Extract the QCD speed of sound in the presence of quantum fluctuations

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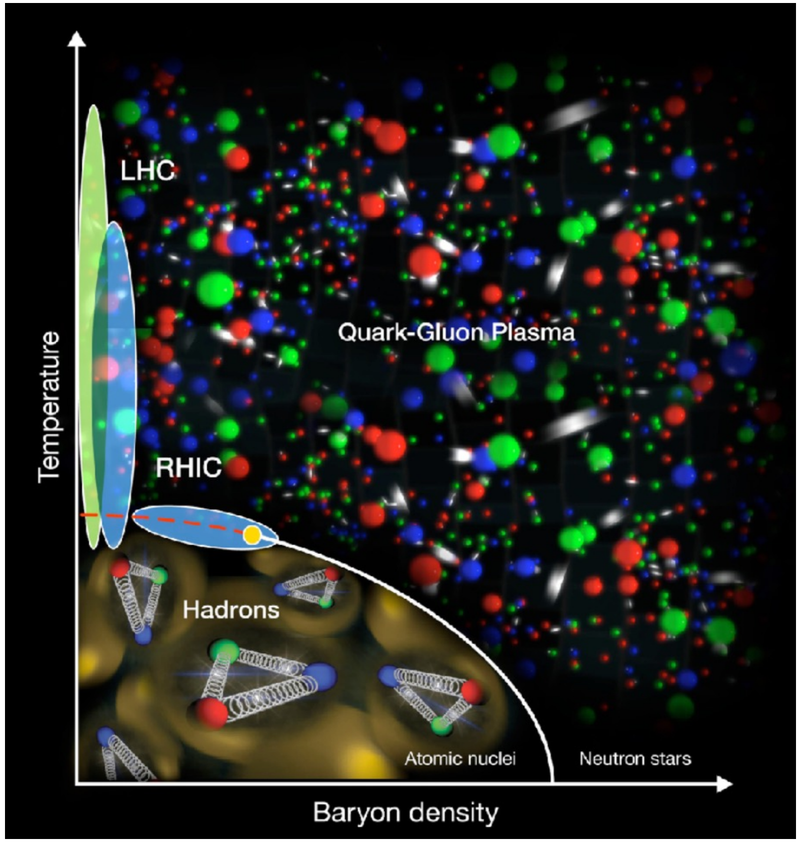
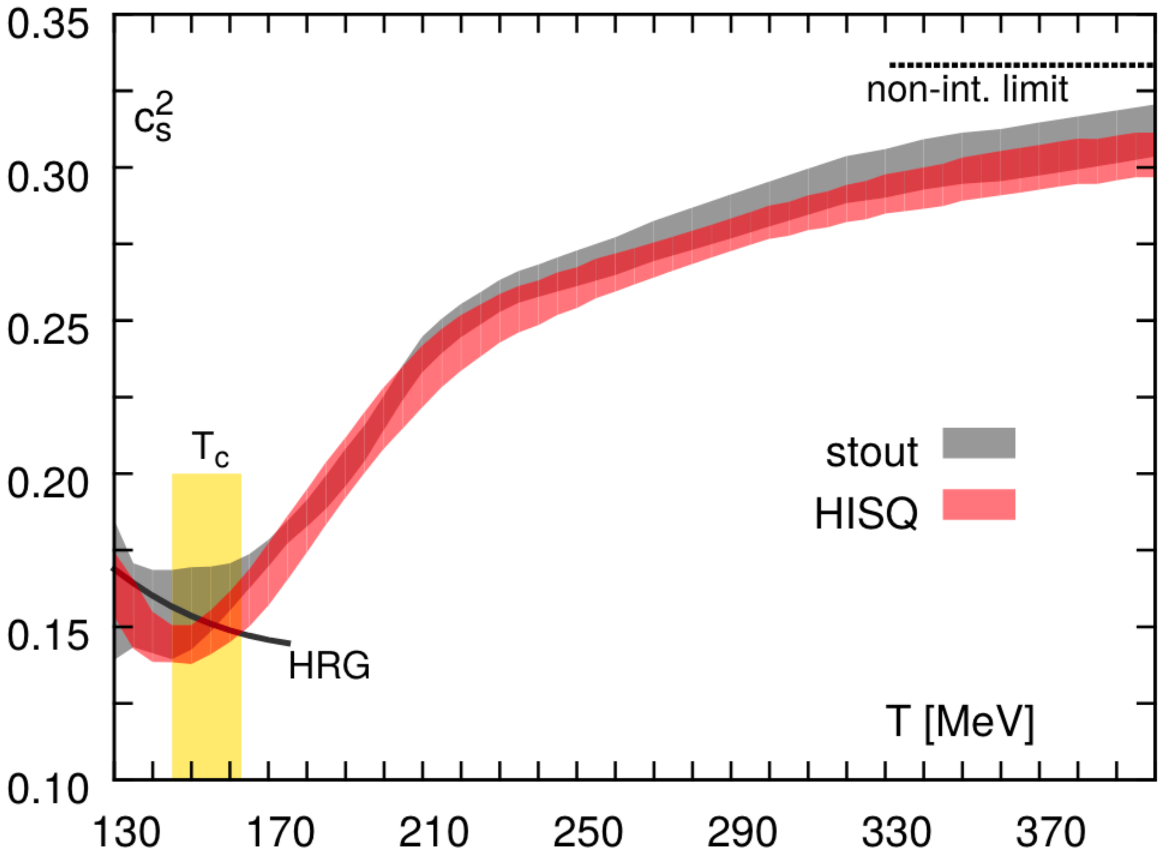
(arXiv:2501.02777)

Relativistic heavy-ion collisions



μ_B=0



A direct measurement of QCD equation of state is challenging in heavy-ion study.

