Assessing the speed of sound in the QGP with ALICE

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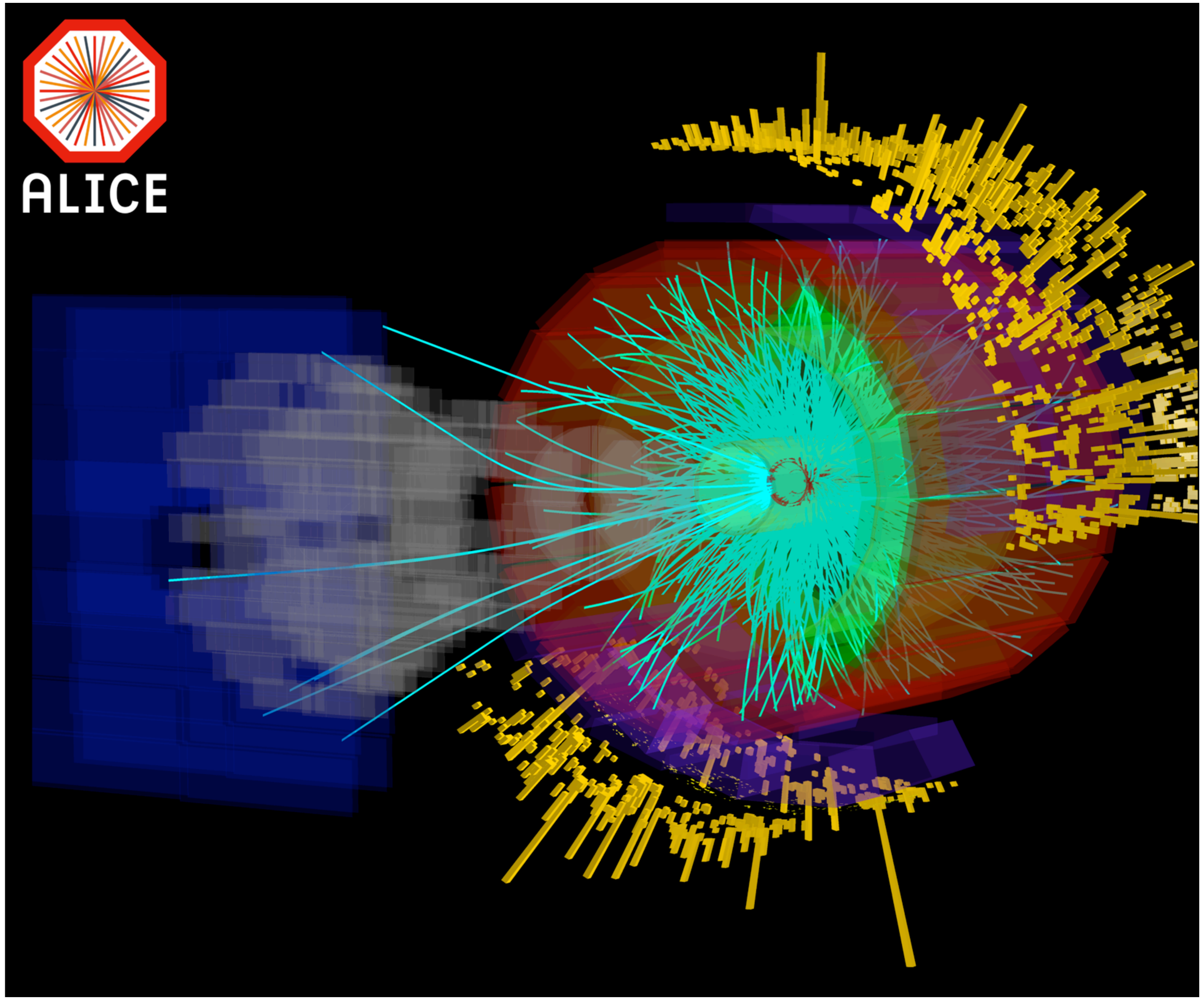
Seminario de Física de Altas Energías

14 August, 2024

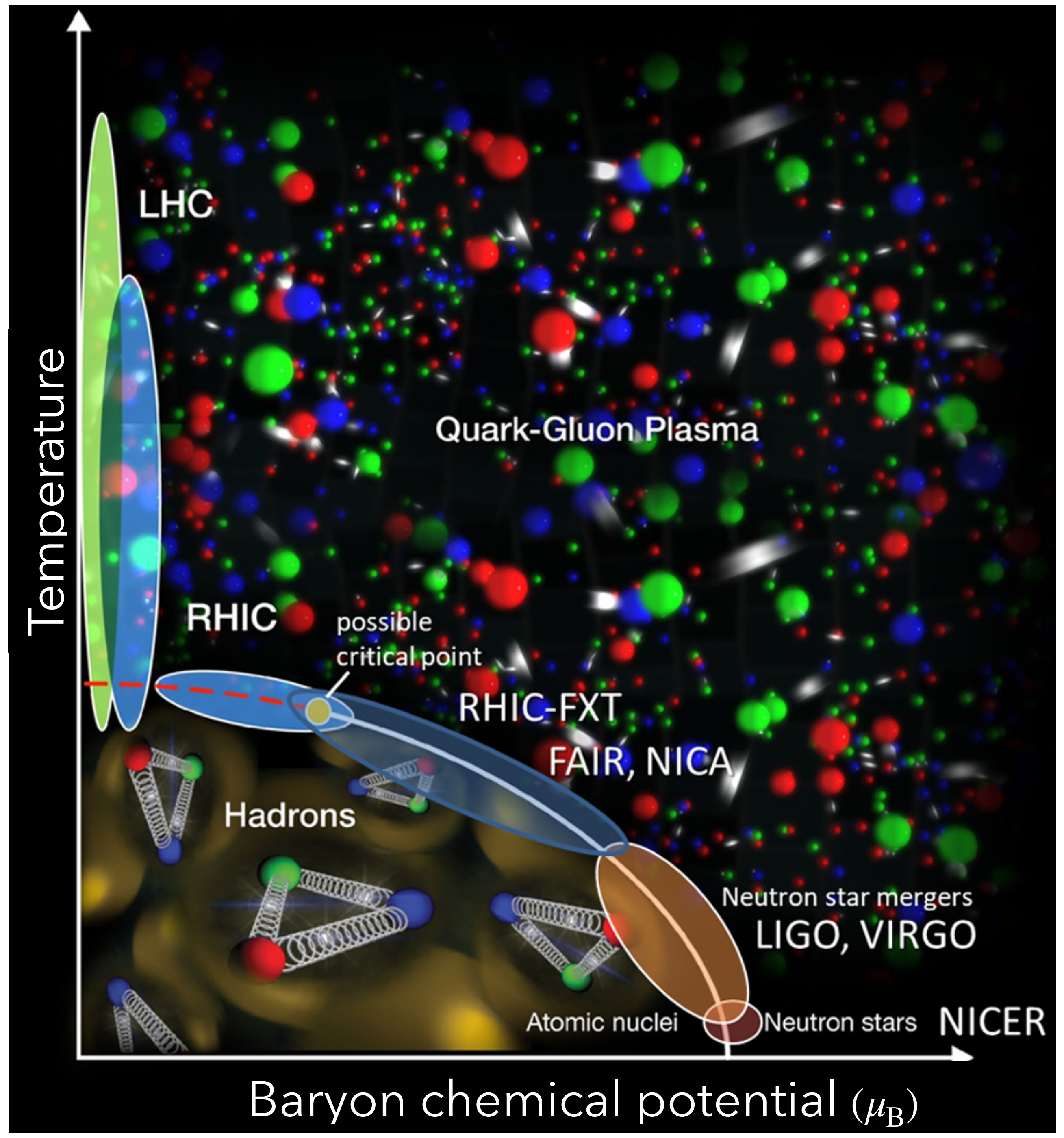
Outline of the talk



- Introduction
  - The QCD phase diagram & the EoS
  - The speed of sound, c_s
  - Ultra-central AA collisions (UCCs)
- The ALICE experiment
- Data analysis
- Results
- Conclusions

Introduction

QCD phase diagram and the equation of state (EoS)

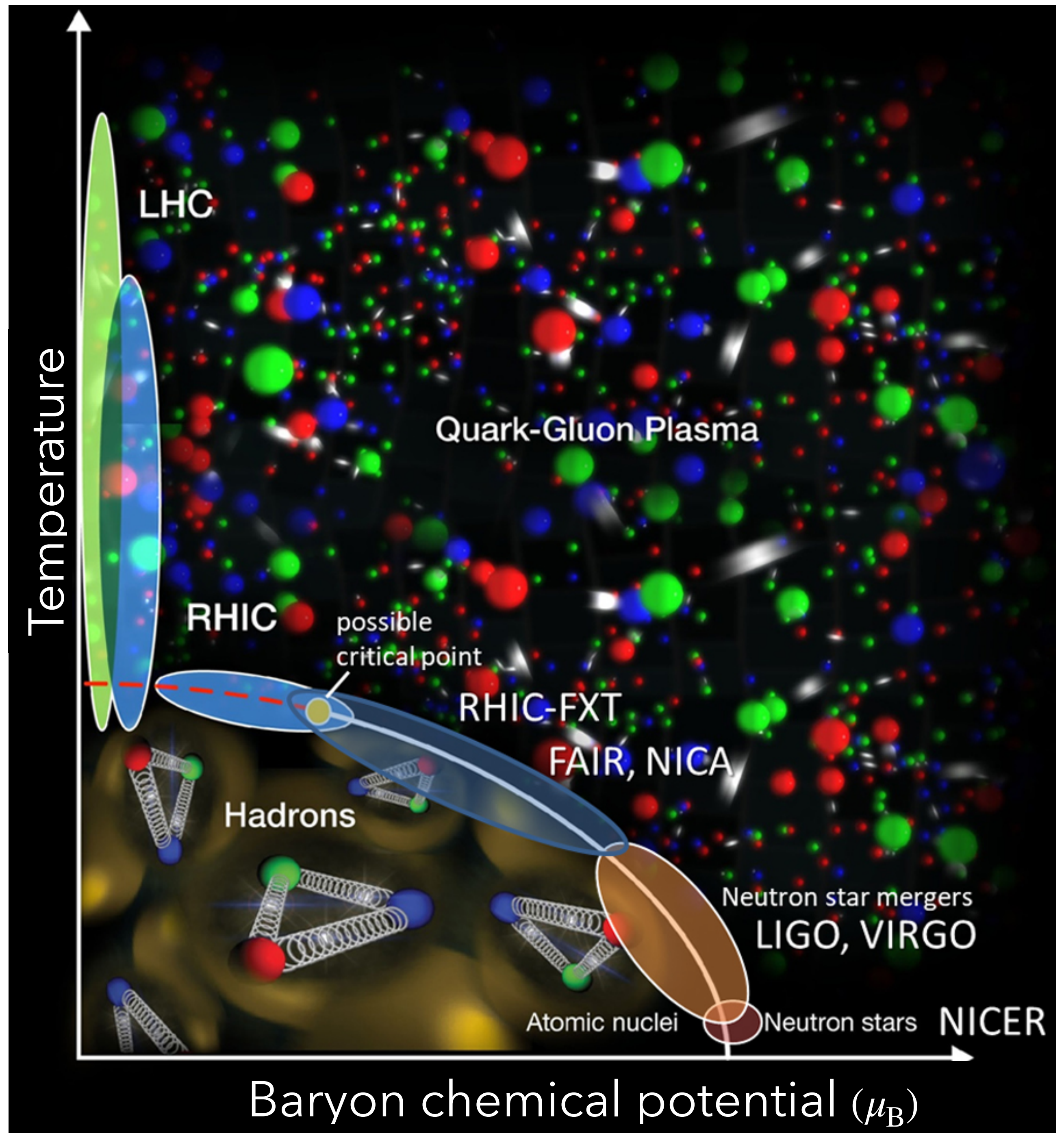


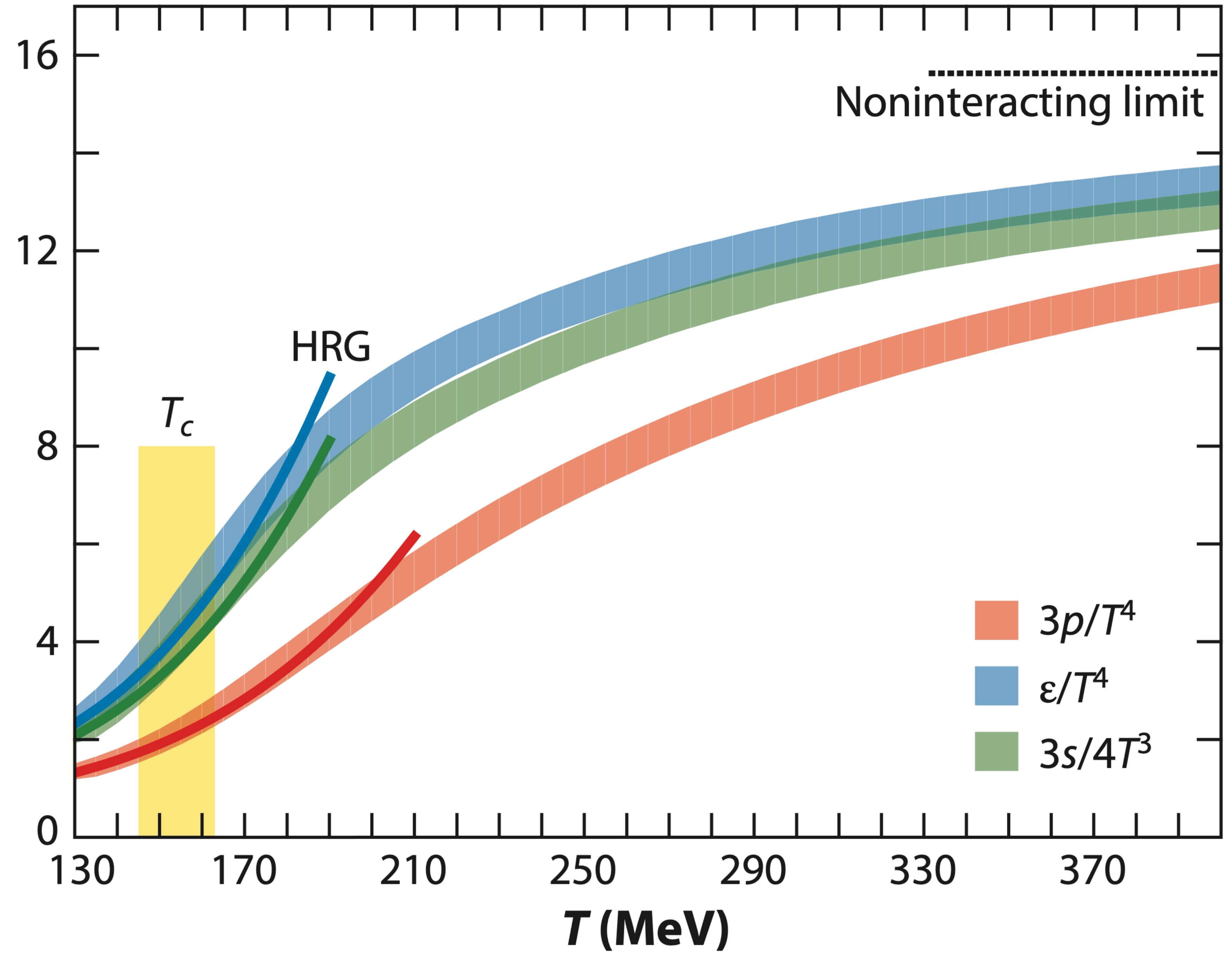
- Ultrarelativistic AA collisions are used to map the **phase diagram** of QCD matter.
- At high temperature (T) or high baryon density (μ_B), nuclear matter undergoes a **phase transition** into an unbound state of quarks, and gluons —a **quark-gluon plasma** (QGP).

Phys. Rev. D90 (2014) 094503

- The EoS governs the dependence of the pressure (P) of QCD matter on the T, and μ_B.
- Lattice QCD predicts that nuclear matter undergoes a phase transition at T~155 MeV and $\mu_B \approx 0$.

