Extracting the speed of sound in the strongly interacting matter in ultrarelativistic nuclear collisions

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On behalf of the CMS Collaboration

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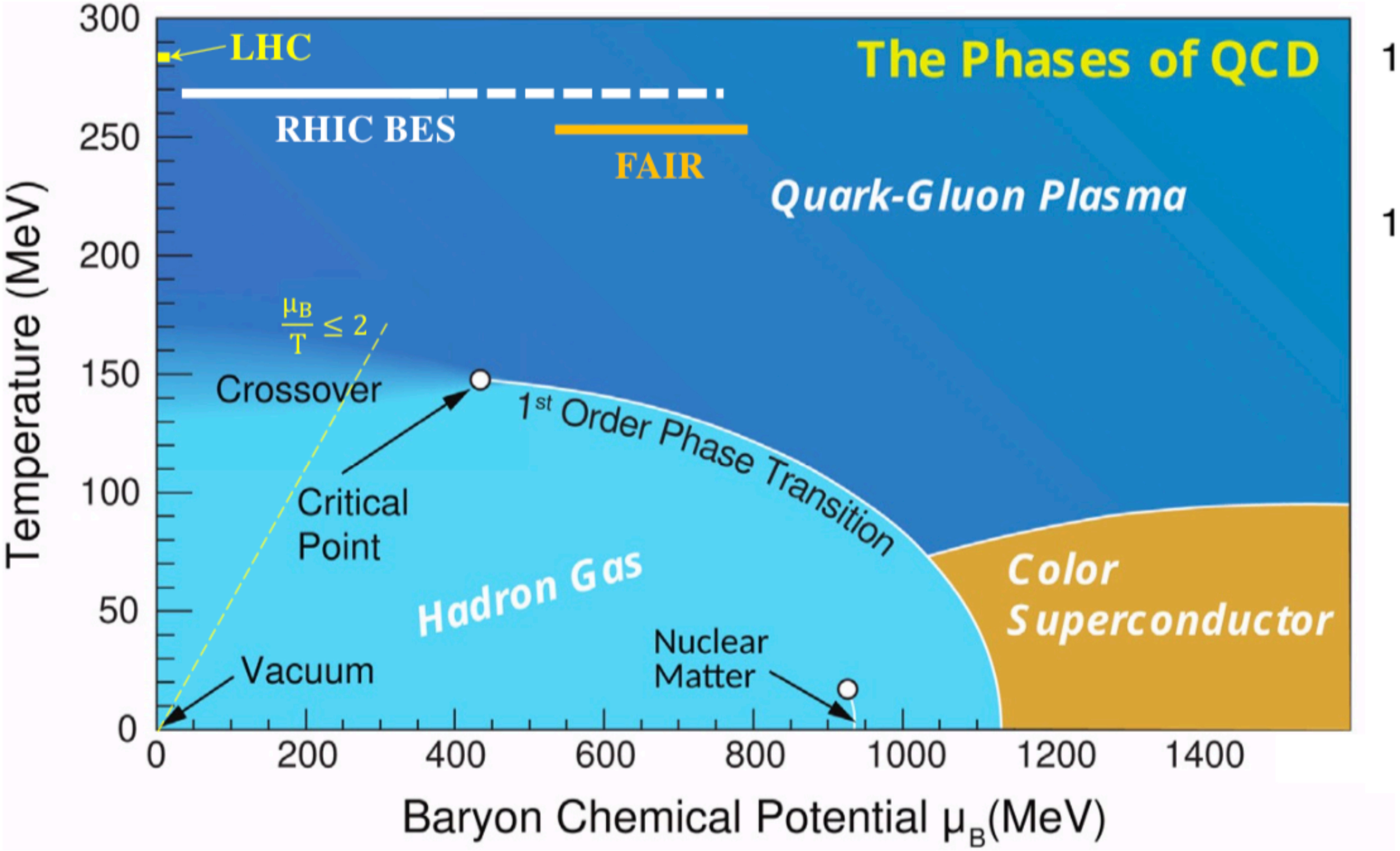
CMS
Compact Muon Solenoid

UIC UNIVERSITY OF ILLINOIS CHICAGO

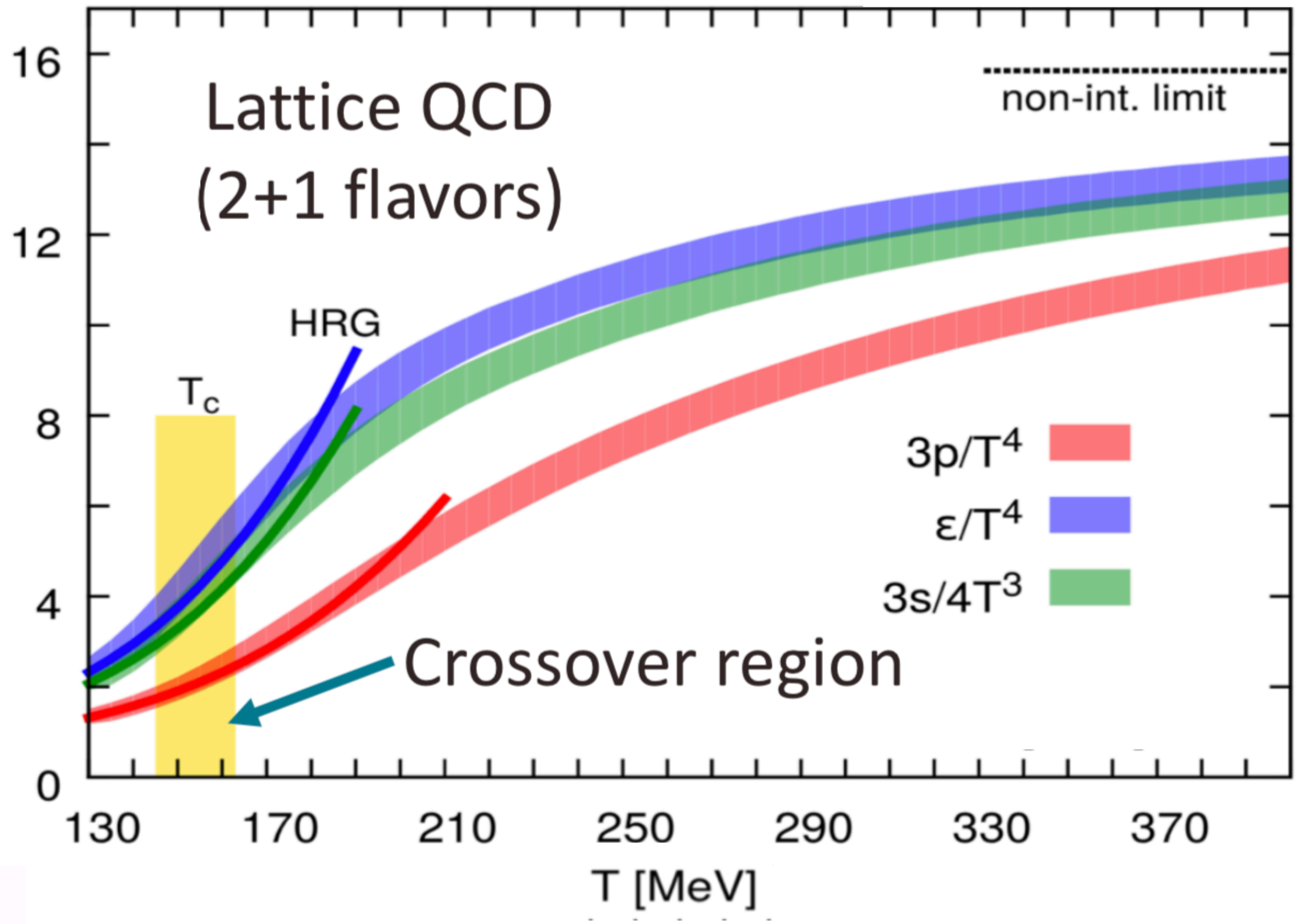
Introduction

- In last 2 decades, have established clear experimental evidence of quark-gluon plasma
  - Deconfined 'perfect fluid'
- Lattice QCD makes specific predictions of QGP degrees-of-freedom vs. T
  - Little *direct* experimental evidence testing these predictions
  - Behavior in 'crossover' region very interesting!

arxiv:1906.00936



PRD **90** (2014) 094503



Speed of Sound

- **Longitudinal compression waves propagate in QGP medium**
  - **Speed of sound related to pressure and energy density via:** $c_s^2 = \frac{dP}{d\epsilon}$
- **Potential direct constraint on QGP Equation of State - but more data needed!**