The QCD speed of sound in heavy-ion collisions

$$c_s^2 \equiv \frac{dP}{de} \xrightarrow{dP = s\,dT,\ de = T\,ds} = \frac{d\ln T}{d\ln s} \xrightarrow[s \propto S]{\text{constant volume}} = \frac{d\ln T}{d\ln S} \xrightarrow[d\ln S = d\ln N_{ch},\ d\ln T = d\ln\langle p_T\rangle]{S \propto N_{ch},\ T \propto \langle p_T\rangle} = \frac{d\ln\langle p_T\rangle}{d\ln N_{ch}}$$

nature physics

LETTERS

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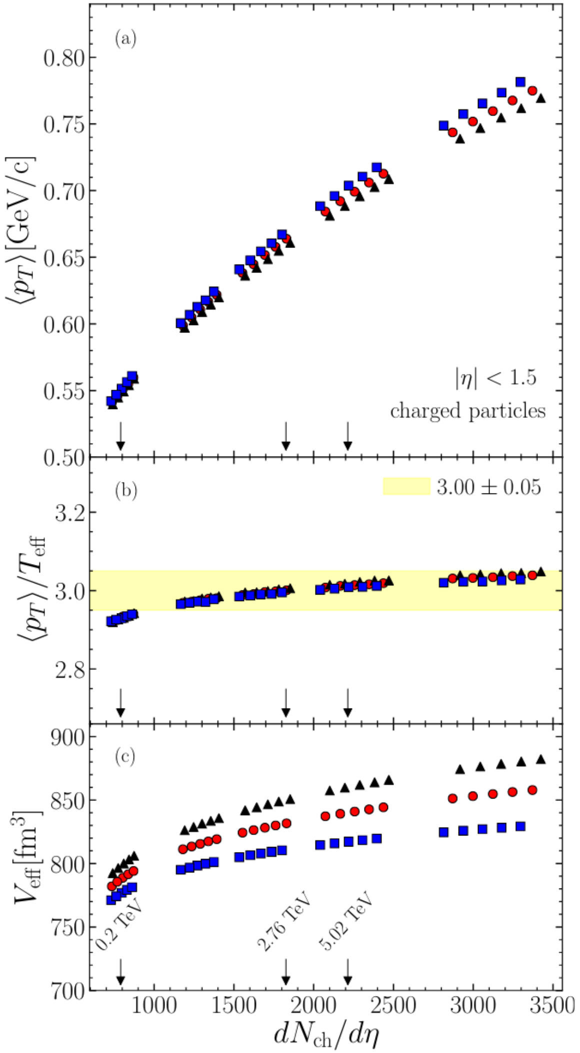
Thermodynamics of hot strong-interaction matter from ultrarelativistic nuclear collisions

Fernando G. Gardim[1,2], Giuliano Giacalone[2], Matthew Luzum[3] and Jean-Yves Ollitrault[2]✉

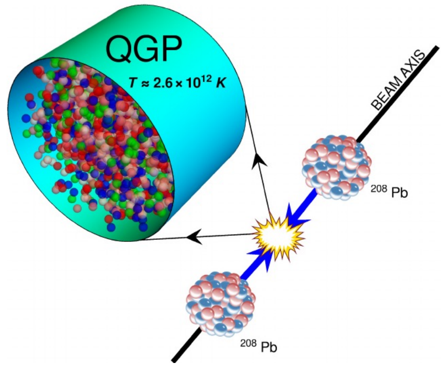
Effective temperature and effective volume



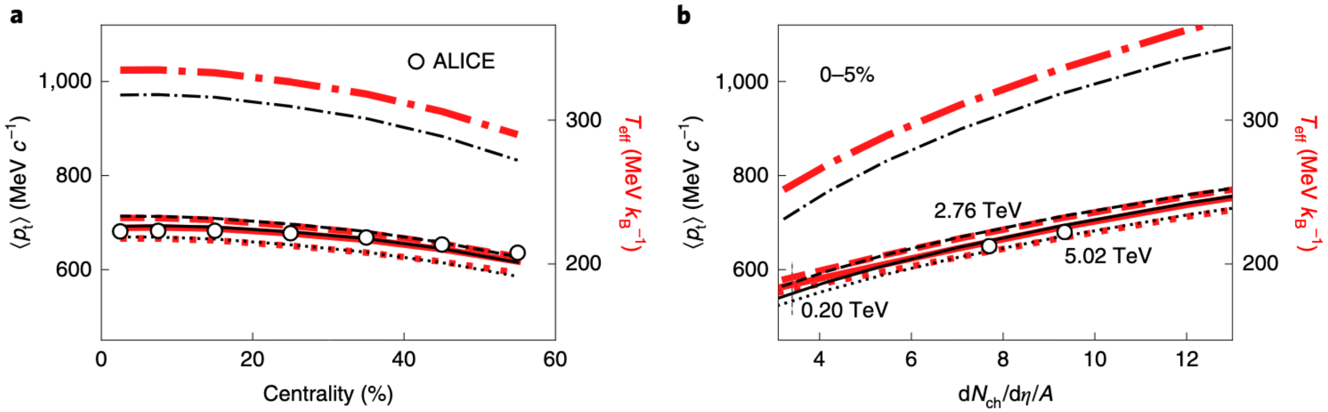
- A uniform fluid at rest with $\mathrm{T_{eff}}$ and $\mathrm{V_{eff}}$:

$$E = \int_{\rm f.o.} T^{0\mu} d\sigma_\mu = \epsilon(T_{\rm eff}) V_{\rm eff}$$

$$S = \int_{\rm f.o.} s u^\mu d\sigma_\mu = s(T_{\rm eff}) V_{\rm eff}$$

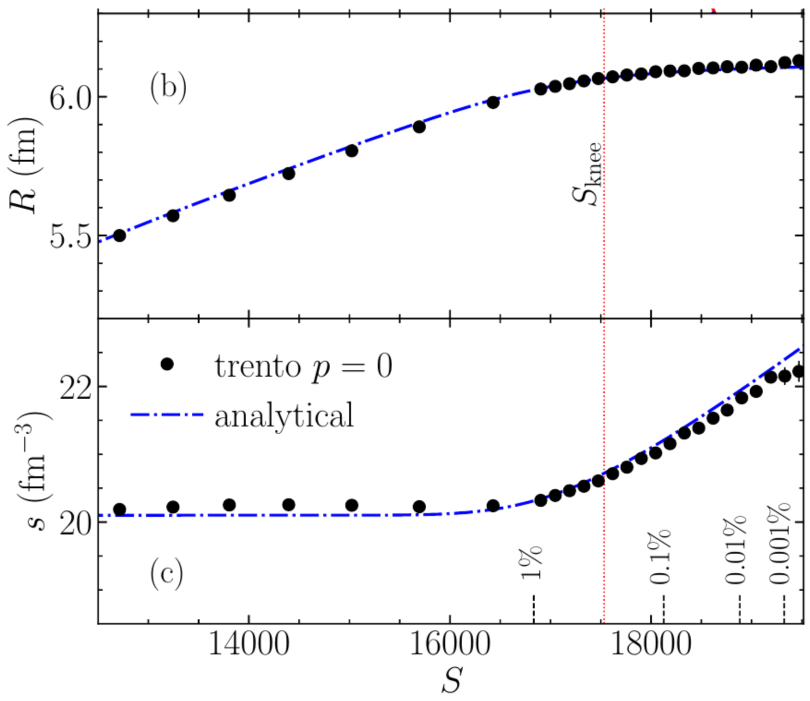


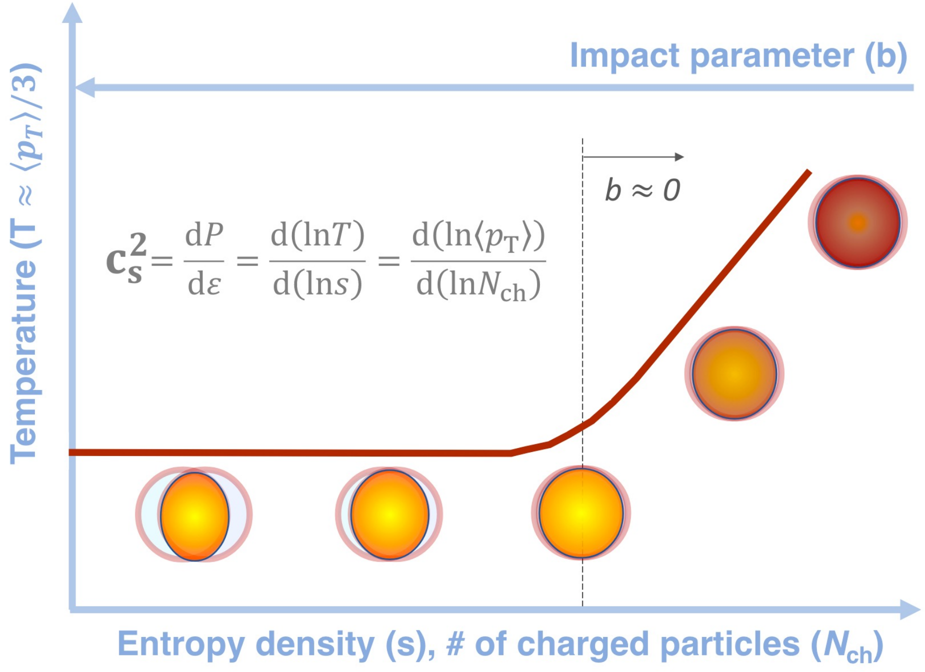
- In boost-invariant fluid, $\langle p_T \rangle \approx 3\, T_{\rm eff}$



[F. Gardim et al , 2403.06052]

Ultra-central nucleus-nucleus collisions (UCC)





[F. Gardim et al , 1909.11609]

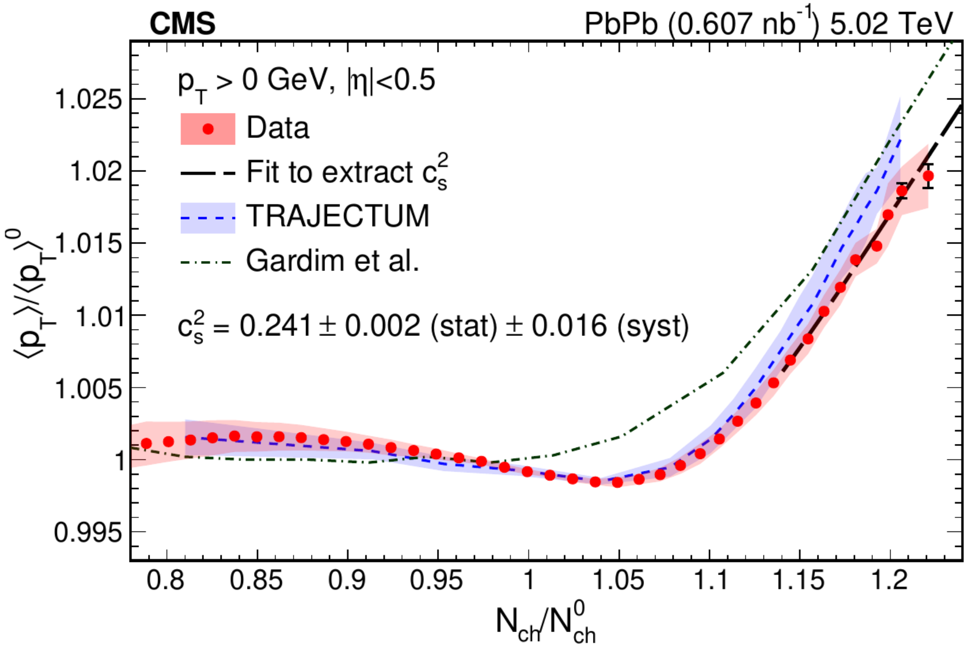
- S_{knee} is the mean value of the entropy at b = 0.
- The volume is fixed in UCC events.
- The differences in N_{ch} and T are driven by fluctuations.

