Scaling properties of the mean multiplicity and pseudorapidity density in $e^{-}+e^{+}$, e+p, p+p, p+A and A+A(B) collisions

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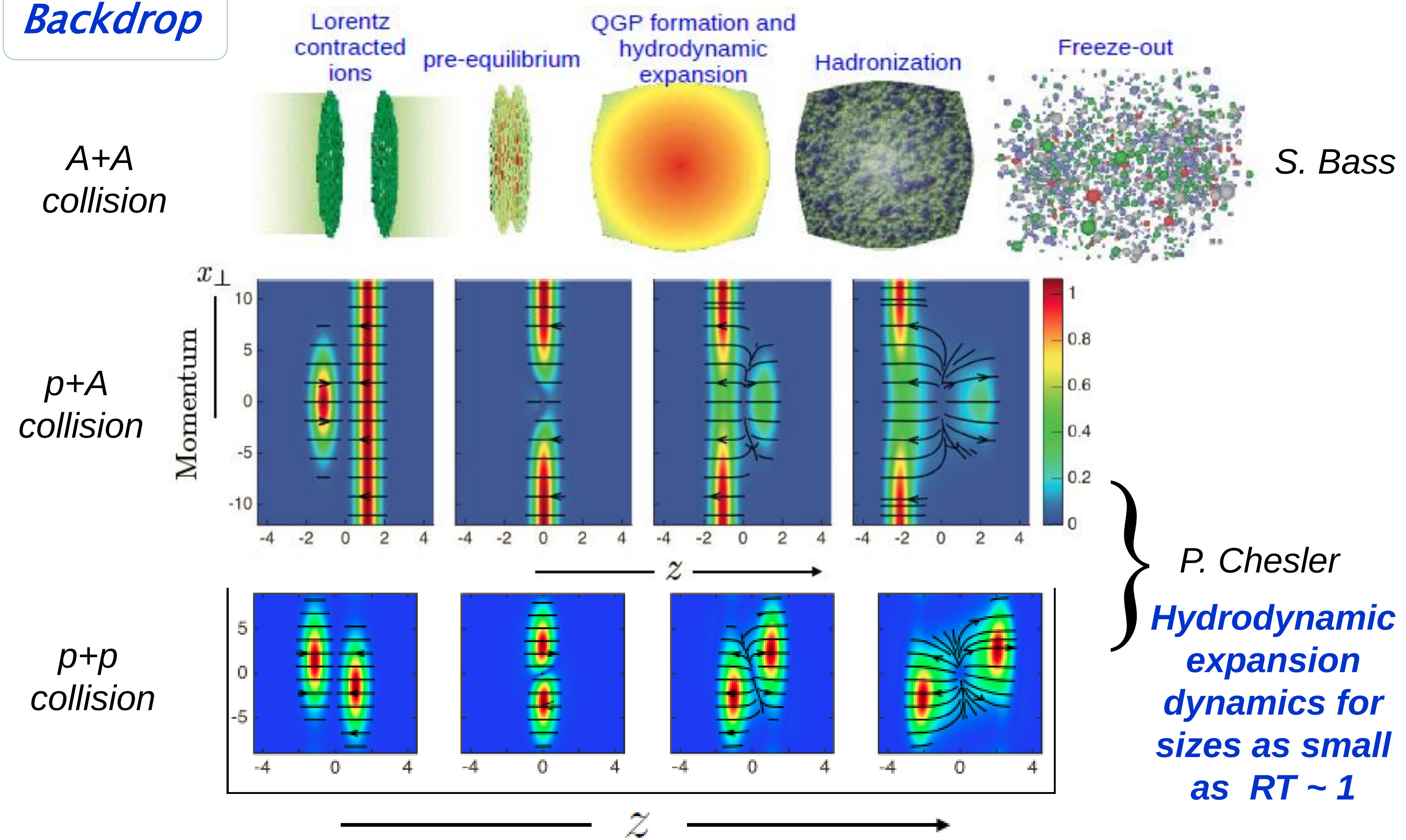

Hydrodynamic expansion dynamics for sizes as small as RT ~ 1

- **Is hydro-like expansion dynamics maintained with reduced system size, and how do we tell?**

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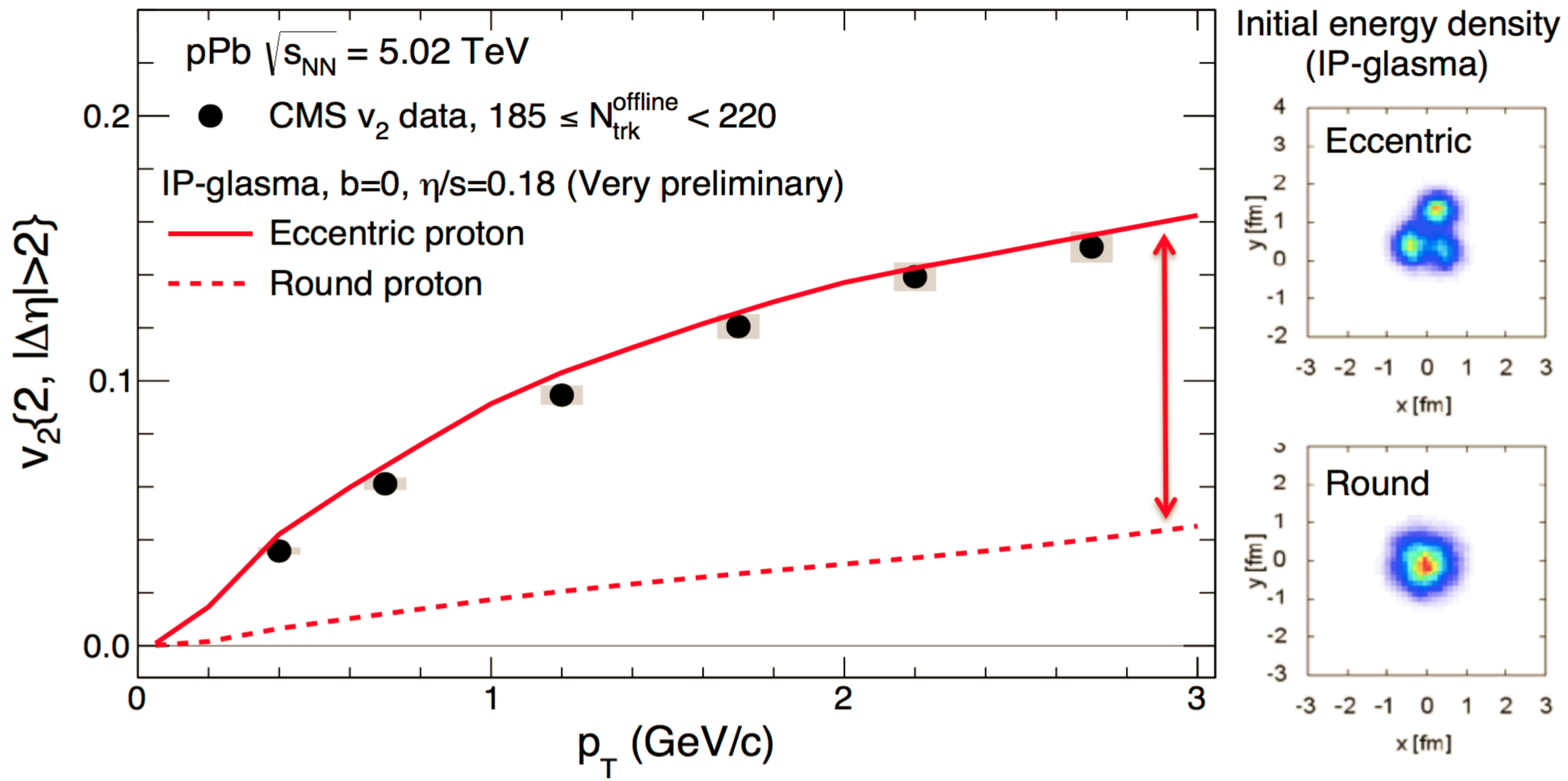
Bjorn – this conference



➢ ***What is the relevant substructure of the nucleon?***
- valence quarks?

