

# $\rho^0$ vector meson elliptic flow ( $v_2$ ) in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV in STAR at RHIC

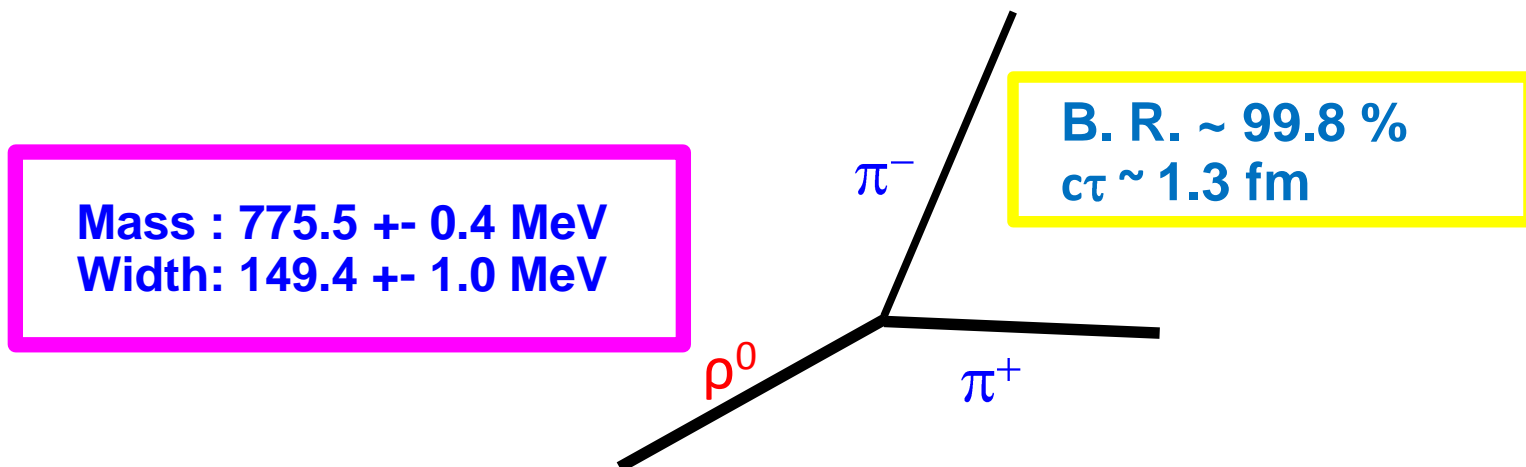


**Prabhat R. Pujahari**  
for  
**The STAR Collaboration**



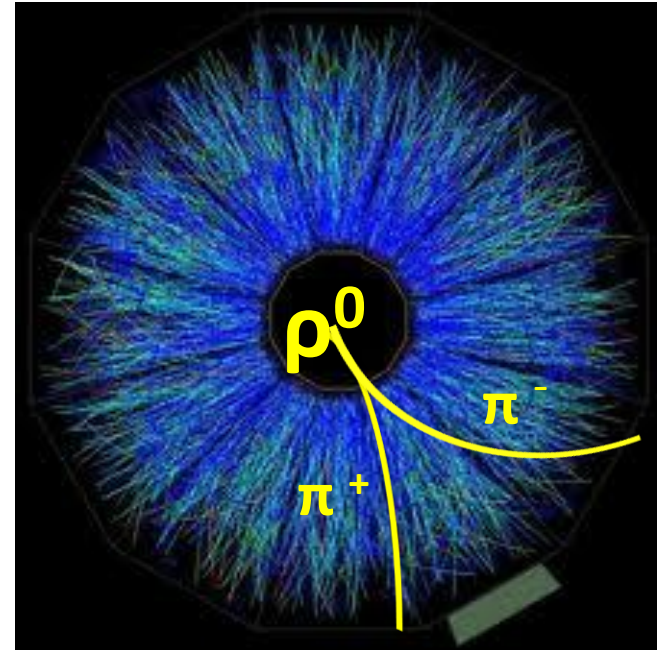
Indian Institute of Technology Bombay, Mumbai

DAE-BRNS HEP Symposium Jaipur, 13– 18<sup>th</sup> Dec. 2010



# Outline

- Introduction: elliptic flow ( $v_2$ )
- Motivation:  $\rho^0$  resonance  $v_2$
- STAR Experiment
- Data Analysis Methods
  - ❖  $(\phi - \Psi_2)$  binning method
  - ❖  $v_2$  vs. Invariant mass method
- Analysis Results
- Summary and Outlook

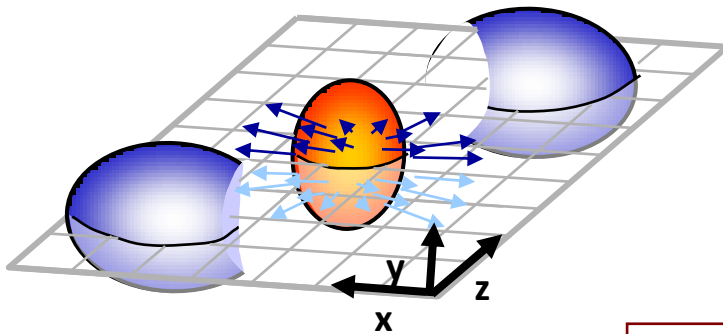


# Elliptic Flow and its Origin

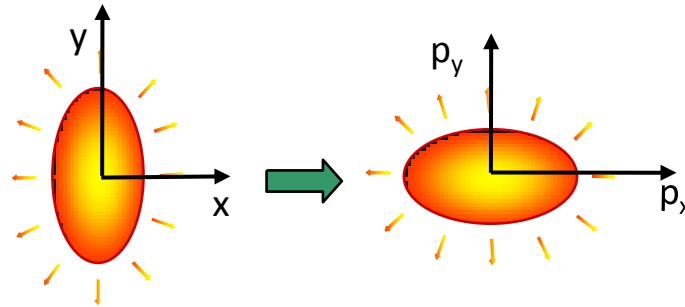
Flow is a phenomenon seen in nucleus-nucleus collisions, which correlates the momentum distributions of the produced particles with the **spatial eccentricity** of the overlap region.



