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Speed of Sound - Experimental Discussion

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IF-UFRGS, SPRACE-UNESP

The 4th International Workshop on QCD Collectivity at the Small Scales
Qingdao, China, June 24-28, 2024

Speed of Sound (c_s)

Access the Equation of State (EoS) of the medium

- ❑ Relativistic hydrodynamics
  - $c_S^2 = \left(\frac{\partial P}{\partial \varepsilon}\right)_{\text{isentropic}}$ P:= pressure, ε:= energy density

    L.D. Landau & E.M. Lifshitz, Fluid Mechanics

Speed of Sound Extraction: SPS

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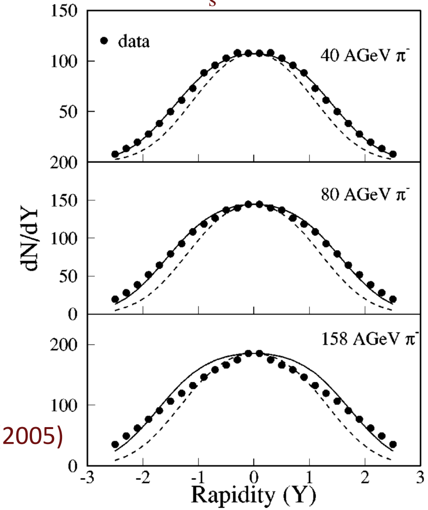
Studies using PbPb collisions at SPS energies

- ❑ Landau hydrodynamics model
  - Rapidity distribution of hadrons related to c_S

Izv. Akad. Nauk. SSSR **17** 51 (1953)
Usp. Fiz. Nauk. **56** 309 (1955)
Nuovo Cimento (Suppl.) **3** 15 (1956)

Dashed line: Ideal gas $c_s^2 = 1/3$

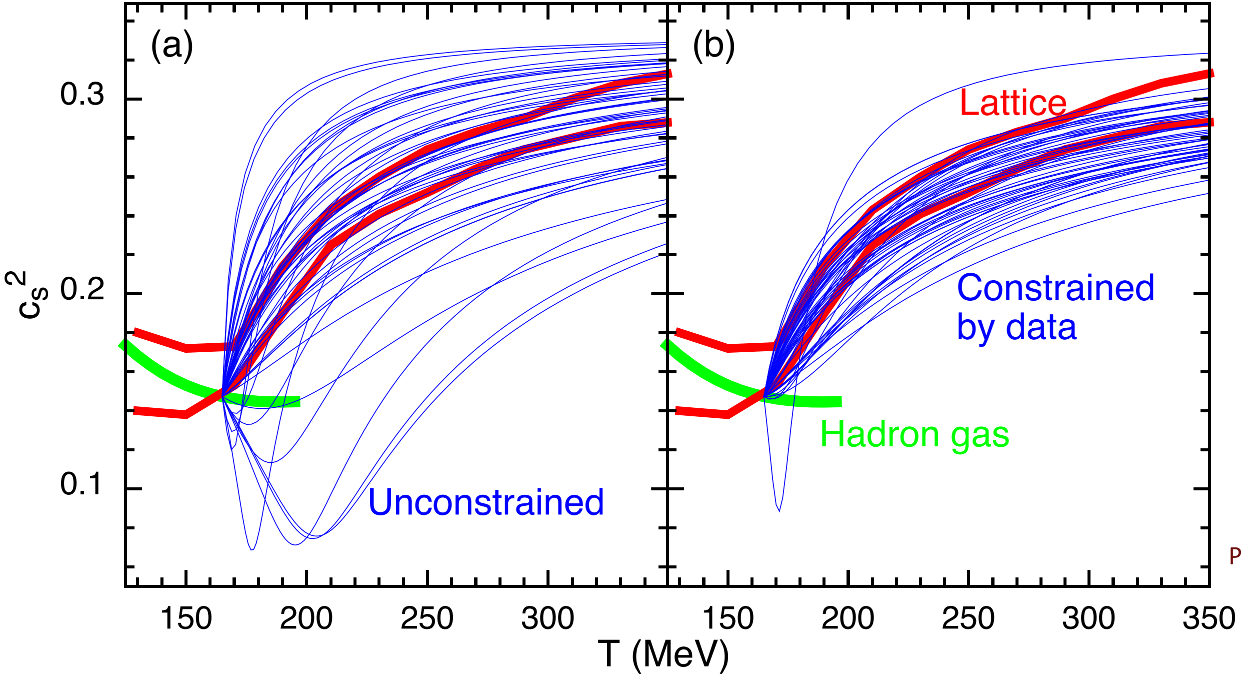
Solid line: $c_s^2 = 1/5$



Phys. Rev. C **68**, 064903 (2003)
J. Phys. G: Nucl. Part. Phys. **31**, 1345 (2005)

Speed of Sound Extraction: RHIC & LHC

Constraints on c_s^2 from data (Bayesian analysis)



Phys. Rev. Lett. **114**, 202301 (2015)

Speed of Sound Extraction: New Ideas

Speed of sound: directly related to the compressibility

- General procedure: maintain "volume≈constante" while varying number of produced particles
  - Two proposed procedures:
    - 1) For the same centrality category, measure $\langle p_{\mathrm{T}} \rangle$ at different collision energies

      Nat. Phys. **16**, 615 (2020)
    - 2) In ultracentral collisions (UCC), measure $\langle p_{\mathrm{T}} \rangle$ as a function of particle multiplicity

      Phys. Lett. B **809**, 135749 (2020)

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From thermodynamics relations and hydrodynamics simulations

- ❑ $c_s^2(T_{\mathrm{eff}}) = \frac{dP}{d\varepsilon} = \frac{sdT}{Tds}\bigg|_{T_{\mathrm{eff}}} = \frac{d\ln\langle p_T \rangle}{d\ln N_{ch}}$ Nat. Phys. **16**, 615 (2020) Phys. Lett. B **118**, 138 (1982)
  - T_{eff} (effective temperature): averaged over the spacetime evolution of the medium
    - ○ Reduced by longitudinal cooling (system expansion)
    - ○ Hydrodynamics simulations: $T_{\mathrm{eff}} \approx \langle p_T \rangle / 3$ Nat. Phys. **16**, 615 (2020)

Procedure 1: Different Energies

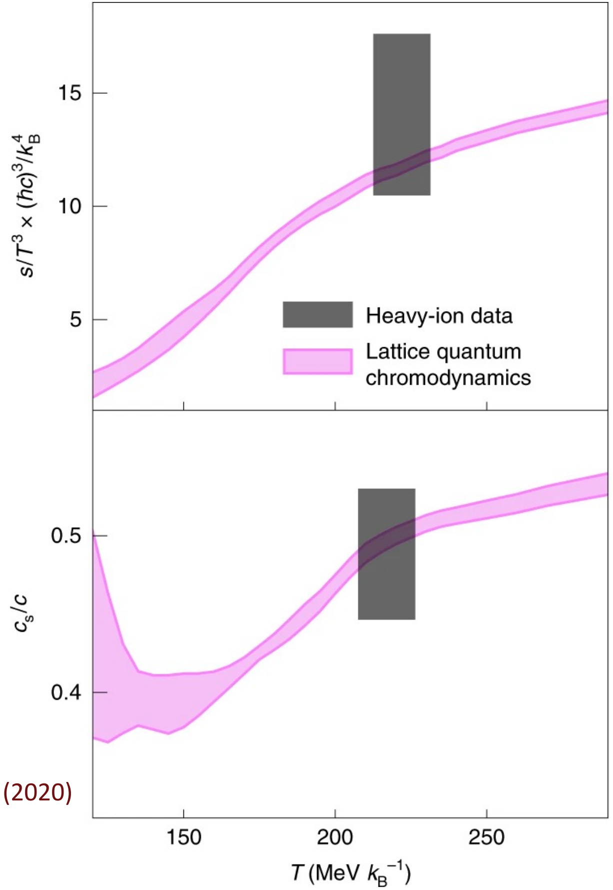
PbPb ALICE data at 2.76 TeV and 5.02 TeV