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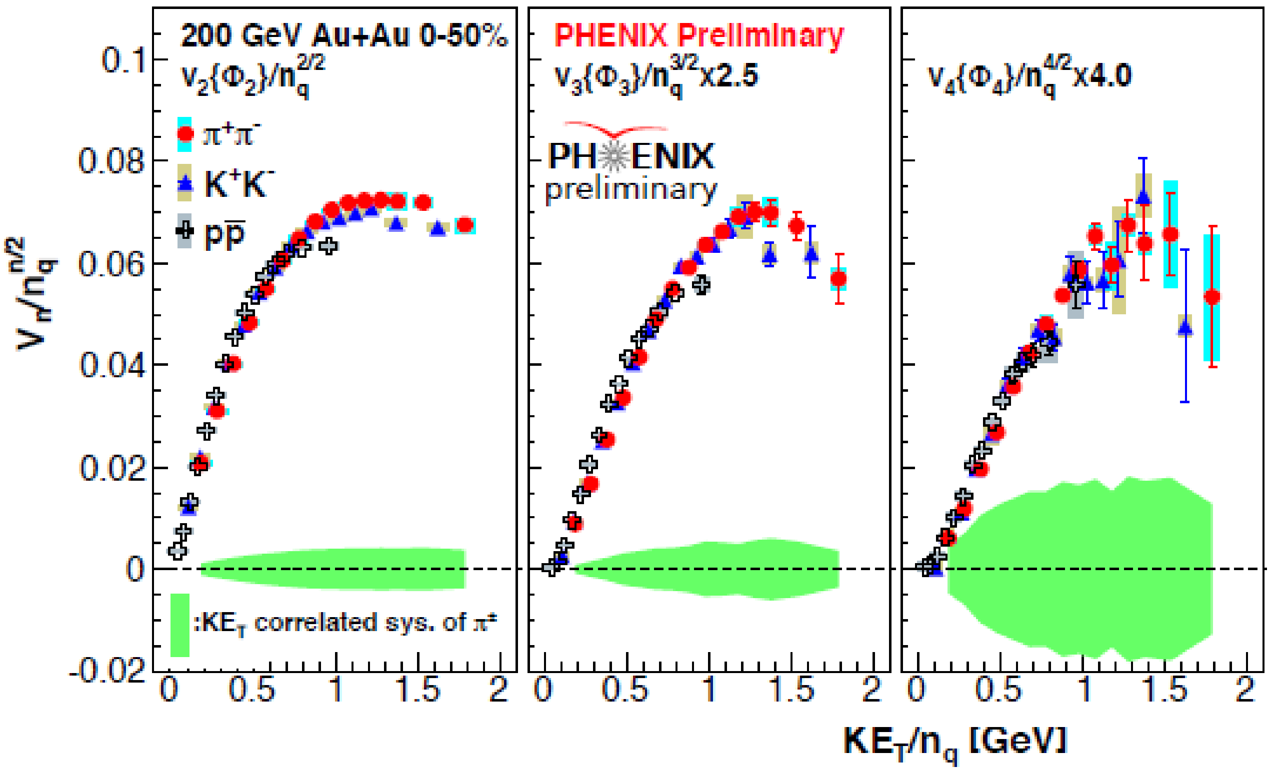
v_n PID scaling



$$\text{Expectation validated: } v_n(KE_T) \sim v_2^{n/2} \text{ or } \frac{v_n}{(n_q)^{n/2}}$$

- ***Are valence quark degrees of freedom relevant?***

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Strategy

Test for similarities in the particle production mechanism for p+p, p+A, A+A(B) collisions

$\langle N_{chg} \rangle$ and $\frac{dN_{chg}}{d\eta}$ scaling

RT link →

Test for similarities in the expansion dynamics for p+p, p+A, A+A(B) collisions

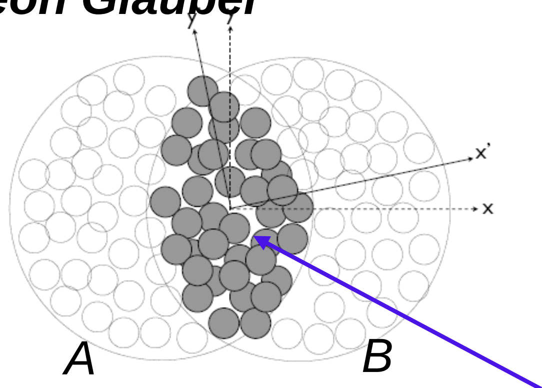
Acoustic scaling of v_n
HBT radii, etc

The scaling properties of $\langle N_{chg} \rangle$, $\frac{dN_{chg}}{d\eta}$, v_n, etc can provide key insights

- ✓ ***Scaling coefficients provide crucial constraints for transport coefficients***

Geometric quantities for scaling

Nucleon Glauber



Phys. Rev. C 81, 061901(R) (2010)

$$S_{nx} \equiv S_n \cos(n\Psi_n^*) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\cos(n\phi)$$

$$S_{ny} \equiv S_n \sin(n\Psi_n^*) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\sin(n\phi),$$

$$\Psi_n^* = \frac{1}{n}\tan^{-1}\left(\frac{S_{ny}}{S_{nx}}\right)$$

$$\varepsilon_n = \left\langle \cos n\left(\phi - \psi_n^*\right)\right\rangle$$

$$\frac{1}{\bar{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$$

σ_x & σ_y → RMS widths of density distribution

Quark Glauber

n-n cross section
p-p profile
- ✓ *Elastic scattering measurements*

rms radius

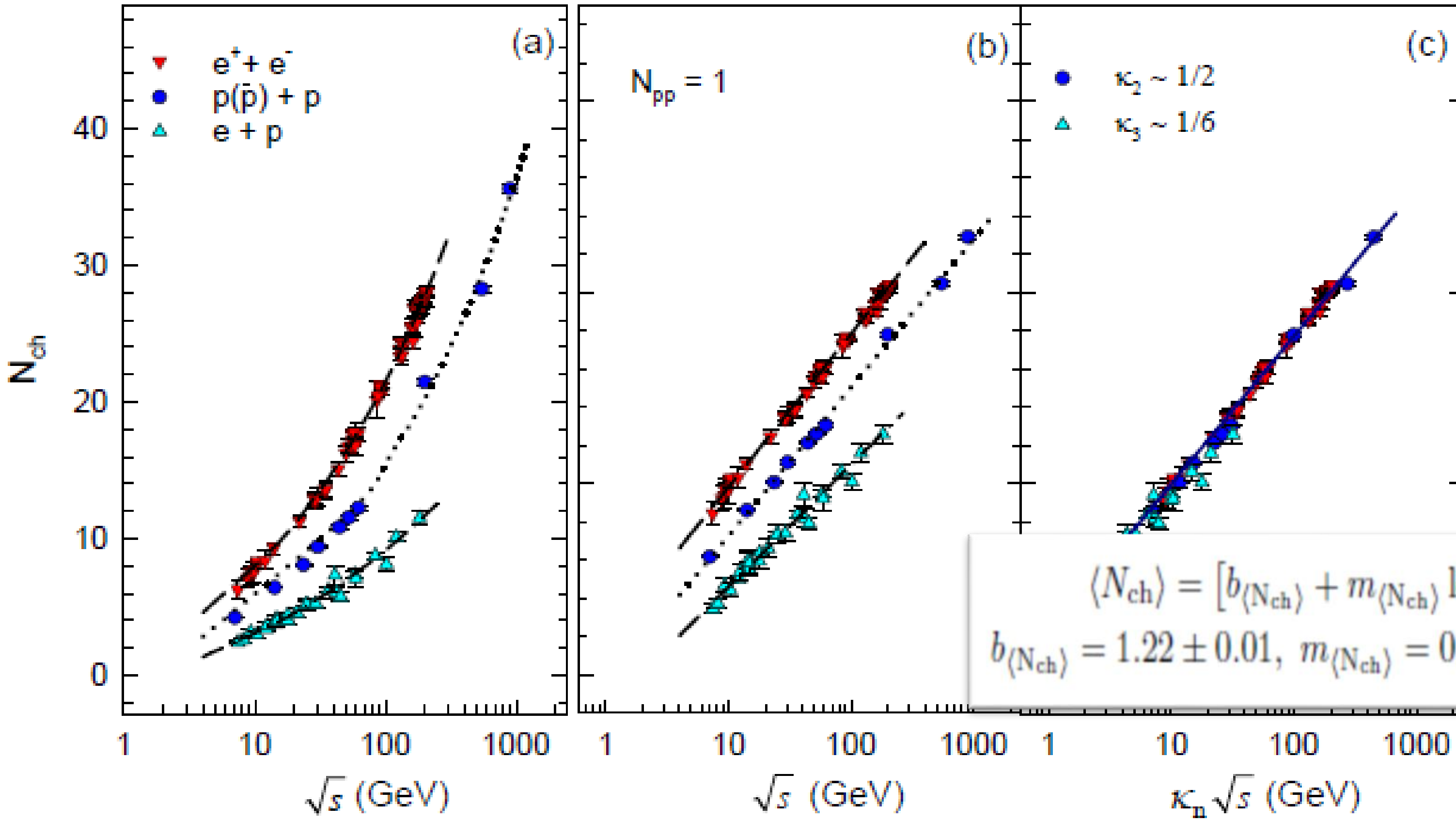
- ➢ ***Consistency between nucleon and quark Glauber***
  - ✓ ***Geometric fluctuations included***

