# Elliptic flow of identified particles in Au + Au collisions at $\sqrt{s_{NN}}$ = 14.6 GeV in BESII

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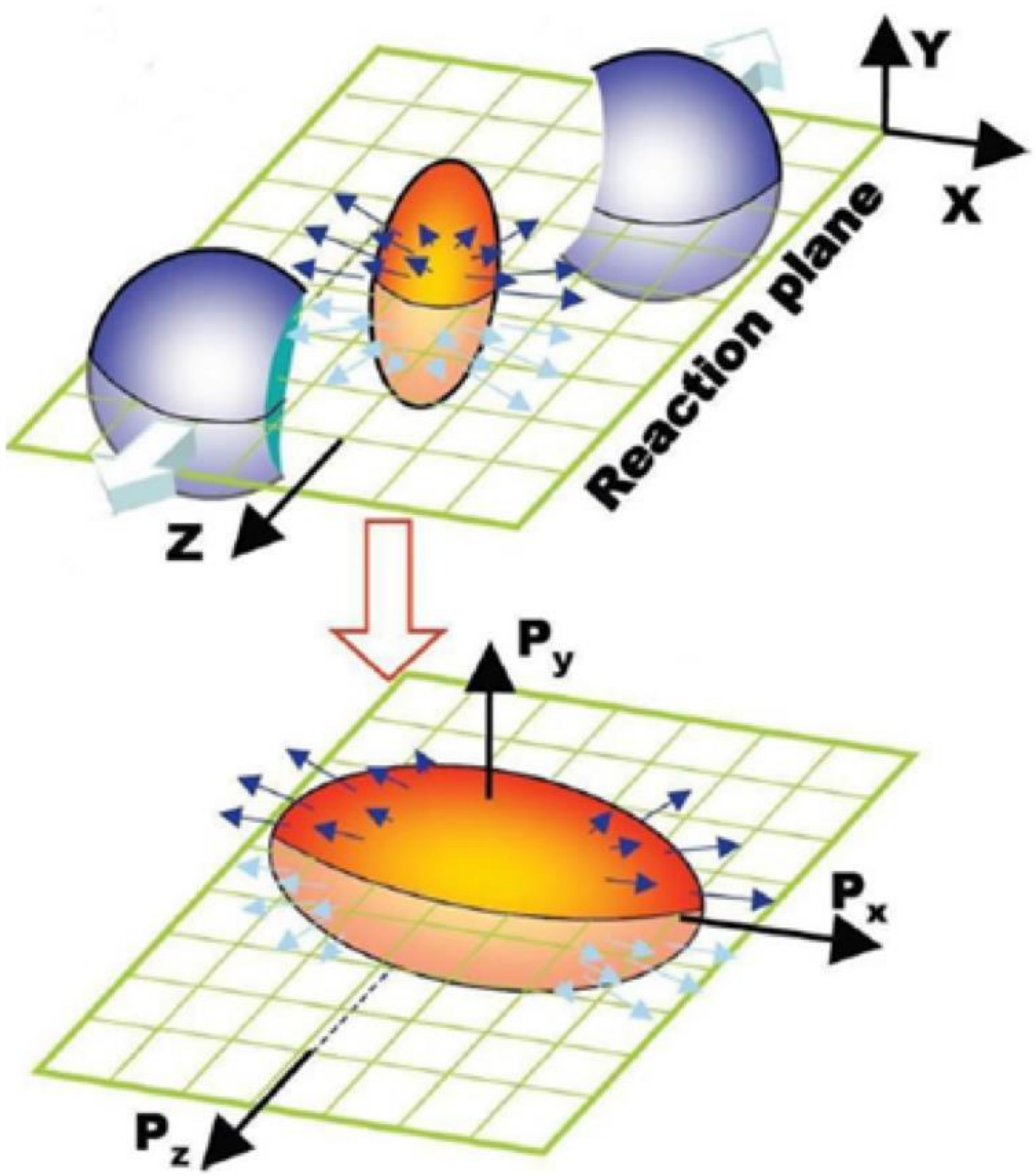
# Outline

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

# Motivation




Initial spatial anisotropy in coordinate space exists in non-central heavy-ion collisions.

Pressure gradient and interaction among constituents lead to conversion from initial spatial anisotropy to final momentum-space anisotropy.

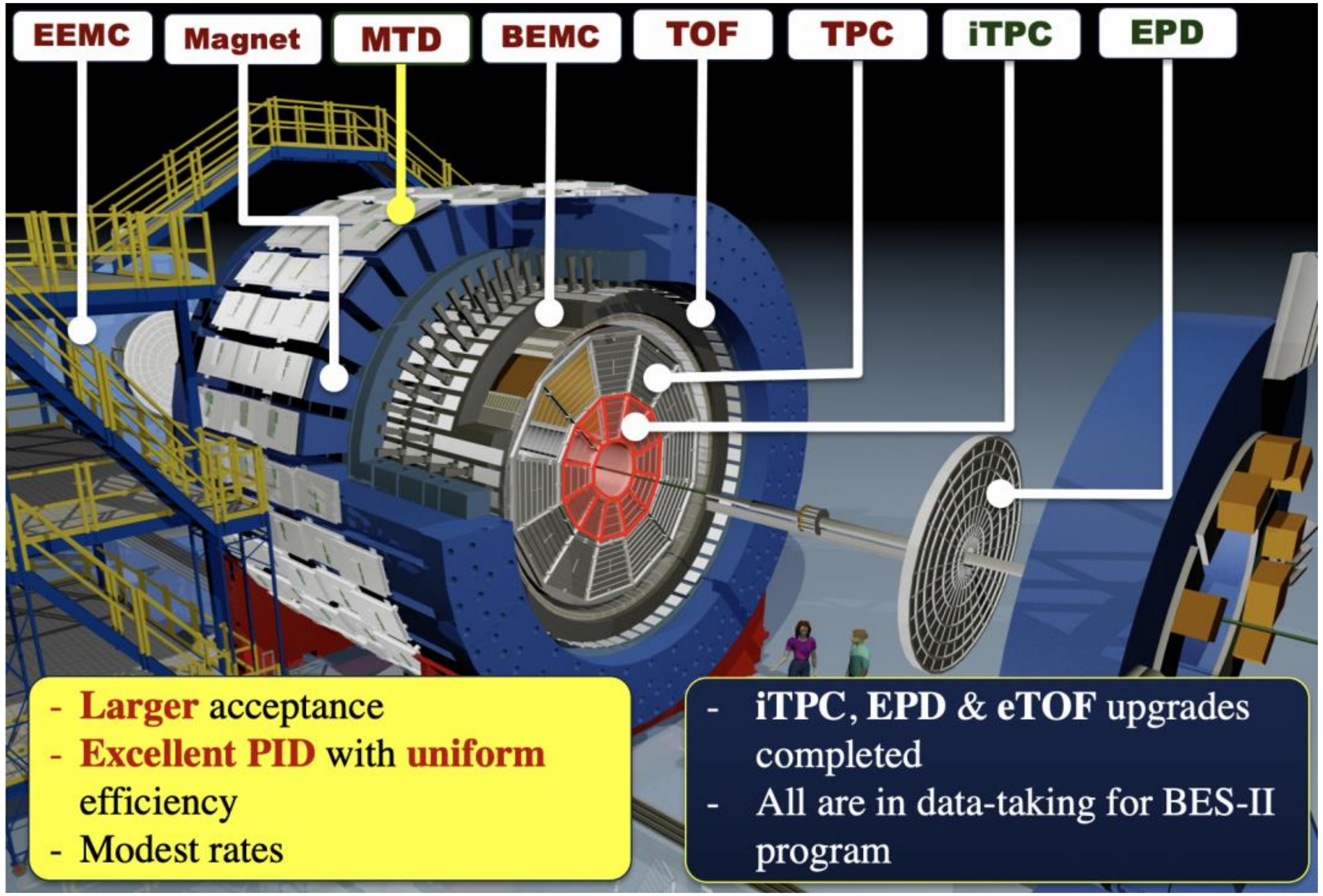
Elliptic flow is sensitive to the degree of freedom and thermalization of the medium

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

$$v_2 = \langle \cos(2(\phi - \psi_{RP})) \rangle$$

A. M. Poskanzer and S. A. Voloshin, PHYSICAL REVIEW C 1671–1678 (1998)

# STAR Detector




The artistic view of the STAR detector

## Time Projection Chamber (TPC)

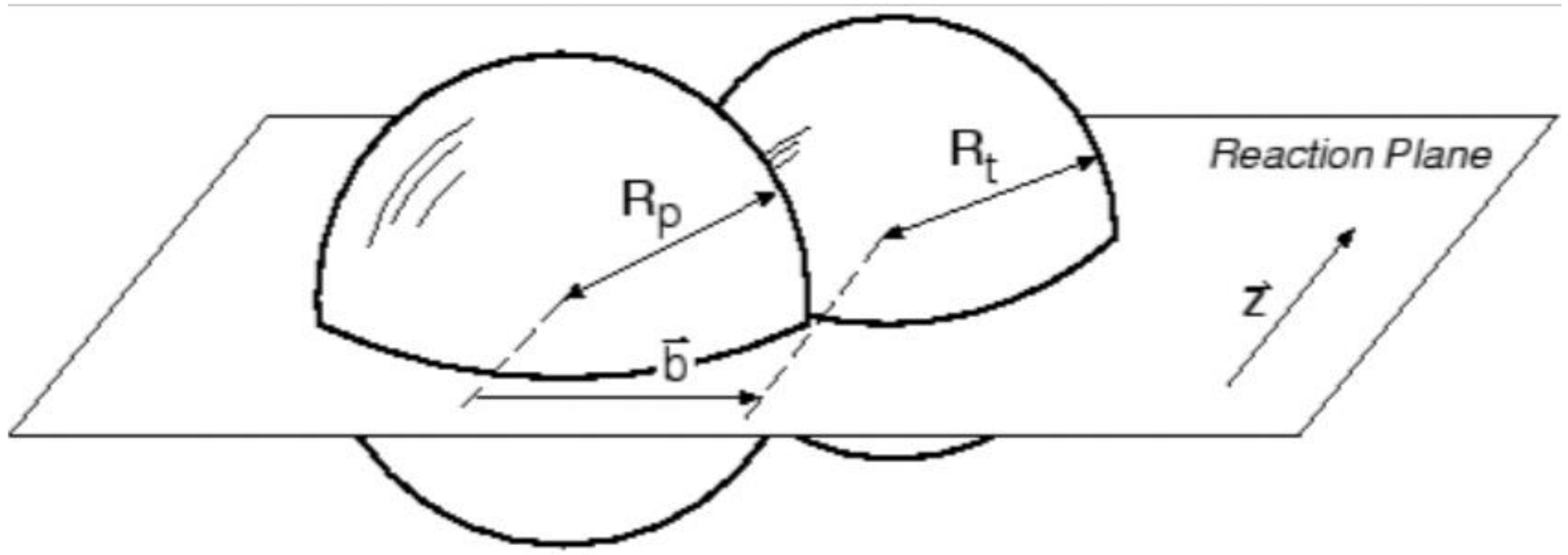
- ✓ Particle identification from ionization energy loss($dE/dx$)
- ✓ Charged Particle Tracking

