Extracting the speed of sound of hot QCD matter with the CMS experiment

(based on arXiv:2401.06896)

Wei Li (Rice University)
for the CMS collaboration

U.S. DEPARTMENT OF ENERGY
Office of Science

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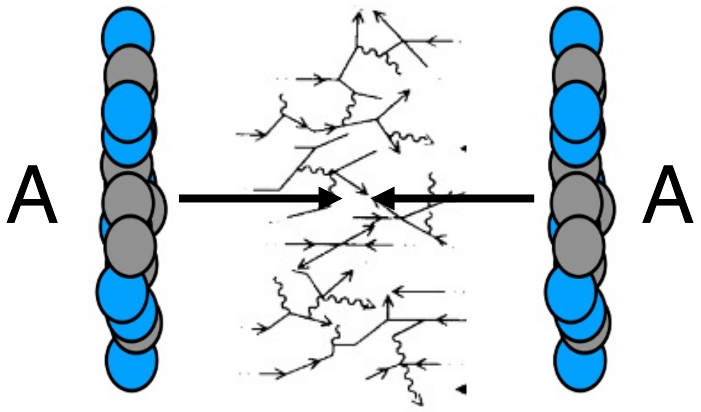
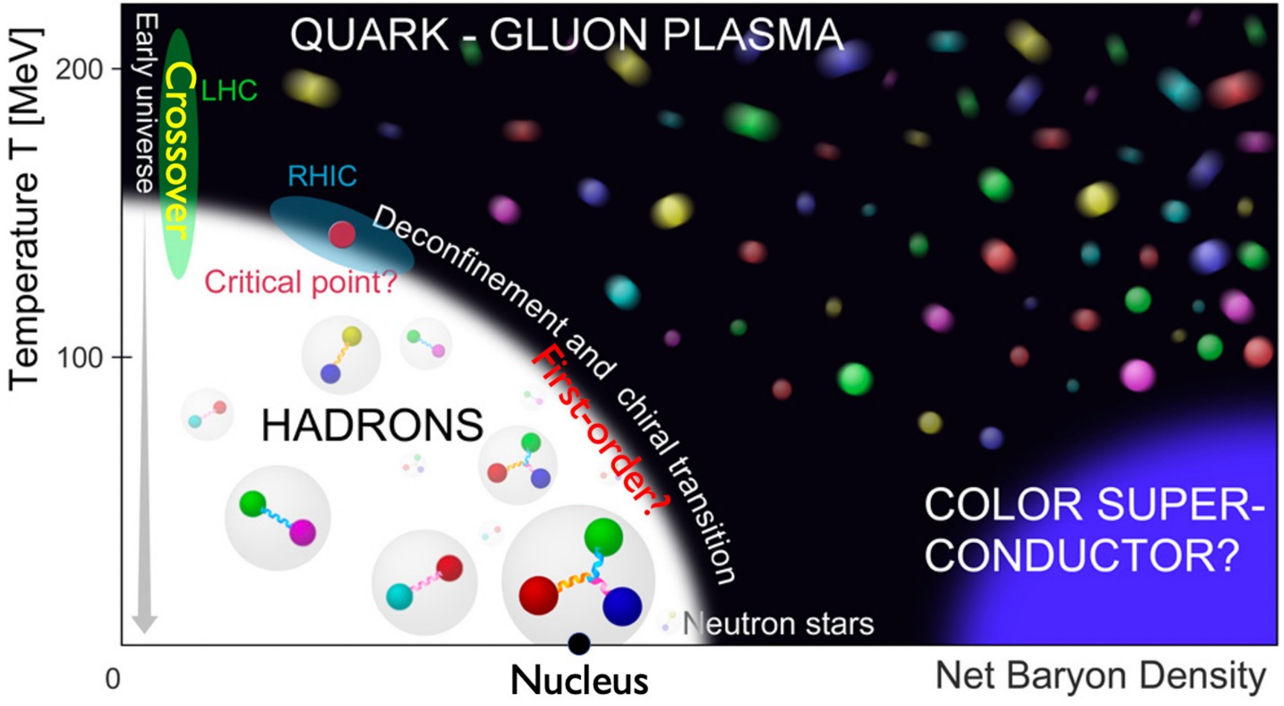
CMS
RICE

Relativistic Nuclear Collisions



In relativistic nuclear collisions, a strongly-coupled, hot and dense matter is created that behaves as a nearly "perfect liquid"



- What is the fundamental degree of freedom of this matter?
- What is the nature of the phase transition? A critical end point?

Can we directly constrain the equation of state (EOS)?

Thermodynamics and the equation of state

A thermodynamic equation that relates state variables (*P*, *E*, *S*, *V*, *T*):

$$f(P, V, T) = 0$$

- Classical ideal gas: $PV - NRT = 0$

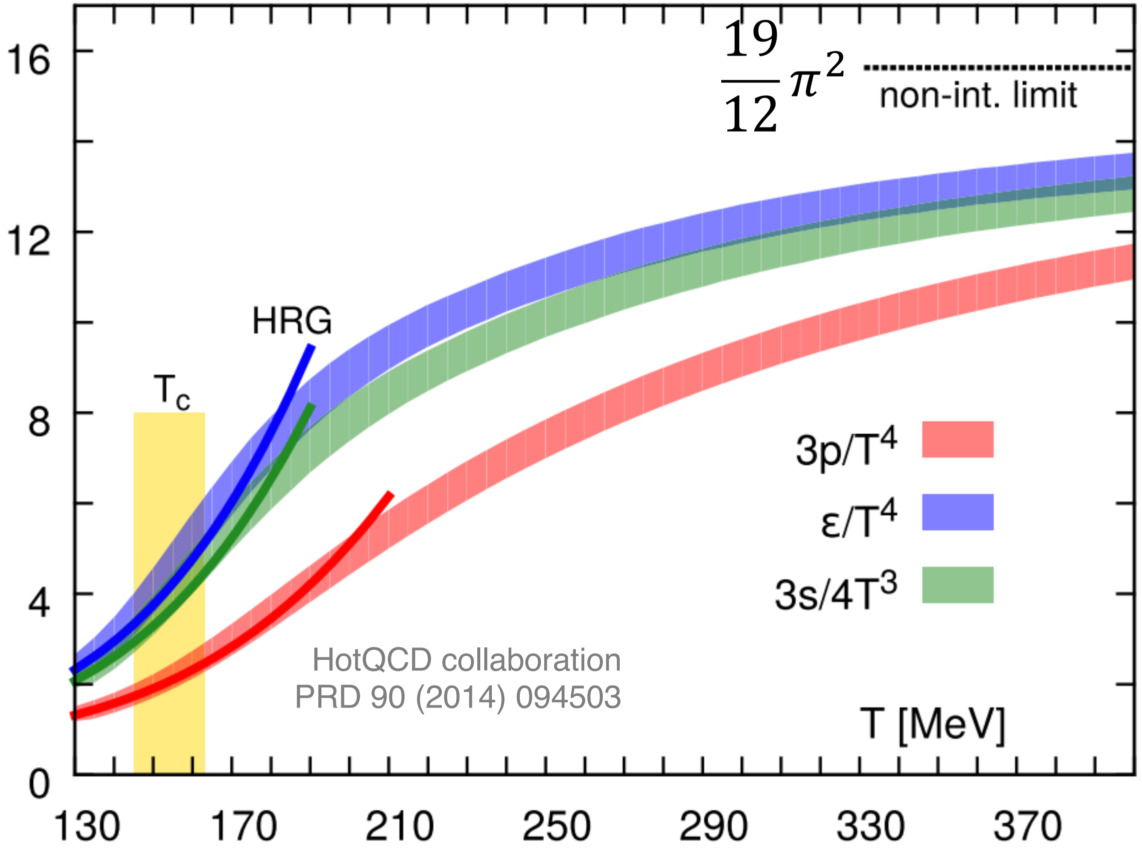
- Black body (massless particle or photon gas):

$$\frac{E}{V} - \sigma T^4 = 0, \quad P - \frac{1}{3}\sigma T^4 = 0, \quad \frac{S}{V} - \frac{4}{3}\sigma T^3 = 0$$

The EoS usually studied by measuring Var1 vs. Var2 with Var3 fixed.

The equation of state (EoS) of hot QCD matter

Lattice QCD at $\mu_B \sim 0$



QCD has predicted a deconfined state at high T. Can we directly test it?

To constrain the EoS, need to measure two thermodynamic quantities at a time with a third one fixed.

However, p, ε, or s, and T, V all vary as a function of time in AA collisions.

The speed of sound

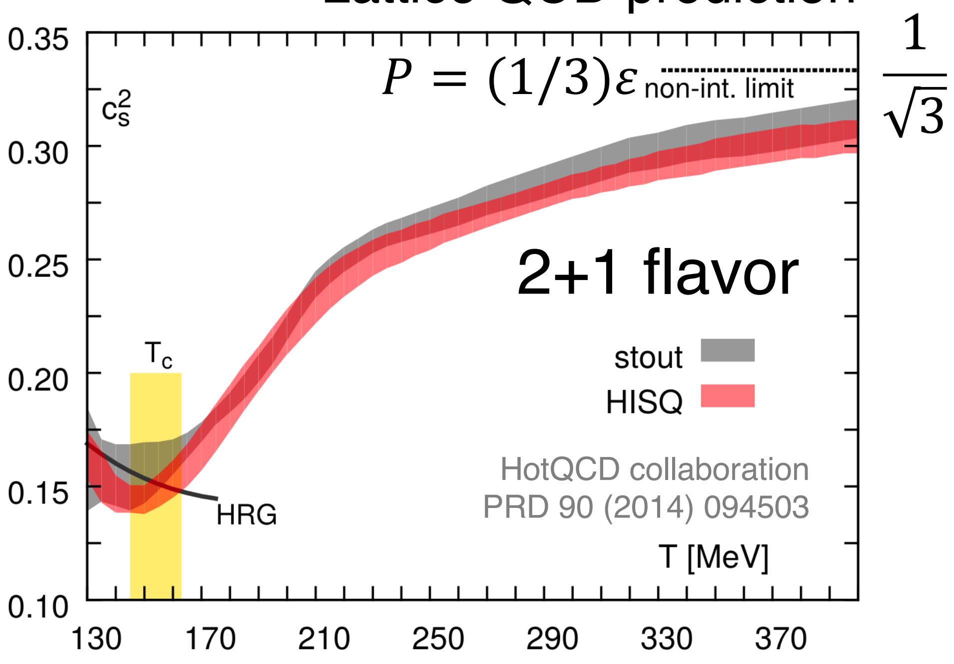
<u>Speed of sound</u> in a relativistic fluid:

$$c_s = \sqrt{\frac{\partial P}{\partial \varepsilon}} \longrightarrow$$

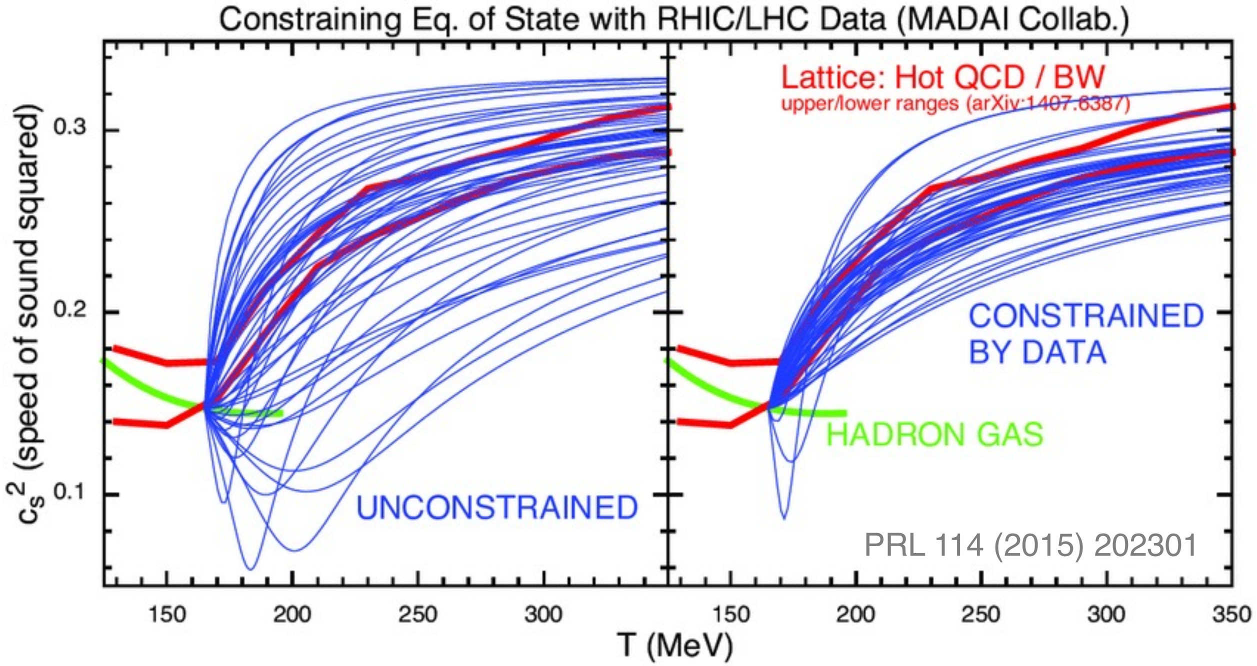
Direct constraint on the **equation of state**

Shock wave when $v>c_s$

Lattice QCD prediction

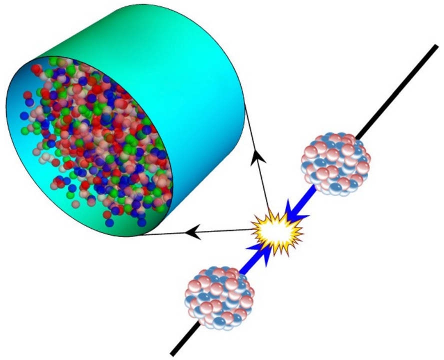


Bayesian analysis (2015)



Direct precise experimental constraint of EoS still lacking

Thermodynamics of hot QCD matter



nature physics
LETTERS
https://doi.org/10.1038/s41567-020-0846-4
Check for updates

Thermodynamics of hot strong-interaction matter from ultrarelativistic nuclear collisions

Fernando G. Gardim[1,2], Giuliano Giacalone[2], Matthew Luzum[3] and Jean-Yves Ollitrault[2]

The medium at freezeout of entropy *S* and energy *E* →
a uniform fluid at rest with an effective V_{eff} and T_{eff}

$$E = \int_{\text{f.o.}} T^{0\mu} d\sigma_\mu = \epsilon(T_{\text{eff}}) V_{\text{eff}}$$