$\langle N_{chg} \rangle$ and $\frac{dN_{chg}}{d\eta}$ scaling

Operational Ansatz

$S \sim (TR)^3 \sim \text{const.},$ $\langle N_{chg} \rangle, \frac{dN_{chg}}{d\eta} \propto S$

$N_{npp,qpp}^{1/3} \propto R$ for early-time thermalization



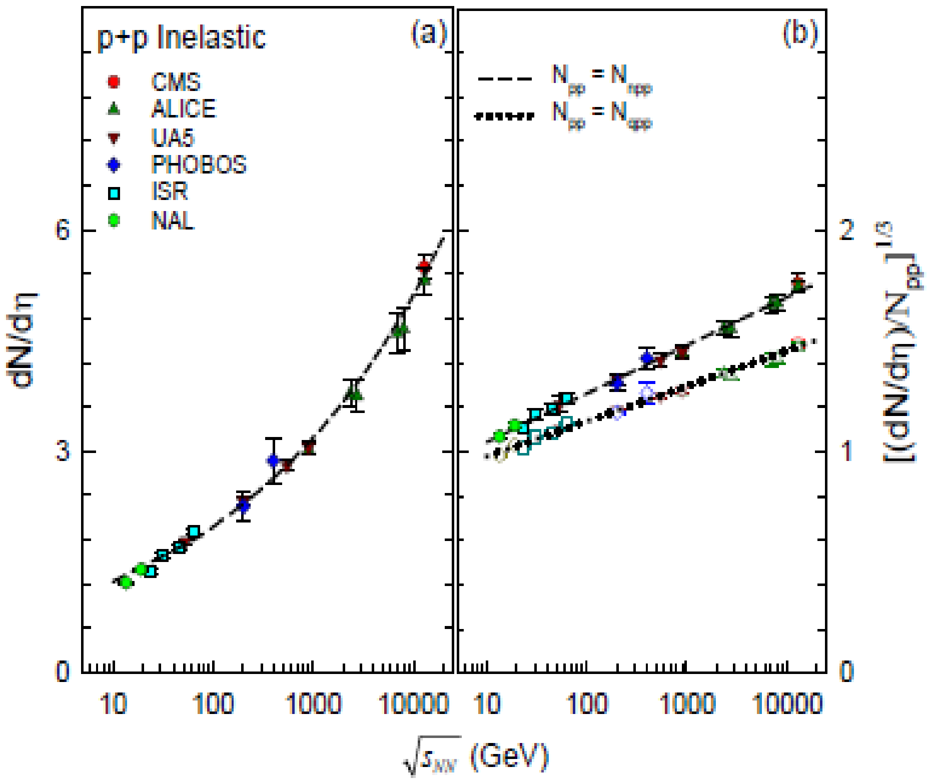
$$\langle N_{ch} \rangle = \left[b_{\langle N_{ch}\rangle} + m_{\langle N_{ch}\rangle} \log(\kappa_n \sqrt{s})\right]^3,$$
$$b_{\langle N_{ch}\rangle} = 1.22 \pm 0.01,\ m_{\langle N_{ch}\rangle} = 0.775 \pm 0.006,$$

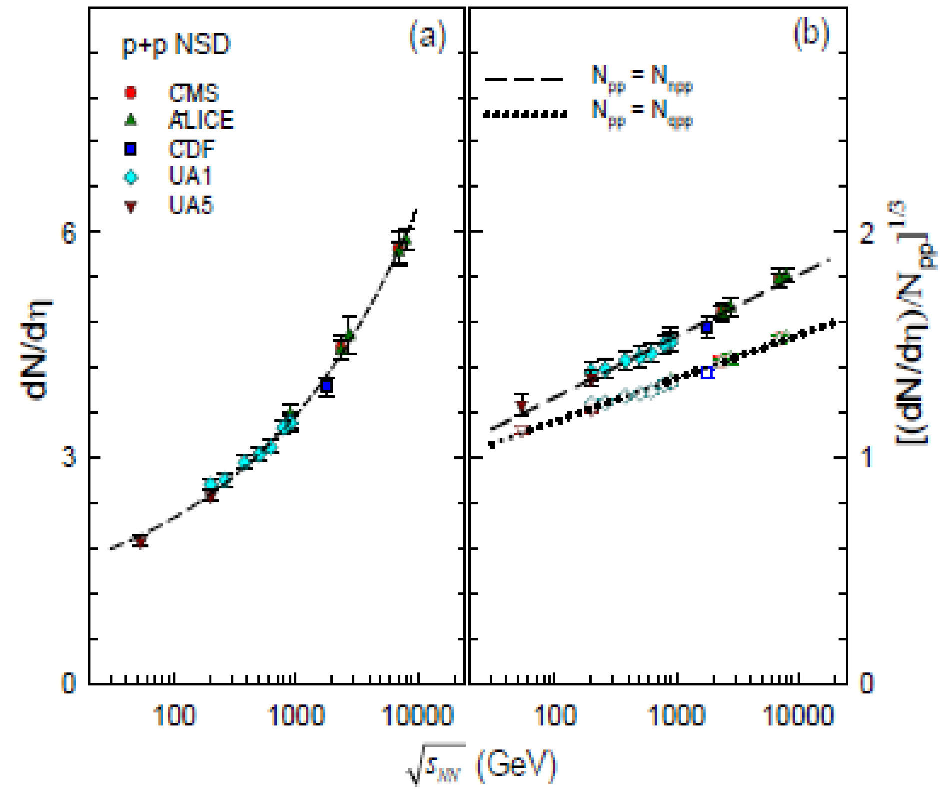
Scaling validates important role of quark participants

- ✓ **Large fluctuations – leading particle effect**
- ✓ **$\kappa_{2,3}$ related to number of quark participants**

→ fraction of available cm energy

$\frac{dN_{chg}}{d\eta}$ scaling p+p





$$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{\mathrm{INE}} = [b_{\mathrm{INE}} + m_{\mathrm{INE}} \log(\sqrt{s_{\mathrm{NN}}})]^3 ,$$
$$b_{\mathrm{INE}} = 0.826 \pm 0.008, \ m_{\mathrm{INE}} = 0.220 \pm 0.004,$$

