Assessing the QGP speed of sound in ultra-central heavy-ion collisions with ALICE

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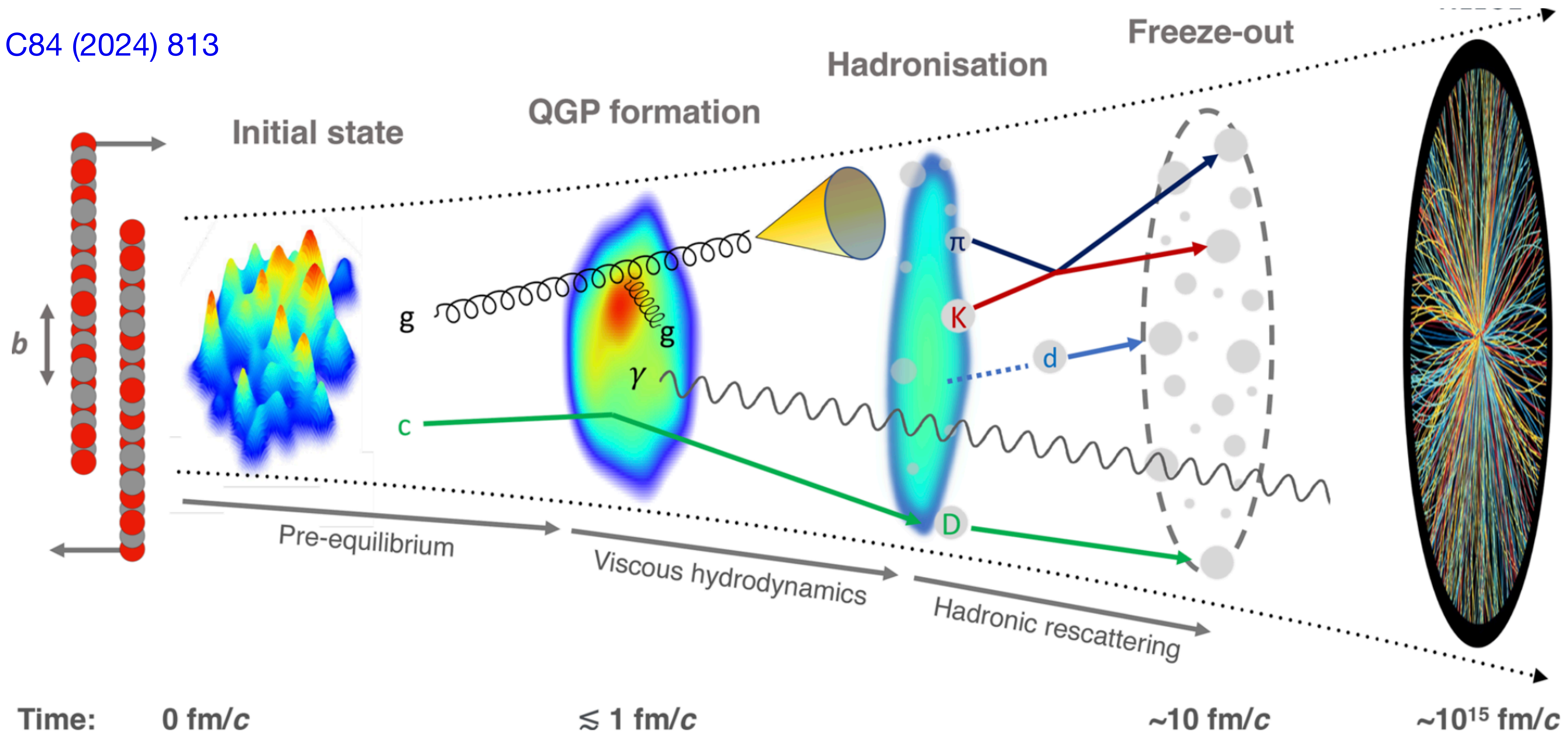
on behalf of the ALICE Collaboration

U.S. DEPARTMENT OF ENERGY

ALICE

Heavy ion collisions

ALICE, EPJ C84 (2024) 813



Heavy ion collisions are proposed as a means for investigating the EoS of hot matter.

The speed of sound (c_s) in the QGP

FG Gardim Nature Physics 16, 615-619 (2020)

- Velocity at which compression waves travel in a fluid.

- First attempt using ALICE heavy-ion data extracted c_s^2 = 0.24 at T_{eff} = 222 MeV.

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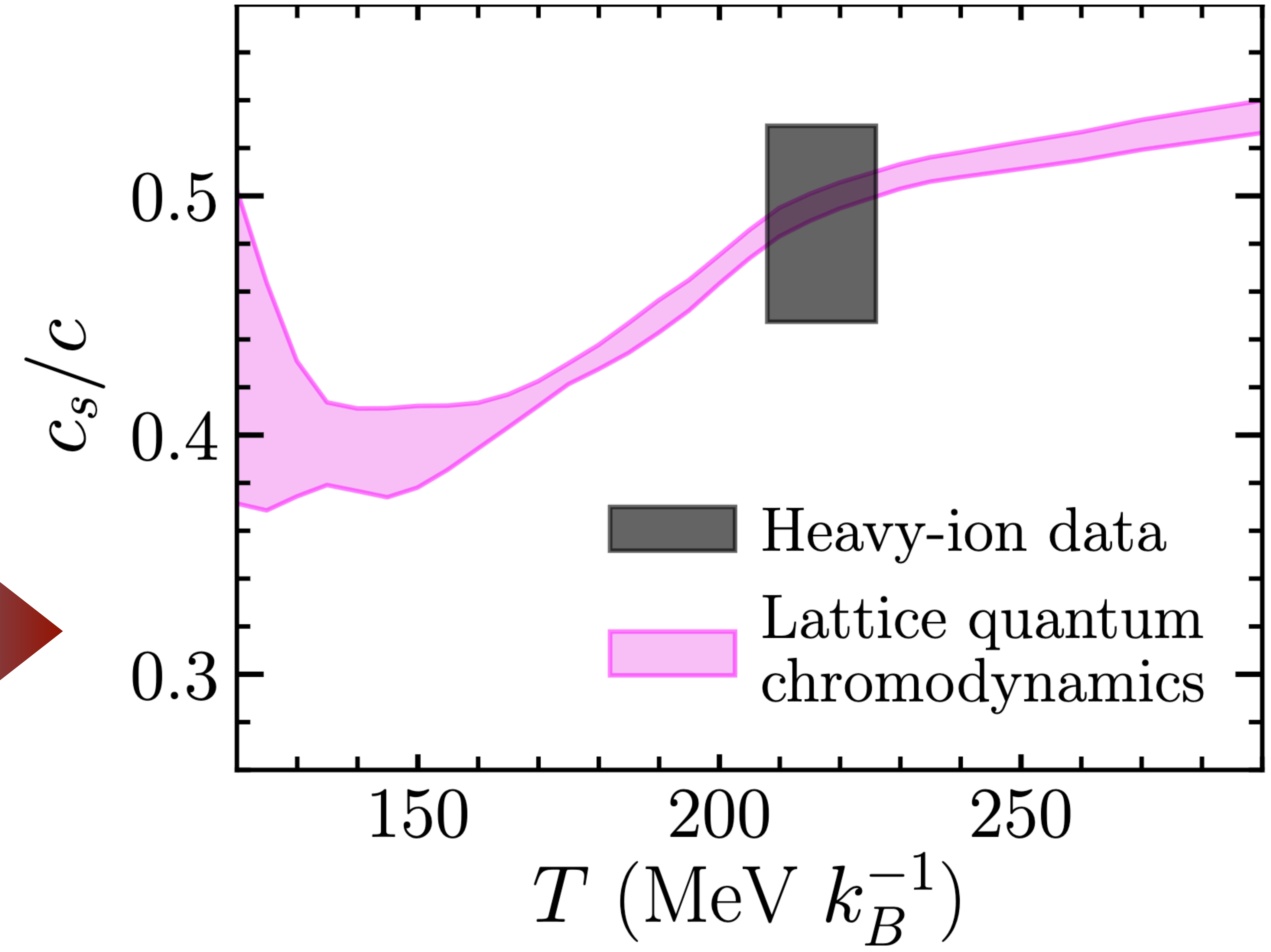
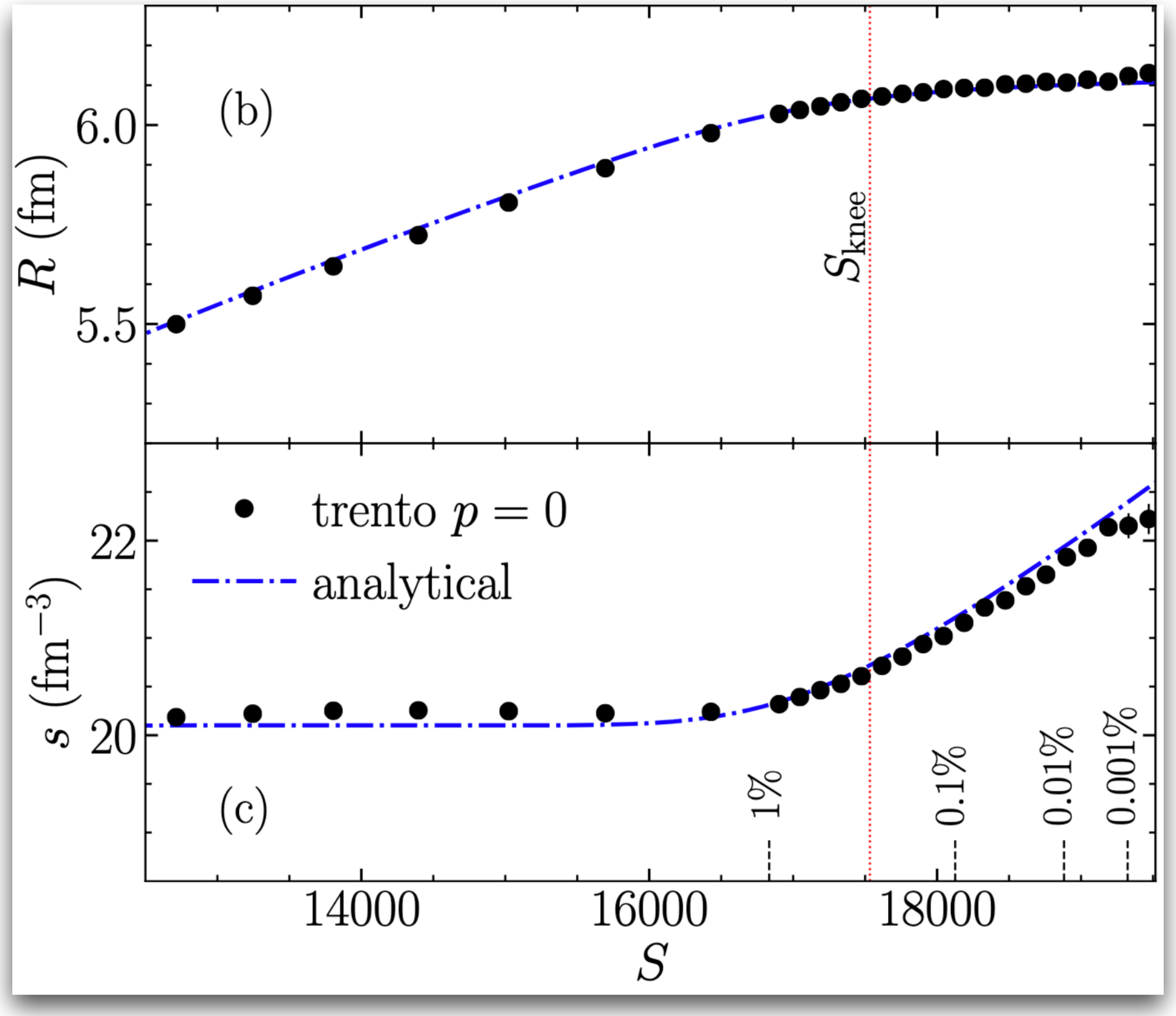
FG Gardim, Nature Physics 16, 615-619 (2020)



Ultra-central Pb—Pb collisions (UCCs)

- **The QGP's volume is mostly fixed** → constrain impact parameter (b) fluctuations.
- **Total entropy (S) can vary significantly** → increase of the charged-particle multiplicity (N_{ch}).
- Higher entropy → **higher temperature (T)** → $\langle p_T \rangle$ increases.



