QGP Speed of Sound measurements at the LHC

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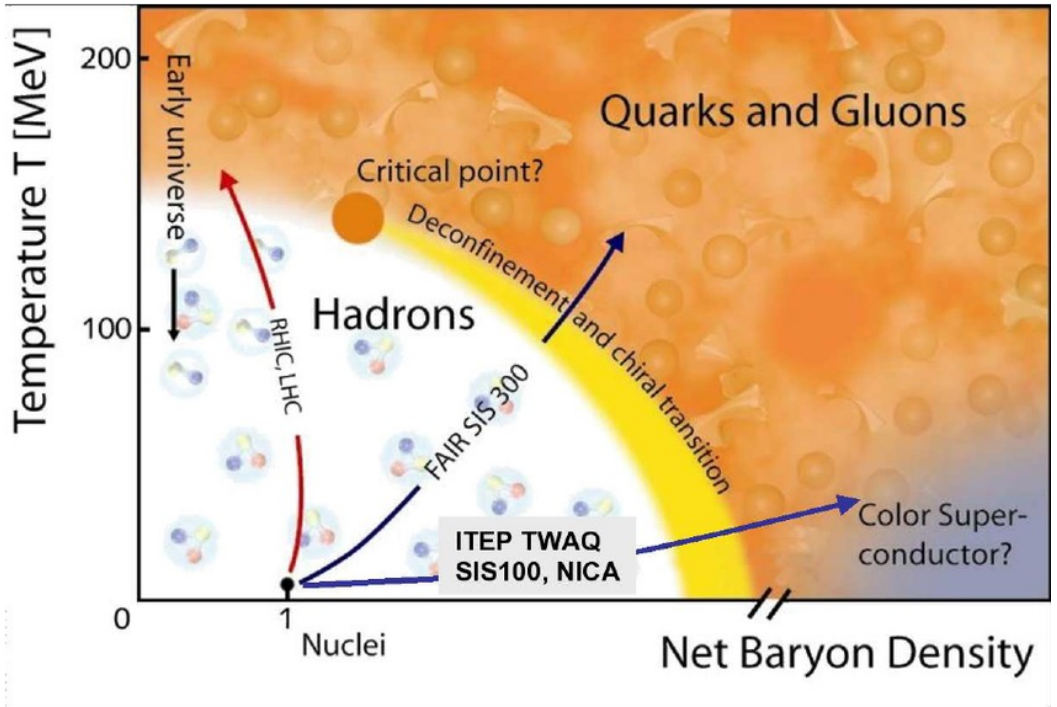
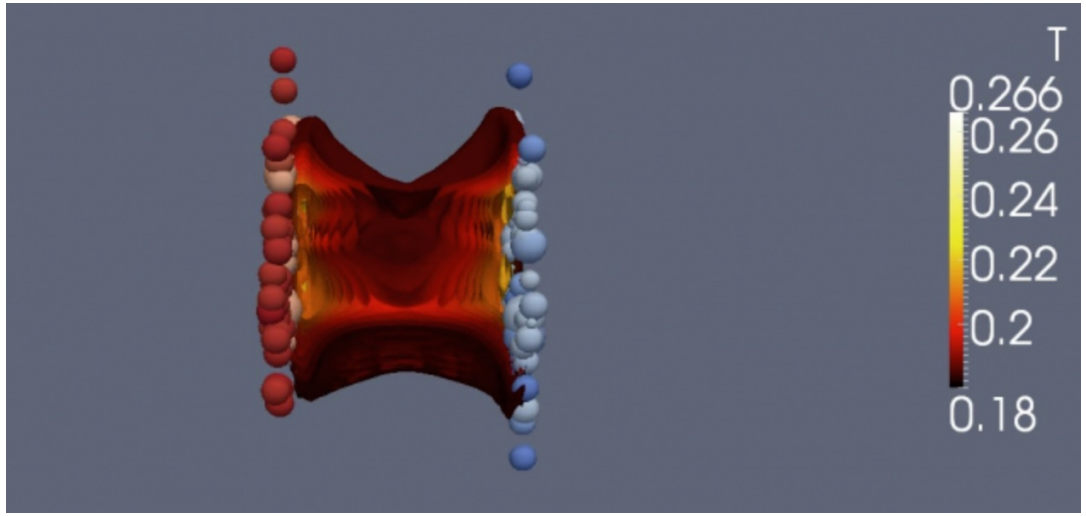
CIPANP 2025, Madison, WI, USA

Speed of sound – a probe of EoS

Equation of State (EoS) of nuclear matter – **Main goal of nuclear physics!**





For the system
- In thermal equilibrium
- Adiabatic process
- Fixed μ

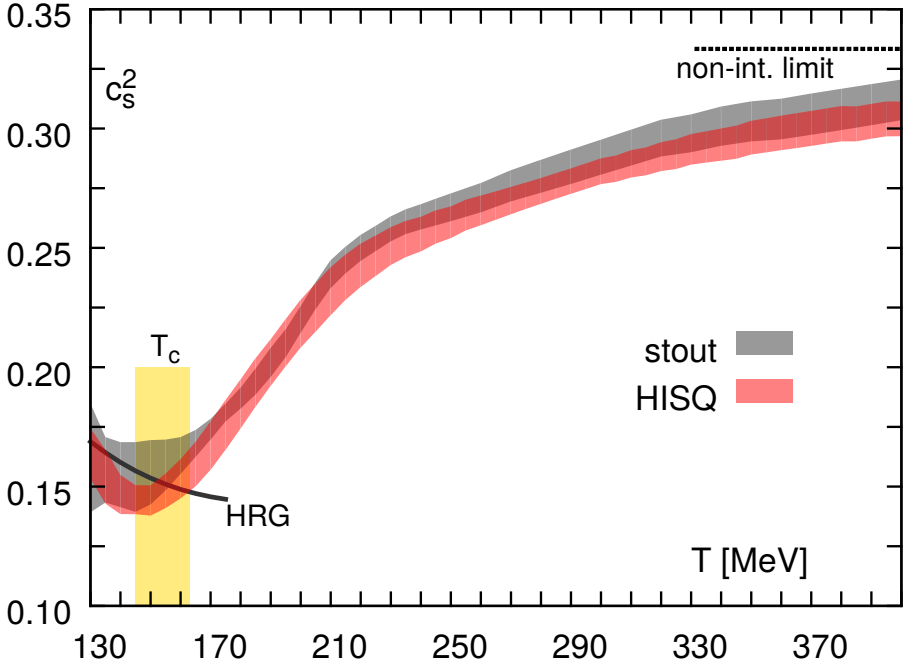
Speed of sound

$$c_s^2 = \frac{dP}{d\varepsilon} \Longrightarrow$$ a direct probe of equation of state

How to measure it?

Lattice QCD calculations

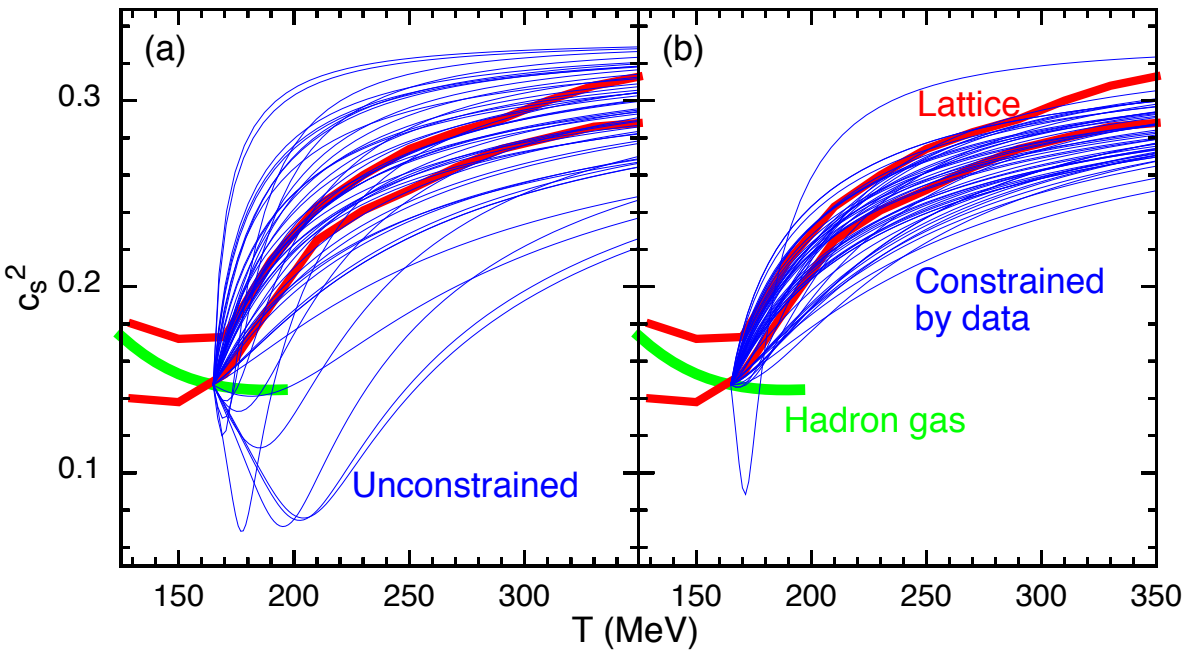
- (2+1)-flavor
- Deconfined medium



PRD 90 (2014) 094503

Bayesian analysis – significant overlap between constrained and predicted c_s^2!

