



# Elliptic and triangular flow of (multi-)strange hadrons and $\phi$ mesons in BES-II energies at STAR

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**for the STAR Collaboration**

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Strangeness in Quark Matter*

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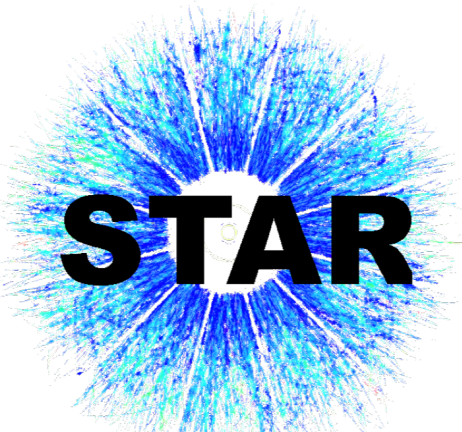


# Outline

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- Motivation
- Experimental Setup
- Analysis Method
- Results and Discussion
- Summary and Outlook



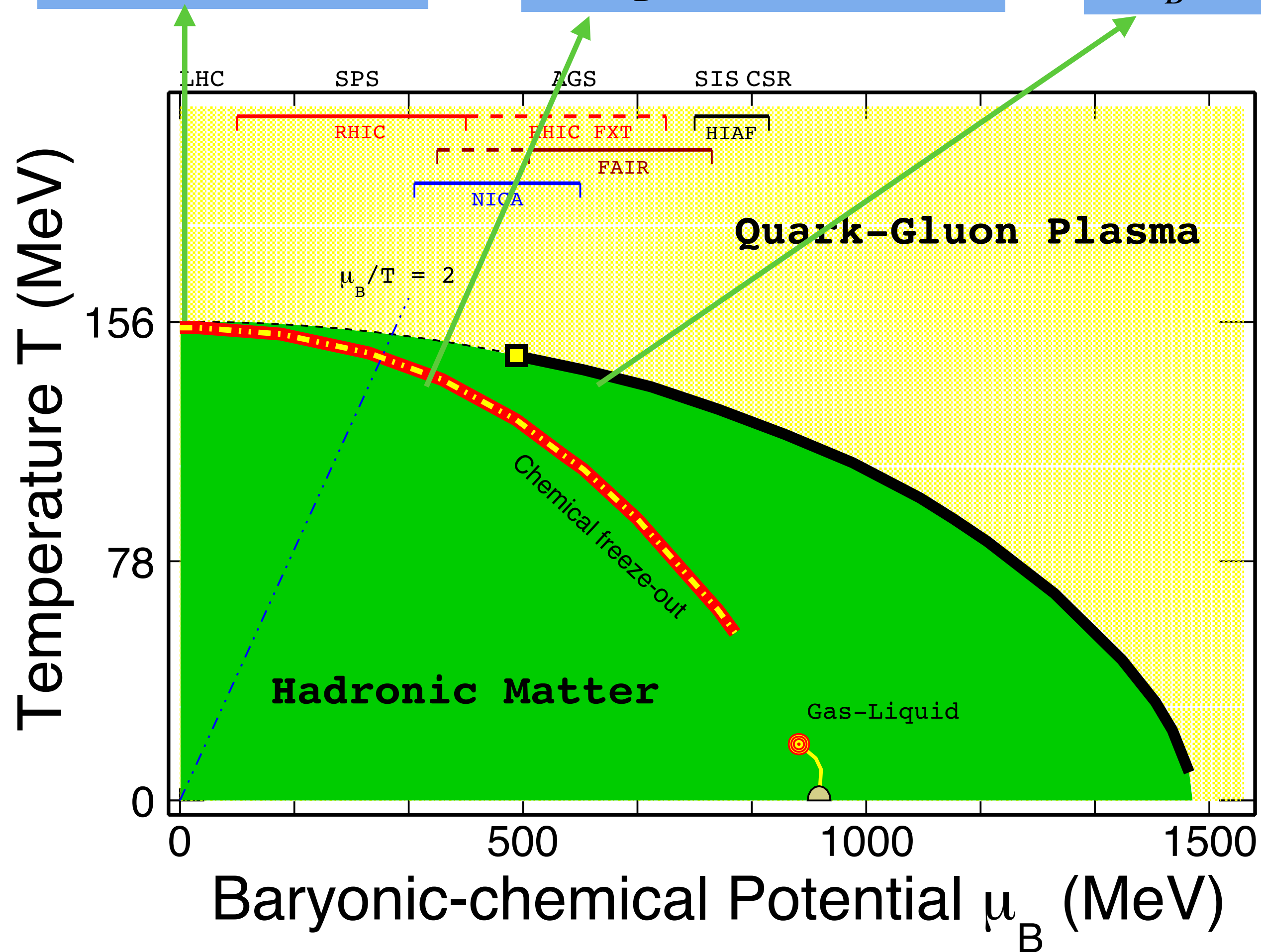
# Motivation



LHC, RHIC 200 GeV  
 $T_c$

RHIC COL: 7.7-62.4 GeV  
 $u_B$ : 73-420 MeV

RHIC FXT: 3.0-7.7 GeV  
 $u_B$ : 420-750 MeV



- RHIC 200 GeV and LHC  
Small viscosity, high temperature  
Evidence of Quark-Gluon Plasma
- Beam energy scan program  
Search for Critical Point  
Locate the first-order phase boundary

A. Bazavov et al., Phys. Rev. D 85, 054503 (2012); K. Fukushima and C. Sasaki, Prog. Part. Nucl. Phys, 72, 99 (2013)



# Motivation

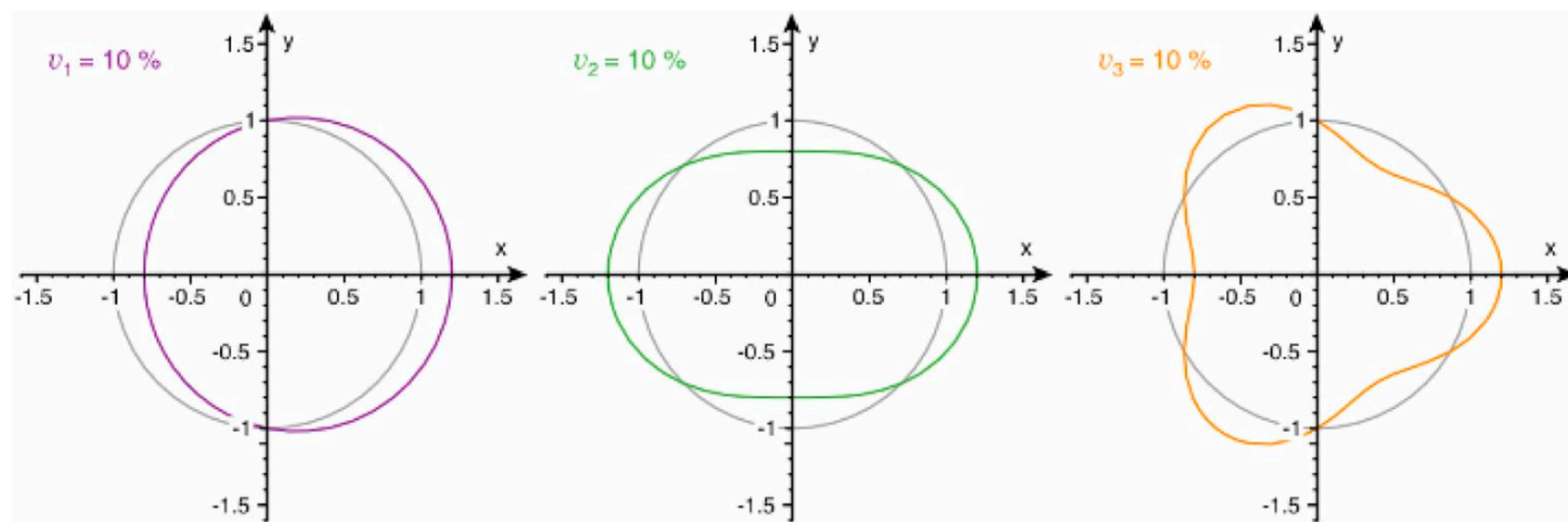


Heavy ion collisions: Initial spatial anisotropy → Pressure gradient → Anisotropic flow

$$E \frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left( 1 + \sum_1^{\infty} 2v_n \cos \left[ n (\phi - \psi_{RP}) \right] \right)$$

## Self-quenching effect

- $v_2$  is sensitive to constituent interactions and degree of freedom
- $v_3$  is sensitive to event-by-event fluctuations in the overlap region
- $\phi$ -meson and strange hadrons less affected by the hadronic phase
  - ▶ Small hadronic interaction cross sections
  - ▶ Freeze-out earlier than other light hadrons



