Probing sound propagation in the QGP via relativistic ultra-central collisions with ALICE

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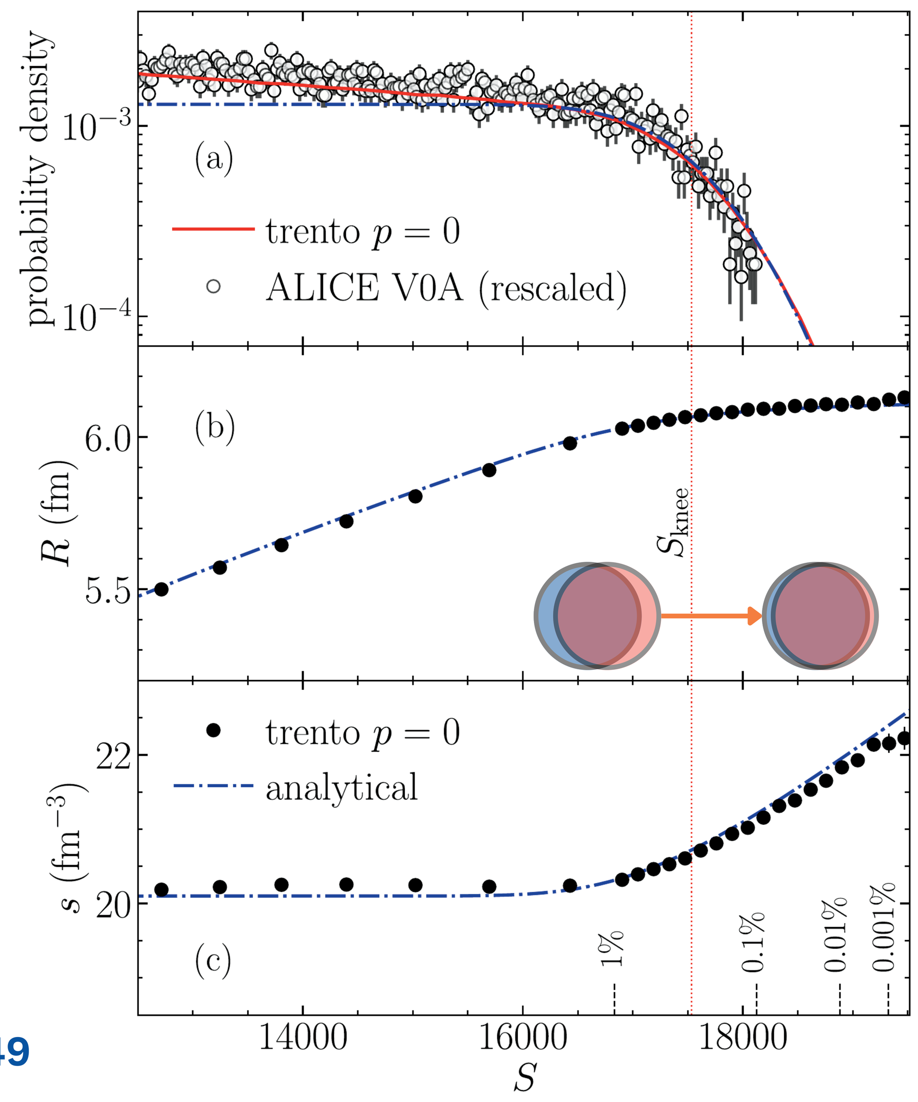
Ultra-central AA collisions

- In **ultra-central collisions** the volume of the QGP is mostly fixed
- At fixed volume, the charged particle multiplicity can vary due to the increase in entropy density
- Larger entropy means larger QGP temperature, leading to an increase in $\langle p_T \rangle$ (faster expansion)
- $S_{\rm knee}$ defined as the average entropy for which collisions happen at zero impact parameter

The squared speed of sound:

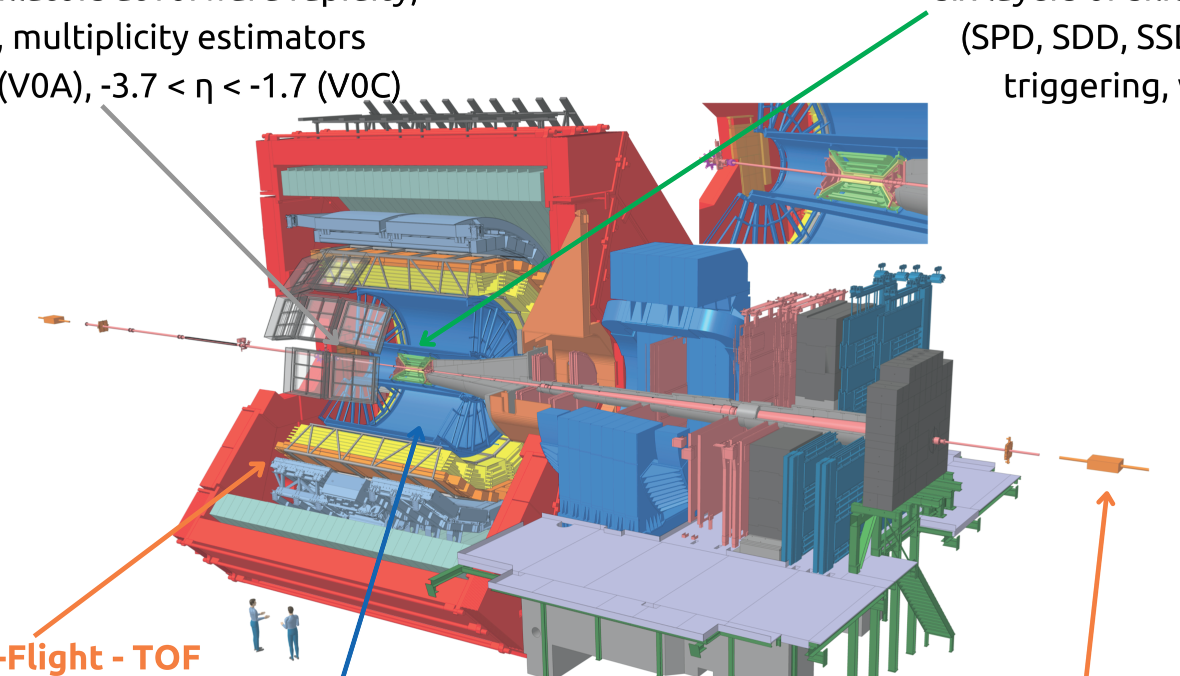
$$c_s^2 = \frac{d\ln T}{d\ln s} \approx \frac{d\ln \langle p_T \rangle}{d\ln N_{ch}}$$

One can extract the value of the speed of sound from the variation of $\langle p_T \rangle$ with multiplicity