**azimuthal dependence of the pressure gradient.**



Reaction plane: z-x plane



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \quad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1} \left( \frac{p_y}{p_x} \right)$$

Elliptic flow is the second coefficient of the **Fourier expansion** of the azimuthal particle distribution:

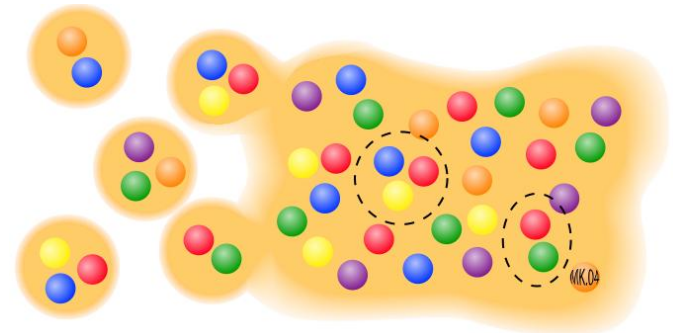
$$E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{dN}{p_t dp_t dy} \left( 1 + \sum_{n=1} 2v_n \cos(n[\varphi - \Psi_{RP}]) \right) \quad v_2 = \langle \cos(2[\varphi - \Psi_2]) \rangle$$

# Motivation - I

## Why Elliptic Flow ( $v_2$ ) ?

**Quark-Gluon Plasma (QGP) definition:** A (locally) thermally equilibrated state of matter in which quarks and gluons are de-confined from hadrons, so that color degrees of freedom become manifest over nuclear, rather than merely nucleonic volume.  
(Nucl. Phys. A 757 (2005) 102)

- Elliptic flow provides early time information on the collectivity of particles from heavy ion collisions.
  - Signal is self - quenching with time – ***EARLY TIME OBSERVABLE !***
- $v_2$  is a measure of the degree of thermalization of the matter produced early in the collisions.
- Hydrodynamics calculation of  $v_2$  involves the equation of state (EoS) of QGP.
- According to coalescence model, number of constituent quark (NCQ) scaling of  $v_2$  suggests the creation of QGP with  $v_2^q$  characterizing the properties of the QGP.



# Motivation - II

## Why $\rho^0$ Elliptic Flow ?

➤ Physics is different in different transverse momentum ( $p_T$ ) regions.

- Low  $p_T$  ( $0 < p_T \leq 1.5$  GeV/c)  $\Rightarrow$  Hydrodynamics applies
- Intermediate  $p_T$  ( $1.5 < p_T \leq 5$  GeV/c)  $\Rightarrow$  Coalescence/recombination model works
- High  $p_T$  ( $p_T \geq 5$  GeV/c)  $\Rightarrow$  Contribution from jets fragmentation

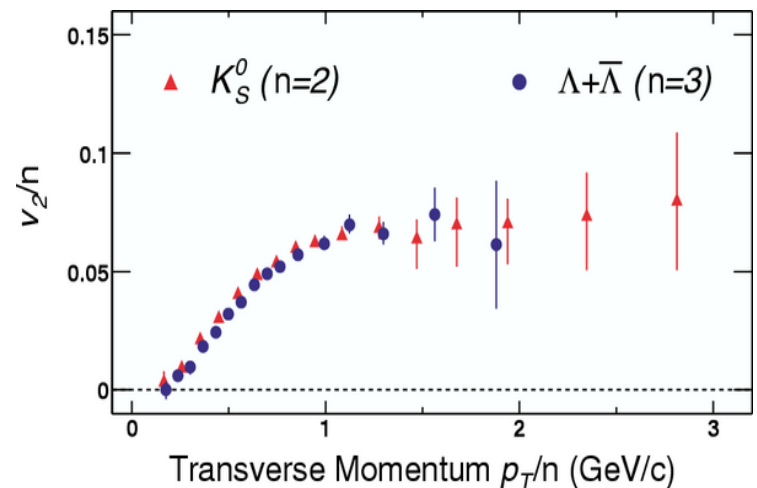
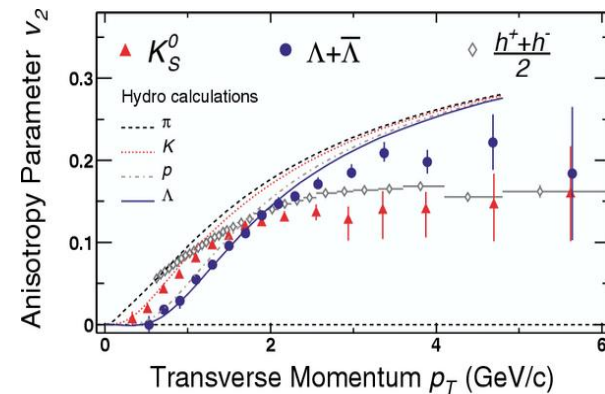
➤ Number of Constituent Quark (NCQ), (2 = mesons, 3 = baryons) scaling at intermediate  $p_T$   $\Rightarrow$  Indication of partonic degrees of freedom.

➤  $\rho^0$  production mechanism.

$\Rightarrow$  scale NCQ  $\Rightarrow v_2/n$

-  $\pi^+\pi^- \rightarrow \rho^0 \Rightarrow n = 4$

-  $q\bar{q} \rightarrow \rho^0 \Rightarrow n = 2$

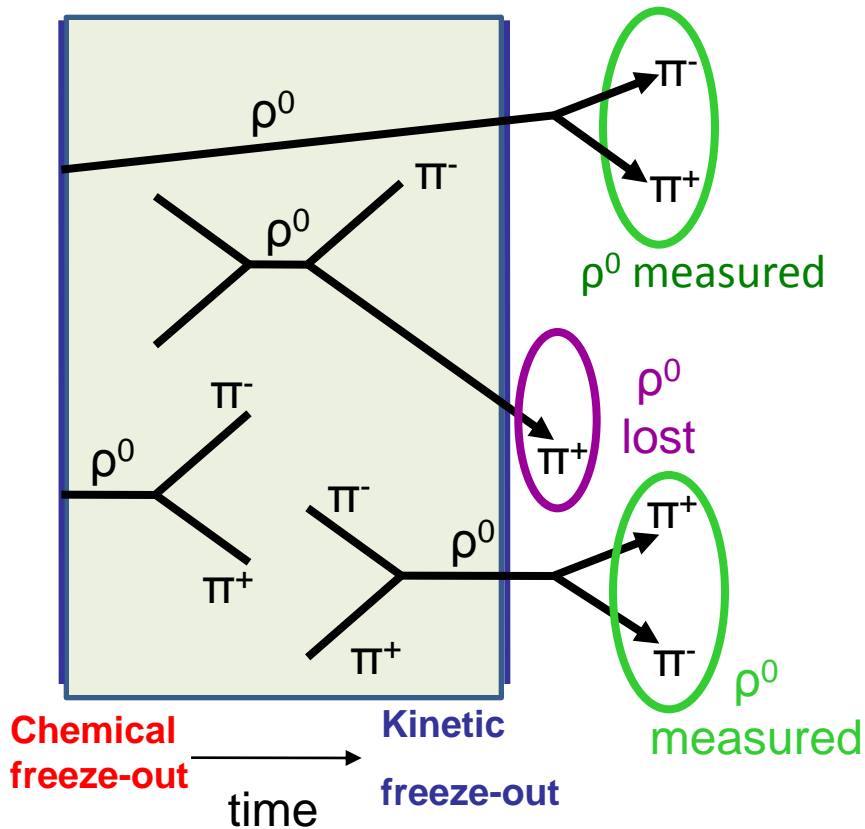


Phys. Rev. Lett. **92** (2004) 52302

# Motivation - III

## Why $\rho^0$ Elliptic Flow ?

- Leptonic decay products are measured directly as they do not interact, but hadronic decay products are sensitive to the medium.
- Study of  $v_2$  from  $\rho^0 \rightarrow \pi^+ \pi^-$  channel may provide information of the dynamical evolution during chemical - kinetic freeze-out.