- ❑ 0-5% centrality

Speed of sound squared directly from

- ❑ $c_s^2(T_{\text{eff}}) = \dfrac{d\ln\langle p_T\rangle}{d\ln N_{ch}}$
- ❑ Using values of $\langle p_{\mathrm{T}}\rangle$ and N_{ch} for the two energies

$$T_{\text{eff}} = 222 \pm 9\ MeV,\ c_s^2/c^2 = 0.24 \pm 0.04$$

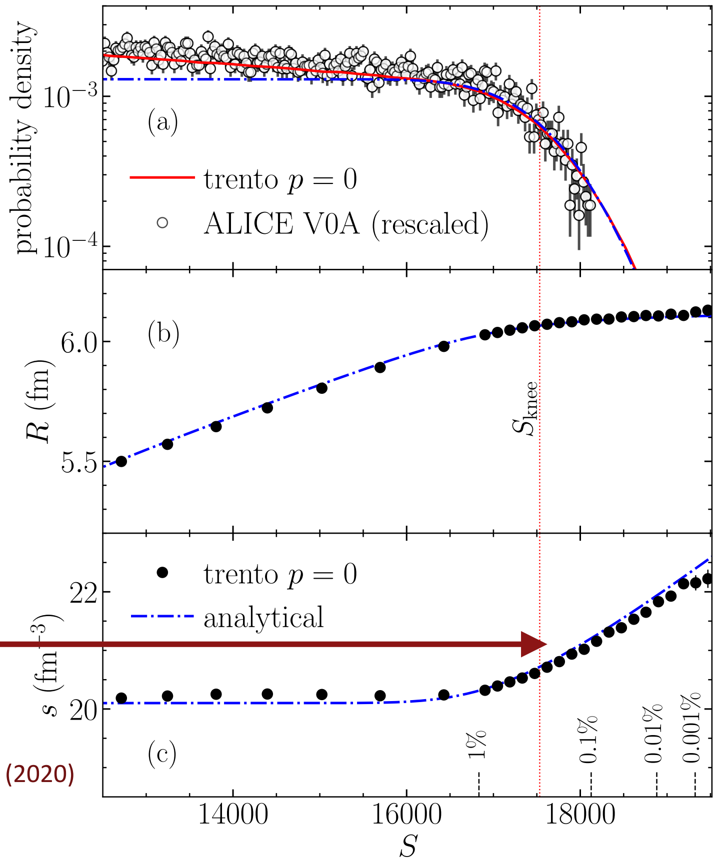


Nat. Phys. **16**, 615 (2020)

Procedure 2: UCC Events

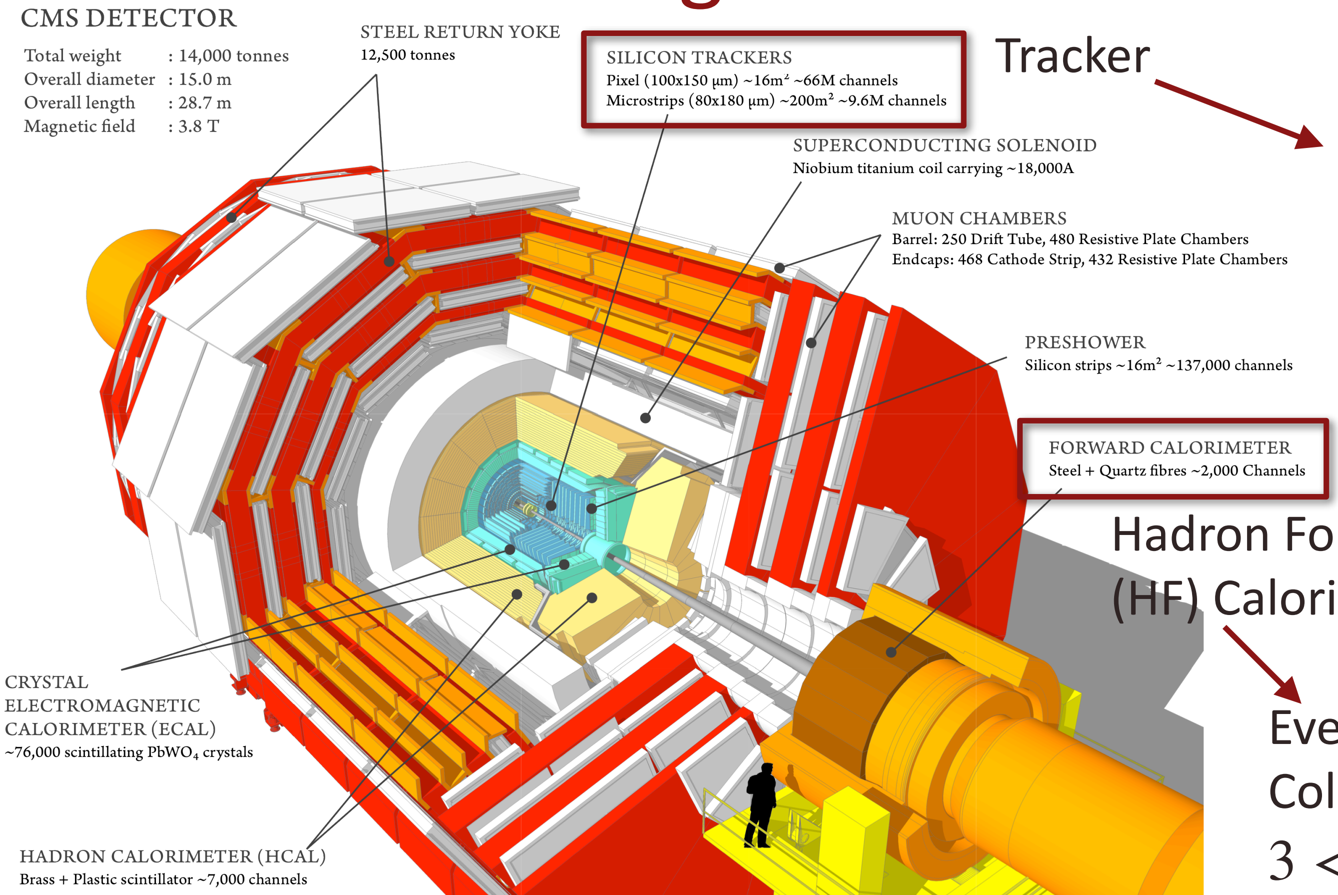
Non-trivial prediction by relativistic hydrodynamics

- When impact parameter $b \approx 0$ (UCC)
  - Increasing entropy $S \sim N_{\mathrm{ch}}$
  - $\uparrow s \Rightarrow \uparrow T \Rightarrow \uparrow \langle p_{\mathrm{T}} \rangle$
- Slope associated with $c_{\mathrm{s}}^2 = d \ln\langle p_T \rangle / d \ln N_{ch}$



Phys. Lett. B **809**, 135749 (2020)

Measurement Using the CMS detector



Tracker

N_{ch}, p_T

Used tracks in

$|\eta| < 0.5$

Hadron Forward (HF) Calorimeters

Event selection

Collision centrality

$3 < |\eta| < 5$

Analysis method - observables

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

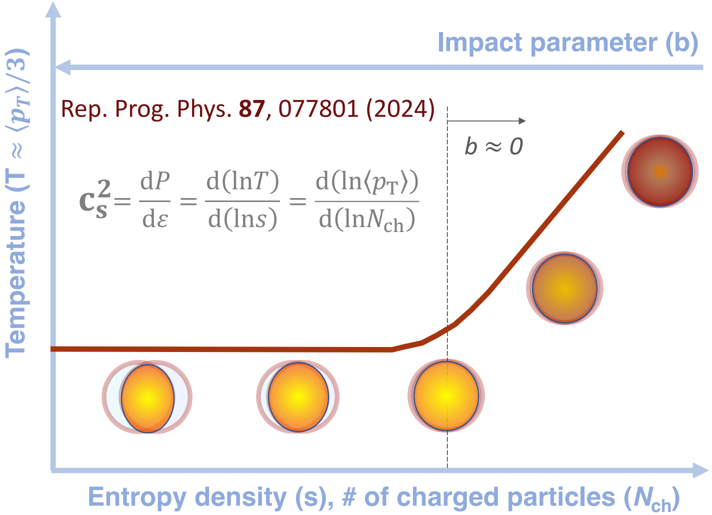
- ❑ Extracted using
  - $\frac{\langle p_T \rangle}{\langle p_T \rangle^0} \sim \left(\frac{N_{\mathrm{ch}}}{N_{\mathrm{ch}}^0} \right)^{c_s^2}$, where $\langle p_T \rangle^0$ and N_{ch}^0 are obtained in 0-5%