The S_{knee} is defined as the $\langle S \rangle$ at zero impact parameter.

- $$c_s^2 = \frac{d \ln T}{d \ln s}$$

Experimental determination: $$c_s^2 = \frac{d \ln \langle p_T \rangle}{d \ln \langle dN_{ch}/d\eta \rangle}$$

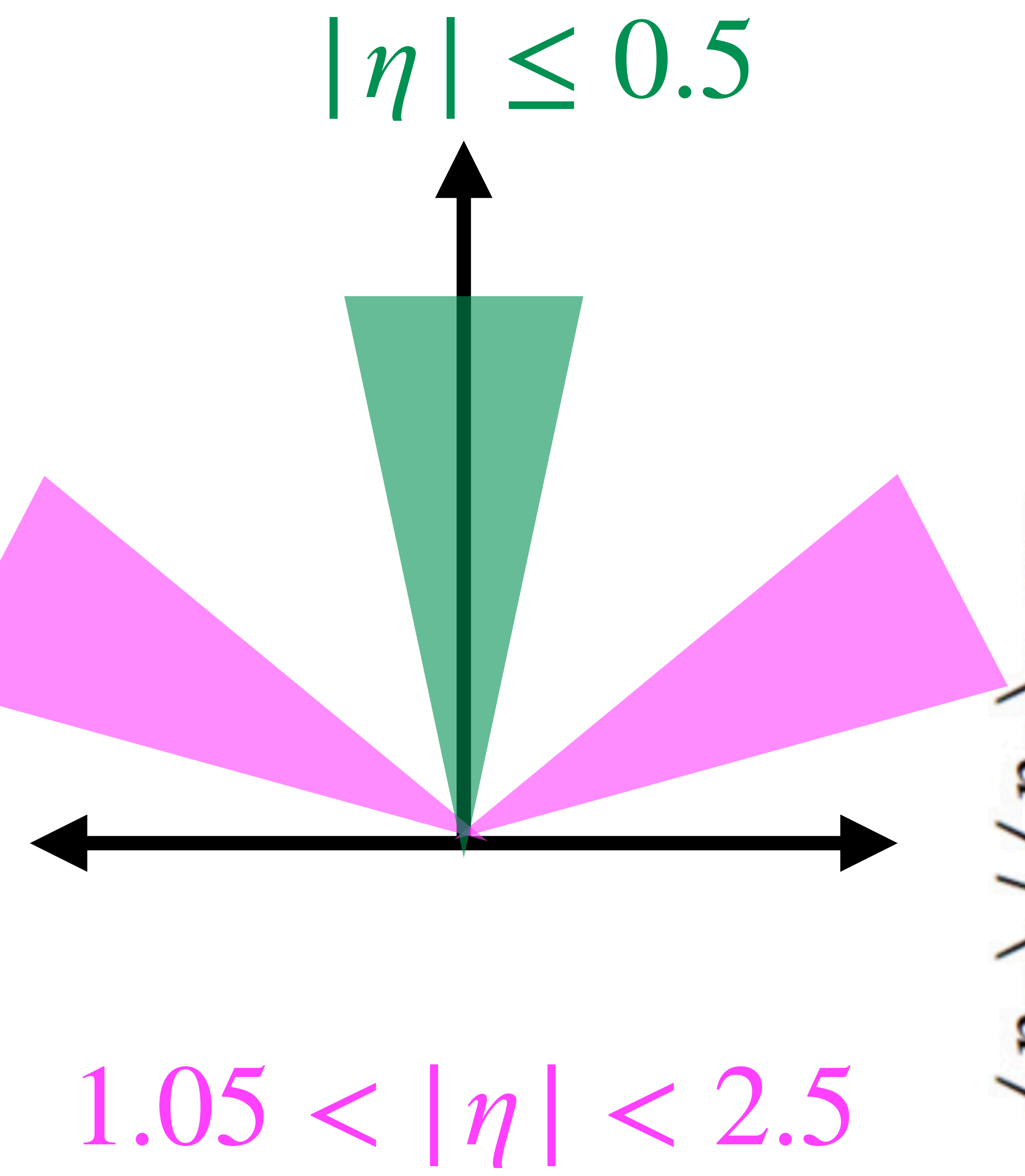
JY Ollitrault, Eur. J. Phys. 29 (2008) 275

FG Garden, Phys. Lett. B 809 (2020) 135749

What drives the rise of <p_T> in UCCs?

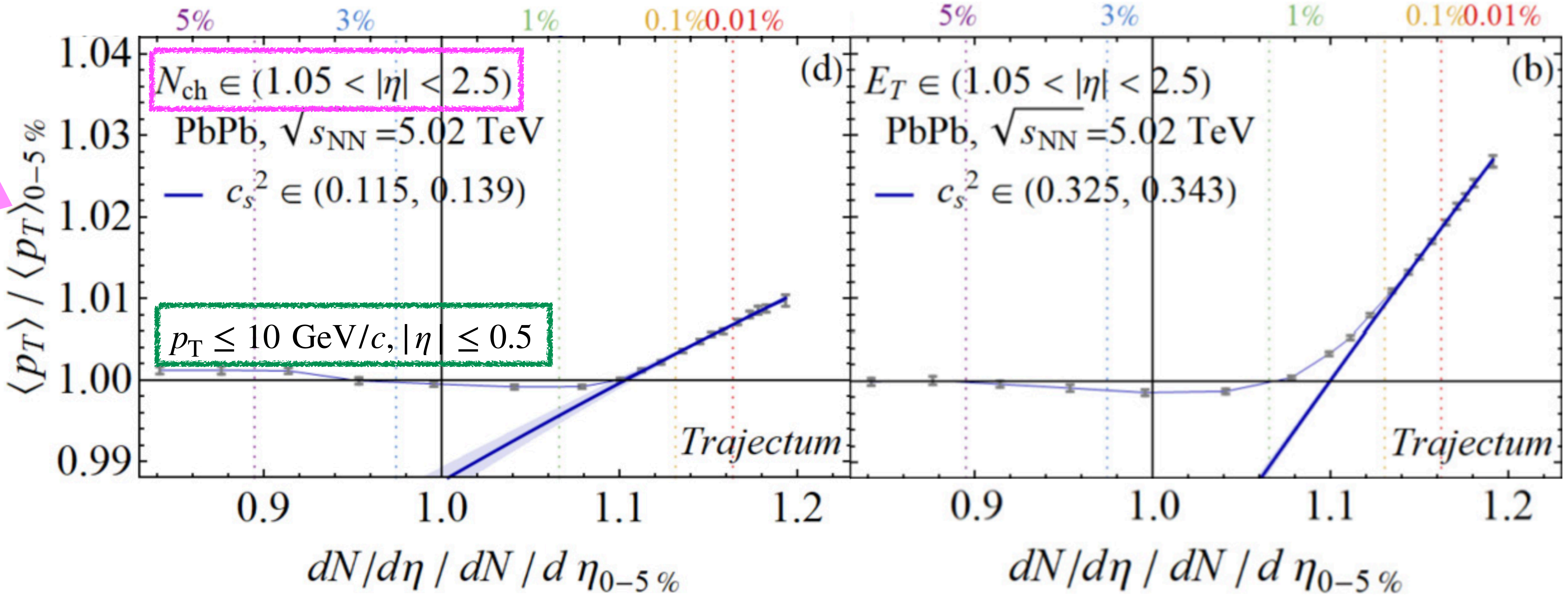
- **Different centrality estimators → different <p_T>.**
- Can have a large effect on the extracted value of speed of sound.

Results for different centrality estimators



N_{ch} centrality estimator

E_T centrality estimator



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

ALICE in Run 2

Relevant detectors:

Time Projection Chamber (15 in figure)

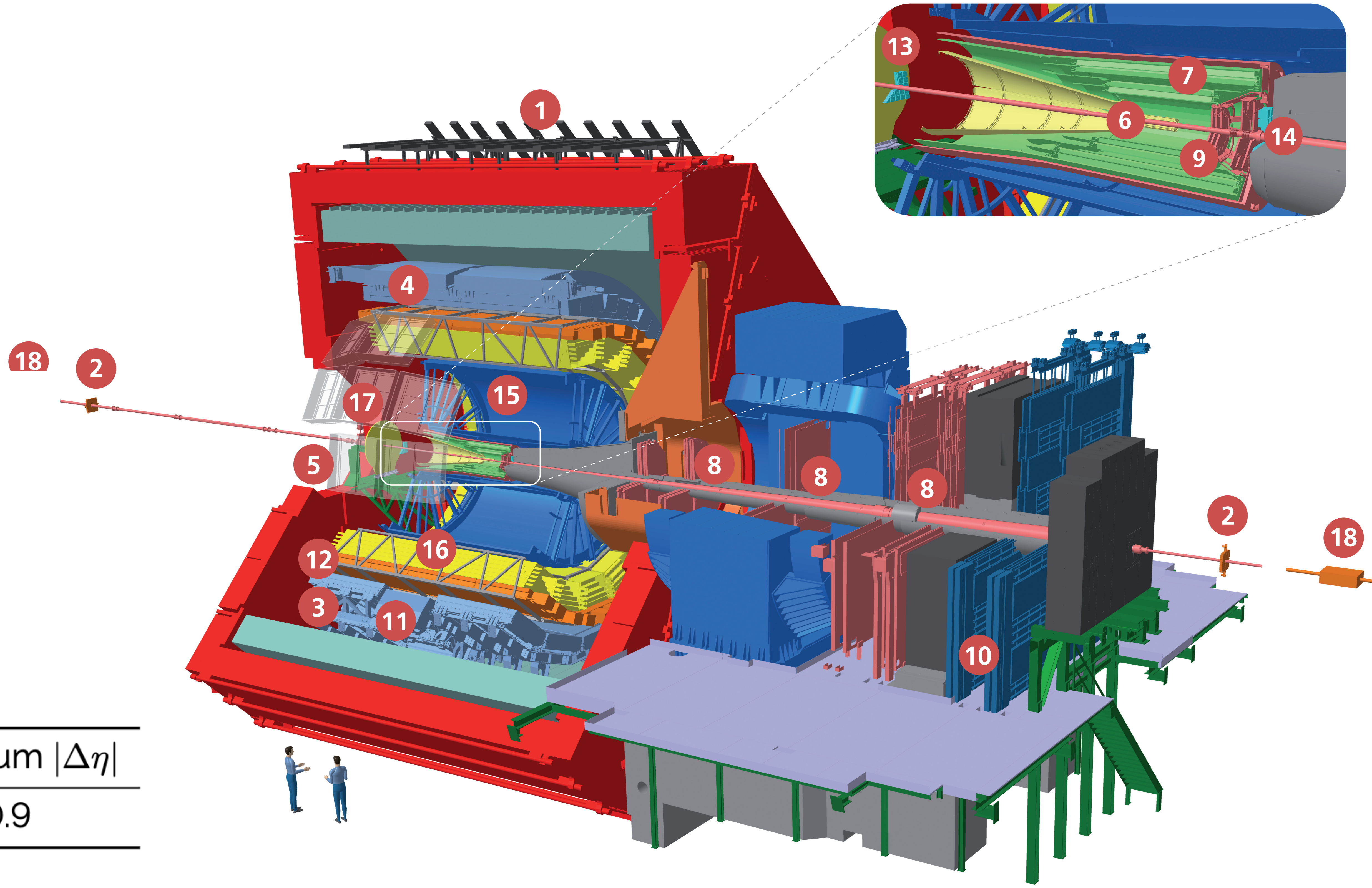
Observable	Label	**Centrality estimation**	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$	Minimum $\lvert\Delta\eta\rvert$
N_{ch} in TPC	I	$\lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.8$	0
	II	$0.5 \leq \lvert\eta\rvert < 0.8$	$\lvert\eta\rvert \leq 0.3$	0.2
E_T in TPC	III	$\lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.8$	0
	IV	$0.5 \leq \lvert\eta\rvert < 0.8$	$\lvert\eta\rvert \leq 0.3$	0.2