$v_1$ : directed flow

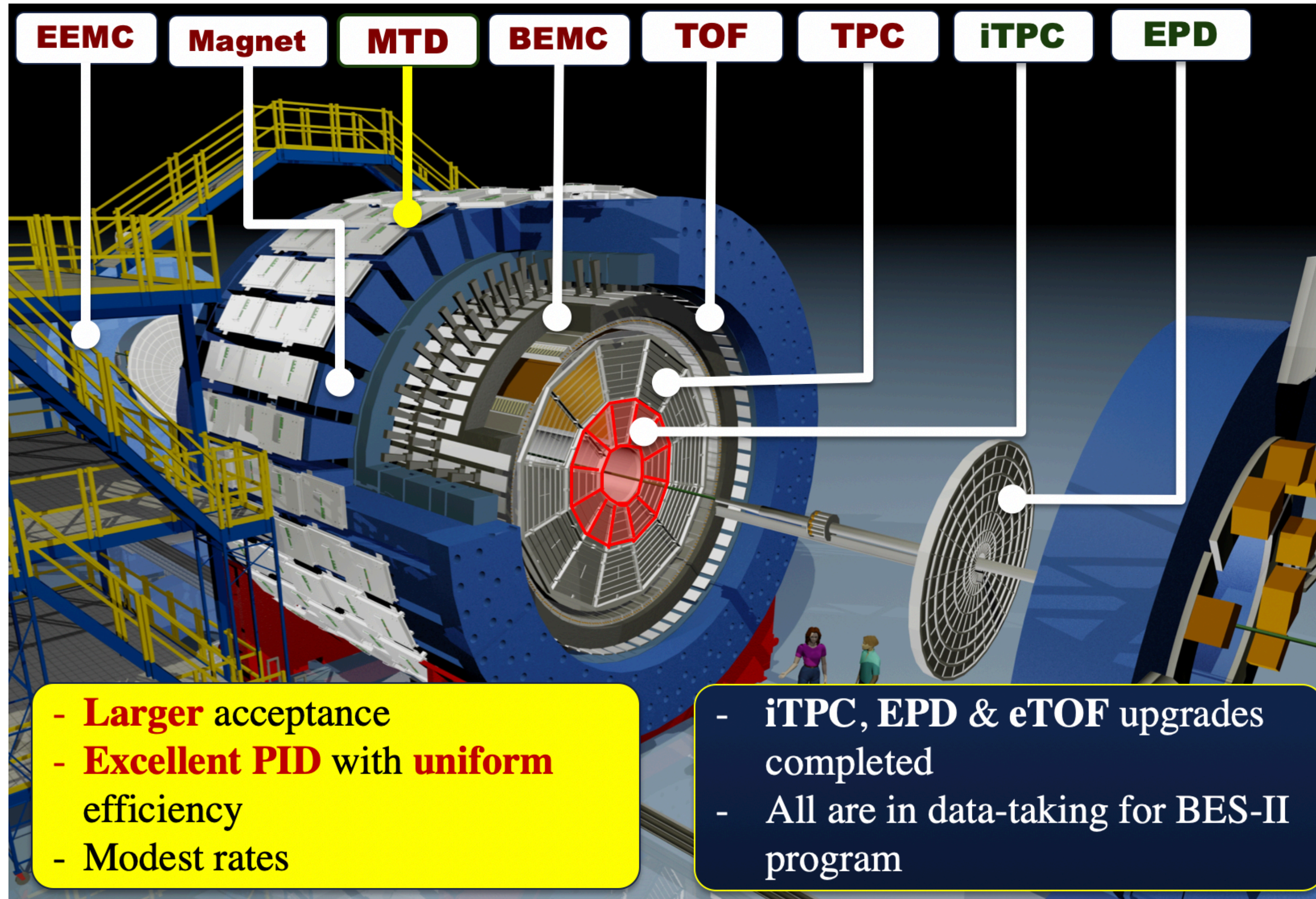
$v_2$ : elliptic flow

$v_3$ : triangle flow

B. Mohanty, N. Xu, Journal of Physics G 36, 064022 (2009); M. Nasim et al. Physical Review C 87, 014903 (2013)



# Experimental Setup



- The STAR Detector
  - ▶ Full  $2\pi$  azimuthal coverage
  - ▶ Large acceptance at mid-rapidity
  - ▶ Excellent particle identification
- Upgrade of inner-TPC
  - ▶ Better track quality
  - ▶ Larger acceptance ( $|\eta| < 1.5$ )



# Event Plane Calculation



A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C58, 1671 (1998)

- The  $n^{\text{th}}$  harmonic event plane was calculated as:

$$\vec{Q} = \begin{pmatrix} Q_y \\ Q_x \end{pmatrix} = \begin{pmatrix} \sum_i w_i \sin(n\phi_i) \\ \sum_i w_i \cos(n\phi_i) \end{pmatrix} \quad \Psi_n = \tan^{-1} \left( \frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)} \right) / n$$

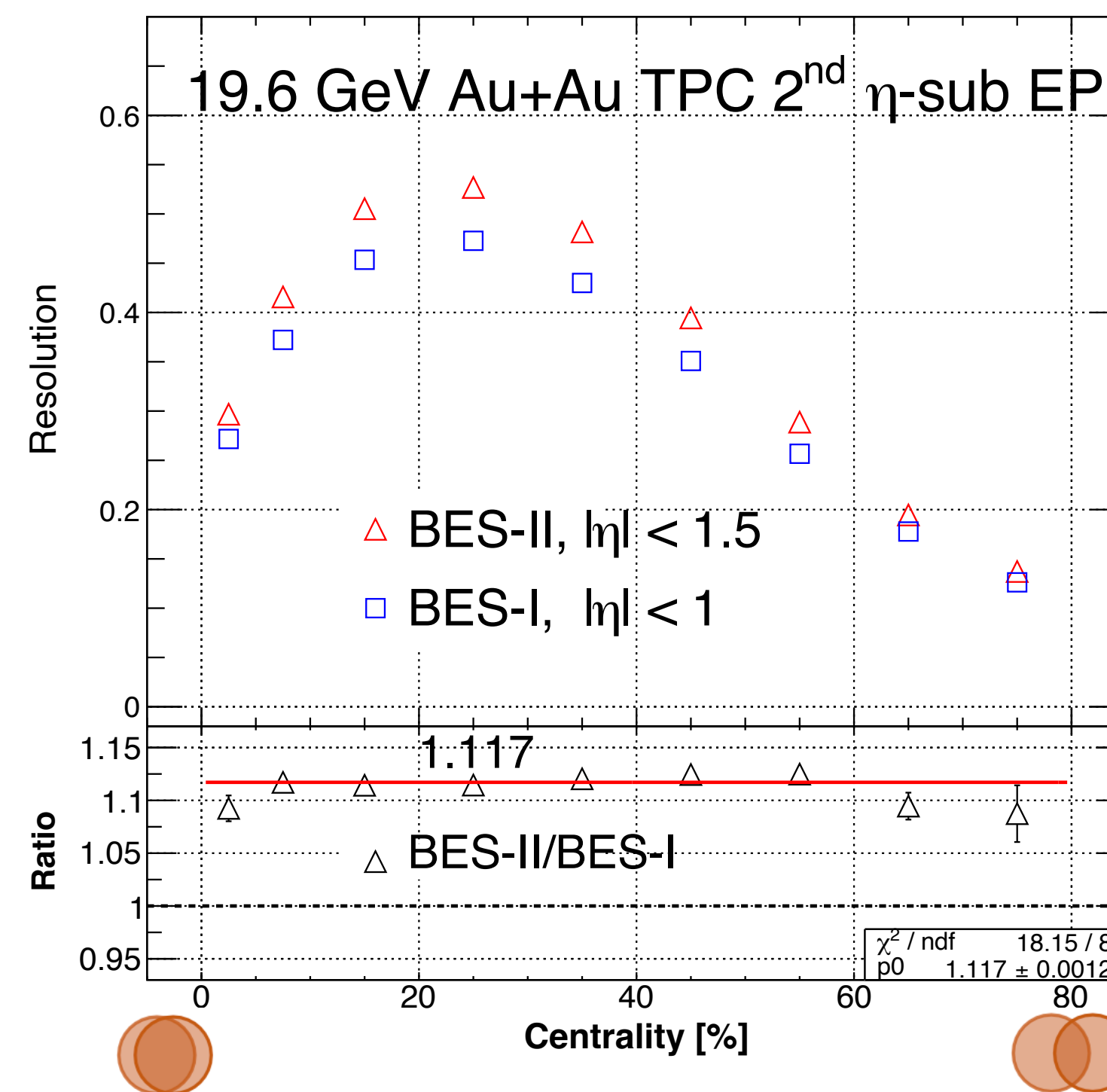
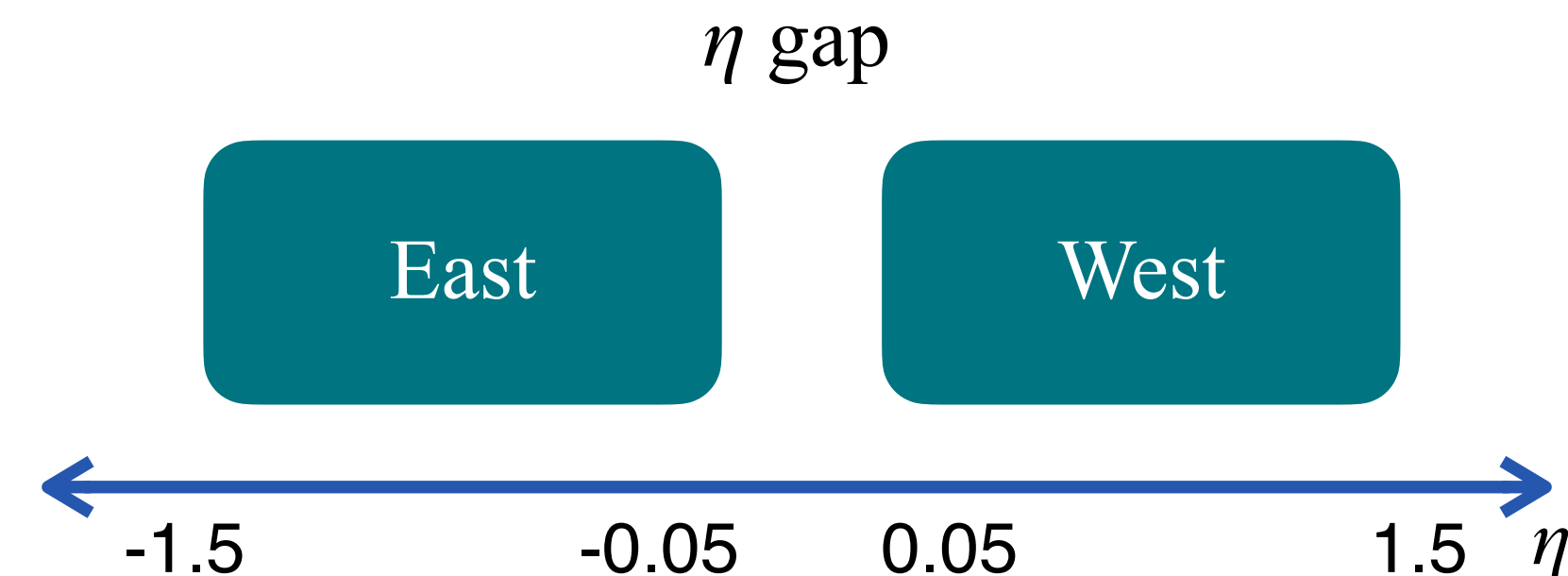
- Since finite multiplicity limits the estimation of the reaction plane, this will bring resolution:

