Extraction of the speed of sound in hot QCD matter at the LHC

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Speed of sound (c_s)

Access the Equation of State (EoS) of the medium

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

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

Speed of sound extraction: SPS

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

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

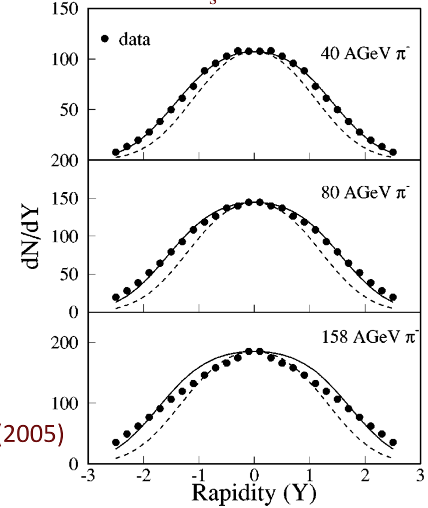
Studies using PbPb collisions at SPS energies

- 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 $c_s^2 = 1/3$

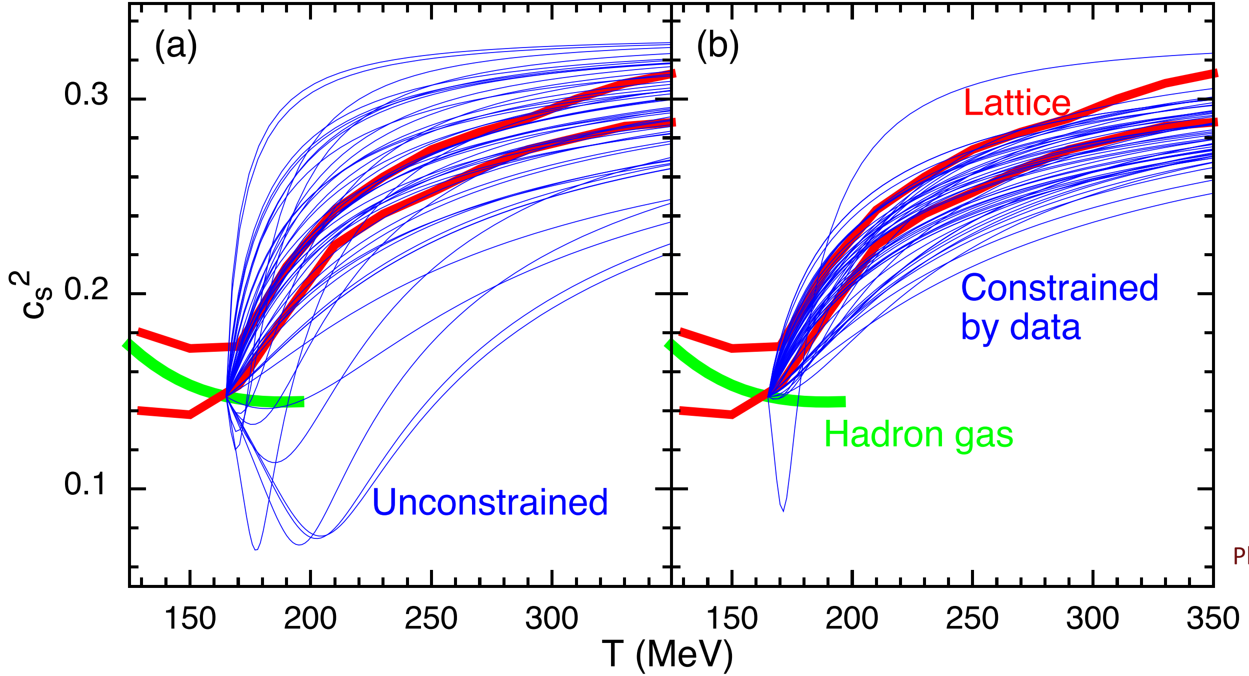
Solid line: $c_s^2 = 1/5$



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)

Speed of sound extraction: new ideas

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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), Phys. Lett. B **703**, 237 (2011)
  - T_{eff} (effective temperature): integrated over a hypersurface at the end of hydro evolution
    - Reduced by longitudinal cooling (system expansion) & includes kinetic energy (radial flow)
    - Hydrodynamics simulations: $T_{\mathrm{eff}} \approx \langle p_T \rangle / 3$ Nat. Phys. **16**, 615 (2020)

      Independent of centrality for PbPb

Thermodynamics of hot QCD matter

The thermodynamic relations in previous slides do not apply to the real collisions

- Dynamic system, out-of-equilibrium, etc…

Idea from Nat. Phys. 16 **615** (2020): consider a medium at the end of hydro evolution with entropy S and energy E

- A uniform fluid at rest with an effective volume (V_{eff}) and temperature (T_{eff})
- $E = \int_{f.o.} T^{0\mu} = \epsilon(T_{eff})V_{eff}$ & $S = \int_{f.o.} su^{\mu} = s(T_{eff})V_{eff}$
  - $\epsilon(T)$ and $s(T)$ EoS used in the hydro calculation
  - By taking the ratio of E and S they solve the equation for T_{eff}
  - They connect with $T_{eff} \sim < p_T > /3$ and $S \sim N_{ch}$

Procedure 1: different energies

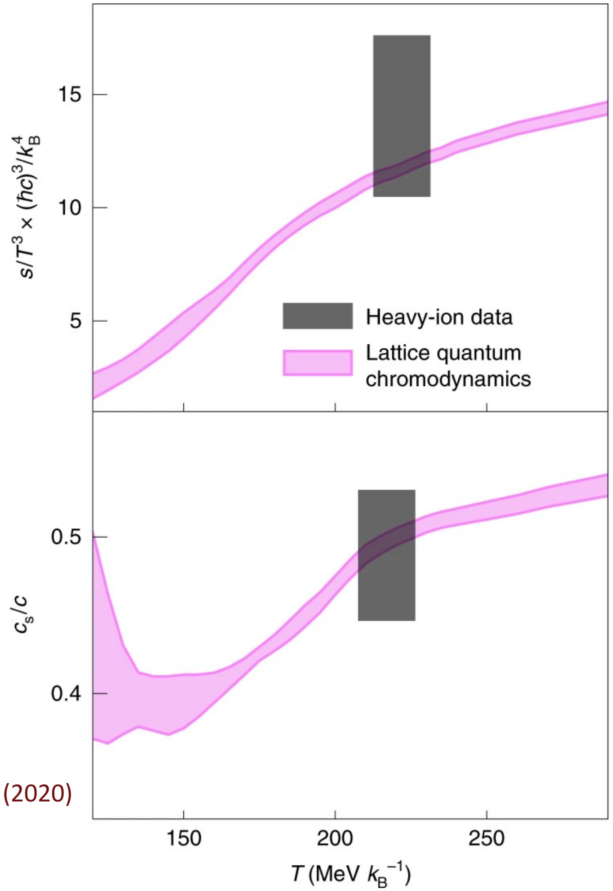
PbPb ALICE data at 2.76 TeV and 5.02 TeV

- 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 $\langle p_{\text{T}} \rangle$ and N_{ch} for the two energies

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

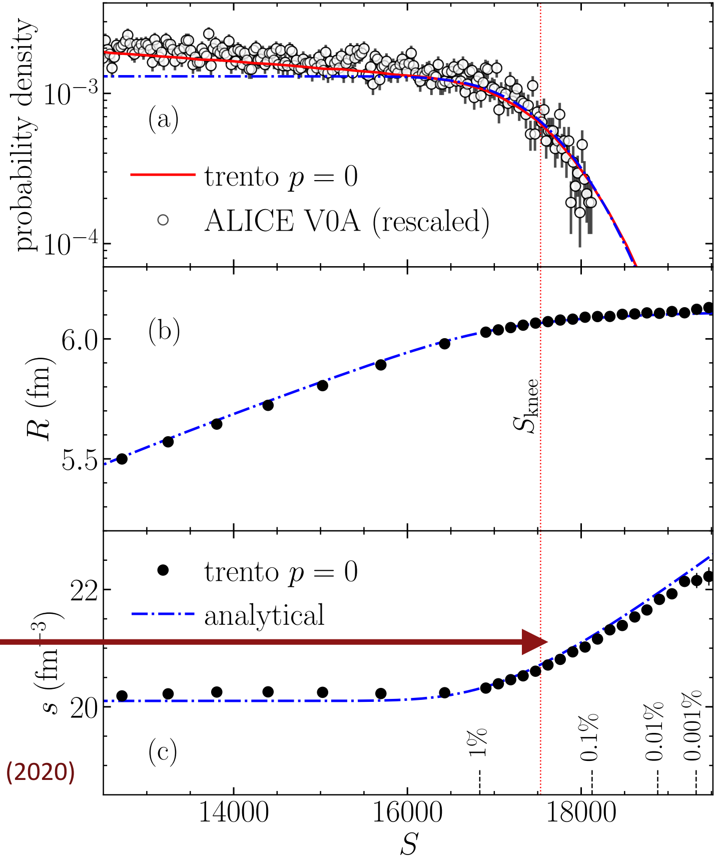


Nat. Phys. **16**, 615 (2020)

