Exploration of the properties of the medium produced in large and small collision-systems with azimuthal anisotropy scaling functions

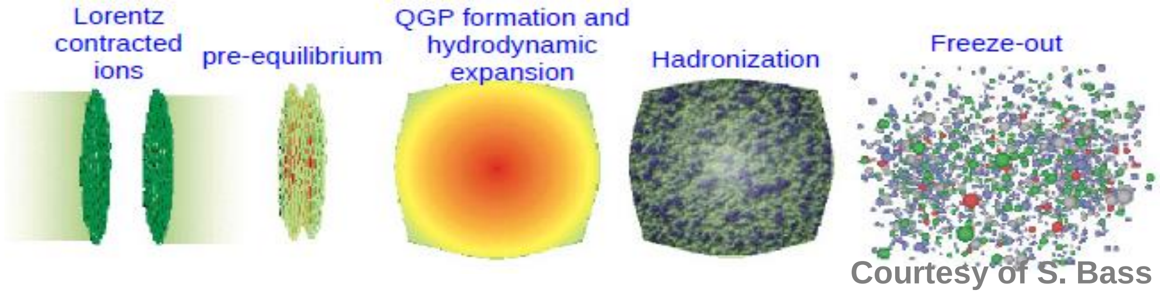
Roy A. Lacey

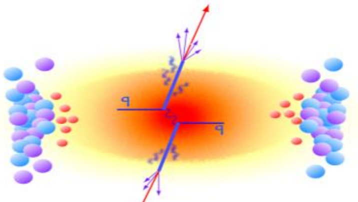
Stony Brook University

Outline

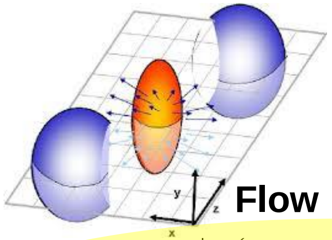
- *Introduction*
  - *Large to small collision systems*
  - *The role of fluctuations in small collision-systems*
- **STAR Measurements (p/d/^{3}He+Au)**
  - *Data & analysis*
  - *Non-flow mitigation and v_n extraction*
- **p/d/^{3}He+Au results**
  - *V_2 & v_3*
  - *Comparison to other measurements*
- **Implications [medium explorations]**
  - *Anisotropy scaling functions*
  - *What/how we learn from them*
- *Epilogue*

Backdrop – A+A(B) Collisions





Jet quenching



P. Staig and E. Shuryak, PRC 84, 034908 (2011)
Roy A. Lacey, et al., arXiv:1305.3341

Azimuthal anisotropy is influenced by initial-state eccentricity and final-state effects

$$v_n = \varepsilon_n e^{-n\left[n\left(\frac{4}{3}\frac{\eta}{s}+\frac{\xi}{s}\right)+\kappa p_T^2\right]\frac{1}{RT}}, \quad RT \propto \langle N_{chg} \rangle^{1/3}$$

Viscous attenuation

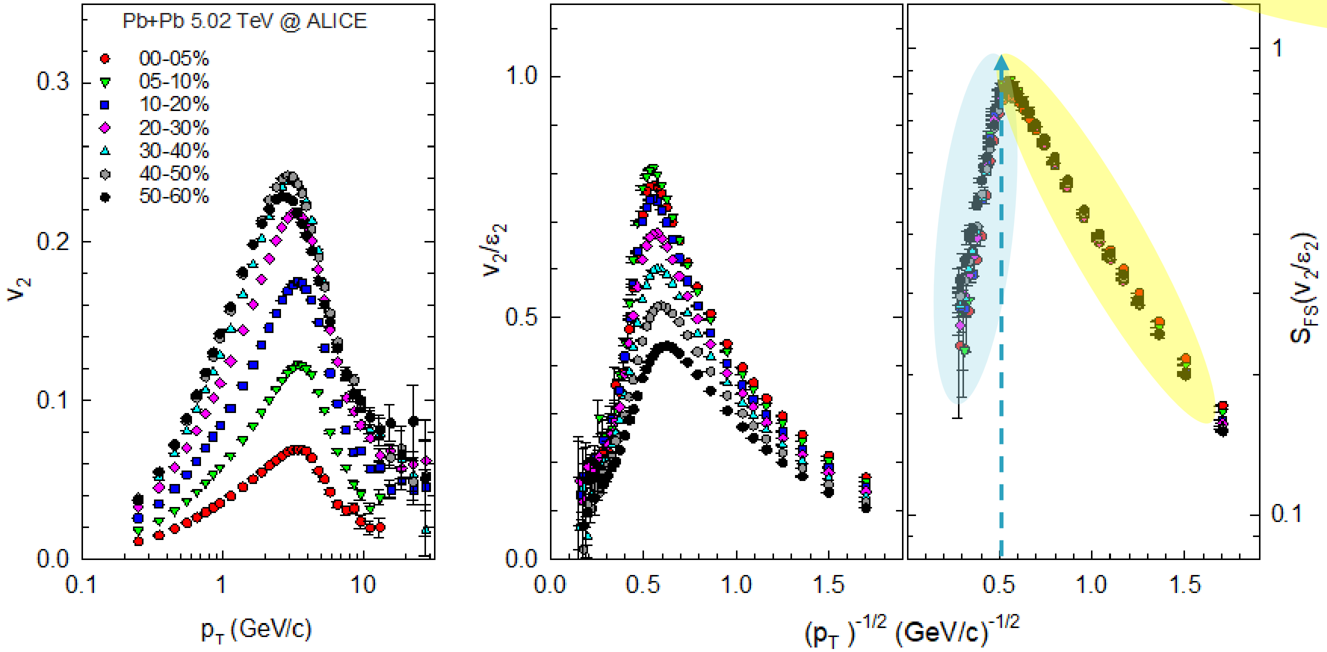
Radiative E-loss

$$R_{AA}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}} L \sqrt{\hat{q}\frac{\mathcal{L}}{p_T}}\right]$$

$$\mathcal{L} \equiv \frac{d}{d\ln p_T}\ln\left[\frac{d\sigma_{pp}}{dp_T^2}(p_T)\right]$$

$$\frac{R_{AA}(90^o, p_T)}{R_{AA}(0^o, p_T)} = \frac{1-2v_2(p_T)}{1+2v_2(p_T)}$$

Dokshitzer & Kharzeev, Phys. Lett. B519, 199 (2001)



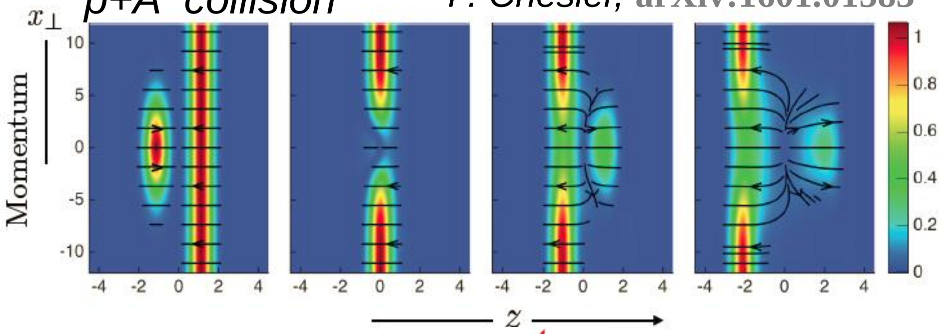
$$\frac{\eta}{s} \sim \left(0.25/\sqrt{\hat{q}/T^3}\right)$$

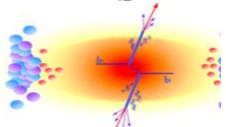
- ✓ **Characteristic scaling patterns for viscous attenuation and jet quenching delineate the respective role of shape (ε_n), size (RT), $\frac{\eta}{s}$, $\hat{q}$, etc.**
  - ✓ **Scaling coefficients provide constraints for $\frac{\eta}{s}(T, \mu_B)$ and $\hat{q}$**

Backdrop – Small collision systems

- **Hydrodynamic expansion-dynamics prevail for sizes as small as RT ~ 1?**

p+A collision   P. Chesler, arXiv:1601.01583





Controlling influence similar to that for A+A collisions – with different coefficients?

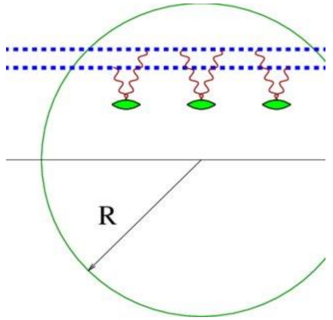
$$v_n = \varepsilon_n e^{-n\left[n\left(\frac{4}{3}\frac{\eta}{s}+\frac{\xi}{s}\right)+\kappa p_T^2\right]\frac{1}{RT}}, \; RT \propto \langle \mathrm{N_{chg}} \rangle^{1/3}$$

Radiative E-loss

$$R_{AA}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}} L \sqrt{\hat{q}\frac{\mathcal{L}}{p_T}}\right]$$

$$\mathcal{L} \equiv \frac{d}{d\ln p_T} \ln\left[\frac{d\sigma_{pp}}{dp_T^2}(p_T)\right]$$

- **The CGC-EFT mechanism prevails**
  - ✓ **Initial-state momentum-driven**



CGC-EFT
M. Mace et al., PLB 788, 161-165

Eikonal-like scattering of quarks off of a gluon dense nuclear target

Characteristically different controlling influence from

$$Q_{s,T} << p_T^{\max},\; Q_{s,p}(B_p)$$

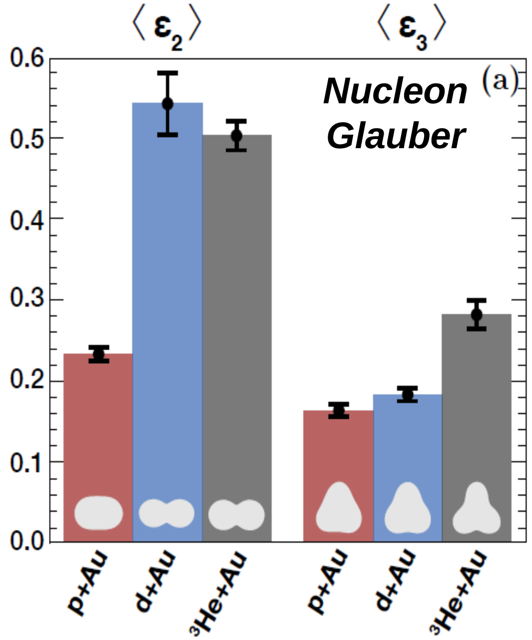
$$v_{2n}\{2\} \propto \mathrm{N}^0_{\mathrm{chg}},\; v_{2n+1}\{2\} \propto \mathrm{N}^{1/2}_{\mathrm{chg}},\; \delta(v_n), C_r(n,m)$$

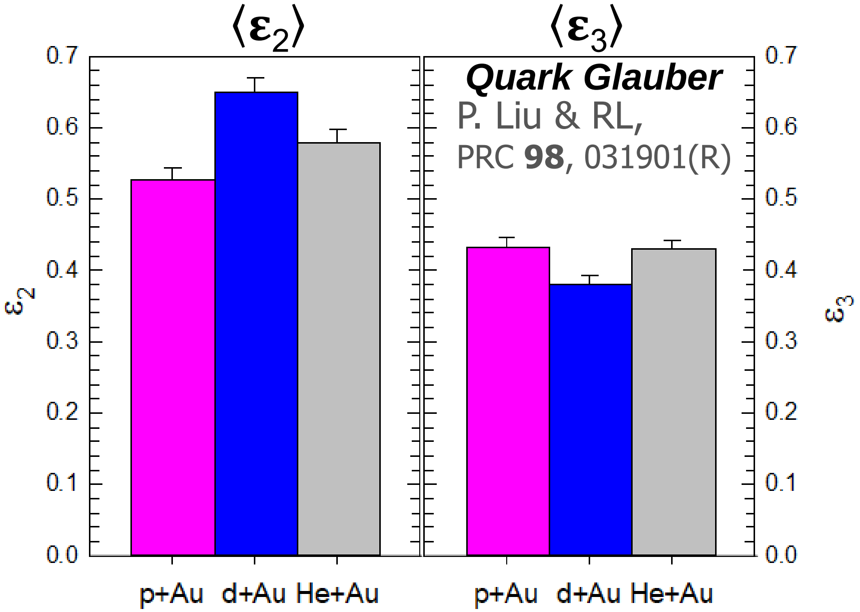
- **STAR measurements can aid quantification of the influence of the respective control variables to:**
  - ✓ *discern between these final- and initial-state models*
  - ✓ *give insight and constraints for the properties of the matter produced in these collisions*