$$R_n = \left\langle \cos \left[ n (\Psi_{n,EP} - \Psi_{RP}) \right] \right\rangle \quad R_{n,sub} = \sqrt{\left\langle \cos \left[ n (\Psi_{n,east} - \Psi_{n,west}) \right] \right\rangle}$$

## STAR detector upgrades and higher statistics:

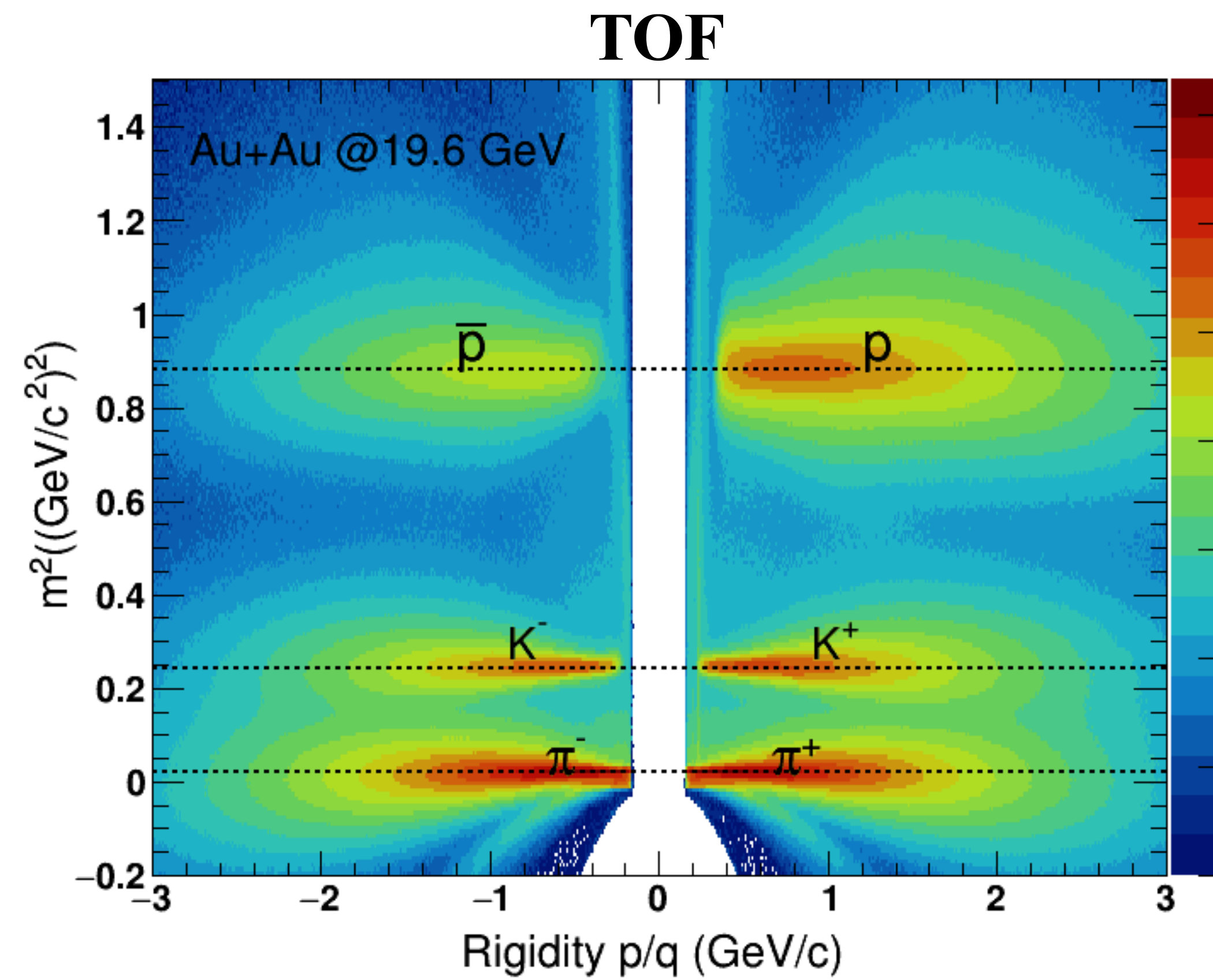
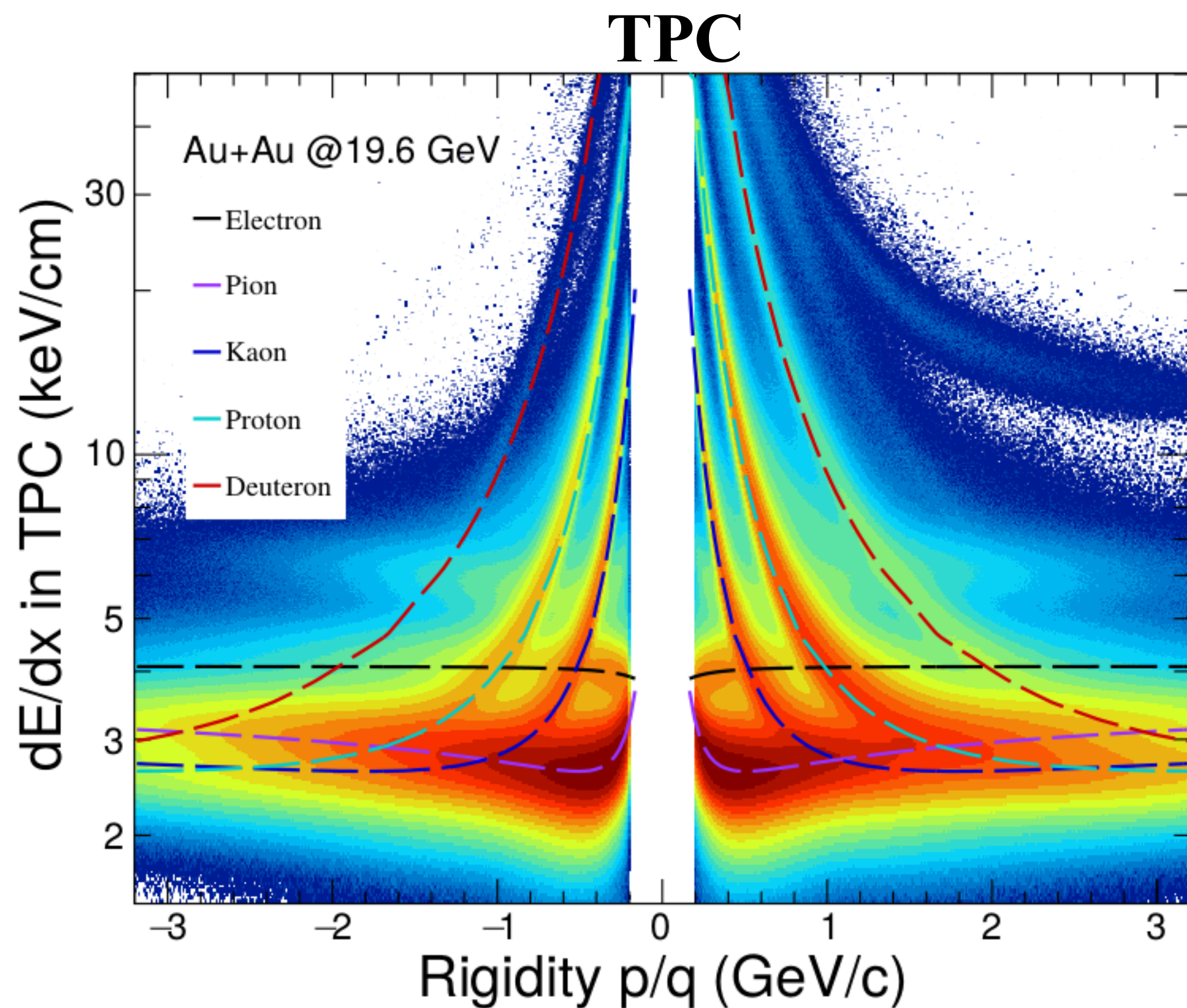
- 11% improvement of 2<sup>nd</sup> EP resolution
- Typical 3<sup>rd</sup> EP resolution achieved and first  $v_3$  measurement