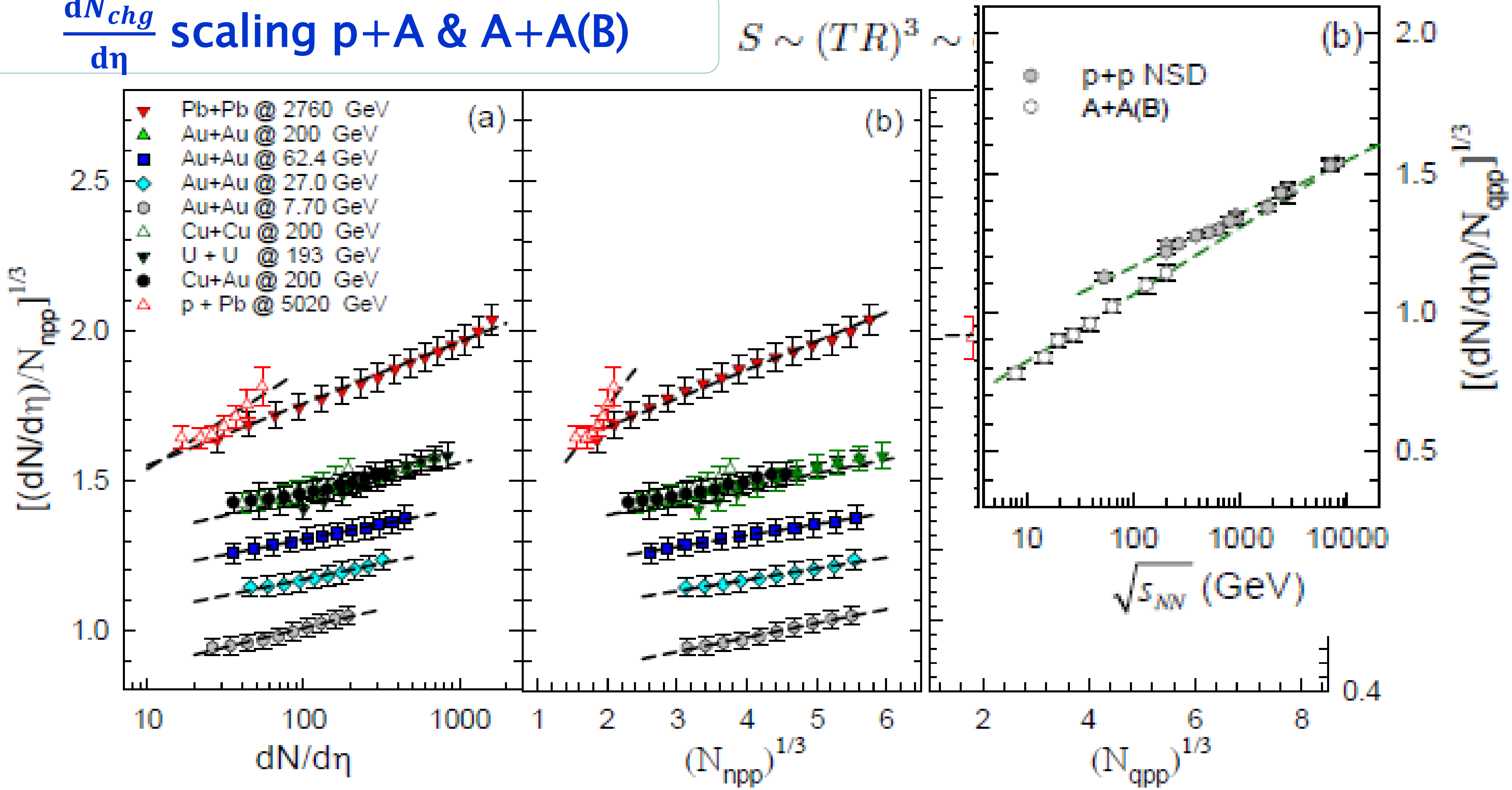
$$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{\mathrm{NSD}} = [b_{\mathrm{NSD}} + m_{\mathrm{NSD}} \log(\sqrt{s_{\mathrm{NN}}})]^3 ,$$
$$b_{\mathrm{NSD}} = 0.747 \pm 0.022, \ m_{\mathrm{NSD}} = 0.267 \pm 0.007,$$

Further scaling validation over full range of $\sqrt{s_{NN}}$ for p+p

✓ **Similar $\sqrt{s_{NN}}$ trend for quark and nucleon scaled multiplicity density**

$\frac{dN_{chg}}{d\eta}$ scaling p+A & A+A(B)

$S \sim (TR)^3 \sim$



$$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{|\eta|=0.5} = N_{\mathrm{qpp}}\left[b_{\mathrm{AA}} + m_{\mathrm{AA}}\log(\sqrt{s})\right]^3,$$
$$b_{\mathrm{AA}} = 0.530 \pm 0.008,\ \ m_{\mathrm{AA}} = 0.258 \pm 0.004,$$

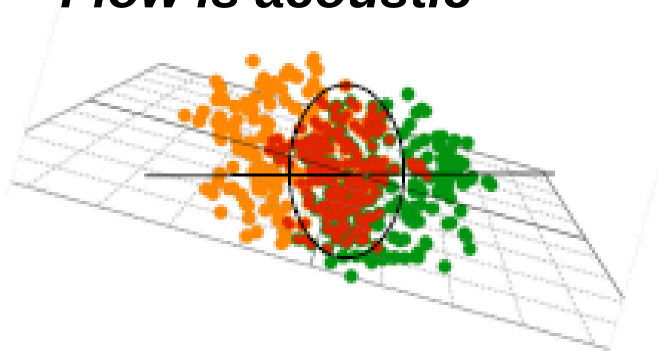
Scaling validated for p+A & A+A(B) systems

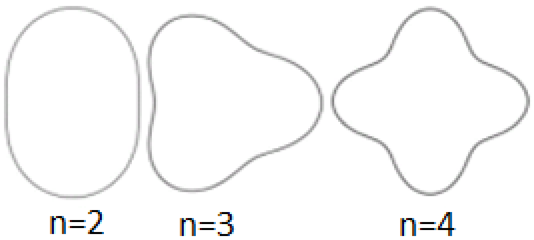
- ✓ **Similar patterns for A+A(B) systems at the same $\sqrt{s_{NN}}$.**
- ✓ **Logarithmic dependence of $\langle p_T \rangle$ on multiplicity**

Expansion Dynamics

Initial Geometry characterized by many shape harmonics (ε_n) → drive v_n

Flow is acoustic





$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

Acoustic viscous modulation of v_n

$$\delta T_{\mu\nu}(t,k) = \exp\left(-\frac{2}{3}\frac{\eta}{s}k^2\frac{t}{T}\right)\delta T_{\mu\nu}(0)$$

Staig & Shuryak **arXiv:1008.3139**

$$k = n / \bar{R} \qquad t \propto \bar{R}$$

$$\delta T_{\mu\nu}(n,t) = \exp\left(-\beta n^2\right)\delta T_{\mu\nu}(0), \quad \beta = \frac{2}{3}\frac{\eta}{s}\frac{1}{\bar{R}^2}\frac{t}{T}$$

Scaling expectations:

Straightforward to include bulk viscosity

n^2 dependence

$$\left(\frac{v_n(p_T)}{\varepsilon_n}\right) \propto \exp\left(-\frac{\beta'}{RT}n^2\right)$$

v_n ‘s are related

$$\frac{\left(v_n(p_T)\right)^{1/n}}{\left(v_{n'}(p_T)\right)^{1/n'}} \sim \frac{\left(\varepsilon_{n'}\right)^{1/n'}}{\left(\varepsilon_n\right)^{1/n}} \cdot \exp\left(-\frac{\beta'}{RT}(n-n')\right)$$

System size dependence

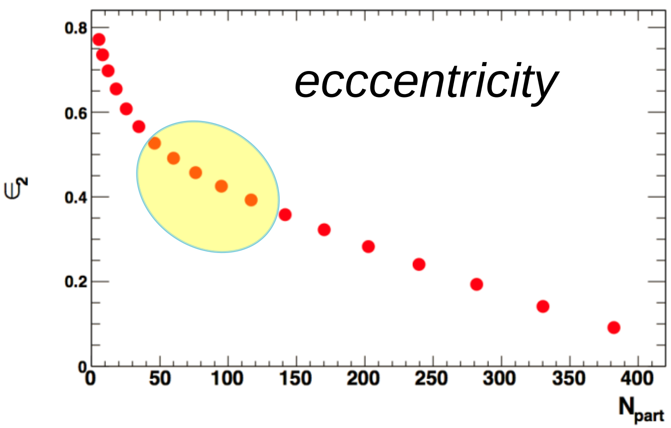
$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{RT}$$