Inner Tracking System (6 and 7 in figure)

Observable	Label	**Centrality estimation**	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$	Minimum $\lvert\Delta\eta\rvert$
$N_{tracklets}$ in SPD	V	$\lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.8$	0
	VI	$0.5 \leq \lvert\eta\rvert < 0.8$	$\lvert\eta\rvert \leq 0.3$	0.2
	VII	$0.3 < \lvert\eta\rvert < 0.6$	$\lvert\eta\rvert \leq 0.3$	0
	VIII	$0.7 \leq \lvert\eta\rvert < 1$	$\lvert\eta\rvert \leq 0.3$	0.4

V0A and V0C (13 and 14 in figure)

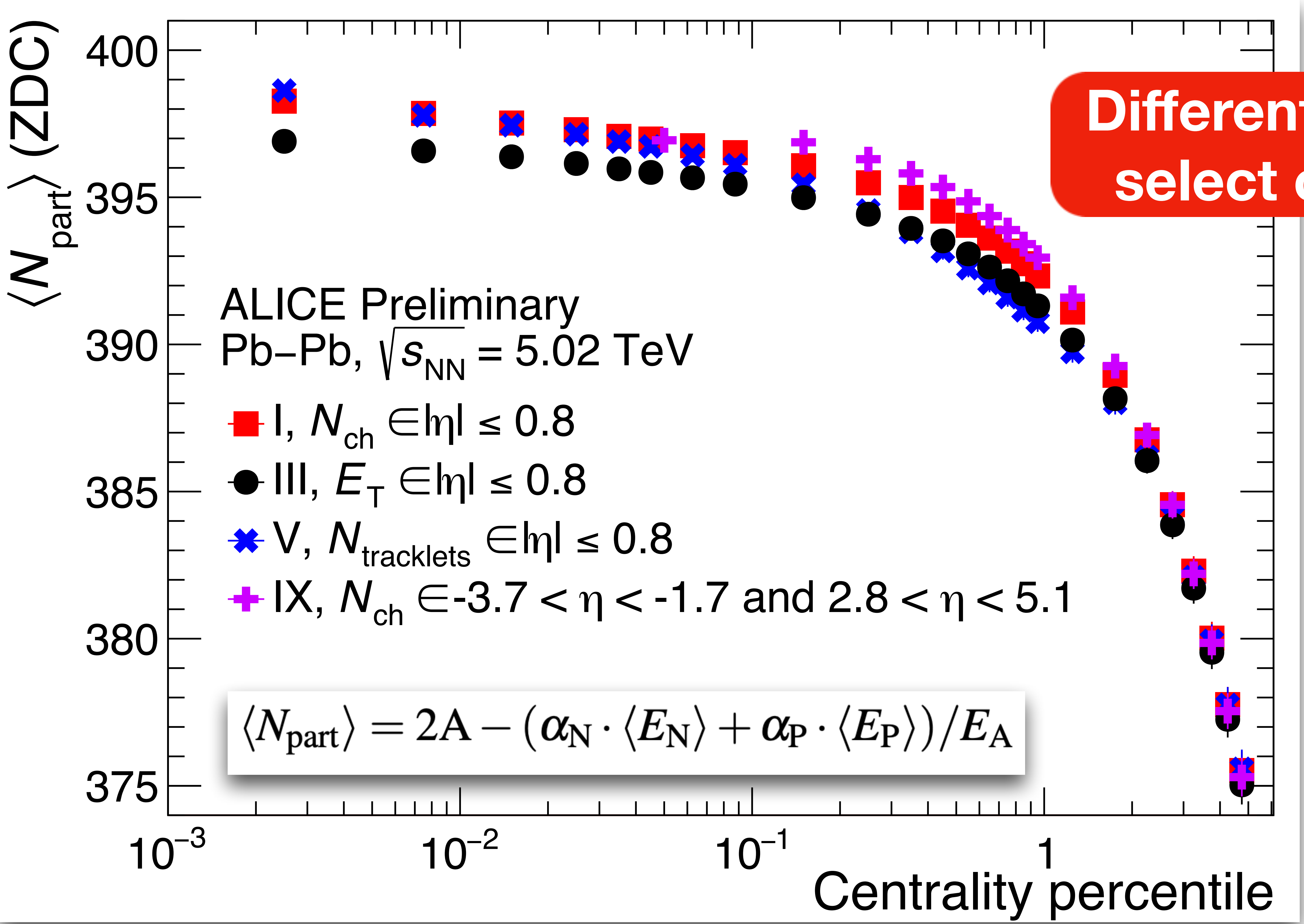
Observable	Label	**Centrality estimation**	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$	Minimum $\lvert\Delta\eta\rvert$
N_{ch} in VZERO	IX	$-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$	$\lvert\eta\rvert \leq 0.8$	0.9



ZDC (18 in figure)

Estimate the mean number of participating nucleons ($\langle N_{part} \rangle$)

Data-driven extraction of <N_{part}> for UCCs



Different estimators on average select on the same geometry.

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<N_{part}> v.s. centrality: indirect measure of the interaction region radius.

A = 208, <E_N> (<E_P>) is the mean neutrons(protons) energy in the ZDC, α_N and α_P are acceptance corrections, and E_A=2.51 TeV.

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Normalized p_T spectra ratios

- Multiplicity-based centrality estimators: enhances yield at $p_T \sim 3$ GeV/*c* (**radial flow bump**).
- E_T-based centrality estimator: enhances yield for $p_T > 1$ GeV/*c*.

$$\text{Normalized ratio} = \frac{(\mathrm{d}^2N/\langle \mathrm{d}N_{ch}/\mathrm{d}\eta\rangle \mathrm{d}\eta \mathrm{d}p_T)^{\text{Centrality percentile}}}{(\mathrm{d}^2N/\langle \mathrm{d}N_{ch}/\mathrm{d}\eta\rangle \mathrm{d}\eta \mathrm{d}p_T)^{0-5\%}}$$