Backdrop – Shape engineering and sub-nucleonic fluctuations

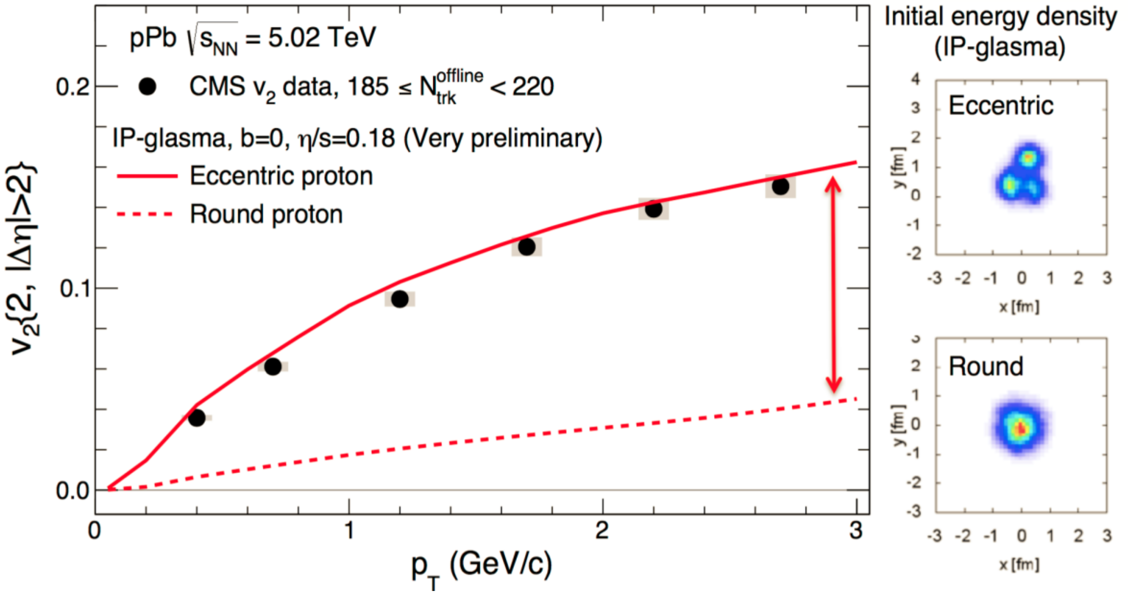
Is shape engineering viable in small systems?

✓ **[or] Do eccentricity fluctuations dominate?**





Bjoern Schenke SQM16



- **Creation of quark–gluon plasma droplets with three distinct geometries:**

PHENIX, Nature Physics 15, 214-220 (2019)

- **Shape engineering NOT viable in ALL current measurements**
  - ✓ ε_2 and ε_3 approx. system-independent *due to sub-nucleonic fluctuations*

- ***Nucleonic substructure plays an important role***
  - ✓ ***Model comparisons without fluctuation constraints are meaningless for "small systems"***

- ***New measurements (especially v_3) can provide additional constraints to address "shape engineering" in small systems***

Backdrop – Shape engineering and sub-nucleonic fluctuations

Bjoern Schenke QM16

Initial eccentricities

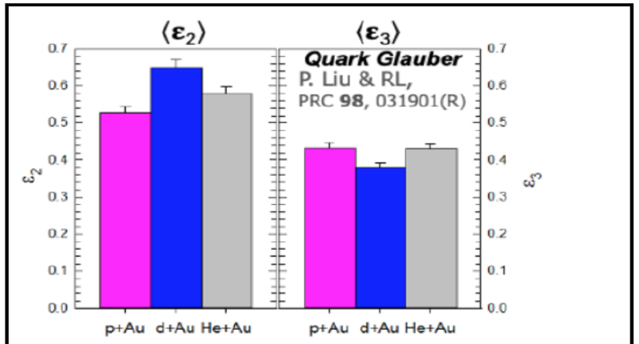
Initial Geometry Models

System	Nagle Nucleons w/o NBD fluctuations	Welsh Nucleons w/ NBD fluctuations	Welsh Quarks w/ NBD and Gluon fluctuations	STAR QM19 No Details
ε_2 p+Au	0.23	0.32	0.38	0.52
ε_2 d+Au	0.54	0.48	0.51	0.65
ε_2 ^{3}He+Au	0.50	0.50	0.52	0.58
ε_3 p+Au	0.16	0.24	0.30	0.43
ε_3 d+Au	0.18	0.28	0.31	0.38
ε_3 ^{3}He+Au	0.28	0.32	0.35	0.43

- Nagle et al: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.113.112301
- Welsh et al: https://journals.aps.org/prc/abstract/10.1103/PhysRevC.94.024919
- STAR QM19: https://indico.cern.ch/event/792436/contributions/3535629/

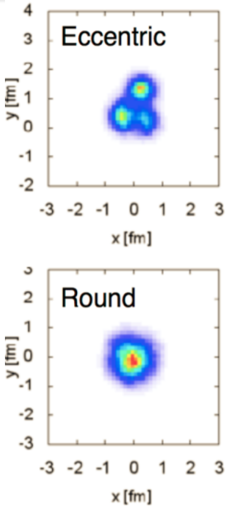
R. Belmont, UNCG WWND 2020, 2 March 2020 - Slide 29

STAR QM19
No mention of p+Au, d+Au, 3He+Au in the PRC reference given!



➤ **Shape engineering NOT viable in ALL current measurements**
✓ ε_2 and ε_3 approx. system-independent *due to sub-nucleonic fluctuations*

Initial energy density (IP-glasma)



; an

ut

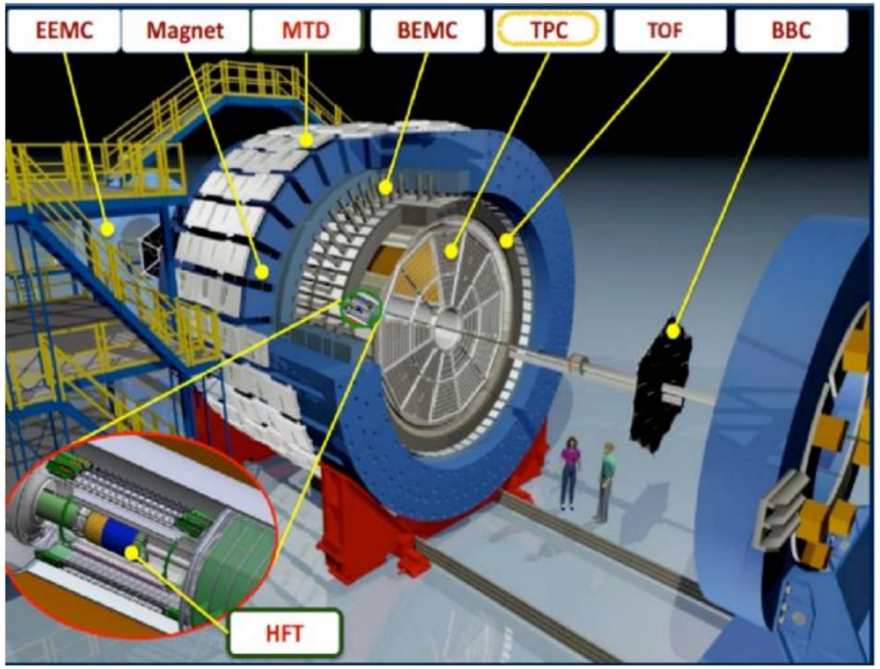
e

ystems”

➤ ***New measurements (especially v_3) can provide additional constraints to address “shape engineering” in small systems***

Data Analyses

STAR Experiment at RHIC



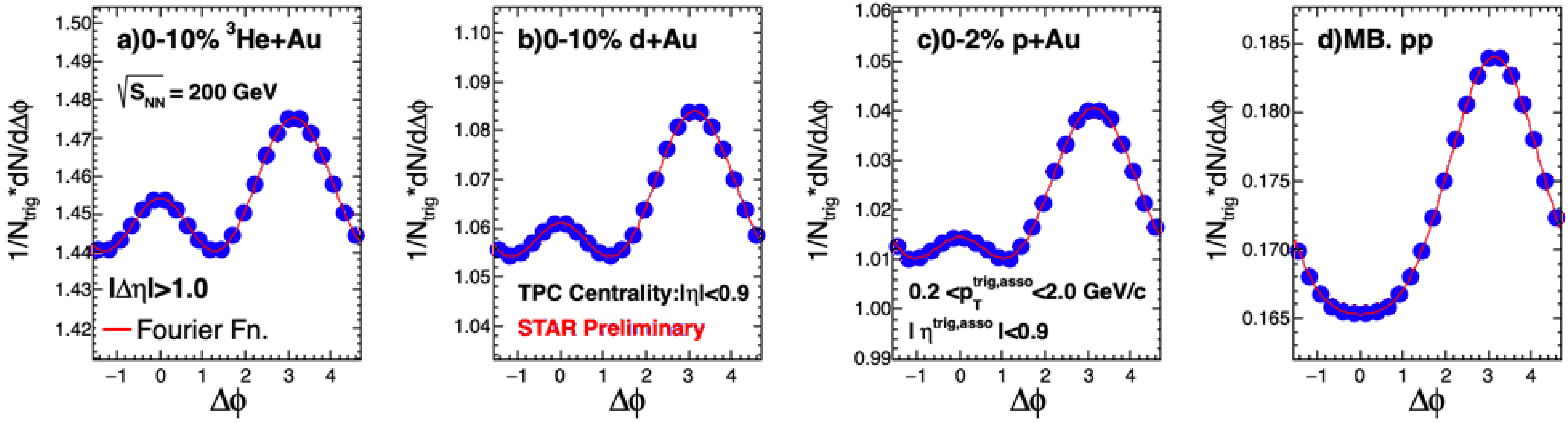
- **The STAR detector is used for the current measurements**

Measurements for p/d/³He+Au collisions @ 200 GeV

- Centrality:
  - i) Number of tracks in 0.2–3.0 GeV/c, $|\eta|<0.9$
  - ii) BBC charge in Au-going direction $-5.0<\eta<-3.3$
- Multiplicity:
  Number of tracks for $0.2 < p_T < 3.0$ GeV/c, $|\eta|<0.9$
  - ✓ efficiency corrected
- Two-particle correlation functions constructed for trigger and associated particles with $0.2 < p_T < 2.0$ GeV/c $|\eta|<0.9$ and $|\Delta\eta| > 1.0$

✓ Differential $v_2\{2\}(p_T)$, $v_3\{2\}(p_T)$ and integral $v_2\{2\}$, $v_2\{4\}$, $v_3\{2\}$ (for $0.2 < p_T < 3.0$ GeV/c, $|\eta|<0.9$) extracted from correlation functions following non-flow subtraction

Long-range two-particle correlators and v_n extraction (I)



*The well-known techniques of leveraging the two-particle p+p correlator to mitigate non-flow, are employed → **Three methods!***

$$\frac{1}{N_{trig}} dN/d\Delta\phi = c_0(1 + 2 * \sum_{n=1}^{4} c_n \cos(n\phi))$$

