



# Extracting the Speed of Sound in the Strongly Interacting Matter in PbPb Collisions

CESAR A. BERNARDES (FOR THE CMS COLLABORATION)



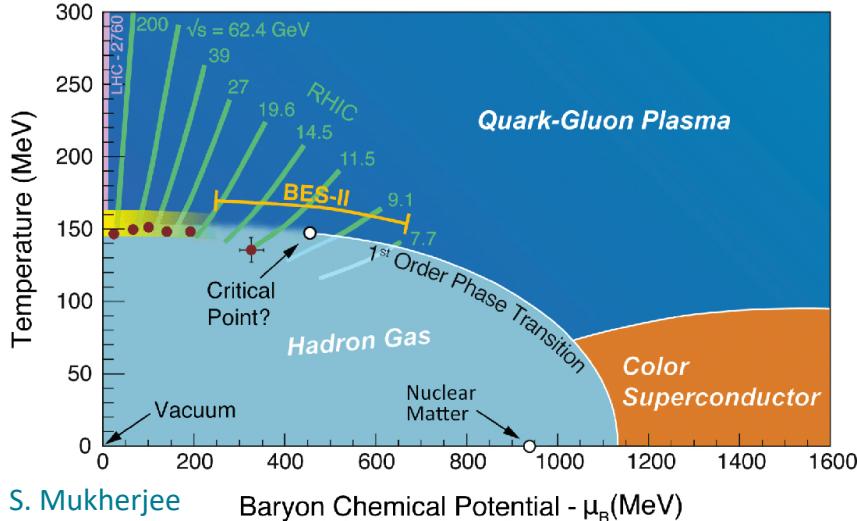
IF-UFRGS, SPRACE-UNESP



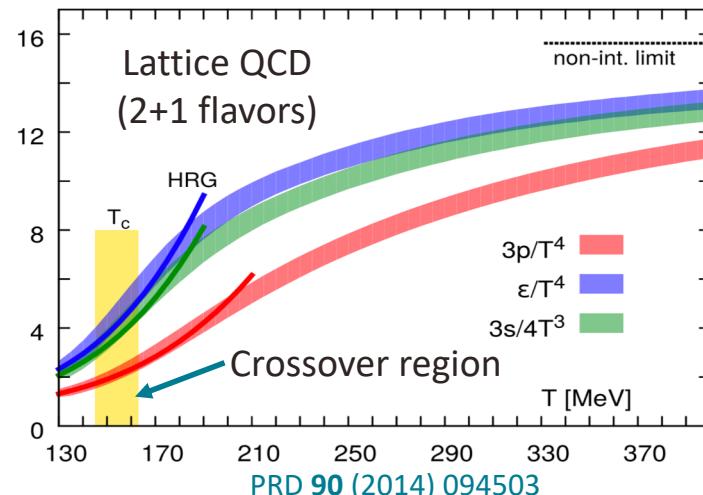
# QCD phase diagram and critical point

Many evidences of the quark-gluon plasma (QGP) phase, but not yet direct observations of...

- ❑ Change in degree of freedom (d.o.f.) at high temperature ( $T$ ) as predicted by Lattice QCD
- ❑ Transition of d.o.f. from low to high- $T$  regions



Normalized pressure, entropy and energy densities vs  $T$



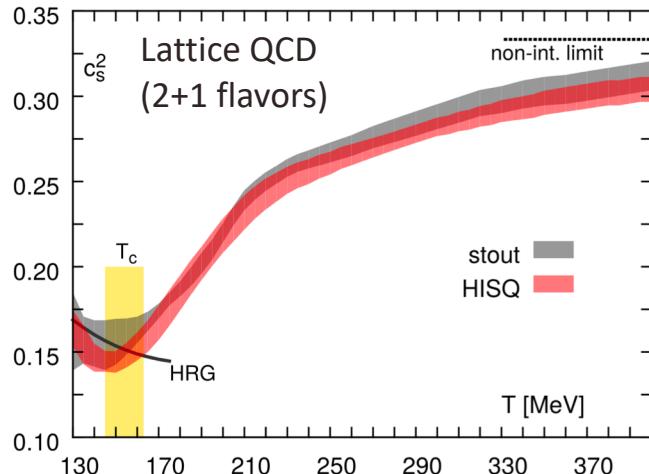
# Speed of sound ( $c_s$ )

In a fluid: velocity of the longitudinal compression wave propagating in the medium

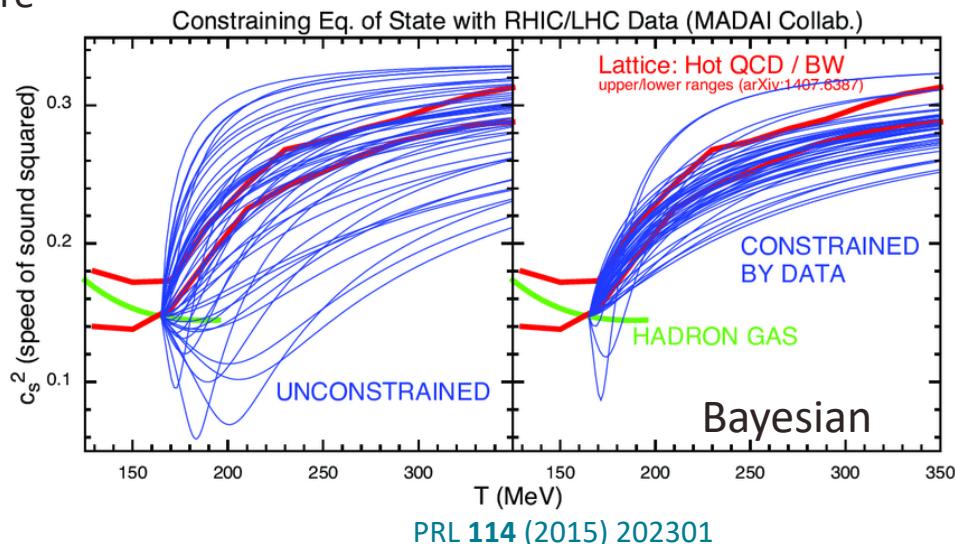
◻  $c_s^2 = dP/d\varepsilon$  ( $P$  is pressure,  $\varepsilon$  is energy density) →

Directly constraint the equation of state (EoS)

Speed of sound squared ( $c_s^2$ ) vs temperature



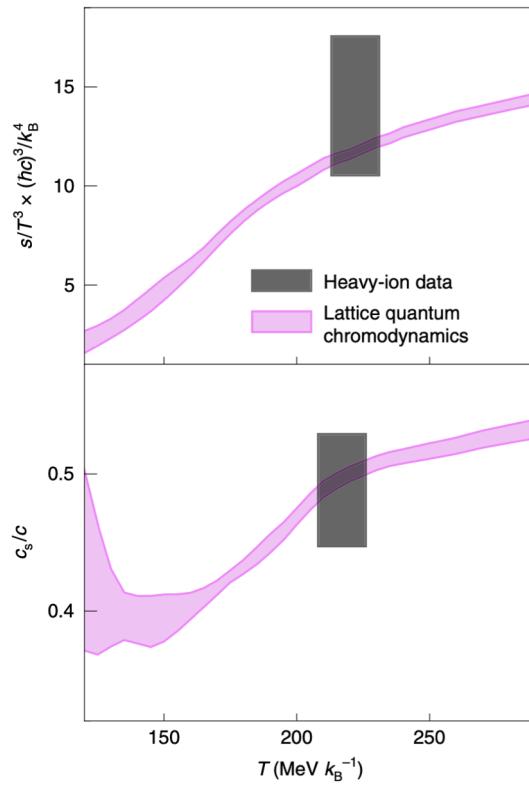
EoS is poorly constrained by data



# Speed of sound extraction using AA data

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- ❑ ALICE PbPb data at 2.76 and 5.02 TeV (0-5% collision centrality)
- ❑ Varied collision energy at a fixed centrality (constant volume)
  - $c_s^2(T_{\text{eff}}) = \frac{dP}{d\varepsilon} = \frac{s dT}{T ds} \Big|_{T_{\text{eff}}} = \frac{d \ln \langle p_T \rangle}{d \ln(dN_{\text{ch}}/d\eta)} = 0.24 \pm 0.04$ 
    - Hydrodynamics simulation:  $T_{\text{eff}} \approx \langle p_T \rangle / 3$ 
      - Longitudinal expansion → smaller than the initial  $T$
  - ❑ Uncertainties limited: only two data points
  - ❑ Energy dependence of  $\langle p_T \rangle$  and  $N_{\text{ch}}$  not unique to AA



