Indications for a non-monotonic pattern in the (T, μ_B)-dependence of the specific viscosity

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<u>*Question*</u>

$\frac{\boldsymbol{\eta}}{\boldsymbol{s}}(\boldsymbol{T}, \boldsymbol{\mu_B}, \boldsymbol{\mu_I}, \boldsymbol{\mu_S})$?

Implications if any?

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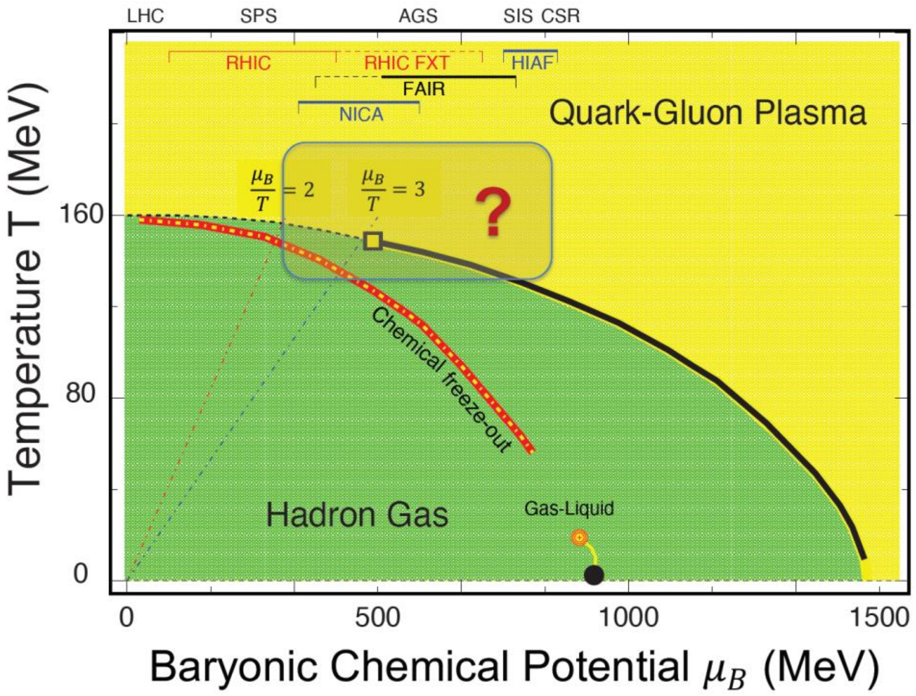
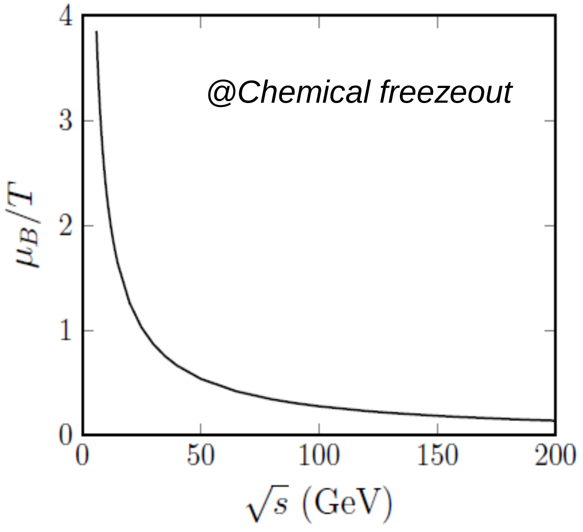
Backdrop – Exploration strategy for the specific viscosity

- **Leverage the wealth of measurements across collision energies ($\sqrt{s_{NN}}$) and collision-systems**

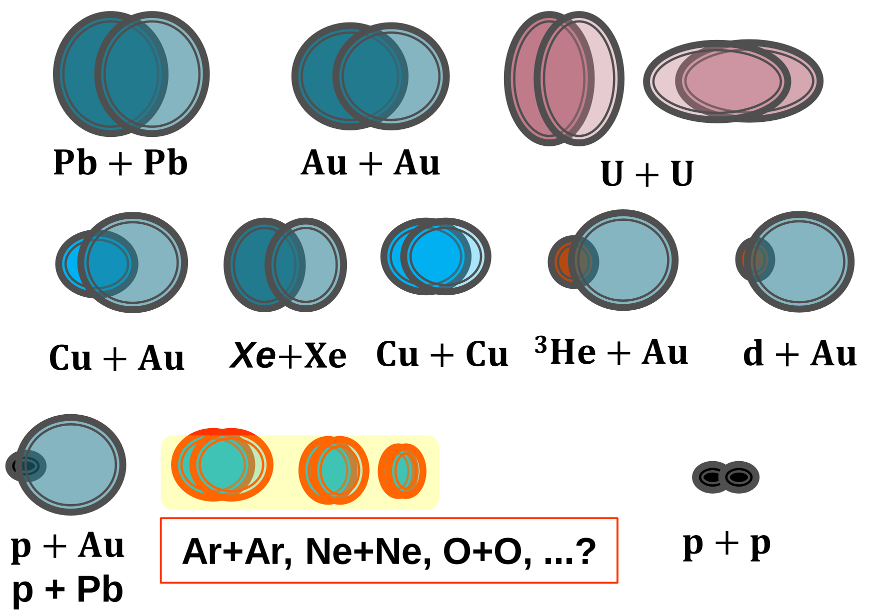
Collision Energies

$$T_f(\mu_B) = T_f(0)\left(1 - \kappa_{f,2}\hat{\mu}_B^2 - \kappa_{f,4}\hat{\mu}_B^4\right)$$





Collision-systems



Use system-dependent measures to constrain initial-state and reaction dynamics;

- ✓ *Initial-shape dependence*
- ✓ *Geometric-size dependence*
- ✓ *Initial-state-fluctuations dependence*
- ✓ *Dimensionless size dependence*
- ✓ …

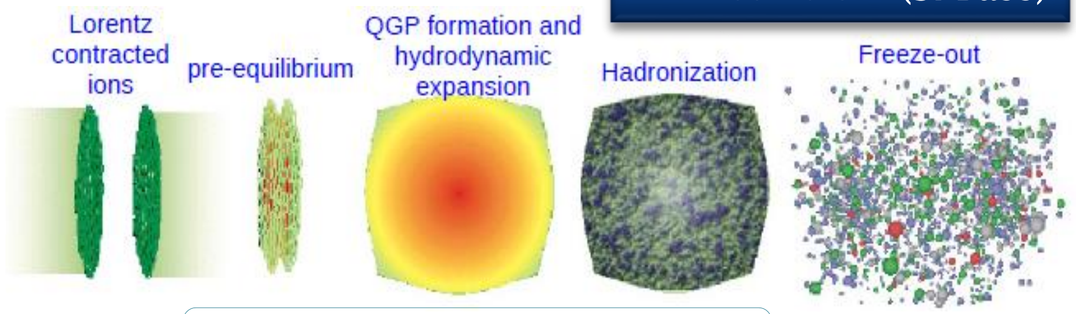
- *Use beam-energy-dependent measures to probe;*
  - ✓ (T, μ_B) – ***domain*** *of the phase diagram*
  - ✓ $\frac{\eta}{s}(T, \mu_B, \mu_S, \mu_I)$

    manifest via charged currents

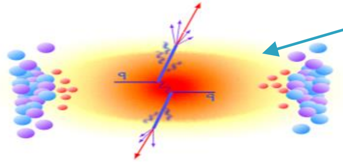
- **The $\sqrt{s_{NN}}$ and system dependencies provide important constraints which can be leveraged in tandem, via scaling functions**

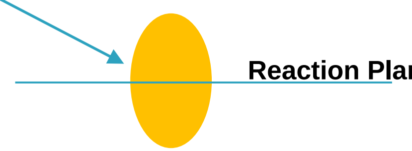
Anisotropy Scaling Functions

A+A collision (S. Bass)



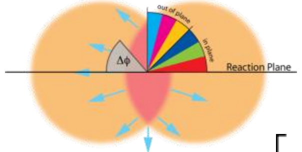
Drives azimuthal Anisotropy





Jet quenching – high p_T

Collective flow – low p_T



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

Phys. Lett. B519, 199 (2001)

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

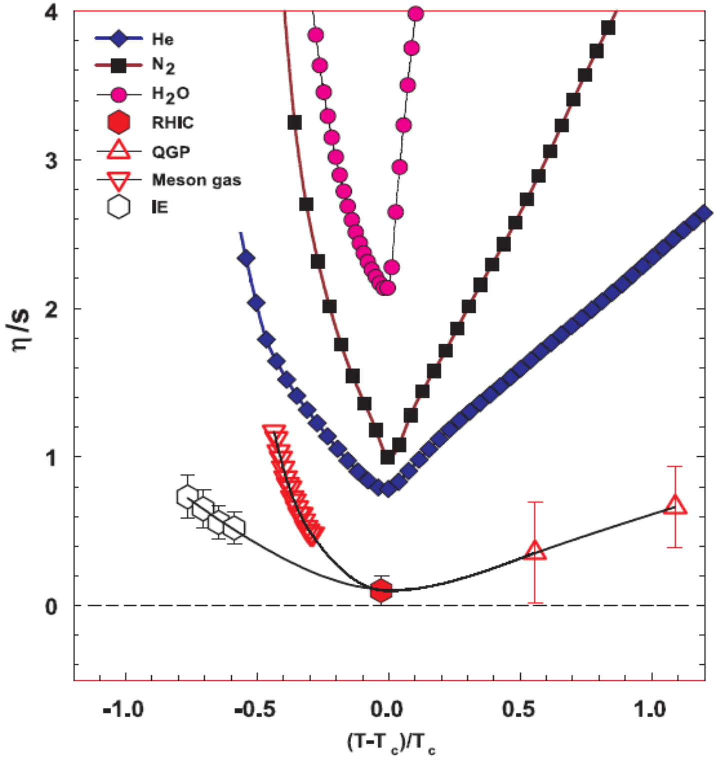
Specific dependencies on p_T, ΔL and $\hat{q}$

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

Specific dependencies on $n, \varepsilon_n, p_T, RT$ and $\frac{\eta}{s}, \frac{\xi}{s}$

<u>Question</u> $\frac{\eta}{s}(T, \mu_B, \mu_I, \mu_S)$?

