Beam-energy dependence of the anisotropy scaling functions for identified particle species

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<u>*Takeaway*</u>

The $\sqrt{s_{NN}}$-dependence of the anisotropy scaling functions for PID species can be used to:

I. Delineate the respective influence of expansion dynamics and viscous attenuation

II. Constrain $\frac{\eta}{s}(T, \mu_B, \mu_I, \mu_S)$]?

✓ Give insight on a possible critical point in the nuclear matter phase diagram

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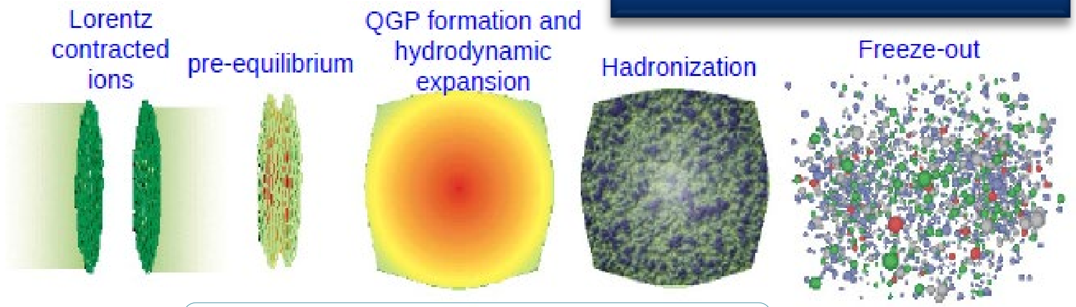
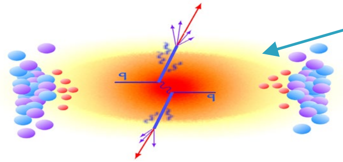
Azimuthal Anisotropy

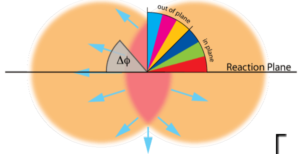
A+A collision (S. Bass)



Drives azimuthal Anisotropy



Jet quenching – high p_T

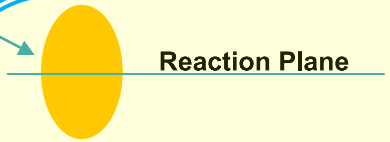


$$R_{AA}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}}\, L\sqrt{\hat{q}\frac{\mathcal{L}}{p_T}}\right]$$

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 $\sqrt{p_T}, \Delta L$ and $\hat{q}$



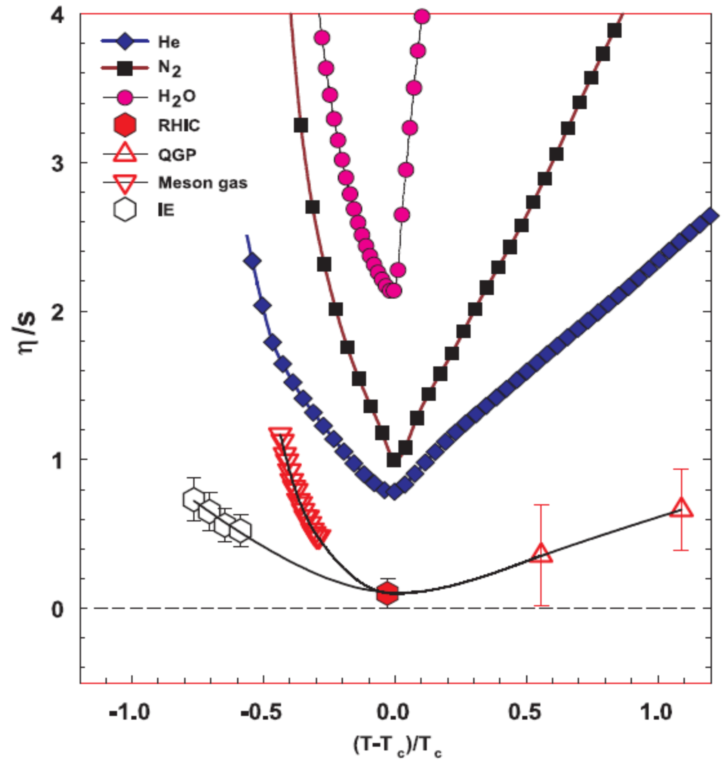
Collective flow – low p_T

$$v_n = \varepsilon_n e^{-\frac{\beta}{RT} n\left(n+\kappa p_T^2\right)}, \; RT \equiv \mathbb{R} \propto \left\langle N_{chg} \right\rangle^{1/3}$$

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 insights on:*
  - ✓ *the location of the critical point in the QCD phase diagram*
  - ✓ *Viscosity of particles vs. antiparticles? (influence of charged currents)*

- **Anisotropy Scaling Functions (ASF) for unidentified and <u>identified</u> particle species are used as constraints**

Anisotropy Scaling Functions

$$v_n(p_T, cent) = \varepsilon_n e^{-\frac{\beta}{RT}\left[n(n+\kappa p_T^2)\right]}, \; RT \equiv \mathbb{R} \propto \langle \mathrm{N}_{\mathrm{chg}} \rangle^{1/3}$$

Same harmonic with variable centrality

$$\frac{v_n(p_T, cent)}{\varepsilon_n} = \left(\frac{v_n^{'}(p_T, cent)}{\varepsilon_n^{'}}\right) e^{-\frac{\beta}{\mathbb{R}}\left[n(n+\kappa p_T^2)\right]\left(1-\frac{\mathbb{R}}{\mathbb{R}^{'}}\right)},$$

For two harmonics at a fixed centrality

$$\frac{v_n(p_T)}{\varepsilon_n} = \left(\frac{v_m(p_T)}{\varepsilon_m}\right)^{\frac{n}{m}} e^{\frac{\beta}{\mathbb{R}}(m-n)},$$

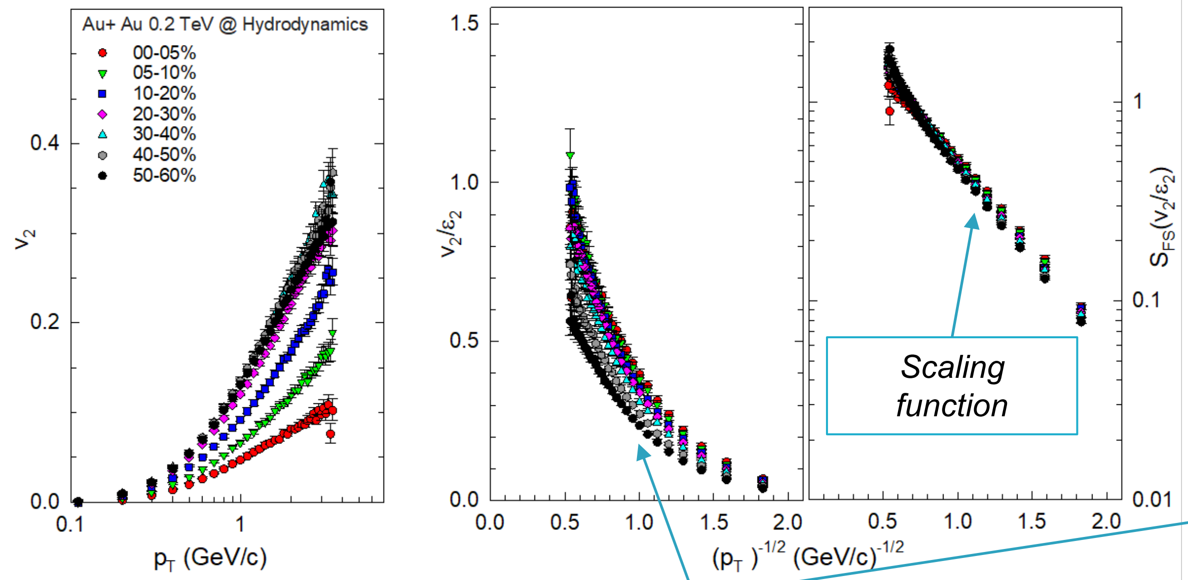
Anisotropy Scaling Functions leverage the specific dependencies of ε_n, viscous attenuation and the expansion dynamics!

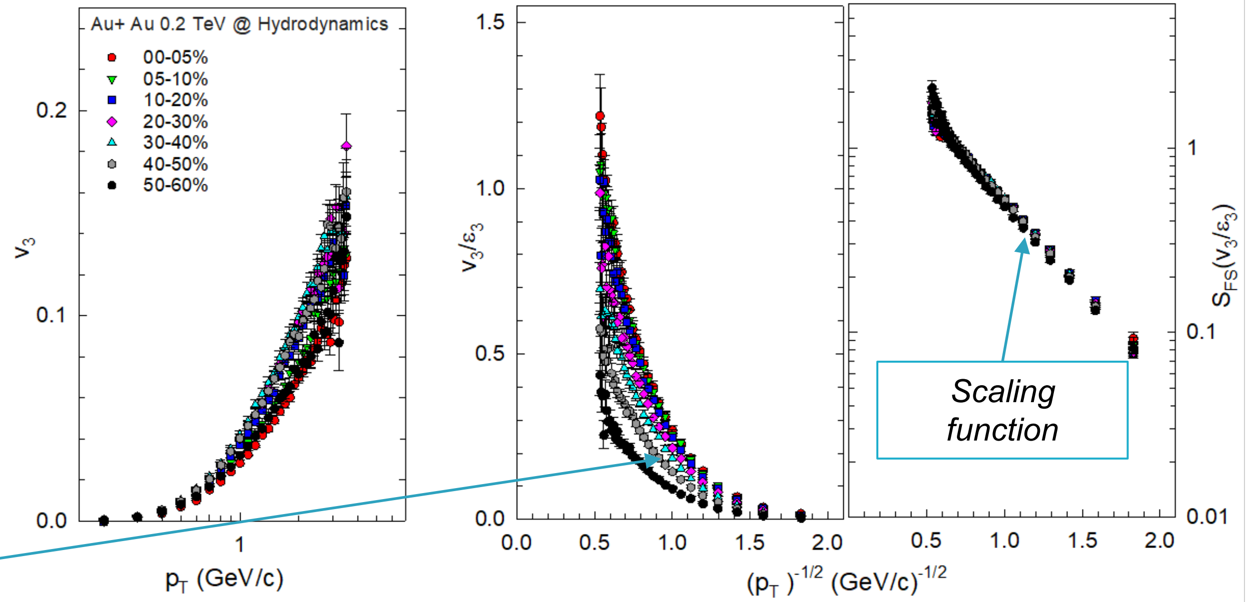
- **Data collapse to a single curve for fully constrained scaling coefficients**
  - ✓ **Scaling coefficients give access to transport coefficients $\frac{\eta}{s}(\mathrm{T}, \mu_\mathrm{B})$, *etc*.**

Anisotropy Scaling Function – proof of principle

$$\frac{v_n(p_T,cent)}{\varepsilon_n} = \left(\frac{v_n'(p_T,cent)}{\varepsilon_n'}\right) e^{-\frac{\beta}{\mathbb{R}}\left[n(n+\kappa p_T^2)\right]\left(1-\frac{\mathbb{R}}{\mathbb{R}'}\right)},$$

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





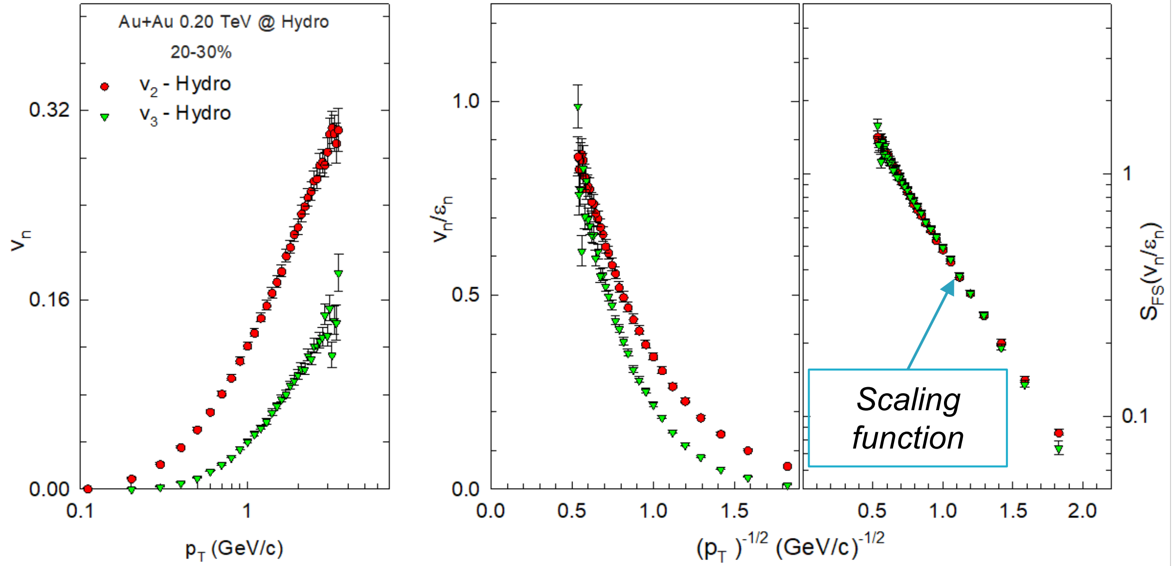
✓ *Eccentricity scaling (alone) is insufficient*