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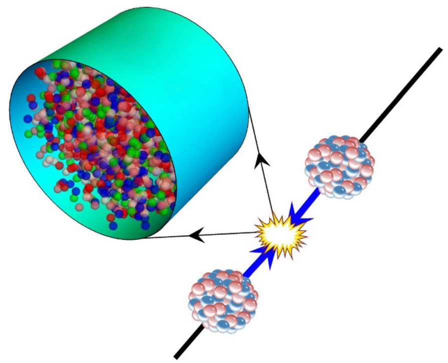

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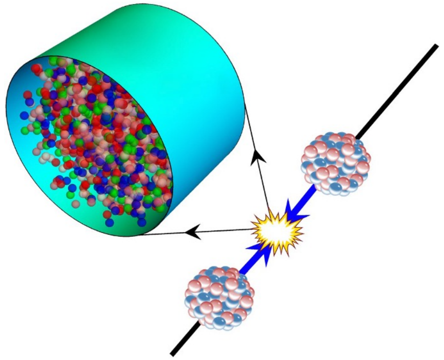
$$S = \int_{\mathrm{f.o.}} s u^\mu \mathrm{d}\sigma_\mu = s(T_{\mathrm{eff}}) V_{\mathrm{eff}}$$

$T_{\mathrm{eff}} \sim \langle p_T \rangle / 3$

$S \sim N_{\mathrm{ch}}$

Speed of sound: $c_s^2(T_{\mathrm{eff}}) \equiv \frac{\mathrm{d}P}{\mathrm{d}\varepsilon} = \left.\frac{s\mathrm{d}T}{T\mathrm{d}s}\right|_{T_{\mathrm{eff}}} = \frac{\mathrm{d}\ln\langle p_t \rangle}{\mathrm{d}\ln(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)}$

Thermodynamics of hot QCD matter



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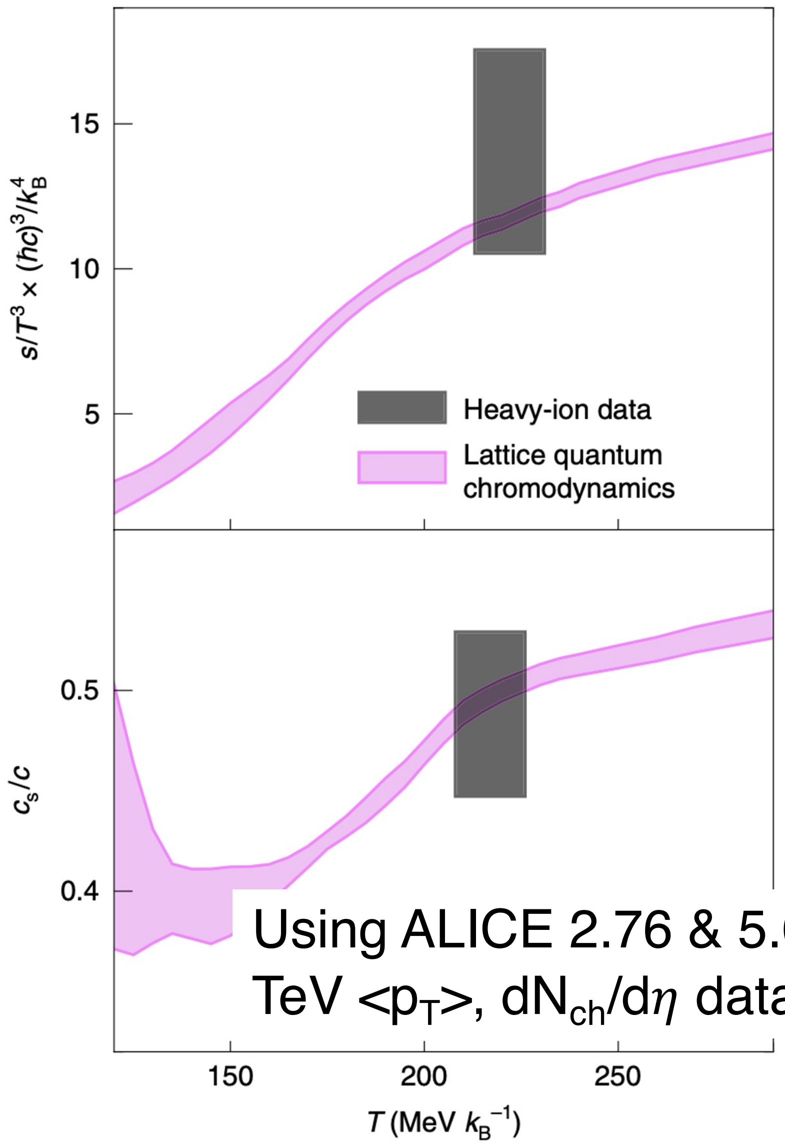
$T_{eff} \sim \langle p_T \rangle / 3$

$S \sim N_{ch}$

Speed of sound: $c_s^2(T_{\text{eff}}) \equiv \frac{dP}{d\varepsilon} = \left.\frac{s dT}{T ds}\right|_{T_{\text{eff}}} = \frac{d\ln \langle p_t \rangle}{d\ln (dN_{ch}/d\eta)}$



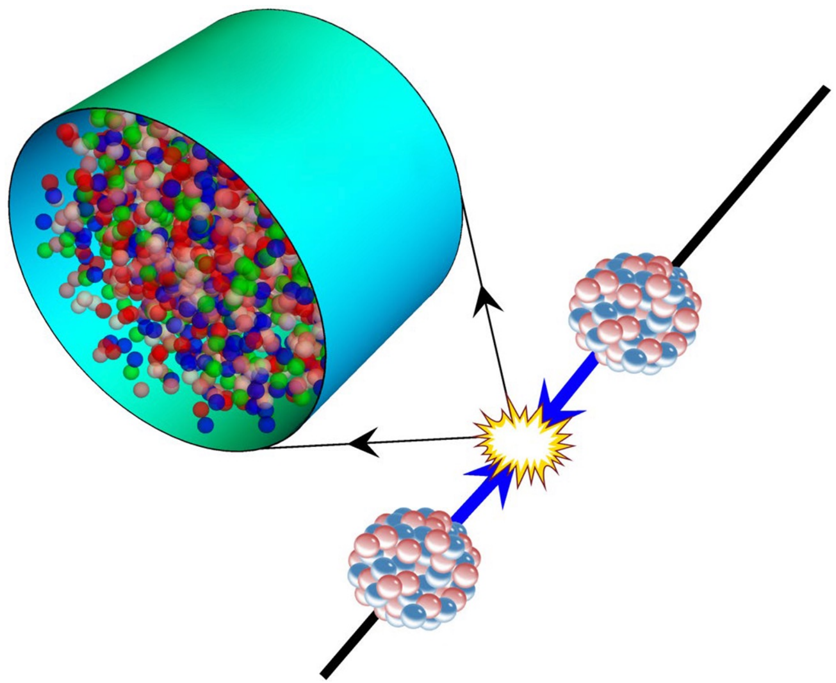
Using ALICE 2.76 & 5.02 TeV $\langle p_T \rangle$, $dN_{ch}/d\eta$ data

Large uncertainties on the early work and energy dependence of $\langle p_T \rangle$ and N_{ch} not unique in AA, either

The effective temperature, T_{eff} and $\langle p_T \rangle$

What T_{eff} is NOT:

- Not freezeout temperature (BW fits), as it also includes kinetic energy (radial flow)
- Not time-averaged temperature (e.g., photons)



The effective temperature, T_{eff} and $<p_T>$

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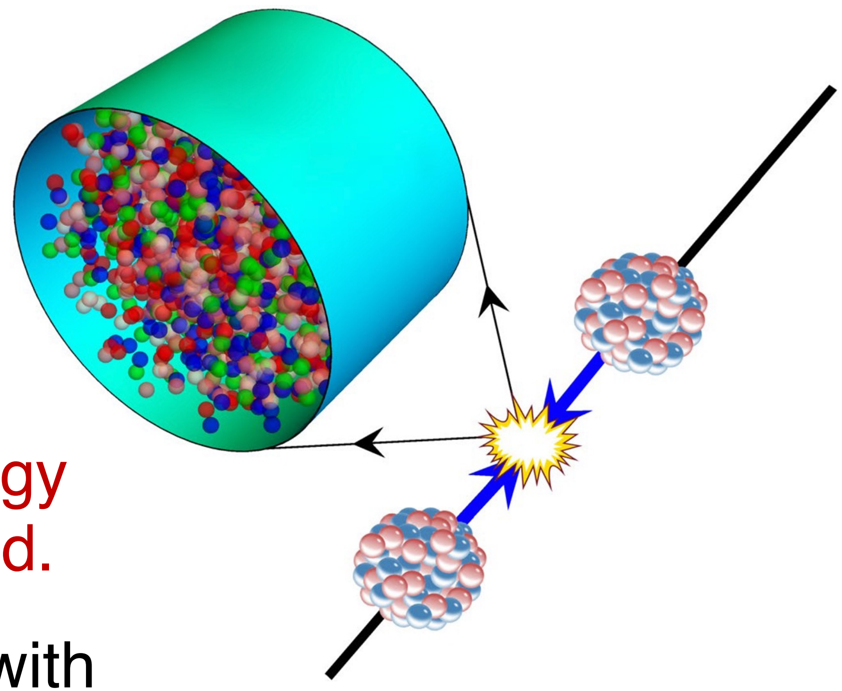


T_{eff} is the initial temperature T_0 of QGP if the total energy all the way to the freezeout is conserved and measured.

However, only a slice of QGP fluid in AA is measured with a built-in longitudinal expansion. Because of negative work by the longitudinal pressure,

$$T_{eff} \leq T_0, \text{ or a lower limit of } T_0$$

T_{eff} is found to be ~ $<p_T>/3$ from hydrodynamic simulations.

(If PID available, $T_{eff} \sim <KE_T>/3$, to be more precise)

Work in 80s to relate $<p_T>$ with T

Volume 118B, number 1, 2, 3 PHYSICS LETTERS 2 December 1982

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

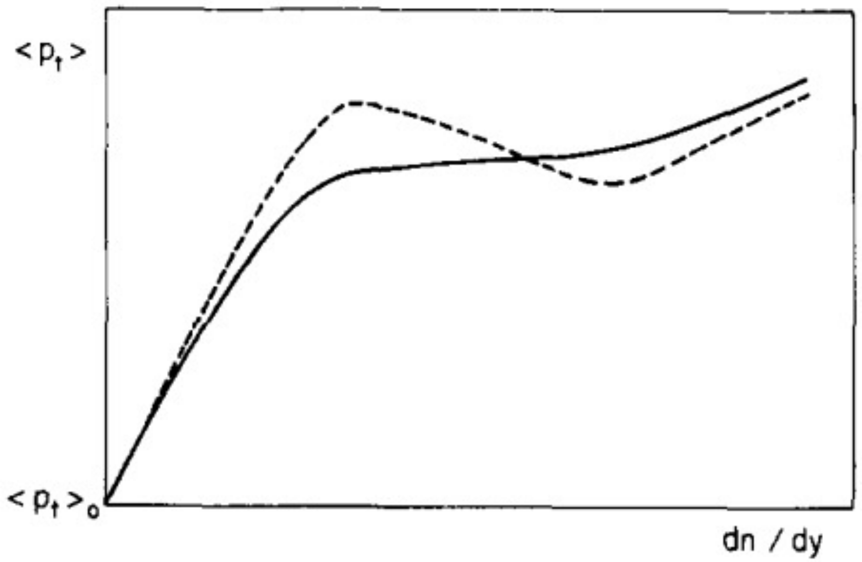
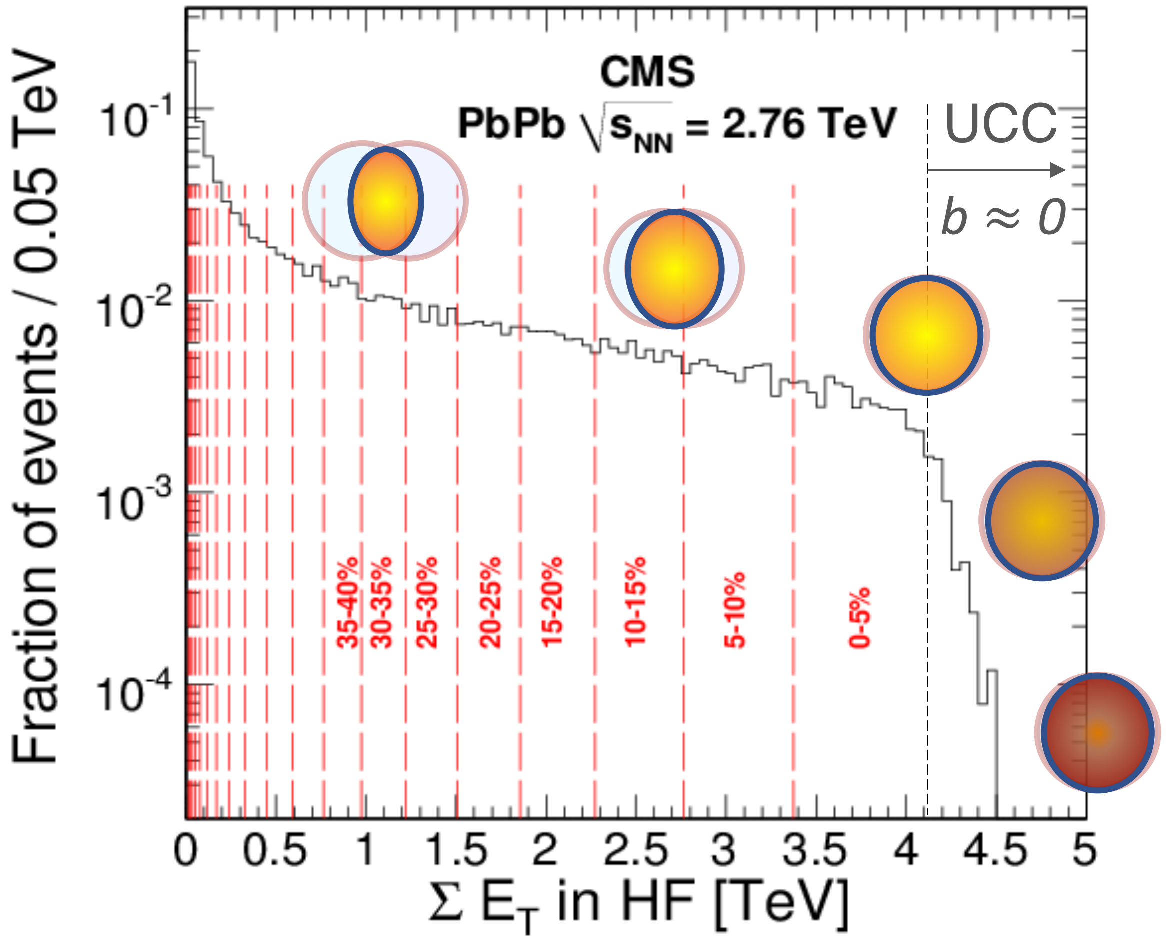


Fig. 2. Expected structure in the $\langle p_t \rangle$ versus dn/dy correlation resulting from the phase transition in fig. 1 (solid line), and sharper structure expected for a given impact parameter (dashed line).

