# Azimuthal Anistropy Results from STAR


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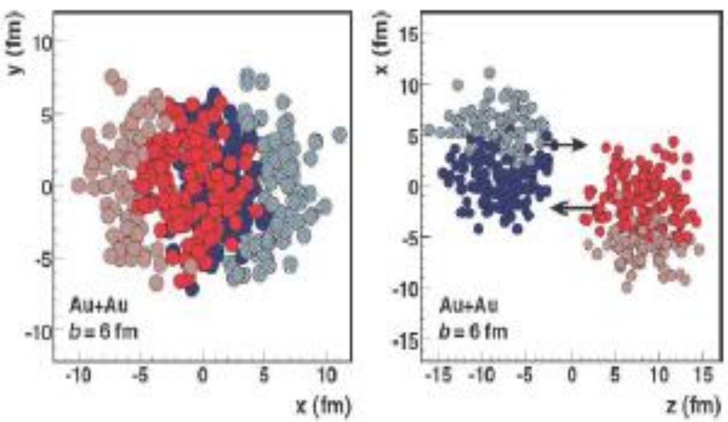
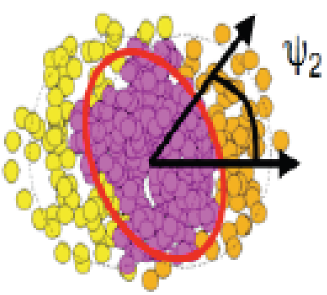
# Azimuthal anisotropy basics

$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right)$$

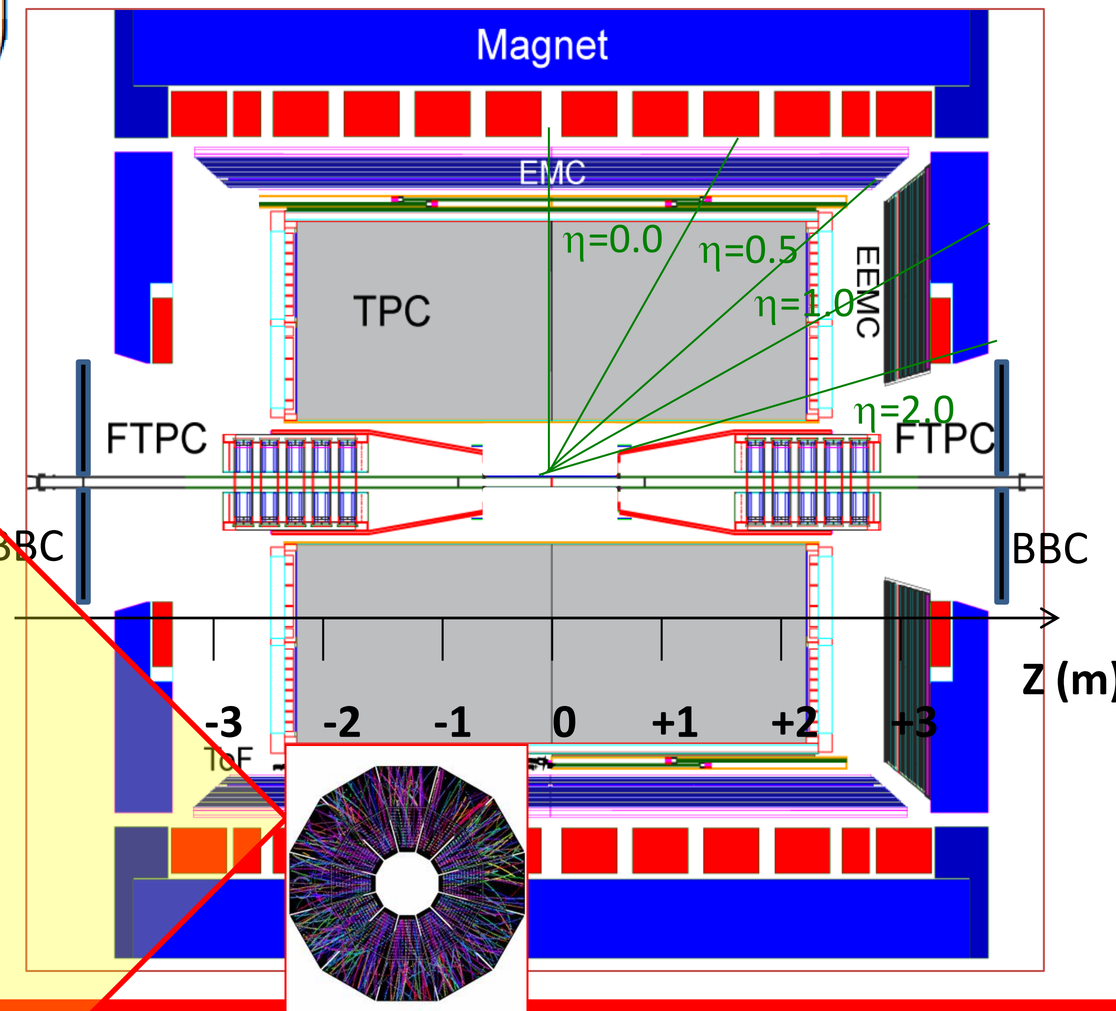
$$v_{\mathrm{n}} = \left\langle \cos n\left(\varphi - \psi_n\right)\right\rangle, \quad n = 1,2,3..,$$



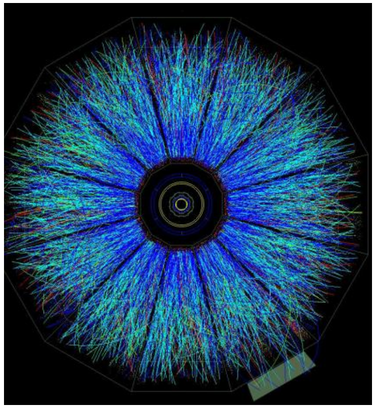




Hydrodynamic Pressure maps the initial coordinate space anisotropy onto a momentum space anisotropy measured by the experiments

Schematic of the STAR Detector

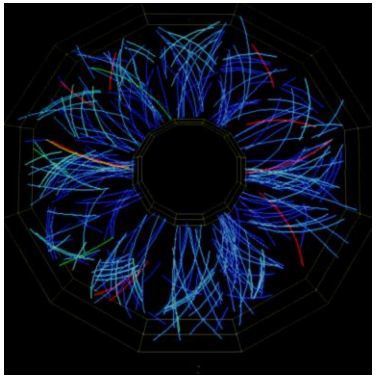


# What is new this year?



## 200 GeV Au+Au

- Flow versus non-flow — Yi Li (W 9:30)
- Precision measurements of $v_2$ — H. Masui (Poster #145)
- $v_2$ results for multi-strange hadrons — M. Nasim (W 10:10)
- Flow harmonics ($v_1$-$v_5$) — Y. Pandit (T 2:55)
- $v_2$ for jets — A. Ohlson (W 11:40)

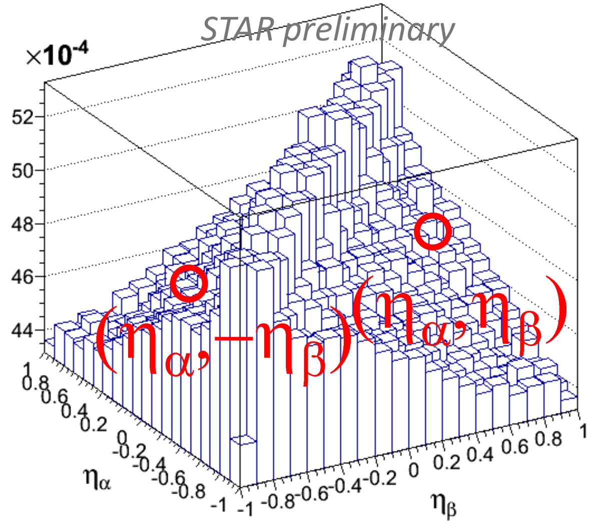


## Beam Energy Scan

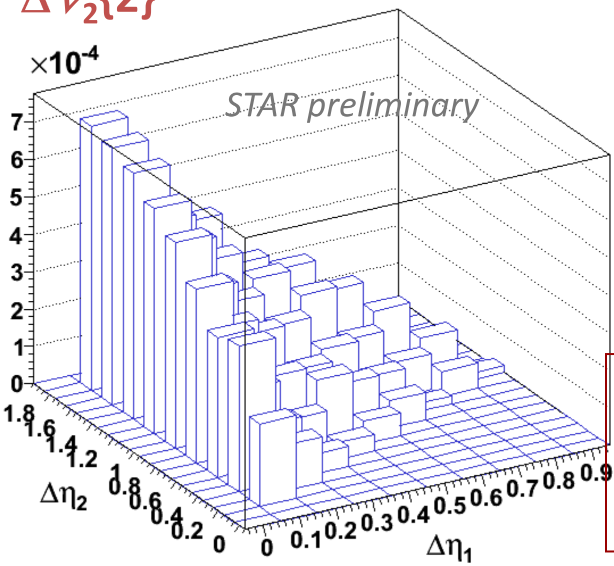
- Directed flow — Y. Pandit (T 2:55)
- Hadron elliptic flow — S. Shi (F 3:20)
- Identified particle elliptic flow — A. Schmah (Poster #141)
- Azimuthally sensitive HBT — N. Shah (T 2:35)

# ‘Flow’ and non-flow in $\sqrt{s_{NN}}$ = 200 GeV Au+Au

$\mathcal{V}_2\{2\}$



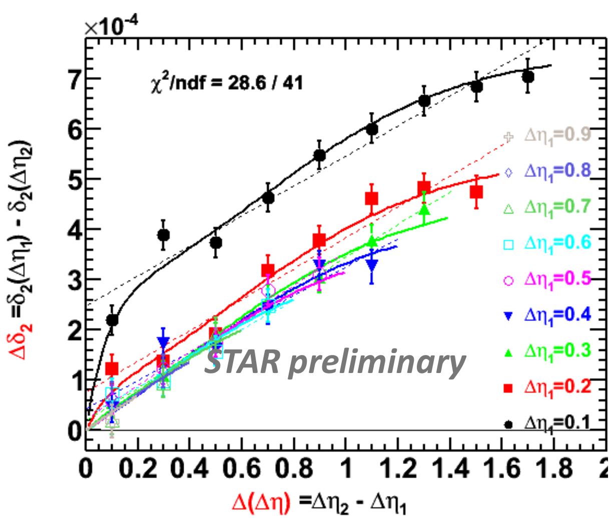

$\Delta\mathcal{V}_2\{2\}$

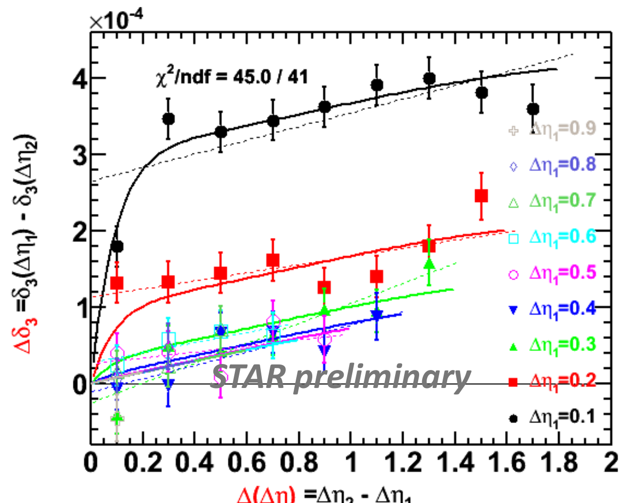



$$\mathcal{V}\{\eta_\alpha,\eta_\beta\} = v(\eta_\alpha)v(\eta_\beta) + \sigma(\eta_\alpha)\sigma(\eta_\beta) + \sigma'(\Delta\eta) + \delta(\Delta\eta)$$