**Prabhupada, 6/14 5:10 pm, POS-BLK-10**





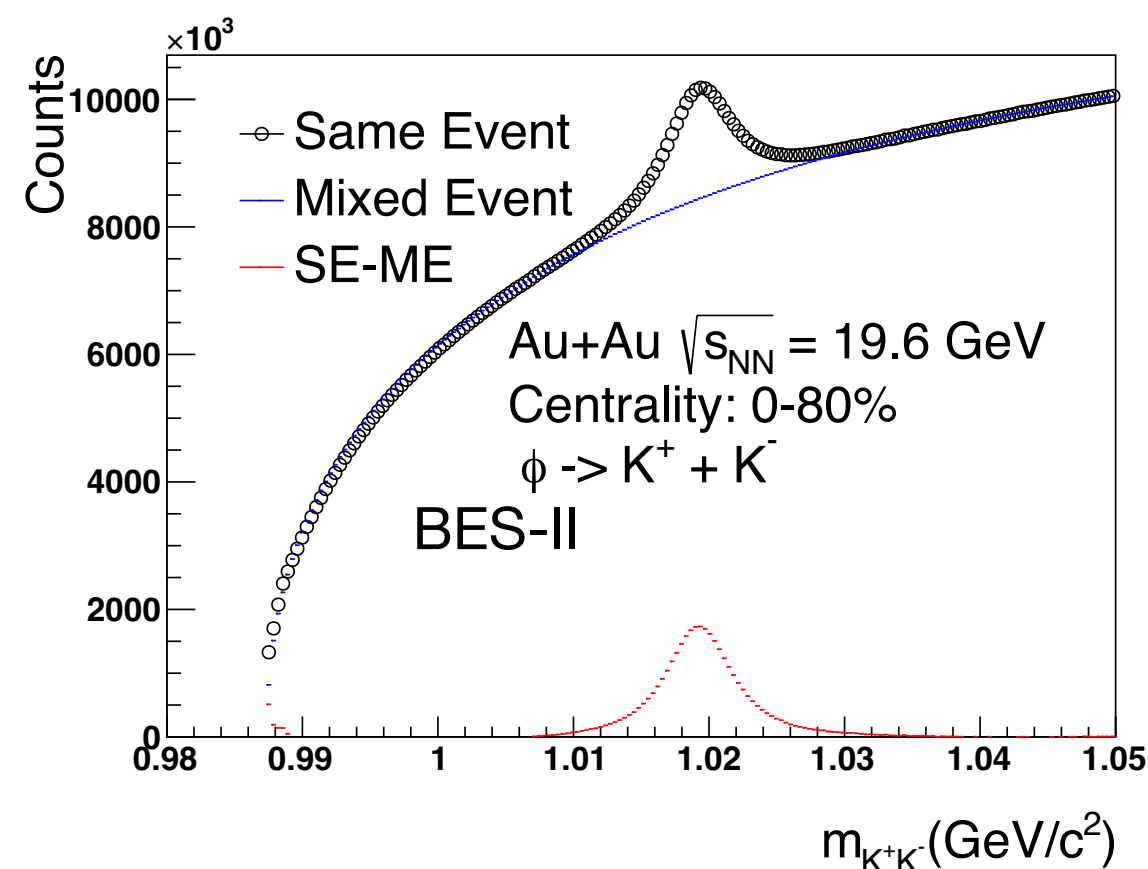
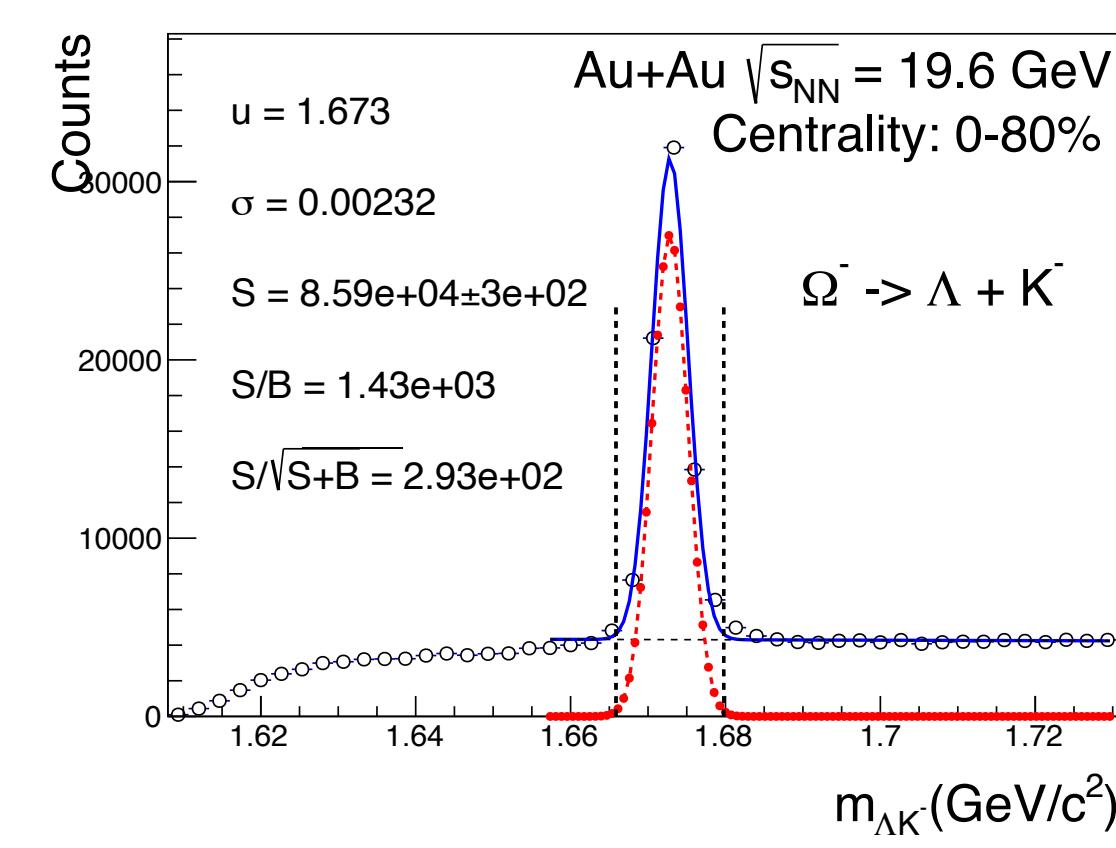
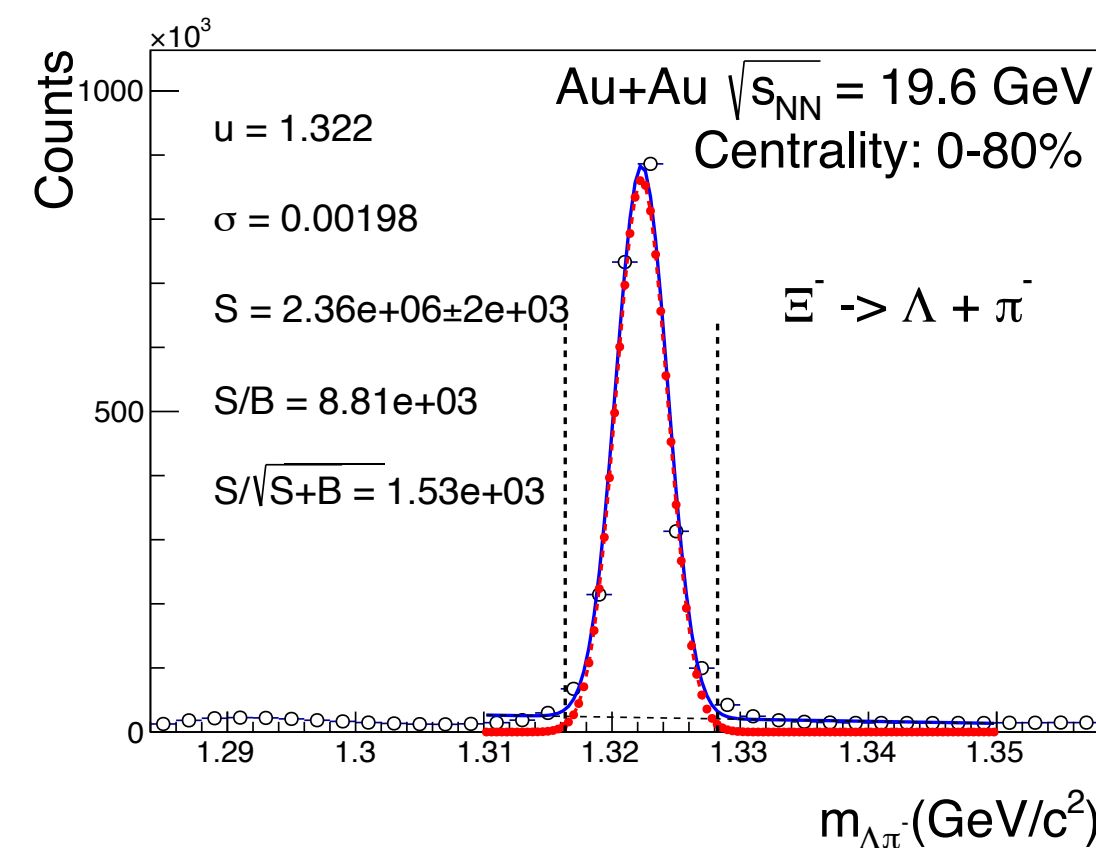
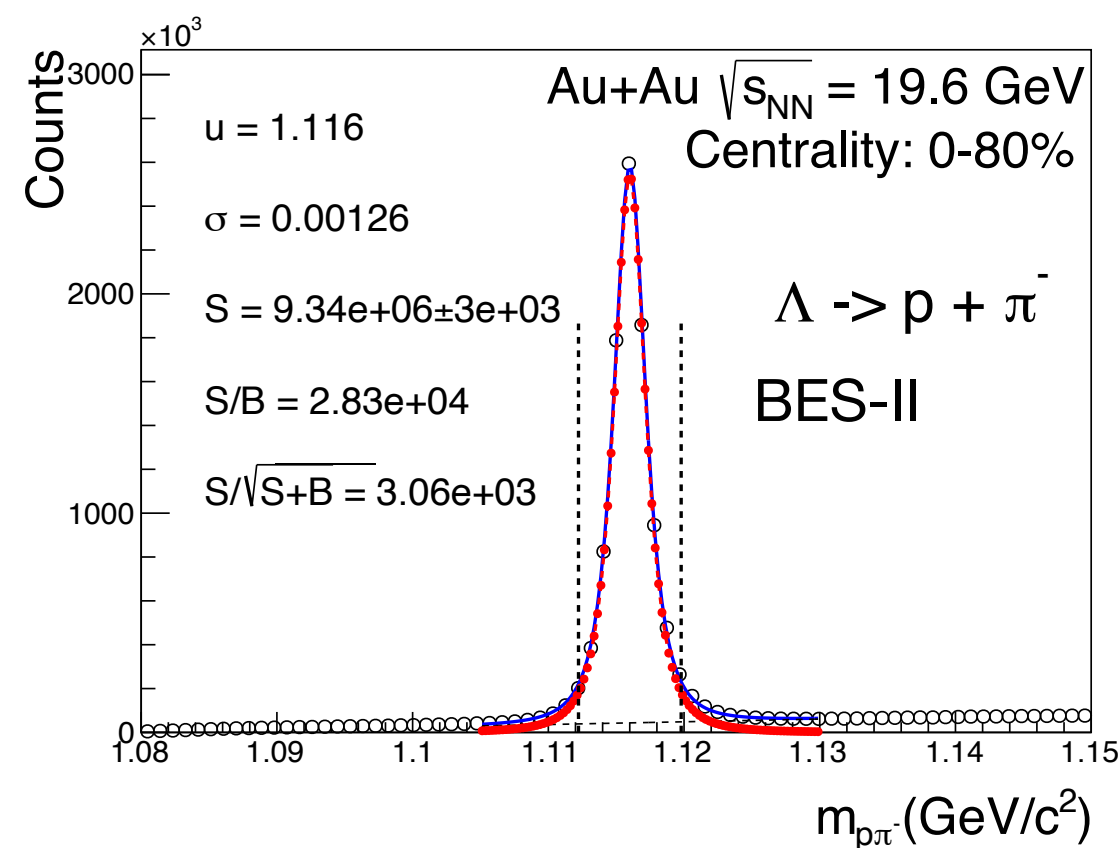
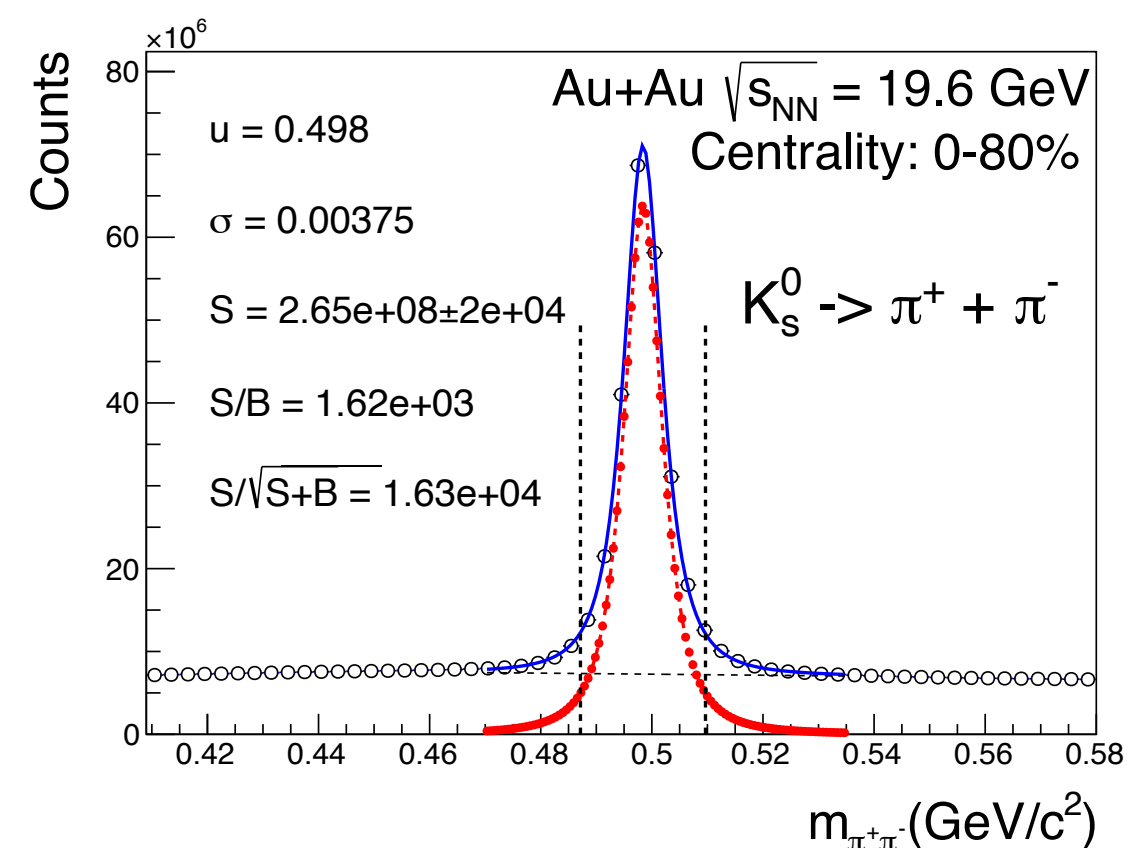
# Particle Identification



