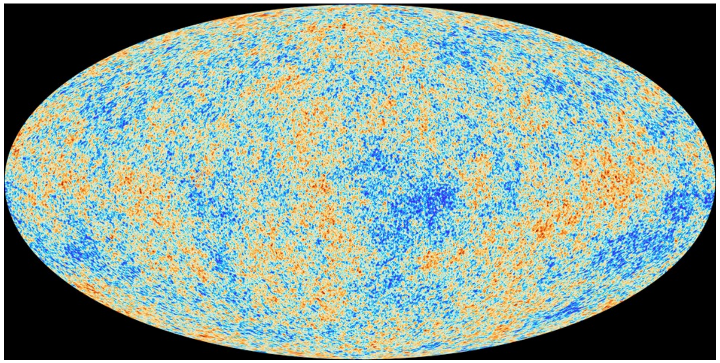
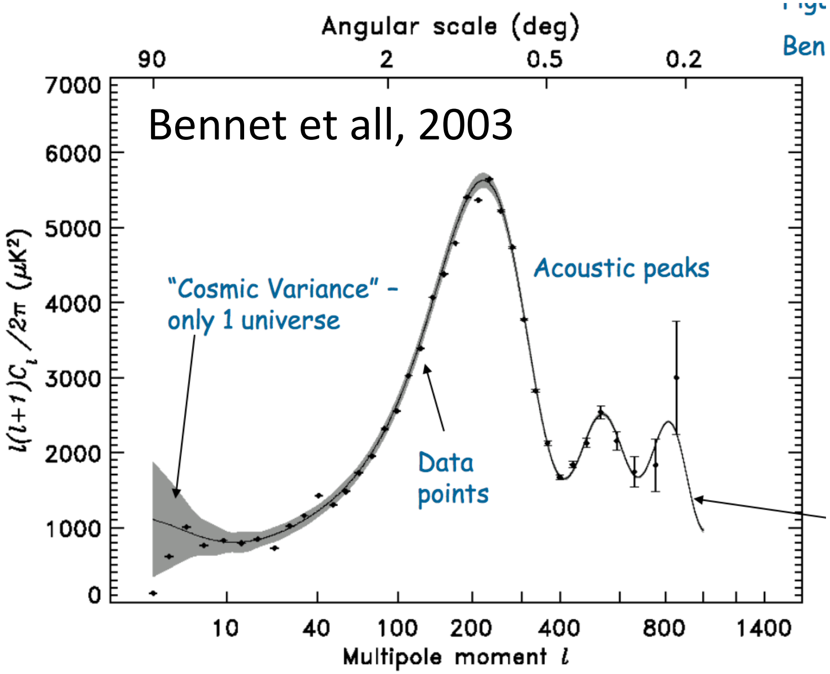
Measuring the speed of sound in the QGP with CMS