***Lacey et. al. Phys.Rev.Lett.* 98 (2007) 092301**



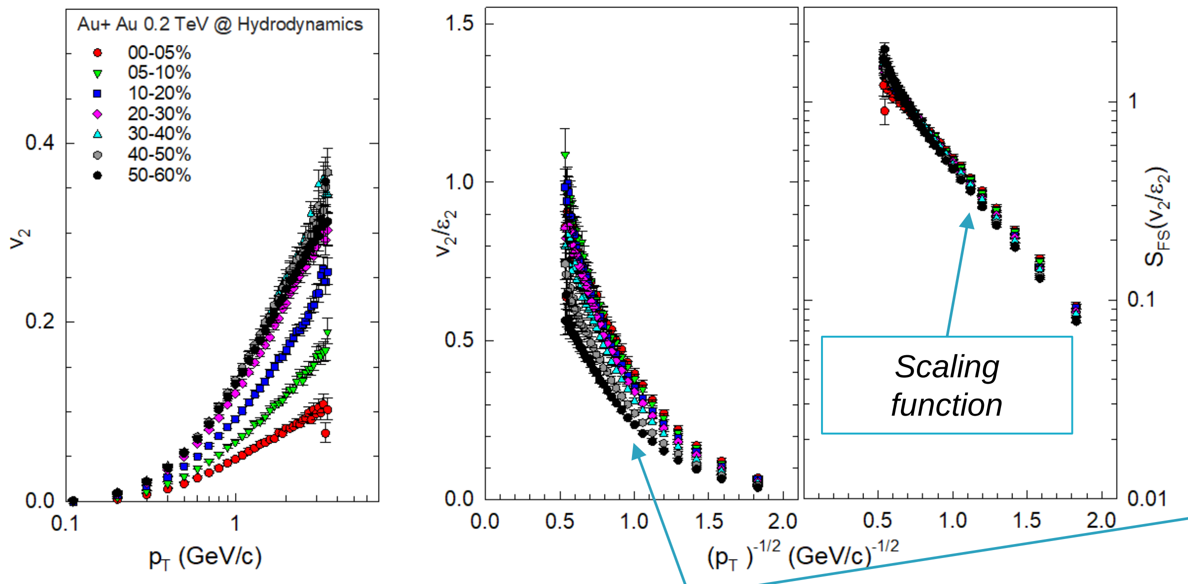
- ✓ *Could give insight on the location of the Critical End Point in the QCD phase diagram*
- ✓ *Viscosity of particles vs. antiparticles?*

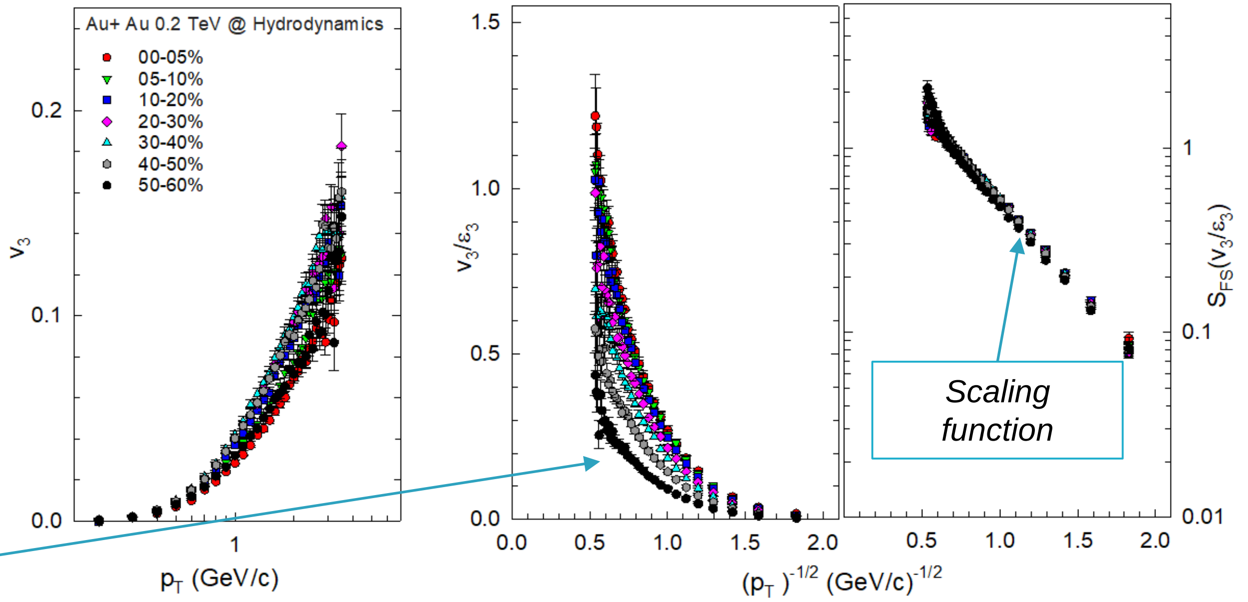
➢ **Anisotropy Scaling Functions (ASF) for unidentified and identified particle species are used as constraints**

Anisotropy Scaling Function – Proof of principle

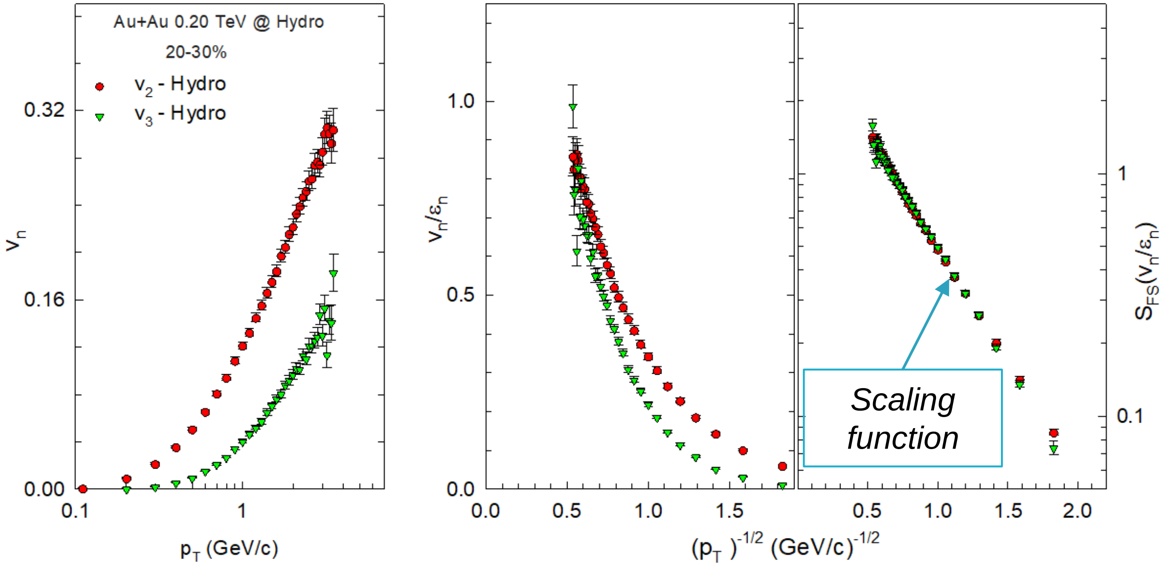
$$v_n \propto \varepsilon_n e^{-n\left[n\left(\frac{4\eta}{3s}+\frac{\xi}{s}\right)+\kappa p_T^2\right]\frac{1}{RT}}, \quad RT \propto \langle N_{chg} \rangle^{1/3}$$

Simulated data [for charged hadrons] from Bjoern Schenke et al.





- ✓ *Eccentricity scaling (alone) is insufficient*
  - ❖ ***Final-state interactions are crucial***
    - ✓ ***Same $\frac{\eta}{s}$ for v_2 & v_3***

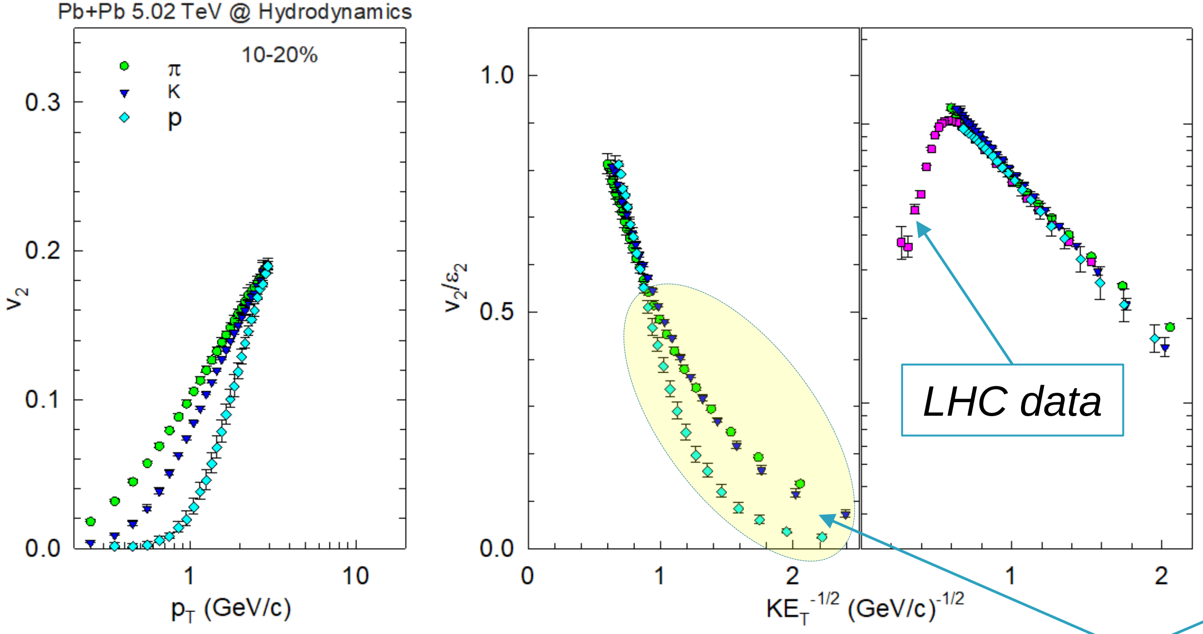


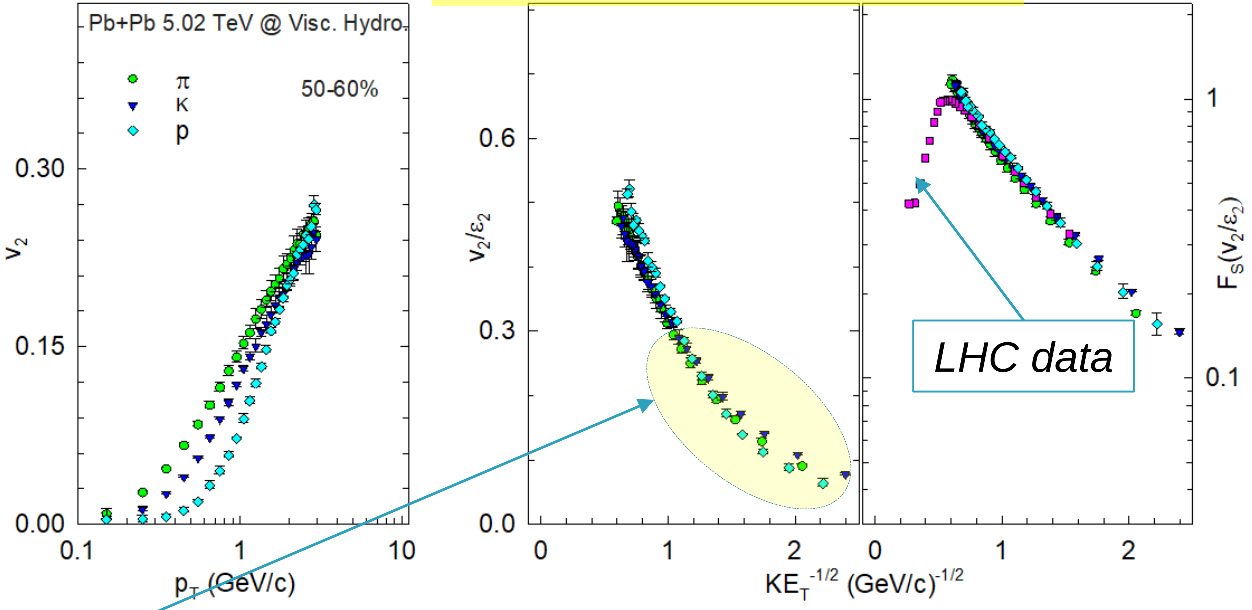
- **Anisotropy data as a function of control variables should collapse on to a single curve for fully constrained scaling coefficients**
  - ✓ **Scaling coefficients are proportional to the respective transport coefficients**