Procedure 2: UCC events

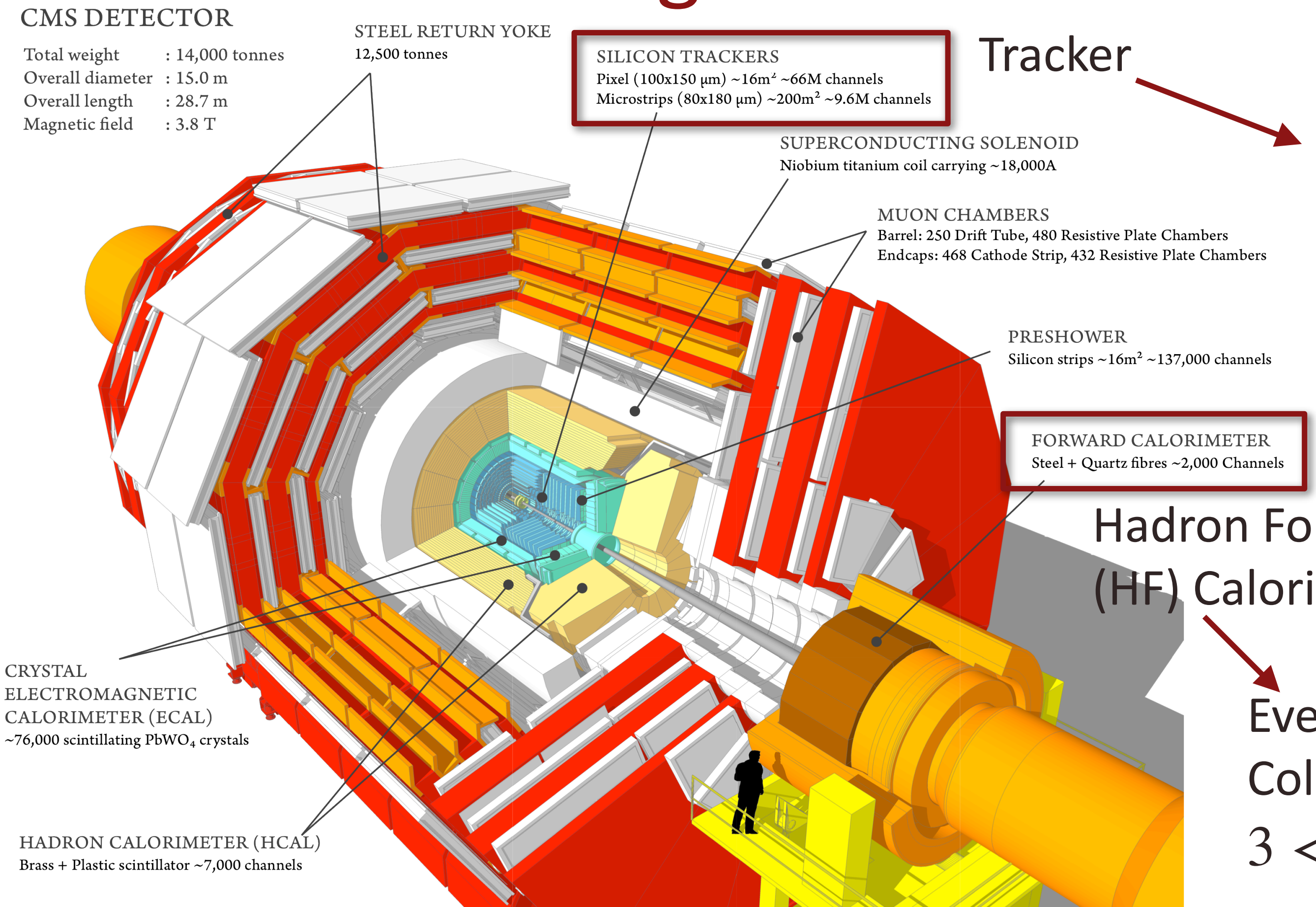
Non-trivial prediction by relativistic hydrodynamics

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



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

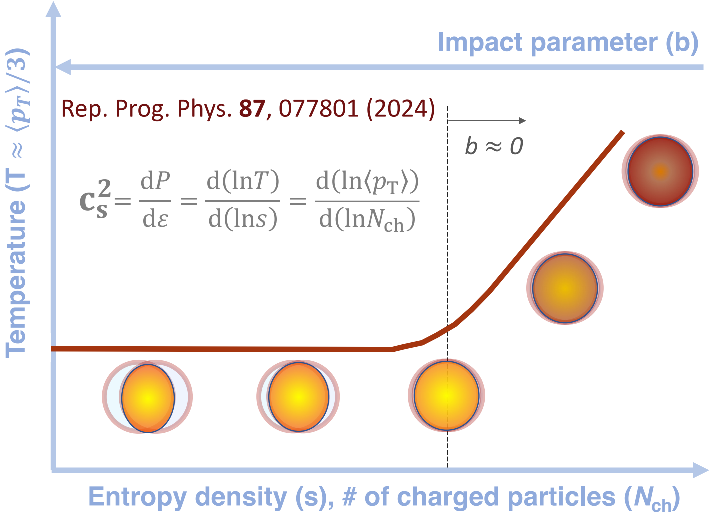
$3 < |\eta| < 5$

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

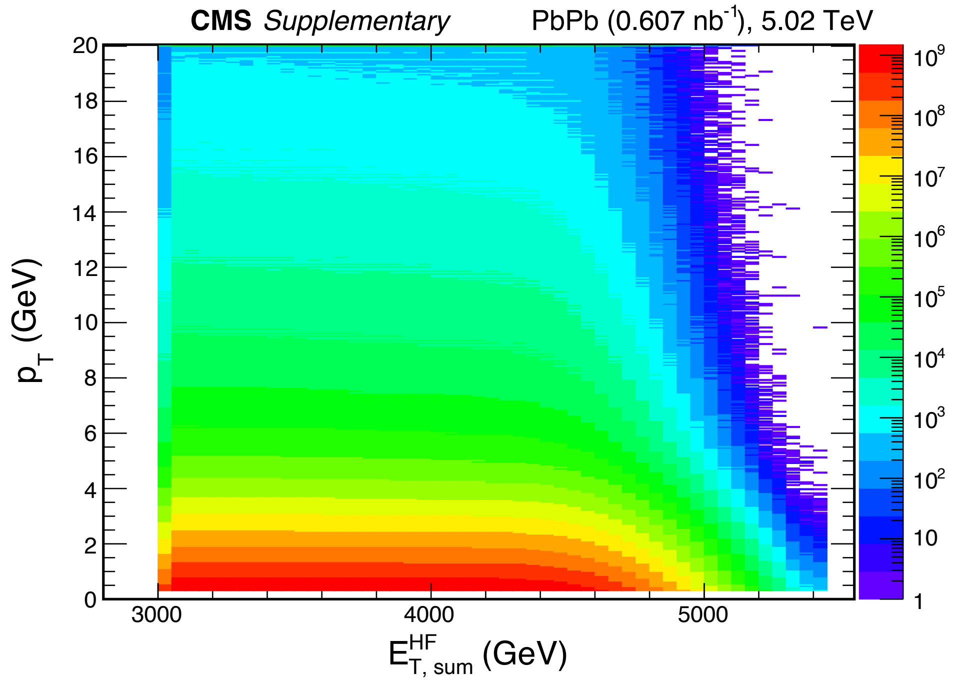
$\langle p_T \rangle^{\mathrm{norm}} = \frac{\langle p_T \rangle}{\langle p_T \rangle^0}$ vs $N_{\mathrm{ch}}^{\mathrm{norm}} = \frac{N_{\mathrm{ch}}}{N_{\mathrm{ch}}^0}$