Very early attempt in relating $<p_T>$ with temperature to probe the EoS and possible a phase transition!

Centrality and Ultra-central collisions



Transverse energy sum in the HFs, $E_{T,\text{sum}}^{\text{HF}}$

Centrality – a control of impact parameter (b), volume and geometry

- **Experimentally** determined by **final-state** total energy or multiplicity

Ultra-Central Collisions (UCC) – b→0

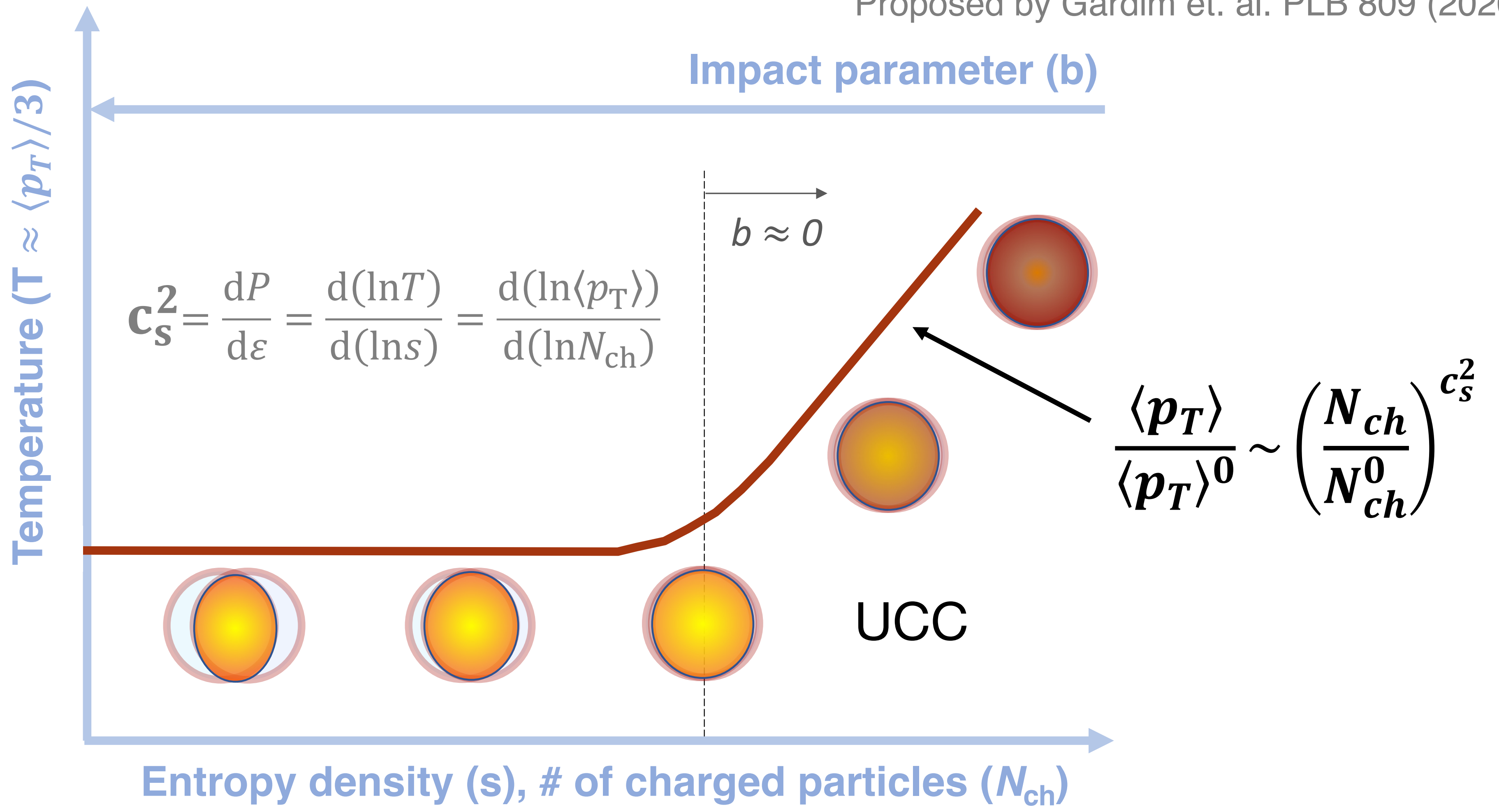
e.g., 0-1% centrality, where the volume or geometry stop varying, but total energy or entropy can still fluctuate

Rare events!

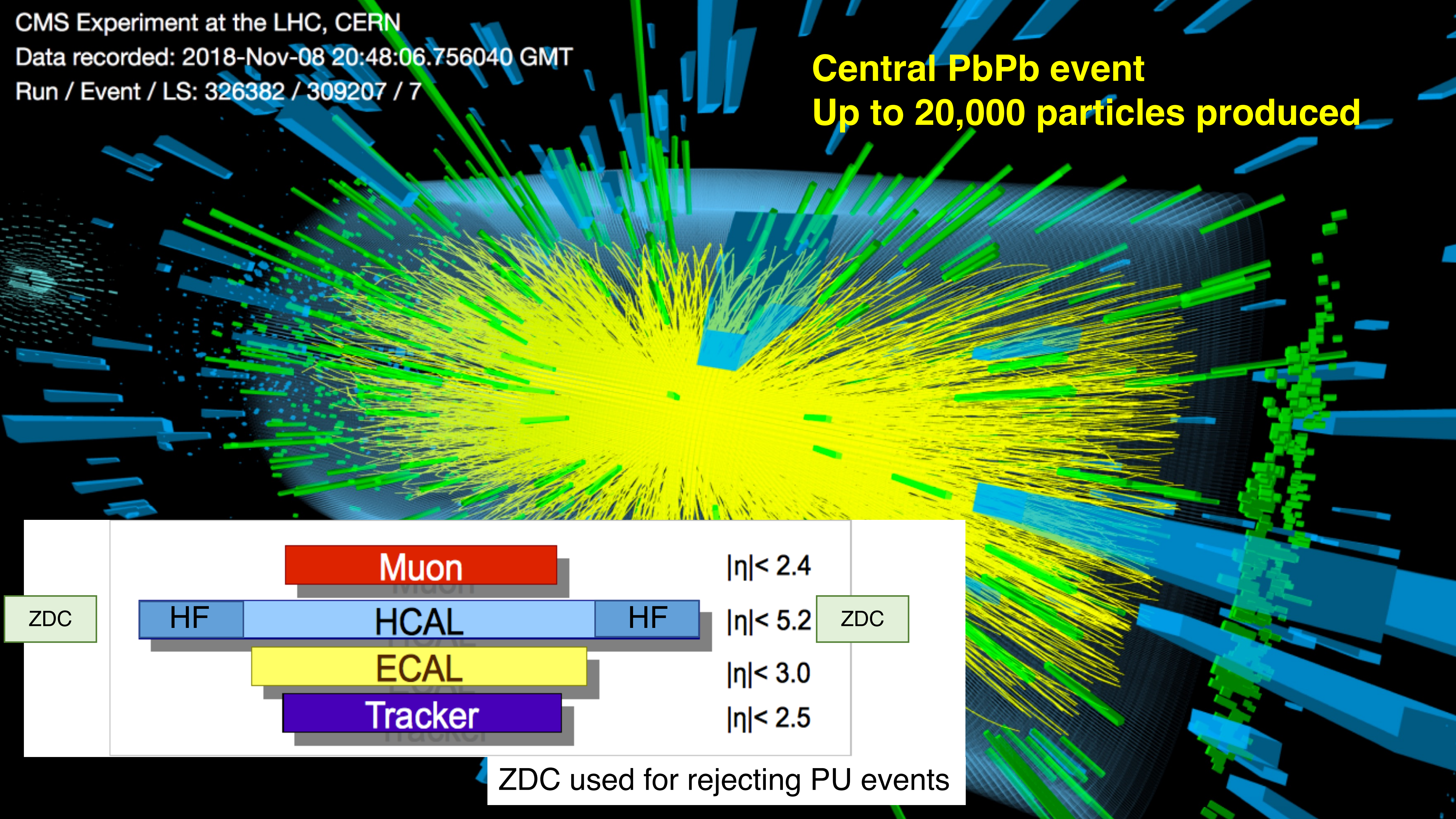
Anisotropy flow in UCC events, CMS, JHEP 02 (2014) 088

Extracting the Speed of Sound in UCC

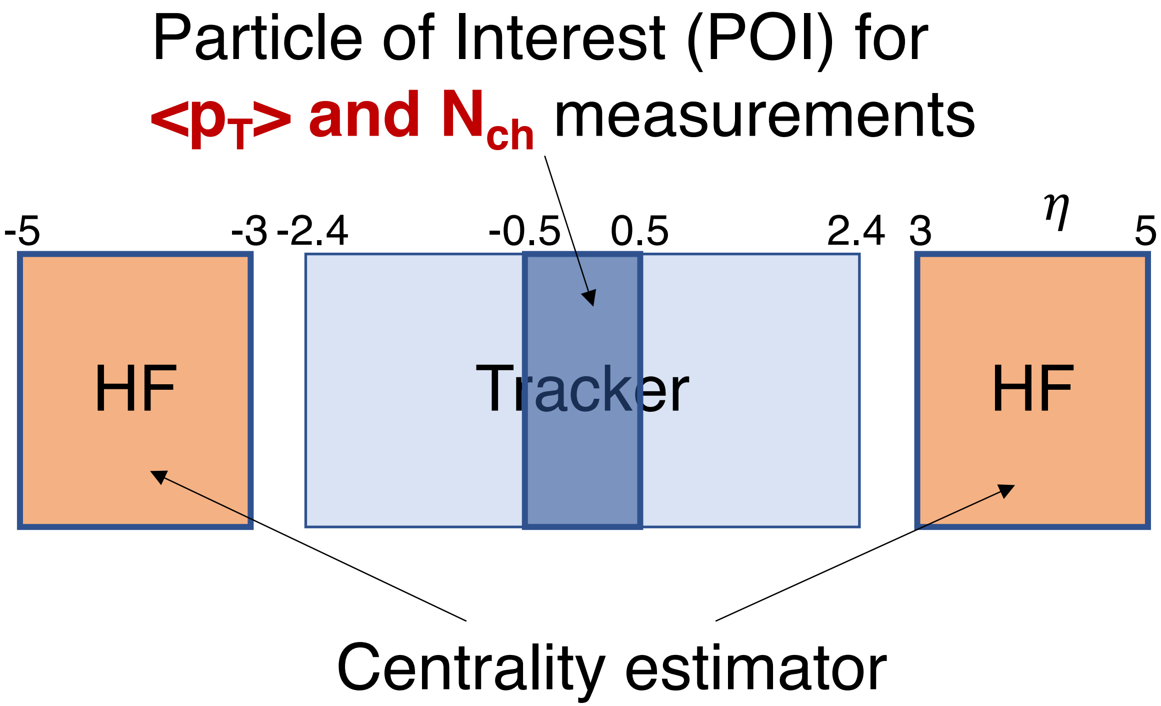
Proposed by Gardim et. al. PLB 809 (2020) 135749

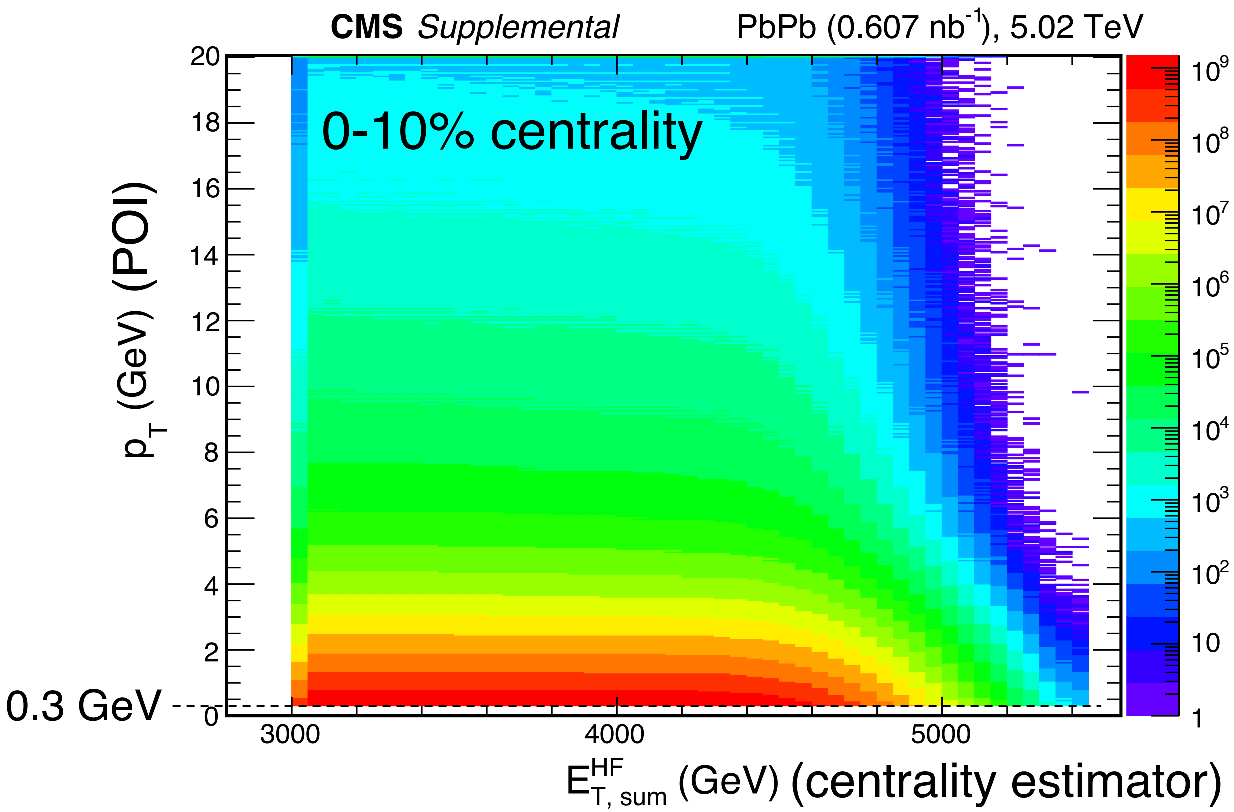


A nontrivial prediction by hydrodynamics on a simple observable that can put directly constraints on the equation of state