Anisotropy Scaling Function – Proof of principle

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

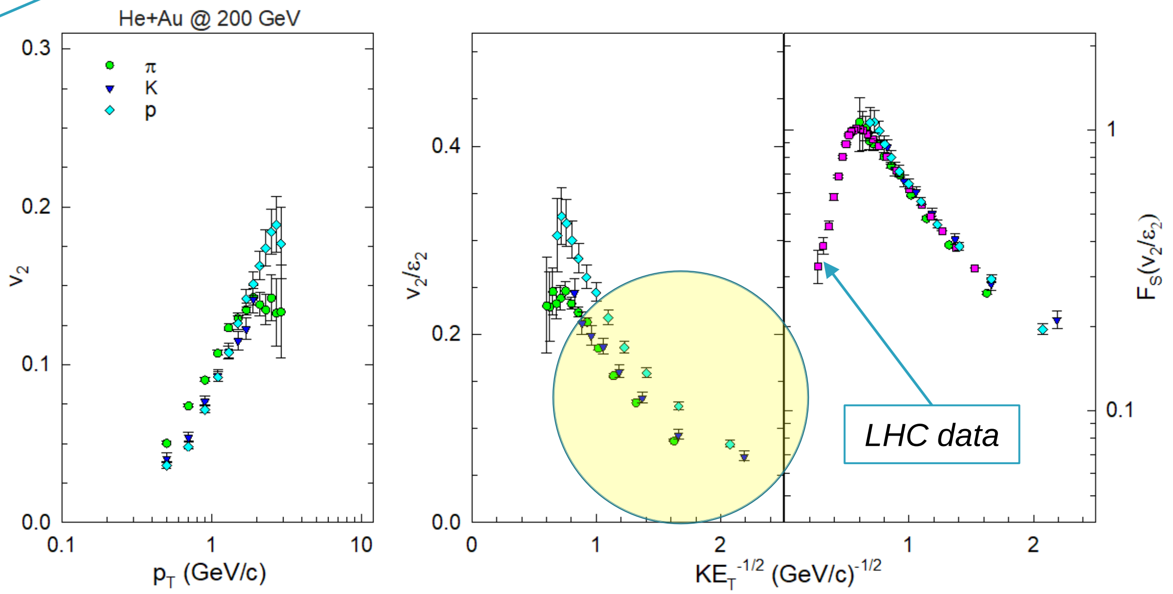
Simulated data [for identified particles] from Huichao Song et al.





Expansion dynamics

- ✓ $\mu_{B,S,I} \sim 0$
- ✓ PID-independent control variables
- ✓ PID-dependent expansion dynamics

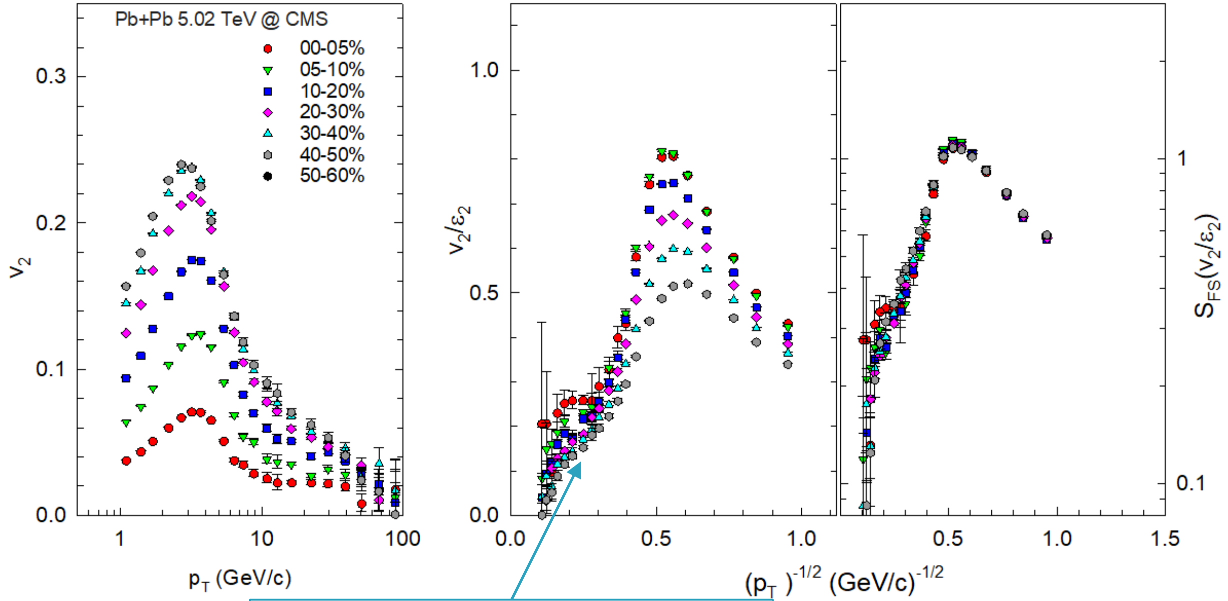


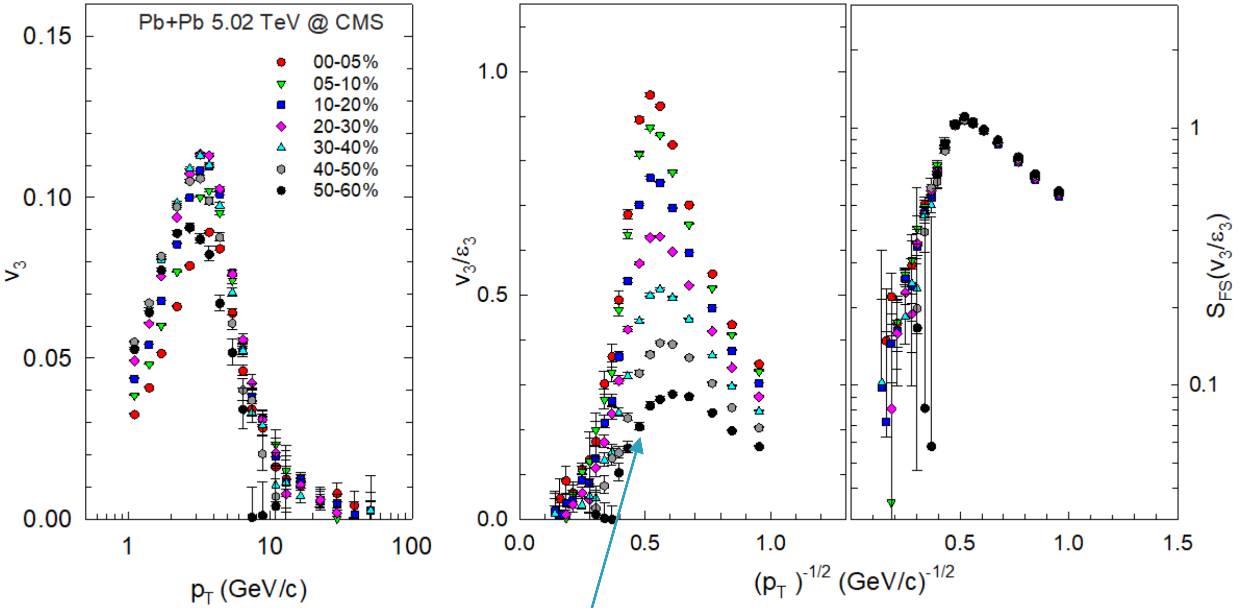
- ➢ **Characteristic patterns for viscous attenuation and expansion dynamics validated!**
  - ✓ **Can serve as a calibration for the scaling coefficient since simulation parameters are known.**