Ratios to cancel some systematic uncertainties

Analysis observables

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

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



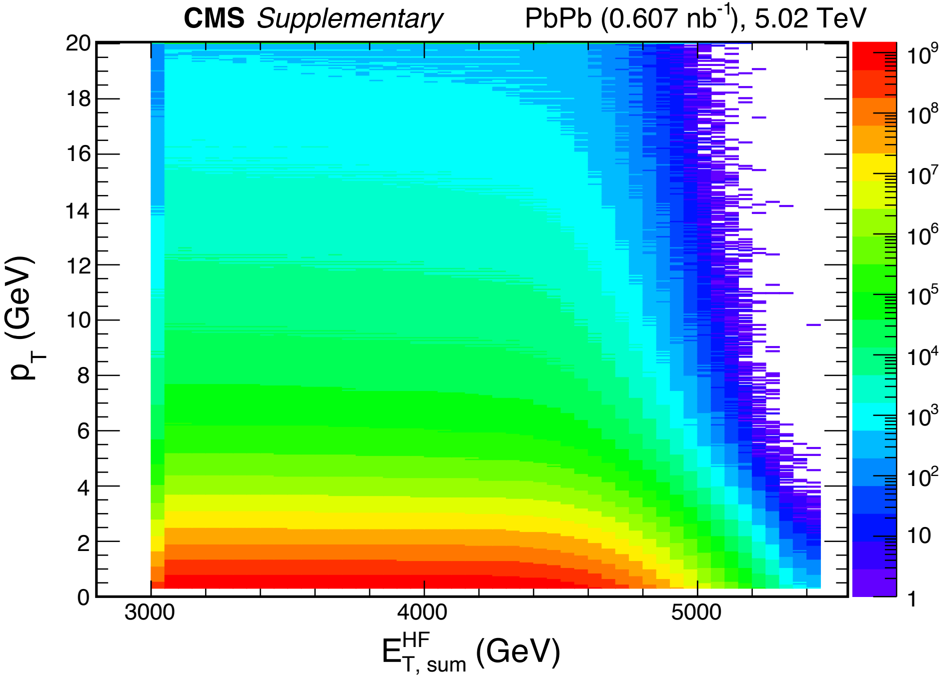
Rep. Prog. Phys. **87**, 077801 (2024)

$$c_s^2 = \frac{dP}{d\varepsilon} = \frac{d(\ln T)}{d(\ln s)} = \frac{d(\ln\langle p_T \rangle)}{d(\ln N_{\mathrm{ch}})}$$

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

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

- ❑ Measured in bins of transverse energy sum in HF $E_{\mathrm{T,sum}}^{\mathrm{HF}}$ (bin width 50 GeV)



η-gap of 2.5 units

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

Analysis method - p_T extrapolation to zero

$\langle p_\mathrm{T}\rangle$ and N_ch: corrected for tracking efficiency

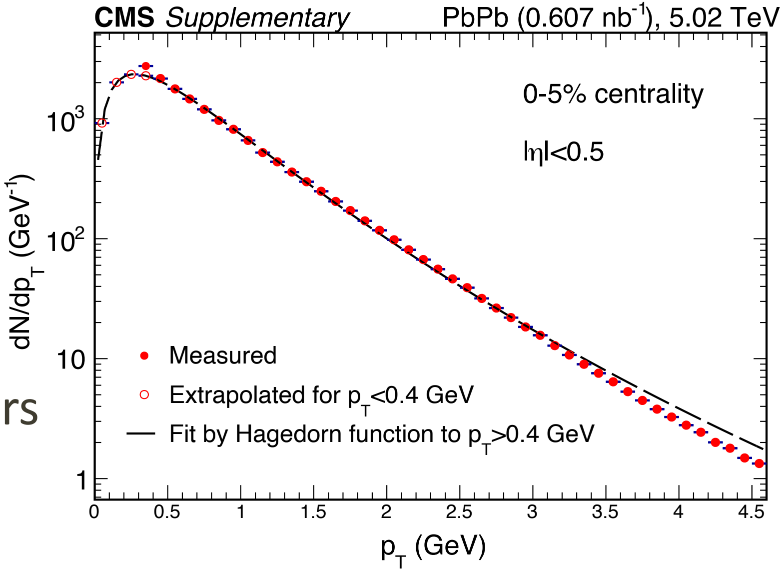
Extrapolation to $p_\mathrm{T} = 0$ by fitting the spectrum in $p_\mathrm{T} > 0.4 GeV$

- ❑ Hagedorn function

$$\frac{dN_\mathrm{ch}}{dp_\mathrm{T}} = p_\mathrm{T}\left(1 + \frac{1}{\sqrt{1-\langle\beta_\mathrm{T}\rangle^2}}\frac{\left(\sqrt{p_T^2+m^2}-\langle\beta_\mathrm{T}\rangle p_\mathrm{T}\right)}{nT}\right)^{-n}$$

- ❑ m:= pion mass & $\langle\beta_\mathrm{T}\rangle$, n, T free parameters

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



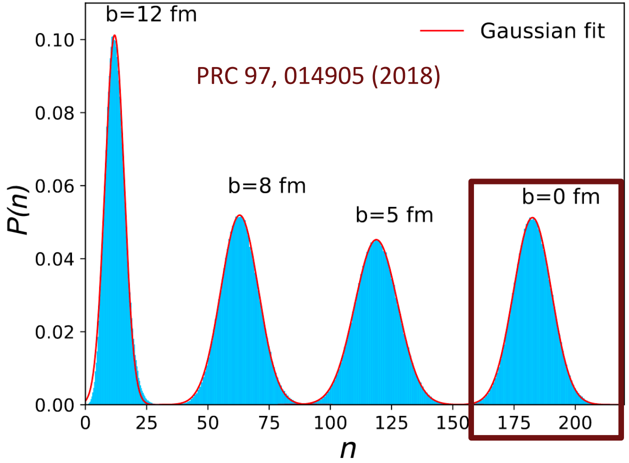
After corrections, for each bin of $E_\mathrm{T,sum}^\mathrm{HF}$ → $\langle p_T\rangle^\mathrm{norm}$ vs $N_\mathrm{ch}^\mathrm{norm}$

Extracting the speed of sound - multiplicity fluctuations

$Prob(N_{\mathrm{ch}}^{\mathrm{norm}})$: analytical model to capture the trends from hydro.

Phys. Lett. B **809**, 135749 (2020)

- $$\langle p_{\mathrm{T}} \rangle^{\mathrm{norm}} = \left(\frac{N_{\mathrm{ch}}^{\mathrm{norm}}}{Prob\left(N_{\mathrm{ch}}^{\mathrm{norm}}\right)} \right)^{c_s^2}$$
  - ○ Below the knee $Prob(N_{\mathrm{ch}}^{\mathrm{norm}}) \approx N_{\mathrm{ch}}^{\mathrm{norm}}$
  - ○ Above the knee $Prob(N_{\mathrm{ch}}^{\mathrm{norm}}) \approx 1$



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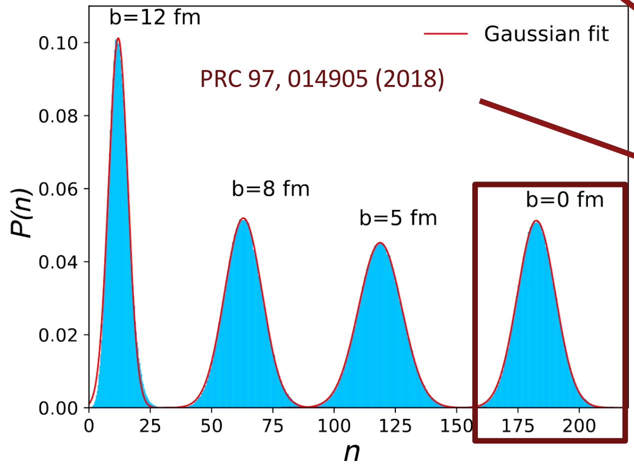
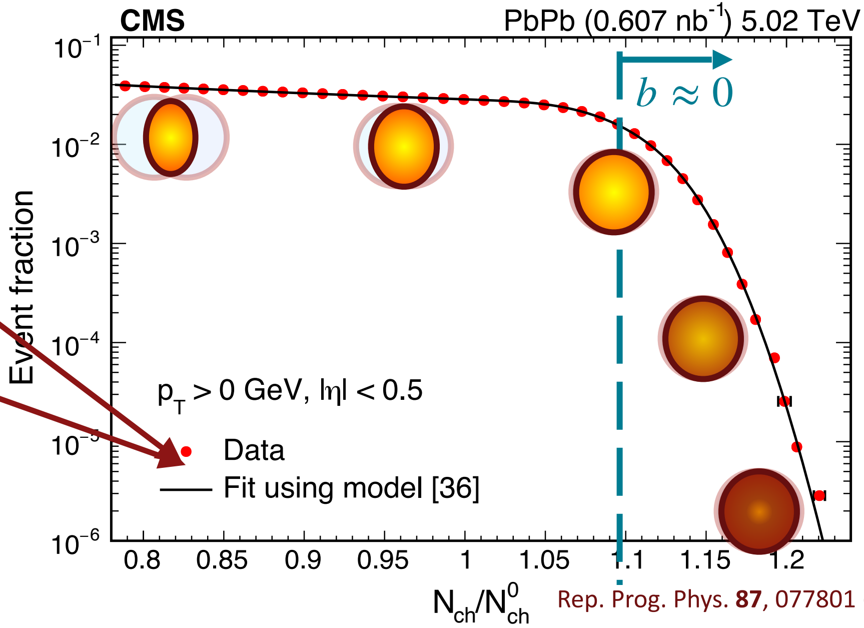


PRC 97, 014905 (2018)

$Prob\left(N_{\mathrm{ch}}^{\mathrm{norm}}\right)$ free parameters values at $b \approx 0$