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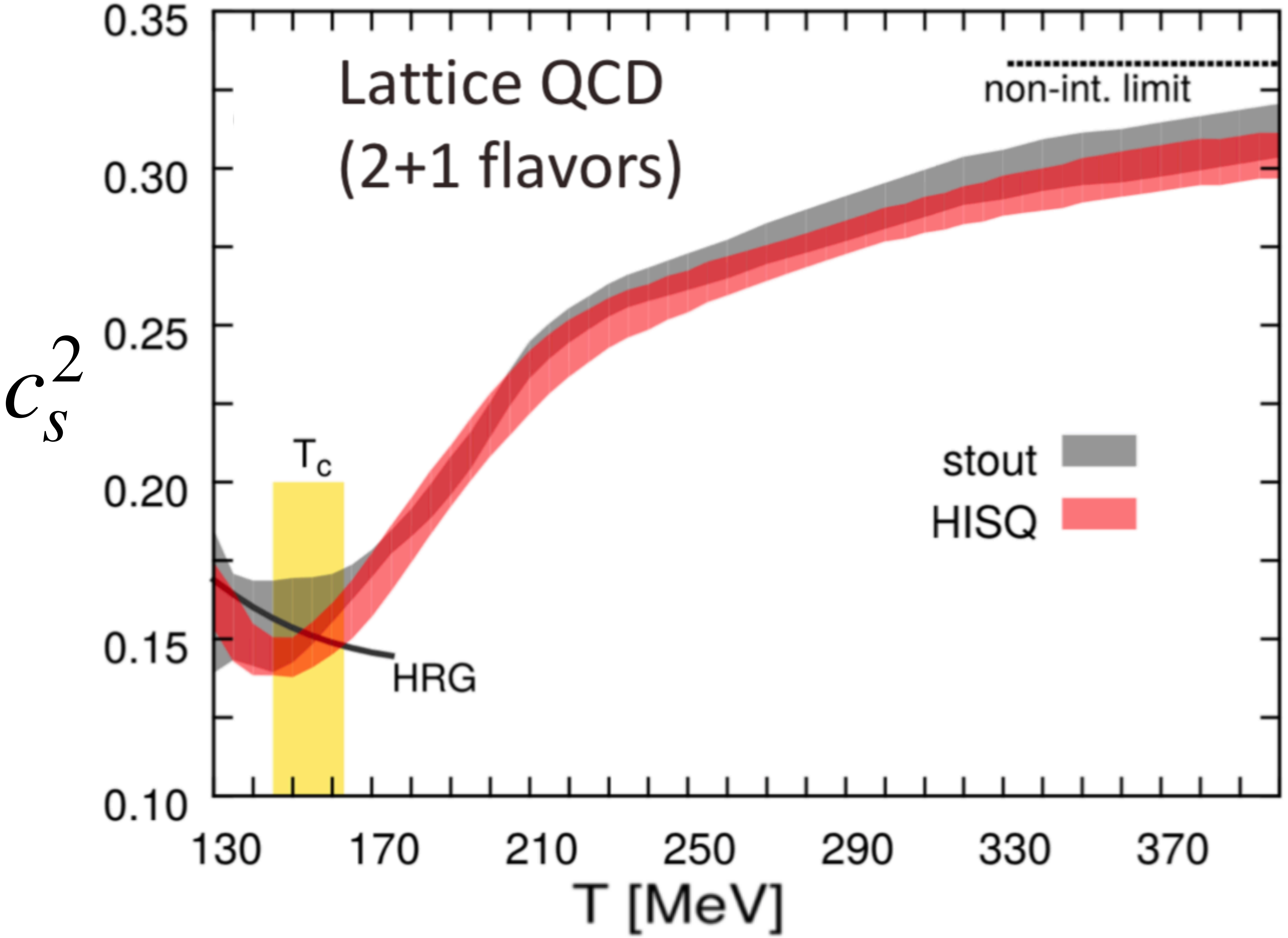
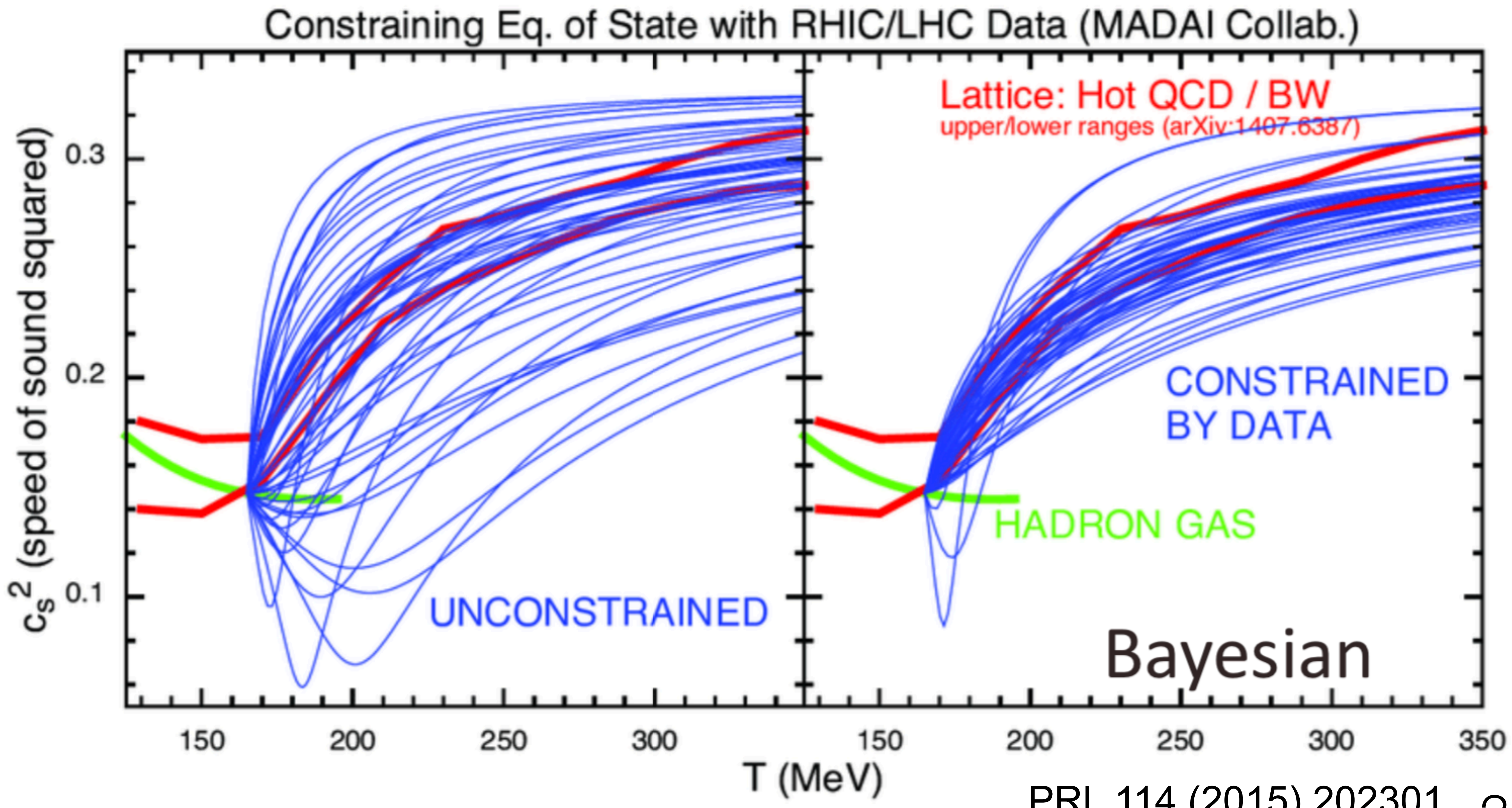


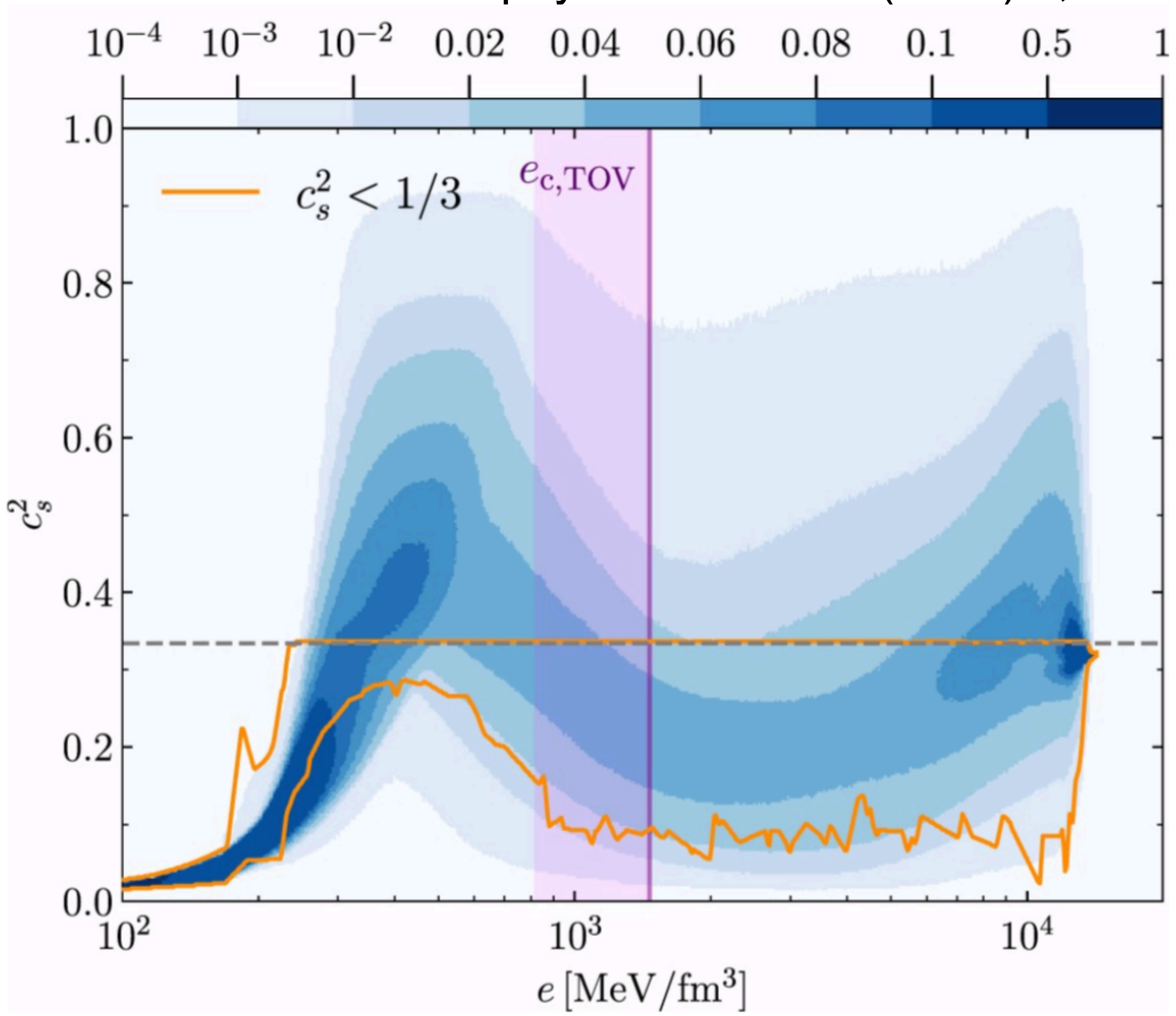


PRL 114 (2015) 202301

Other implications

- **Similar efforts to constrain QCD EoS from astrophysical data (at lower T)**
  - **What is the matter at the center of a neutron star?**