F. Gardim et al., Phys. Lett. B 809 (2020) 135749

The ALICE detector

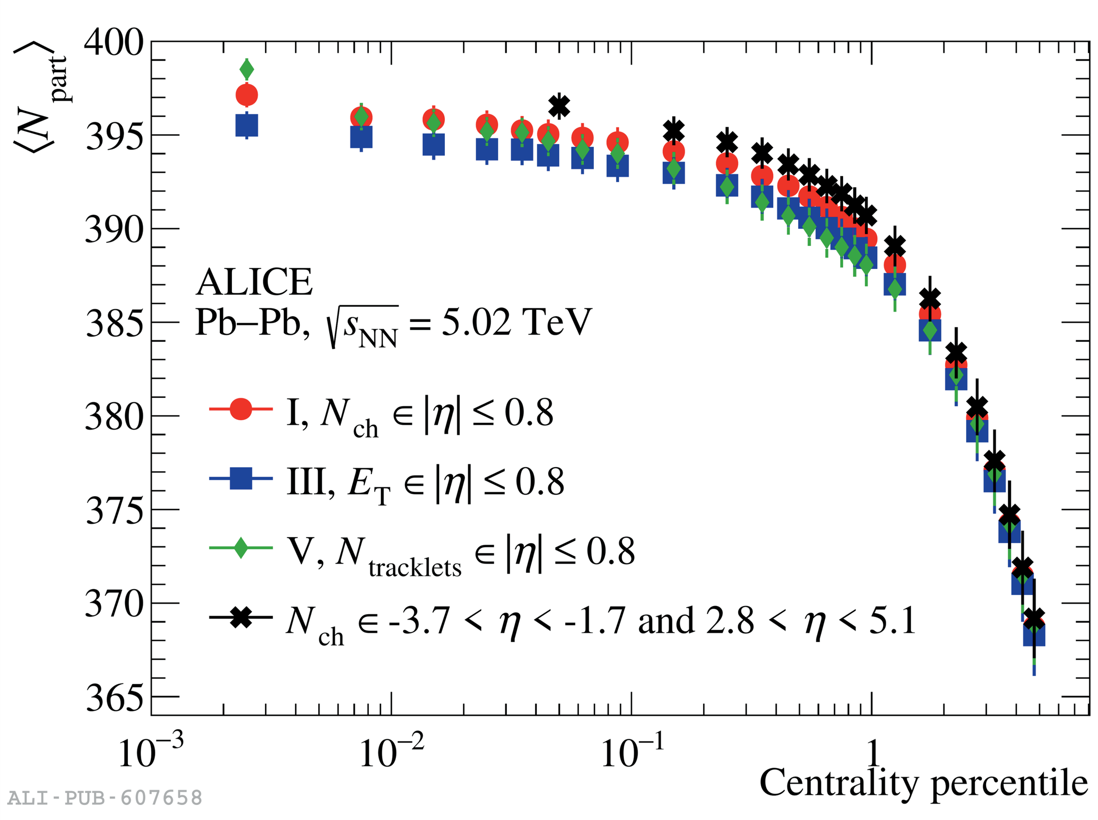


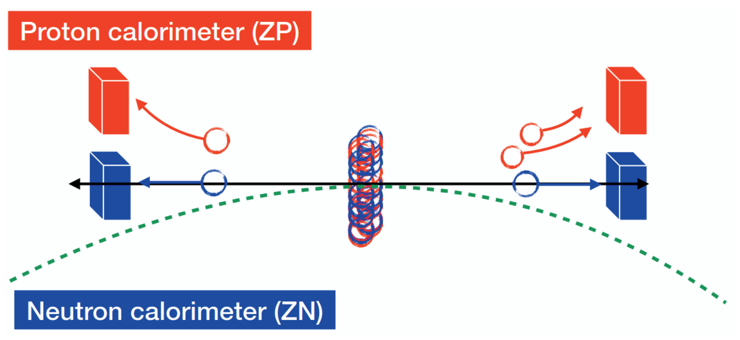
Centrality estimators

Transverse energy based

Multiplicity based

Observable	Label	Centrality estimation	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$	Minimum $\lvert\Delta\eta\rvert$
N_{ch} in TPC	I	$\lvert\eta\rvert \le 0.8$	$\lvert\eta\rvert \le 0.8$	0
	II	$0.5 \le \lvert\eta\rvert < 0.8$	$\lvert\eta\rvert \le 0.3$	0.2
E_T in TPC	III	$\lvert\eta\rvert \le 0.8$	$\lvert\eta\rvert \le 0.8$	0
	IV	$0.5 \le \lvert\eta\rvert < 0.8$	$\lvert\eta\rvert \le 0.3$	0.2
$N_{\rm tracklets}$ in SPD	V	$\lvert\eta\rvert \le 0.8$	$\lvert\eta\rvert \le 0.8$	0
	VI	$0.5 \le \lvert\eta\rvert < 0.8$	$\lvert\eta\rvert \le 0.3$	0.2
	VII	$0.3 \le \lvert\eta\rvert < 0.6$	$\lvert\eta\rvert \le 0.3$	0
	VIII	$0.7 \le \lvert\eta\rvert < 1$	$\lvert\eta\rvert \le 0.3$	0.4
N_{ch} in V0	IX	$-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$	$\lvert\eta\rvert \le 0.8$	0.9
ZDC		Located at 112.5 m away from the IP. In this analysis, it is used only for measuring $\langle N_{\rm part} \rangle$		