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

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

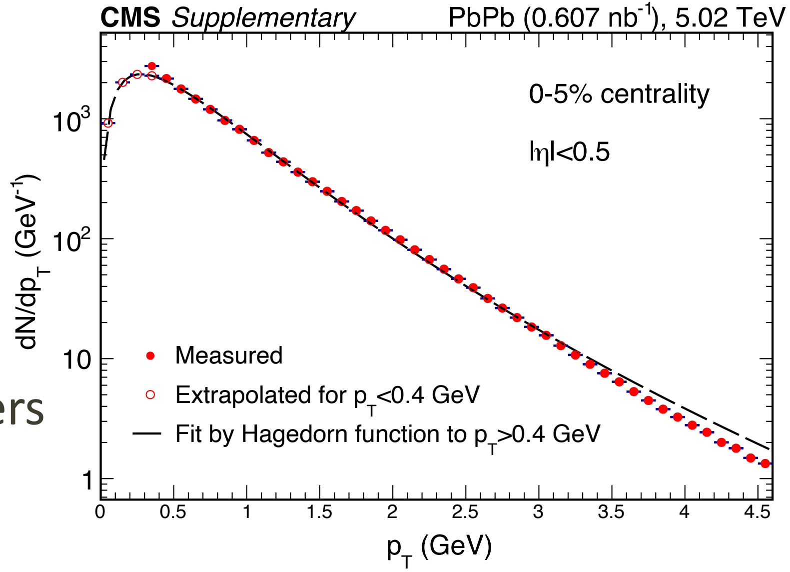
Extrapolation to $p_\mathrm{T} = 0$ by fitting the spectrum in $p_\mathrm{T} > 0.4 GeV$

- 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 $N_\mathrm{ch}^\mathrm{norm}$

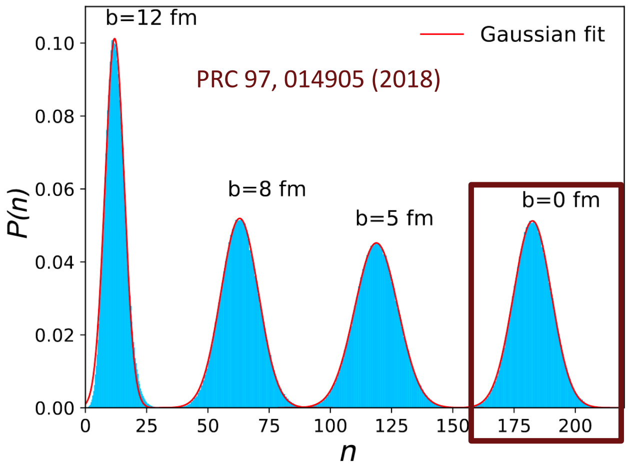
Extracting the speed of sound - multiplicity fluctuations

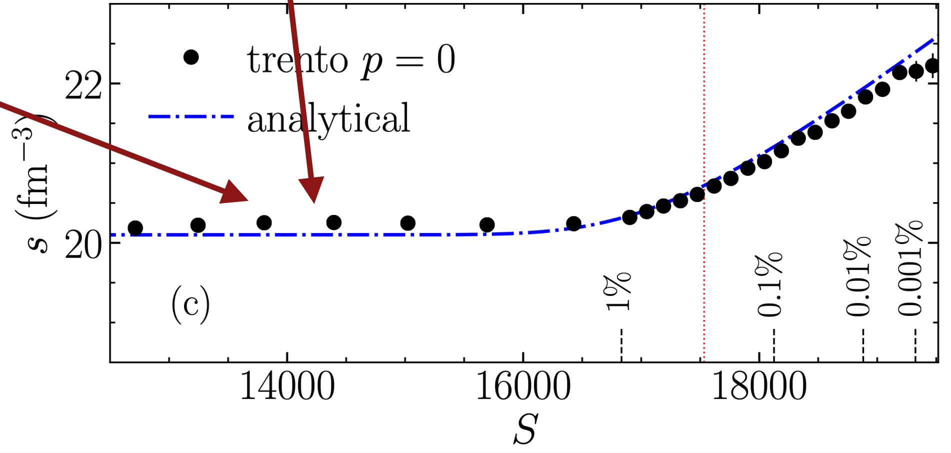
$Prob(N_{\rm ch}^{\rm norm})$: analytical model to capture the trends from hydro.

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

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

Plateau outside UCC



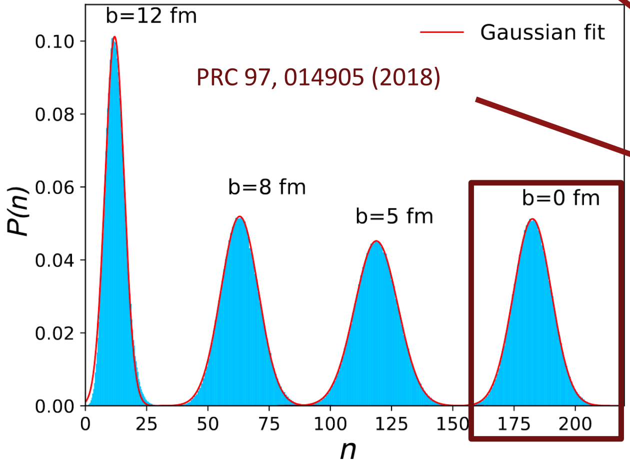


Extracting the speed of sound - multiplicity fluctuations

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

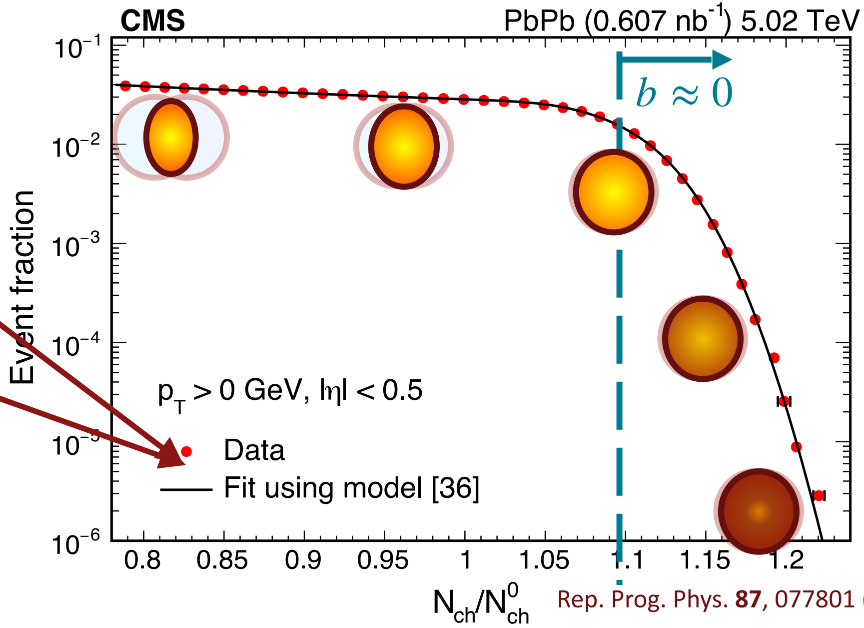
Phys. Lett. B **809**, 135749 (2020)