Fit $N_{\mathrm{ch}}^{\mathrm{norm}}$ distribution



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

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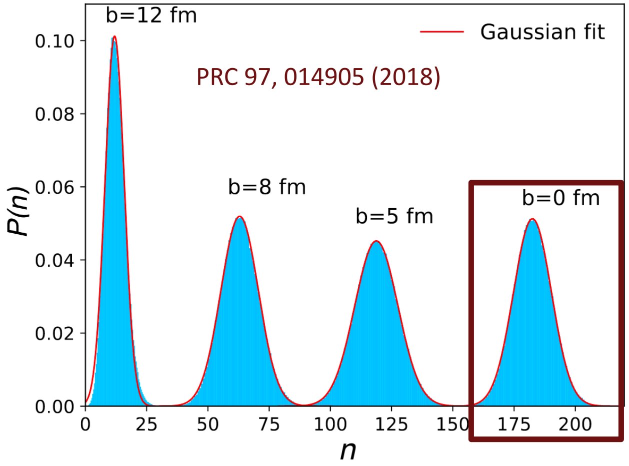
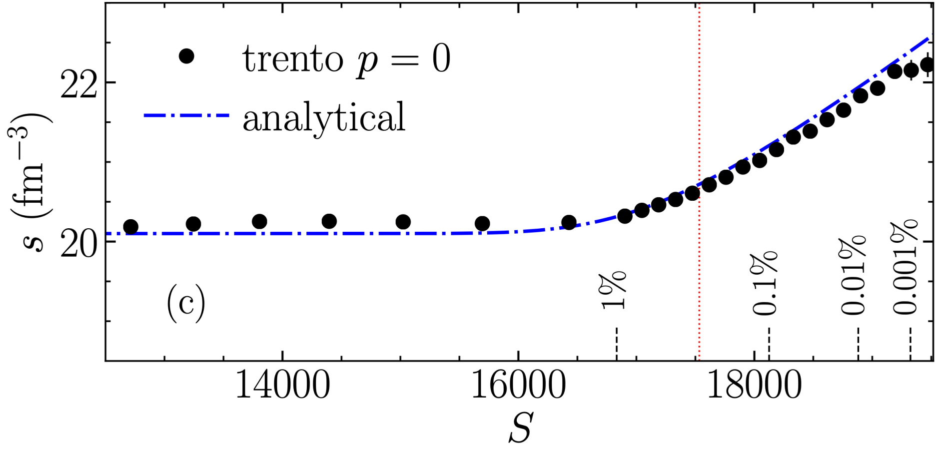


PRC 97, 014905 (2018)



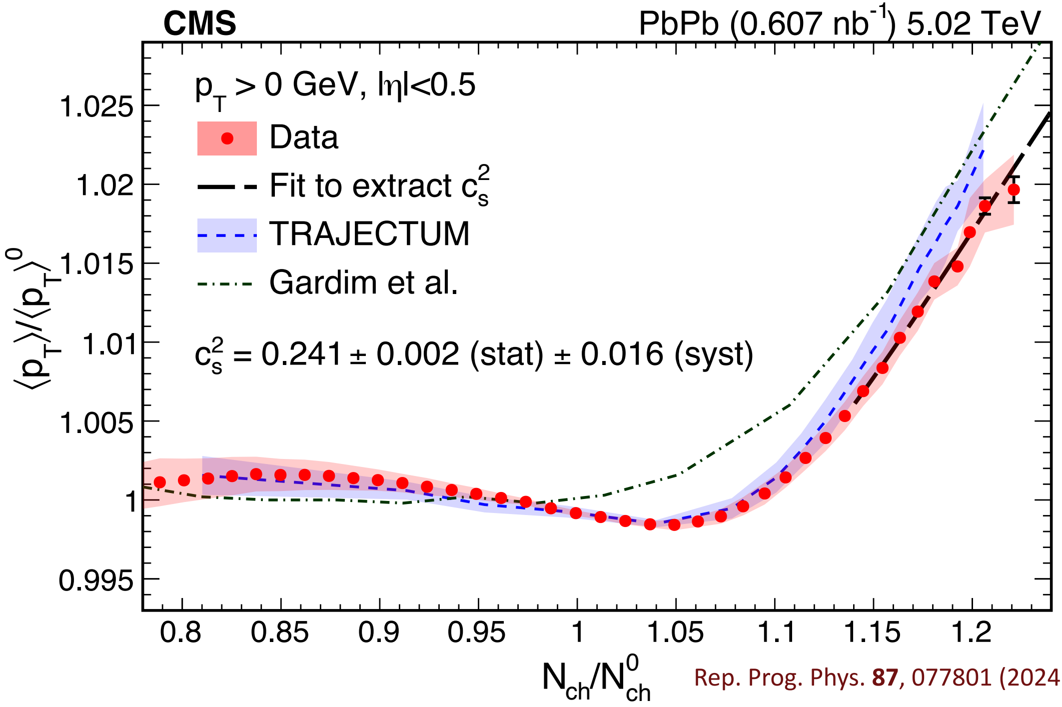
Extracting the speed of sound: CMS data

Fit $\langle p_{\mathrm{T}}\rangle^{\mathrm{norm}}$ vs $N_{\mathrm{ch}}^{\mathrm{norm}}$ using

- $$\langle p_{\mathrm{T}}\rangle^{\mathrm{norm}} = \left(\frac{N_{\mathrm{ch}}^{\mathrm{norm}}}{Prob\left(N_{\mathrm{ch}}^{\mathrm{norm}}\right)}\right)^{c_s^2}$$

Do not model the dip

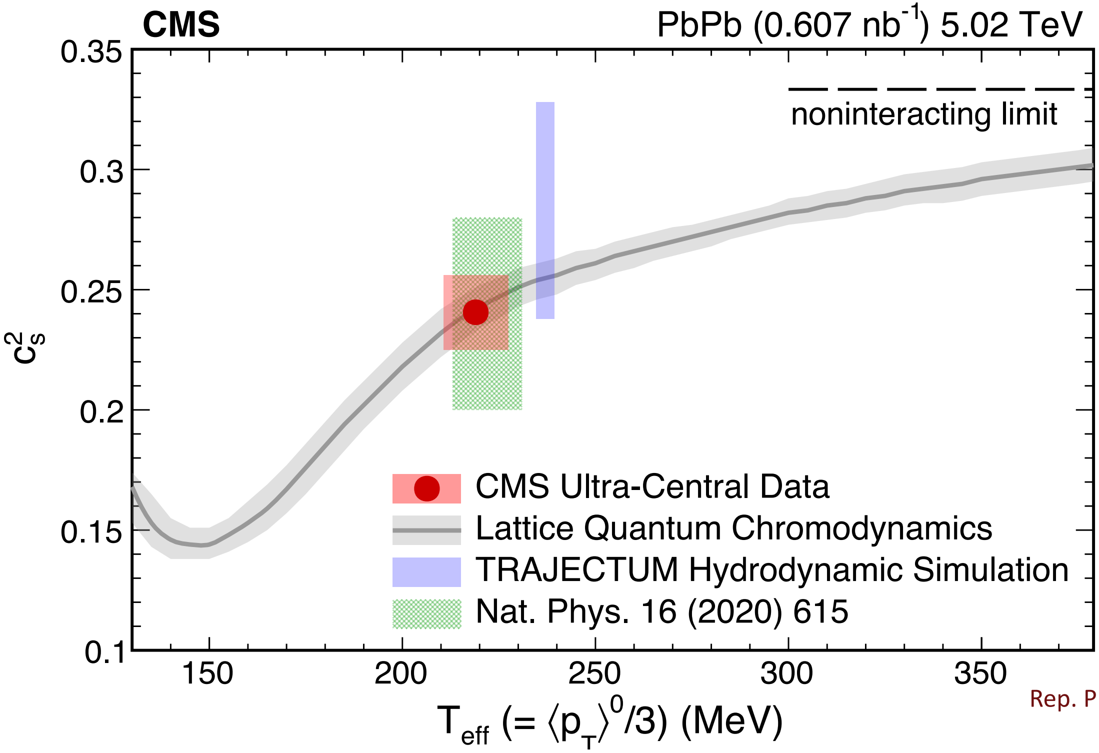
Fit starts from better χ^2 at $N_{\mathrm{ch}}^{\mathrm{norm}} > 1.12$



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

$$T_{\mathrm{eff}} \approx \langle p_{\mathrm{T}}\rangle^0/3 = 219 \pm 8(syst)MeV$$