Final-state interactions are crucial

✓ *Same $\frac{\eta}{s}$ for v_2 & v_3*

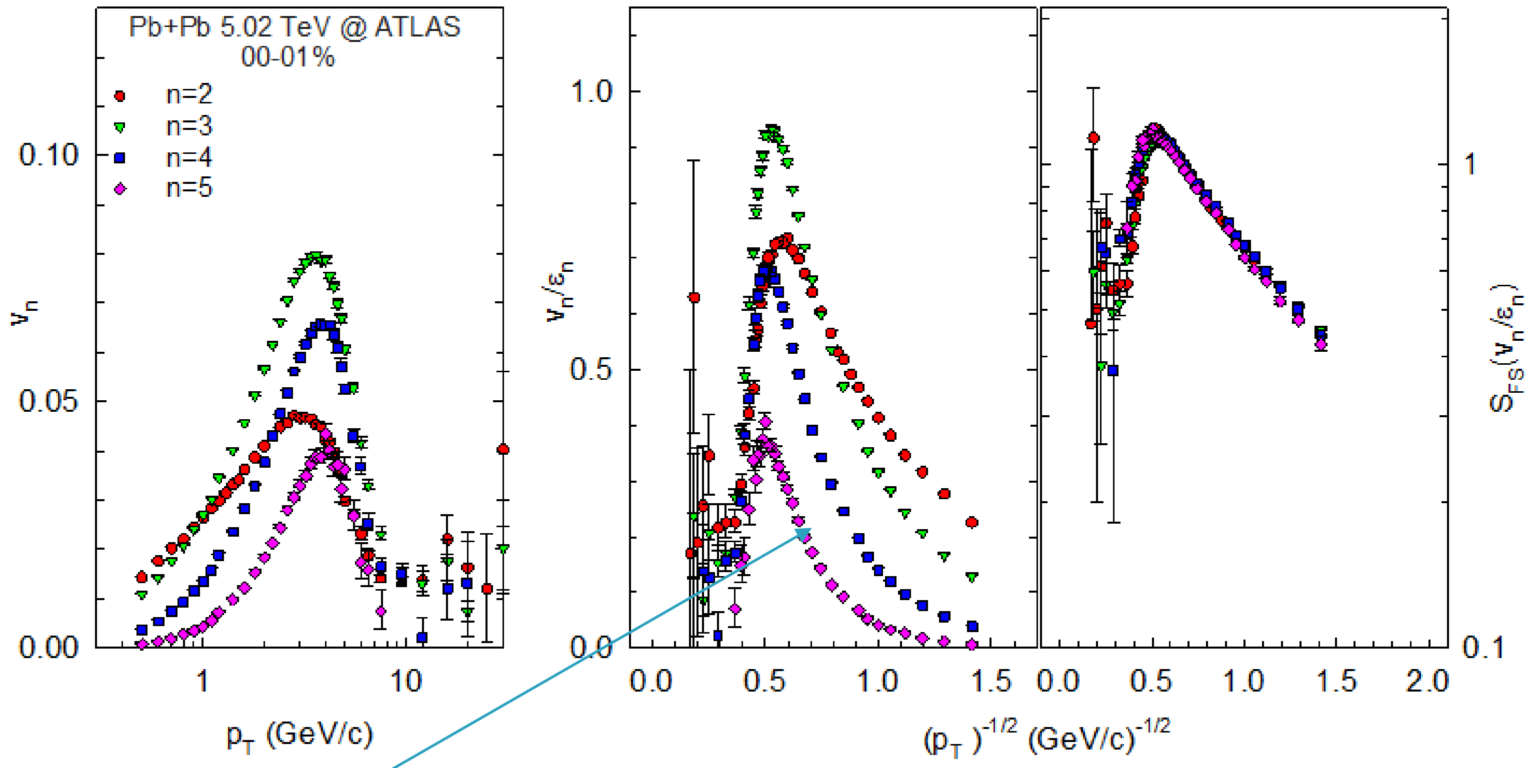
➢ **Anisotropy data as a function of control variables collapse on to a single curve for fully constrained scaling coefficients**

✓ **Scaling coefficients are proportional to the respective transport coefficients**



Anisotropy Scaling Functions

n & p_T dependence



n^2-dependent viscous attenuation apparent

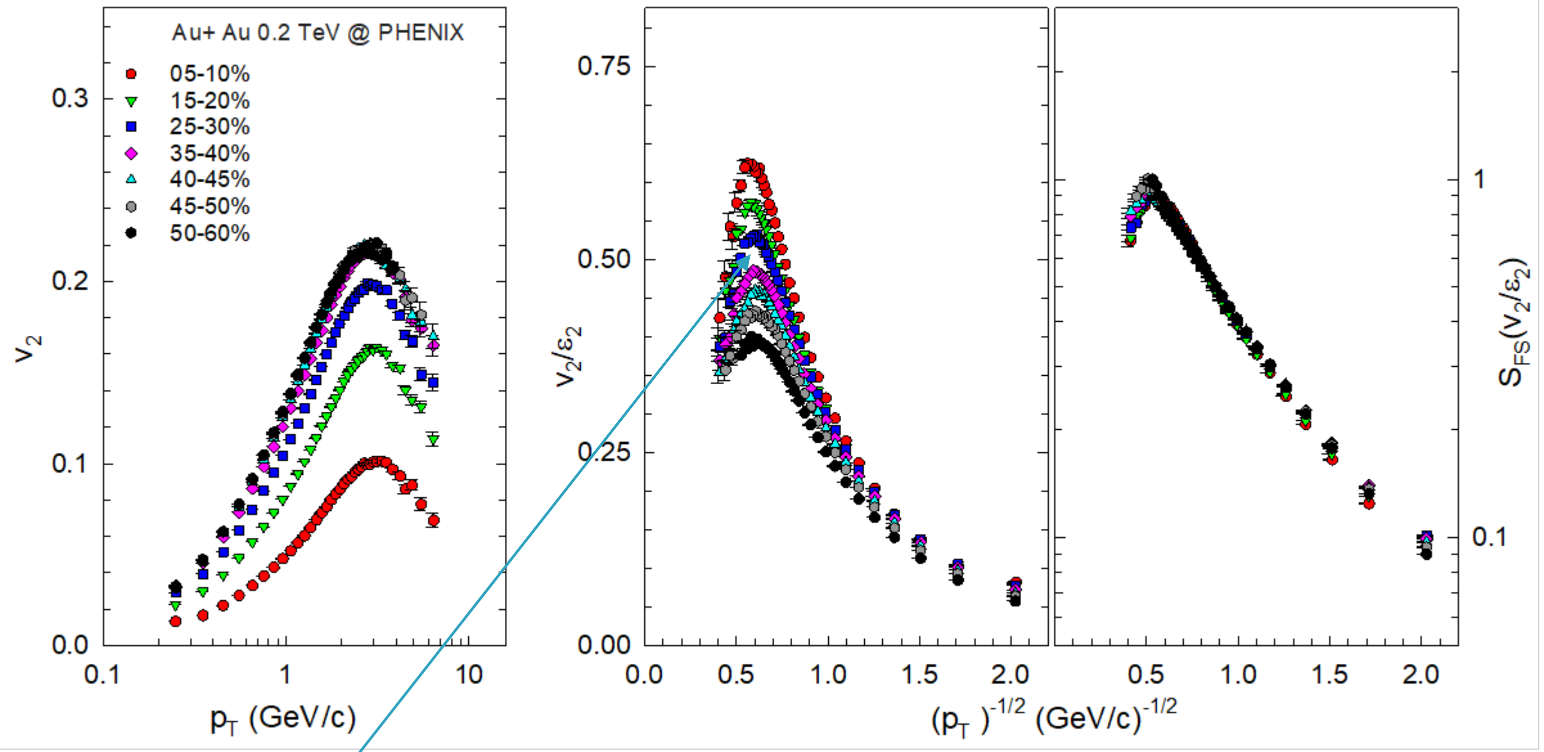
- **Characteristic patterns of viscous attenuation validated**
  - ✓ **n^2 dependence of the viscous coefficient confirmed**
    - ✓ **Small influence from expansion dynamics**
    - ✓ **Scaling breaks when mode-coupled harmonics contribute**
- **Scaling coefficient provides constraint for $\frac{\eta}{s}(T)$**

Anisotropy Scaling Functions

Centrality & p_T dependence

$$\frac{v_n(p_T)}{\varepsilon_n} = \left(\frac{v_n'(p_T)}{\varepsilon_n'}\right) e^{-\frac{\beta}{\mathbb{R}}\left[n(n+\kappa p_T^2)\right]\left(1-\frac{\mathbb{R}}{\mathbb{R}'}\right)},$$

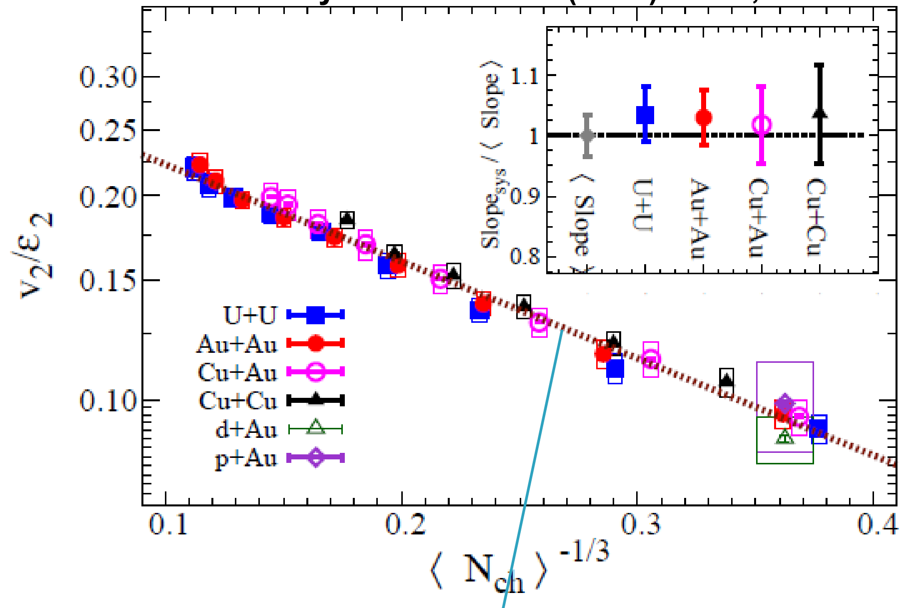
$$\ln\left(\frac{v_n}{\varepsilon_n}\right) = -\frac{\beta}{\mathbb{R}}\left[n(n+\kappa p_T^2)\right], \quad RT \equiv \mathbb{R} \propto \langle N_{chg} \rangle^{1/3}$$



Centrality/pT-dependent viscous attenuation

Collision-system & centrality dependence of p_T-integrated v_2/ε_2

STAR - Phys.Rev.Lett. 122 (2019) no.17, 172301



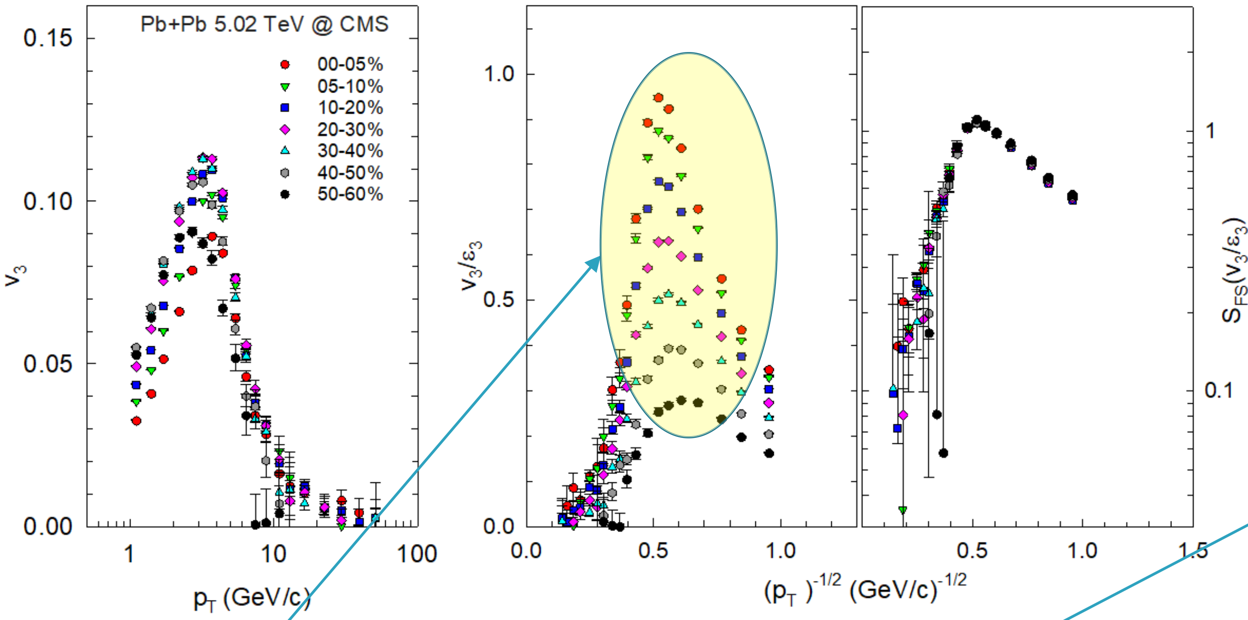
System-independent but RT-dependent viscous attenuation?