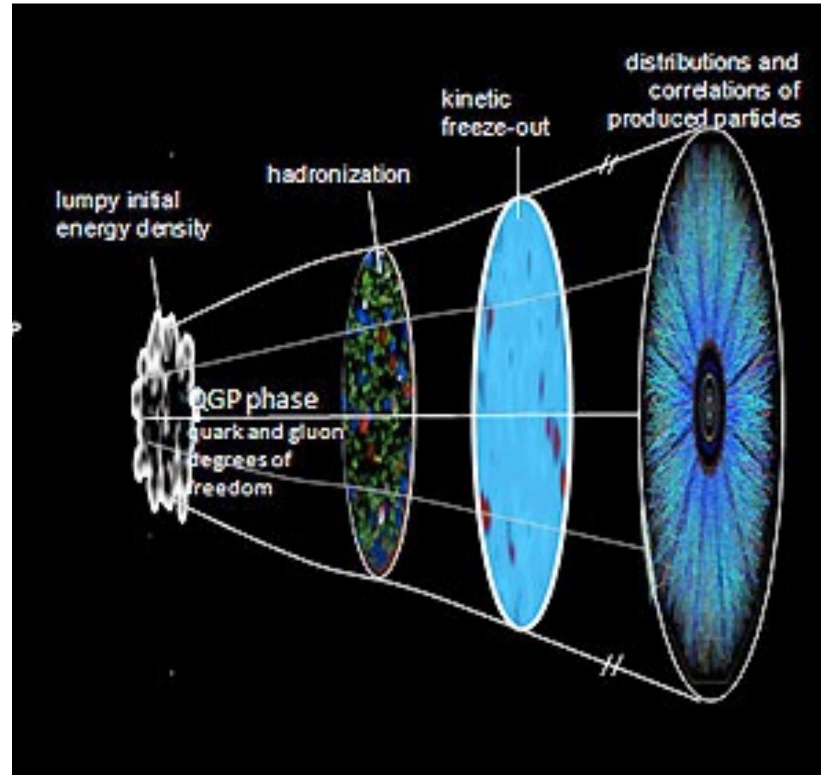
https://arxiv.org/abs/2401.06896

Michael Murray, SQM 2024 4th June 2024

Density variations drive sound waves







1. **Can we hear the QGP?**
2. **What can the sound tell us?**

Speed of sound depends upon medium

Speed of sound depends upon relation of pressure to energy density

$$c_s^2 = \frac{dP}{d\varepsilon}$$

Sound travels faster in stiffer materials

What if c_s^2 is negative?

- When $c_s^2 > 0$ sound propagates as sin(x-c_st)
- If $c_s^2 < 0$ sound propagates as shin(x-c_st) and we get spinodal decomposition, See Zhang & Li https://arxiv.org/abs/2208.00321v2