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



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

Fit N_{ch}^{norm} distribution



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

Extracting the speed of sound: CMS data

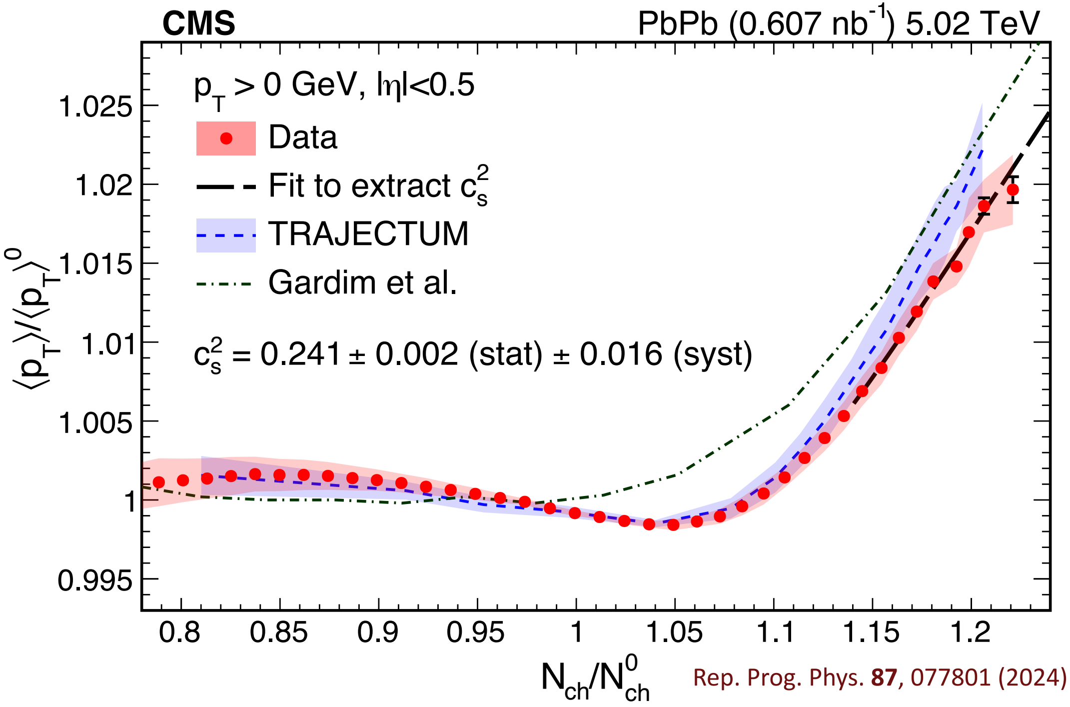
Fit $\langle p_{\mathrm{T}}\rangle^{\mathrm{norm}}$ vs $N_{\mathrm{ch}}^{\mathrm{norm}}$ using

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

Do not model the dip

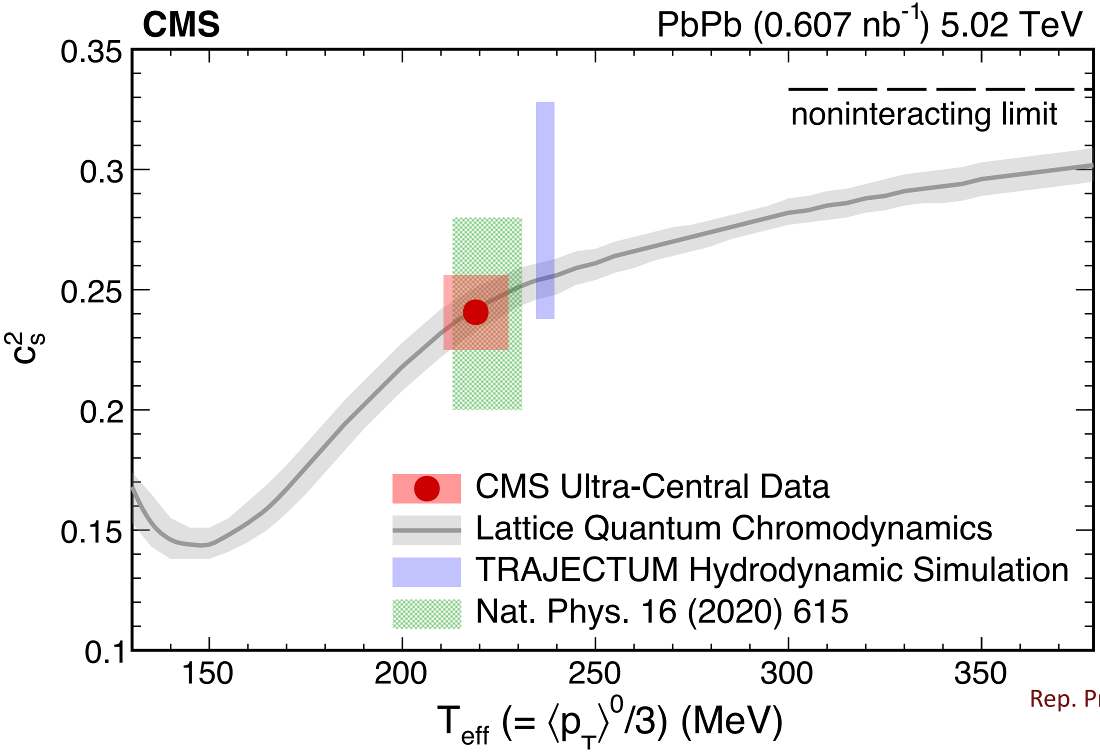
Fit starts from better χ^2 at $N_{\mathrm{ch}}^{\mathrm{norm}} > 1.12$

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



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

Comparison with lattice QCD & hydrodynamics models



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

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

Studies by ATLAS - no fitting procedure

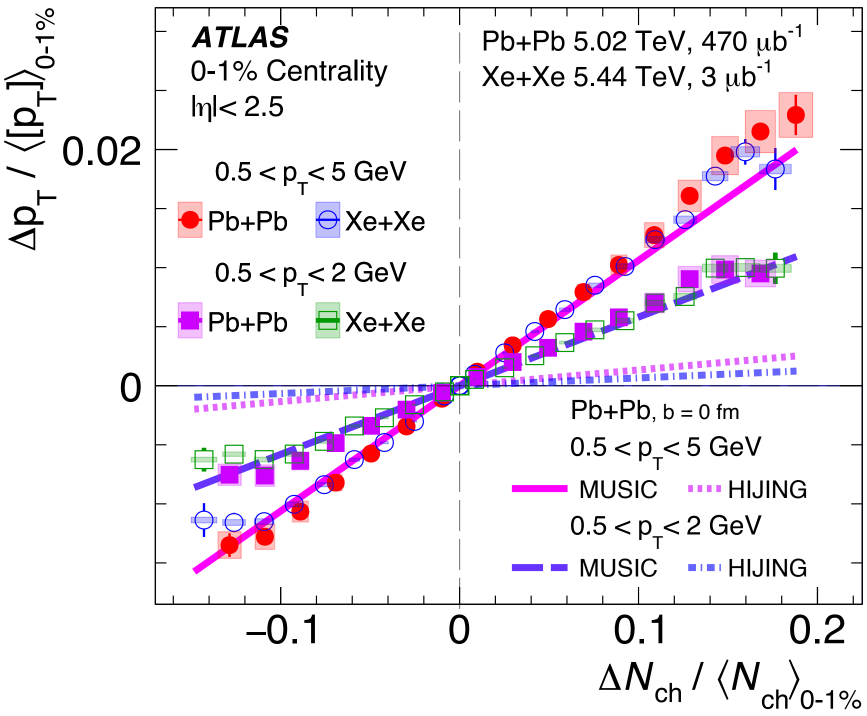
Reasonable agreement with MUSIC when using

Phys. Rev. C **82**, 014903 (2010)