Extract the speed of sound in experiments

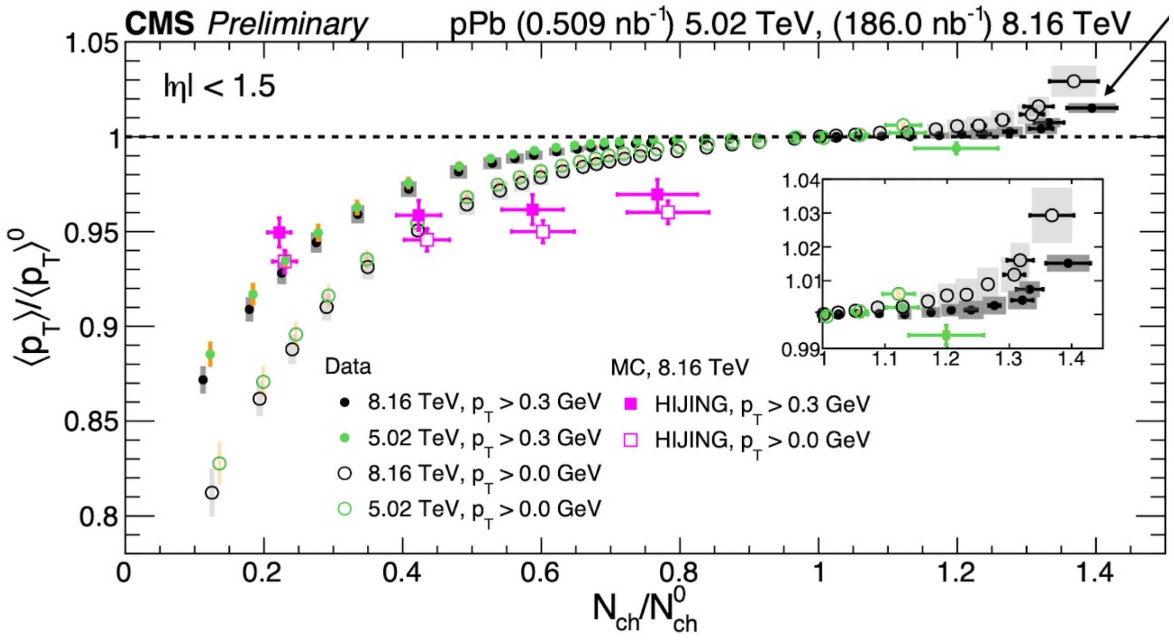
$$c_s^2 = \frac{d\ln\langle p_t\rangle}{d\ln N_{\rm ch}} \rightarrow \frac{\Delta_p}{\langle p_T\rangle_0} = c_s^2\frac{\Delta_N}{N_0} \quad \text{with} \begin{cases} \Delta_p \equiv \langle p_T\rangle - \langle p_T\rangle_0 \\ \Delta_N \equiv N_{ch} - N_0 \end{cases}$$

where $\langle p_T\rangle_0$ and N_0 are the averaged values over the ultra-central events

[CMS collaboration, 2401.06896]

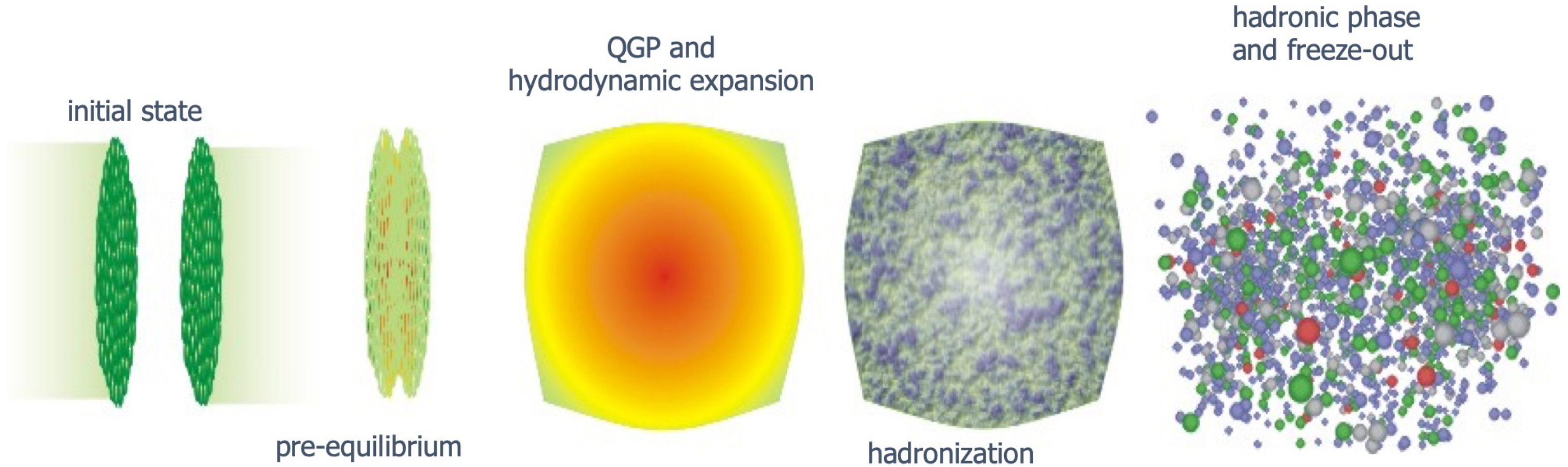


[CMS collaboration, QM2025]



Two sets of model studies

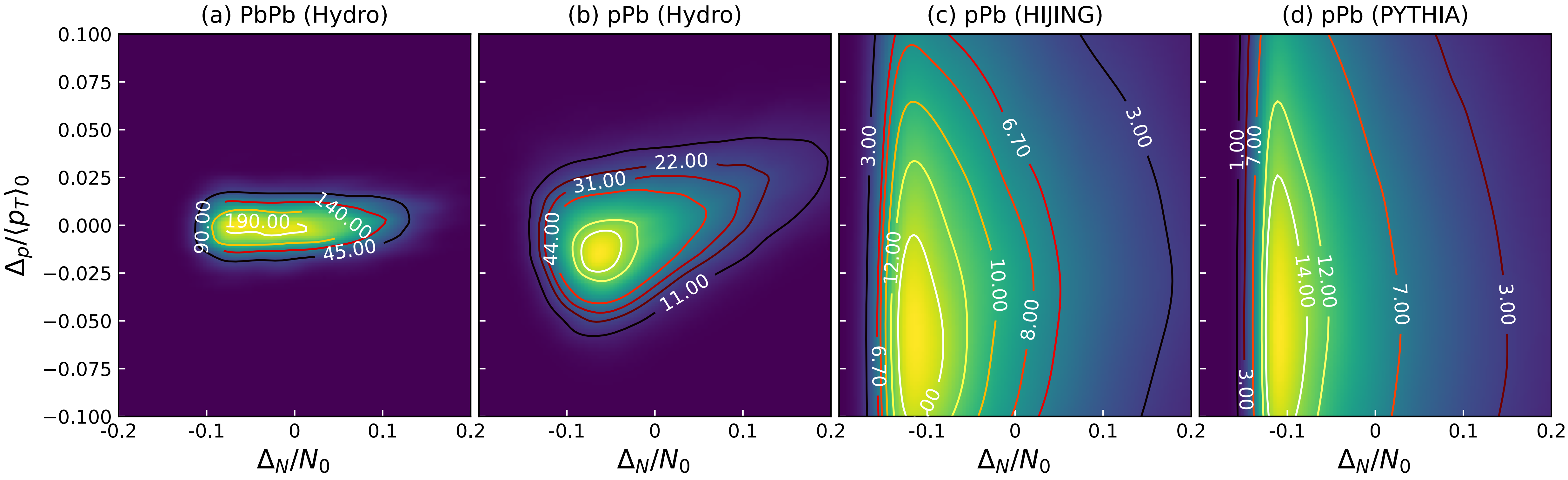
- Thermal model



$\underbrace{\hspace{6em}}_{\text{TRENTo}}$ + $\underbrace{\hspace{6em}}_{\text{MUSIC}}$ + $\underbrace{\hspace{10em}}_{\text{UrQMD}}$