Astrophys. J. Lett. 939 (2022) 2, L34



Other implications

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  - **What is the matter at the center of a neutron star?**

- **Shockwave may form when color charge moves at $v > c_s$**
  - **Is this an observable phenomenon?**

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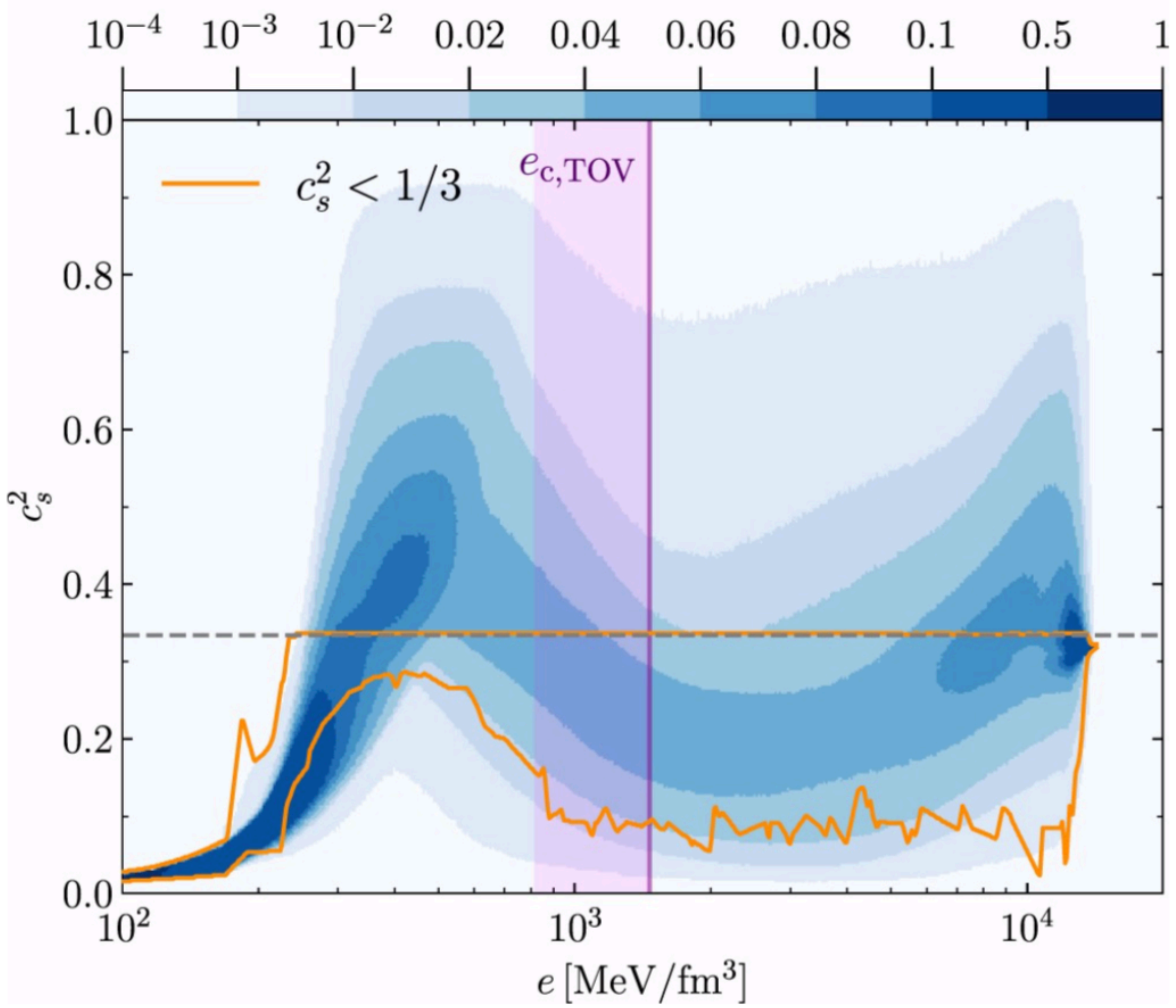
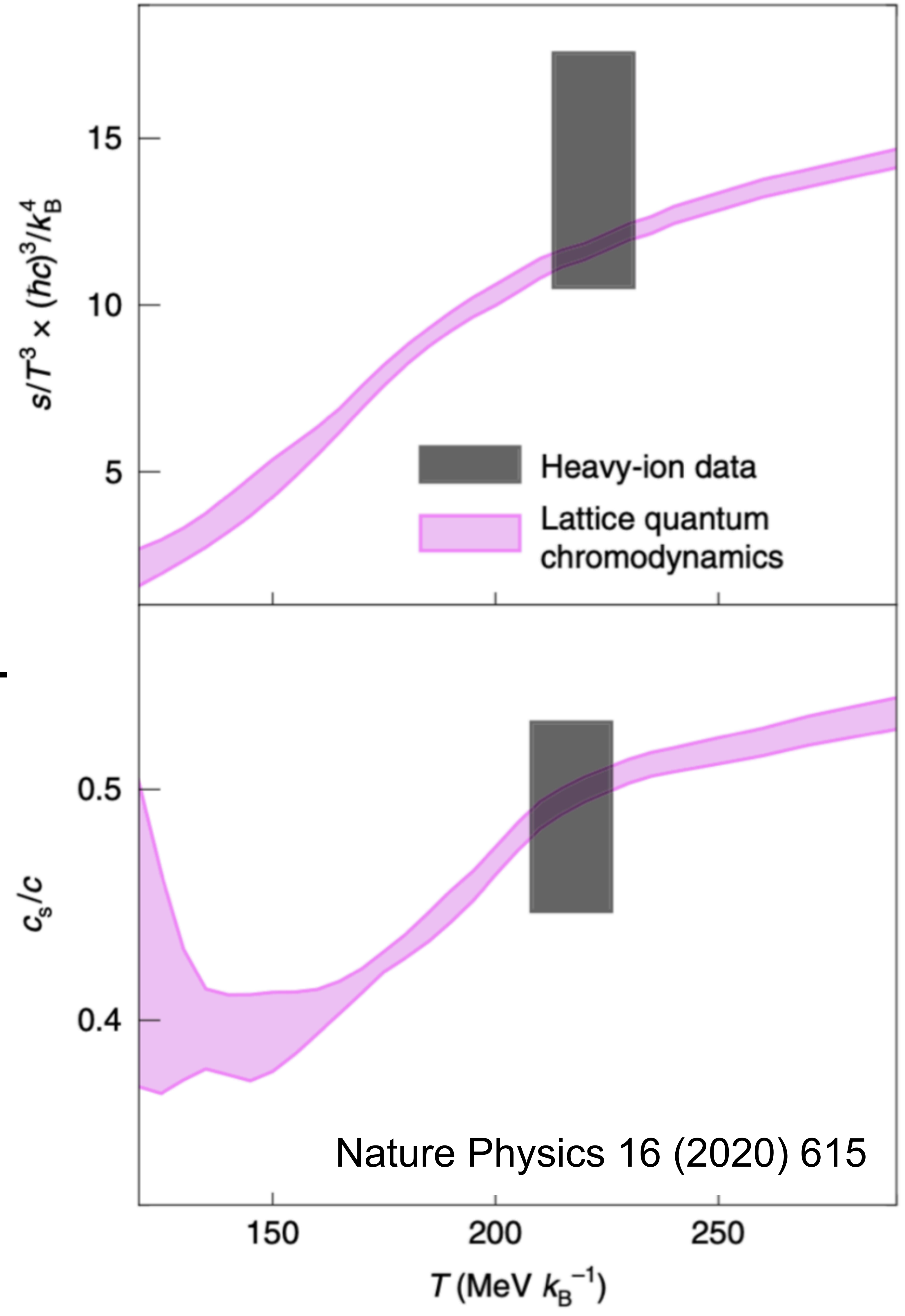


Previous Extractions of c_s

- Extraction of c_s using ALICE data
  - Comparison of 0-5% 2.76 and 5.02 TeV data
  - Changing energy density at fixed volume

$$c_s^2(T_{eff}) = \frac{dP}{d\epsilon} = \frac{sdT}{Tds}\Big|_{T_{eff}} = \frac{d\ln\langle p_T\rangle}{d\ln(dN_{ch}/d\eta)} = 0.24 \pm 0.04$$