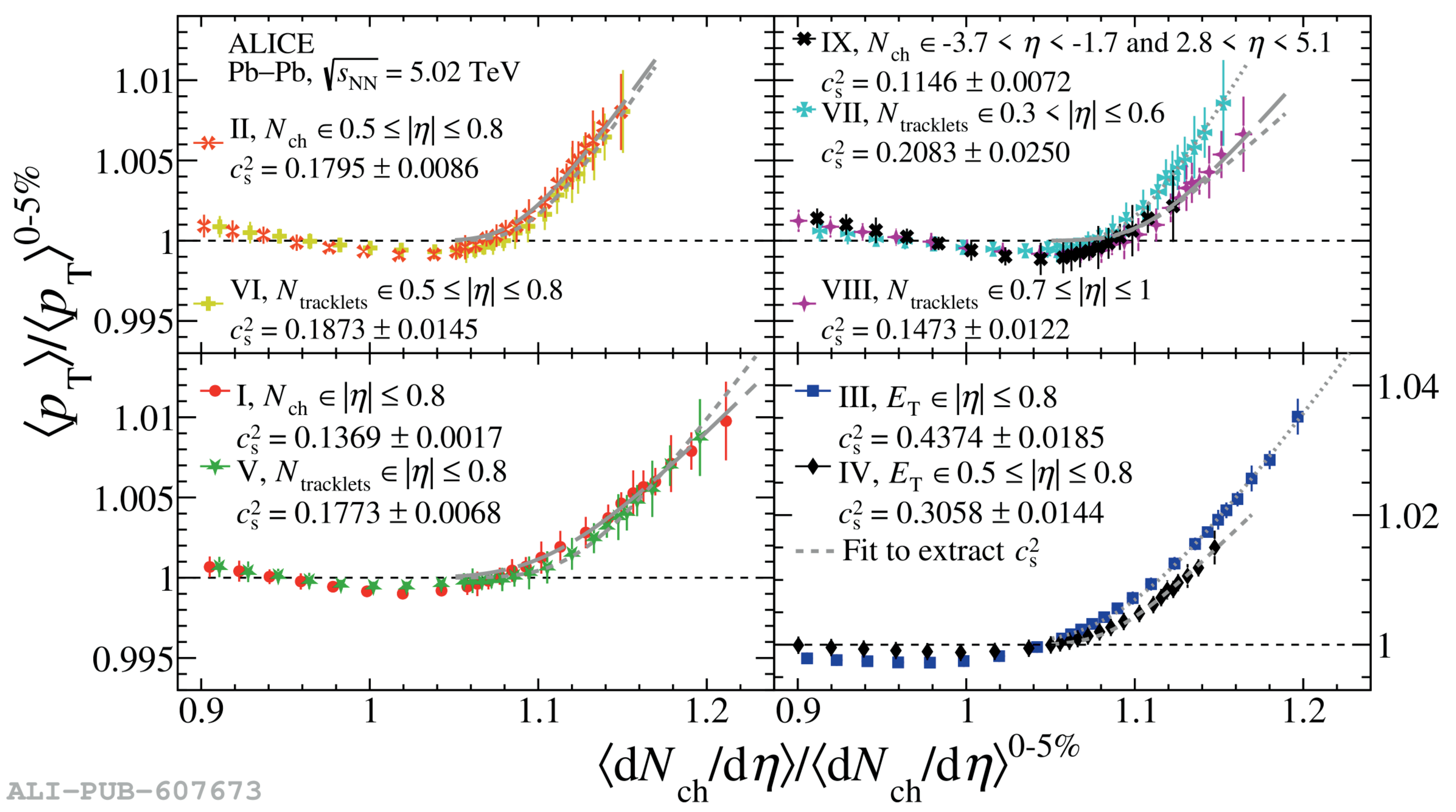




$$\langle N_{\rm part} \rangle = 2A - (\langle E_N \rangle/\alpha_N + \langle E_P \rangle/\alpha_P)/E_A$$

- Average number of participating nucleons is estimated through the ZDC
- Centrality obtained with different estimators
- Same trend independently of the centrality estimator
- In ultracentral collisions the average number of participating nucleons saturates quickly, almost independently on the estimator

Measuring c_s^2



c_s^2 parameter extracted from a fit to the $\langle p_T \rangle / \langle p_T \rangle^{0-5\%}$