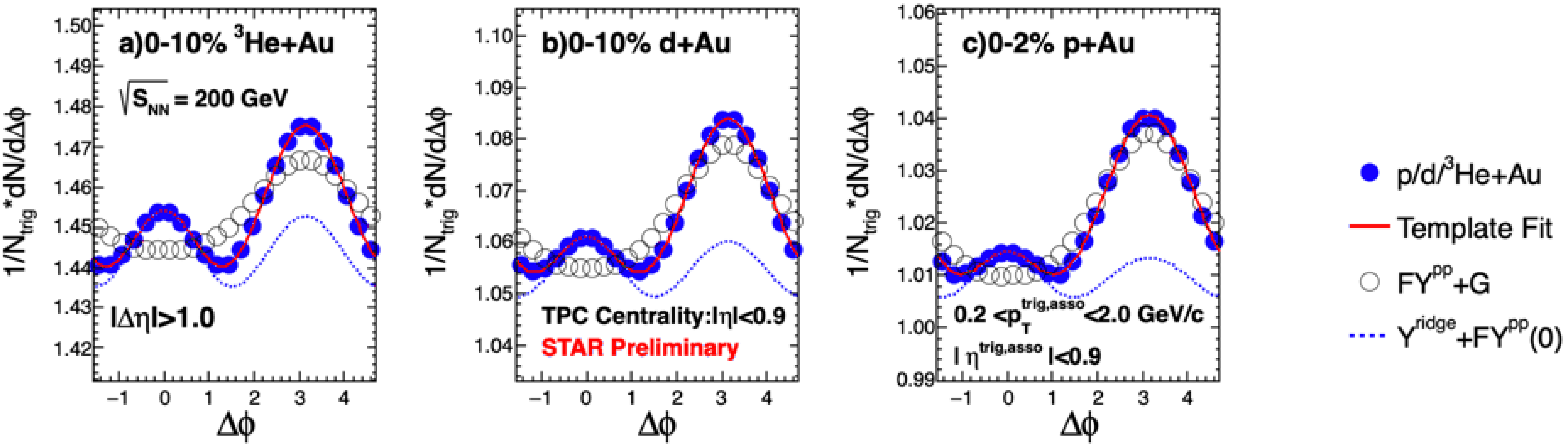
- ✓ 1. via c_0: $c_{n,sub}^{sys.} = c_n^{sys.} - (c_0^{pp}/c_0^{sys.}) \times c_n^{pp}$; n=2,3
- ✓ 2. via c_1: $c_{n,sub}^{sys.} = c_n^{sys.} - (c_1^{sys}/c_1^{pp}) \times c_n^{pp}$; n=2,3

$$v_{n,sub}^{sys.} = \sqrt{c_{n,sub}^{sys.}}$$

- ➢ **Characteristic ridge apparent for *p/d/*³He+*Au; little, if any, for min. bias p+p***
  - ✓ **Suggests the leveraging of the p+p correlator for non-flow mitigation**

- ➢ ***Methodologies validated with closure test***
  - ✓ **Results are method-independent within uncertainties**

Long-range two-particle correlators and v_n extraction (II)



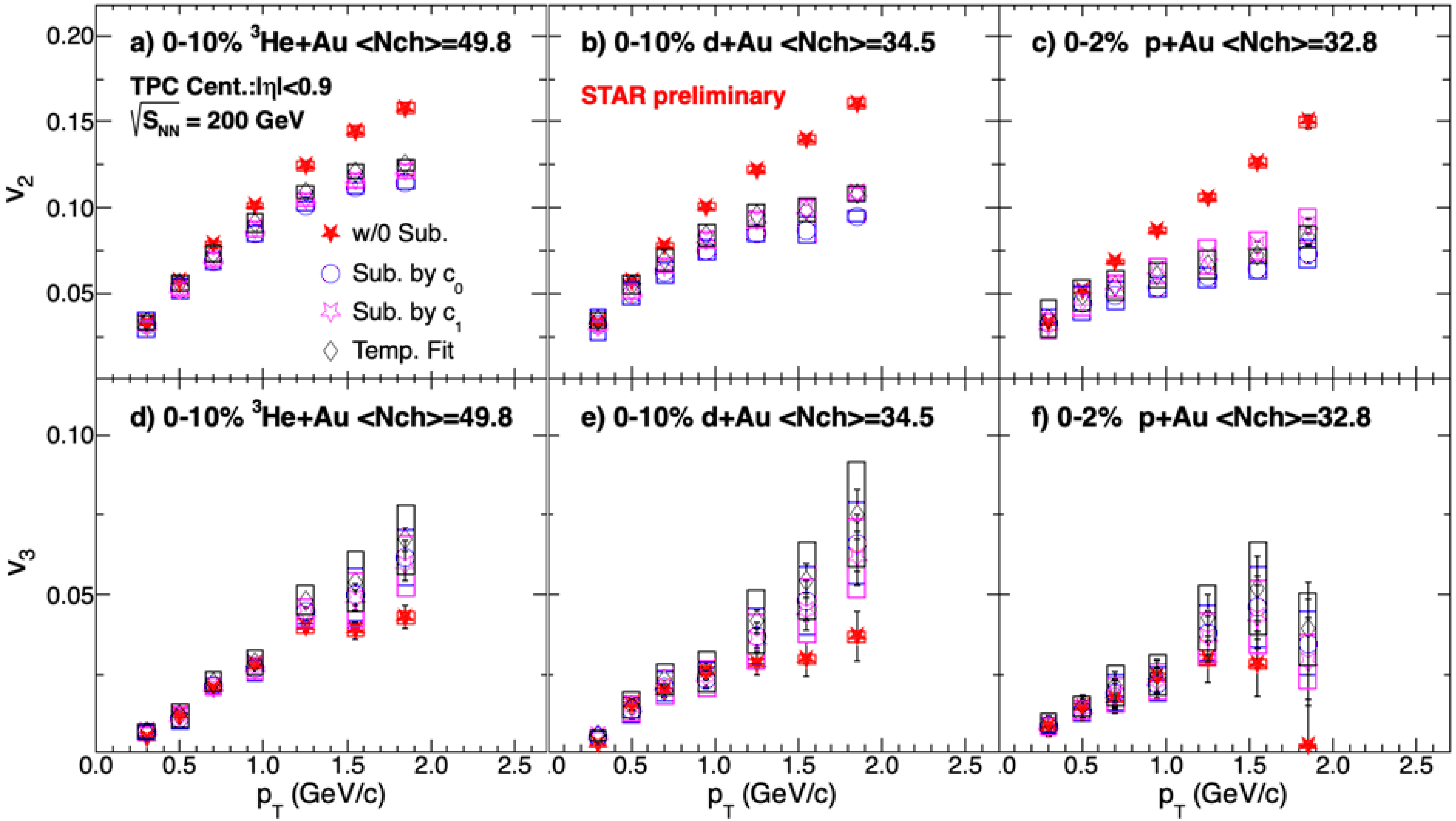
3. Template Fit *(ATLAS, PRL 116, 172301 (2016))*

$$Y_{templ.}(\Delta\phi) = F \times Y_{pp.}(\Delta\phi) + Y_{ridge}(\Delta\phi)$$
$$Y_{ridge}(\Delta\phi) = G \times (1 + 2 \times \sum_{n=2}^{4} c_n^{sub} \times \cos(n\Delta\phi))$$

*"F" represents the jet modification for the long-range away-side jet between **p/d/³He+Au and p+p***

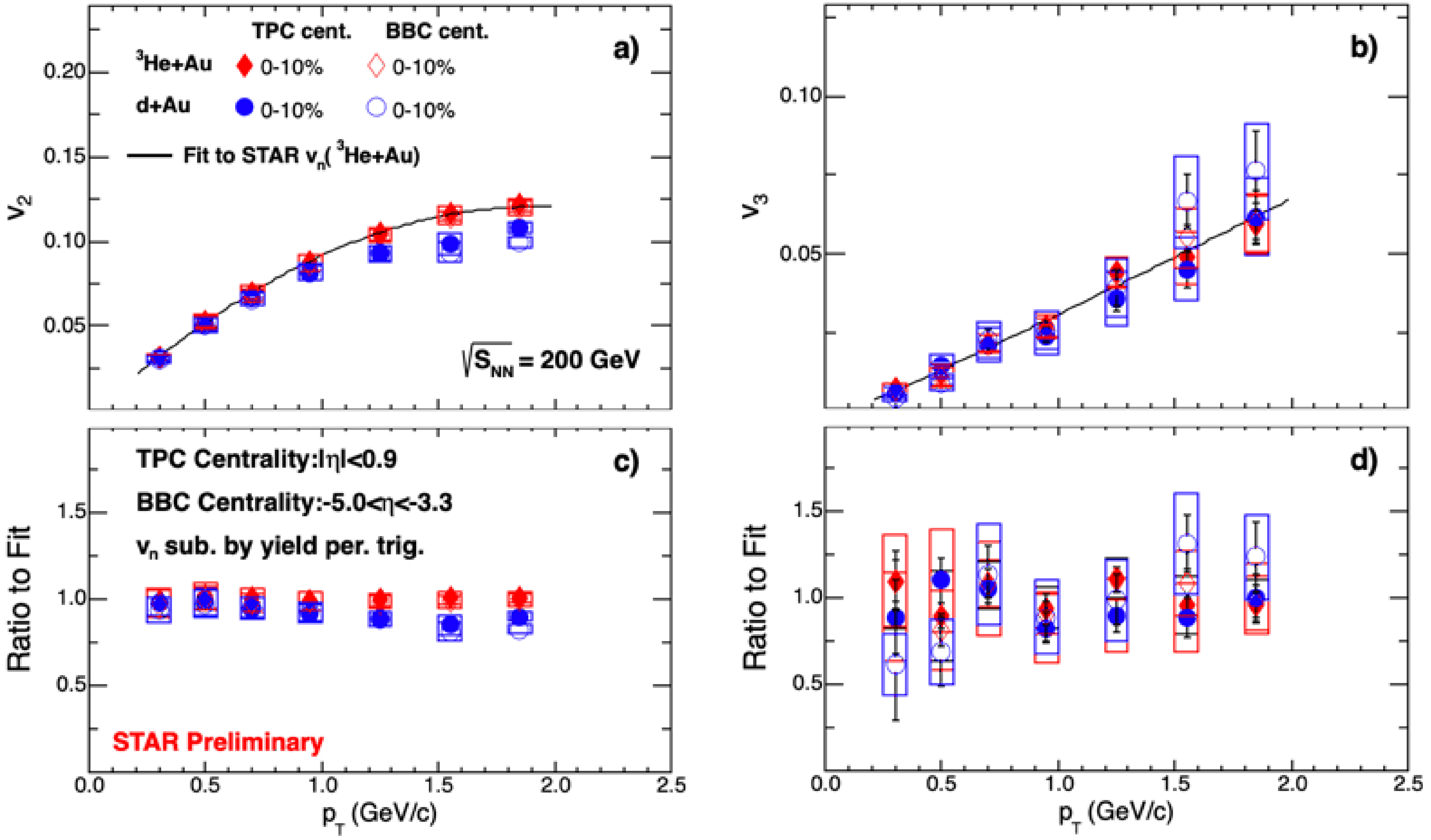
- ***Method validated with closure test***
  - ✓ **Results are method-independent within uncertainties**

STAR differential v_n measurements for p/d/^{3}He+Au



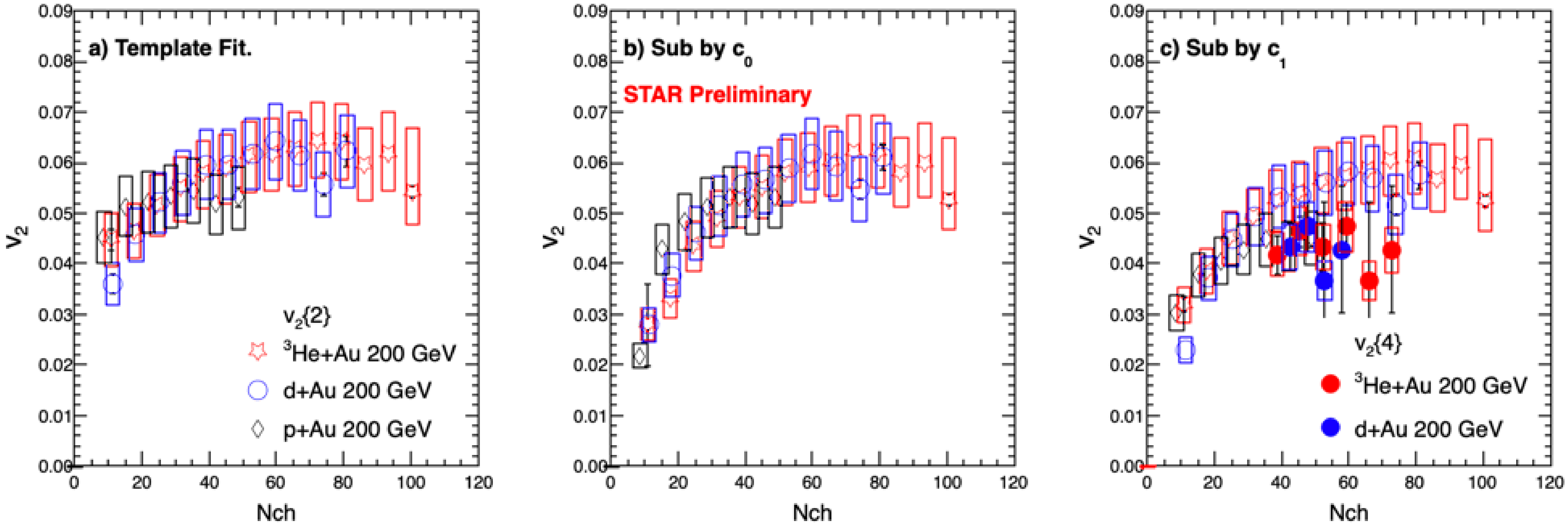
- **Non-flow mitigation is important and is system dependent**
  - ✓ **The $v_{2,3}$ results are method-independent within uncertainties**
    - ✓ **Note that the un-subtracted v_3 is a lower limit**