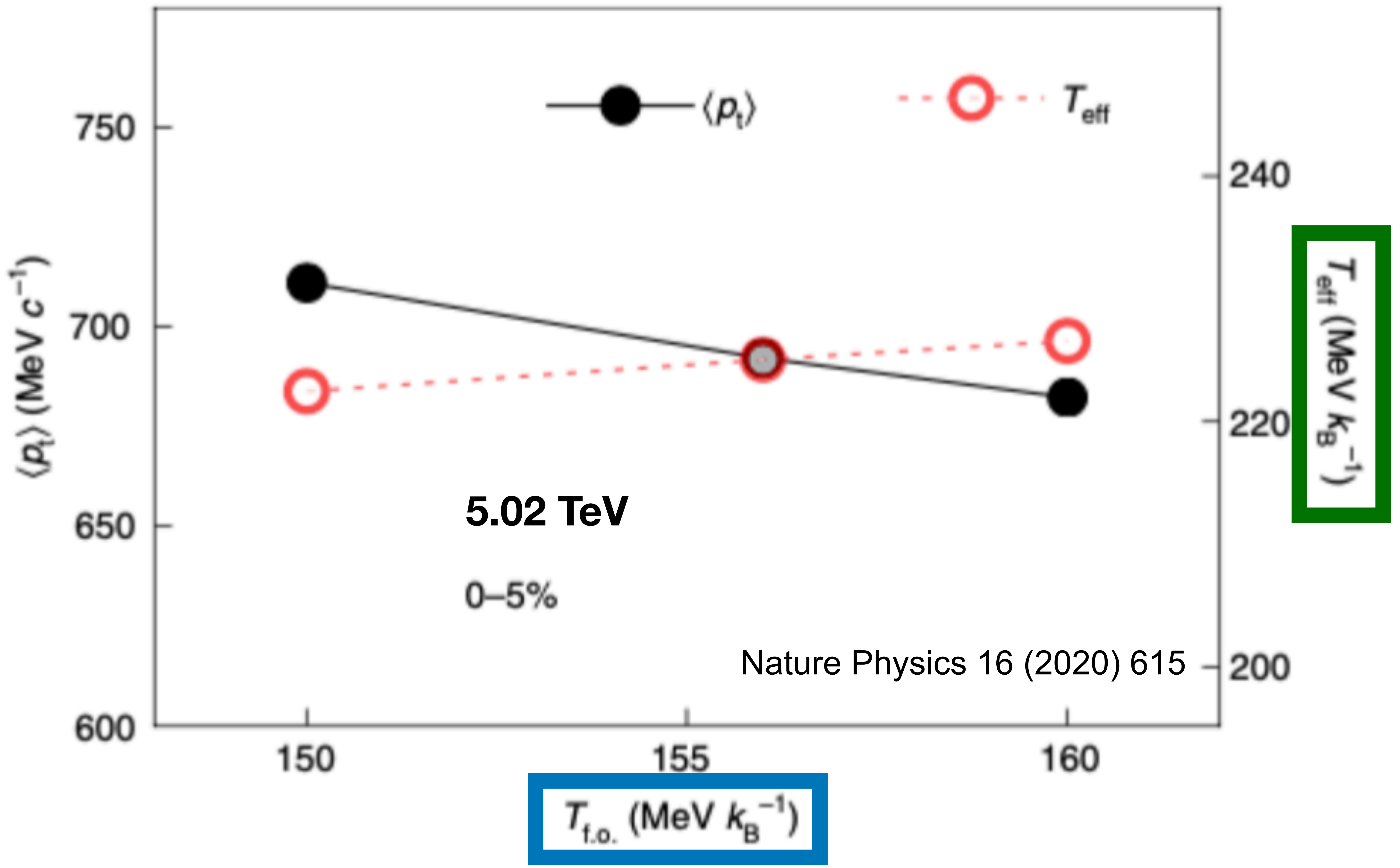
- Uncertainties limited by only having 2 energies
  - Used available published ALICE data
- Energy dependence of p_T, N_{ch} not unique to AA

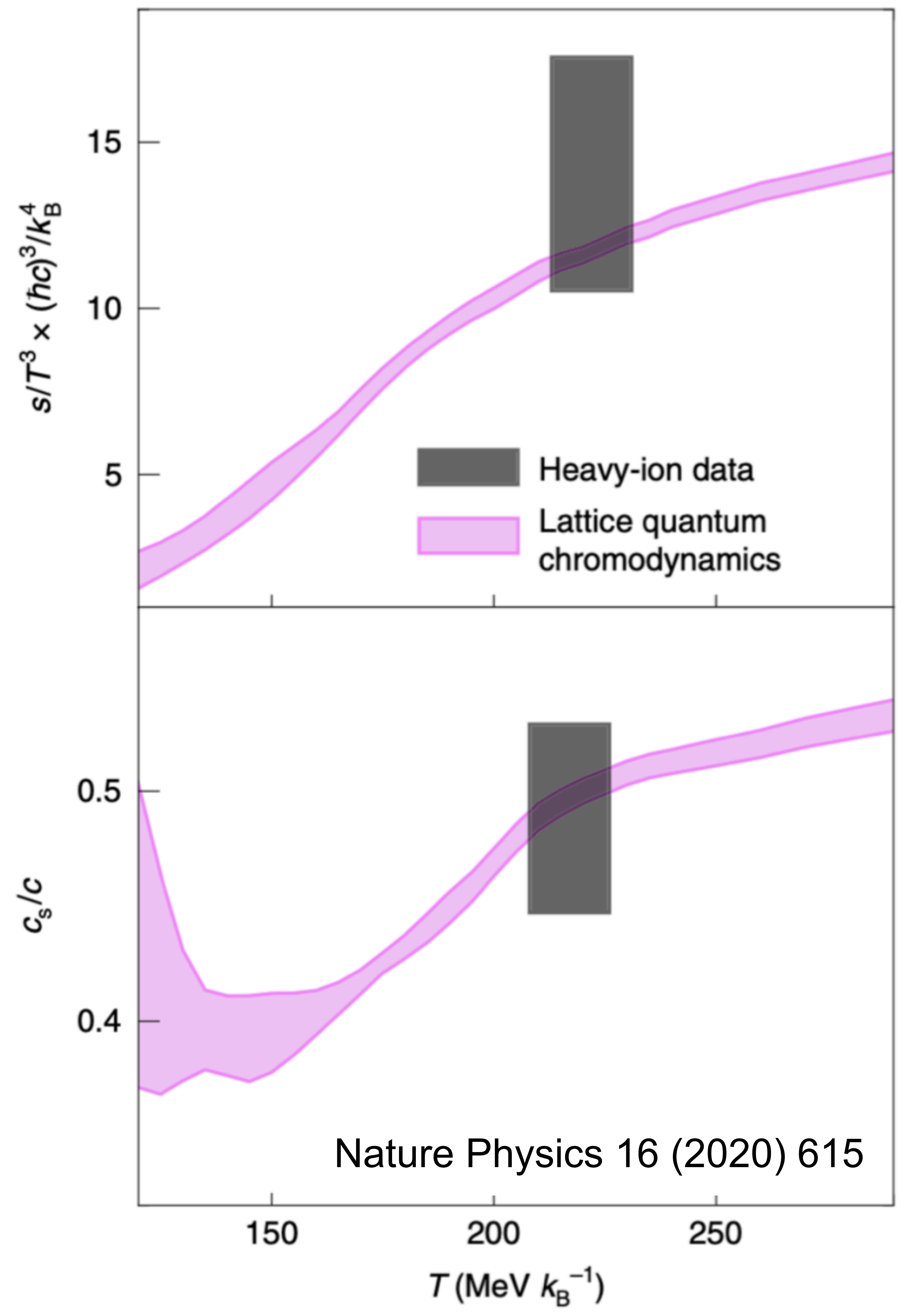


Nature Physics 16 (2020) 615

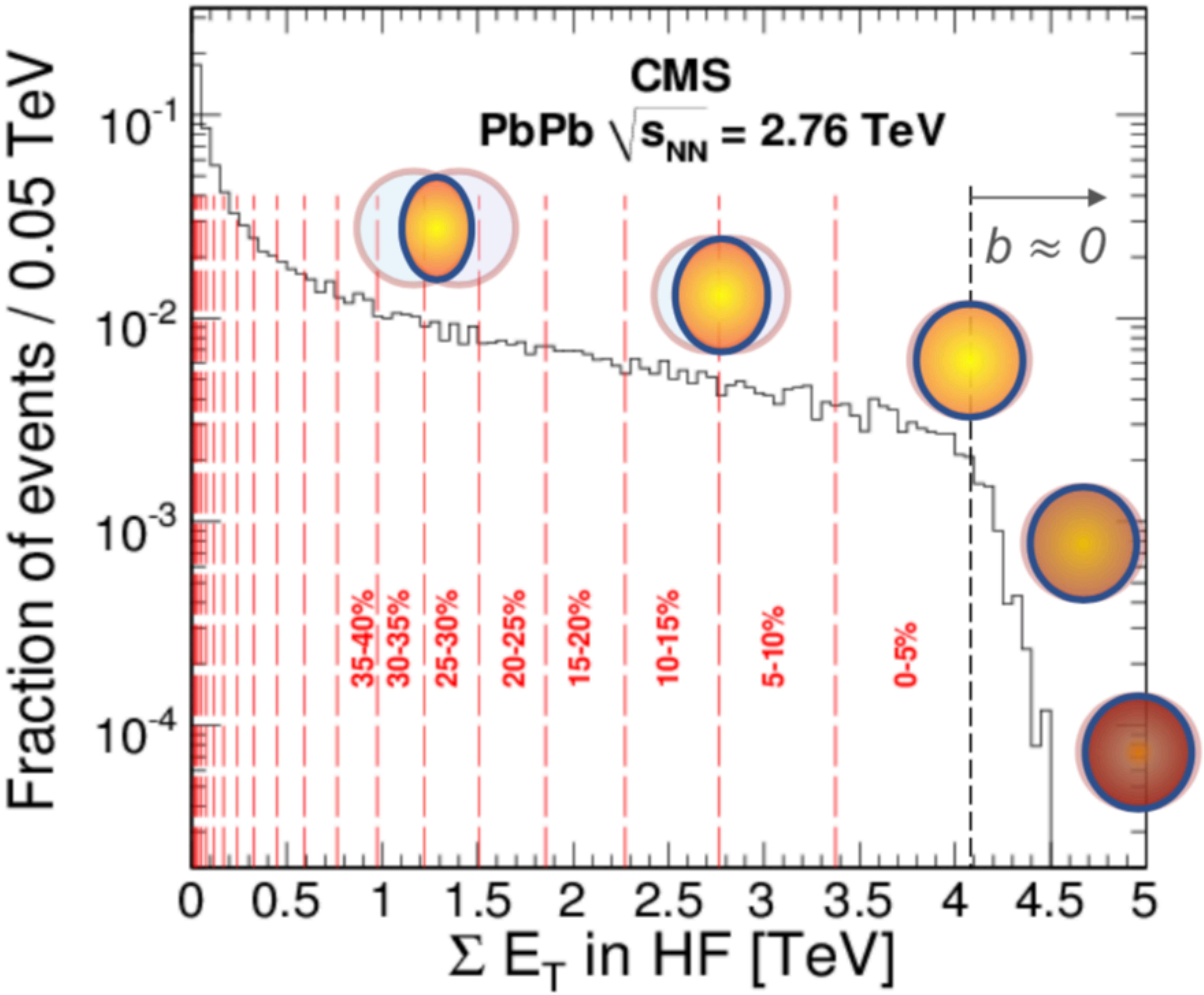
Meaning of T_{eff}

- **Effective Temperature calculated as** $T_{eff} \approx \langle p_T \rangle / 3$
- **Motivated from ideal hydro calculations**
  - **Larger than freeze-out Temp**
  - **Less than initial Temp (longitudinal expansion)**