# In this work - analysis method

Proposed by PLB 809 (2020) 135749

$\langle p_T \rangle$  (related to  $T_{\text{eff}}$ ) vs  $N_{\text{ch}}$  (related to  $s$ )

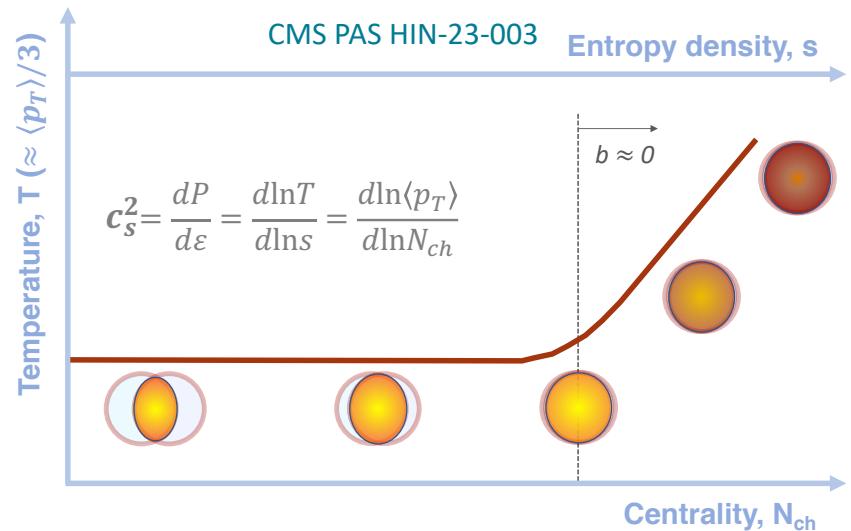
- ❑ Expected an increase in  $\langle p_T \rangle$  when reaching  $b \approx 0$

Similarly as in the previous procedure: fixed volume...

- ❑ But varying  $\langle p_T \rangle$  and  $N_{\text{ch}}$

Non trivial prediction by hydrodynamics!

Slope → squared speed of sound ( $c_s^2$ )



# The CMS detector

## CMS DETECTOR

Total weight : 14,000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T

STEEL RETURN YOKE  
12,500 tonnes

SILICON TRACKERS  
Pixel ( $100 \times 150 \mu\text{m}$ )  $\sim 16\text{m}^2 \sim 66\text{M}$  channels  
Microstrips ( $80 \times 180 \mu\text{m}$ )  $\sim 200\text{m}^2 \sim 9.6\text{M}$  channels

Tracker

$N_{\text{ch}}, p_T$

SUPERCONDUCTING SOLENOID  
Niobium titanium coil carrying  $\sim 18,000\text{A}$

MUON CHAMBERS  
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER  
Silicon strips  $\sim 16\text{m}^2 \sim 137,000$  channels

FORWARD CALORIMETER  
Steel + Quartz fibres  $\sim 2,000$  Channels

Hadron Forward  
(HF) Calorimeters

Event selection  
Collision centrality

CRYSTAL  
ELECTROMAGNETIC  
CALORIMETER (ECAL)  
 $\sim 76,000$  scintillating PbWO<sub>4</sub> crystals

HADRON CALORIMETER (HCAL)  
Brass + Plastic scintillator  $\sim 7,000$  channels

# Samples and track selections

Minimum bias PbPb collisions at 5.02 TeV

- ❑ About 4.27 billion events,  $L_{\text{int}} = 0.607 \text{ nb}^{-1}$

Monte Carlo (MC) simulations: HYDJET generator

- ❑ Efficiency corrections, cross-checks, closure tests, etc...

Track selection:  $p_T > 0.3 \text{ GeV}$ ,  $|\eta| < 0.5$

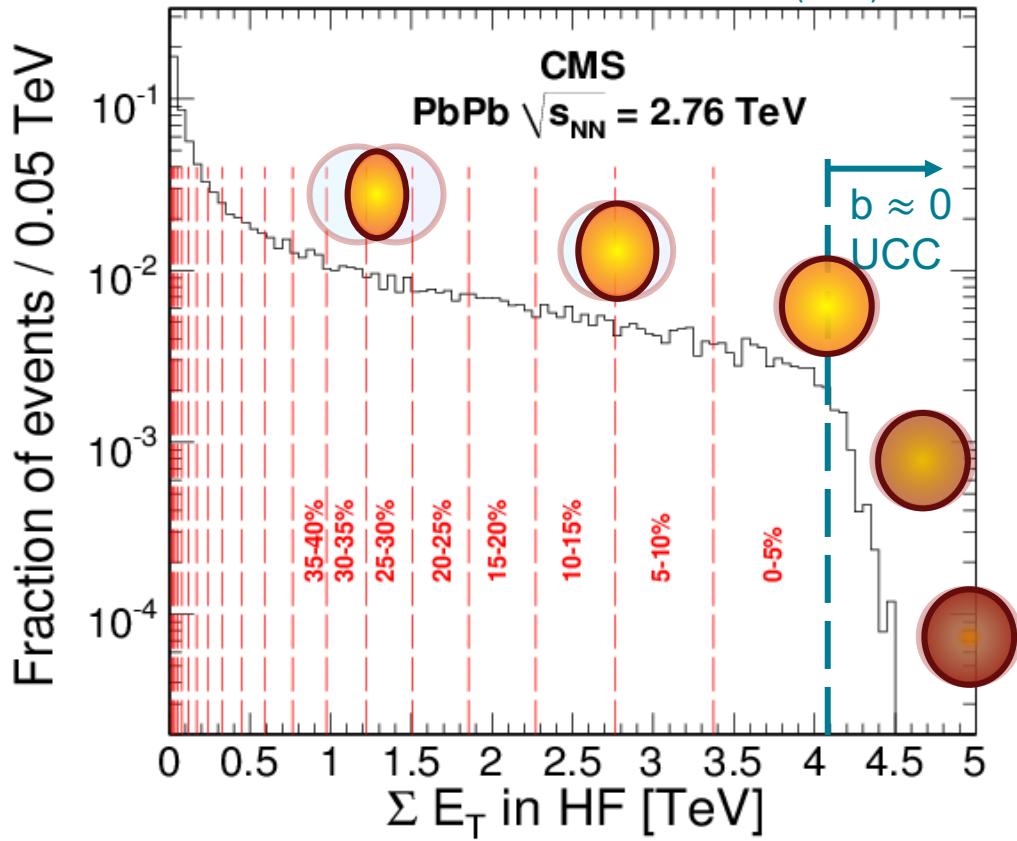
- ❑ Better tracking performance

# Ultracentral (UCC) PbPb collisions

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## Collision centrality

- ❑ Experimentally: sum of transversal energy ( $E_T$ ) in HF
- ❑ Related to impact parameter ( $b$ ), system volume/geometry
- ❑ For  $b \approx 0$  (~0-1% centrality)
  - Volume almost constant
  - But energy density can fluctuate

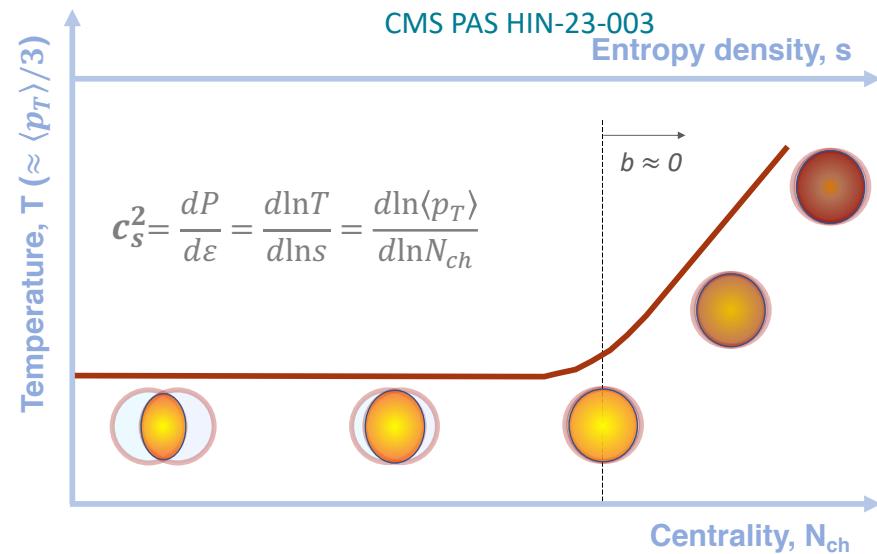


# Analysis method - observables

The  $c_s^2$  depends on the relative variation of  $\langle p_T \rangle$  vs  $N_{ch}$

