Results on Soft Physics from Quark Matter 2012 HIP/HIC @ Nagoya University Sep. 6th 2012

Takahito Todoroki
University of Tsukuba
RIKEN Nishina Center

Contents

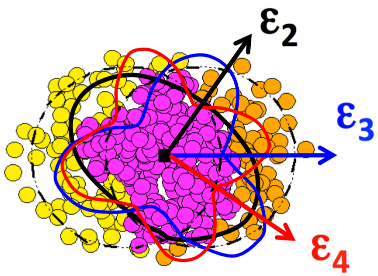
- ✧ Event plane correlations & Event-by-Event v_n
- ✧ High p_T hadron and jet v_2
- ✧ Direct photon v_2
- ✧ PIDed v_n and scaling property
- ✧ BW fit to PIDed v_n, HBT w.r.t. Φ_3
- ✧ Beam Energy Scan

Event plane correlations

7D, Mohapatra

Measured planes : Ψ_n

True planes : Φ_n



Desired correlator

Observed correlator

$$\left\langle \cos k\left(\Phi_n - \Phi_m\right)\right\rangle = \frac{\left\langle \cos k\left(\Psi_n - \Psi_m\right)\right\rangle}{\mathrm{Res}\{k\Psi_n\}\mathrm{Res}\{k\Psi_m\}}$$

arXiv: 1105.3928 PHENIX but no corrections for reso.

Resolution for individual planes

$$\mathrm{Res}\{k\Psi_n\} = \left\langle \cos\left(k\Psi_n - k\Phi_n\right)\right\rangle$$

- Can generalize into multi-plane correlations

Variable: $c_1\Phi_1 + 2c_2\Phi_2 ... + lc_l\Phi_l$ satisfying: $c_1 + 2c_2 ... + lc_l = 0$

arXiv:1104.4740, Bhalerao, Luzum, Ollitrault

$$\langle\cos(c_1\Phi_1 + ... + lc_l\Phi_l)\rangle = \frac{\langle\cos(c_1\Psi_1 + ... + lc_l\Psi_l)\rangle}{\mathrm{Res}\{c_1\Psi_1\}...\mathrm{Res}\{c_l l\Psi_l\}}$$

$$\mathrm{Res}\{c_n n\Psi_n\} = \langle\cos c_n n(\Psi_n - \Phi_n)\rangle$$

arXiv:1203.5095 1205.3585

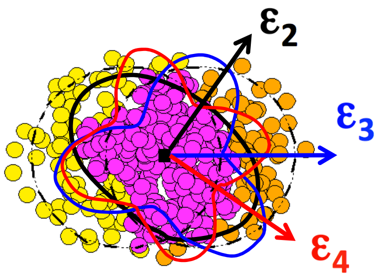
$$\mathrm{Res}\{(c_1\Psi_1 + ... + lc_l\Psi_l)\} = \mathrm{Res}\{c_1\Psi_1\}...\mathrm{Res}\{c_l l\Psi_l\}$$

Event plane correlations

7D, Mohapatra

Measured planes : Ψ_n

True planes : Φ_n



Desired correlator

Observed correlator

$$\left\langle \cos k\left(\Phi_n - \Phi_m\right)\right\rangle = \frac{\left\langle \cos k\left(\Psi_n - \Psi_m\right)\right\rangle}{\mathrm{Res}\{k\Psi_n\}\mathrm{Res}\{k\Psi_m\}}$$

arXiv: 1105.3928
PHENIX but no
corrections for reso.

Resolution for individual planes

$$\mathrm{Res}\{k\Psi_n\} = \left\langle \cos\left(k\Psi_n - k\Phi_n\right)\right\rangle$$

- Can generalize into multi-plane correlations

Variable: $c_1\Phi_1 + 2c_2\Phi_2 ... + lc_l\Phi_l$ satisfying: $c_1 + 2c_2 ... + lc_l = 0$

arXiv:1104.4740,
Bhalerao, Luzum,

$$2\Phi_2 + 3\Phi_3 - 5\Phi_5 = 3(\Phi_3 - \Phi_2) - 5(\Phi_5 - \Phi_2)$$

$$-8\Phi_2 + 3\Phi_3 + 5\Phi_5 = 3(\Phi_3 - \Phi_2) + 5(\Phi_5 - \Phi_2)$$

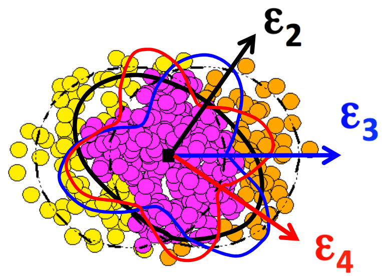
$$\mathrm{Res}\{(c_1\Psi_1 + ... + lc_l\Psi_l)\} = \mathrm{Res}\{c_1\Psi_1\}...\mathrm{Res}\{c_l l\Psi_l\}$$

Event plane correlations

7D, Mohapatra

Measured planes : Ψ_n

True planes : Φ_n



Desired correlator

Observed correlator

$$\langle \cos k(\Phi_n - \Phi_m) \rangle = \frac{\langle \cos k(\Psi_n - \Psi_m) \rangle}{\mathrm{Res}\{k\Psi_n\}\mathrm{Res}\{k\Psi_m\}}$$

arXiv: 1105.3928

ATLAS Conference Note

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-049/

- Can generalize into multi-plane correlations

Variable: $c_1\Phi_1 + 2c_2\Phi_2 ... + lc_l\Phi_l$ satisfying: $c_1 + 2c_2 ... + lc_l = 0$

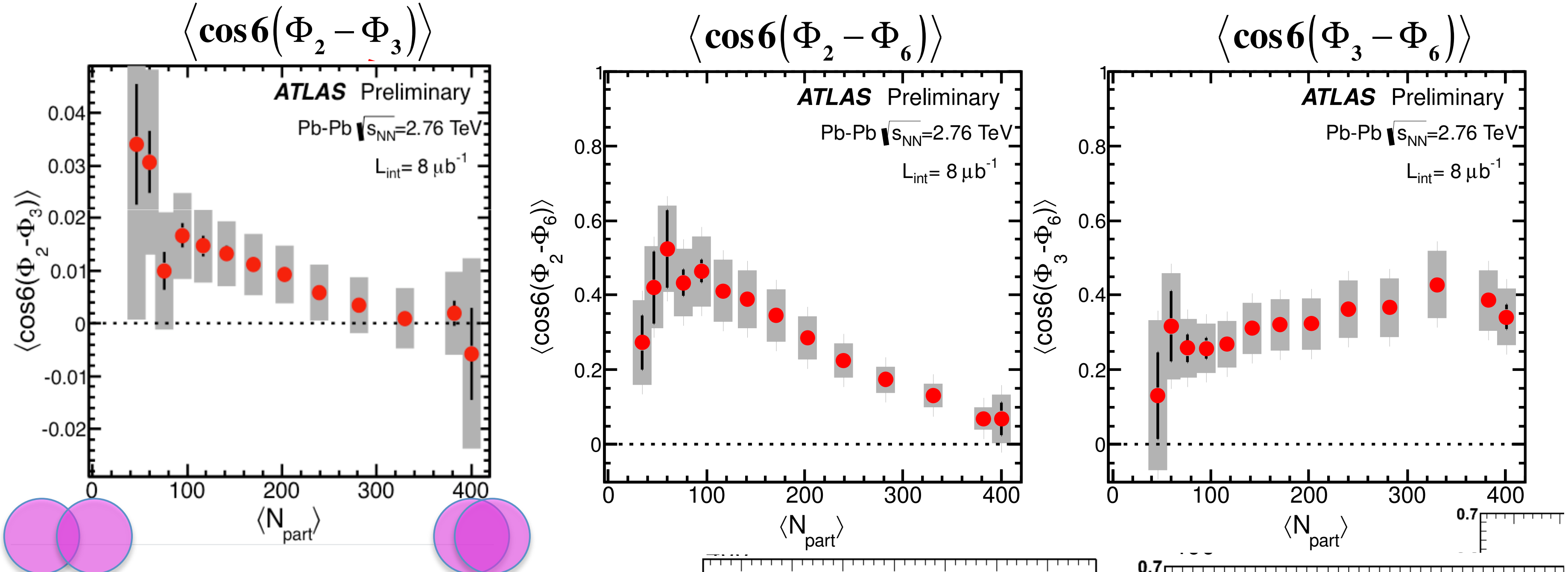
arXiv:1104.4740, Bhalerao, Luzum,

$$2\Phi_2 + 3\Phi_3 - 5\Phi_5 = 3(\Phi_3 - \Phi_2) - 5(\Phi_5 - \Phi_2)$$

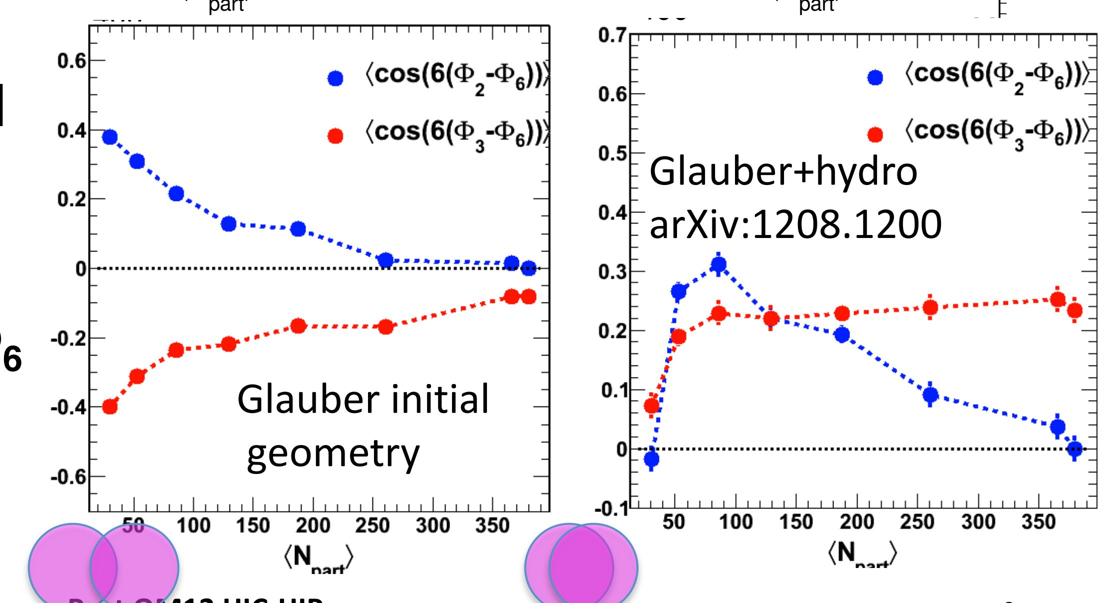
$$-8\Phi_2 + 3\Phi_3 + 5\Phi_5 = 3(\Phi_3 - \Phi_2) + 5(\Phi_5 - \Phi_2)$$

$$\mathrm{Res}\{(c_1\Psi_1 + ... + lc_l\Psi_l)\} = \mathrm{Res}\{c_1\Psi_1\}...\mathrm{Res}\{c_l l\Psi_l\}$$

Two plane correlations

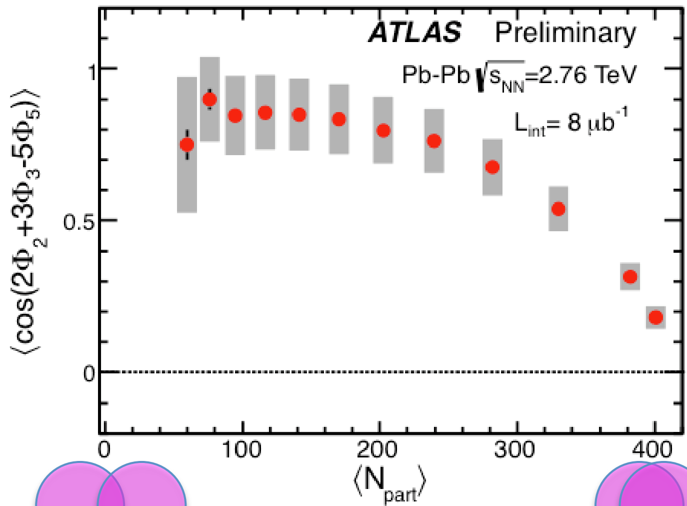


- ✧ Φ_2 & Φ_3 weakly correlated
- ✧ Both strongly correlated with Φ_6
  - Alignment between Φ_{23} & Φ_6
- ✧ Opposite centrality dependence

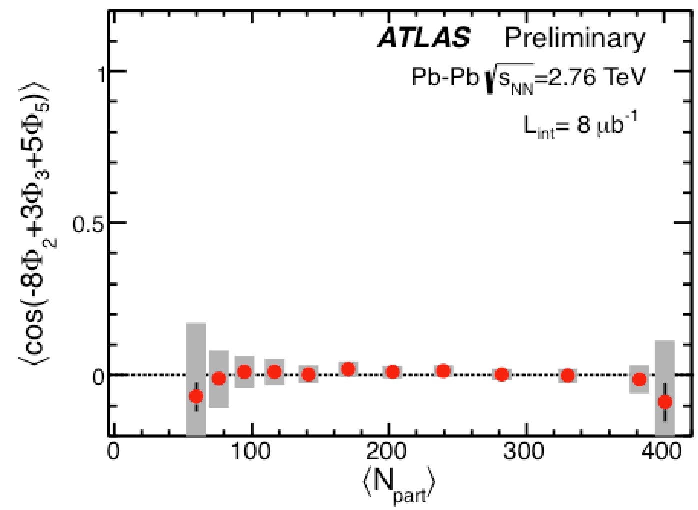


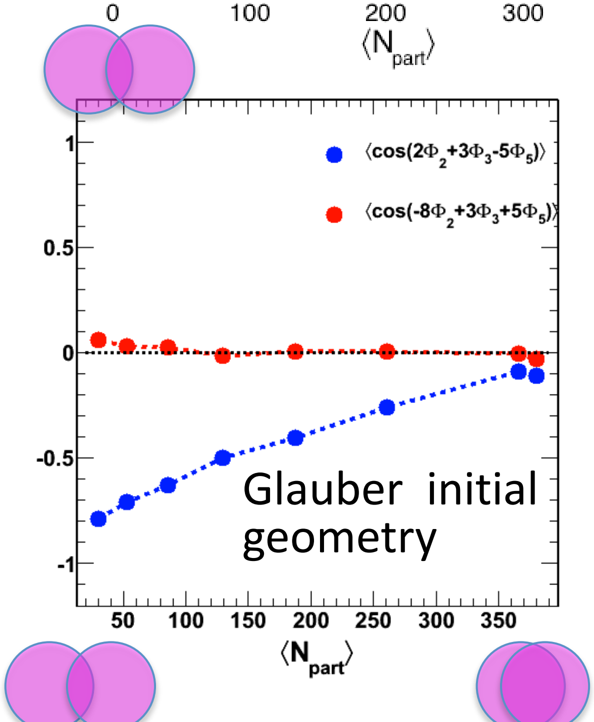
Three plane correlations

$$\left\langle \cos\left(2\Phi_2 + 3\Phi_3 - 5\Phi_5\right)\right\rangle$$



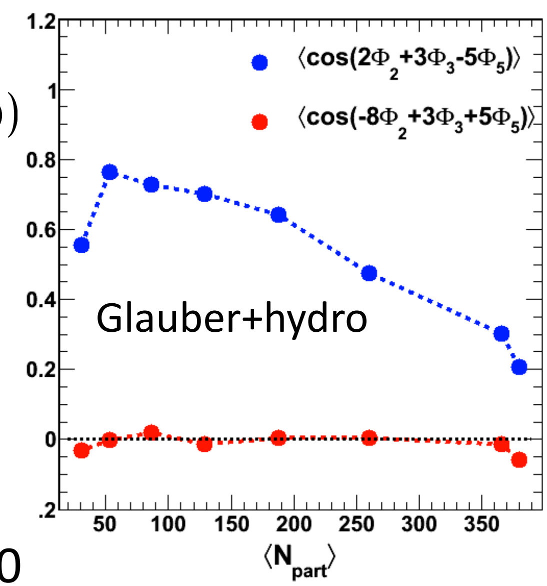
$$\left\langle \cos\left(-8\Phi_2 + 3\Phi_3 + 5\Phi_5\right)\right\rangle$$





Glauber geometry does not match the $\cos\left(2\Phi_2 + 3\Phi_3 - 5\Phi5)\right)$ correlation