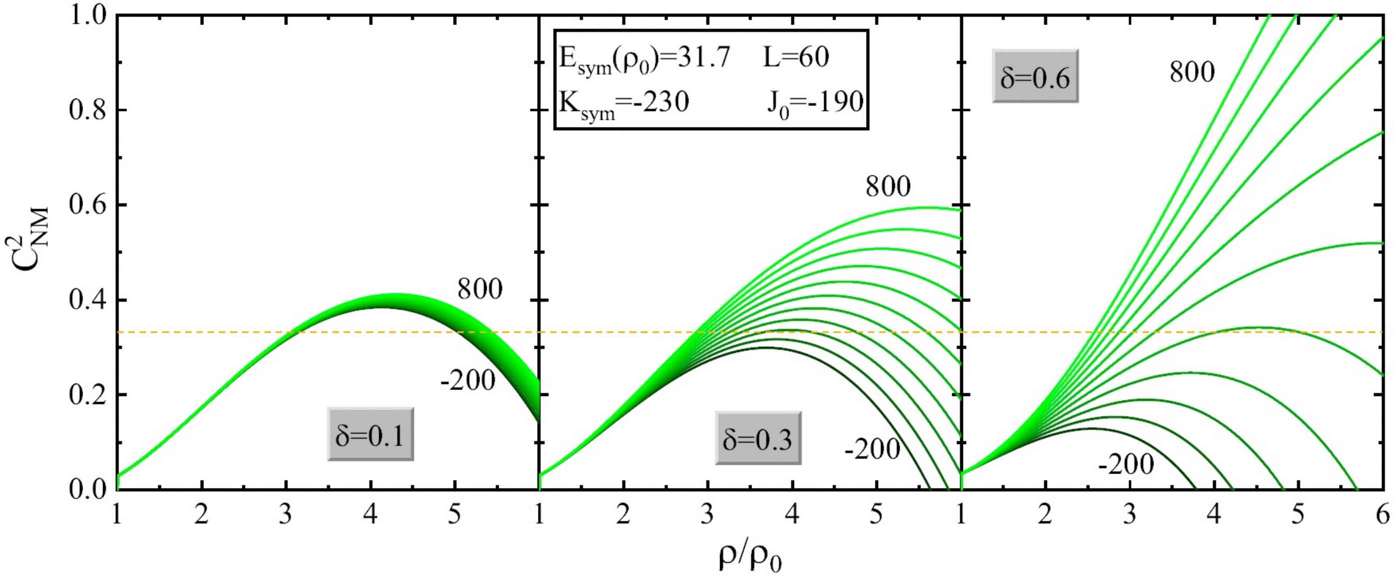
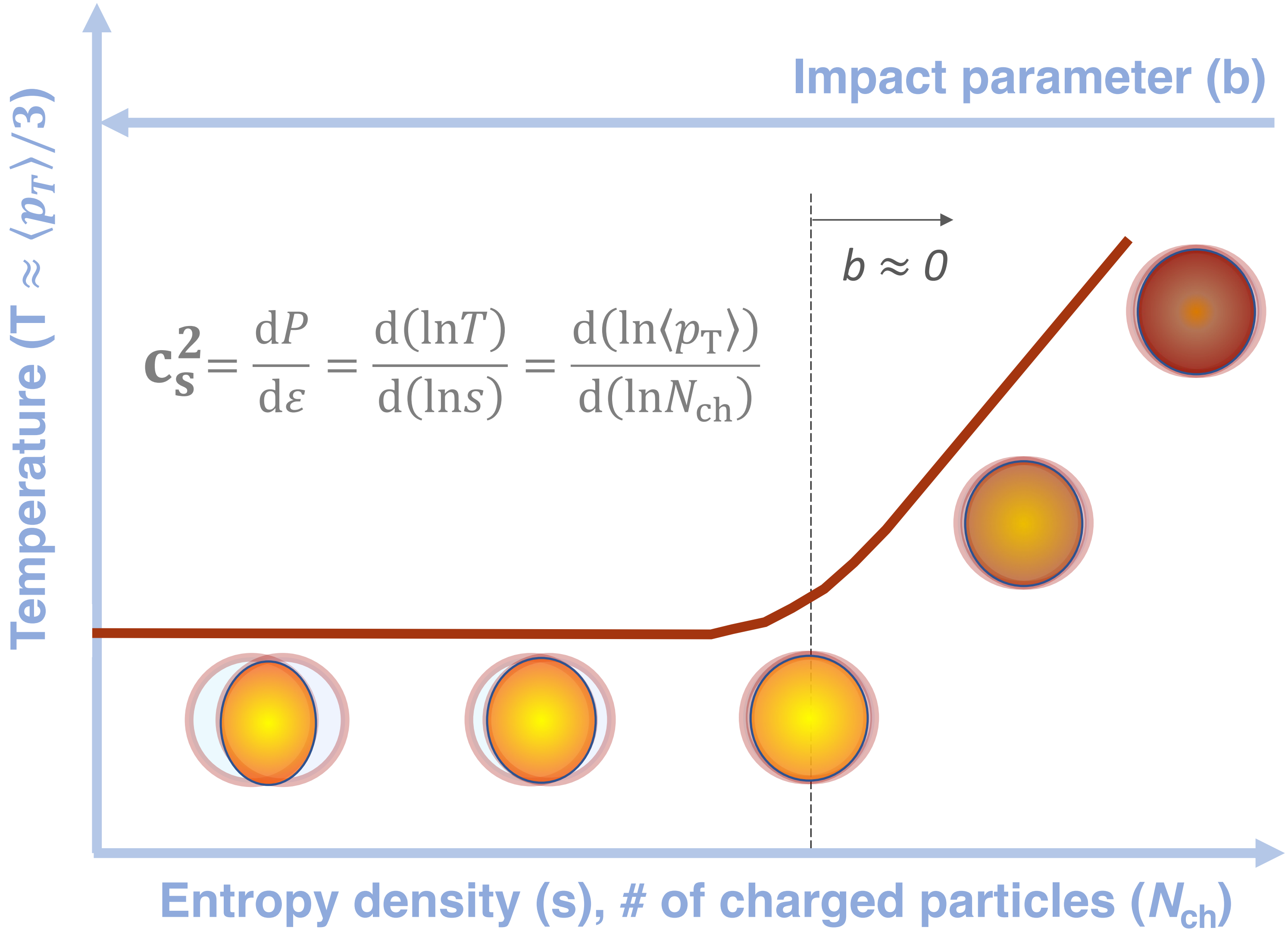