## Time-of-Flight (TOF)

- ✓ Particle identification using $m^2$

# Event Plane Method

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n cos\left(n(\phi - \Psi_{RP})\right)\right)$$




Reaction plane is spanned by the vector of impact parameter and beam direction

**We introduce event plane which is the estimate of the true reaction plane**

## Sub-event method:

| (-1.0,-0.05) | (0.05,1.0) |
|---|---|
| East | West |

η

$$q_x = \sin(n\phi_i) \qquad Q_{n,x} = \sum_i w_i \cos(n\phi_i) = Q_n cos(n\Psi_n)$$

$$q_y = \cos(n\phi_i) \qquad Q_{n,y} = \sum_i w_i \sin(n\phi_i) = Q_n sin(n\Psi_n)$$

Recentering:

$$Q_{x,n,rc} = \sum_i^n (q_{n,i,x} - \langle q_x \rangle),$$

$$Q_{y,n,rc} = \sum_i^n (q_{n,i,y} - \langle q_y \rangle),$$

$$\Psi_{n,rc} = \frac{1}{n}[tan^{-1}\frac{Q_{x,n,rc}}{Q_{y,n,rc}}],$$

Shift: $$\boldsymbol{n\Delta\psi_{n,shift} = \sum_{i=1}^{imax} \frac{2}{i}[\langle \sin(in\psi_{n,rc})\rangle \cos(in\psi_{n,rc}) + \langle \cos(in\psi_{n,rc})\rangle \sin(in\psi_{n,rc})]}$$

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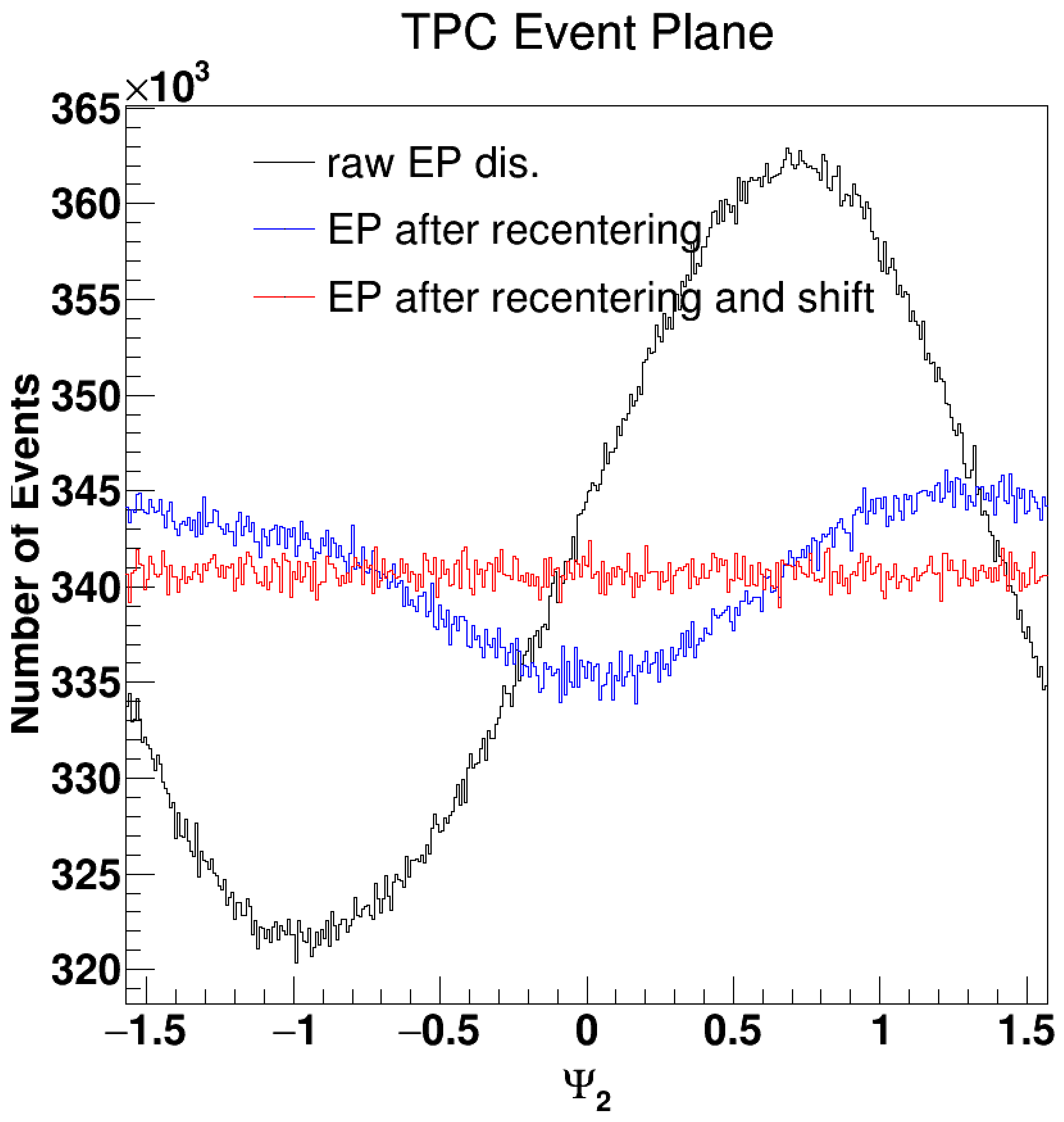
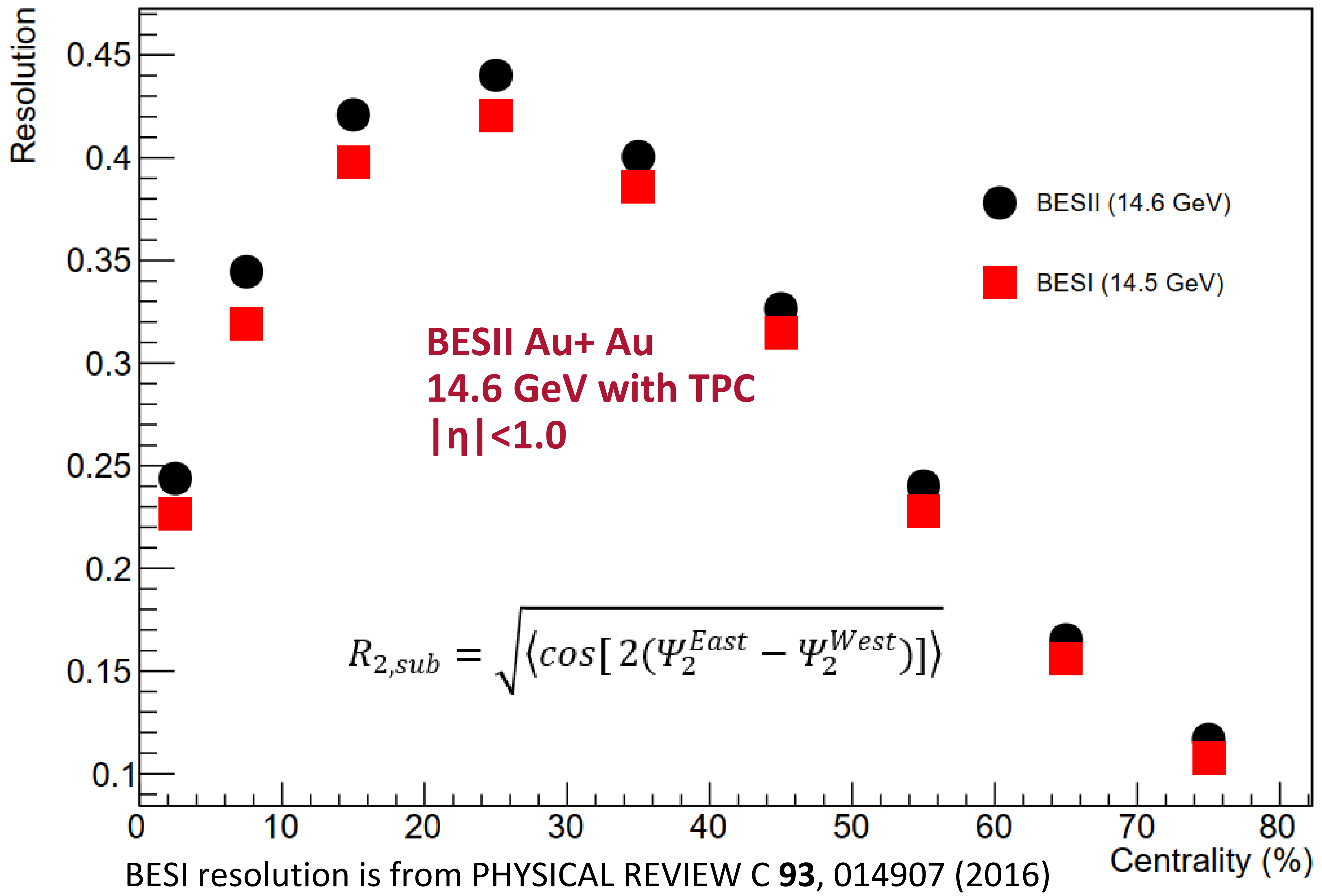
# Event Plane and Resolution