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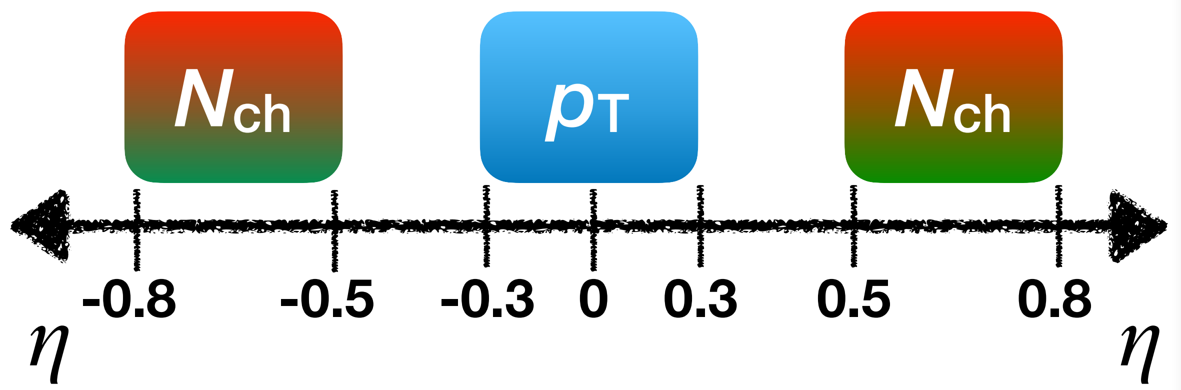
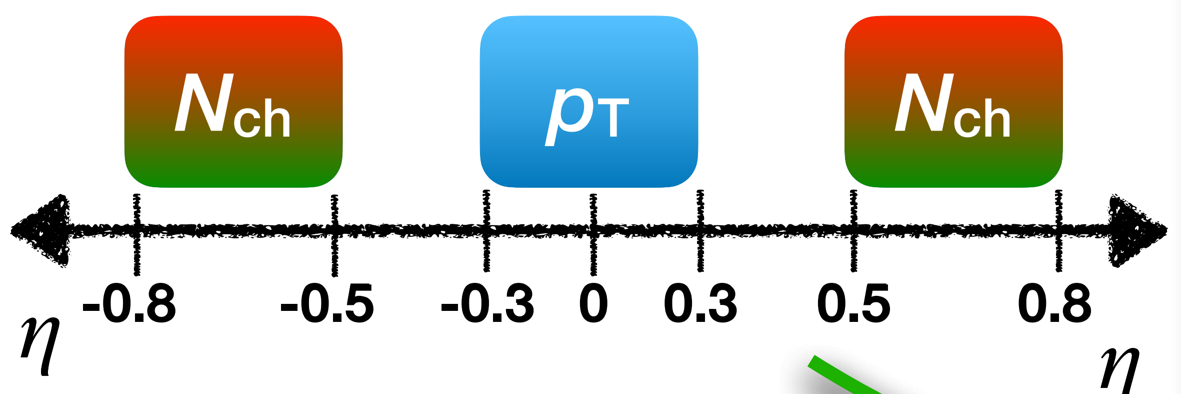
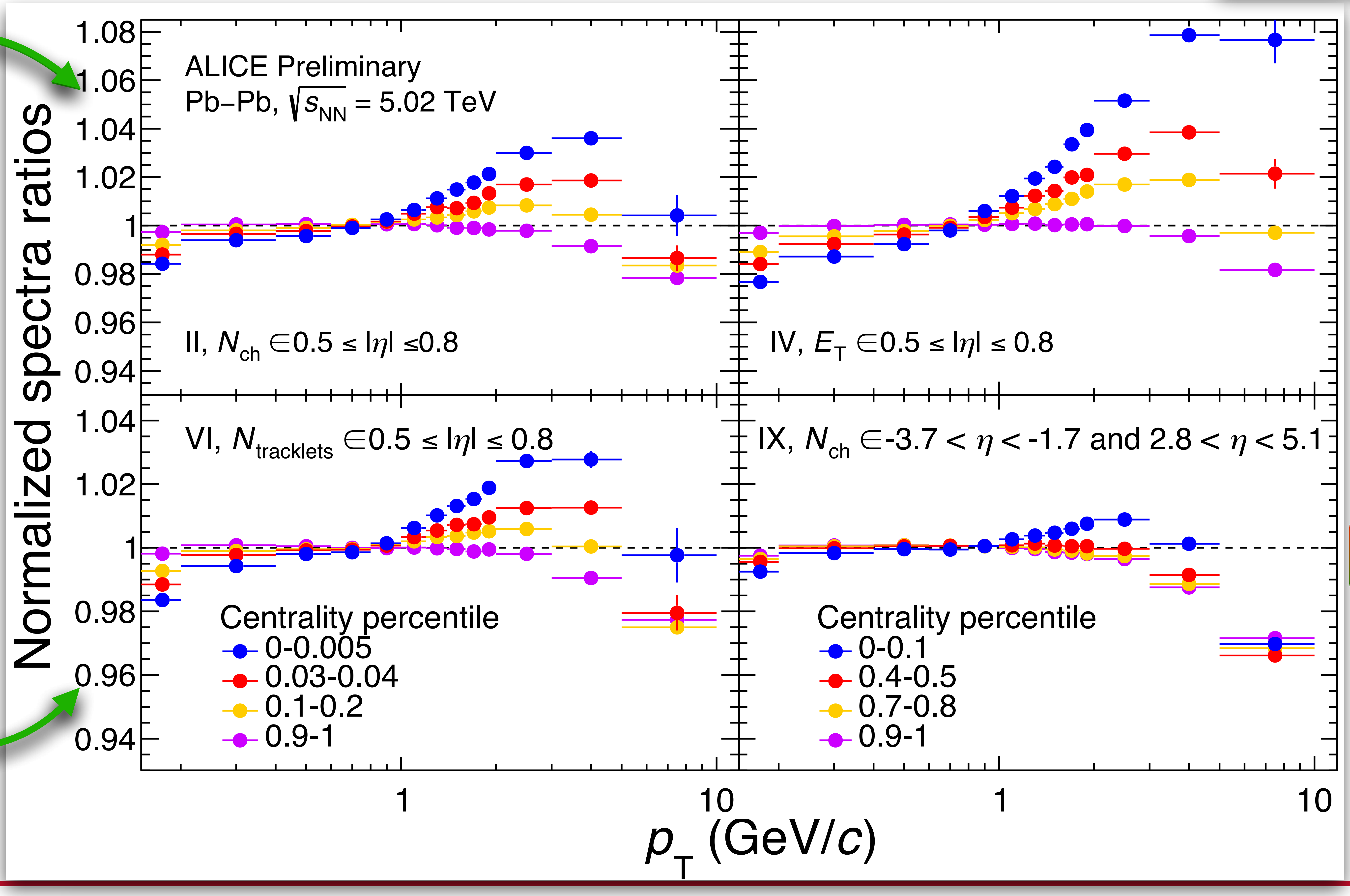
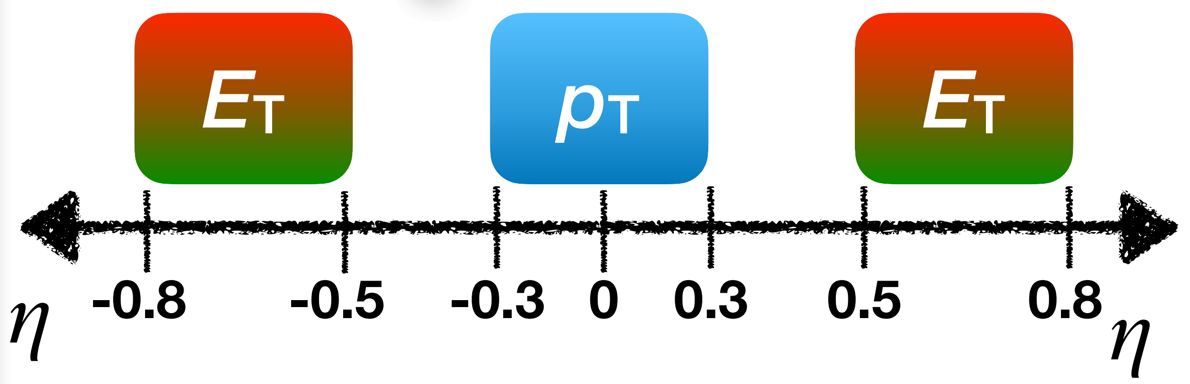
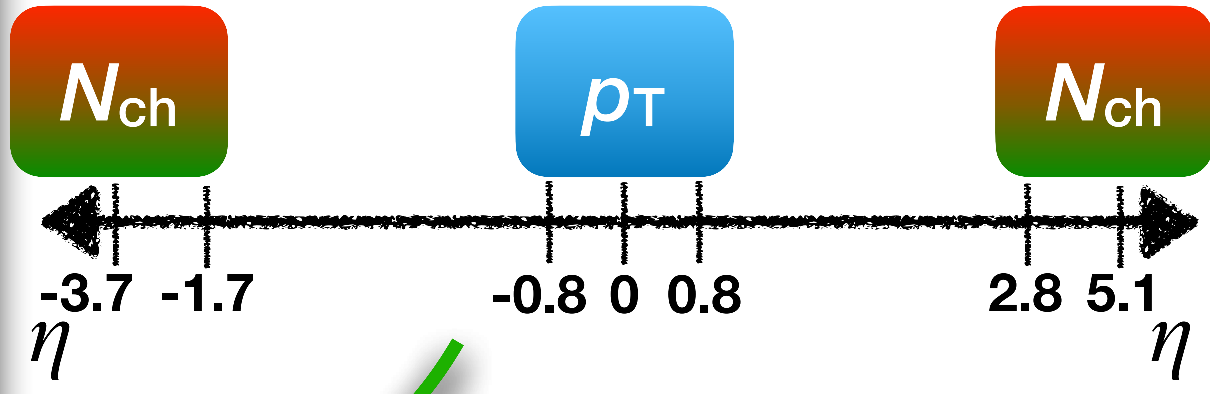










Extracting the squared speed of sound, c_s^2

Primary observable: $\langle p_T \rangle / \langle p_T \rangle^{0-5\%}$ versus $\langle dN_{ch}/d\eta \rangle / \langle dN_{ch}/d\eta \rangle^{0-5\%}$ correlation

$$\langle p_T \rangle / \langle p_T \rangle^{0-5\%} = \left[\frac{N^*_{ch}}{f(N^*_{ch}, N^*_{ch,knee}, \sigma_0)} \right]^{c_s^2}$$

Gaussian distribution of the number of emitted particles for a fixed impact parameter

Where N^*_{ch} = <dN/dη>/<dN/dη>$^{0\text{-}5\%}$

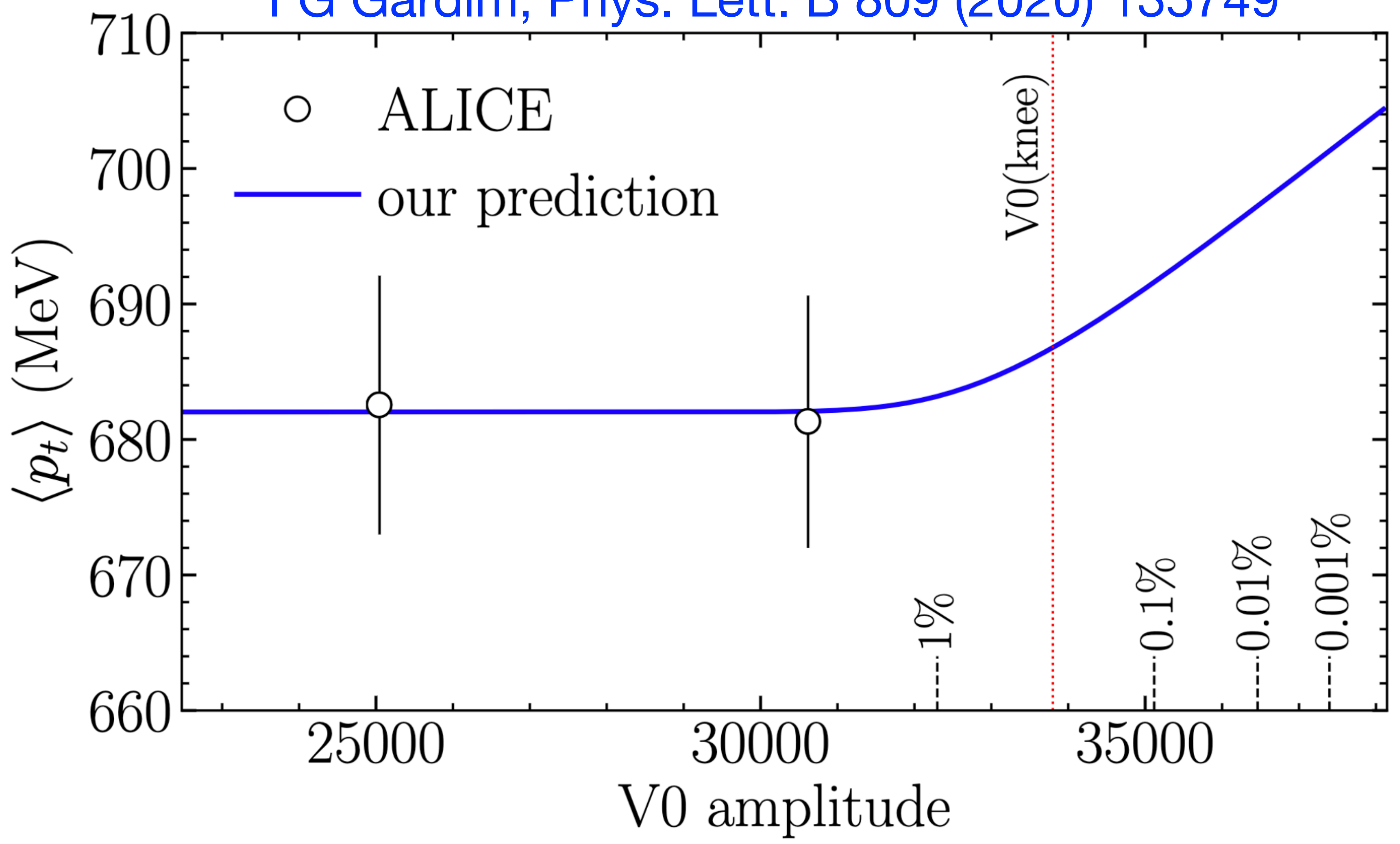
Below the knee

$$\langle p_T \rangle / \langle p_T \rangle^{0-5\%} = 1$$

Above the knee

$$\langle p_T \rangle / \langle p_T \rangle^{0-5\%} \propto \left(\frac{N^*_{ch}}{N^*_{ch,knee}} \right)^{c_s^2}$$

FG Gardim, Phys. Lett. B 809 (2020) 135749



Estimating the $N^*_{\mathrm{ch,knee}}$ and σ_0

- Model the event fraction distribution with a convolution of Gaussian distributions, each describing the number of emitted particles for a fixed impact parameter.
- $N^*_{\mathrm{ch,\,knee}}$: average charged-particle multiplicity in collisions at $b = 0$.