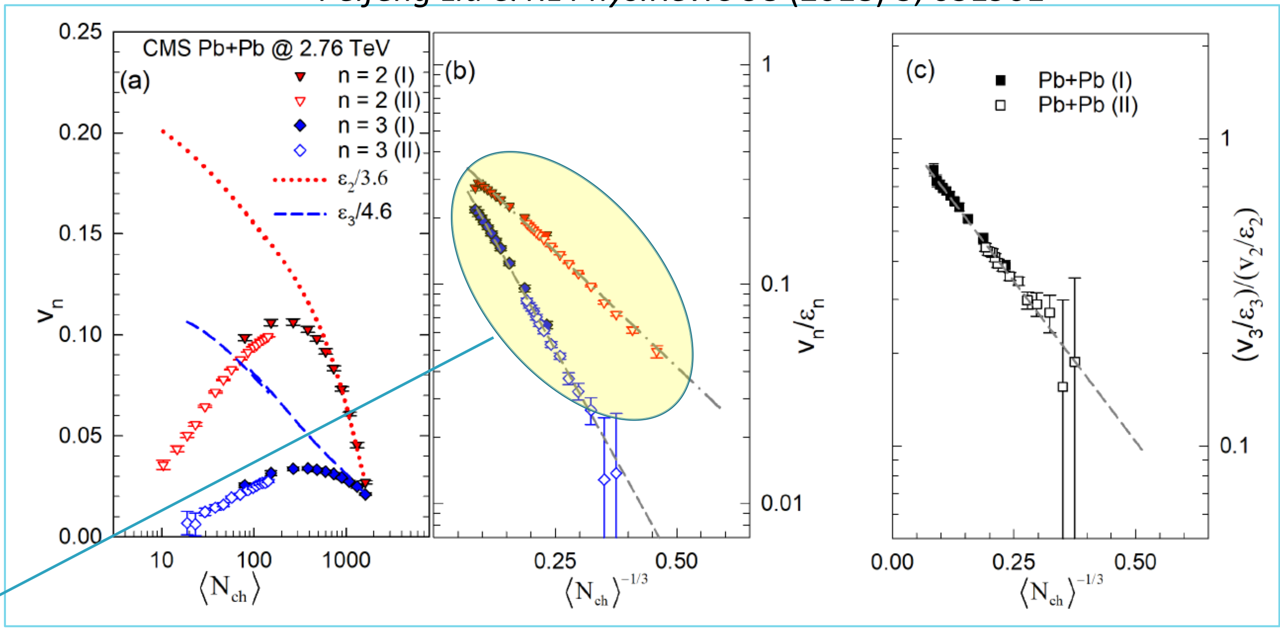
Similar patterns for other beam energies

- ➢ **Characteristic patterns of viscous attenuation validated**
  - ✓ **1/RT dependence of the viscous coefficient confirmed**
    - ❖ **Scaling coefficient provides constraint for $\frac{\eta}{s}(T)$**

Anisotropy Scaling Functions

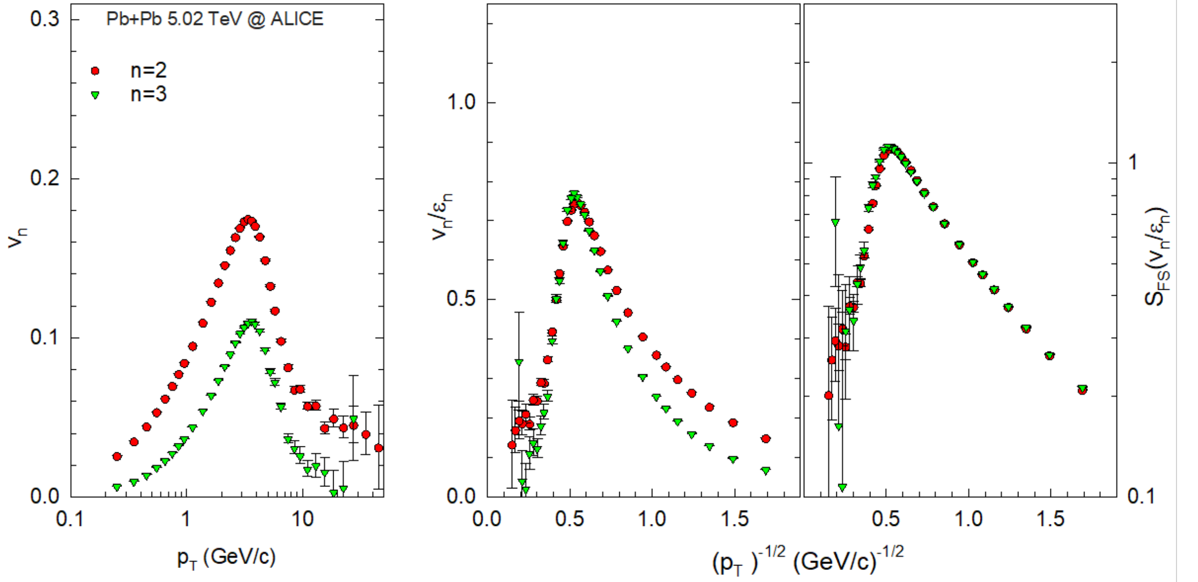
Peifeng Liu & RL Phys.Rev.C 98 (2018) 3, 031901





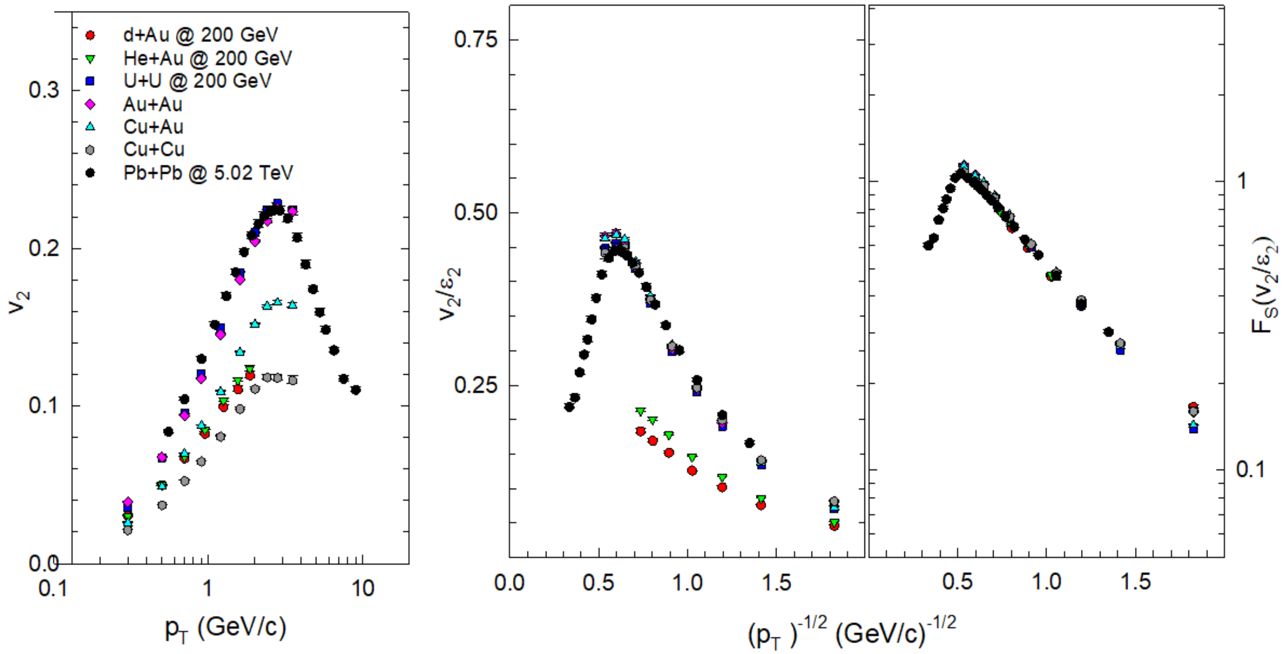
p_T - & RT-dependent viscous attenuation?

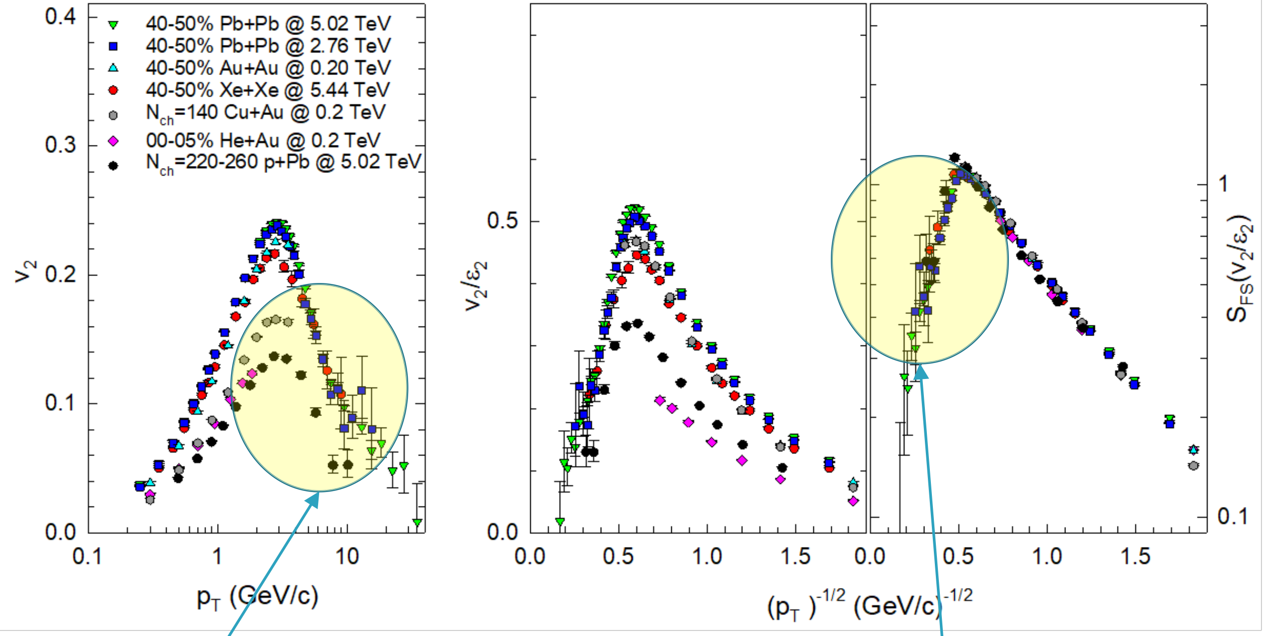
n- & RT-dependent viscous attenuation?



- **Characteristic patterns of viscous attenuation validated**
  - **Scaling coefficient provides constraint for $\frac{\eta}{s}(T)$**

Anisotropy Scaling Functions – Systems & Energies





➢ **High-p_T p+Pb**

➢ **Jet quenching in p+Pb?**

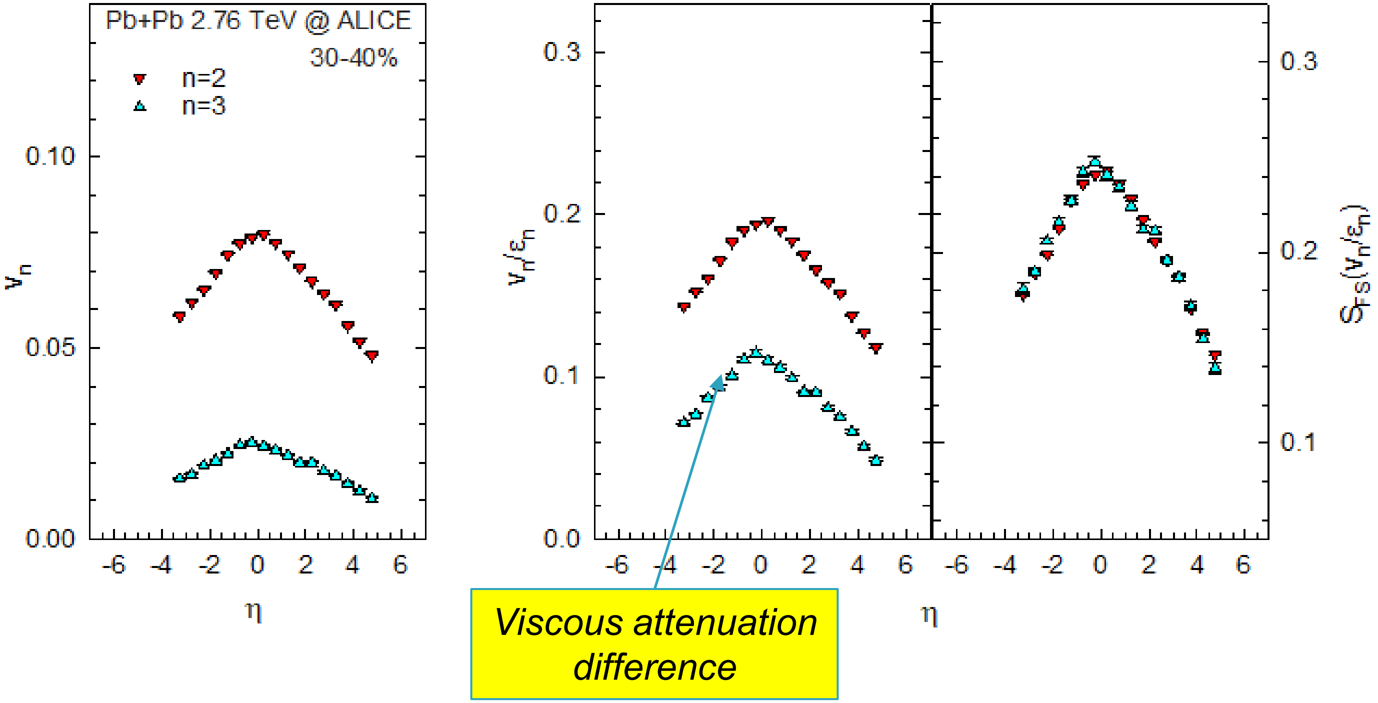
- ✓ **Same $\langle N_{chg} \rangle$ for U+U, Pb+Pb, Au+Au, Cu+Au and Cu+Cu**
- ✓ **Different $\langle N_{chg} \rangle$ for d(^{3}He)+Au**