The factors which influence anisotropic flow – well understood

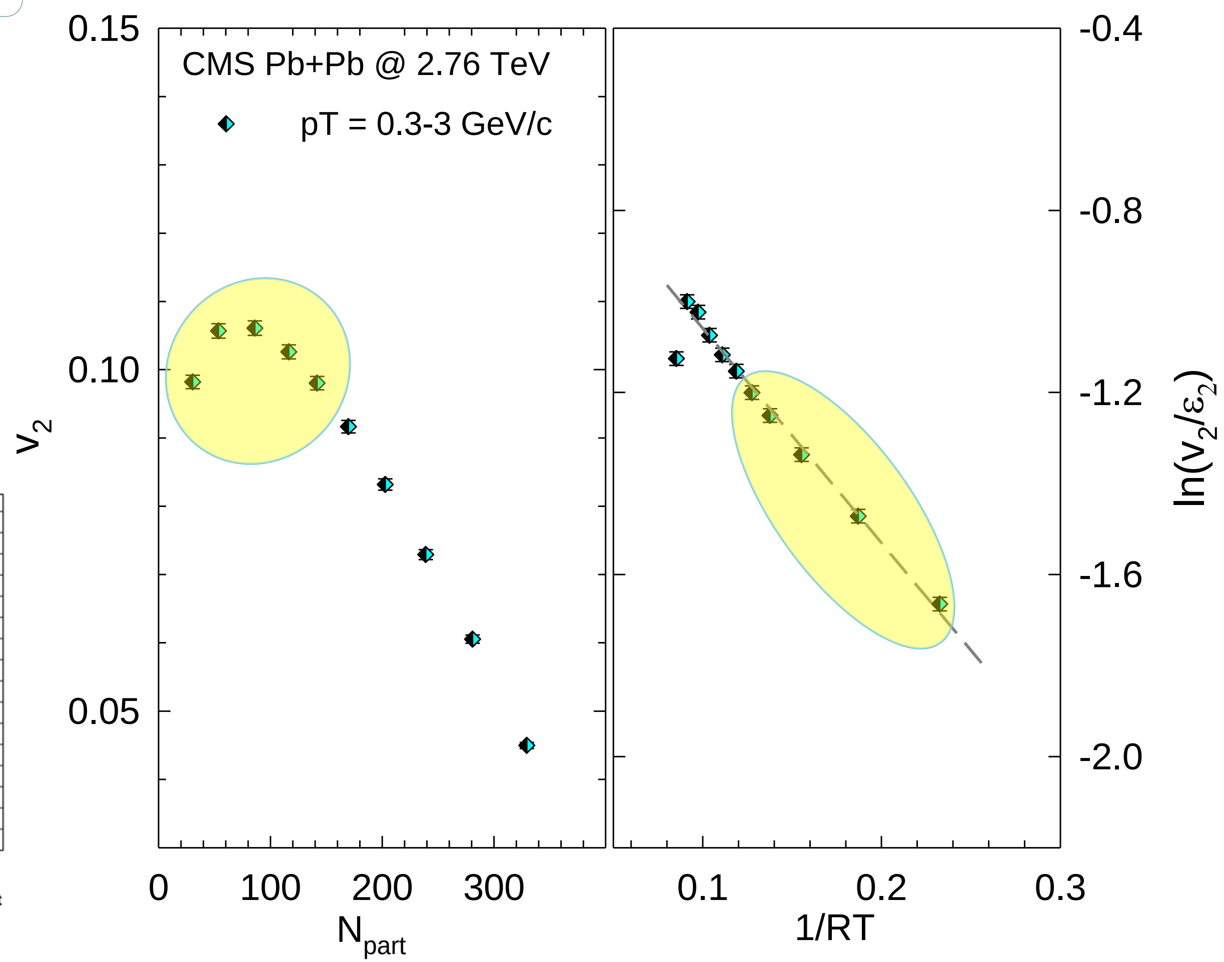
Acoustic Scaling – RT

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{RT}$$

$$RT \propto \left(\frac{dN_{chg}}{d\eta}\right)^{1/3}$$



- **Eccentricity change <u>alone</u> is not sufficient**



- ✓ **Characteristic 1/(RT) viscous damping validated**
- ✓ **Similar patterns for other p_T selections**
- ✓ ***Important constraint for η/s & ζ/s***

Acoustic Scaling – RT

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{RT}$$

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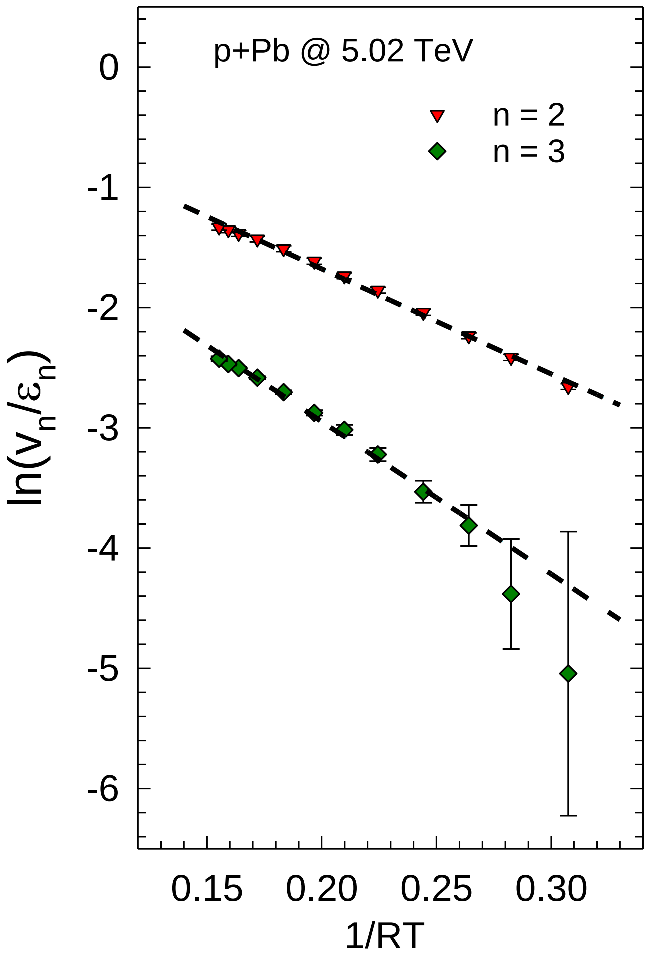
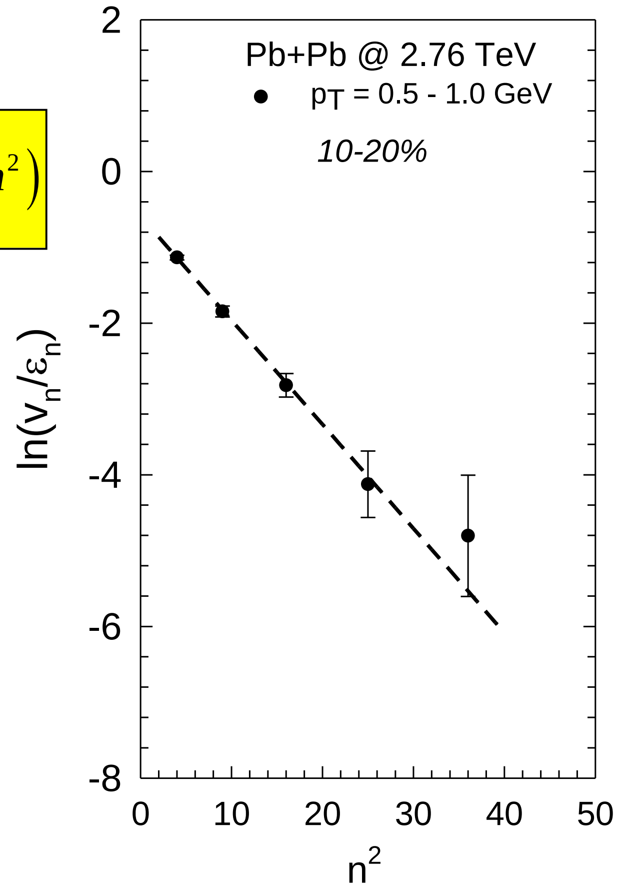


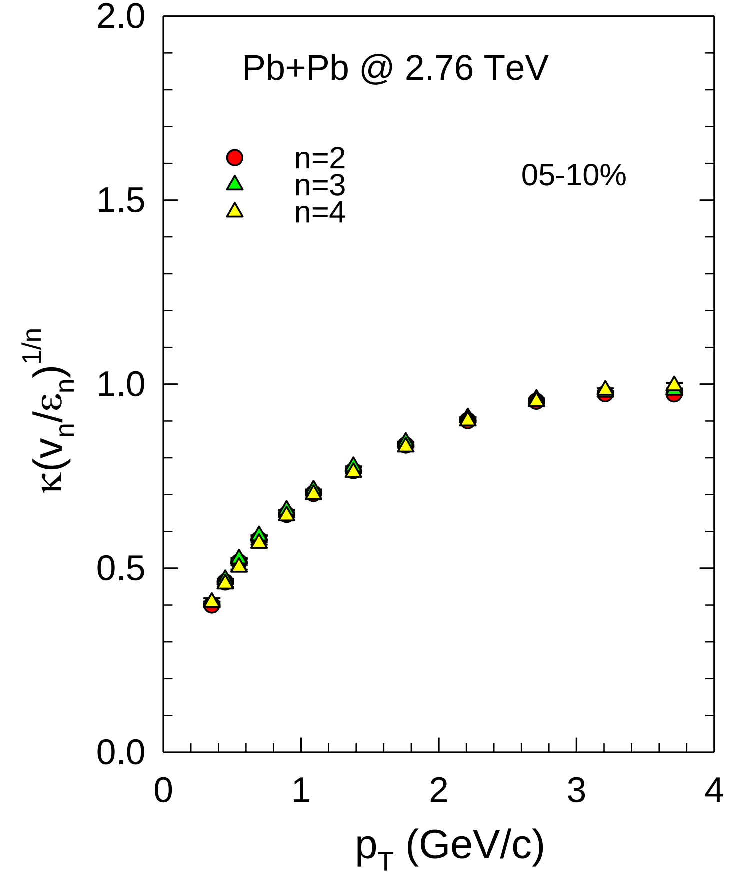
- ✓ **Characteristic 1/(RT) viscous damping validated**
- ✓ ***Important constraint for η/s & ζ/s***