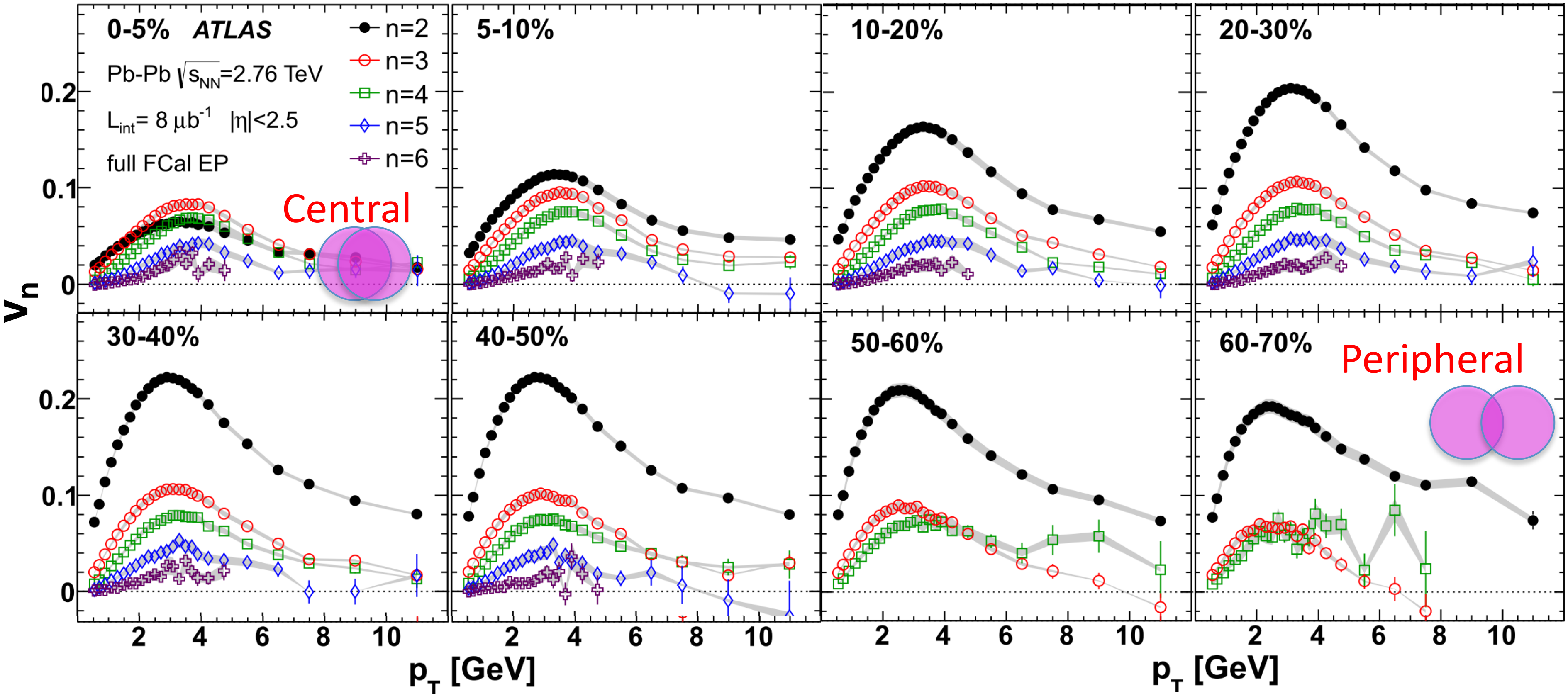
Hydro evolution qualitatively reproduces the centrality dependence



Glauber+hydro
arXiv:1208.1200

Event averaged v_n (n=2-6) in broad p_T range

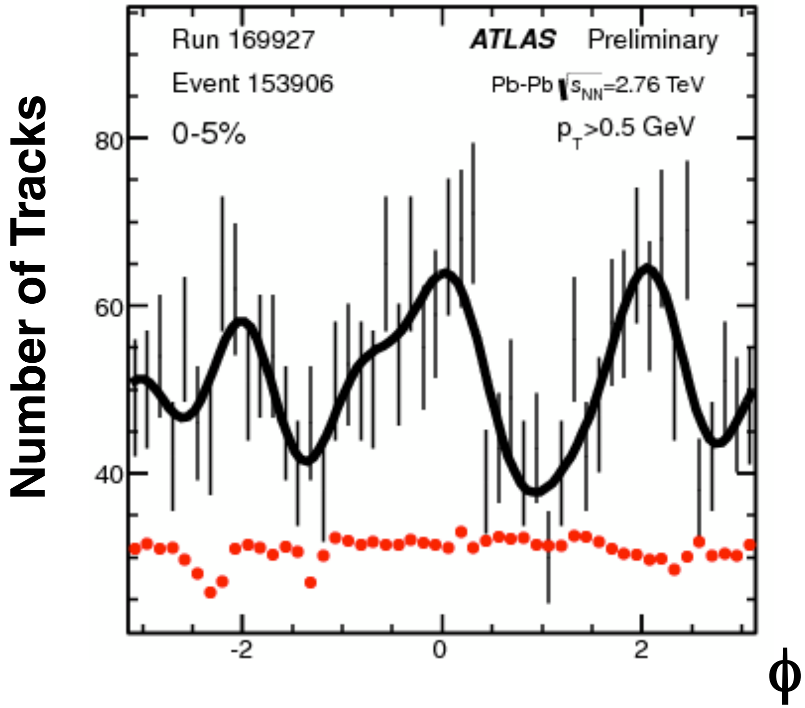
ATLAS, Phys. Rev. C 86, 014907 (2012)



- ✧ Significant v_2 - v_6 in broad p_T and centrality
- ✧ Similar p_T dependence
- ✧ In most central collisions(0-5%): v_3 & v_4 > v_2

Event-by-Event v_n

Singles



- **Event by Event single particle distributions**

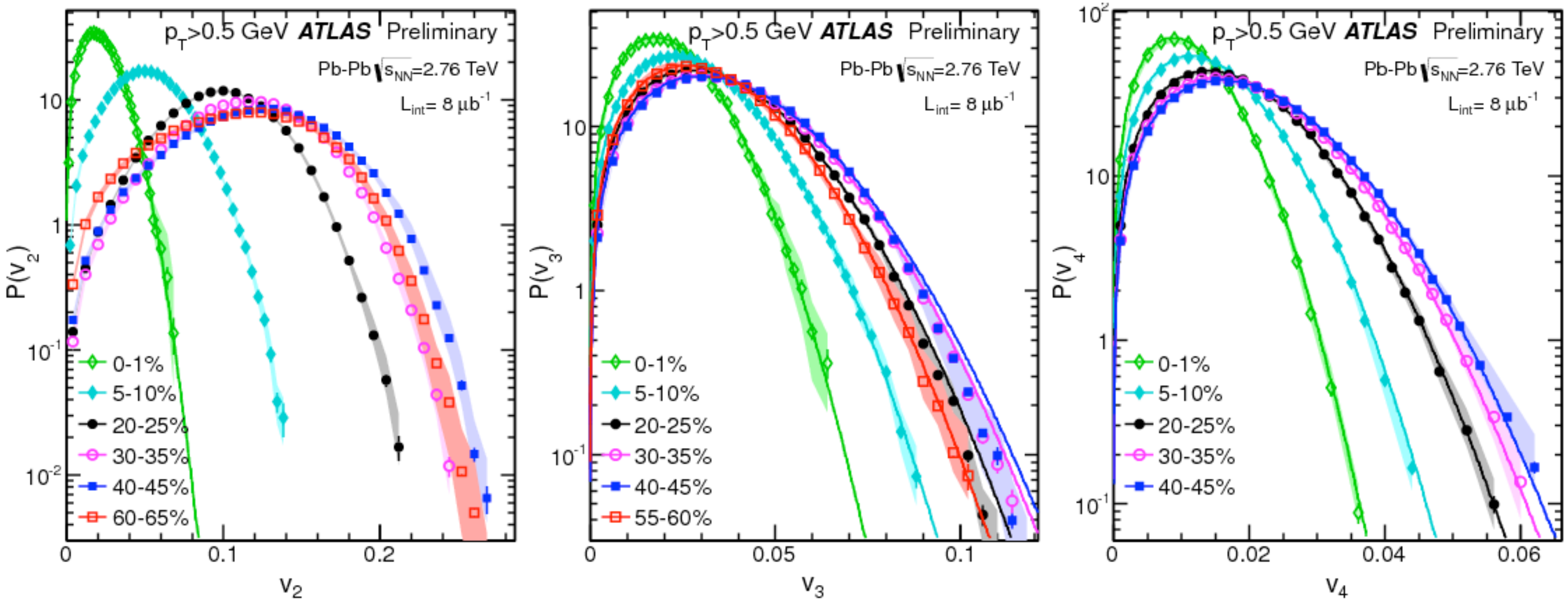
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n^{\rm obs} \cos n(\phi - \Psi_n^{\rm obs}) = 1 + 2\sum_{n=1}^{\infty}\left(v_{n,{\rm x}}^{\rm obs}\cos n\phi + v_{n,{\rm y}}^{\rm obs}\sin n\phi\right)$$

- **Obtaining amplitude and correction & unfolding**

$$\vec{v}_n^{\rm obs} = (v_{n,{\rm x}}^{\rm obs}, v_{n,{\rm y}}^{\rm obs})$$

Event-by-Event v_n

4A, Jia



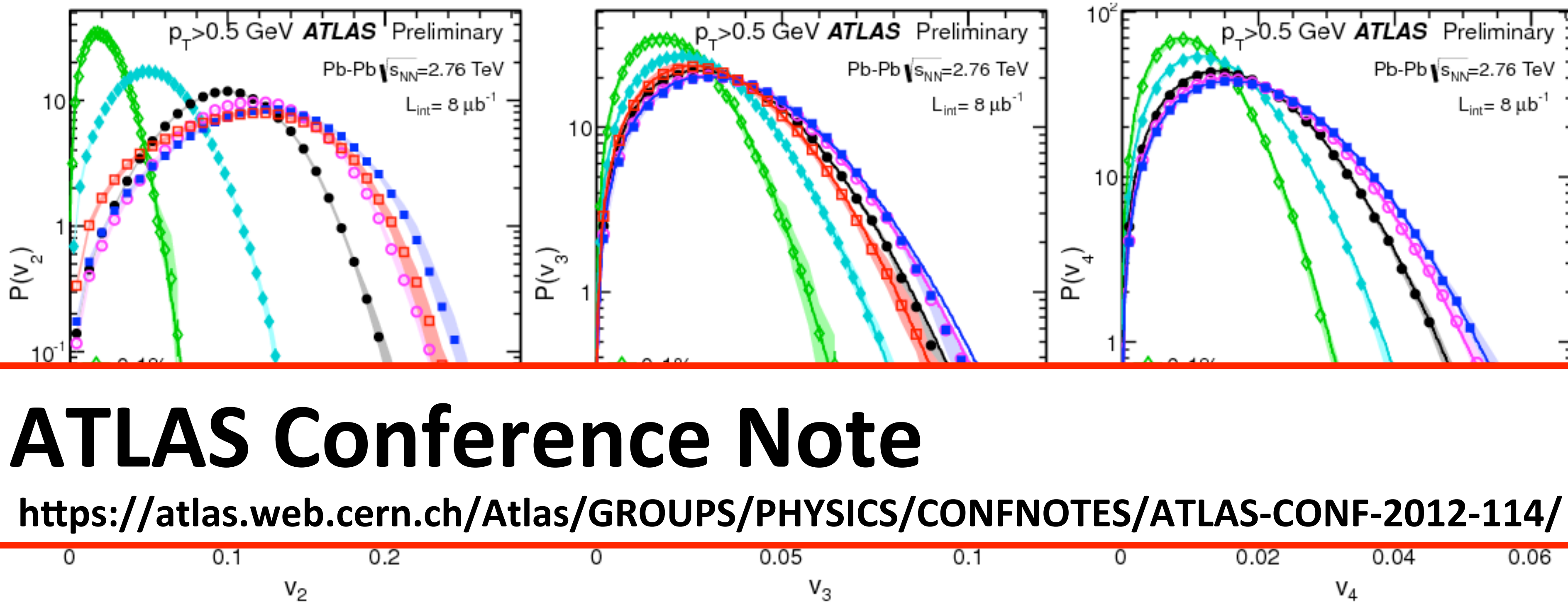
✧ **Event by Event single particle distributions**

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n^{\rm obs} \cos n(\phi - \Psi_n^{\rm obs}) = 1 + 2\sum_{n=1}^{\infty} \left(v_{n,\rm x}^{\rm obs} \cos n\phi + v_{n,\rm y}^{\rm obs} \sin n\phi\right)$$

✧ **Obtaining amplitude and correction & unfolding**

$$\vec{v}_n^{\rm obs} = (v_{n,\rm x}^{\rm obs}, v_{n,\rm y}^{\rm obs})$$

Event-by-Event v_n



ATLAS Conference Note

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-114/

- **Event by Event single particle distributions**

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n^{\text{obs}} \cos n(\phi - \Psi_n^{\text{obs}}) = 1 + 2\sum_{n=1}^{\infty} \left(v_{n,\text{x}}^{\text{obs}} \cos n\phi + v_{n,\text{y}}^{\text{obs}} \sin n\phi\right)$$

- **Obtaining amplitude and correction & unfolding**

$$\vec{v}_n^{\,\text{obs}} = (v_{n,\text{x}}^{\text{obs}}, v_{n,\text{y}}^{\text{obs}})$$