- Can be extracted using

- $\frac{\langle p_T \rangle}{\langle p_T \rangle^0} \sim \left( \frac{N_{ch}}{N_{ch}^0} \right)^{c_s^2}$ , where  $\langle p_T \rangle^0$  and  $N_{ch}^0$  are obtained in 0-5%



# Analysis method - observables

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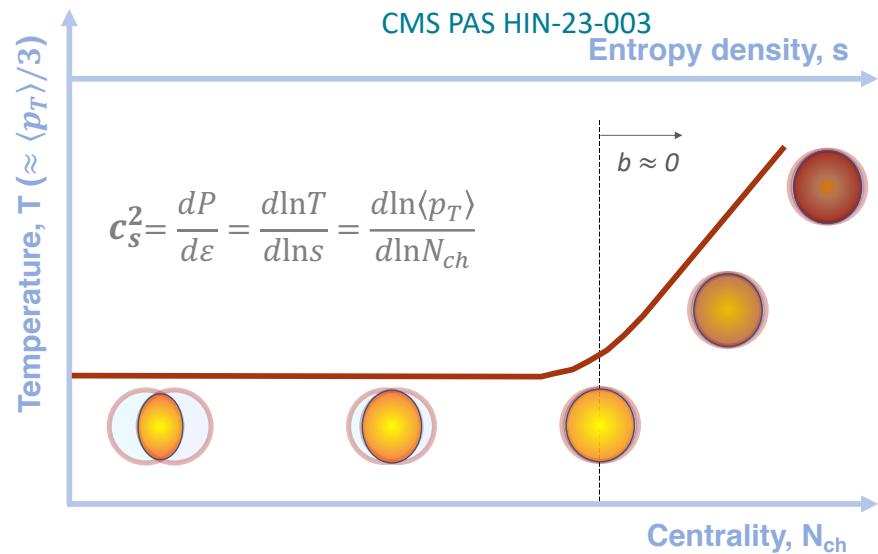
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## Analysis observables

$$\langle p_T \rangle^{\text{norm}} = \frac{\langle p_T \rangle}{\langle p_T \rangle^0} \quad \text{vs} \quad N_{ch}^{\text{norm}} = \frac{N_{ch}}{N_{ch}^0}$$

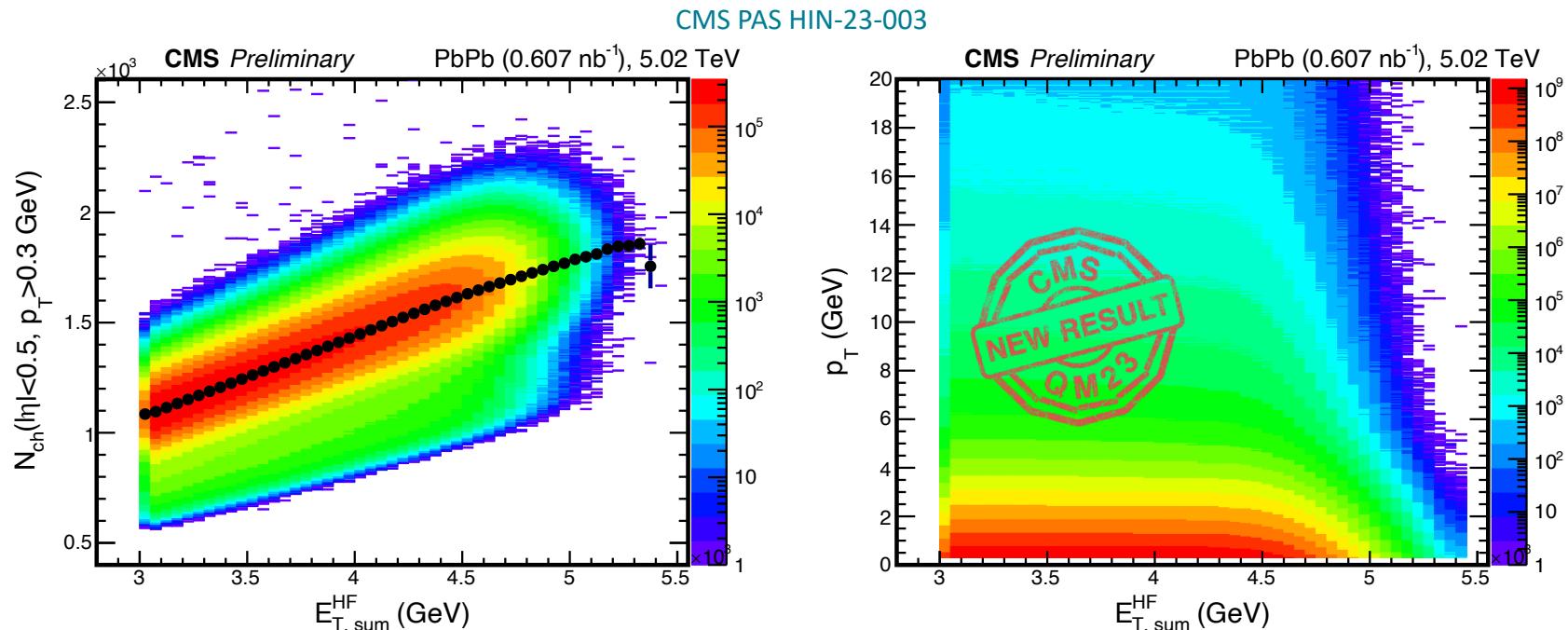
$\langle p_T \rangle^0$  (used to estimate  $T_{\text{eff}}$ )



# Analysis method - $\langle p_T \rangle$ and $N_{\text{ch}}$

To avoid other sources of correlations between  $\langle p_T \rangle$  and  $N_{\text{ch}}$

- ❑ Both are measured first in bins of  $E_{T, \text{sum}}^{\text{HF}}$  (bin width of 50 GeV)



# Analysis method - $p_T$ extrapolation to zero

$\langle p_T \rangle$  and  $N_{\text{ch}}$  are corrected for tracking efficiency

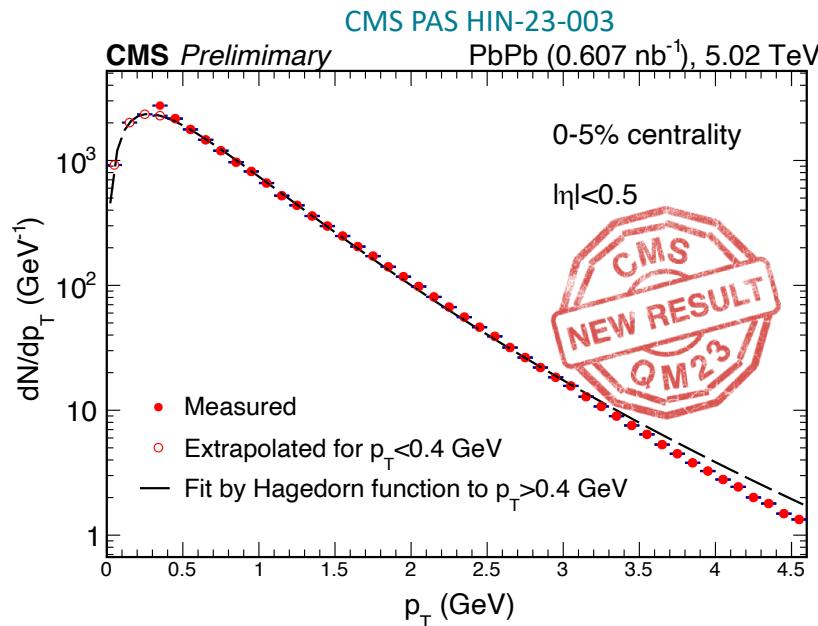
Extrapolation to  $p_T \approx 0$  by fitting the spectrum in  $p_T > 0.4$  GeV

- ❑ Hagedorn function

$$\frac{dN_{\text{ch}}}{dp_T} = p_T \left( 1 + \frac{1}{\sqrt{1 - \langle \beta_T \rangle^2}} \frac{\left( \sqrt{p_T^2 + m^2} - \langle \beta_T \rangle p_T \right)}{nT} \right)^{-n}$$

- ❑  $m$  is the pion mass and  $\langle \beta_T \rangle$ ,  $n$ ,  $T$  are free parameters