CMS Experiment at the LHC, CERN
Data recorded: 2018-Nov-08 20:48:06.756040 GMT
Run / Event / LS: 326382 / 309207 / 7
Central PbPb event
Up to 20,000 particles produced
Muon
ZDC
HF
HCAL
HF
ZDC
ECAL
Tracker
|η|< 2.4
|η|< 5.2
|η|< 3.0
|η|< 2.5
ZDC used for rejecting PU events

Observables and measurements



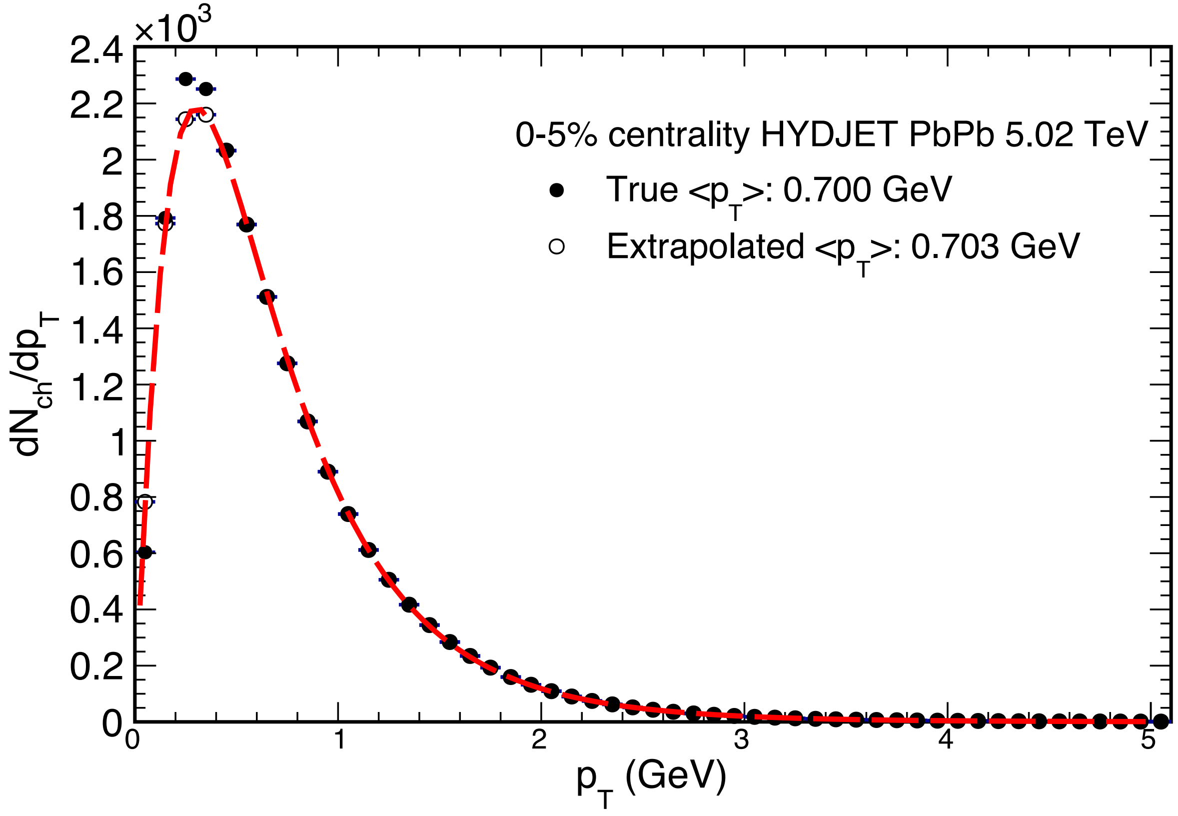


In each $E^{HF}_{T,sum}$ bin, the POI p_T spectra for tracks $|\eta|<0.5$ and $p_T>0.3$ GeV is measured with efficiency correction and extrapolation to $p_T>0$

- A subtle dependence of efficiency on the multiplicity is accounted for

$\langle p_T \rangle$ and N_{ch} are obtained from the mean and integral of corrected spectra.

Extrapolation to the full p_T range



Hagedorn function used to extrapolate the full p_T phase space:

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

m is fixed at pion mass, rest are free parameters

Extrapolated <p_T> agrees with the true value in HYDJET at 0.5% level.

Similar conclusion when tested using TRAJECTUM p_T spectra.

Contributes to ~4% systematic uncertainty on the extracted c_s^2 in the data

A few remarks

- The full p_T range is required. Otherwise, extracted c_s^2 is smaller.
- Phase space for c_s^2 extraction and centrality estimator separated in rapidity
- Total energy, instead of multiplicity, centrality estimator preferred
- Self-normalized observables to minimize systematic uncertainties

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- Self-normalized observables to minimize systematic uncertainties

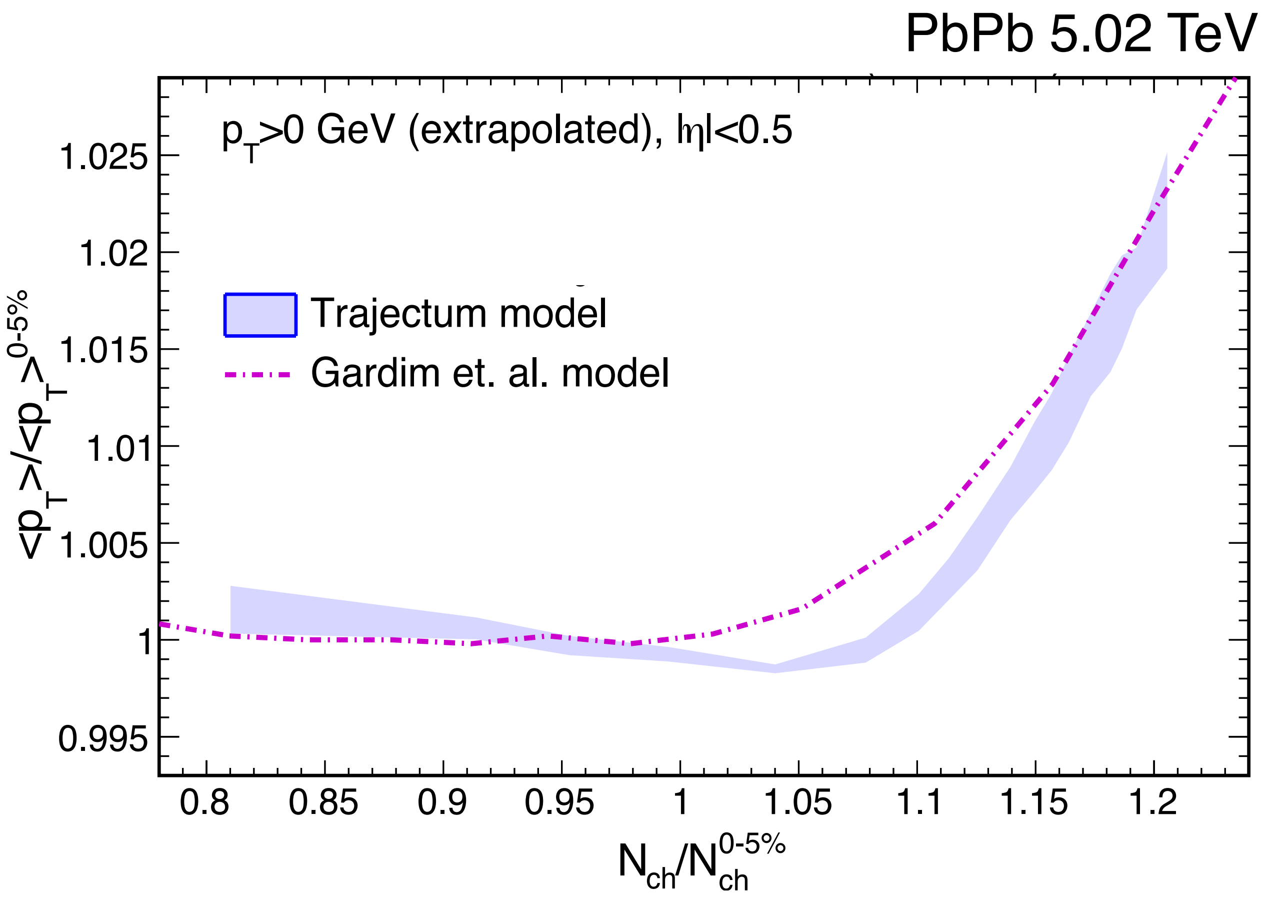
Observables in this work:

- $\langle p_T\rangle^{\mathrm{norm}} \left(= \frac{\langle p_T\rangle}{\langle p_T\rangle^0}\right)$ **vs.** $N_{ch}^{\mathrm{norm}} \left(= \frac{N_{ch}}{N_{ch}^0}\right)$
- $\langle p_T\rangle^0$ (for estimating T_{eff})

The reference $\langle p_T\rangle^0$, N_{ch}^0 chosen from the 0-5% centrality

Systematic uncertainties: 1) efficiency correction; 2) p_T extrapolation; 3) fit range for c_s^2

Theoretical **Pred**ictions

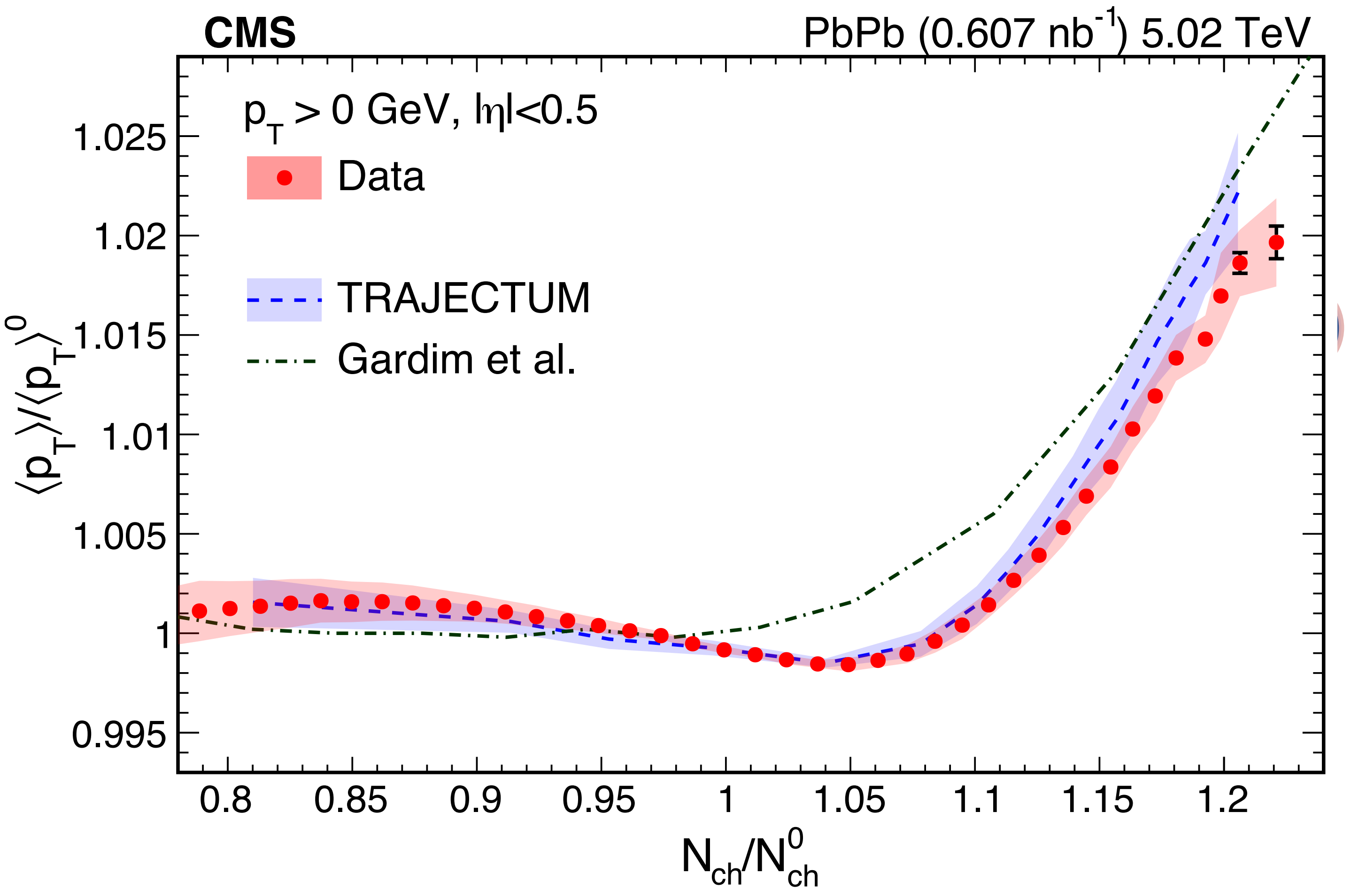


Both are hydro. models using Lattice QCD EoS. Differences in details.

Significant increase of $<p_T>$ toward UCC events predicted by both models **with similar slopes at very high N_{ch}**

A dip at N_{ch} ~ 1.05 N_{ch}(0-5%) present in TRAJECTUM but not *Gardim et. al.* The origin is unclear.