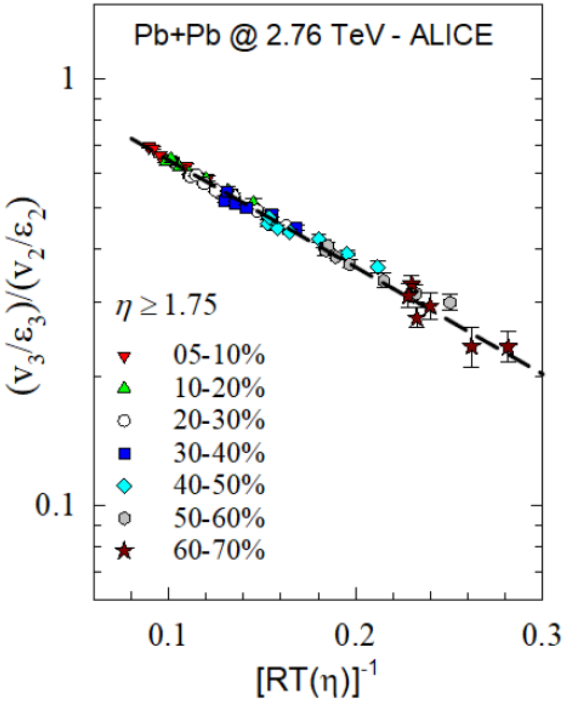
➢ **Indications for viscous attenuation and jet quenching across systems.**
  - ✓ **Signal attenuation very important for small dimensionless sizes.**

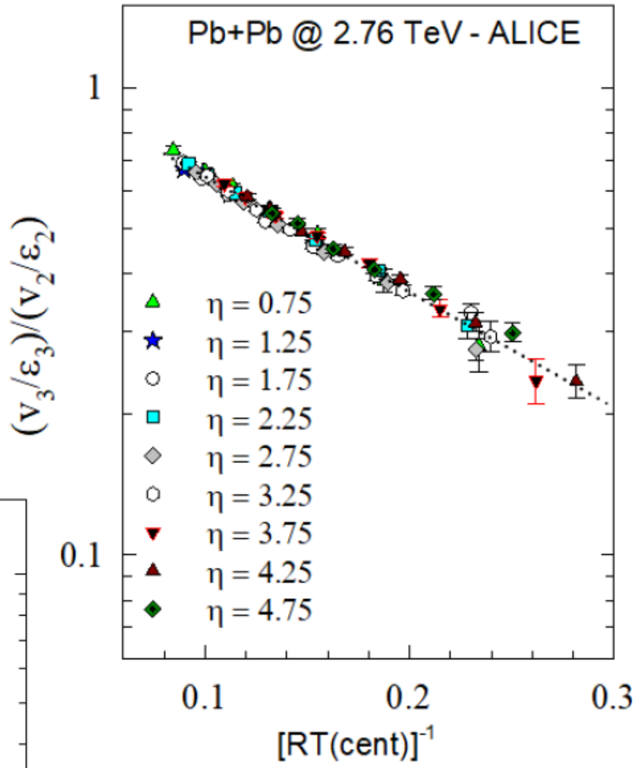
❖ ***Scaling coefficients indicate;***
  - ✓ ***an increase in η/s from RHIC to LHC.***
  - ✓ **A modest increase in *η/s from large to small systems.***

Anisotropy Scaling Functions

η - dependence





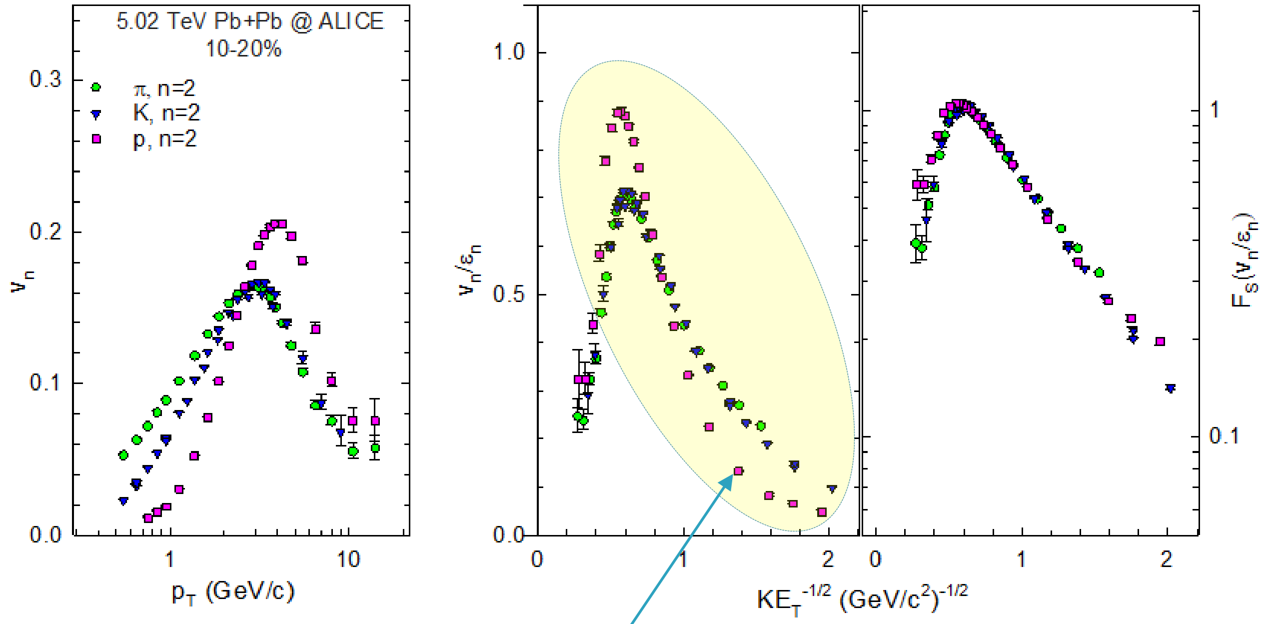


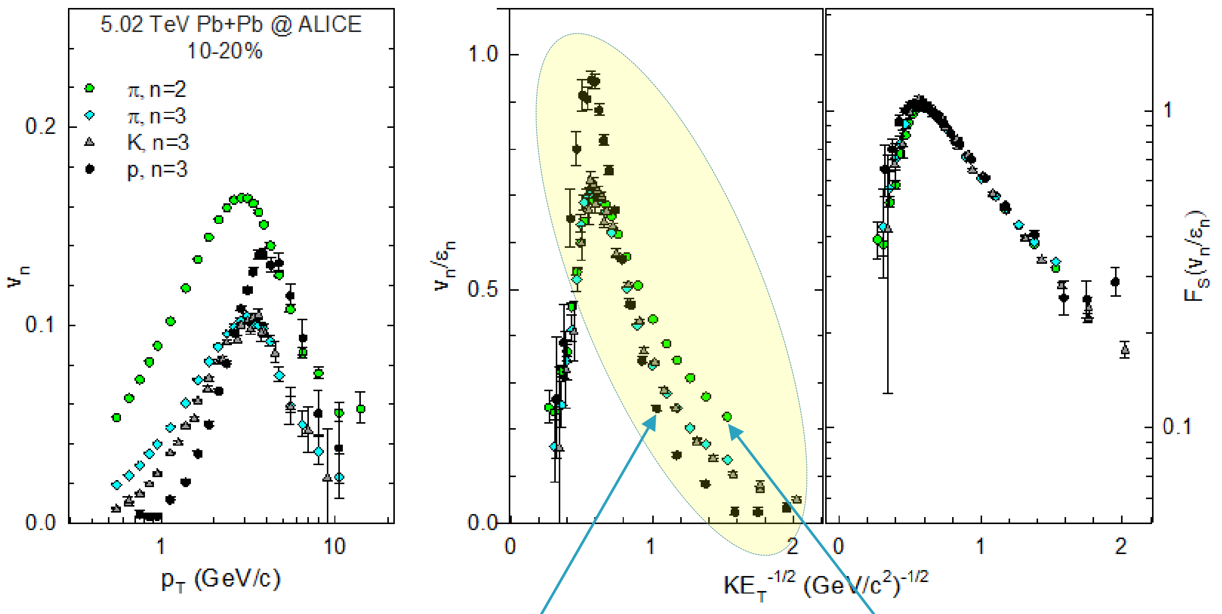
- $\eta - dependent$ **patterns of viscous attenuation validated**
  - ✓ **Scaling coefficient provide a further constraint for $\frac{\eta}{s}(T)$**
  - ✓ **Factorization across η does not hold**

Viscous_attenuation(cent, p_T, η) understood!