$$c_s^2 \approx 0.23 \;\&\; T_{eff} \approx 222MeV$$

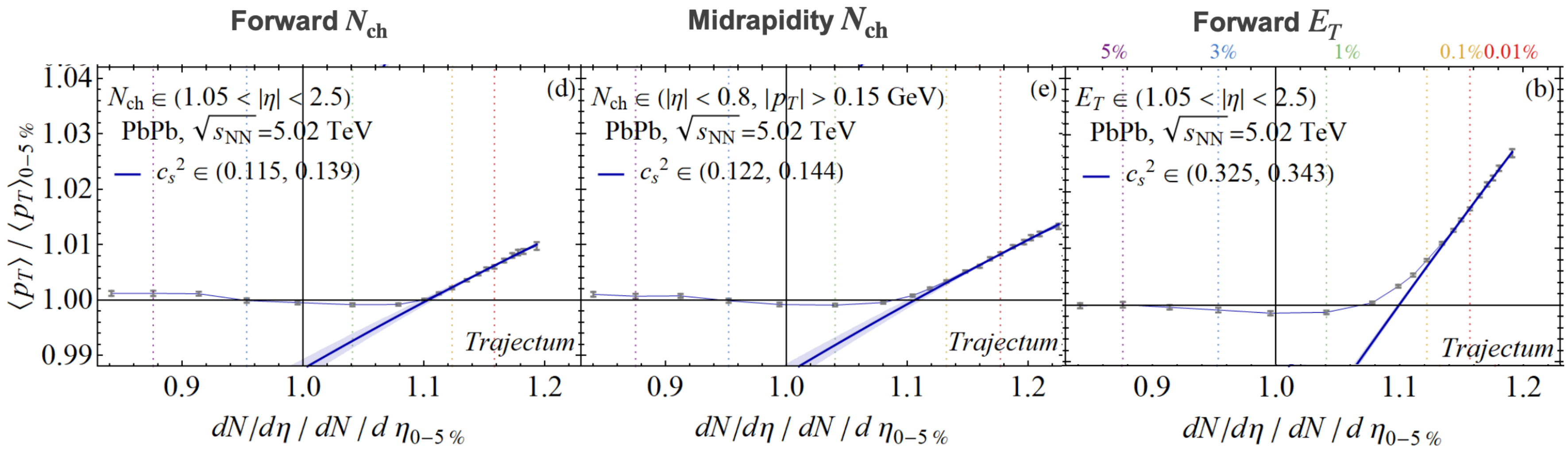
- Captures different trends due to p_{T} cut
- Similar trends in PbPb and XeXe
- Compatible with CMS results
- Gap in η of 0.7 (E_T-based centrality estimator)

arXiv:2407.06413



Trajectum: 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 $\langle p_{\mathrm{T}} \rangle$ with small (or no) η-gap

ALICE: centrality estimator bias

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

ALICE-PUBLIC-2024-002

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

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

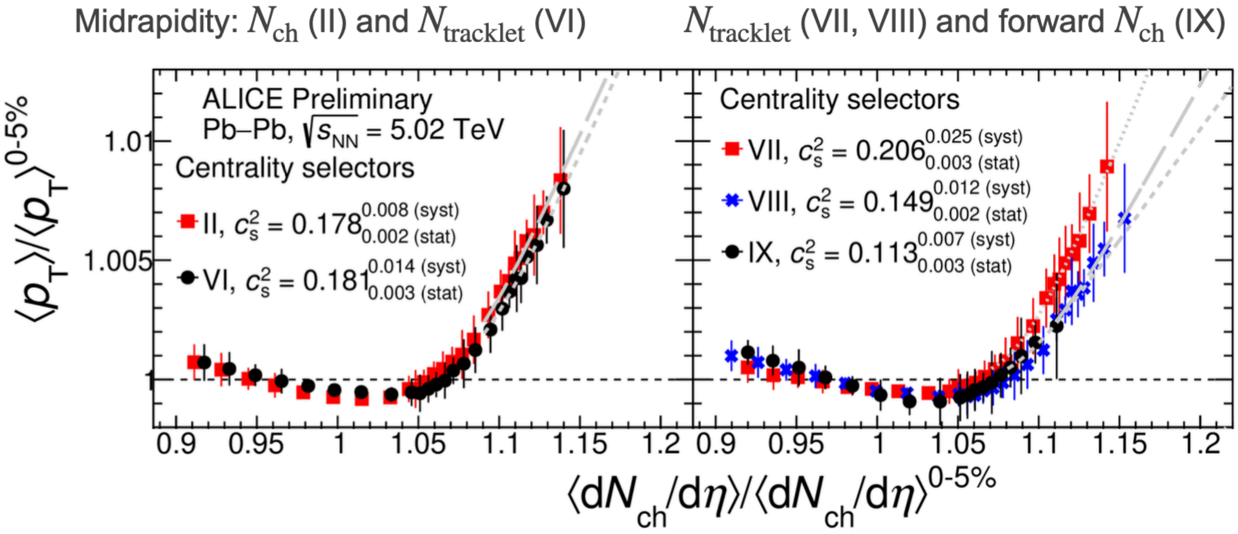
ALICE: centrality estimator bias

ALICE-PUBLIC-2024-002

Non E_T-based

Lower values compared to CMS

Observable	Label	Centrality estimation	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$
N_{ch} in TPC	II	$0.5 \leq \|\eta\| \leq 0.8$	$\|\eta\| \leq 0.3$
$N_{tracklets}$ in SPD	VI	$0.5 \leq \|\eta\| \leq 0.8$	$\|\eta\| \leq 0.3$
	VII	$0.3 < \|\eta\| \leq 0.6$	$\|\eta\| \leq 0.3$
	VIII	$0.7 \leq \|\eta\| \leq 1$	$\|\eta\| \leq 0.3$
N_{ch} in V0	IX	$-3.7 < \eta < -1.7 + 2.8 < \eta < 5.1$	$\|\eta\| \leq 0.8$



ALICE: centrality estimator bias

ALICE-PUBLIC-2024-002

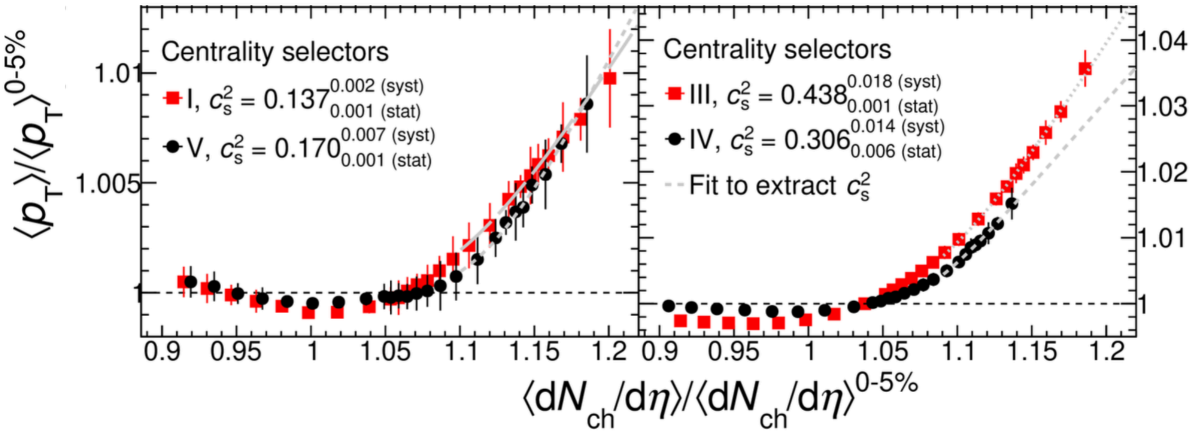
Observable	Label	Centrality estimation	$\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$
N_{ch} in TPC	I	$\|\eta\| \leq 0.8$	$\|\eta\| \leq 0.8$
E_T in TPC	III	$\|\eta\| \leq 0.8$	$\|\eta\| \leq 0.8$
	IV	$0.5 \leq \|\eta\| \leq 0.8$	$\|\eta\| \leq 0.3$
$N_{tracklets}$ in SPD	V	$\|\eta\| \leq 0.8$	$\|\eta\| \leq 0.8$

E_T-based

Higher values compared to CMS

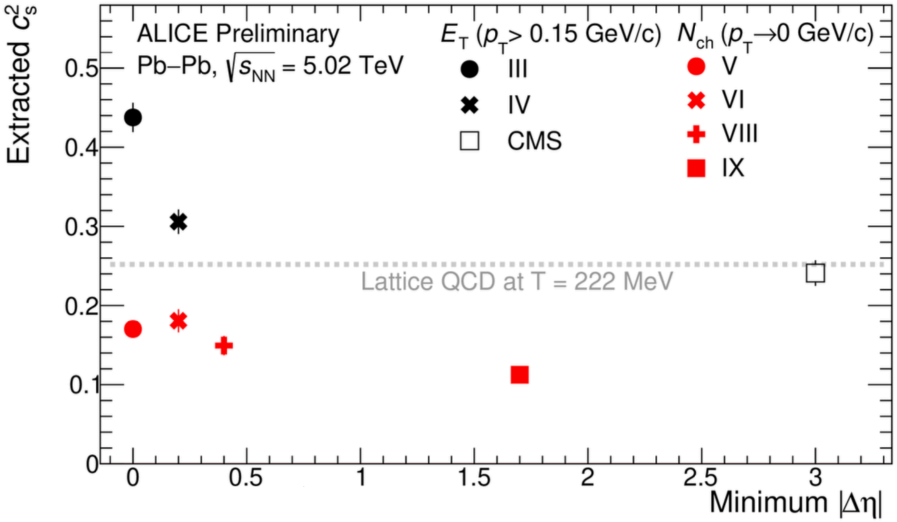
Midrapidity: N_{ch} (I) and $N_{tracklet}$ (V)