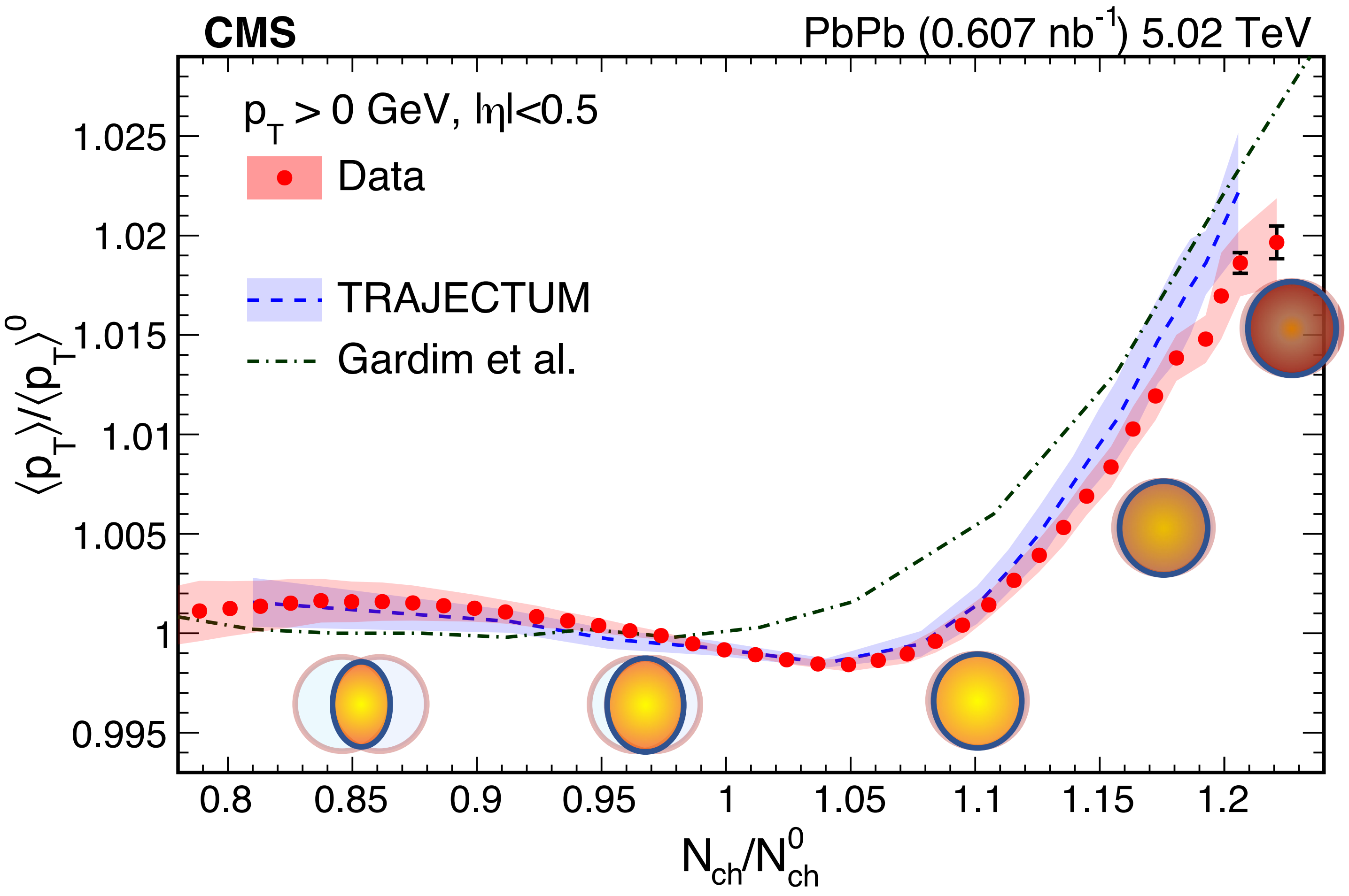
Extracting the speed of sound



Significant increase of <p_T> toward UCC events observed, as predicted

A dip at N_{ch} ~ 1.05 N_{ch} (0-5%) clearly observed also in the data

Extracting the speed of sound



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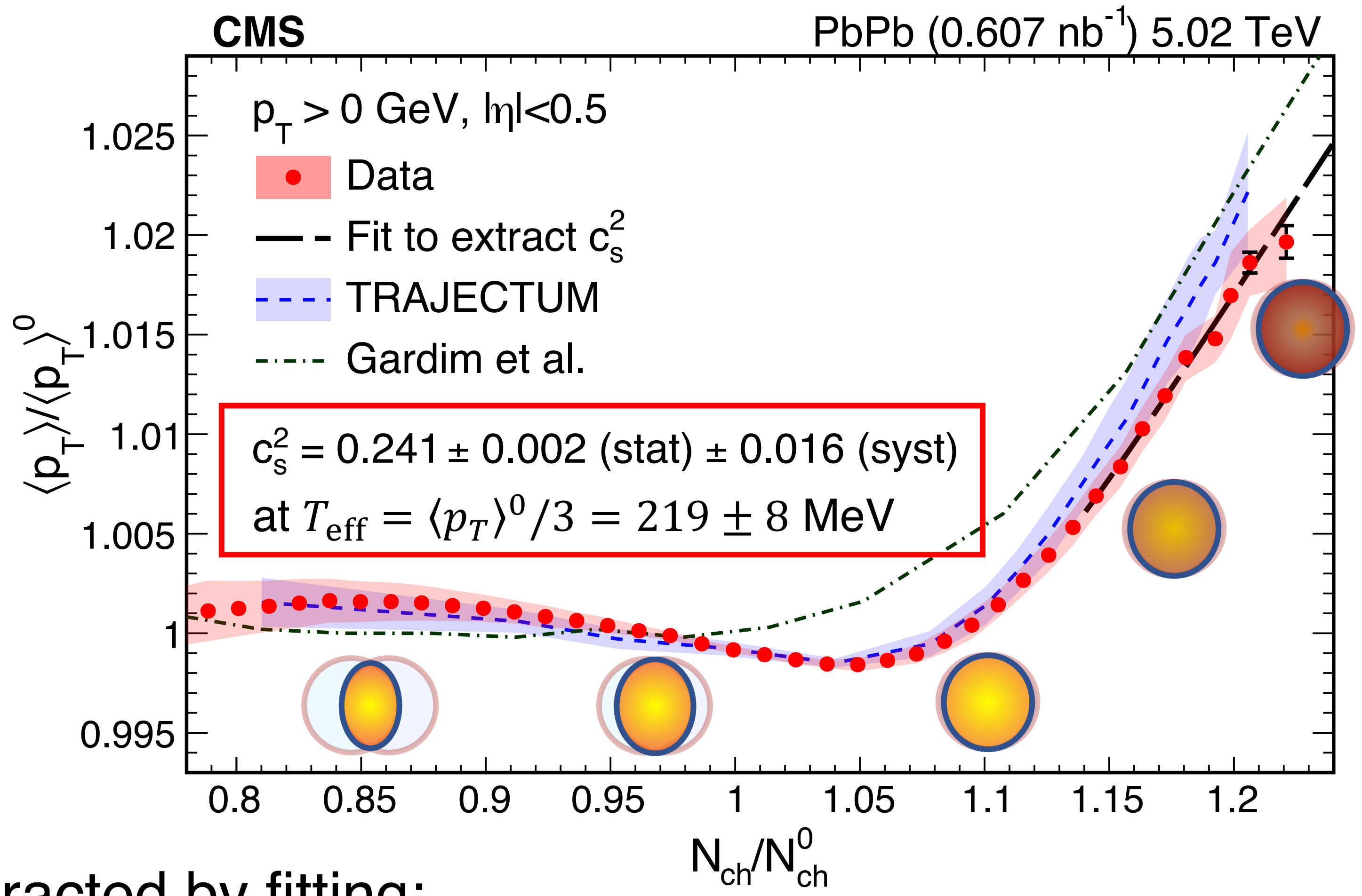


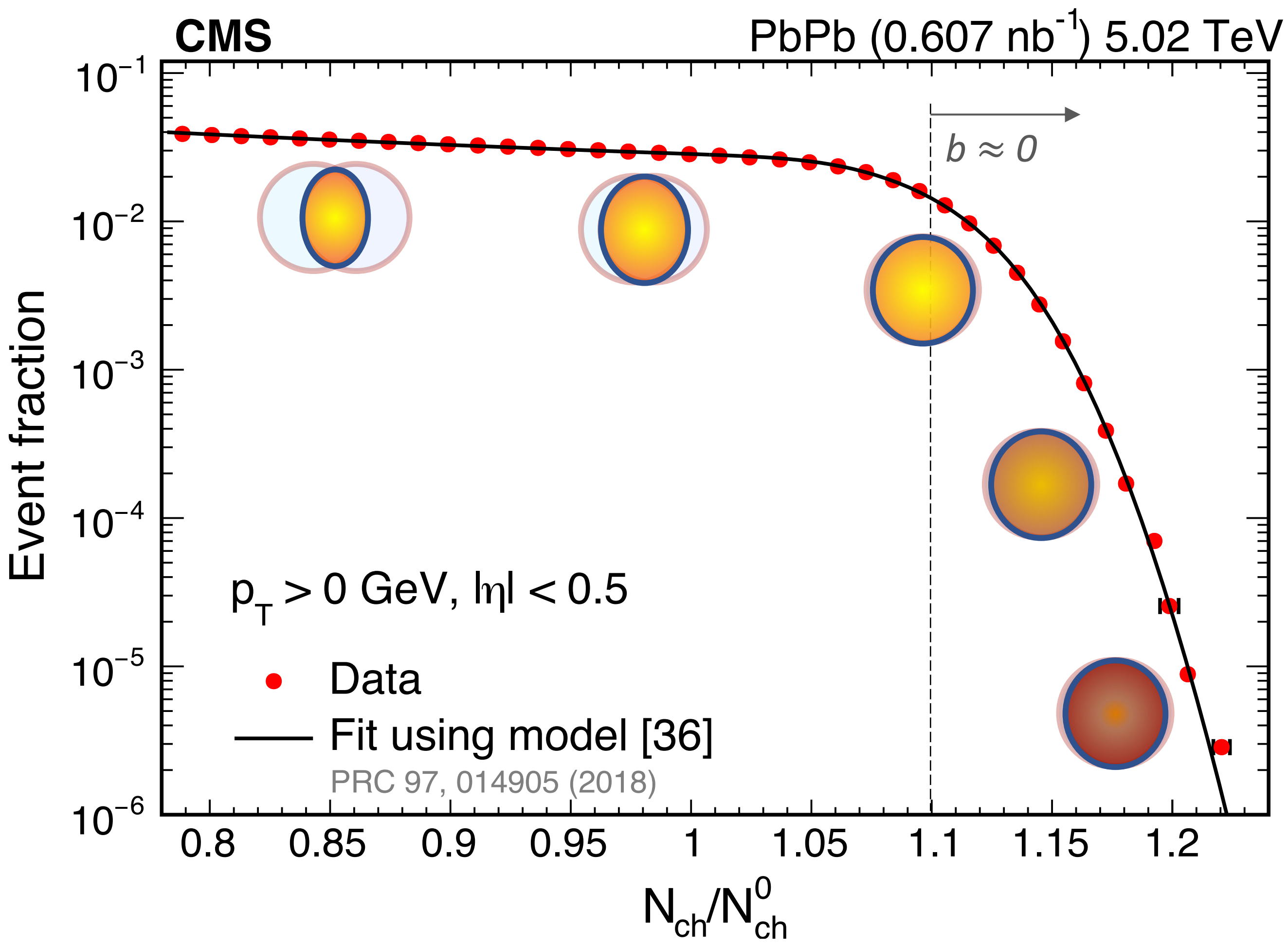
The c_s^2 extracted by fitting:

$$\langle p_{\text{T}} \rangle^{\text{norm}} = \left(\frac{N_{\text{ch}}^{\text{norm}}}{\langle \overline{N_{\text{ch}}^{\text{knee}}} | N_{\text{ch}}^{\text{norm}} \rangle} \right)^{c_s^2}$$

, where

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

Multiplicity fluctuations in UCC

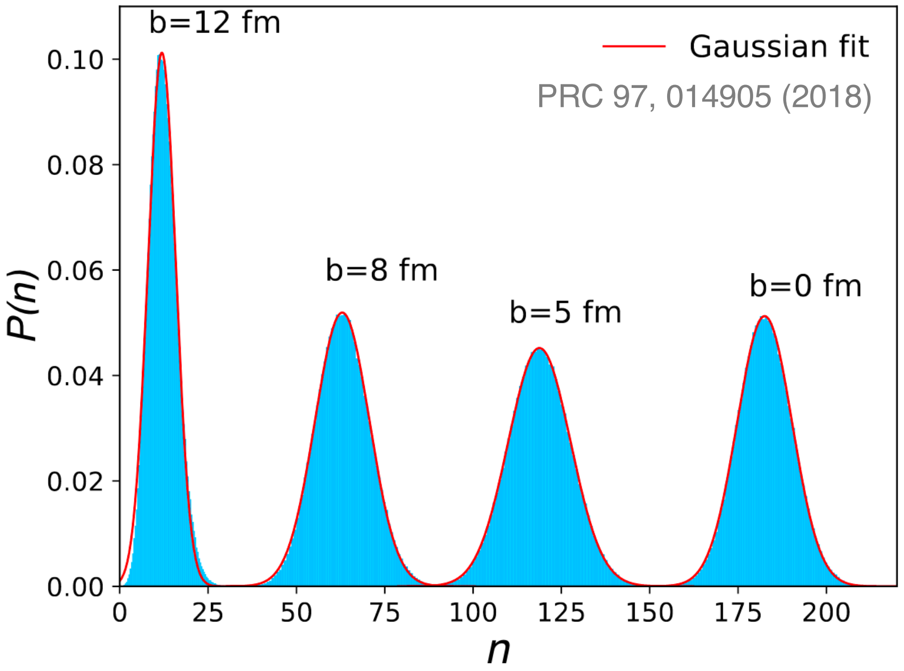


Excellent description by the model fit!