PRL 114 (2015) 202301



Can we measure it directly?

Early attempts

Volume 118B, number 1, 2, 3 PHYSICS LETTERS

MULTIPLICITY DEPENDENCE OF p_t SPECTRUM AS A POSSIBLE SIGNAL FOR A PHASE TRANSITION IN HADRONIC COLLISIONS

L. VAN HOVE
CERN, Geneva, Switzerland

Received 25 August 1982

- ❑ Multiplicity – directly proportional to the entropy
- ❑ Temperature – 1/3 of energy per particle for massless ideal gas
  $\Longrightarrow T = \langle p_{\mathrm{T}} \rangle / 3$ in ultra-relativistic collisions at midrapidity

Ideas go back to 80s

- proposed $\langle p_{\mathrm{T}} \rangle$ vs dN_{ch}/dy to search for phase transition

New approach

In HI experiment thermodynamic relations do not apply directly:

- Longitudinal expansion
- Limited acceptance

Idea: a **hypothetical** system at the end of hydro evolution of the collision with entropy S and energy E

- An uniform fluid at rest with an effective volume (V_{eff}) and temperature (T_{eff})
- In this "effective system" E and S are conserved!

$$c_s^2 = \frac{dP}{d\varepsilon} = \left.\frac{sdT}{Tds}\right|_{T_{eff}} = \left.\frac{d\ln T}{d\ln S}\right|_{T_{eff}} = \frac{d\ln\langle p_T\rangle}{d\ln N_{ch}}$$

Method 1

For the same centrality (same V_{eff}):

- $\langle p_T\rangle$ vs N_{ch} at different (close) collision energies

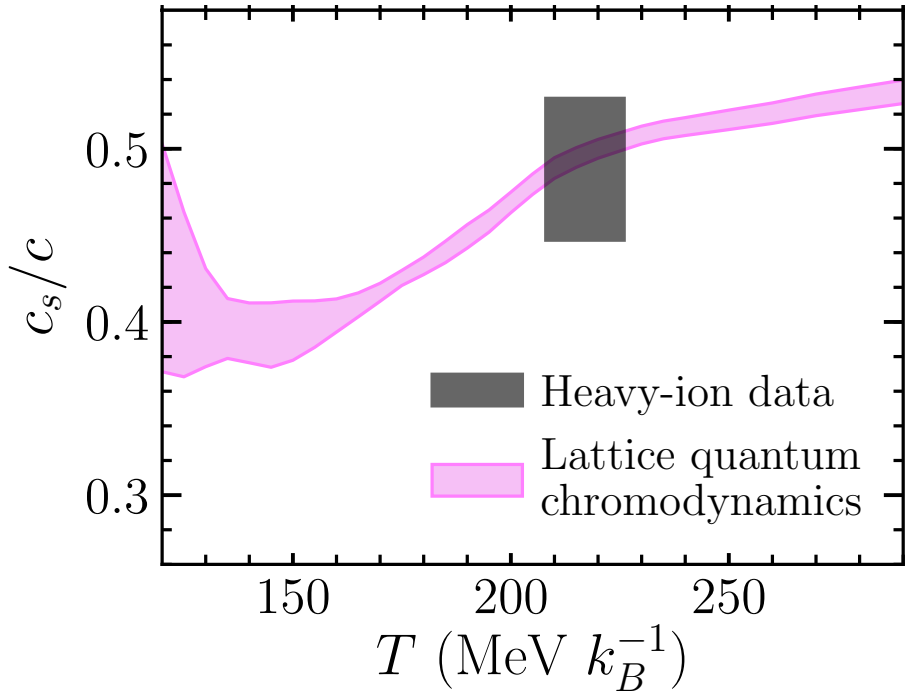
Nature Physics 16 (2020) 615

First Direct Constraint

$$c_s^2 = \frac{dP}{d\varepsilon} = \frac{sdT}{Tds}\bigg|_{T_{eff}} = \frac{d\ln T}{d\ln S}\bigg|_{T_{eff}} = \frac{d\ln\langle p_T\rangle}{d\ln N_{ch}}$$

The c_s^2 extraction done with ALICE data

- Using 2.76 and 5.02 TeV
- Agreement with prediction
- Large uncertainties due to only two points



Nature Physics 16 (2020) 615

Method 1

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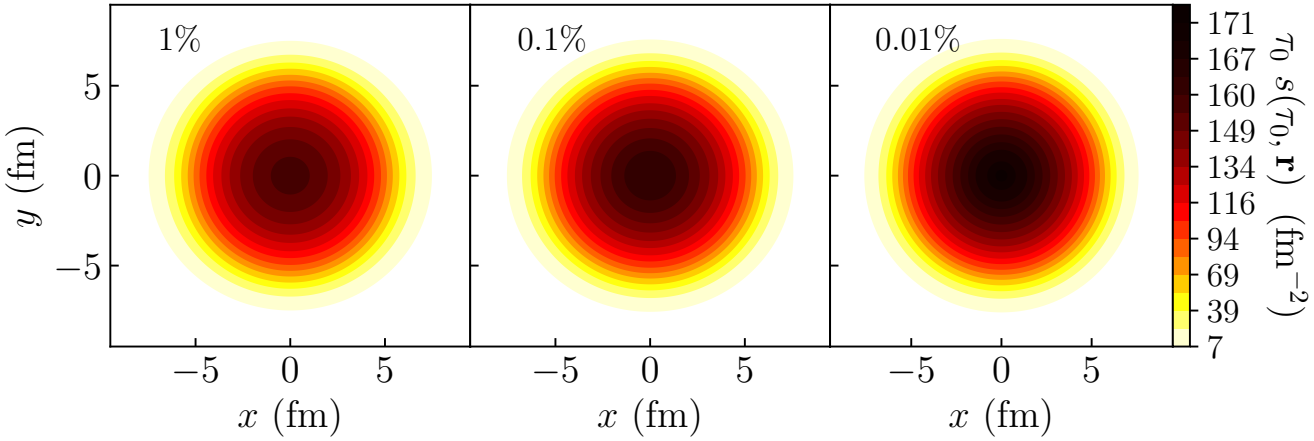
Another method

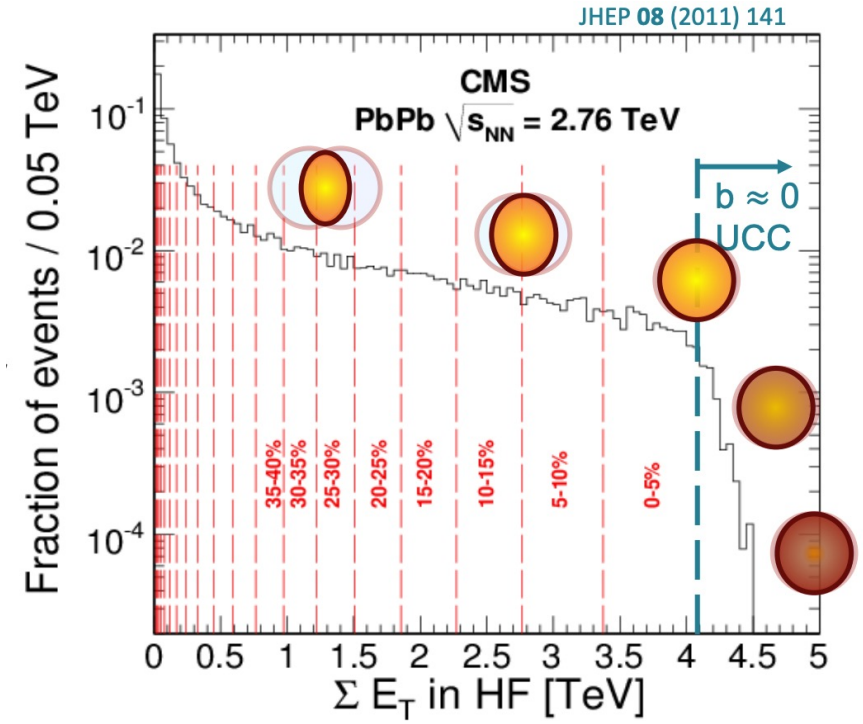
Ultracentral (UCC) collisions



Radius change ~1% ⟶ Same V_{eff}

Entropy density change ~ 13%

Centrality estimation



Method 2

For the same same energy:

- $\langle p_T \rangle$ vs N_{ch} at different UCC centralities
  ⟶ same V_{eff}

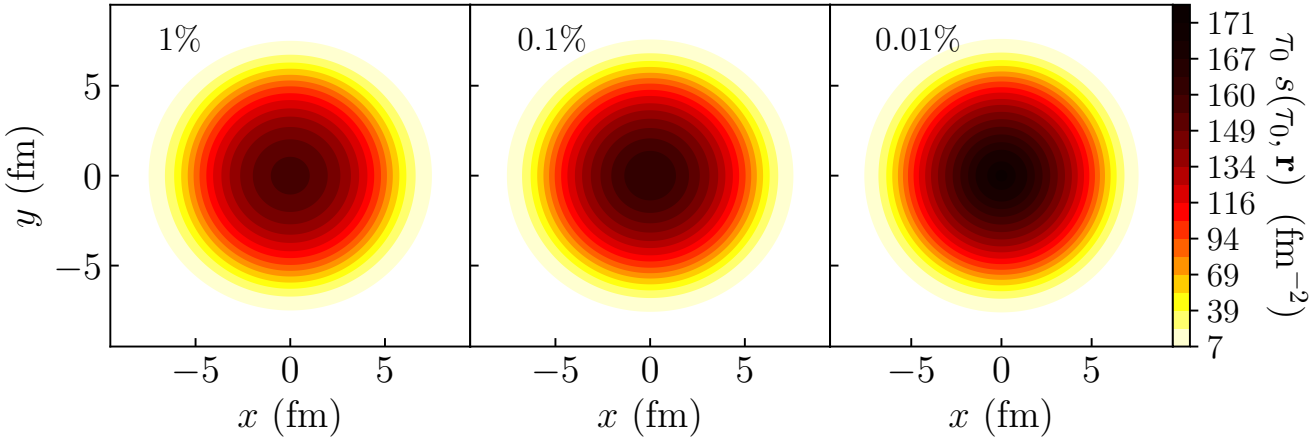
Centrality percentile:

- fraction of events based on ΣE_T distribution

Proposed by: PLB 809 (2020) 135749

Another method

Ultracentral (UCC) collisions



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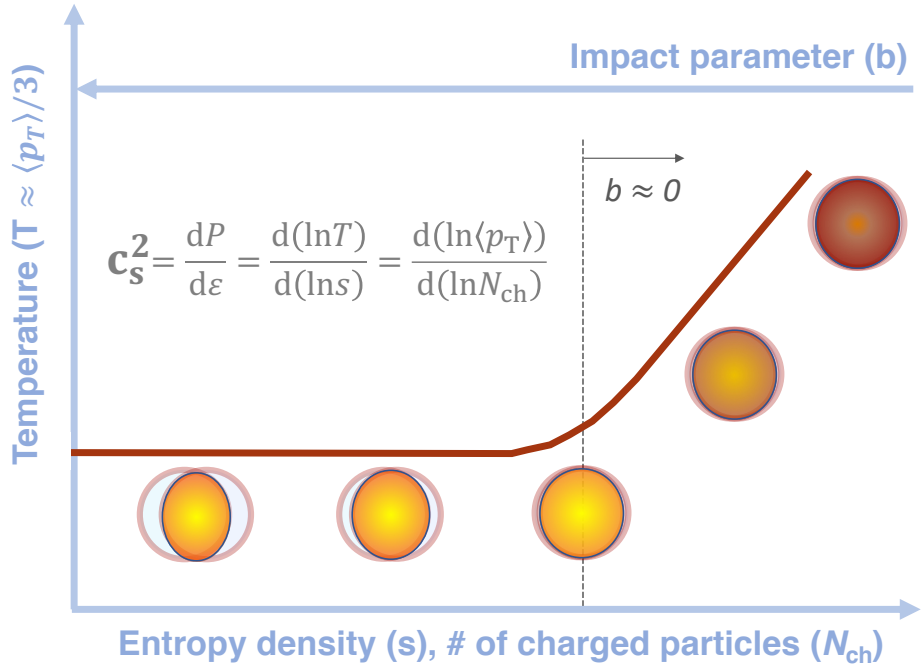


Method 2

For the same same energy:

- $\langle p_T \rangle$ vs N_{ch} at different UCC centralities
  ⟶ same V_{eff}

Nontrivial prediction by hydrodynamics

- direct constraints on the equation of state

Proposed by: PLB 809 (2020) 135749

CMS measurement

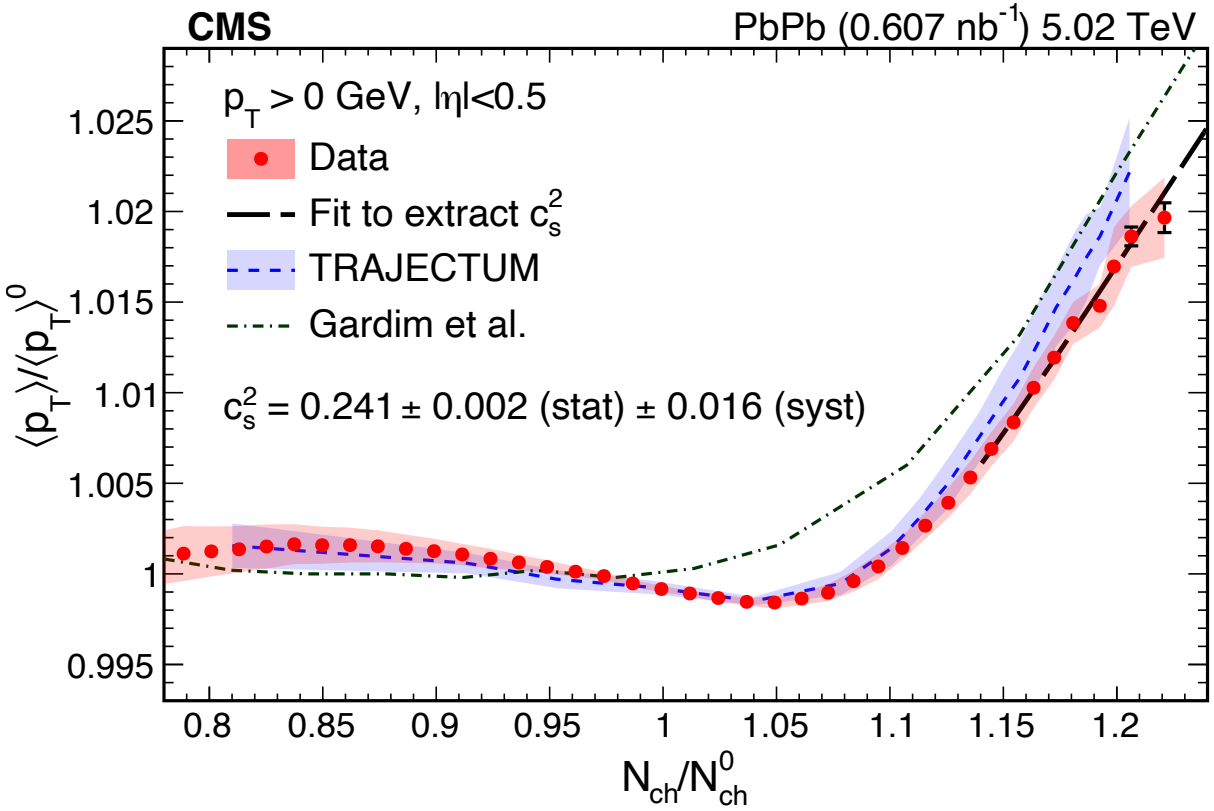
Method 2

Significant increase of $\langle p_{\mathrm{T}} \rangle$ toward UCC events

- as predicted by the simulations
- dip before the rise

c_s^2 extracted from fit

- Region $N_{\mathrm{ch}}/N_{\mathrm{ch}}^0 > 1.12$



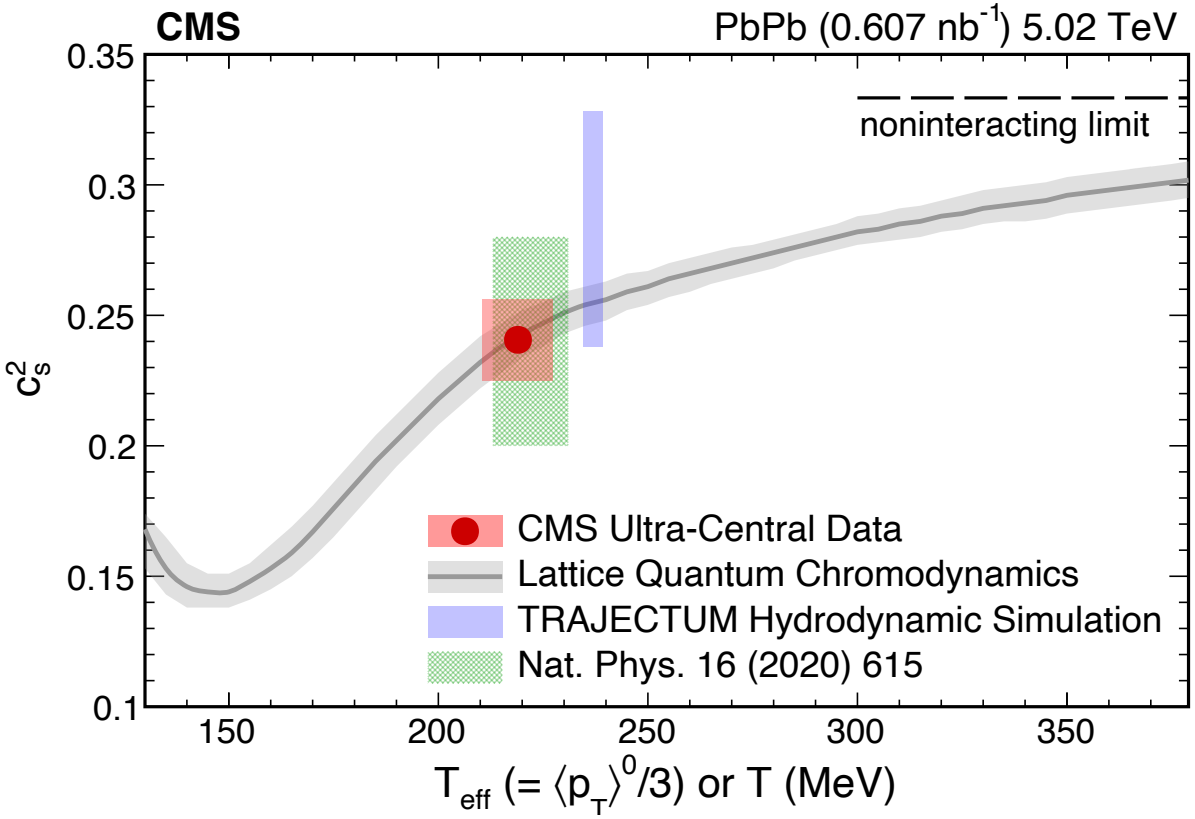
CMS Measurement

Method 2

Good agreement with Lattice QCD calculations

- Deconfined phase
- $\mu_B = 0$ and (2+1)-flavors

Significantly higher precision compared to the previous result



Rep. Prog. Phys. 87, 077801 (2024)

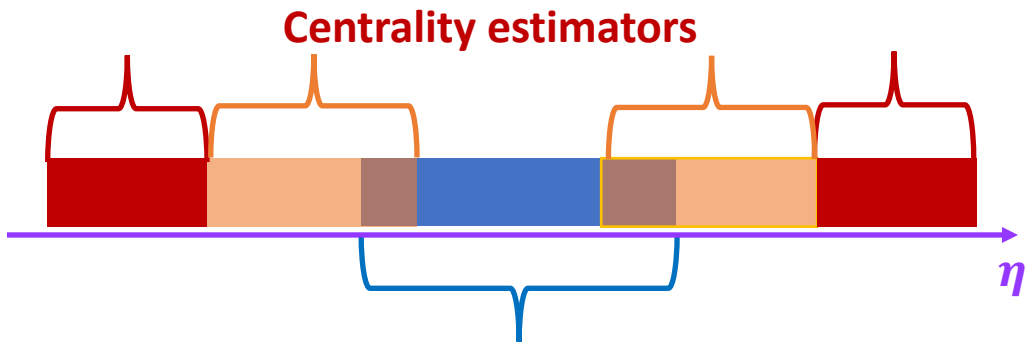
How reliable is the measurement?

ALICE study of potential centrality bias

ALICE-PUBLIC-2024-002

Different centrality estimators

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
$N_{tracklets}$ 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
N_{ch} in V0	IX	$-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$	$\lvert\eta\rvert \leq 0.8$	0.9



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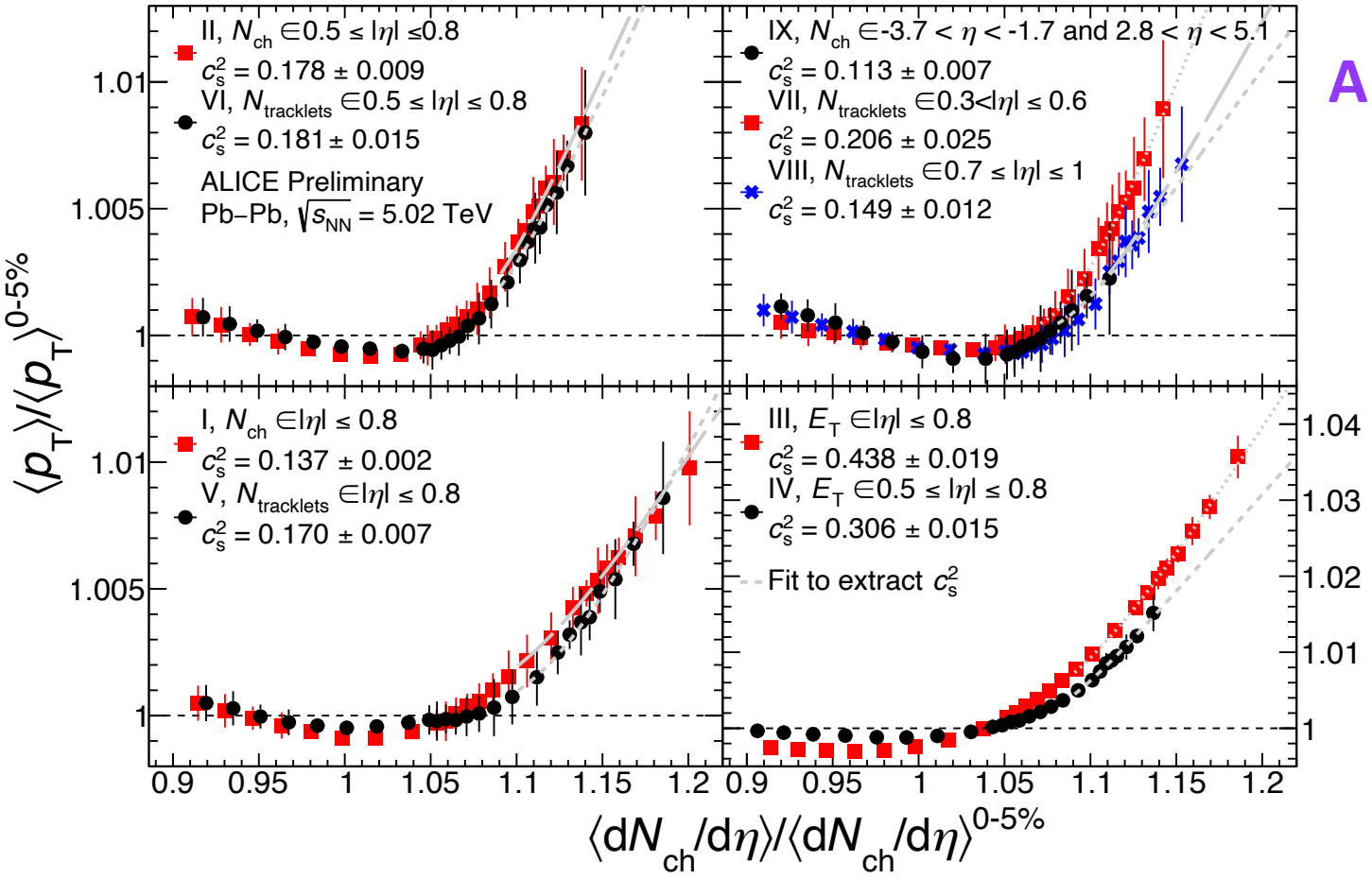


ALICE-PUBLIC-2024-002

ALICE study of potential centrality bias

Selection biases

- different $\langle p_T \rangle$ vs $dN_{ch}/d\eta$ for different selections
- c_s^2 depends on the centrality definition

How reliable is the measurement?

