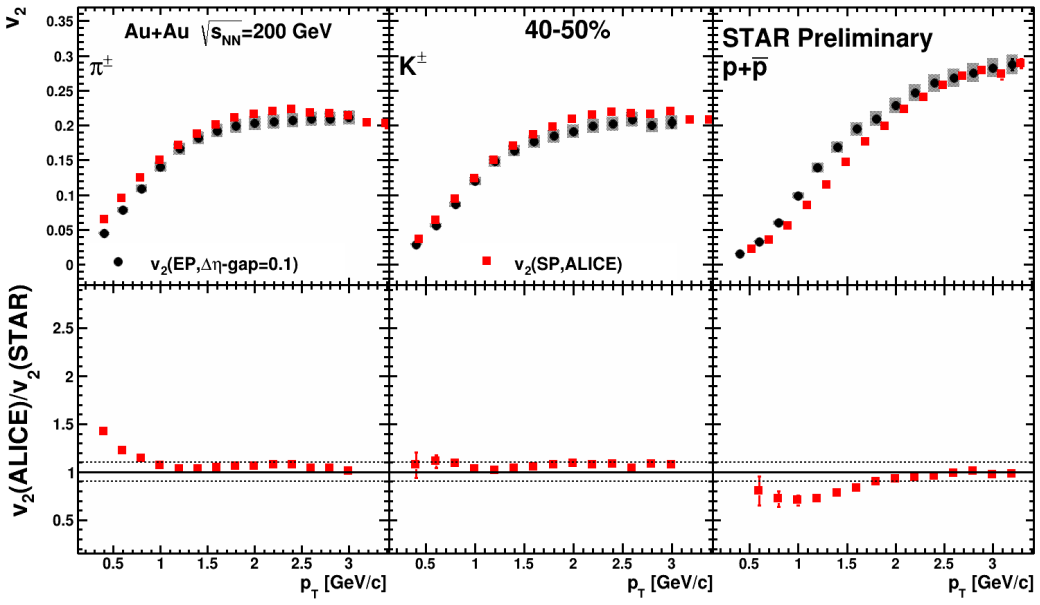




$$v_{2,3}^{\mathrm{sub}} = v_{2,3} - \delta_{2,3}^{AA,pp}, \quad \delta_{2,3}^{AA,pp} \text{ - non-flow}$$

Comparison of v_2 results for Au+Au at $\sqrt{s_{NN}}$= 200 GeV with Pb+Pb at $\sqrt{s_{NN}}$=2.76 TeV (ALICE)