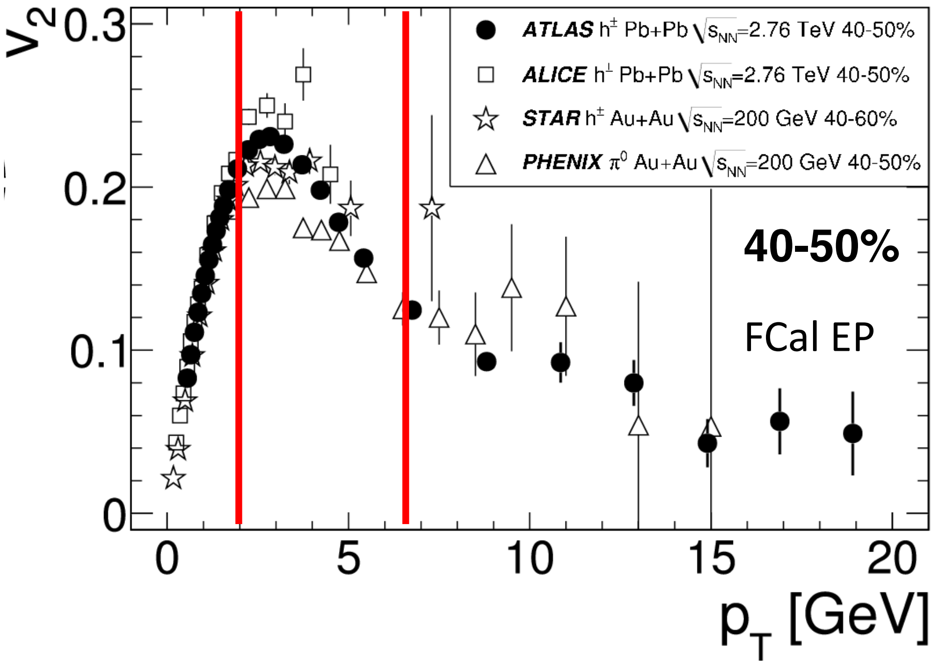
High p_T single hadron and jet v_2

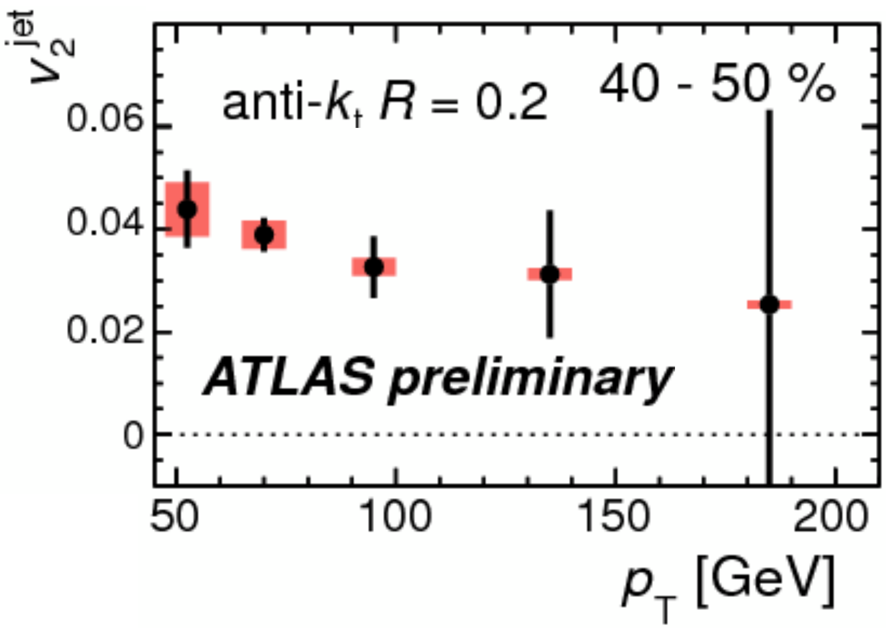
Low p_T: hydro expansion

Medium p_T: coalescence

High p_T: jet quenching

2B, Angerami





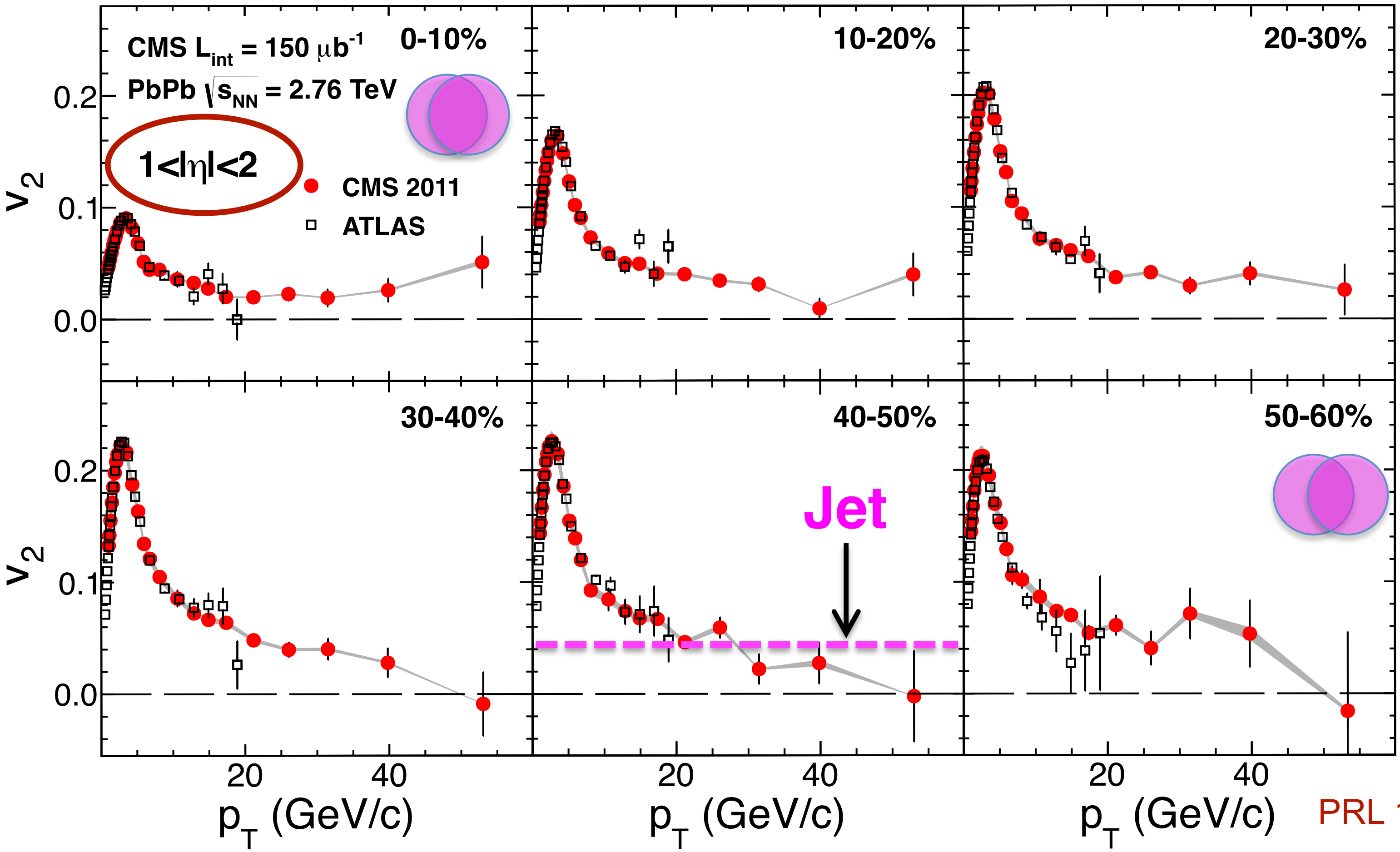
✧ **None-zero v2 of single hadrons at high p_T**

✧ **Jet v2 is qualitatively consistent with high p_T single hadron v2**

- **Path length dependence of parton energy loss**

Very high p_T v_2 via 2PC

1C, Zhukova



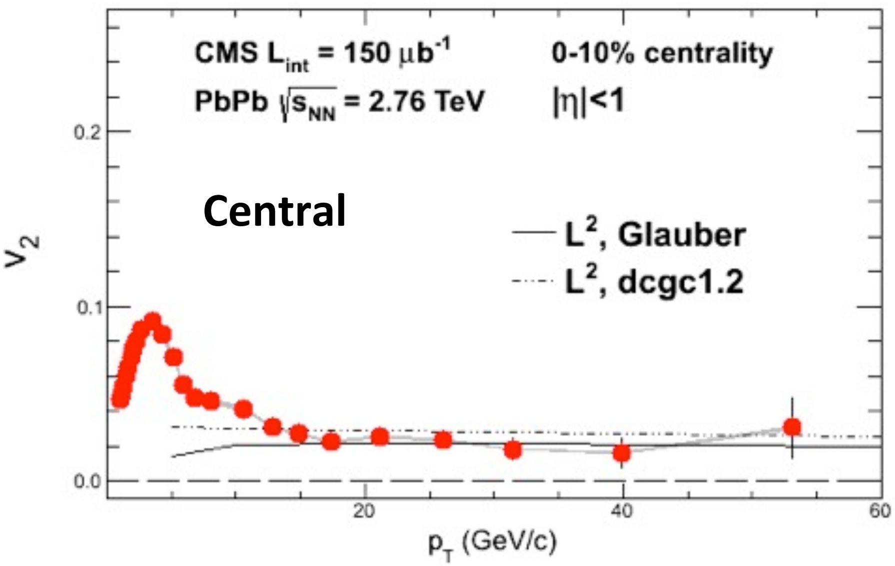
PRL 109, 022301(2012)

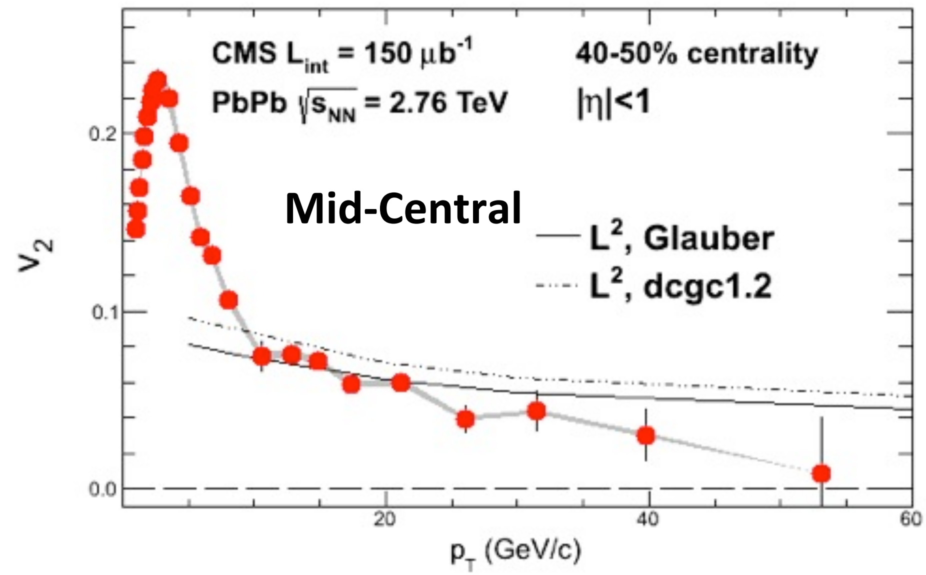
- ✧ None zero v_2 up to p_T 40 GeV/c
- ✧ Comparable to jet v_2 above 20 GeV/c

Theory Comparison

1C, Zhukova

Data: PRL 109.022301(2012)



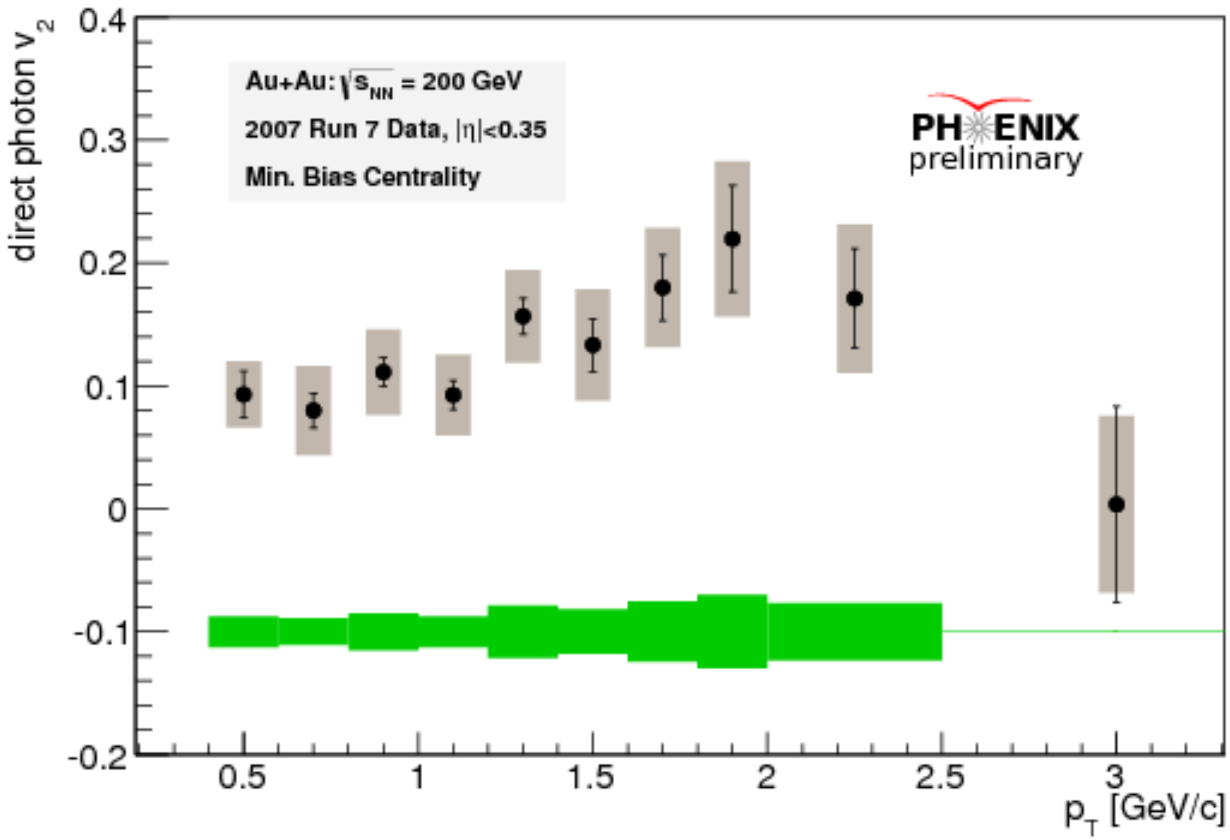


Theory: B.Betz,M.Gyulassy;arXiv:1201.0281

-Data can constrain different theoretical scenarios

Direct Photon v_2

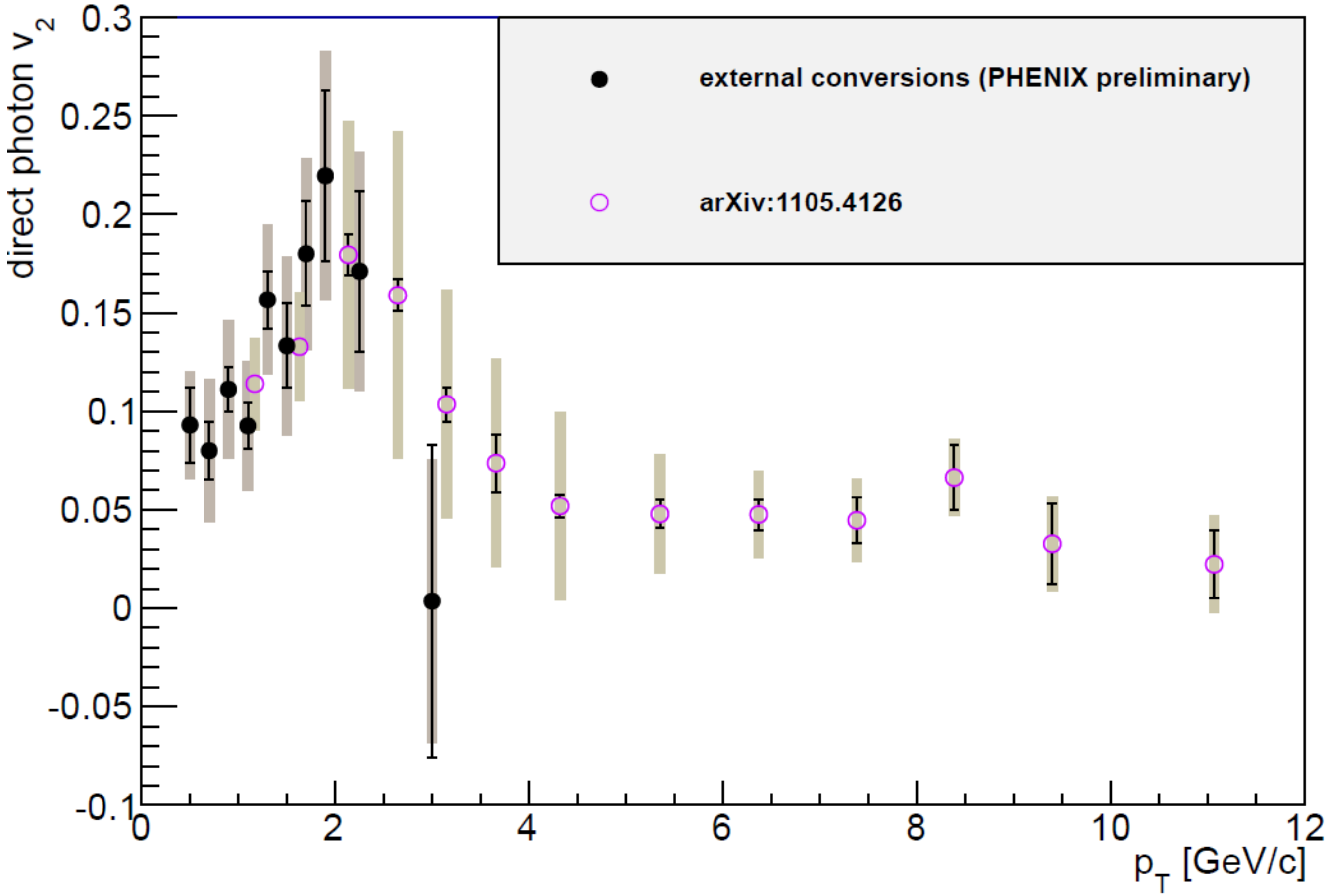
IVA, Tserruya



- v_2 down to 0.5 GeV via external conversion di-electron pairs
- Consistency check with previous measurements via photon
- Agreement up to 2 GeV, None-zero v_2 is conclusive