- Non-thermal model HIJING, Pythia

Quantum fluctuations in realistic collisions



The presence of quantum fluctuations leads to 2D distribution of Δ_N and Δ_p.

Extracting the speed of sound in the presence of quantum fluc.

- In a thermalized system,

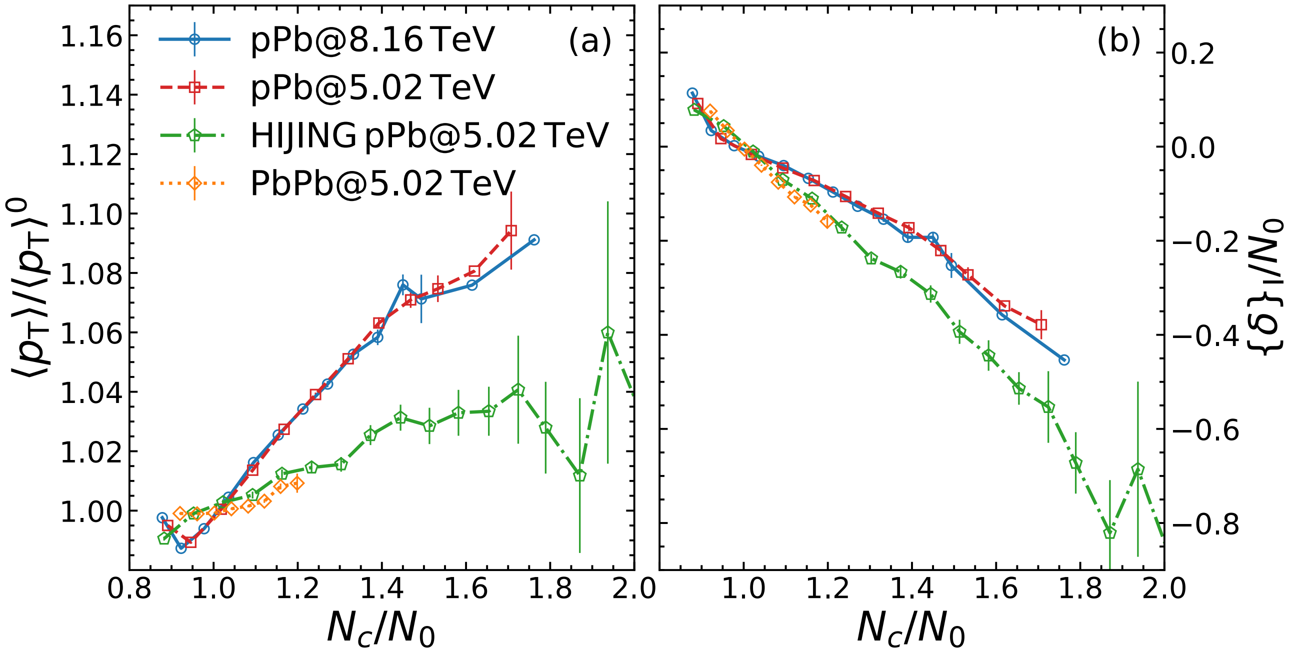
$$\frac{\Delta_p}{\langle p_T\rangle_0} = c_s^2 \frac{\Delta_N + \delta}{N_0} \longrightarrow \delta = \frac{N_0}{c_s^2 \langle p_T\rangle_0}\Delta_p - \Delta_N$$

- δ denotes a quantum contribution.
- The distribution of δ is Gaussian according to Central Limit Theorem (CLT).
- Zero skewness condition: $\{\delta^3\}_c = 0$

$$(c_s^2)^3 \underline{\frac{\{\Delta_N^3\}}{N_0^3}} - 3(c_s^2)^2 \underline{\frac{\{\Delta_N^2 \Delta_p\}}{N_0^2 \langle p_T\rangle_0}} + 3c_s^2 \underline{\frac{\{\Delta_N \Delta_p^2\}}{N_0 \langle p_T\rangle_0^2}} - \underline{\frac{\{\Delta_p^3\}}{\langle p_T\rangle_0^3}} = 0$$