‘flow’ — flow fluct. — Δη-dep fluct. — Δη-dep nonflow

- $\delta(\Delta\eta_2)-\delta(\Delta\eta_1)$ linear in $\Delta\eta_2-\Delta\eta_1$ at a given $\Delta\eta_1$ with similar slopes
- Intercept changes with $\Delta\eta_1$ exponentially



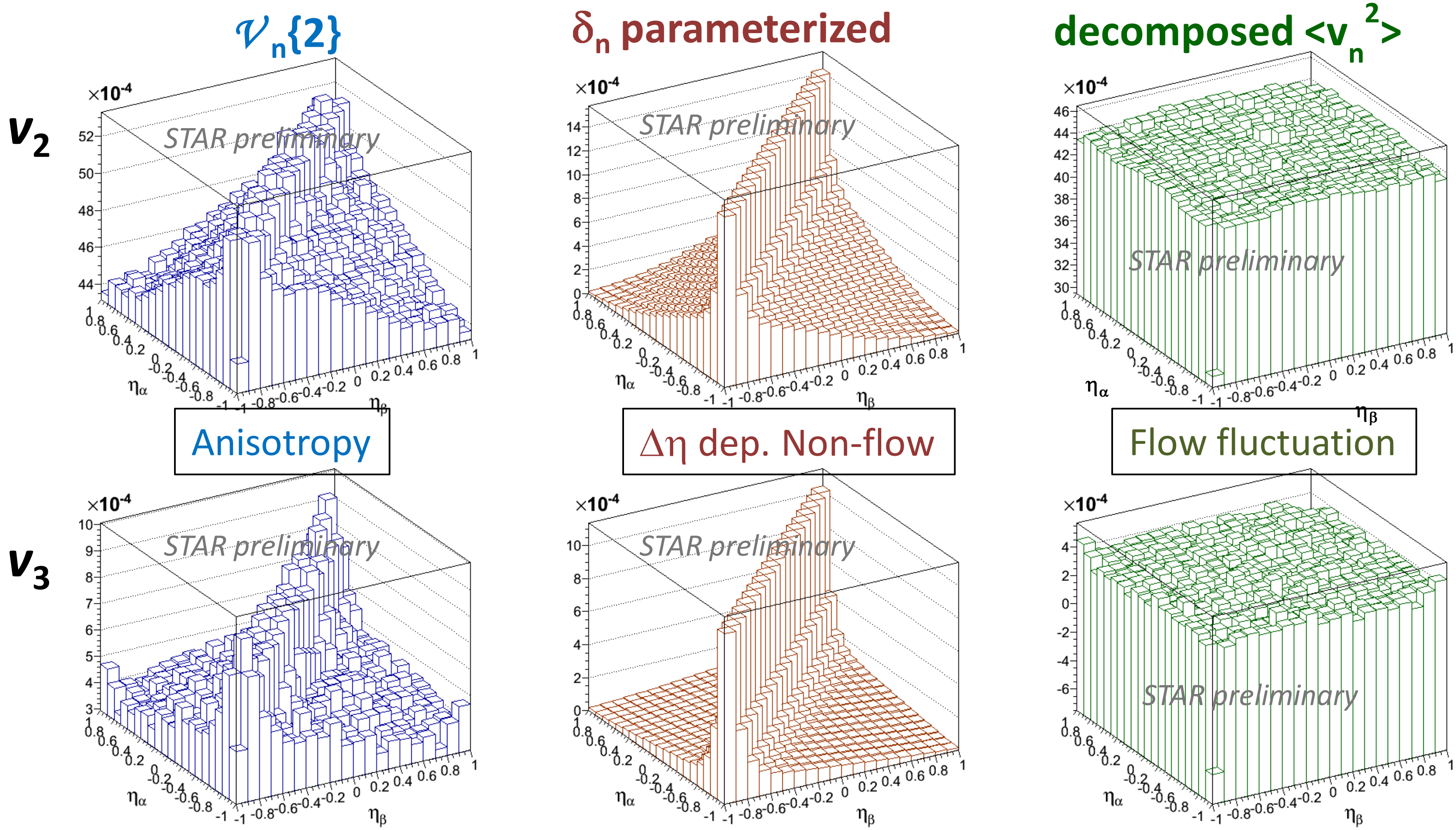

statistics error only

$$\Delta\delta(\Delta\eta_1,\Delta\eta_2) = a(e^{-\Delta\eta_1/b} - e^{-\Delta\eta_2/b}) + A(e^{-\Delta\eta_1^2/2\sigma^2} - e^{-\Delta\eta_2^2/2\sigma^2})$$

$$\delta(\Delta\eta) = ae^{-\Delta\eta/b} + Ae^{-\Delta\eta^2/2\sigma^2}$$

**AuAu@200GeV 20-30%**

# ‘Flow’ $v_n\{2\}$, non-flow $\delta_n$, and flow fluctuations $\langle v_n^2 \rangle$




AuAu@200GeV 20-30%

- This technique allows us to estimate the magnitude of the non-flow and the flow fluctuations
- The decomposed 'flow' appears to be independent of $\eta$ .

Yi Li (W 9:30)

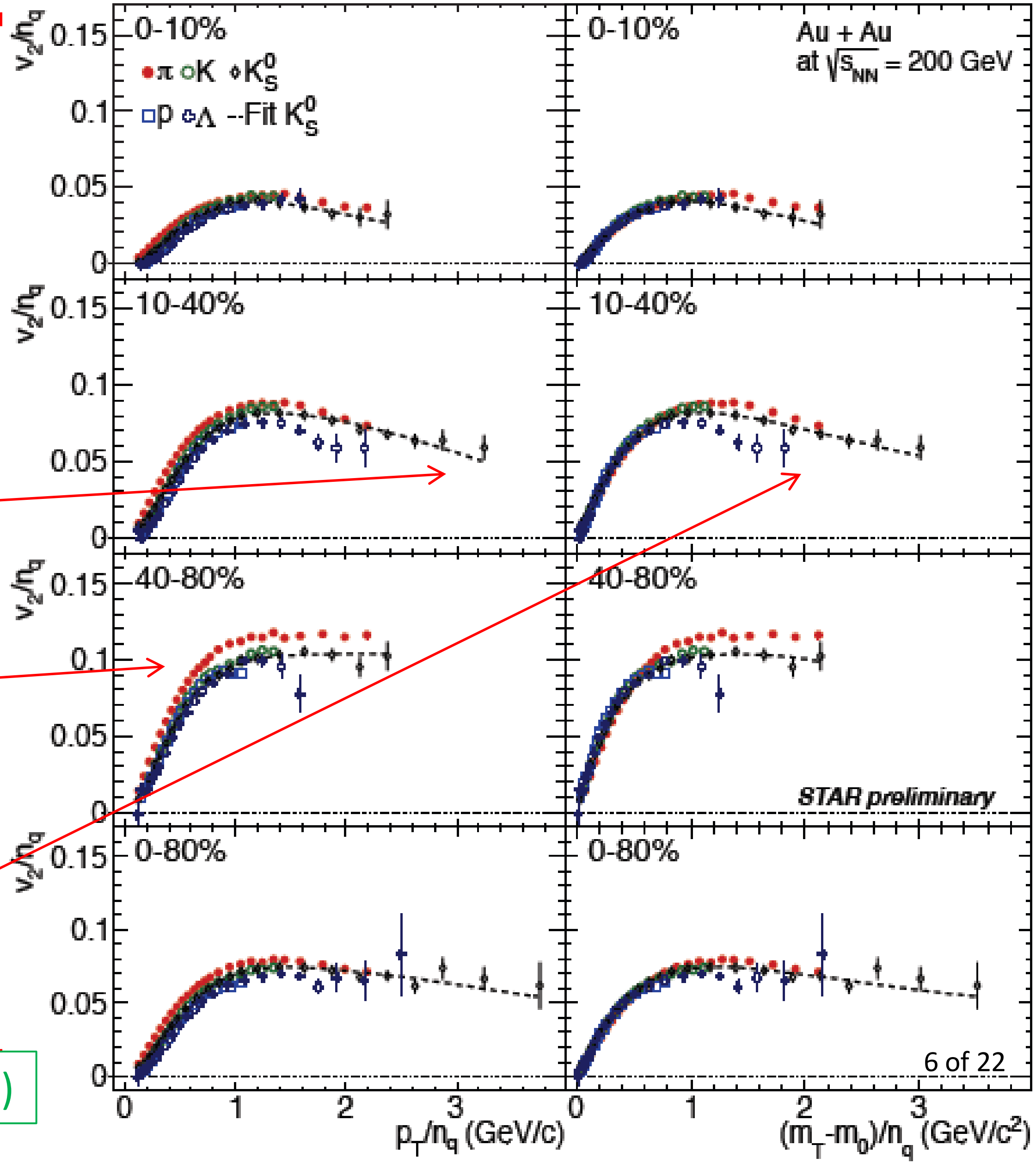
# Precision measurements in $\sqrt{s_{NN}}$ = 200 GeV Au+Au

The high statistics dataset available at full energy allows for precision tests of the scaling by the number of constituent quarks (NCQ), which has been interpreted as a signature of partonic collectivity.

We can measure $v_2$ of identified particles up to $p_T$ =8 GeV/c.

There is mass ordering for all centralities below $p_T$=2 GeV/c.

At high $p_t$, there is a hint of a breakdown of the scaling for $(m_T\text{-}m_0)n_q$>1 GeV/$c^2$ for 10-40% centrality.