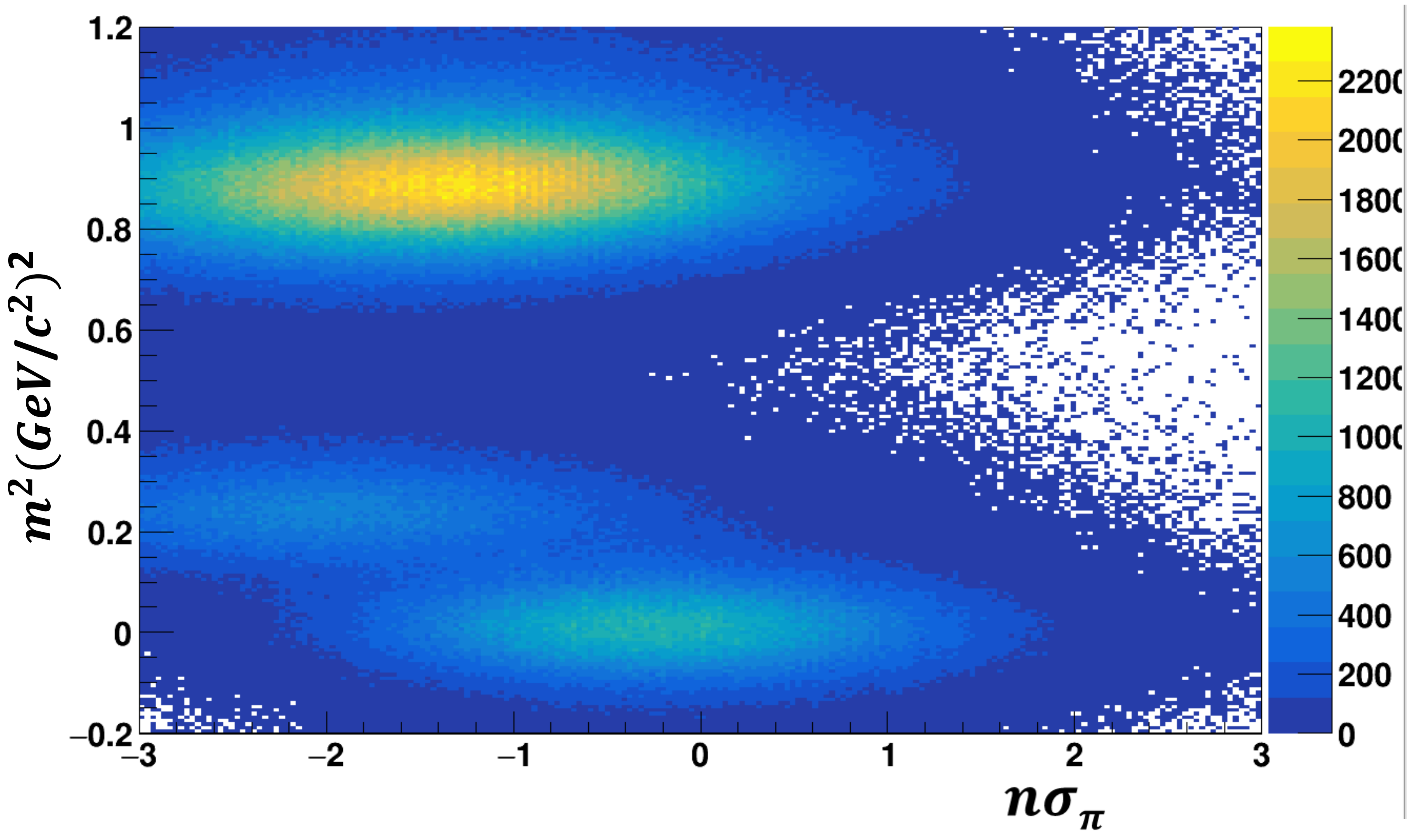

BESI resolution is from PHYSICAL REVIEW C **93**, 014907 (2016)

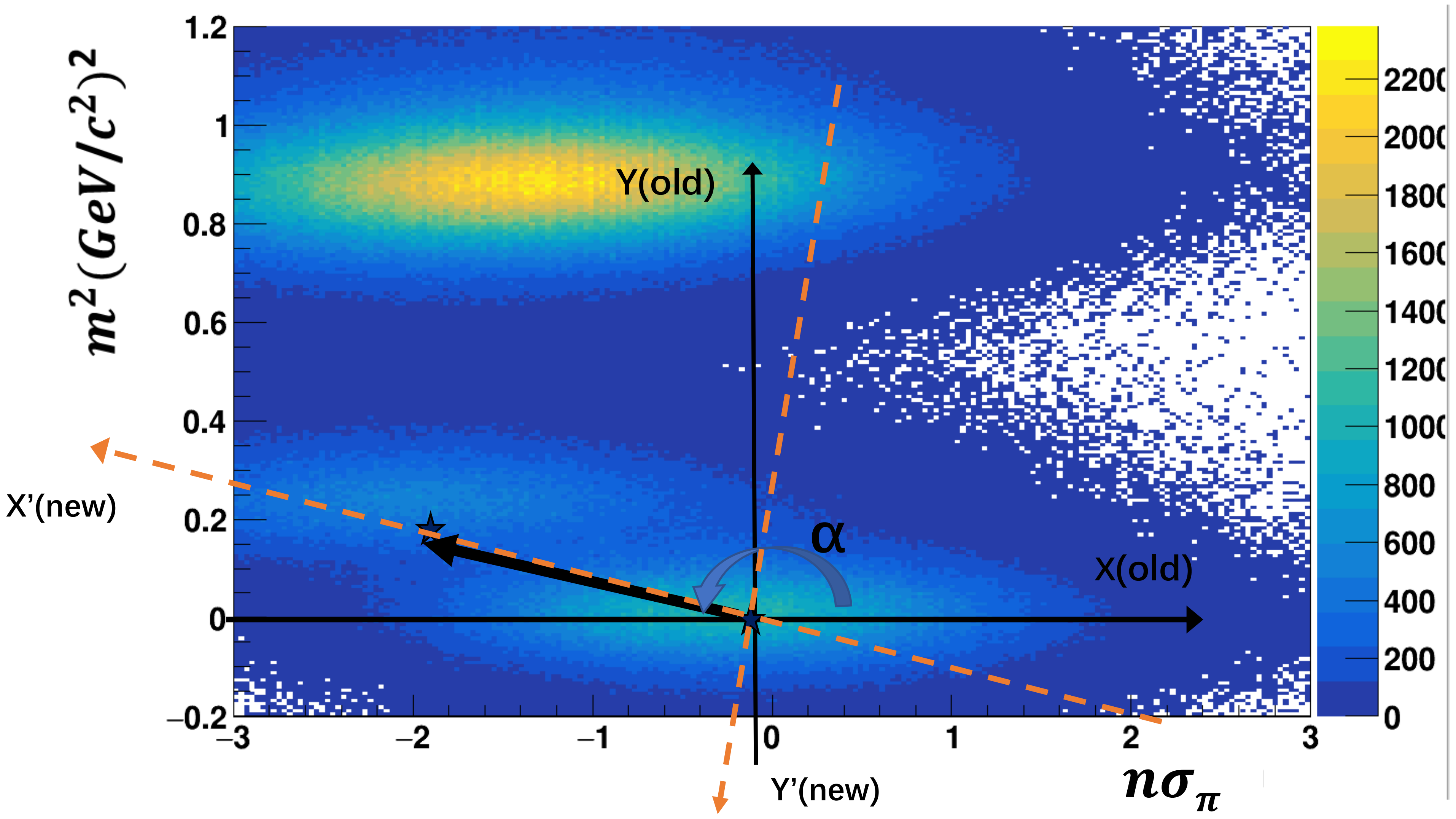
**A uniform event plane distribution obtained by recentering and shift calibration**