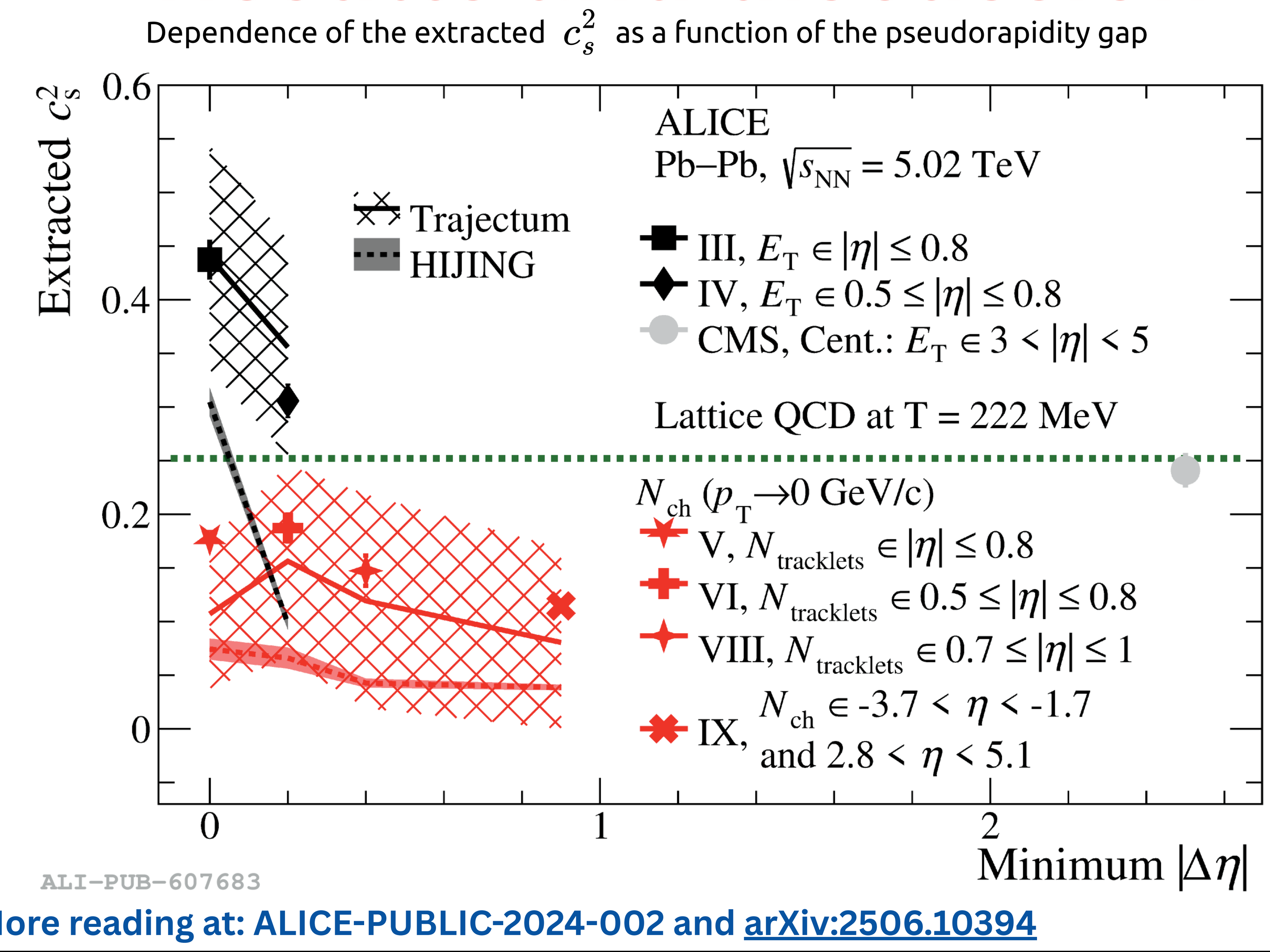
$$\langle p_T \rangle^{\rm scaled} = \left(\frac{\langle N_{ch} \rangle^{\rm norm}}{f(\langle N_{ch} \rangle^{\rm norm}, \langle N_{ch} \rangle^{\rm knee}, \sigma_0)} \right)^{c_s^2}$$

Gaussian distribution for N_{ch} at a fixed impact parameter

$$f(\langle N_{ch} \rangle^{\rm norm}, \langle N_{ch} \rangle^{\rm knee}, \sigma_0) = \langle N_{ch} \rangle^{\rm norm} - \sigma_0 \sqrt{\frac{2}{\pi}} \frac{\exp\left(-\frac{(\langle N_{ch} \rangle^{\rm norm} - \langle N_{ch} \rangle^{\rm knee})^2}{2\sigma_0^2}\right)}{\mathrm{erfc}\left(\frac{\langle N_{ch} \rangle^{\rm norm} - \langle N_{ch} \rangle^{\rm knee}}{\sqrt{2}\sigma_0}\right)}$$

Results and discussion

Dependence of the extracted c_s^2 as a function of the pseudorapidity gap



- Selection biases on the centrality estimators give different $\langle p_T \rangle$
- Different c_s^2 depending on the centrality definition
- Extracted c_s^2 is higher with the E_T based estimator with respect to the N_{ch} based estimator at fixed $\lvert\Delta\eta\rvert$
- The extracted c_s^2 decreases with increasing $\lvert\Delta\eta\rvert$