Fit by $P(n) = \int_0^1 P(n|c_b)dc_b$, where

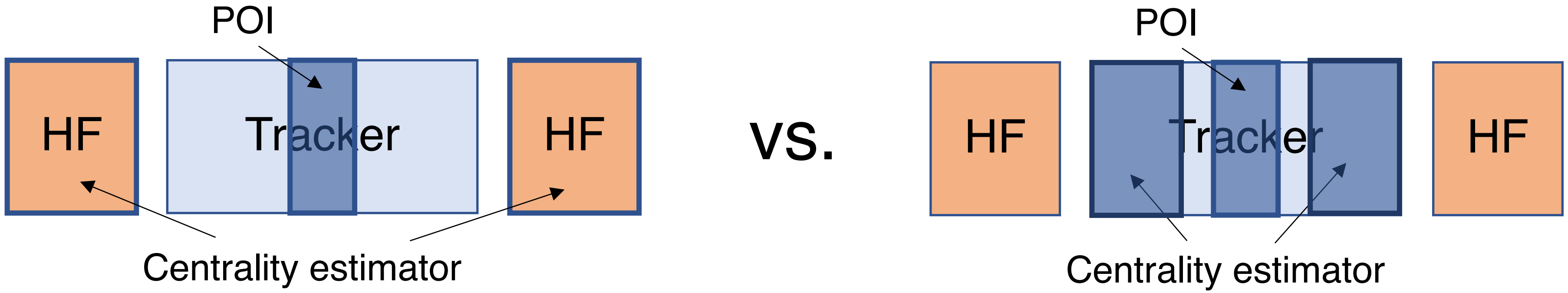
$$P(n|c_b) = \frac{\eta(c_b)}{\sigma(c_b)\sqrt{2\pi}} \exp\left(-\frac{(n-\bar{n}(c_b))^2}{2\sigma(c_b)^2}\right)$$

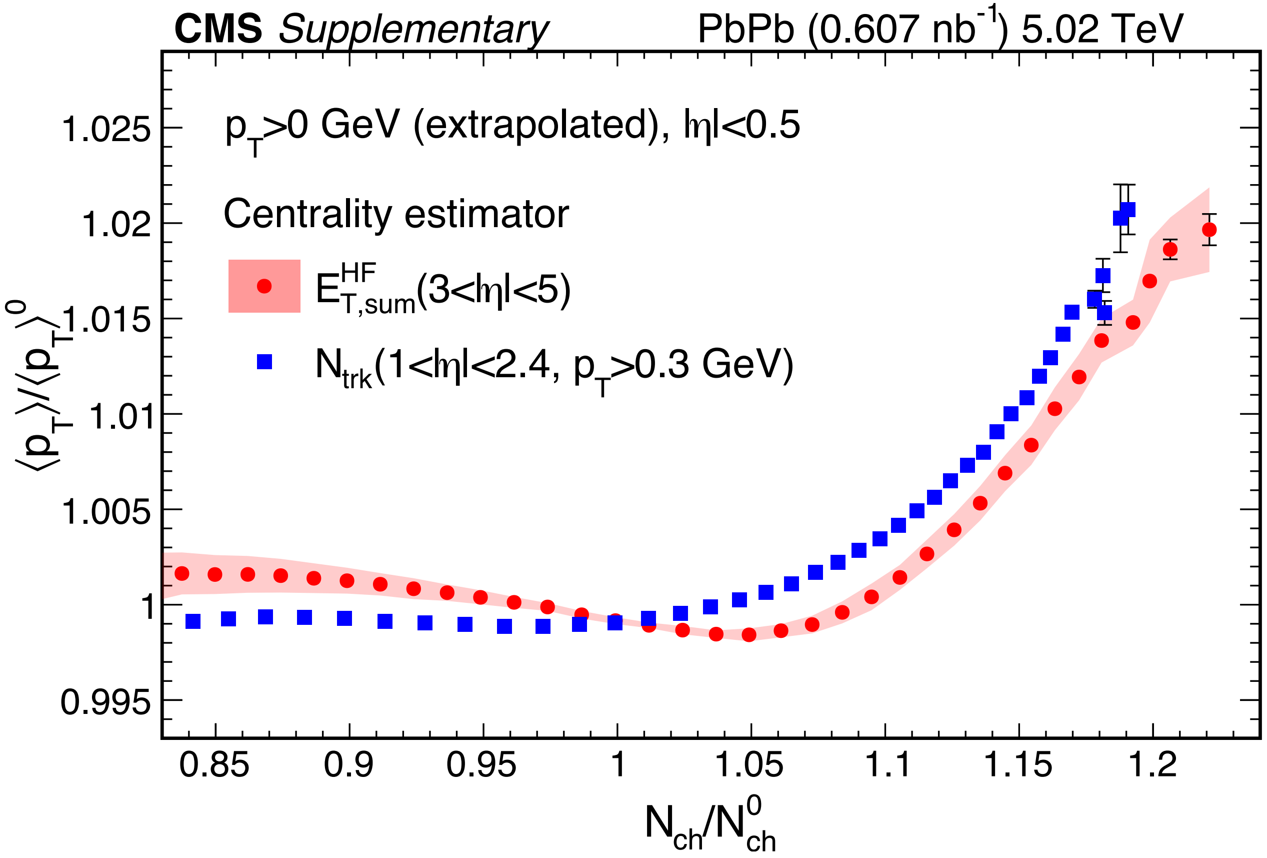
– multiplicity distribution at fixed b



Fitted values: $N_{\mathbf{ch}}^{\mathbf{knee}} = 1.1$, $\boldsymbol{\sigma} = 0.027$

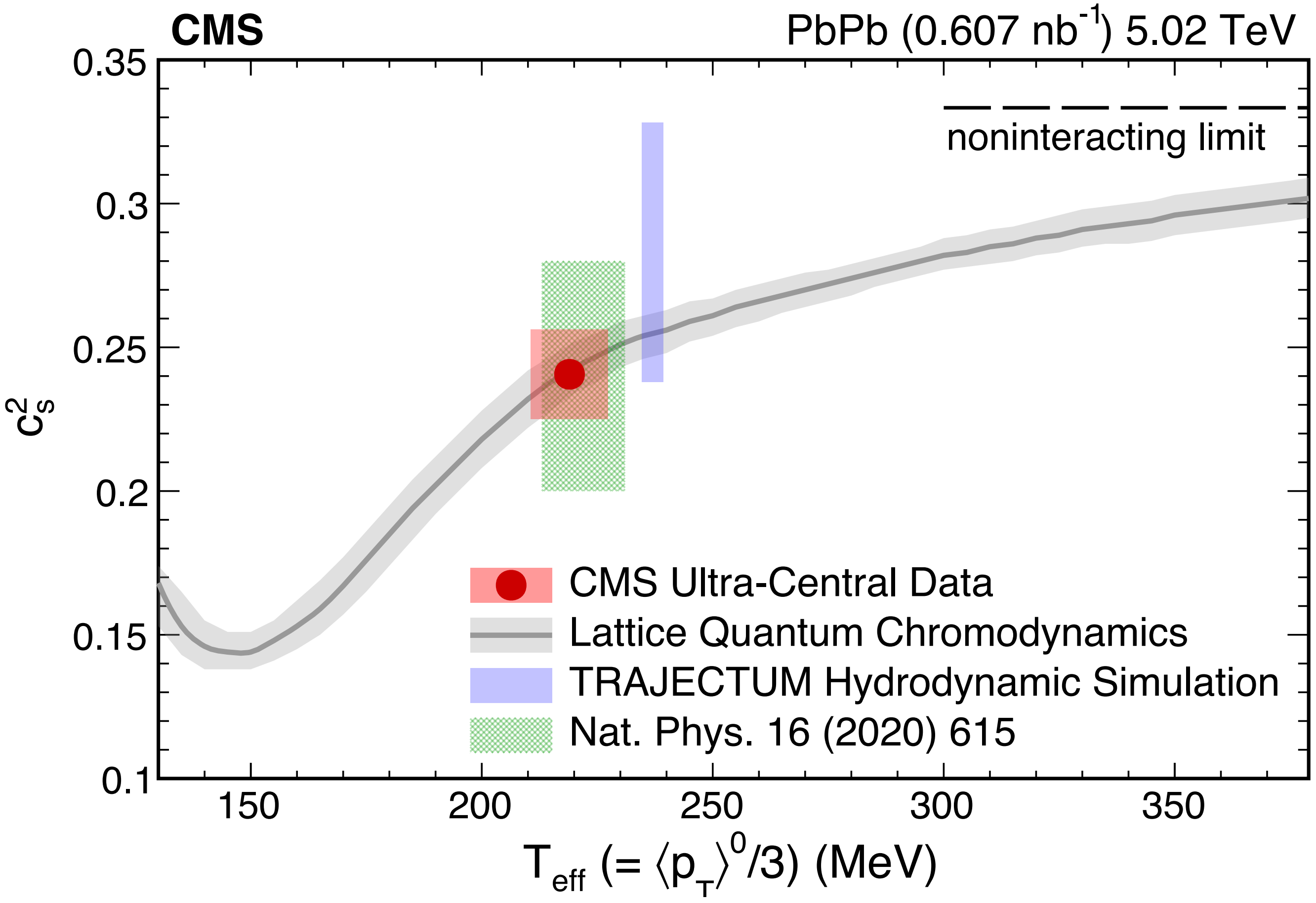
Choices of centrality estimator





Slopes at very high N_{ch} largely independent of centrality estimator

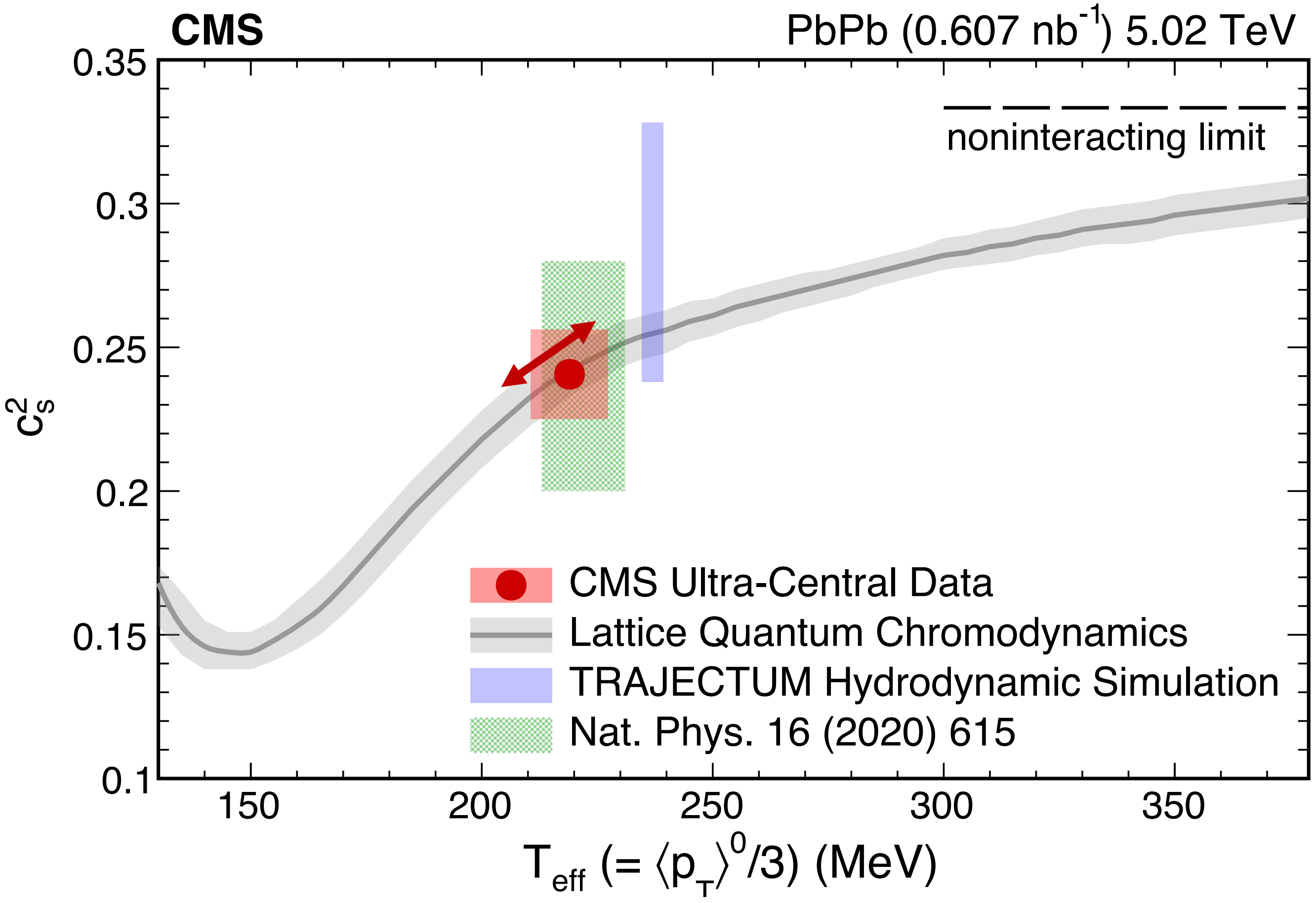
Constraining the QCD Equation of State



Precise determination of **the speed of sound** of the hot medium created in AA

Good agreement with lattice QCD, where a deconfined phase is predicted.

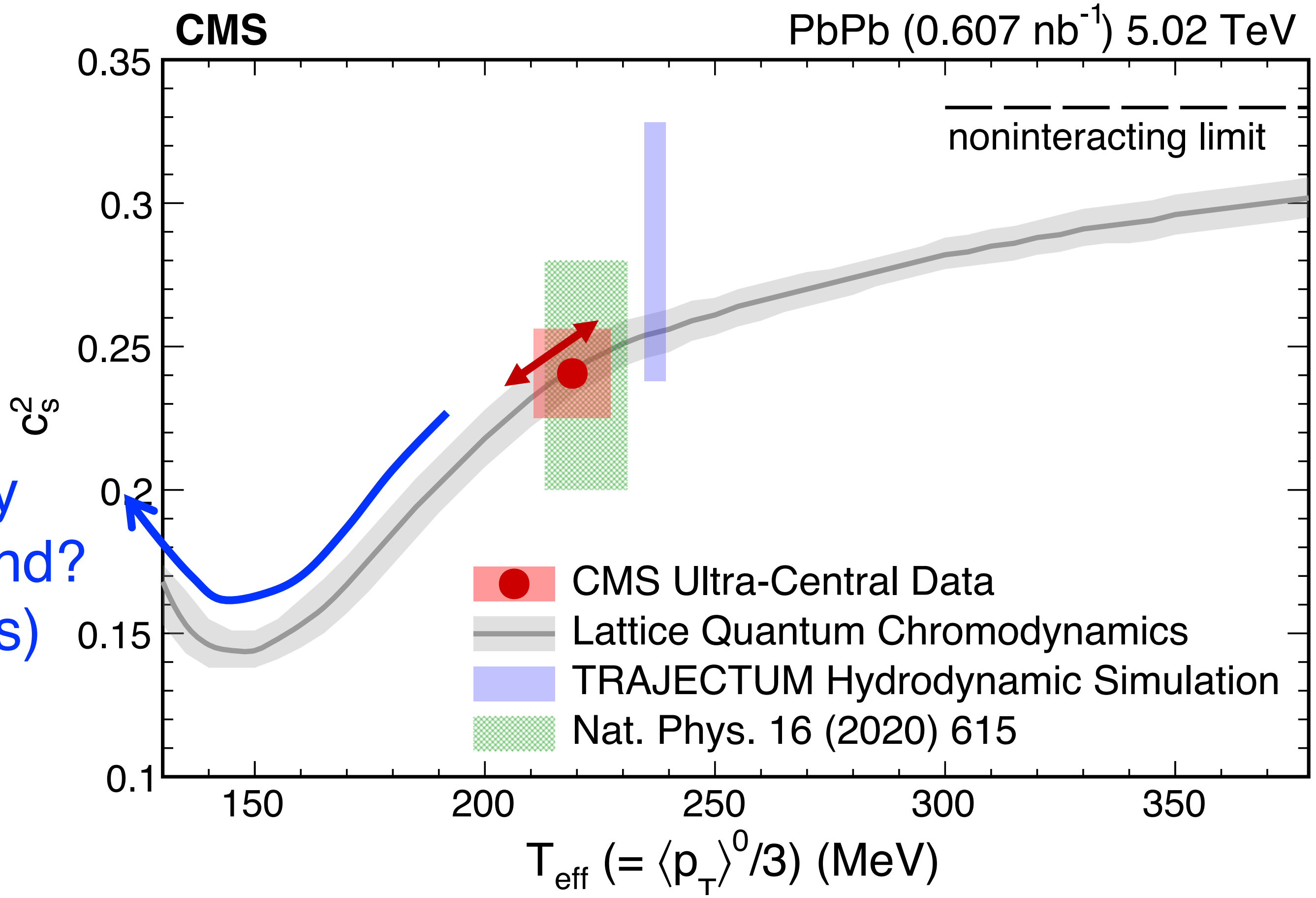
Outlook



To vary T_{eff} at LHC energies,

- 2.76, 5.02, 5.36 TeV
- Rapidity dependence – a few % variation over 2-3 units
- A short run at injection energy, 355 GeV?