**The observed $v_2$ corrected by event plane resolution**

# π and K Identification

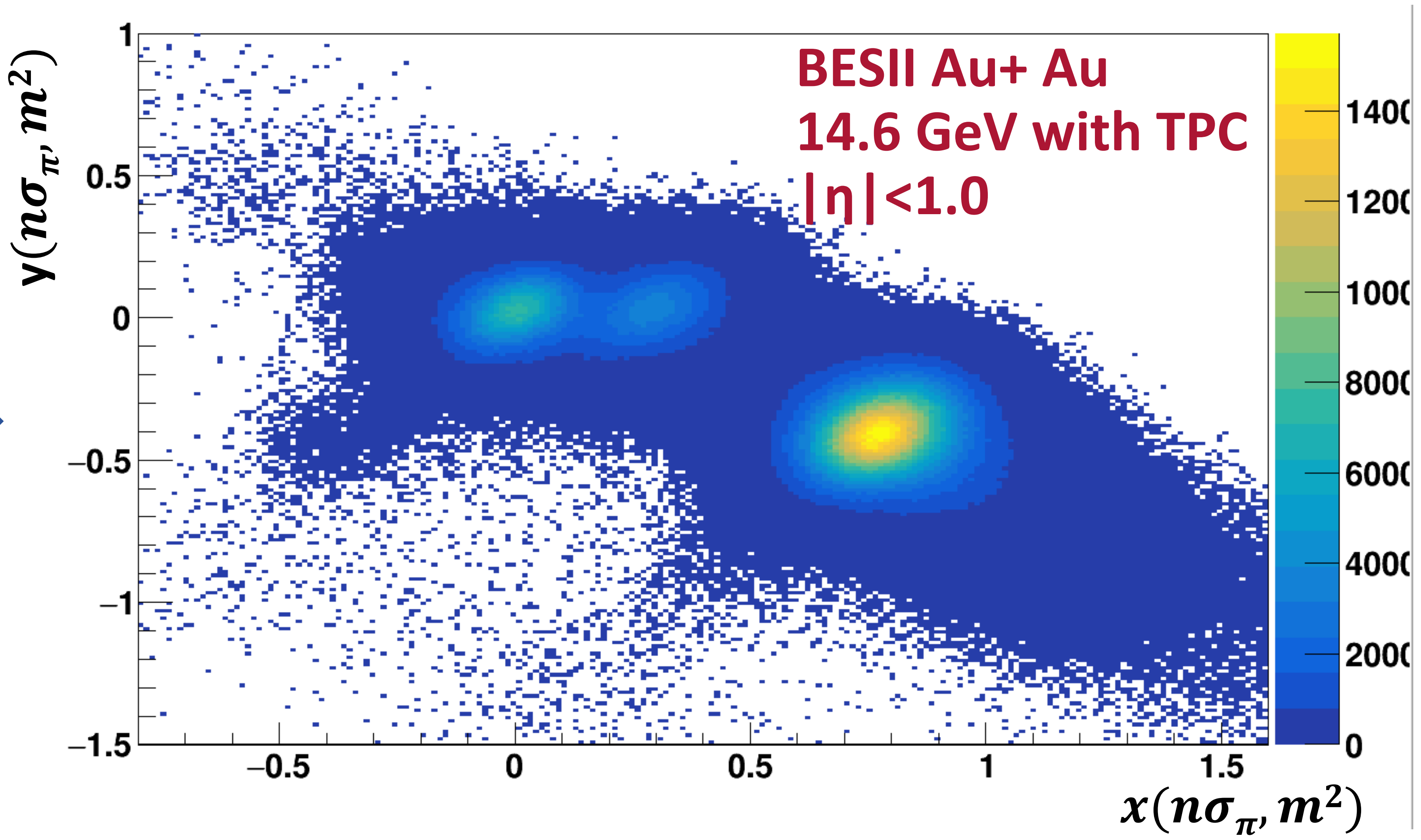
1.8<$p_T$<2.0 GeV/c,0-80%




Rotate

1.8<$p_T$<2.0 GeV/c,0-80%




**Shift and scale:** $(\mu_\pi(n\sigma_\pi), \mu_\pi(m^2)) = (0,0.019)$

$$f_{scale} = \sigma_\pi(n\sigma_\pi / n\sigma_\pi(m^2))$$

**Rotation:**

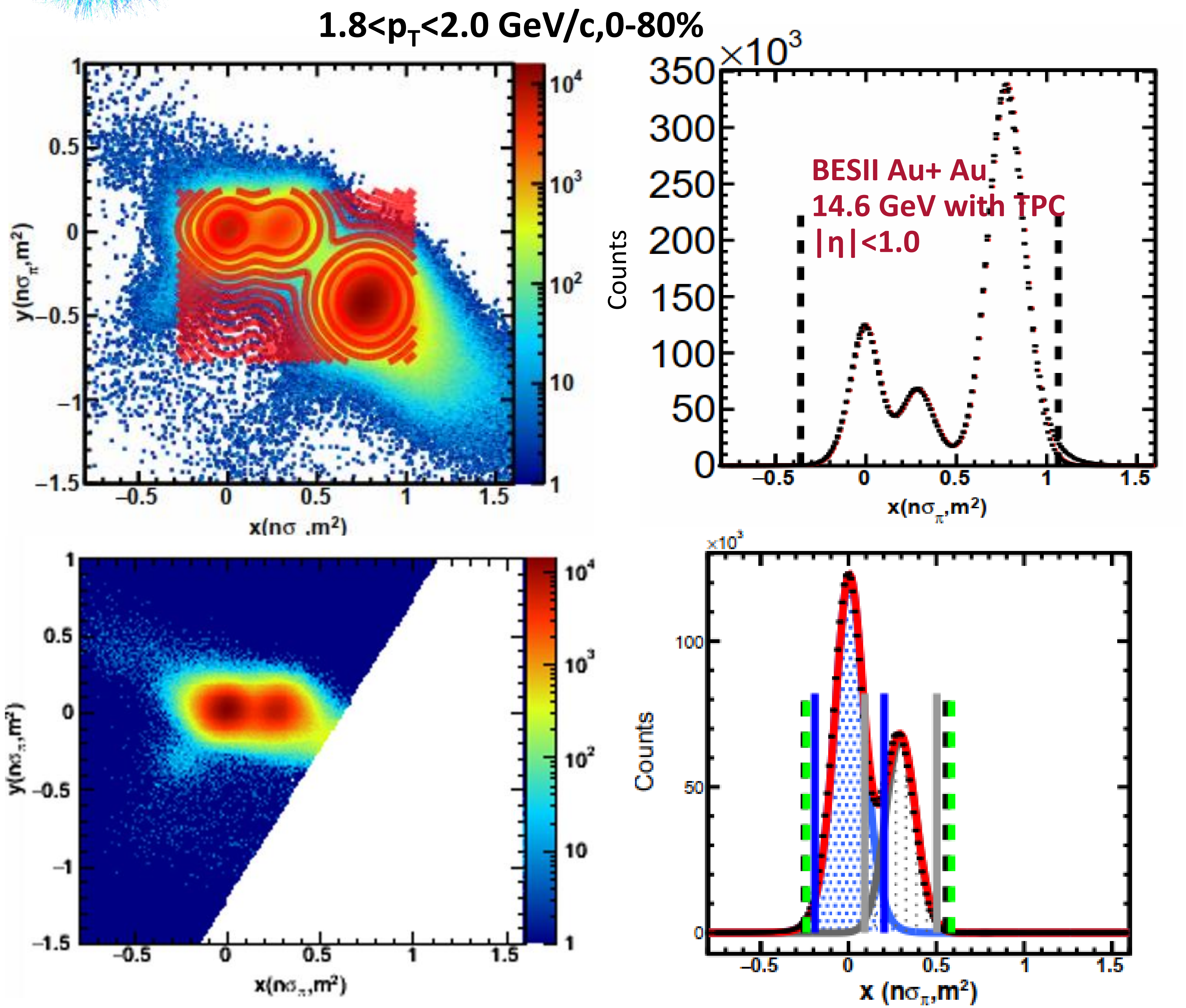
$$\alpha = -\tan^{-1}\left(\frac{y_k}{x_k}\right) = -\tan^{-1}\left(\frac{\mu_k(m^2) - \mu_\pi(m^2)}{\mu_k(n\sigma_\pi) - \mu_\pi(n\sigma_\pi) * f_{scale}}\right)$$

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$= \begin{pmatrix} cos\,\alpha & -sin\,\alpha \\ sin\,\alpha & cos\,\alpha \end{pmatrix} \begin{pmatrix} n\sigma_\pi * f_{scale} \\ m^2 - \mu_\pi(m^2) \end{pmatrix}$$

STAR, PHYSICAL REVIEW C 88, 014902 (2013)