H. Masui (Poster)

# Precision measurements in $\sqrt{s_{NN}}$ = 200 GeV Au+Au

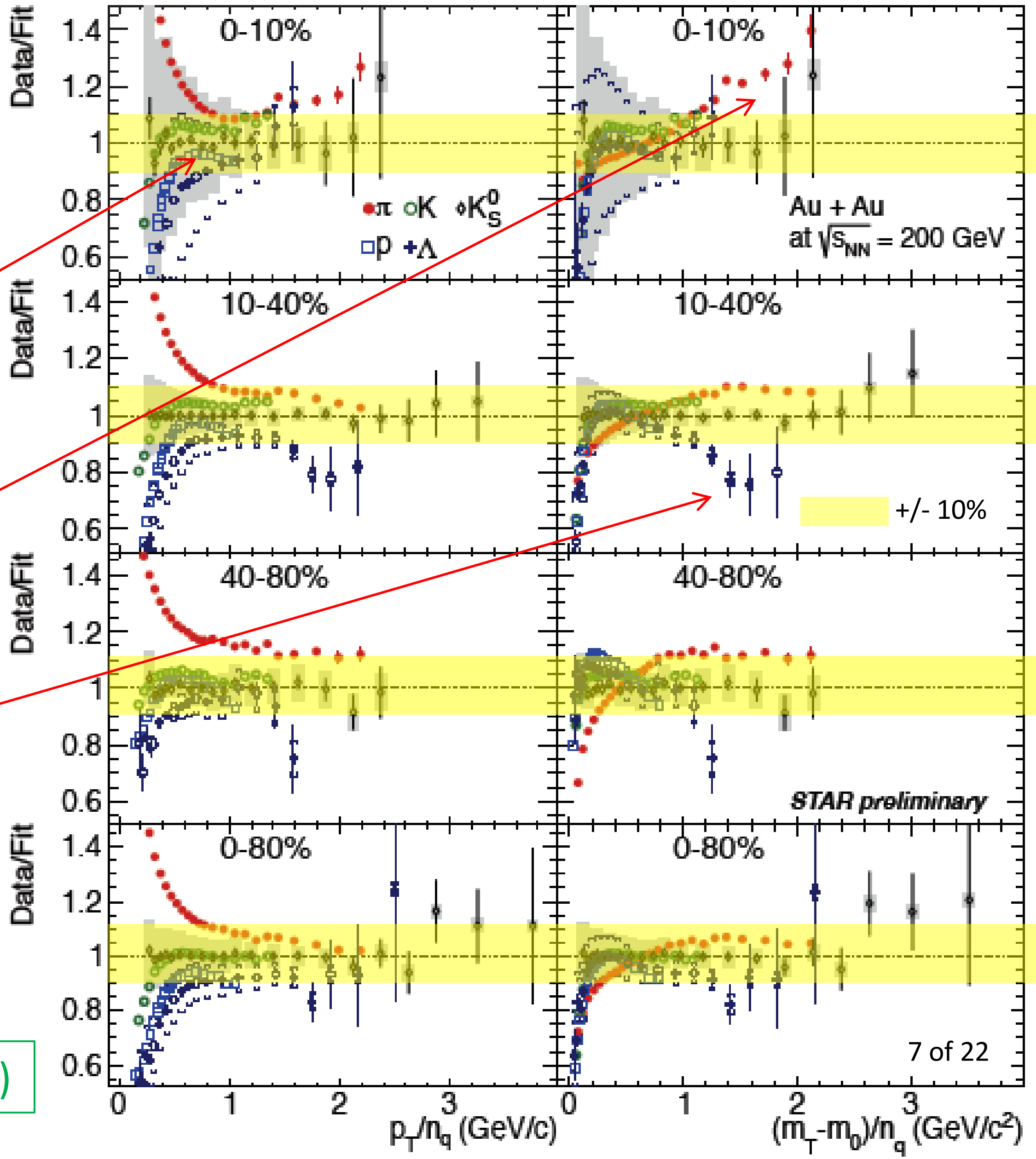
The scaling breakdown can be explored further by taking ratios to a fit to the $K_S^0$

NCQ mostly holds among the measured hadrons to within 10% for $p_T/n_q$> 1 GeV/c.

At high $p_T$, $\pi$>$K^0_s$ → Is this non-flow effect due to jets?

There are 20-30% deviations between the results for $\pi$ and $\Lambda$ in the 10-40% centrality bin.

**There would be a change in the scaling behavior at high $p_t$ where jet processes dominate.**



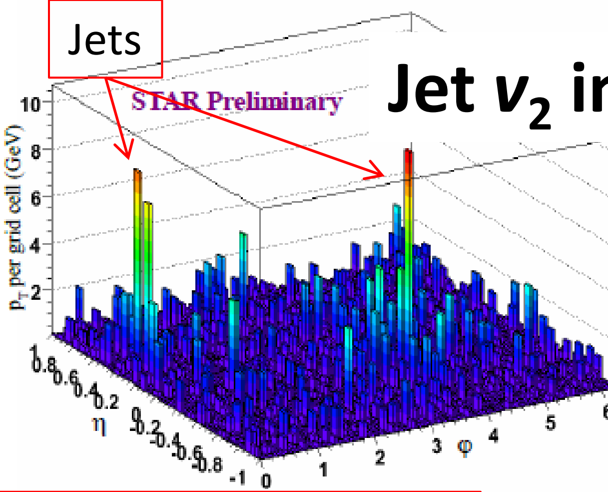



Daniel Cebra
8/13/2012

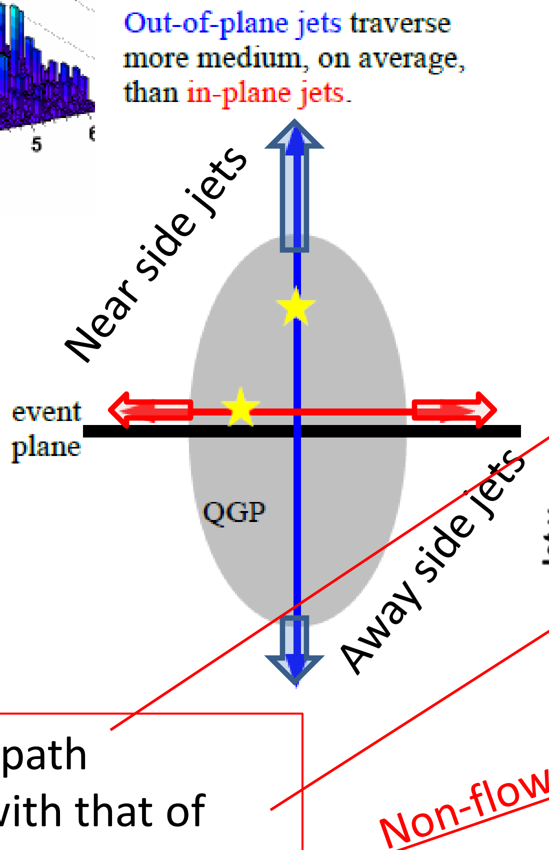
H. Masui (Poster #145)

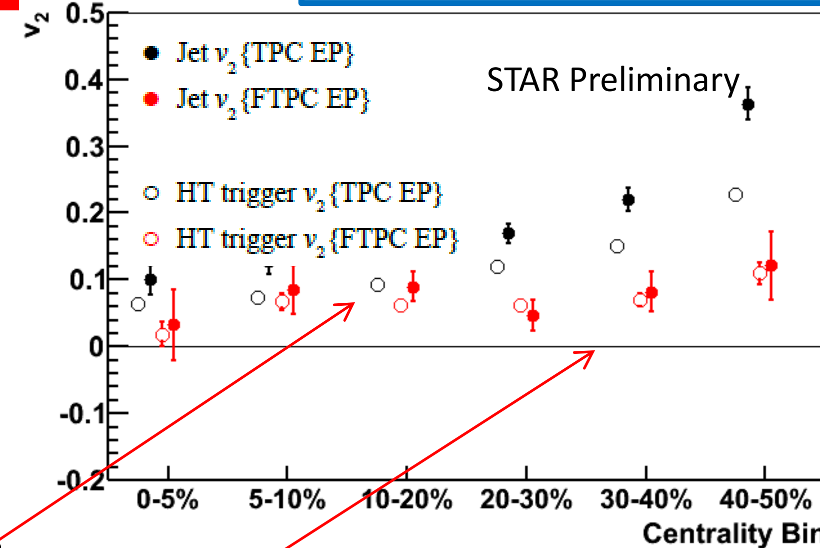
# Jet $v_2$ in $\sqrt{s_{NN}}$ =200 GeV Au+Au

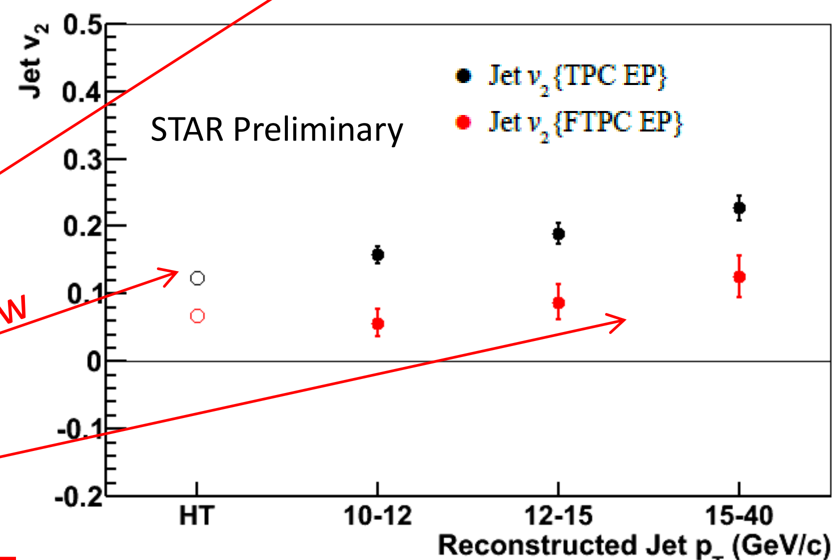
**Jet definition (anti-$k_T$):**
Trigger $E_t$ > 5.5 GeV
Constituent $p_t^{cut}$ >2 GeV/c




**Why measure jet $v_2$?**
- Provides information about the path length dependent energy loss
- Necessary for subtraction of backgrounds in jet-hadron correlations



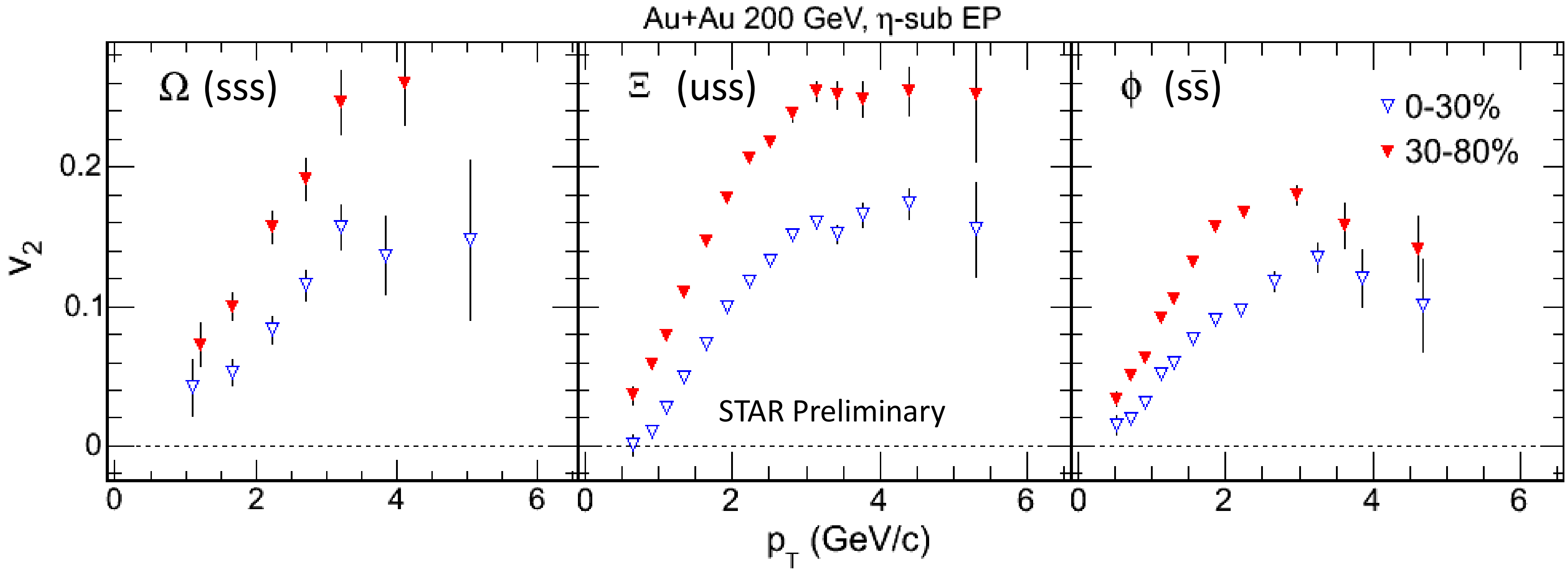




- non-zero jet $v_2$ → $E_{loss}$ on path
- jet $v_2${FTPC} is consistent with that of trigger hadrons
- Midrapidity measures of the event plane are biased by the presence of a jet
- Jet $v_2$ increases with $p_T$