QCD phase diagram and the equation of state (EoS)





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The speed of sound, c_s

- Velocity at which compression waves travel in a fluid.

$$c_s^2 = \frac{\mathrm{d}P}{\mathrm{d}\epsilon}$$

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

Nature Physics 16, 615-619 (2020)

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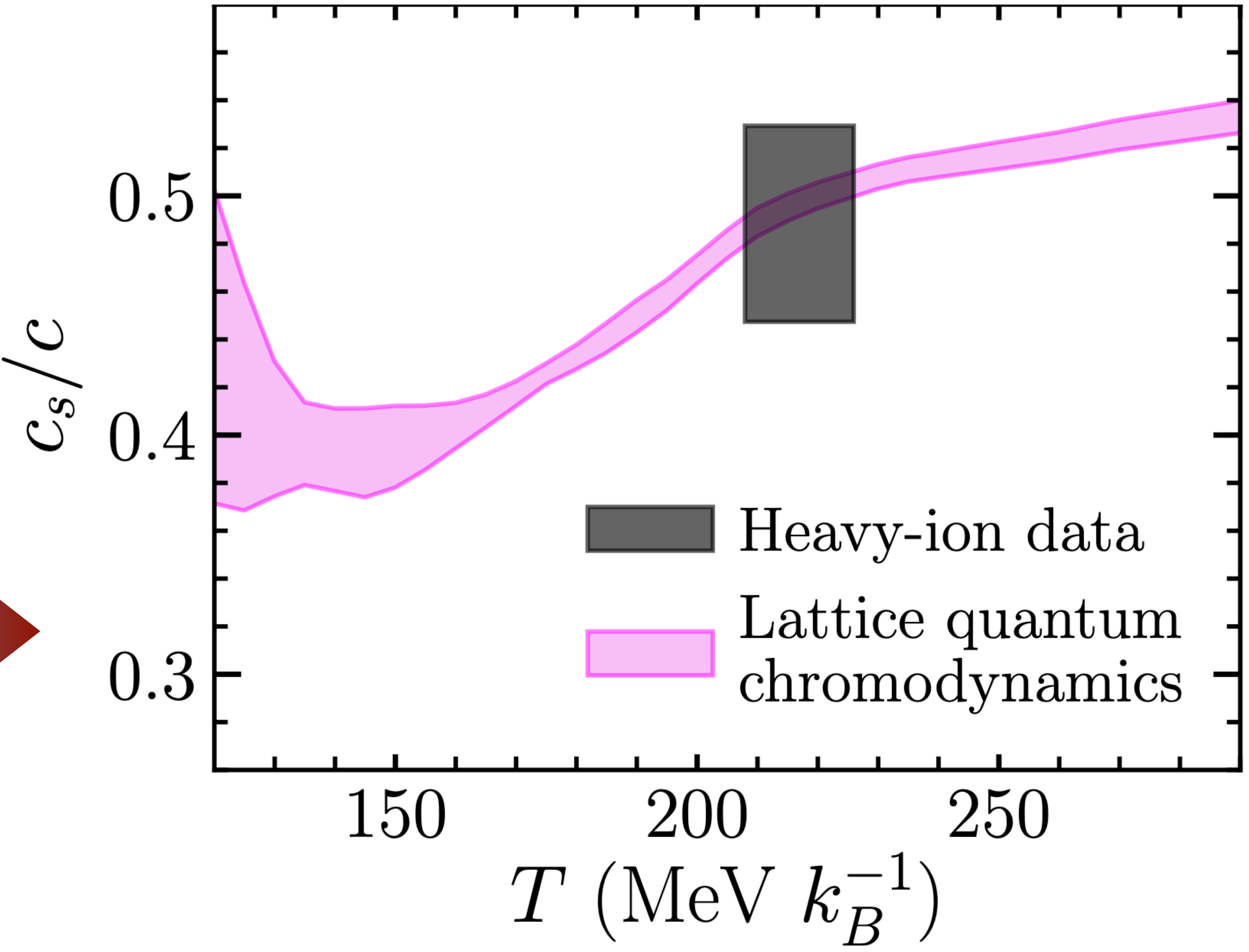


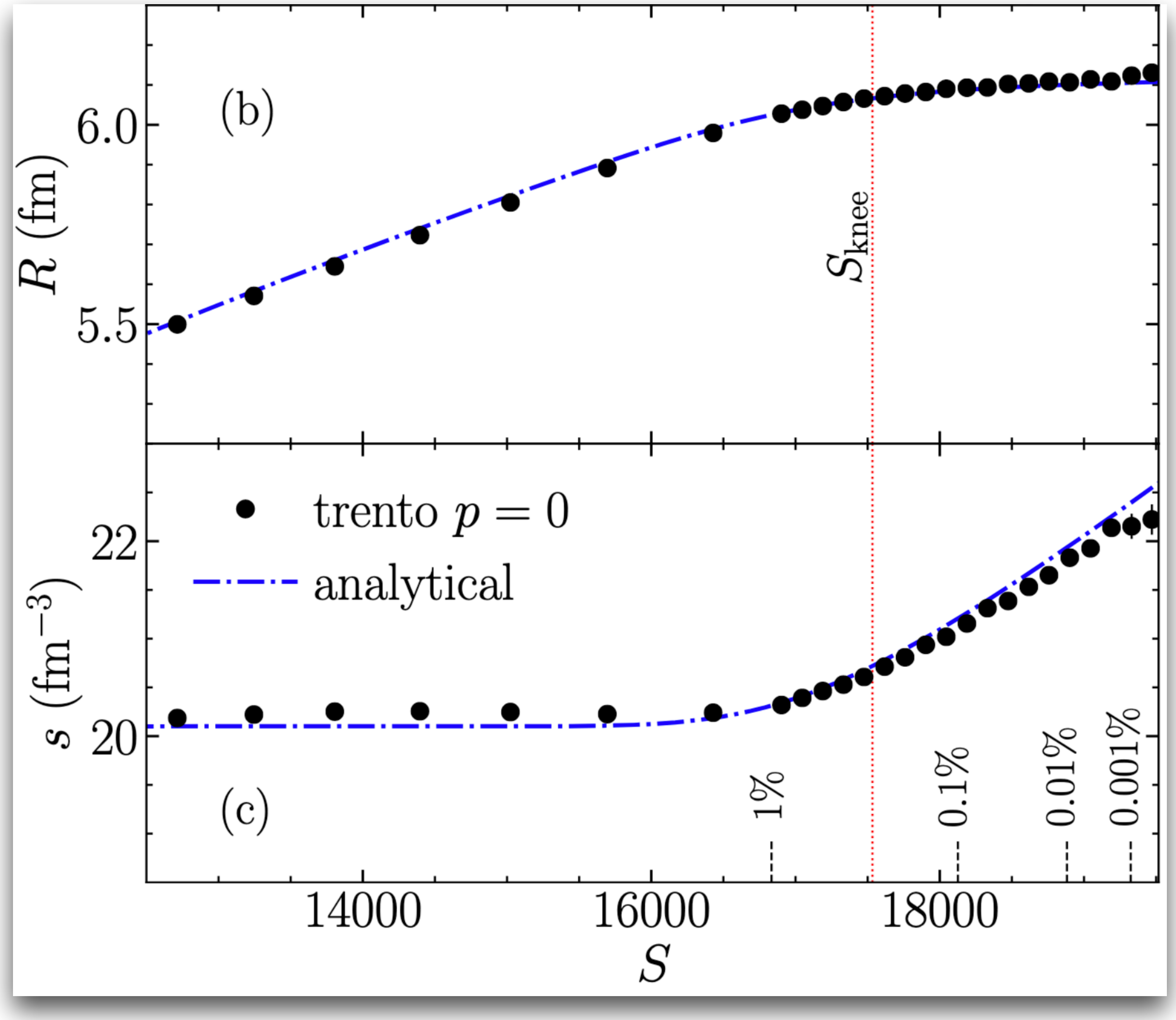
Ultra-central Pb-Pb collisions

- The volume of the QGP in UCCs is constant.
- Total entropy (S) can vary significantly → increase of the N_{ch}.
- Larger entropy density →higher temperature, T, → $\langle p_T \rangle$ increases.

- $$c_s^2 = \frac{dP}{d\epsilon} = \frac{s\,dT}{T\,ds} .$$
- Experimental determination of $c_s^2 = \dfrac{d\ln\langle p_T\rangle}{d\ln\langle dN_{ch}/d\eta\rangle}$.

Nature Physics 16, 615-619 (2020)

Phys. Lett. B 809 (2020) 135749



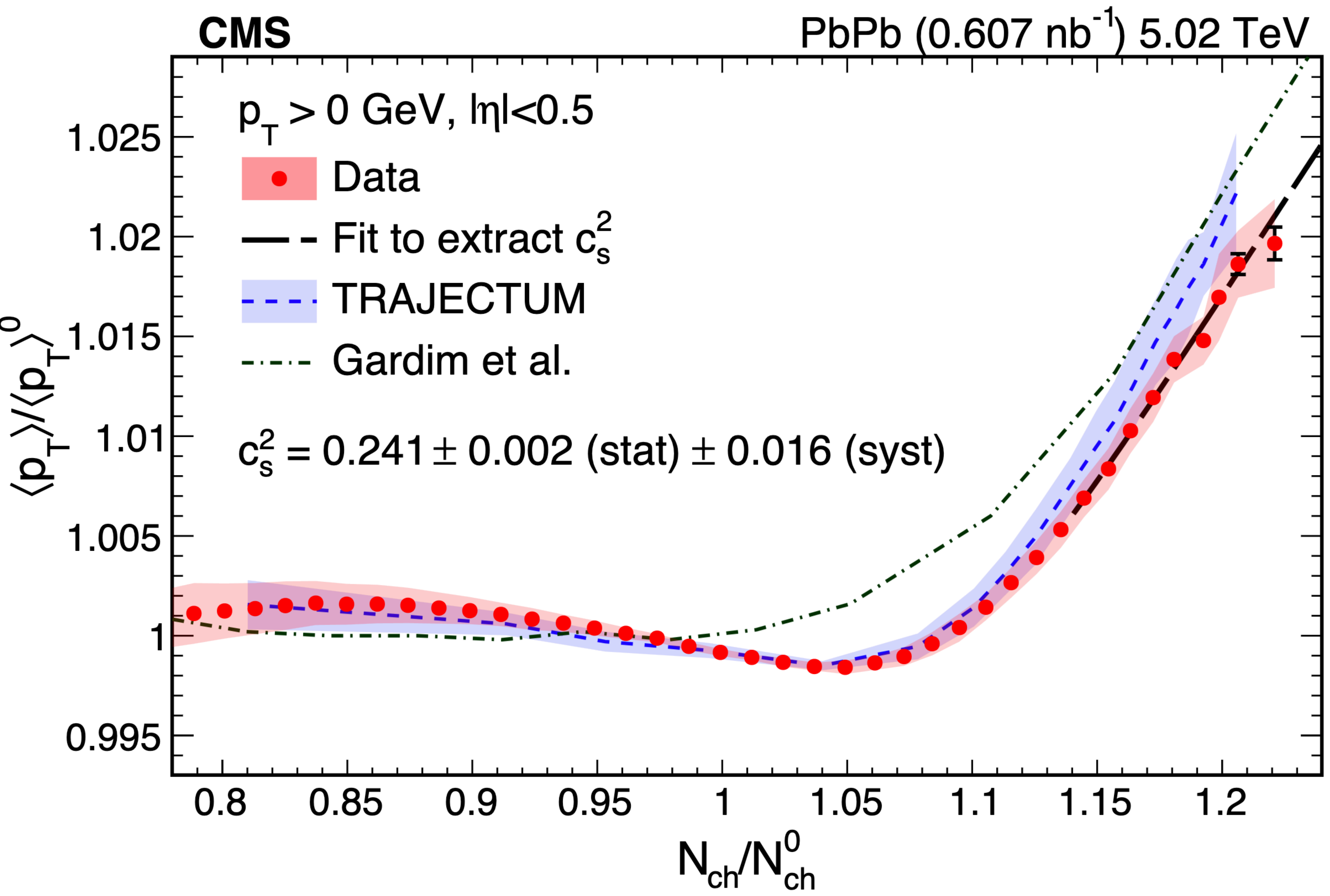
The S_{knee} is defined as the $\langle S \rangle$ at b=0.

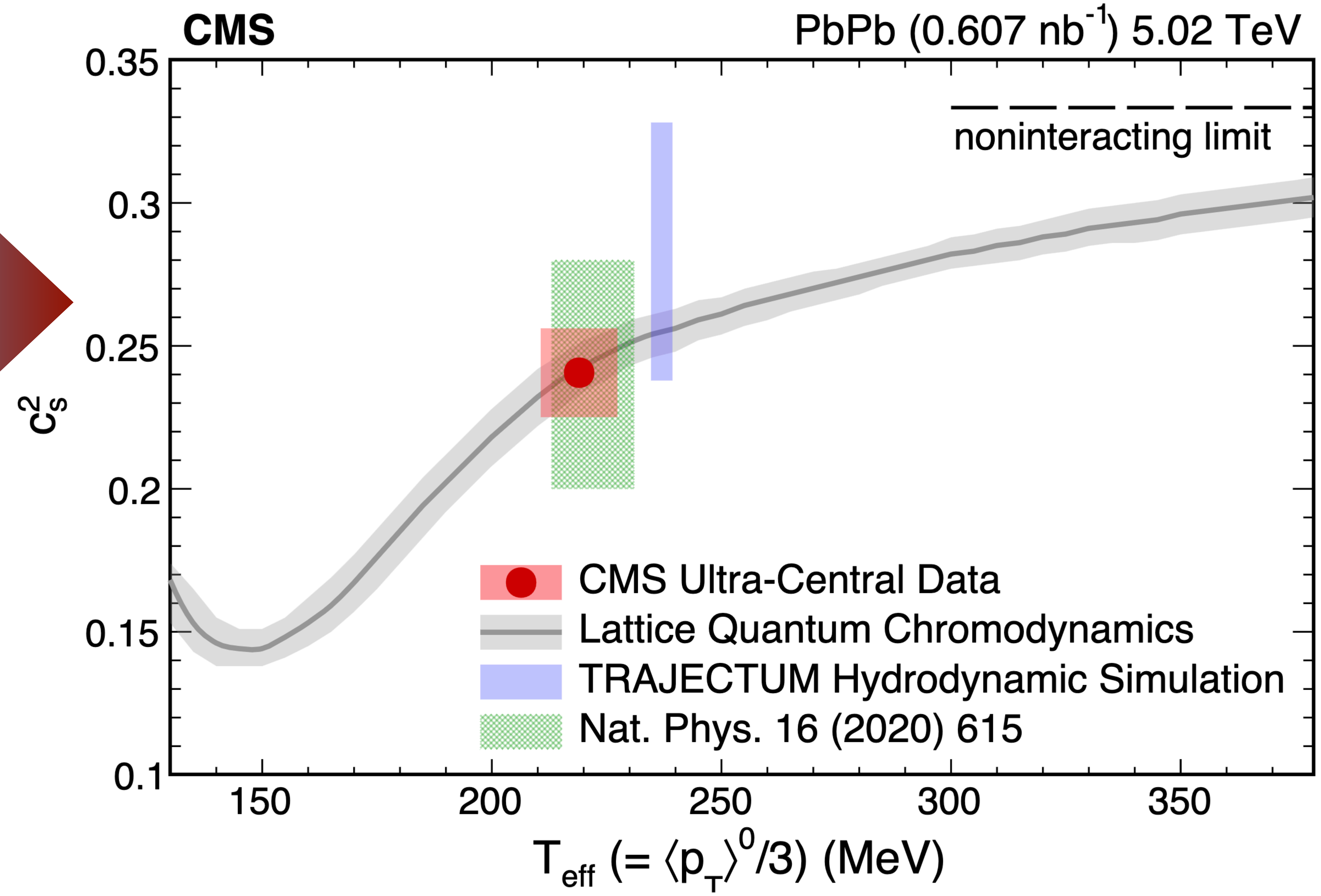
s ∝ S/R^3

First measurement of c_s^2 by the CMS Collaboration

- CMS made the first measurement using UCCs to extract c_s^2 at the LHC energies.
  - Uses the <p_T>/<p_T>^{0} v.s. N_{ch}/N_{ch}^0 correlation → minimizes the total systematic uncertainty.
- The extracted c_s^2 agrees well with lattice QCD predictions.

arXiv: 2401.06896

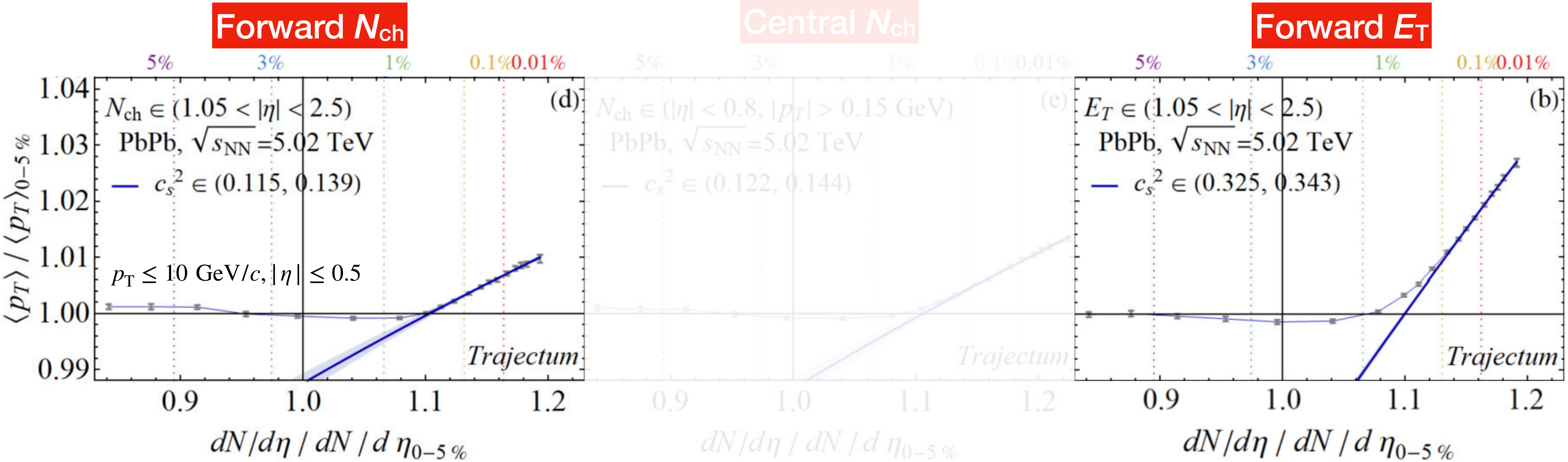




What drives the rise of <p_T> in UCCs?