E_T: No subevent (V) and subevent (IV)



ALICE: centrality estimator bias

Summary of extracted values of c_s^2



ALICE-PUBLIC-2024-002

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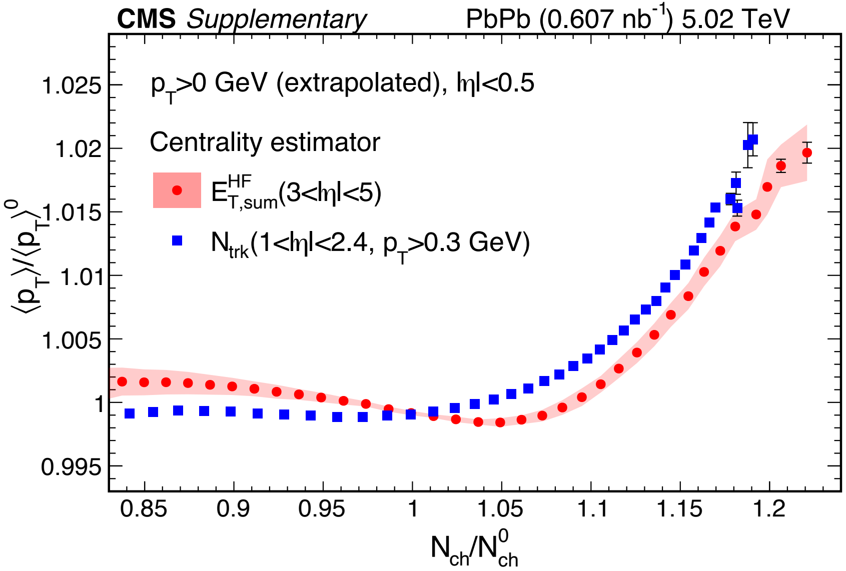
	VII	$0.3 < \lvert\eta\rvert \leq 0.6$	$\lvert\eta\rvert \leq 0.3$
	VIII	$0.7 \leq \lvert\eta\rvert \leq 1$	$\lvert\eta\rvert \leq 0.3$
N_{ch} in V0	IX	$-3.7 < \eta < -1.7 + 2.8 < \eta < 5.1$	$\lvert\eta\rvert \leq 0.8$

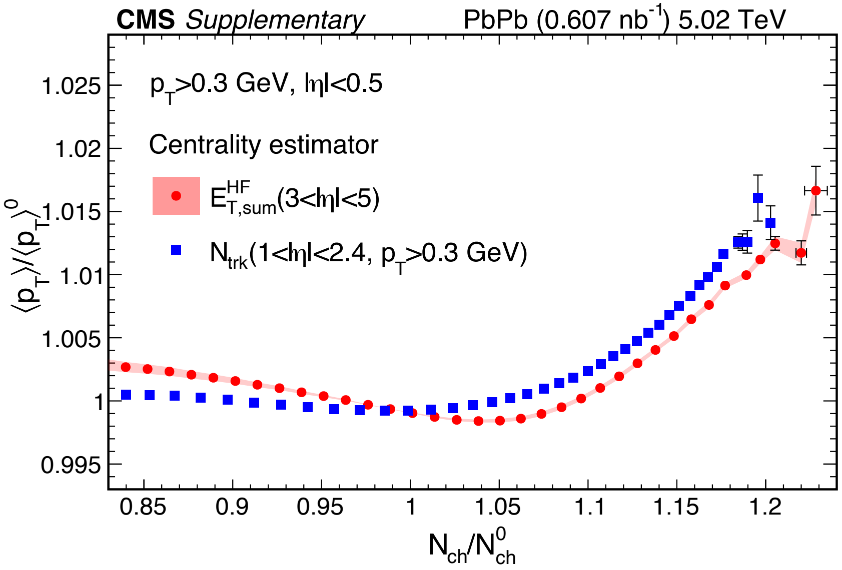
CMS: centrality estimator bias

Initial checks from CMS: no considerable bias in the slope

- Probably due to large η gap ?

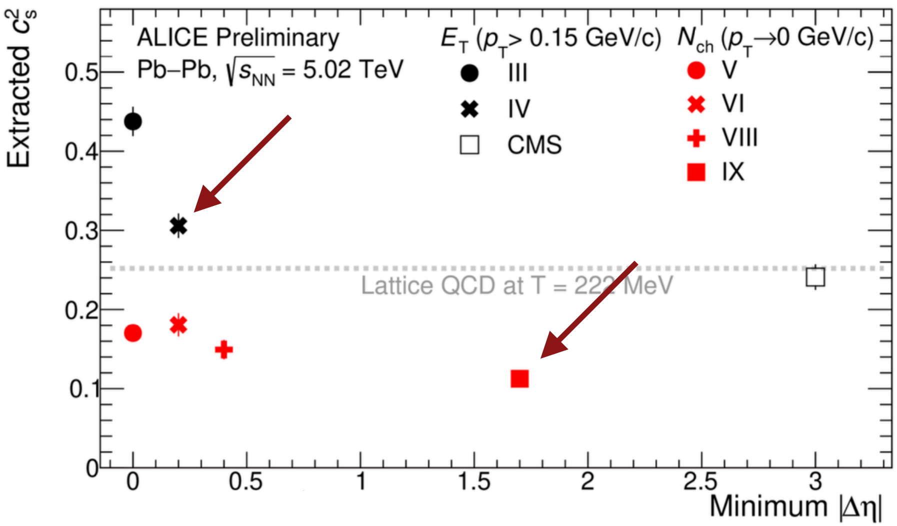
Will perform more studies about the η-gap





ALICE: centrality estimator bias

Summary of extracted values of c_s^2



ALICE-PUBLIC-2024-002

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

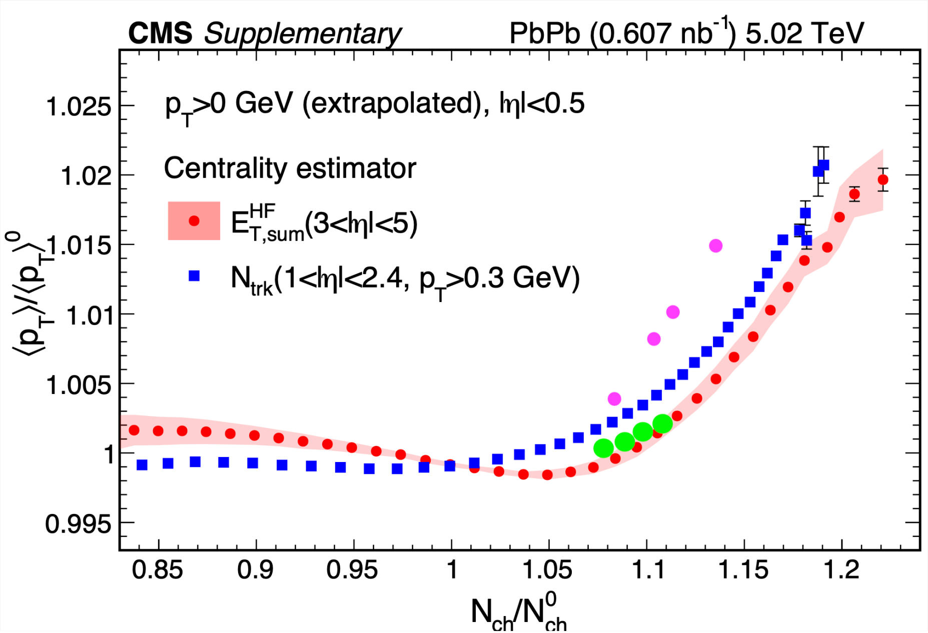
Rough comparison using few points

No uncertainties included

(IV) E_T in TPC $(0.5 < |\eta| < 0.8)$ - Eta Gap 0.2

(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

Future studies & open questions

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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

Future studies & open questions

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- 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