- Good particle identification capability based on TPC and TOF



# Decay Particle Reconstruction



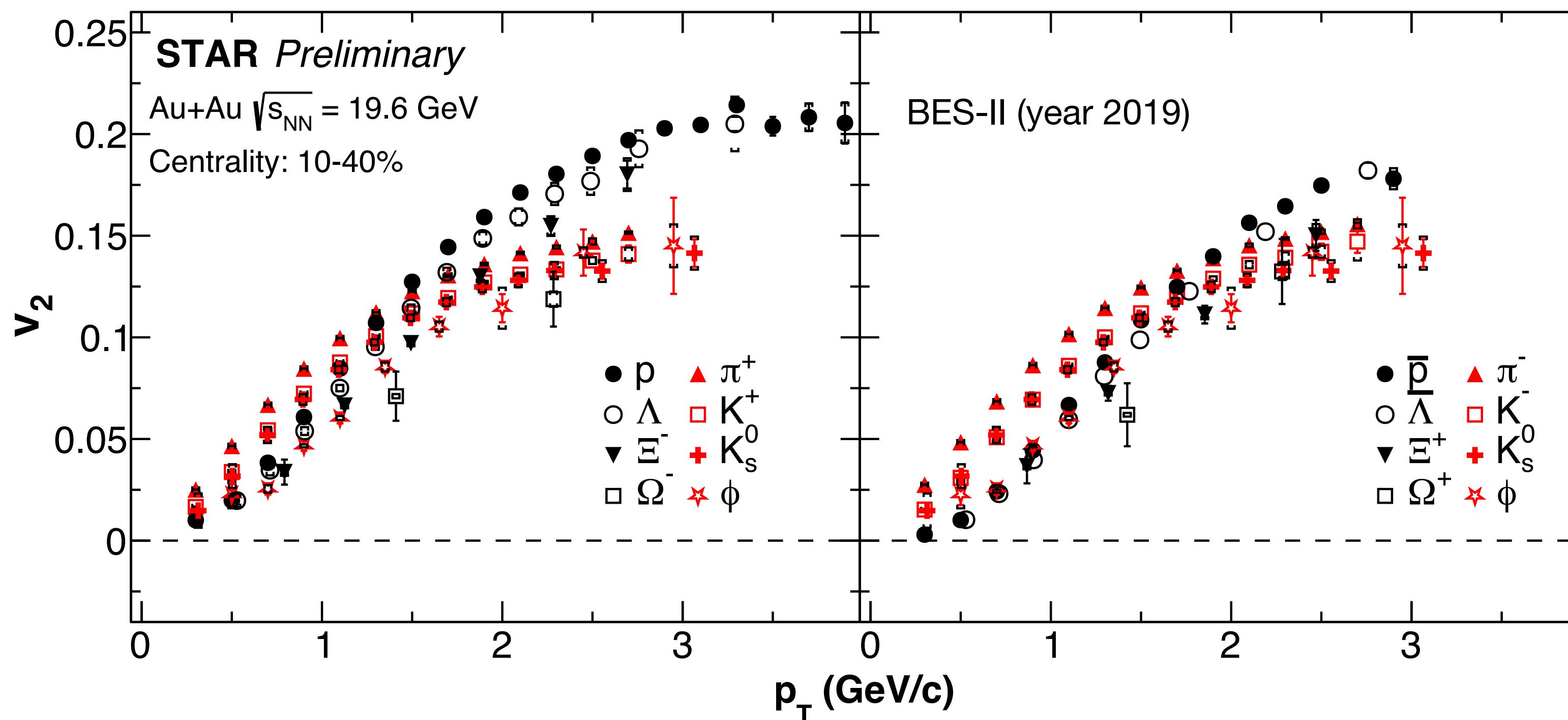
- $K_S^0$ ,  $\Lambda$ ,  $\bar{\Lambda}$ ,  $\Xi^\pm$ ,  $\Omega^\pm$  are reconstructed by KF particle package
  - background described by first order polynomial
- $\phi$ -mesons are reconstructed by  $K^+K^-$  channel
  - background estimated by using mixed event method