Differential $v_{2,3}$ measurements for different centrality definitions



✓ **Results for 0-10% central *d*/^{3}He+*Au*, using different definitions for centrality, are similar**

STAR integral v_2 measurements for p/d/^{3}He+Au

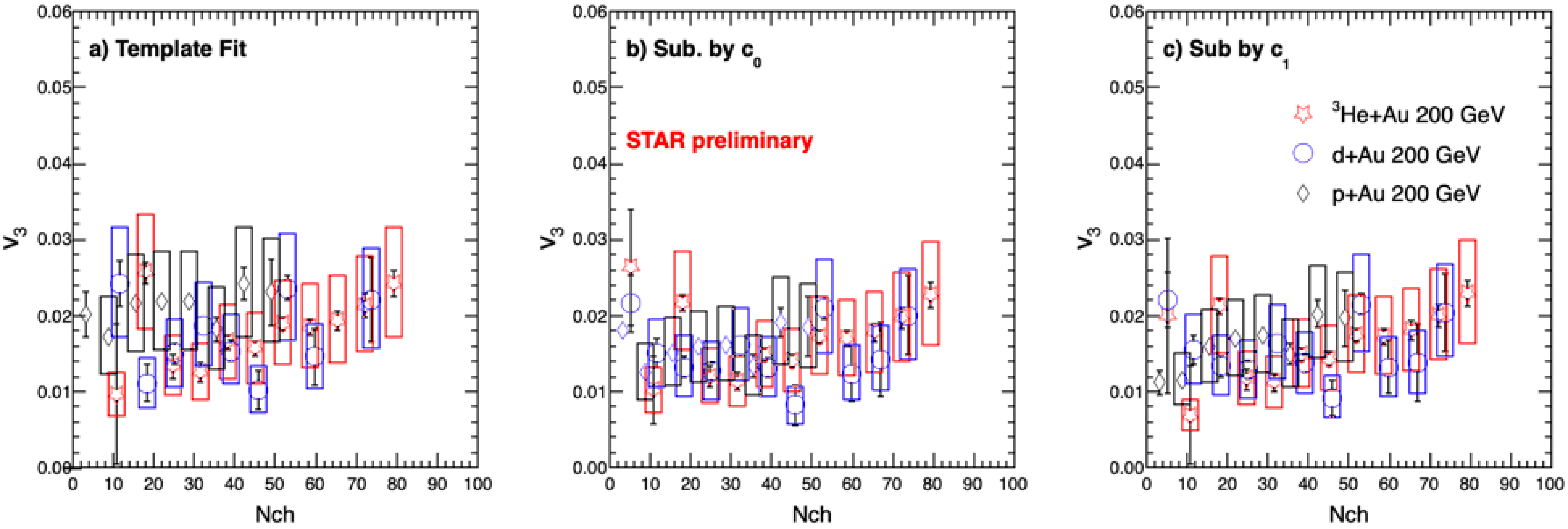


- **System-independent values of $v_2\{2\}$ for similar multiplicity, regardless of method**
  - **$V_2\{4\}$ N_{ch}-independent over the range of the measurements**
    - ✓ $\frac{v_2\{4\}}{v_2\{2\}}$ **consistent with expectation for eccentricity fluctuations, within uncertainties**
    - ✓ **Results incompatible with CGC-EFT over the full range of the measurements**

$v_{2n}\{2\} \propto N^0_{chg}$

M. Mace et al., PLB 788, 161-165

STAR integral v_3 measurements for p/d/^{3}He+Au



- $V_3\{2\}$ is method-independent within the uncertainty of the measurements
  - Significantly weaker multiplicity dependence for v_3 than for v_2

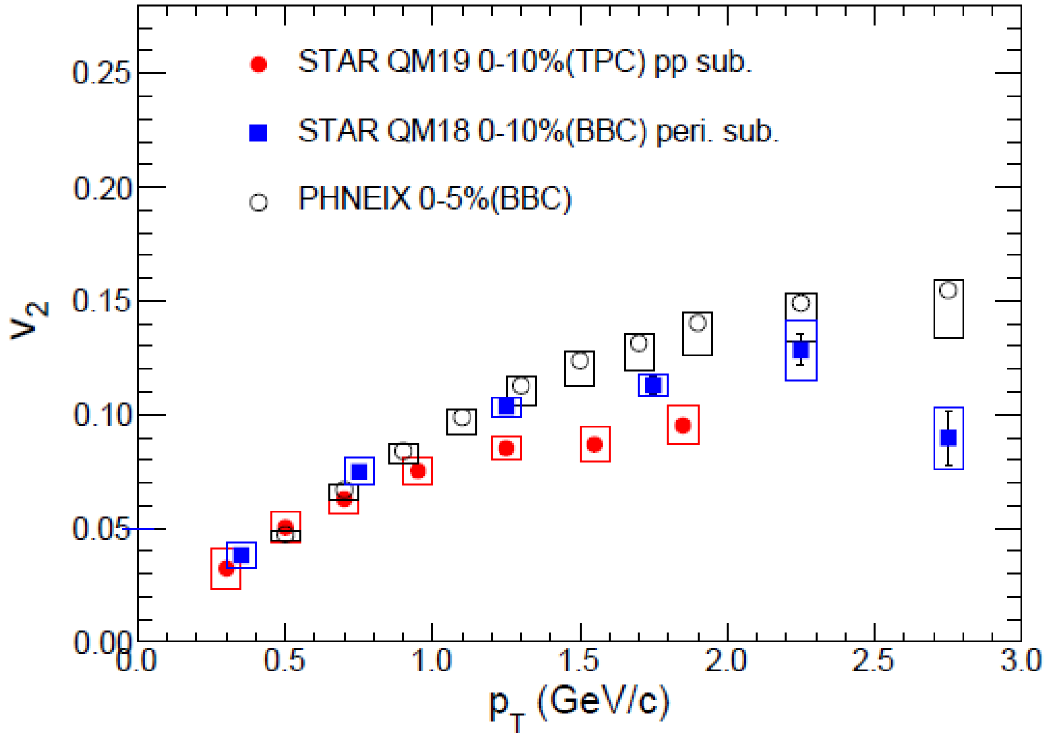
✓ Results incompatible with CGC-EFT

$$v_{2n+1}\{2\} \propto N_{chg}^{1/2}$$

M. Mace et al., PLB 788, 161-165

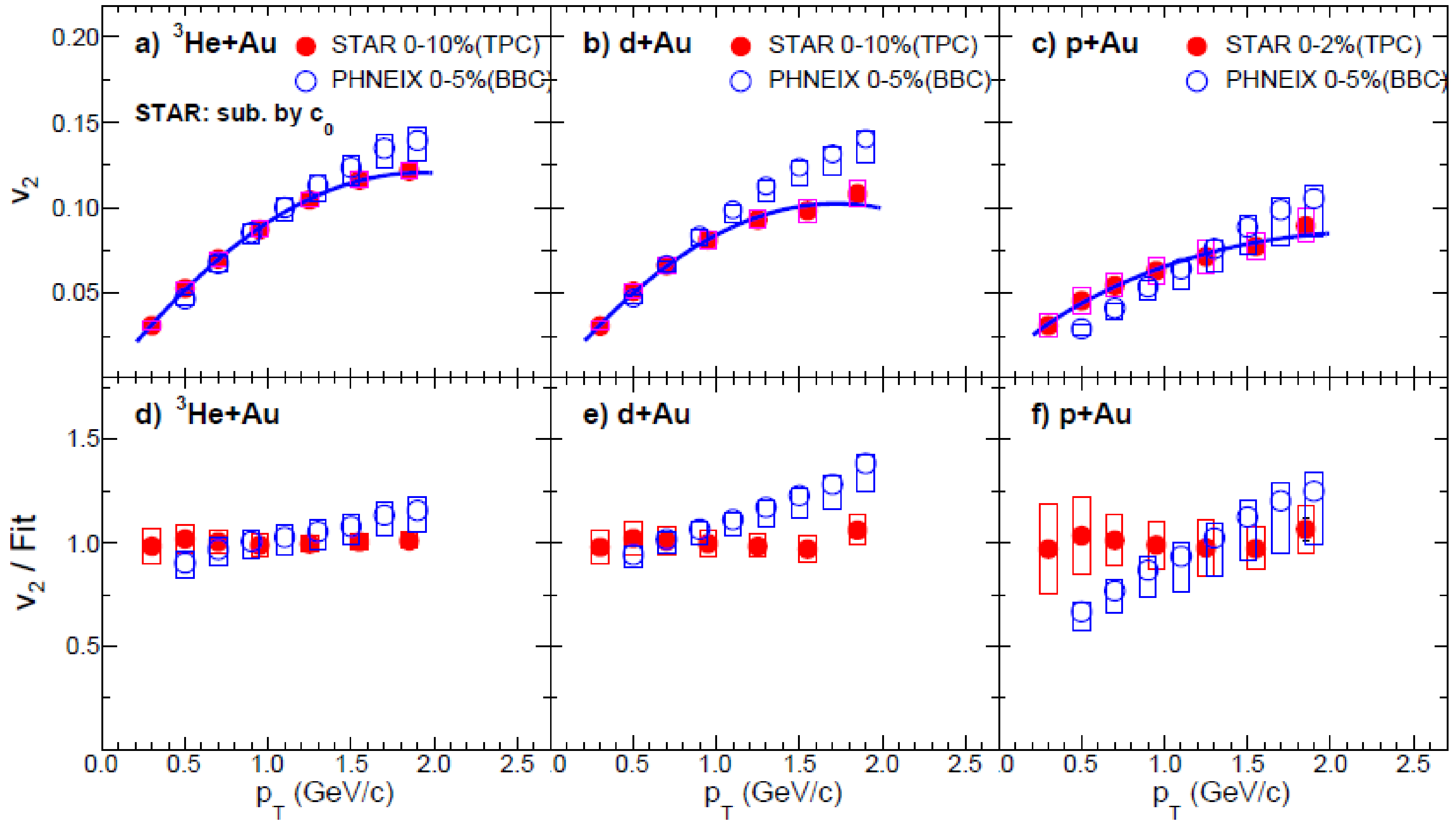
✓ Magnitudes of v_3 differ from those of prior measurements