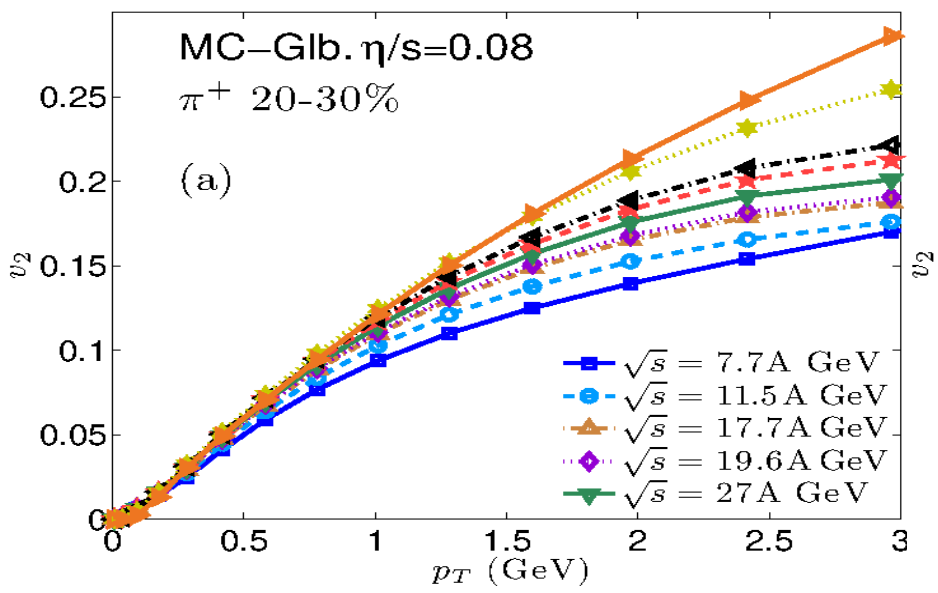


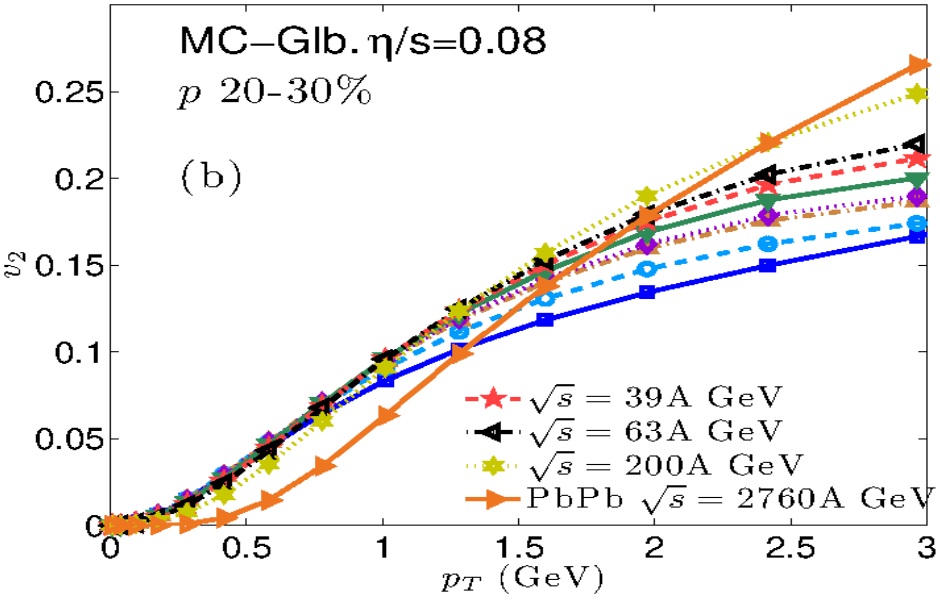


- ✔ For pions $v_2(p_T)$ varies with $\sqrt{s_{NN}}$ very similarly to the total charged hadron $v_2(p_T)$.
  - ✔ For protons the strong radial flow "blueshifts" the entire flow signal to higher p_T.

v_2 of identified hadrons from RHIC to LHC (viscous hydrodynamics)

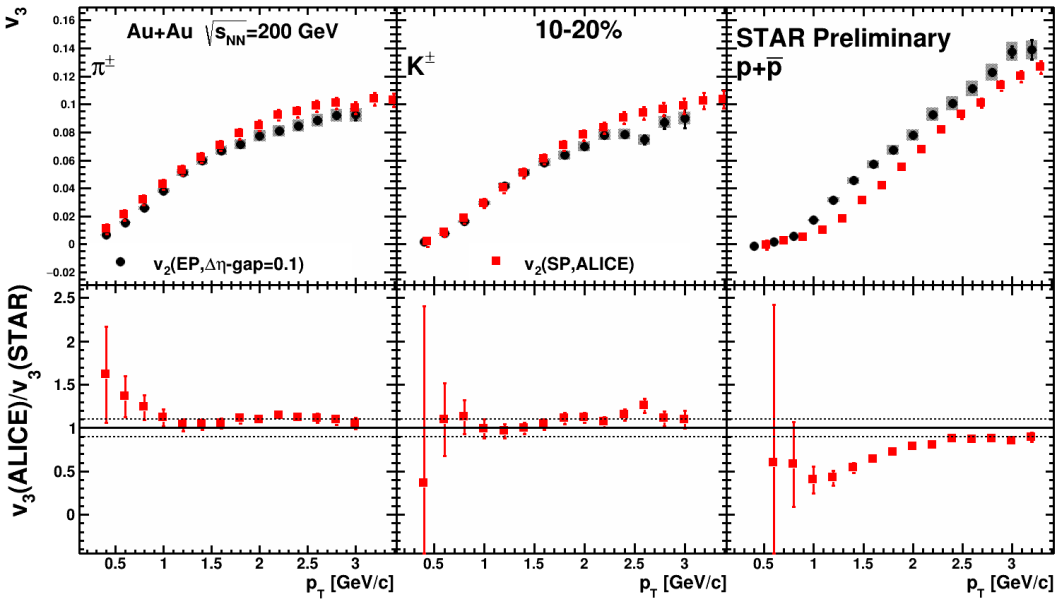
Chun Shen and Ulrich Heinz, Phys. Rev. C 85, 054902(2012), VISH2+1 model calculations

