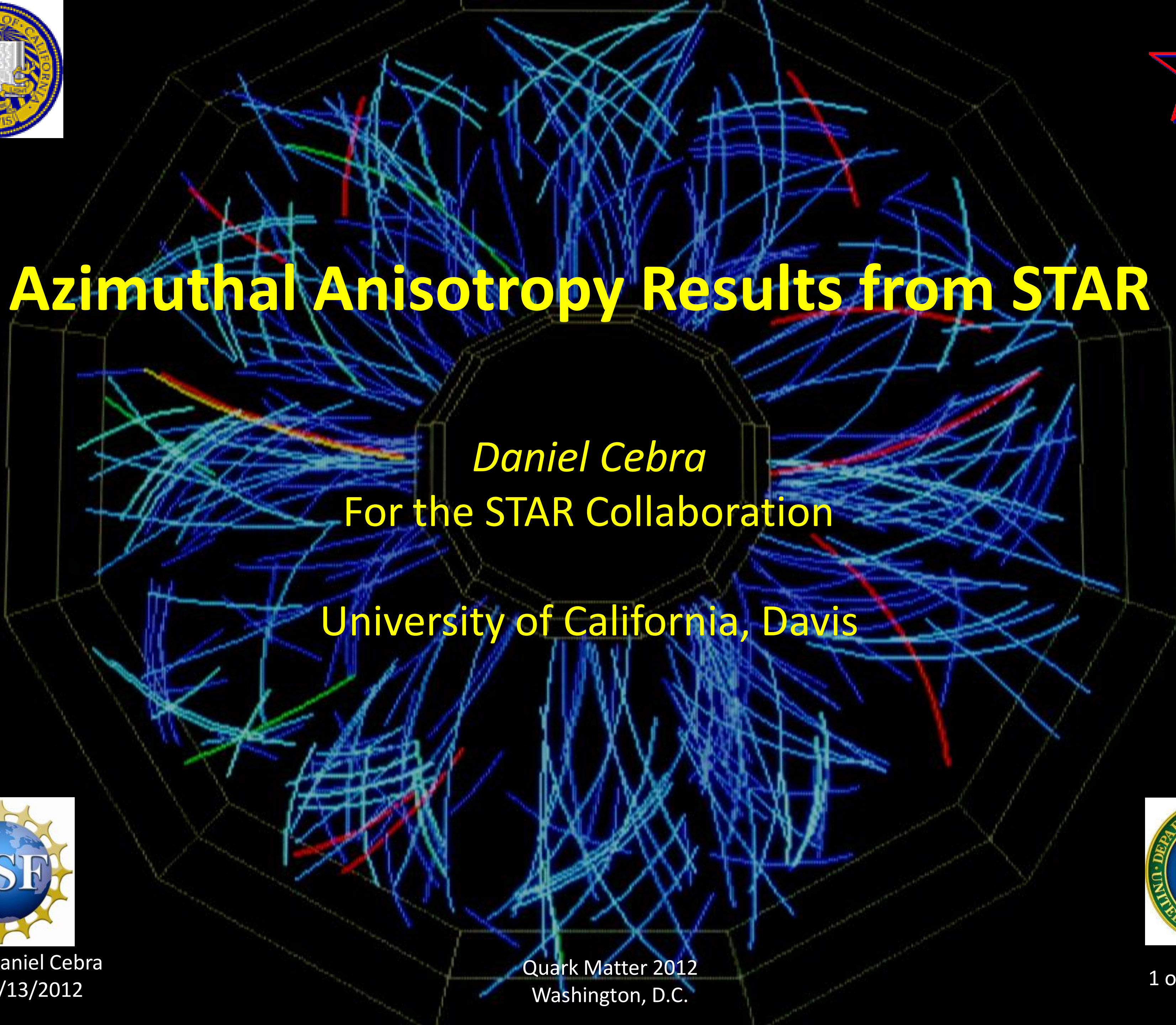
Azimuthal Anisotropy Results from STAR



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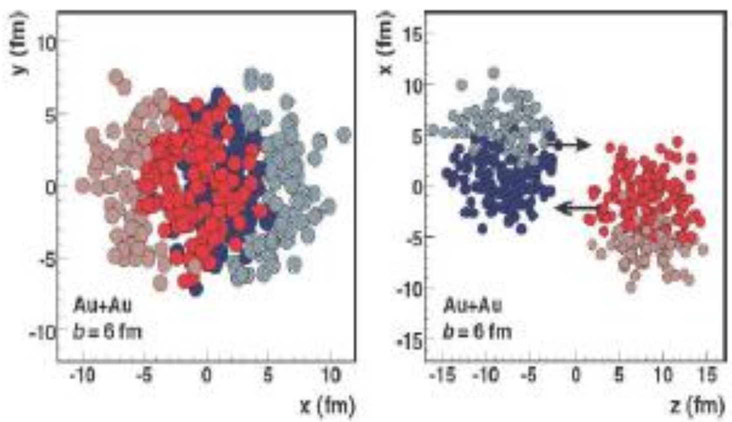
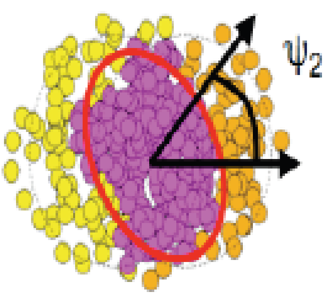
Azimuthal anisotropy basics

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

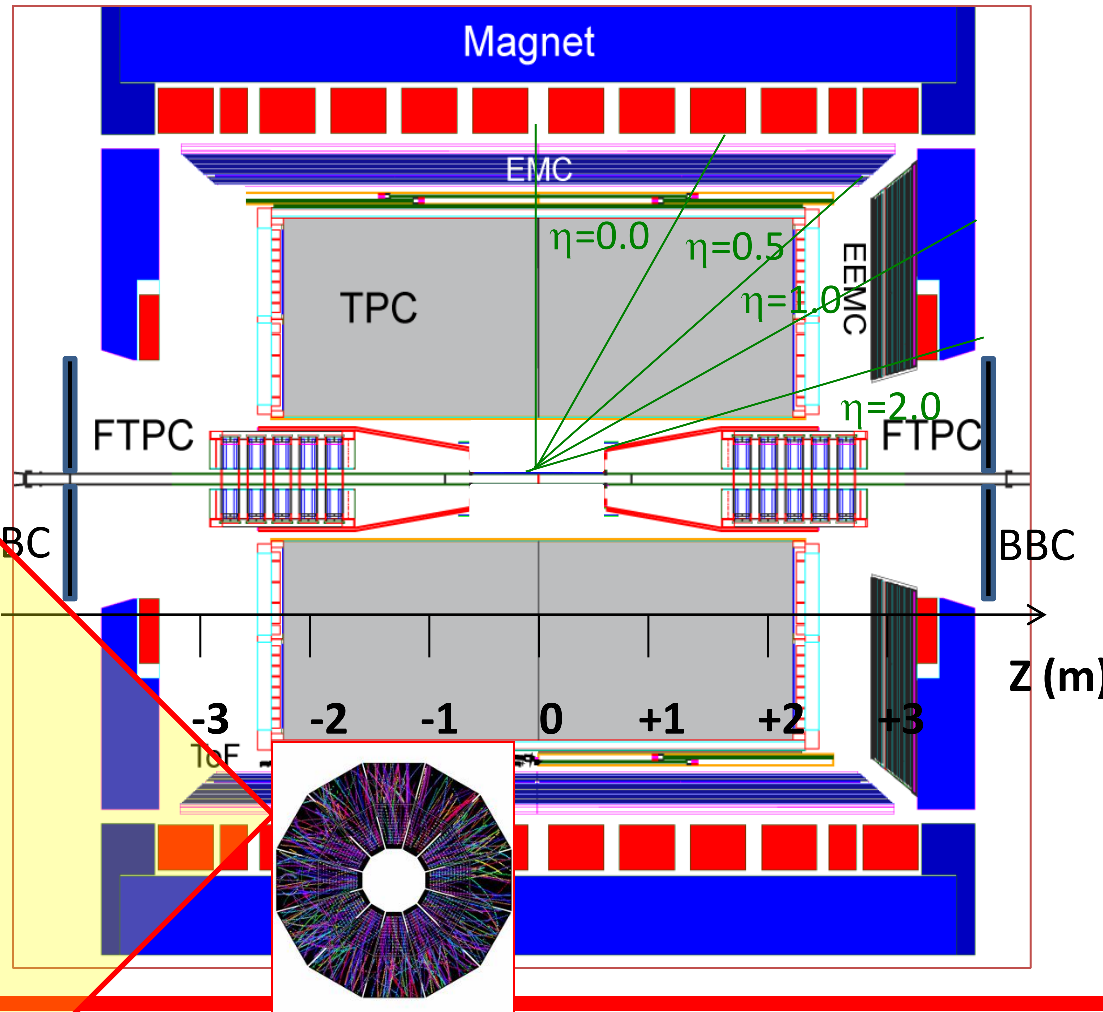
$$v_{\mathrm{n}} = \left\langle \cos n\left(\varphi - \psi_n\right)\right\rangle, \quad n = 1,2,3..,$$



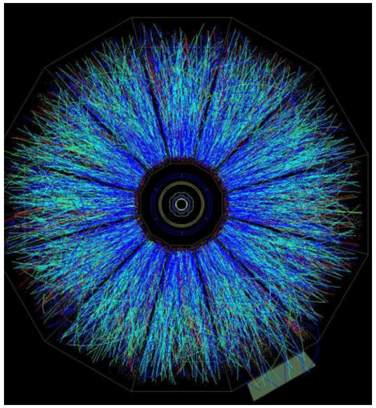


Hydrodynamic Pressure maps the initial coordinate space anisotropy onto a momentum space anisotropy measured by the experiments

Schematic of the STAR Detector

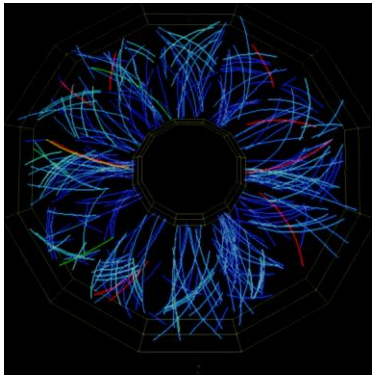


What is new this year?