A. Banerjee, I. Kisel and M. Zyzak, Int. J. Mod. Phys. A 35, 2043003 (2020)





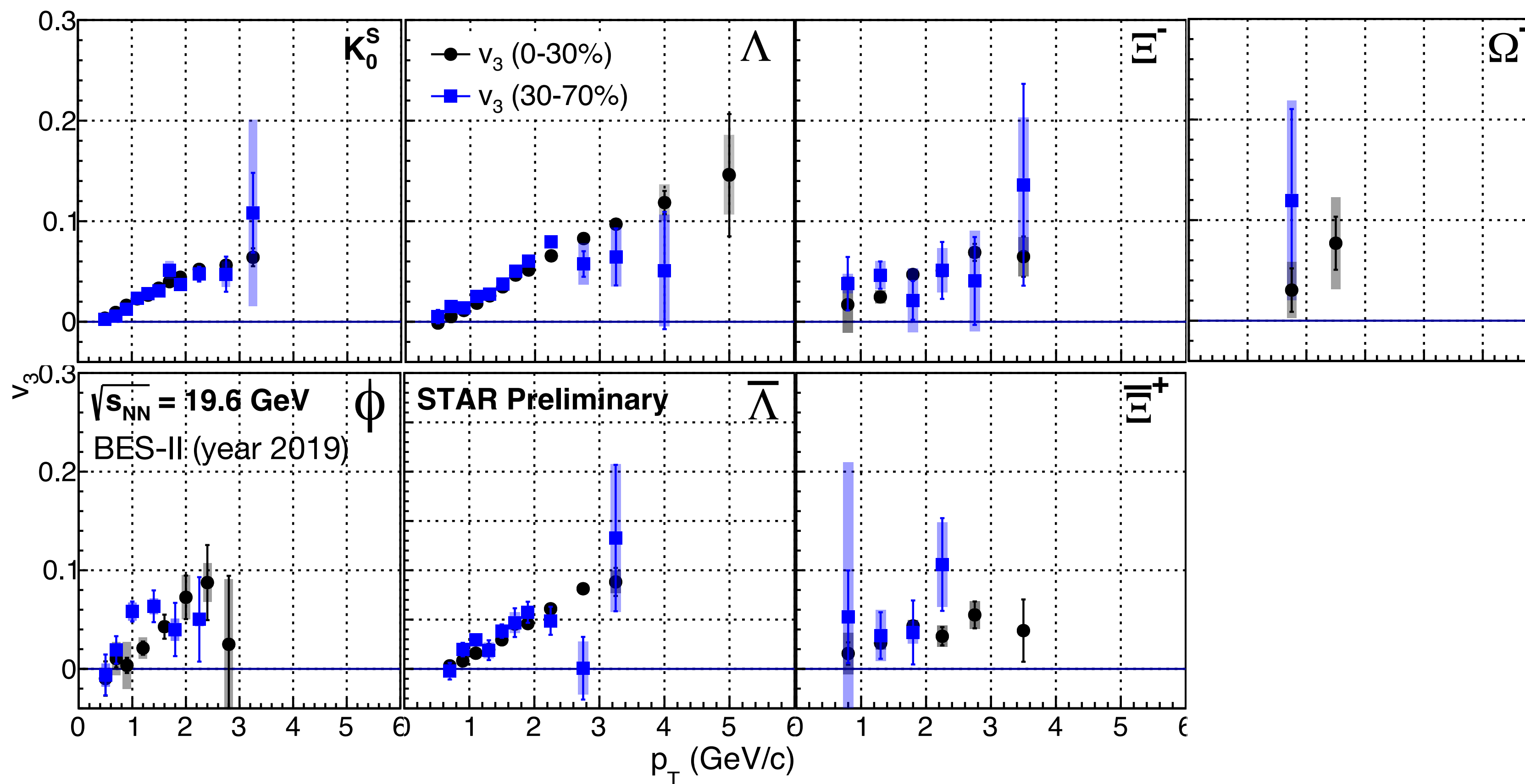
# $v_2$ of Identified Particles



- Clear mass ordering of  $v_2(p_T)$  when  $p_T < 1.5$  GeV/c **radial flow**
- Particles grouped according to hadron type (baryon or meson) when  $p_T > 1.5$  GeV/c **quark coalescence**



# $v_3$ of Identified Particles



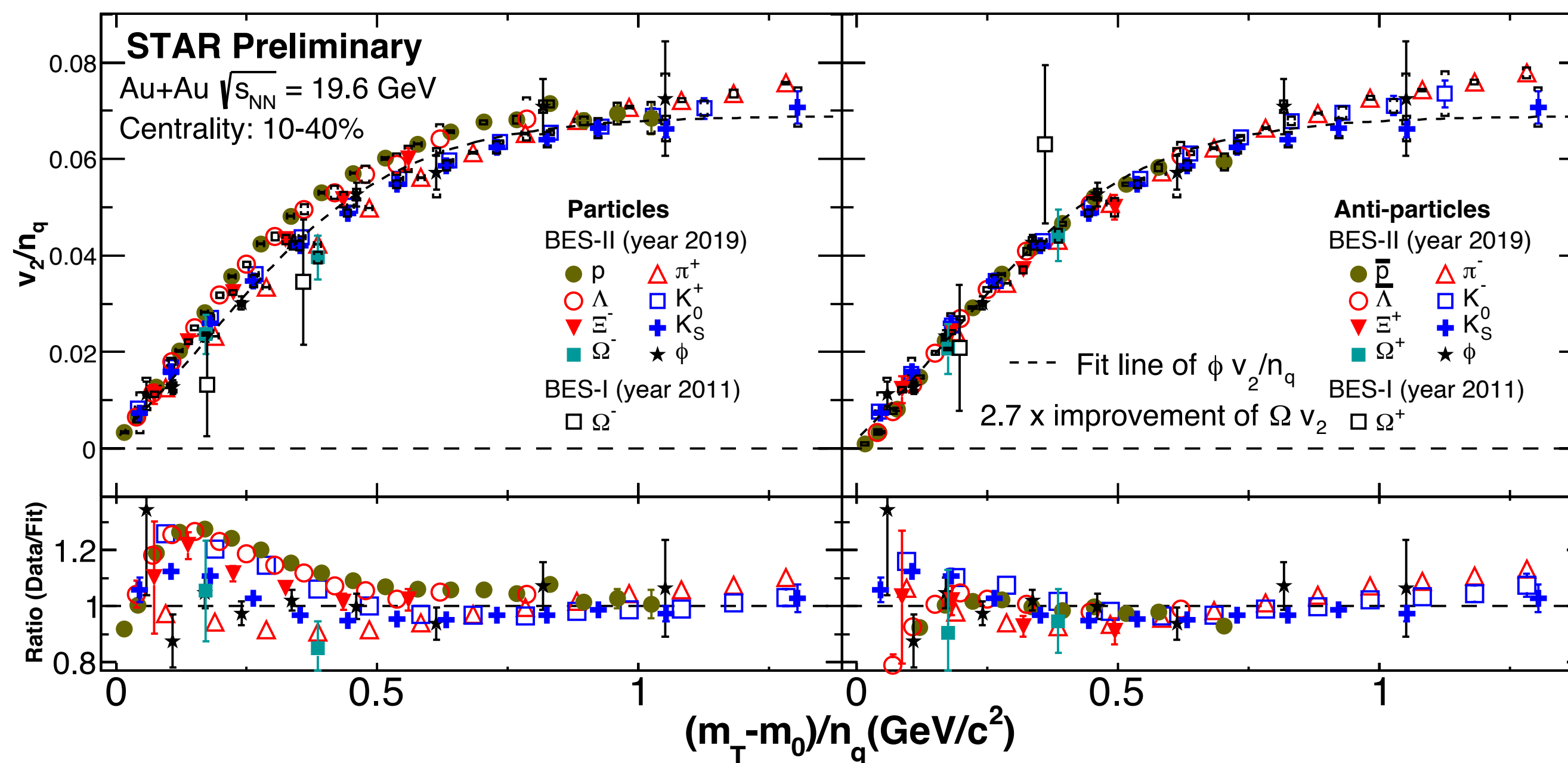
- Weak centrality dependence for  $v_3$   
**Event-by-event fluctuation is the dominant source**