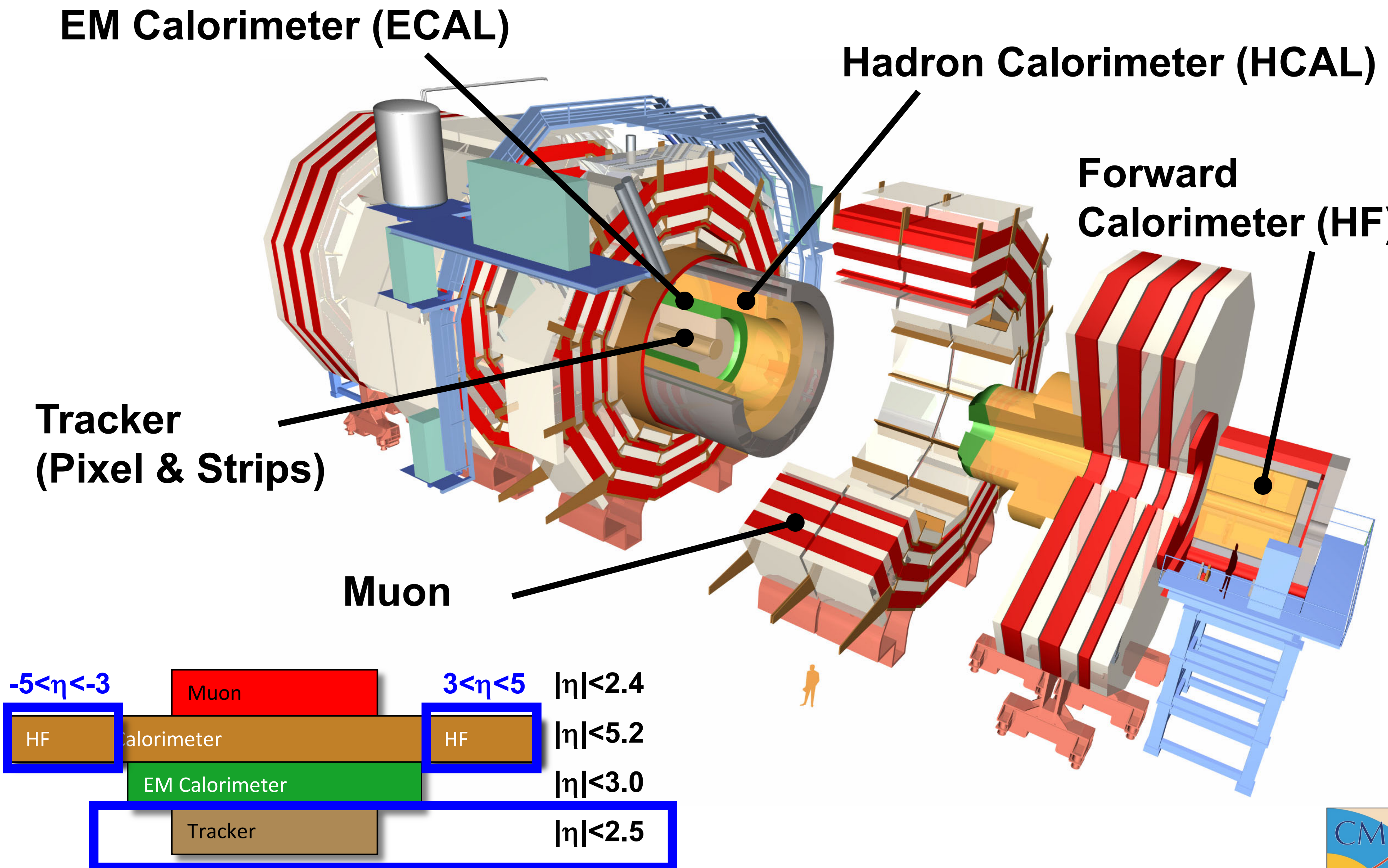
Fig. 3. The speed of sound C^2_{NM} in unit of c^2 in nucleonic matter with fixed isospin asymmetries as a function of density using the symmetry energy $E_{\rm sym}(\rho)$ functions with $J_{\rm sym}$ varying between -200 and 800 MeV as shown in the right panel of Fig. 2. The orange dashed line corresponds to the conformal limit $C^2 < 1/3$.