Outlook



BES to look for any non-monotonic trend? (n_B also contributes)

To vary T_{eff} at LHC energies,

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- Rapidity dependence – a few % variation over 2-3 units
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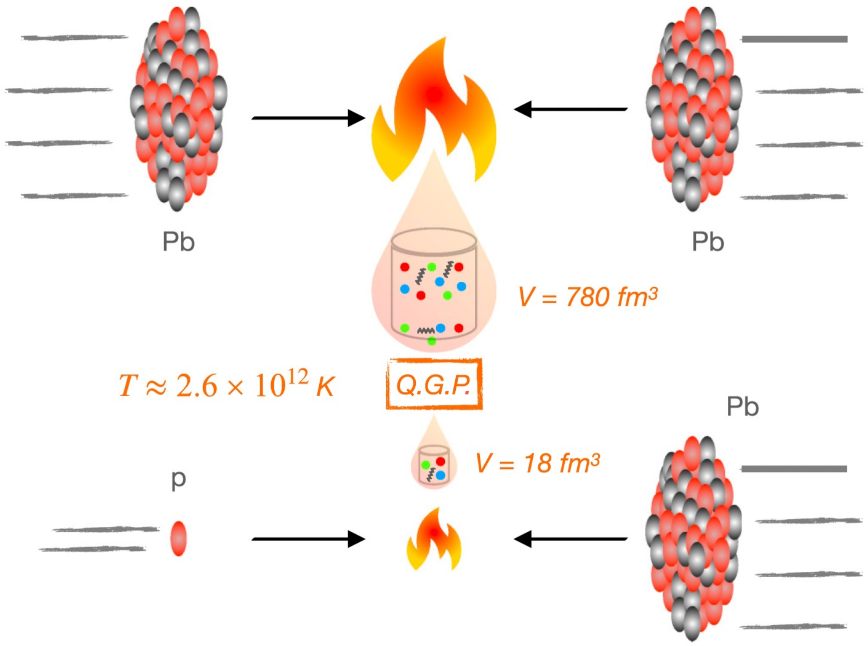
Outlook

PHYSICAL REVIEW C **109**, 014904 (2024)

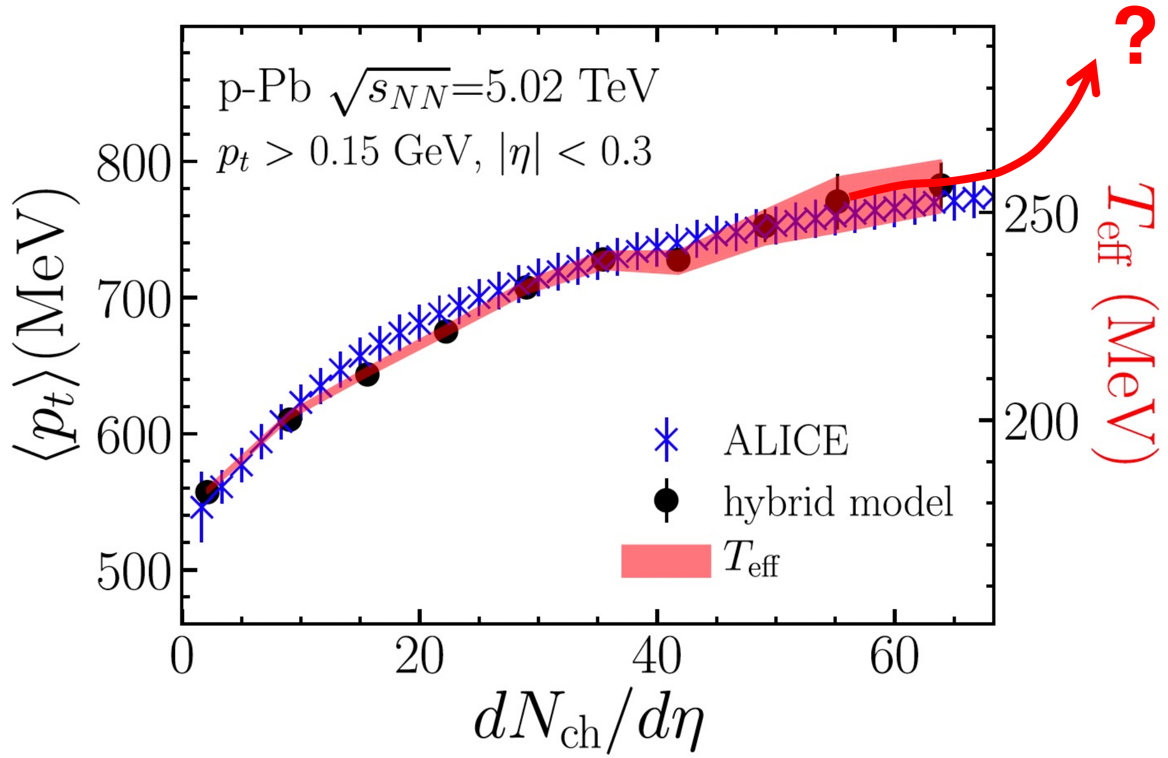
Smallest drop of QGP: Thermodynamic properties of *p*-Pb collisions

Fernando G. Gardim,[1,*] Renata Krupczak,[2] and Tiago Nunes da Silva[2]
[1]*Instituto de Ciência e Tecnologia, Universidade Federal de Alfenas, 37715-400 Poços de Caldas, MG, Brazil*
[2]*Departamento de Física, Centro de Ciências Físicas e Matemáticas, Universidade Federal de Santa Catarina, Ca*
Universitário Reitor João David Ferreira Lima, Florianópolis 88040-900, Brazil



QGPs that are drastically different in size

Even higher T_{eff} in pPb than PbPb



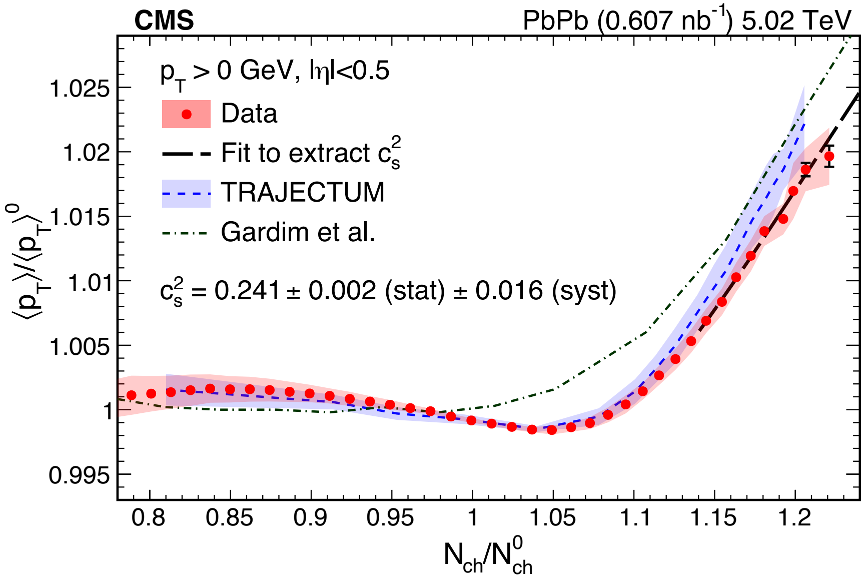
Summary

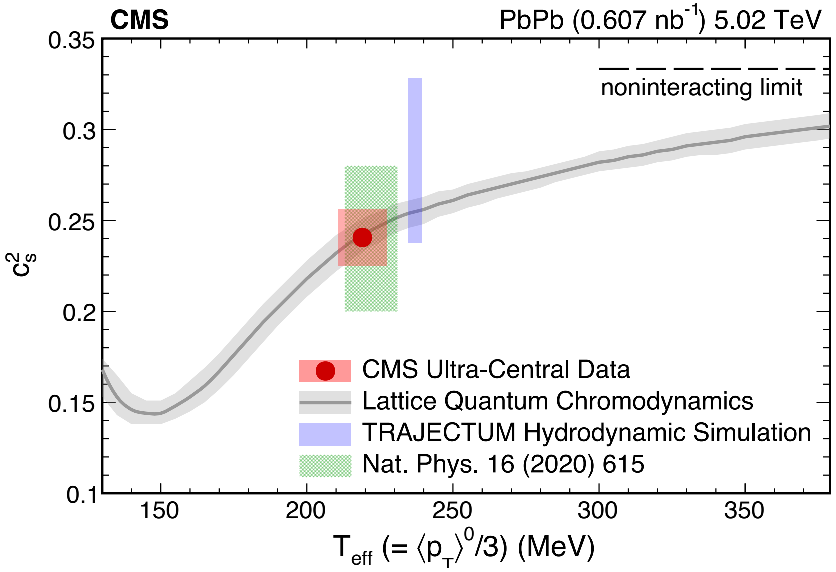
Precise extraction of the speed of sound with ultra-central PbPb events:

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

Good agreement with lattice QCD at $\mu_B \sim 0$, providing direct evidence for a deconfined phase at high temperatures.

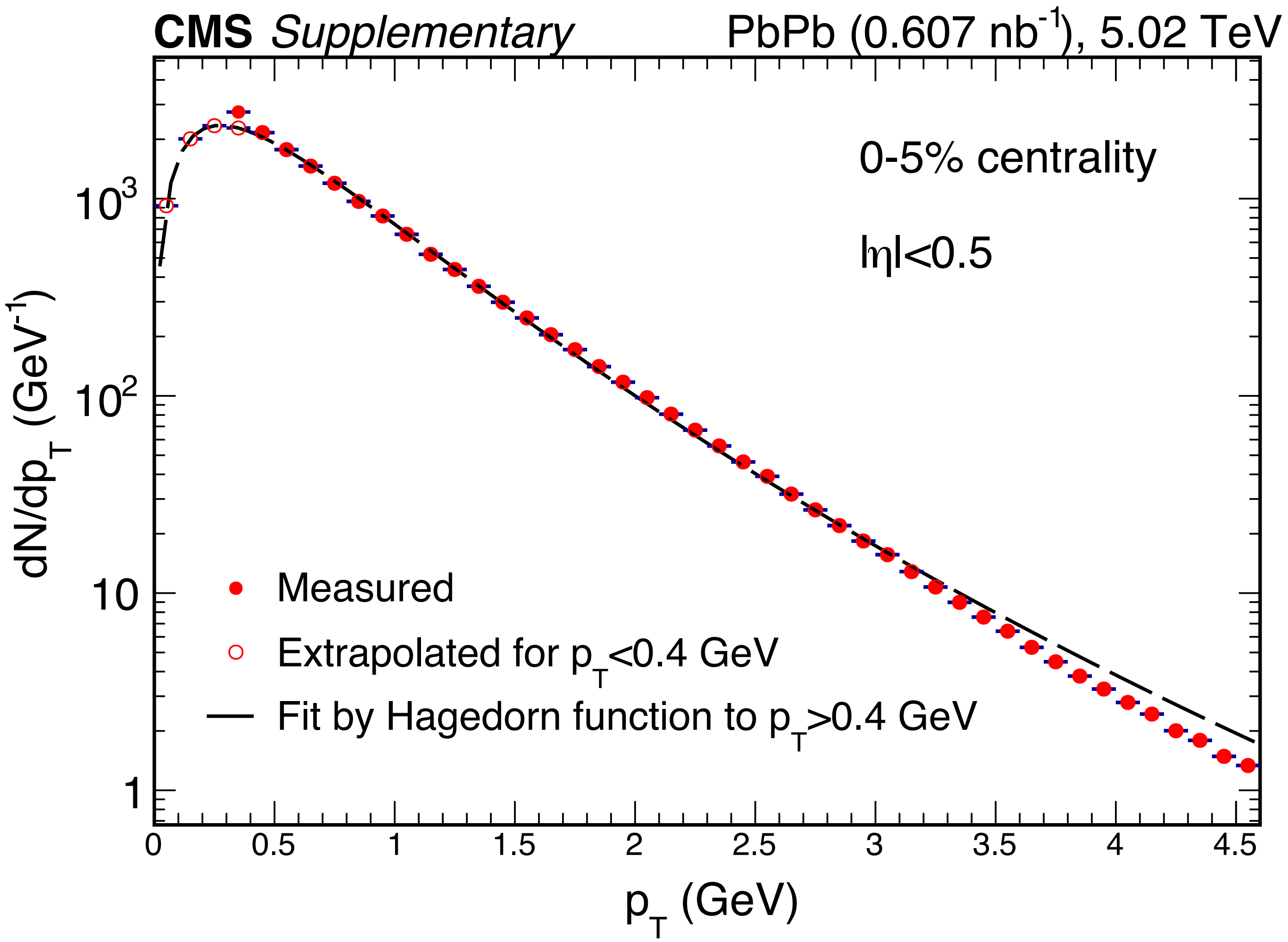
Future measurements at other energies and in small systems, in comparison with theoretical models, promising to mapping out the QCD Phase diagram.