Direct Photon v_2

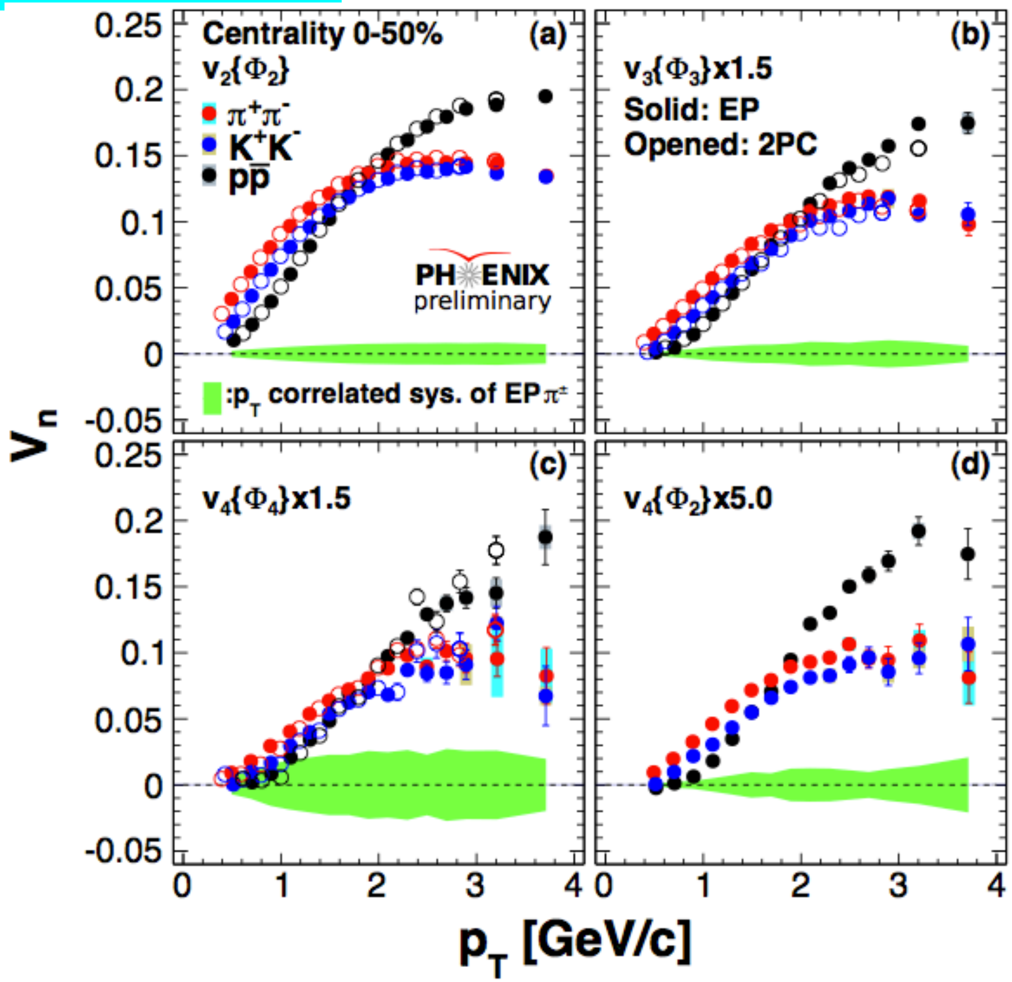
IVA, Tsserruya



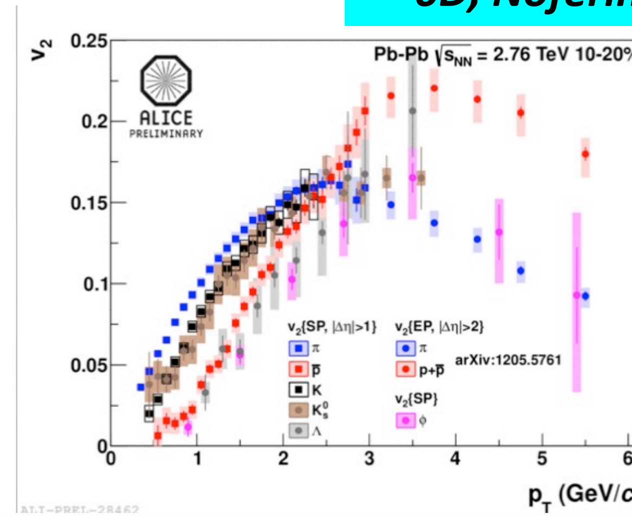
- ✧ v_2 down to 0.5 GeV via external conversion di-electron pairs
- ✧ Consistency check with previous measurements via photon
- ✧ Agreement up to 2 GeV, None-zero v_2 is conclusive

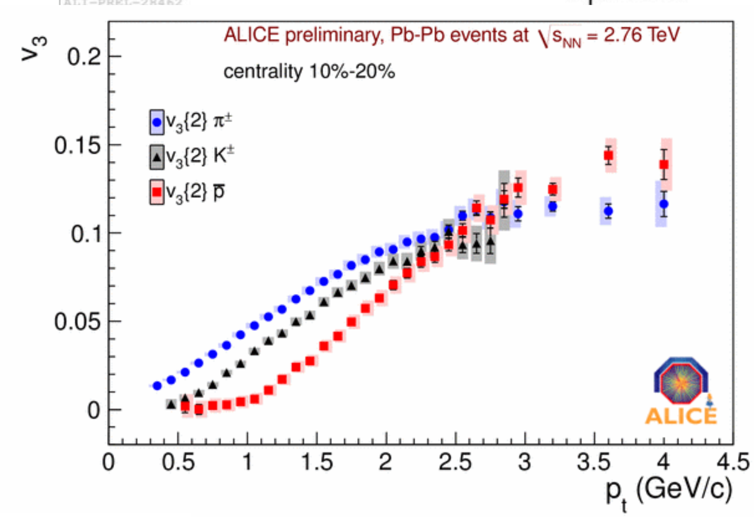
Identified particle v_n

2A, Yi Gu



6D, Noferini

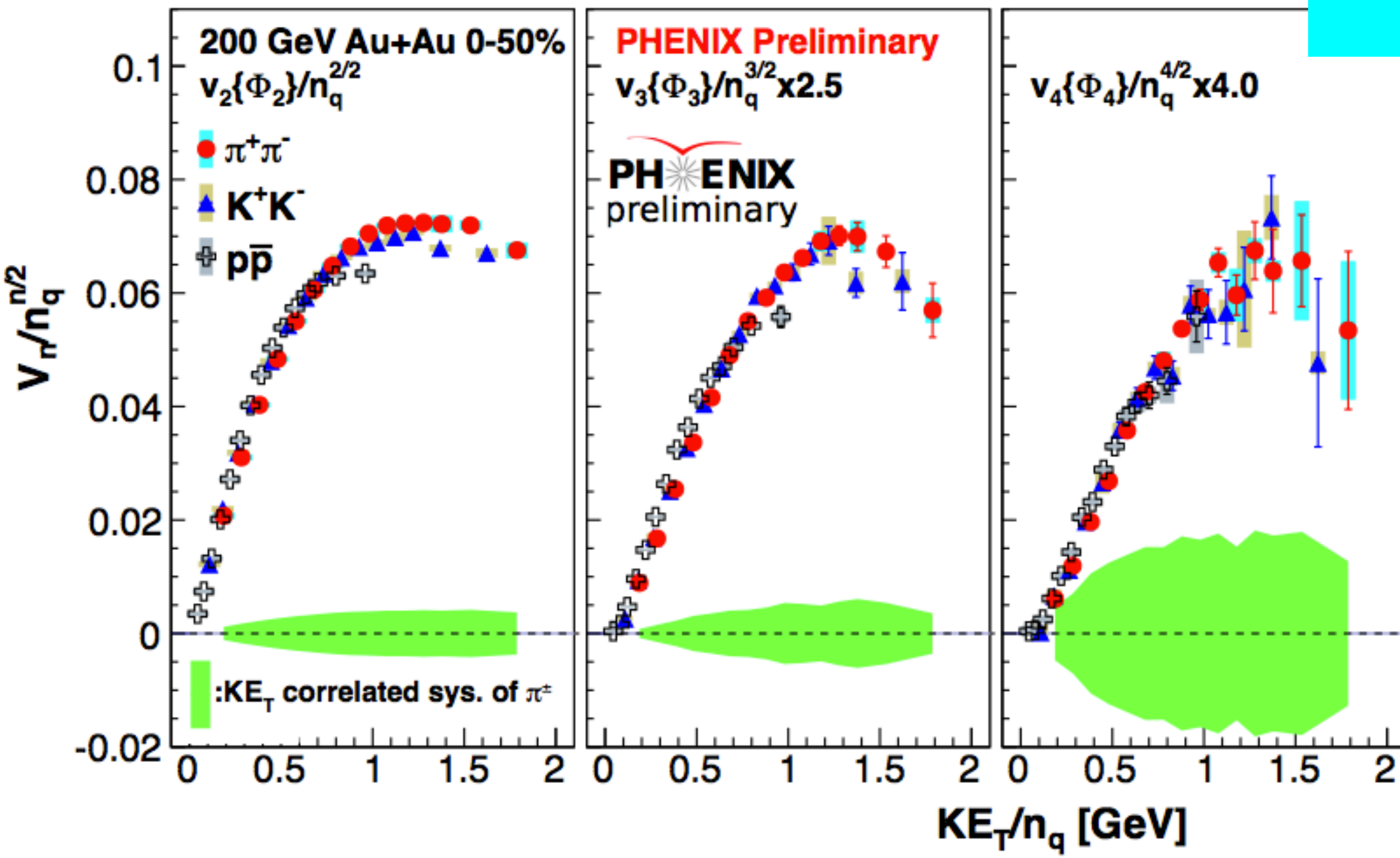




- ✧ **Mass ordering at low p_T**
- ✧ **Coalescence at intermediate p_T**

Number of constituent quark : N_q scaling of vn

2A, Yi Gu



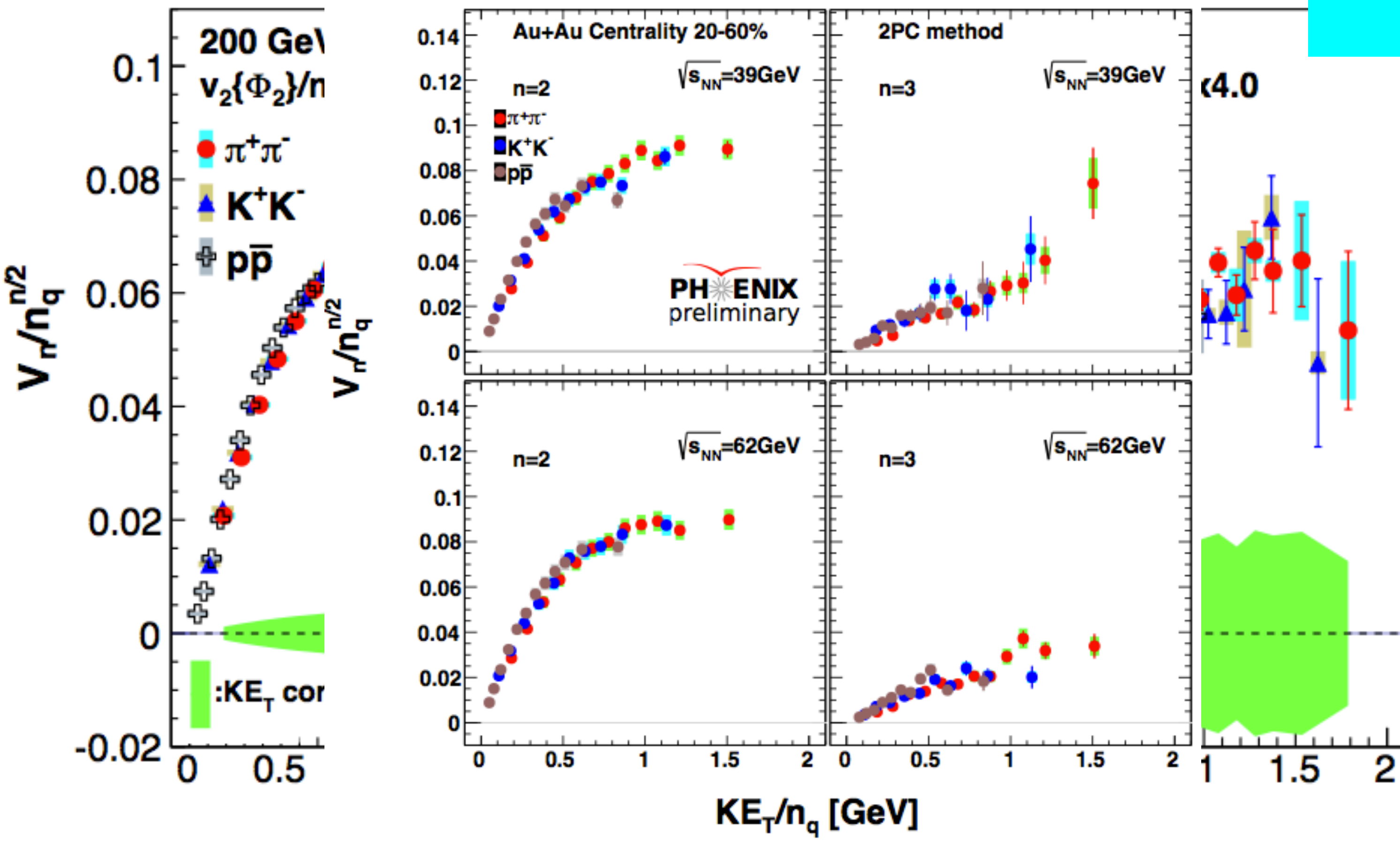
✧ N_q scaling up to KE_T/n_q = 0.7 GeV for v_2, v_3, and v_4

- Down to 39 GeV for v_2 and v_3

✧ Scaling of higher harmonics originating from $v_n^{1/n} \propto v_2^{1/2}$

Number of constituent quark : N_q scaling of vn

2A, Yi Gu



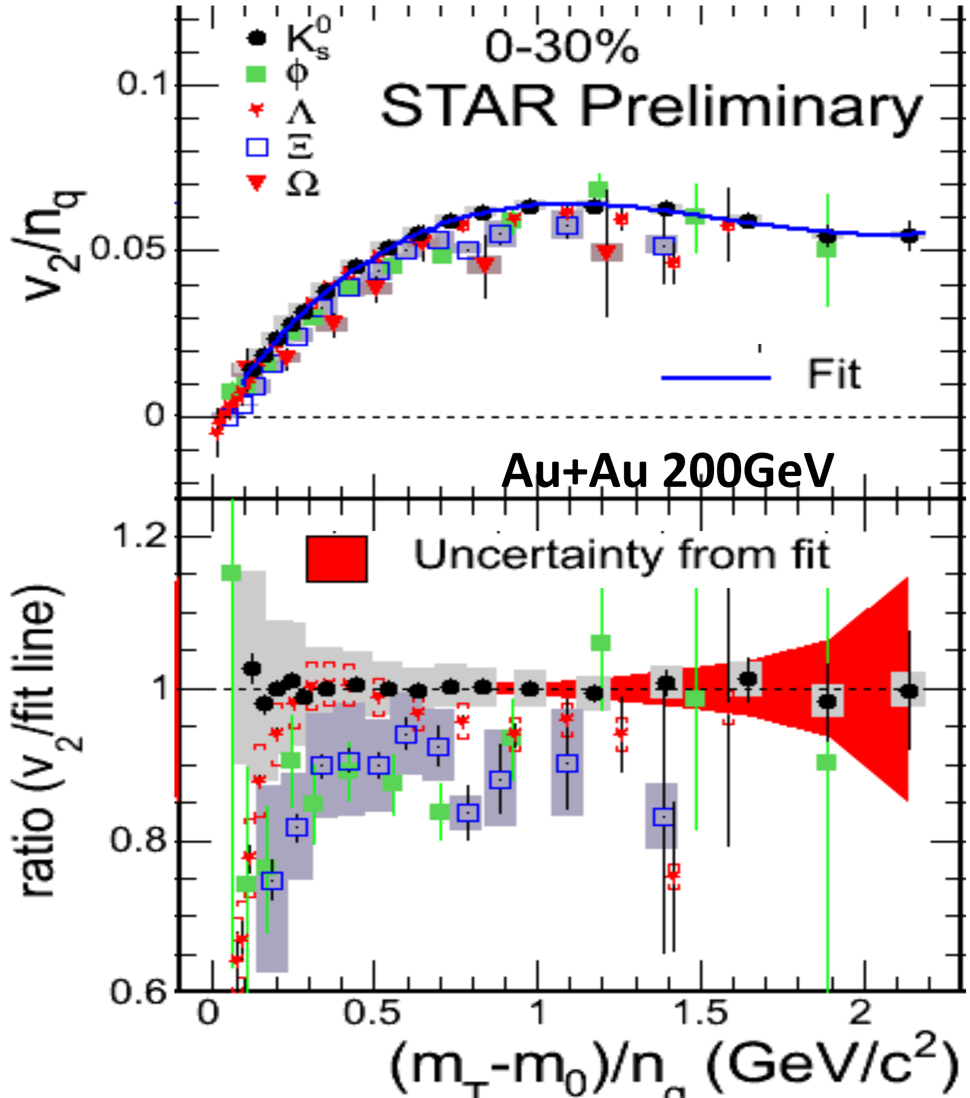
✧ N_q scaling up to KE_T/n_q = 0.7 GeV for v_2, v_3, and v_4