Acoustic Scaling – n²

$$\left(\frac{v_n(p_T)}{\varepsilon_n}\right)^{1/n} \propto \exp(-\beta' n)$$

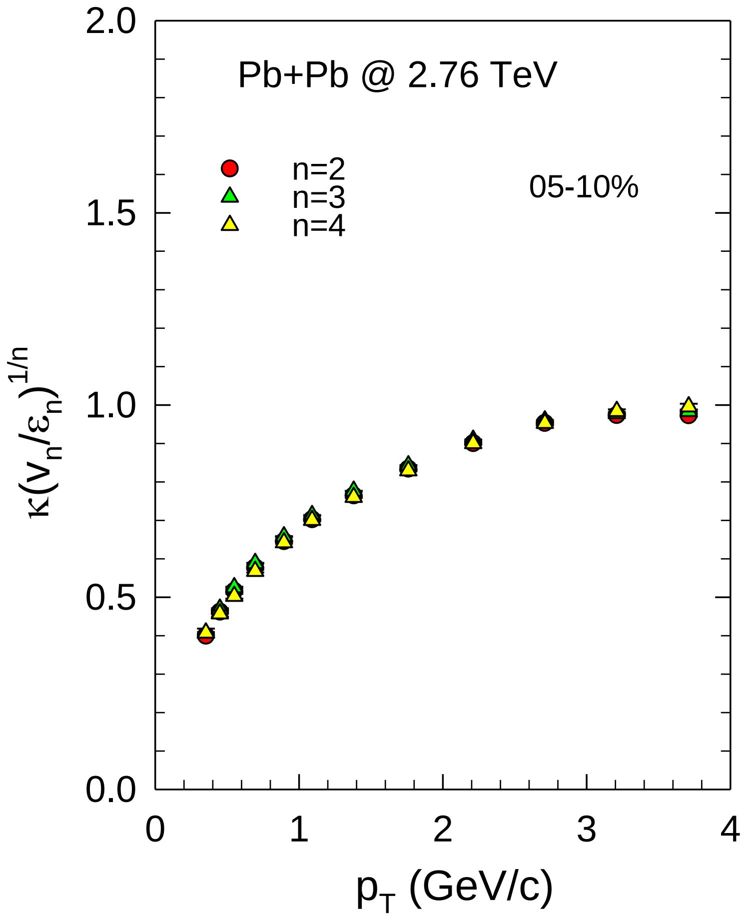
$$\left(\frac{v_n}{\varepsilon_n}\right) \propto \exp(-\beta' n^2)$$

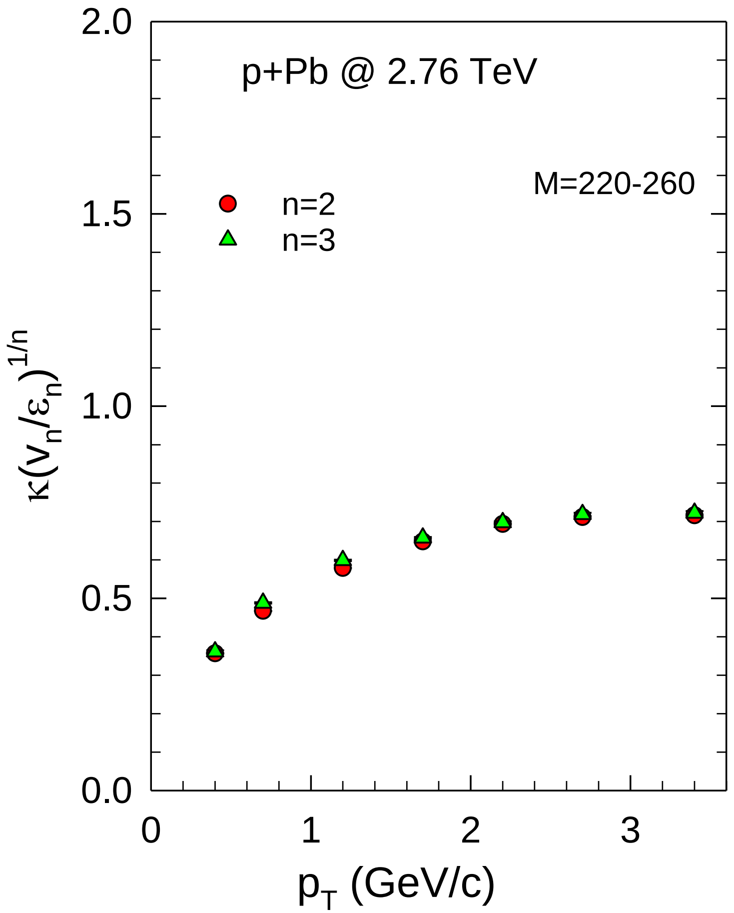




- ✓ **Characteristic n² viscous damping validated**
- ✓ **Similar patterns for other centrality selections**
- ✓ ***Important constraint for η/s & ζ/s***

System-size dependence





- ✓ **Similar acoustic patterns for p+Pb and Pb+Pb**
- ✓ ***Similar results for other small systems***

Epilogue

No fundamental change in the particle production mechanism and expansion dynamics, with reduced system size

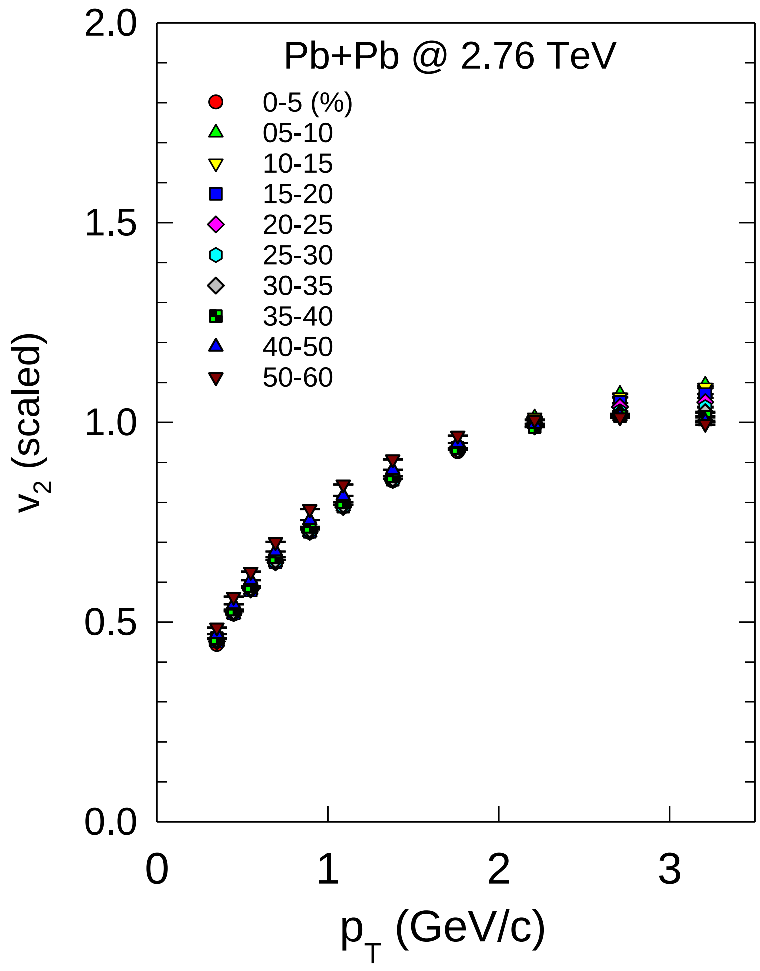
- ***Similar particle production mechanism for large (A+A(B)) and small (p+p, p+A) system***
  - ✓ $\langle N_{chg} \rangle$ and $\frac{\mathrm{d}N_{chg}}{\mathrm{d}\eta}$ scaling over ~ four orders of magnitude *in* $\sqrt{s_{NN}}$
  - ✓ ***Important role for quark participants***