- Regeneration is a key phenomenon in resonance study.

- $\rho^0$  regeneration  $\Rightarrow \sigma(\pi\pi)$

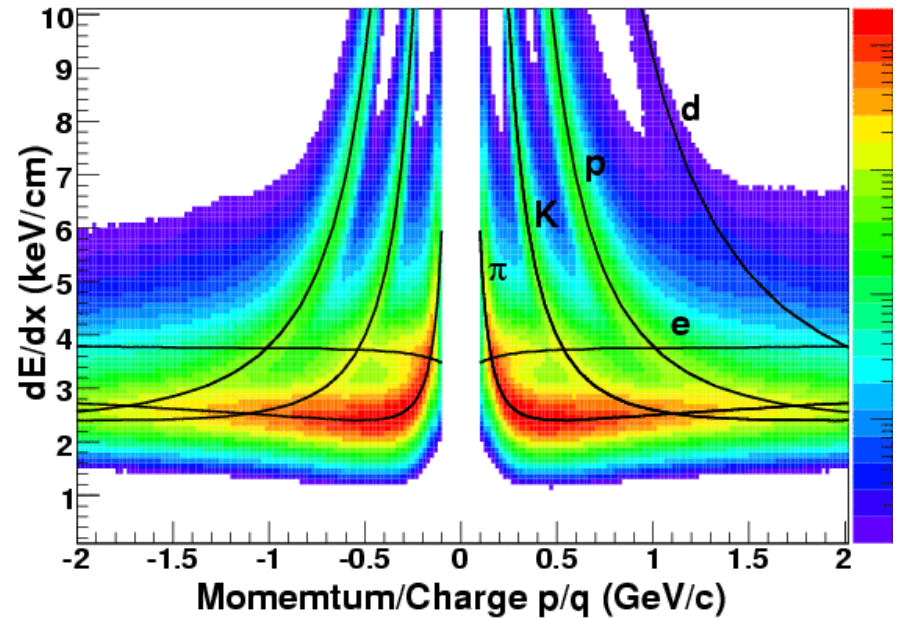
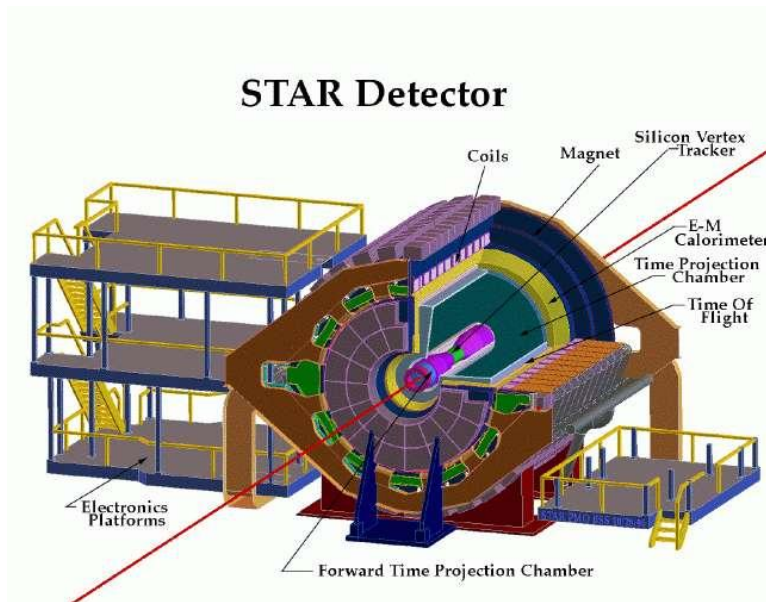
- $v_2$  can help to understand the hadronic daughters regeneration effects in the medium.

# The STAR Experiment

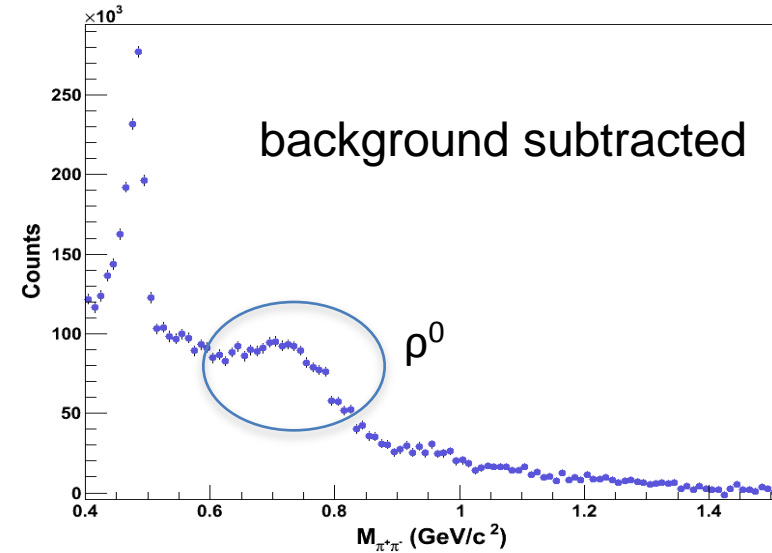
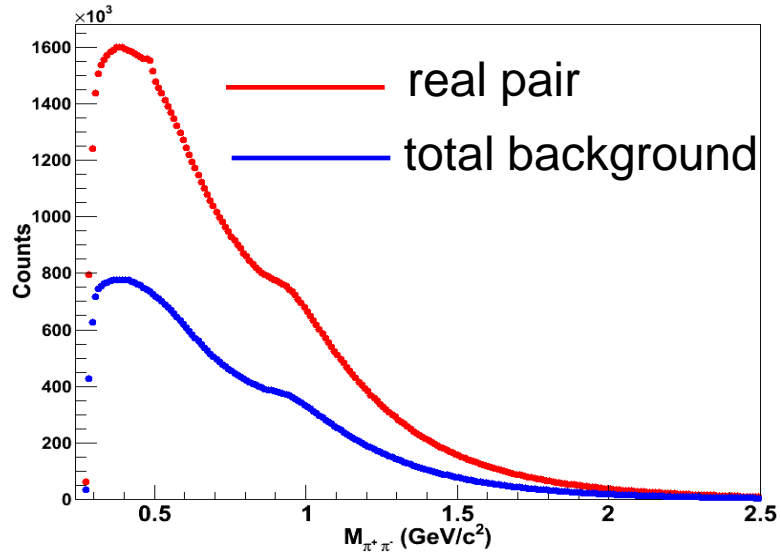
*We used the high statistics 200 GeV Au+Au data to measure the  $\rho^0$  observables.*

- ~ 25M events in peripheral (40-80% centrality) collisions.

STAR TPC is used to identify pion via  $dE/dx$  in TPC gas.