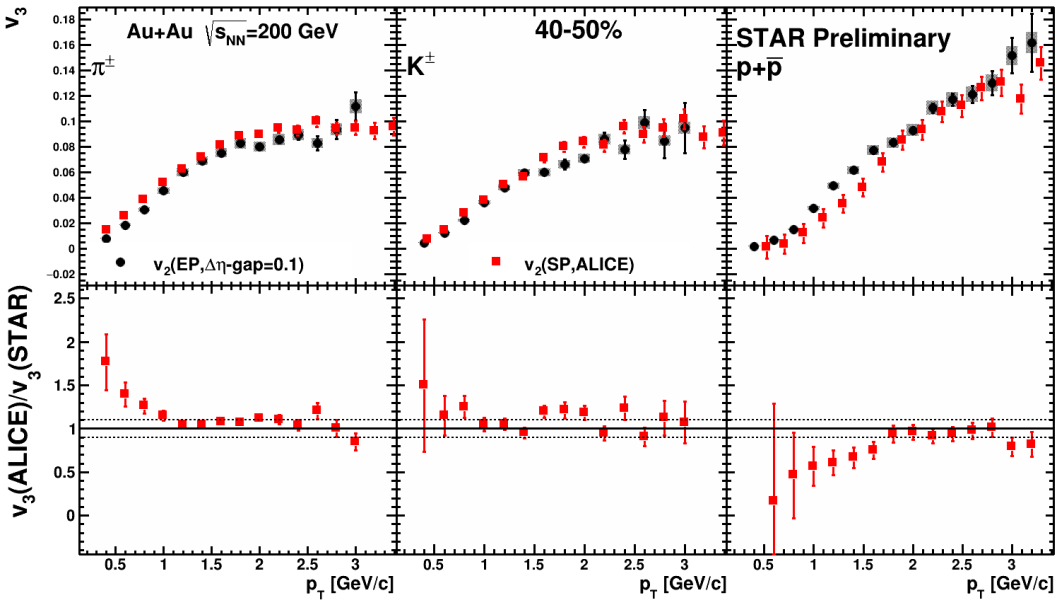




- ✔ For pions $v_2(p_T)$ varies with $\sqrt{s_{NN}}$ very similarly to the total charged hadron $v_2(p_T)$.
  - ✔ For protons the strong radial flow "blueshifts" the entire flow signal to higher p_T.

Comparison of v_3 results for Au+Au at $\sqrt{s_{NN}}$= 200 GeV with Pb+Pb at $\sqrt{s_{NN}}$=2.76 TeV (ALICE)





- ✔ For pions $v_3(p_T)$ varies with $\sqrt{s_{NN}}$ very similarly to the total charged hadron $v_3(p_T)$.
  - ✔ For protons the strong radial flow "blueshifts" the entire flow signal to higher p_T .

Summary & Outlook

Results of (p_T, centrality)-differential elliptic (v_2) and triangular (v_3) flow measurements of identified hadrons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV are presented.

- Strong centrality dependence of $v_2(p_T)$ and weak dependence of $v_3(p_T)$.
- Mass ordering for p_T < 2 GeV/c and baryon/meson grouping for p_T > 2 GeV/c.
- Approximate NCQ scaling holds.