Data Comparisons



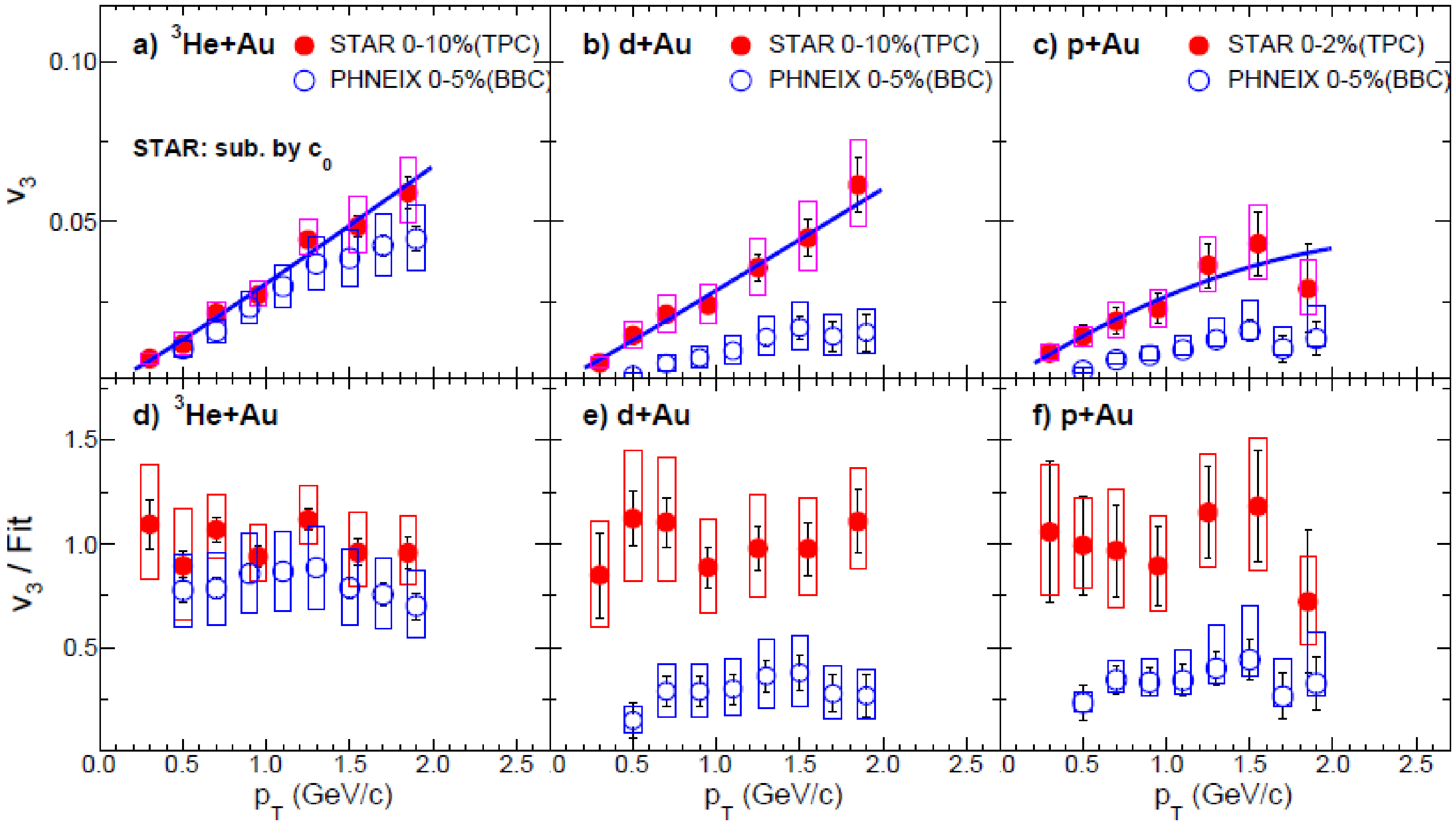
- **Reasonable agreement between the current and earlier results**
  - **STAR QM18 obtained via peripheral subtraction**
    - ✓ **Possibly an underestimate**
  - ✓ **STAR QM19 obtained via p+p subtraction**

Data Comparisons – v_2



- The STAR and PHENIX measurements for $v_2\{2\}$ are in reasonable agreement for all systems
  - ✓ Some difference for pT>1 GeV/c [d+Au] and pT<1 GeV/c [p+Au]
- System-dependent trends consistent with “shape-size” dependencies

Data Comparisons – v_3



- **The STAR and PHENIX $v_3\{2\}$ measurements for p/d+Au differ by more than a factor of 3-4**
  - ✓ **System independent STAR v_3**
  - ✓ **System dependent PHENIX v_3**

PHENIX: PRC95, 034910, *Nature Physics 15, 214–220*

PHENIX EP	^{3}He+Au	d+Au	p+Au
(ψ_2^{BBCS})	0.110	0.1073	0.062
(ψ_3^{BBCS})	0.034	0.057	0.067

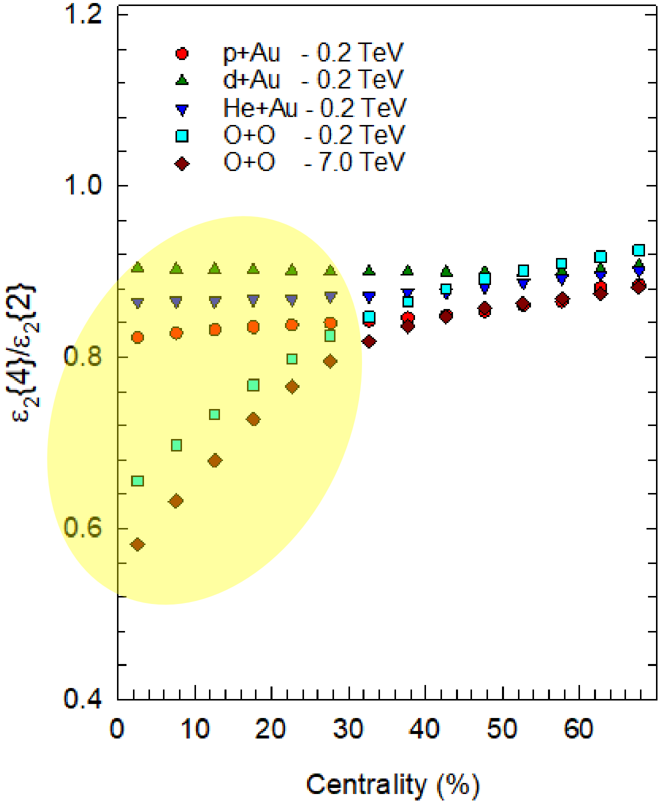
✓ ***Note that EP resolution is proportional to v_n and $\sqrt{N_{ch}}$***

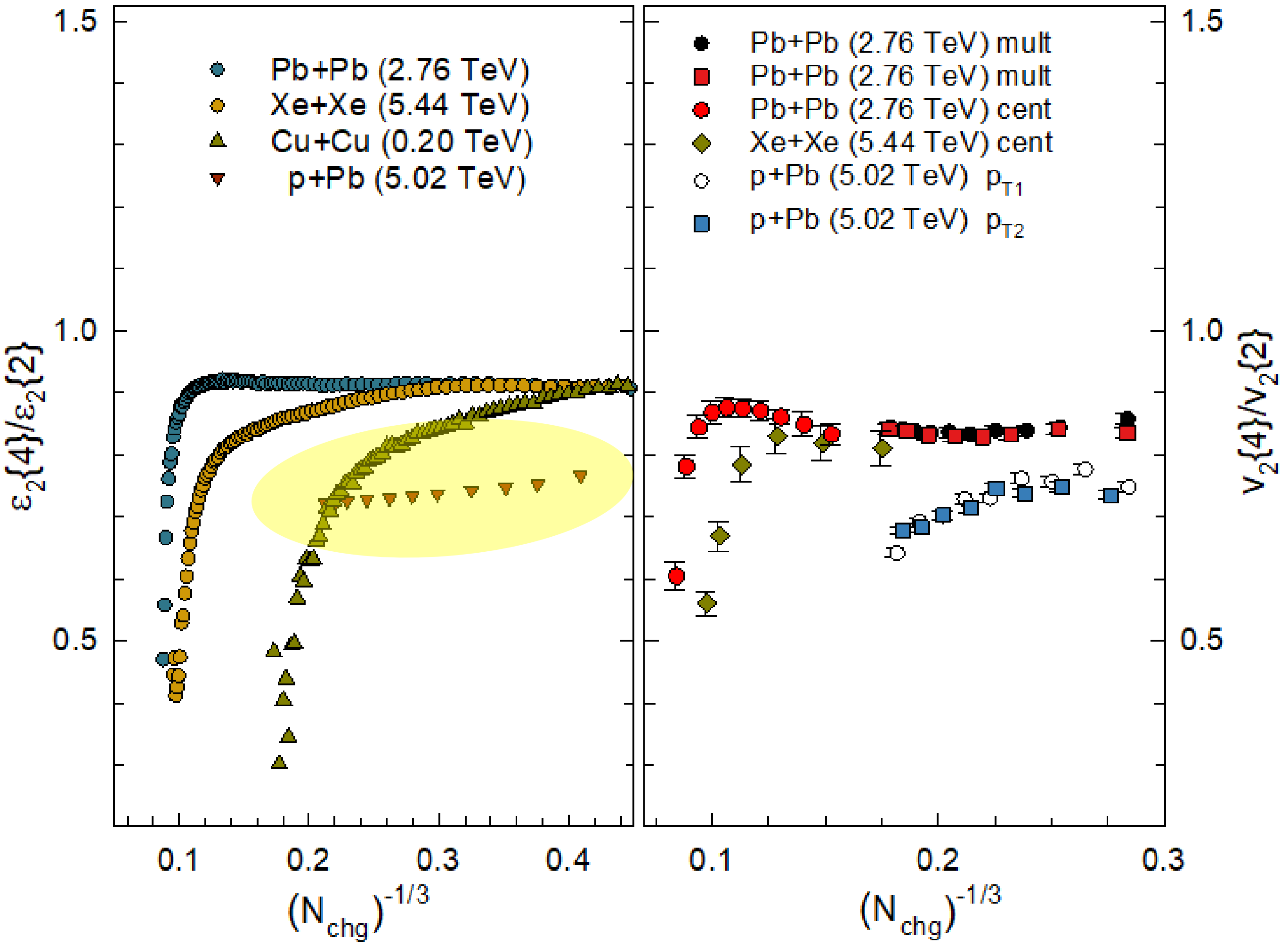
v_2 and v_3 for p+Au and d+Au differ by more than a factor of 7, while the respective event-plane resolutions are nearly identical

- **The STAR measurements are consistent with the important role of "size" (N_{ch}) in addition to the fluctuations-driven eccentricity ($\epsilon_{2,3}$)**
  - ✓ **This observation is also consistent with recent hydrodynamic calculations which incorporates sub-nucleonic fluctuations**

Improving constraints – fluctuations?

- ***The fluctuations constraint is crucial***
  - ✓ ***Additional measurements are invaluable***





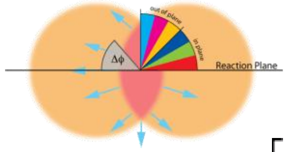
- ✓ ***Eccentricity fluctuations dominate flow fluctuations***
  - ***Fluctuation measurements for O+O could provide additional model constraints***

- ***Future precision measurements of fluctuations and v_n correlations for small systems @ RHIC, are crucial***
  - ✓ ***Initial-eccentricity constraint***

Implications for the properties of the medium produced in small systems

- *Questions of interest*
  - ✓ *Are the medium properties for small and large systems different?*
  - ✓ *Jet quenching in small systems?*
- **Anisotropy scaling functions can give detailed insight**
  - ✓ **They leverage the specific dependencies of viscous attenuation and jet quenching on the control variables**

Anisotropy Scaling Functions



$$R_{AA}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}} L \sqrt{\hat{q}\frac{\mathcal{L}}{p_T}}\right]$$

$$R_{v_2}(p_T, \Delta L) = \frac{R_{AA}(90^o, p_T)}{R_{AA}(0^0, p_T)} = \frac{1 - 2v_2(p_T)}{1 + 2v_2(p_T)}$$

High p_T

$$v_n \propto \varepsilon_n e^{-n\left[n\left(\frac{4}{3}\frac{\eta}{s} + \frac{\xi}{s}\right) + \kappa p_T^z\right]\frac{1}{RT}}, \quad RT \propto \langle N_{chg} \rangle^{1/3}$$