# Measurement – $\rho^0$ invariant mass reconstruction

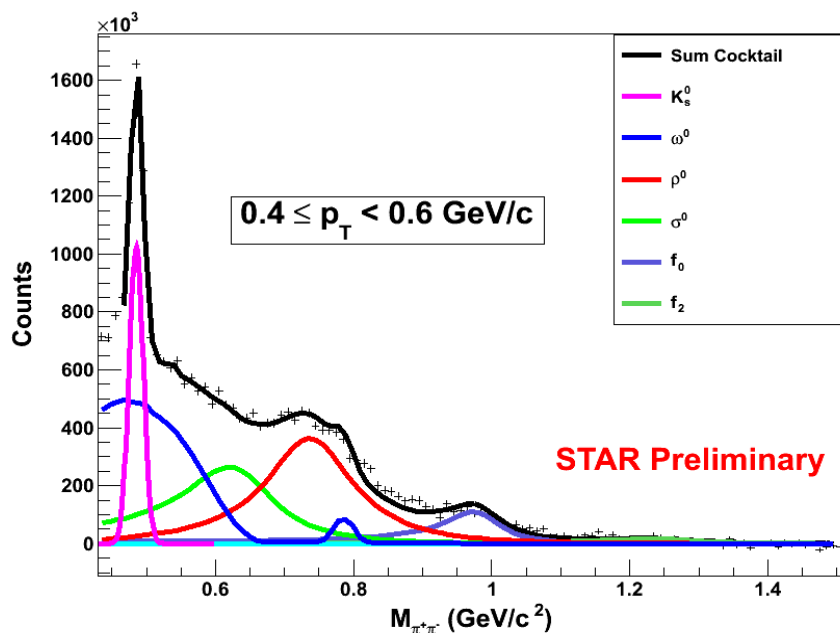


- Real pair:-  $\pi^+ \pi^-$
- Same event like-sign method used to estimate background from un-correlated  $\pi^+\pi^+$  and  $\pi^-\pi^-$  pairs.

$$\text{Total background} = \sqrt{\pi^+ \pi^+ * \pi^- \pi^-}$$

# Measurement – Hadronic Cocktail

- Final background subtracted  $M_{\pi^+\pi^-}$  invariant mass distribution fitted with a cocktail function to extract the  $\rho^0$  yield.



## • Hadronic cocktail

- ✓  $K_s^0$  is fitted to a gaussian function.
- ✓  $\omega^0$  and  $K^*$  shapes obtained from HIJING event generator.
- ✓  $\rho^0$ ,  $\sigma^0$ ,  $f_0$  and  $f_2$  are fitted with relativistic Breit-Weigner times the Boltzmann factor which takes the phase space in account.

- ✓ The masses of  $K_s^0$  and  $\rho^0$  are free parameter in the above fit.
- ✓ The  $\omega^0$ ,  $f_0$  and  $f_2$  masses are fixed according to PDG values .
- ✓ The  $\rho^0$ ,  $f_0$  and  $f_2$  widths are fixed in the cocktail fit.
- ✓ The mass and width of  $\sigma^0$  is fixed at  $630 \text{ MeV}/c^2$  and  $160 \text{ MeV}/c^2$  respectively.

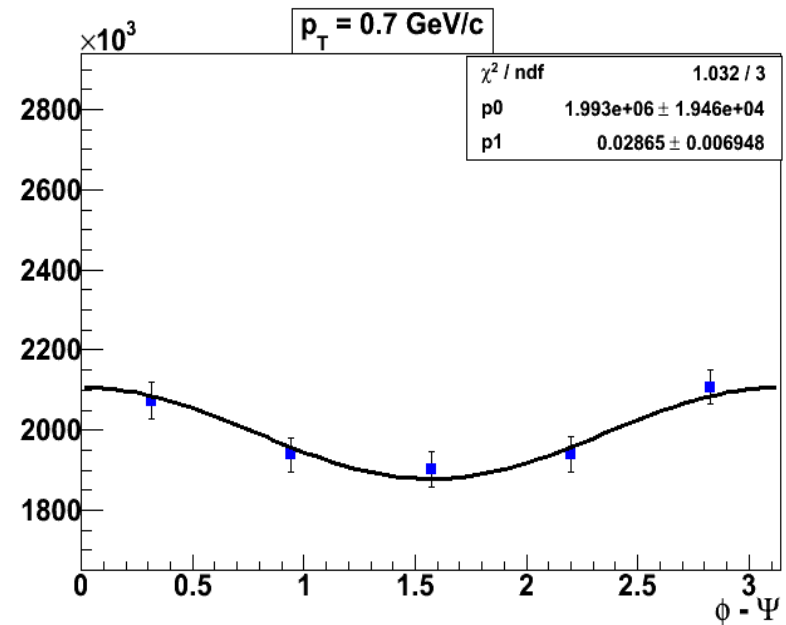
# Analysis: ( $\phi$ - $\Psi_2$ ) bin method

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos[2(\phi - \Psi_2)]$$

Elliptic flow

TPC event plane

- The  $\rho^0$  counts as a function of  $(\phi - \psi_2)$  are plotted.
- The  $\rho^0$  counts as a function of  $(\phi - \psi_2)$  are fitted to  
 $A [1 + 2v_2^{\text{obs}} \cos 2(\phi - \psi_2)]$
- Final  $v_2 = v_2^{\text{obs}} / \text{event plane resolution}$



# Analysis: $v_2$ vs $M_{inv}$ method

- Multi-parameter fitting function to get  $v_2$  observed values.

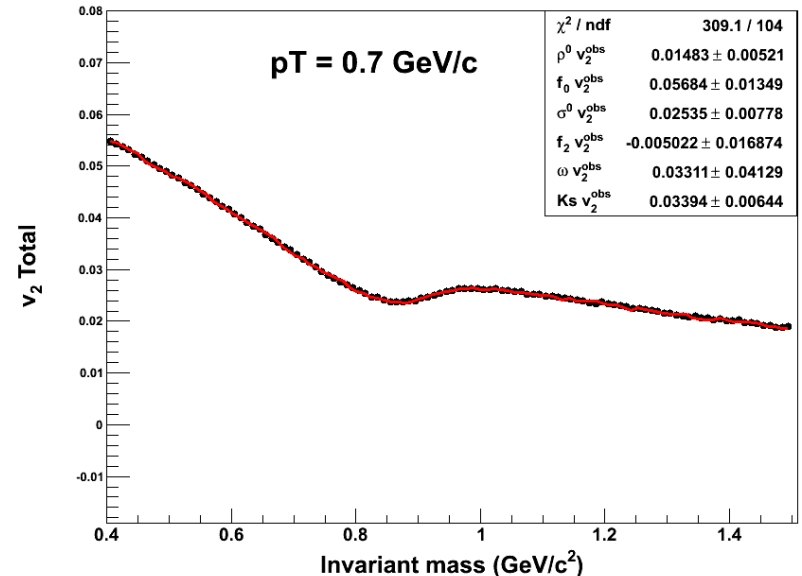
$$v_2^{Total} \langle M \rangle = v_2^{\rho^0} * \frac{N_{\rho^0}}{N_{Total}} \langle M \rangle + v_2^{\sigma^0} * \frac{N_{\sigma^0}}{N_{Total}} \langle M \rangle + v_2^{\omega^0} * \frac{N_{\omega}}{N_{Total}} + \dots + v_2^{Bkg} \langle M \rangle * \frac{N_{BKG}}{N_{Total}} \langle M \rangle$$

$v_2^{Bkg} \langle M \rangle$  is calculated from  $\pi^+ \pi^+$  and  $\pi^- \pi^-$  distributions.