Detailed comparison between these results at top RHIC energy and ALICE results for Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (ALICE, JHEP 1609 (2016) 164) shows that

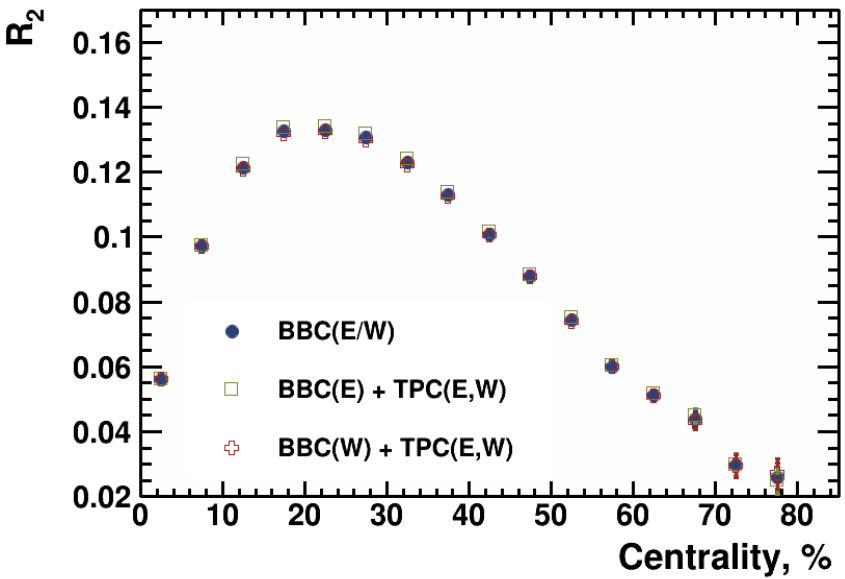
- **For p_T < 1.0 GeV/c the charged pion $v_{2,3}(p_T)$ rise with increasing $\sqrt{s_{NN}}$ very similarly to the total charged hadron $v_{2,3}(p_T)$ and show little change for p_T > 1.0 GeV/c.**

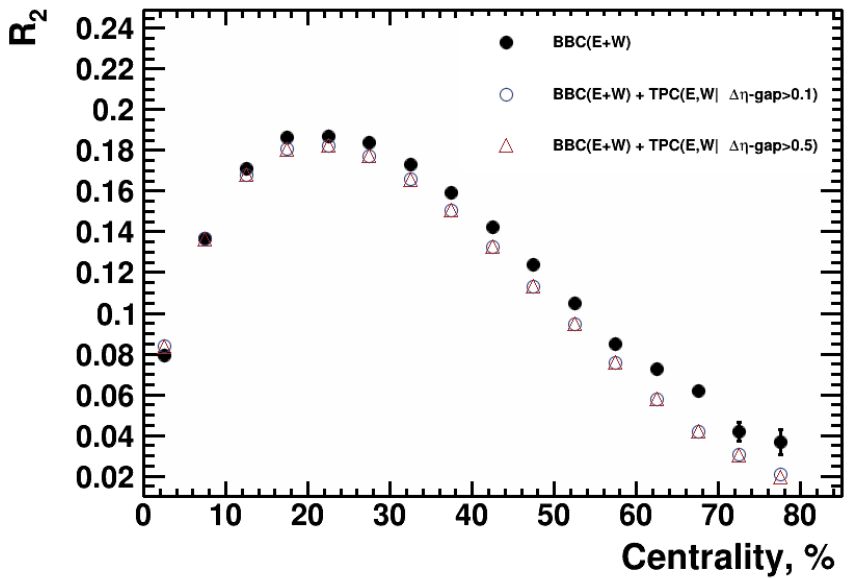
- **For protons the strong radial flow at LHC "blueshifts" the entire flow signal $v_{2,3}(p_T)$ to higher p_T and for LHC the $v_{2,3}(p_T)$ values are smaller in the low p_T region.**

Thank you for your attention

Backup

Event plane resolution





Good agreement between 2-sub & 3-sub event methods