- Down to 39 GeV for v_2 and v_3

✧ Scaling of higher harmonics originating from $v_n^{1/n} \propto v_2^{1/2}$

N_q scaling of strange hadron v_2

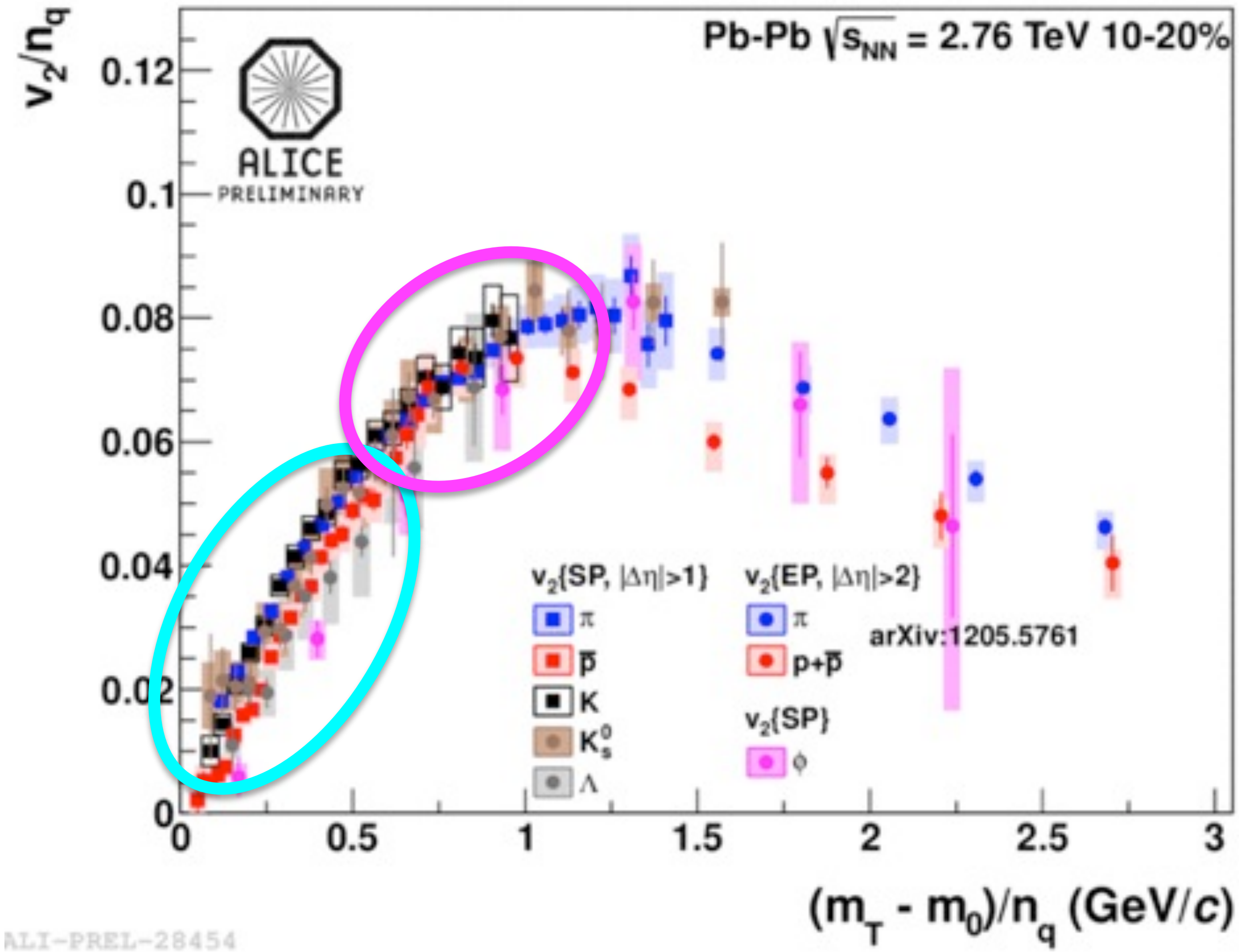
3A, Nasim



- ✧ **K^0_S follows scaling curve of π, K, & P**
- ✧ **Multi-strangeness hadrons deviate from K^0_S**

N_q scaling of v_2 at LHC

6D, Noferini



✧ **Deviation from pi, K for P, Λ, φ at low p_T**

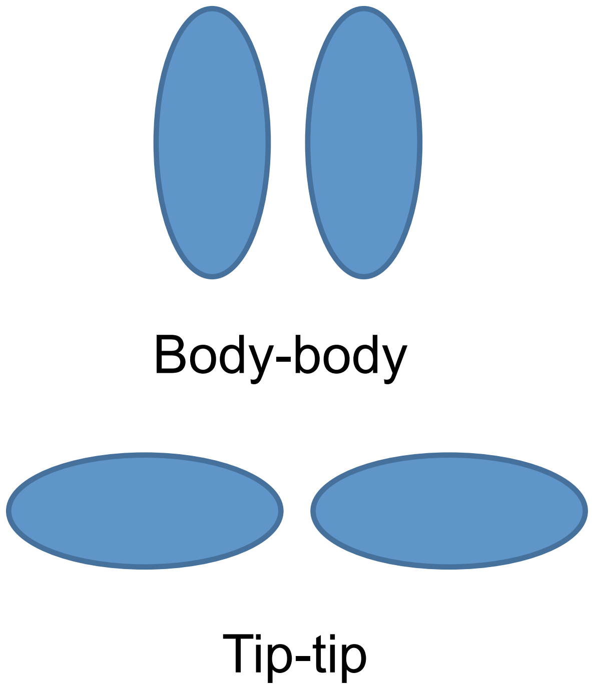
- **Due to stronger radial flow at LHC than RHIC?**

✧ **N_q scaling survives at intermediate p_T**

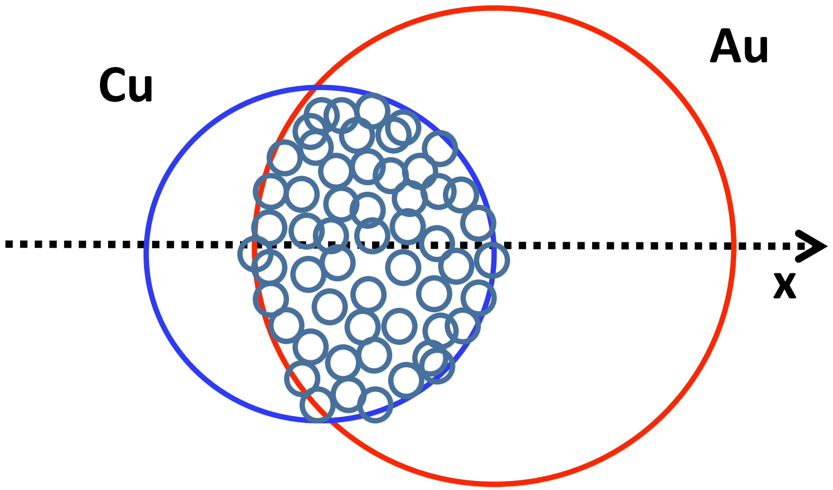
Geometry controlled collision systems

4A, Huang

U+U collisions



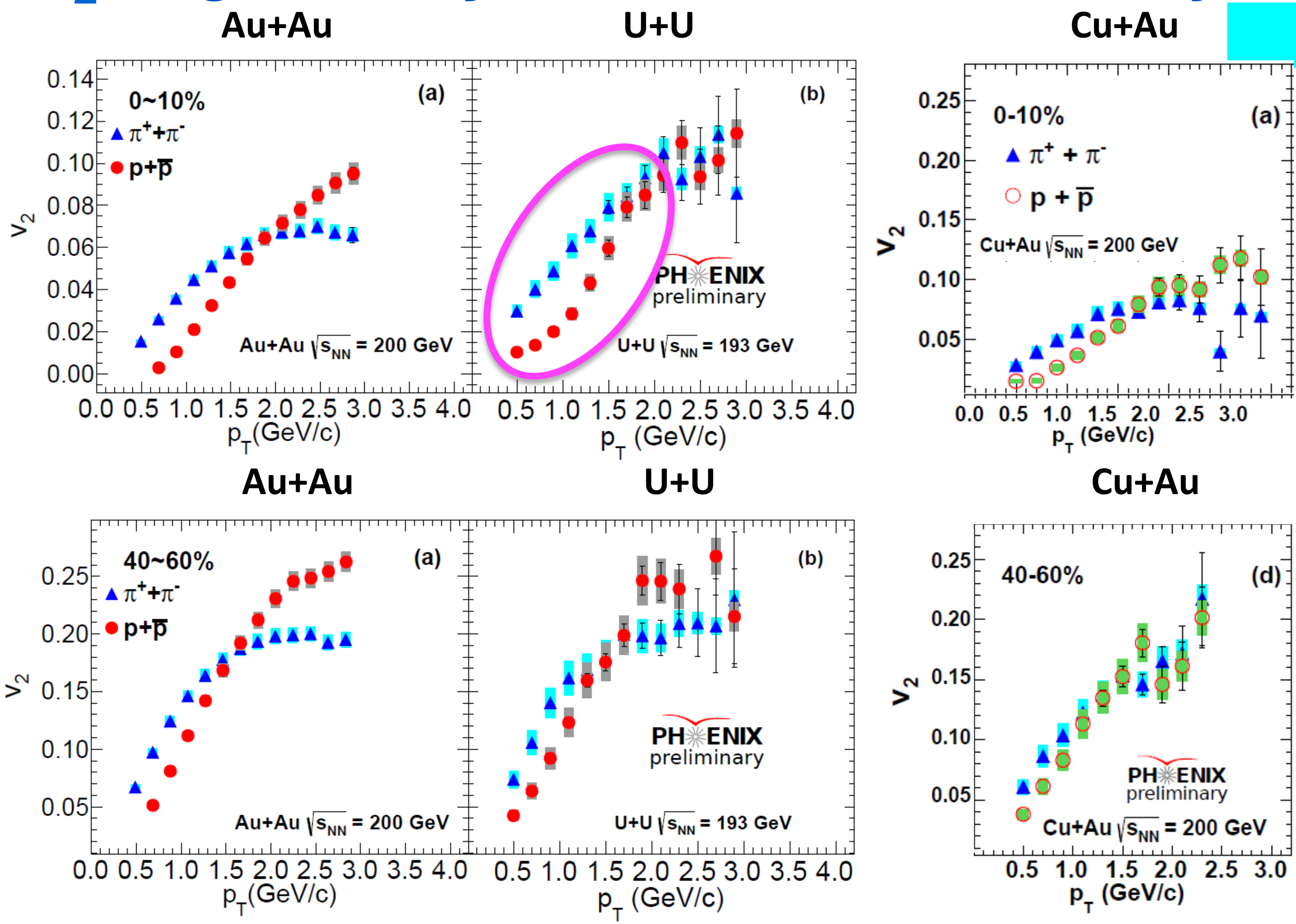
Cu+Au collisions



- ✧ **Various collision geometry**
- ✧ **This time only centrality selected**
- ✧ **Rich constraints to models in future**

v_2 in geometry controlled collision systems

4A, Huang



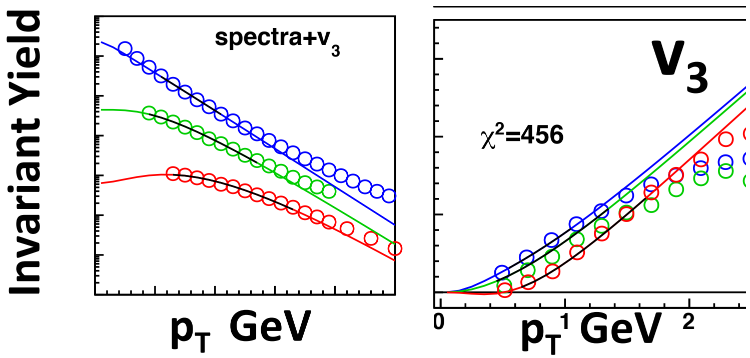
✧ **Stronger mass splitting in most central U+U collisions**

Triangularity at freeze-out

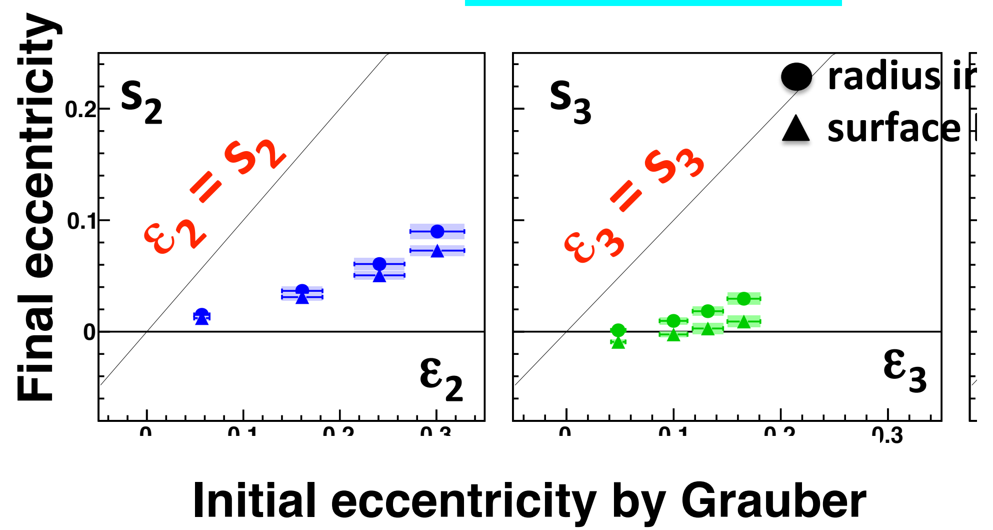
BW fitting to PID v_n

$$\frac{dN}{p_T dp_T} \propto \int\int r\,dr\,d\phi\, m_T I_0(\alpha_T) K_1(\beta_T)$$

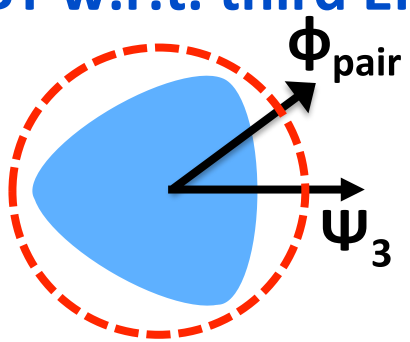
$$v_n = \frac{\int\int r\,dr\,d\phi \cos(n\phi) I_n(\alpha_T) K_1(\beta_T)\{1+2s_n\cos(n\phi)\}}{\int\int r\,dr\,d\phi I_0(\alpha_T) K_1(\beta_T)\{1+2s_n\cos(n\phi)\}}$$