Anisotropy Scaling Function for PID species

Compare v_2 and v_3





Effects of expansion dynamics
- ✓ *Scaling for this effect required*

✓ ***Same*** $\frac{\eta}{s}$

Effects of expansion dynamics

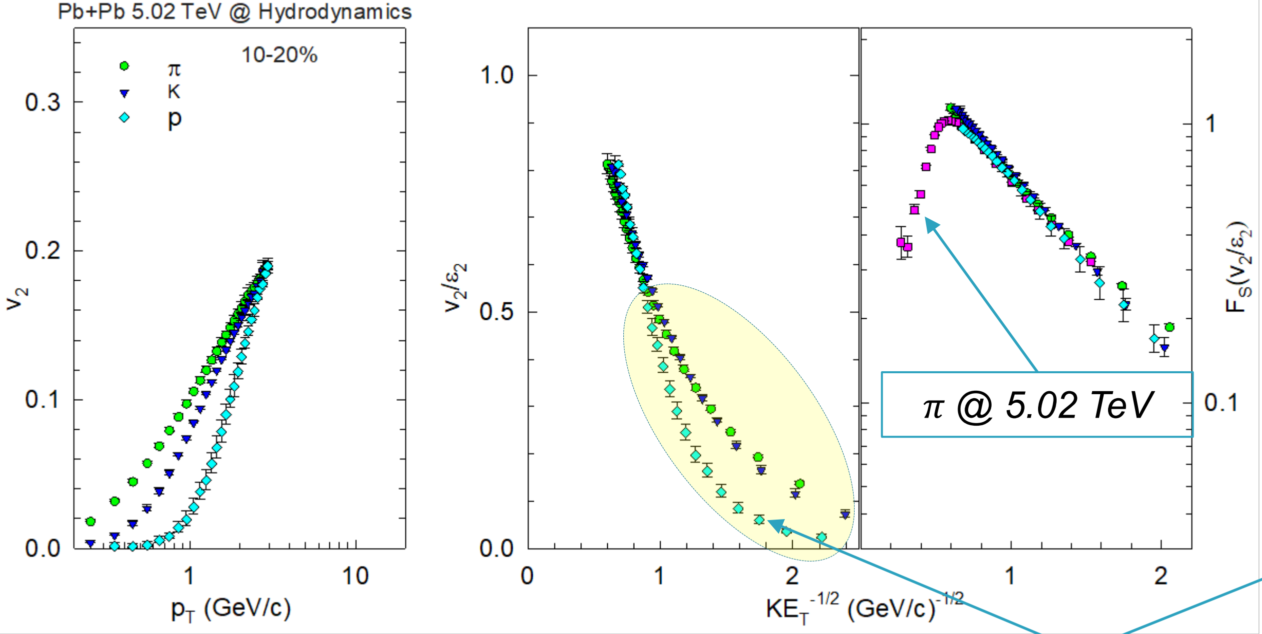
Effects of Viscous attenuation

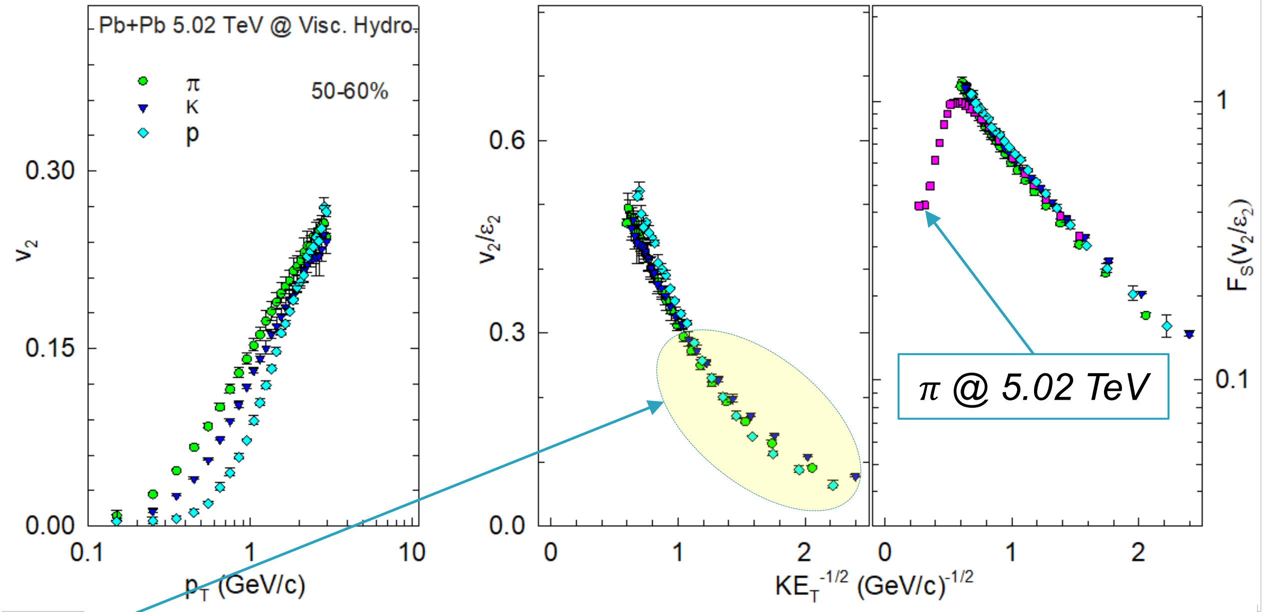
Start @ 5 TeV
- ✓ $\mu_{B,S,I} \sim 0$
- ✓ **PID-independent control variables**
- ✓ **PID-dependent expansion dynamics**

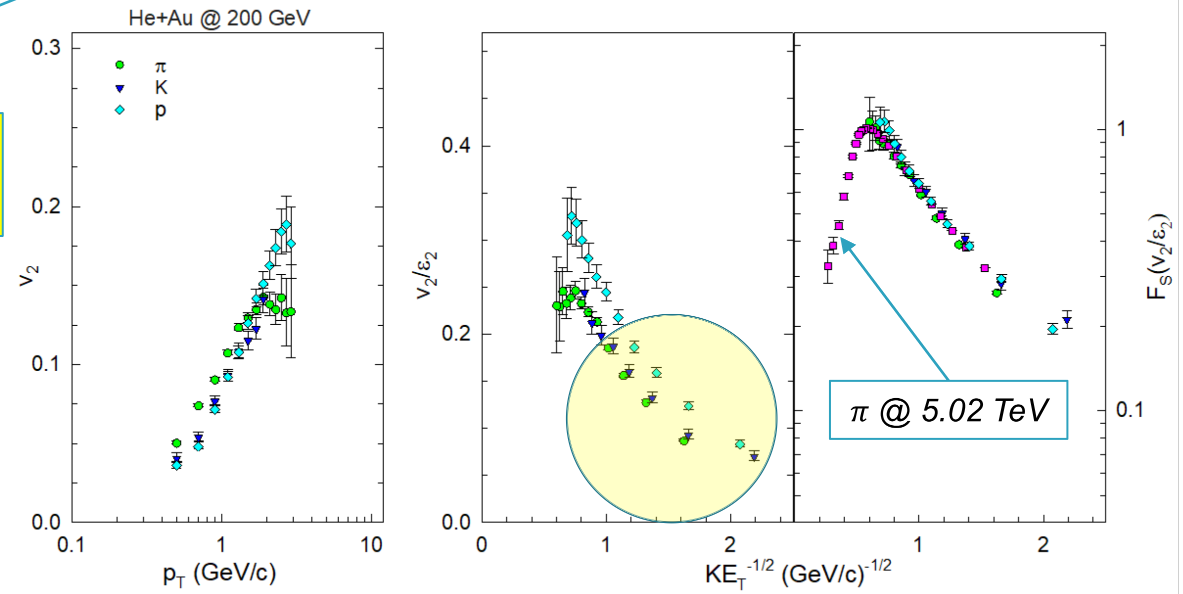
➢ **Scaling for viscous attenuation and expansion dynamics validated.**

PID Scaling Functions – Further proof of principle

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





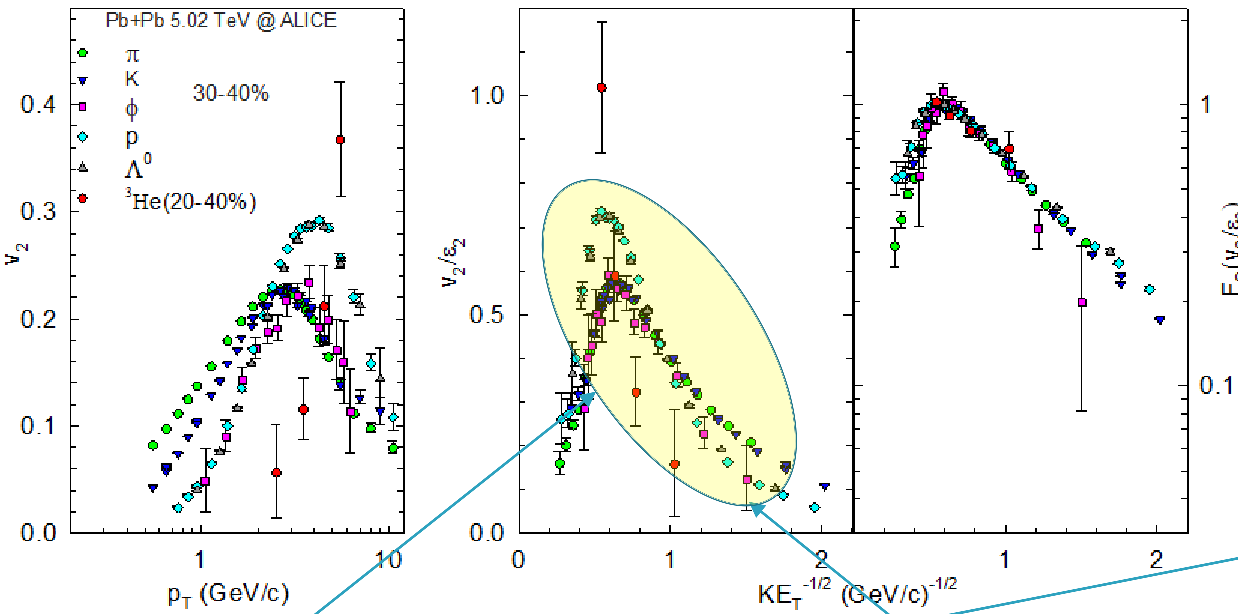


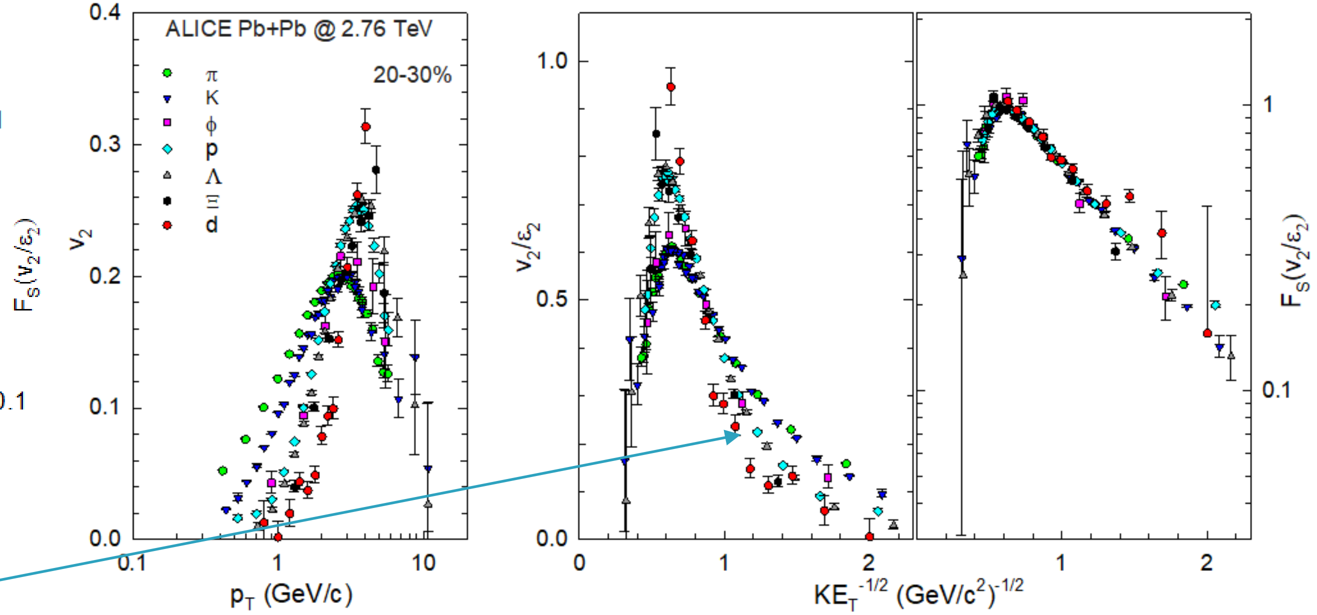
- ✓ $\mu_{B,S,I}$ ~ 0
- ✓ PID-independent control variables
- ✓ PID-dependent expansion dynamics

Diff. expansion dynamics
✓ *Same η/s*

- ➢ **Scaling for viscous attenuation and different expansion dynamics validated.**
  - ✓ **Expansion dynamics is centrality-, system- and beam-energy dependent**

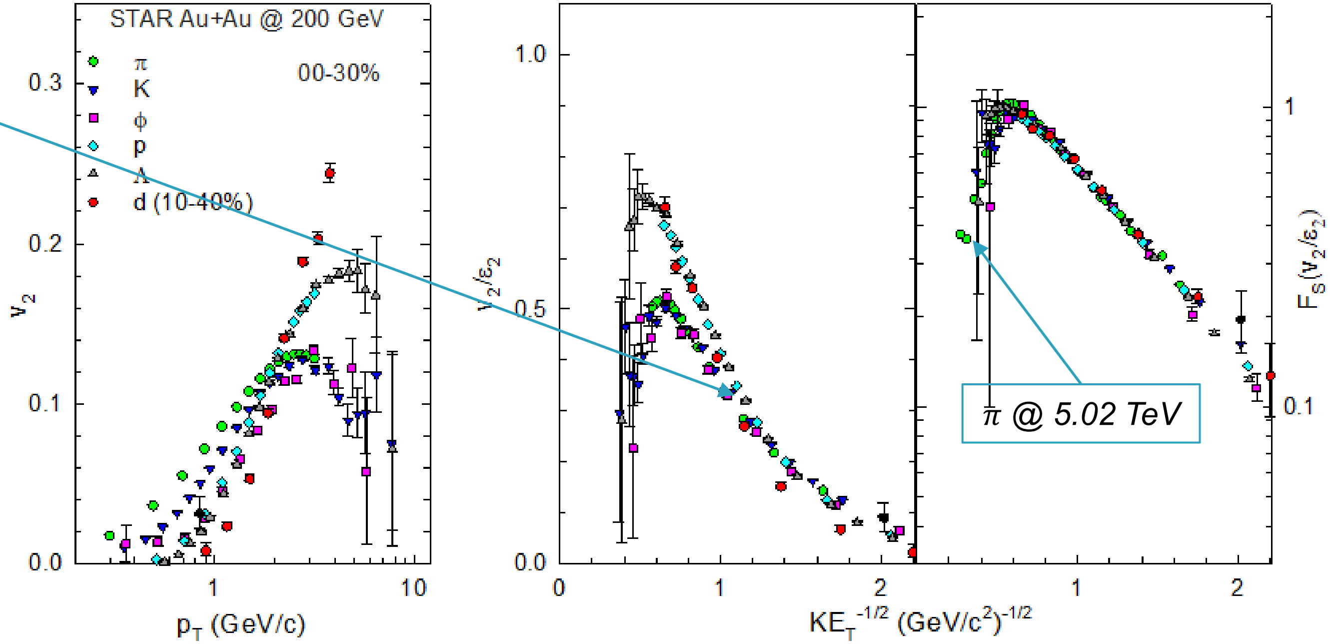
Anisotropy Scaling Functions – species across systems & energies