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

Results for different centrality estimators



Phys. Lett. B 853 (2024) 138636

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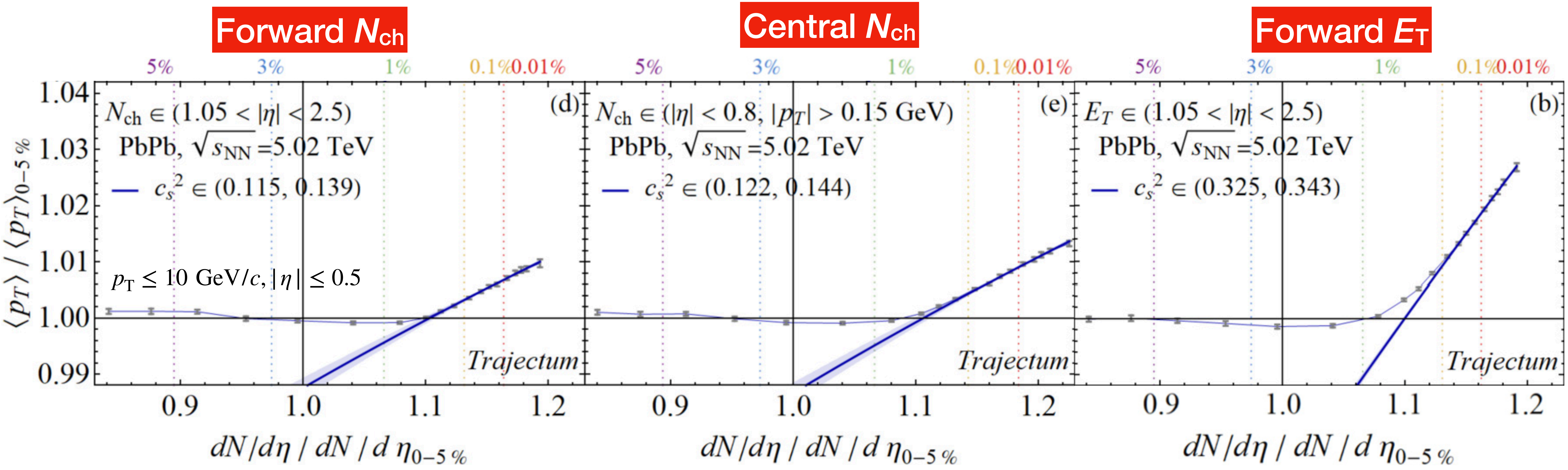

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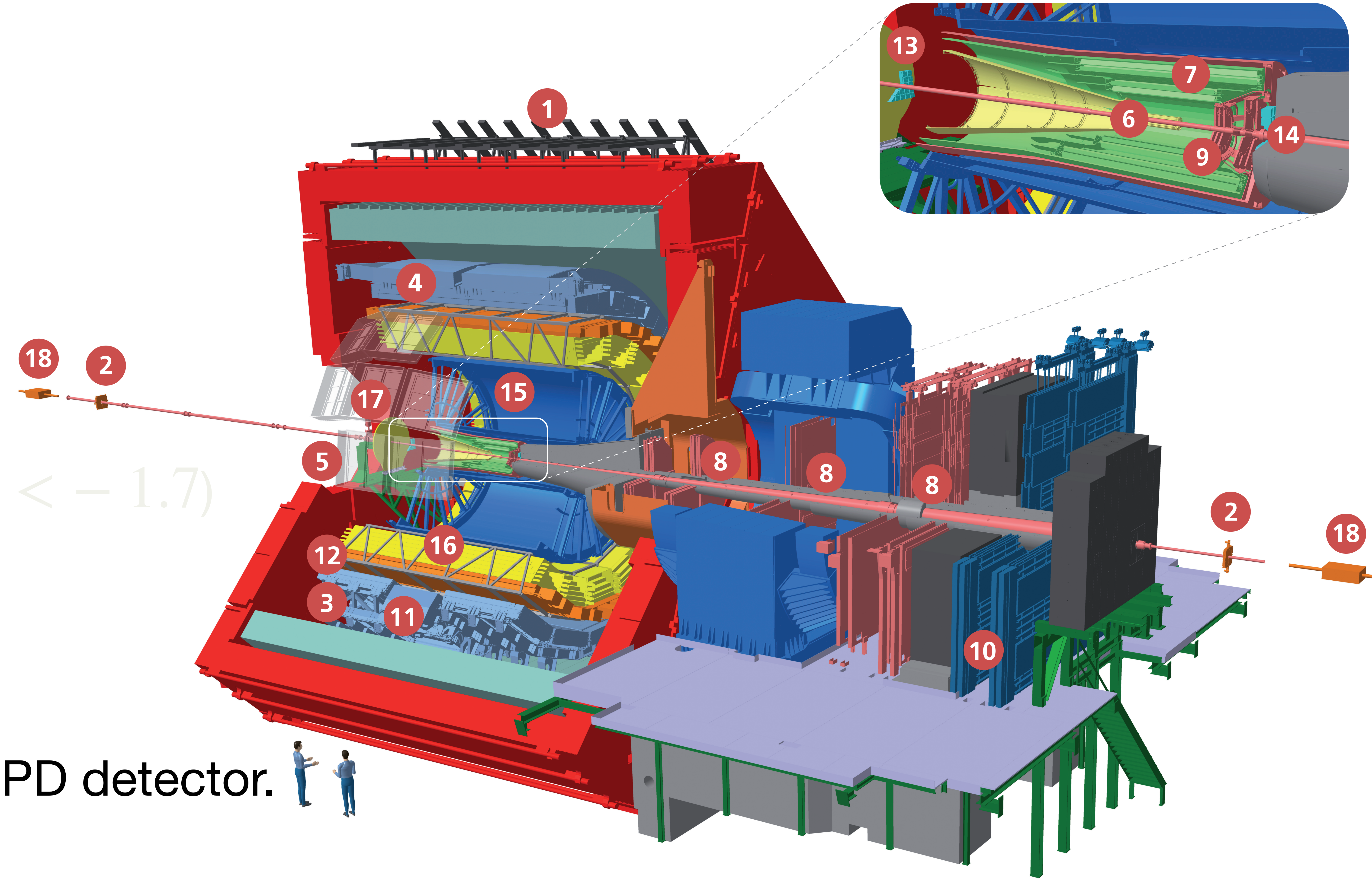
The ALICE experiment

ALICE in Run 2

Relevant detectors:

- Silicon Pixel Detector (SPD)
  Vertex reconstruction, tracking, and Multiplicity estimation ($N_{tracklets}$).
- Time-Projection Chamber (TPC)
  Tracking, PID, and multiplicity estimation (N_{ch}).
- V0A ($2.8 < \eta < 5.1$) and V0C ($-3.7 < \eta < -1.7$)
  Triggering, multiplicity estimation (N_{ch}).
- ZDC
  Centrality estimation.



Tracklet: track segment joining hits in the SPD detector.

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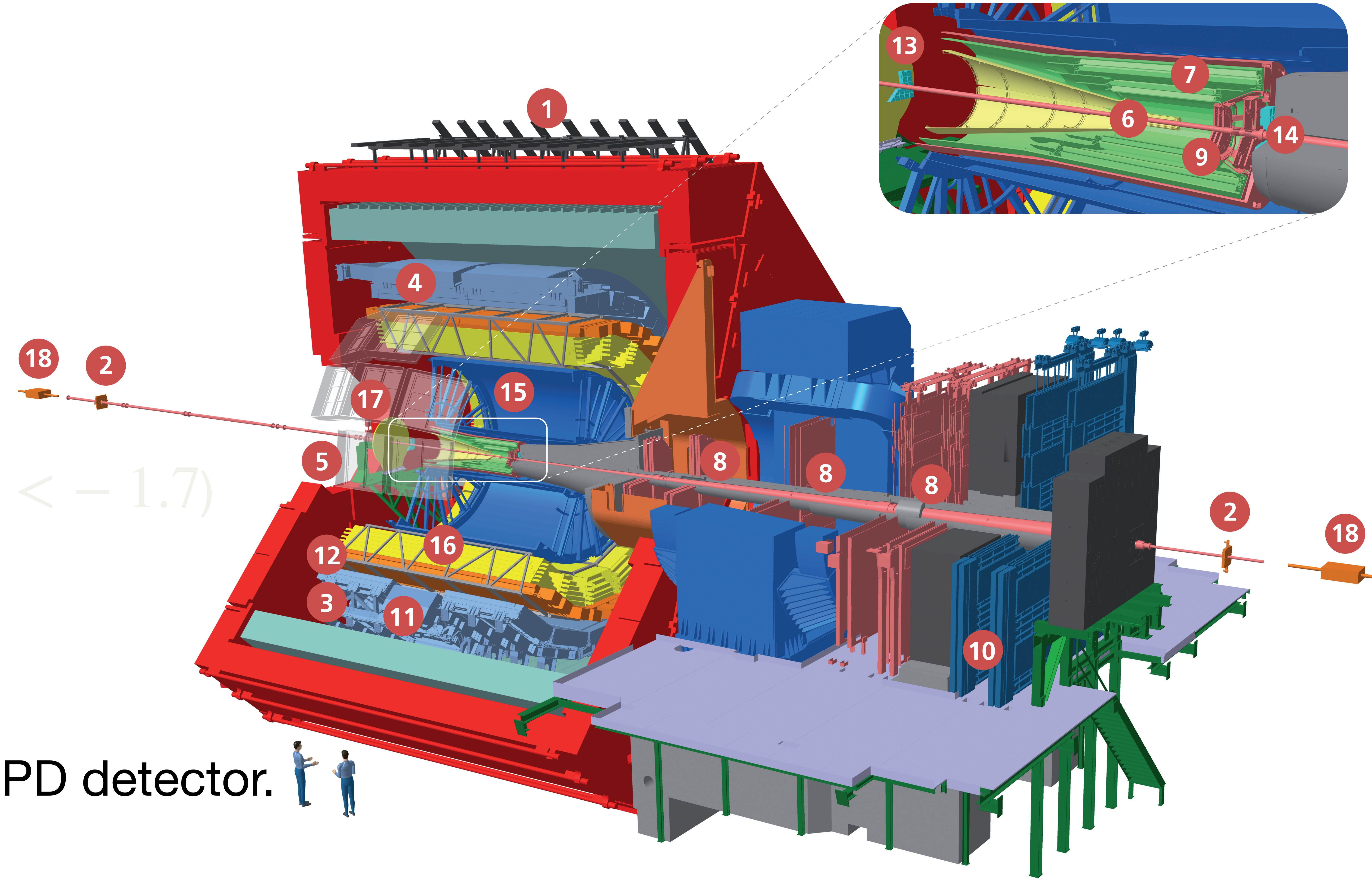

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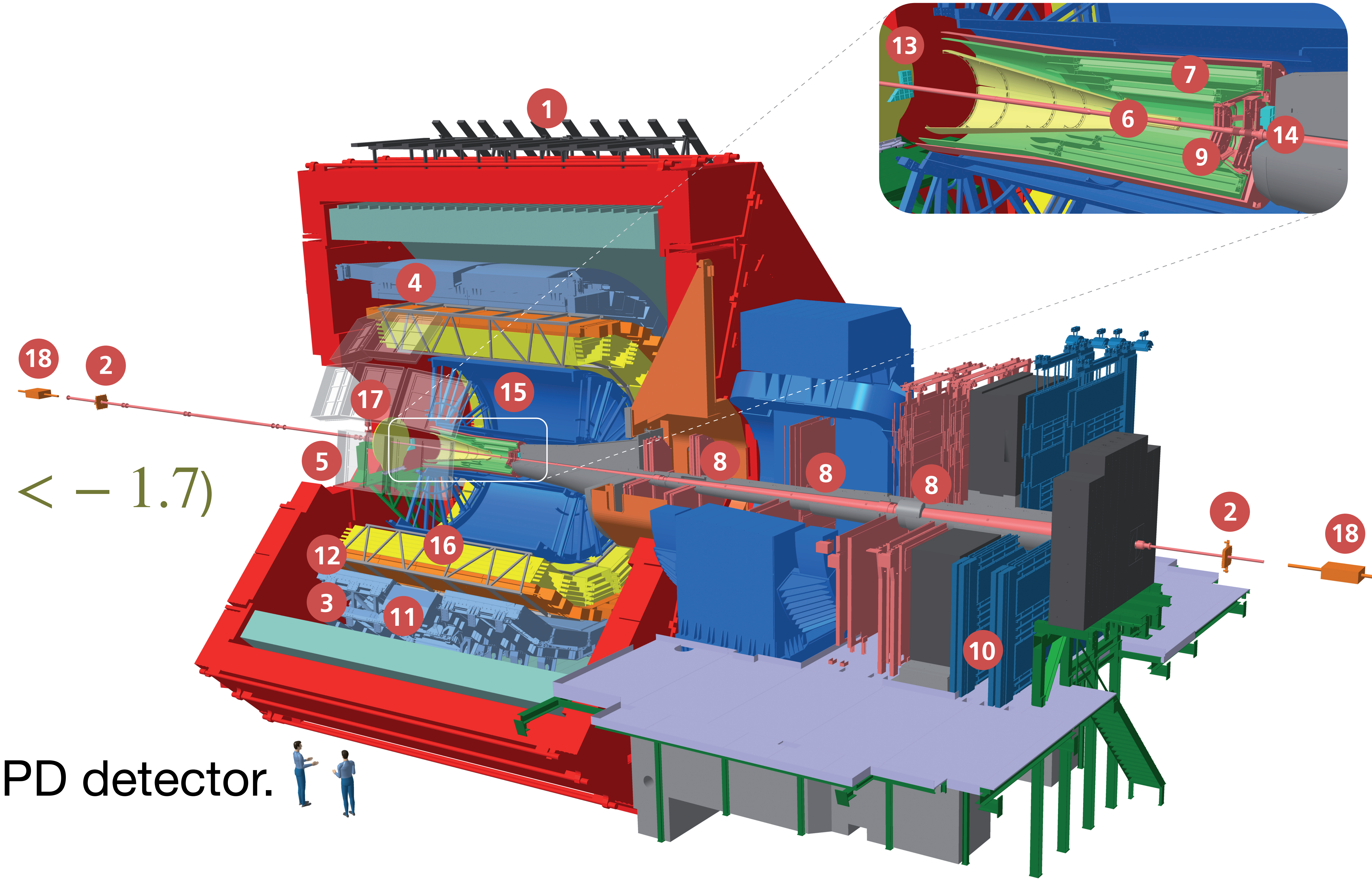

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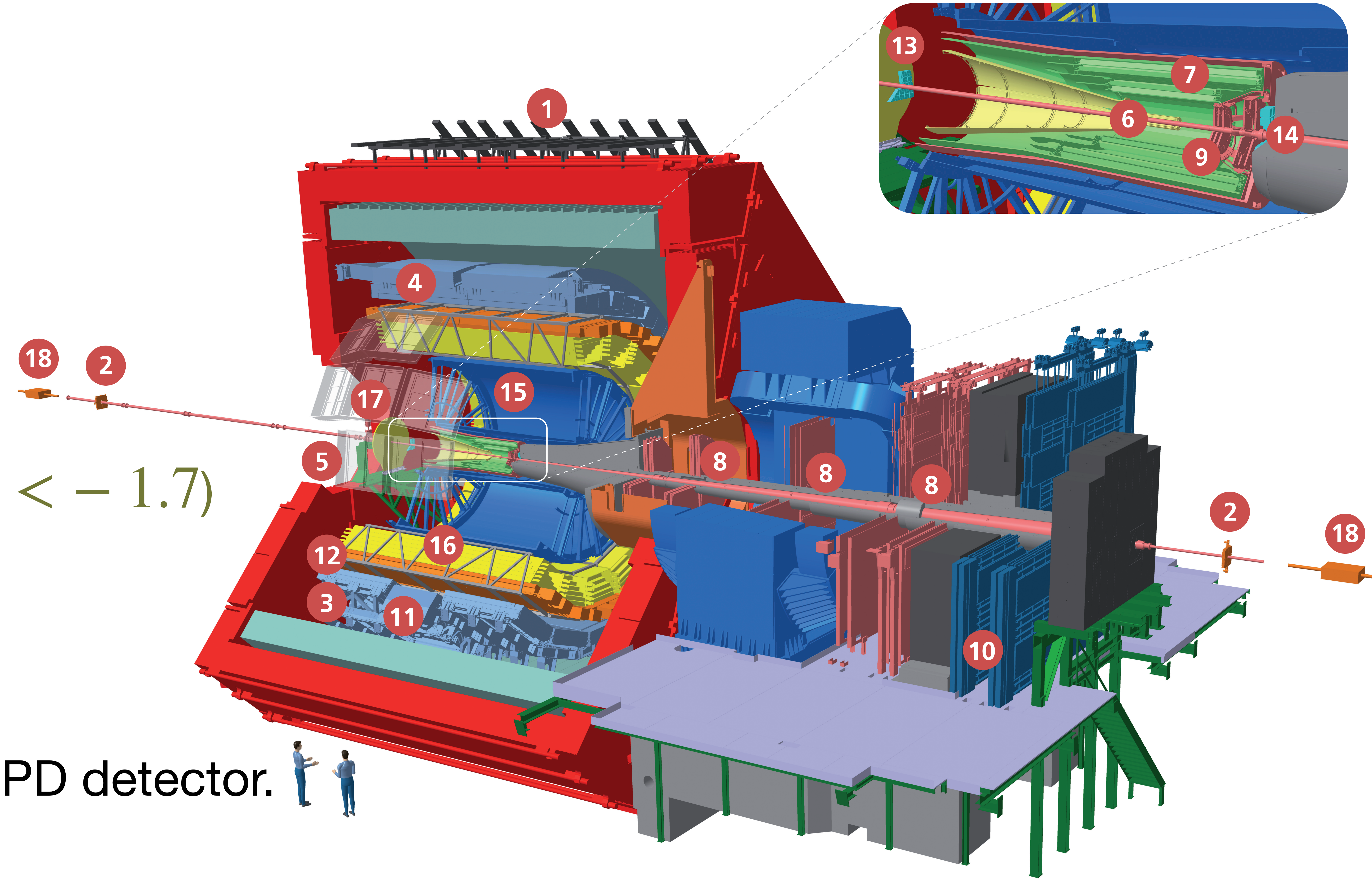