Use multiplicity & p_T to measure c_s



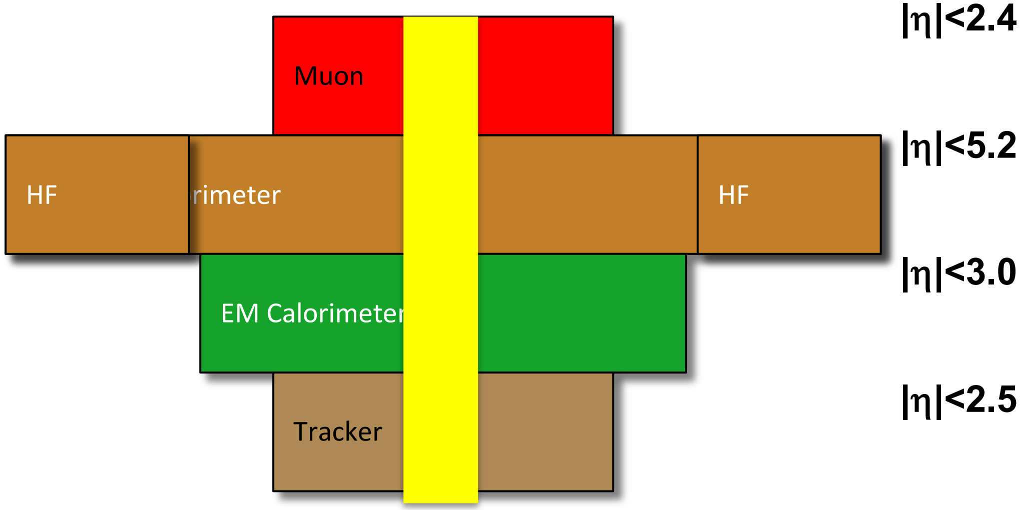
F. G. Gardim, G. Giacalone, and J.-Y. Ollitrault, doi:10.1016/j.physletb.2020.135749, arXiv:1909.11609.

The Compact Muon Solenoid



Estimating entropy and temperature

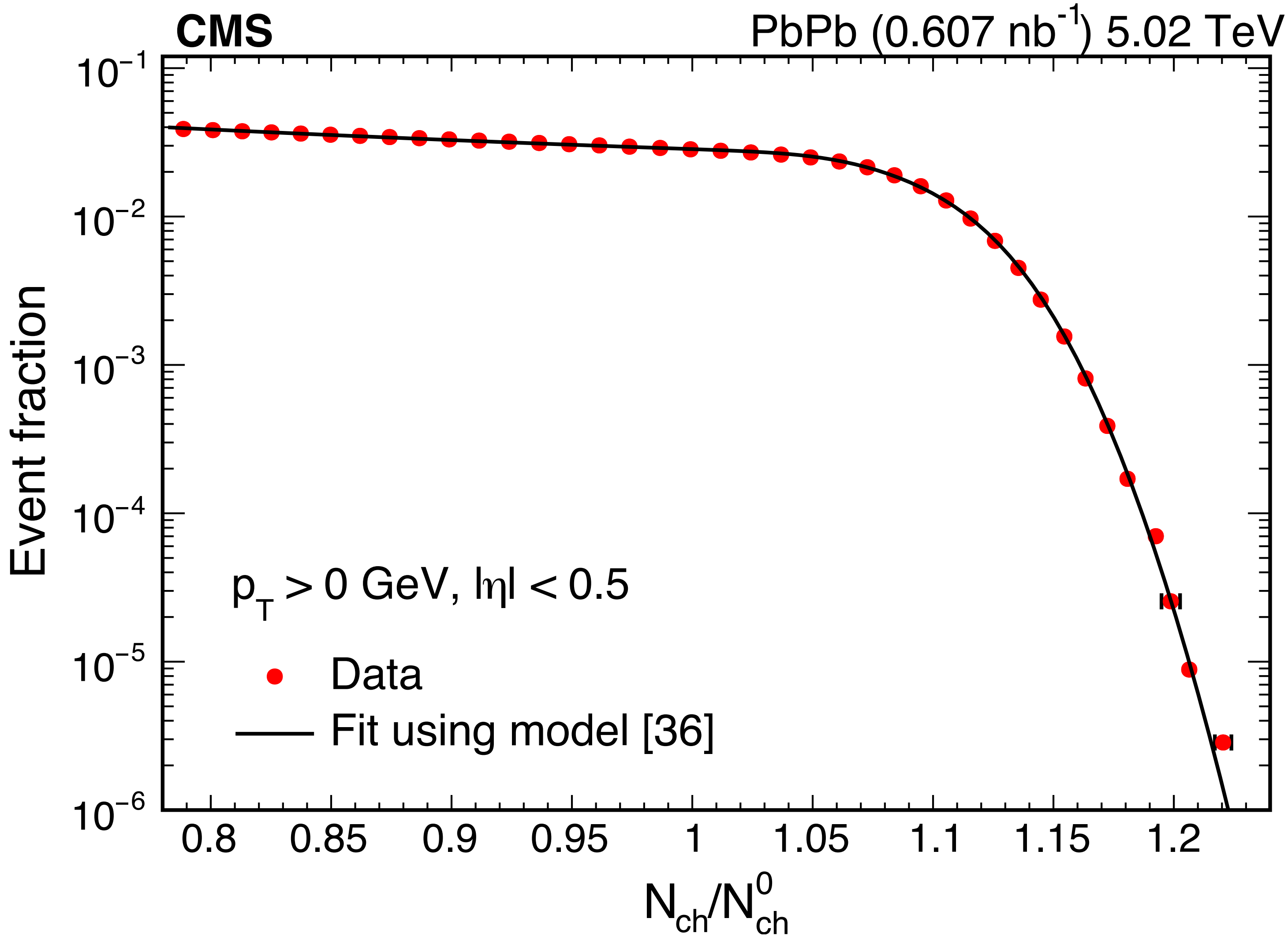
- The multiplicity of the system s ∝ multiplicity
- Temperature ∝ p_T
- Select PbPb events with HF forward calorimeters
- Measure spectra for tracks with $|\eta|<0.5$
- Extrapolate p_T spectra to $p_T = 0$ in small bins of HF
- Fit spectra with Hagadorn function to get $<p_T>$, N_{ch}