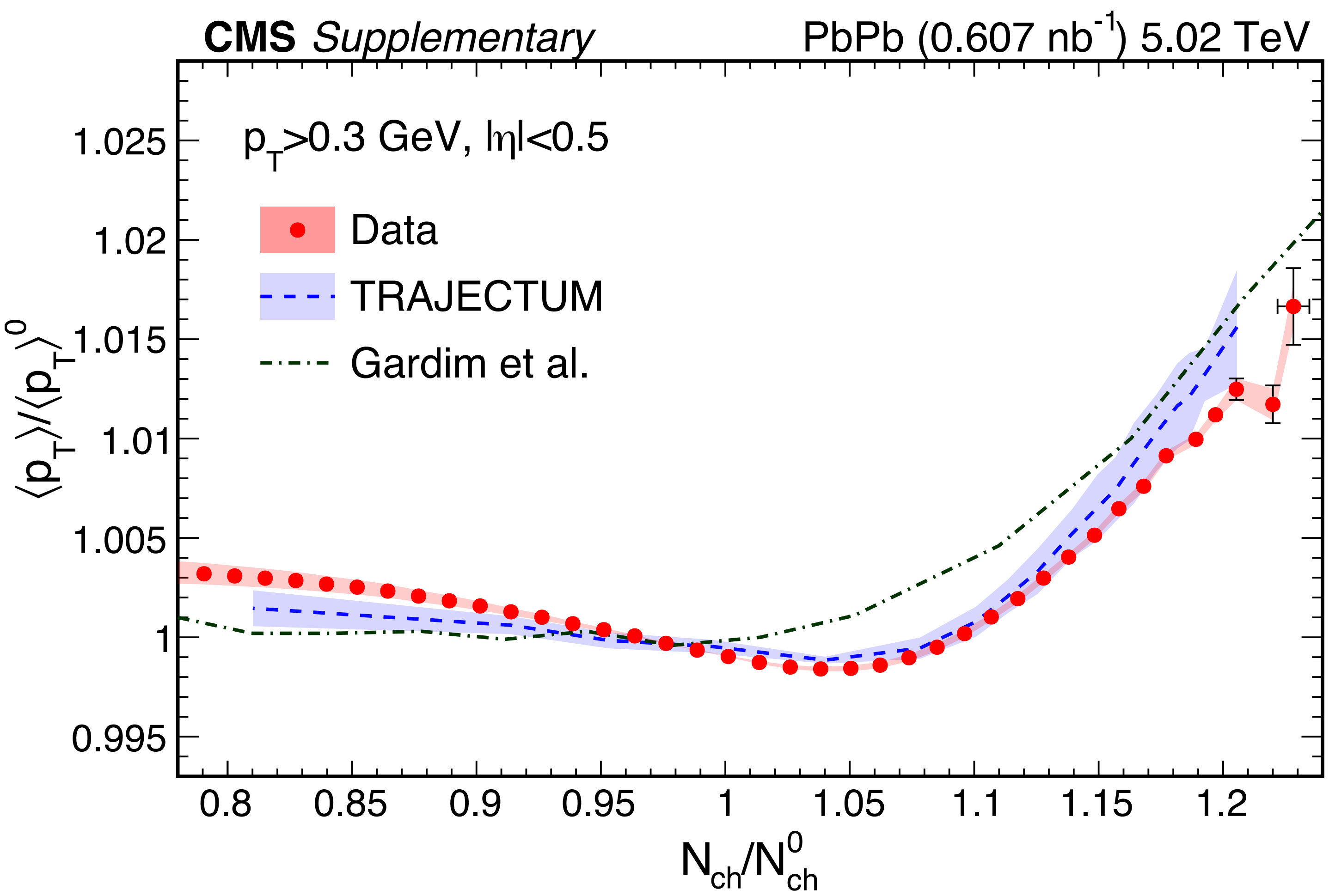


Backups

Extrapolation to the full p_T range



Contributes to ~4% systematic uncertainty on the extracted c_s^2 in the data



CMS Supplementary
PbPb (0.607 nb^{-1}) 5.02 TeV
p_T>0.3 GeV, |η|<0.5
Data
TRAJECTUM
Gardim et al.
$\langle p_T\rangle/\langle p_T\rangle^0$
N_{ch}/N_{ch}^0
1.025
1.02
1.015
1.01
1.005
1
0.995
0.8
0.85
0.9
0.95
1
1.05
1.1
1.15
1.2

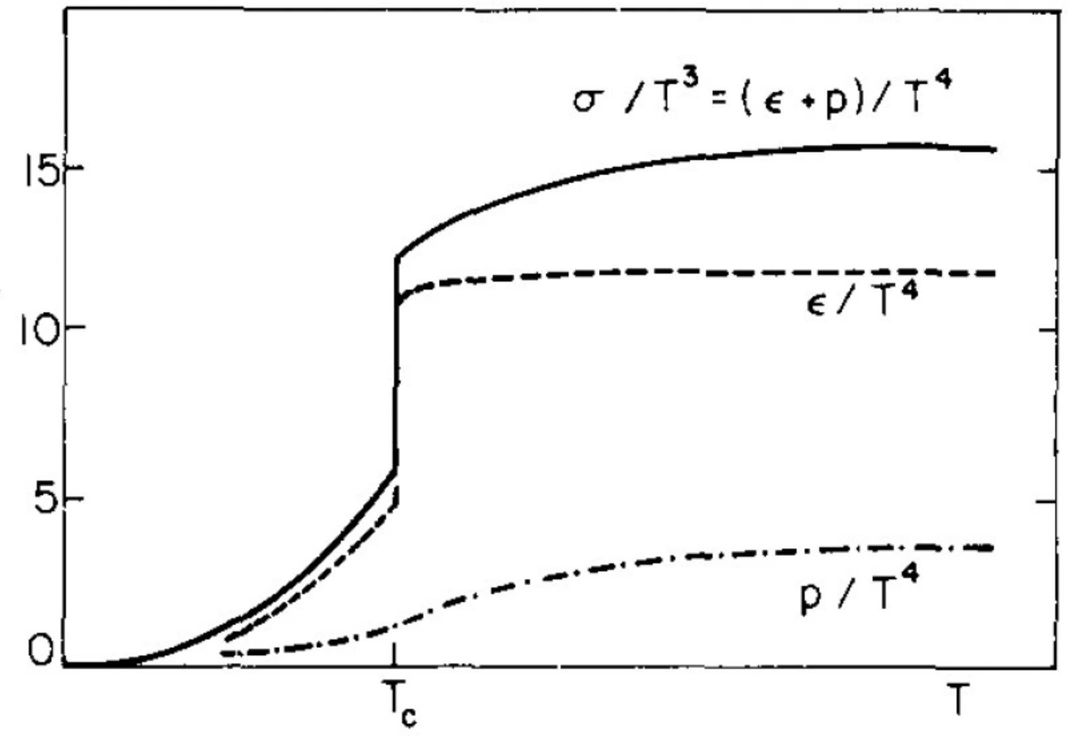
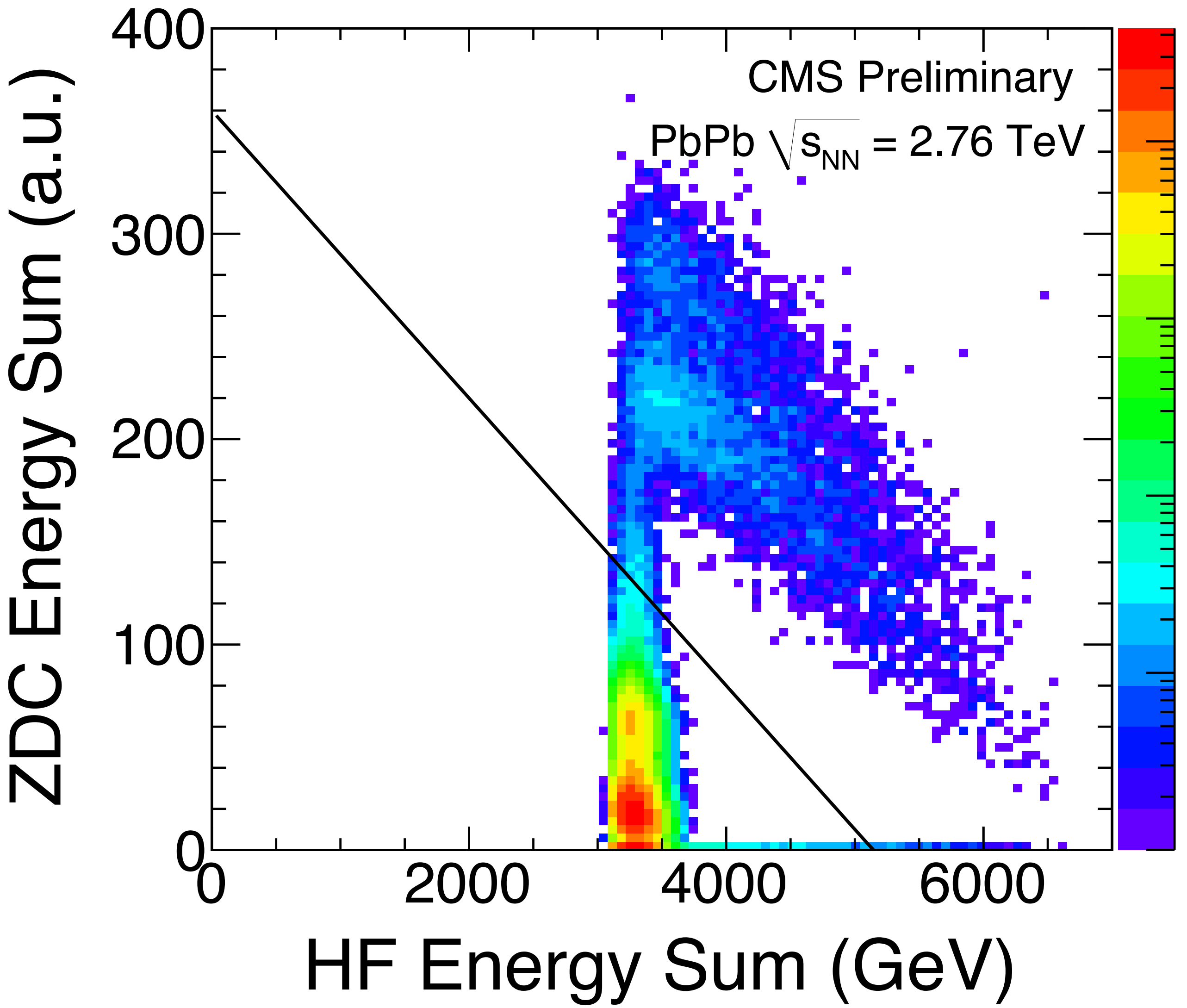


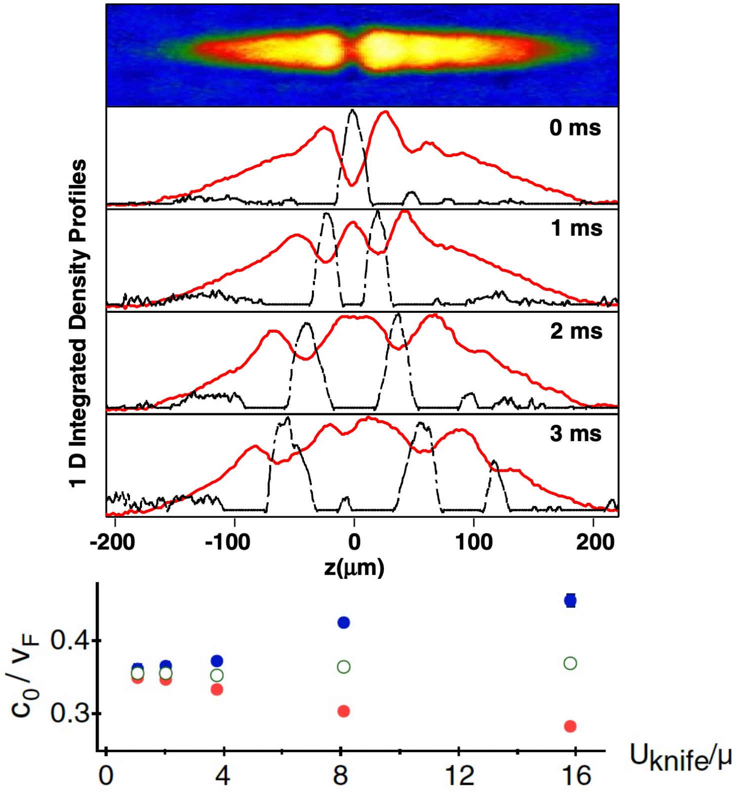
Fig. 1. An example of the expected qualitative dependence on temperature T of entropy density σ, energy density ϵ and pressure p for hadronic matter at zero chemical potential.


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
ZDC Energy Sum (a.u.)
HF Energy Sum (GeV)
400
300
200
100
0
0
2000
4000
6000

The speed of sound

Cold atoms:

PRL 98, 170401 (2007)

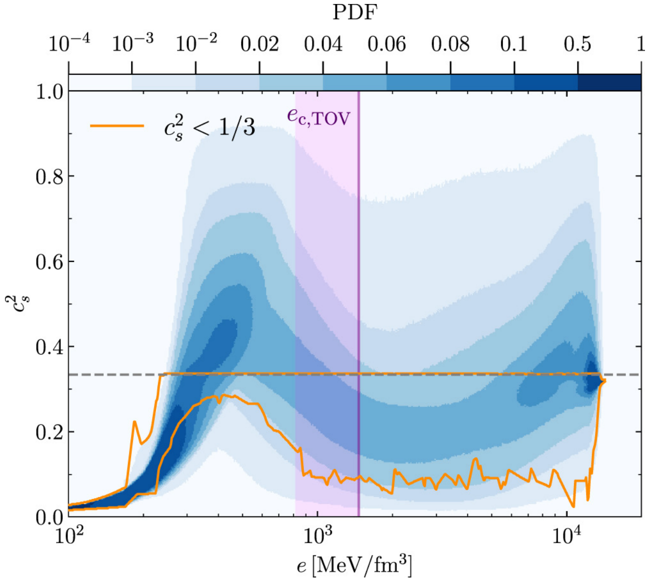


Sound wave near Feshbach resonance

Dense QCD matter:

What is the state of matter inside the neutron star?

Astro phys. J. Lett. 939 (2022) 2, L34



Large uncertainties in EoS and c_s

Broad interests in sound wave propagation within strongly correlated systems!