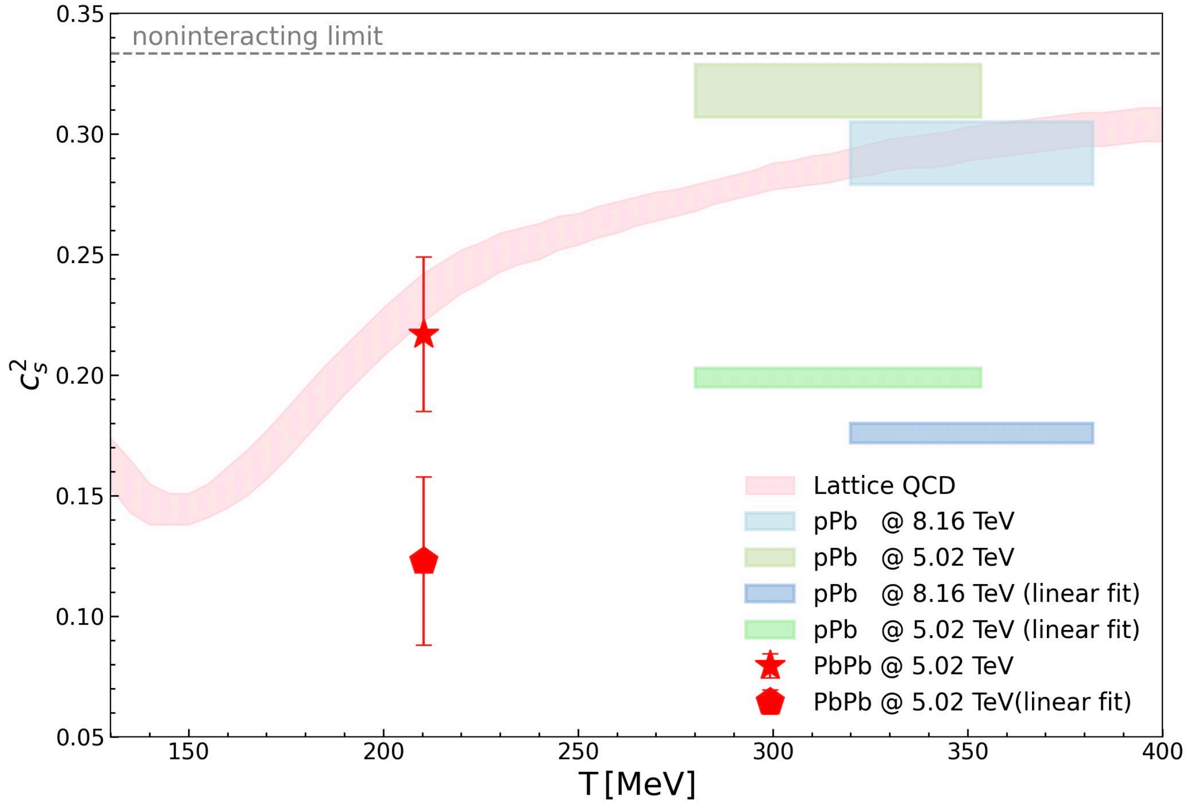
mixed skewness of $\langle p_T\rangle$ and N_{ch}
which can be measured in experiments

Quantum fluctuations are anti-correlated with N_{ch}



- $\frac{\{\Delta_p\}_I}{\langle p_T \rangle_0} = c_s^2 \frac{\{\Delta_N\}_I + \{\delta\}_I}{N_0}$
- $\{\delta\}_I = -\alpha \{\Delta_N\}_I$ which leads to $c_s^2 \to c_s^2 - \alpha$.
- The slope from simple linear fit can be suppressed by the quantum fluctuations.

Extracted speed of sound from different methods



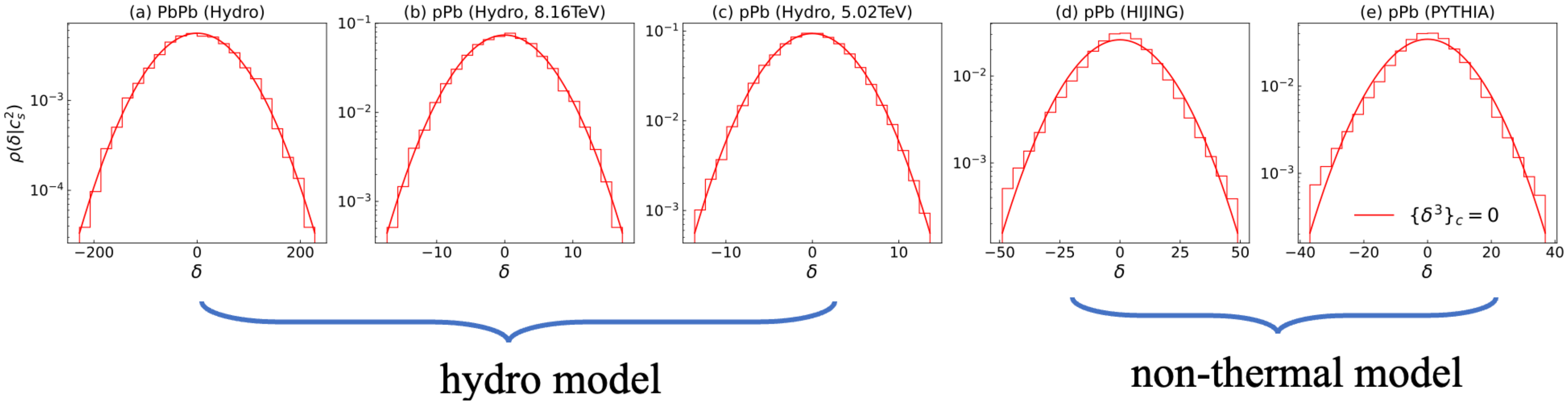
c_s^2	Sub-bin slope	$\{\delta^3\}_c = 0$	$\{\delta^5\}_c = 0$	LEOS	T_{eff} (MeV)
PbPb (Hydro, 5.02 TeV)	0.123 ± 0.035	0.217 ± 0.032	0.216 ± 0.041	0.222–0.242	210.3
pPb (Hydro, 8.16 TeV)	0.176 ± 0.004	0.292 ± 0.013	0.287 ± 0.012	0.282–0.309	319.9–382.1
pPb (Hydro, 5.02 TeV)	0.197 ± 0.004	0.318 ± 0.011	0.313 ± 0.008	0.269–0.304	280.2–353.4

Probe of thermalization

- δ behaves differently in thermalized and non-thermalized systems.