Anisotropy Scaling Functions – LHC data

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

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

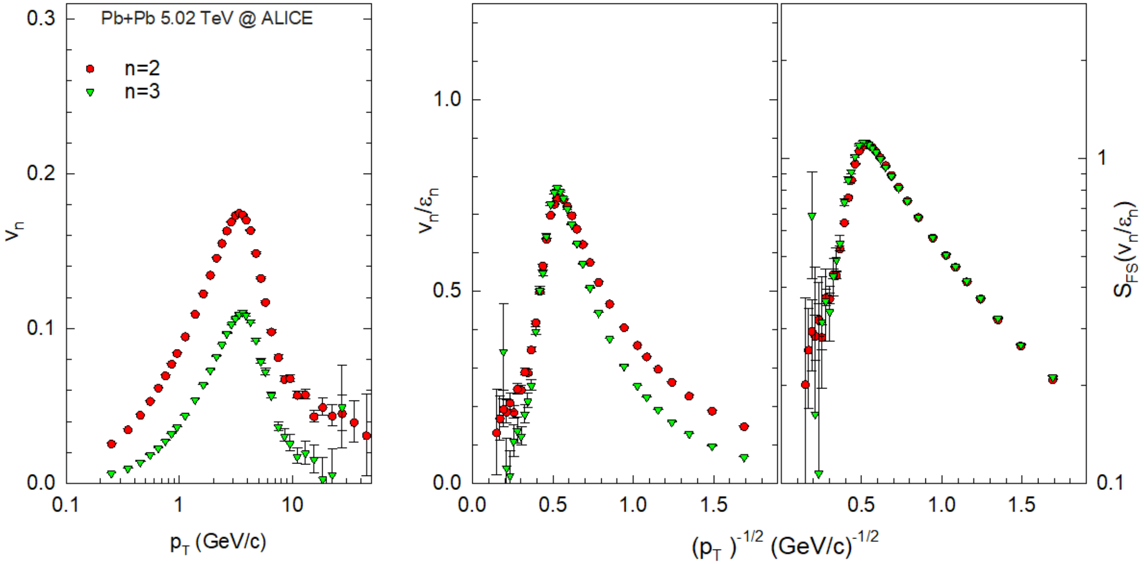




Final-state interactions are important

Final-state interactions are important

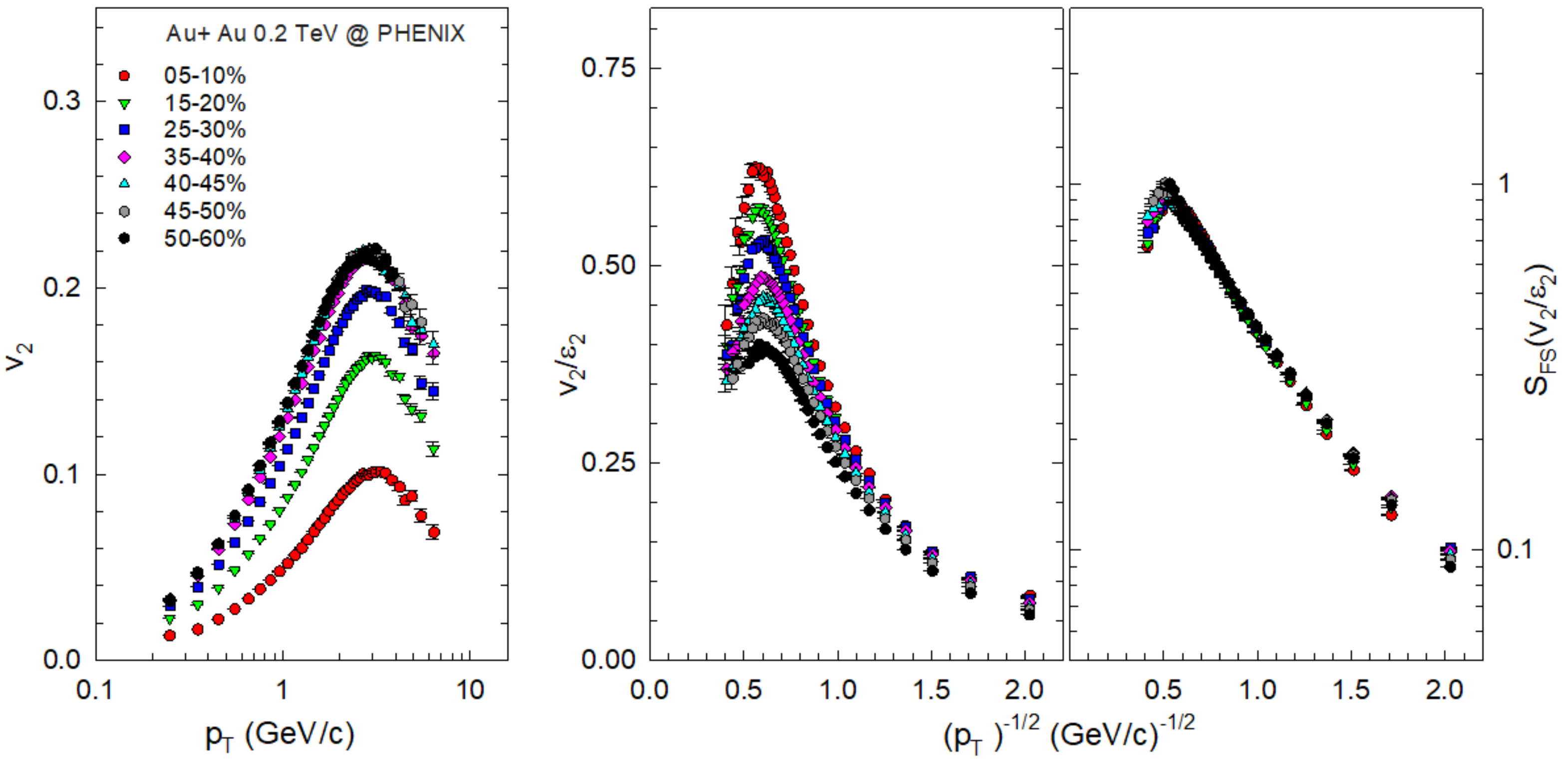
- **Characteristic patterns of viscous damping and jet quenching validated over an extended pT range.**
  - ✓ **Scaling coefficients provide constraints for** $\frac{\eta}{s}(T, \mu_B,)$ **and** $\hat{q}(T, \mu_B)$



Anisotropy Scaling Functions

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

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

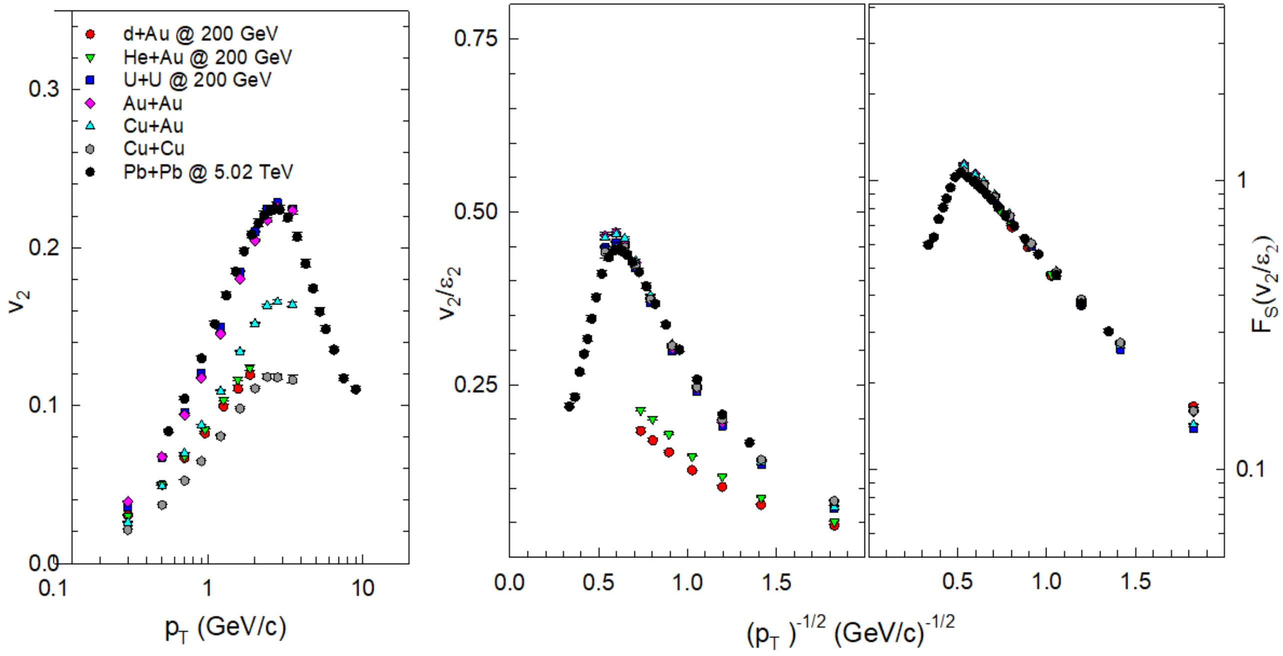


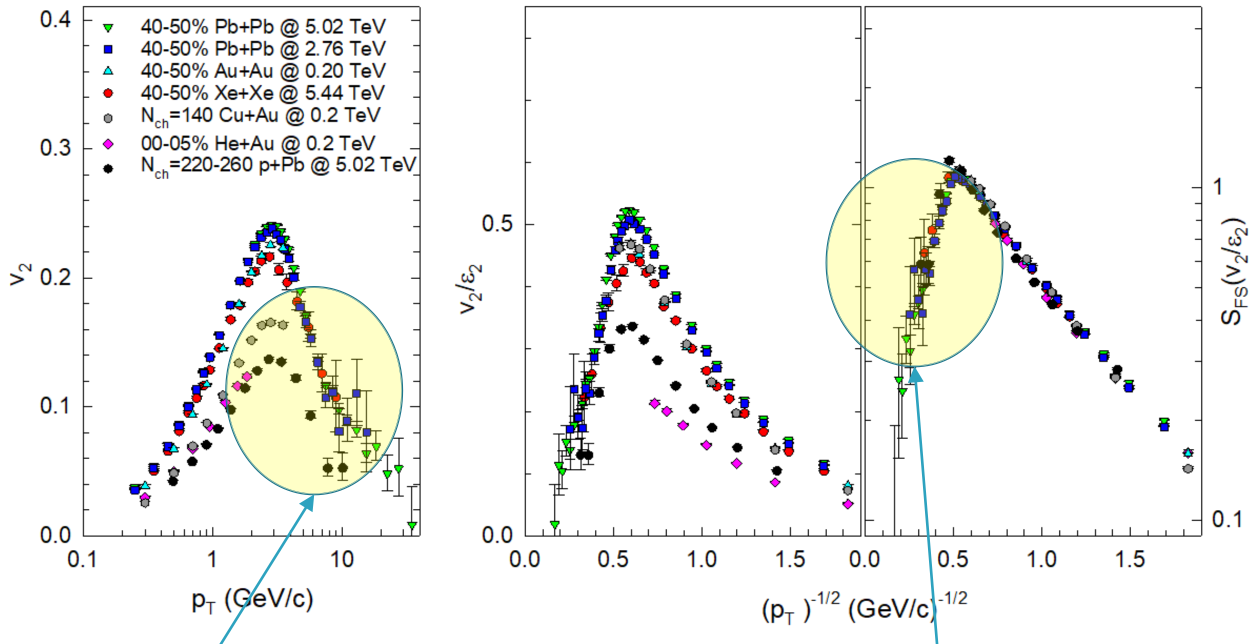
- ✓ **Characteristic patterns of viscous damping and jet quenching validated for the same parameters**
  - ✓ **Scaling coefficients indicate an increase of $\frac{\eta}{s}$ from RHIC to LHC**

Anisotropy Scaling Functions – Systems & Energies

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

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





➢ High-p_T p+Pb

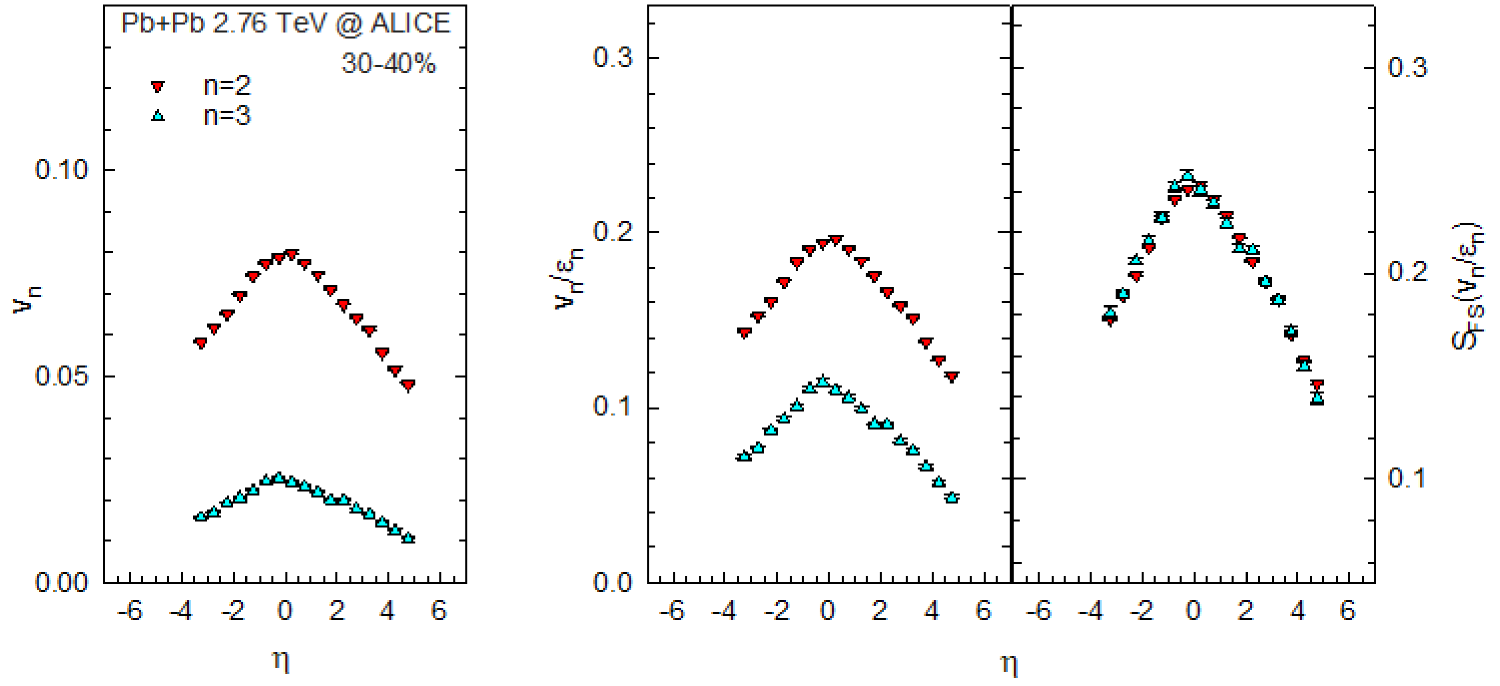
➢ Jet quenching in p+Pb?