SJ Das, PRC 97, 014905 (2018)

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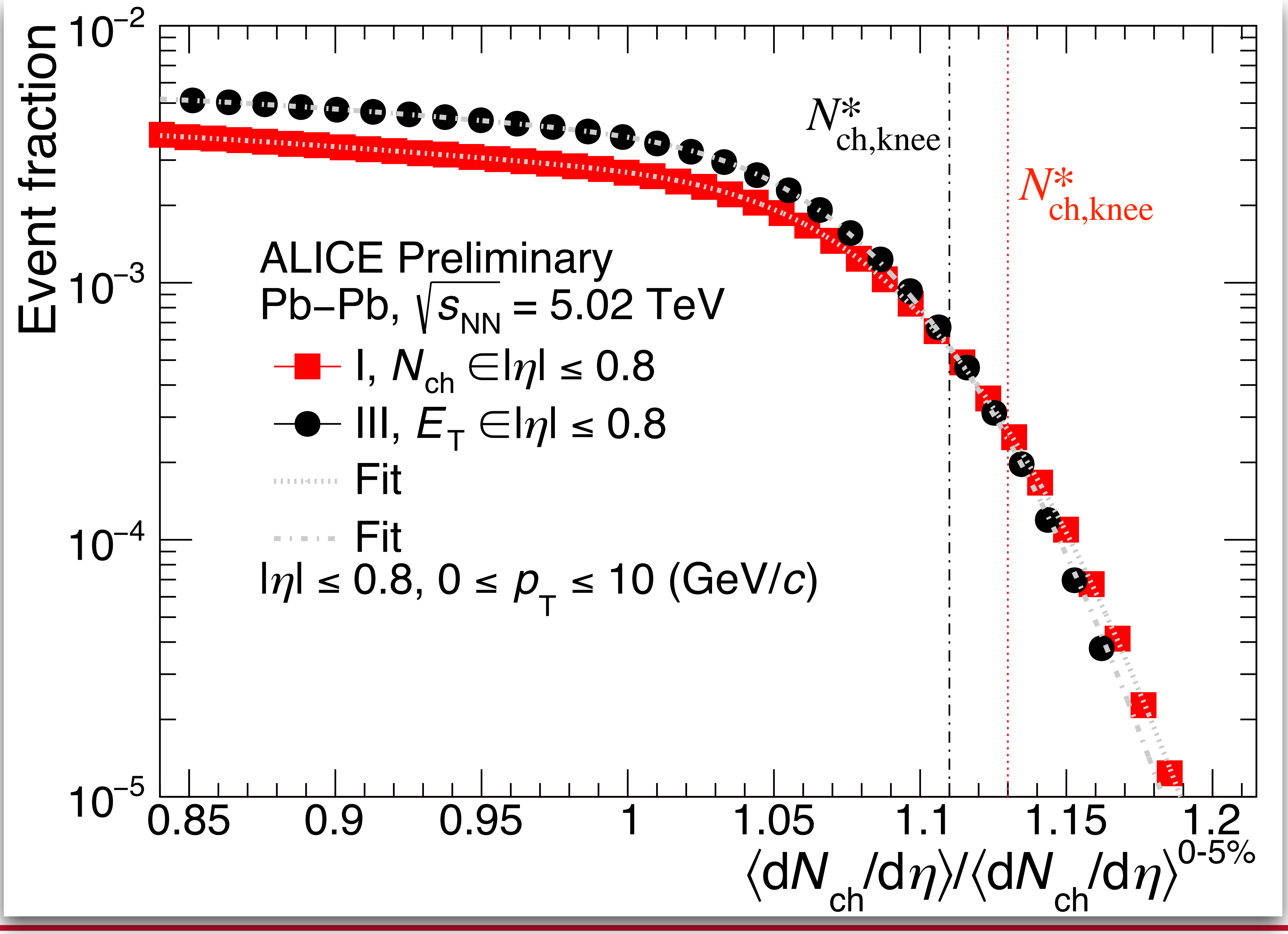
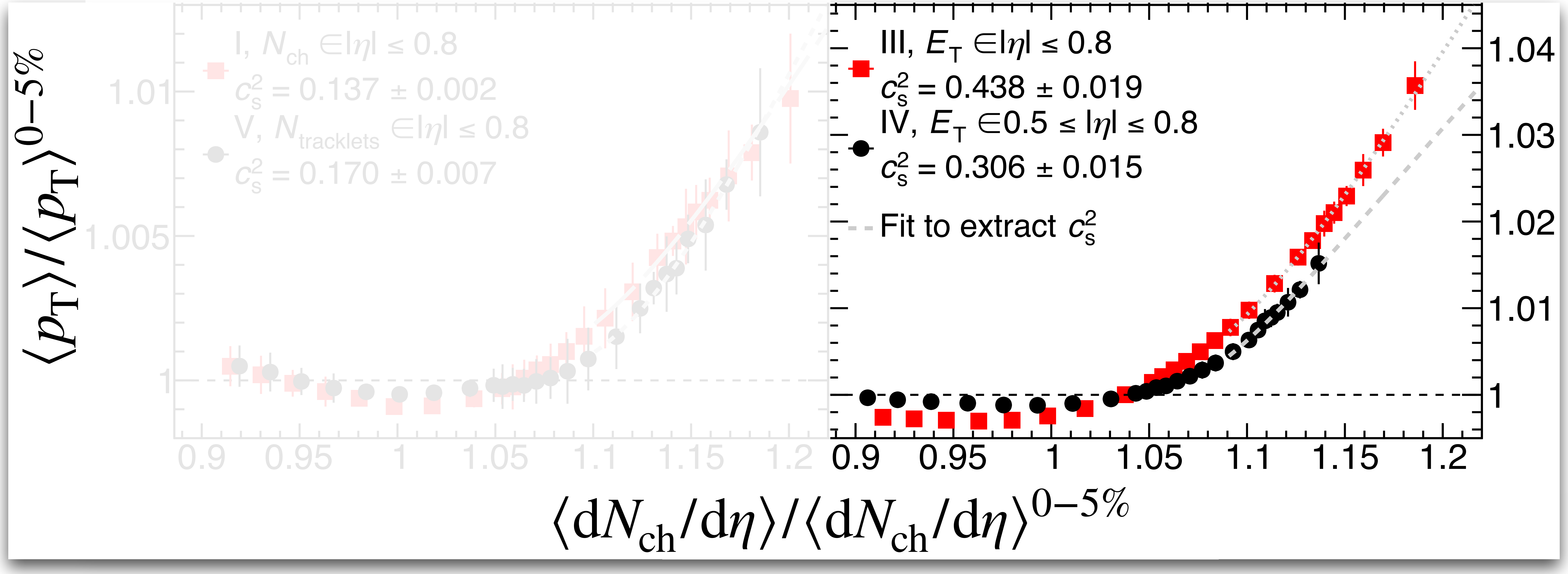
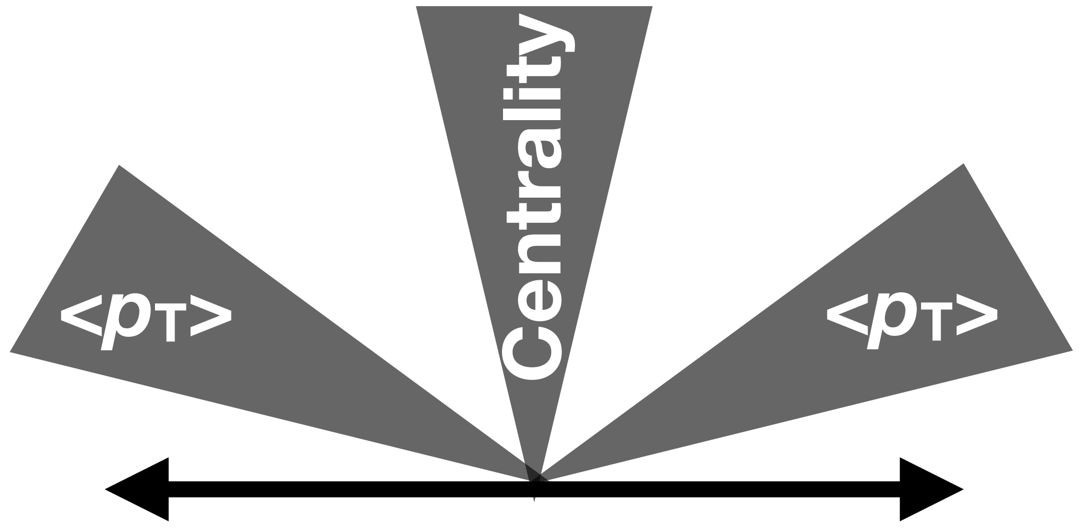
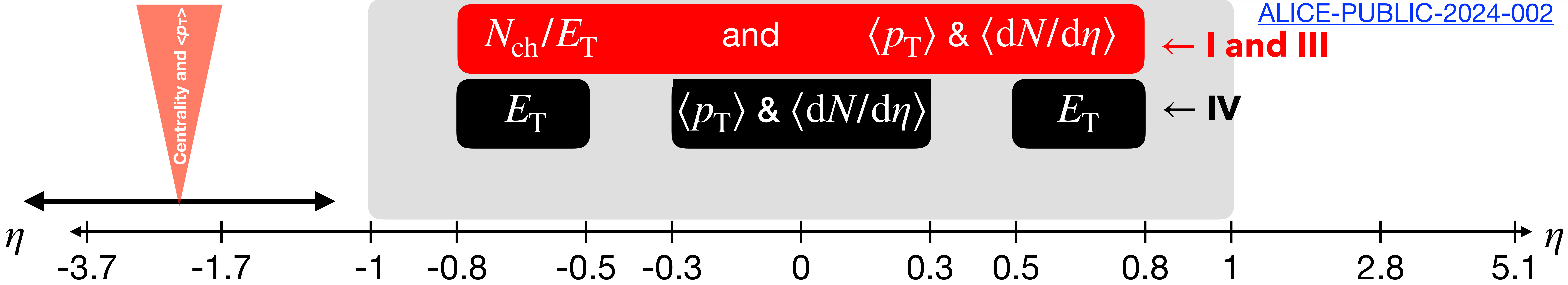


Extracting the squared speed of sound, c_s^2

- Large range of c_s^2 values when N_{ch} or E_{T} overlaps with region of measurements to extract c_s^2.