Comparison with Lattice QCD & Hydrodynamics Models



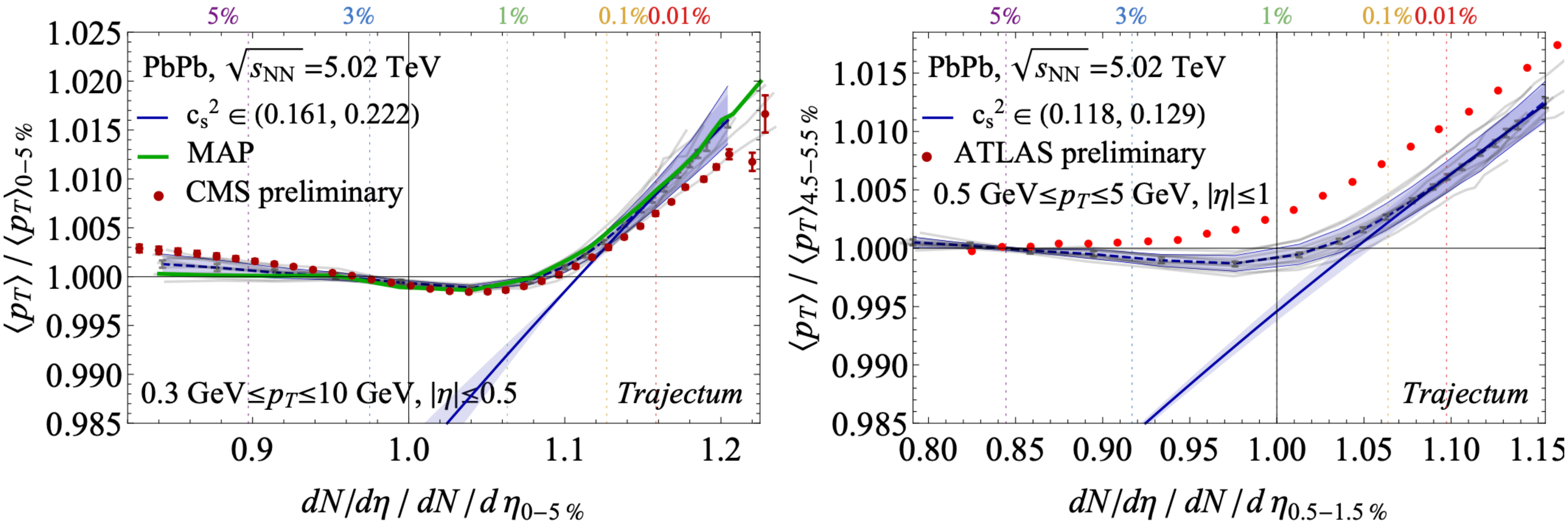
Rep. Prog. Phys. **87**, 077801 (2024)

Lattice QCD ($\mu_B \approx 0$ and 2+1 flavors)

No extrapolation to $p_{\mathrm{T}} = 0$

CMS (left) & ATLAS (right) comparison with Trajectum model

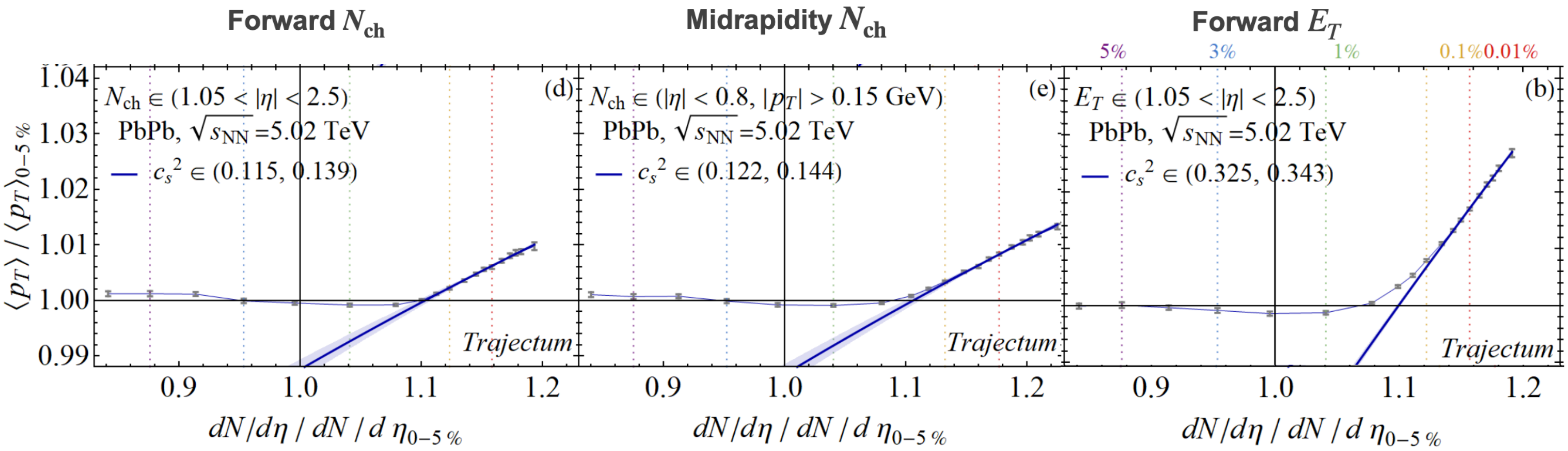
Phys. Lett. B **853**, 138636 (2024)



The slope has a clear dependence on the p_{T} cut

Trajectum: possible bias from centrality estimator?

Tested with different η ranges for centrality estimator



Phys. Lett. B **853**, 138636 (2024)

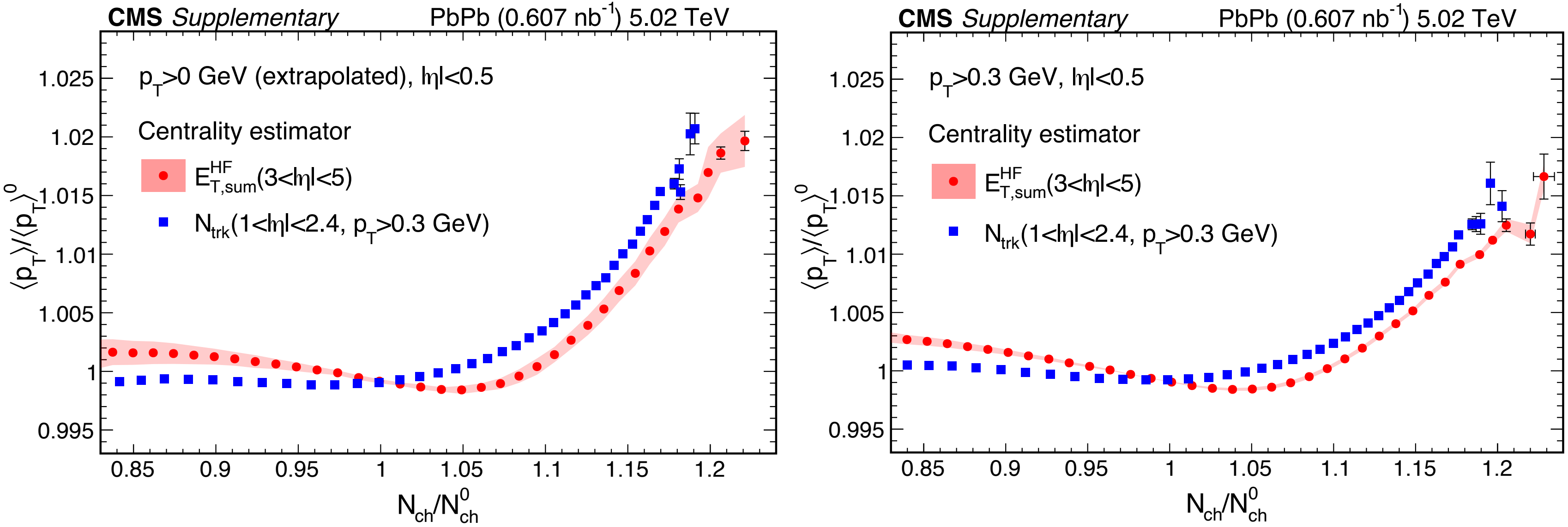
E_T based seems to bias toward higher values of $\langle p_T \rangle$ with small (or no) η-gap

CMS: centrality estimator bias

Initial studies from CMS: no considerable bias in the slope

Probably due to large η gap used in E_T based measurements???