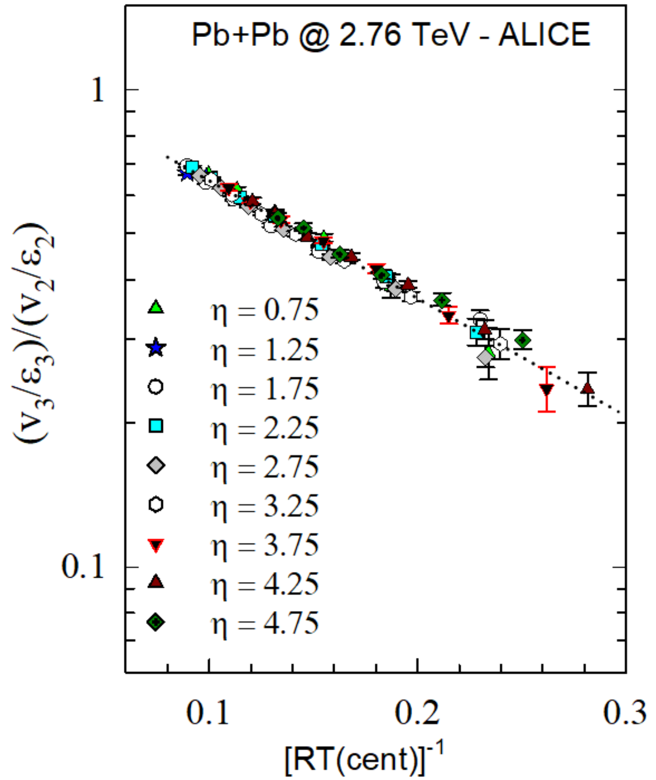
- ✓ Same $\langle N_{chg} \rangle$ for U+U, Pb+Pb, Au+Au, Cu+Au and Cu+Cu
- ✓ Different $\langle N_{chg} \rangle$ for d(^{3}He)+Au

➢ **Indications for viscous attenuation and jet quenching across systems.**
  - ✓ **Signal attenuation very important for small dimensionless sizes.**

❖ ***Scaling coefficients indicate;***
  - ✓ *an increase in η/s from RHIC to LHC.*
  - ✓ **A modest increase in** *η/s from large to small systems.*

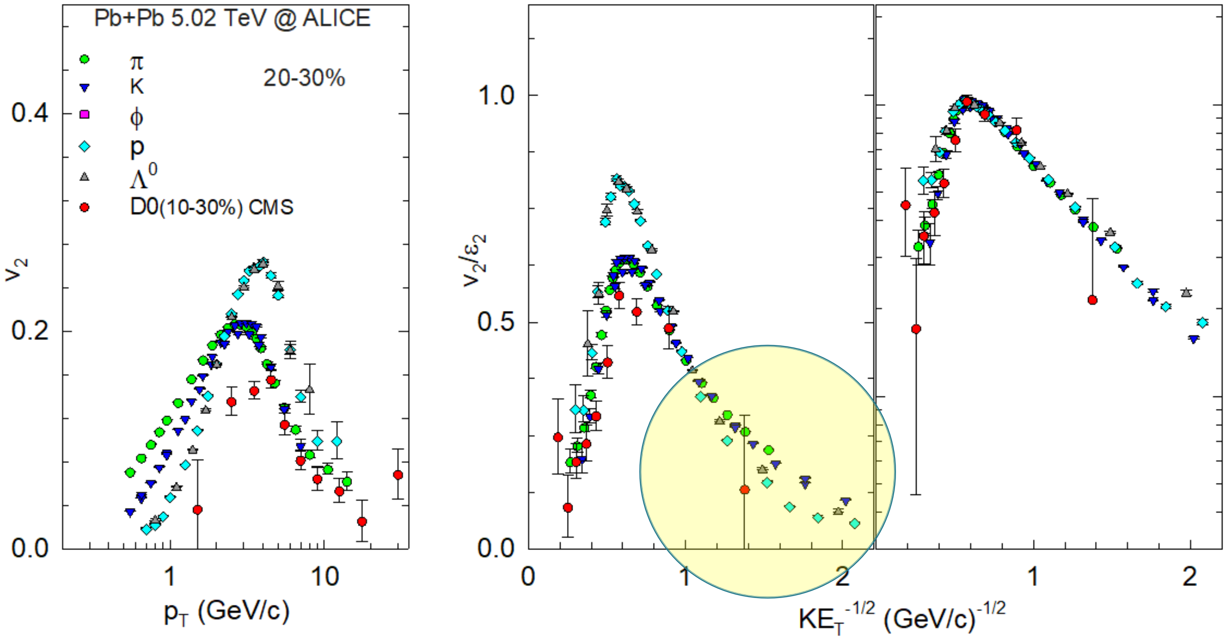
Anisotropy Scaling Functions – LHC data





- $\boldsymbol{\eta - dependent}$ **patterns of viscous attenuation** **Scaling coefficients provide constraints for $\frac{\eta}{s}(T, \mu_B,)$**

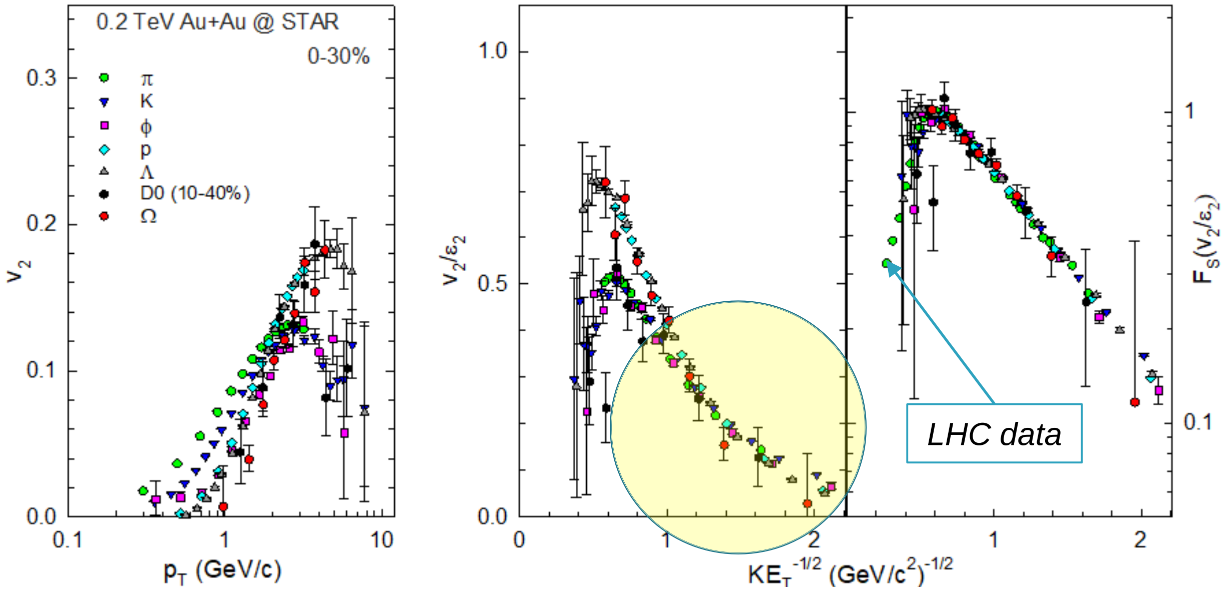
Anisotropy Scaling Functions – Identified particles

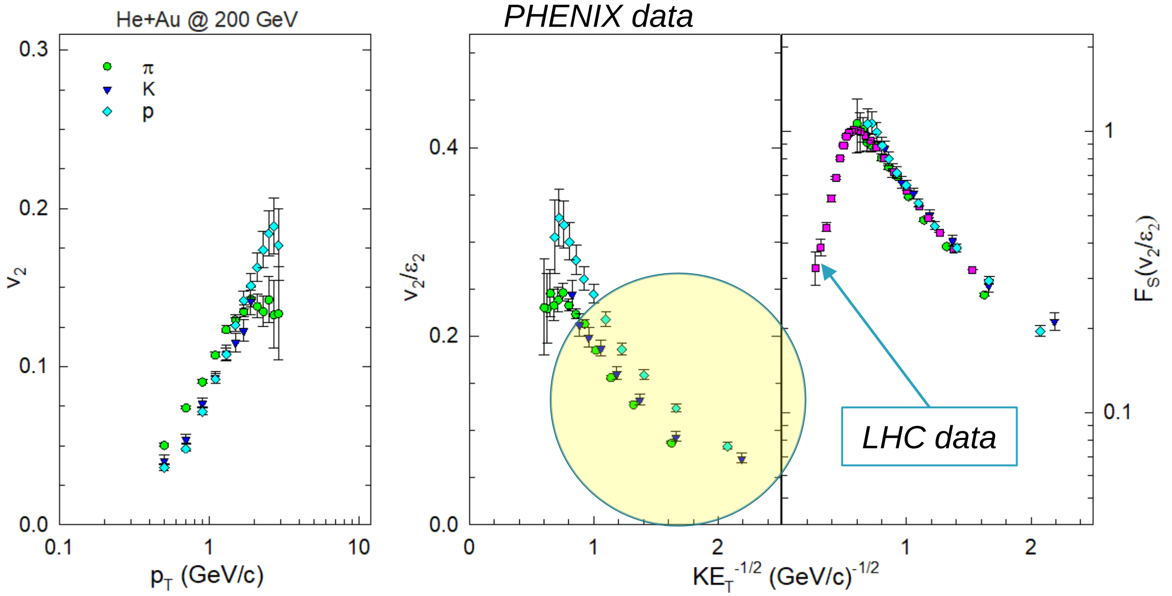


✓ *PID-independent control variables*

✓ *PID-dependent expansion dynamics*

- **Characteristic patterns of viscous damping and jet quenching validated for identified particles**
- ***Scaling coefficients indicate;***
  - ✓ ***an increase in η/s from RHIC to LHC***
  - ✓ **Smaller $\frac{\hat{q}}{T^3}$ for charmed mesons at the LHC**
  - ✓ **An increase in *η/s from large to small systems.***