Data analysis

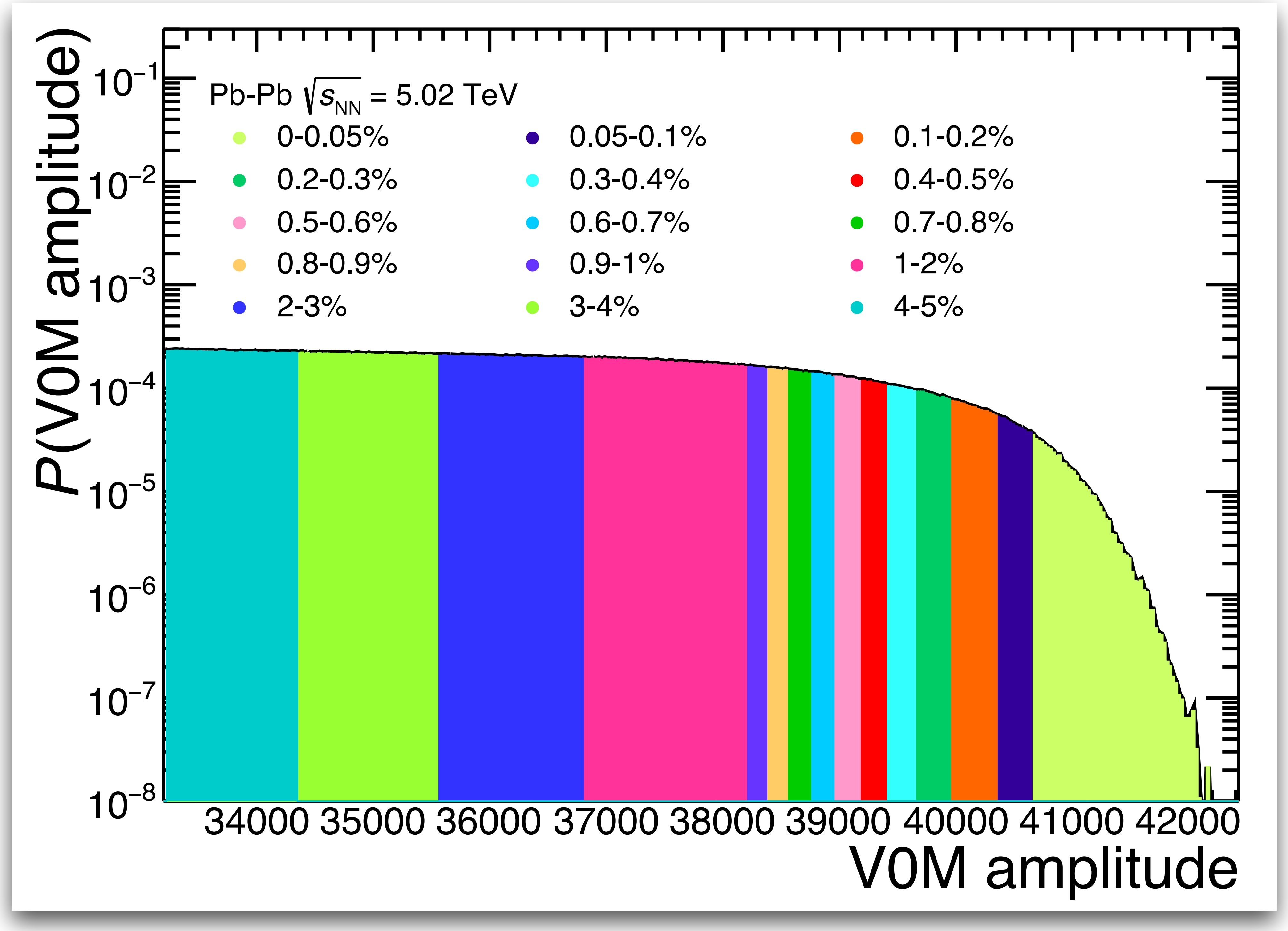
Centrality estimators

Observable	Label	Centrality estimation	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$	η gap
N_{ch} in TPC	I	$\|\eta\| \leq 0.8$	$\|\eta\| \leq 0.8$	0
	II	$0.5 \leq \|\eta\| \leq 0.8$	$\|\eta\| \leq 0.3$	0.2
E_T in TPC	III	$\|\eta\| \leq 0.8$	$\|\eta\| \leq 0.8$	0
	IV	$0.5 \leq \|\eta\| \leq 0.8$	$\|\eta\| \leq 0.3$	0.2
$N_{tracklets}$ in SPD	V	$\|\eta\| \leq 0.8$	$\|\eta\| \leq 0.8$	0
	VI	$0.5 \leq \|\eta\| \leq 0.8$	$\|\eta\| \leq 0.3$	0.2
	VII	$0.3 < \|\eta\| \leq 0.6$	$\|\eta\| \leq 0.3$	0
	VIII	$0.7 \leq \|\eta\| \leq 1$	$\|\eta\| \leq 0.3$	0.4
N_{ch} in V0	IX	$-3.7 < \eta < -1.7 + 2.8 < \eta < 5.1$	$\|\eta\| \leq 0.8$	0.9

- N_{ch} and E_T have a lower (upper) p_T cut of 0.15 (50) GeV/c.
- $N_{tracklets}$: lower p_T cut of 0.03 GeV/c.

Measuring the p_T spectra

- 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.



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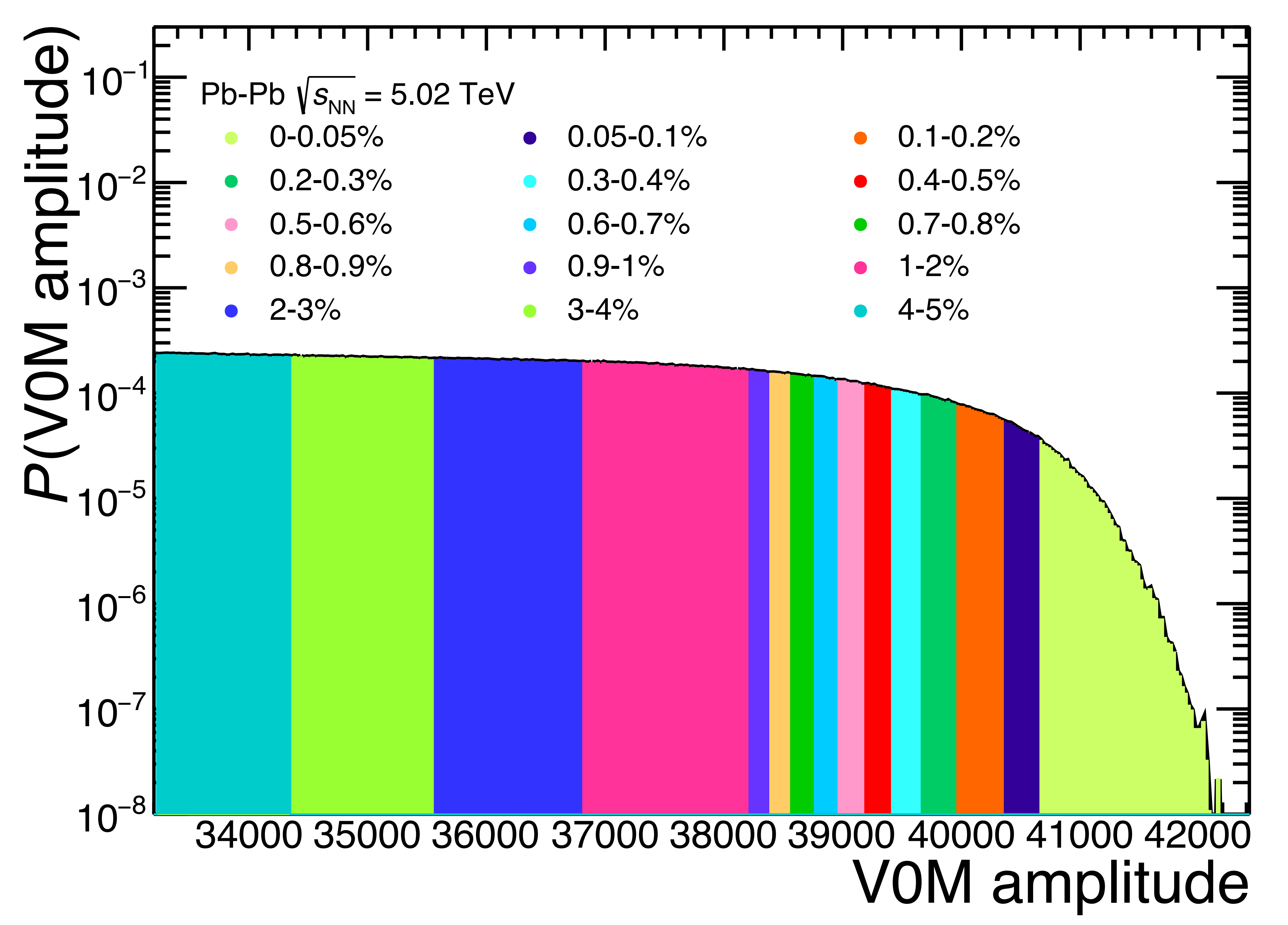
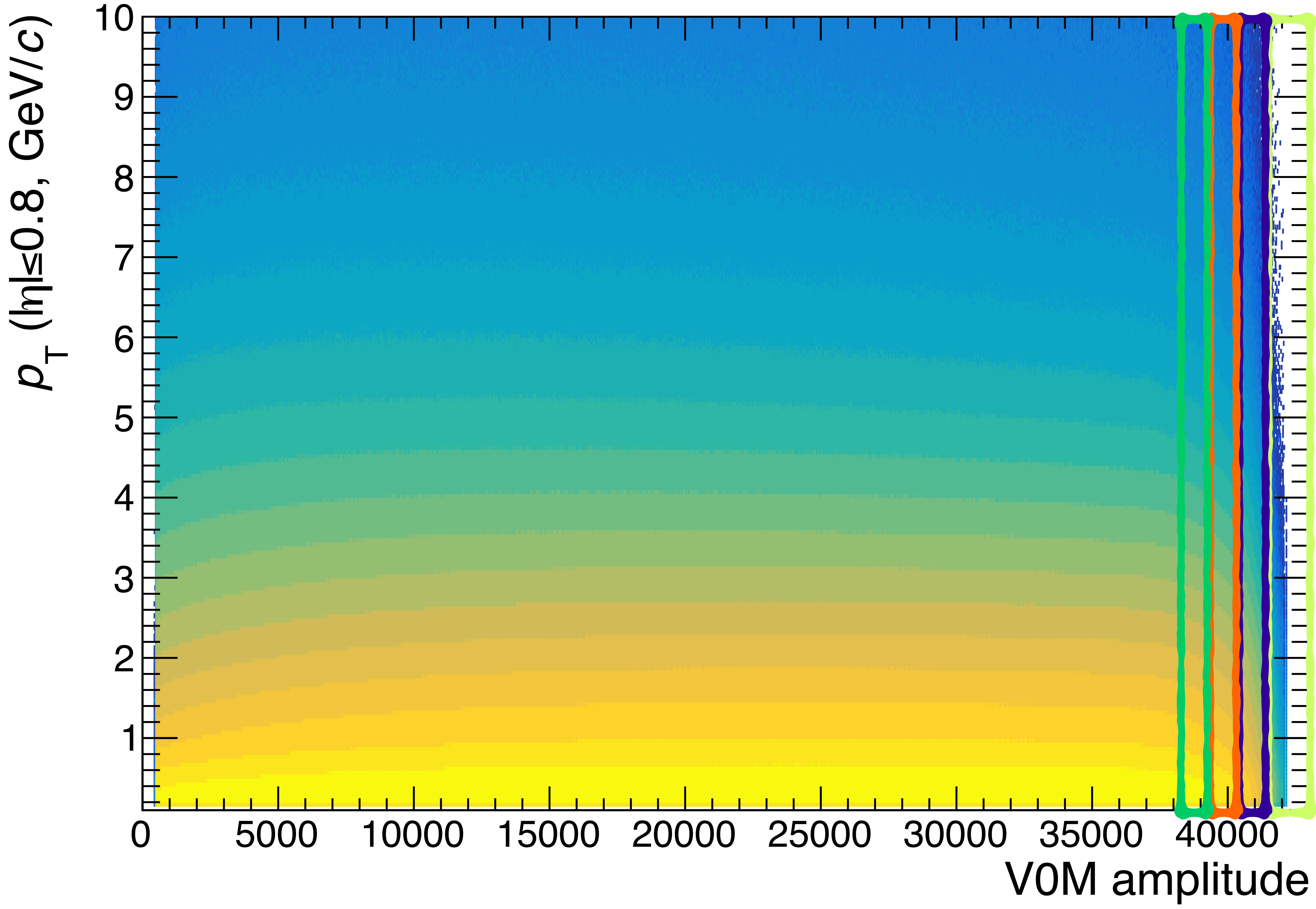
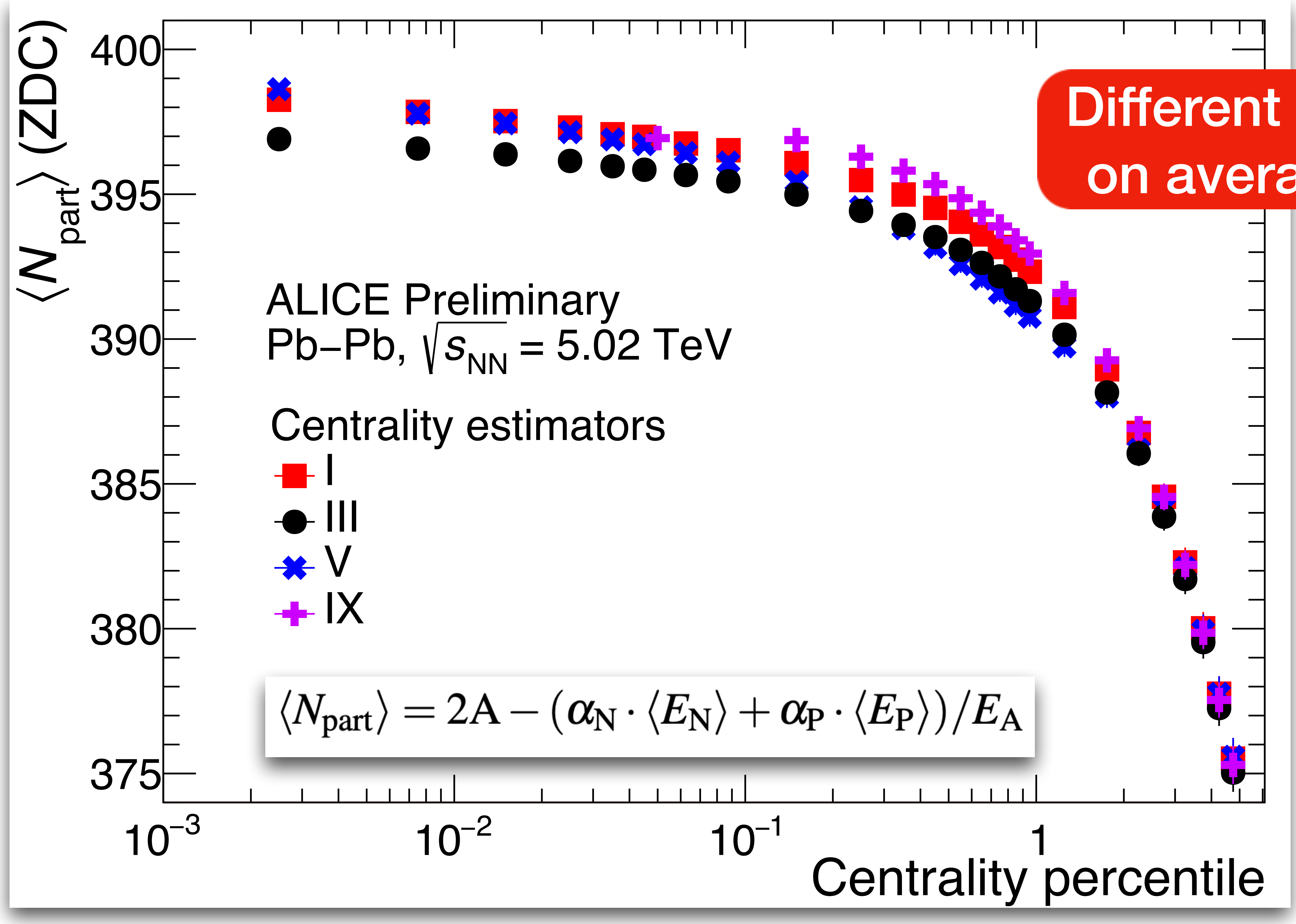