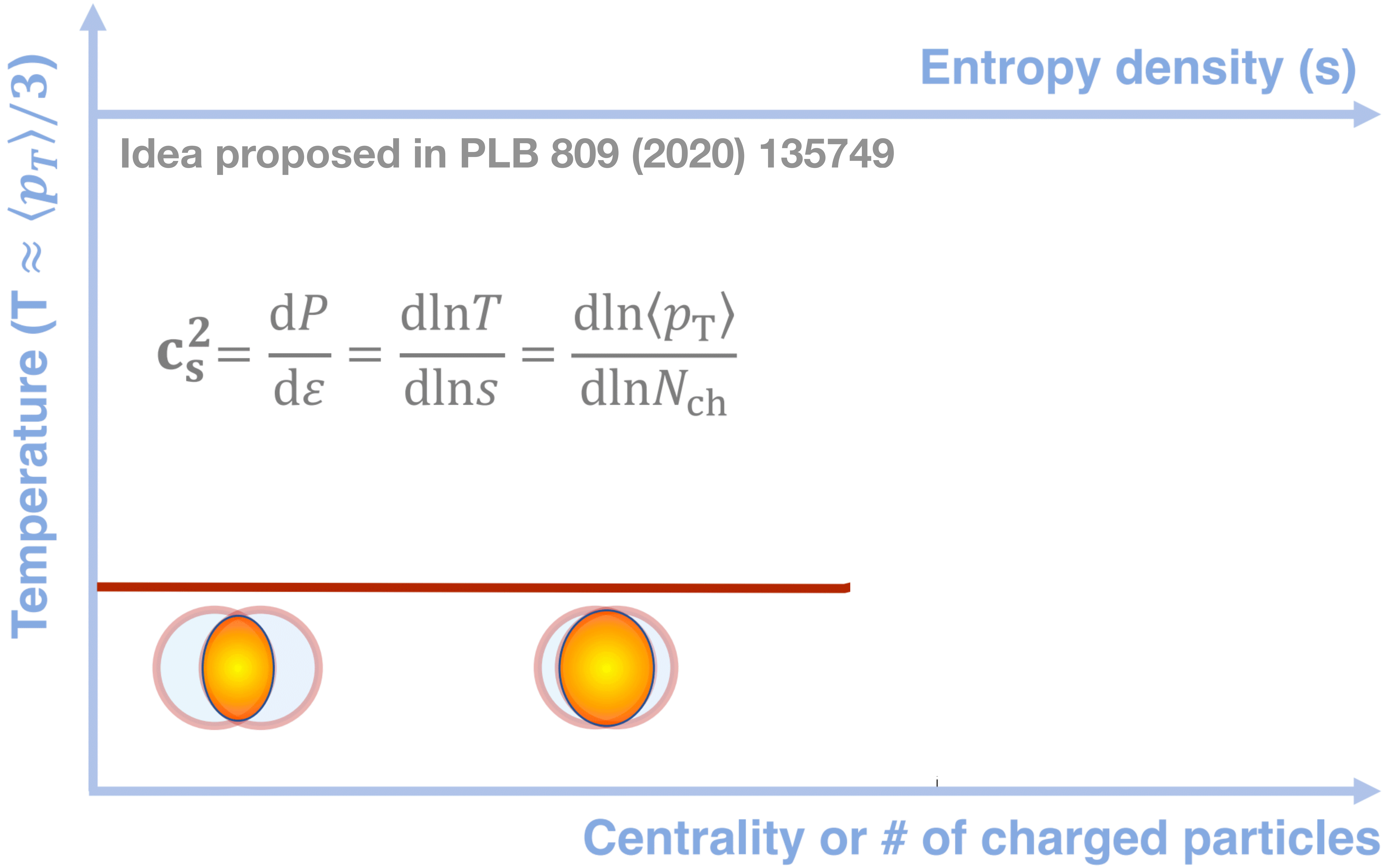
Ultracentral Collisions (UCC)



- **Centrality - controls impact parameter (b) and geometry**
- **Experimentally determined by forward transverse energy sum**
- **Ultracentral collisions (0-1%) has ~fixed volume with b=0**
- **Energy deposition still fluctuates!**

New analysis method

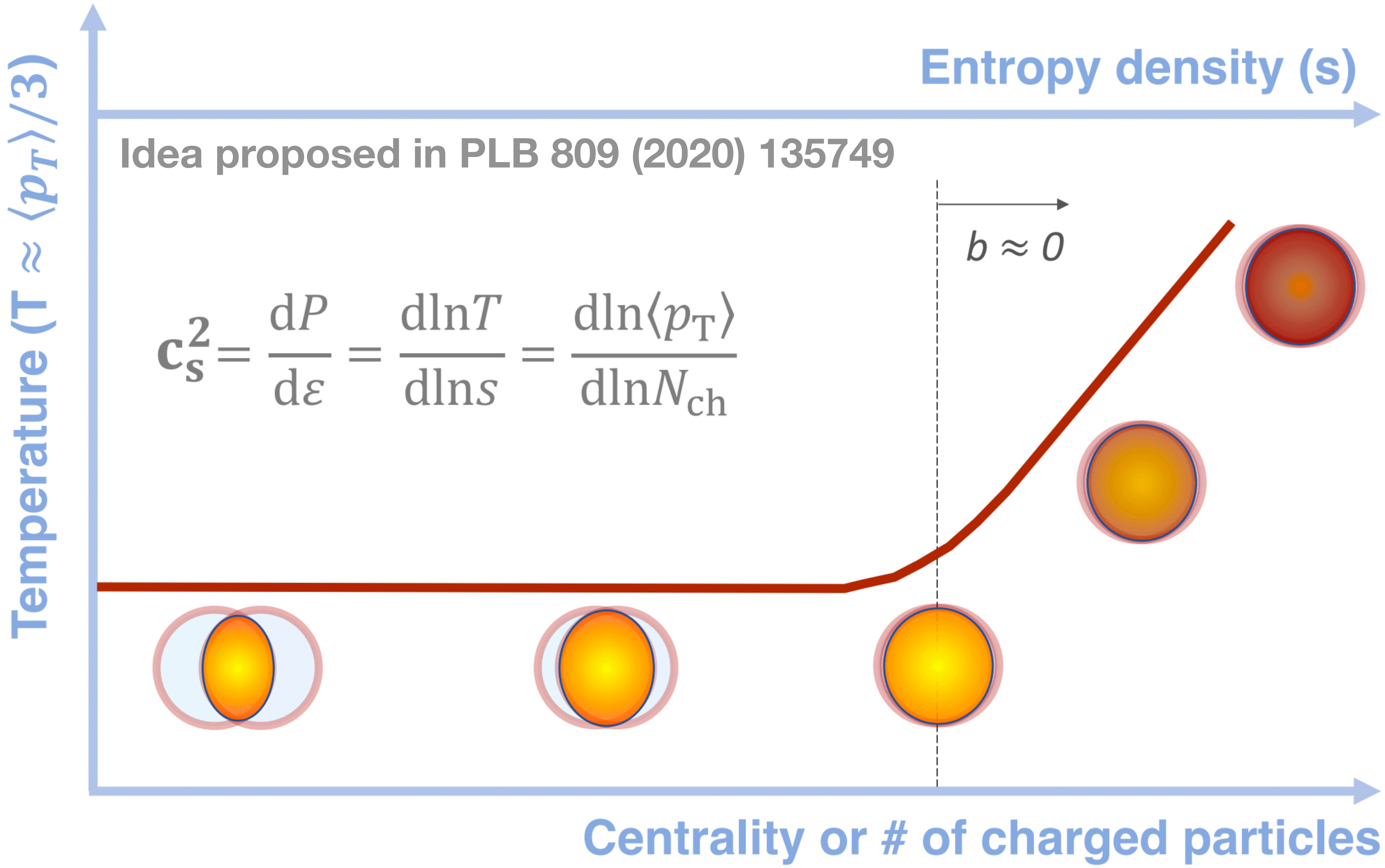
- QGP c_s extracted from measurements of $\langle p_T \rangle$ vs N_{ch} vs centrality at same $\sqrt{s_{NN}}$



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

New analysis method

- QGP c_s extracted from measurements of <p_T> vs N_{ch} vs centrality at same $\sqrt{s_{NN}}$
- Use fluctuations in b=0 collisions to vary energy density at fixed volume



Summary of target observables

At b=0

$$\frac{\langle p_T\rangle}{\langle p_T\rangle^0} \sim \left(\frac{N_{ch}}{N_{ch}^0}\right)^{c_s^2}$$