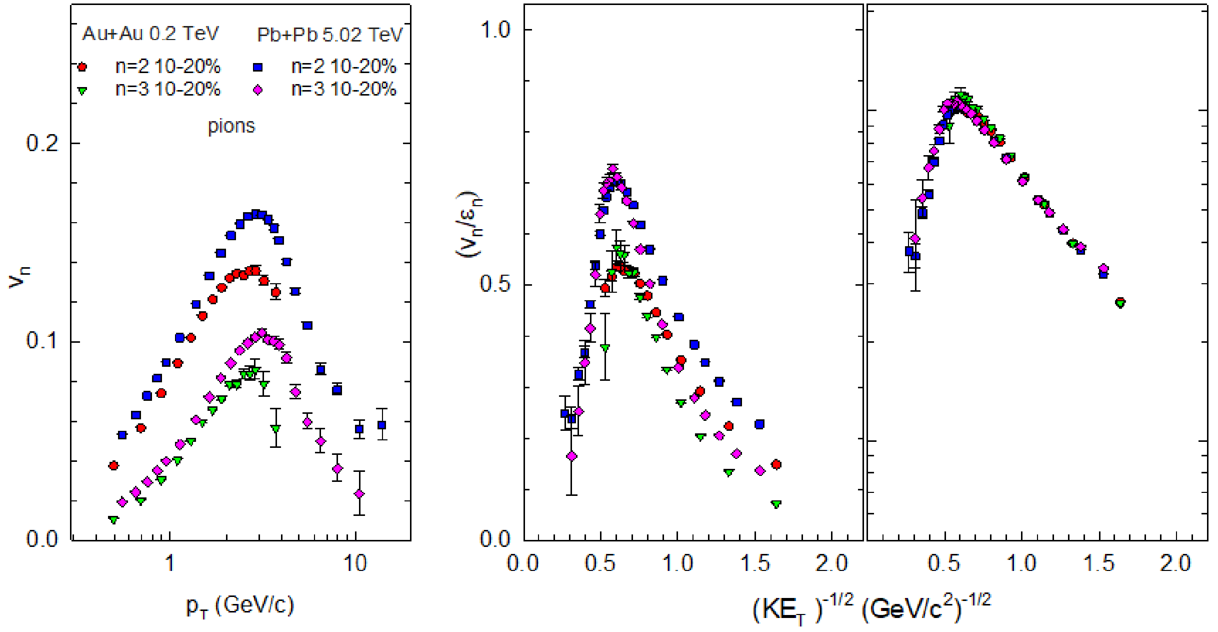


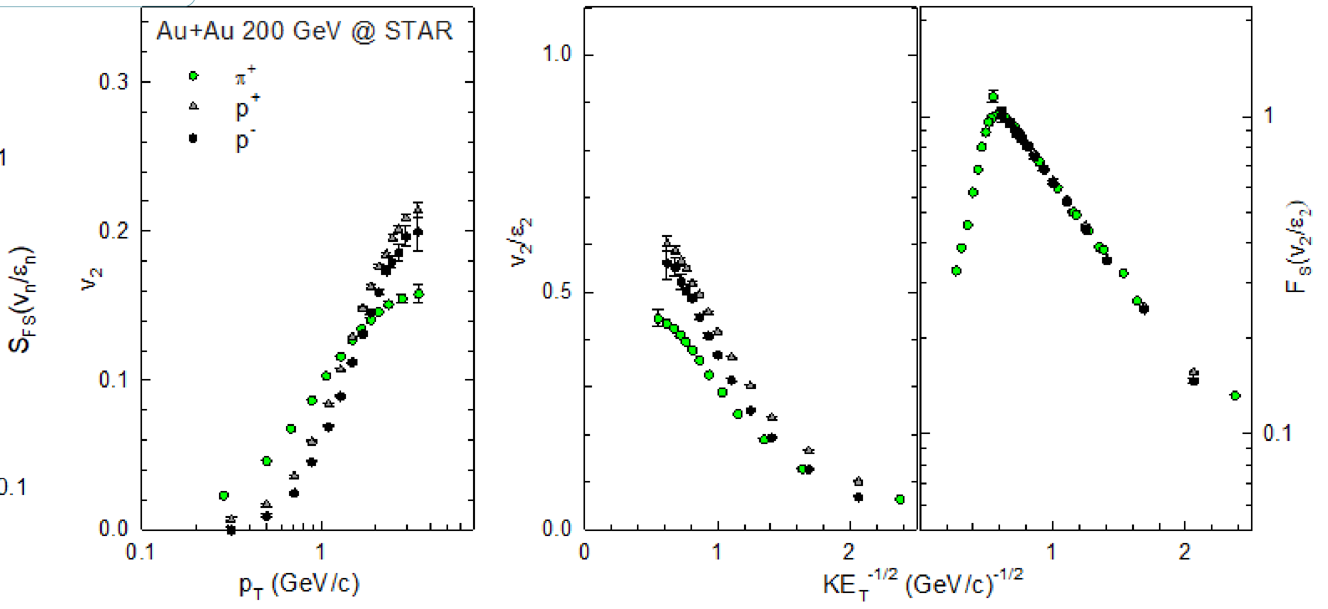


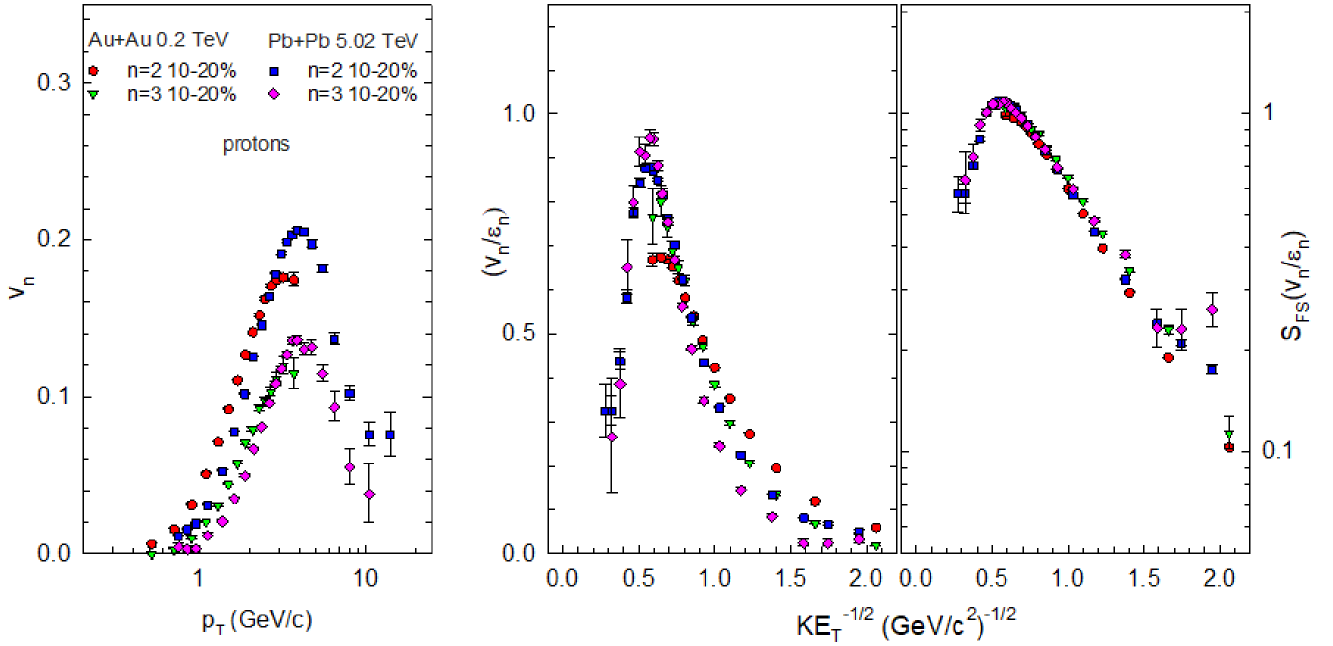
✓ *PID-dependent expansion dynamics*

✓ *Size-dependent expansion dynamics*

Anisotropy Scaling Functions – Systems species & Energies



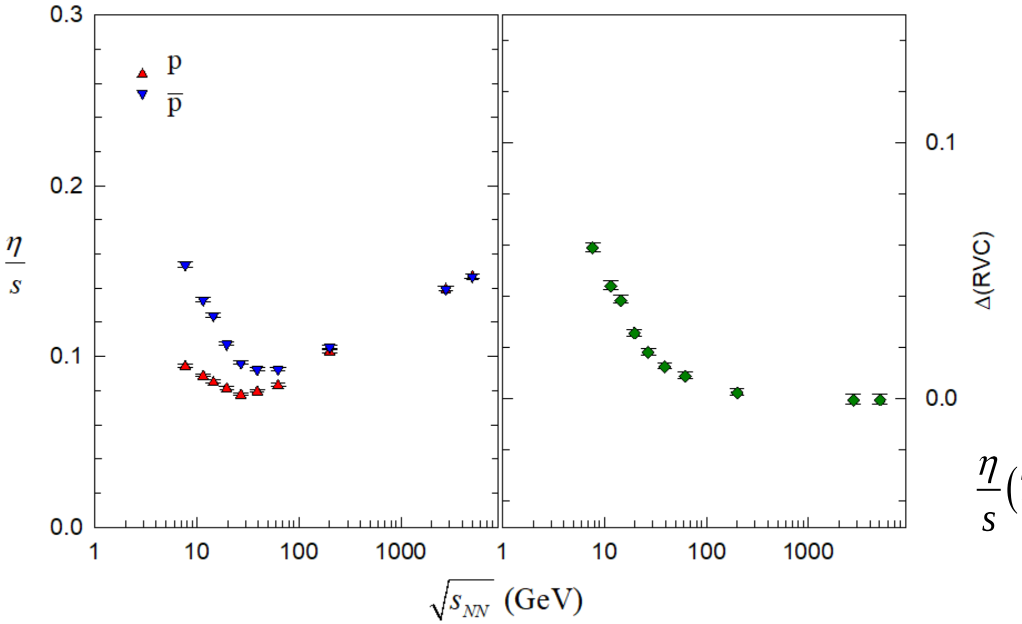




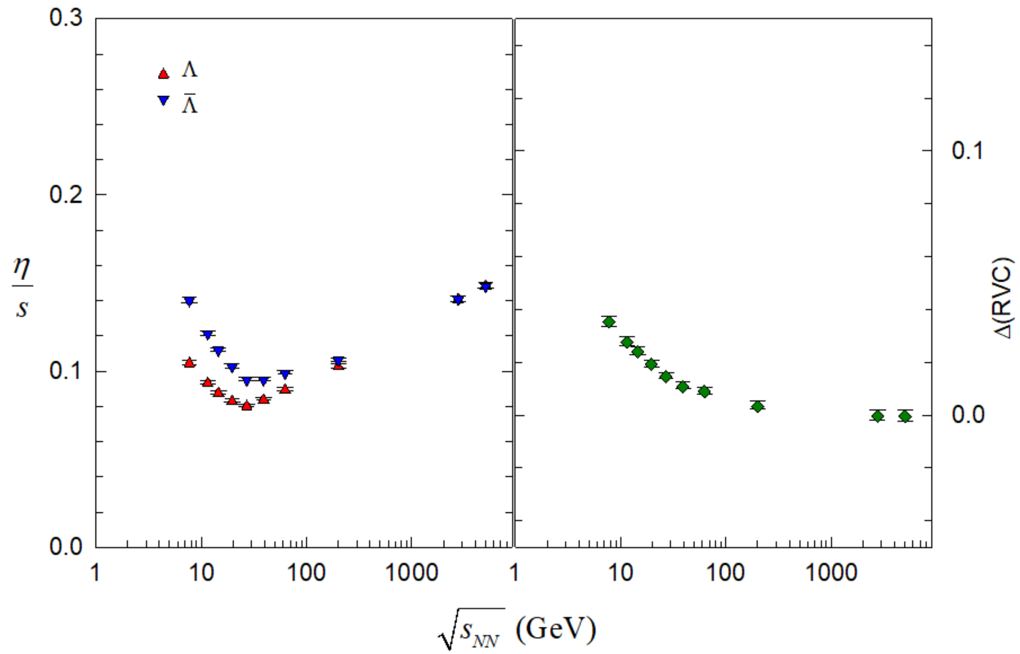
- ***Scaling coefficients indicate;***
  - ✓ ***an increase in η/s from RHIC to LHC.***
  - ✓ **A modest increase in *η/s from large to small systems.***
  - ✓ **Particle/anti-particle dependence**