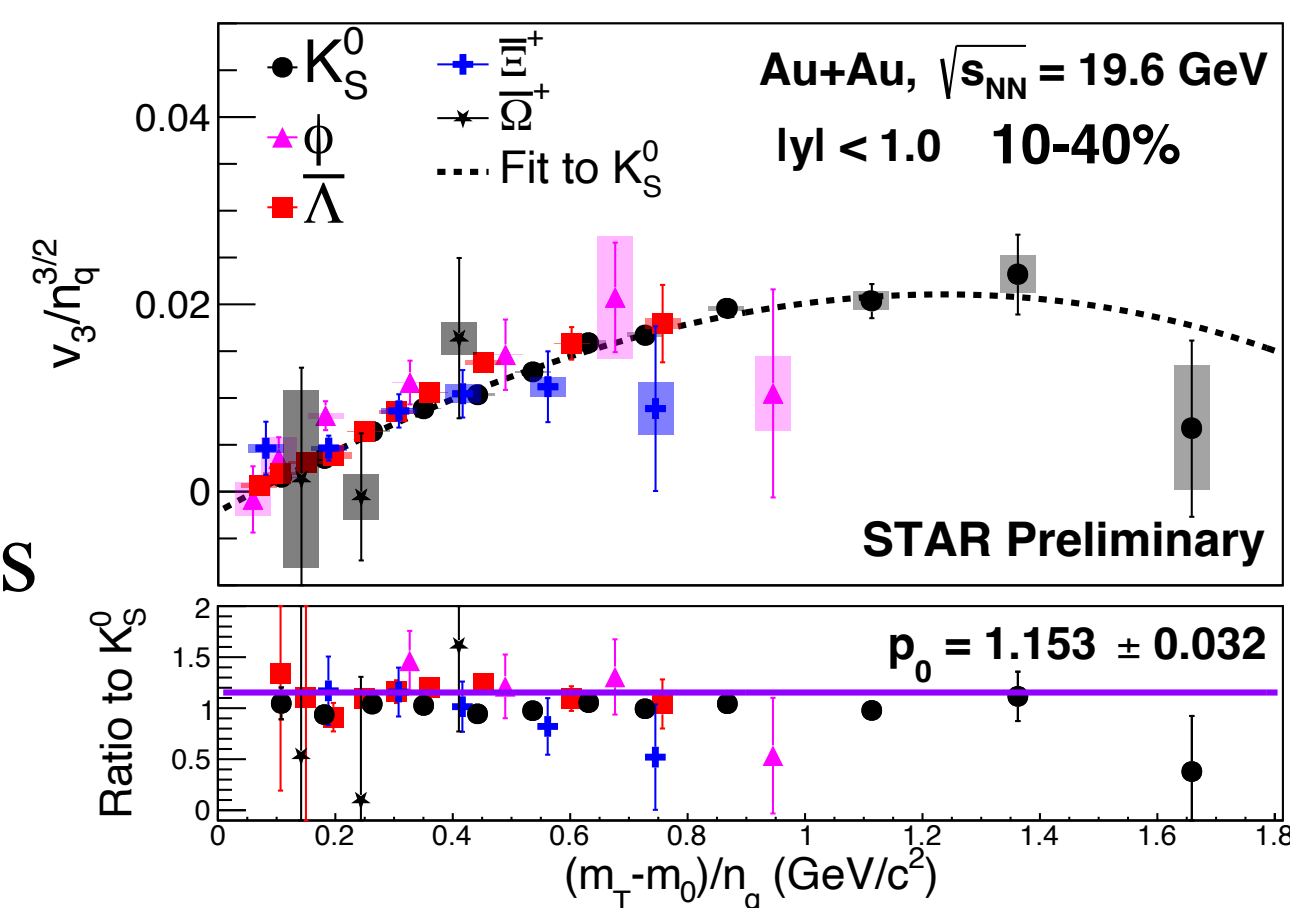
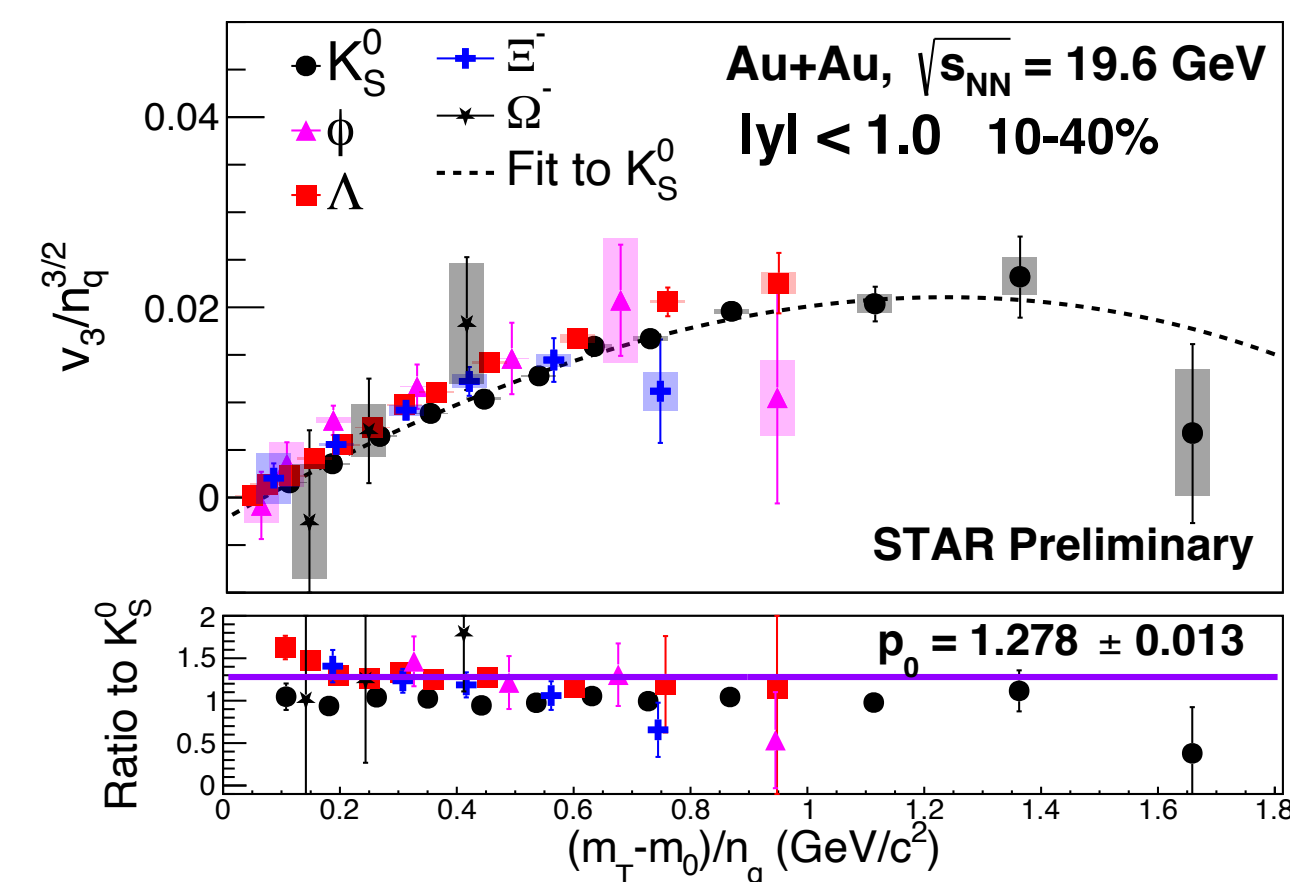
# Test of NCQ Scaling at 19.6 GeV



## NCQ scaling of $v_2$



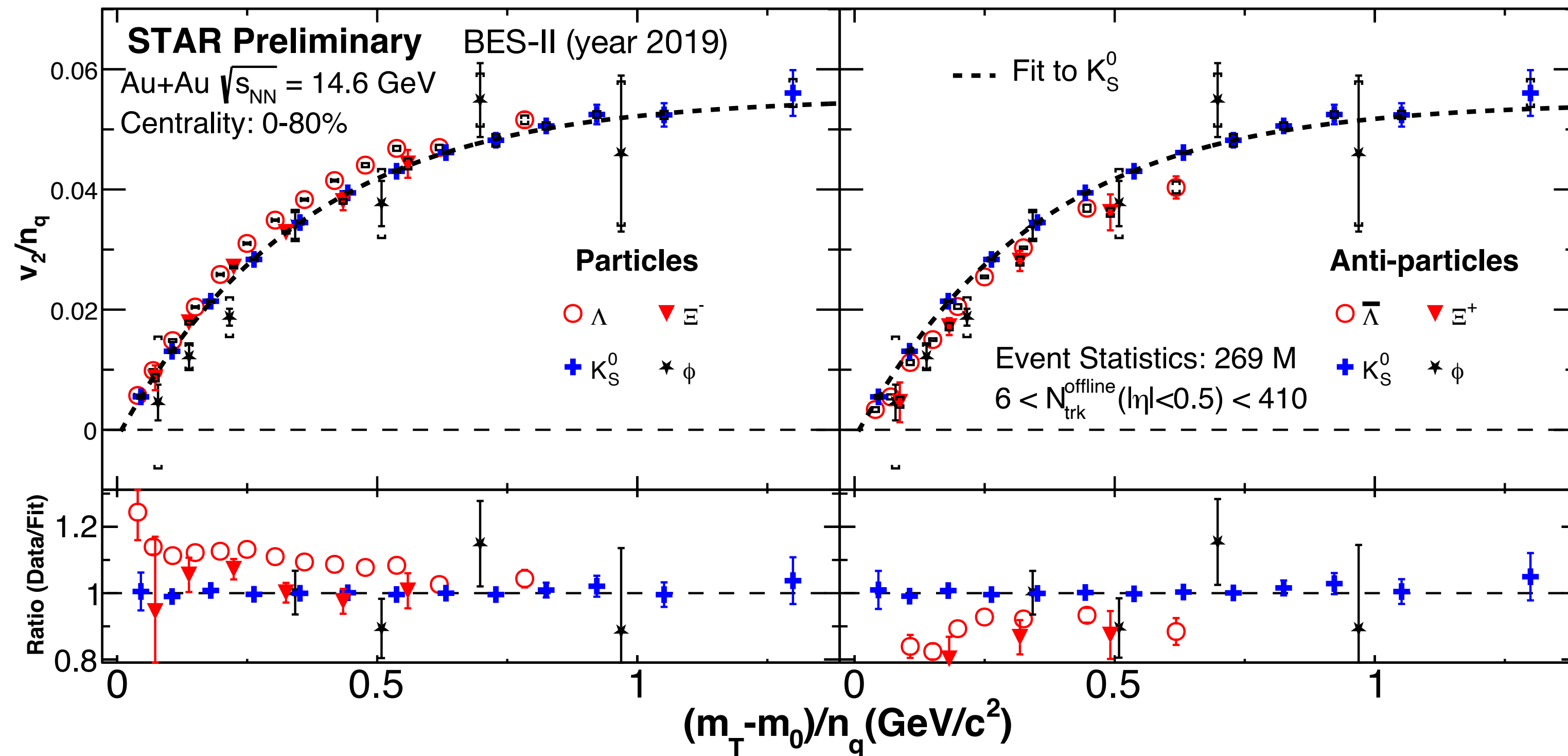
## NCQ scaling of $v_3$



- NCQ scaling of  $v_2$  ( $v_3$ ) holds within 10(15)% for anti-particles, 20(30)% for particles  
quantify the NCQ scaling -> benefit from enhanced statistics of BES-II
- Indicating the collective flow has been built up in the **partonic stage**
- NCQ scaling of anti-particles is better than particles: **produced vs. transported quarks**