The extracted c_s^2 is higher with the ET estimator than the N_{ch} estimator

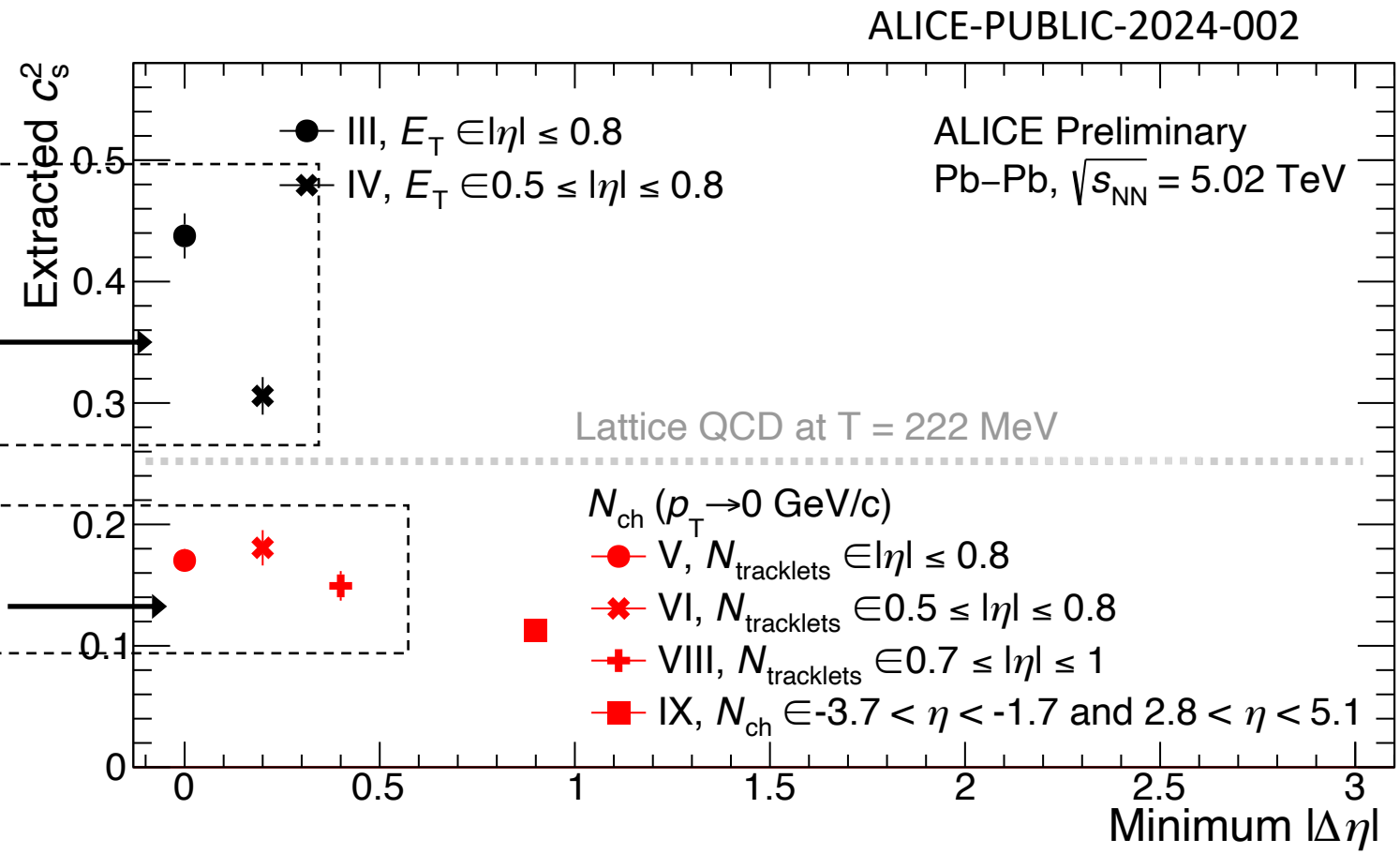
E_T based
effects from hard scattering

Nch-based
reduced by multiplicity fluctuation

$$c_s^2(T_{\mathrm{eff}}) = \left(1 - \frac{\langle N_{ch}\rangle}{\sigma^2_{N_{ch}}}\right)^{-1/2} \frac{d\ln\langle p_T\rangle}{d\ln N_{ch}}$$

Gardim et. al., PLB 856 (2024) 138937

Extracted c_s^2 vs minimum $|\Delta\eta|$ gap



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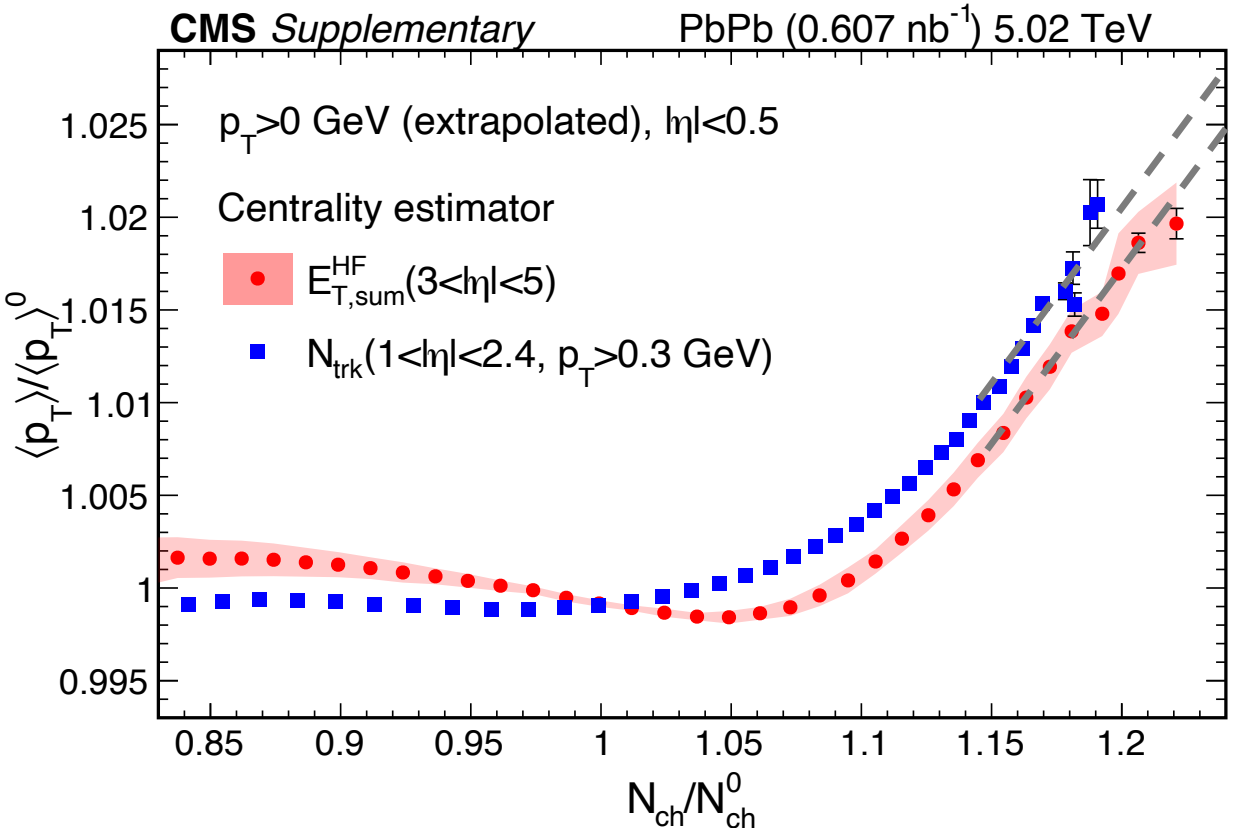


CMS study of potential centrality bias

Slope **does NOT depend** on centrality estimators:

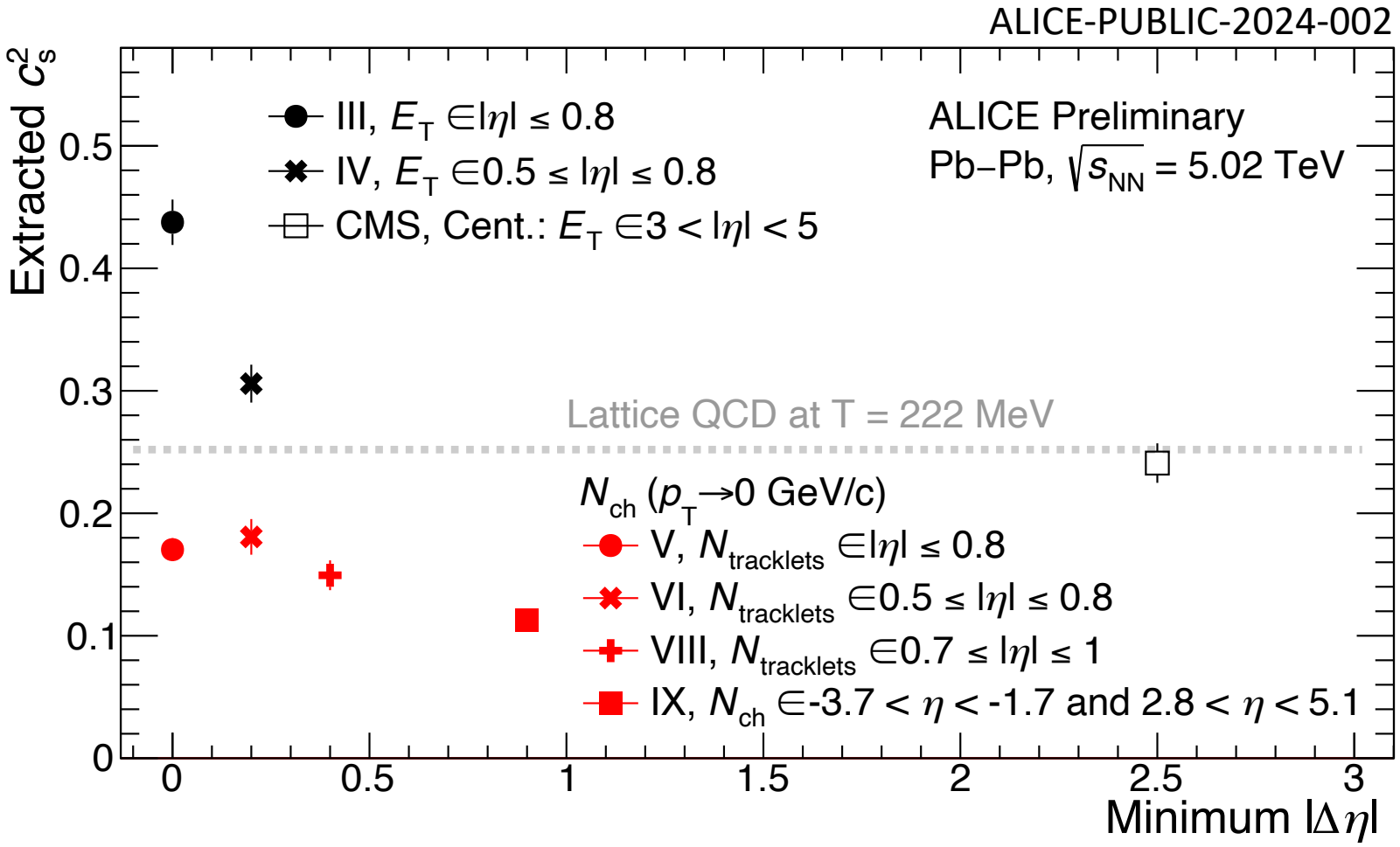
- at **high N_{ch}** &
- if there is **significant η separations** from POI

How reliable is the measurement?

Centrality estimator choice

- a critical role

Extracted c_s^2 vs minimum $|\Delta\eta|$ gap



What else can we learn from <pT> vs Nch

Slightly different observable

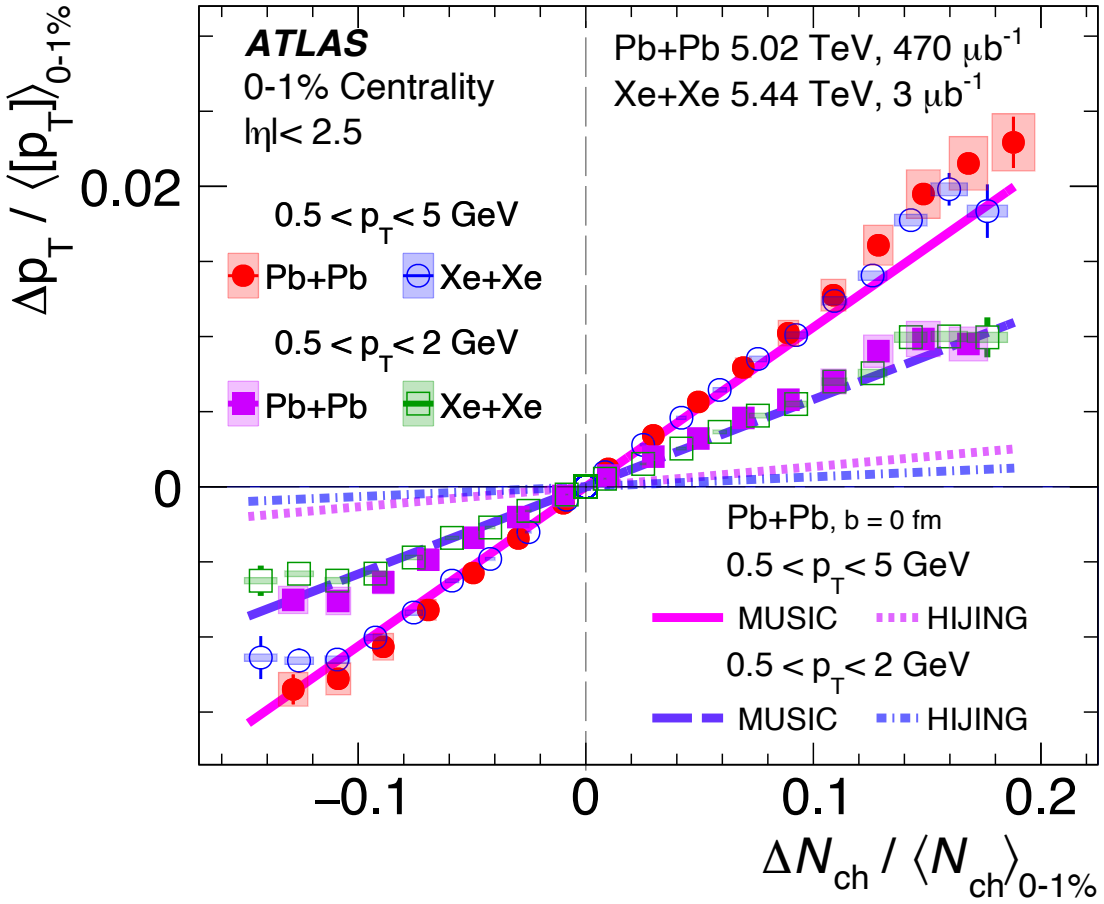
Nch - <[pT] > correlations

Sensitive to the speed of sound

- $c_s^2 = 0.23$ at $T_{eff} = 0.22$ GeV used as input to MUSIC
  - ➢ Value consistent with measurements

Hydro calculations consistent with data

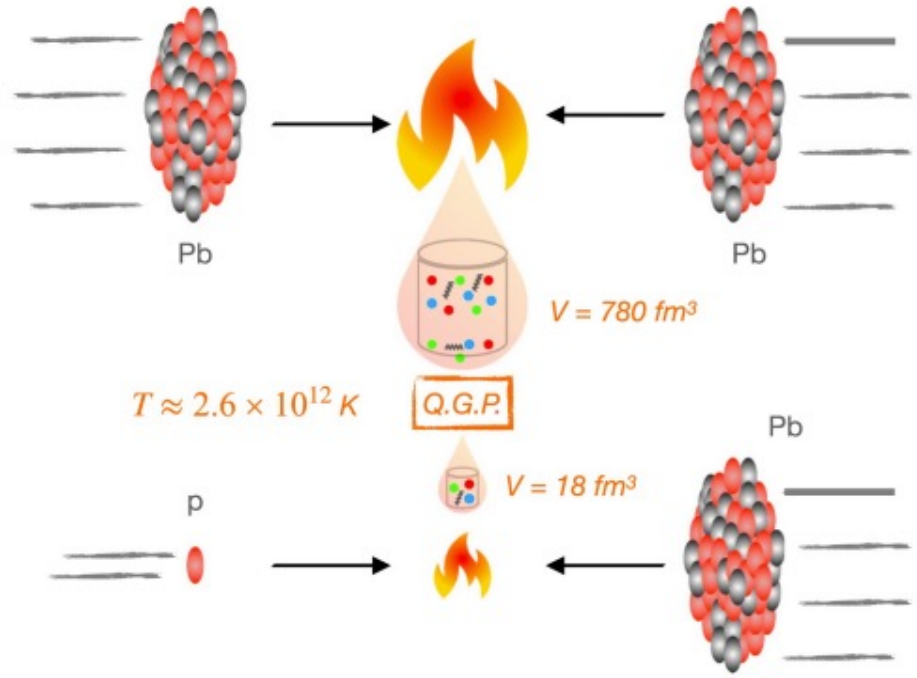
No significant difference between PbPb & XeXe



PRL 133 (2024) 252301

Applying to small systems?