- ***Similar Acoustic dynamics validated in "large" and "small" systems***
  - ✓ ***Strong evidence for the important role of final-state interactions.***
  - ✓ ***Important constraints for transport coefficients***

Acoustic dynamics fully predictable for other systems and energies

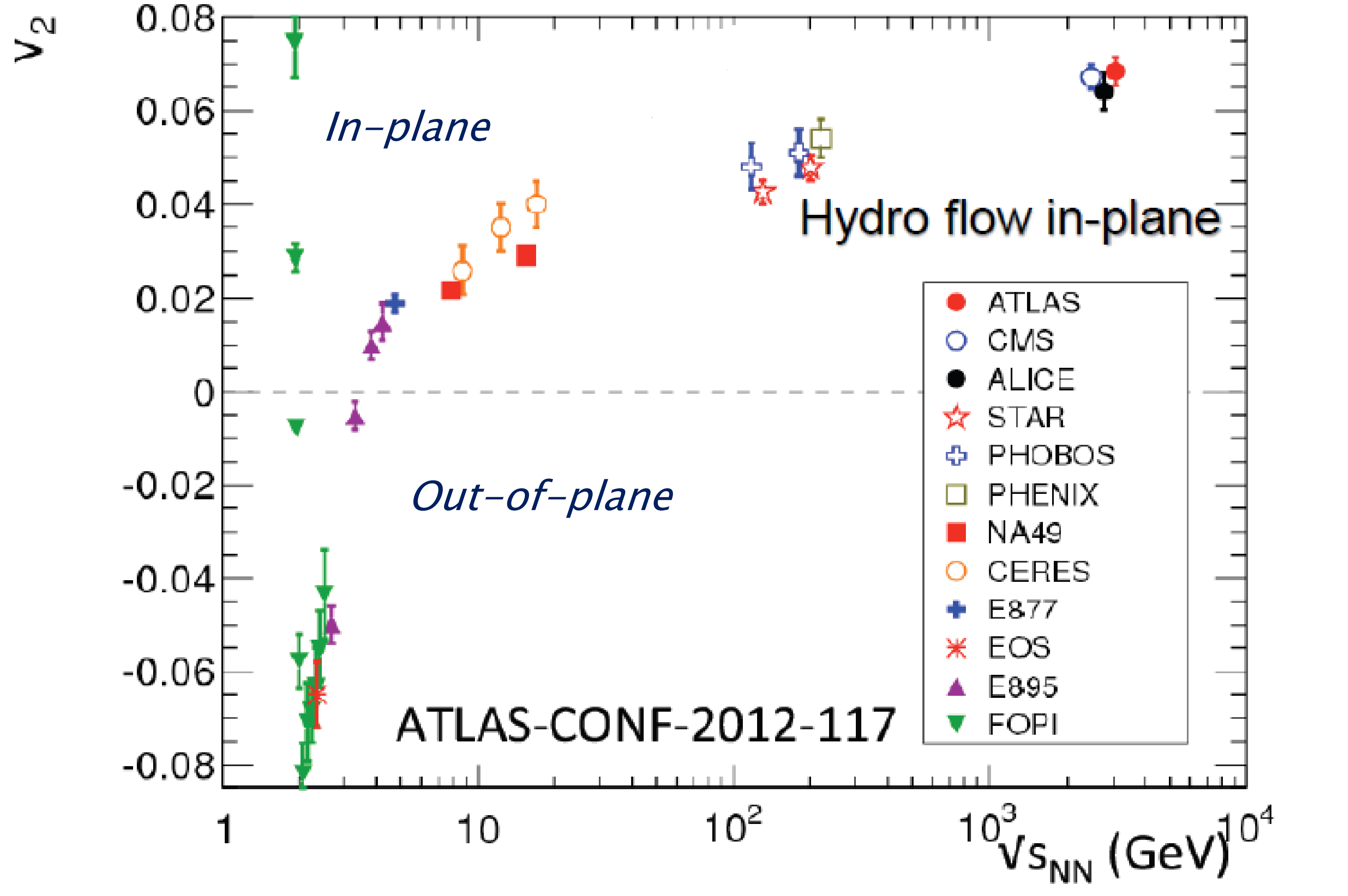
End

Scaling properties of flow



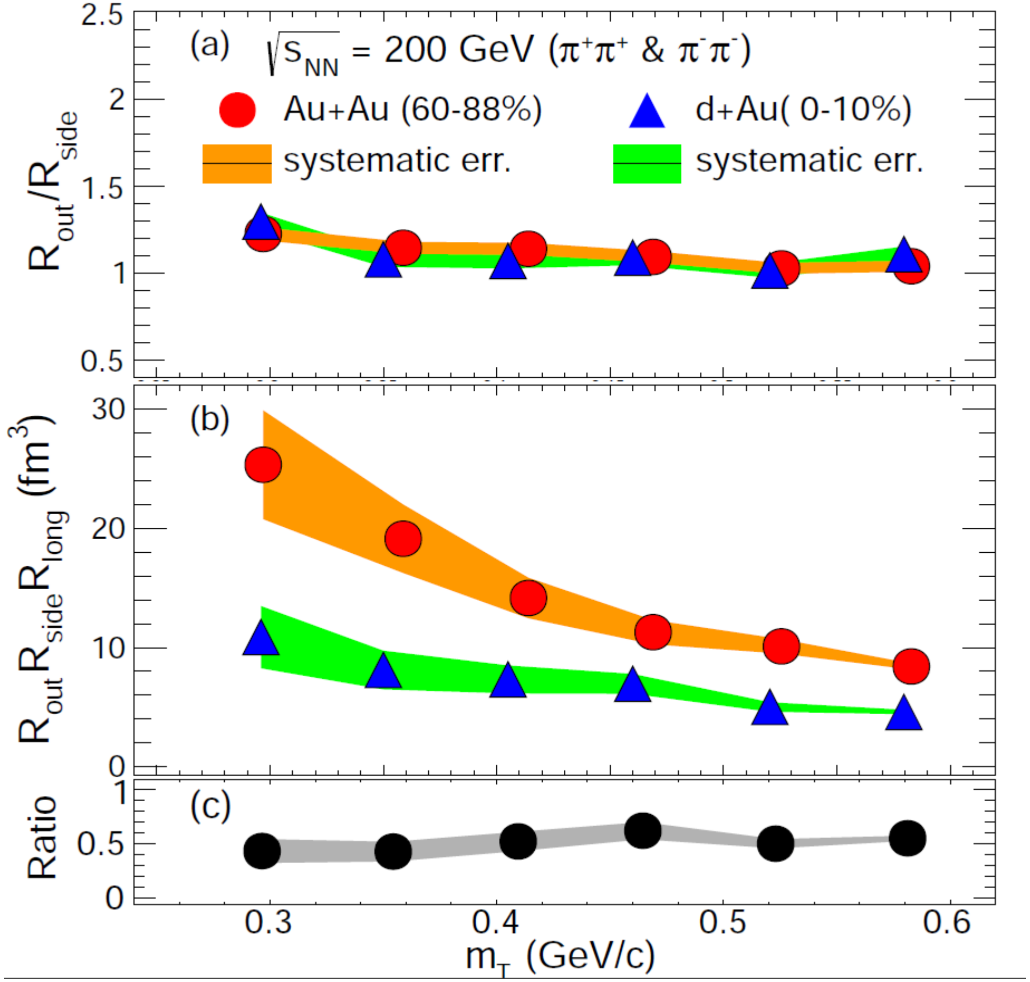
✓ ***Combined scaling understood***

flow



v_2
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
In-plane
Out-of-plane
Hydro flow in-plane
ATLAS-CONF-2012-117
ATLAS
CMS
ALICE
STAR
PHOBOS
PHENIX
NA49
CERES
E877
EOS
E895
FOPI
1
10
10^2
10^3
10^4
$\sqrt{s_{NN}}$ (GeV)