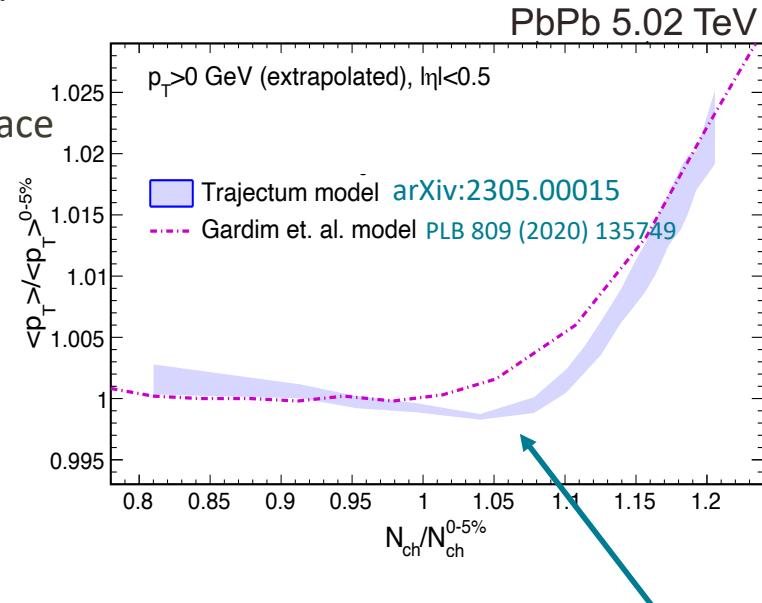
After corrections, for each bin of  $E_{T,\text{sum}}^{\text{HF}}$   $\rightarrow \langle p_T \rangle^{\text{norm}}$  vs  $N_{\text{ch}}^{\text{norm}}$



# Theoretical predictions

Trajectum & Gardim et. al. models (hybrid simulation models)

- ❑ Trajectum: global Bayesian analysis based on many data observables
  - Uncertainties within the allowed parameter space
- ❑ Gardim et.al.: EoS from 2+1 flavors Lattice QCD



# Theoretical predictions

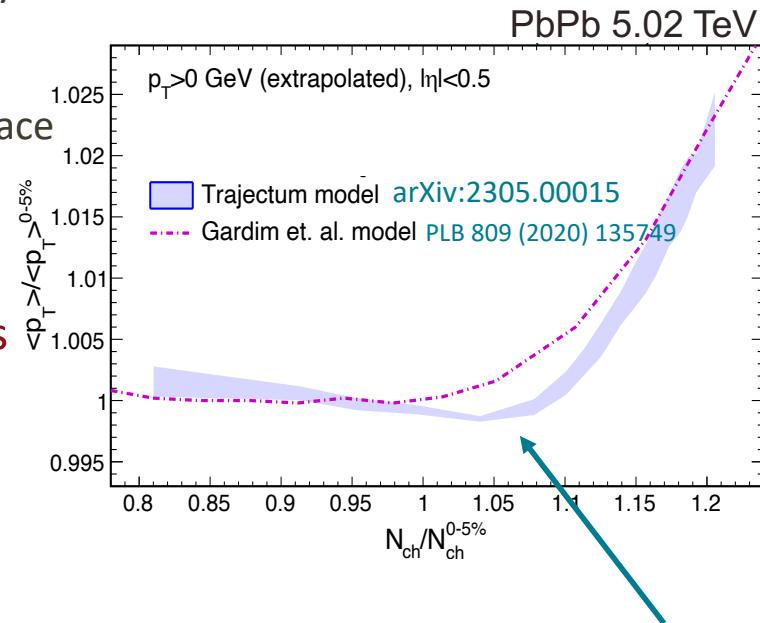
Trajectum & Gardim et. al. models (full heavy ion collision process)

- ❑ Trajectum: global Bayesian analysis based on many data observables
  - Uncertainties within the allowed parameter space
- ❑ Gardim et.al.: EoS from 2+1 flavors Lattice QCD

Significant increase of  $\langle p_T \rangle$  toward UCC events

Trajectum → dip at  $N_{\text{ch}} \sim 1.05 N_{\text{ch}}(0-5\%)$

- ❑ The physical origin is unclear!



# Extracting the speed of sound - general

Fit  $\langle p_T \rangle^{\text{norm}}$  vs  $N_{\text{ch}}^{\text{norm}}$  using

$$\square \quad \langle p_T \rangle^{\text{norm}} = \left( \frac{N_{\text{ch}}^{\text{norm}}}{\text{Prob}(N_{\text{ch}}^{\text{norm}})} \right)^{c_s^2}$$

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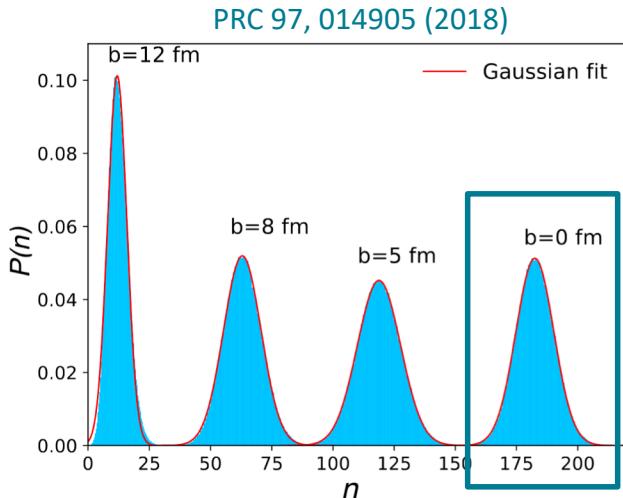


Multiplicity fluctuations at fixed  $b$   
Sum of Gaussians corresponding to each  $b$   
Details on the backup

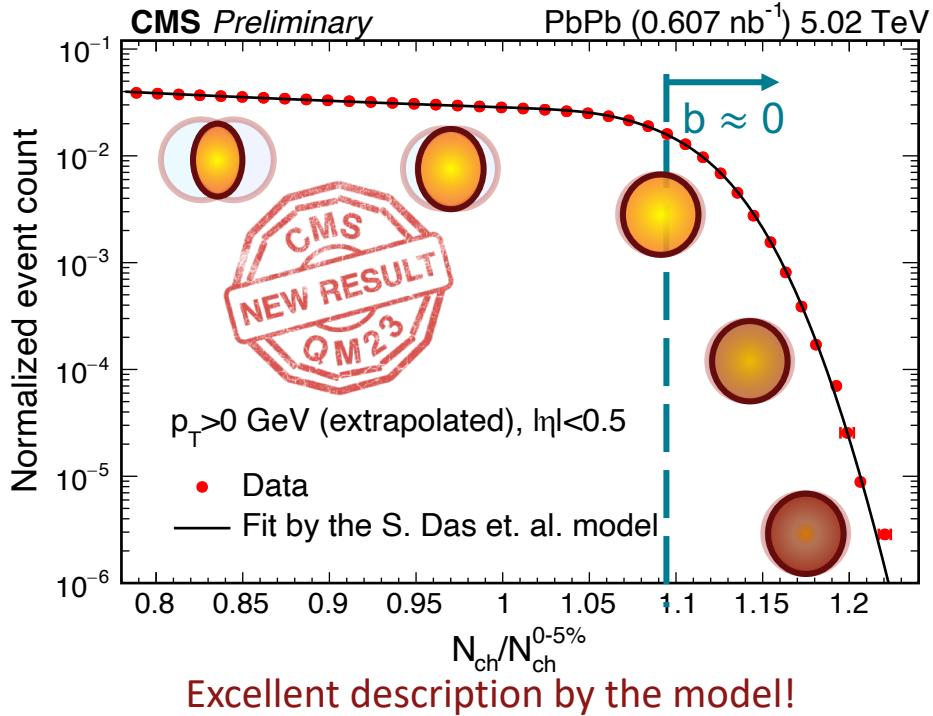
# Extracting the speed of sound - general

Fit  $\langle p_T \rangle^{\text{norm}}$  vs  $N_{\text{ch}}^{\text{norm}}$  using

□  $\langle p_T \rangle^{\text{norm}} = \left( \frac{N_{\text{ch}}^{\text{norm}}}{\text{Prob}(N_{\text{ch}}^{\text{norm}})} \right)^{c_s^2}$



Prob( $N_{\text{ch}}^{\text{norm}}$ ) free parameters values at  $b \approx 0$   
Fit  $N_{\text{ch}}^{\text{norm}}$  distribution