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)

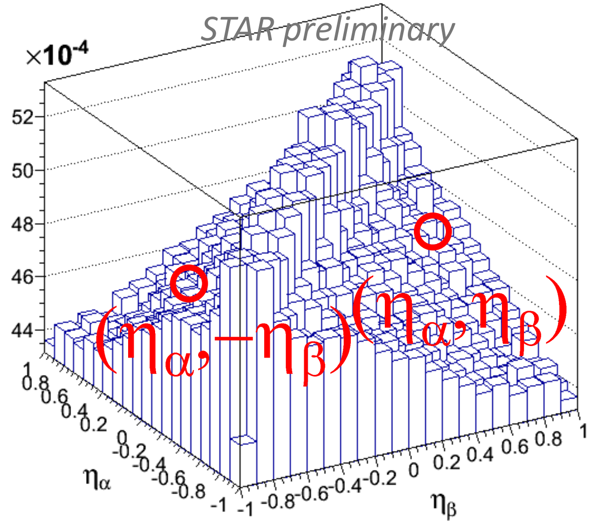


Beam Energy Scan

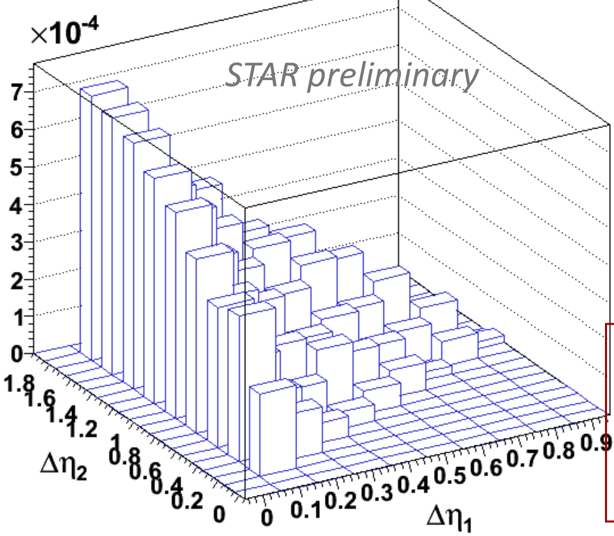
- Directed flow — Y. Pandit (T 2:55)
- Hadron elliptic flow — S. Shi (F 3:20)
- Identified particle elliptic flow — A. Schmah (Poster #141)
- Azimuthally sensitive HBT — N. Shah (T 2:35)

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

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



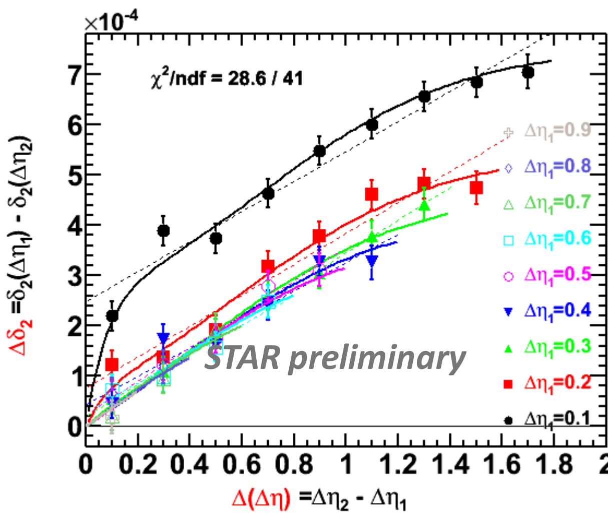
$\Delta\mathcal{V}_2\{2\}$

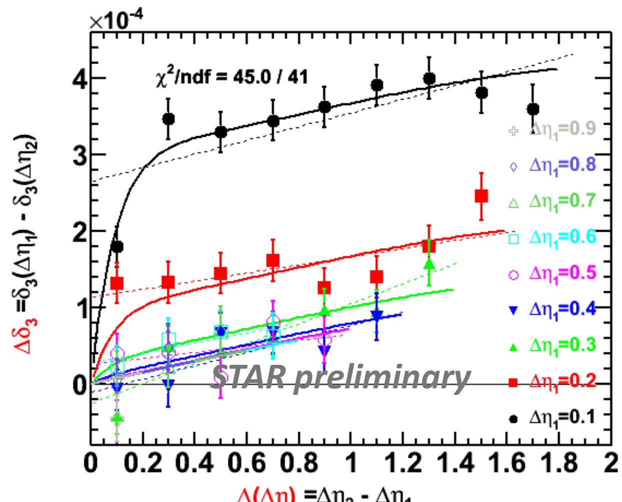


$$\mathcal{V}\{\eta_\alpha,\eta_\beta\} = v(\eta_\alpha)v(\eta_\beta) + \sigma(\eta_\alpha)\sigma(\eta_\beta) + \sigma'(\Delta\eta) + \delta(\Delta\eta)$$

‘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

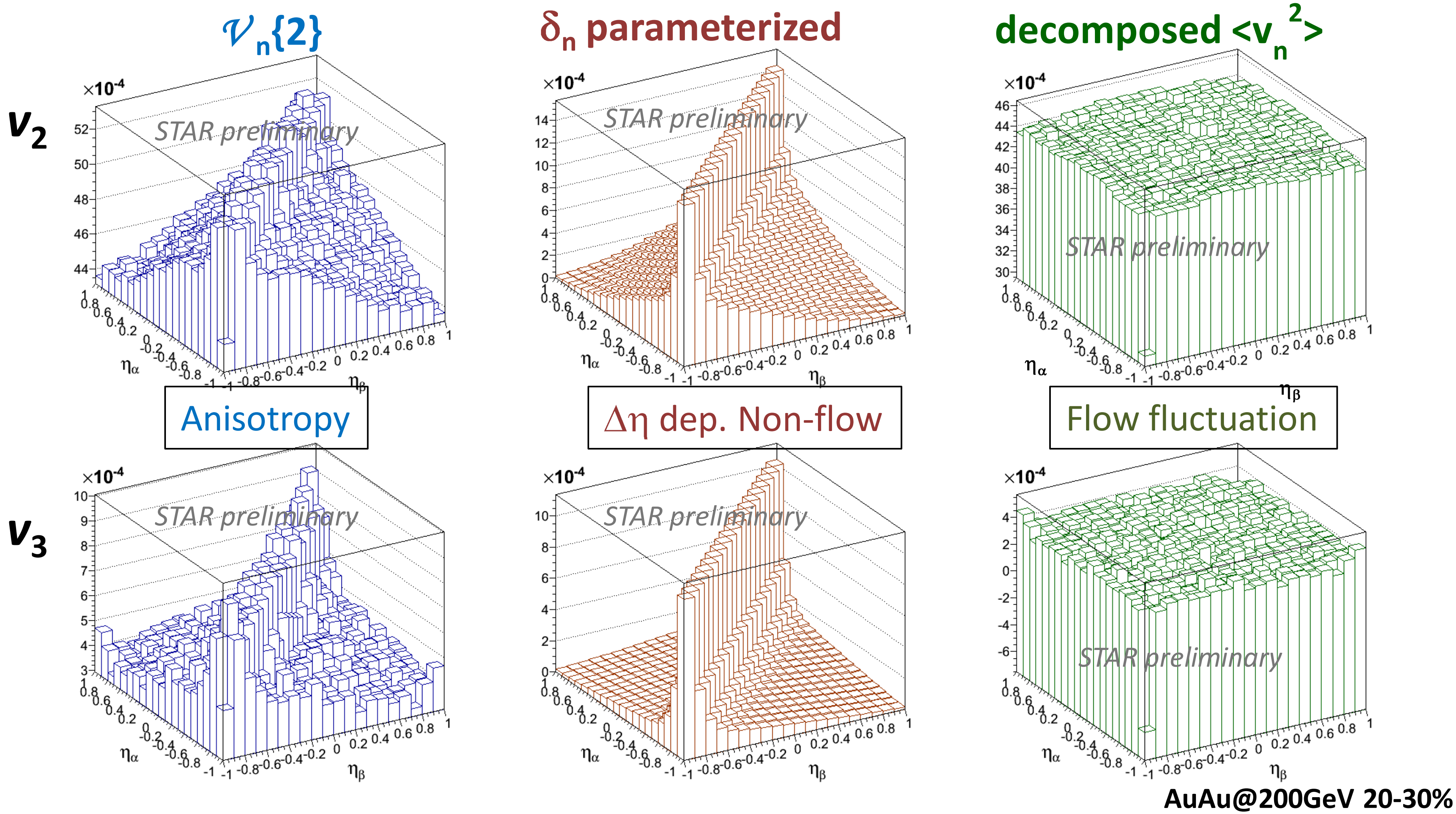
$$\Delta\delta(\Delta\eta_1,\Delta\eta_2) = a(e^{-\Delta\eta_1/b} - e^{-\Delta\eta_2/b}) + A(e^{-\Delta\eta_1^2/2\sigma^2} - e^{-\Delta\eta_2^2/2\sigma^2})$$

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

AuAu@200GeV 20-30%

Yi Li (W 9:30)

'Flow' $v_n\{2\}$, non-flow δ_n, and flow fluctuations $\langle v_n^2 \rangle$



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

Yi Li (W 9:30)