Can one use the same observable ($\langle p_T \rangle$ vs dN_{ch}) to probe thermodynamics in small systems?



PRC 109 (2024) 014904

Mu et. al.: arXiv:2501.02777

Limitations/Complications

- Quantum fluctuations tend to reduce the extracted c_s^2

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

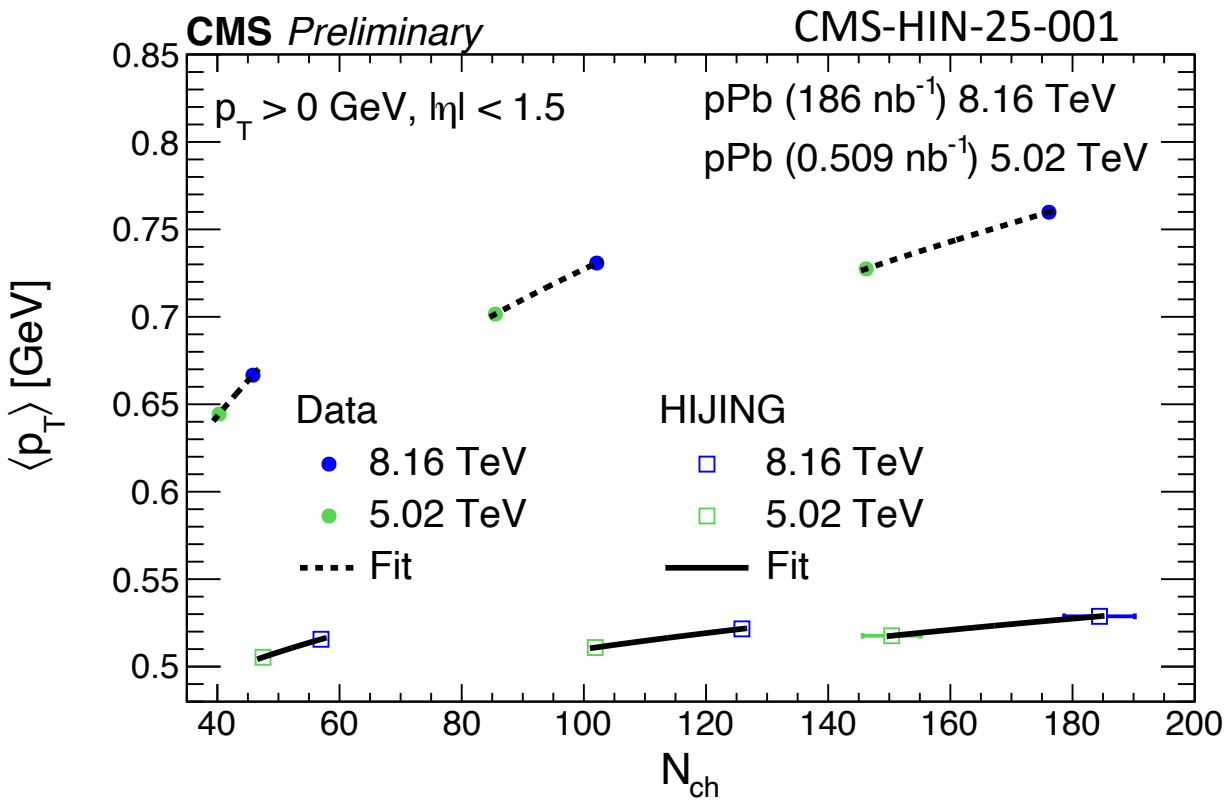
esp. for smaller systems

- T_{eff} not well defined for non-boost invariant system

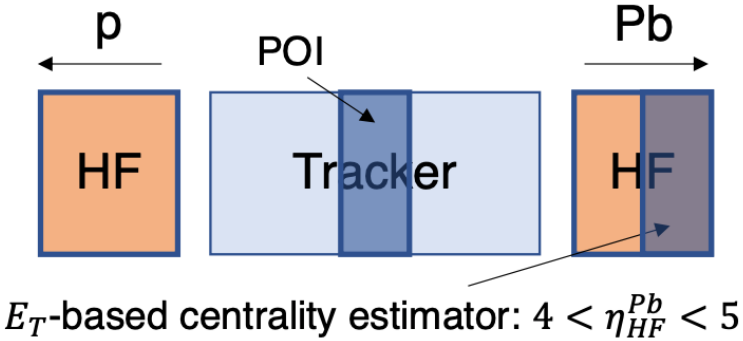
$\langle p_T \rangle \approx 2.22 \sim 2.8\, T_{\rm eff}$ for 5.02 TeV

$\langle p_T \rangle \approx 2.16 \sim 2.58\, T_{\rm eff}$ for 8.16 TeV

Applying to small systems?



Fit with $\langle p_{\mathrm{T}} \rangle \sim (N_{\mathrm{ch}})^{c_s^2}$



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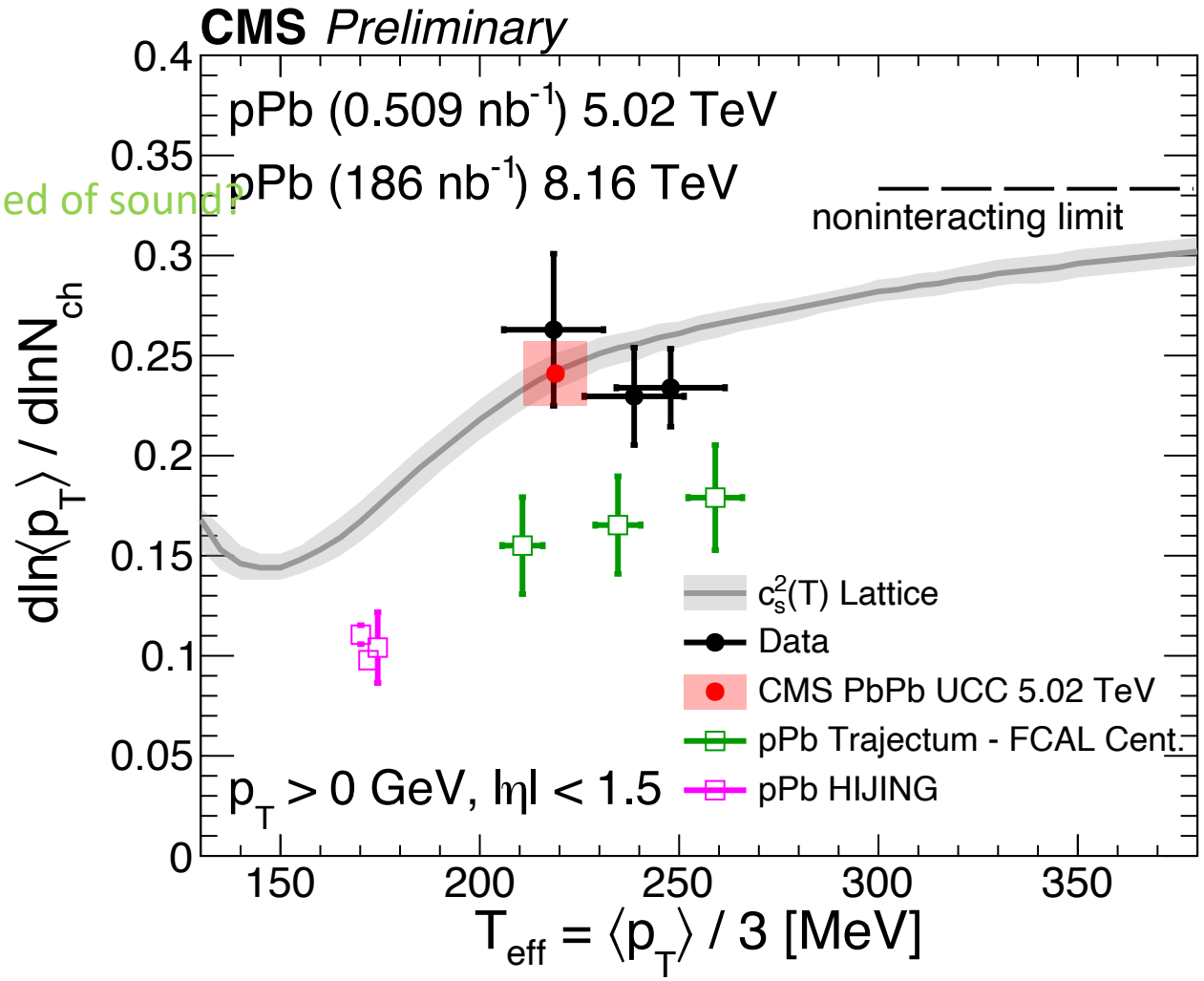
Applying to small systems?