# Extracting the speed of sound - general

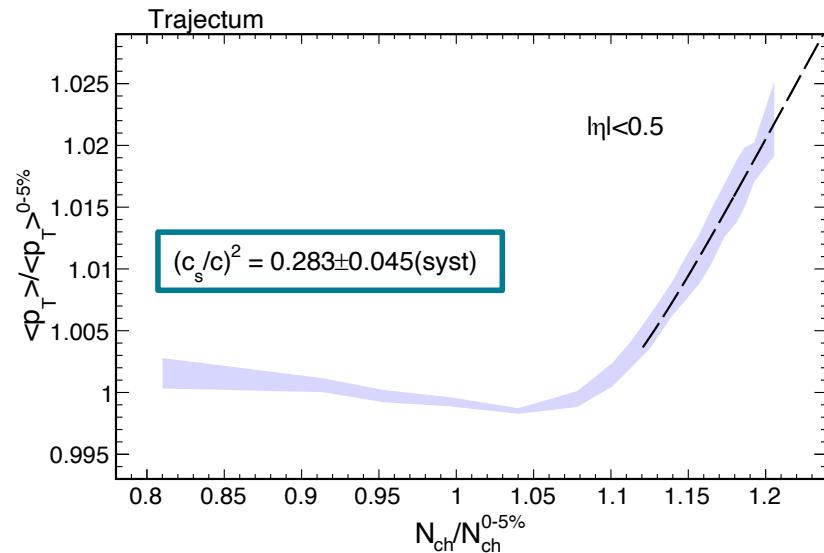
Example: Traectum simulation [arXiv:2305.00015](https://arxiv.org/abs/2305.00015)

Fit  $\langle p_T \rangle^{\text{norm}}$  vs  $N_{\text{ch}}^{\text{norm}}$  using

$$\square \quad \langle p_T \rangle^{\text{norm}} = \left( \frac{N_{\text{ch}}^{\text{norm}}}{\text{Prob}(N_{\text{ch}}^{\text{norm}})} \right)^{c_s^2}$$

Do not model the dip

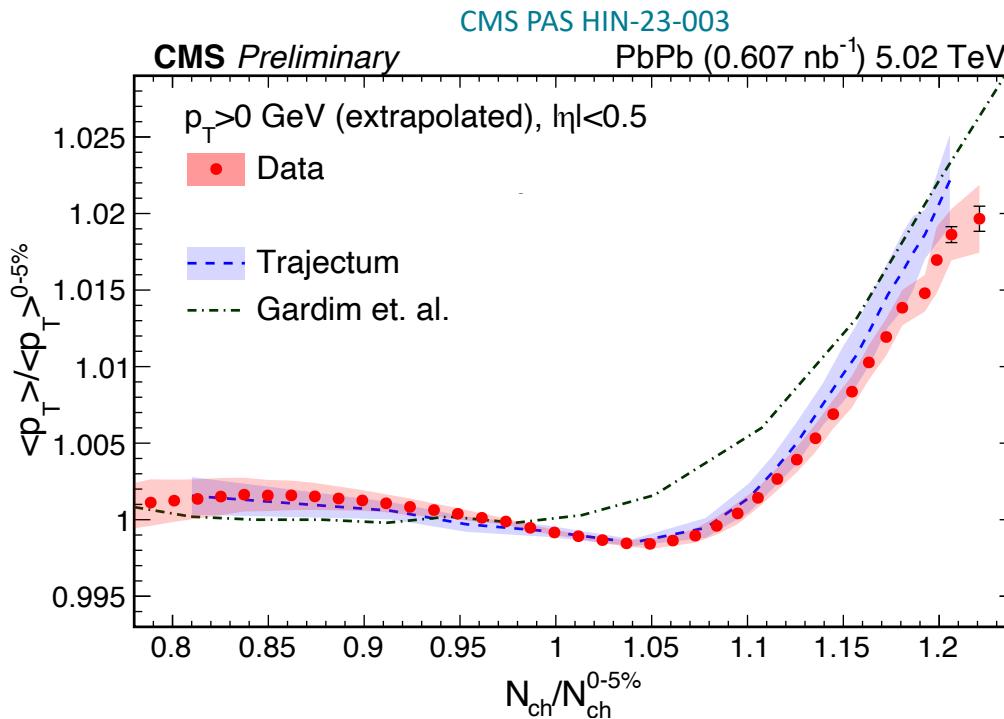
Fit starts from better  $\chi^2$  at  $N_{\text{ch}}^{\text{norm}} > 1.12$



# Results

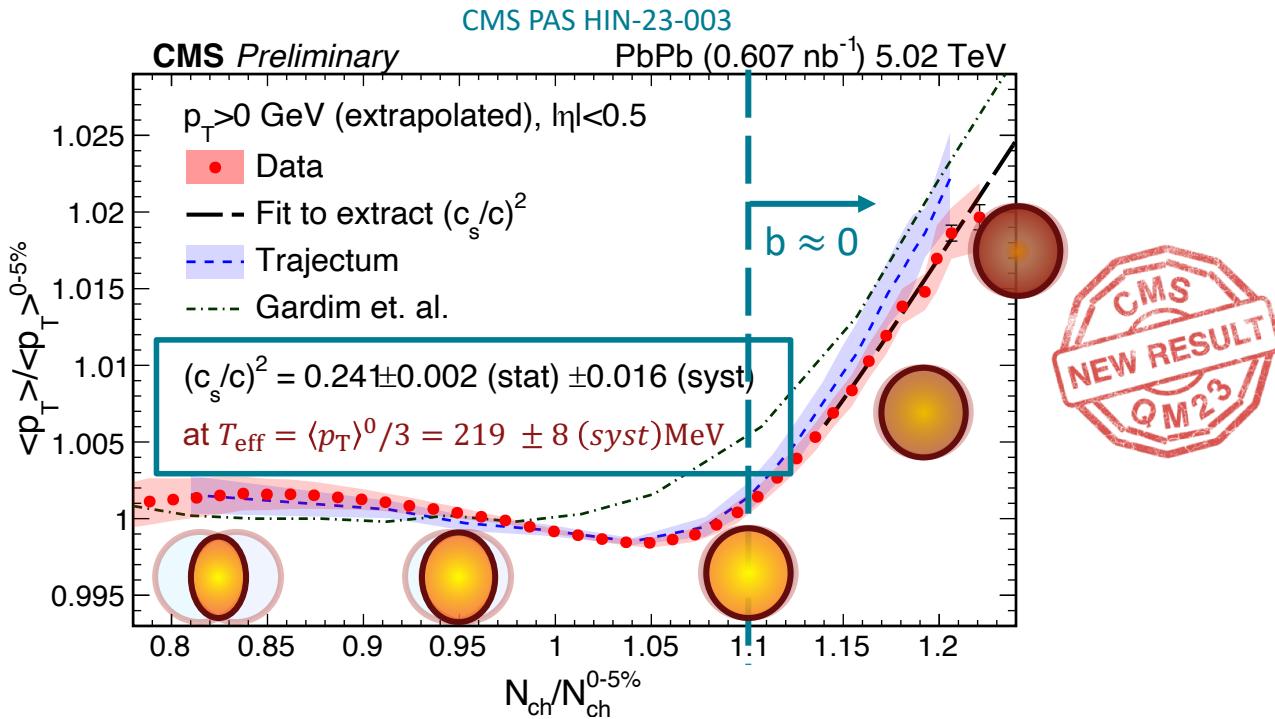
# Results

Significant increase of  $\langle p_T \rangle$  toward UCC events as predicted by the simulations



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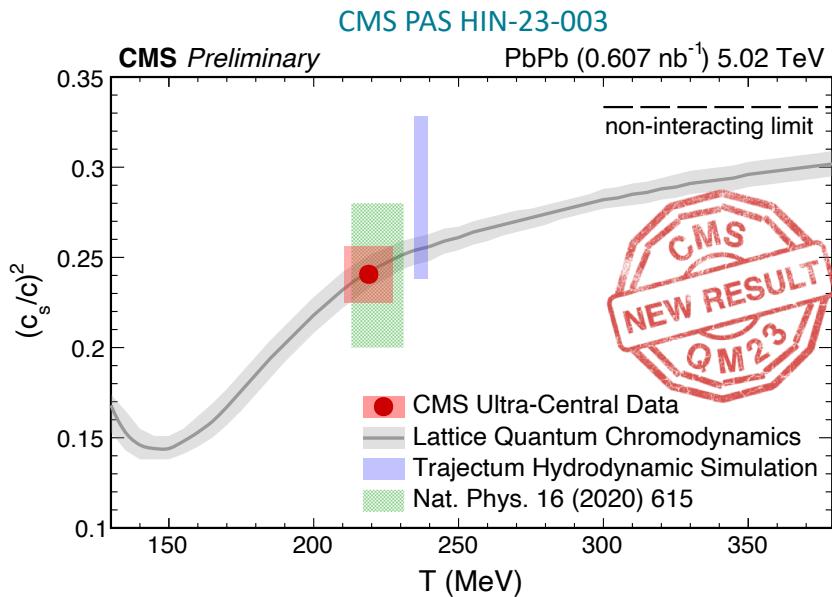
Speed of sound extracted from the fit and  $T_{\text{eff}}$  from  $\langle p_T \rangle^0$