# 2D($n\sigma_\pi + m^2$) PID for $\pi^\pm$, $K^\pm$

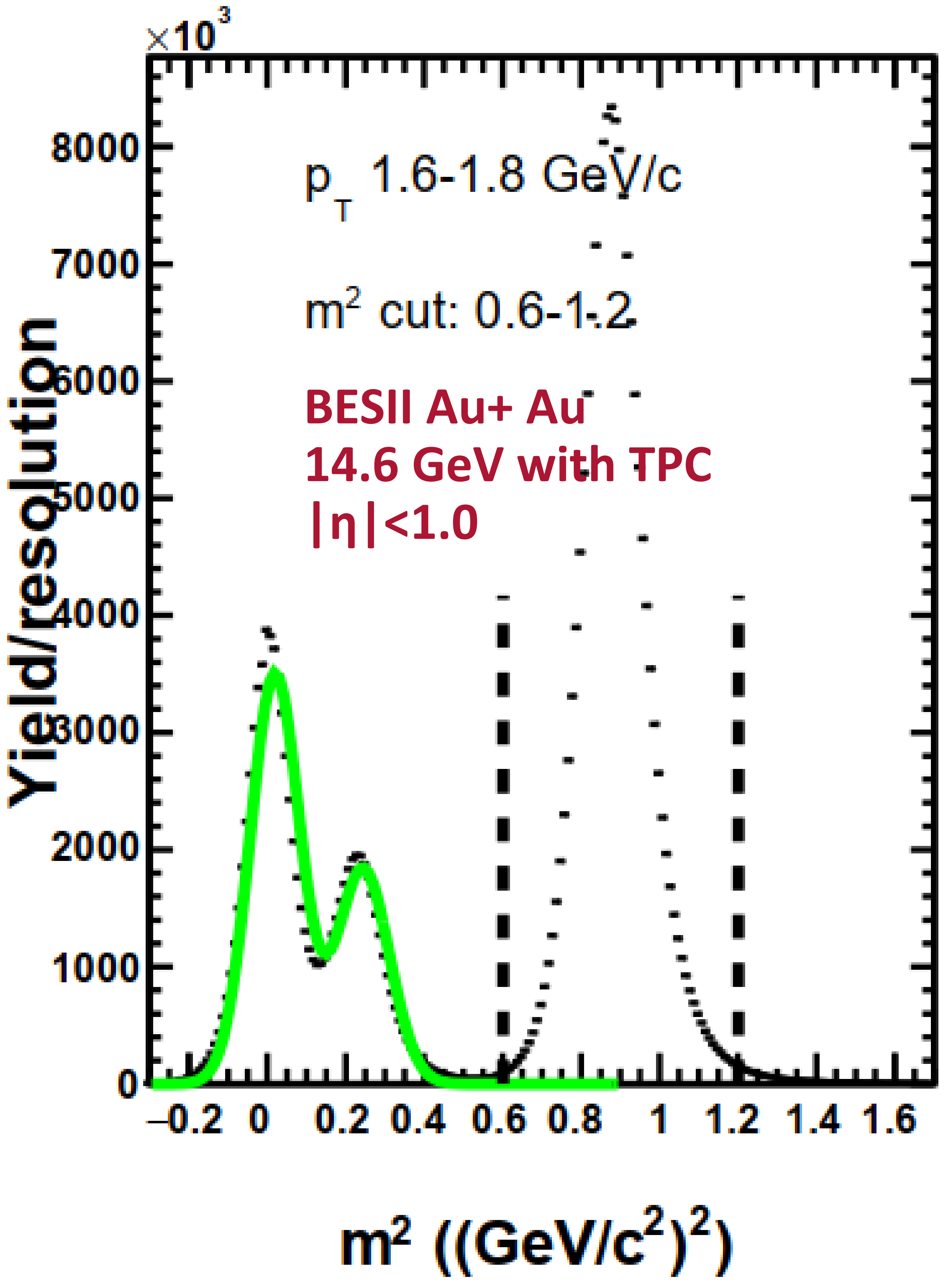


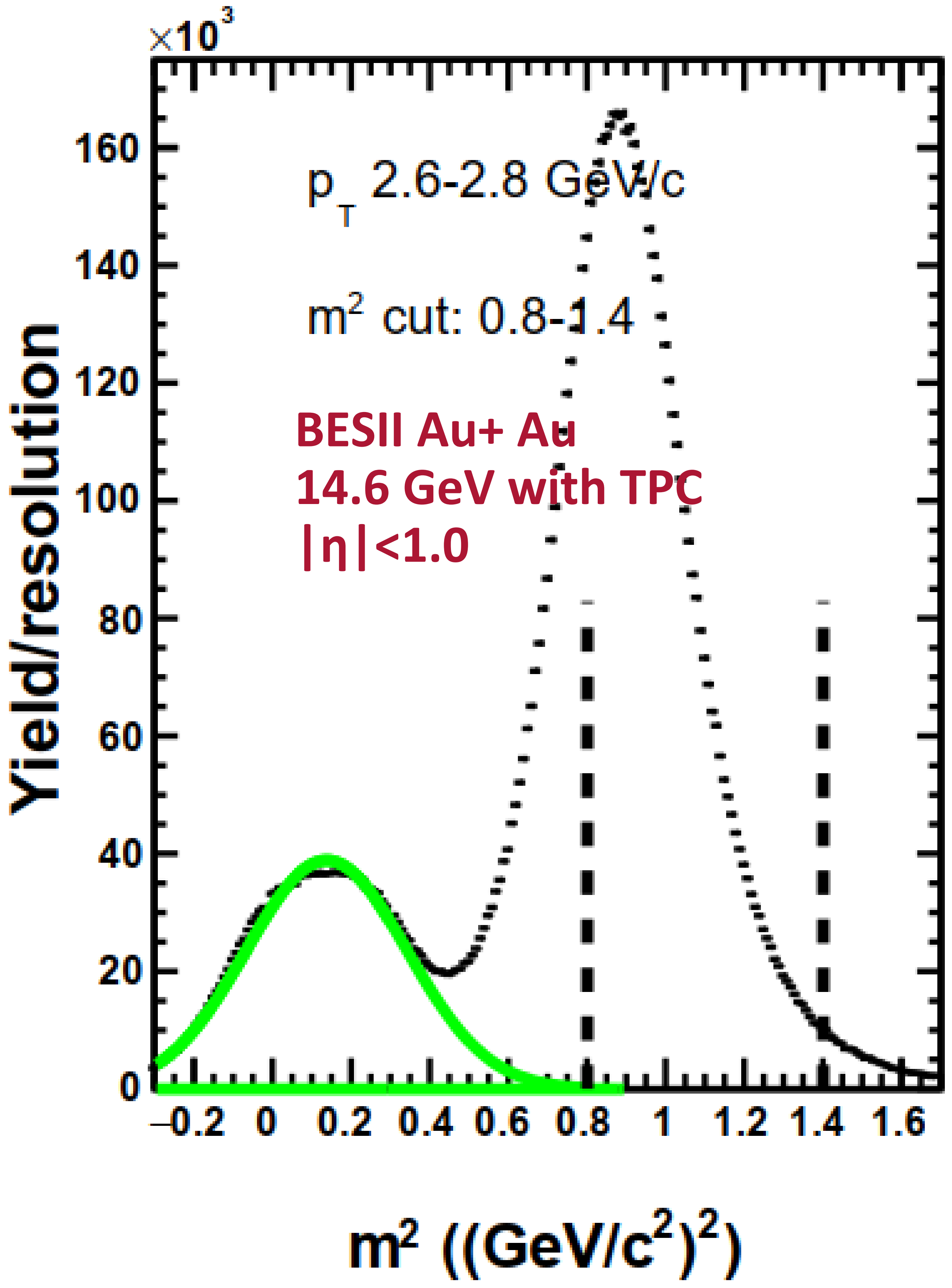

The goal of this transformation is to have a maximal separation between pion and kaon distribution.

Projection on x-axis of 2D distribution after excluding proton contamination

Using the student-t function to fit the distribution

# Proton Identification




**Protons are identified by $m^2$ up to $p_T$ 3.2 GeV/c**

Event-by-event resolution correction: H. Masui, et. al., Nucl. Instrum. Meth. A 833 (2016) 181-185

# Systematic Uncertainties

| Systematic cuts for $p$ , $\bar{p}$ | | | |
|---|---|---|---|
| Cuts | Default | var1 | var2 |
| nHitsFit(>) | 15 | 12 | 18 |
| Dca(<) | 1 | 0.7 | 1.3 |
| $n\sigma_{particles}$ | 2.5 | 2 | 3 |

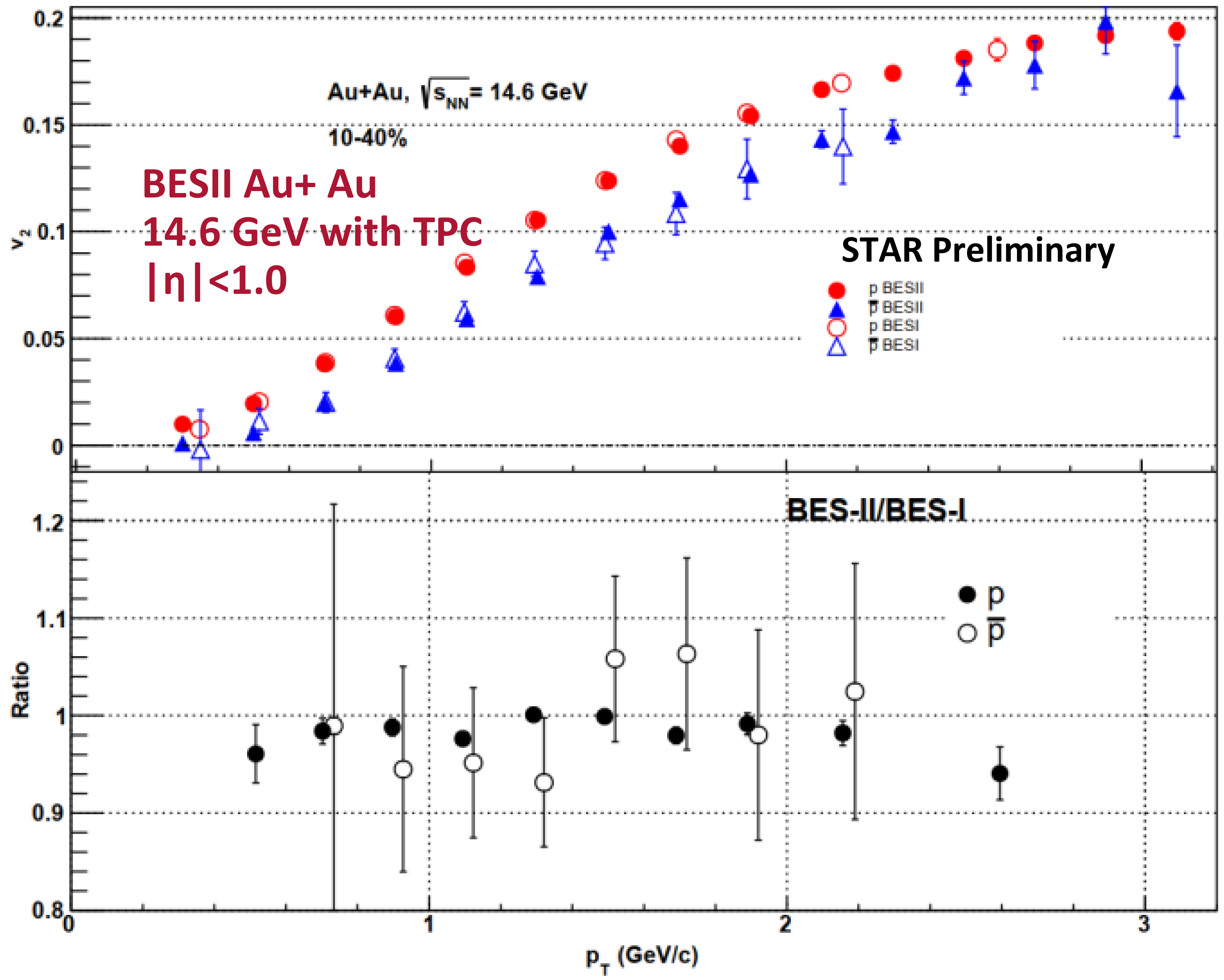
| Systematic cuts for π , $K$ | | | |
|---|---|---|---|
| Cuts | Default | var1 | var2 |
| nHitsFit(>) | 15 | 12 | 18 |
| Dca(<) | 3 | 2 | 2.5 |
| $n\sigma_{particles}$ | 2.5 | 2 | 3 |