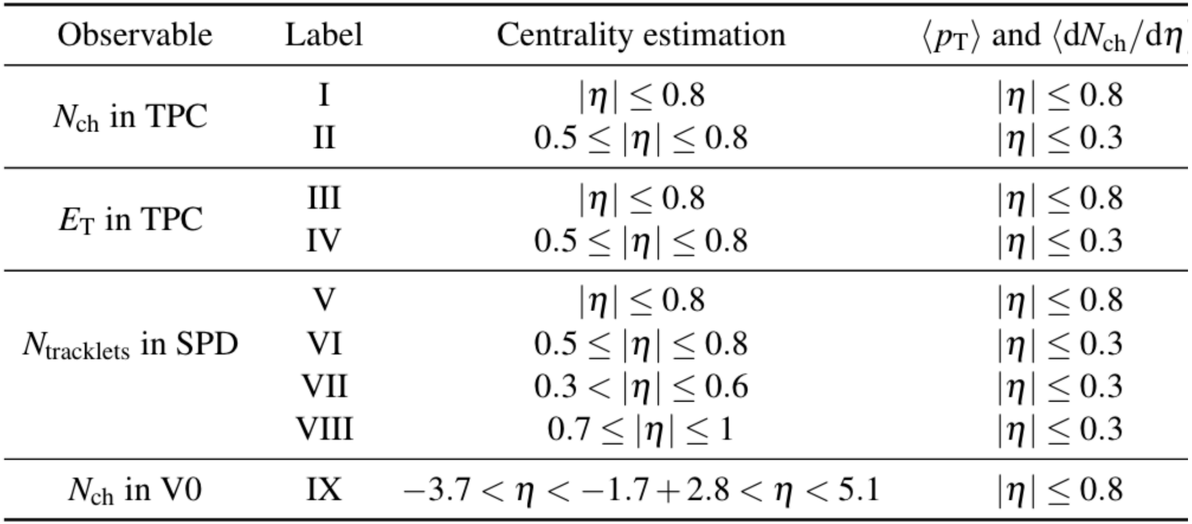
Will perform more studies about the η-gap



ALICE: centrality estimator bias

Tested several η ranges for centrality estimator and $\langle p_{\mathrm{T}} \rangle$ & N_{ch}

Adapted from ALICE Collab., SQM2024



Observable	Label	Centrality estimation	$\langle p_{\mathrm{T}} \rangle$ and $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$
N_{ch} in TPC	I	$\lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.8$
	II	$0.5 \leq \lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.3$
E_{T} in TPC	III	$\lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.8$
	IV	$0.5 \leq \lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.3$
$N_{\mathrm{tracklets}}$ in SPD	V	$\lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.8$
	VI	$0.5 \leq \lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.3$
	VII	$0.3 < \lvert\eta\rvert \leq 0.6$	$\lvert\eta\rvert \leq 0.3$
	VIII	$0.7 \leq \lvert\eta\rvert \leq 1$	$\lvert\eta\rvert \leq 0.3$
N_{ch} in V0	IX	$-3.7 < \eta < -1.7 + 2.8 < \eta < 5.1$	$\lvert\eta\rvert \leq 0.8$

Ref. arXiv:2403.06052: for centrality estimation region overlapping with the region used for $\langle p_{\mathrm{T}} \rangle$ & N_{ch} => apply correction for self-correlation

ALICE: centrality estimator bias

Adapted from ALICE Collab., SQM2024

Observable	Label	Centrality estimation	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$
N_{ch} in TPC	II	$0.5 \le \lvert\eta\rvert \le 0.8$	$\lvert\eta\rvert \le 0.3$
$N_{tracklets}$ in SPD	VI	$0.5 \le \lvert\eta\rvert \le 0.8$	$\lvert\eta\rvert \le 0.3$
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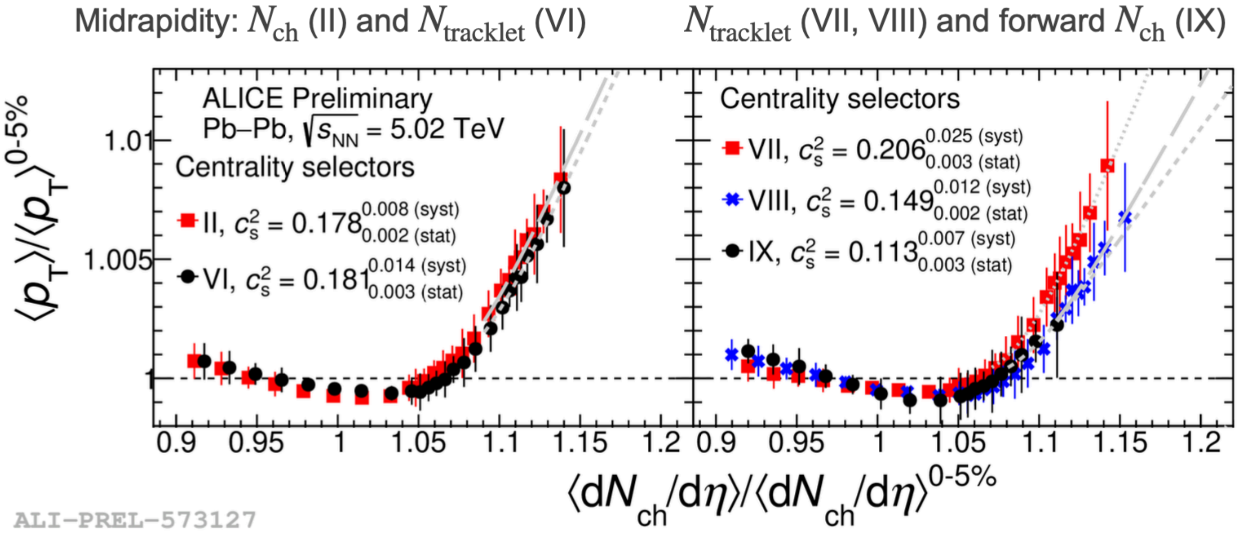
Non E_T-based

Lower values compared to CMS



ALICE: centrality estimator bias

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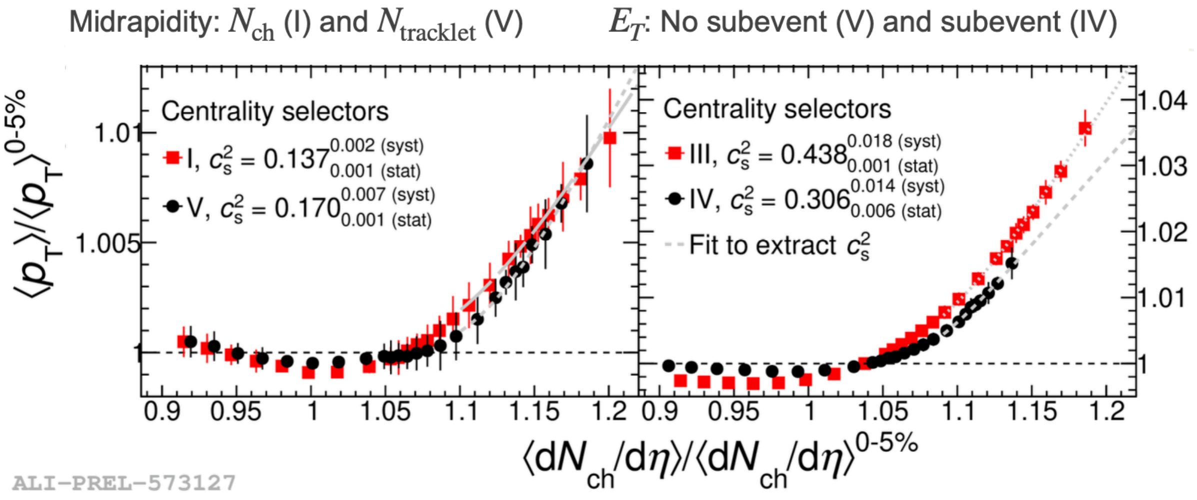
$N_{tracklets}$ in SPD	V	$\lvert\eta\rvert \leq 0.8$	$\lvert\eta\rvert \leq 0.8$