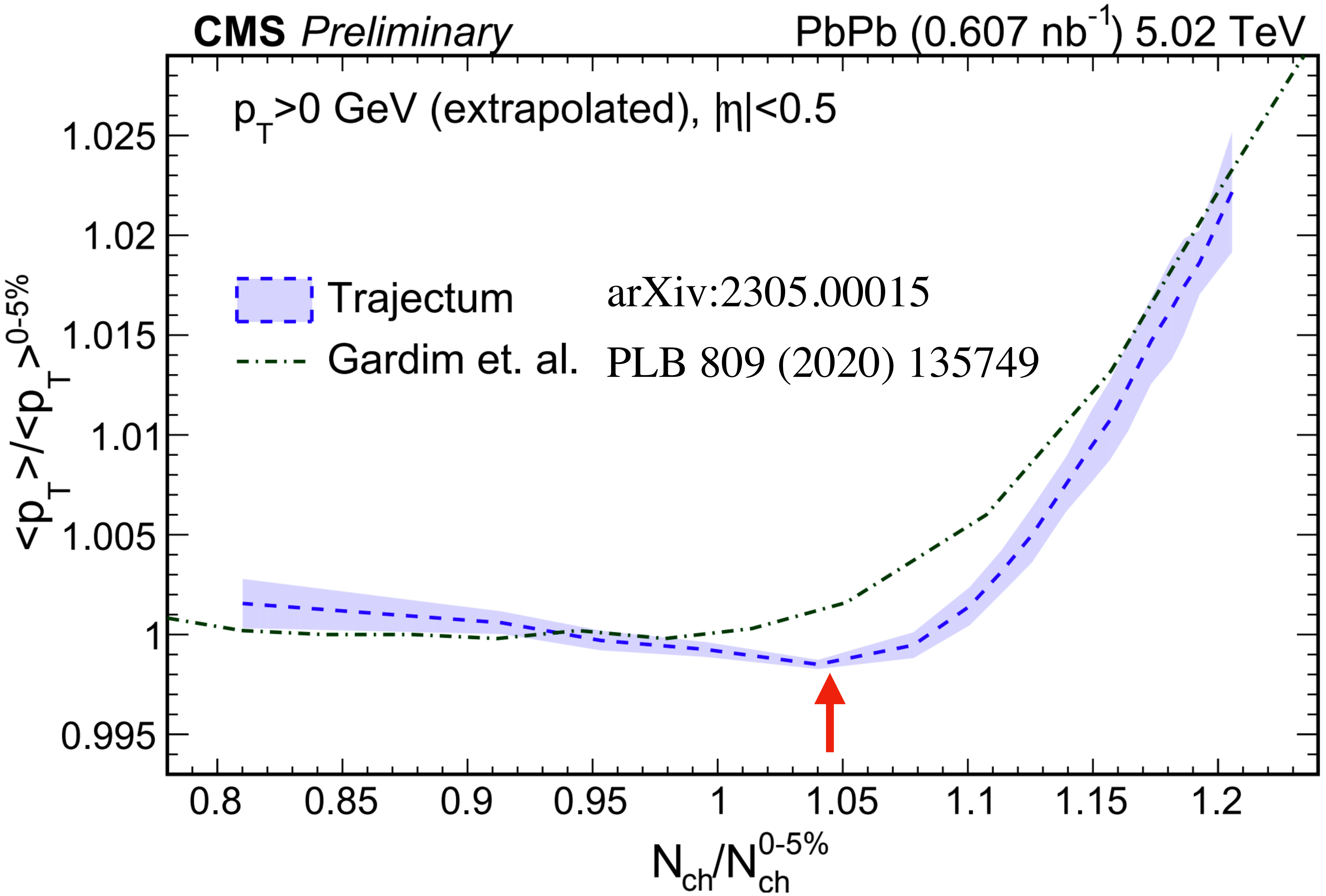
Observables in this analysis:

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

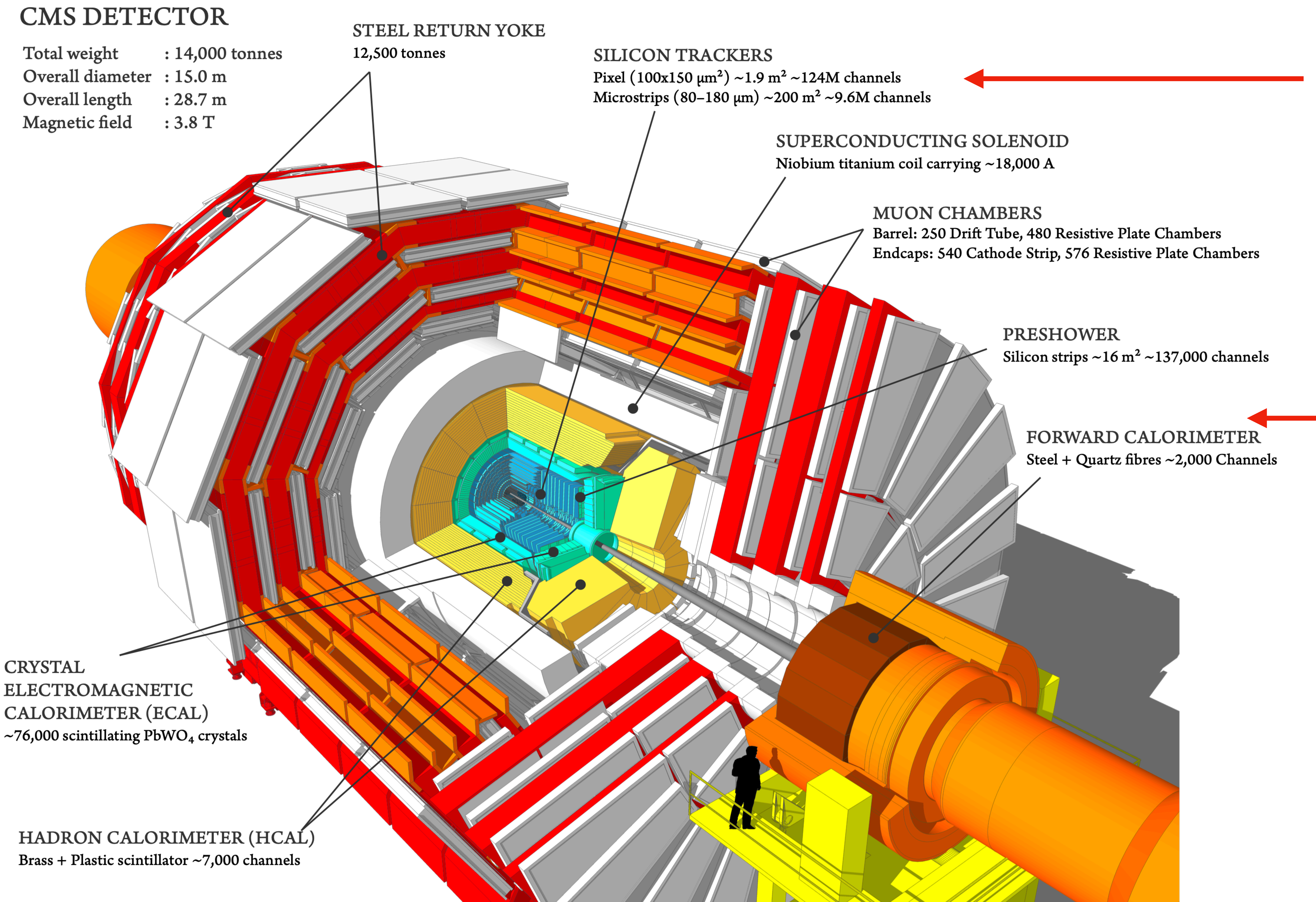
$\langle p_T\rangle^0$, N_{ch}^0 chosen from the 0-5% centrality

Hydrodynamic predictions

- **Two hybrid simulation models predict a rising slope**
  - **Gardim et. al. - equation of state from 2+1 flavor lattice QCD**
  - **Trajectum model - Bayesian analysis of available data**
    - **Has dip around 1.05 - not understood yet!**