A. Ohlson (W 11:40)

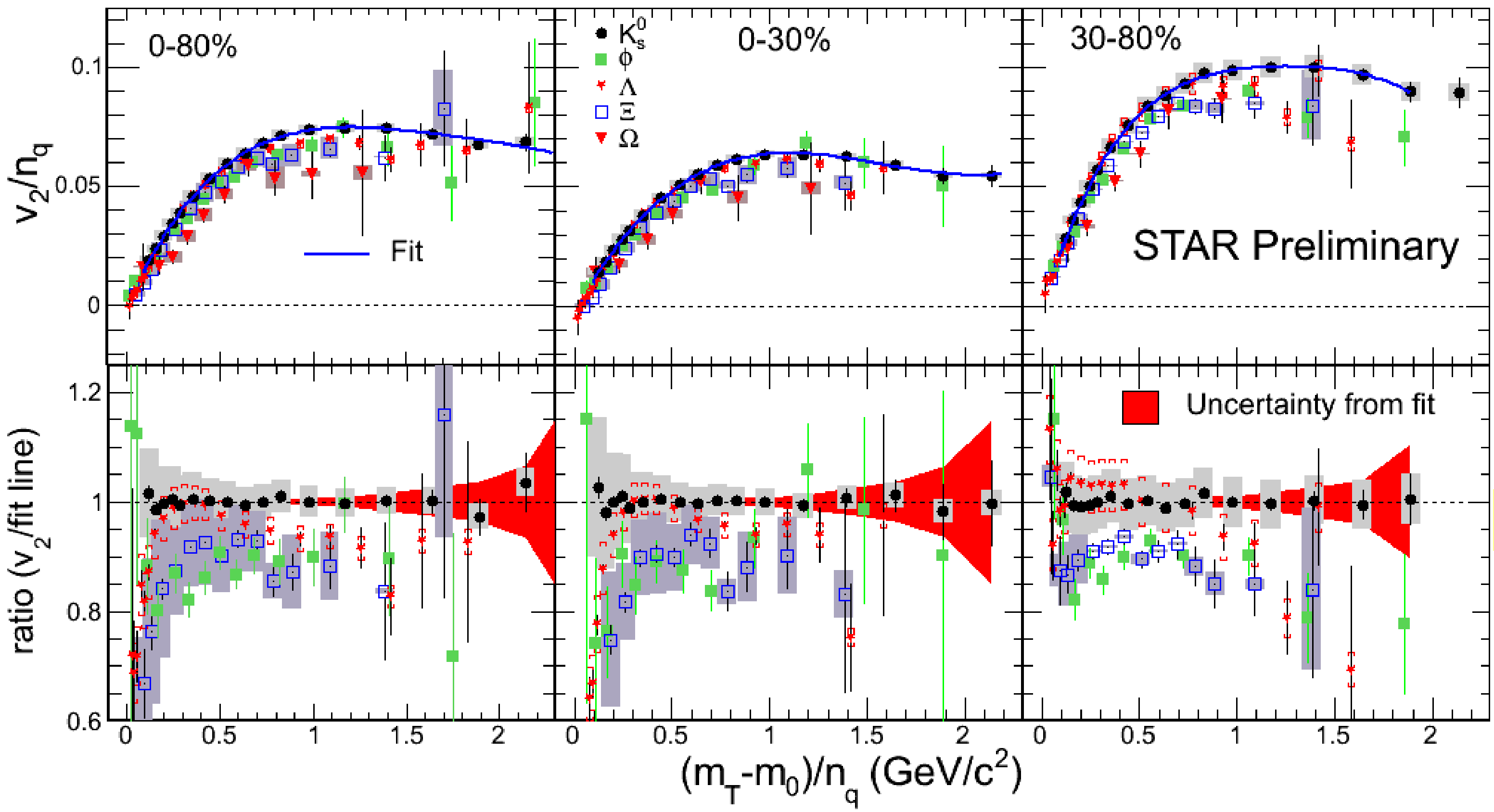
# Elliptic flow of Ω, Ξ, and ϕ in $\sqrt{s_{NN}}$ = 200 GeV Au+Au




- Multi-strange hadrons are more sensitive to the partonic stage
- Do hadrons with multiple strange quarks flow similarly to those made of more common quarks?
- Qualitatively, the behavior is similar. However we now add details about the centrality dependence.

M. Nasim (W 10:10)

# Elliptic flow of Ω, Ξ, and ϕ in $\sqrt{s_{NN}}$ = 200 GeV Au+Au



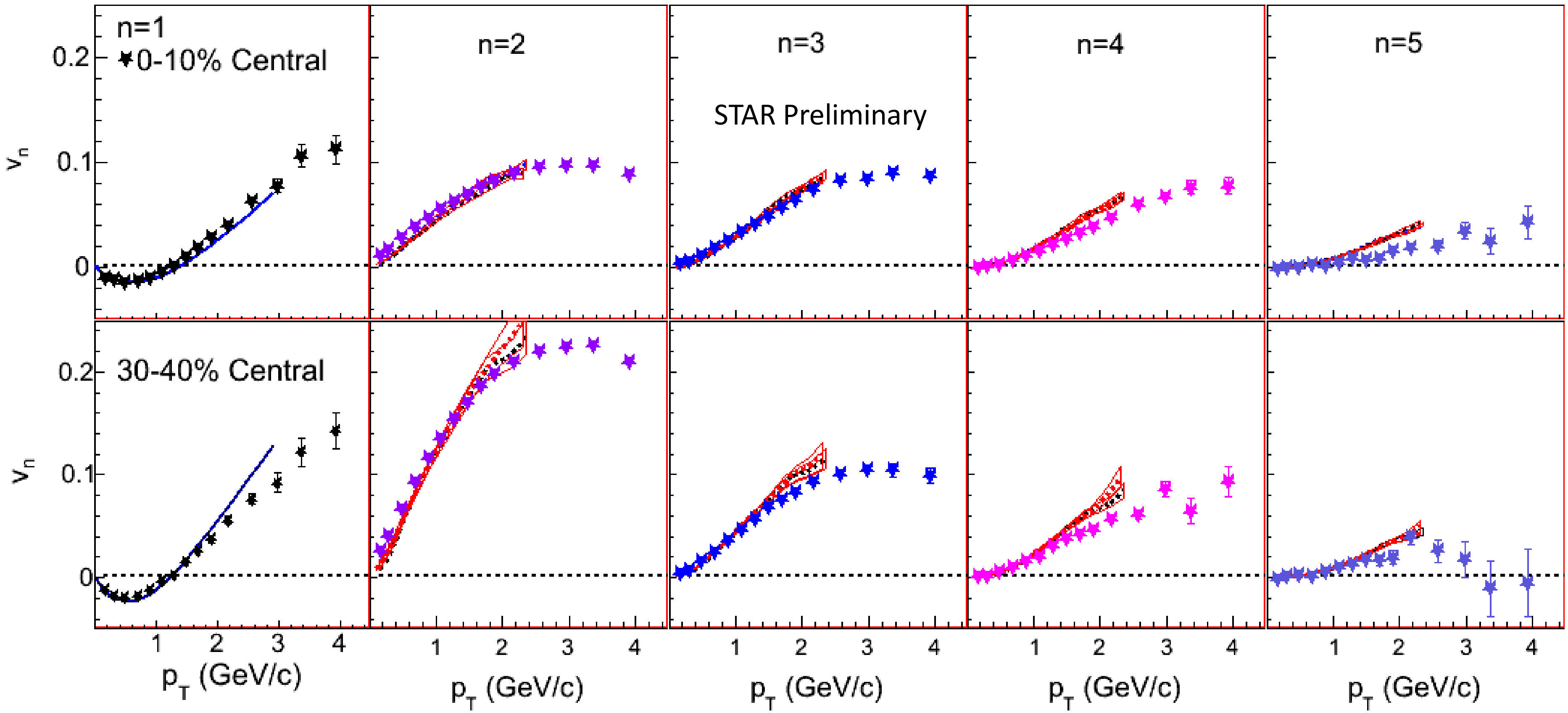

**With scaling and with a ratio of the fit to the $K^0_S$, it is evident that:**

- Deviation of phi $v_2$ for $(m_T-m_0)/n_q$ > 0.6 GeV/$c^2$ is larger for 30-80% than for 0-30%
- Strangeness counts → $v_2(\Xi)<v_2(\Lambda)$, $v_2(\phi)<v_2(K^0_S)$ at 30-80% centrality for $m_T-m_0$>1 GeV/$c^2$

M. Nasim (W 10:10)

# Flow Harmonics in $\sqrt{s_{NN}}$ = 200 GeV Au+Au

Models by Reinskya et al. PRL 108, 252302 (2012) and Gardim et al. arXiv: 1293.2882




- Flow Harmonics couple initial spatial fluctuations to the final momentum distribution and are therefore sensitive to the initial conditions.
- Harmonics are also able to tells us about the viscosity of the medium
- The models do a good job describing the general features of the data.