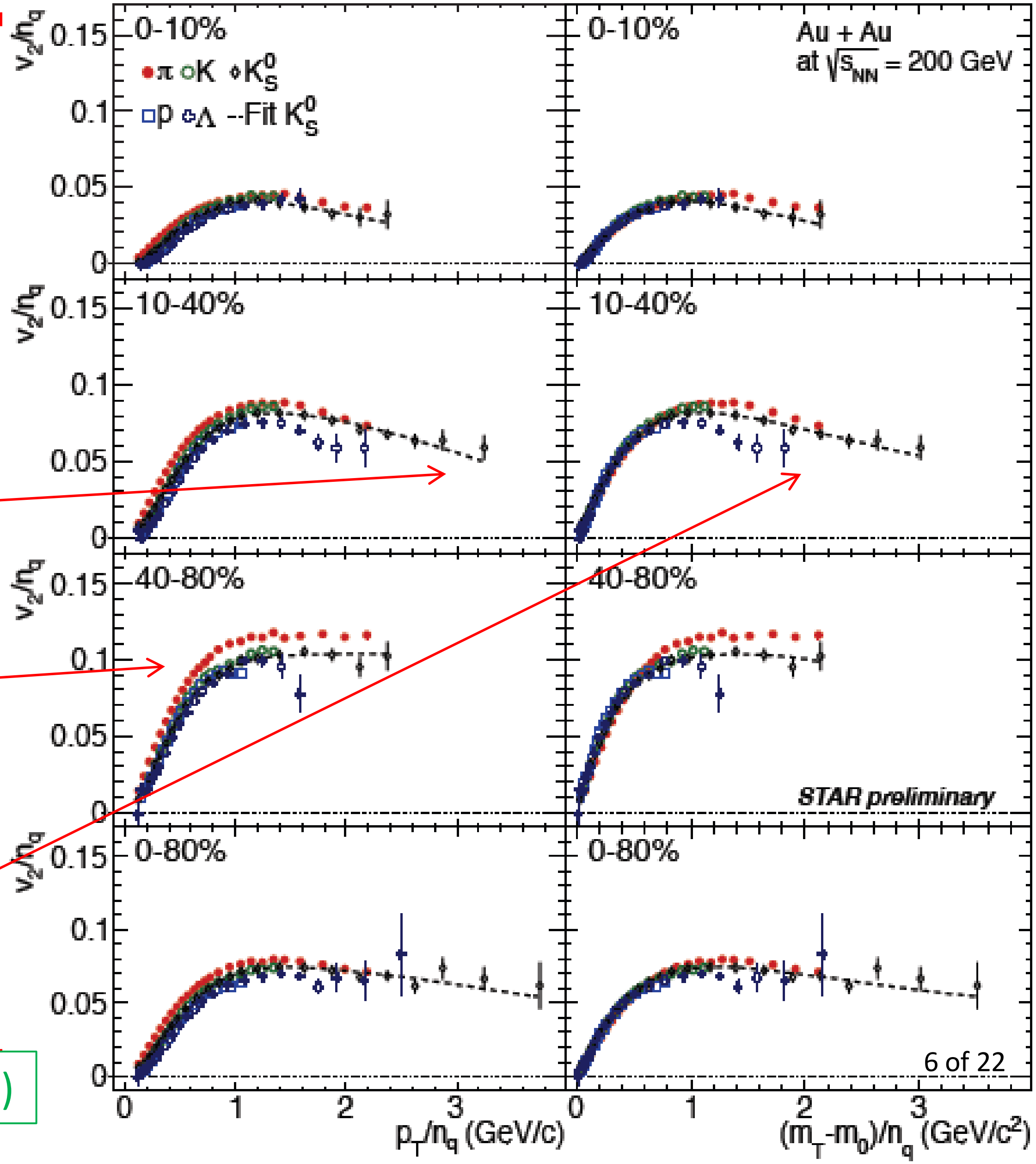
Precision measurements in $\sqrt{s_{NN}}$ = 200 GeV Au+Au

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 $(m_T-m_0)n_q$>1 GeV/c^2 for 10-40% centrality.



H. Masui (Poster)

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

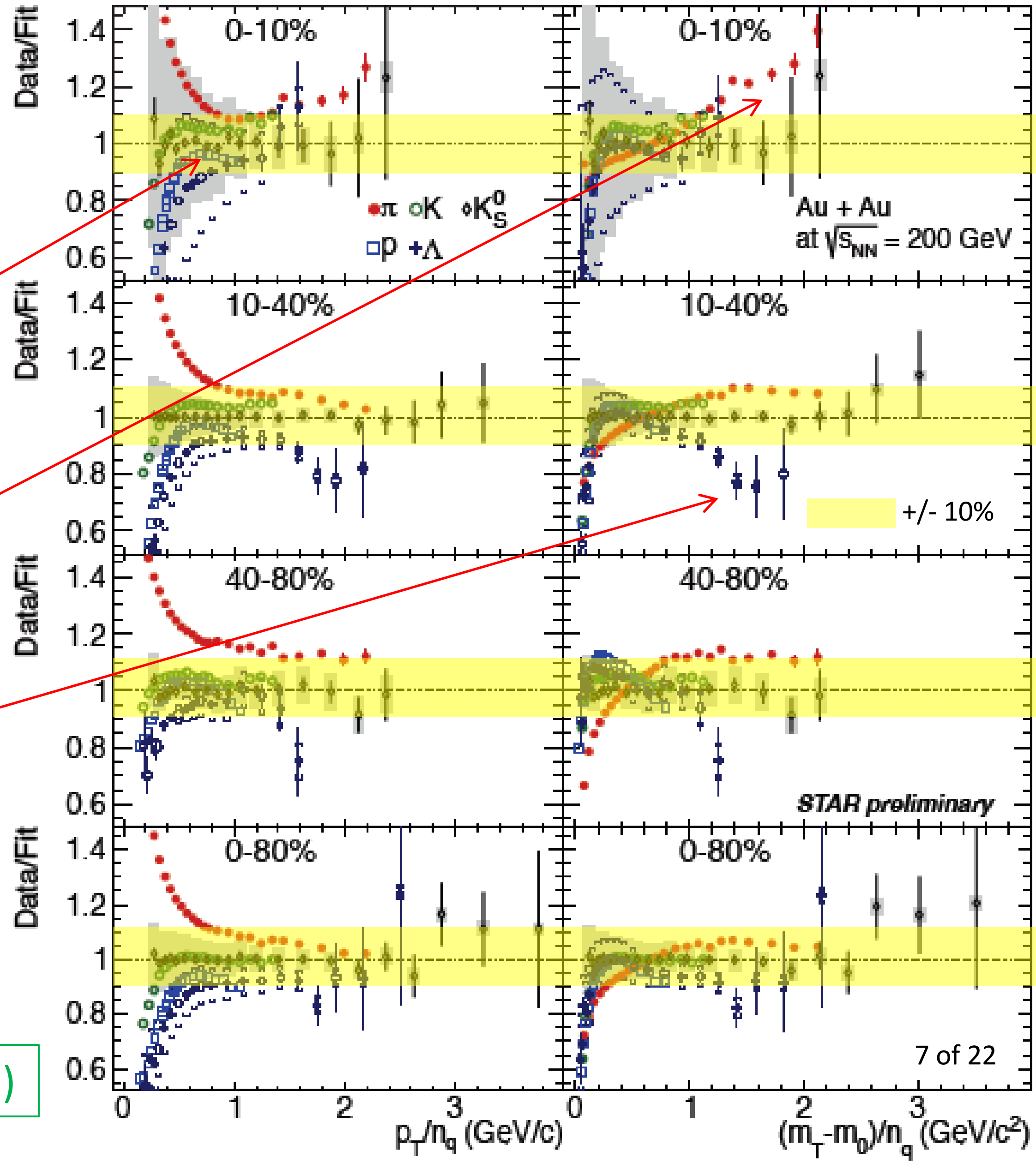
The scaling breakdown can be explored further by taking ratios to a fit to the K_S^0

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?

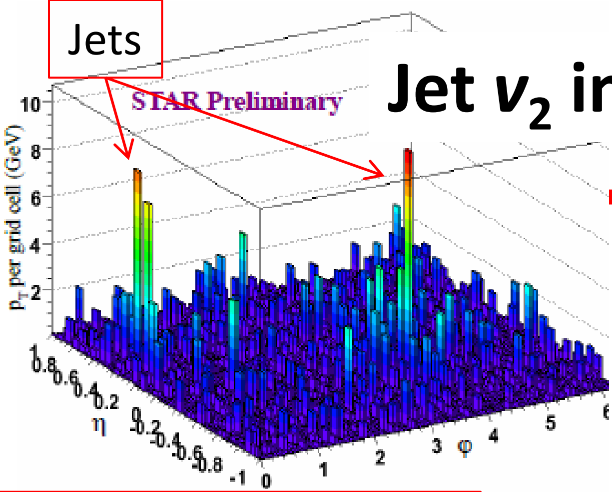
There are 20-30% deviations between the results for π and Λ in the 10-40% centrality bin.

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



H. Masui (Poster #145)

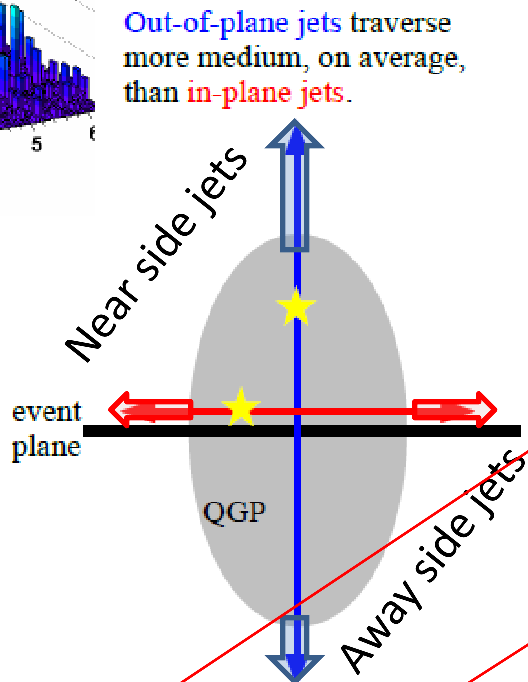
Jet v_2 in $\sqrt{s_{NN}}$ =200 GeV Au+Au

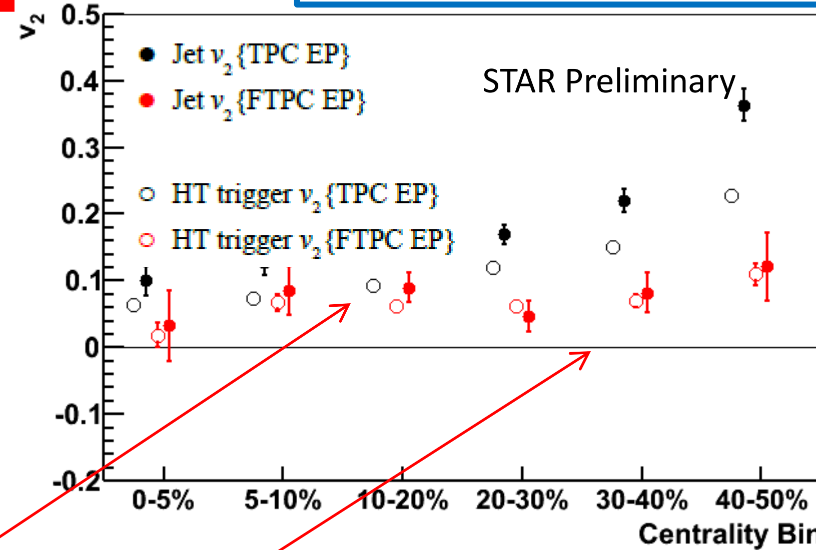


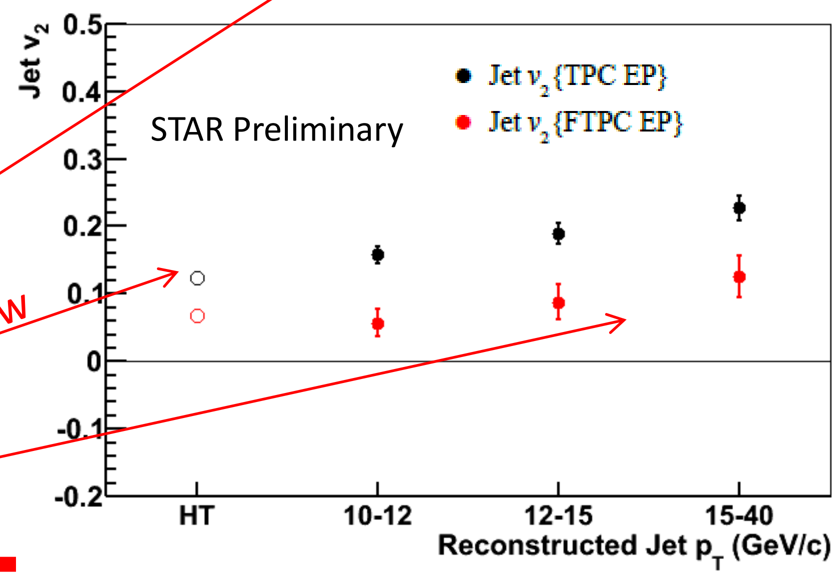
Jet definition (anti-k_T):
Trigger E_t > 5.5 GeV
Constituent p_t^{cut} >2 GeV/c

Why measure jet v_2?