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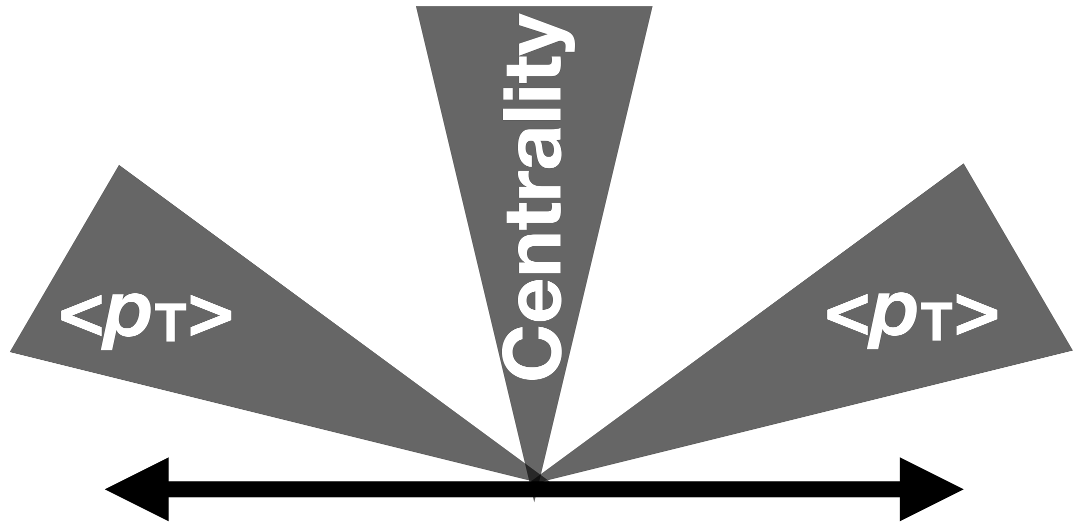

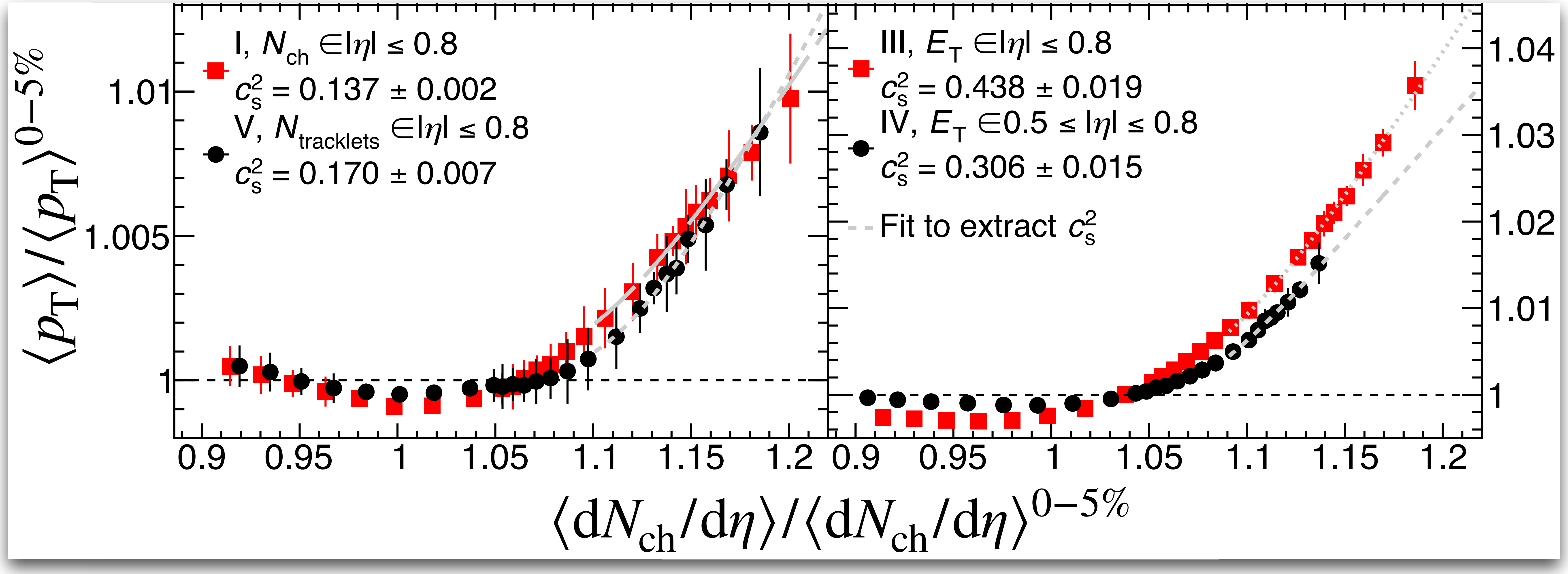

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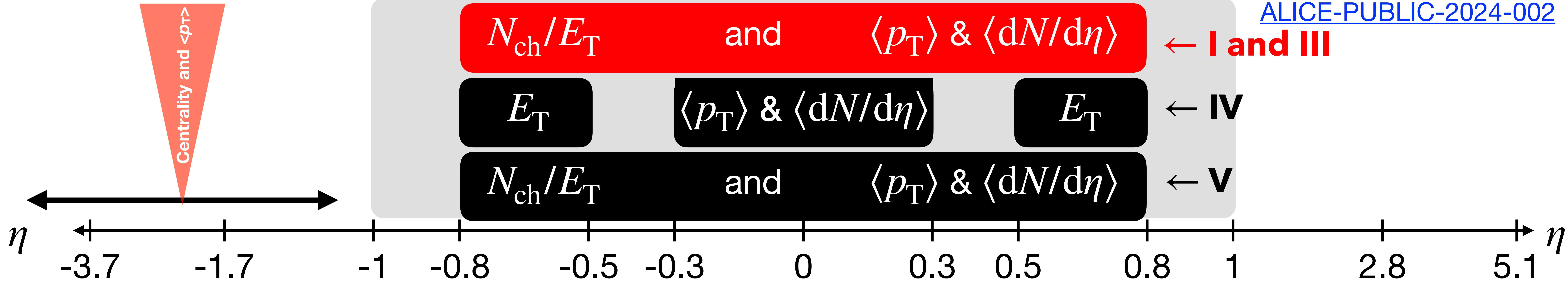
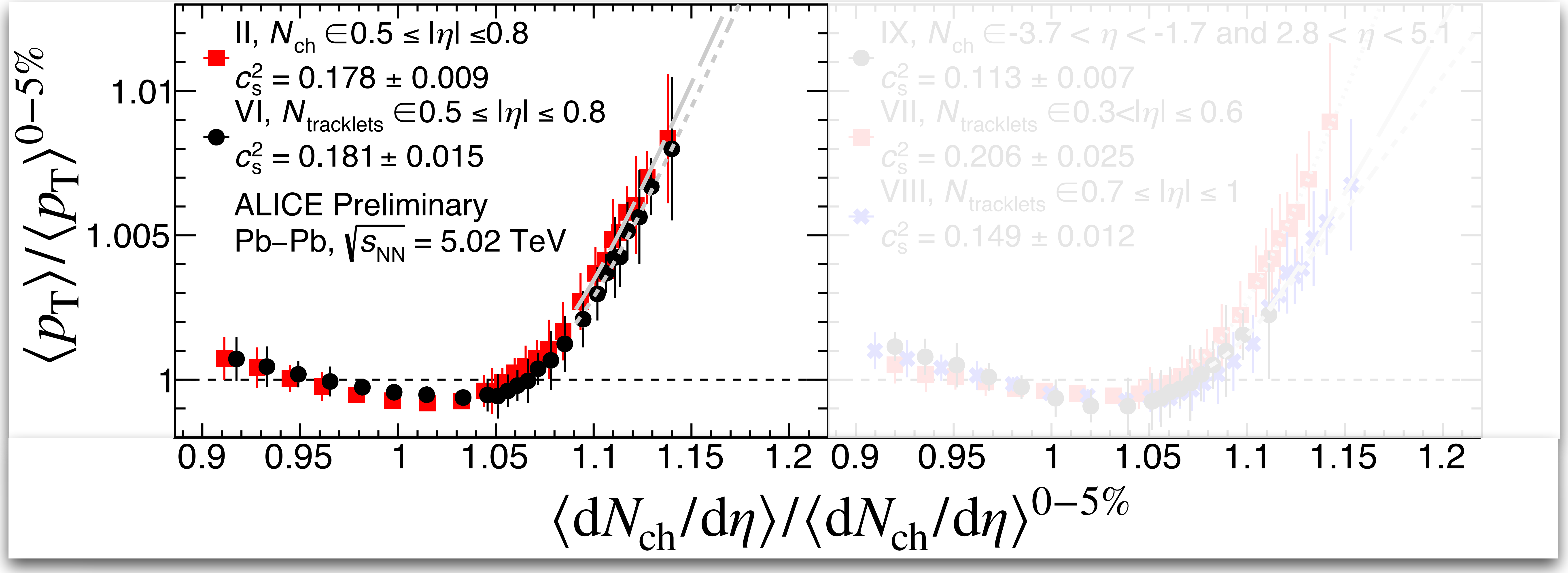


Extracting the squared speed of sound, c_s^2

- Extraction of c_s^2 depends on the centrality estimation.
- Speed of sound also decreases with N_{ch} centrality estimator when η gap placed.



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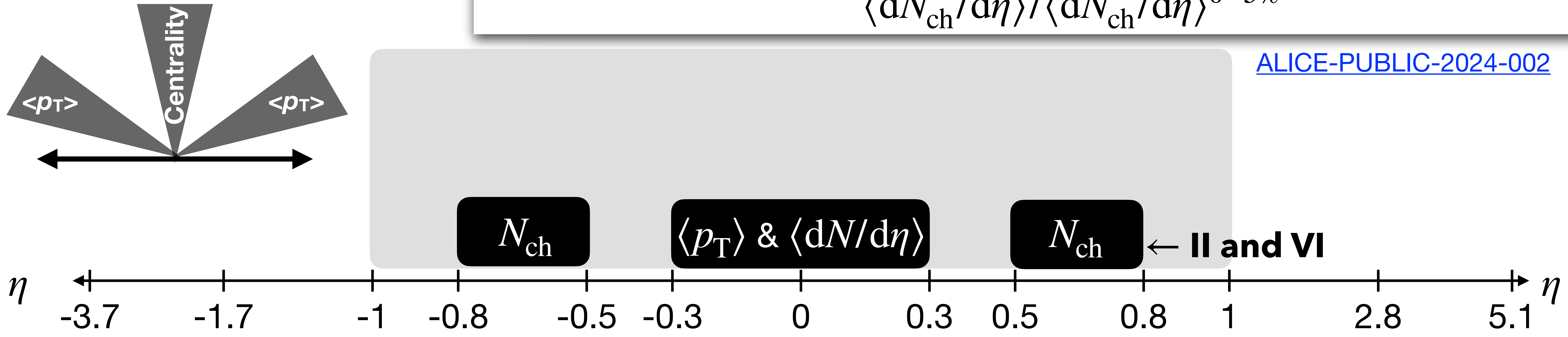