**We use the maximum deviation from default value and assume these sources are uncorrelated for nHitsFit , dca , nσ**

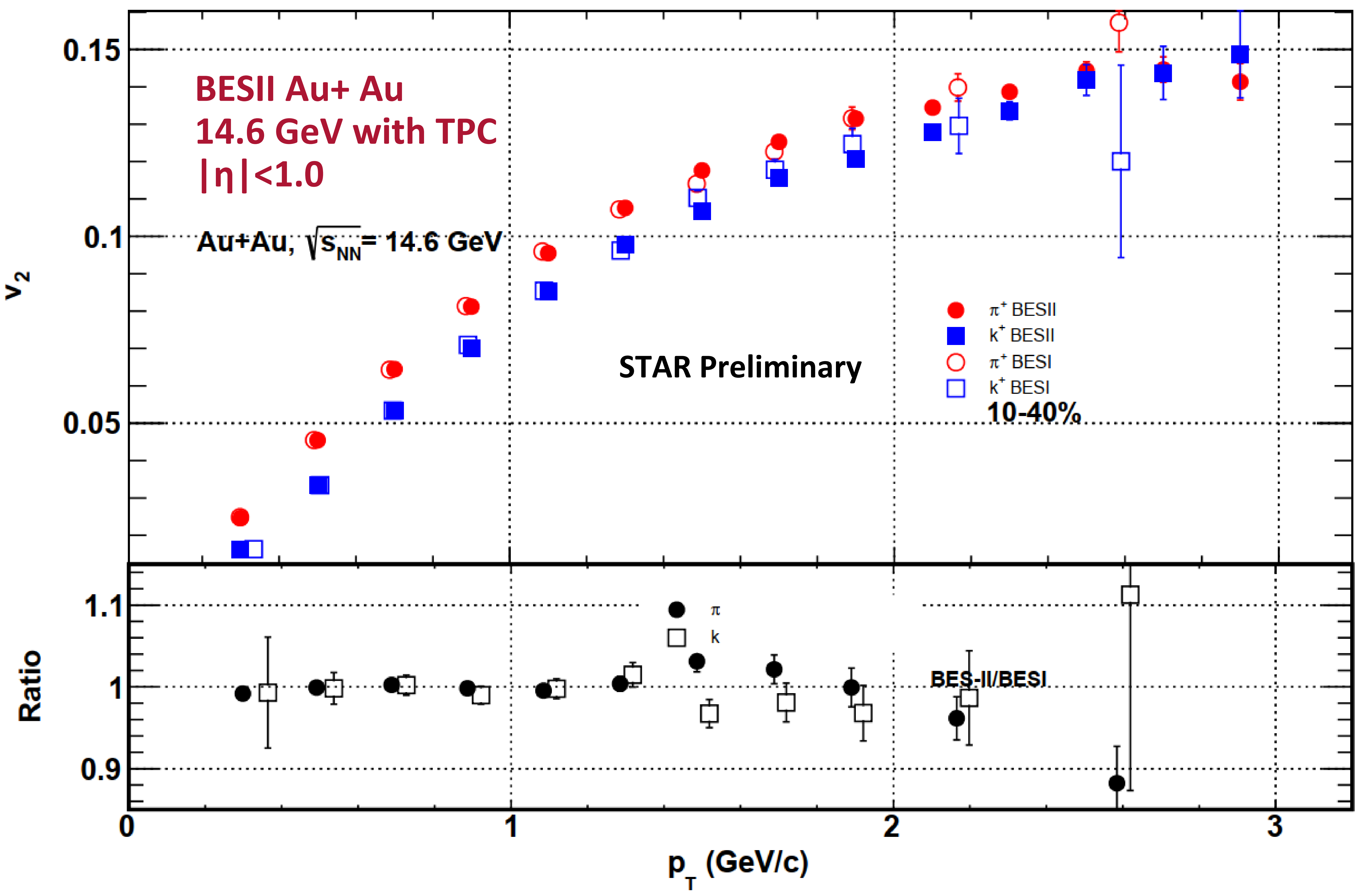
$$sys_{total} = \sqrt{(y_{dca} - y_{def})^2 + (y_{nHit} - y_{def})^2 + (y_{n\sigma} - y_{def})^2}$$

# Comparison to BESI

## Protons




## Pions and Kaons

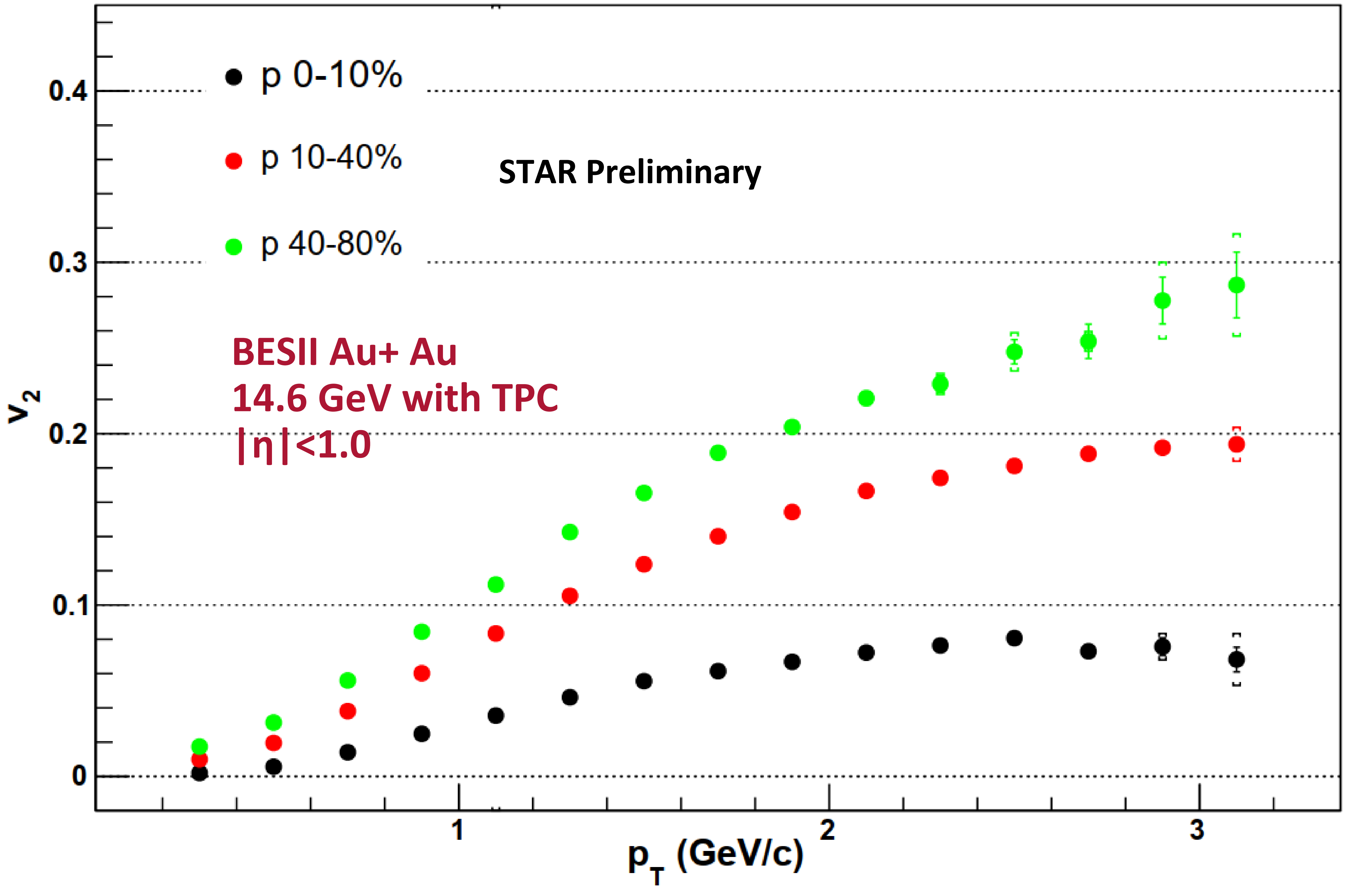



The results are consistent with BESI

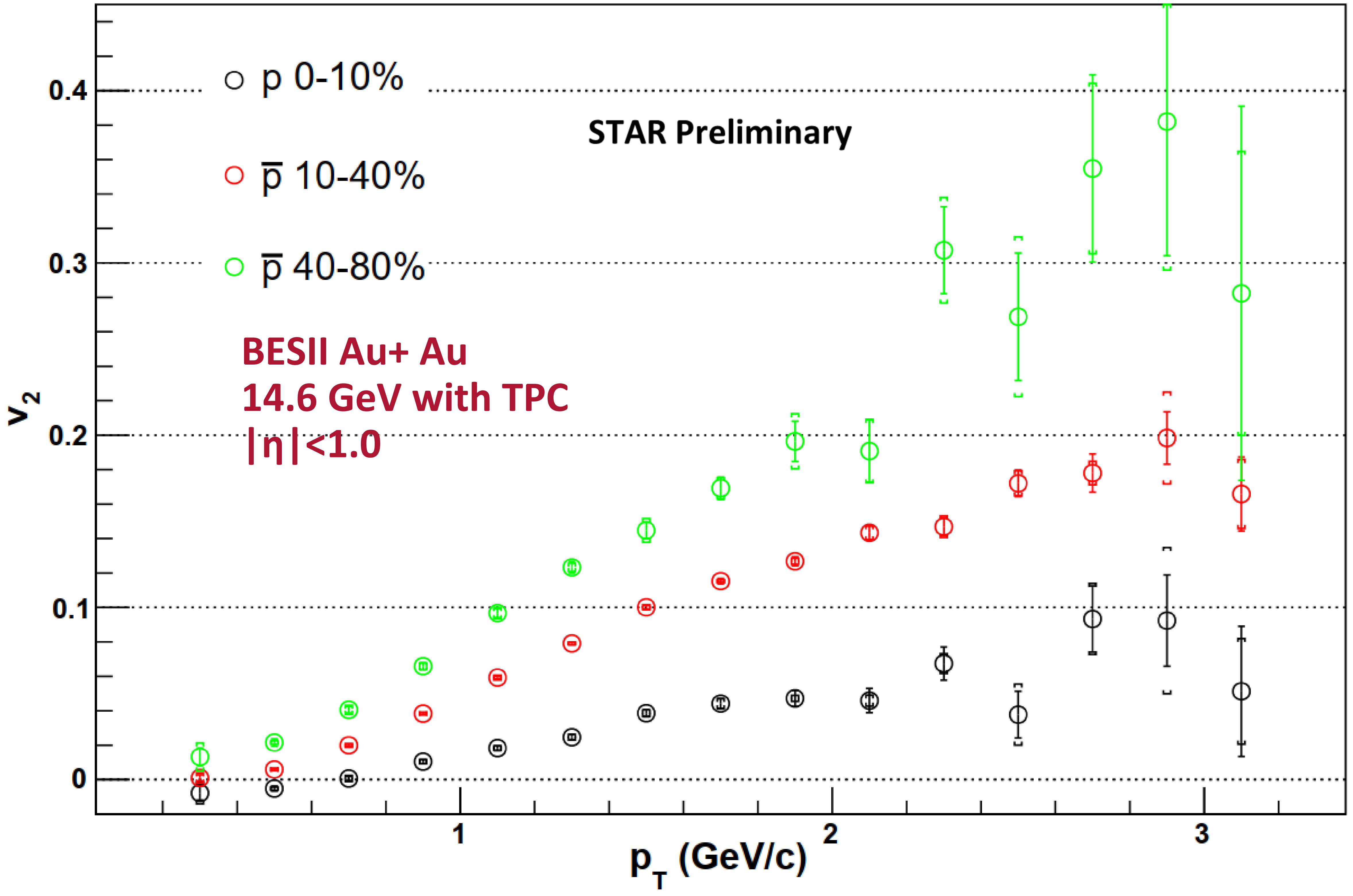
The statistical errors are reduced by a factor of ~3 compared to BES-I