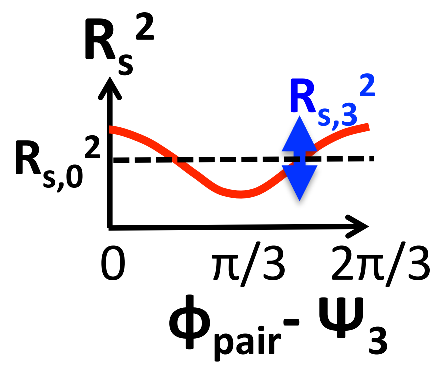


Poster, Mizuno

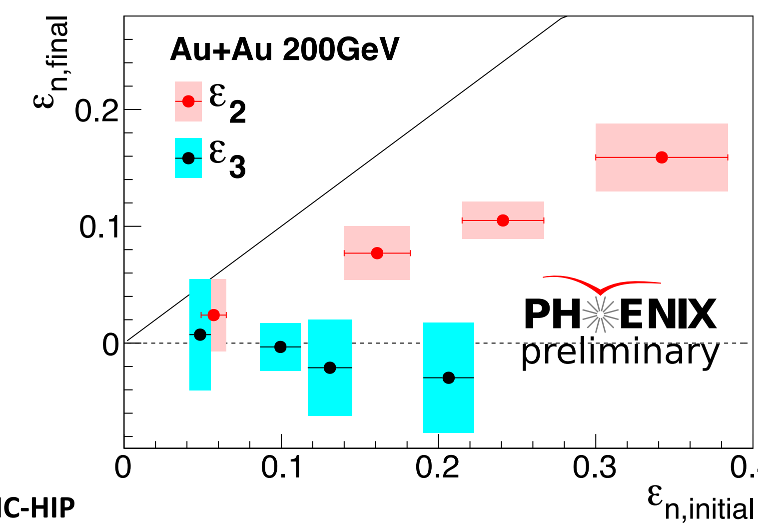


HBT w.r.t. third EP





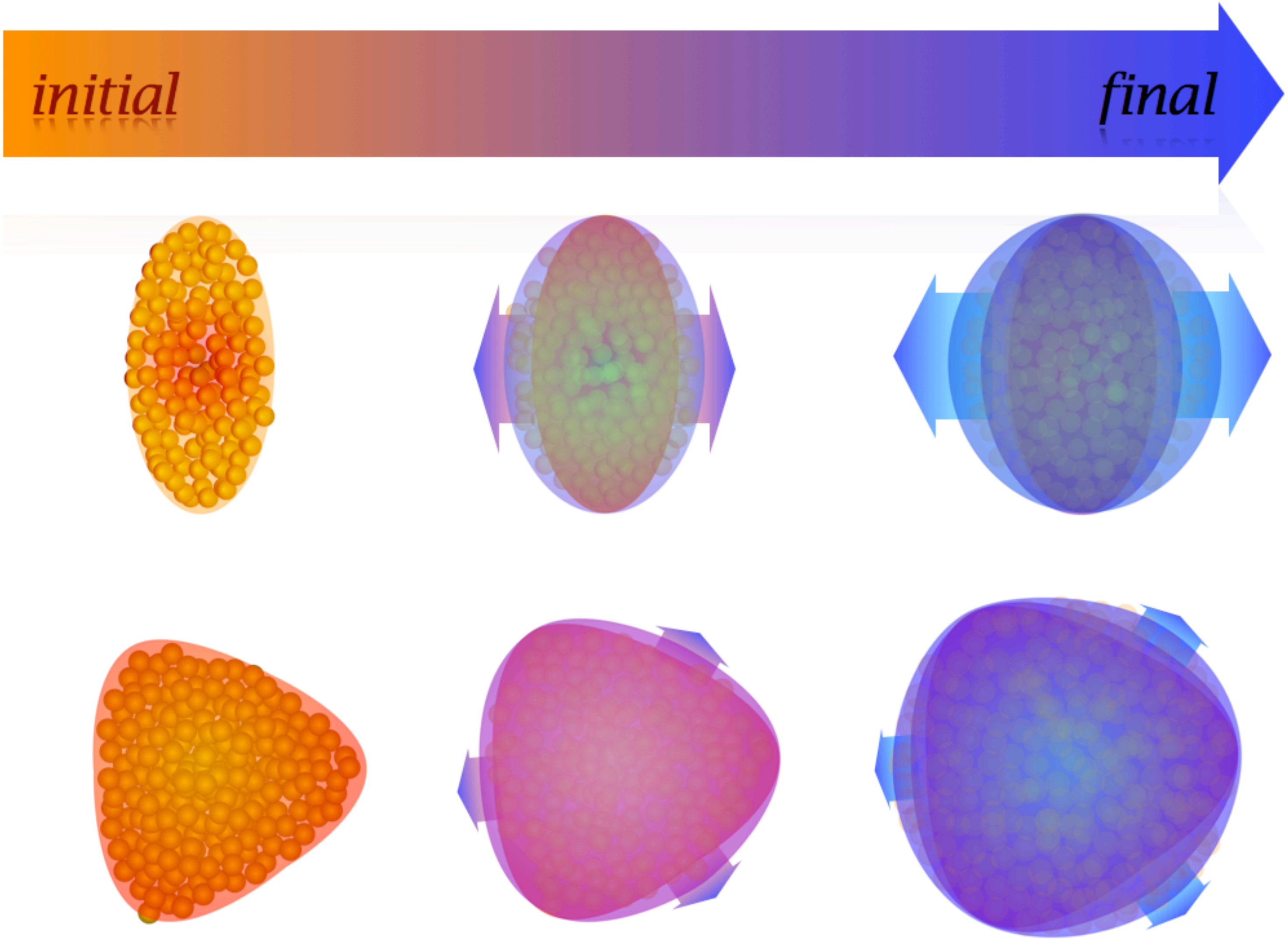
1C, Niida



Final eccentricity in HBT (including expansion effect) →

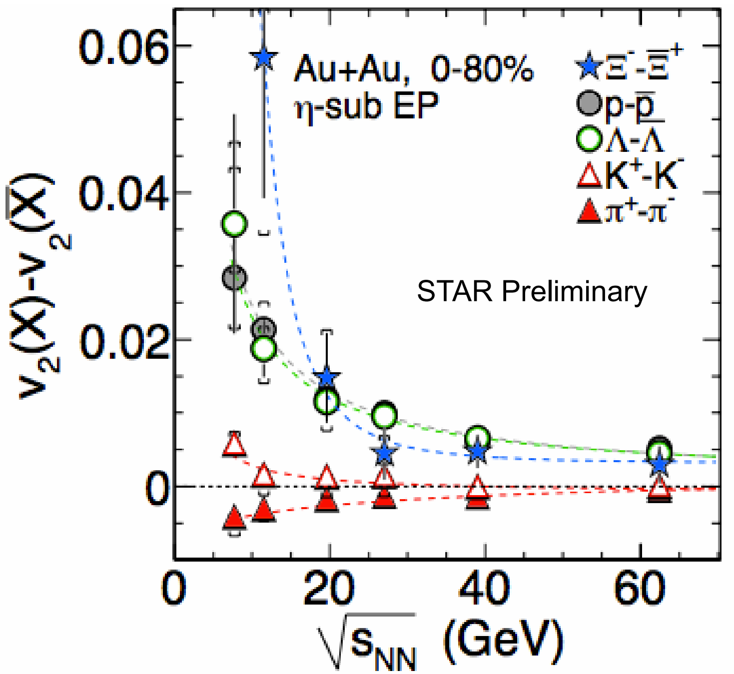
$$\varepsilon_{3,final} = 2\frac{R_{s,3}^2}{R_{s,0}^2}$$

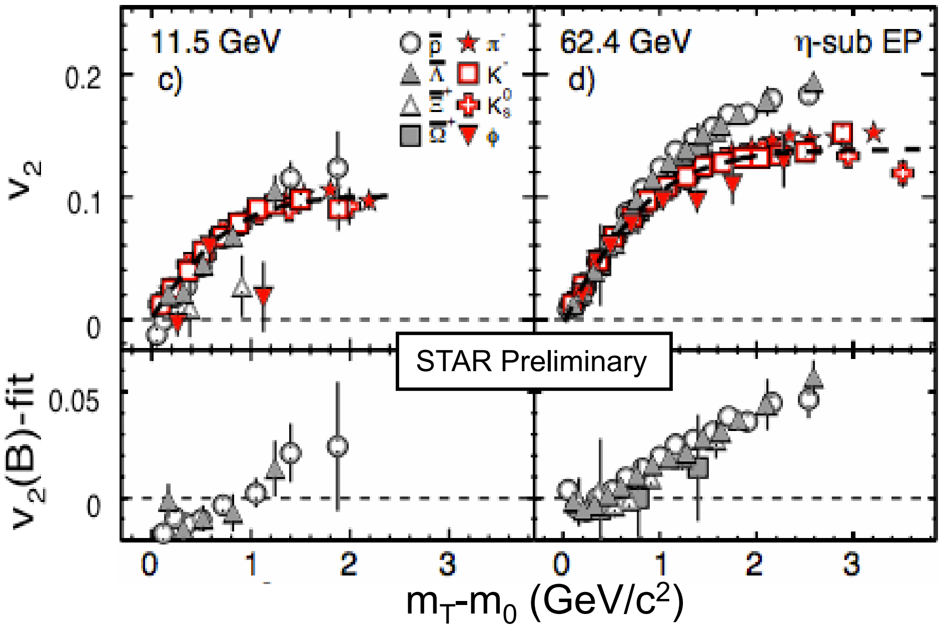
Triangularity washed out?



Beam Energy Scan – N_q scaling

6B, Shi

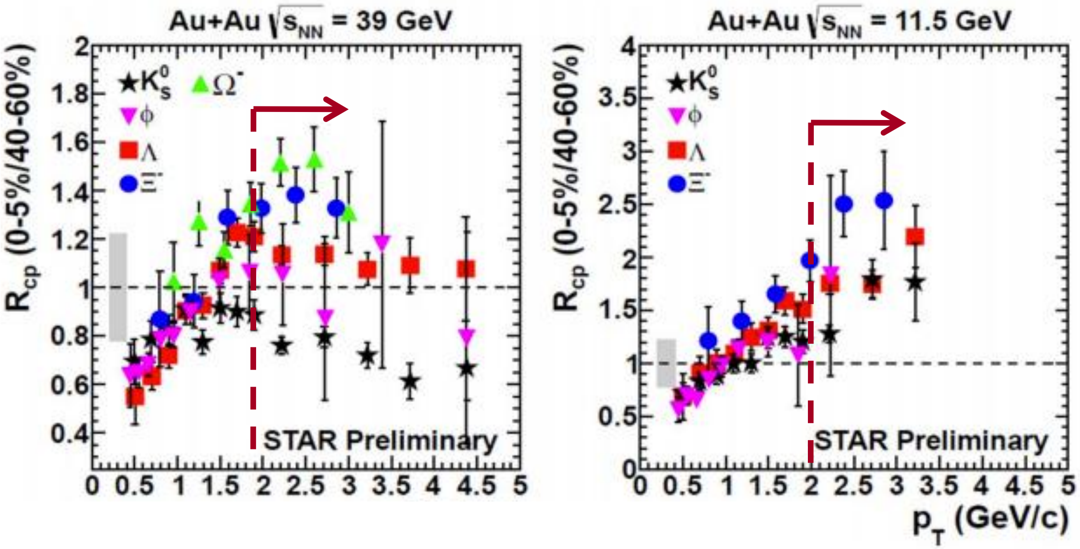


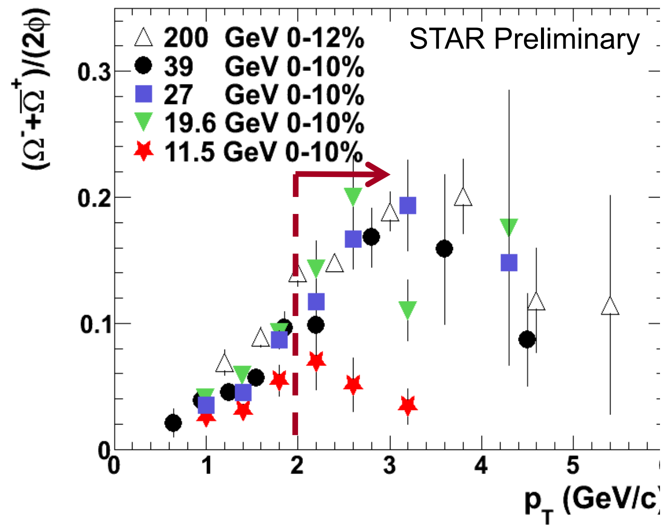


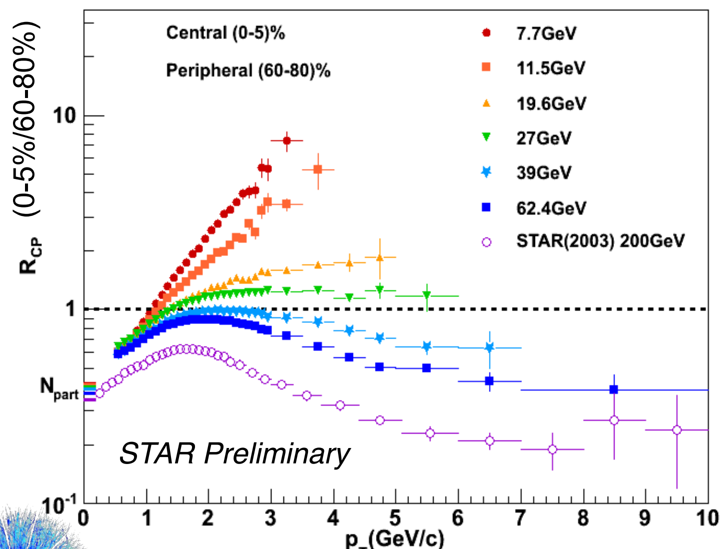
- Significant difference between baryon-antibaryon v_2 at lower energies.
- No clear baryon/meson grouping for anti-particles at <=11.5 GeV.

NCQ scaling is broken!

BES-Modifications of R_{CP}







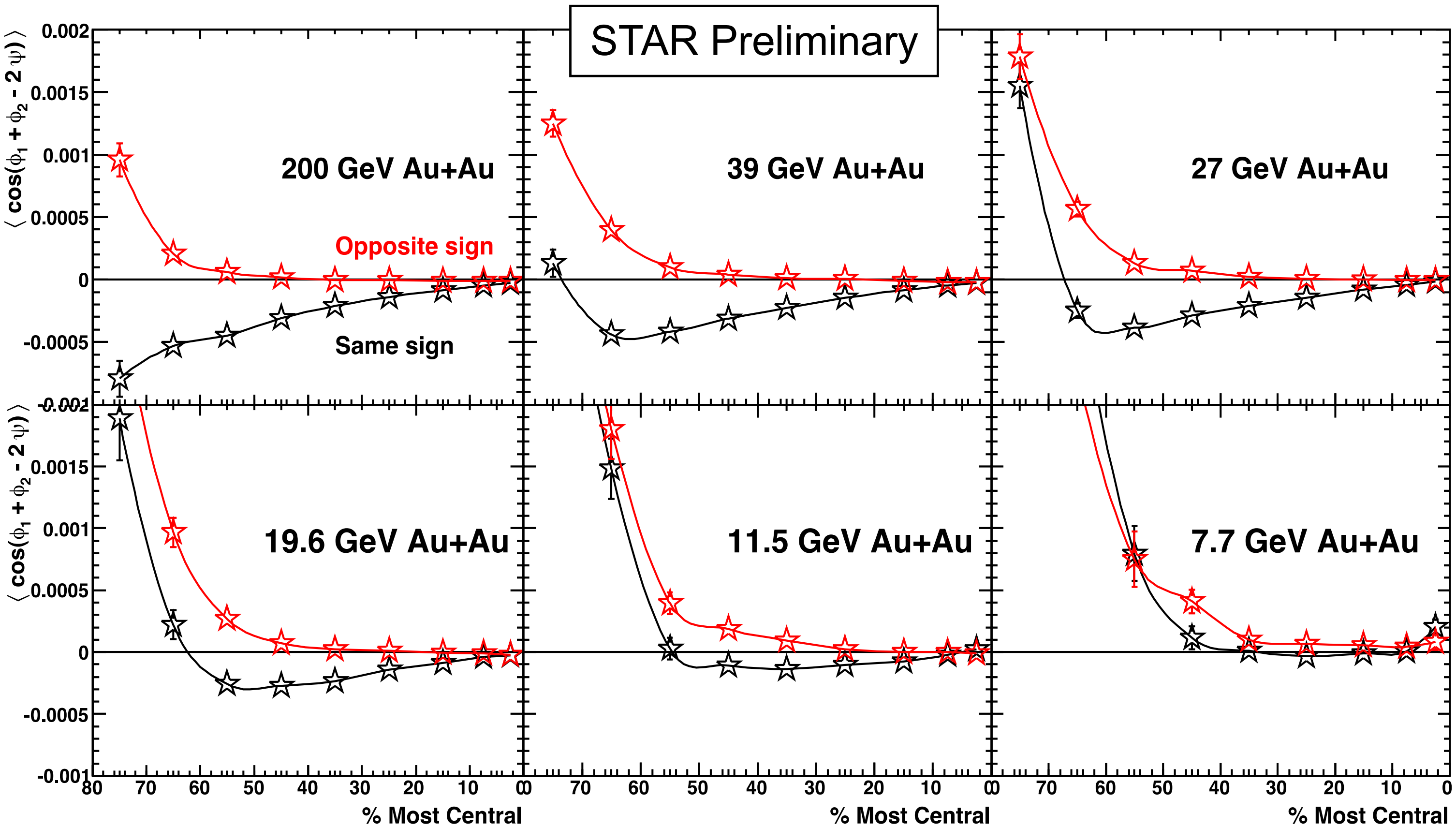
- Baryon-meson splitting reduces and disappears with decreasing energy.
- Ω/ϕ ratio falls off at 11.5 GeV.

- R_{cp} >~ 1 at 11.5, 7.7 GeV. - Cronin effect?

R_{cp} suppression NOT seen at lower energies!

Zhang, 5A, Thu. Sangaline, 5C, Thu. Horvat, poster #94

BES-Disappearance of Charge Separation w.r.t. EP



Wang, IVB, Thu.

- Motivated by search for local parity violation. Require sQGP formation.
- The splitting between OS and LS correlations (charge separation) seen in top RHIC energy Au+Au collisions.

This charge separation signal disappears at lower energies (<= 11.5 GeV)!

Summary-1

✧ **EP correlations and Event-by-Event v_n**

- **More constraints to Hydro. Calculations**

✧ **None-zero high p_T hadron & jet v_2**

- **Qualitatively consistent behavior with each other**
- **Path length dependence of parton energy loss**

✧ **Direct photon v_2 down to 0.5 GeV/c via conversion di-electrons**

- **Conclusive none-zero v_2 at low p_T**

Summary-2

✧ N_q scaling for v_2, v_3 & v_4

- Deviation from scaling curve of v_2 as strangeness increase at RHIC
- P, Λ, ϕ v_2 don't follow scaling curve of v_2 at LHC

✧ BW fit to PID v_n & HBT w.r.t. Φ_3

- Triangularity may be washed out by space time evolution

✧ Beam Energy Scan

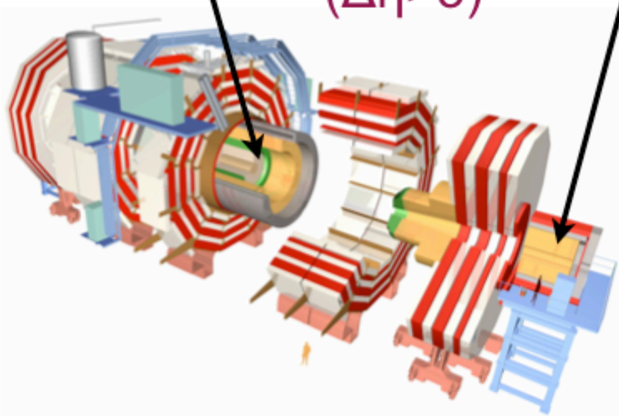
- Trends of observables change around 11 GeV

Back Up Slides

Elliptic Flow (n=2)

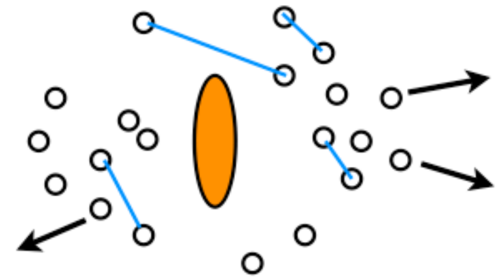
Event Plane

Correlate particles in tracker with those in HF. ($\Delta\eta > 3$)



Two-particle Cumulant

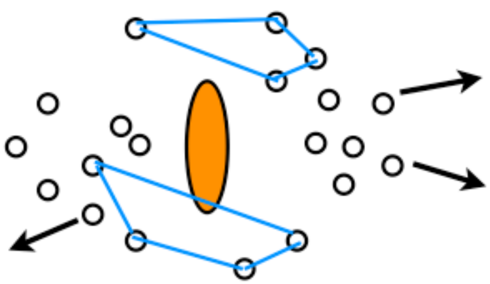
Consider all two-particle correlations.