Comparison of Au+Au and d+Au collisions – m_T dependence



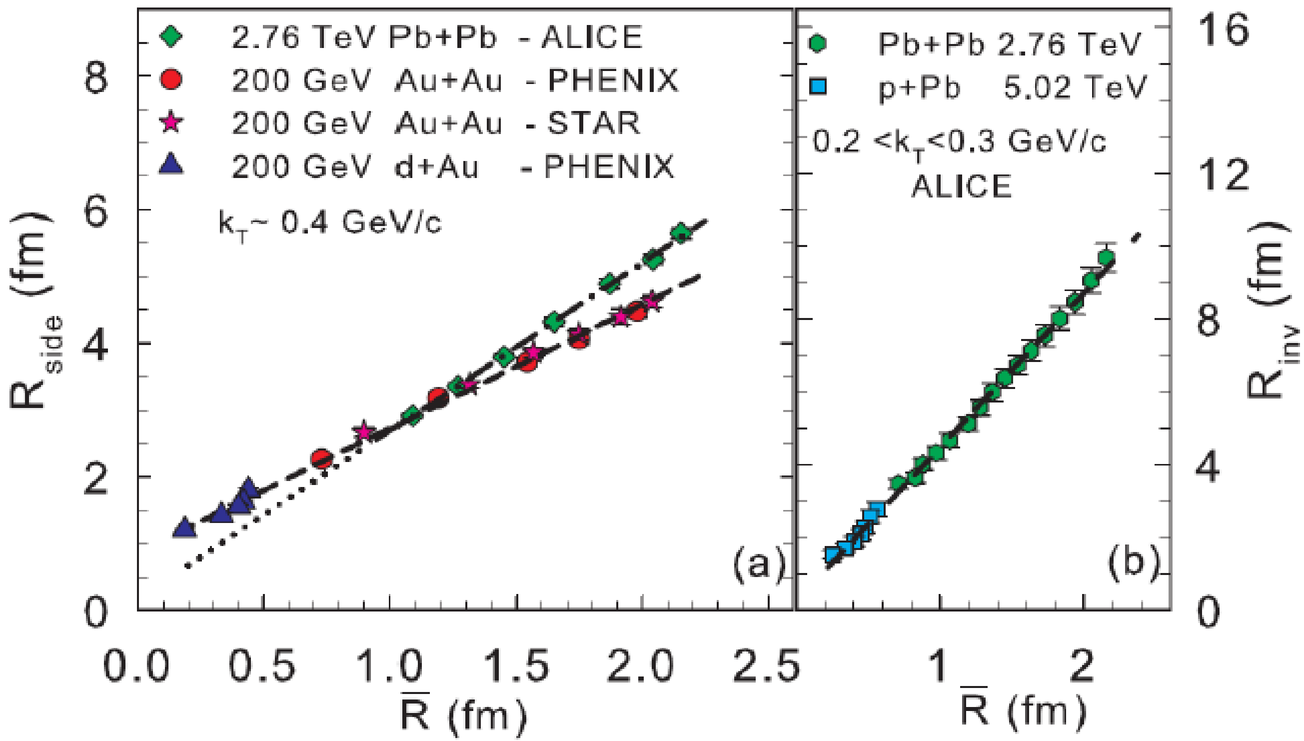
$$R_{out}^2 = \frac{R_{geom}^2}{1+\frac{m_T}{T}\upsilon^2} + \frac{1}{2}\left(\frac{T}{m_T}\right)^2 \beta_T^2 \tau_0^2 \qquad R_{side}^2 = \frac{R_{geom}^2}{1+\frac{m_T}{T}\upsilon^2}$$

$$\frac{R_{out}}{R_{side}} \propto \Delta\tau$$

Similar m_T dependence for Both systems

d+Au indicates a smaller freeze-out volume!

Scaling of the transverse radii



d+Au, Cu+Cu and Au+Au radii scale for the same beam energy

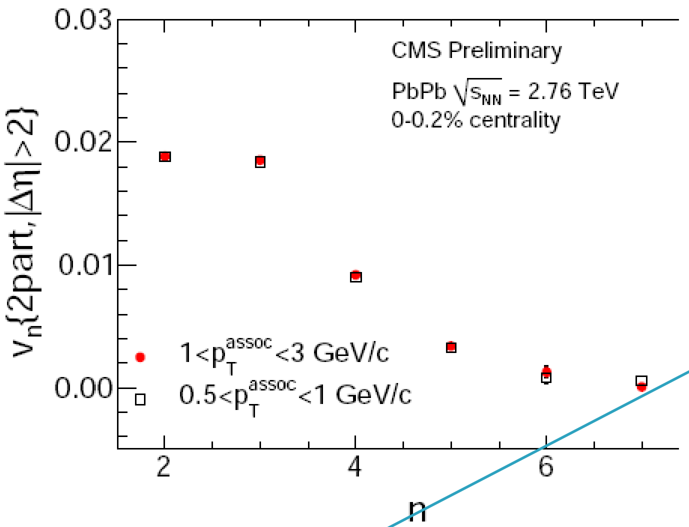
- Expansion dynamics of the d+Au system appears to be strongly influenced by final state effects

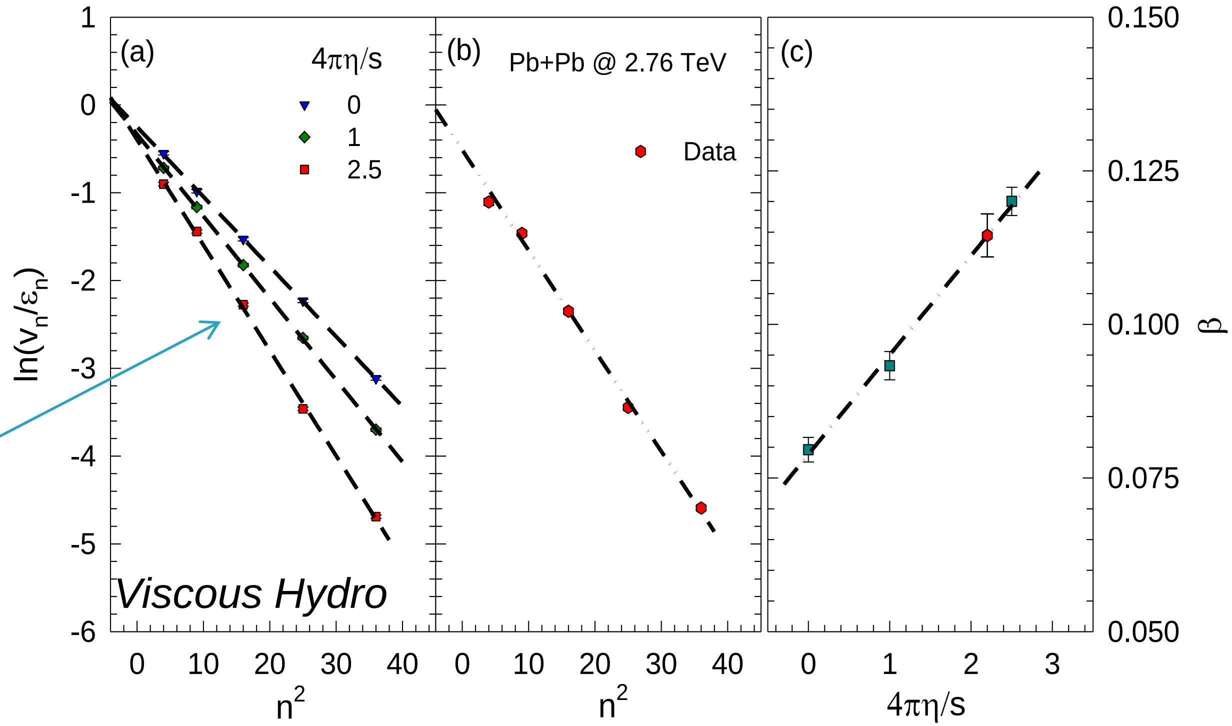
- Larger expansion rate at the LHC

Extraction of η/s

$$\frac{v_n(p_T)}{\varepsilon_n} \propto \cdot \exp\left(-\beta' n^2\right)$$

arXiv:1301.0165 & CMS PAS HIN-12-011





Slope sensitive to η/s

Characteristic n^2 viscous damping validated in viscous hydrodynamics; calibration → 4π*η/s* ~ 2.2 ± 0.2

Extracted η/s value (LHC) insensitive to initial conditions