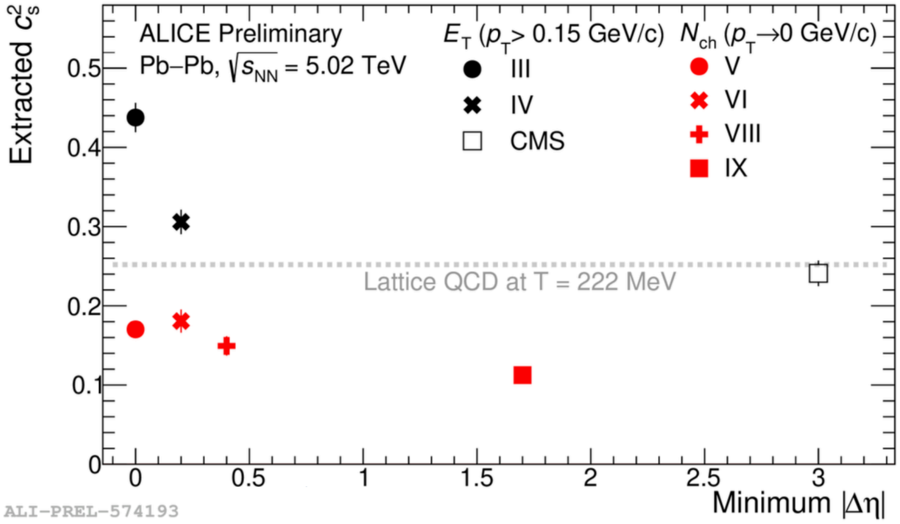
E_T-based

Higher values compared to CMS

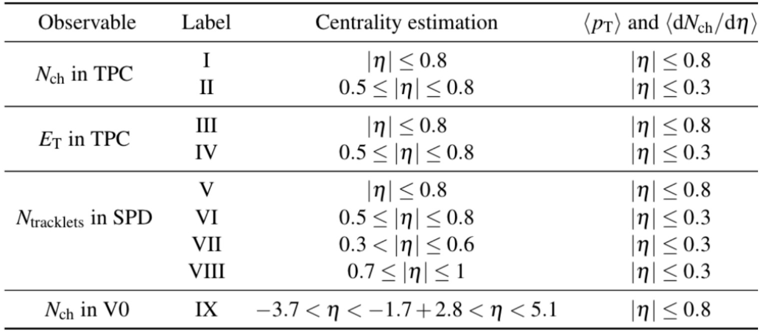


ALICE: centrality estimator bias

Summary of extracted values of c_s^2



Adapted from ALICE Collab., SQM2024



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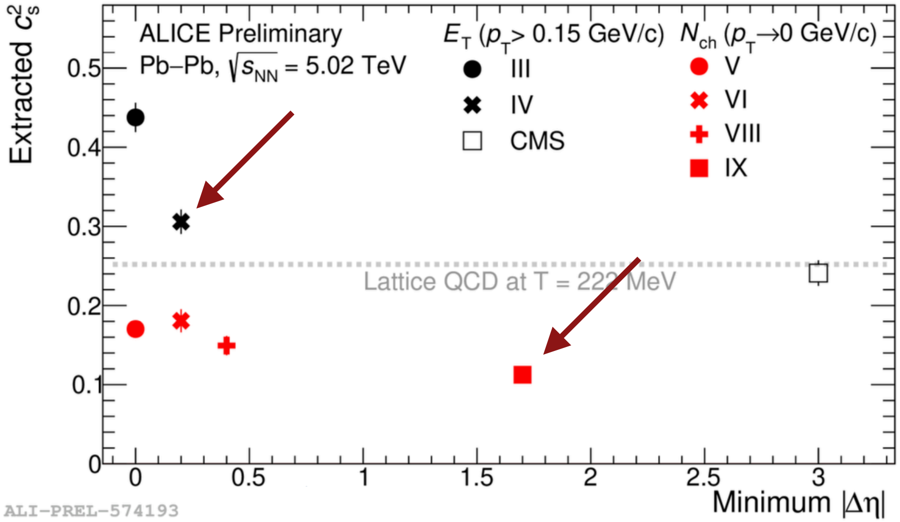
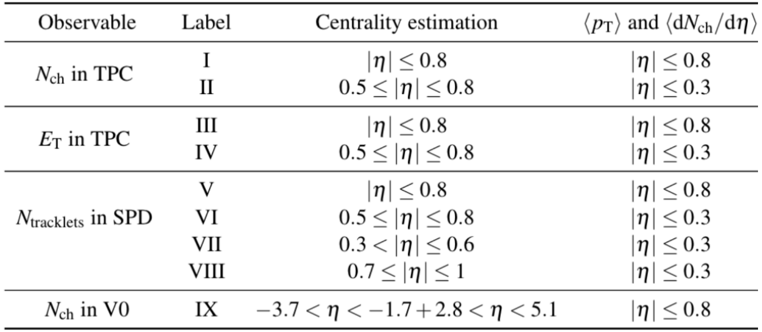


Adapted from ALICE Collab., SQM2024



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

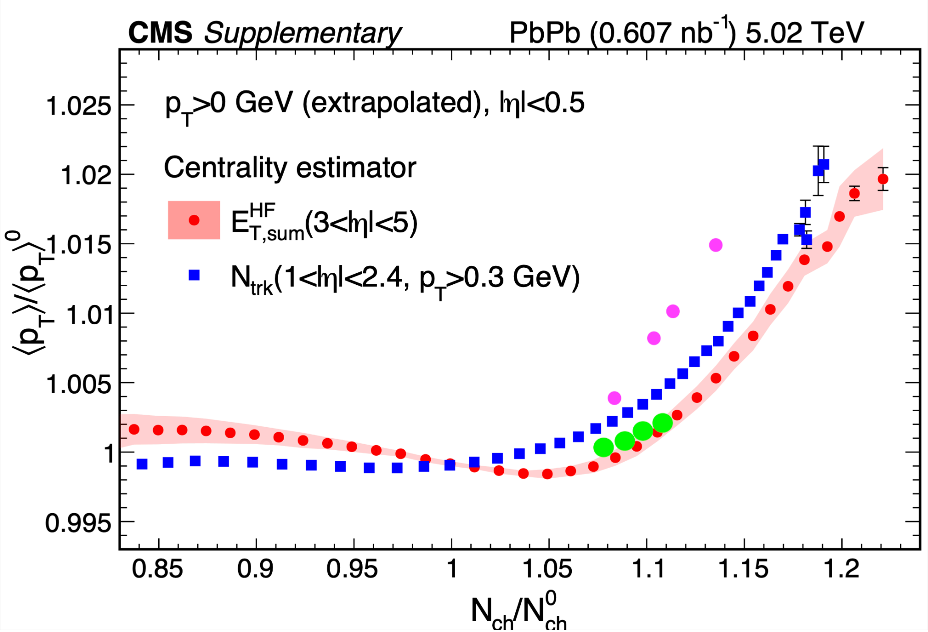
Rough comparison using few points

No uncertainties included

(IV) E_{T} in TPC $(0.5 < |\eta| < 0.8)$

(IX) N_{ch} in V0 $(-3.7 < \eta < -1.7, +2.8 < \eta < 5.1)$

For this last one added the 4 points used in the fit



The one with larger eta-gap looks not very far from CMS measurement. It seems (to be checked with the authors) that the c_s^2 was extracted fitting these last four points.

NB.: added few points from ALICE Collaboration by hand.
Any discrepancy from original ALICE values is a fault from the author of this presentation.

Future Studies & Open Questions

Continue investigation on the effects from centrality estimator

- ❑ NB.: For overlapping regions between centrality estimator and $\langle p_{\mathrm{T}} \rangle$ & N_{ch}
  - Needed a correction due to self-correlations

arXiv:2403.06052

Effect of initial density fluctuations profile

- ❑ How initial fluctuations affect the hypotheses: $\langle p_{\mathrm{T}} \rangle / T_{\mathrm{eff}}$ and V_{eff} independent of multiplicity ???
- ❑ Relation between $\langle p_{\mathrm{T}} \rangle$ & T_{eff} seems not to be affected Nucl. Phys. A 1005, 121999 (2021)
- ❑ But effective volume seems not very constant ($\uparrow N_{\mathrm{ch}} \Rightarrow \downarrow V_{\mathrm{eff}}$) Phys. Lett. B **853**, 138636 (2024)
- ❑ Compare increase of $\langle p_{\mathrm{T}} \rangle$: as a function of N_{ch} in the same collision energy Vs using different collision energies

arXiv:2403.06052

This is a new hydrodynamics probe

- ❑ Study other colliding systems: XeXe, OO, high-multiplicity pPb, etc…

Phys. Lett. B **853**, 138636 (2024)
Phys. Rev. C **109**, 014904 (2024)

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Thank You!

SPRACE

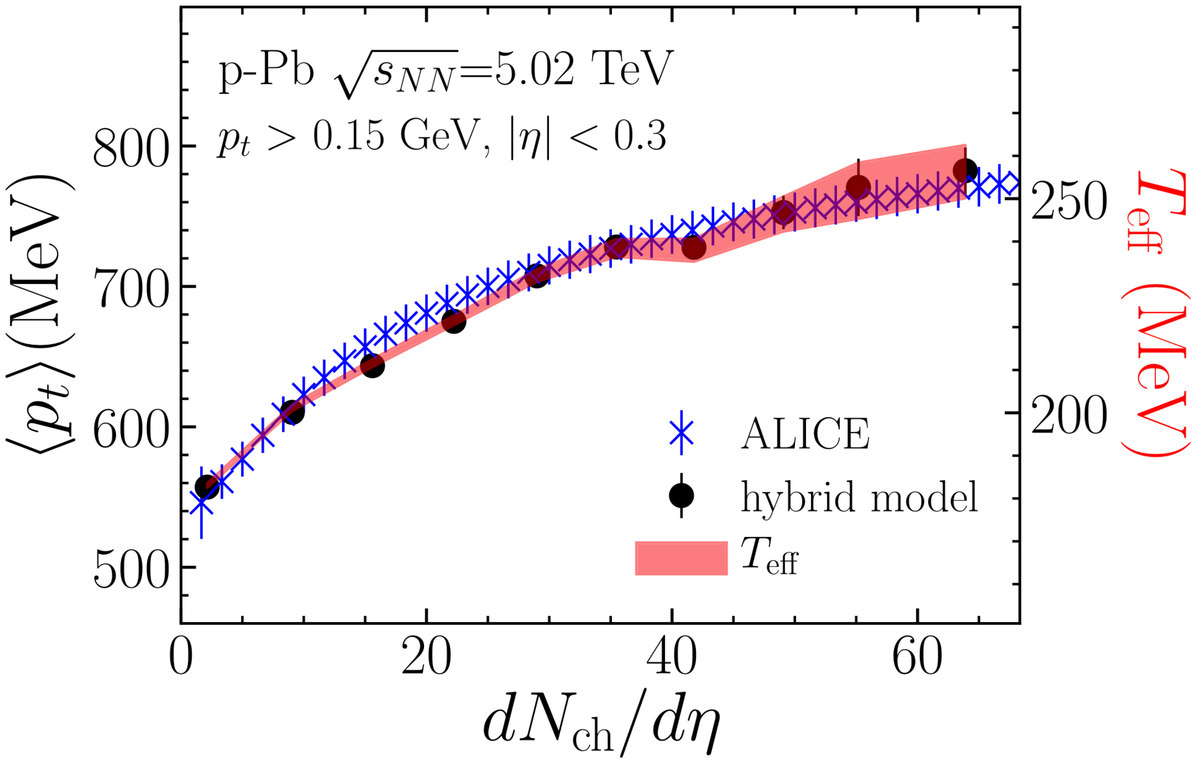
Thank You!