# Results

First time determination of the speed of sound with high precision in AA ultracentral collisions

In agreement with Lattice QCD ( $\mu_B \sim 0$  and 2+1 flavors) and previous measurements

Compatible with a deconfined phase at high-T

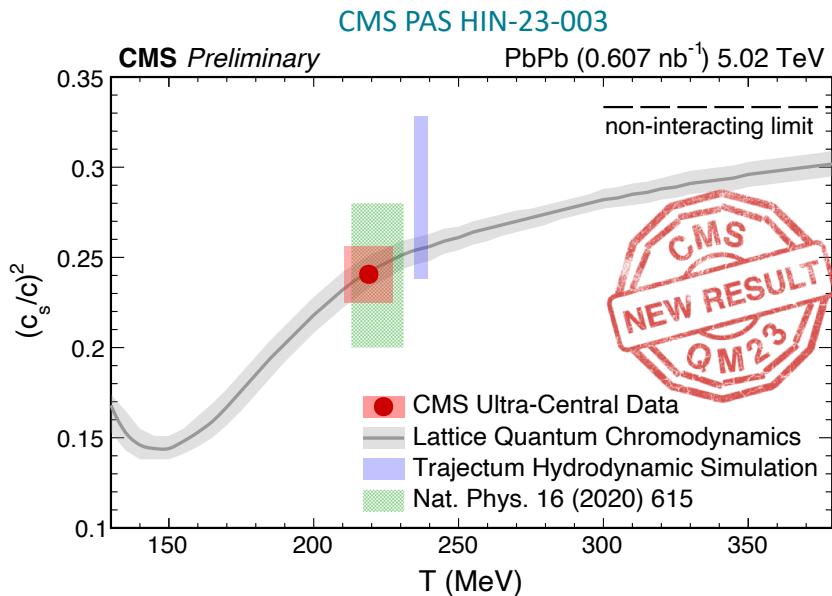


# Results

First time determination of the speed of sound with high precision in AA ultracentral collisions

Robust method to extract  $c_s^2$  from UCC events → scan of  $c_s^2$  at low energies

Important implications to the search of the critical point



# Summary

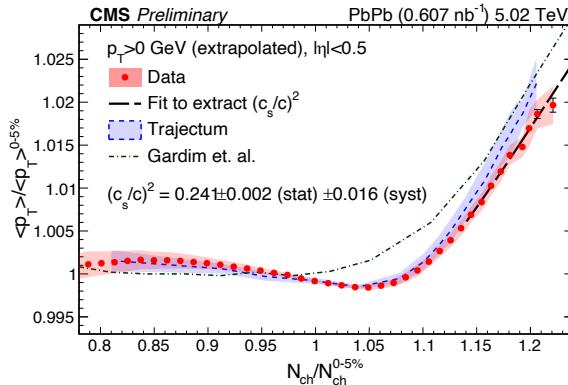
Extracted the speed of sound for the first time using ultra-central AA events

- $c_s^2 = 0.241 \pm 0.002 \text{ (stat)} \pm 0.016 \text{ (syst)}$  at  $T_{\text{eff}} = 219 \pm 8 \text{ (syst) MeV}$

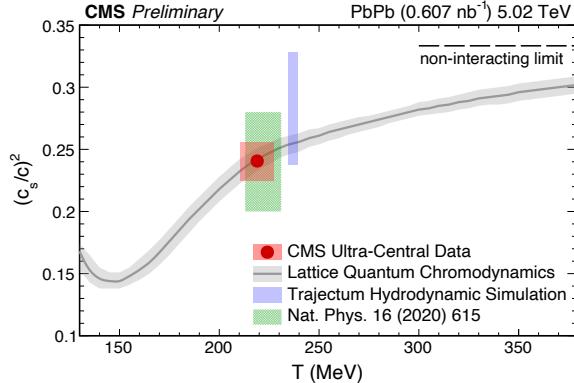
Under assumptions, in agreement with Lattice QCD ( $\mu_B \sim 0$  and 2+1 flavors)

- Constraint on the QCD equation of state
- Compatible with a deconfined phase at high temperature

Robust method to extract  $c_s^2 \rightarrow$  Scan of  $c_s^2$  at low energies  $\rightarrow$  Search for the critical point



CMS PAS HIN-23-003





Thank You!!! 2023





THIS MATERIAL IS BASED UPON WORK SUPPORTED BY THE SÃO PAULO RESEARCH FOUNDATION (FAPESP) GRANTS NO. 2018/01398-1 AND NO. 2013/01907-0. ANY OPINIONS, FINDINGS, AND CONCLUSIONS OR RECOMMENDATIONS EXPRESSED IN THIS MATERIAL ARE THOSE OF THE AUTHOR(S) AND DO NOT NECESSARILY REFLECT THE VIEWS OF FAPESP.

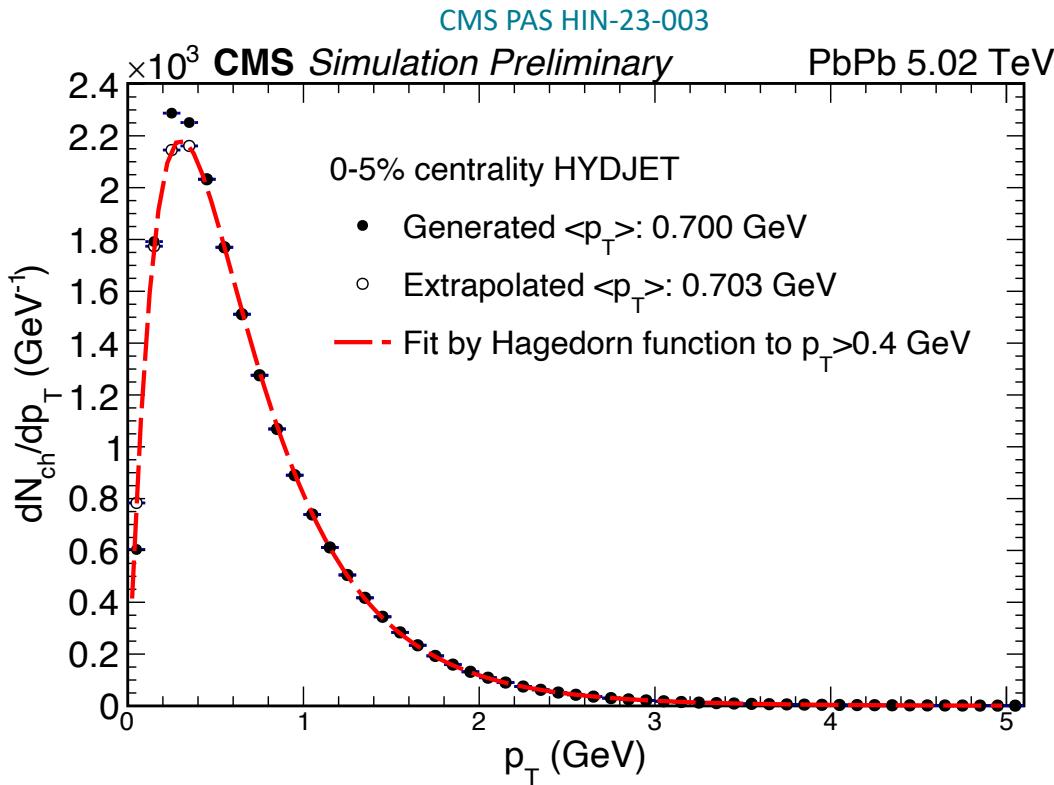
FAPERGS GRANT 22/2551-0000595-0, CNPQ GRANT 407174/2021-4.