The CMS Detector

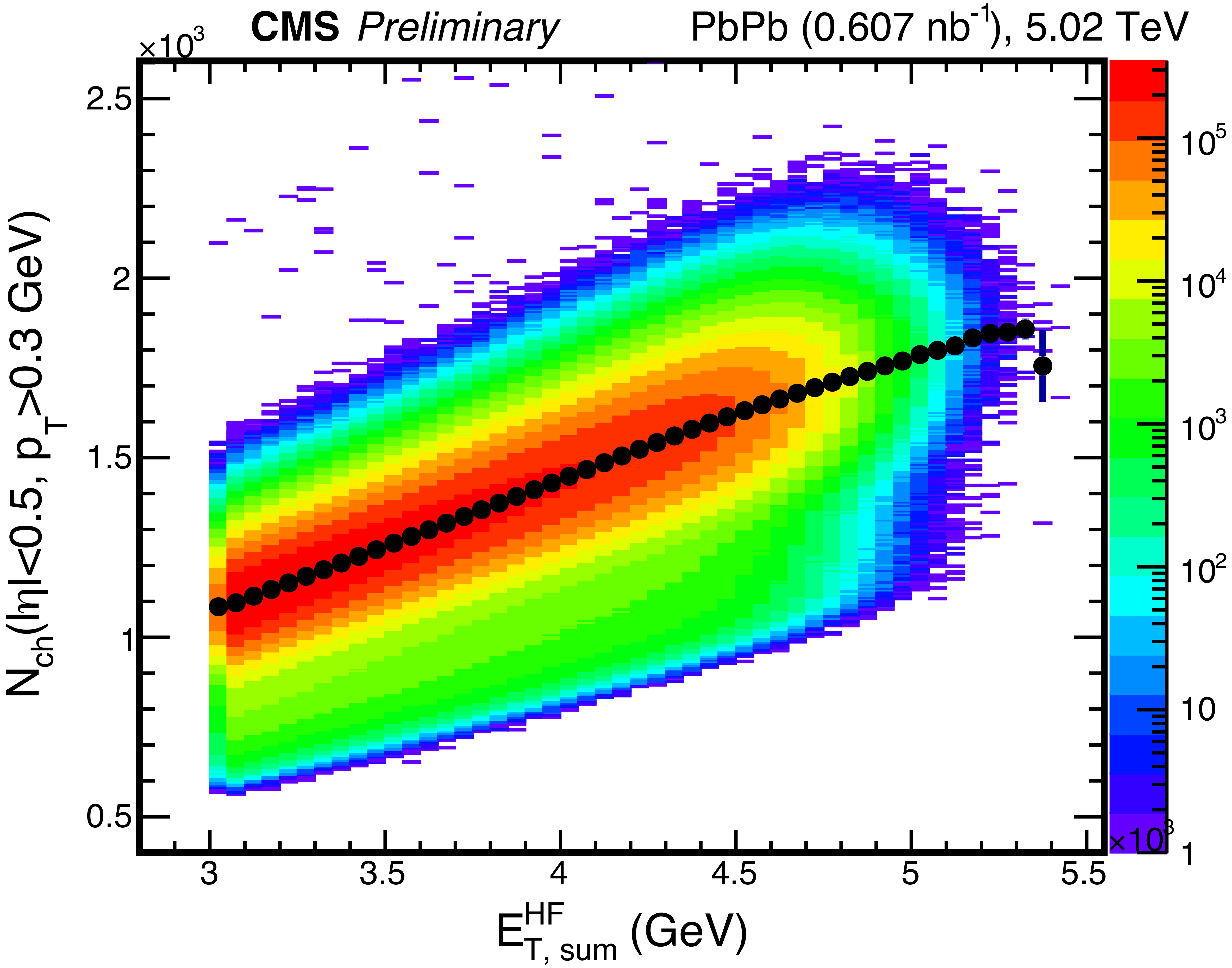


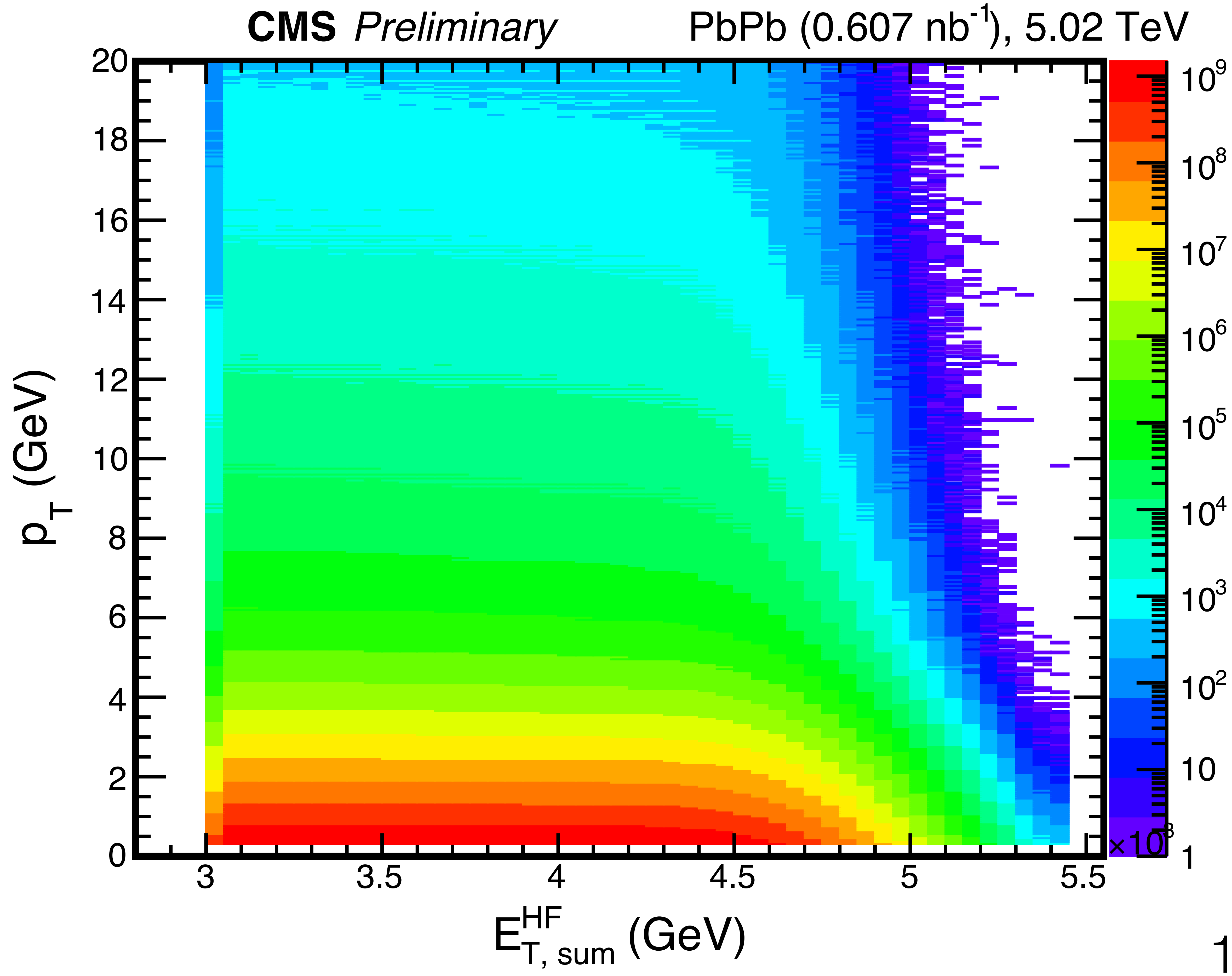
Tracks for $\langle p_T \rangle$, N_{ch}

Forward calorimeters for centrality

Measuring <p_T> and <N_{ch}>

- **Centrality defined with forward transverse energy sum (3<|η|<5)**
  - **Different region than multiplicity measurement (|η|<0.5) to avoid autocorrelations**
- **Narrow 50 GeV binning to scan behavior at b=0**



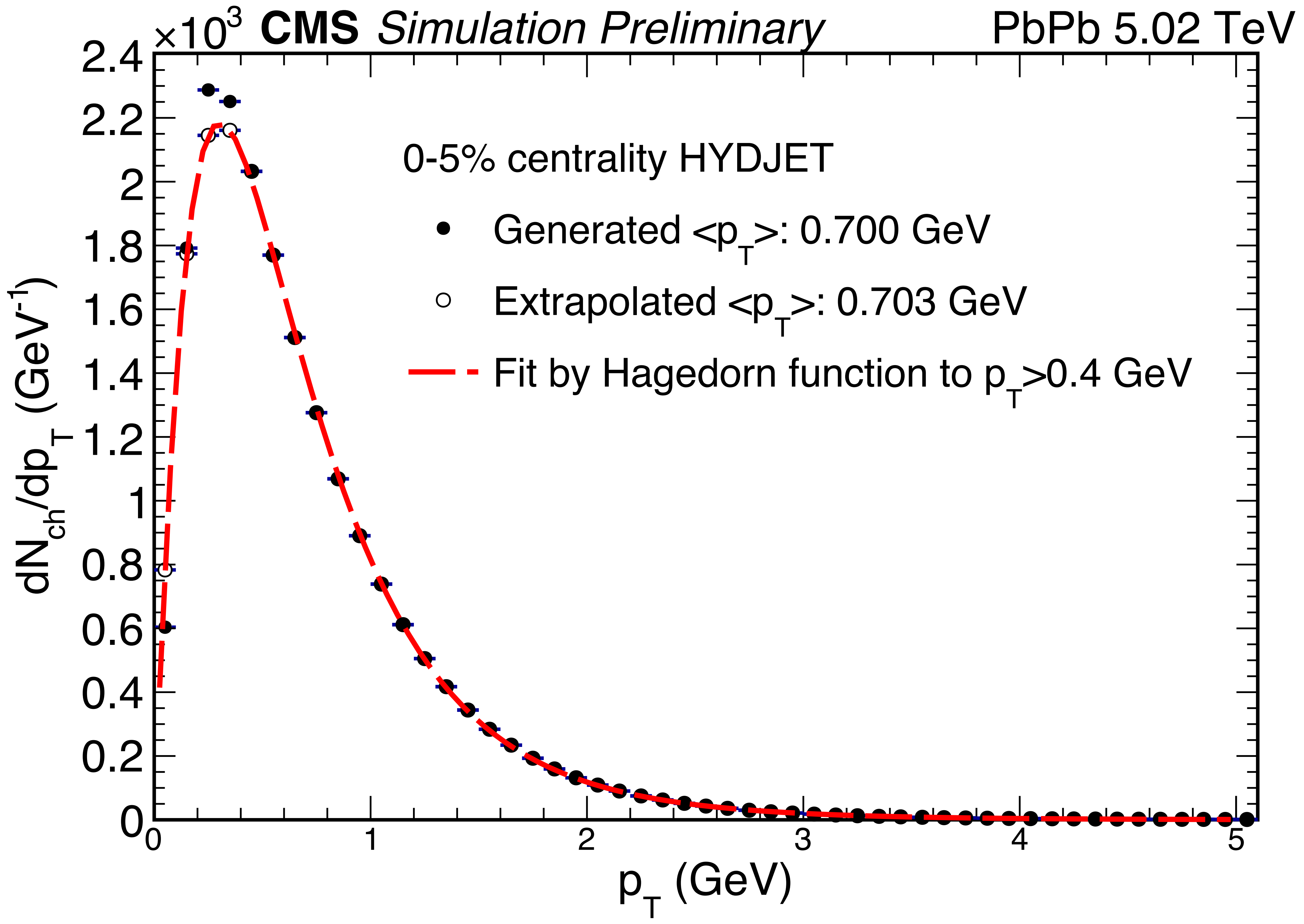


Extrapolation to $p_T = 0$

- p_T and N_{ch} spectra corrected for detector inefficiencies
- Spectra extrapolated to 0 p_T with Hagedorn function
  - m is pion mass, β_T, n, T are free parameters