Y. Pandit (T 2:55)

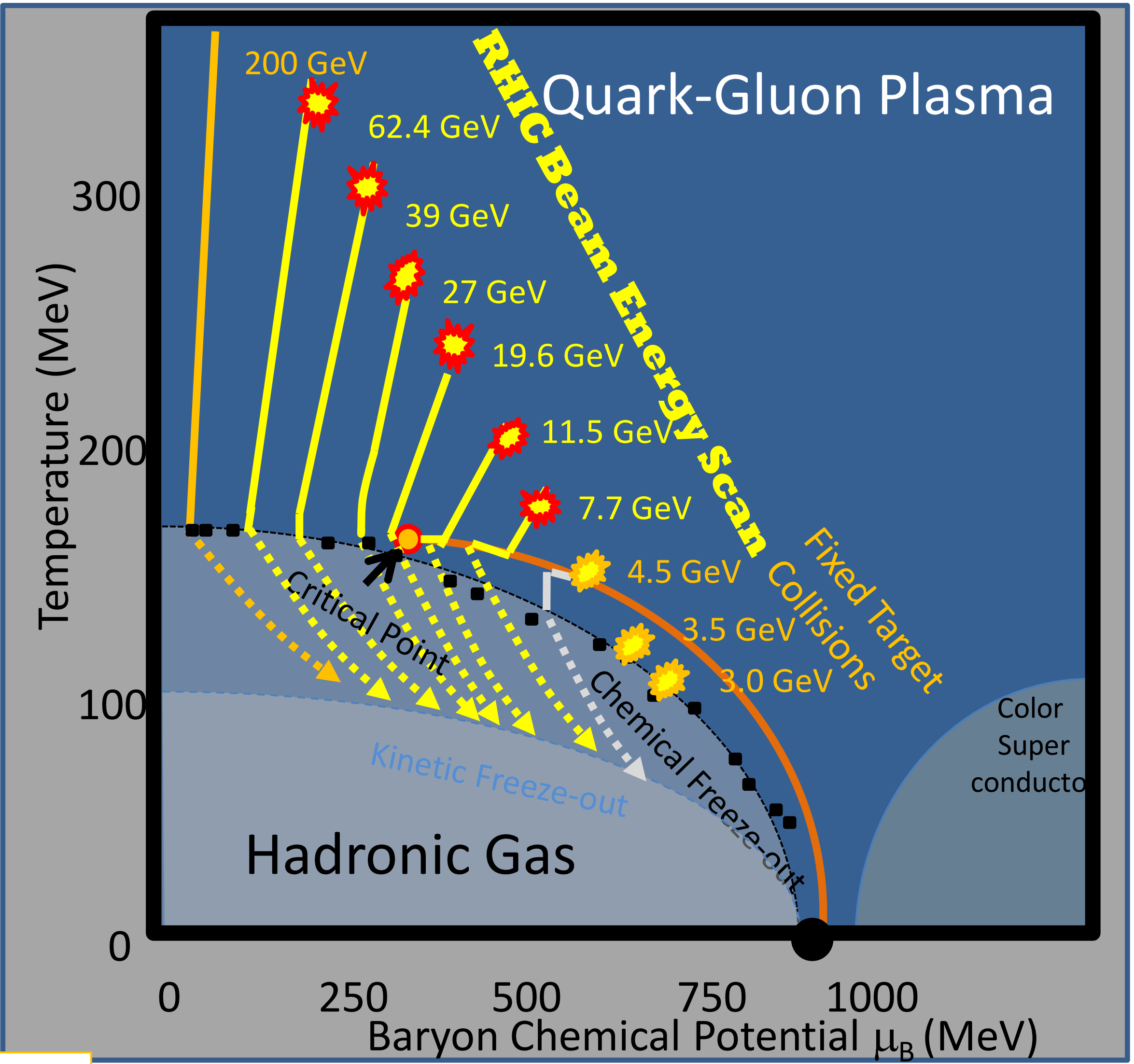
# Beam energy scan

**Goals of the Scan:**

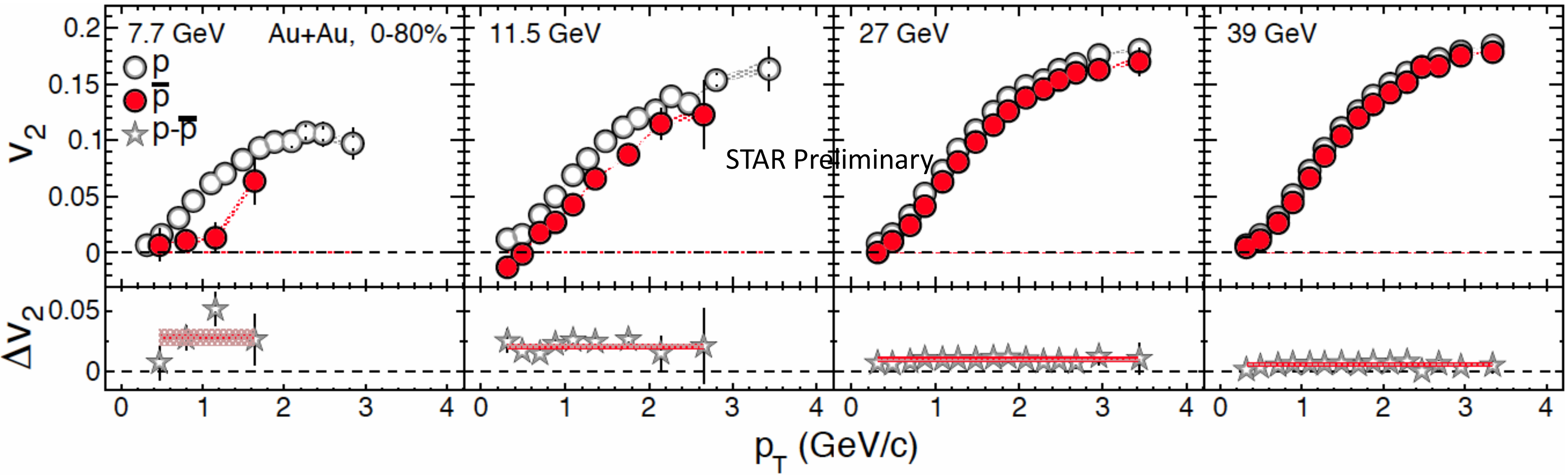
1) Disappearance of QGP signatures
2) Critical point Search
3) Evidence of a first order phase transition

| **Beam Energy Scan** | |
|---|---|
| **Phase-I:** | **Phase-II:** |
| 62.4 | 19.6 |
| 39 | 15 |
| 27 | 11.5 |
| 19.6 | 7.7 |
| 11.5 | 5.0 |
| 7.7 | 4.5 – 2.5 |

Fixed-target



# Proton and anti-proton elliptic flow; Energy Scan




- We observe a difference in $v_2$ between protons and anti-protons
- This difference is largest at the lowest energies
- We define $\Delta v_2$ as the $v_2$ of the proton minus that of the anti-proton
- $\Delta v_2$ is constant in the measured $p_T$ range and decreasing with increasing energy

S. Shi (F 3:20)

A. Schmah (Poster #141)

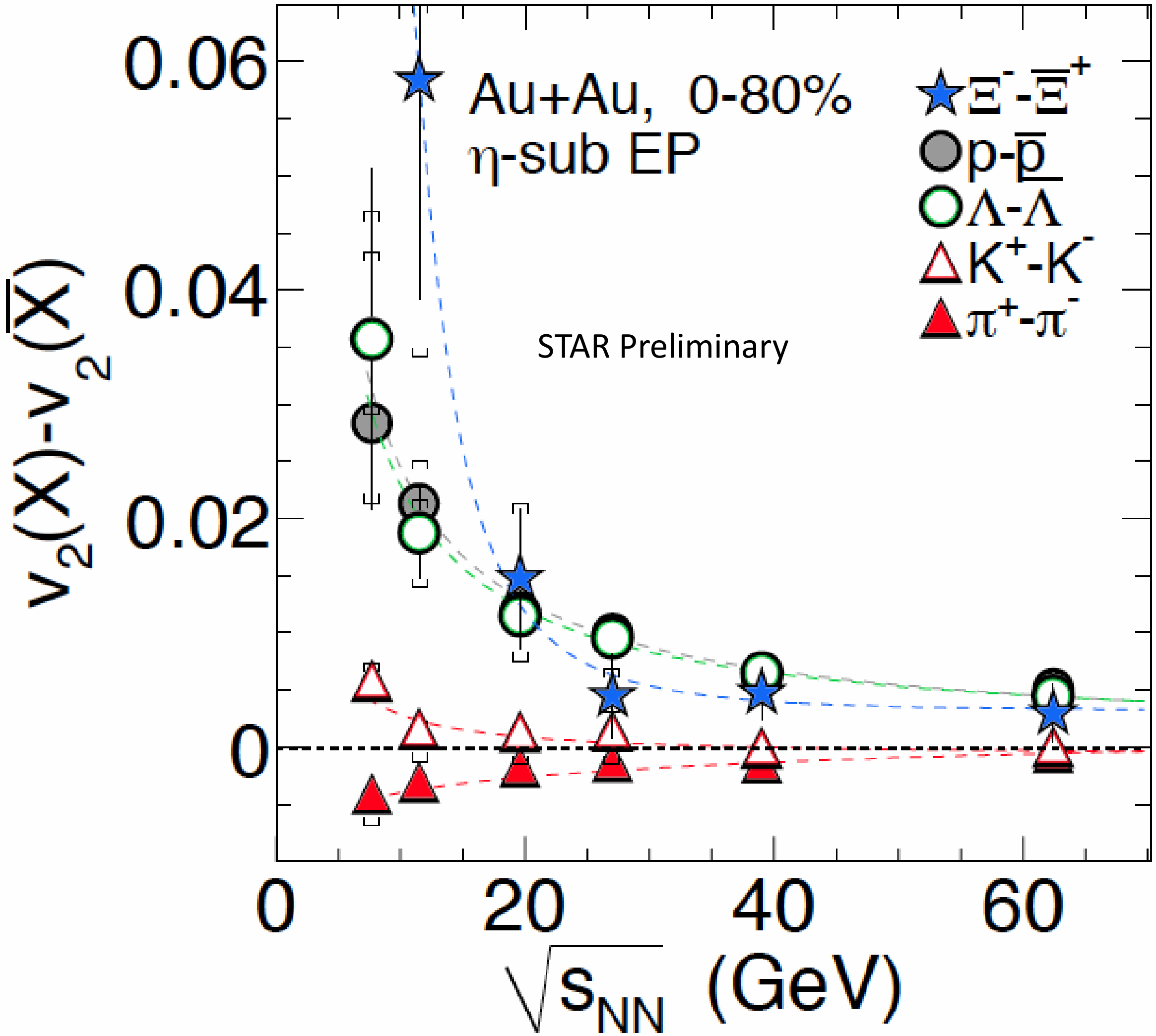
# Particle-anti-particle elliptic flow; Energy Scan

- There is a remarkable difference between particles and their anti-particles, especially for the lowest energies in the range.