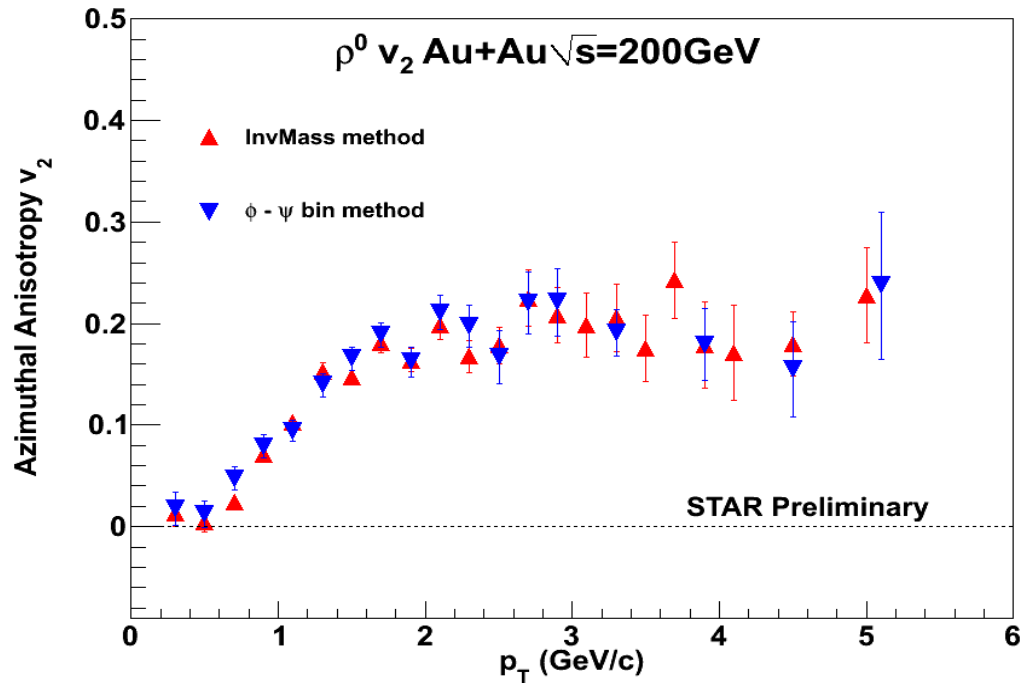
Where,

$$N_{BKG} = N_{Real\ pairs} - (N_{\rho^0} + N_{\sigma^0} + N_{\omega} + \dots)$$

$\rho^0$  final  $v_2 = v_2^{\rho^0} / \text{event plane resolution}$



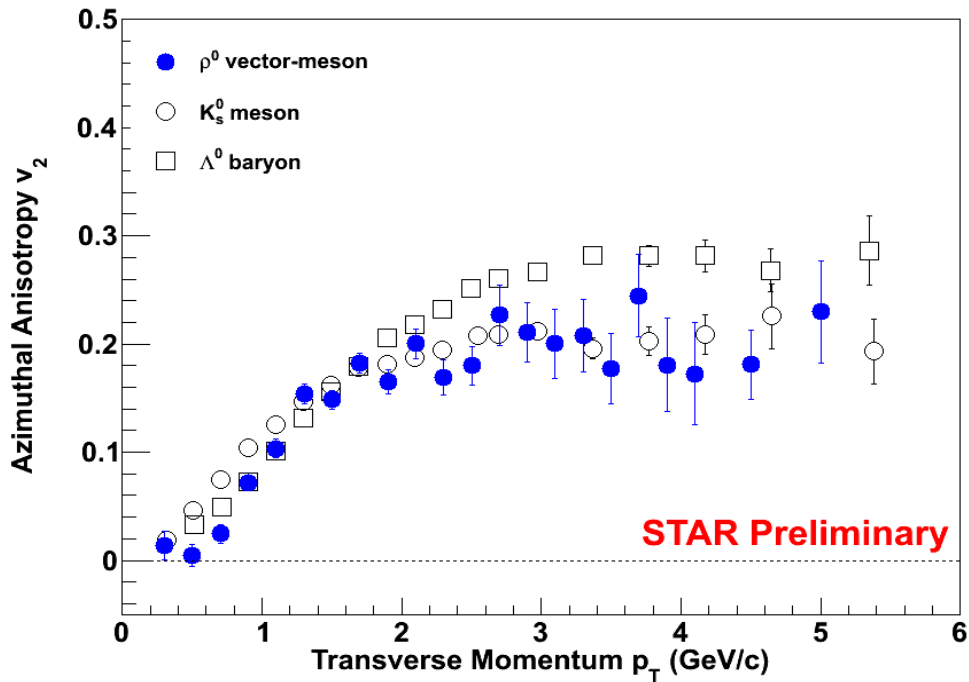
# Analysis: Methods Comparison



- The  $\rho^0 v_2$  results from the above two methods consistent with each other within statistical error bars.
- Systematic error calculation is in progress.