Diff. expansion dynamics
✓ *Same η/s ?*

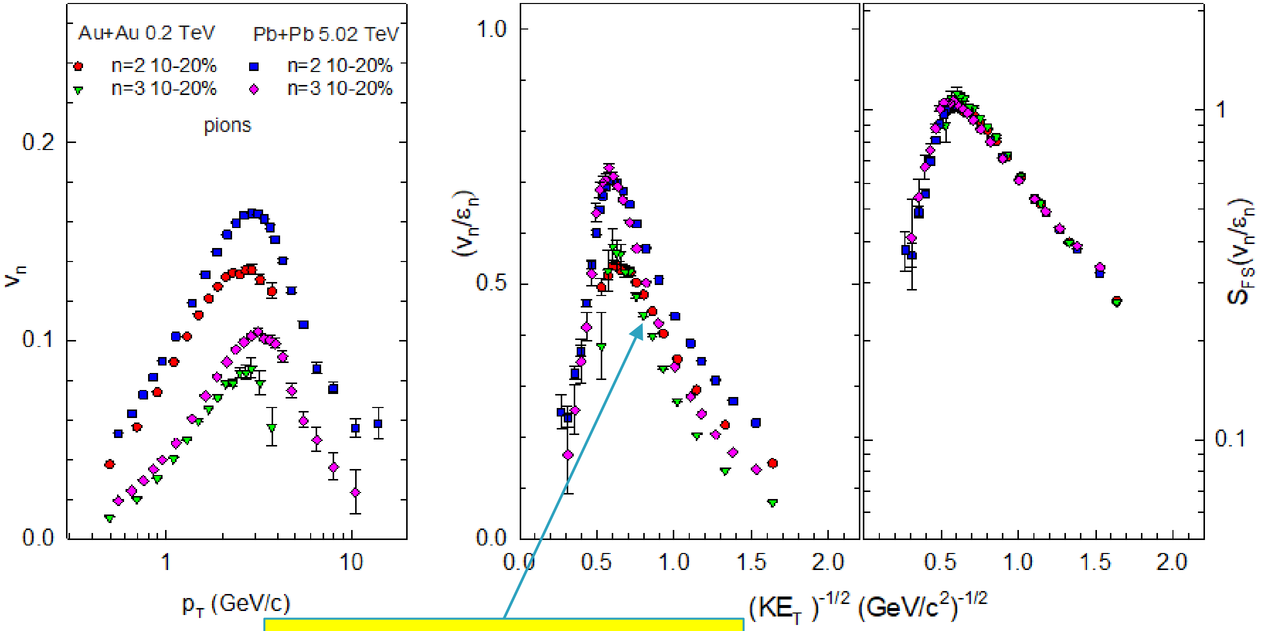
✓ *1 meson branch*
✓ *2 baryon branches*

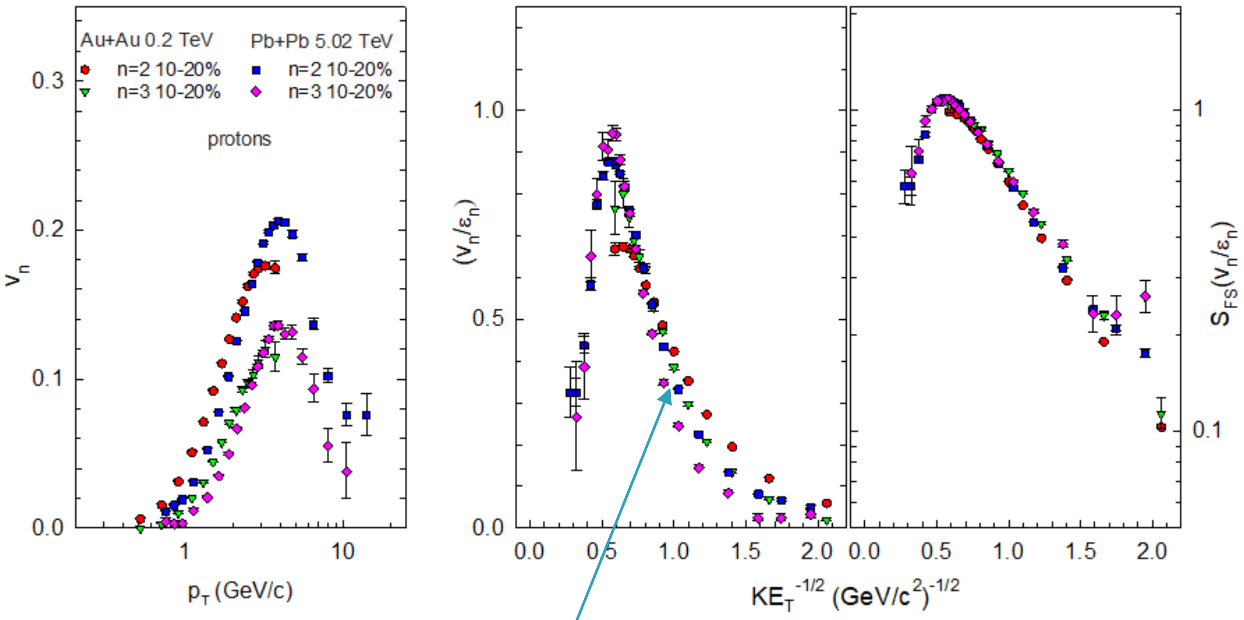


- **Scaling for viscous attenuation and expansion dynamics validated for all beam energies studied**
  - ✓ **Scaling observed for all particle species** **(multiple mechanisms superfluous)**
  - ✓ **Baryon-number-dependent expansion dynamics - <u>not</u> mass**

PID Scaling Functions – Systems, species & Energies

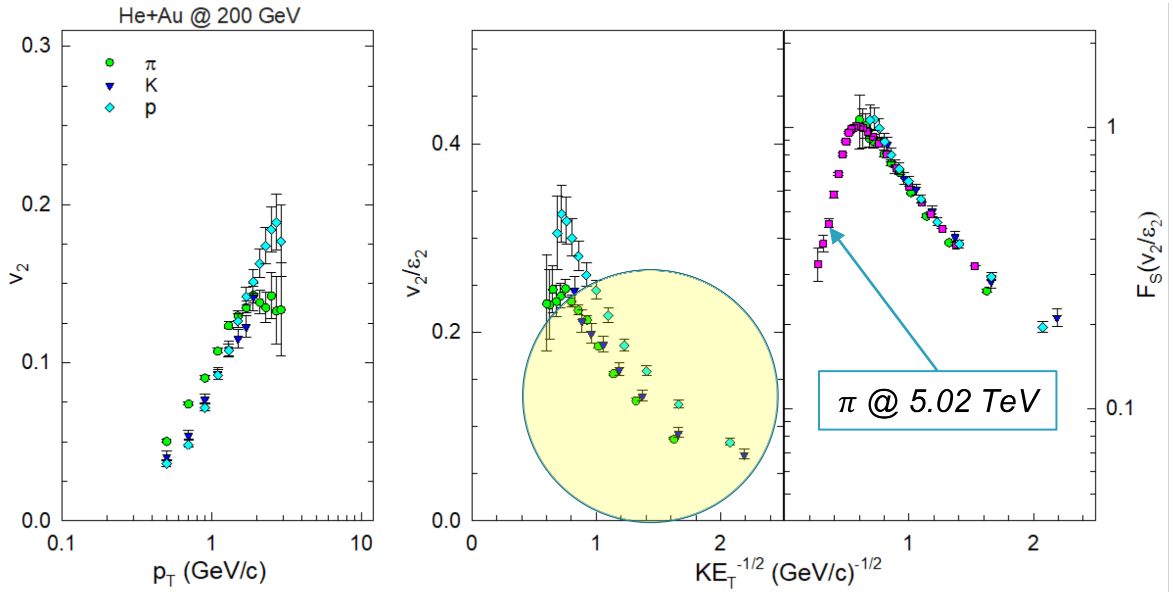
Compare $\sqrt{s_{NN}}$ = 0.2 and 5.02 TeV





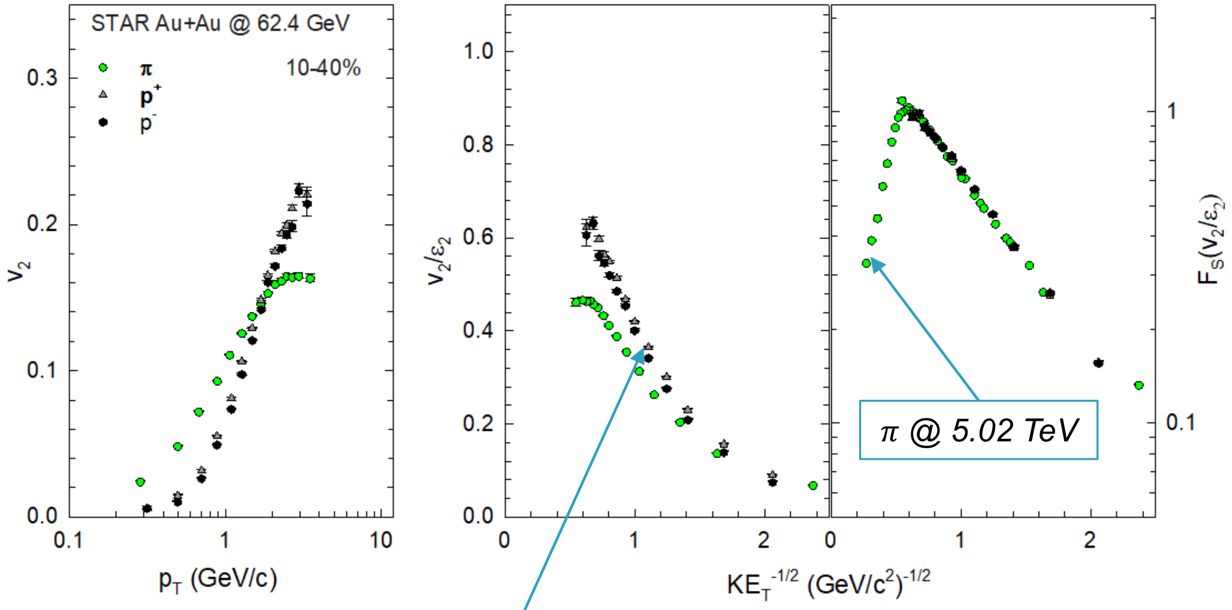
Diff. η/s & expansion dynamics

Indications for diff. η/s

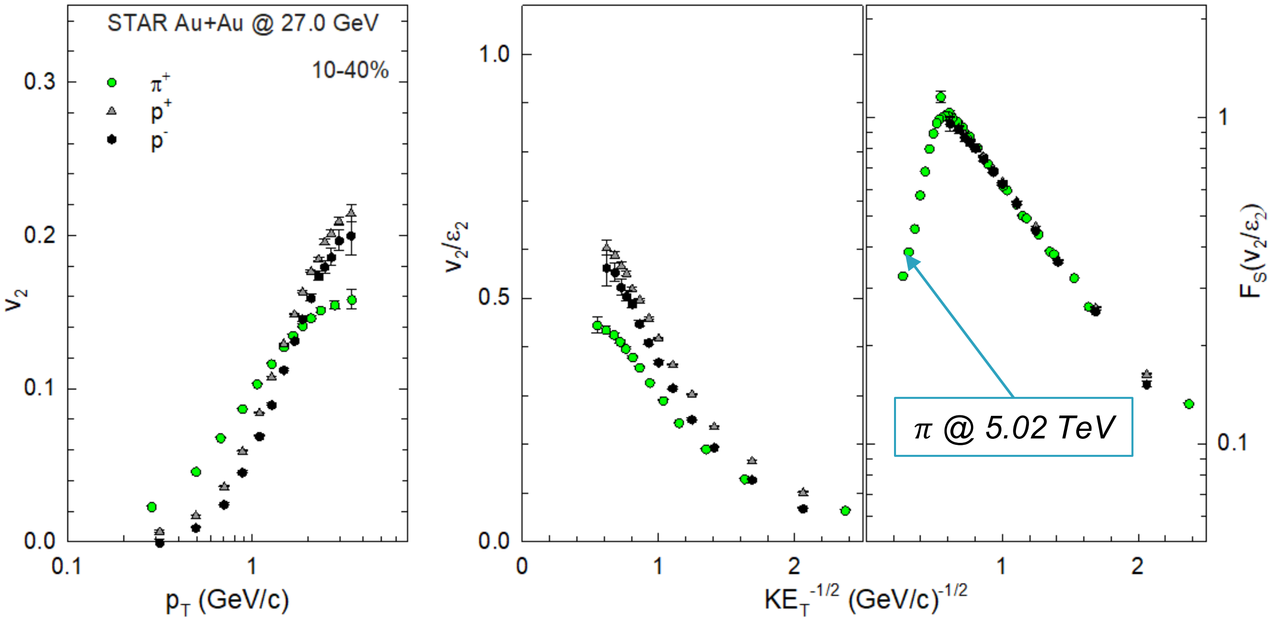


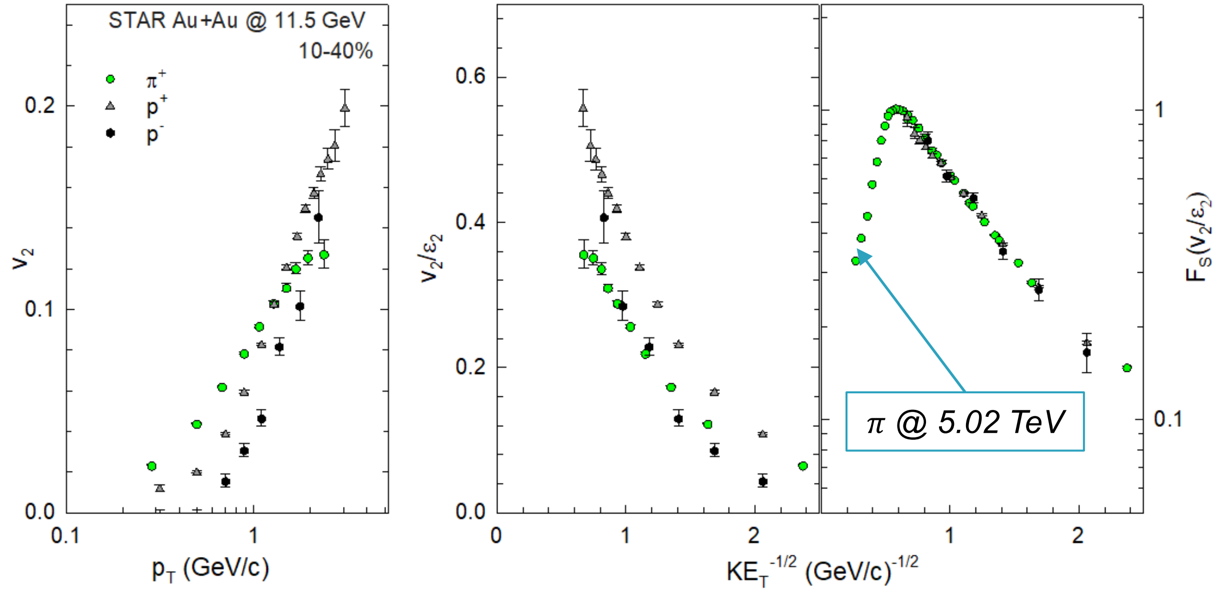
- **Scaling for viscous attenuation and expansion dynamics validated across beam energies and systems**
  - ✓ **Scaling observed for all particle species**
    (multiple mechanisms superfluous)
    - ❖ ***Scaling coefficients indicate;***
      - ✓ ***an increase in η/s from RHIC to LHC.***
      - ✓ ***A modest increase in η/s from large to small systems.***