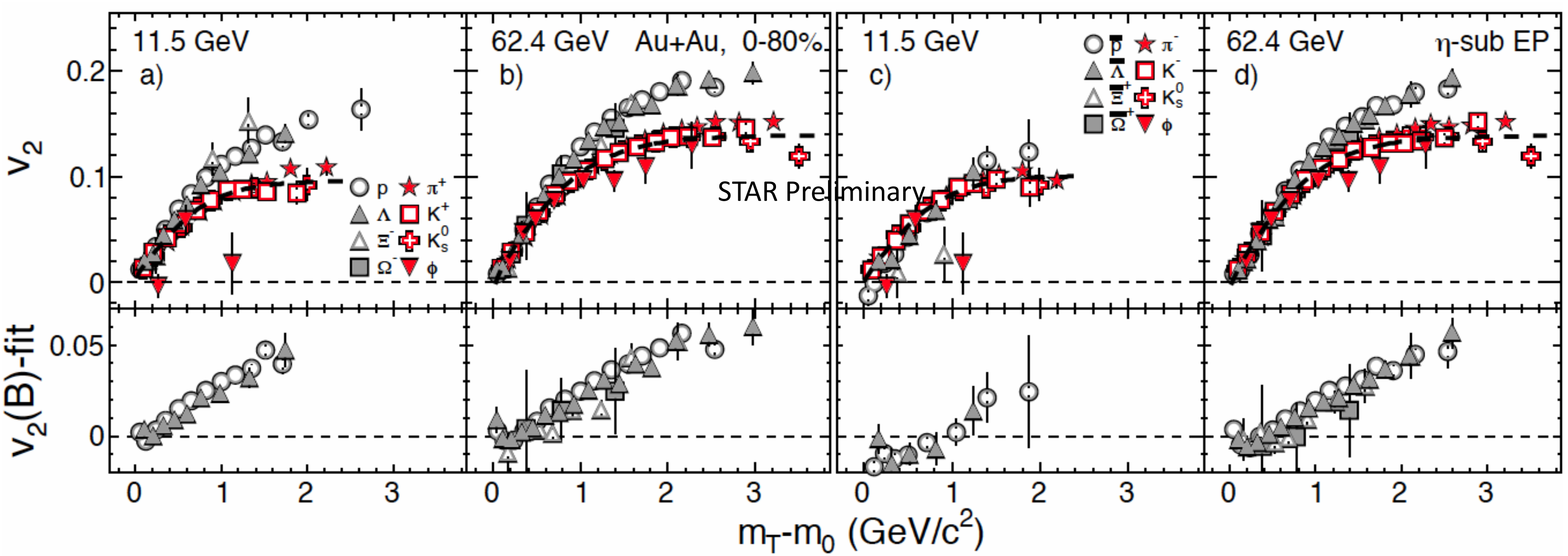
- Difference between particles and their anti-particle decreases with increasing beam energy

**Possible explanation**

- **Baryon transport to mid-rapidity** [J. Dunlop et al., PRC 84, 044914 (2011)]
- **Hadronic potential** [J. Xu et al., PRC 85, 041901 (2012)]



# Scaling of elliptic flow; Energy dependence




- **Baryon - meson $v_2$ splitting is observed for energies larger than 11.5 GeV**

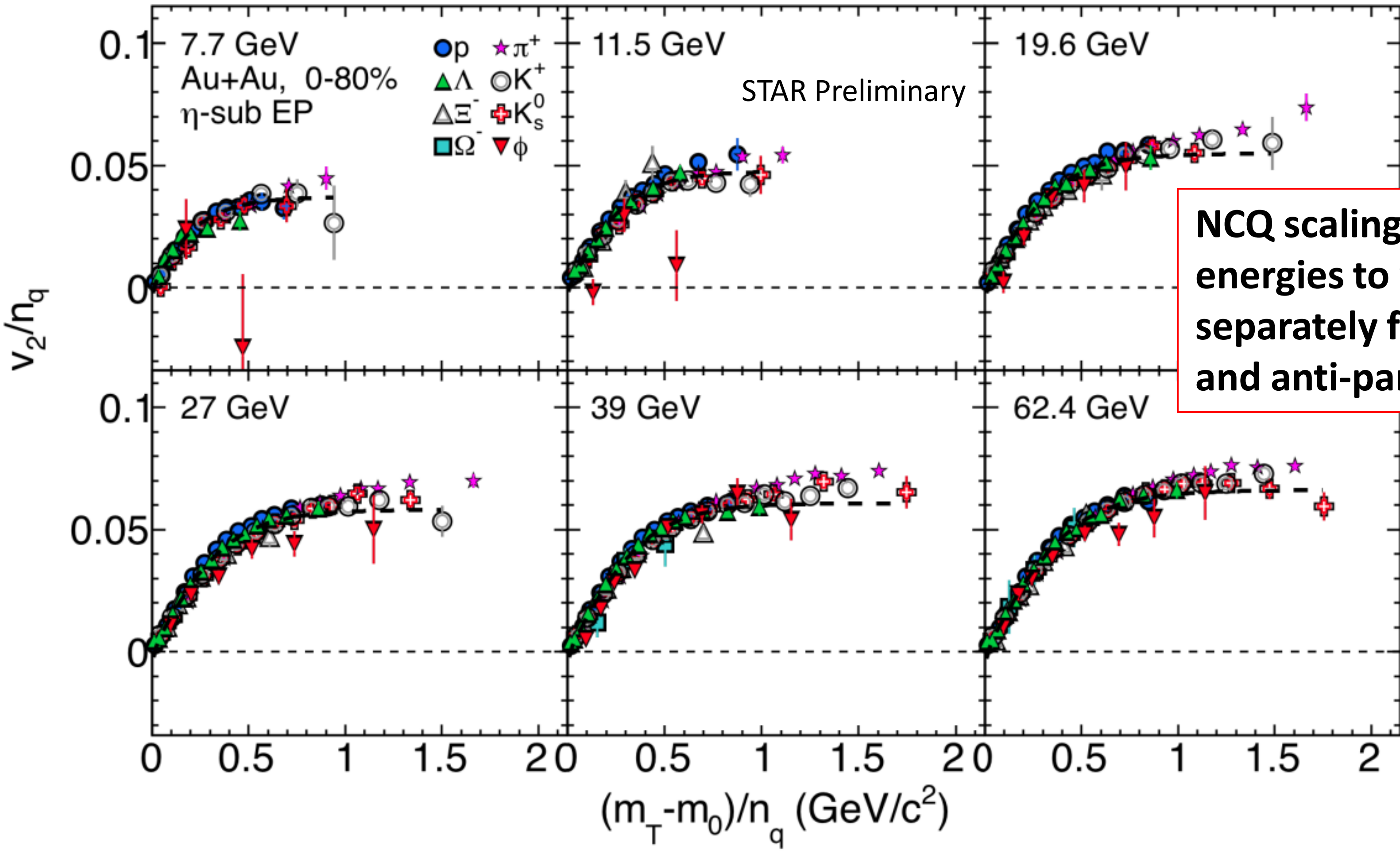
- **Splitting for anti-particles is gone at 11.5 GeV, for particles the splitting is still evident at 11.5 GeV, however it is small at 7.7 GeV**