The rise of $< p_T >$ vs N_{ch} in UCC: 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)

Future studies & open questions

Few selected recent theoretical studies

- Analytical studies of the relation between c_s^2 & $\ln < p_T >$ vs $\ln N_{ch}$ arXiv:2405.10401
  - Inviscid hydrodynamics with a constant c_s^2 (Gubser hydro solution)
  - Effects from rapidity cuts
    - The c_s^2 is extracted more precisely for higher center-of-mass energies

$$c_s^2 = \frac{d\ln(E_{\rm tot}/N_{\rm tot})}{d\ln N_{\rm tot}} = \lim_{T_{\rm FO}\to 0} \frac{d\ln\langle p_T\rangle}{d\ln N_{\rm mr}}$$

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    - The c_s^2 is extracted more precisely for higher center-of-mass energies

$$c_s^2 = \frac{d\ln(E_{\rm tot}/N_{\rm tot})}{d\ln N_{\rm tot}} = \lim_{T_{\rm FO}\to 0} \frac{d\ln\langle p_T\rangle}{d\ln N_{\rm mr}}$$

- Volume effect on the extraction of c_s^2 arXiv:2407.05570
  - Use Trento model to simulate initial conditions
  - Initial fluctuations lead to sizable volume effect
    - Provide quantitative estimate of required corrections for c_s^2

$$c_s^2 = \frac{dP}{de} = \left(1 - \frac{\Delta\ln V_{\rm eff}}{\Delta\ln S}\right)^{-1} \frac{\Delta\ln T_{\rm eff}}{\Delta\ln S}$$

$$\Delta\ln V_{eff}/\Delta\ln S = 0.065 \pm 0.025$$

Thank You!

SPRACE

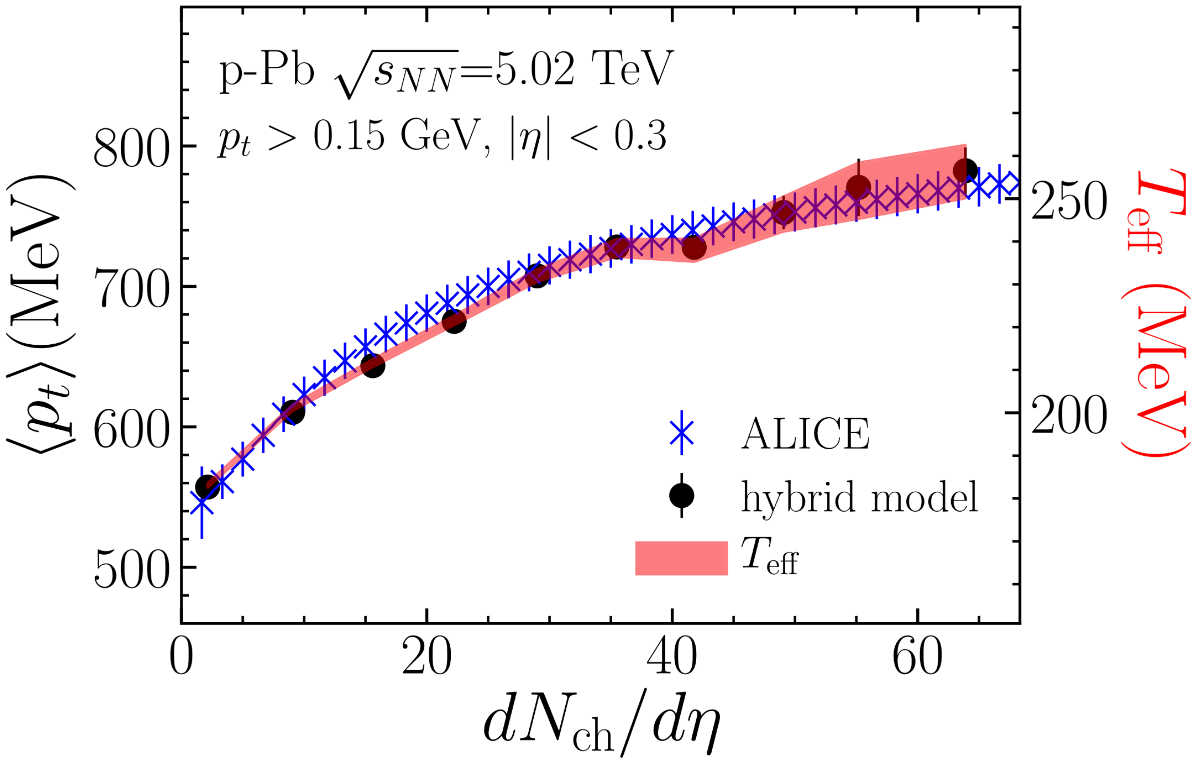
Thank You!

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.

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

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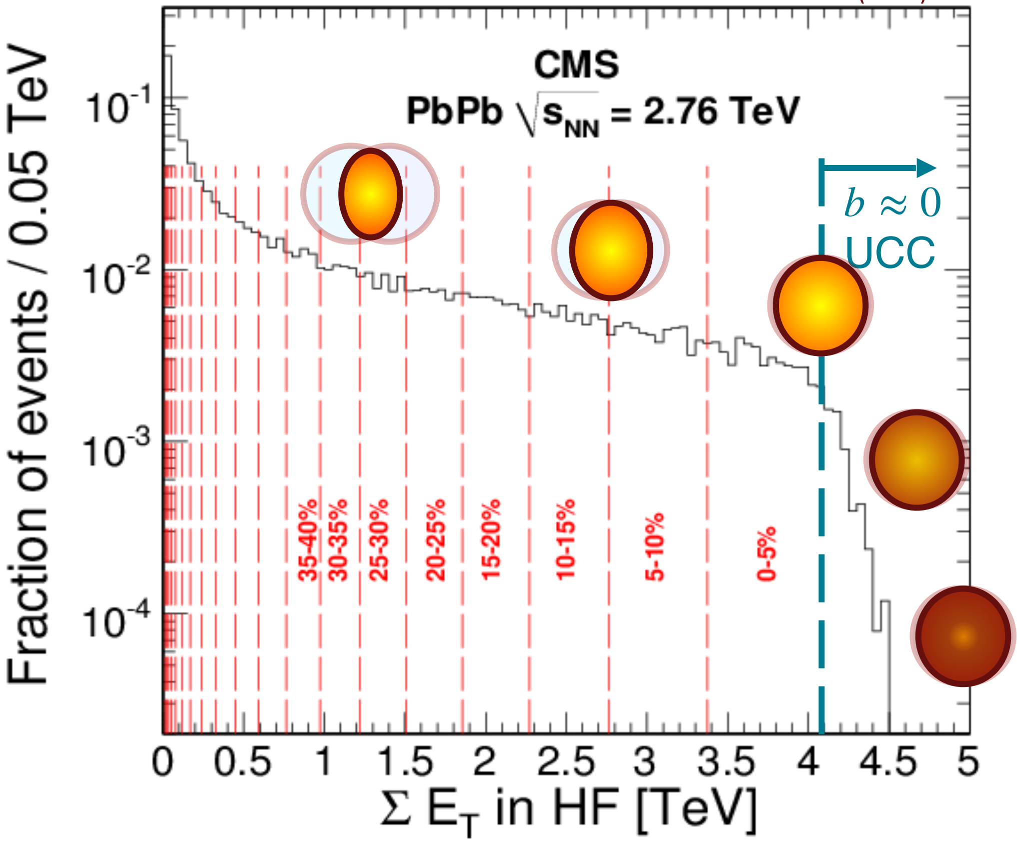