PID Scaling Functions – particles vs. anti-particles



Particle/Anti-particle difference
✓ *Same expansion dynamics*

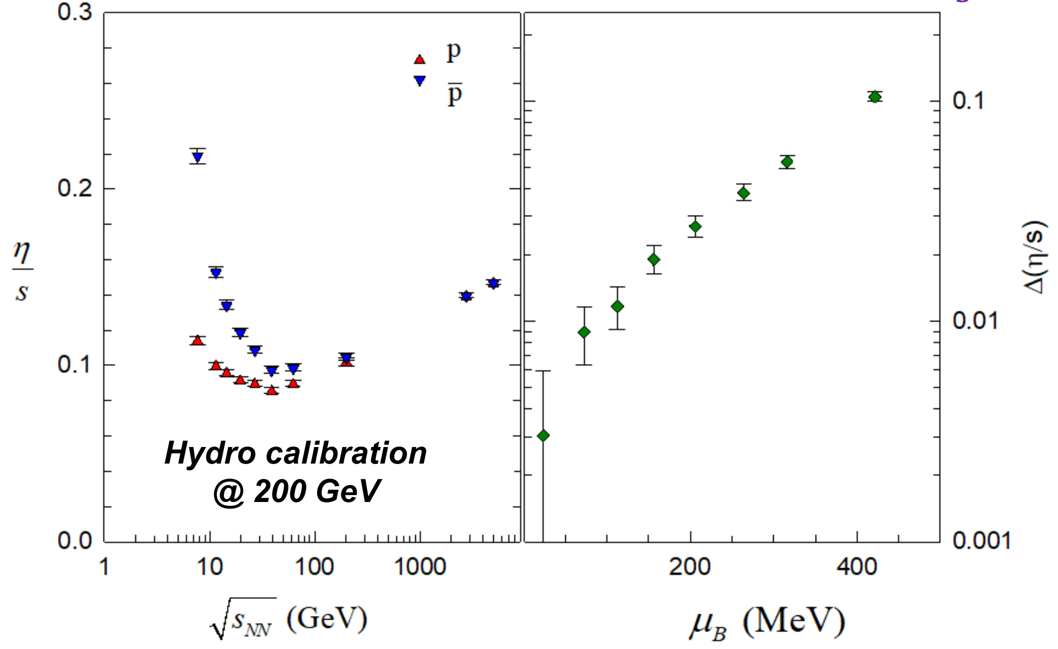


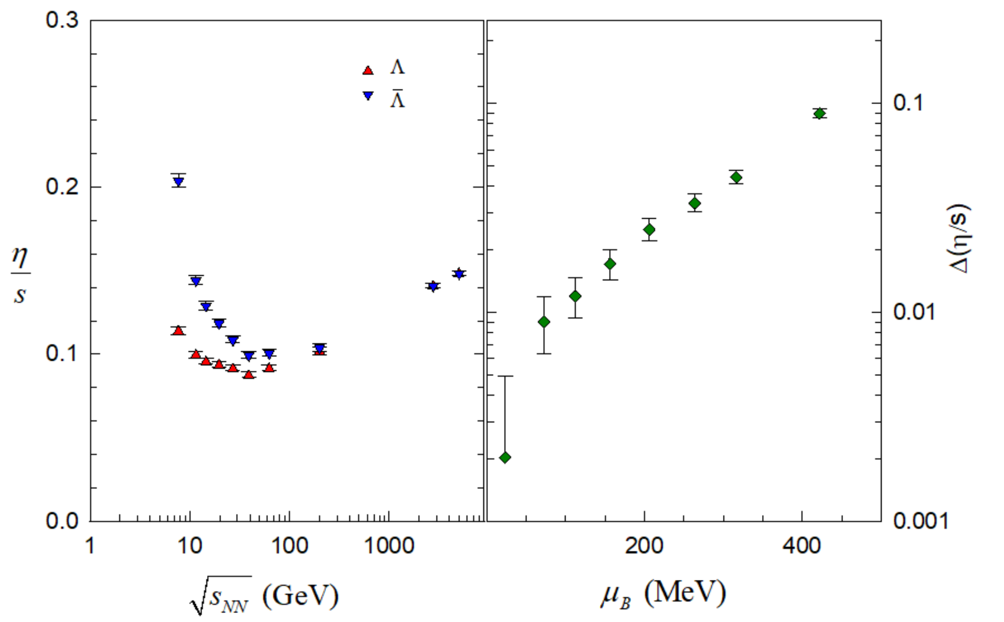


- **Scaling for viscous attenuation and expansion dynamics validated for particles and anti-particles across beam energies**
  - ✓ **Scaling coefficients indicate particle/anti-particle-dependent viscosity**

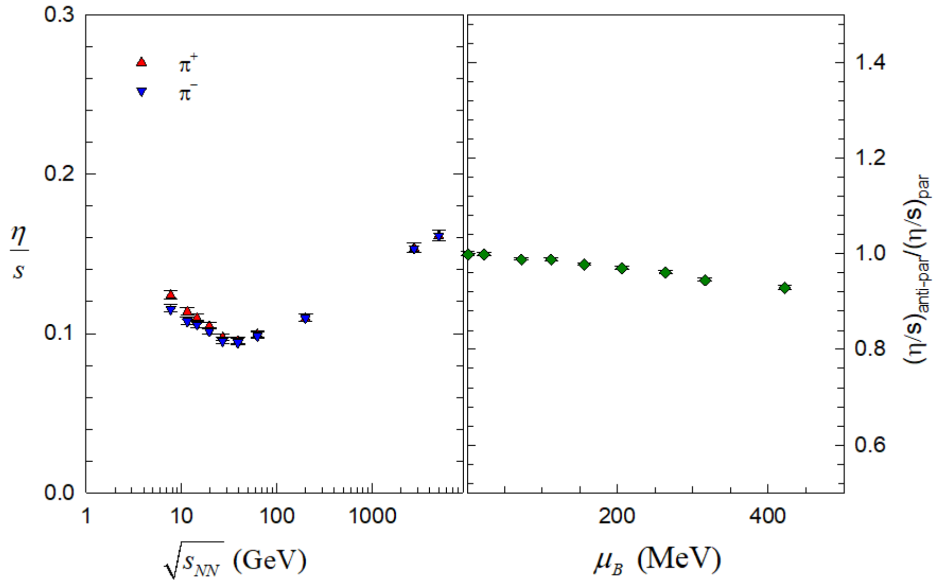
Beam-energy-dependent specific viscosity

$\sqrt{s_{NN}}$ dependence of the extracted values of $\frac{\eta}{s}$





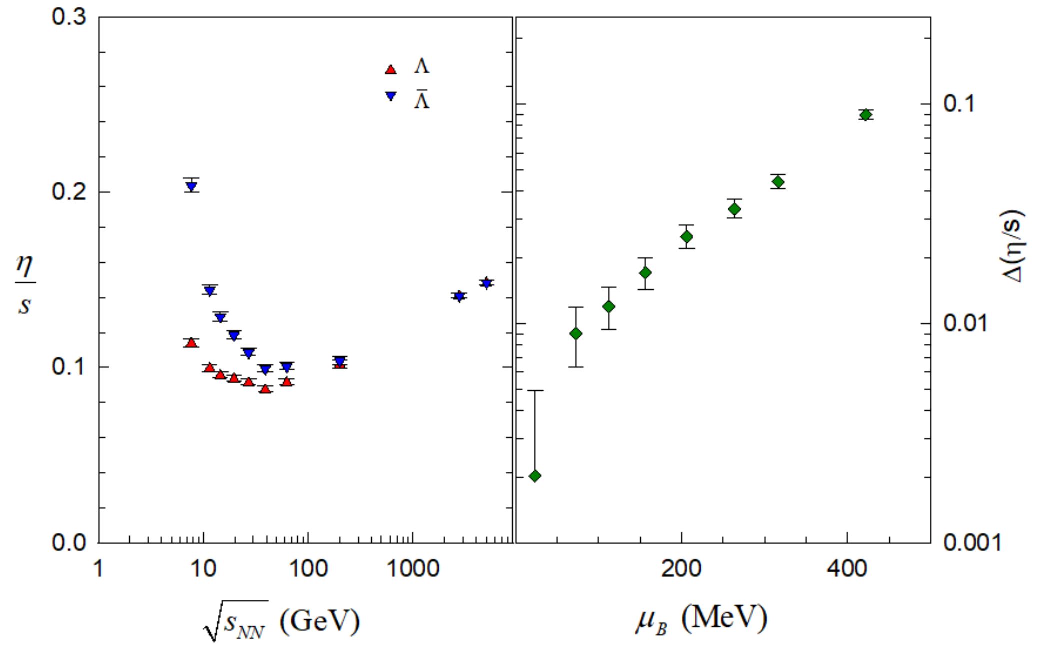
$$\frac{\eta}{s}(T, \mu_B, \mu_S, \mu_I)$$



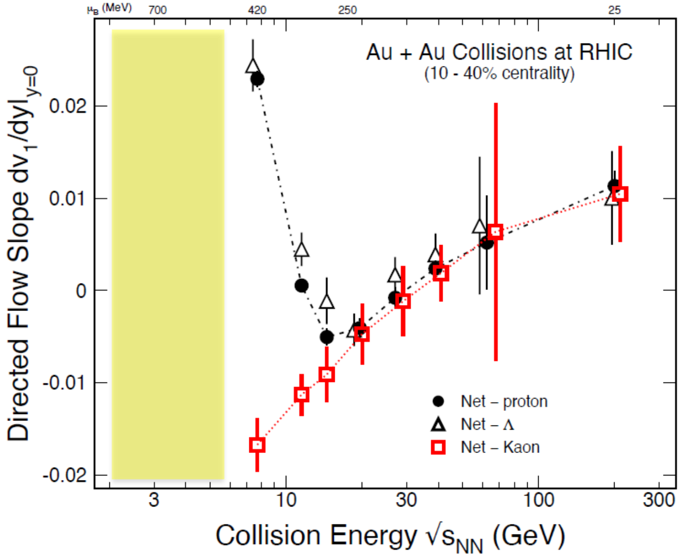
- Specific viscosity extracted across beam energies
  - ✓ Nonmonotonic patterns suggestive of critical behavior?
  - ✓ μ_B –dependent particle/anti-particle dependence

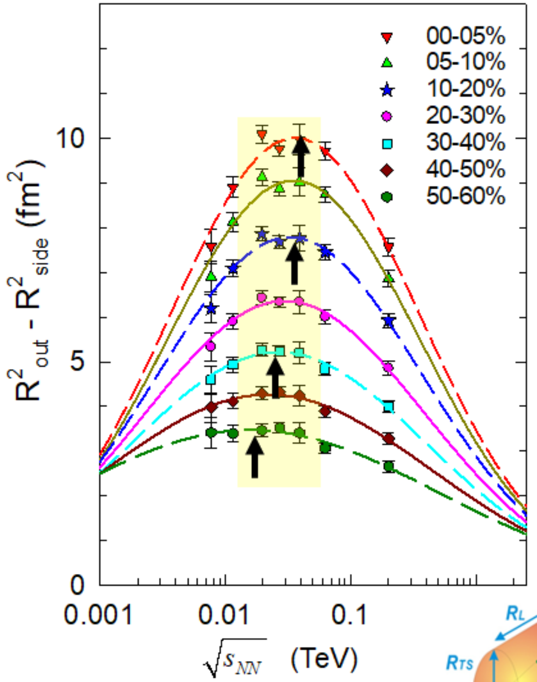
Charged currents drive particle/anti-particle viscosity difference