Data-driven extraction of <N_{part}> for UCCs



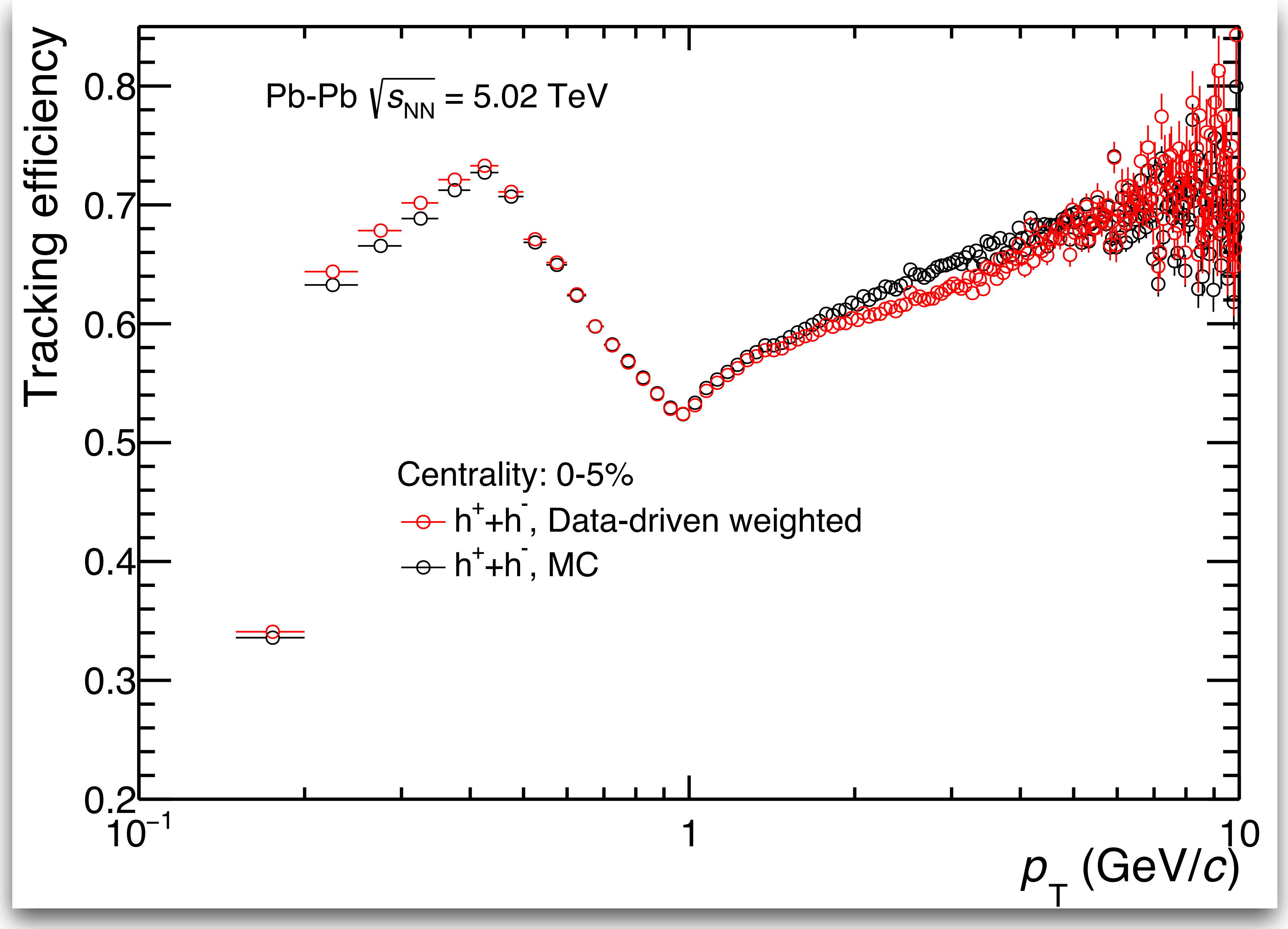
Different estimators are selecting on average the same geometry.

- **<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. ALICE-PUBLIC-2020-001

Corrections to the p_T spectra

Tracking efficiency



$$\varepsilon = \frac{\text{Reconstructed } p_T \text{ spectrum}}{\text{True } p_T \text{ spectrum}}$$

Secondary particle contamination

Residual secondary particle contamination estimated by fitting data DCA_{xy} distributions in p_T bins using MC templates.

p_T (GeV/c)

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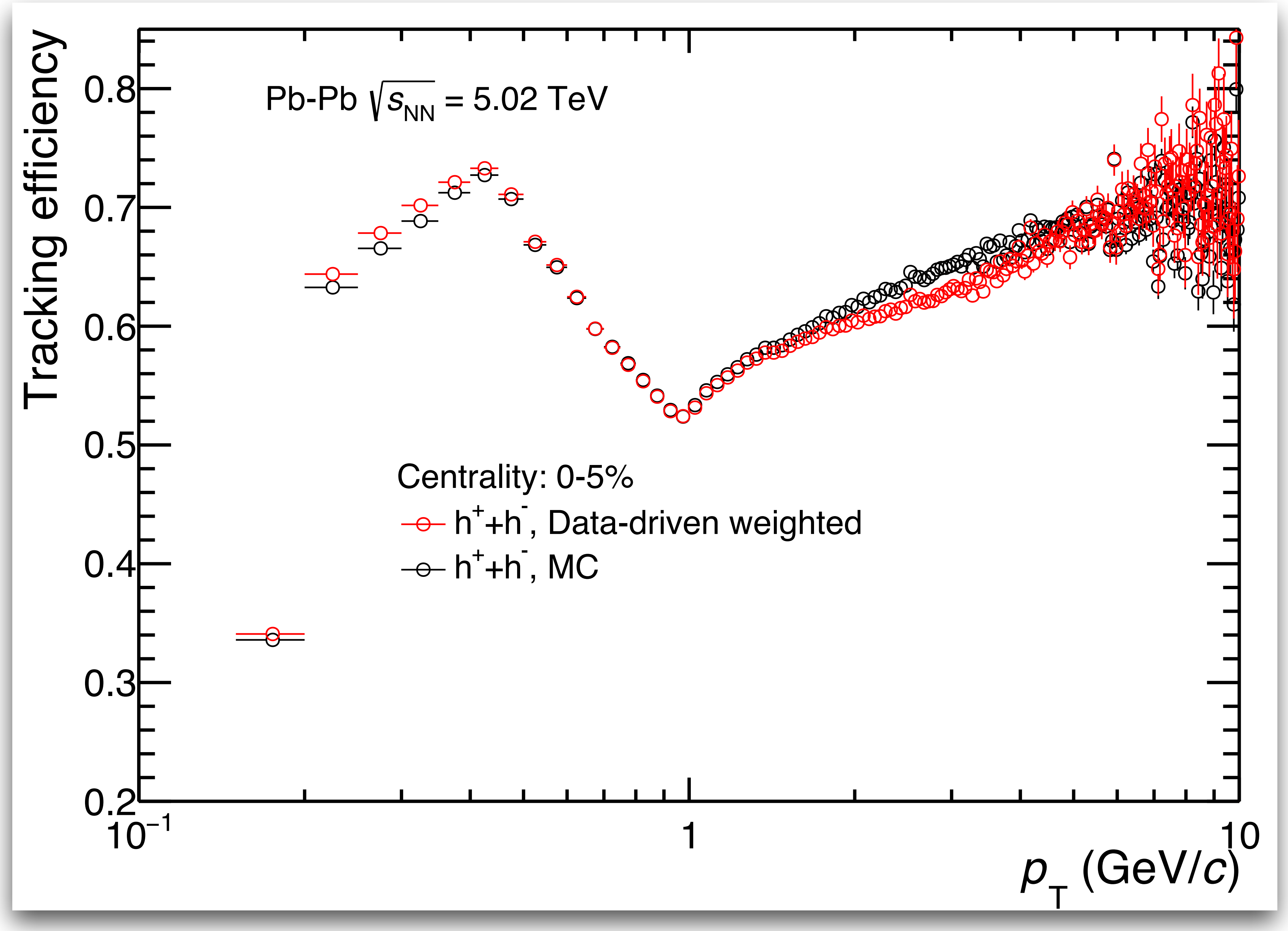

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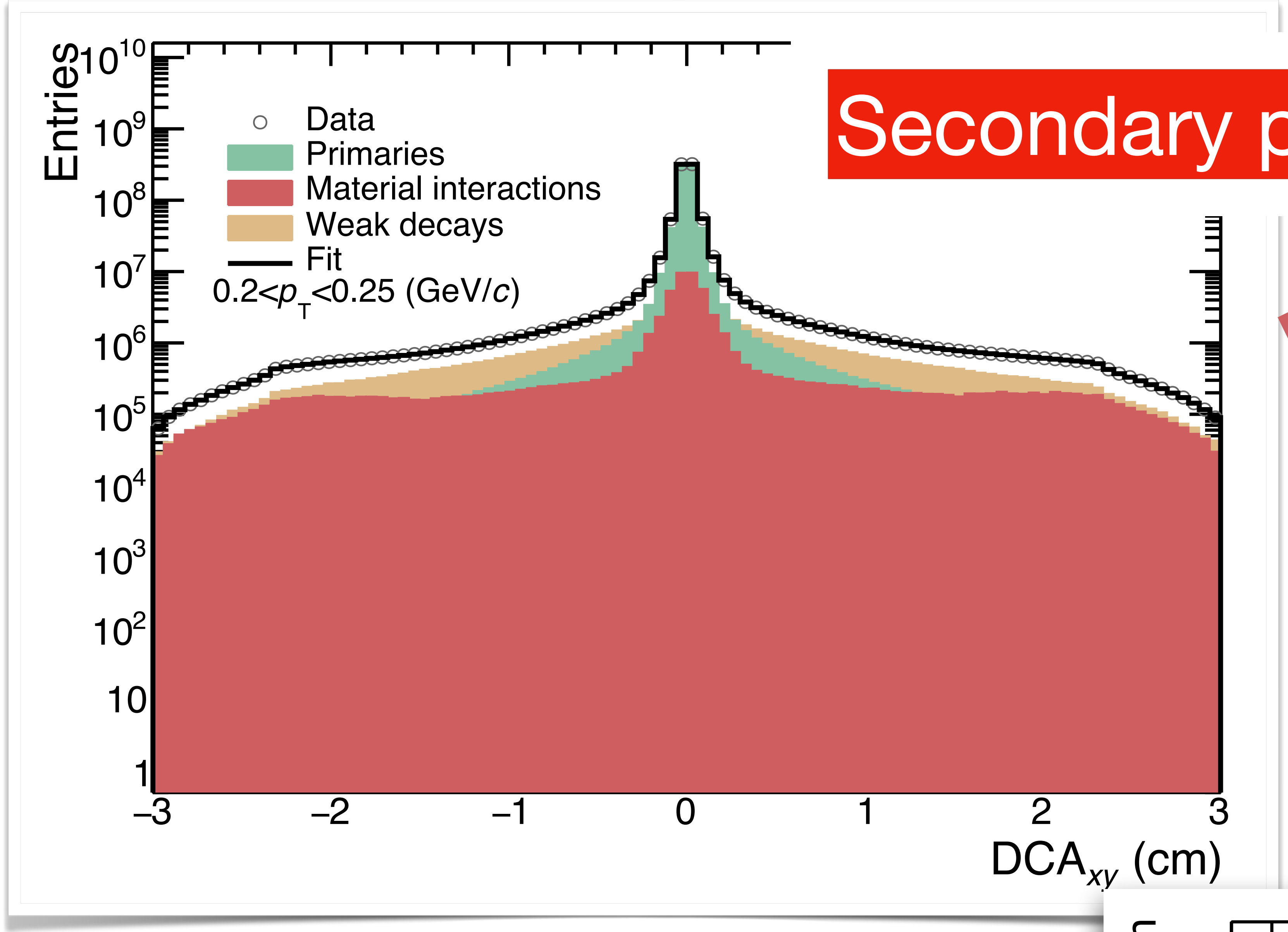

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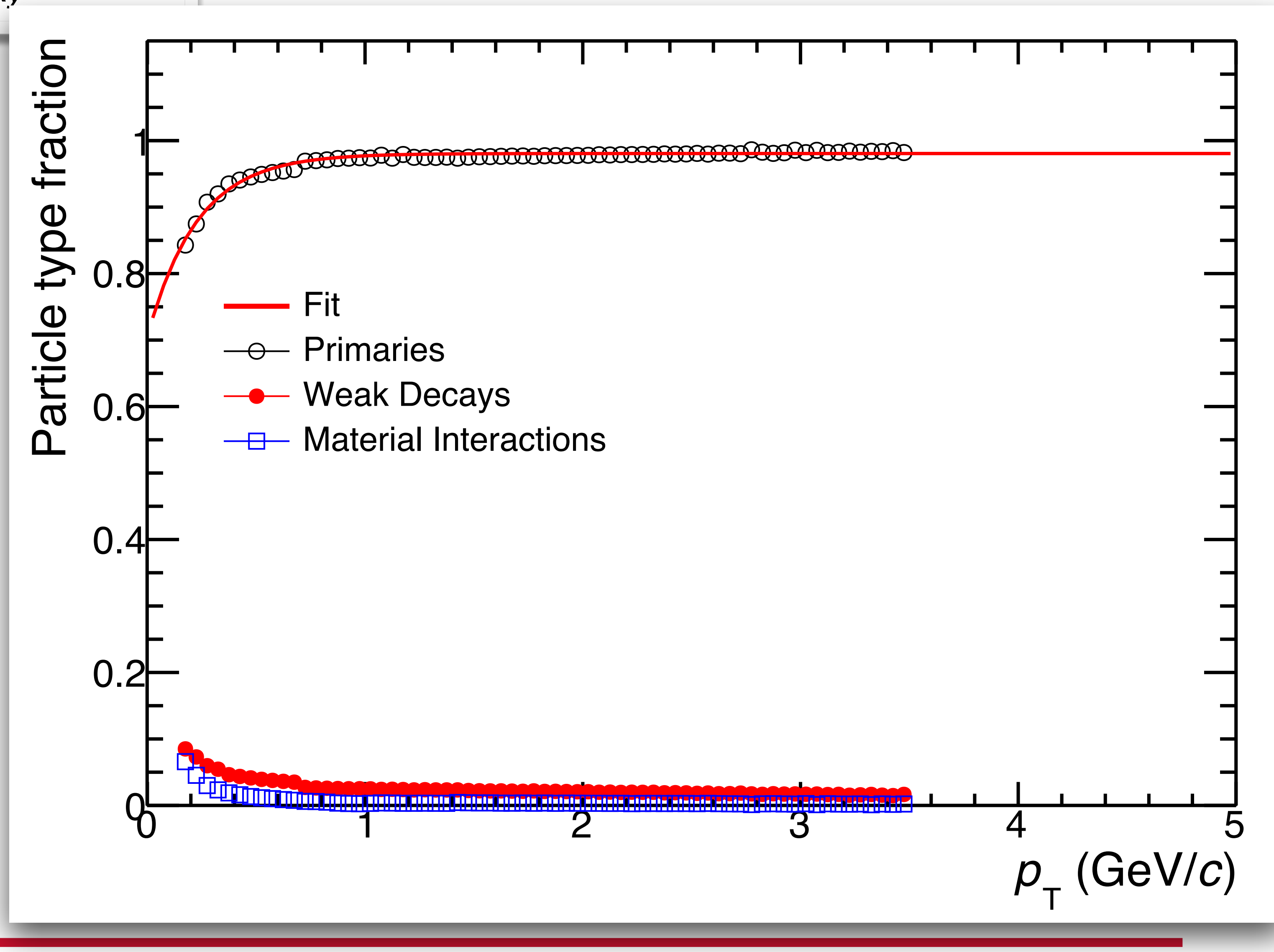
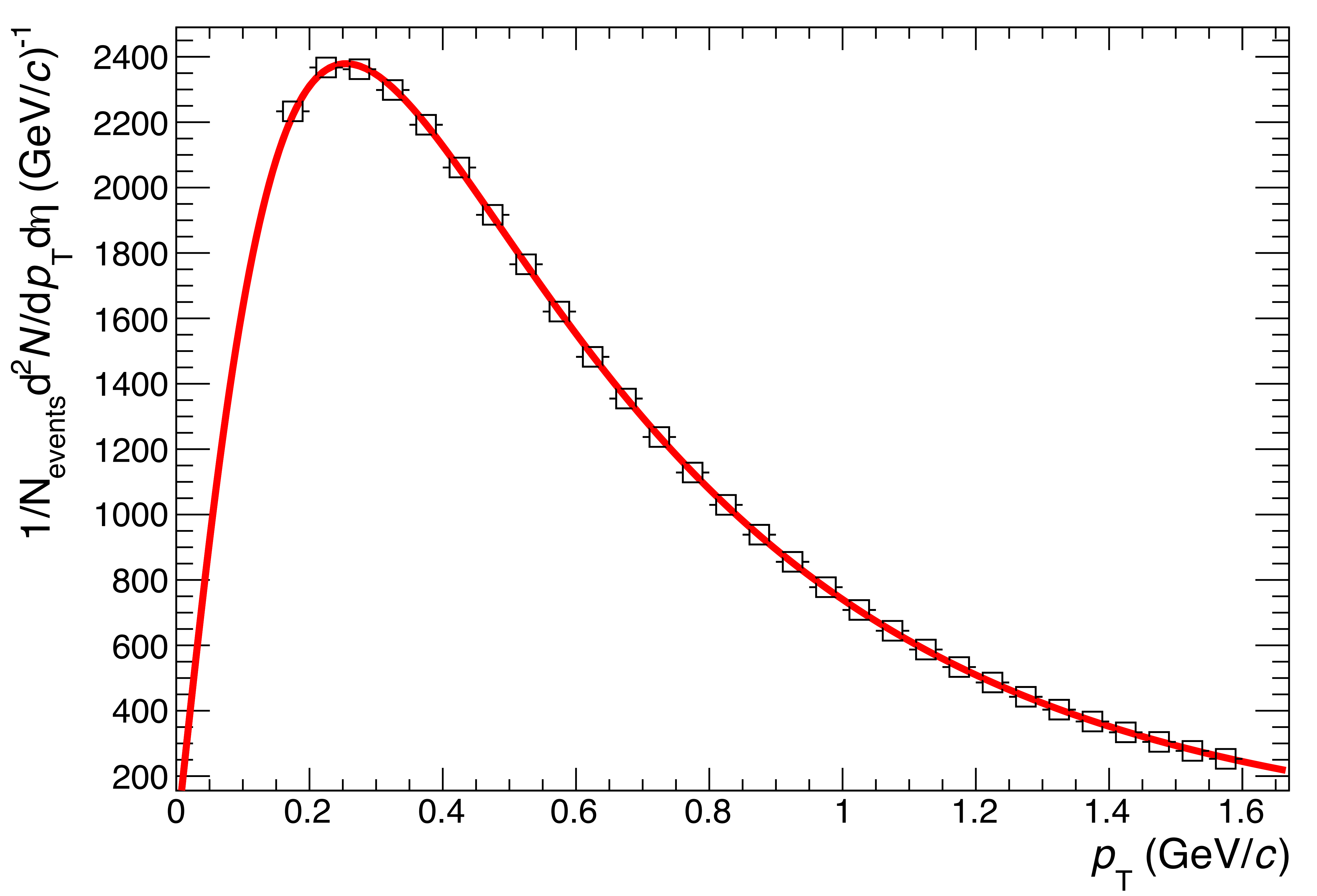


p_T (GeV/c)

Extrapolation to $p_T = 0$

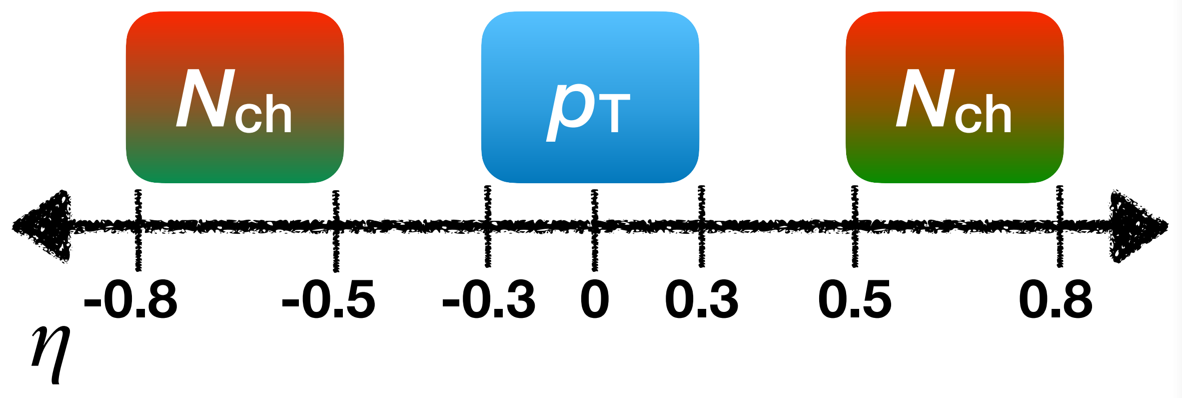
- Extrapolation to p_T=0 by fitting the spectra in 0.15< p_T < 1.5 GeV/*c* with a Boltzmann-Gibbs Blast-Wave model.
- Measure <p_T> and <d*N*/dη> in the p_T interval between 0 and 10 GeV/*c*.
- Fraction of extrapolated yields is about 9%.