# BACKUP

# Extrapolation to $p_T \approx 0$ - Monte Carlo

HYDJET generator



# Extracting the speed of sound - general

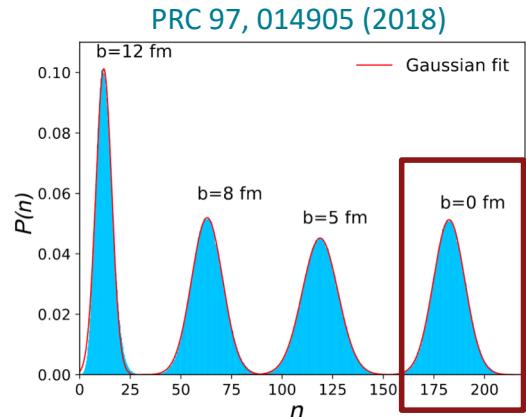
Fit the curve using

$$\square \quad \langle p_T \rangle^{\text{norm}} = \left( \frac{N_{\text{ch}}^{\text{norm}}}{\langle N_{\text{ch}}^{\text{knee}} | N_{\text{ch}}^{\text{norm}} \rangle} \right)^{c_s^2}$$

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$$\blacksquare \quad \left\langle N_{\text{ch}}^{\text{knee}} | N_{\text{ch}}^{\text{norm}} \right\rangle = N_{\text{ch}}^{\text{norm}} - \sigma \sqrt{\frac{2}{\pi}} \frac{\exp\left(-\frac{(N_{\text{ch}}^{\text{norm}} - N_{\text{ch}}^{\text{knee}})^2}{2\sigma^2}\right)}{\operatorname{erfc}\left(\frac{N_{\text{ch}}^{\text{norm}} - N_{\text{ch}}^{\text{knee}}}{\sqrt{2}\sigma}\right)}$$

- $N_{\text{ch}}^{\text{knee}}$  and  $\sigma$  (mean and r.m.s. width of  $N_{\text{ch}}^{\text{norm}}$  at  $b = 0$ )
- Used to correct for multiplicity fluctuation effects



To fit  $N_{\text{ch}}$  (next slide), integrate over all  $b$  values.

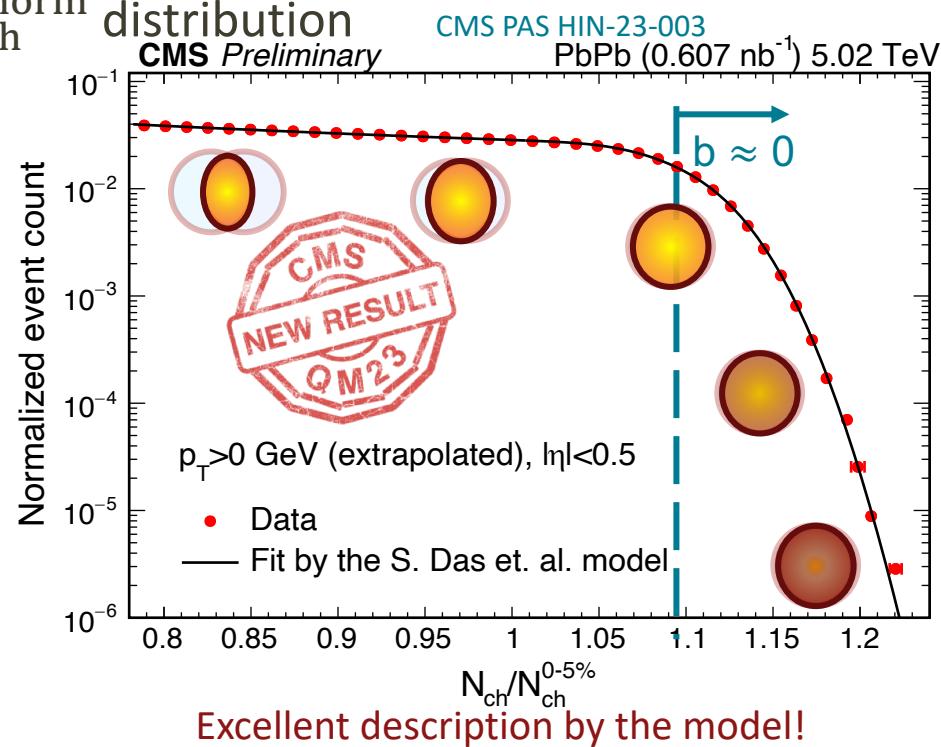
# Extracting the speed of sound - $N_{\text{ch}}^{\text{knee}}$ and $\sigma$

Exactly same procedure is performed with Trajectum

- ❑ Fit  $\langle \overline{N_{\text{ch}}^{\text{knee}}} | N_{\text{ch}}^{\text{norm}} \rangle$  function to  $N_{\text{ch}}^{\text{norm}}$  distribution
- ❑ Here with CMS data

- Extract  $N_{\text{ch}}^{\text{knee}}$  and  $\sigma$
- Extracted values
  - $N_{\text{ch}}^{\text{knee}} = 1.1, \sigma = 0.027$

Negligible statistical uncertainties



$$P(n) = \int_0^1 P(n|c_b) dc_b.$$

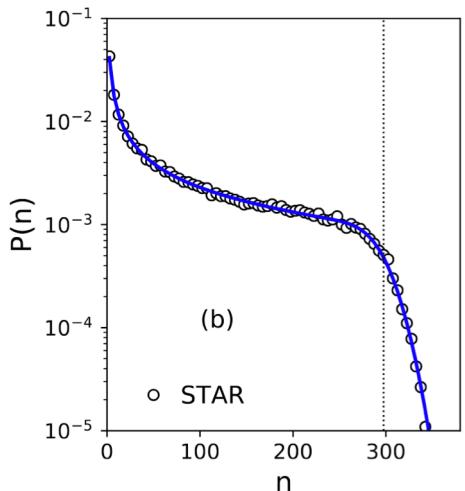
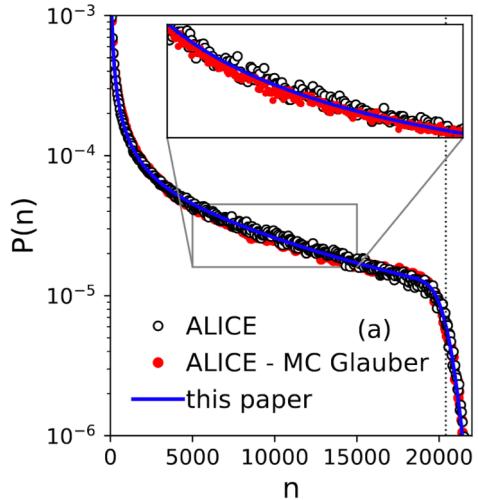
$$P(n|c_b) = \frac{\eta(c_b)}{\sigma(c_b)\sqrt{2\pi}} \exp\left(-\frac{(n - \bar{n}(c_b))^2}{2\sigma(c_b)^2}\right), \quad (3)$$

$$\eta(c_b) = 2 \left[ 1 + \text{erf}\left(\frac{\bar{n}(c_b)}{\sigma(c_b)\sqrt{2}}\right) \right]^{-1}$$

$$\bar{n}(c_b) = n_{\text{knee}} \exp(-a_1 c_b - a_2 c_b^2 - a_3 c_b^3)$$

$$\sigma(c_b) = \sigma(0) \sqrt{\bar{n}(c_b)/\bar{n}(0)}$$

<sup>1</sup> The results in this paper use the variable  $c_b$ , but one can easily express them in terms of  $b$  by using the change of variables  $c_b = \pi b^2/\sigma_{\text{inel}}$ . The value of  $\sigma_{\text{inel}}$  needs to be taken from either data or some collision model.



# Systematic uncertainties and cross-checks

## Systematics

- ❑ Tracking efficiency corrections
- ❑ Extrapolation to  $p_T \approx 0$
- ❑ Choice of fit range (only for  $c_s^2$ )