- Provides information about the path length dependent energy loss
- Necessary for subtraction of backgrounds in jet-hadron correlations





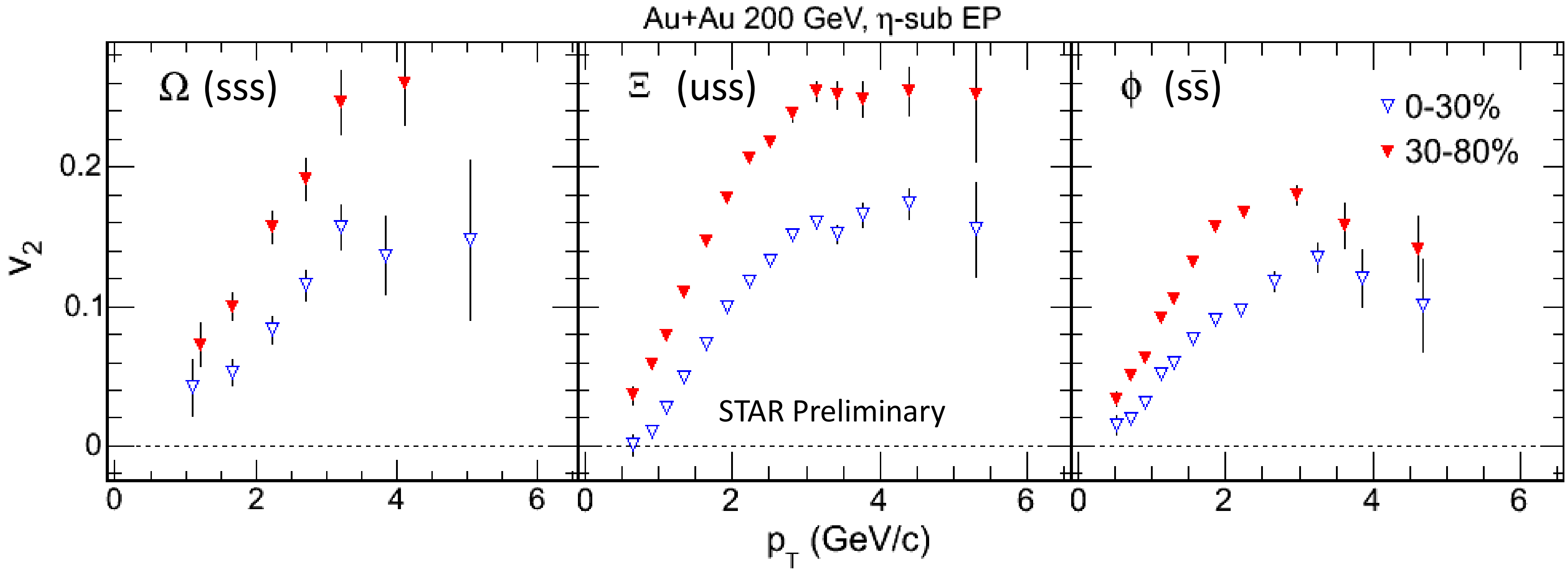


- non-zero jet v_2 → E_{loss} on path
- jet v_2{FTPC} is consistent with that of trigger hadrons
- Midrapidity measures of the event plane are biased by the presence of a jet
- Jet v_2 increases with p_T

Non-flow

A. Ohlson (W 11:40)

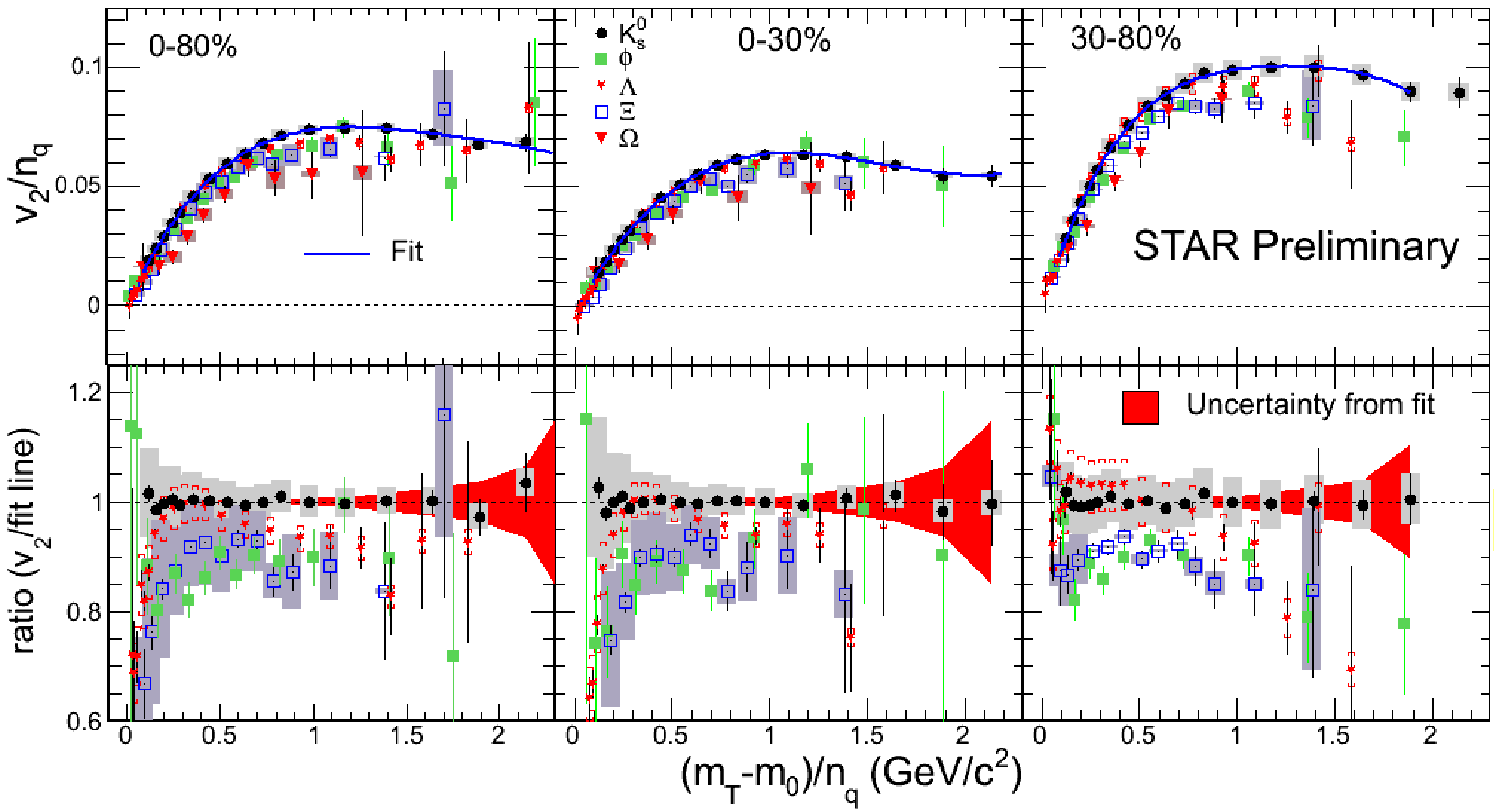
Elliptic flow of Ω, Ξ, and ϕ in $\sqrt{s_{NN}}$ = 200 GeV Au+Au



- 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



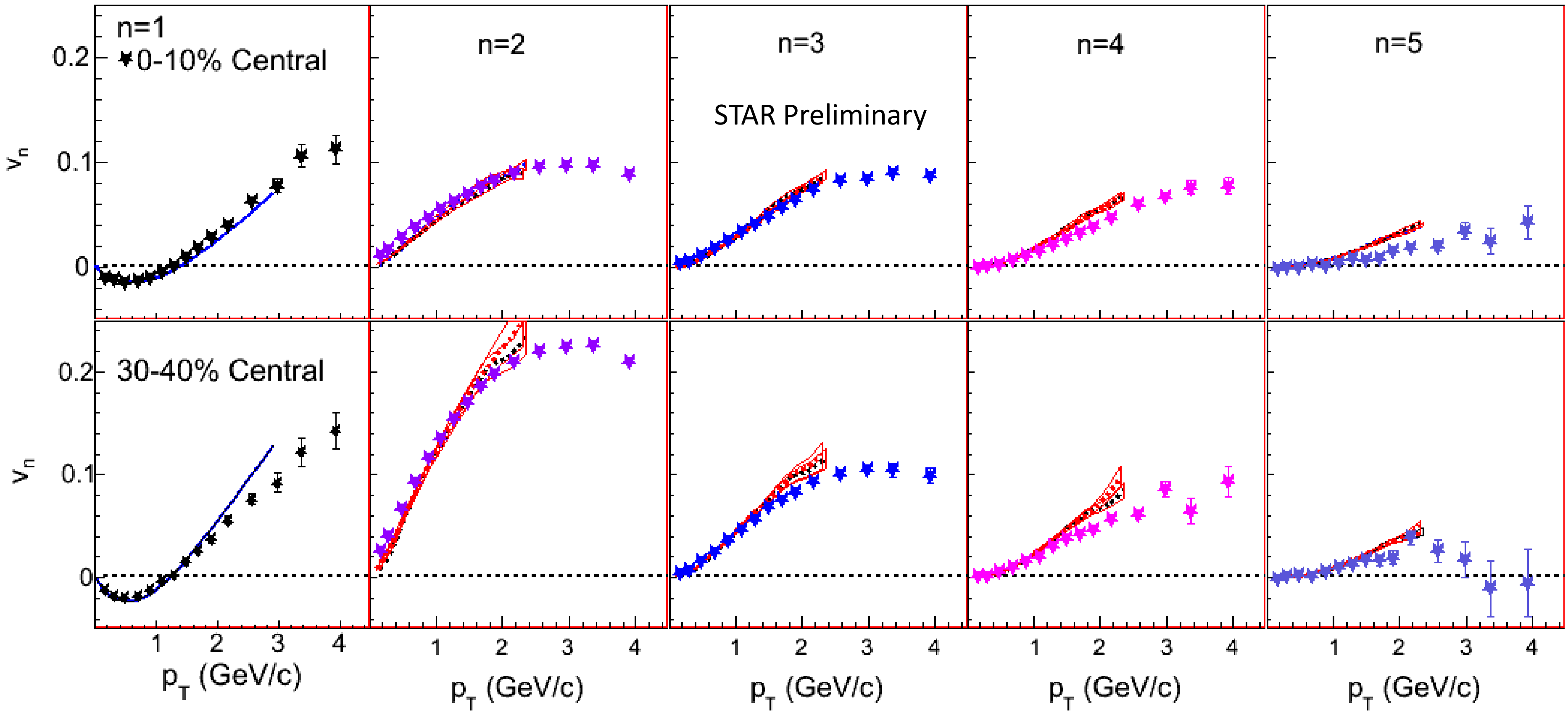
With scaling and with a ratio of the fit to the K^0_S, it is evident that:

- 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

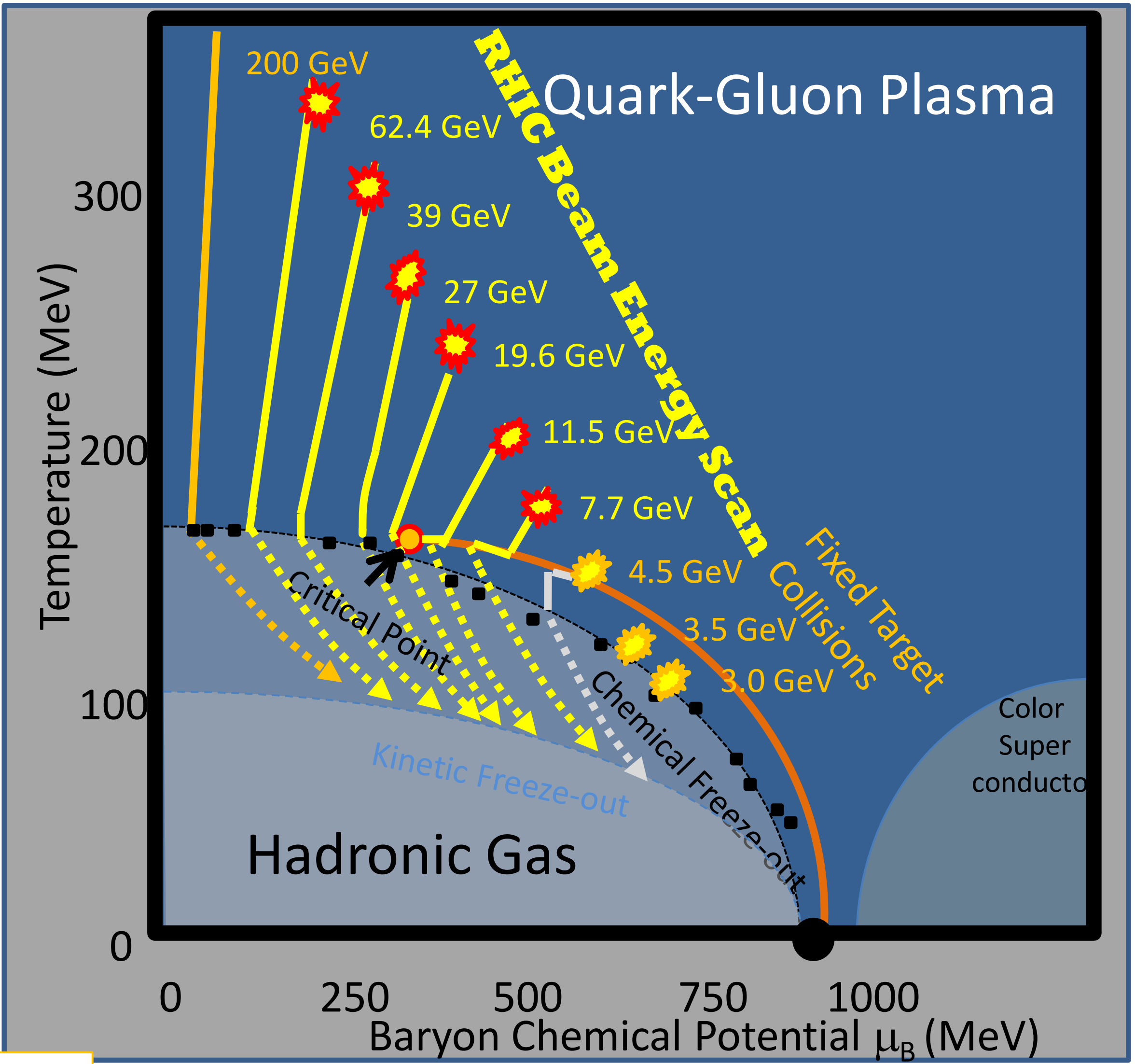
Goals of the Scan:

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

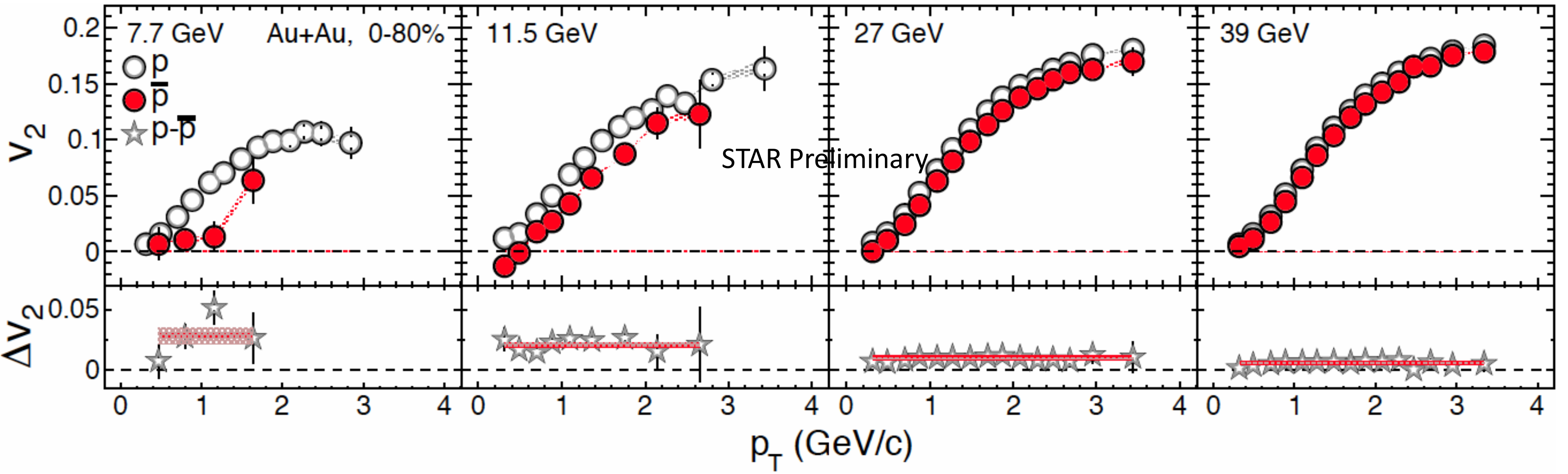
Beam Energy Scan

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 Δv_2 as the v_2 of the proton minus that of the anti-proton
- Δv_2 is constant in the measured p_T range and decreasing with increasing energy

S. Shi (F 3:20)

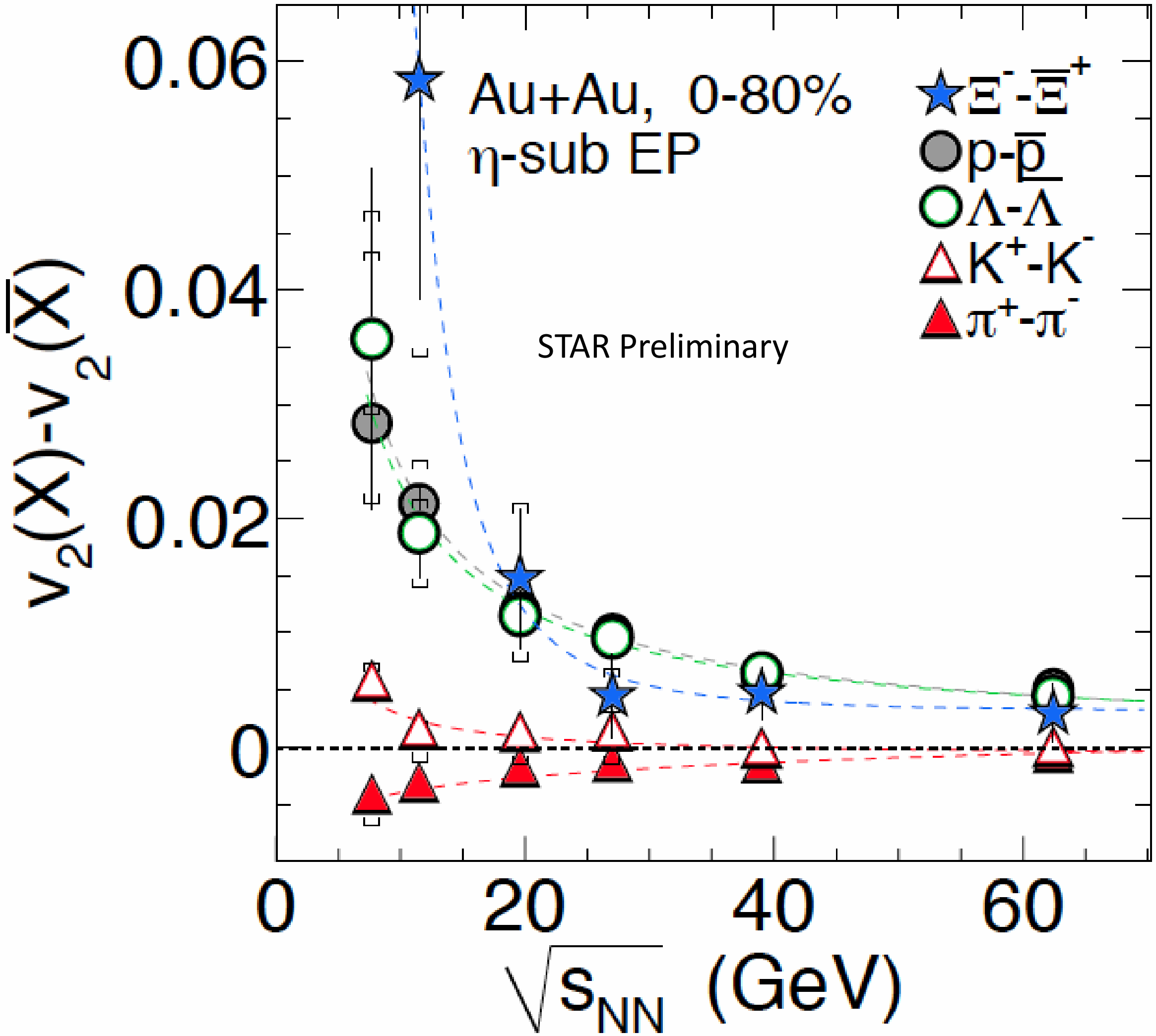
A. Schmah (Poster #141)