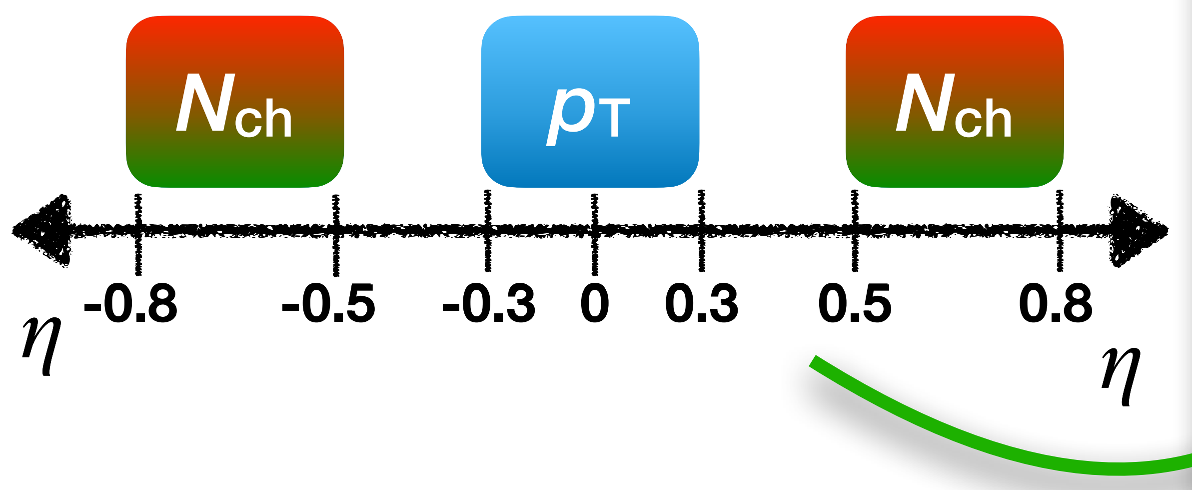


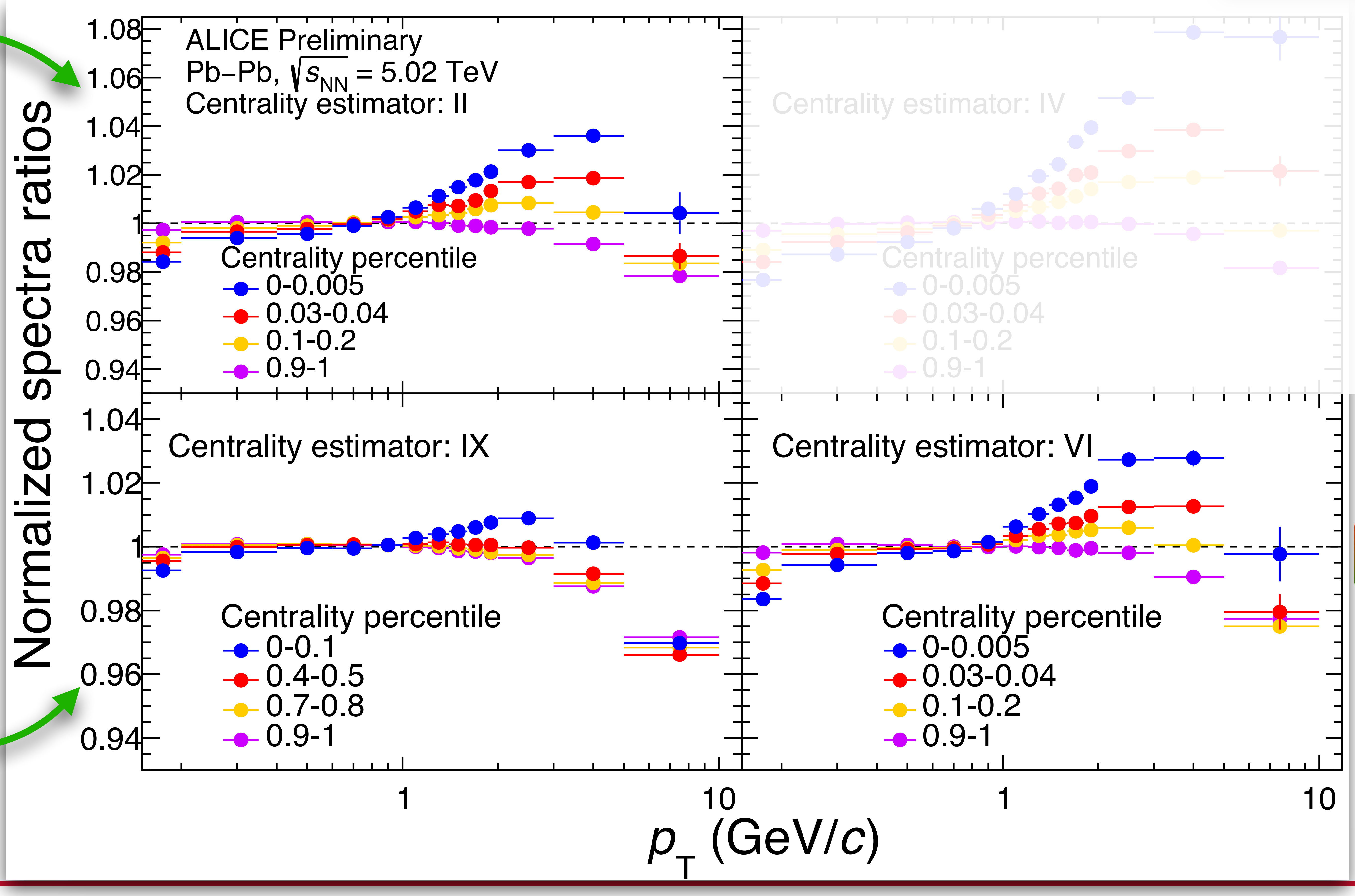
Normalized p_T spectra ratios

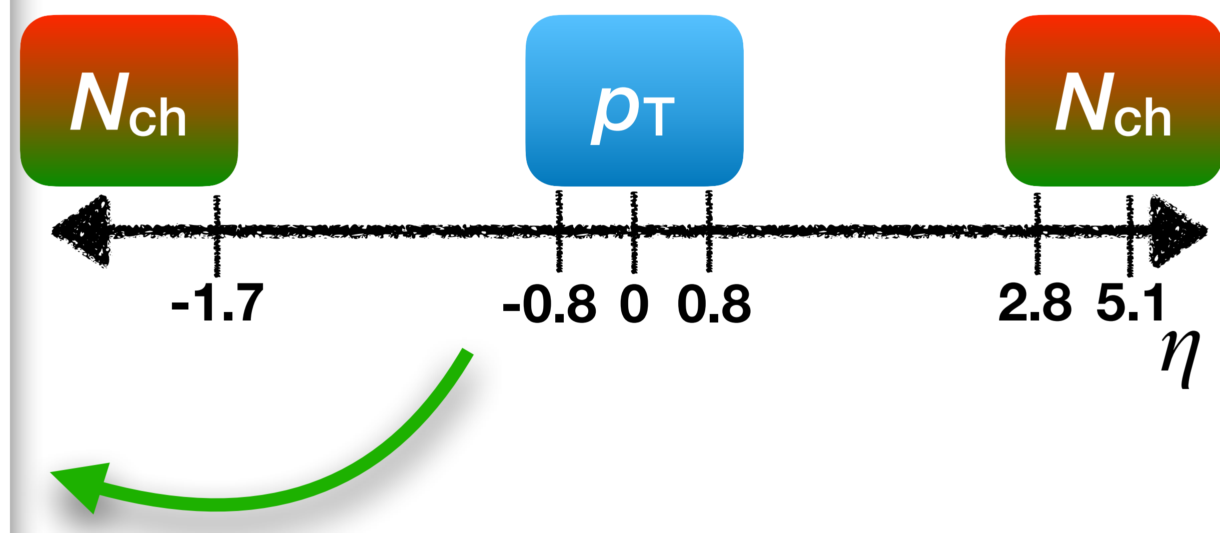
- N_{ch} based centrality estimators: enhances yield at mid p_T only (radial flow bump).
- E_T based centrality estimator: enhances yield at both mid and high p_T.

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









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Extracting the squared speed of sound, c_s^2

Primary observable: $\langle p_T \rangle / \langle p_T \rangle^{0\text{-}5\%}$ v.s. $\langle dN/d\eta \rangle / \langle dN/d\eta \rangle^{0\text{-}5\%}$ correlation

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

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

$N^*_{\rm ch}$ = $\langle dN/d\eta \rangle / \langle dN/d\eta \rangle^{0\text{-}5\%}$.

Below the knee

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

Above the knee

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

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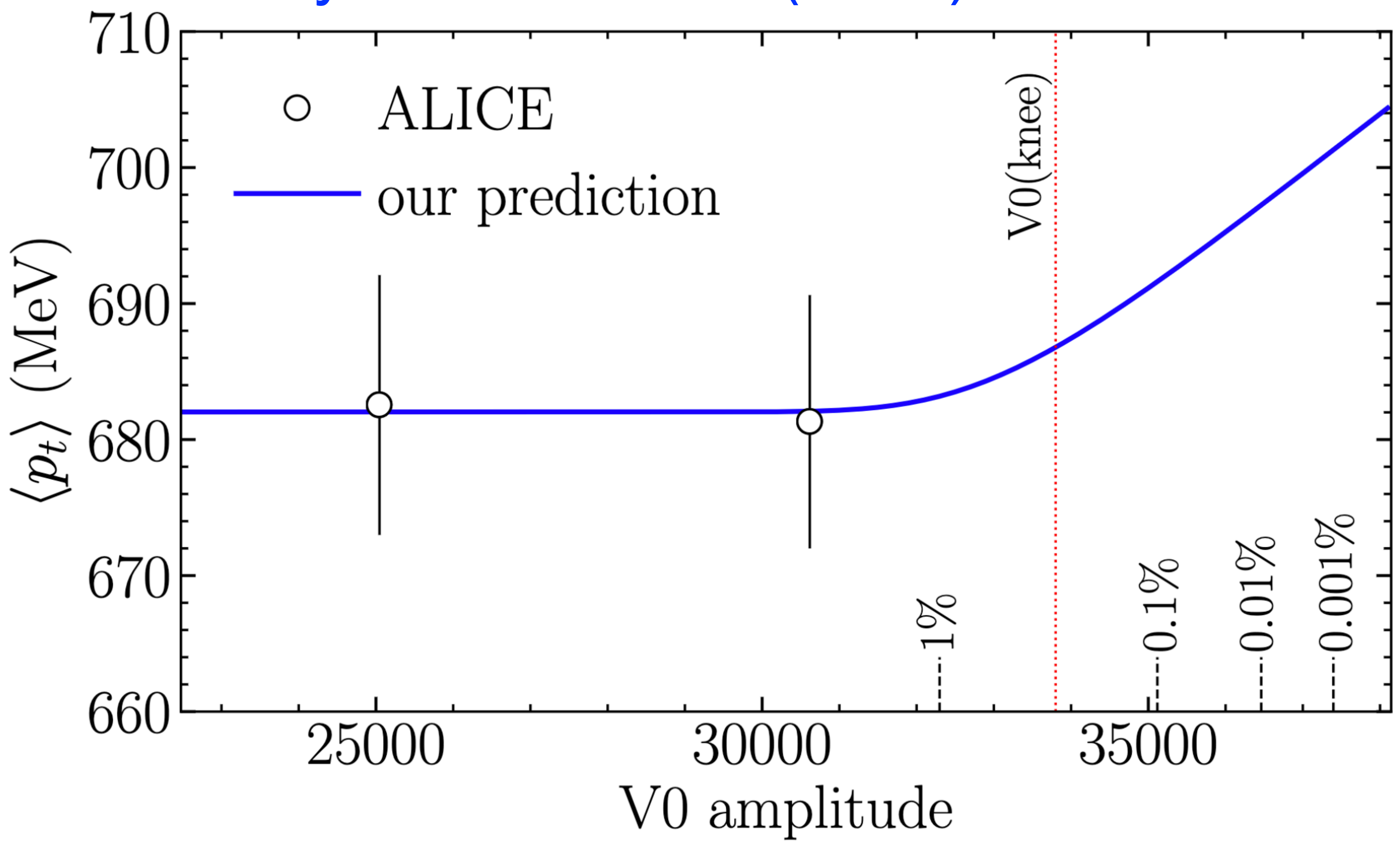
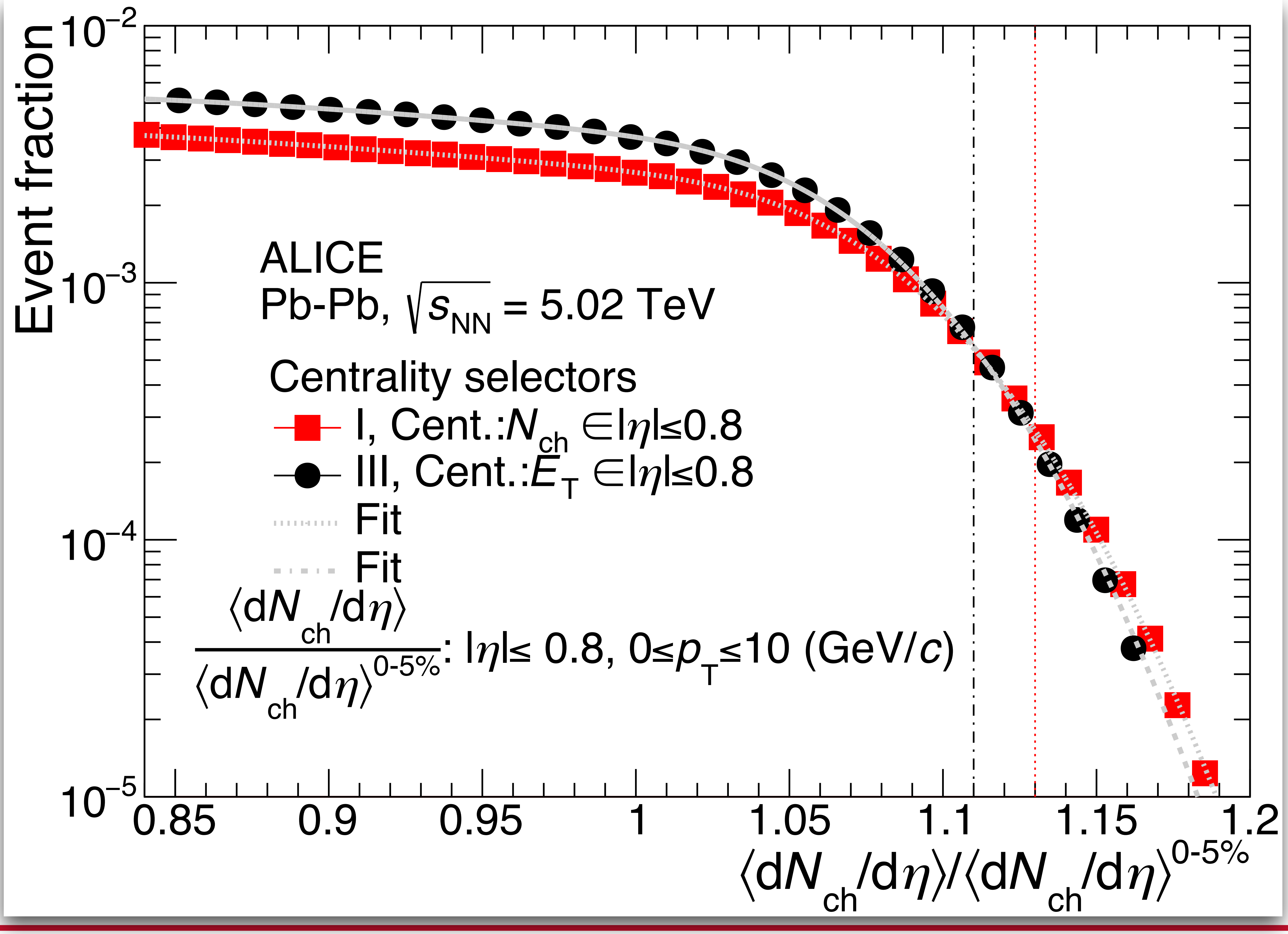