S. Shi (F 3:20)

A. Schmah (Poster #141)

# NCQ scaling of elliptic flow; Energy dependence

**Particles**



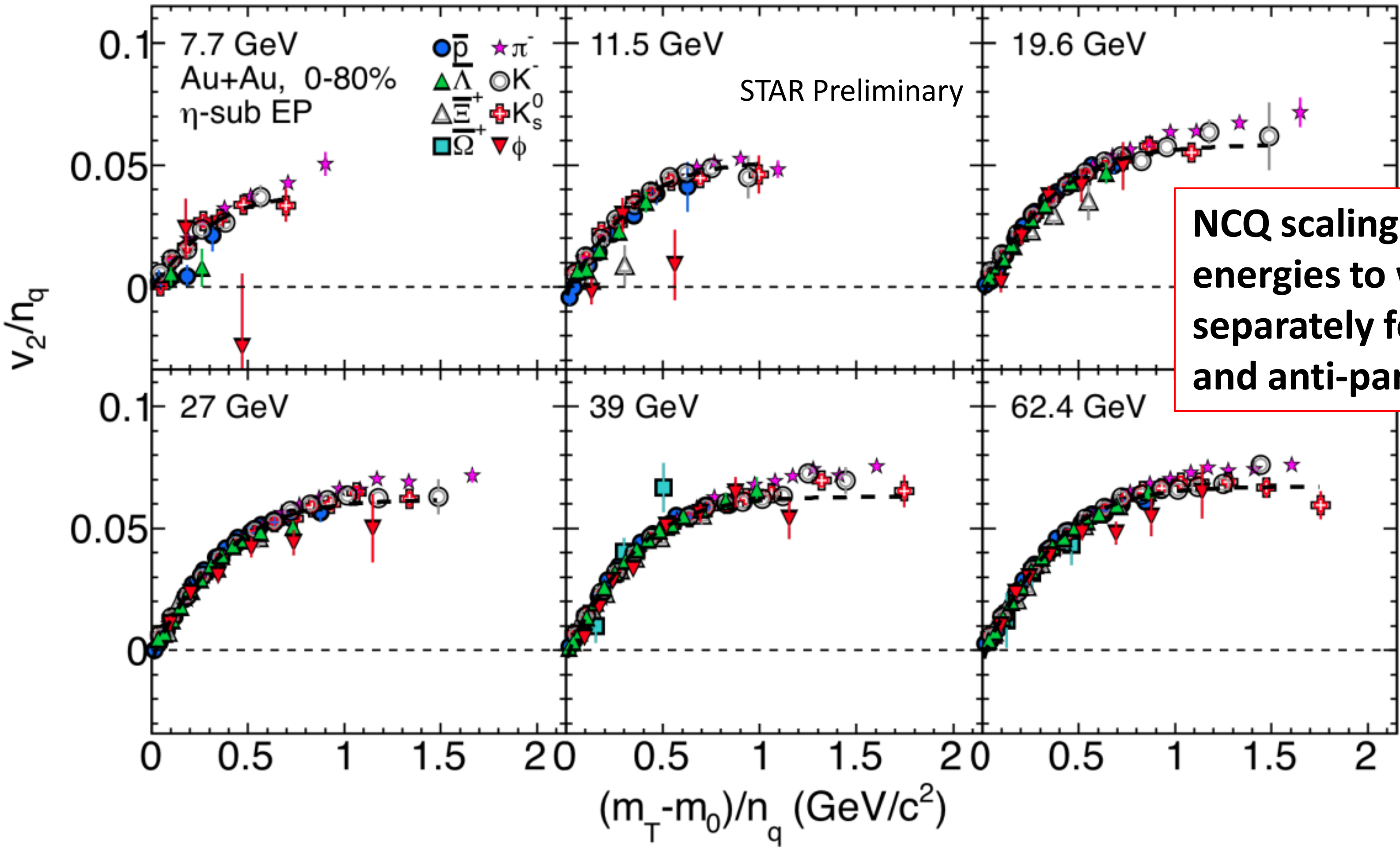

**NCQ scaling holds at all energies to within ±10% separately for particles and anti-particles**

S. Shi (F 3:20)

A. Schmah (Poster #141)

# NCQ scaling of elliptic flow; Energy dependence

**Anti-Particles**

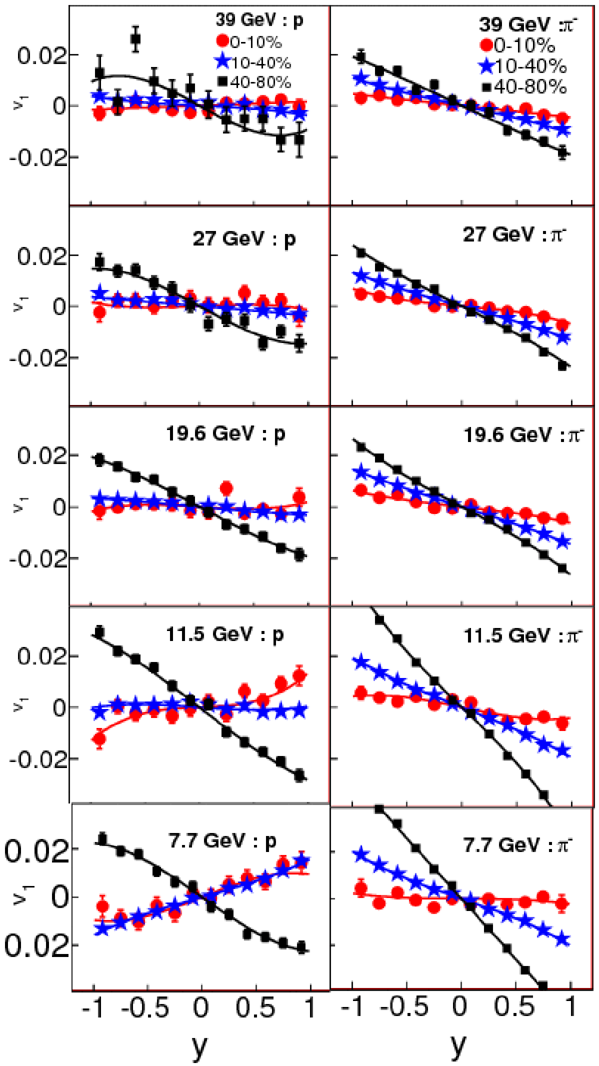


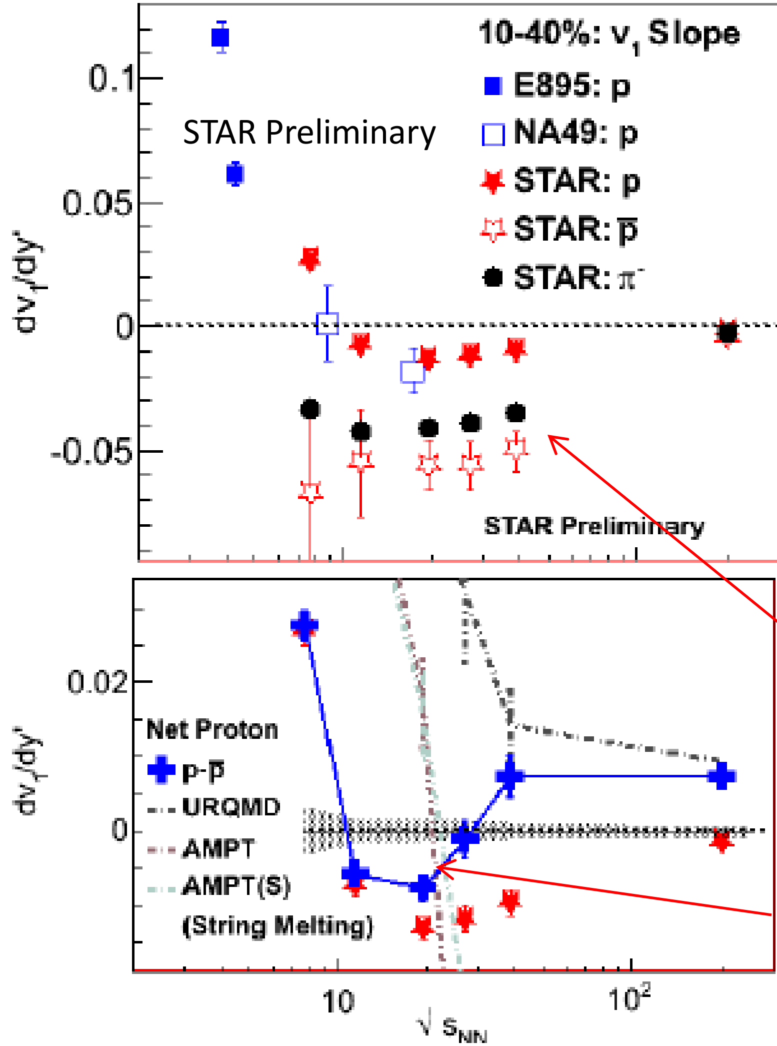

**NCQ scaling holds at all energies to within ±10% separately for particles and anti-particles**

S. Shi (F 3:20)

A. Schmah (Poster #141)

# Directed flow in $\sqrt{s_{NN}}$ = 7.7 to 39 GeV Au+Au

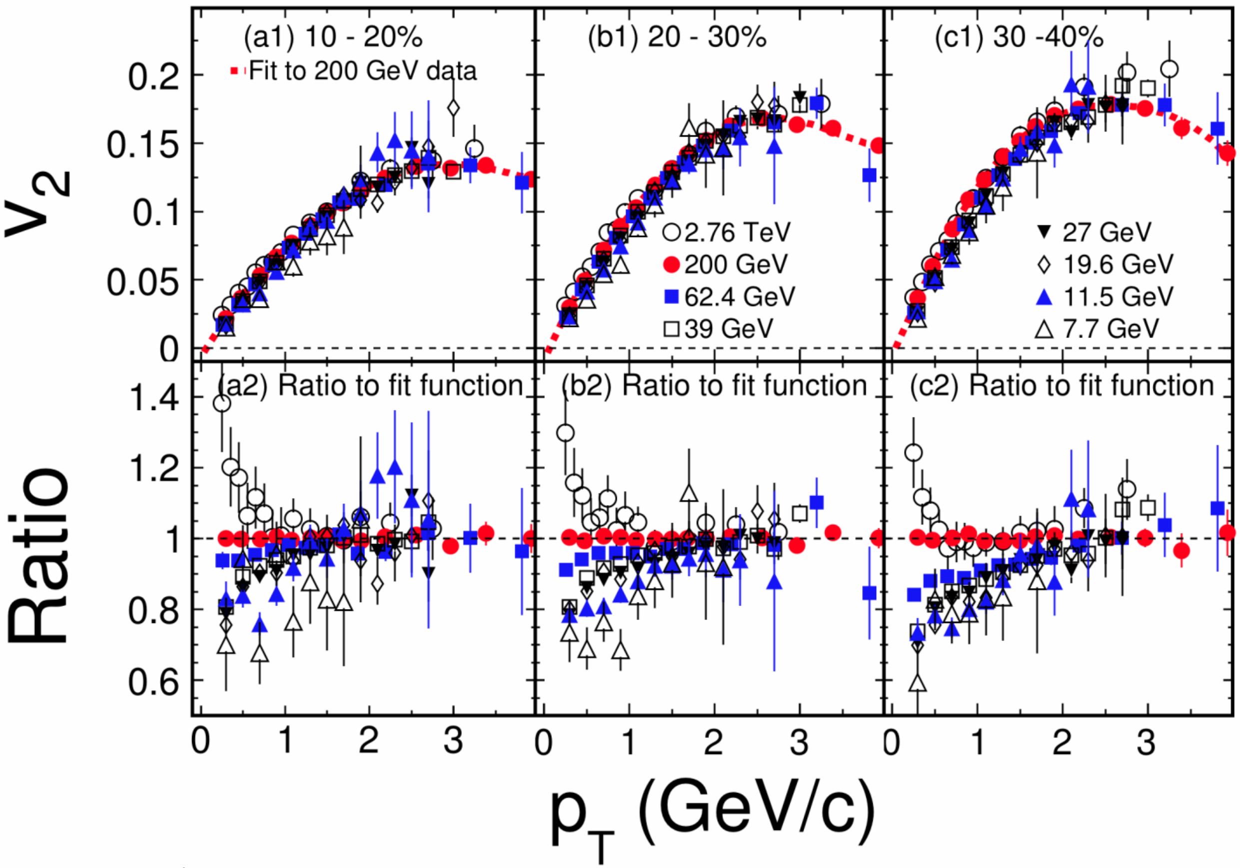



- Directed flow is sensitive to compression
- Proton $v_1$ slope changes sign from positive to negative between 7.7 and 11.5
- The pion, kaon, and anti-proton $v_1$ slopes are always negative.
- **net-protons shows a non-monotonic behavior.**

Y. Pandit (T 2:55)

# Hadron elliptic flow; Energy dependence



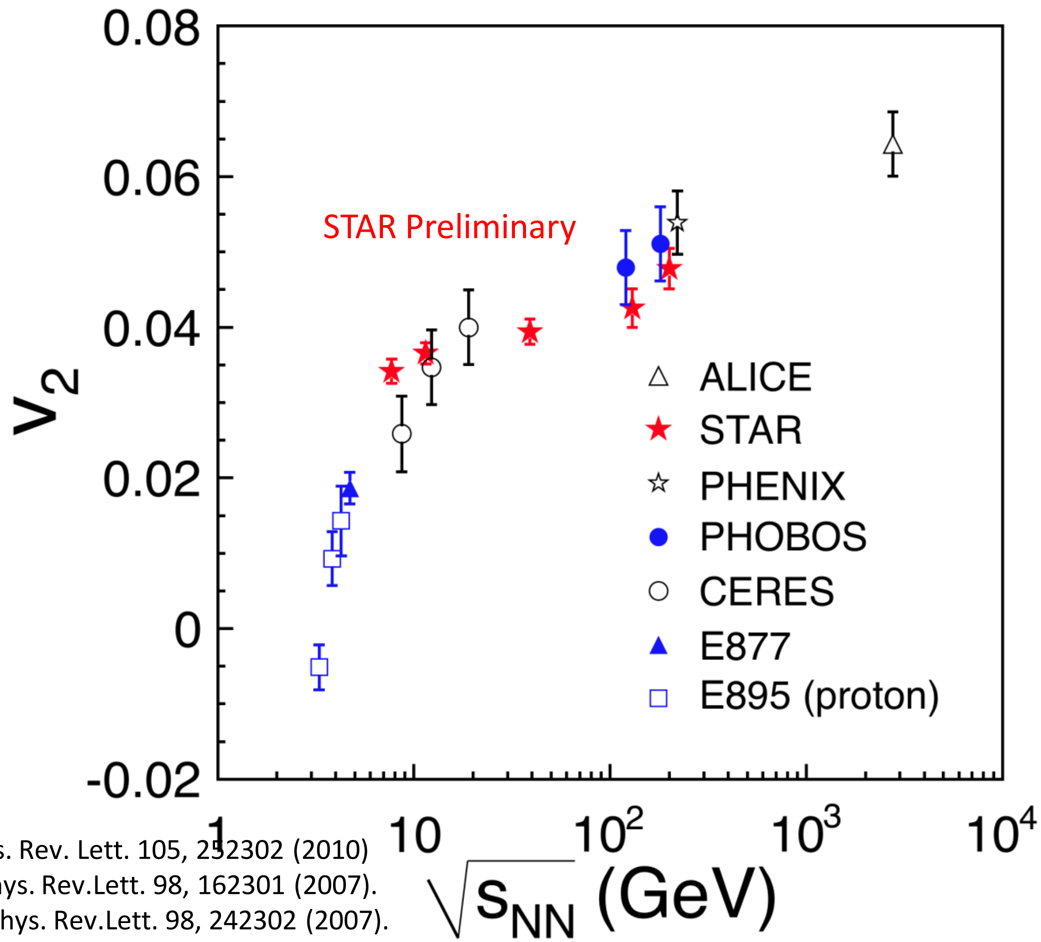

STAR: arXiv:1206.5528

ALICE data: Phys. Rev. Lett. 105, 252302 (2010)