# Analysis: Results

## $v_2$ vs. $M_{inv}$



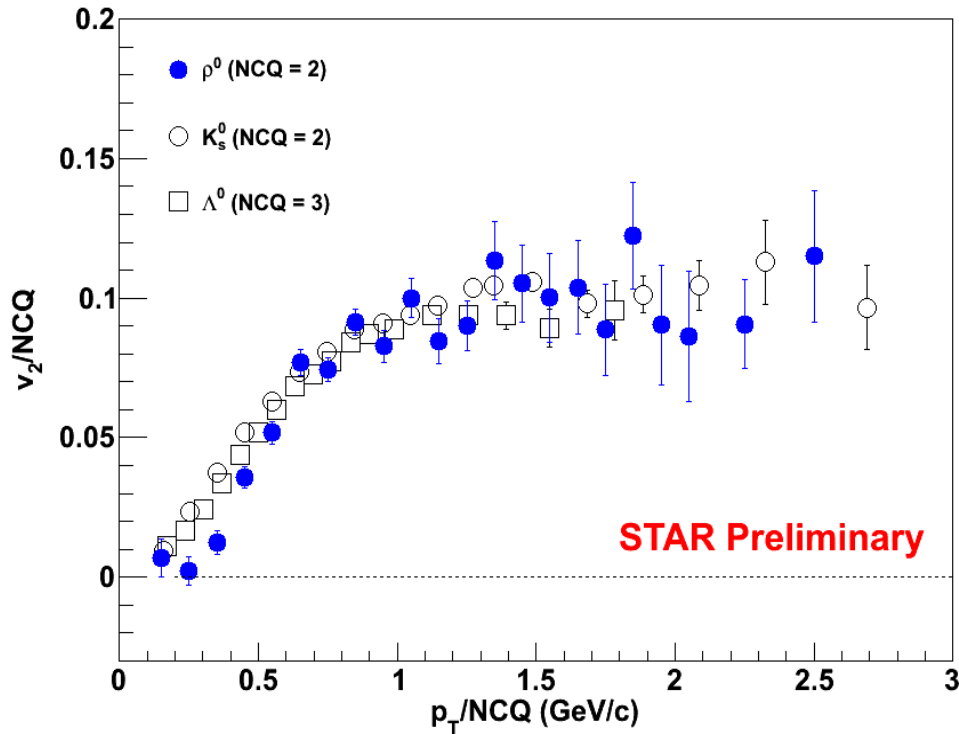
## $v_2$ as a function of $p_T$

- For  $p_T > 1.5$  GeV/c,  $v_2$  of  $\rho^0$  is more consistent with  $v_2$  of  $K_s^0$  than  $v_2$  of  $\Lambda^0$ .

$K_s^0$  and  $\Lambda^0$   $v_2$  results are obtained from Phys. Rev. C 77 (2008) 54901

# Analysis: Quark Scaling of $v_2$

NCQ = 2 for  $\rho^0$



## Early Time Information:

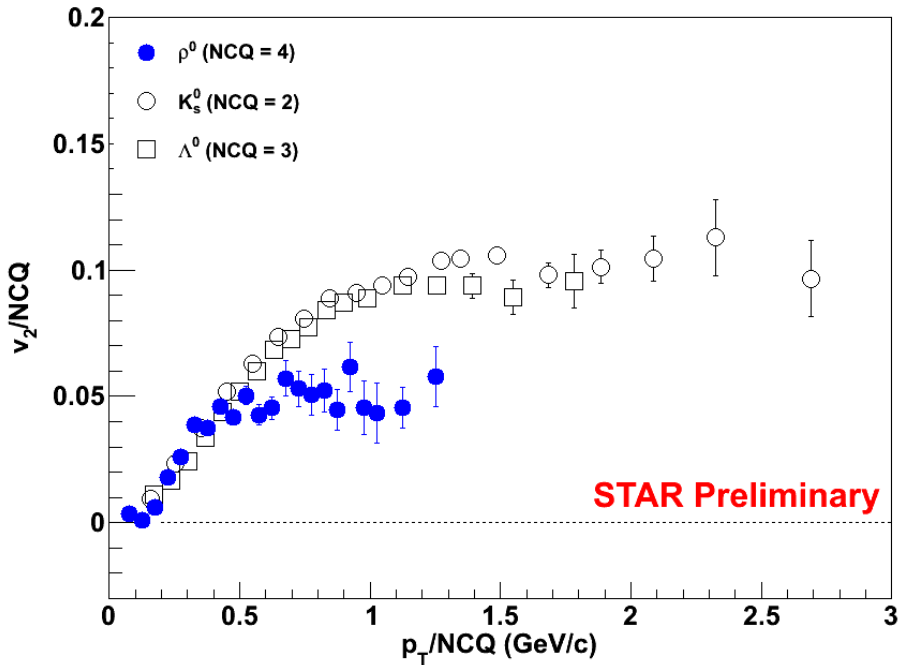
- The number of constituent quark scaling of  $v_2$  of  $\rho^0$  vector-meson in the intermediate  $p_T$  follows  $n=2$ .



The  $\rho^0$  production mechanism is dominated by the early stage quark – anti-quark coalescence.

- $\pi^+ \pi^-$  regeneration might be playing an important role in the low  $p_T$  region.

# Analysis: $n=4$ scaling of $\rho^0 v_2$



- $n=4$  scaling of  $\rho^0 v_2$  does not hold in the intermediate  $p_T$ .



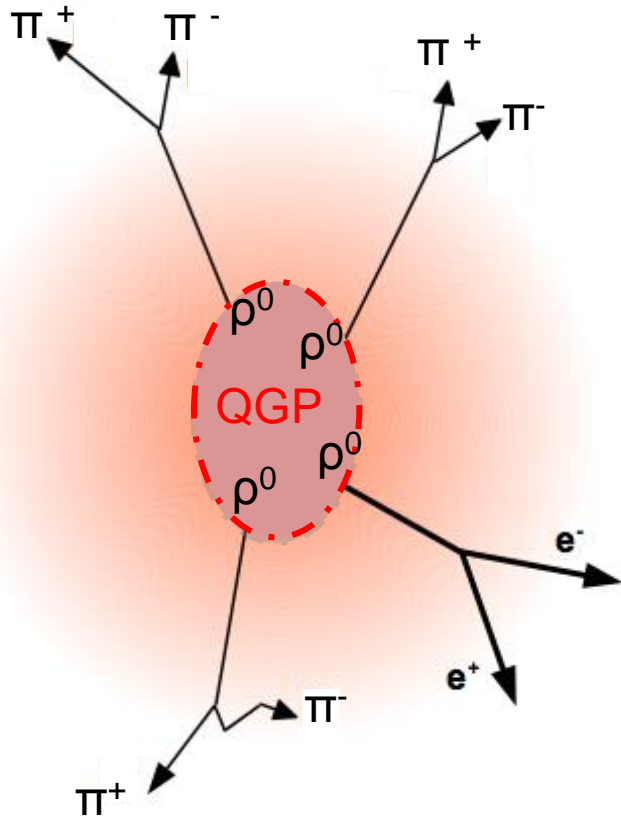
Intermediate  $p_T$   $\rho^0$ s are not generated from the late stage  $\pi^+\pi^-$  interaction rather the  $\rho^0$ s are produced from the early stage quark coalescence.

# Summary

- ✓  $\rho^0 v_2$  measured in Au+Au 200 GeV collisions in TPC ( $\phi - \Psi_2$ ) bin method and invariant mass method.
- ✓ The final results obtained in the above two methods were compared and they are consistent within the statistical error bars.
- ✓ In the intermediate transverse momentum ( $1.5 < p_T < 5$  GeV/c), the  $\rho^0 v_2$  scales with  $n=2$  quarks.
- ✓ In the low  $p_T$ , we observed the deviation of mass ordering of the  $\rho^0 v_2$ . Study is going on to understand the mass ordering effect in the low  $p_T$  region.