Estimating the $N^*_{\mathrm{ch,knee}}$ and σ_0

- Construct the event fraction distribution as a function of $N^*_{\mathrm{ch}} = \langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle / \langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle^{0-5\%}$.
- Fit the data with a model that assumes a Gaussian distribution of the number of emitted particles for a fixed impact parameter. PRC 97, 014905 (2018)

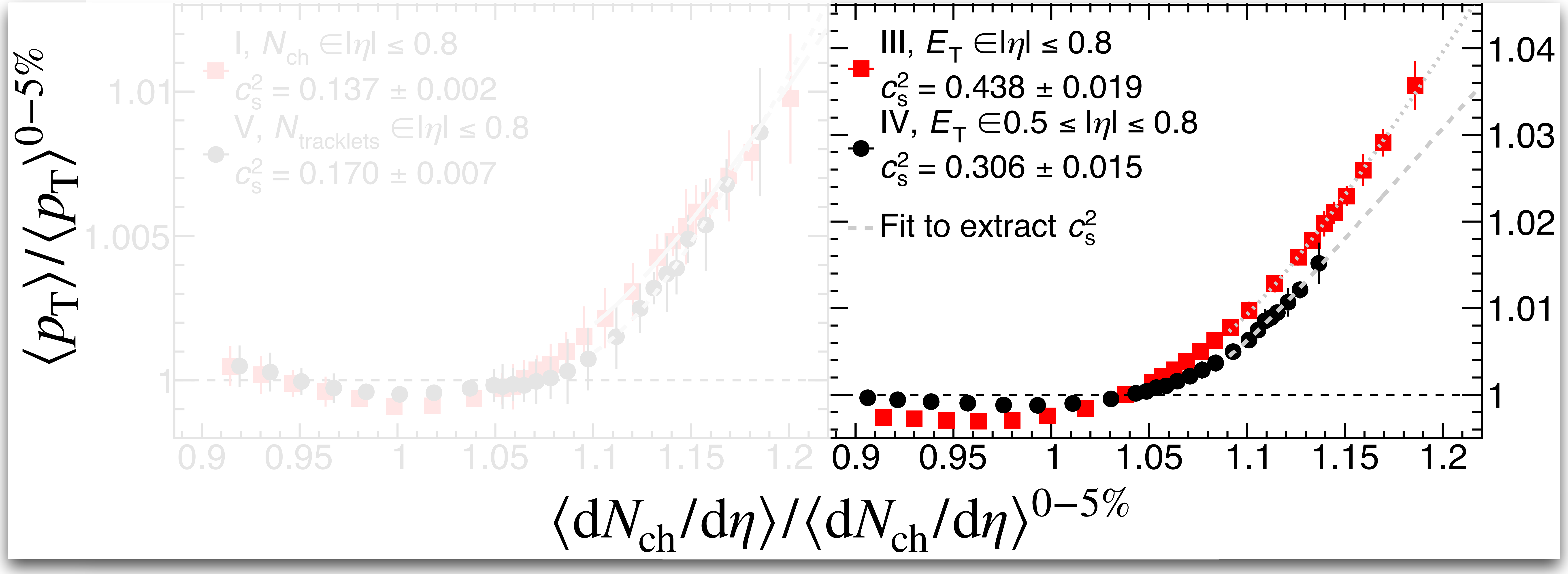


ALICE-PUBLIC-2024-002

Results

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 to extract c_s^2.
- Introducing a η gap for E_T reduces the extracted c_s^2.



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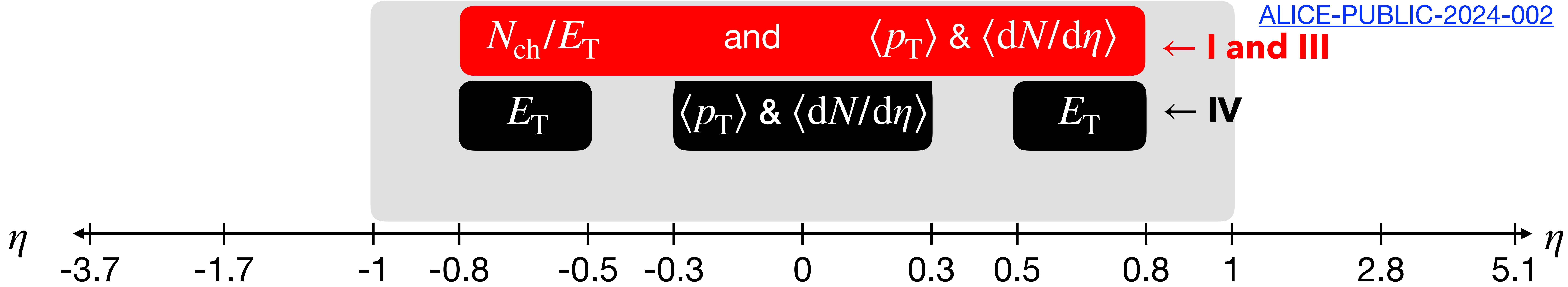

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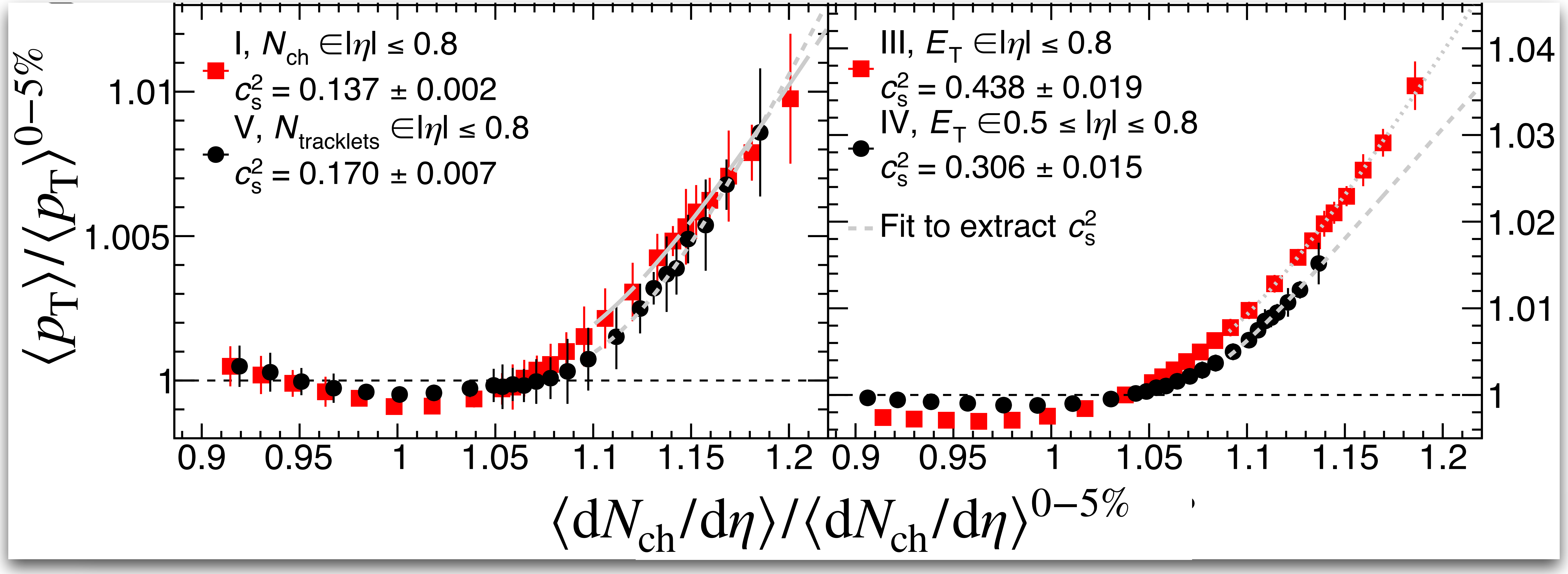

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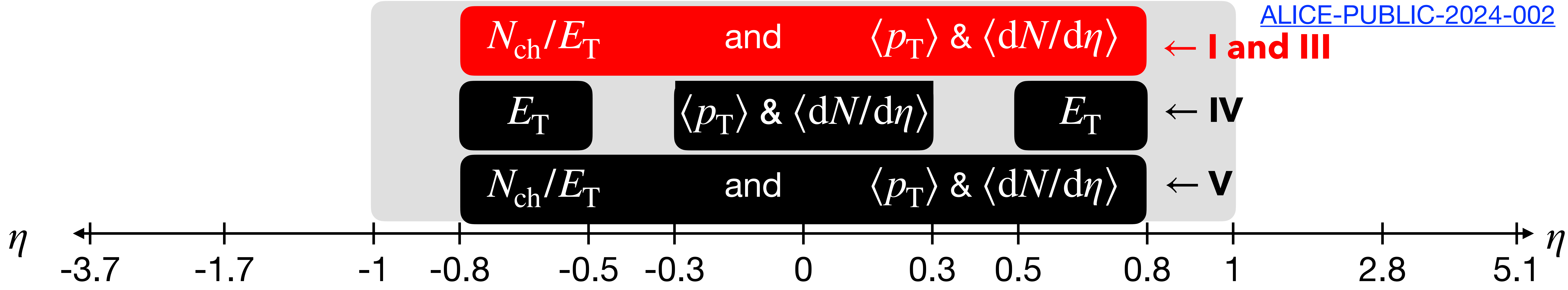
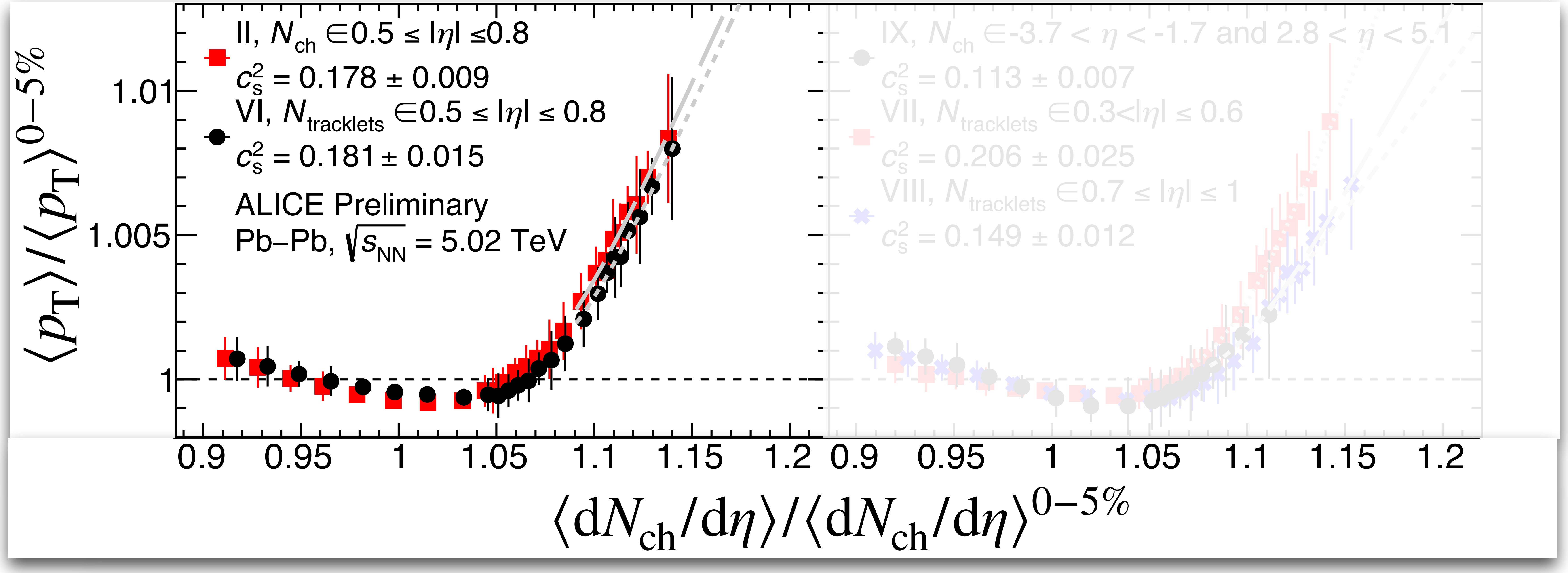


Extracting the squared speed of sound, c_s^2

- 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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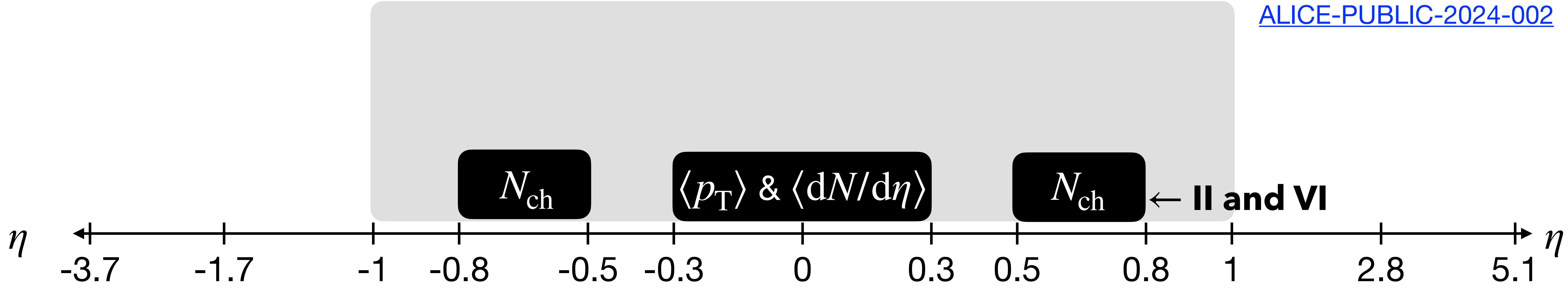

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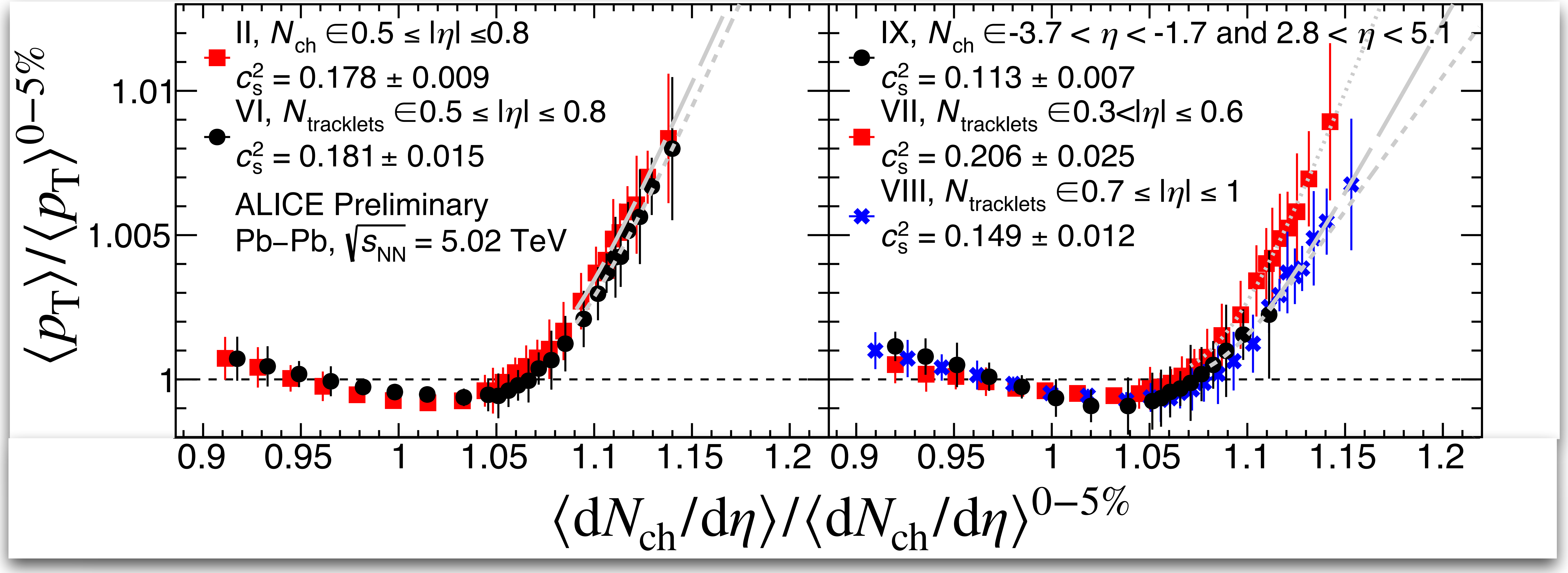