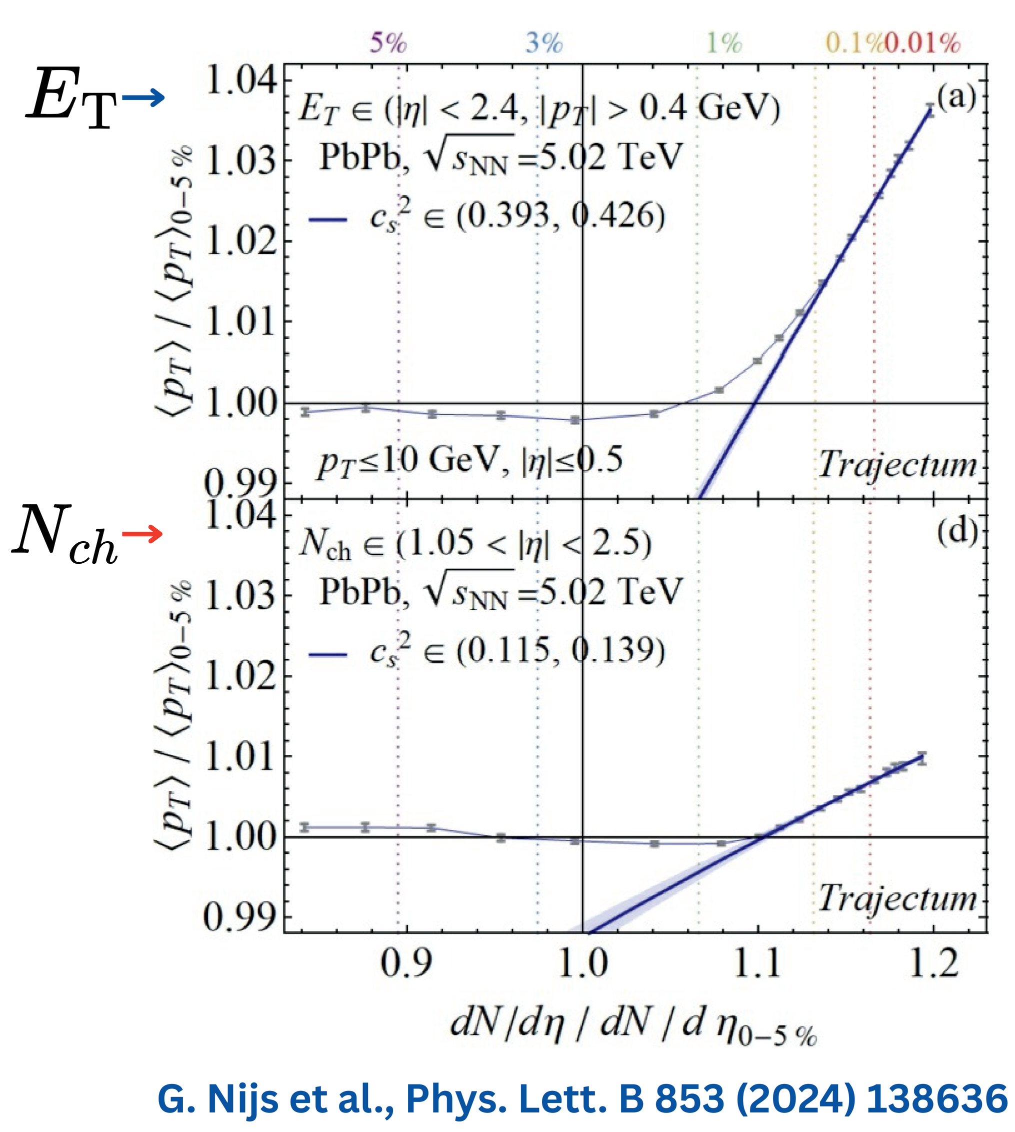
ALICE measurement is compared to the CMS one (Rep. Prog. Phys. 87 (2024) 077801)

- Centrality determined in the forward pseudorapidity ($3 \le \lvert\eta\rvert \le 5$) region using a E_T based estimator
- Reported values are in agreement with the estimates from the lattice QCD calculations

ALICE data shows the **importance of the bias** due to the centrality determination in obtaining c_s^2

- Results confirm the bias predicted by the Trajectum hydrodynamic model
- New results call for a reevaluation of how the c_s^2 parameter can be extracted from heavy-ion collisions

Trajectum predictions



G. Nijs et al., Phys. Lett. B 853 (2024) 138636

More reading at: ALICE-PUBLIC-2024-002 and arXiv:2506.10394