- **$v_2\{4\}$ results**
  - Three centrality bins
- **Consistent $v_2(p_T)$ from 7.7 GeV to 2.76 TeV for $p_T > 2$ GeV/c**
- **$p_T < 2$GeV/*c***
  - The $v_2$ values rise with increasing collision energy
    ->
    Large collectivity
    Particle composition

S. Shi (F 3:20)

# Hadron elliptic flow; Energy dependence




ALICE: Phys. Rev. Lett. 105, 252302 (2010)
PHENIX: Phys. Rev.Lett. 98, 162301 (2007).
PHOBOS: Phys. Rev.Lett. 98, 242302 (2007).
CERES: Nucl. Phys. A 698, 253c (2002).
E877: Nucl. Phys. A 638, 3c(1998).
E895: Phys. Rev. Lett. 83, 1295 (1999).
STAR 130 and 200 GeV: Phys. Rev. C 66,873 034904 (2002); Phys. Rev. C 72,790 014904 (2005)

- **STAR, ALICE: $v_2\{4\}$ results**
  - Centrality: 20-30%
- **An increasing trend is observed for $p_T$ integrated $v_2$ from AGS to LHC**
  - The rate of increase with collision energy is slower from 7.7 to 39 GeV compared to that between 3 to 7.7 GeV

S. Shi (F 3:20)

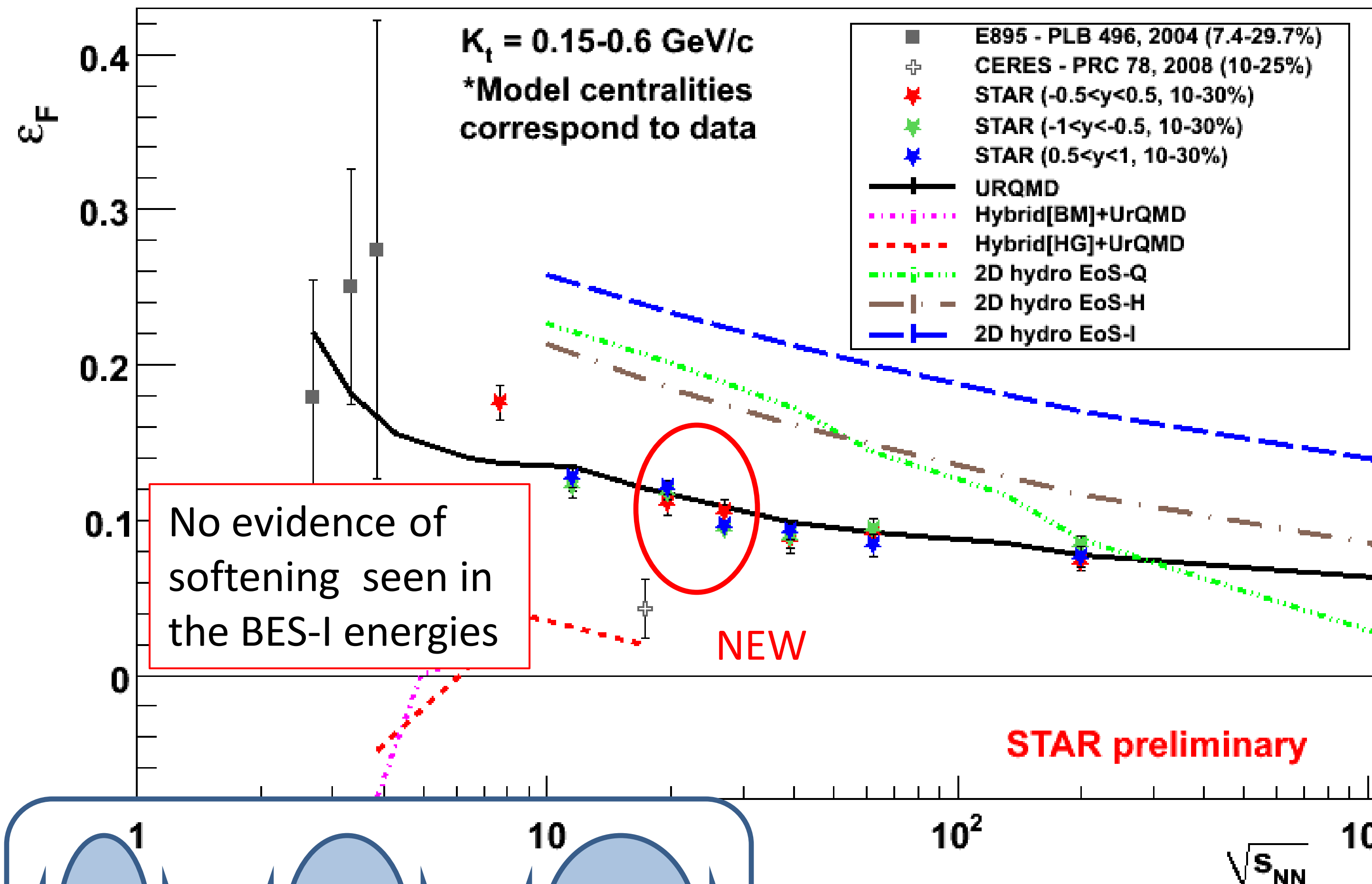
# Azimuthally sensitive HBT; Energy dependence

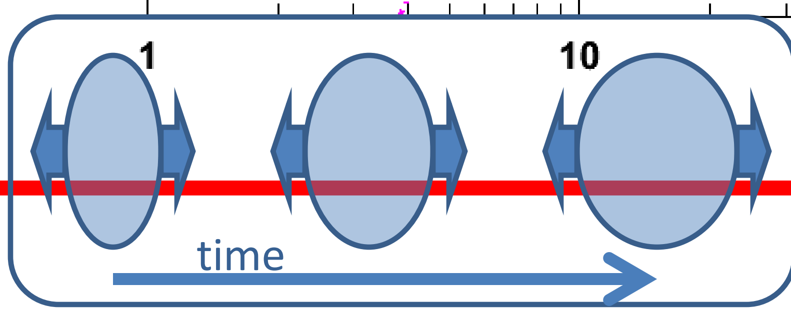
**Excitation function for freeze-out eccentricity, $\varepsilon_F$**

Correlations functions of identical bosons (pions) can yield outward, sideward, and longitudinal radii.

Couple this analysis with a reaction plane constraint, and you get $R_x$, $R_y$, and $R_z$.

Pressure causes expansion, lowering spatial eccentricity




N. Shah (T 2:35)

# Conclusions

## The high statistics 200 GeV datasets have allowed us study:

- The role of non-flow effects (jets) in $v_2$ analyses
- The $p_T$ limits of the NCQ scaling regime
- The behavior of hadrons with multiple strange quarks
- The higher flow harmonics

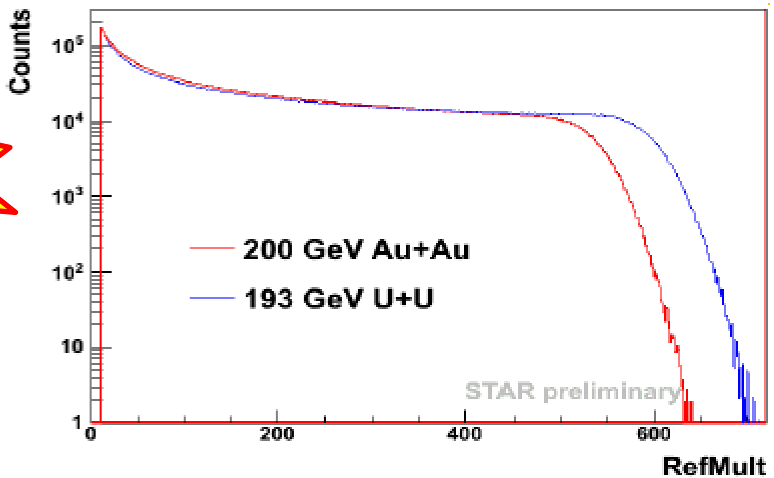
## The Beam Energy Scan (phase I) datasets have allowed us to study:

- The breakdown of NCQ scaling → specifically particle anti-particle differences
- A non-monotonic behavior of the proton directed flow
- The systematics of the $p_t$ averaged elliptic flow
- The spatial expansion of the source (through azimuthally sensitive HBT)

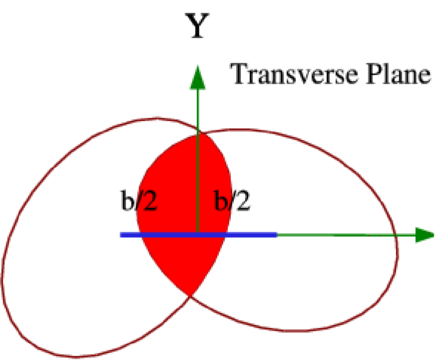
# Backups

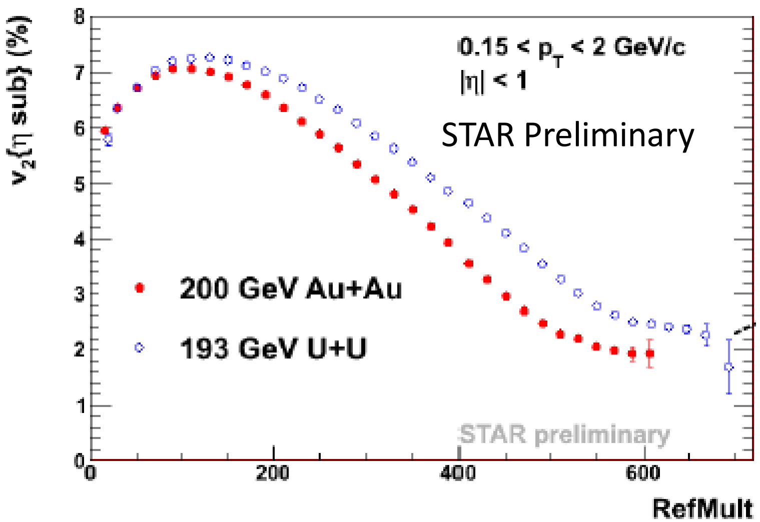
# Hadron elliptic flow in $\sqrt{s_{NN}}$ = 193 GeV U+U

New




- Uranium; a larger and more very deformed system. Higher multiplicity
- $v_2$ in U+U is higher than that in Au+Au, but not as high as expected in central collisions
- We will further study the most central 1% triggered events.




G. Wang (R 12:20)