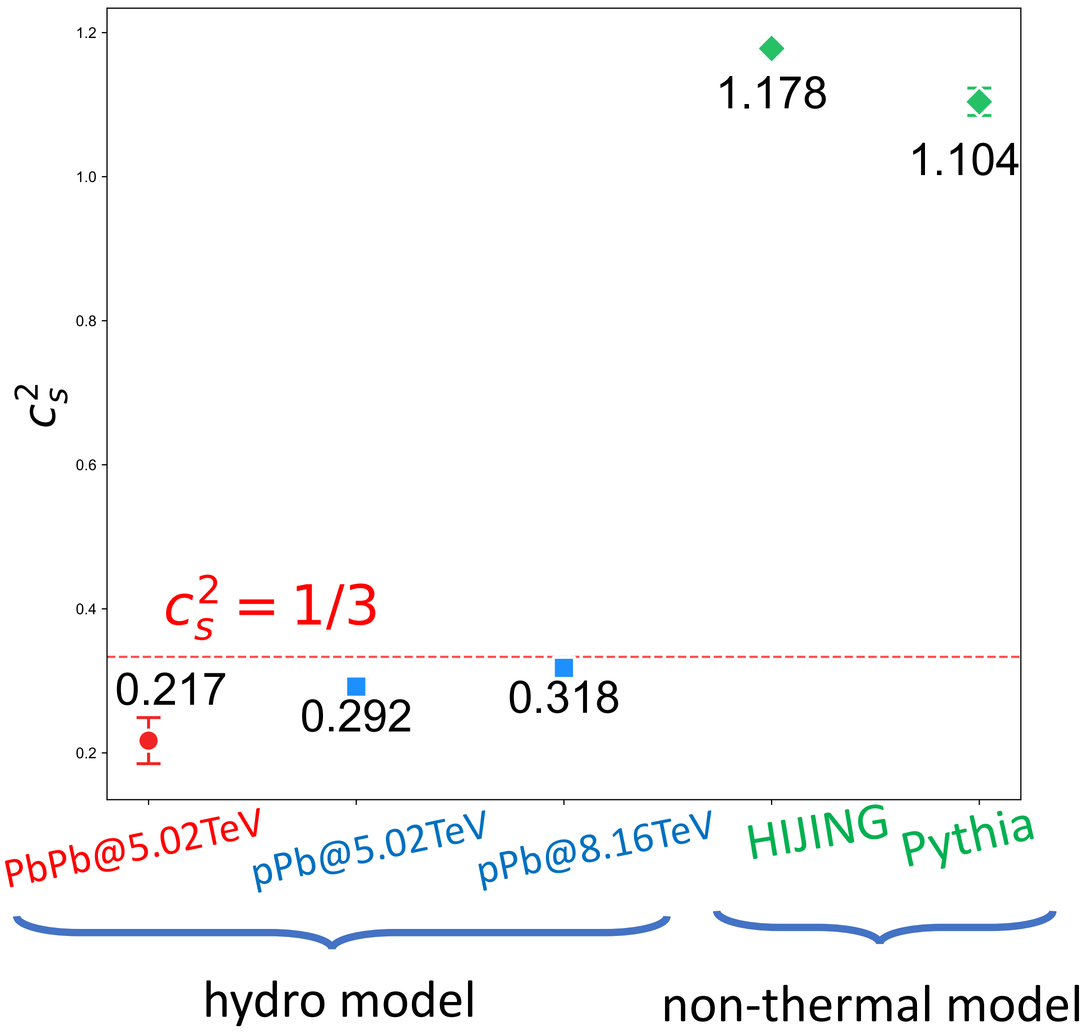
Thermalized system: $$\frac{\Delta_p}{\langle p_T \rangle_0} = c_s^2 \frac{\Delta_N + \delta}{N_0}$$ → thermal response + quantum noise

Non-thermalized system: $$\frac{\Delta_p}{\langle p_T \rangle_0} = \kappa \frac{\Delta_N + \delta}{N_0}$$ → quantum response + quantum noise



Probe of thermalization

- The extracted value is physical only in thermalized systems.

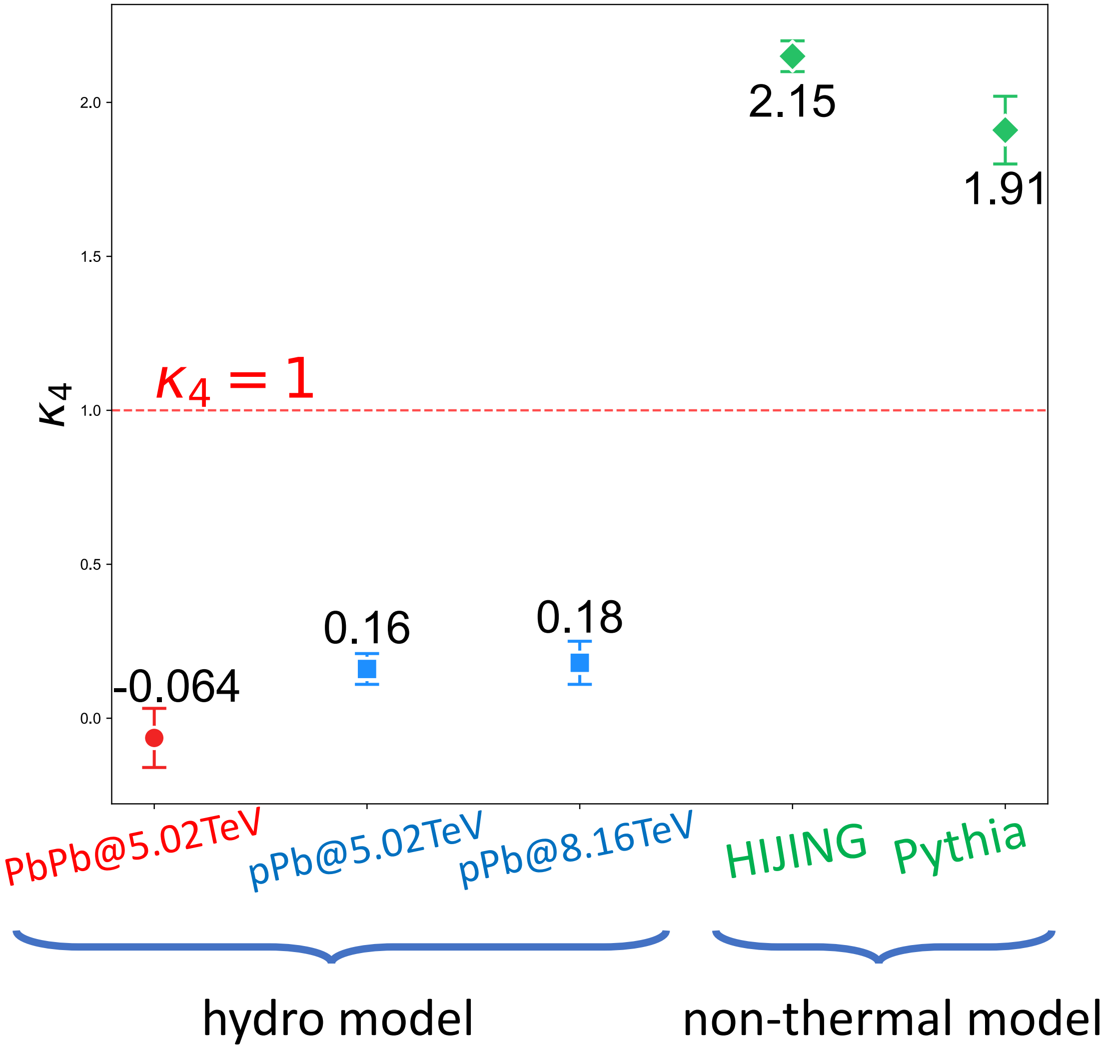


Thermalized system: $\frac{\Delta_p}{\langle p_T \rangle_0} = c_s^2 \frac{\Delta_N + \delta}{N_0}$