# The Future ...

*Further interesting predictions can be investigated using  $\rho^0$  vector-meson observables*



- $\rho^0$  di-lepton decay channel is a very clean probe from the early stage ( $e^\pm$  do not interact strongly)



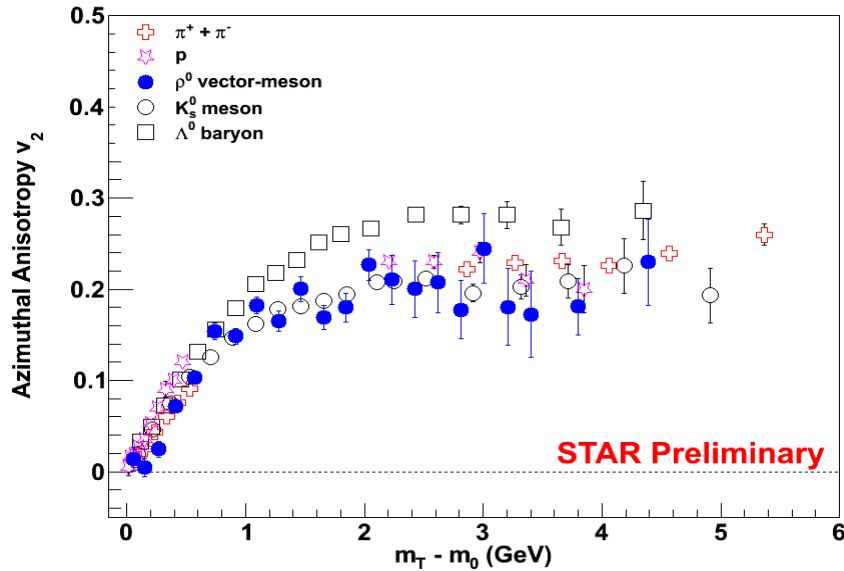
- Good channel to search for modifications of hadrons properties due to the hot medium.
- **Will be a challenge:**  $\rho^0 \longrightarrow e^+ e^-$  (B.R  $\sim 10^{-5}$ )
- STAR **Full barrel Time of Flight (TOF)** detector (installed 2008) will be a huge asset in making this measurement.



# STAR Collaborators

# ***Back up slides***

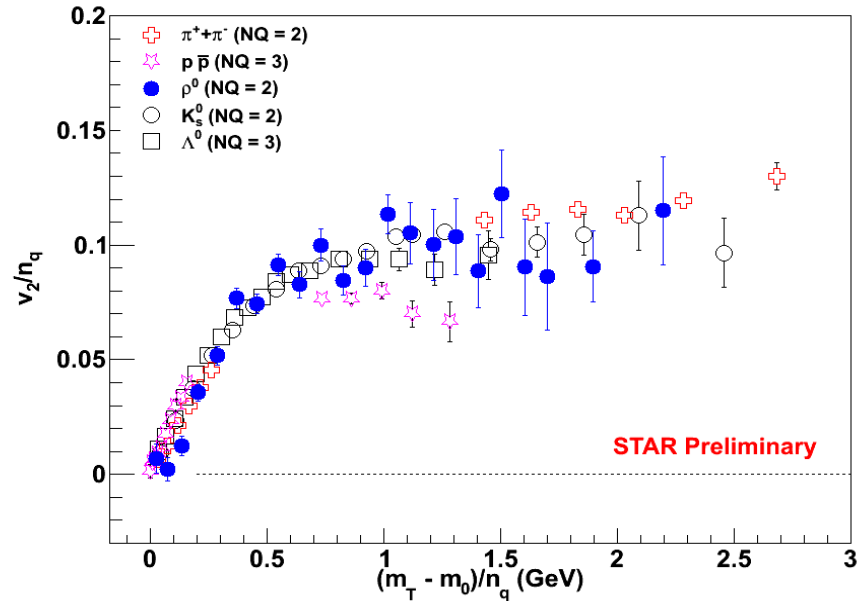
# Analysis: $v_2$ vs. Transverse Kinetic Energy ( $m_T - m_0$ )



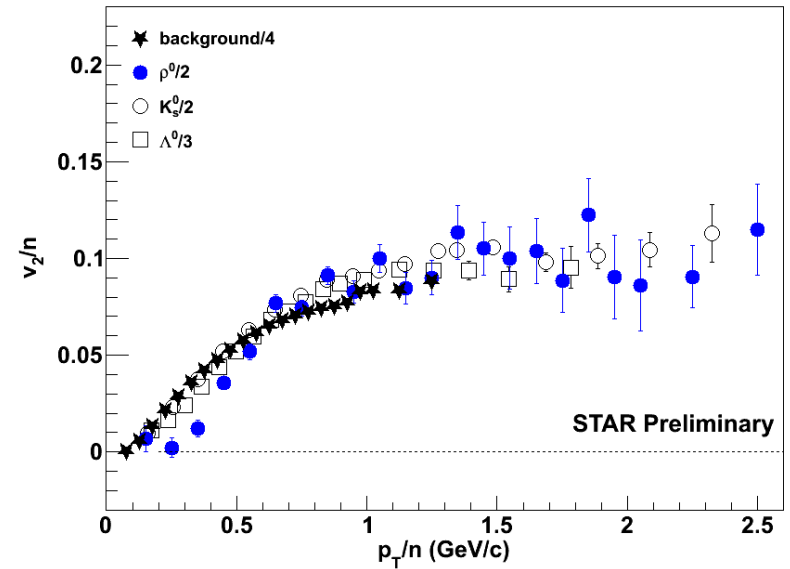
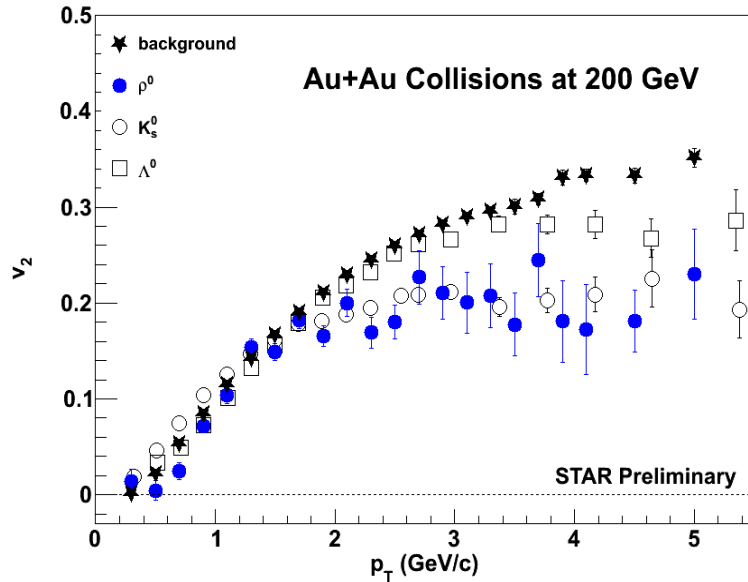
➤ At  $m_T - m_0 > 0.9 \text{ GeV}/c^2$   
 $v_2/n_q$  vs.  $(m_T - m_0)/n_q$   
 holds good for  $\rho^0$  with  $n_q = 2$ .

➤  $v_2$  of  $\rho^0$  below  $m_T - m_0 = 0.9 \text{ GeV}/c^2$   
 is deviating from the universal curve.

Systematic error is in study ...