Methods have different sensitivity to event-by-event fluctuations and non-flow effects.

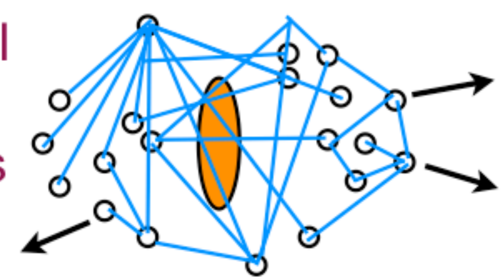
Four-particle Cumulant

Consider all four-particle correlations.

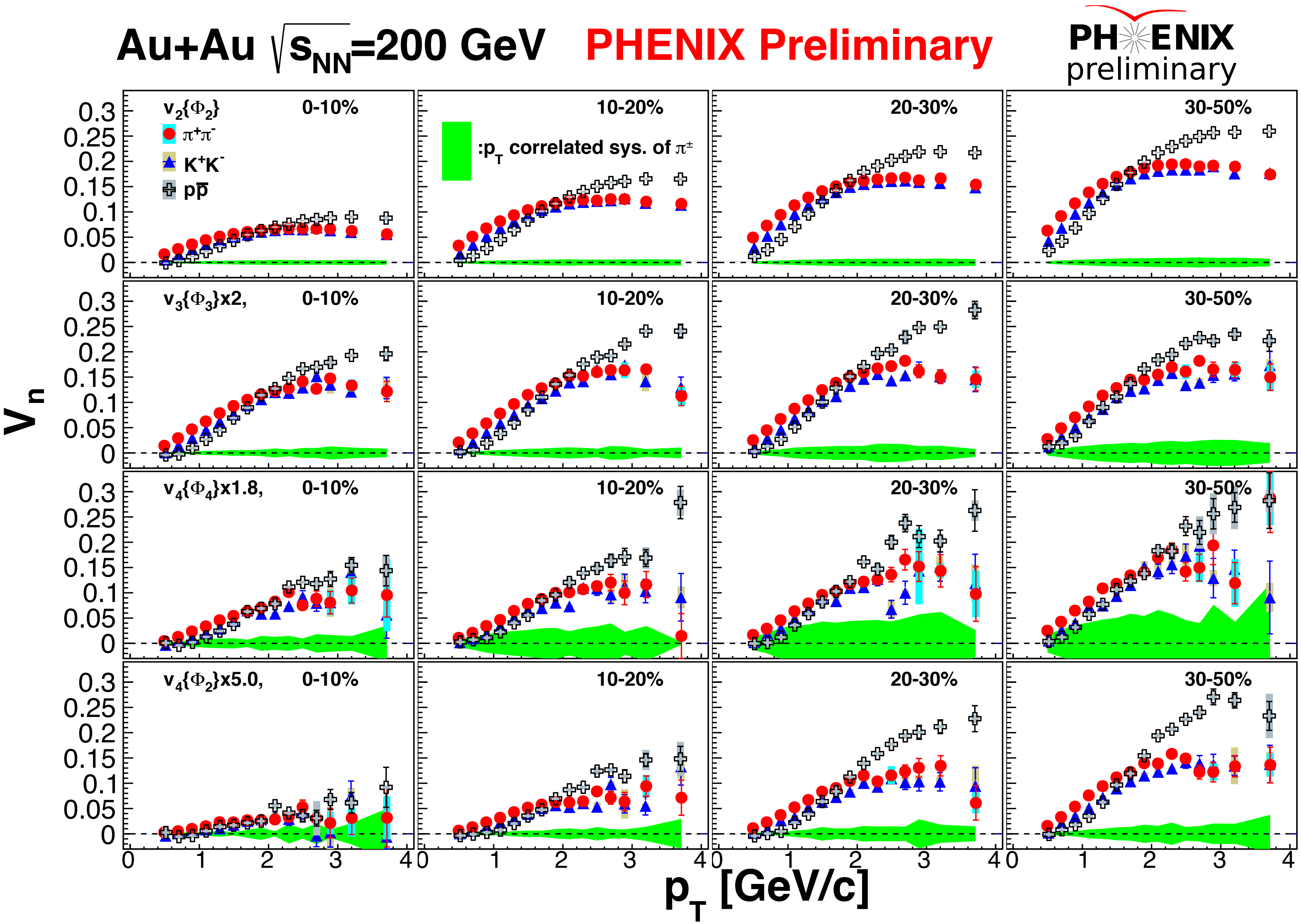


Lee-Yang Zeros

Consider all particle correlations -(Not all shown!).

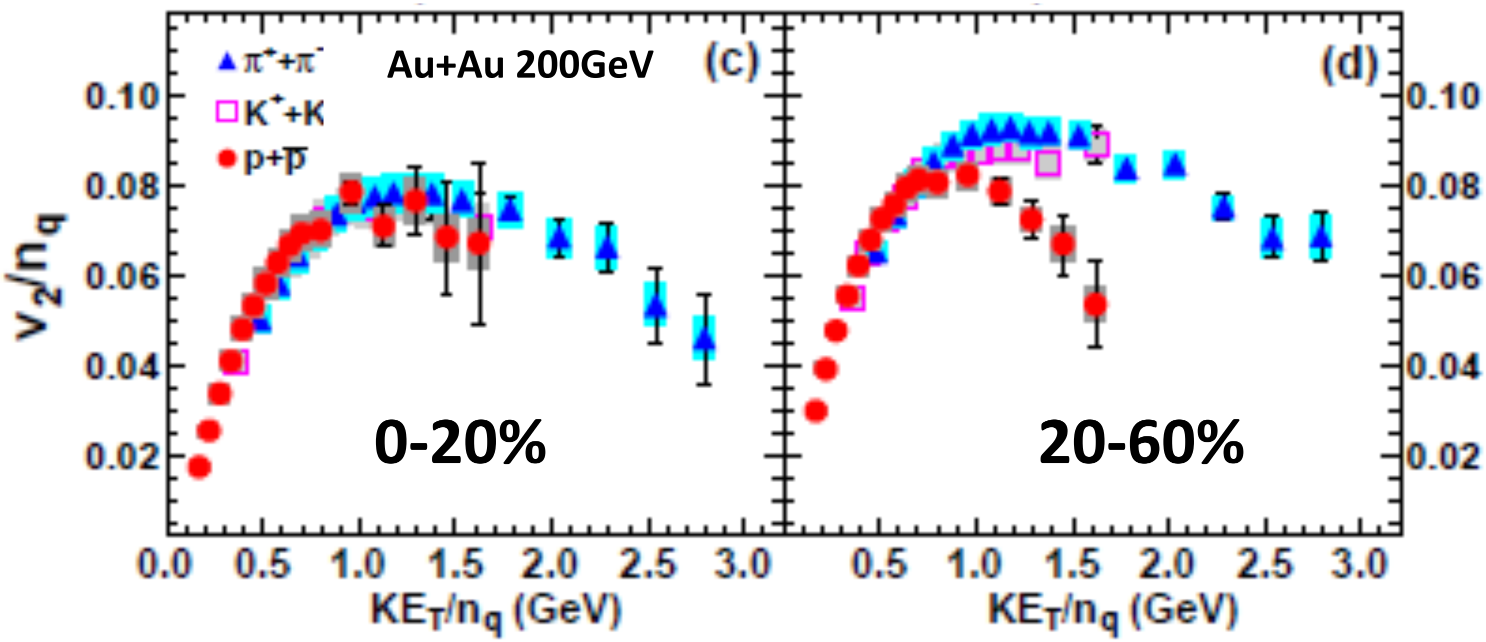


Identified particle v_n



Break of N_q scaling of v_2 at high p_T

4A, Huang

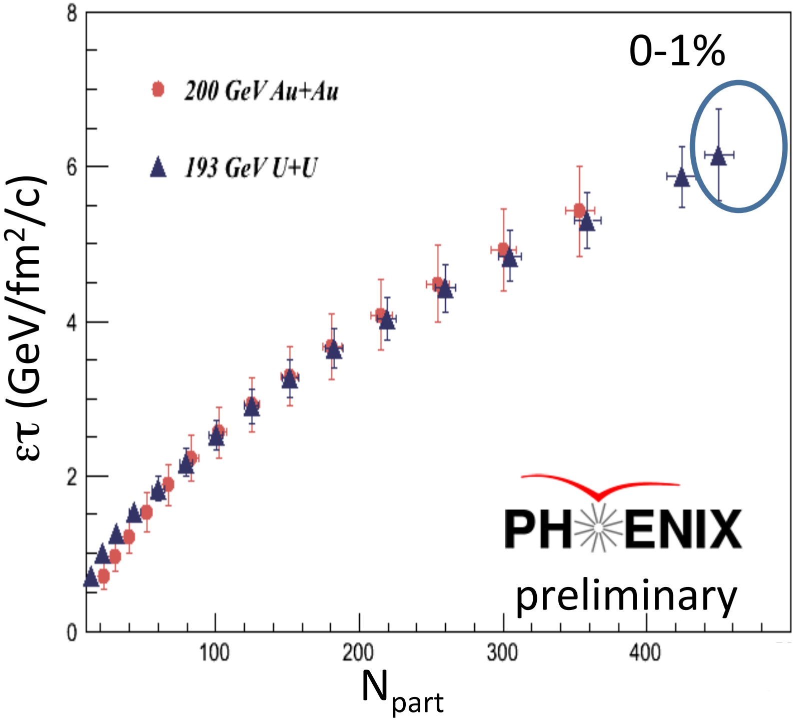


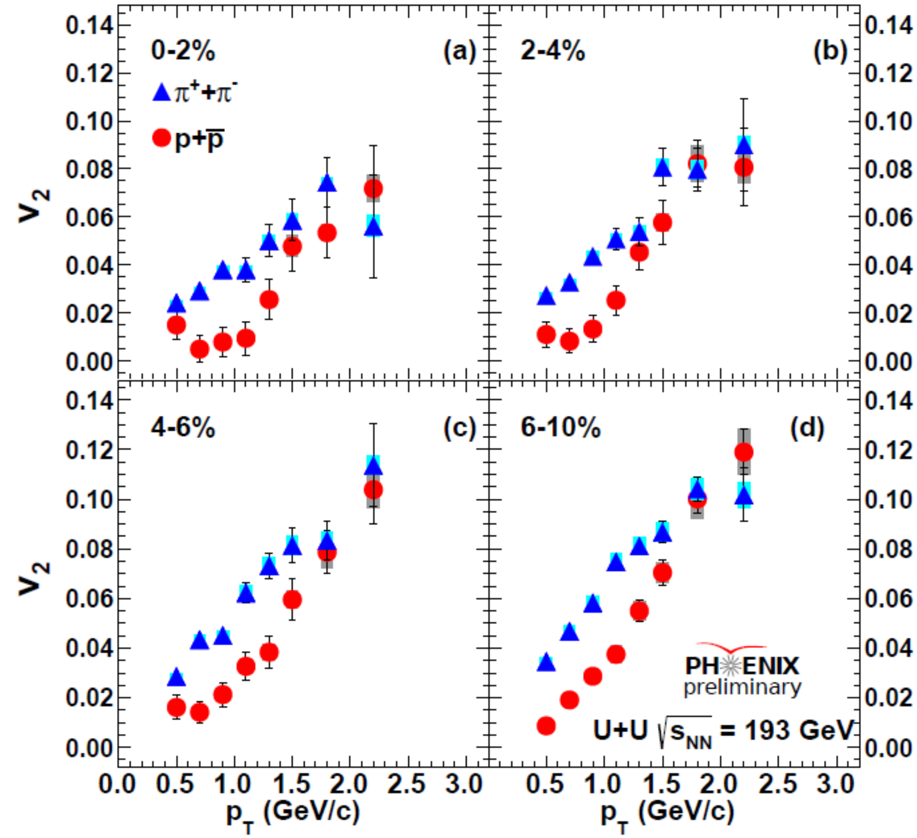
PHENIX PRC 85, 064914 (2012)

- A break of n_q scaling in 20-60% centrality at KE_T > 0.7 GeV.
- In the 0-20% centrality, scaling is still roughly kept.
- Different mechanisms for pion and proton production at intermediate p_T for different centralities

π & p v_2 in 0-2% central U + U collision

4A, Huang

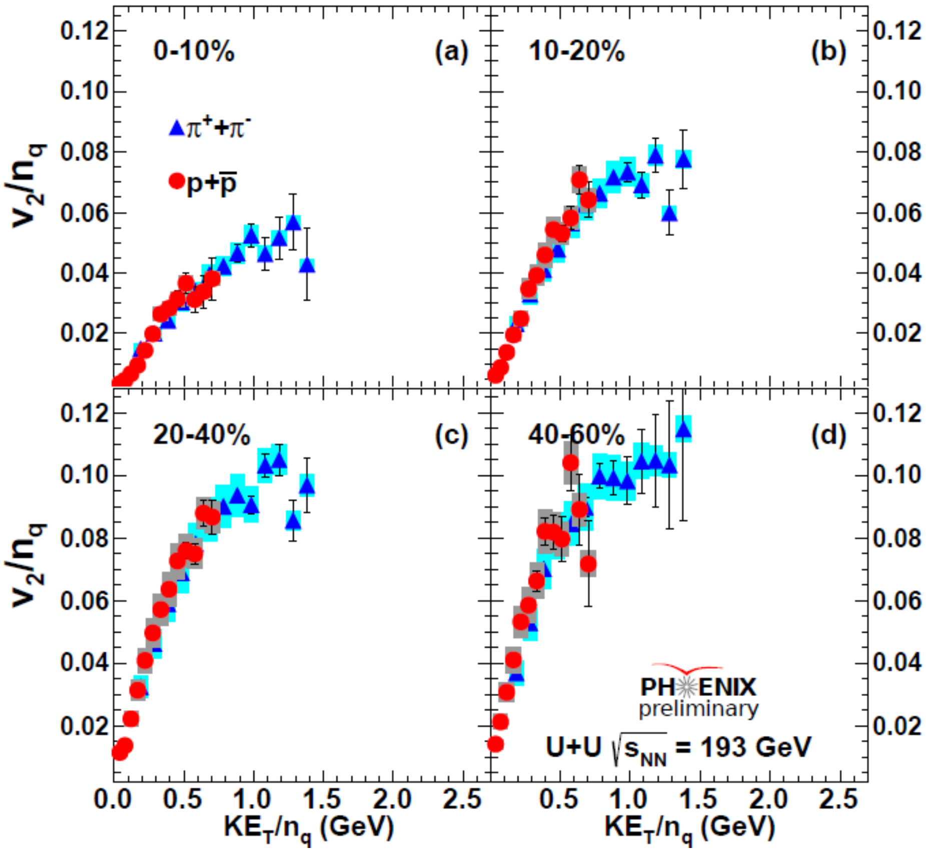




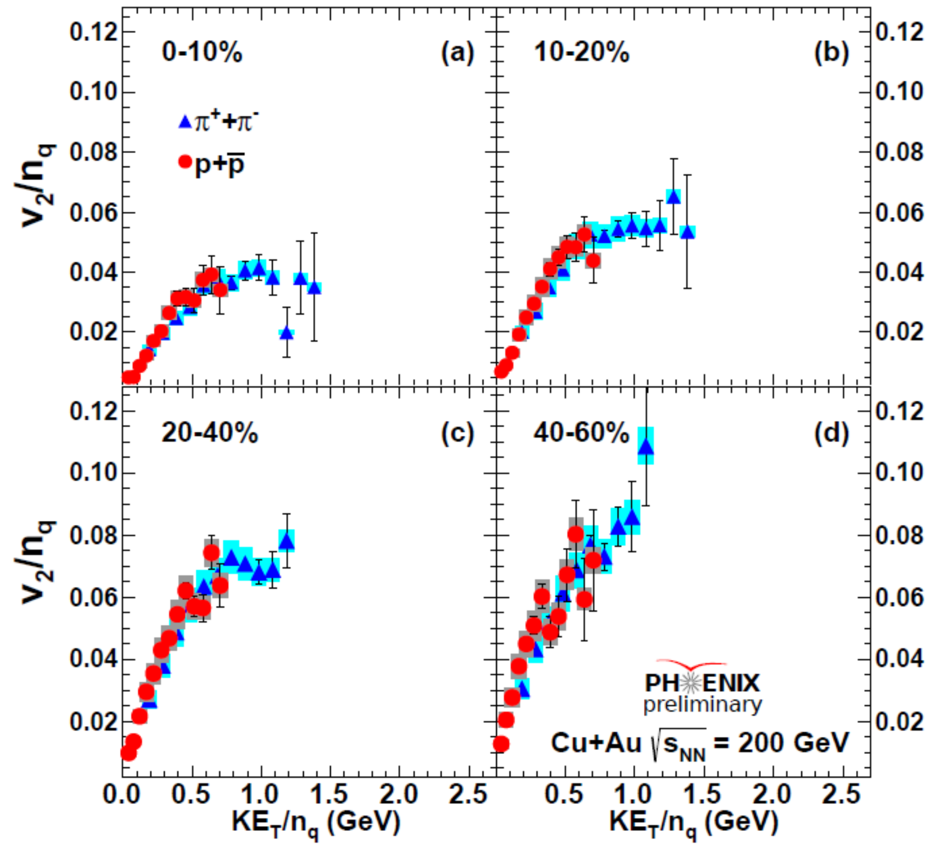
- ετ increase about 20% from 0-10% Au+Au to 0-1% U+U collisions
- Strong mass ordering for v_2 in 0-2% central U+U collision at 193 GeV despite of relatively small increase of ετ.
- Radial flow or geometry?
- The geometry separation will be done in near future