Particle-anti-particle elliptic flow; Energy Scan

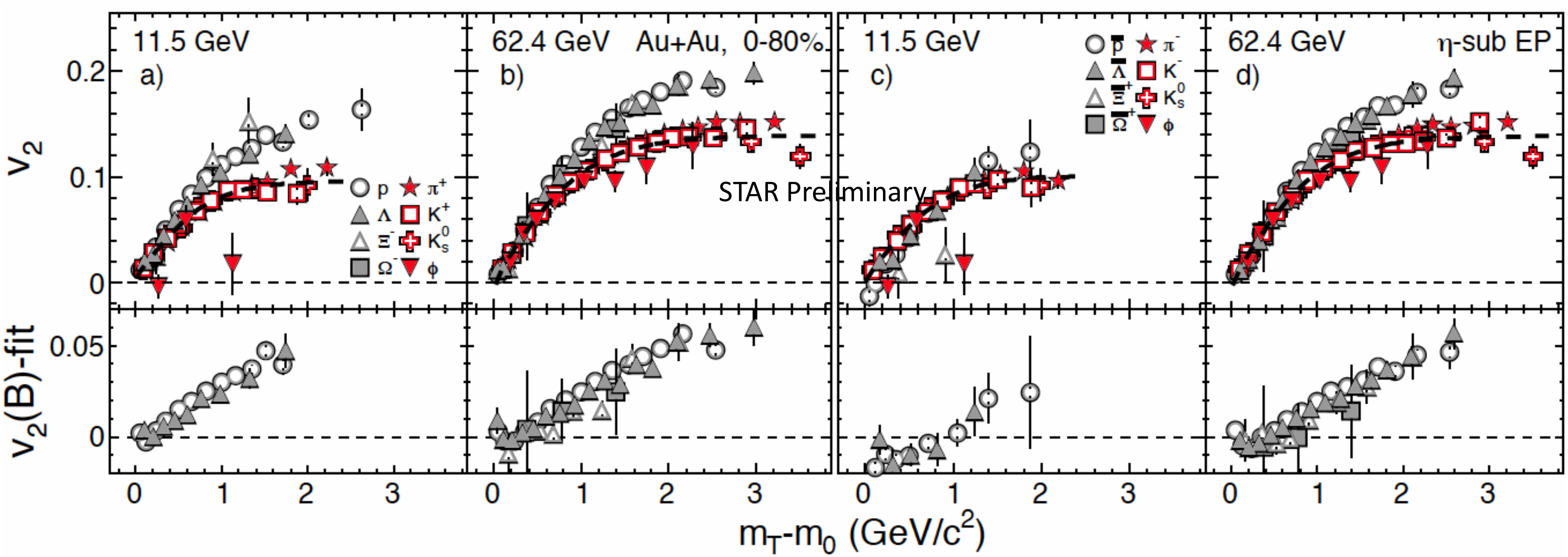
- **There is a remarkable difference between particles and their anti-particles, especially for the lowest energies in the range.**
- **Difference between particles and their anti-particle decreases with increasing beam energy**

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**

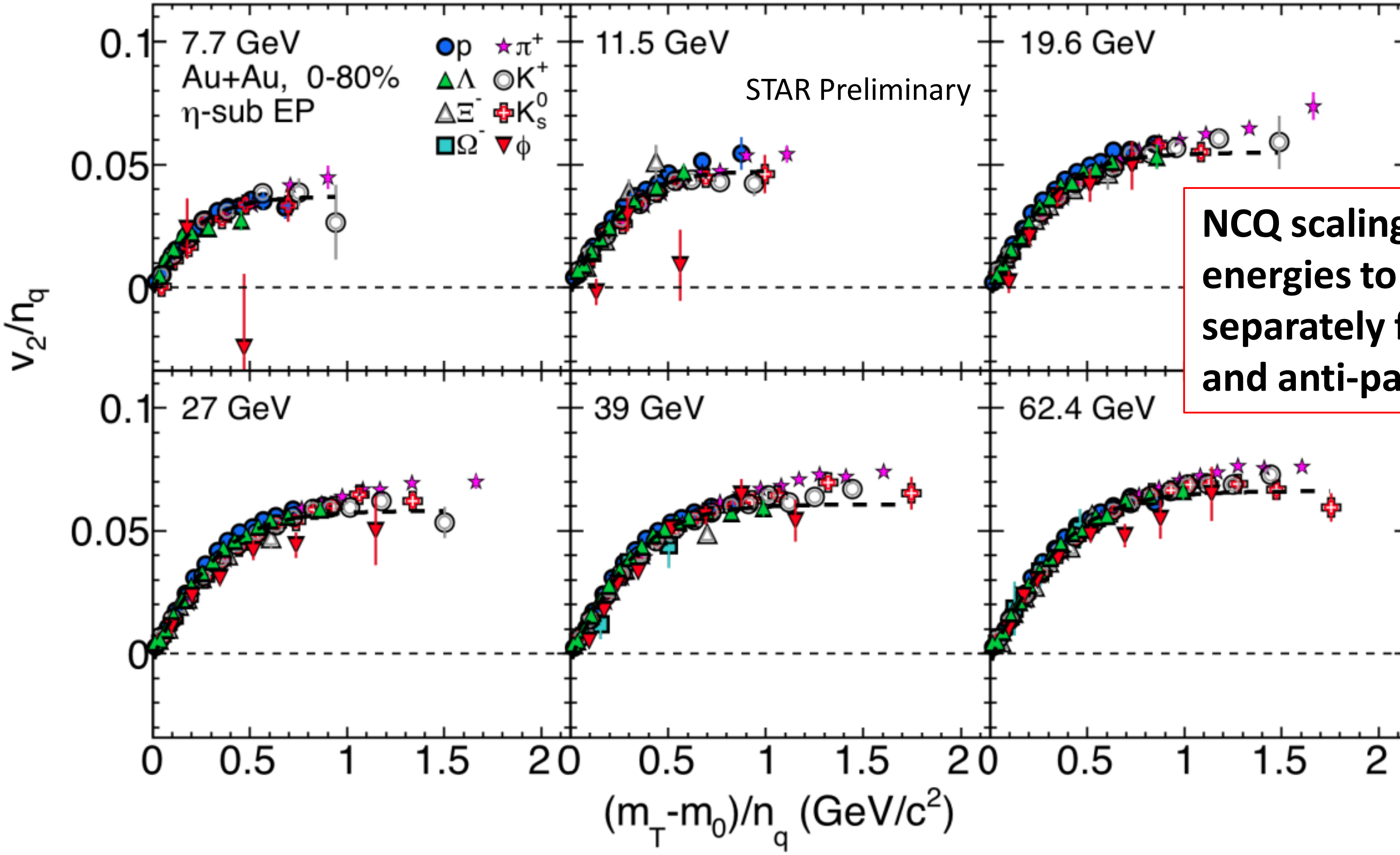
- **Splitting for anti-particles is gone at 11.5 GeV, for particles the splitting is still evident at 11.5 GeV, however it is small at 7.7 GeV**

S. Shi (F 3:20)

A. Schmah (Poster #141)

NCQ scaling of elliptic flow; Energy dependence

Particles



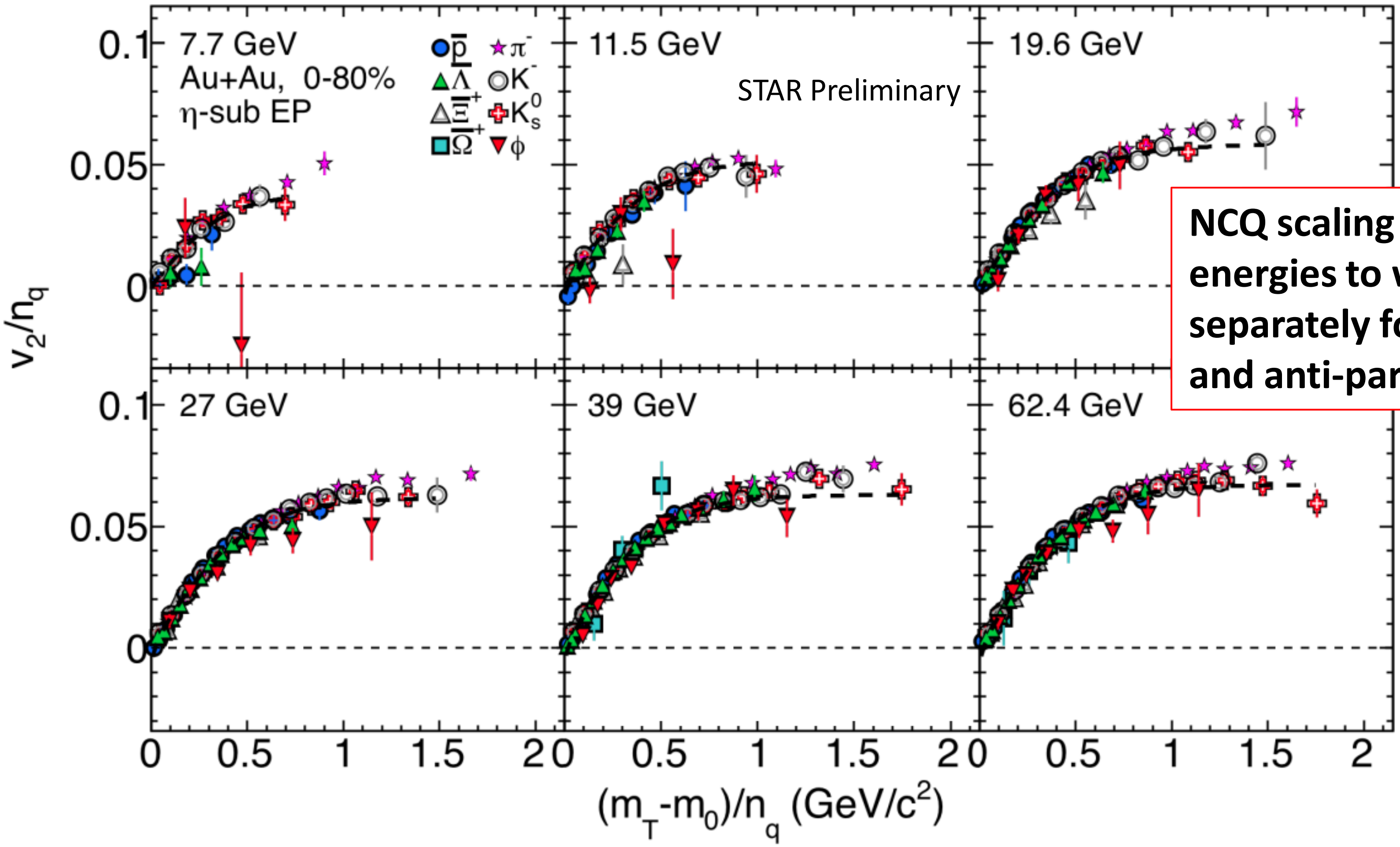
NCQ scaling holds at all energies to within ±10% separately for particles and anti-particles