# Centrality Dependence of $v_2$

## Protons

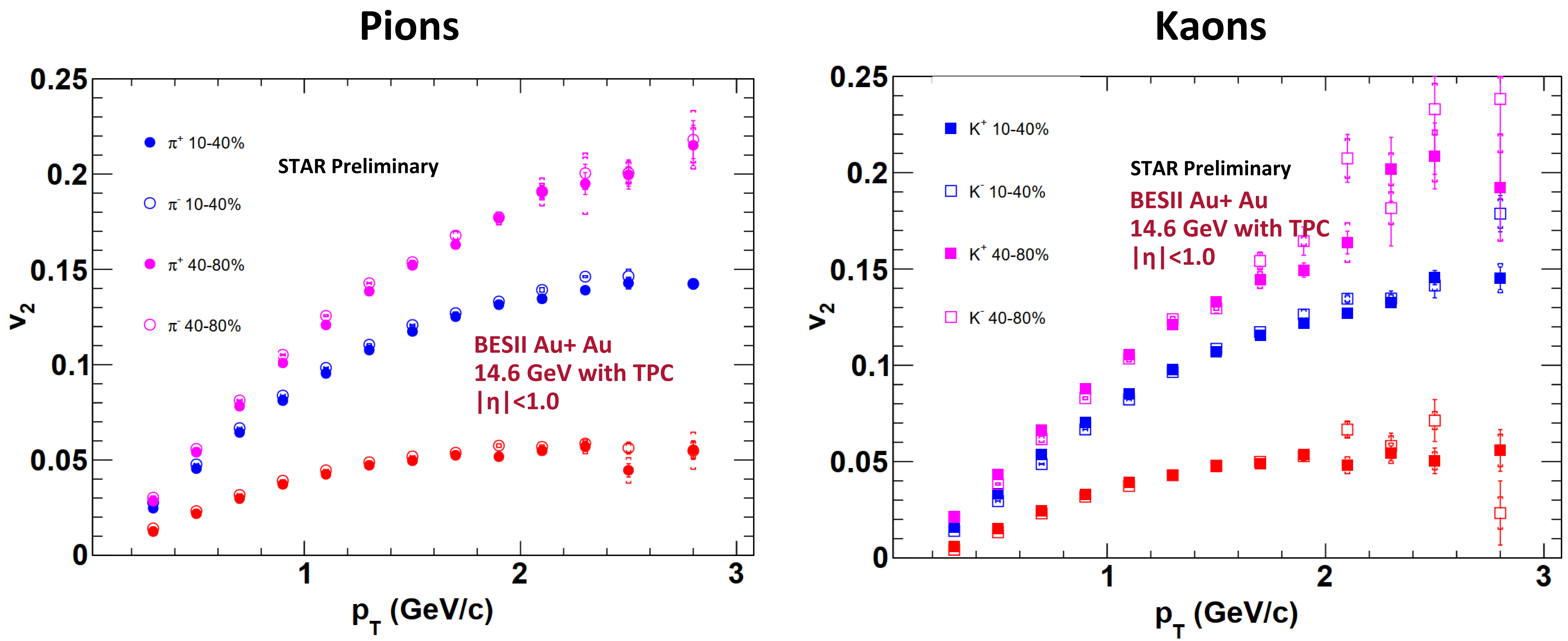



## Anti-Protons




Clear centrality dependence: $v_2$ driven by initial anisotropy of the participants
Proton $v_2$ > anti-Proton $v_2$