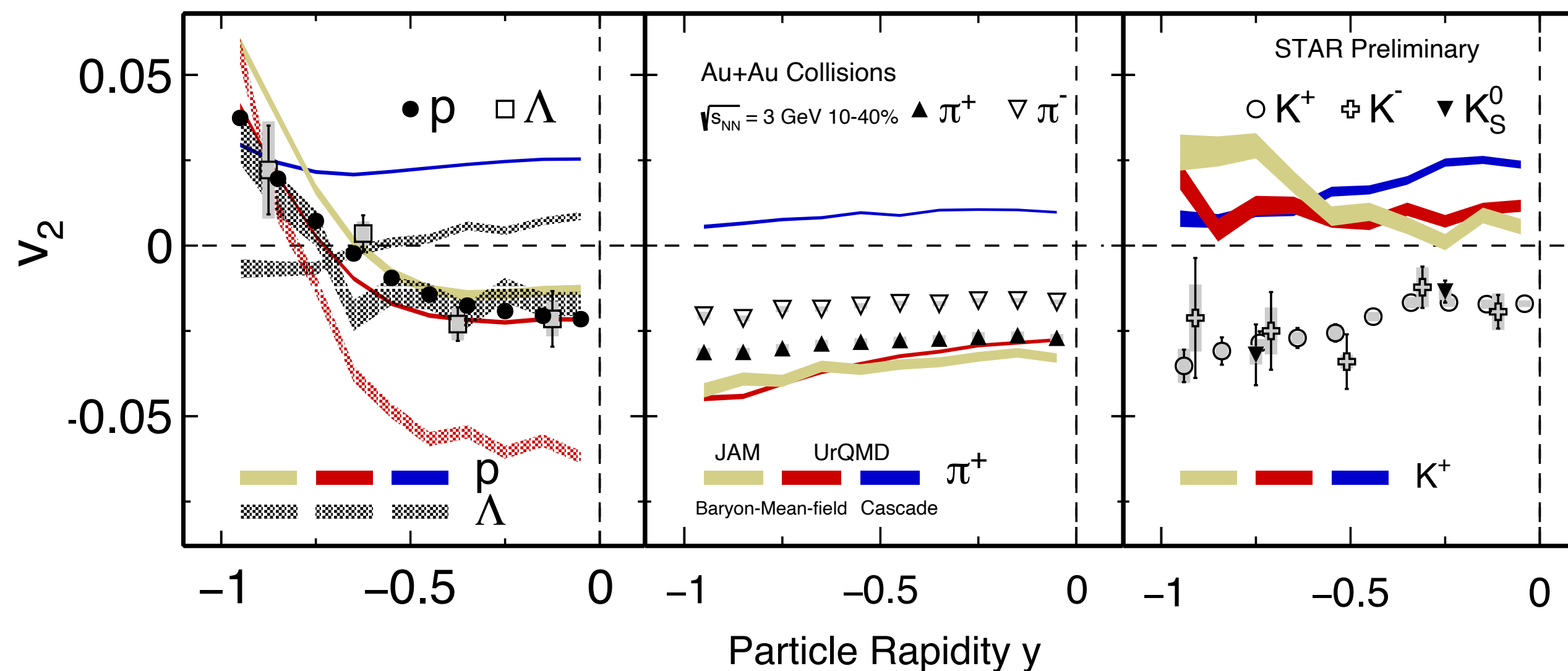
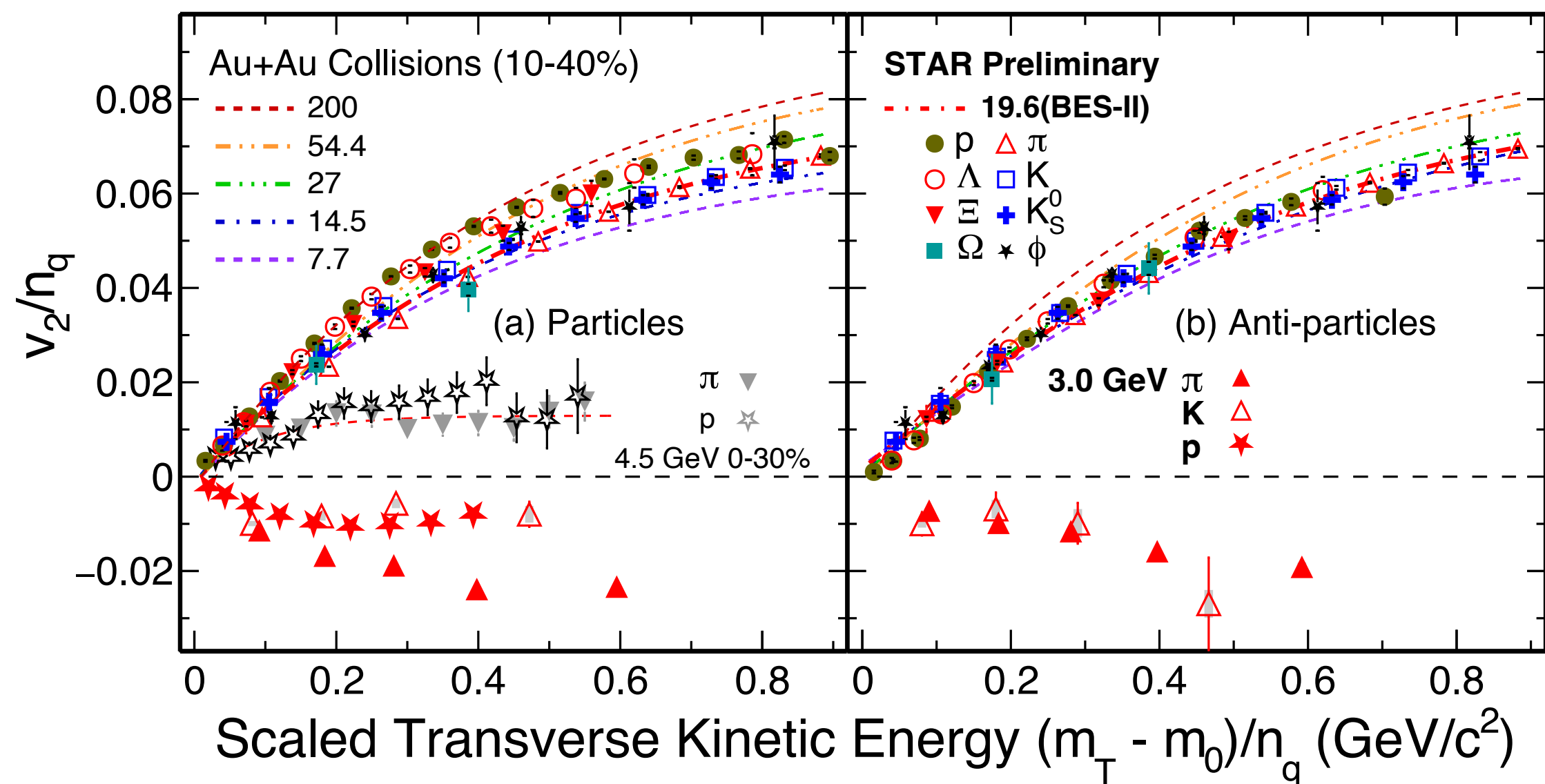
# Test of NCQ Scaling at 14.6 GeV



- NCQ scaling holds at 20% level



# $v_2$ results at 3 GeV



- At this energy,  $\mu_B \sim 750$  MeV, high baryon density region
- The values of  $v_2$  for all particles are negative, and the NCQ scaling is absent
- The data can be qualitatively reproduced by baryonic mean-field transport models

**disappearance of partonic collectivity and likely dominated by baryonic interactions**



# Summary

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- NCQ scaling of  $v_2$  and  $v_3$  holds well at 19.6 GeV
  - ▶ **Signature of partonic collectivity**
  - ▶ **Difference between transported and produced quarks**
  
- NCQ scaling is absent at 3 GeV
  - ▶ **Medium likely dominated by baryonic interactions**



# Outlook



$\sqrt{s_{NN}}$ (GeV)	$\mu_B$ (MeV)	Events	Date collected
19.6	206	478 M	2019
14.6	262	324 M	2019
11.5	316	235 M	2020
9.2	373	162 M	2020
7.7	422	101M+163 M	2021
6.2	487	118 M	2020
5.2	541	103 M	2020
4.5	589	108 M	2020
3.9	632	170 M	2020
3.5	666	116 M	2020
3.2	697	201 M	2019
3.0	721	2361 M	2021

Collider mode

Fixed target mode

- The data taking of BES-II has been finished, enhanced statistics, upgraded detectors
  - ▶ **Precise measurements of multi-strange hadron and  $\phi$  meson  $v_n$**
- Explore the QCD phase diagram with BES-II 3-20 GeV datasets

Thank you for your attention!