S. Shi (F 3:20)

A. Schmah (Poster #141)

NCQ scaling of elliptic flow; Energy dependence

Anti-Particles

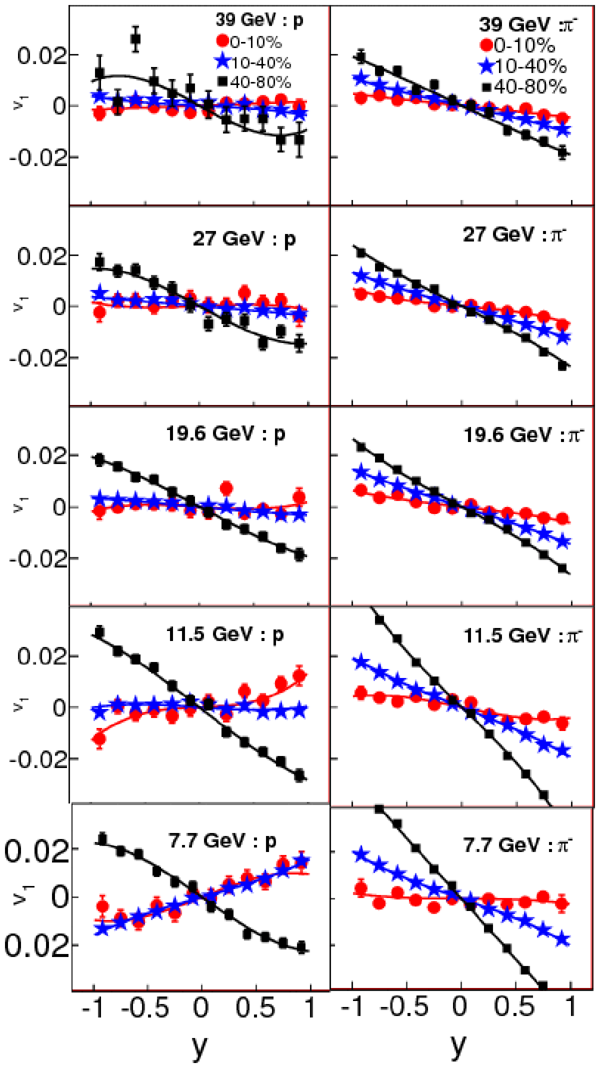


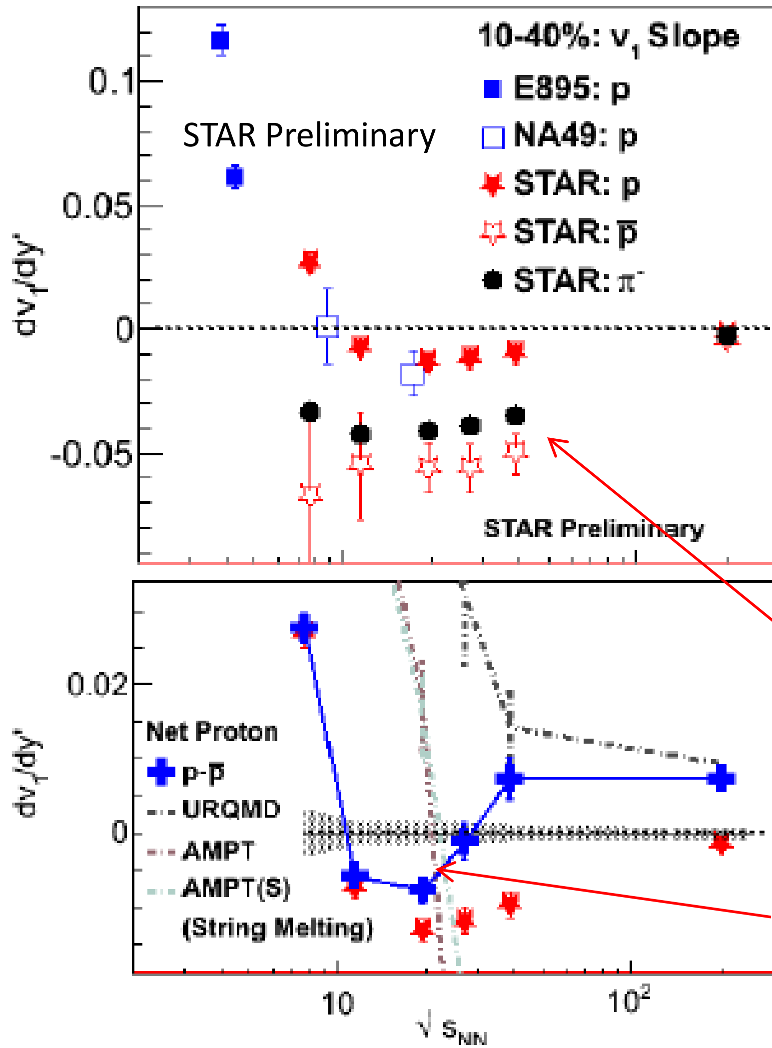
NCQ scaling holds at all energies to within ±10% separately for particles and anti-particles

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

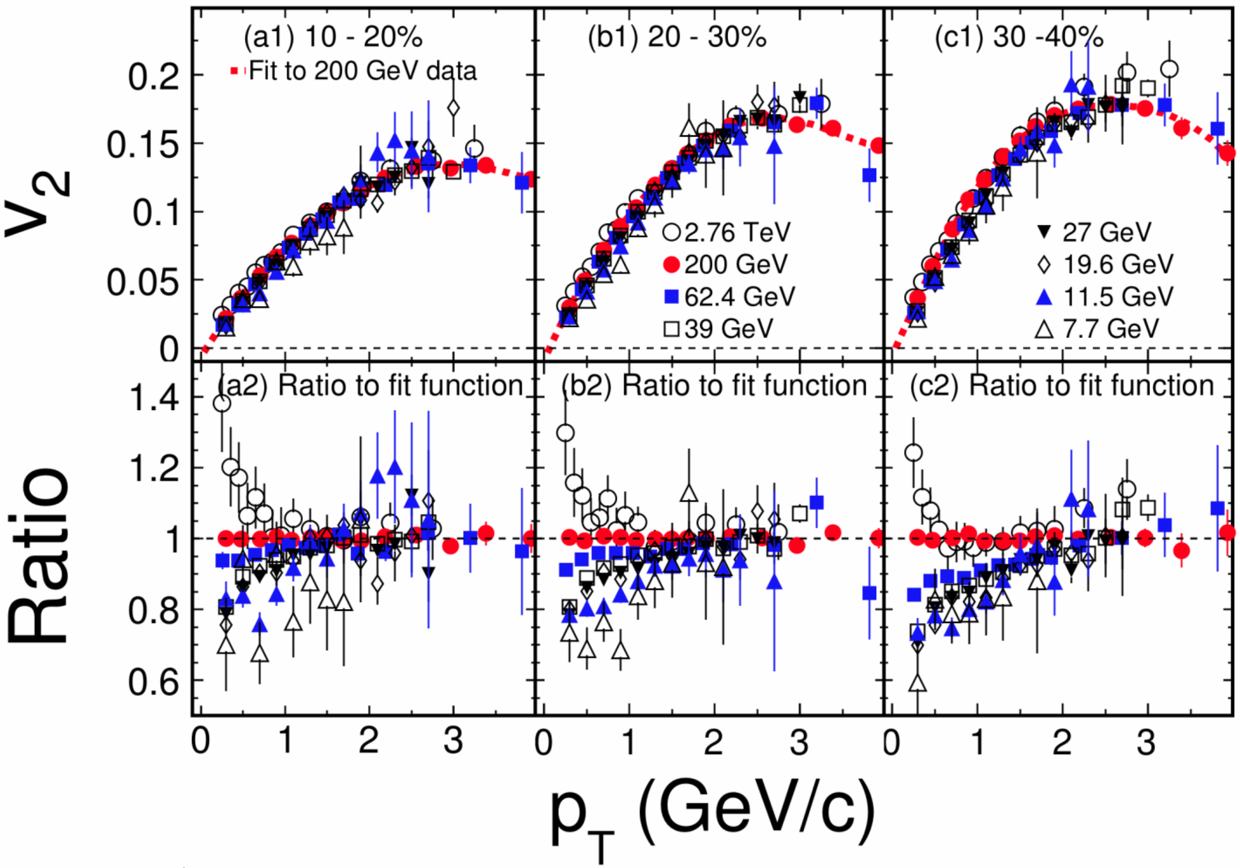
- Proton v_1 slope changes sign from positive to negative between 7.7 and 11.5

- 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)