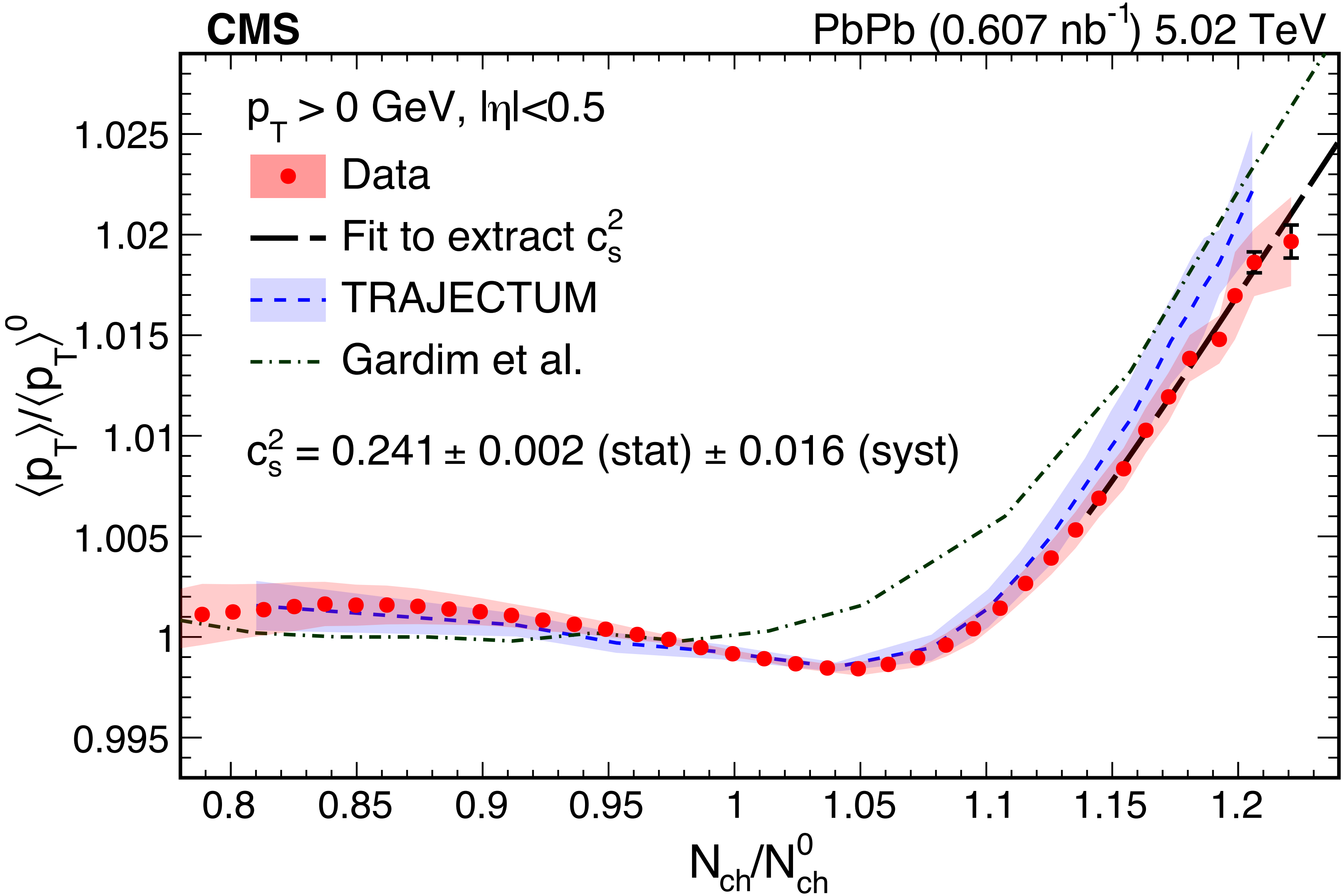
Minimizing systematics

- Since we only need to know the logarithm of the multiplicity and $\langle p_T \rangle$ we can reduce our systematics by normalizing these variables to their values for 0-5% central events