Non–monotonic patterns

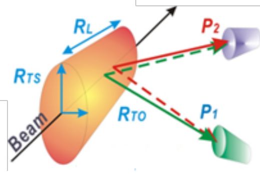


Other dynamics-driven non-monotonic patterns

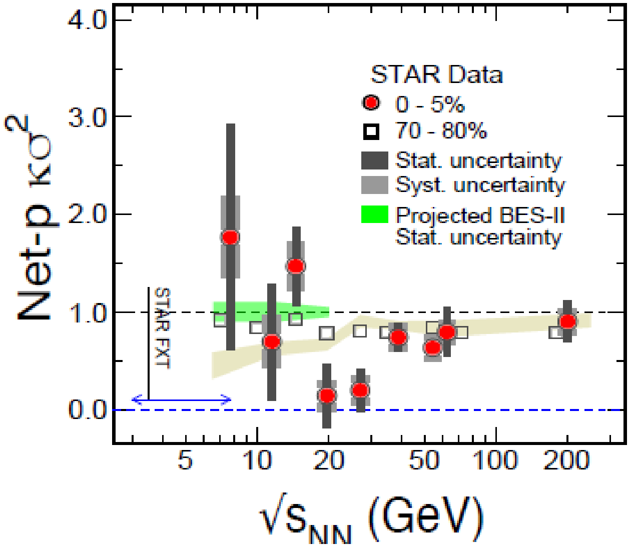




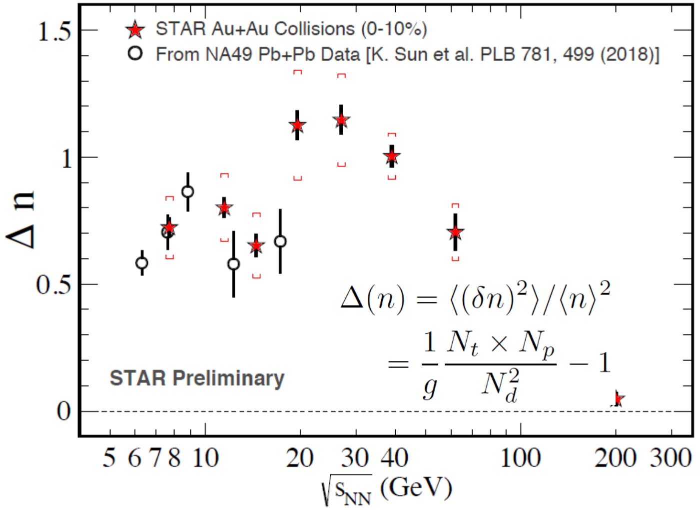
$$c_s^2 = \frac{1}{\rho\kappa}$$



Non-monotonic fluctuations pattern



Neutron relative density fluctuations

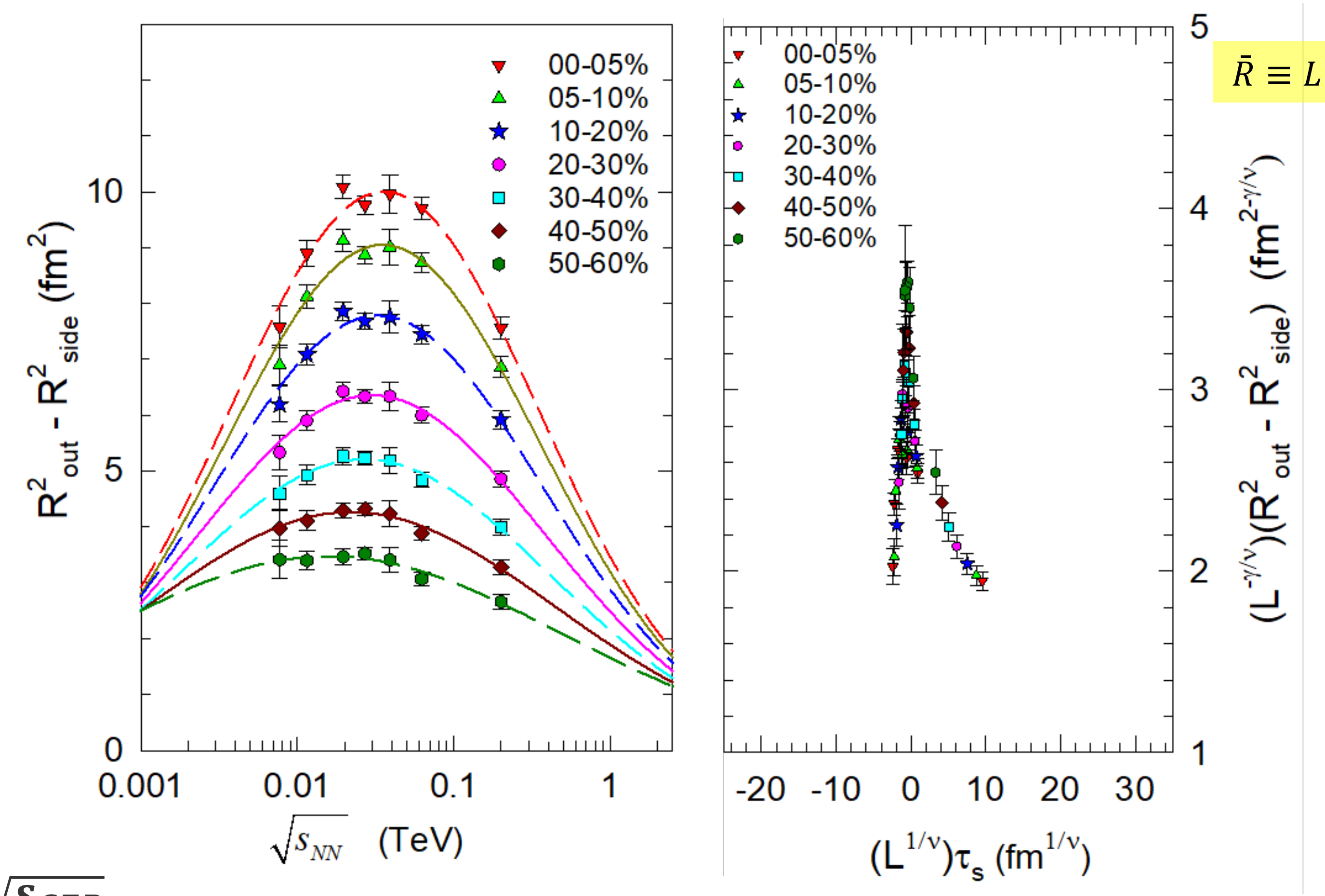


- **Anisotropy scaling functions indispensable for extraction of transport coefficients**
  - ✓ **Non-monotonic pattern observed ⟶ CEP?**
  - ✓ **Charged current dependence @ lower $\sqrt{s_{NN}}$**

- **Persistent non-monotonic pattern observed for several observables in similar $\sqrt{s_{NN}}$ range ⟶ CEP?**

Succeptiblity Scaling Function

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



$\bar{R} \equiv L$

$\sqrt{s_{CEP}} = 45\ GeV$

$\nu \sim 0.66$

$\gamma \sim 1.2$

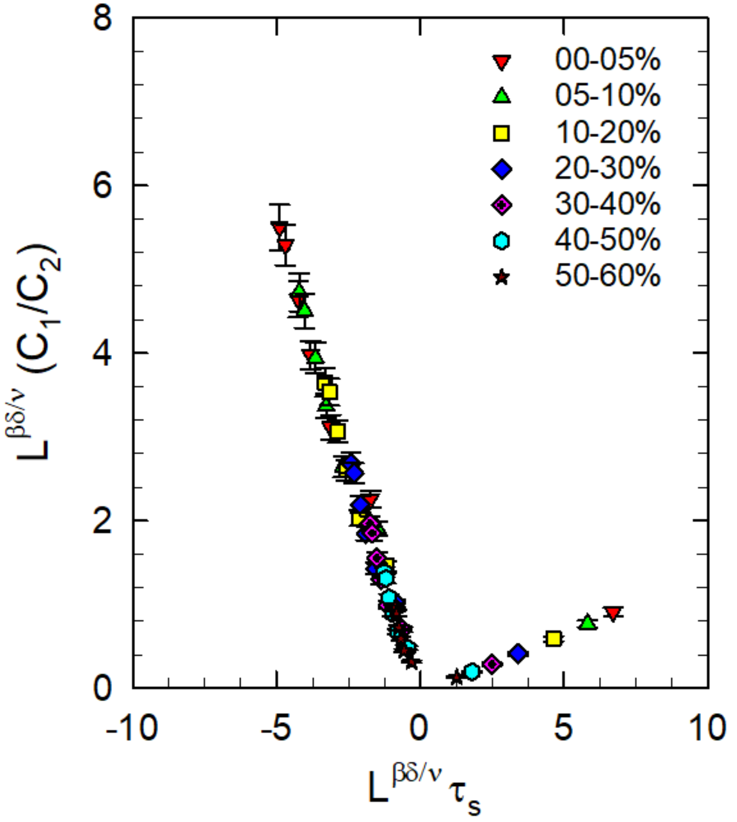
s= $(\sqrt{s} - \sqrt{s_{CEP}})/\sqrt{s_{CEP}}$

Finite-size scaling leads to data collapse for 3D Ising critical exponents.

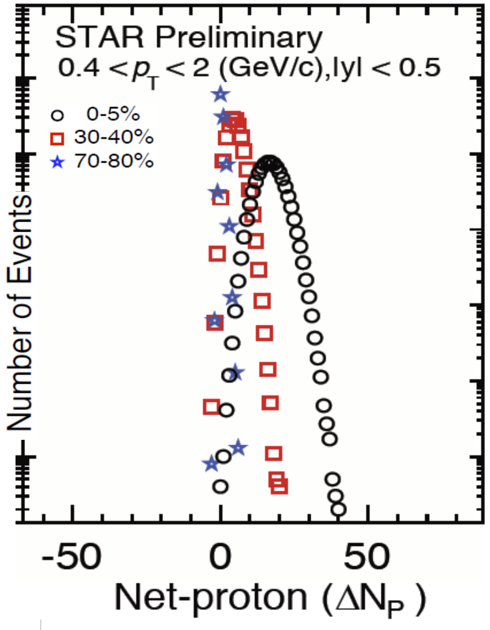
- ✓ **Slow quench in KZ language**

Scaling Function for Net baryon Succeptiblity ratio

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

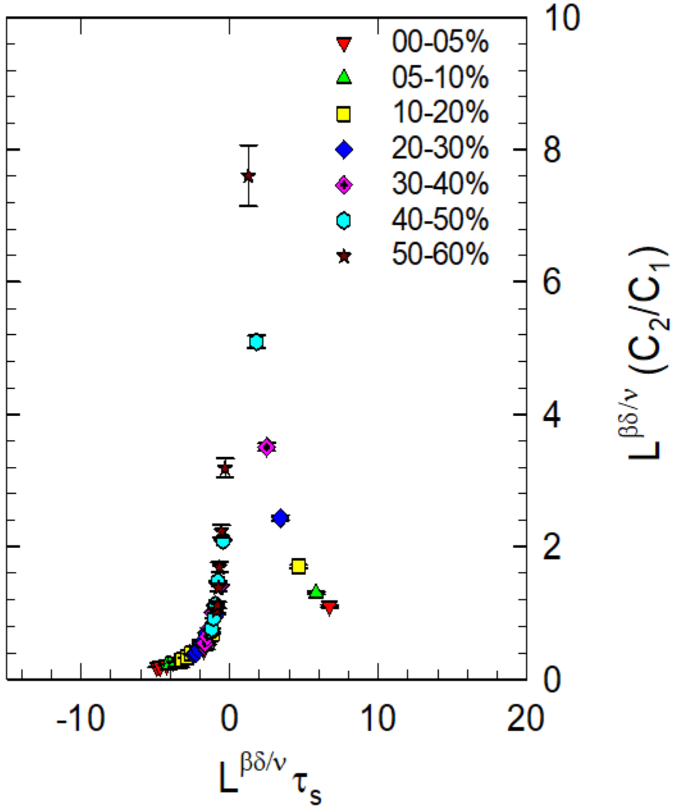


$C_n^{\Delta N_p}$ extracted from distributions



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

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



$\nu \sim 0.66$

$\beta \sim 0.33$

$\delta \sim 4.8$

Finite-size scaling leads to data collapse for 3D Ising critical exponents.

- ✓ **Slow quench in KZ language**

Summary

The $\sqrt{s_{NN}}$-dependence of the anisotropy scaling functions for PID species can be used to:

- *Delineate the respective influence of expansion dynamics and viscous attenuation*
- *Constrain $\frac{\eta}{s}(T, \mu_B, \mu_I, \mu_S)$]?*

The scaling functions extracted from the wealth of the flow data indicate:

- μ −dependent particle/anti-particle $\frac{\eta}{s}$ dependence
- *non-monotonic patterns for;*
  - ✓ $\frac{\eta}{s}(T, \mu_B)$,
  - ✓ $\frac{\eta}{s}(T, \mu_S)$,
  - ✓ $\frac{\eta}{s}(T, \mu_I)$,

Consistent with earlier indications for the CEP

End