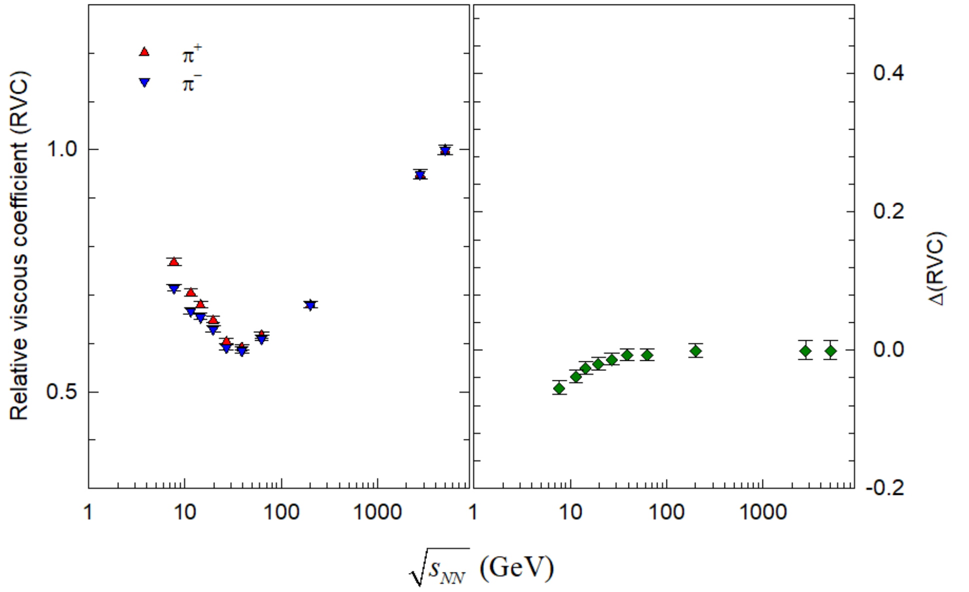
Extracting transport coefficients

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



$$\frac{\eta}{s}(T, \mu_B, \mu_S, \mu_I)$$

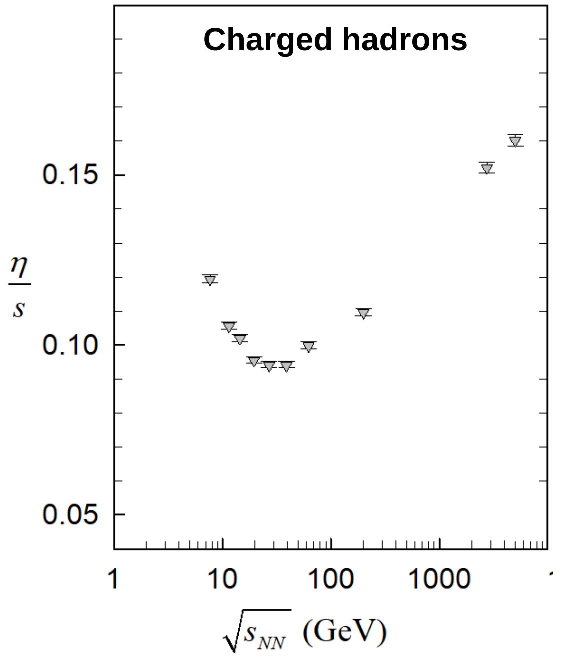




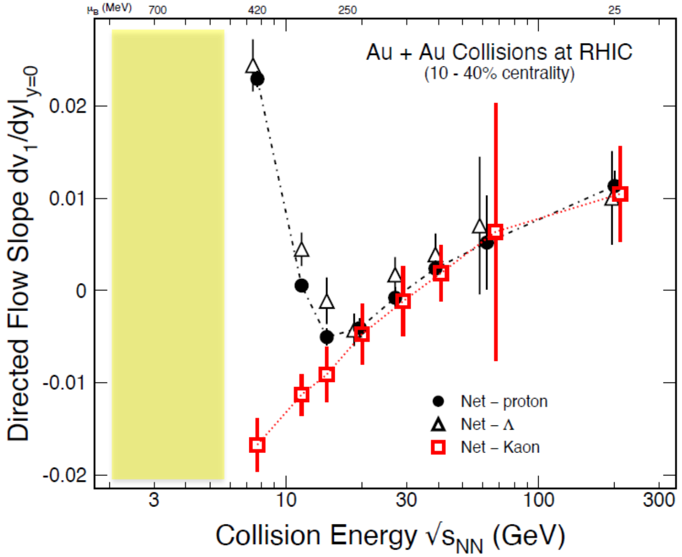
- ➢ Transport coefficients extracted across beam energies
- ✓ Nonmonotonic patterns suggestive of critical behavior?

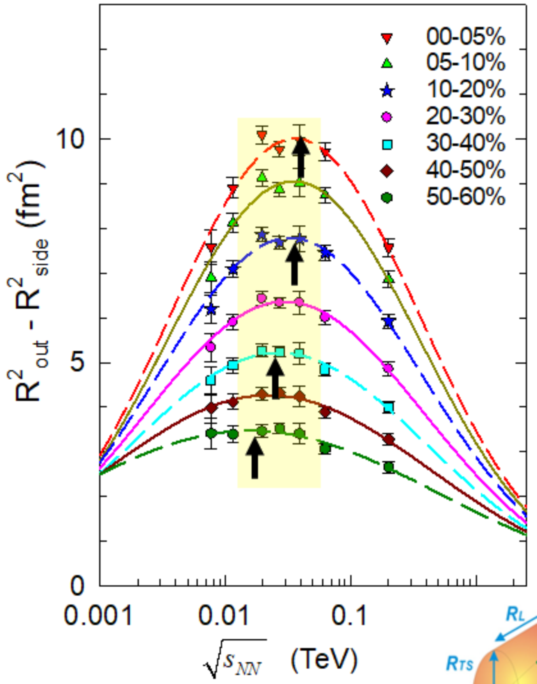
Charged currents drive particle/anti-particle viscosity difference