- N_{ch}^0 = multiplicity for 0-5% centrality
- $\langle p_T \rangle^0$ = mean p_T for 0-5% centrality
- Temperature estimated by $\langle p_T \rangle/3$

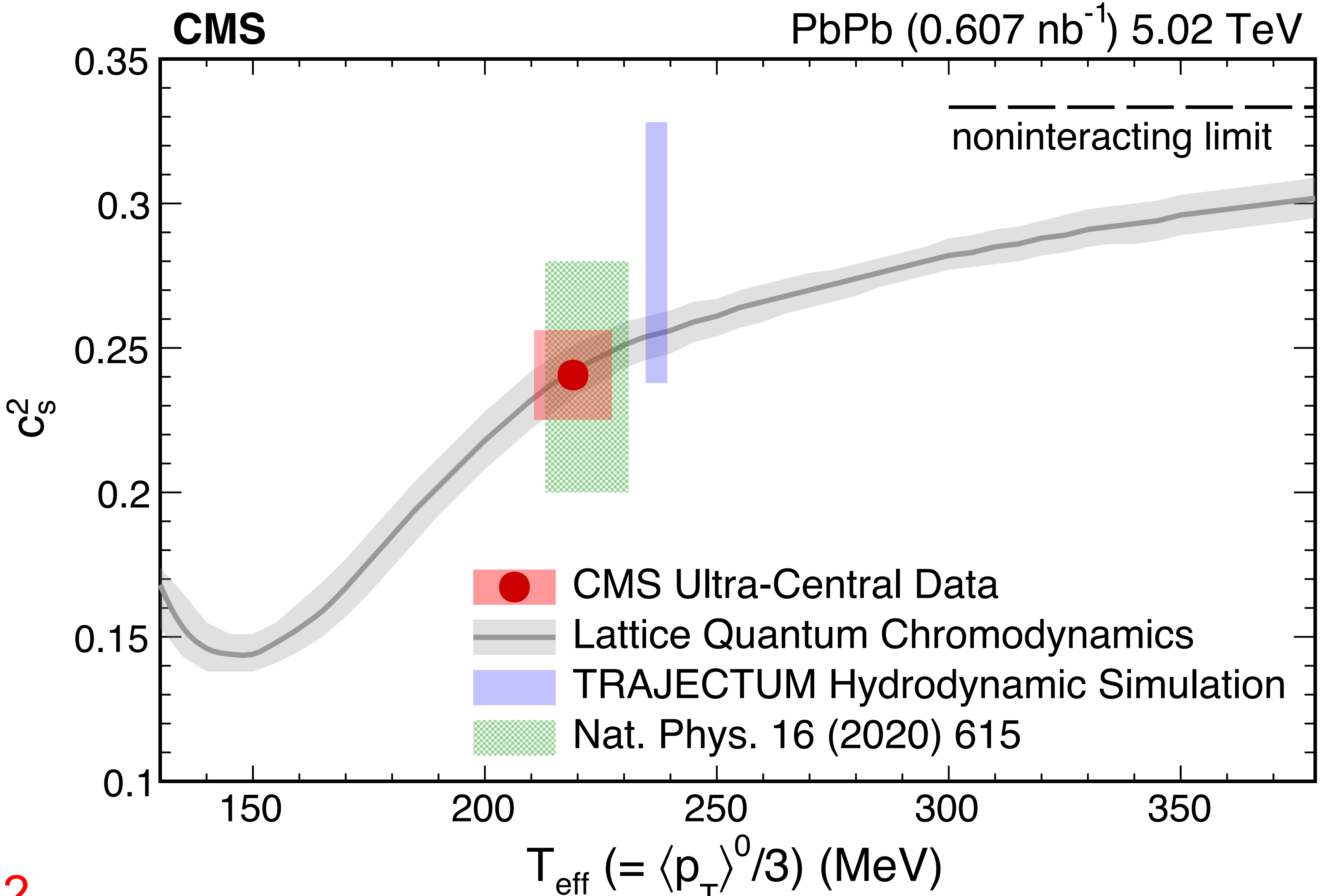
Look on tails of multiplicity distribution