Samples and track selections

Minimum bias PbPb collisions at 5.02 TeV

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

Monte Carlo (MC) simulations: HYDJET generator

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

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

- Better tracking performance

Systematic uncertainties and cross-checks

Systematics

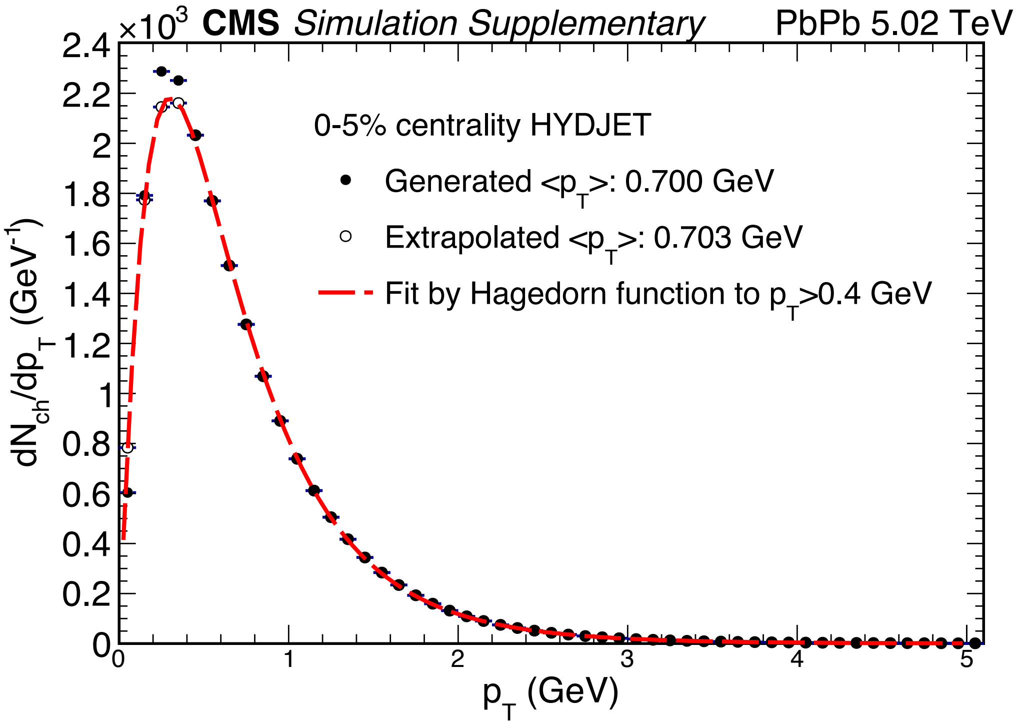
- Tracking efficiency corrections
- Extrapolation to $p_{\mathrm{T}} \approx 0$
- Choice of fit range (only for c_{s}^2)

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 $p_T \approx 0$ - Monte Carlo

HYDJET generator

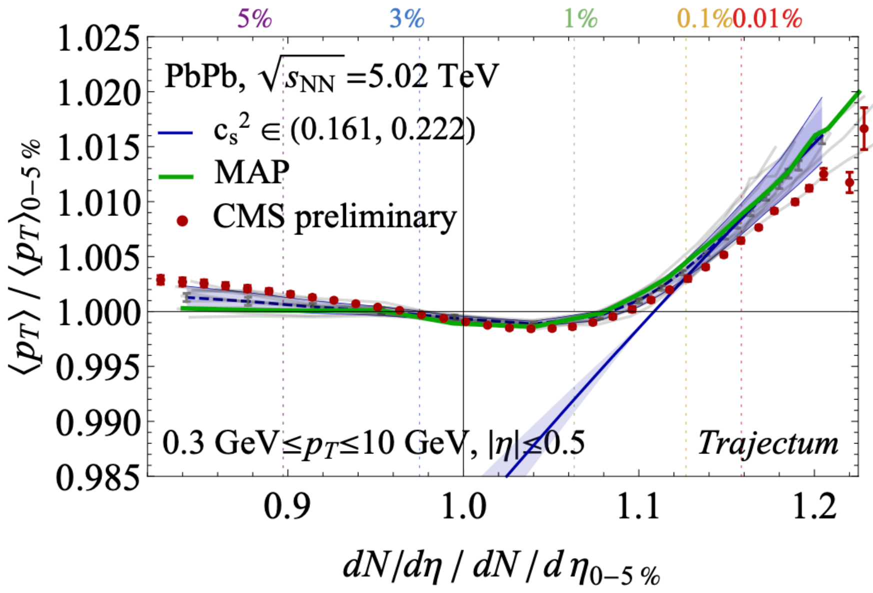


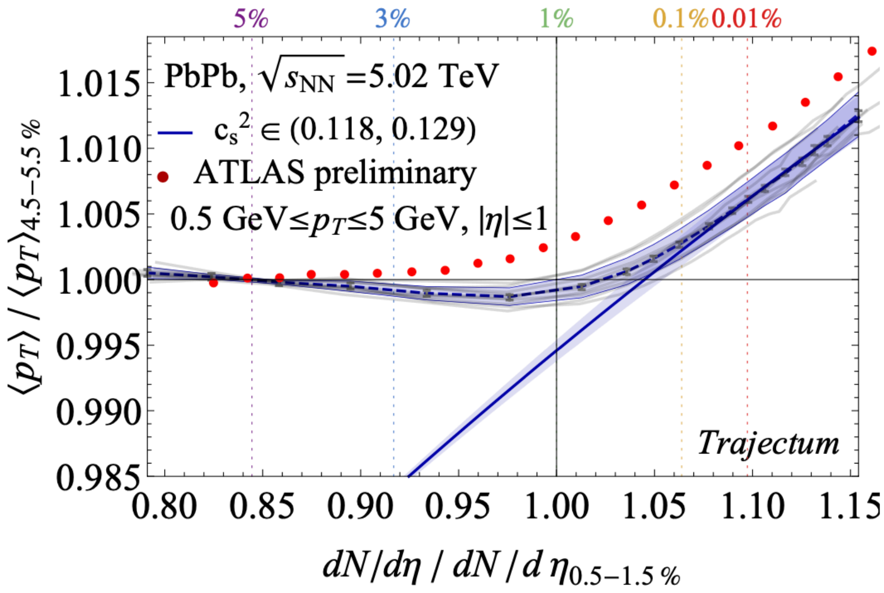
arXiv:2401.06896

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

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

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

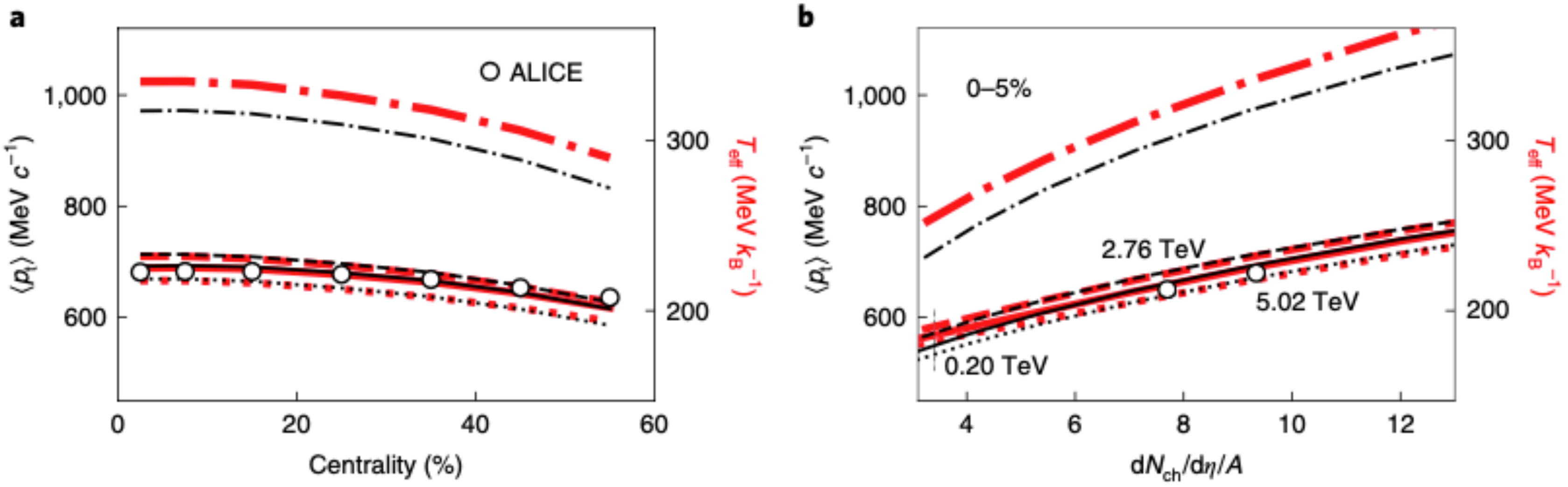




The slope has a clear dependence on the p_T cut

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

Nature Physics **16** (2020) 615



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

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

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

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

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

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