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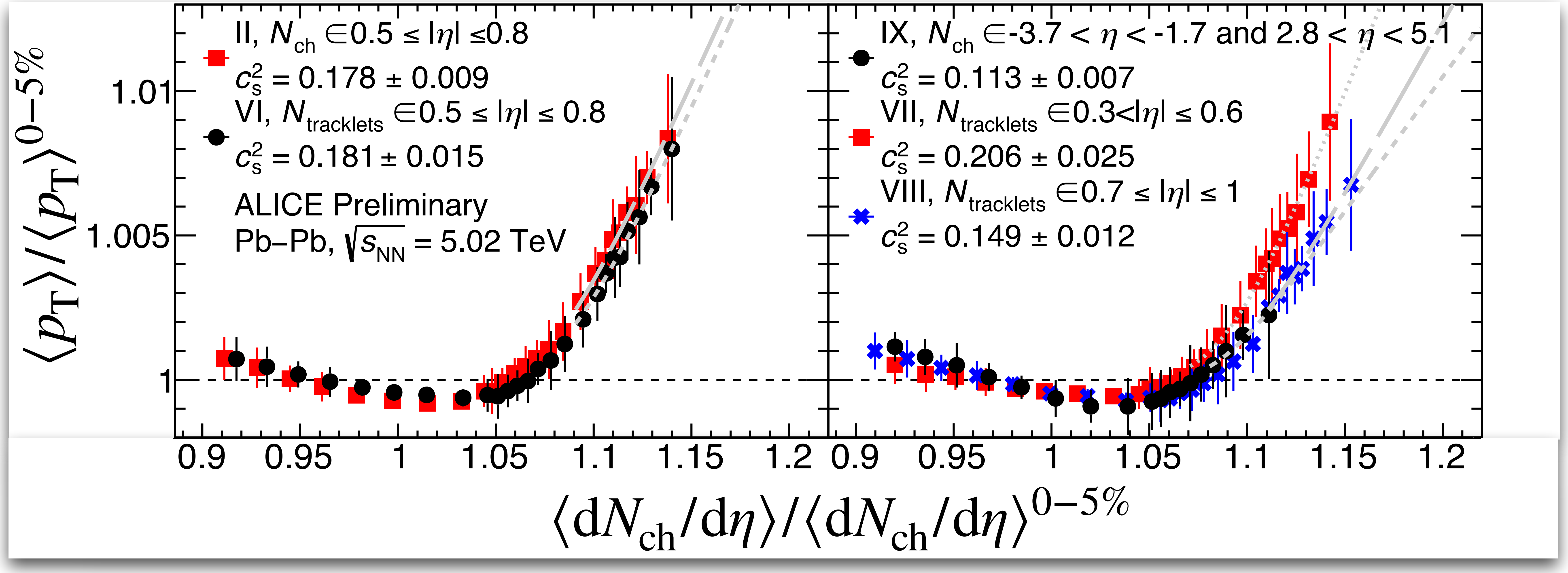

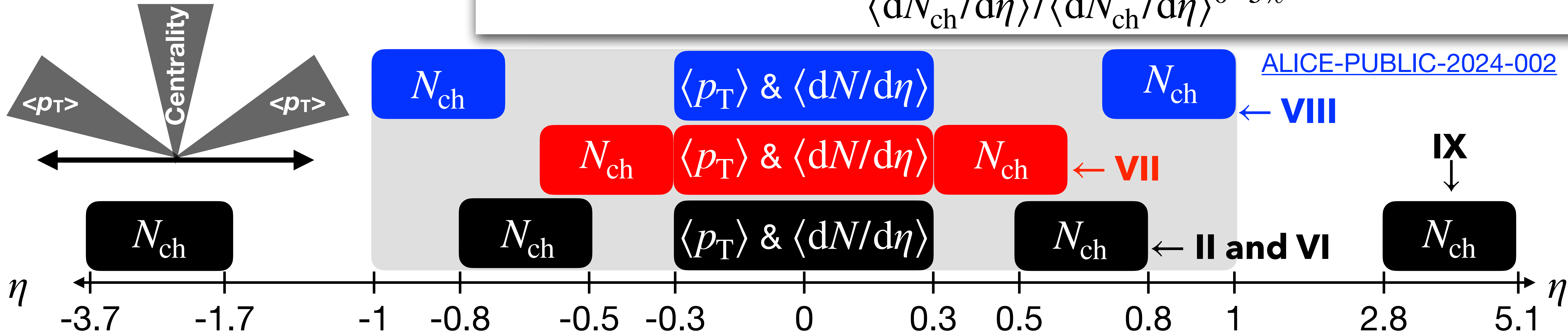

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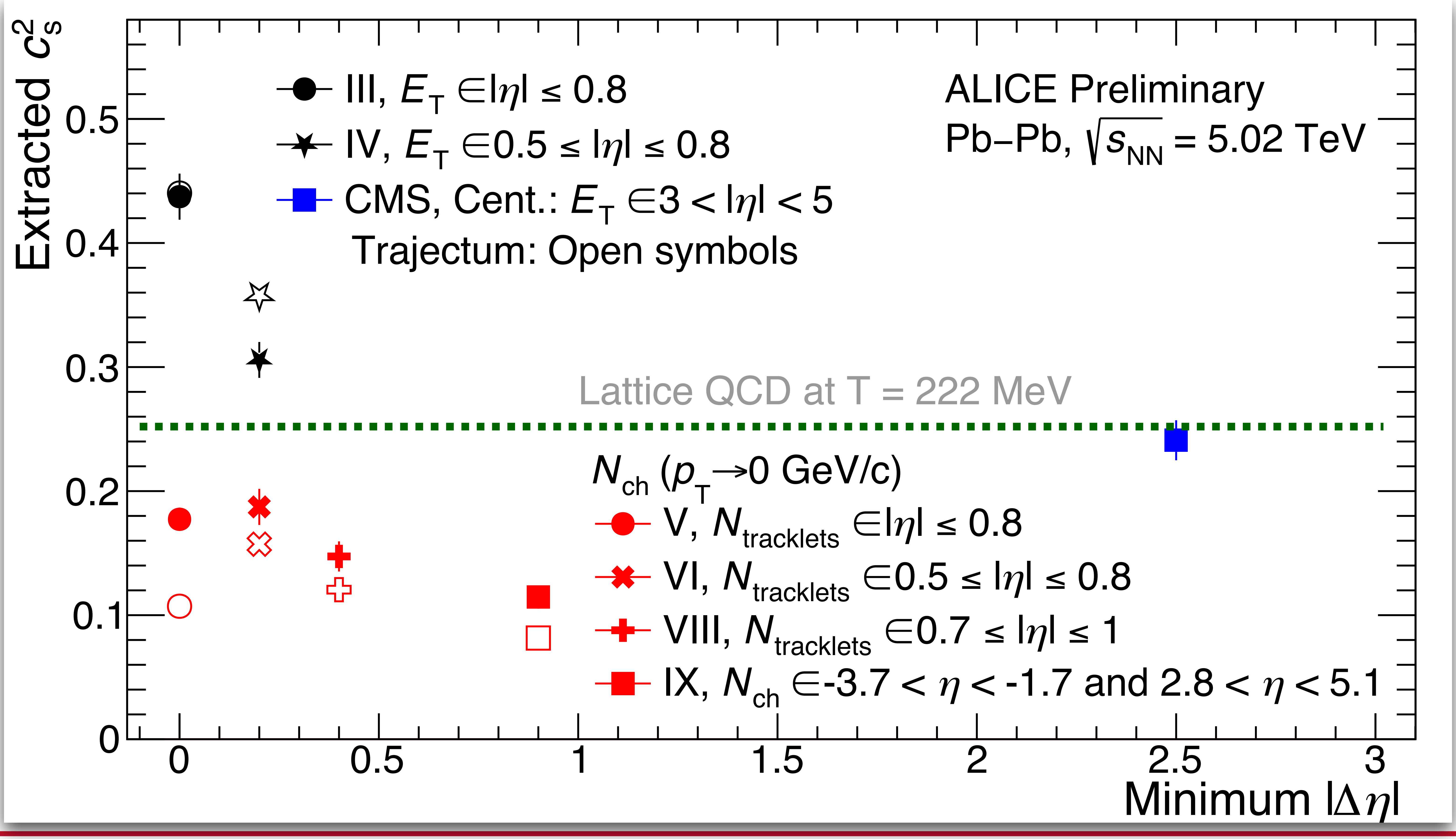
Extracted c_s^2 v.s. pseudorapidity gap

- A clear picture emerges → Extracted speed of sound higher for E_T compared to N_{ch} centrality estimator with fixed eta gap for ALICE.
- Different events are selected depending on the centrality definition. ALICE-PUBLIC-2024-002