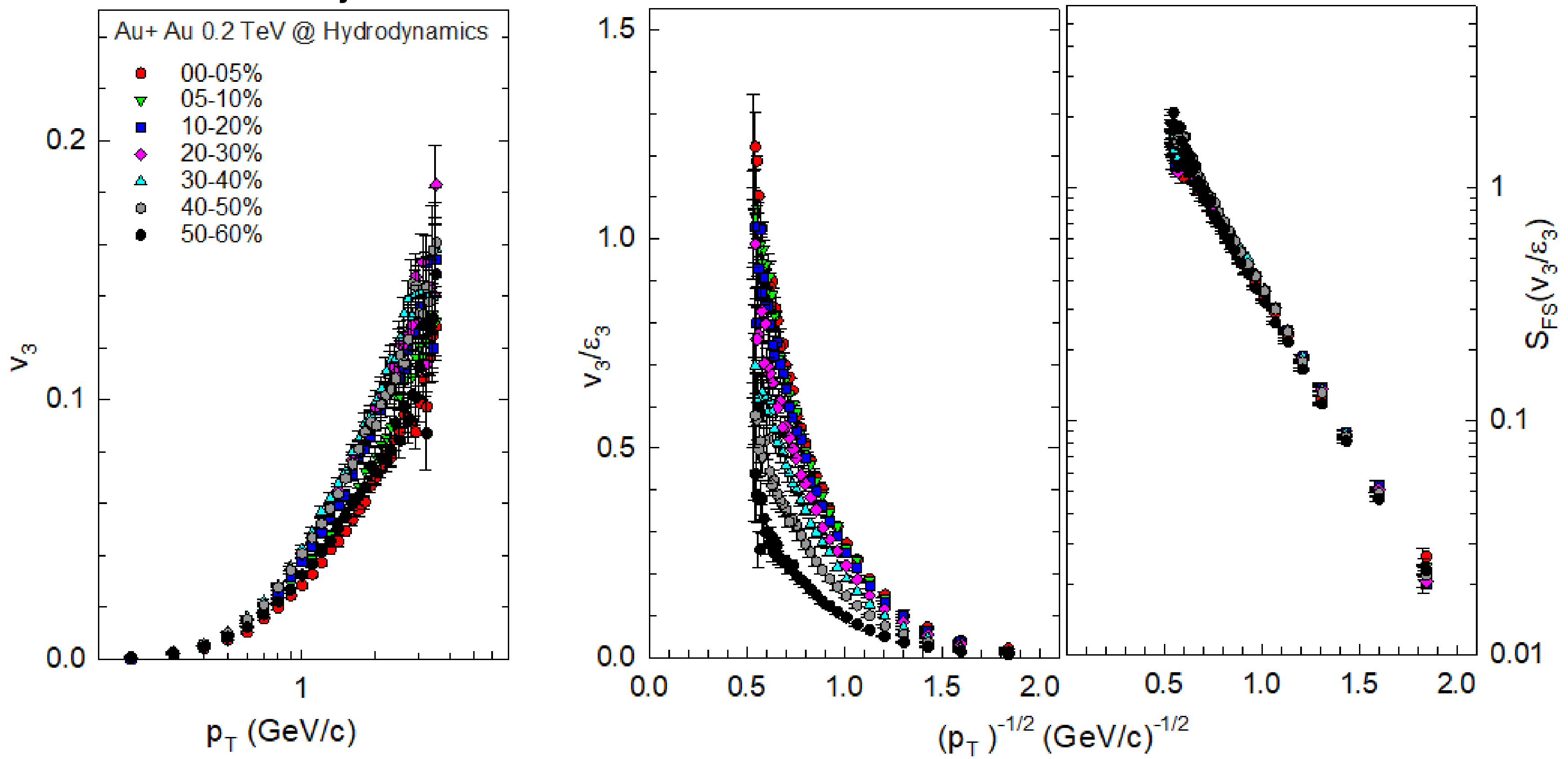
Low p_T

- ✓ **Data should collapse on to a single curve for fully constrained scaling coefficients**
  - **Scaling coefficients give access to transport coefficients $\frac{\eta}{s}(T, \mu_B)$, $\hat{q}$, *etc.***

Anisotropy Scaling Functions

Simulated data from Bjoern Schenke et al.

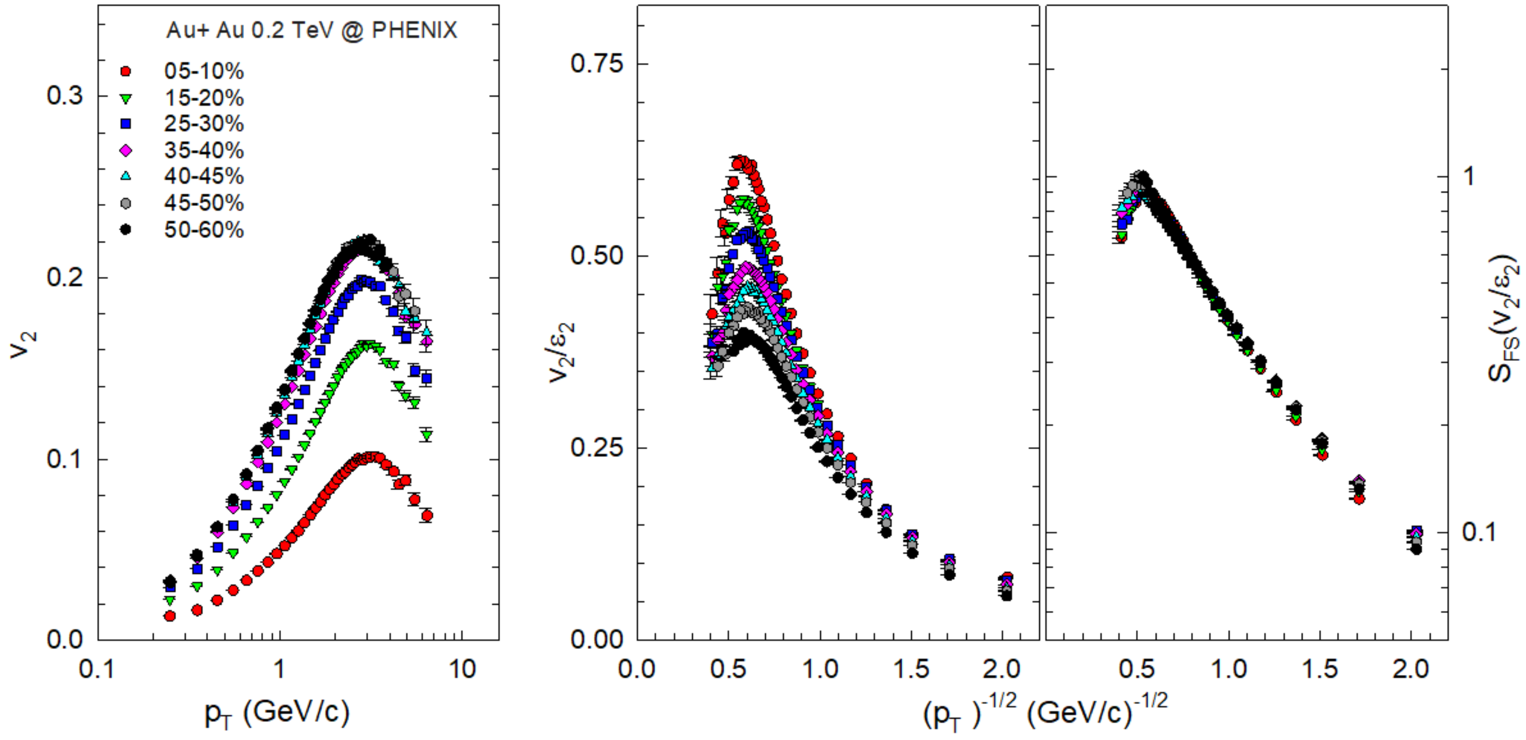
$$v_n \propto \varepsilon_n e^{-n\left[n\left(\frac{4}{3}\frac{\eta}{s}+\frac{\xi}{s}\right)+\kappa p_T^z\right]\frac{1}{RT}}, \quad RT \propto \langle N_{chg} \rangle^{1/3}$$



- ✓ **Characteristic patterns of viscous damping validated for viscous hydrodynamics!**
  - ✓ **Calibration of scaling coefficients since $\frac{\eta}{s}$ is known.**

Anisotropy Scaling Functions

$$v_n \propto \varepsilon_n e^{-n\left[n\left(\frac{4}{3}\frac{\eta}{s}+\frac{\xi}{s}\right)+\kappa p_T^z\right]\frac{1}{RT}}, \quad RT \propto \langle N_{chg} \rangle^{1/3}$$



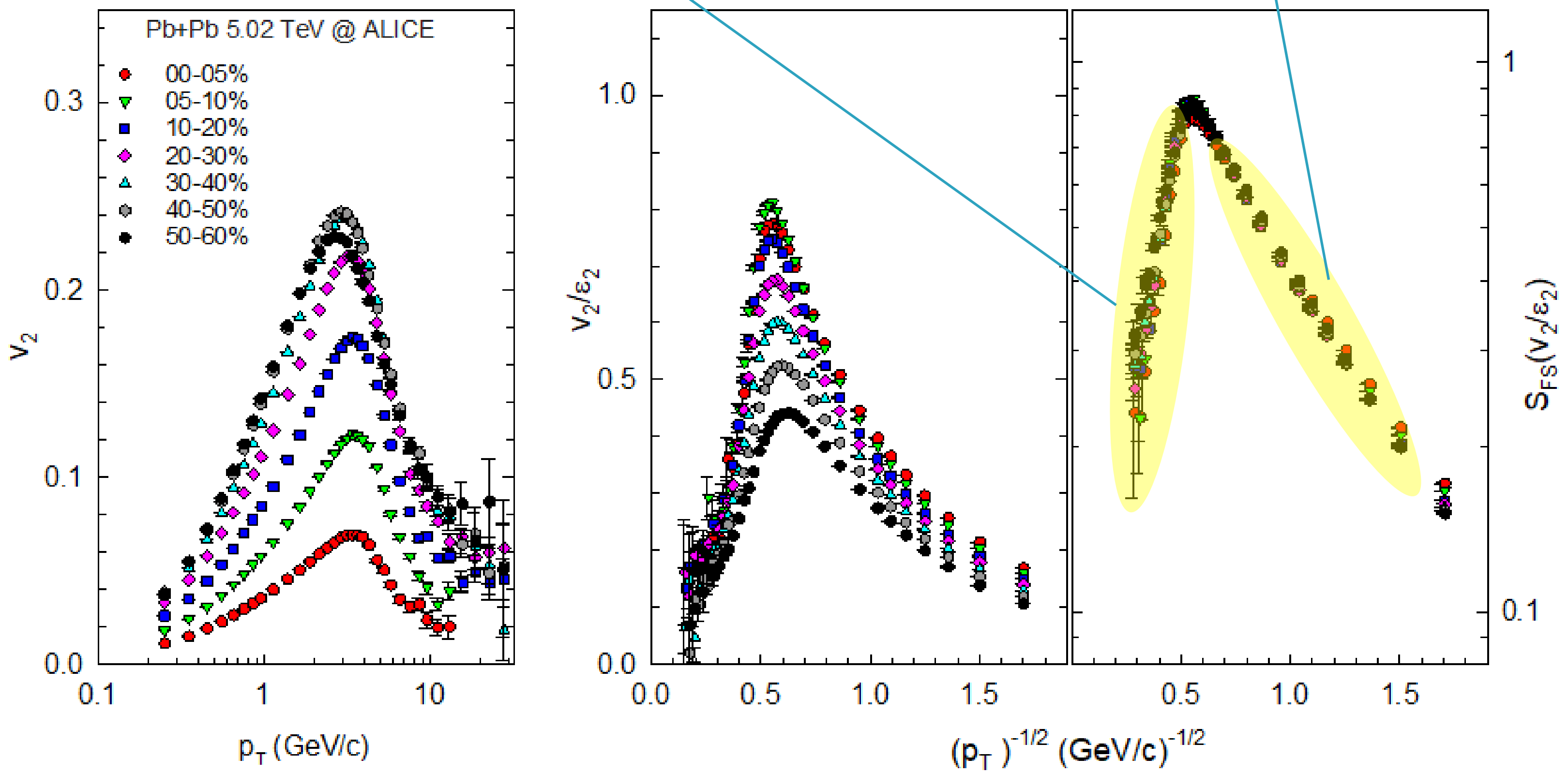
- ✓ **Characteristic patterns of viscous damping and jet quenching validated for the same parameters**
  - ✓ **Scaling coefficients provide constraints for $\frac{\eta}{s}(T, \mu_B)$ and $\hat{q}$**

Anisotropy Scaling Functions

$$\frac{\eta}{s} \sim \left(0.25 / \sqrt{\hat{q} / T^3}\right)$$

$$R_{AA}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}} L \sqrt{\hat{q} \frac{\mathcal{L}}{p_T}}\right]$$

$$v_n \propto \varepsilon_n e^{-n\left[n\left(\frac{4}{3}\frac{\eta}{s} + \frac{\xi}{s}\right) + \kappa p_T^z\right]\frac{1}{RT}}, \quad RT \propto \langle N_{chg} \rangle^{1/3}$$