Non-thermalized system: $\frac{\Delta_p}{\langle p_T \rangle_0} = \kappa \frac{\Delta_N + \delta}{N_0}$

Probe of thermalization

- Deviations from thermalization can be quantified by the standardized kurtosis



$$\kappa_4 = \frac{\{\delta^4\}}{\{\delta^2\}^2} - 3$$

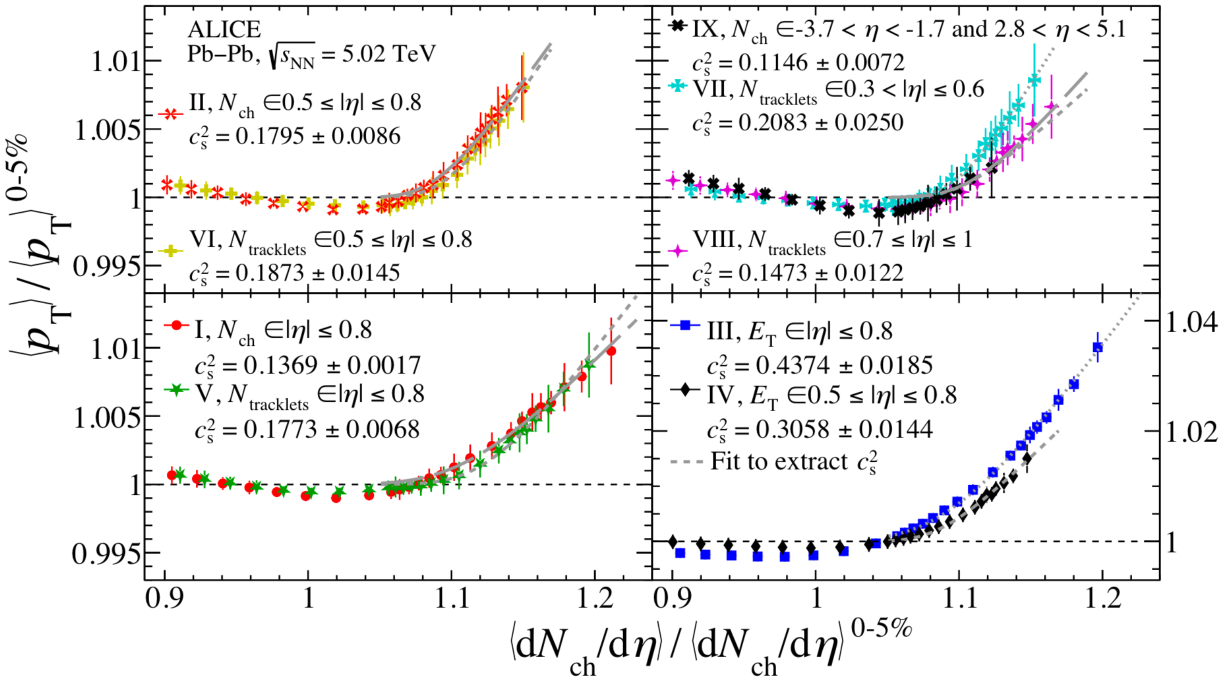
$$\begin{cases} 0\text{: absolute thermalization} \\ [0,1]\text{ : partial thermalization} \\ \gg 1\text{ : non-thermal} \end{cases}$$

Summary

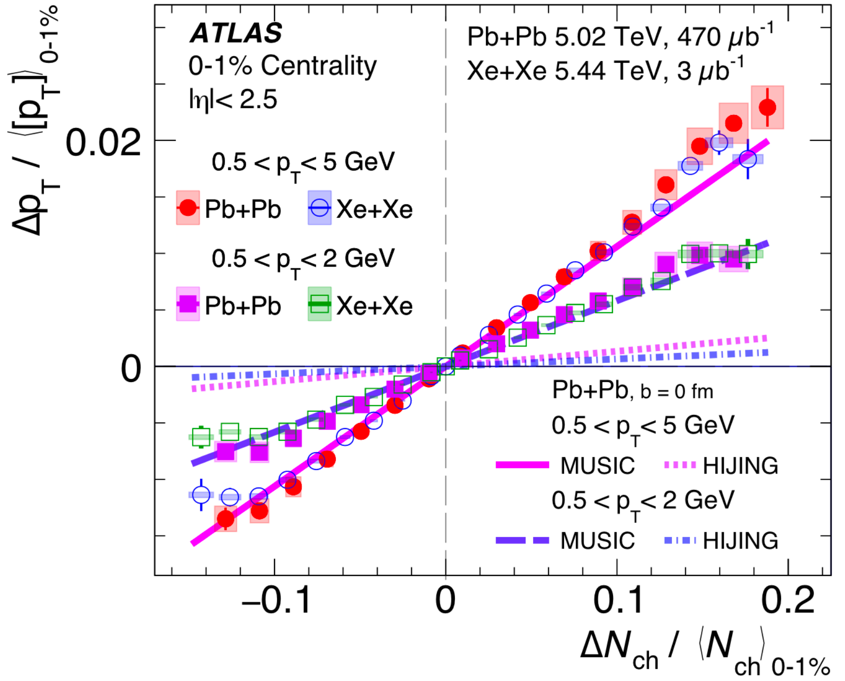
- The QCD speed of sound can be extracted even in the presence of quantum fluctuations;
- Thermalization can be probed by examining the Gaussianity of quantum fluctuation δ and the physical validity of the extracted speed of sound, which can be quantified by the standardized kurtosis of δ.

Back up

[ALICE collaboration, 2506.10394]



[ATLAS collaboration, 2407.068413]



The extracted value depends on kinematic cut and centrality estimators