S. Shi (F 3:20)

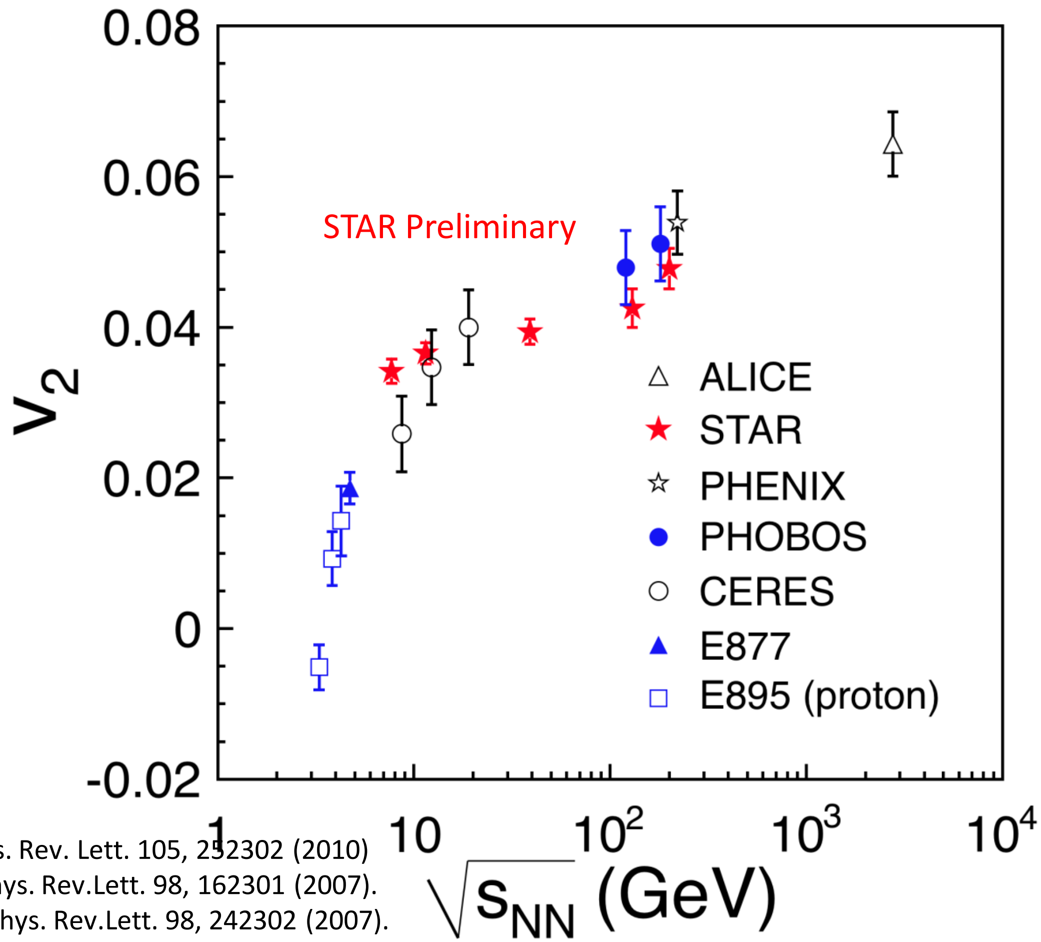
- **$v_2\{4\}$ results**
  - Three centrality bins
- **Consistent $v_2(p_T)$ from 7.7 GeV to 2.76 TeV for $p_T > 2$ GeV/c**
- **$p_T < 2$ GeV/*c***
  - The v_2 values rise with increasing collision energy

    ->

    Large collectivity

    Particle composition

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)

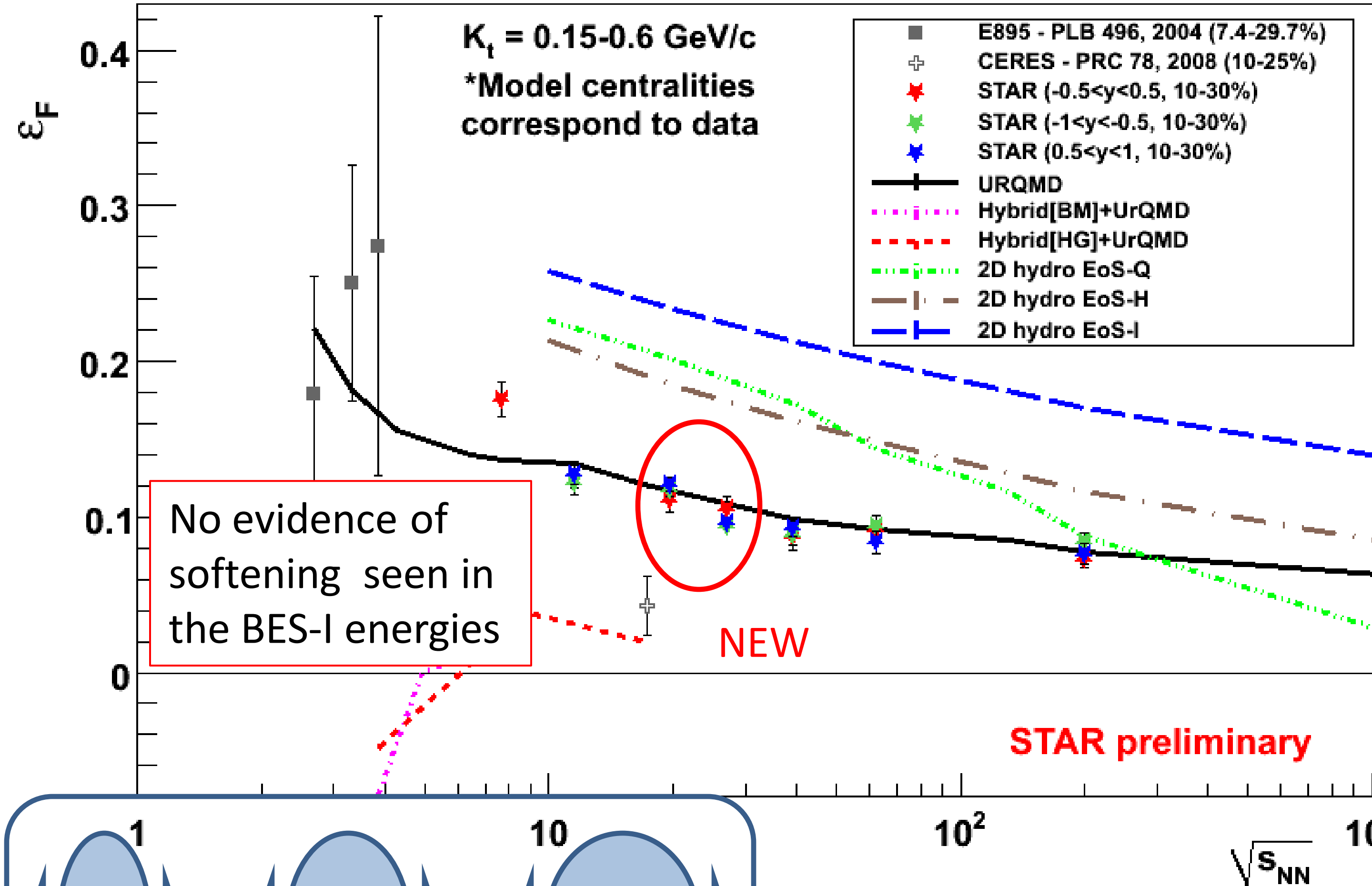
Azimuthally sensitive HBT; Energy dependence

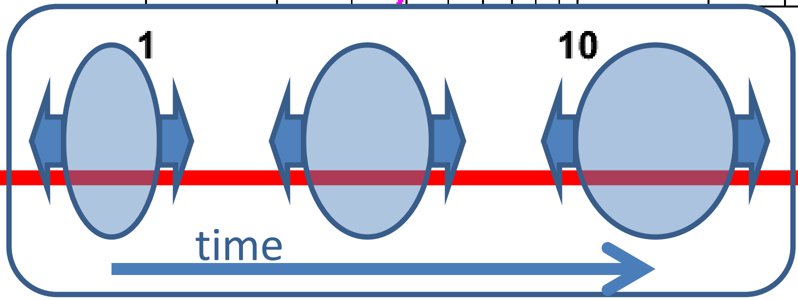
Correlations functions of identical bosons (pions) can yield outward, sideward, and longitudinal radii.

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

Pressure causes expansion, lowering spatial eccentricity

Excitation function for freeze-out eccentricity, ε_F





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

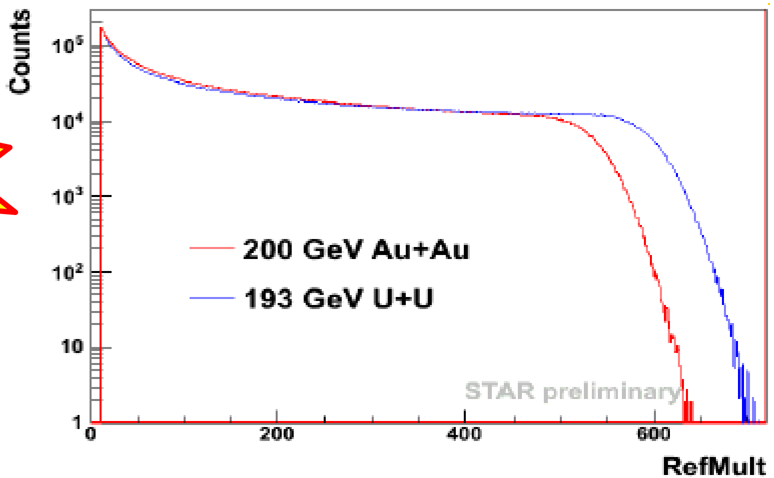
The Beam Energy Scan (phase I) datasets have allowed us to study:

- 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)

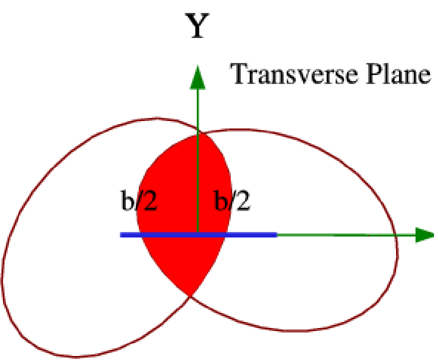
Backups

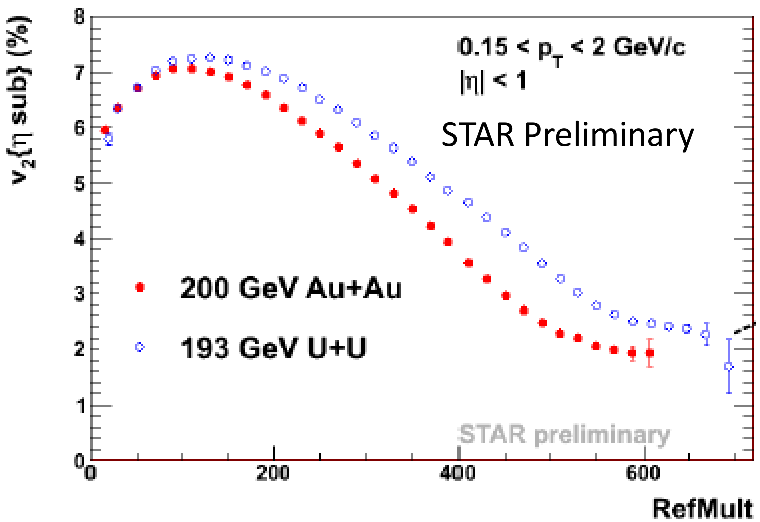
Hadron elliptic flow in $\sqrt{s_{NN}}$ = 193 GeV U+U

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)