✓ **Characteristic patterns of viscous damping and jet quenching validated**

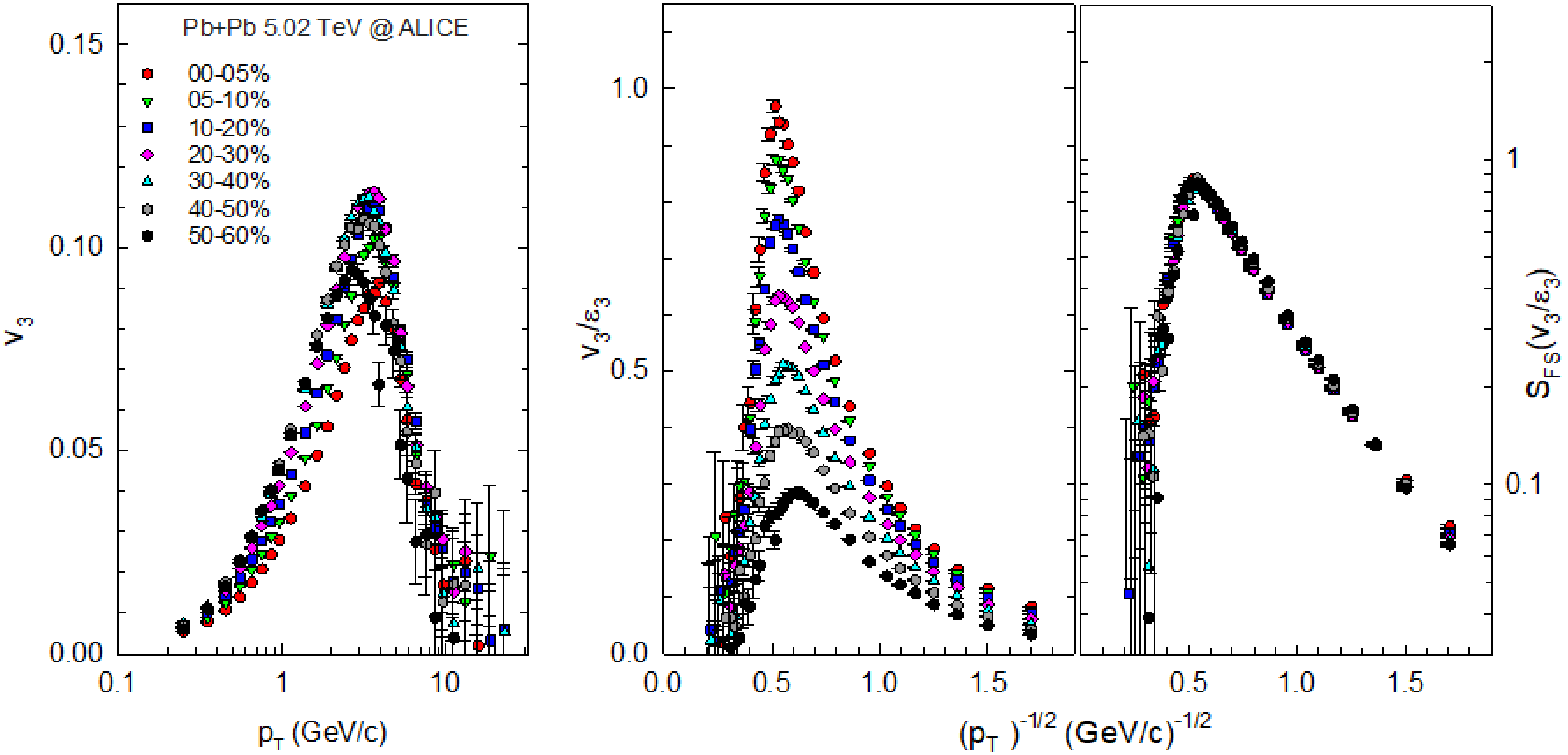
✓ **Scaling coefficients provide constraints for $\frac{\eta}{s}(T, \mu_B)$ and $\hat{q}$**

Anisotropy Scaling Functions

$$\frac{\eta}{s} \sim \left(0.25/\sqrt{\hat{q}/T^3}\right)$$

$$R_{AA}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}} L \sqrt{\hat{q}\frac{\mathcal{L}}{p_T}}\right]$$

$$v_n \propto \varepsilon_n e^{-n\left[n\left(\frac{4}{3}\frac{\eta}{s}+\frac{\xi}{s}\right)+\kappa p_T^z\right]\frac{1}{RT}}, \; RT \propto \langle \mathrm{N}_{\mathrm{chg}} \rangle^{1/3}$$

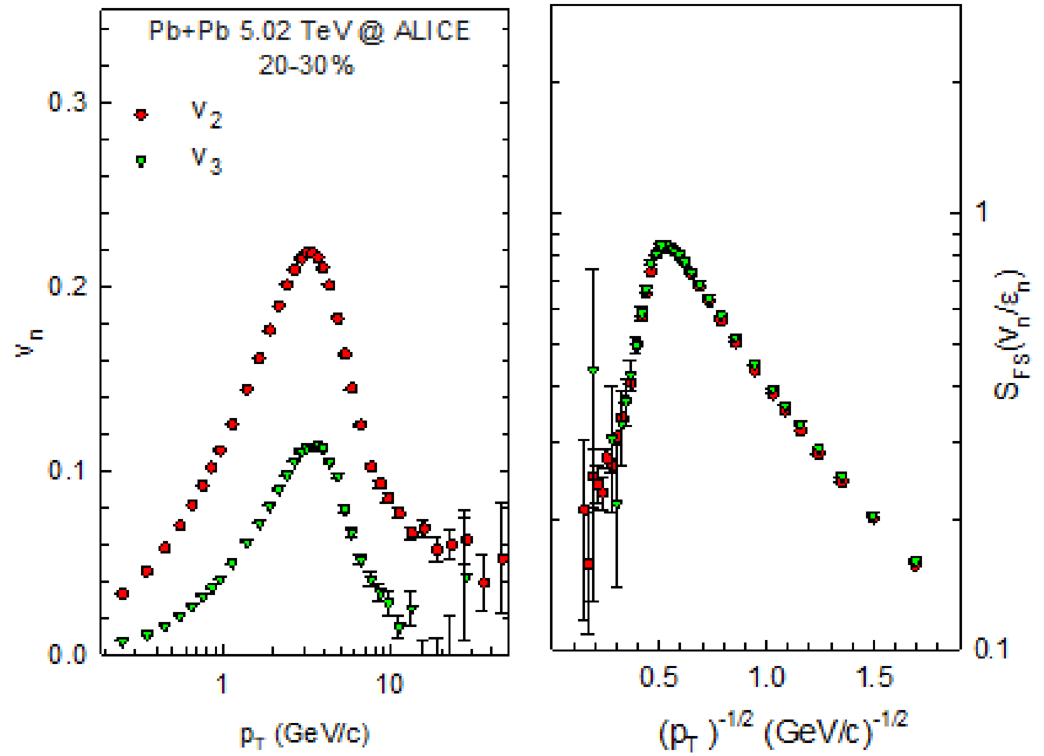


- ✓ **Characteristic patterns of viscous damping and jet quenching validated for the same parameters**
  - ✓ **Scaling coefficients provide constraints for $\frac{\eta}{s}(T, \mu_B)$ and $\hat{q}$**

Anisotropy Scaling Functions

$$R_{\mathrm{AA}}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}}\ L\sqrt{\hat{q}\frac{\mathcal{L}}{p_T}}\right]$$

$$v_n \propto \varepsilon_n e^{-n\left[n\left(\frac{4}{3}\frac{\eta}{s}+\frac{\xi}{s}\right)+\kappa p_T^z\right]\frac{1}{RT}}, \quad RT \propto \langle \mathrm{N}_{\mathrm{chg}} \rangle^{1/3}$$

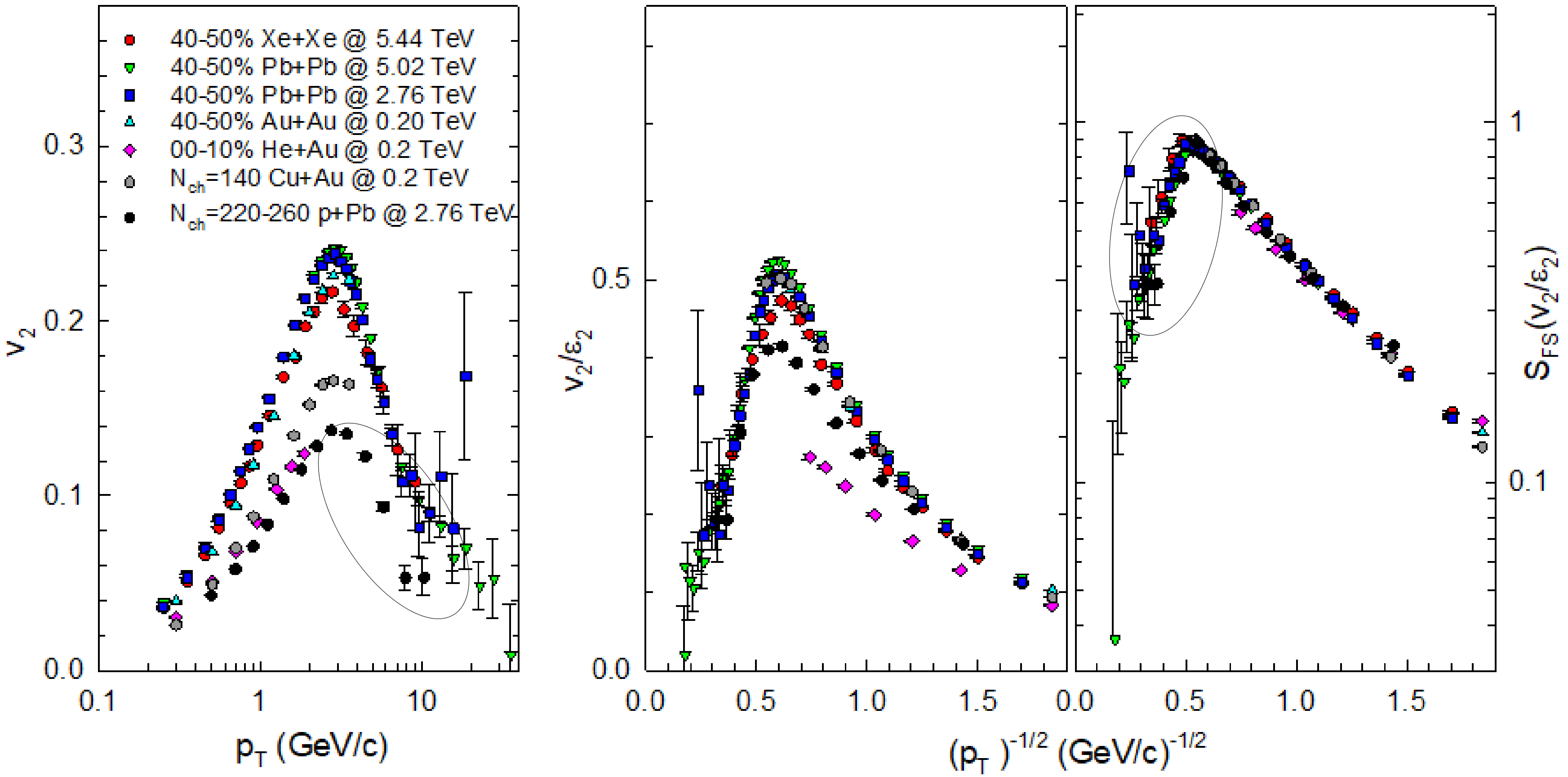


✓ **Characteristic patterns of viscous damping and jet quenching validated for the same scaling coefficient.**

✓ **Scaling coefficients provide constraints for $\frac{\eta}{s}(T, \mu_B)$ and $\hat{q}$**

Anisotropy Scaling Functions

$$v_n \propto \varepsilon_n e^{-n\left[n\left(\frac{4}{3}\frac{\eta}{s}+\frac{\xi}{s}\right)+\kappa p_T^z\right]\frac{1}{RT}}, \quad RT \propto \left\langle \mathrm{N}_{\mathrm{chg}} \right\rangle^{1/3}$$