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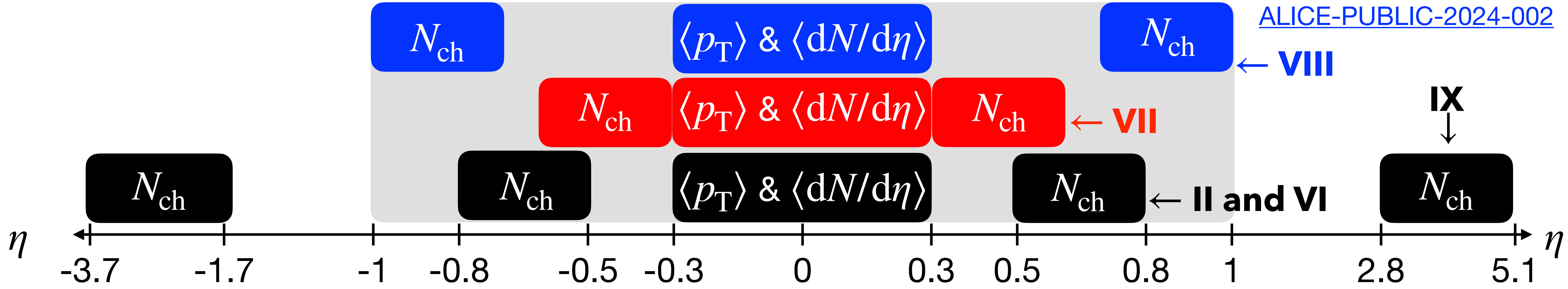
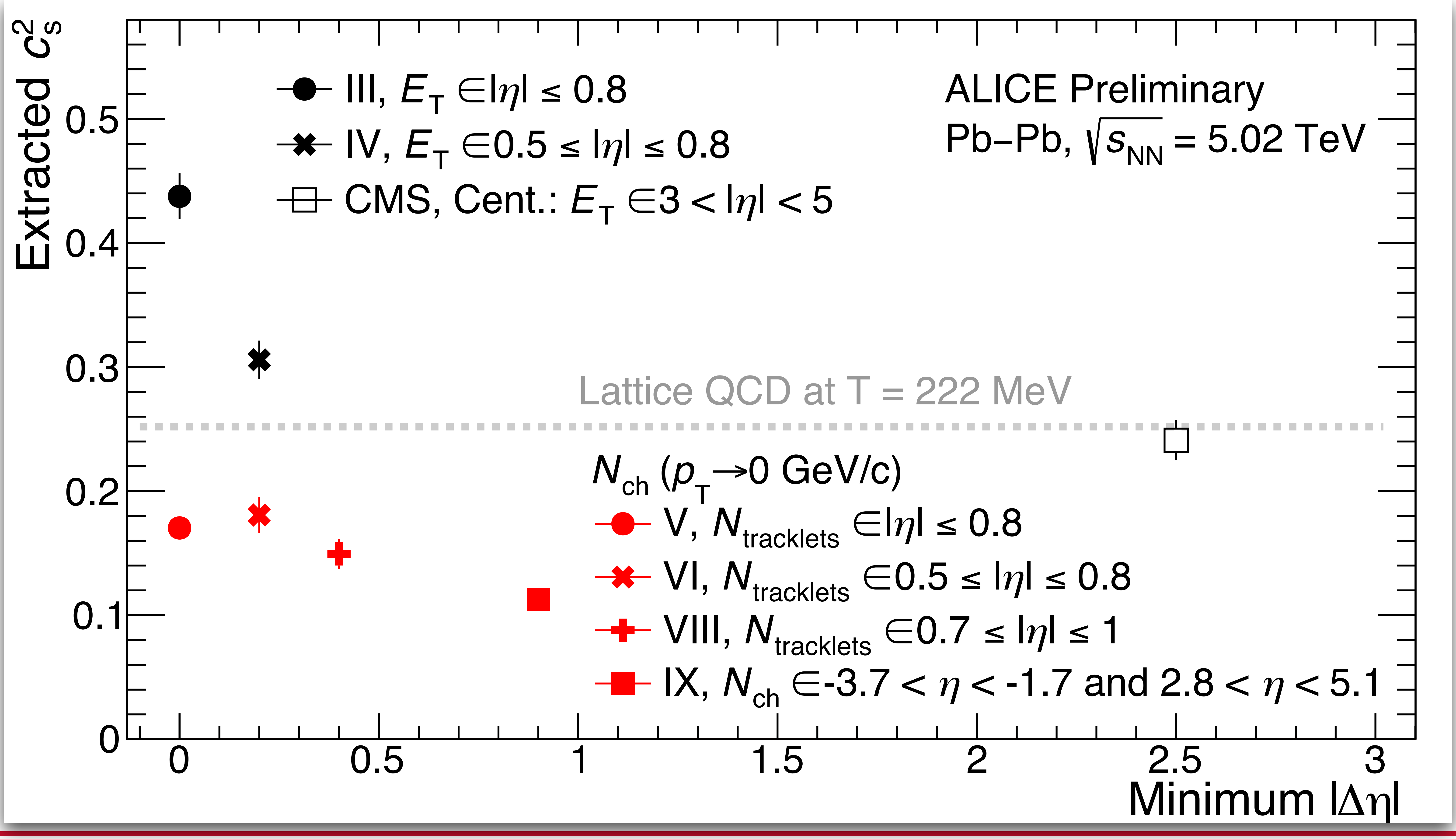


Extracted c_s^2 v.s. pseudorapidity gap

- 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



Trajectum predictions

- Trajectum predictions are in good agreement with the data.

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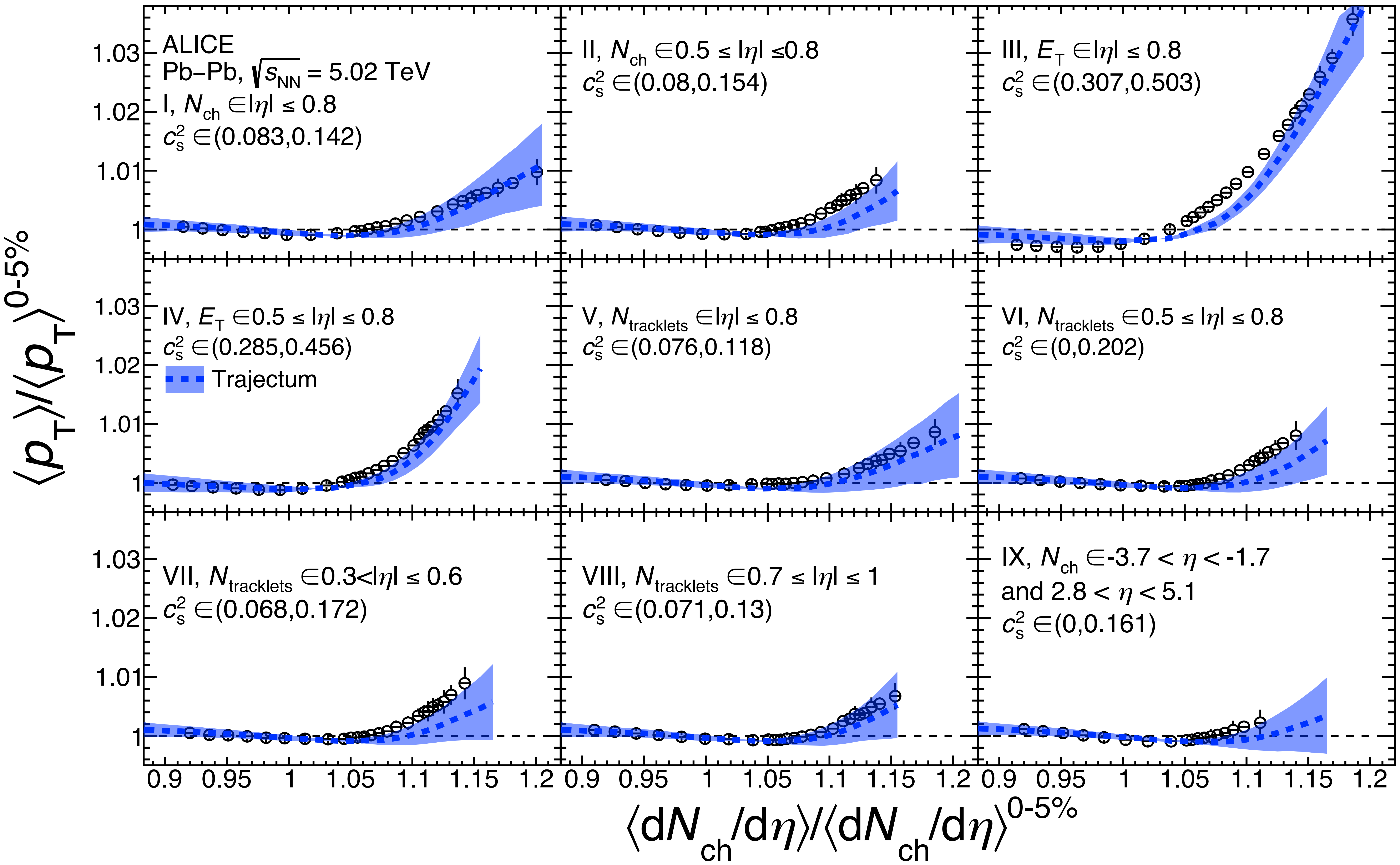
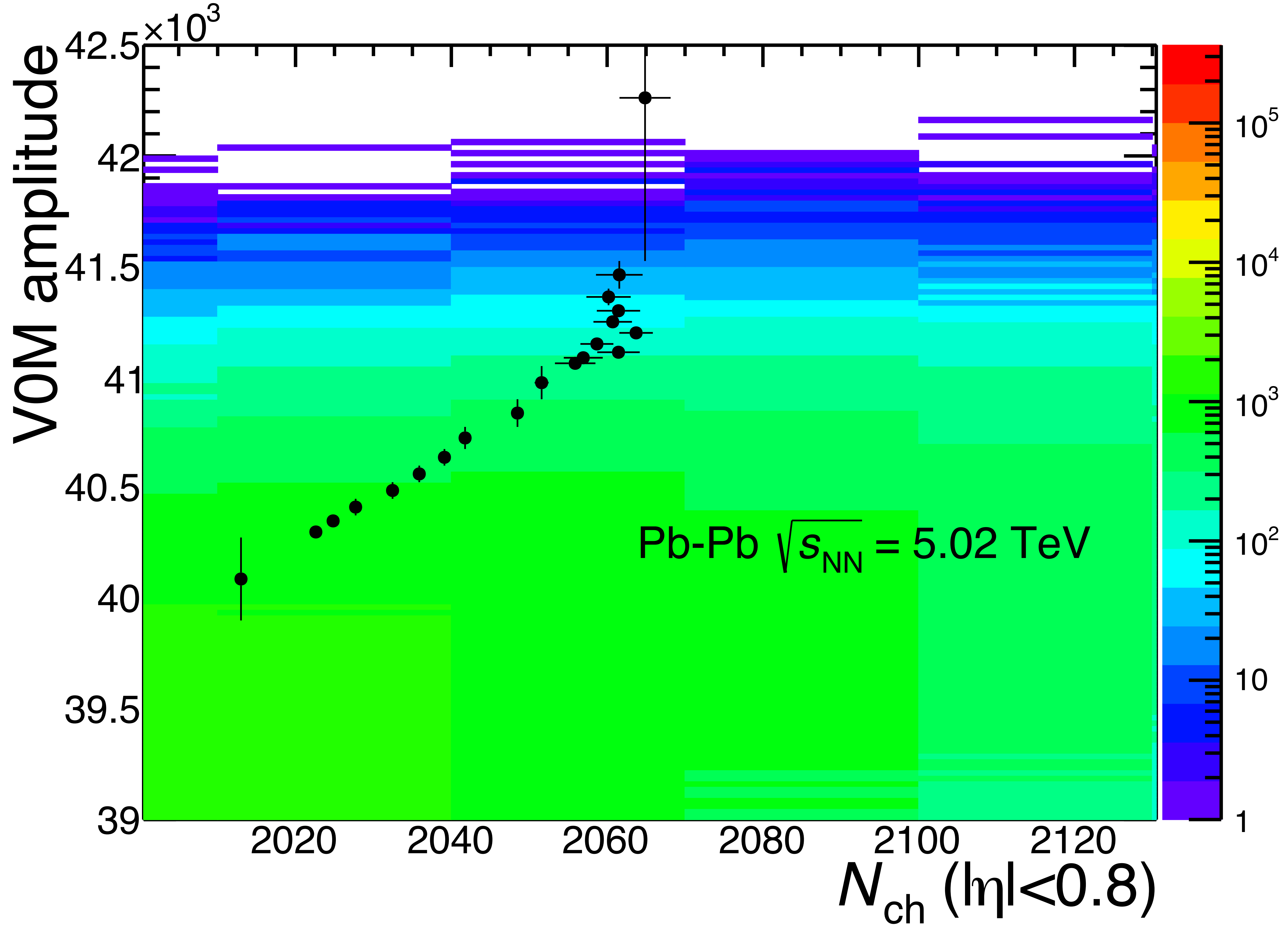


Conclusions

- Both ALICE and CMS observe an increase of $<p_{\mathrm{T}}>$ with $<\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta>$ in UCCs -> new opportunity to investigate QGP equation of state.
- The $<p_{\mathrm{T}}>/<p_{\mathrm{T}}>^{0\text{-}5\%}$ versus $<\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta>/<\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta>^{0\text{-}5\%}$ 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 $<p_{\mathrm{T}}>$-$<p_{\mathrm{T}}>$ correlations.
  - The measured c_s^2 decreases with increasing pseudorapidity gap.
- Range of ALICE values (c_s^2 = 0.2 ± 0.1) consistent with CMS value, c_s^2 = 0.24 ± 0.016. Further studies needed to reduce uncertainty.

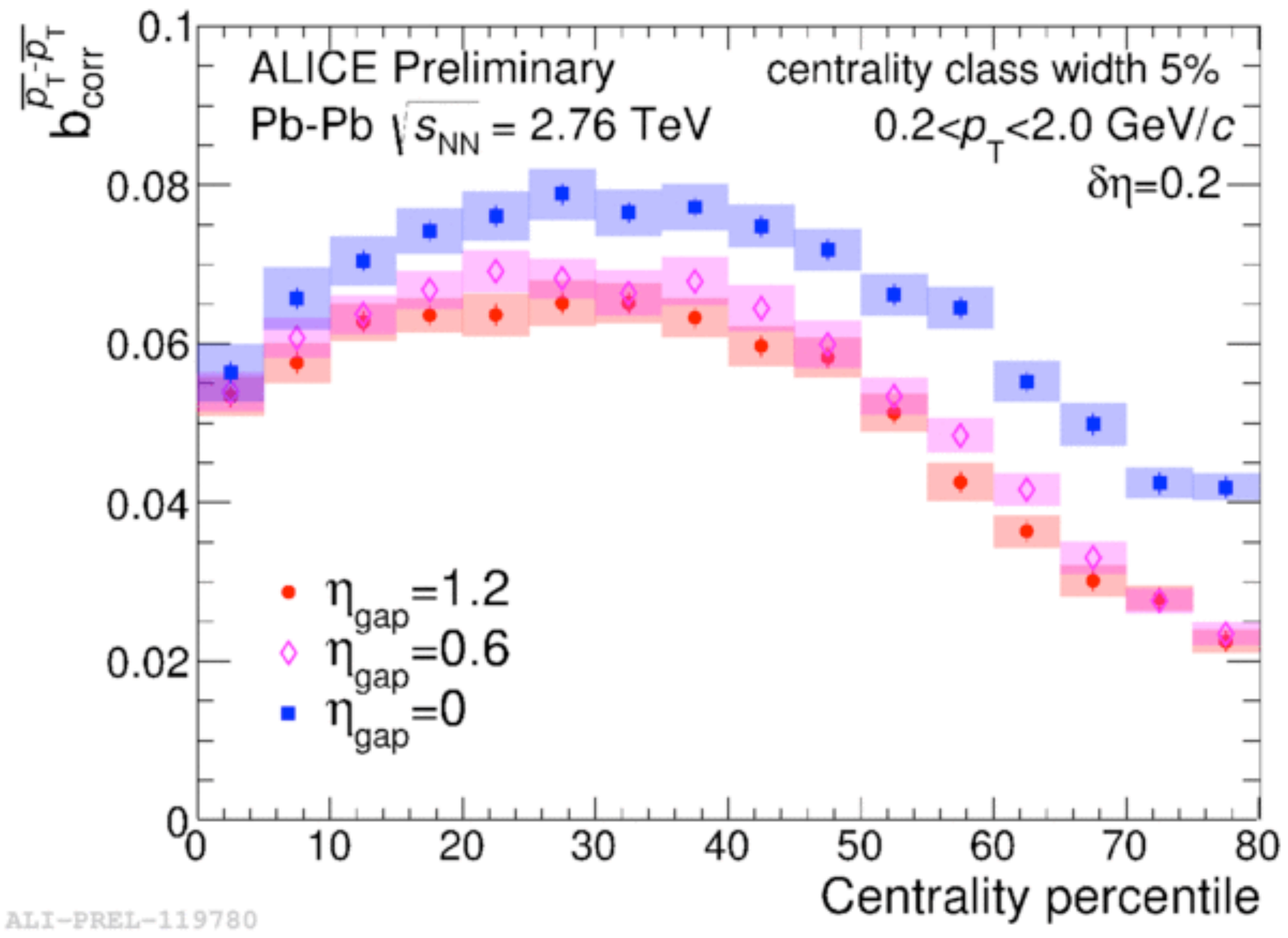
Backup

N_{ch} ($|\eta| < 0.8$) vs V0 amplitude



- N_{ch} at mid-rapidity flattens out beyond V0 amplitude ~41x10³ if using very narrow percentiles.

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.