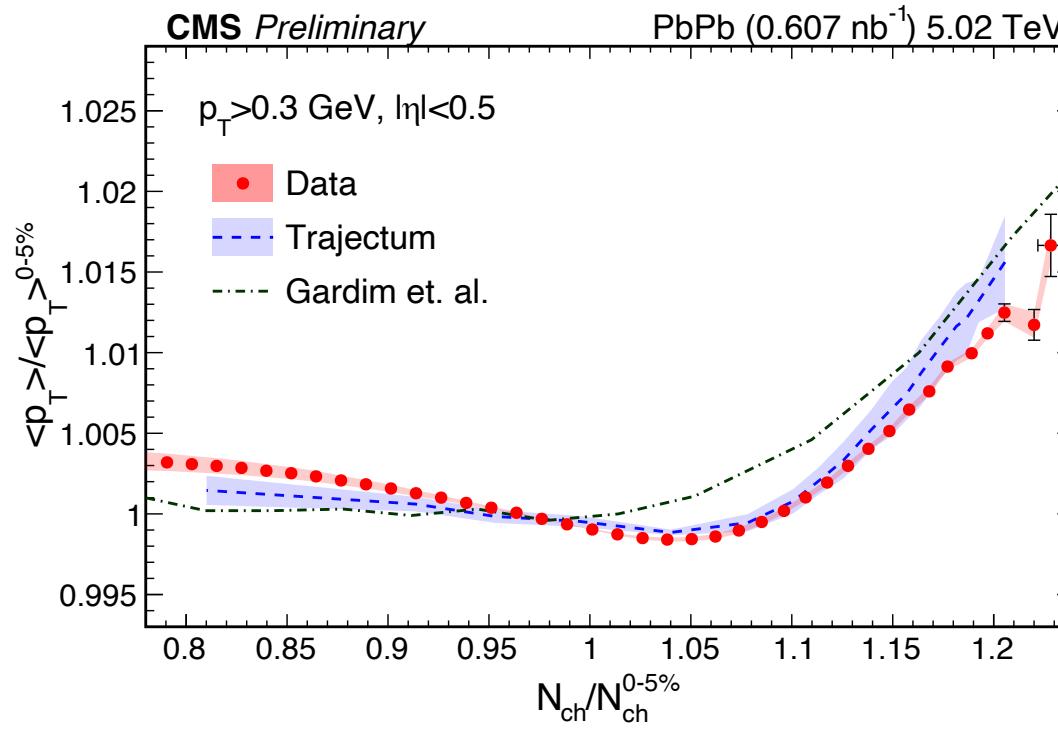
## Main cross-checks

- ❑ HF energy resolution
  - Data HF energy smearing
  - Vary bin width
    - 50GeV → 25GeV and 100GeV
- ❑ Efficiency correction
  - Dependence on particle species
- ❑ Extrapolation to  $p_T \approx 0$ 
  - Use of different fit function
  - Closure using simulations

# Results

Tracks with  $p_T > 0.3$  GeV

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# Effective temperature

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and total entropy,  $S$ , at freeze-out. Precisely, we define the effective temperature,  $T_{\text{eff}}$ , and the effective volume,  $V_{\text{eff}}$ , as those of a uniform fluid at rest which would have the same energy and entropy as the fluid at freeze-out (see the illustration in Fig. 1). They are defined by the equations

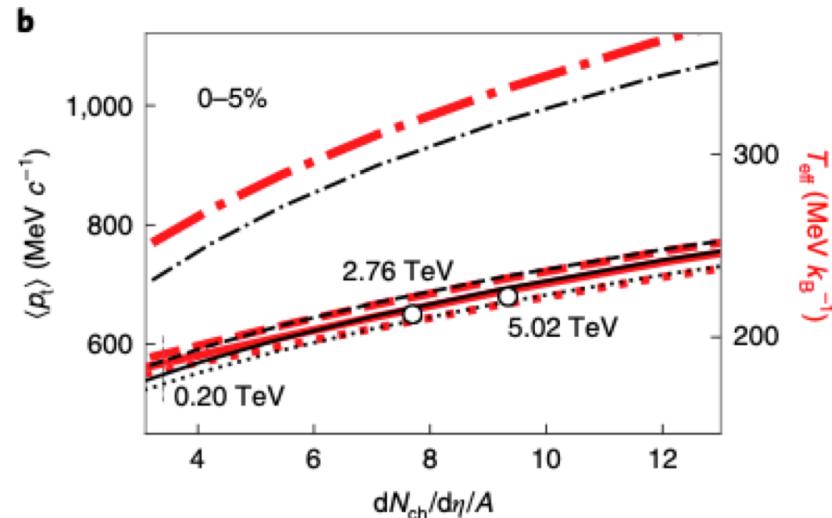
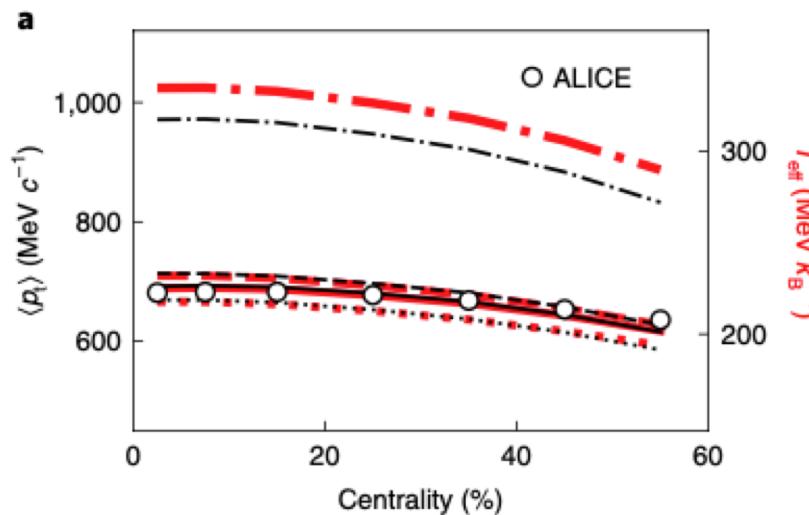
$$\begin{aligned} E &= \int_{\text{f.o.}} T^{0\mu} d\sigma_\mu = \epsilon(T_{\text{eff}}) V_{\text{eff}} \\ S &= \int_{\text{f.o.}} s u^\mu d\sigma_\mu = s(T_{\text{eff}}) V_{\text{eff}} \end{aligned} \quad (1)$$

where  $d\sigma_\mu$  denotes the elementary hypersurface element, and the integrals run over the freeze-out (f.o.) hypersurface.  $T^{0\mu}$  is the first line of the stress-energy tensor  $T^{\mu\nu}$  of the fluid, and  $u^\mu$  denotes the fluid 4-velocity<sup>12</sup>.  $\epsilon$  and  $s$  denote, respectively, the energy and entropy density in the fluid rest frame. By taking the ratio  $E/S$ , one eliminates  $V_{\text{eff}}$  and one can solve the resulting equation for  $T_{\text{eff}}$  using the same equation of state as in the hydrodynamic calculation.

Note that  $T_{\text{eff}}$  and  $s(T_{\text{eff}})$  are related by the equation of state of the fluid by construction. The effective temperature is smaller than the initial temperature because of the longitudinal cooling. However, it is larger than the freeze-out temperature, because the energy  $E$  defined by equation (1) contains the kinetic energy due to the collective motion of the fluid.

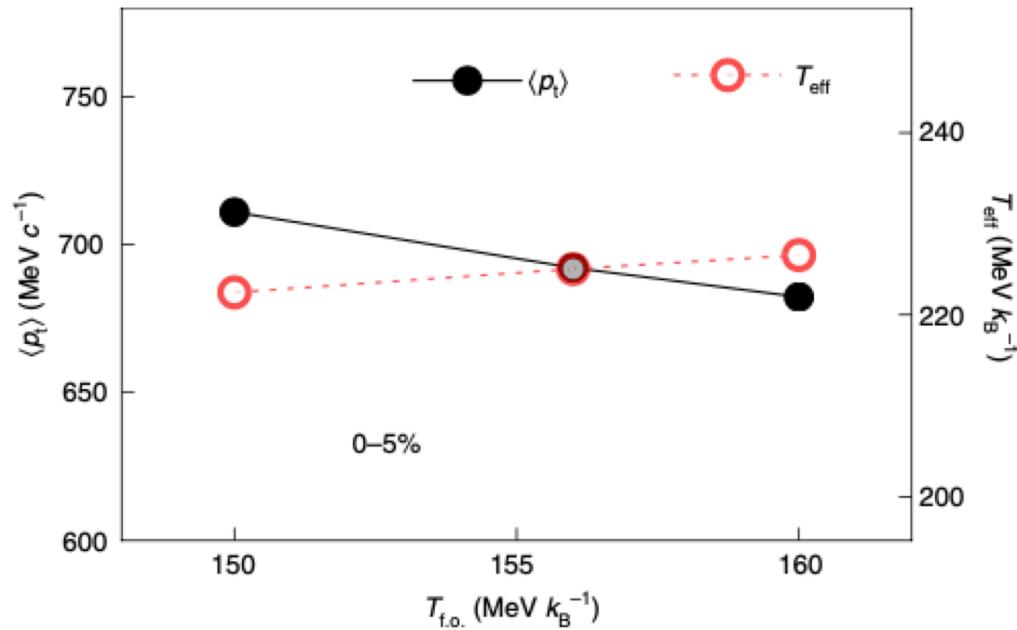
# $\langle p_T \rangle$ vs T (Hydrodynamic simulation)

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# $\langle p_T \rangle$ vs T (Hydrodynamic simulation)

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**Fig. 3 | Estimate of the theoretical uncertainty on the effective temperature.** Variation of  $\langle p_t \rangle$  and  $T_{\text{eff}}$  as a function of the freeze-out temperature in ideal hydrodynamic simulations of central Pb + Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ . Lines are drawn to guide the eye.