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 , CNPQ GRANT 309962/2023-4

pPb Analysis

What happens at very high multiplicities?

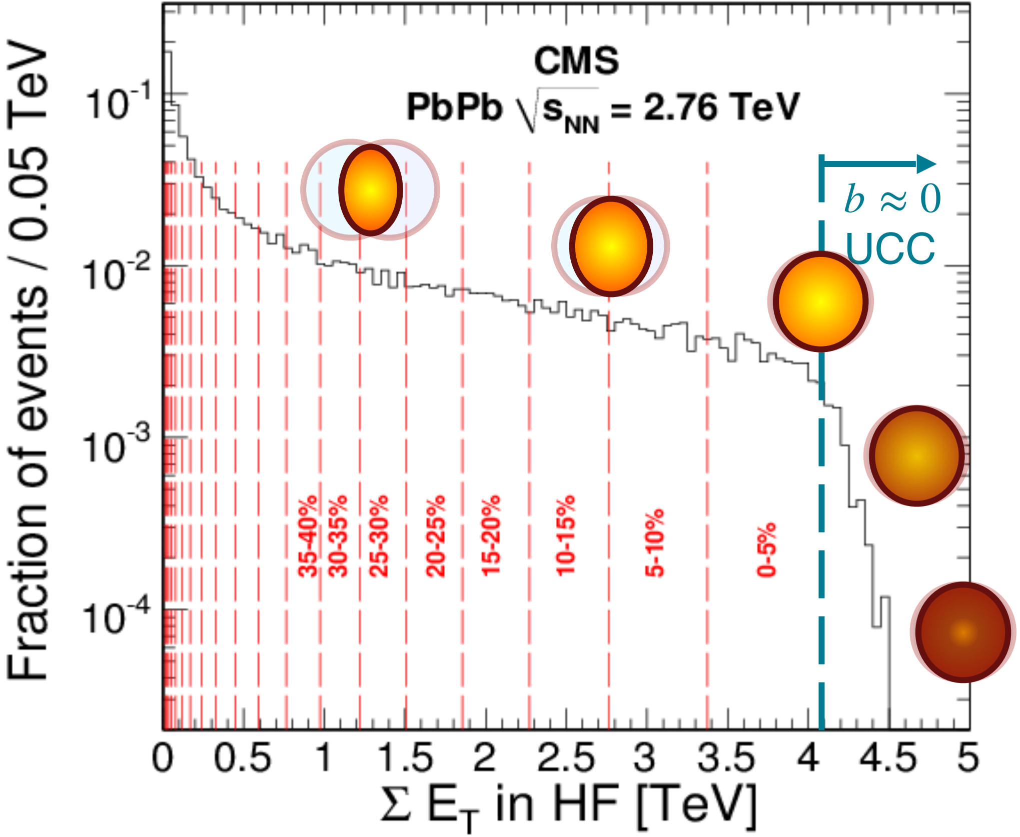


UCC PbPb collisions

Collision centrality

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

JHEP **08** (2011) 141



Samples and track selections

Minimum bias PbPb collisions at 5.02 TeV

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

Monte Carlo (MC) simulations: HYDJET generator

- ☐ Efficiency corrections, cross-checks, closure tests, etc…

Track selection: $p_{\mathrm{T}} > 0.3\ \mathrm{GeV},\ \left|\eta\right| < 0.5$

- ☐ Better tracking performance

Systematic uncertainties and cross-checks

Systematics

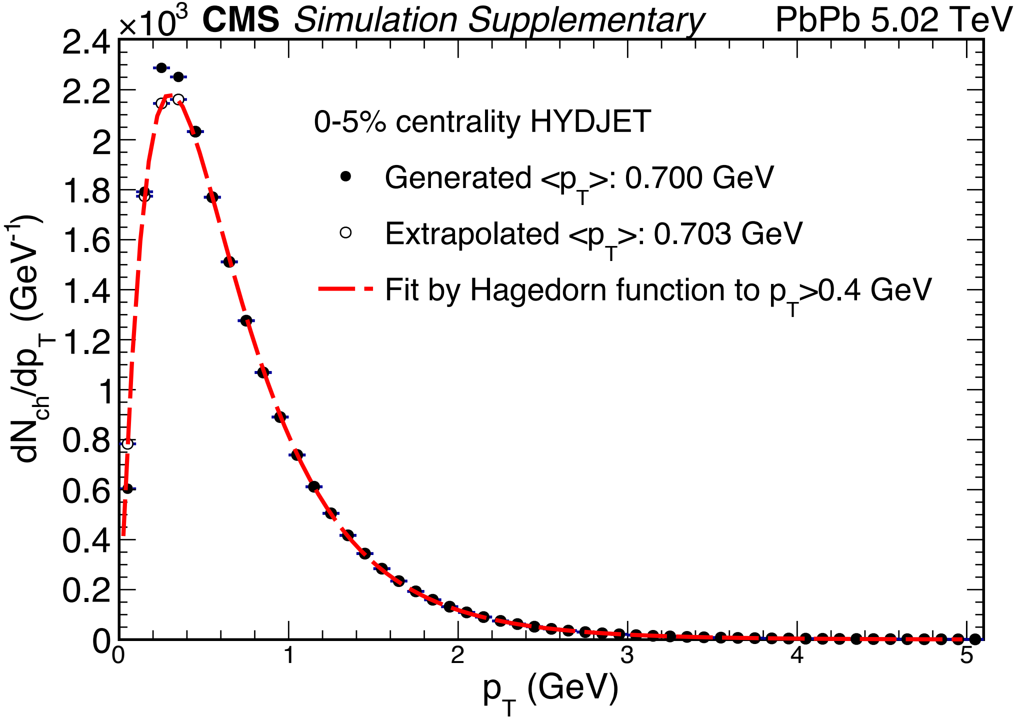
- Tracking efficiency corrections
- Extrapolation to $p_{\mathrm{T}} \approx 0$
- Choice of fit range (only for c_{s}^{2})

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 $p_{\mathrm{T}} \approx 0$
  - Use of different fit function
  - Closure using simulations

Extrapolation to $p_\mathrm{T} \approx 0$ - Monte Carlo

HYDJET generator



arXiv:2401.06896

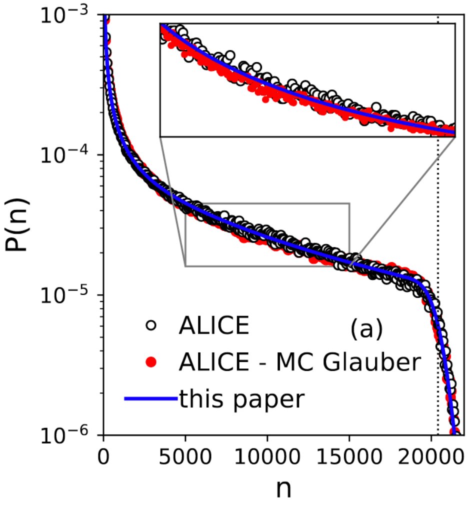
$$P(n) = \int_0^1 P(n|c_b)dc_b.$$

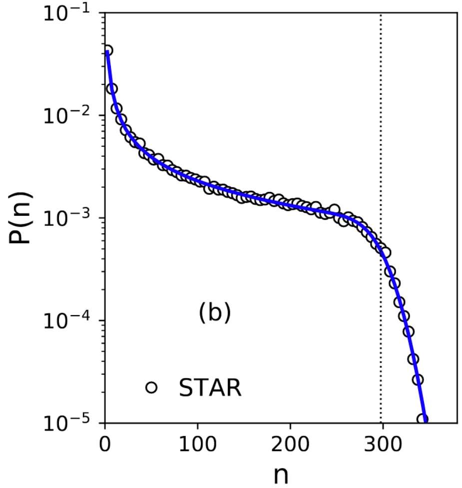
$$P(n|c_b) = \frac{\eta(c_b)}{\sigma(c_b)\sqrt{2\pi}} \exp\left(-\frac{(n-\bar{n}(c_b))^2}{2\sigma(c_b)^2}\right), \qquad (3)$$

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

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

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





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[1] 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 $c_b = \pi b^2/\sigma_{\mathrm{inel}}$. The value of σ_{inel} needs to be taken from either data or some collision model.

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

Nature Physics **16** (2020) 615