N_q scaling in U+U and Cu+Au collisions

U+U



Cu+Au

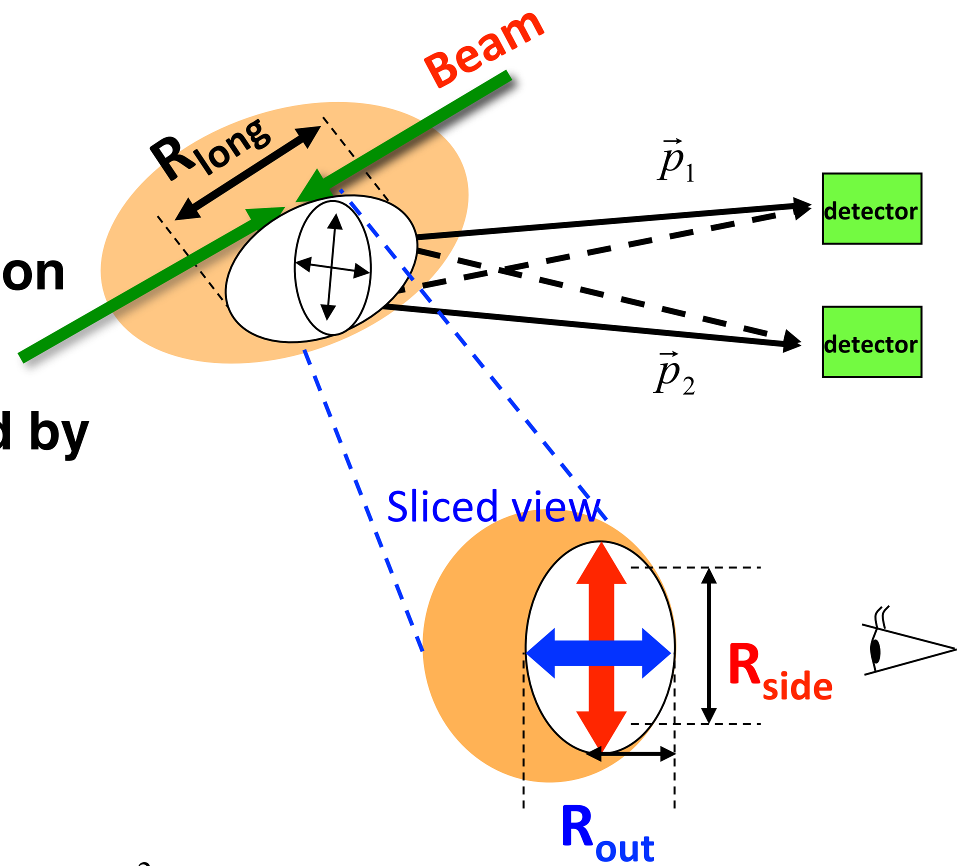


- ✧ N_q scaling works for U+U and Cu+Au for π , P

3D HBT radii

✧ "Out-Side-Long" system
- Bertsch-Pratt parameterization

✧ Core-halo model
- Particles in core are affected by coulomb interaction



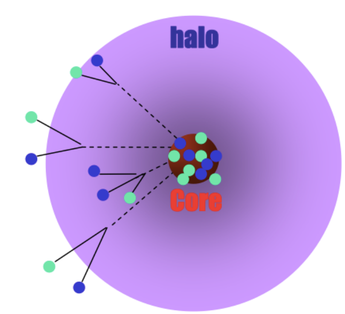
$$C_2 = C_2^{core} + C_2^{halo}$$

$$= \quad N[\lambda(1+G)F] + [1-\lambda]$$

$$G = \exp(-R_{inv}^2 q_{inv}^2)$$

$$= \exp(-R_{side}^2 q_{side}^2 - R_{out}^2 q_{out}^2 - R_{long}^2 q_{long}^2 - 2R_{os}^2 q_{side} q_{out})$$

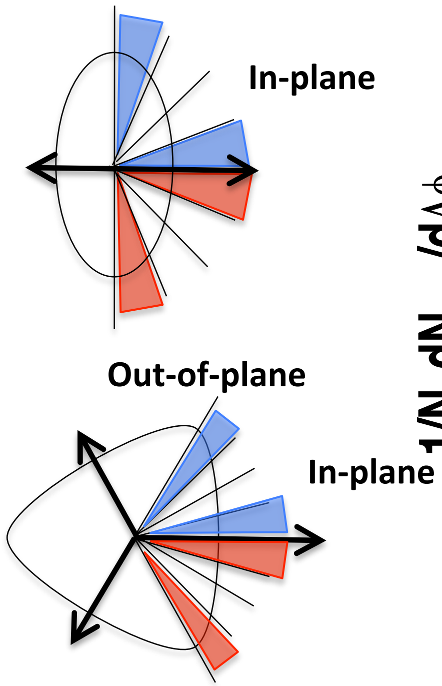
R_{long}: Longtudinal size
R_{side}: Transverse size
R_{out}: Transverse size + emission duration
R_{os}: Cross term between Out and Side

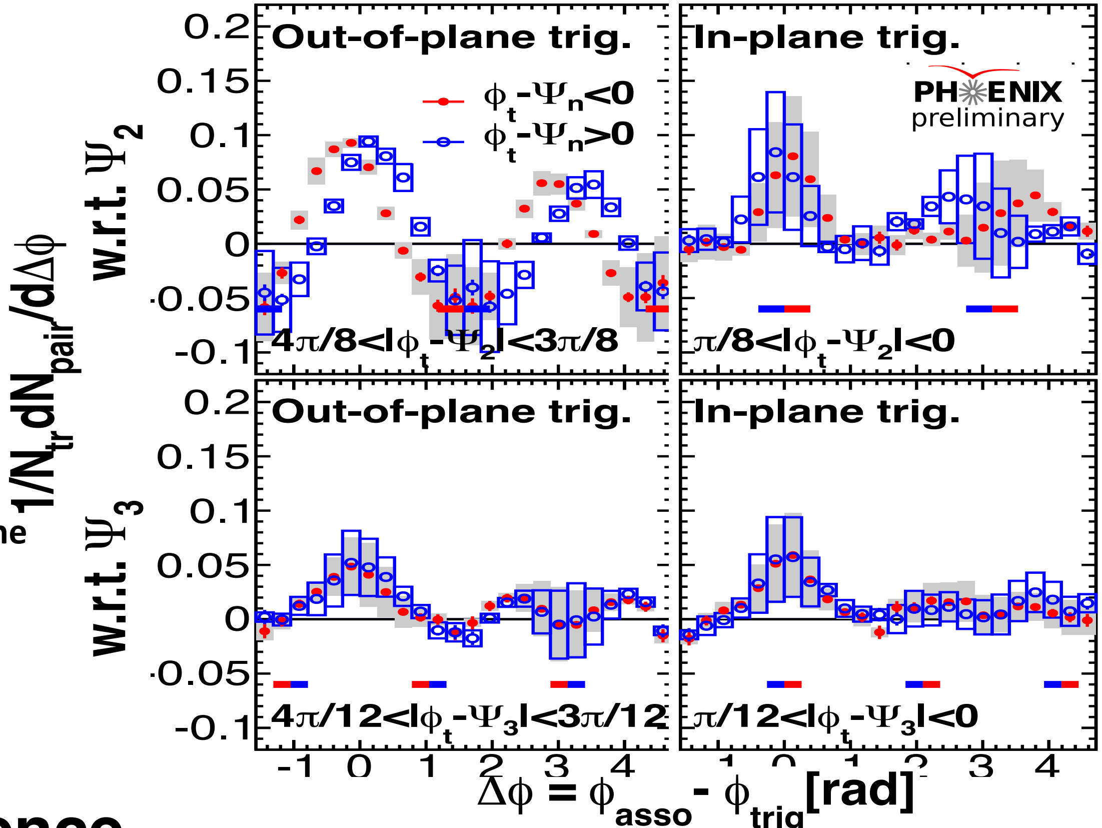


Correlations relative to $\Psi_{2,3}$ 0-10%

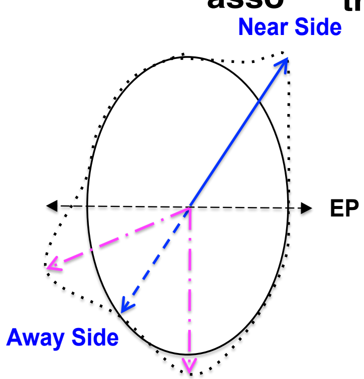
6D, Todoroki

2-4⊗1-2 GeV, $v_2v_3v_4(\Psi_4)$ subtracted with $\langle\cos4(\Psi_2-\Psi_4)\rangle=v_4(\Psi_2)/v_4(\Psi_4)$ by ZYAM



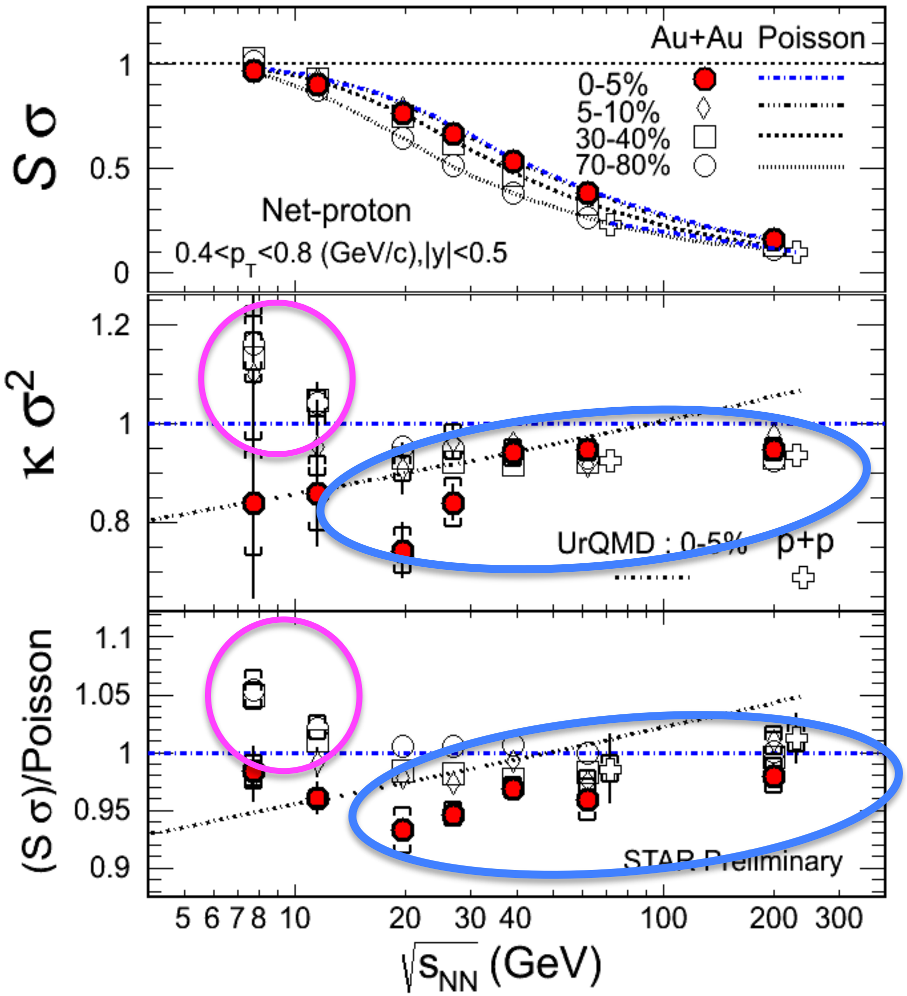


- ✧ Ψ_2 dependence
  - Left/Right asymmetry
- ✧ No Ψ_3 dependence
  - No Left/Right asymmetry
- ✧ Relation to source shape?



Unfolding on EP Res. not applied

BES-Higher Moments of Net-protons



$$\sigma^2 = \langle (N - \langle N \rangle)^2 \rangle$$
$$S = \langle (N - \langle N \rangle)^3 \rangle / \sigma^3$$
$$\kappa = \langle (N - \langle N \rangle)^4 \rangle / \sigma^4 - 3$$

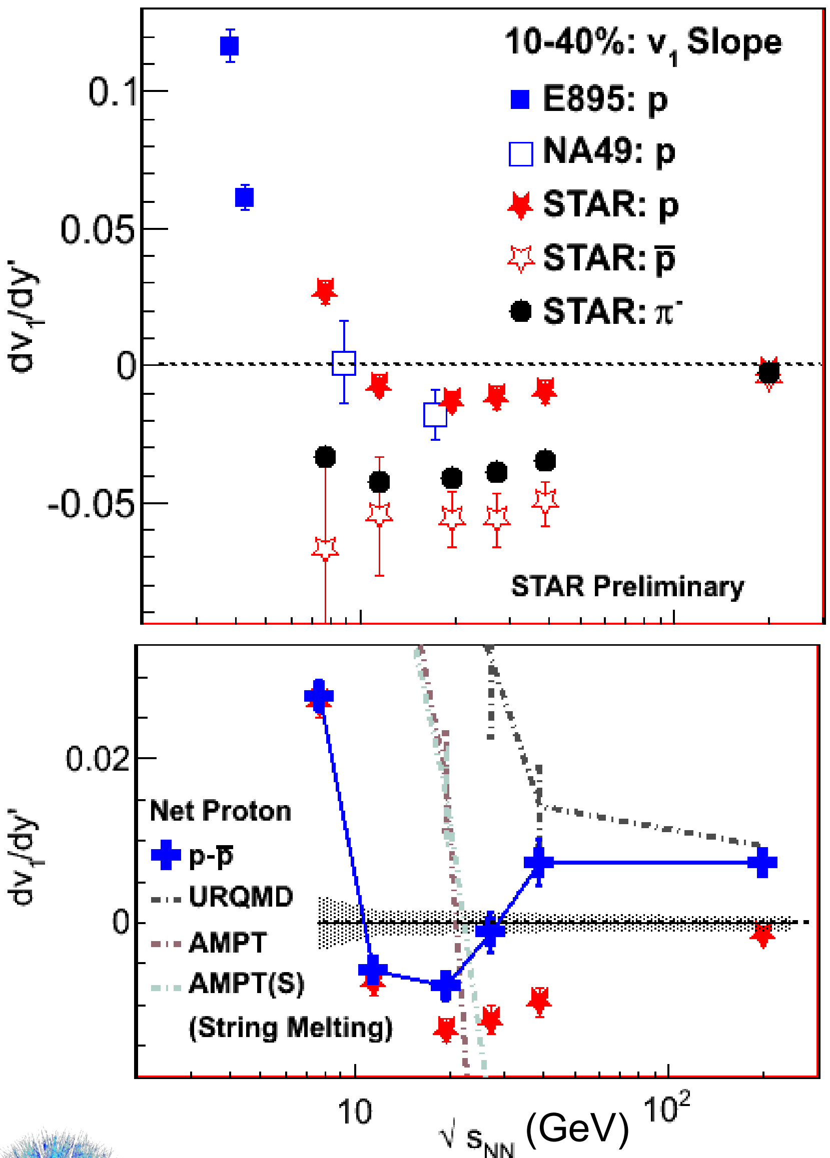
- Higher moments - more sensitive to Critical Point induced fluctuations.
- Deviation from Poisson baseline in 0-5% collisions at >7.7 GeV.
- Above Poisson baseline in peripheral collisions below 19.6 GeV.
- UrQMD shows monotonic behavior.
- Need precision measurements at low energies.

Net-proton/Net-charge/Net-kaon

Luo, 7B, Fri.; McDonald, 7B, Fri.

Li/Sahoo/Sarkar, poster #215/557/394

BES-Directed Flow of Protons



- Directed flow (v_1) slope: sensitive to 1st order phase transition.
- Proton v_1 slope changes sign from + to – between 7.7 and 11.5 GeV and remains small but negative up to 200 GeV.
- v_1 slopes for other particles are all negative.
- "net-proton" v_1 slope shows a minimum around 11.5-19.6 GeV.
- AMPT/UrQMD models cannot explain data.

Pandit, 1A, Tue.