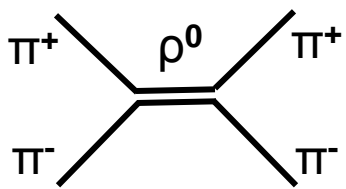


# Analysis: $v_2$ of the uncorrelated pion pairs



- ✓ It was observed that the real pair  $v_2$  (which is basically background dominated), follows the  $n=4$  scaling and which is expected.

# Phase Space

$$\text{Phase Space} = \frac{M}{\sqrt{M^2 + p_T^2}} e^{-\frac{\sqrt{M^2 + p_T^2}}{T}}$$


The Feynman diagram shows a central horizontal line representing a  $\rho^0$  resonance. From the left end of this line, two lines branch out downwards and outwards, labeled  $\pi^+$  and  $\pi^-$ . From the right end of the line, two lines branch out upwards and outwards, labeled  $\pi^+$  and  $\pi^-$ .

- $M$  = Invariant Mass;  $p_T$  = transverse momentum;  $T$  = Temperature
- Chemical and kinetic freeze-out  $\Rightarrow$  resonances formed until particles too far apart  $\Rightarrow$  resonances emitted  **$T = 120 \text{ MeV}$**

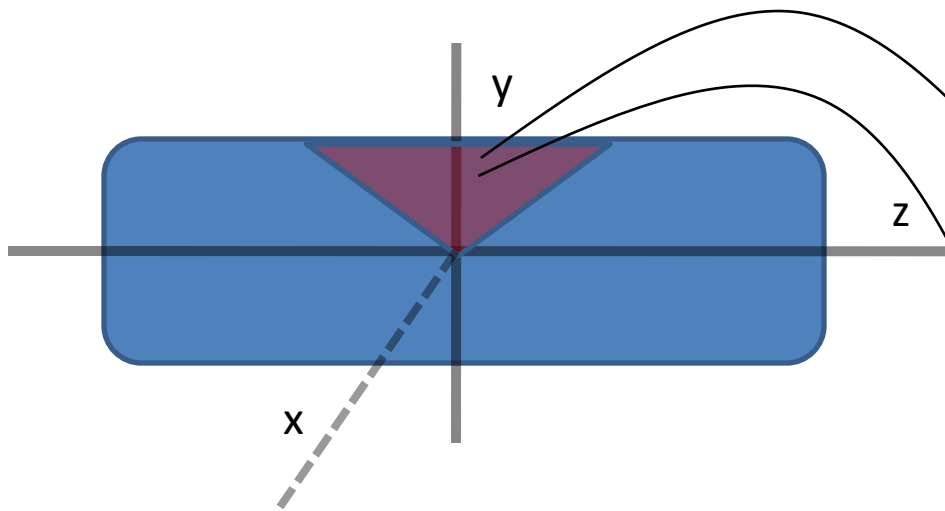
E.V. Shuryak and G.E. Brown, Nucl. Phys. A 717 (2003) 322

$$\text{BW}(M) = \frac{\Gamma(M)}{(M^2 - M_\rho^2)^2 + M_\rho^2 \Gamma(M)^2} \quad \Gamma(M) = \Gamma_\rho \left[ \frac{M^2 - 4m_\pi^2}{M_\rho^2 - 4m_\pi^2} \right]^{\frac{3}{2}} \frac{M_\rho}{M}$$

P. Braun-Munzinger *et al.*, CERES Int. Note, March 2000, unpublished; E.V. Shuryak and G.E. Brown, Nucl. Phys. A 717 (2003) 322; P.K. Kolb and M. Prakash, nucl-th/0301007; H.W. Barz *et al.*, Phys. Lett. B 265, 219 (1991); R. Rapp, hep-ph/0305011.

# Methods of Approach for $\rho^0 v_2$ measurement

- Reaction plane is estimated taking all primary tracks with  $|\eta| < 1.0$ , same particles are used for  $v_2$  calculation



**With autocorrelation**

$$\Psi_{rp} = \frac{1}{2} \tan^{-1} \left( \frac{\sum_i \omega_i \sin \phi_i}{\sum_i \omega_i \cos \phi_i} \right)$$

$$v_2 = \left\langle \cos \left( \phi_i - \Psi_{rp} \right) \right\rangle$$

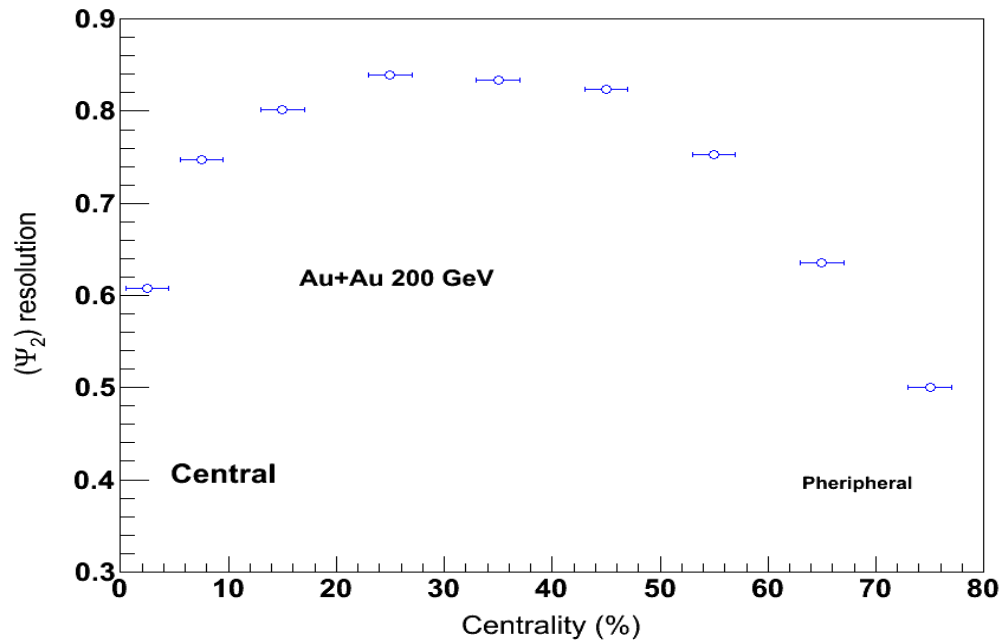
- Reaction plane is recalculated removing the tracks those are used as pion tracks in calculating the  $\rho^0 v_2$ .

**Remove autocorrelation**

$$\Psi_{rp} = \frac{1}{2} \tan^{-1} \left( \frac{\sum_i \omega_i \sin \phi_i - \omega_{\pi^+} \sin(2\phi_{\pi^+}) - \omega_{\pi^-} \sin(2\phi_{\pi^-})}{\sum_i \omega_i \cos \phi_i - \omega_{\pi^+} \cos(2\phi_{\pi^+}) - \omega_{\pi^-} \cos(2\phi_{\pi^-})} \right)$$

# Reaction plane resolution determination

- Due to finite number of particles detected there is a limited resolution in the event plane angle.



A. M. Poskanzer and S. A. Voloshin 1998