Correlate average p_T with multiplicity



Starting to map c_s^2 versus temperature



Conclusions

- $C_s^2 = 0.241 \pm 0.002$ (stat) $\pm\ 0.016$ (sys)
- Data in good agreement with lattice QCD
- It would be very interesting to look at lower energy data to map the temperature dependence of the speed of sound.

Backup

Extracting the speed of sound

To extract the speed of sound, the expression that describes $\langle p_{\mathrm{T}} \rangle^{\mathrm{norm}}$ as a function of $N_{\mathrm{ch}}^{\mathrm{norm}}$ is taken from Ref. [16], as

$$\langle p_{\mathrm{T}} \rangle^{\mathrm{norm}} = \left(\frac{N_{\mathrm{ch}}^{\mathrm{norm}}}{\langle \overline{N_{\mathrm{ch}}^{\mathrm{knee}}} | N_{\mathrm{ch}}^{\mathrm{norm}} \rangle} \right)^{c_s^2}, \tag{2}$$

where,

$$\langle \overline{N_{\mathrm{ch}}^{\mathrm{knee}}} | N_{\mathrm{ch}}^{\mathrm{norm}} \rangle = N_{\mathrm{ch}}^{\mathrm{norm}} - \sigma \sqrt{\frac{2}{\pi}} \frac{\exp\left(-\frac{(N_{\mathrm{ch}}^{\mathrm{norm}} - \overline{N_{\mathrm{ch}}^{\mathrm{knee}}})^2}{2\sigma^2} \right)}{\mathrm{erfc}\left(\frac{N_{\mathrm{ch}}^{\mathrm{norm}} - \overline{N_{\mathrm{ch}}^{\mathrm{knee}}}}{\sqrt{2}\sigma} \right)}. \tag{3}$$

Here, $\overline{N_{\mathrm{ch}}^{\mathrm{knee}}}$ and σ represent the mean and root-mean-square width of the charged-particle multiplicity distribution at $b = 0$, normalized by N_{ch}^{0}. In Fig. 2, the $\overline{N_{\mathrm{ch}}^{\mathrm{knee}}}$ value corresponds to the vicinity of the location beyond which the knee-shaped distribution starts rapidly falling. For the region of $N_{\mathrm{ch}}^{\mathrm{norm}} < \overline{N_{\mathrm{ch}}^{\mathrm{knee}}}$, the $\langle \overline{N_{\mathrm{ch}}^{\mathrm{knee}}} | N_{\mathrm{ch}}^{\mathrm{norm}} \rangle$ variable approximately reduces to $N_{\mathrm{ch}}^{\mathrm{norm}}$, so Eq. (2) yields a value of unity. For the region of $N_{\mathrm{ch}}^{\mathrm{norm}} > \overline{N_{\mathrm{ch}}^{\mathrm{knee}}}$, the $\langle \overline{N_{\mathrm{ch}}^{\mathrm{knee}}} | N_{\mathrm{ch}}^{\mathrm{norm}} \rangle$ variable saturates at $\overline{N_{\mathrm{ch}}^{\mathrm{knee}}}$ for sufficiently large $N_{\mathrm{ch}}^{\mathrm{norm}}$. In this limit, Eq. (2) becomes a simple power function, with c_s^2 being the power of the function. The parameters $\overline{N_{\mathrm{ch}}^{\mathrm{knee}}}$ and σ can be constrained by fitting the measured multiplicity distribution using the procedure described in Ref. [37]. The

Lawrence is ½ way between Eudora and Wakarusa