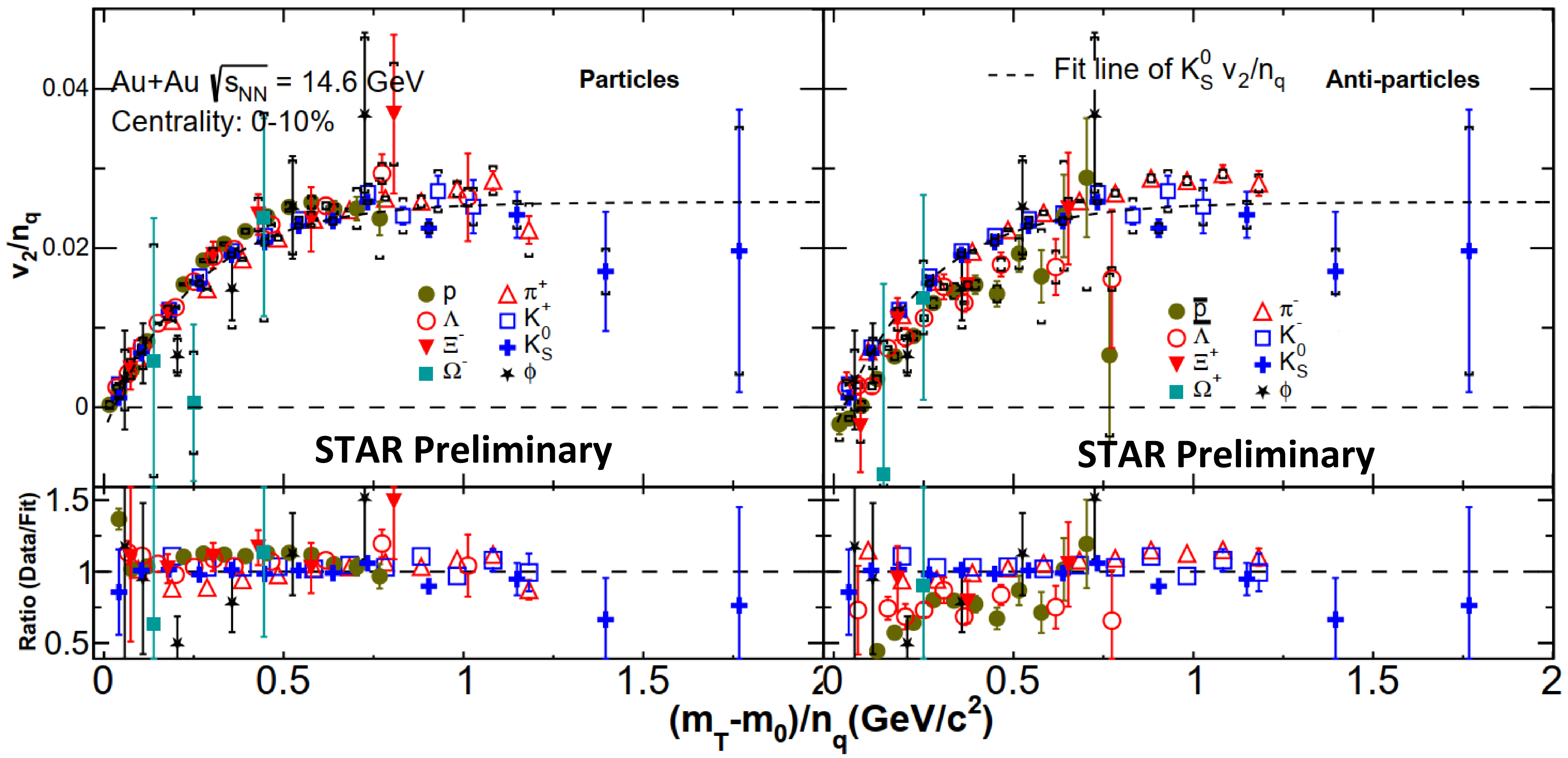
# Centrality Dependence of $v_2$

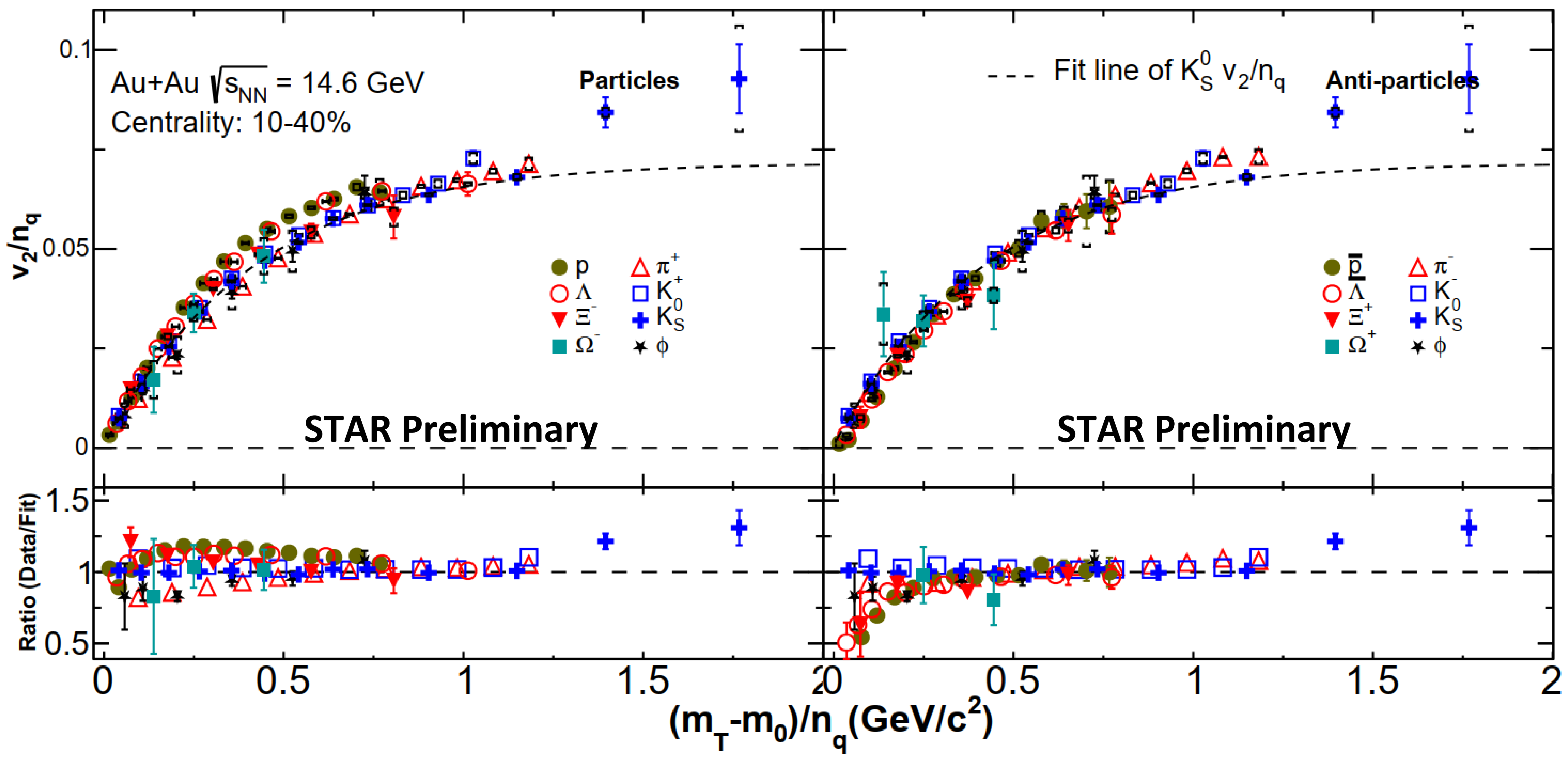



Clear centrality dependence: $v_2$ driven by initial anisotropy of the participants

$v_2$ difference between particles and anti-particles observed

# NCQ Scaling: Centrality Dependence



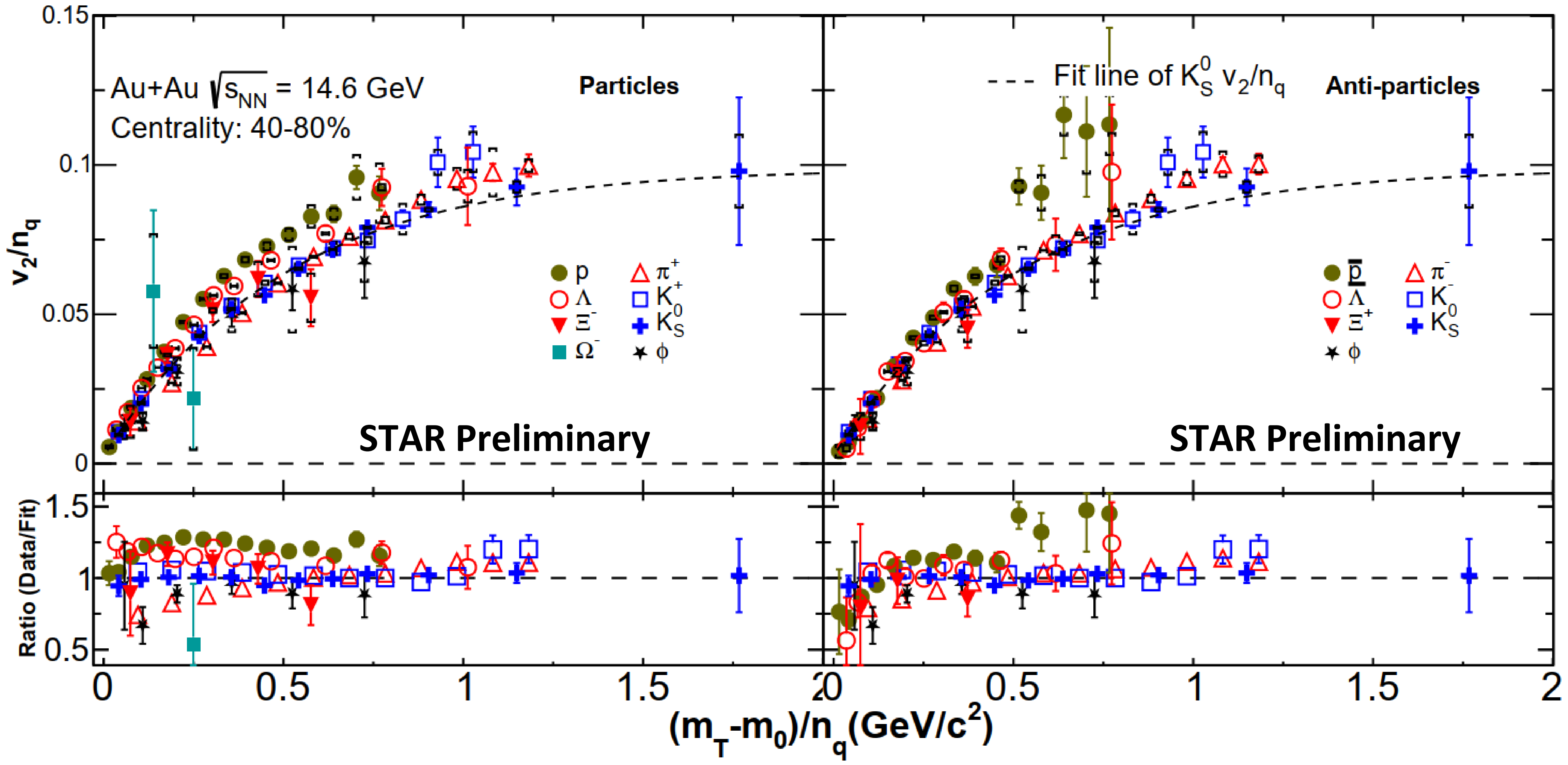



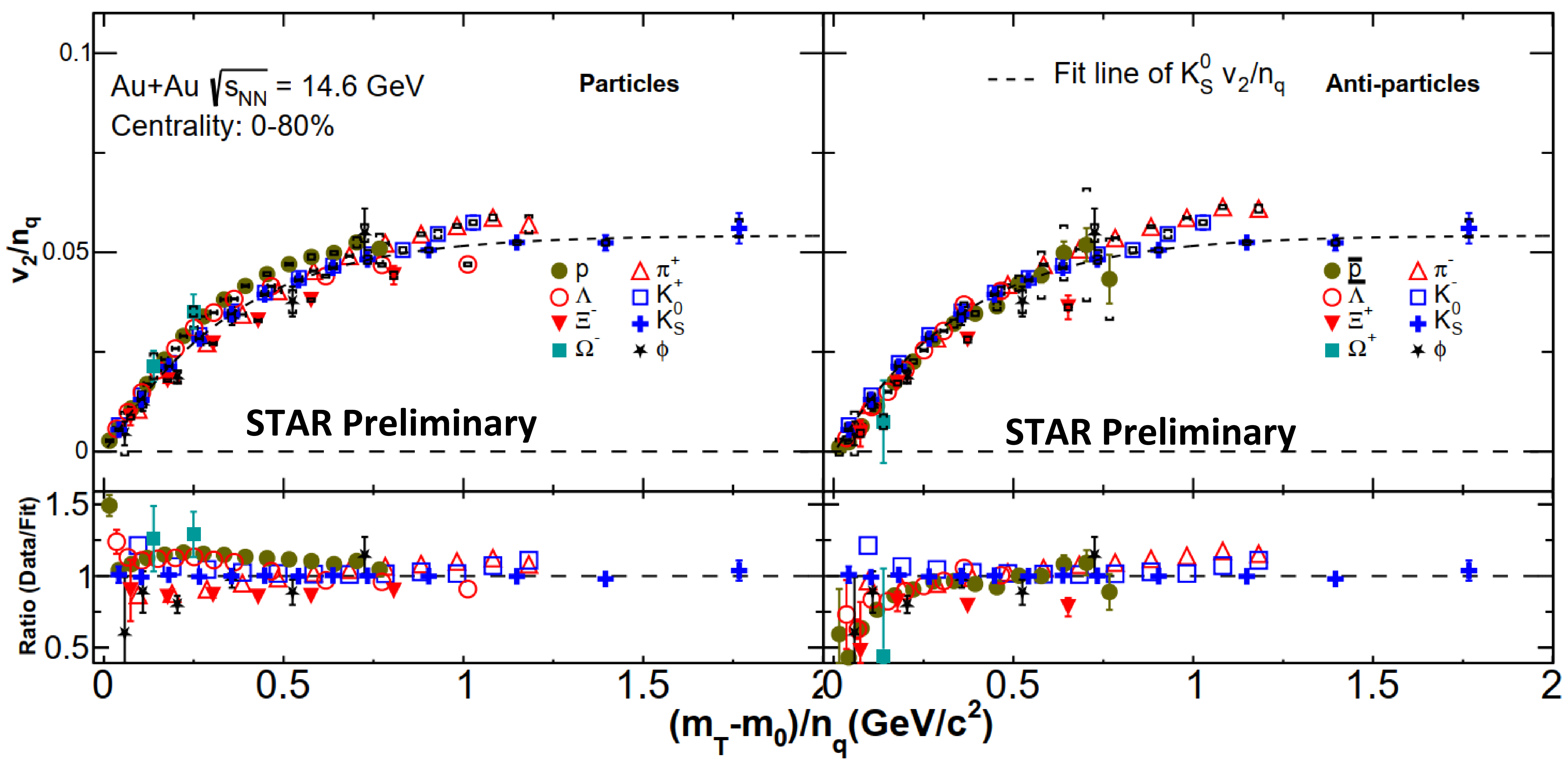

**Fit function:** $f(x) = a/(1.0 + \exp\left(-\frac{x-b}{c}\right)) - d$

NCQ scaling holds at 20% level except low $p_T$ anti-proton and anti-Λ

**P. Dixit, Wed, 11/30 for strangeness**

# NCQ Scaling: Centrality Dependence




NCQ scaling holds at 20% level

NCQ scaling works in all centralities

# Summary

- Centrality dependence $v_2$ of pions, kaons and protons at 14.6 GeV

  The statistical errors are reduced by a factor of ~3 compared to BES-I

  $v_2$ is driven by initial geometry of participants

- NCQ scaling test at 14.6 GeV

  Scaling holds for light, strange and multi-strange particles within 20%

- Medium produced at 14.6 GeV

  Partonic collectivity is built-up

**Thank you!**