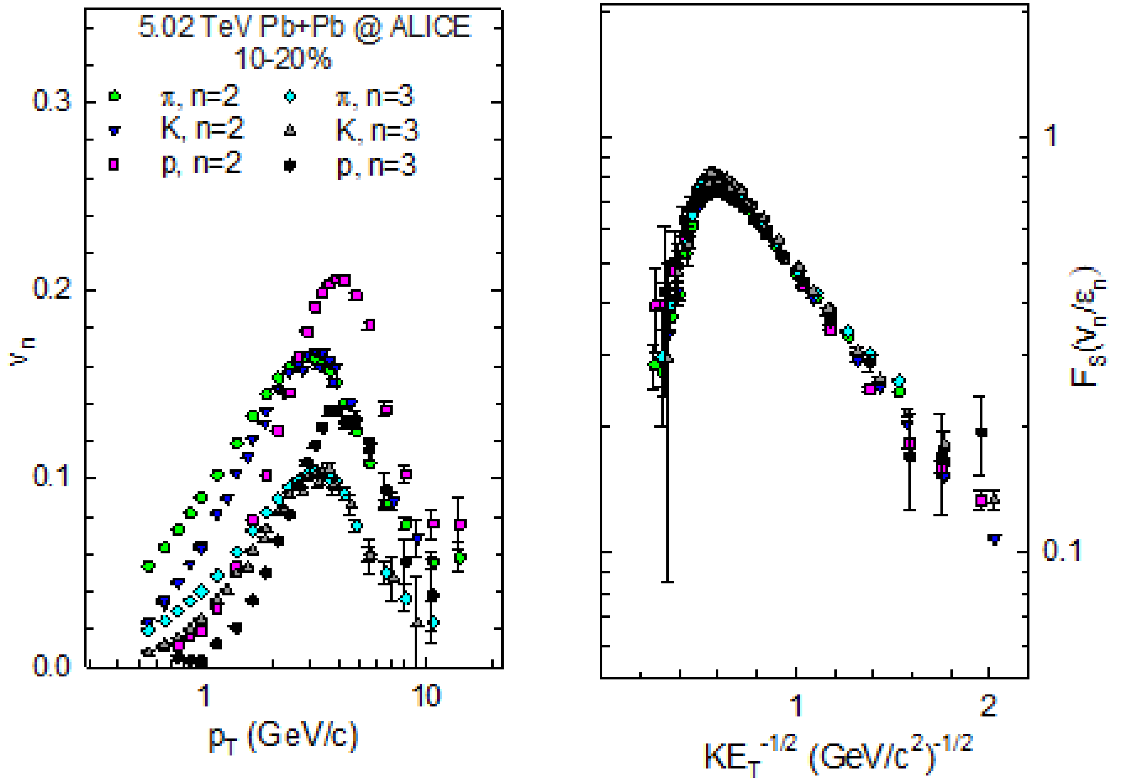


- ➢ **Indications for viscous damping and jet quenching across systems.**
  - ✓ **Viscous damping very important for small dimensionless sizes.**
    - ✓ ***Scaling coefficients indicate;***
      - ✓ ***an increase in η/s from RHIC to LHC.***
      - ✓ **A “small” increase in *η/s from large to small systems.***

Anisotropy Scaling Functions – PID

$$R_{AA}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}}\, L \sqrt{\hat{q}\frac{\mathcal{L}}{p_T}}\right]$$

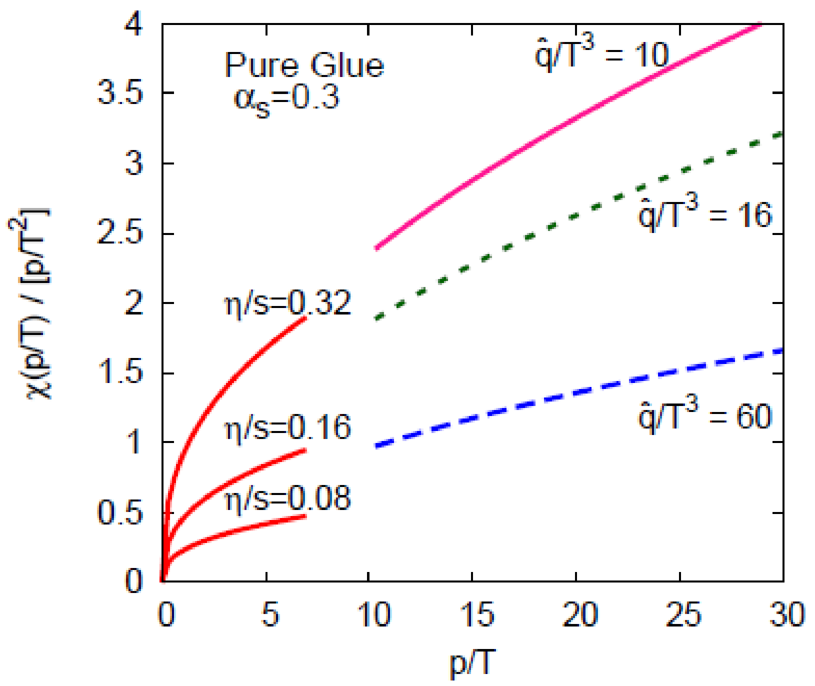
$$v_n \propto \varepsilon_n e^{-n\left[n\left(\frac{4}{3}\frac{\eta}{s}+\frac{\xi}{s}\right)+\kappa p_T^z\right]\frac{1}{RT}}, \quad RT \propto \langle N_{chg} \rangle^{1/3}$$



- ✓ **Characteristic patterns of viscous damping and jet quenching validated for different particle species.**
  - ✓ **Scaling coefficients provide constraints for $\frac{\eta}{s}(T, \mu_B)$ and $\hat{q}$**

Extracting transport coefficients

K. Dusling et. al. Phys.Rev.C81:034907,2010



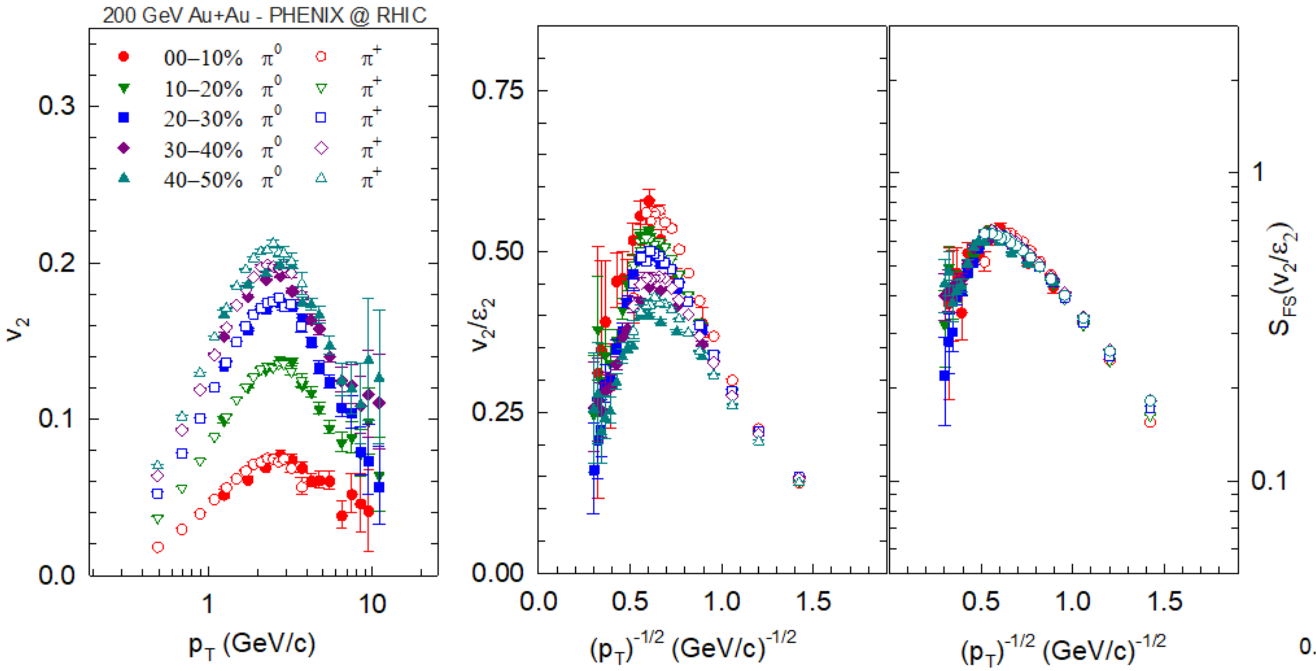
$$\chi(p) \propto p^2$$

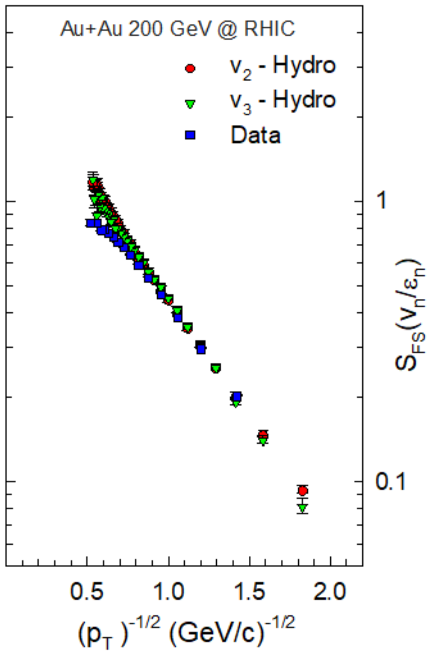
$$\chi_g(p) \approx \frac{0.7}{\alpha_s T\sqrt{\hat{q}}}p^{3/2}$$

- **The off equilibrium correction is controlled by two nonperturbative parameters**
  - ✓ $\frac{\eta}{s}$ **at low momentum**
  - ✓ $\hat{q}$ **at high momentum**

The smooth merger of the low and high pT regions is a crucial constraint

Extracting transport coefficients





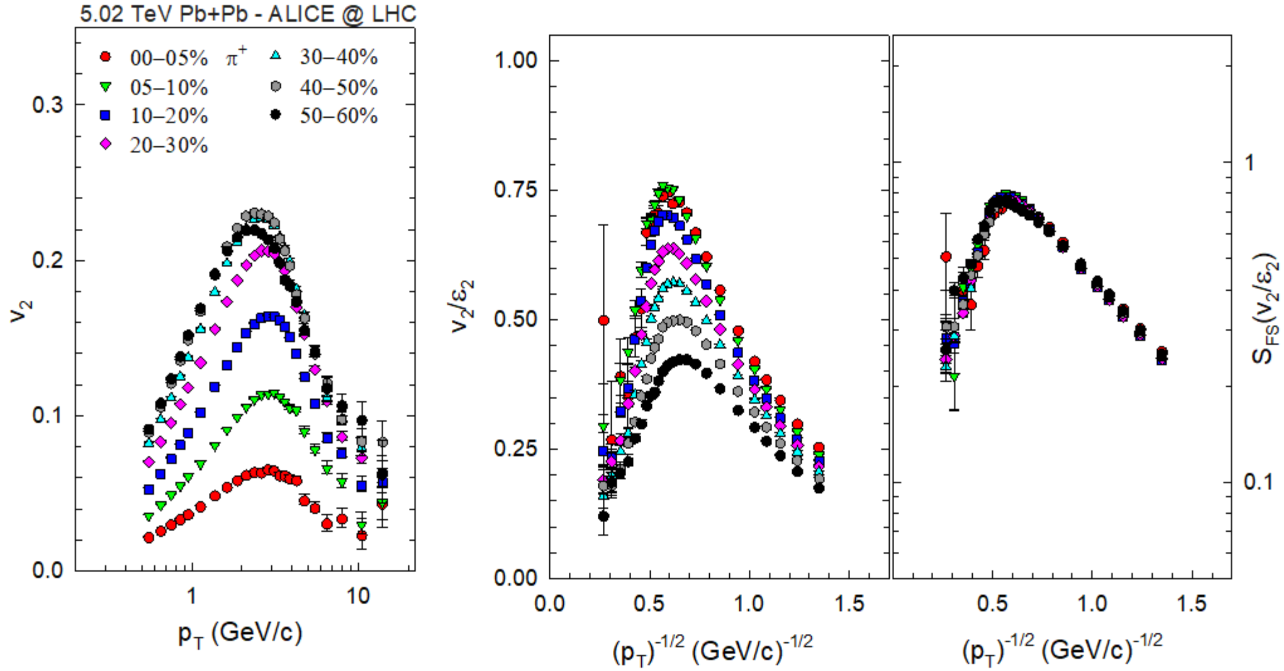
Hydro calibration

$\frac{\eta}{s}$(RHIC) ~0.11

$\frac{\eta}{s}$(LHC) ~0.15

$\frac{\hat{q}}{T^3}$(RHIC) ~ 4.5

$\frac{\hat{q}}{T^3}$(LHC) ~ 2.4



Epilogue

- New STAR *differential and integral* v_n *measurements that explicitly account for the effects of non-flow, are presented for p/d/*^{3}He+*Au*
  - ✓ Non-flow mitigated by leveraging two-particle p+p correlation function via several methods.
  - ✓ The measurements are method-independent within uncertainties

❖ *For similar multiplicity*

- ✓ *The observed* v_2 *and* v_3 *are consistent with the important role of both "size" (*N_{ch}*)* and the fluctuations-driven eccentricity (ϵ_n)
  - ✓ *The measurements [especially* v_3*] are inconsistent with the notion of shape engineering in p/d/*^{3}He+*Au collisions*

❖ *Anisotropy scaling functions allow seamless leveraging of the diverse measurements to constrain models & transport coefficients*

- ✓ *Initial indications for change in transport coefficients with beam energy, small collision-system sizes, conserved currents, etc.*

- *Future anisotropy measurements for symmetric small systems, as well as high* p_T *data are crucial for improved constraints and insights*
  - ✓ STAR is well positioned for such measurements post BES-II

End