Non-monotonic patterns

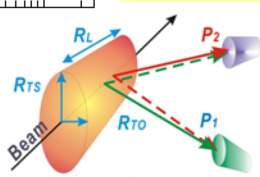


Other expansion-dynamics-driven non-monotonic patterns

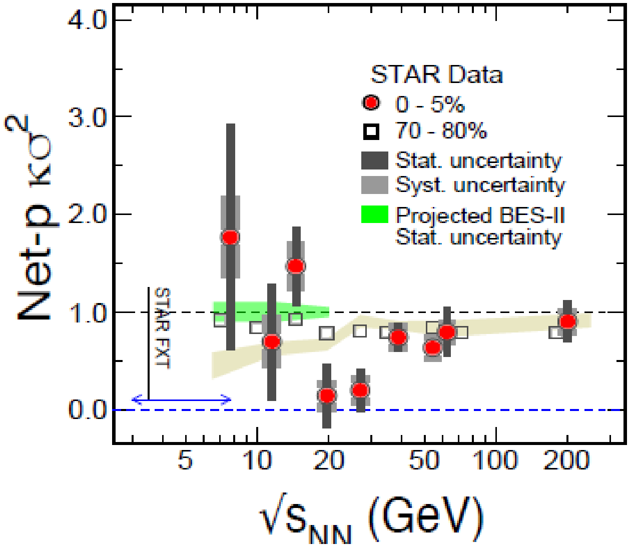




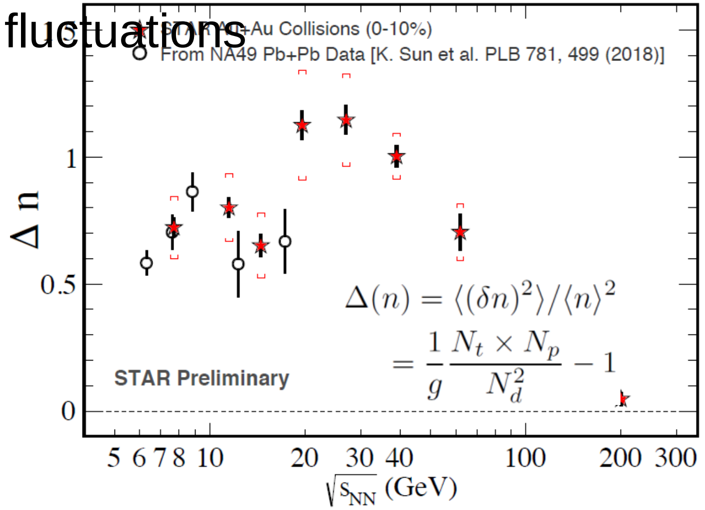
$$c_s^2 = \frac{1}{\rho\kappa}$$



Fluctuations-driven non-monotonic patterns



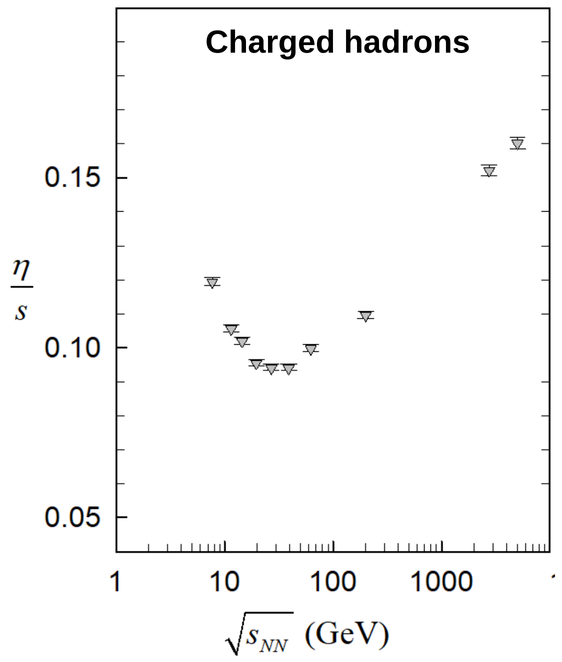
Neutron relative density fluctuations

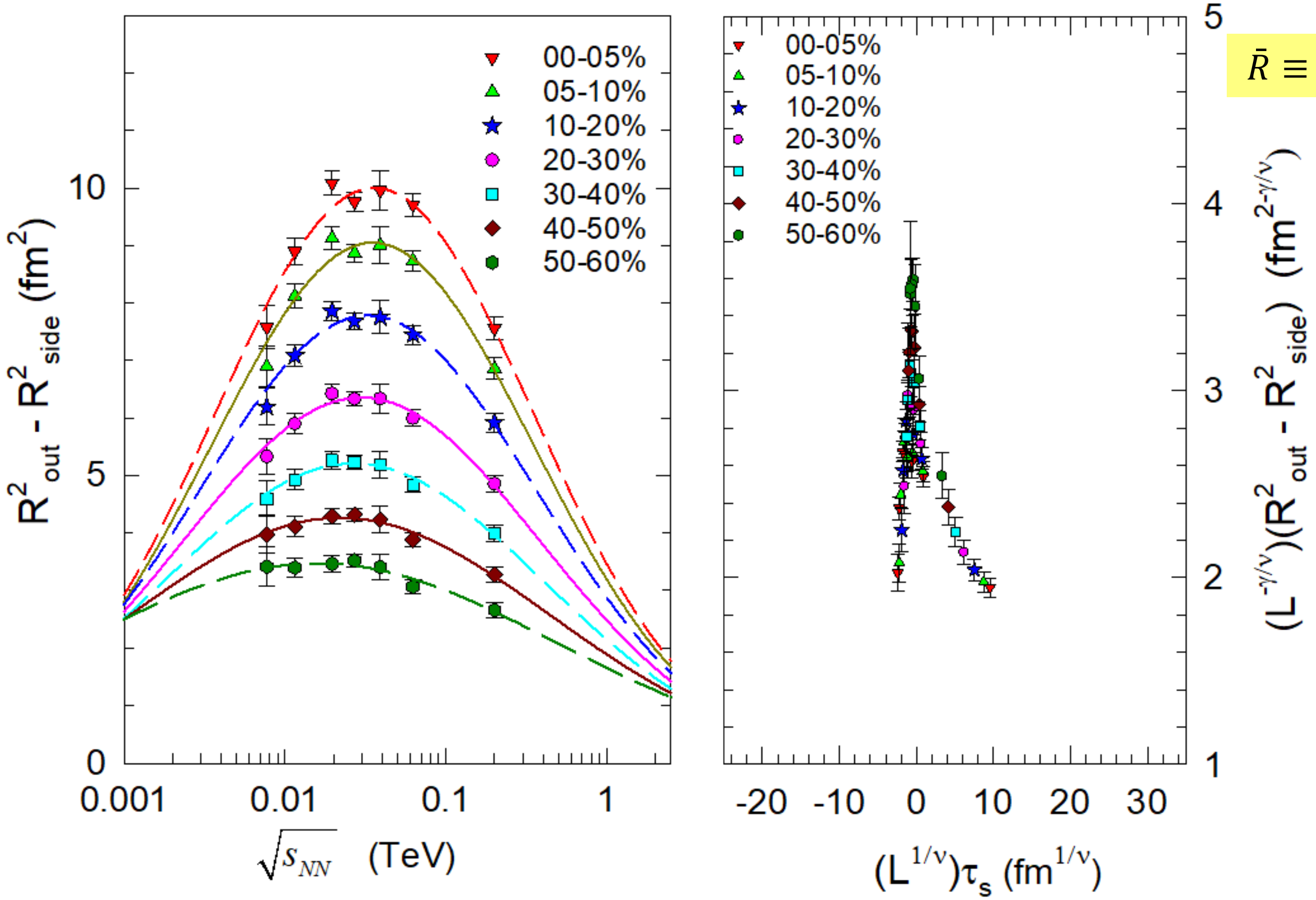


- **Anisotropy scaling functions indispensable for extraction of transport coefficients**
  - ✓ Non-monotonic pattern observed ⟶ CEP?
  - ✓ Charged current dependence @ low $\sqrt{s_{NN}}$
    - **Persistent non-monotonic pattern observed for several observables in similar $\sqrt{s_{NN}}$ range ⟶ CEP?**

Succeptiblity Scaling F

$$L^{-\gamma/\nu}\chi(s,L) = f_2^s(sL^{1/\nu})$$





$\bar{R} \equiv L$

$T^{cep} \sim 155$ MeV, $\mu_B^{cep} \sim 90$ MeV

$\nu \sim 0.66$

$\gamma \sim 1.2$

$\beta \sim 0.33$

$\delta \sim 4.8$

s= $\left(\sqrt{s} - \sqrt{s_{CEP}}\right)/\sqrt{s_{CEP}}$

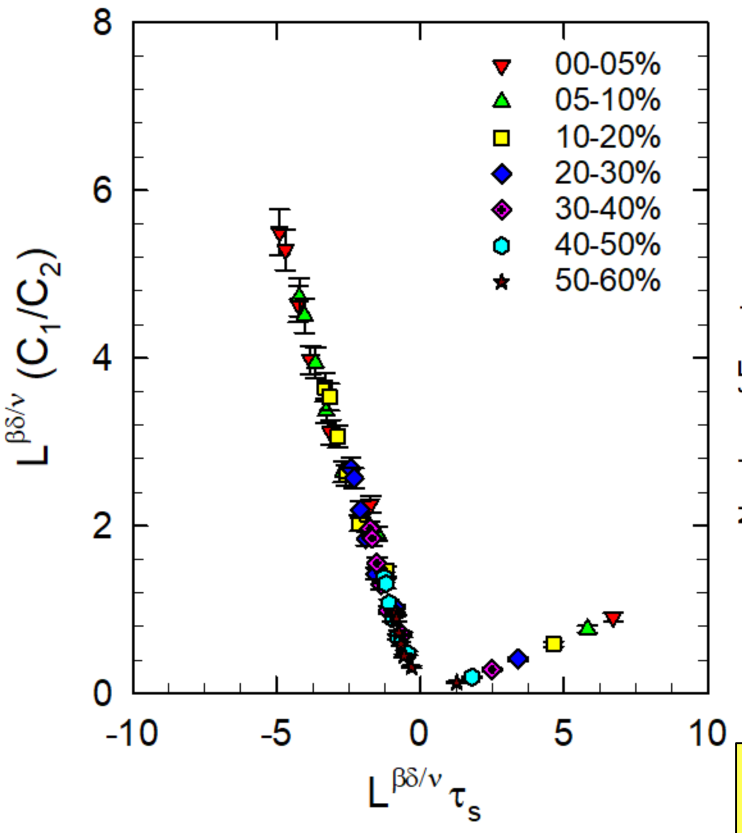
Data collapse onto a single curve, confirms the expected non-singular scaling function.

Scaling Function for Net baryon Succeptiblity ratio

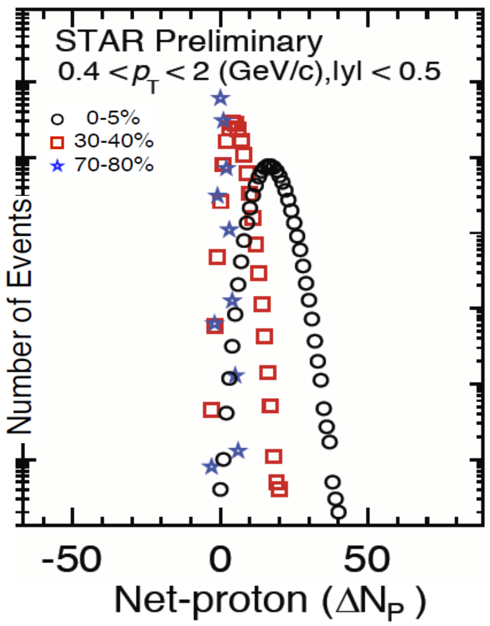
$T^{cep} \sim 155$ MeV, $\mu_B^{cep} \sim 90$ MeV

$\nu \sim 0.66$
$\gamma \sim 1.2$
$\beta \sim 0.33$
$\delta \sim 4.8$

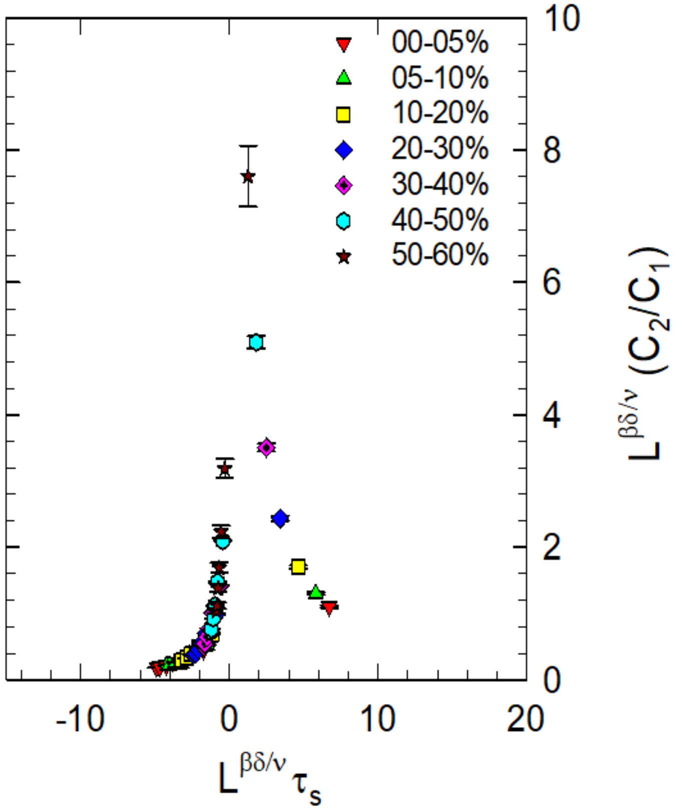
$\chi(\mu_s, \mathrm{L}) = L^{-\beta\delta/\nu} f_1^{\mu}(\mu_s L^{\beta\delta/\nu})$



$C_n^{\Delta N_p}$ *extracted from distributions*



$\chi(\mu_s, \mathrm{L}) = L^{\beta\delta/\nu} f_1^{\mu}(\mu_s L^{\beta\delta/\nu})$



$$\kappa_T \propto \frac{\langle C_2^{\Delta N_p}\rangle - \langle C_2^{\Delta N_p}\rangle^2}{\langle \Delta N_p \rangle} = \frac{C_2^{\Delta N_p}}{C_1^{\Delta N_p}}$$

Data collapse onto a single curve, confirms the expected non-singular scaling function.

Summary

Anisotropy scaling functions provide a powerful tool for systematic study of <u>ALL</u> of the anisotropy data. They indicate;

- ✓ $\frac{\eta}{s}(T, \mu_B, \mu_S, \mu_I)$,
- ✓ $\frac{\hat{q}}{T^3}(T, \mu_B, \mu_S, \mu_I)$
- ✓ **Nonmontonic patterns for** $\frac{\eta}{s}(T, \mu_B, \mu_S, \mu_I)$ **and** $\frac{\hat{q}}{T^3}(T, \mu_B, \mu_S, \mu_I)$ **consistent with earlier indications for the CEP**

End

$$\frac{v_m}{v_n} = \frac{\varepsilon_m}{\varepsilon_n} e^{-(m^2-n^2)[\beta]\frac{1}{RT}}, \quad RT \propto \left\langle \mathrm{N}_{\mathrm{chg}} \right\rangle^{1/3}$$