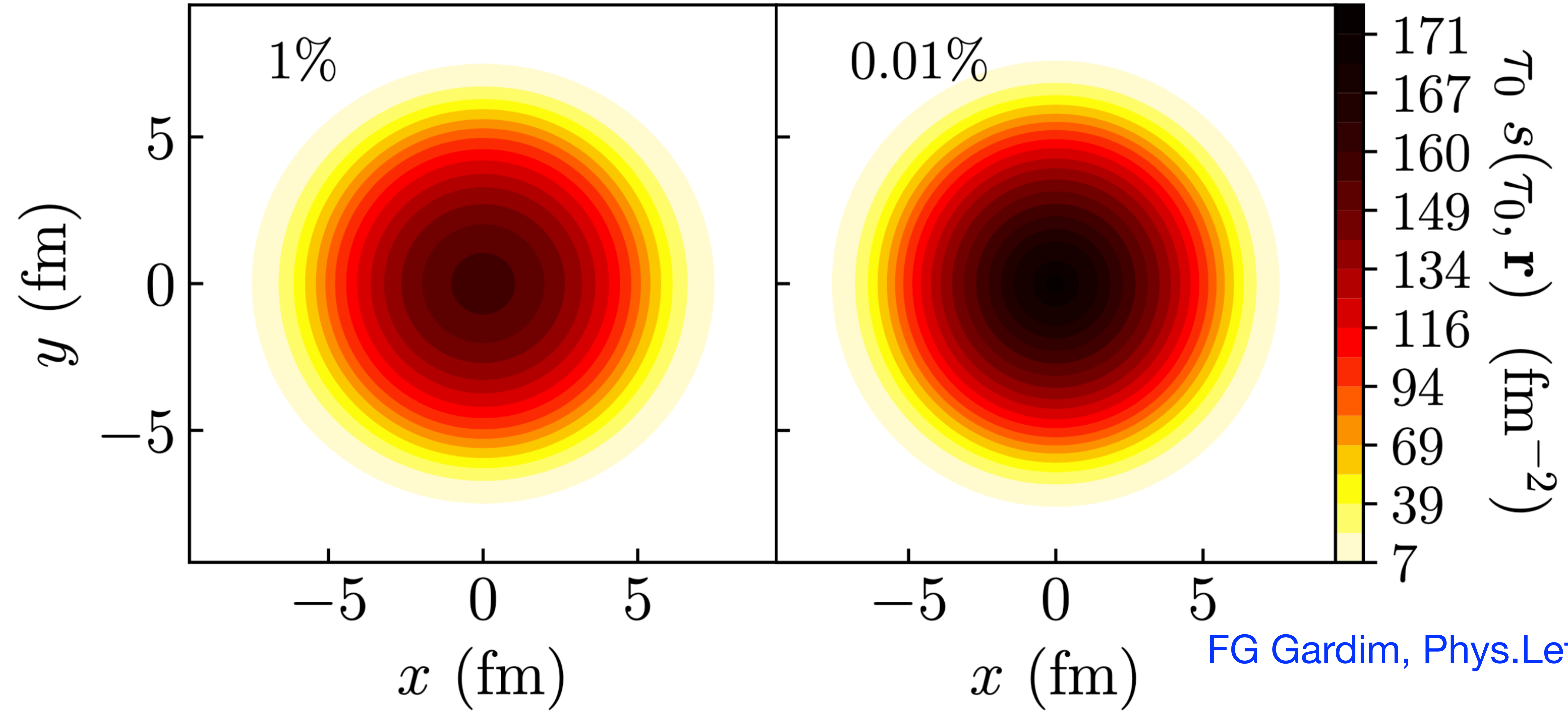
Conclusions

- ALICE observes an increase of $\langle p_T \rangle$ with $\langle dN_{ch}/d\eta \rangle$ in UCCs → new opportunity to investigate QGP equation of state.
- The $\langle p_T \rangle / \langle p_T \rangle^{0\text{-}5\%}$ versus $\langle dN_{ch}/d\eta \rangle / \langle dN_{ch}/d\eta \rangle^{0\text{-}5\%}$ correlation depends on the definition of centrality.
  - Experimental confirmation of Trajectum model prediction.
- The extraction of c_s^2 is not trivial → **biases are significant.**
  - The extracted c_s^2 using E_T-based centrality estimators is larger compared to that using the N_{ch}-based estimators → short and long-range $\langle p_T \rangle$-$\langle p_T \rangle$ correlations.
- Call for a reevaluation of how the c_s^2 can be extracted from heavy-ion data.

Backup

Ultra-central Pb—Pb collisions (UCCs)

- The QGP's volume is mostly fixed → constrain impact parameter fluctuations.
- Total entropy (S) can vary significantly → increase of the charged-particle multiplicity (N_{ch}).

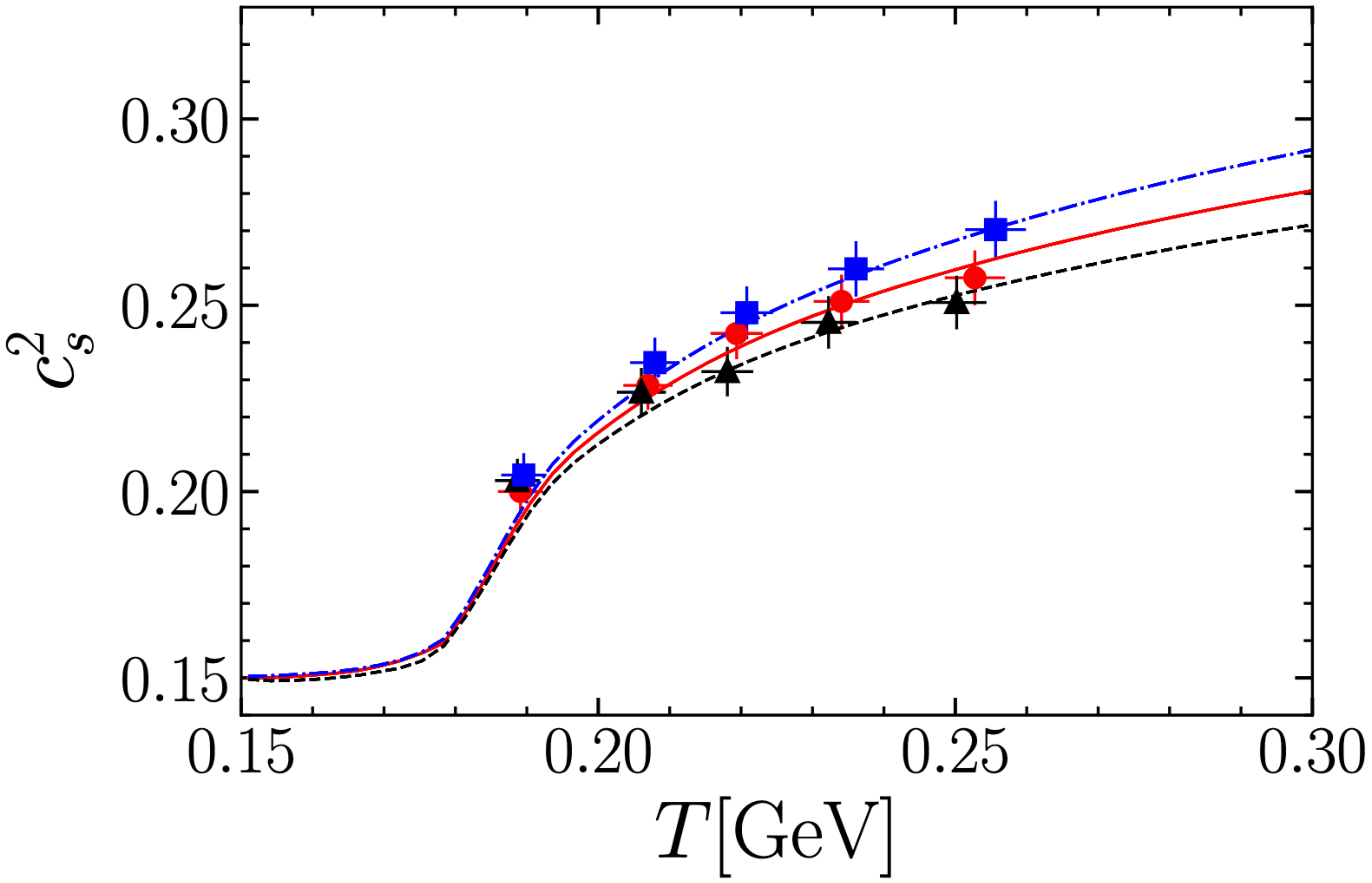


FG Gardim, Phys.Lett.B 809 (2020) 135749

Entropy density per unit transverse as a function of transverse coordinates of Pb-Pb collisions @ 5.02 TeV

c_s^2 from the EoS compared to the extracted values

arXiv:2403.06052v2

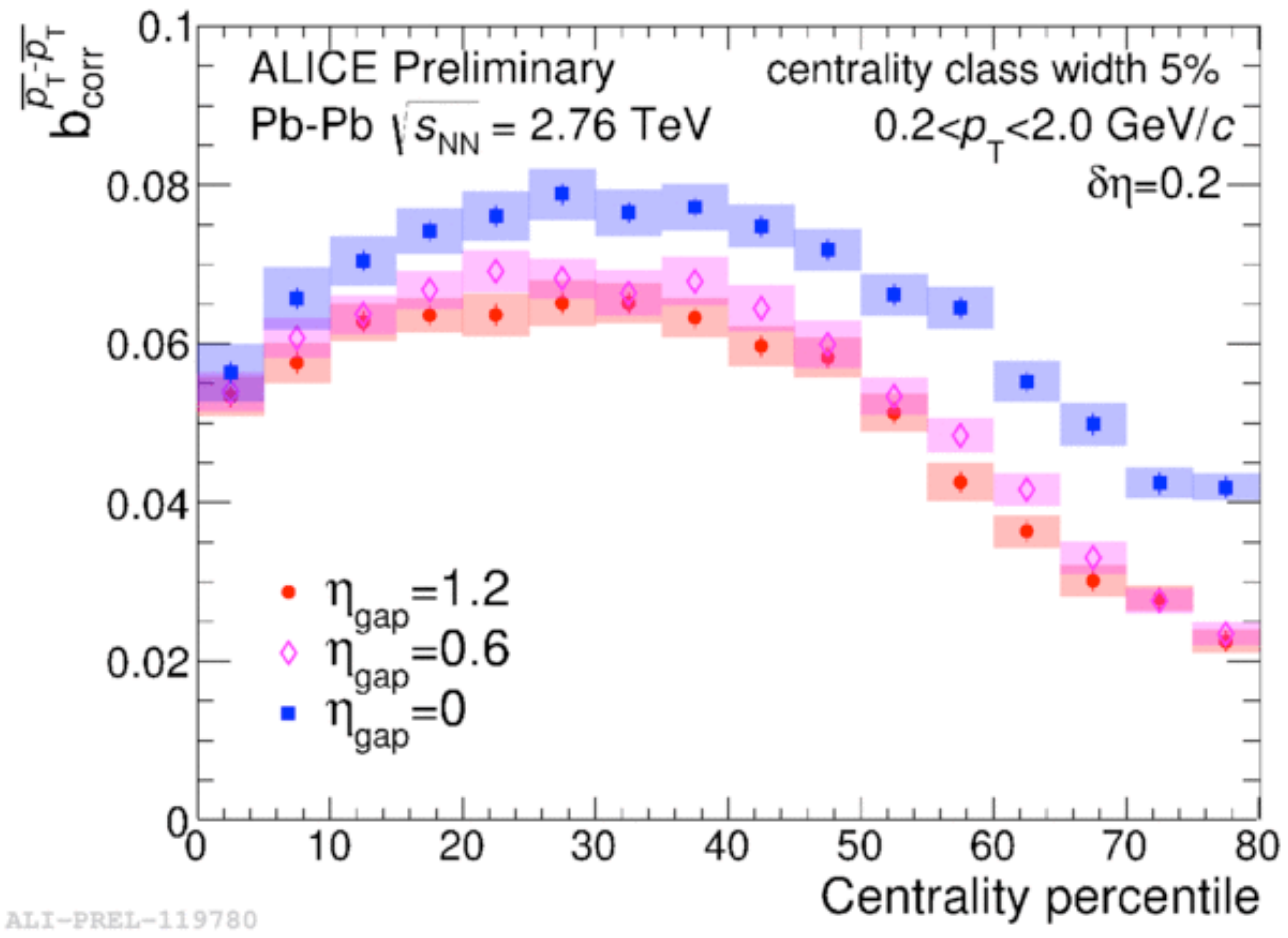


Measuring the <p_T> and <dN/dη> in UCCs

- Pb—Pb data at $\sqrt{s_{NN}} = 5.02$ TeV.
- Use high multiplicity and high transverse energy events to select UCCs.
- Measure the p_T spectra in narrow percentile bins.
- Correct the spectra by tracking inefficiency and secondary particle contamination.

- Extrapolation to p_T=0
- By fitting the spectra in 0.15< p_T < 1.5 GeV/c with a Boltzmann-Gibbs Blast-Wave model.
- Measure <p_T> and <dN/dη> in the p_T interval between 0 and 10 GeV/c.
- The fraction of extrapolated yields is about 9%.

Forward-backward <p_T> correlations



Dependence of <*b*> on the centrality estimator

Trajectum simulations; the average impact parameter (<*b*>) decreases slowly for ultra-central collisions (<0.01%).

The centrality selector based on N_{ch} without p_T bias does best at selecting ultra-central collisions because <*b*> is both, constant and lowest.