Speed of sound?

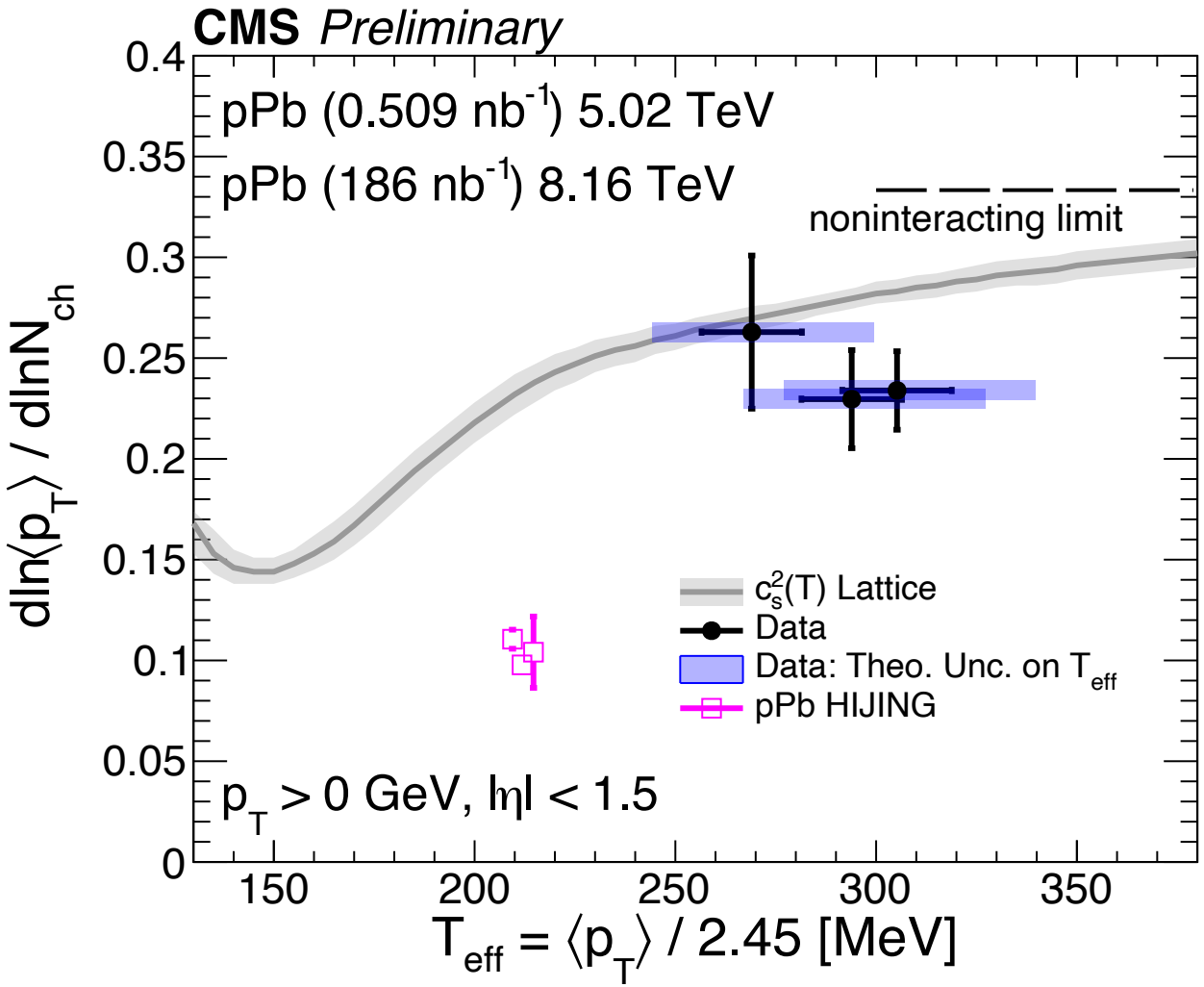
Assuming boost invariant medium

$$T_{eff} = \langle p_{\mathrm{T}} \rangle / 3$$

Trajectum systematically below data

HIJING unable to describe data

Applying to small systems?



Assuming **non-boost** invariant medium

$$T_{eff} = \langle p_T \rangle / 3$$

$$T_{eff} = \langle p_T \rangle / 2.45$$

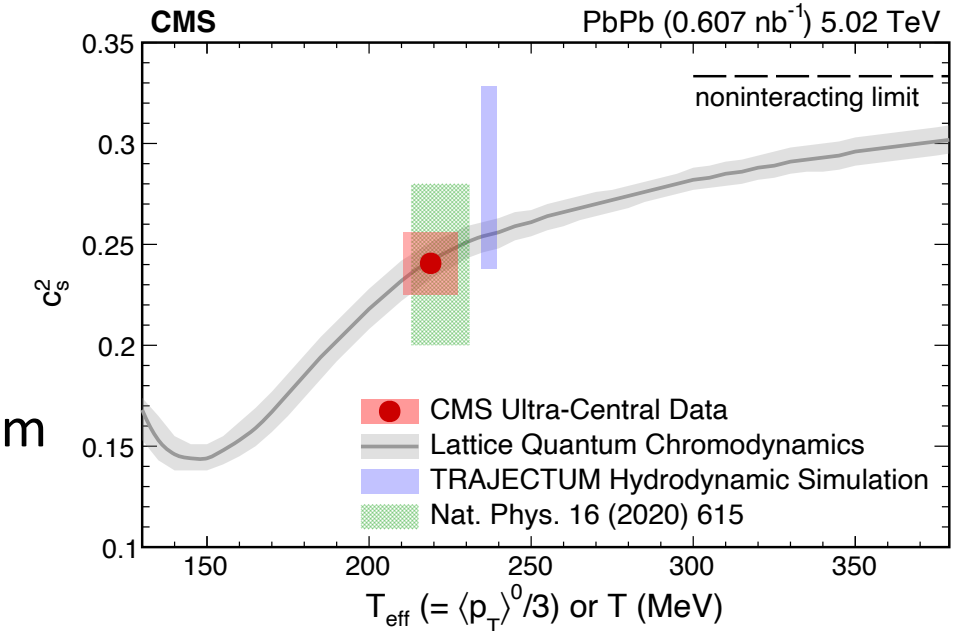
Trajectum systematically below data

HIJING unable to describe data

Summary

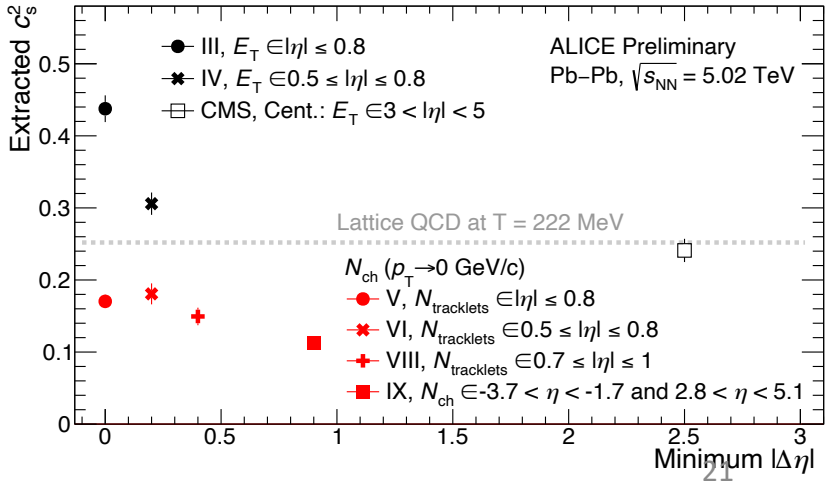
First direct measurements of speed of sound in QGP

- Using $c_s^2 = \frac{dP}{d\varepsilon} = \frac{d\ln\langle p_T\rangle}{d\ln N_{ch}}$
- Good agreement with Lattice QCD for deconfined medium
- A critical choice of centrality estimator



$\frac{d\ln\langle p_T\rangle}{d\ln N_{ch}}$ – way to probe hydrodynamics in small systems

- Models fail to describe data



Open Questions and Future Work

- Validity of the thermodynamic assumptions
  - Discussed more in: arXiv:2407.05570 and arXiv:2503.20765
- Further investigation on the effects from centrality estimator
- Effect of initial density fluctuations
- Look for the rise of $\langle p_{\mathrm{T}} \rangle$ vs N_{ch} in different systems
- Scan of c_s at different energies