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

Simulation



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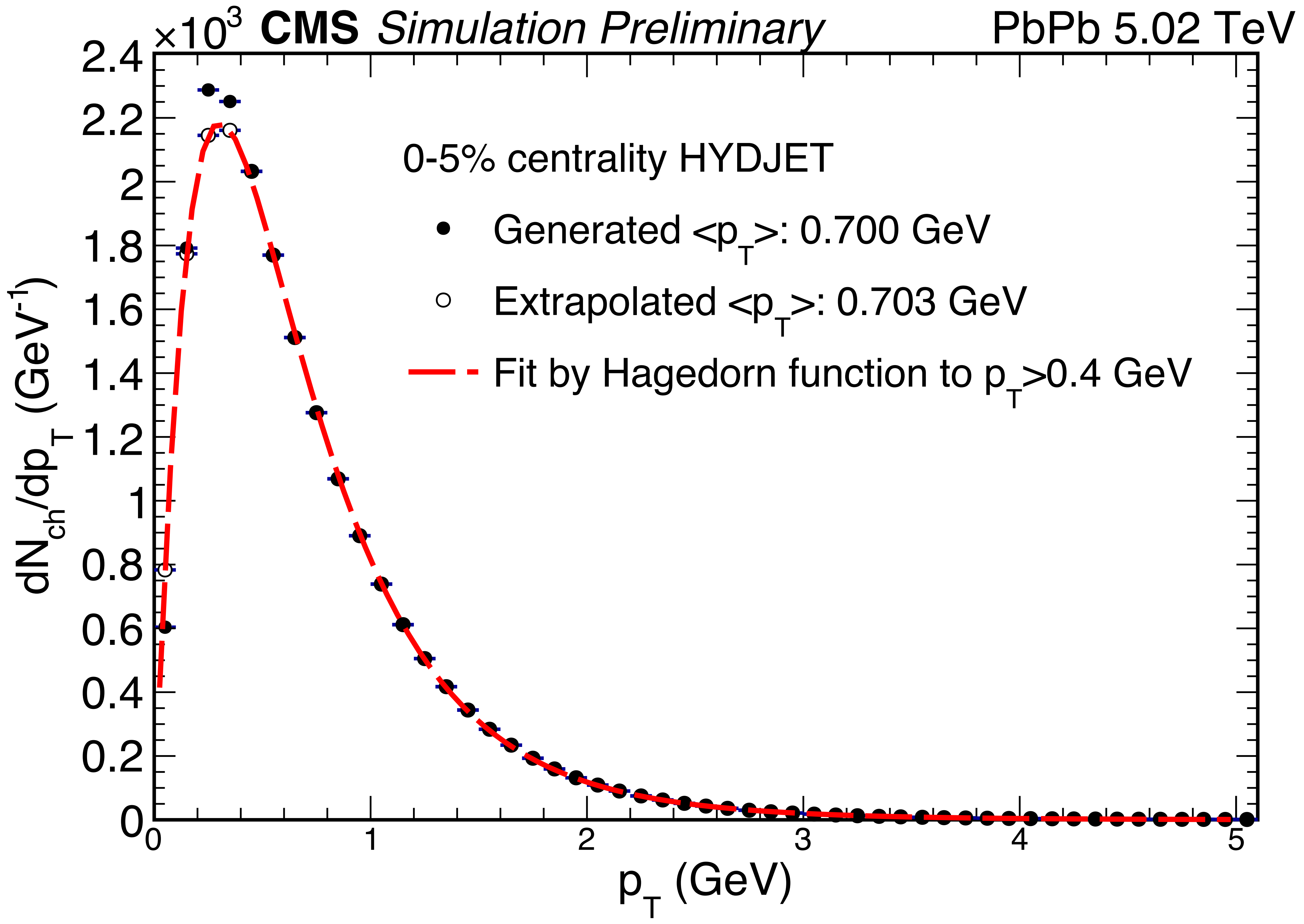
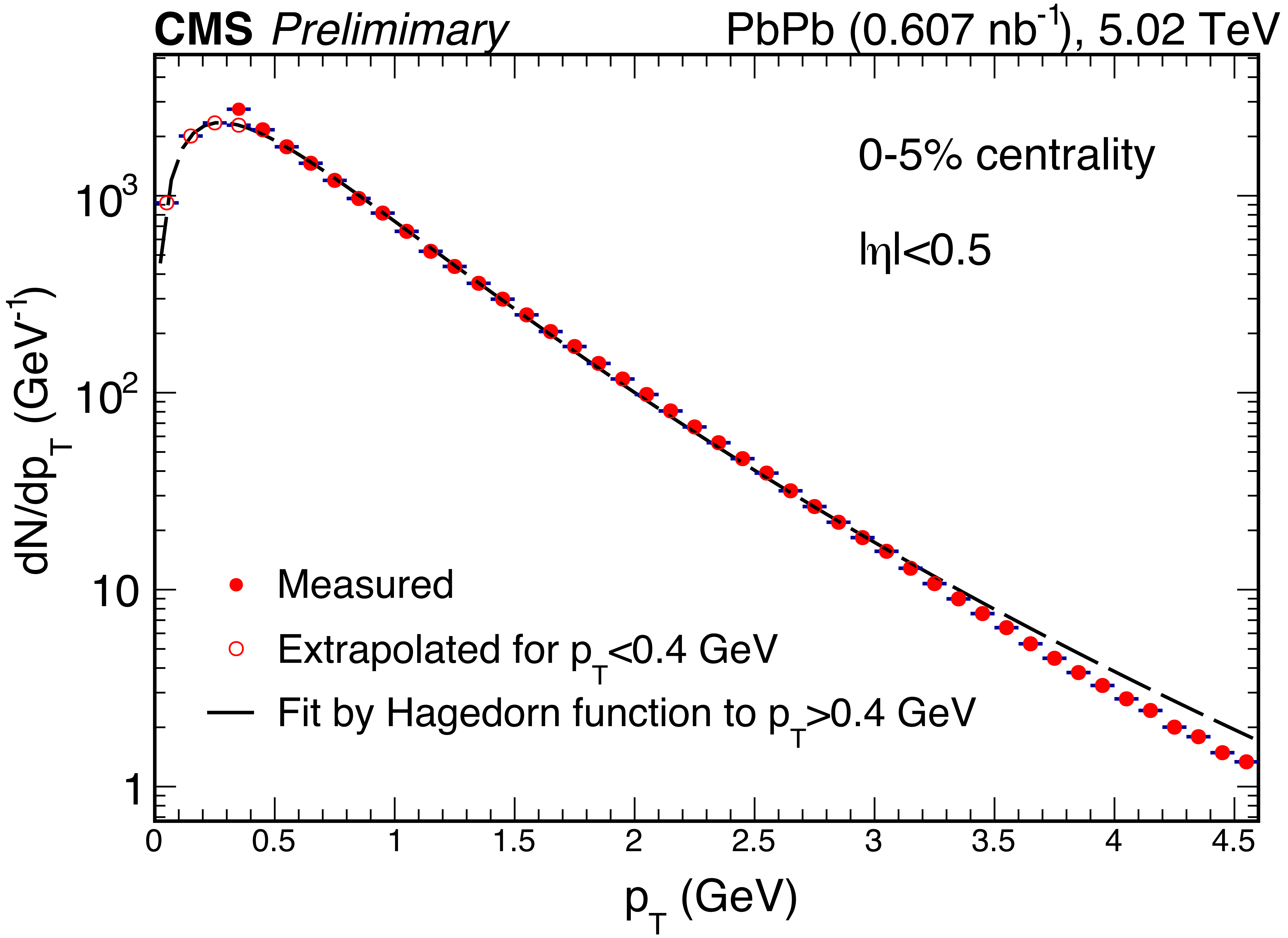


Data



Extrapolation to p_T = 0

- p_T and N_{ch} spectra corrected for detector inefficiencies
- Spectra extrapolated to 0 p_T with Hagedorn function
  - m is pion mass, β_T, n, T are free parameters
- 2 of 3 target observables measured

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

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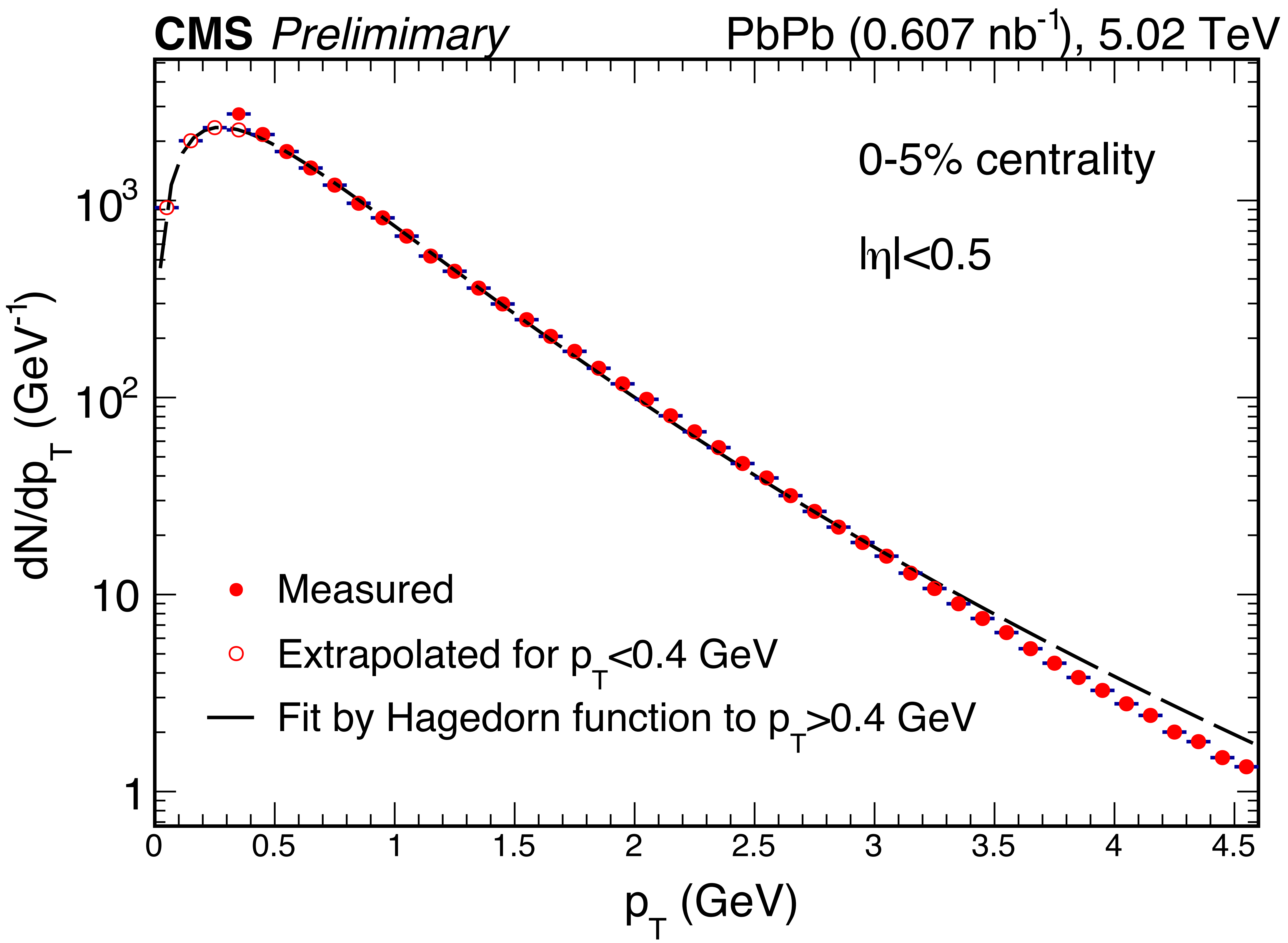
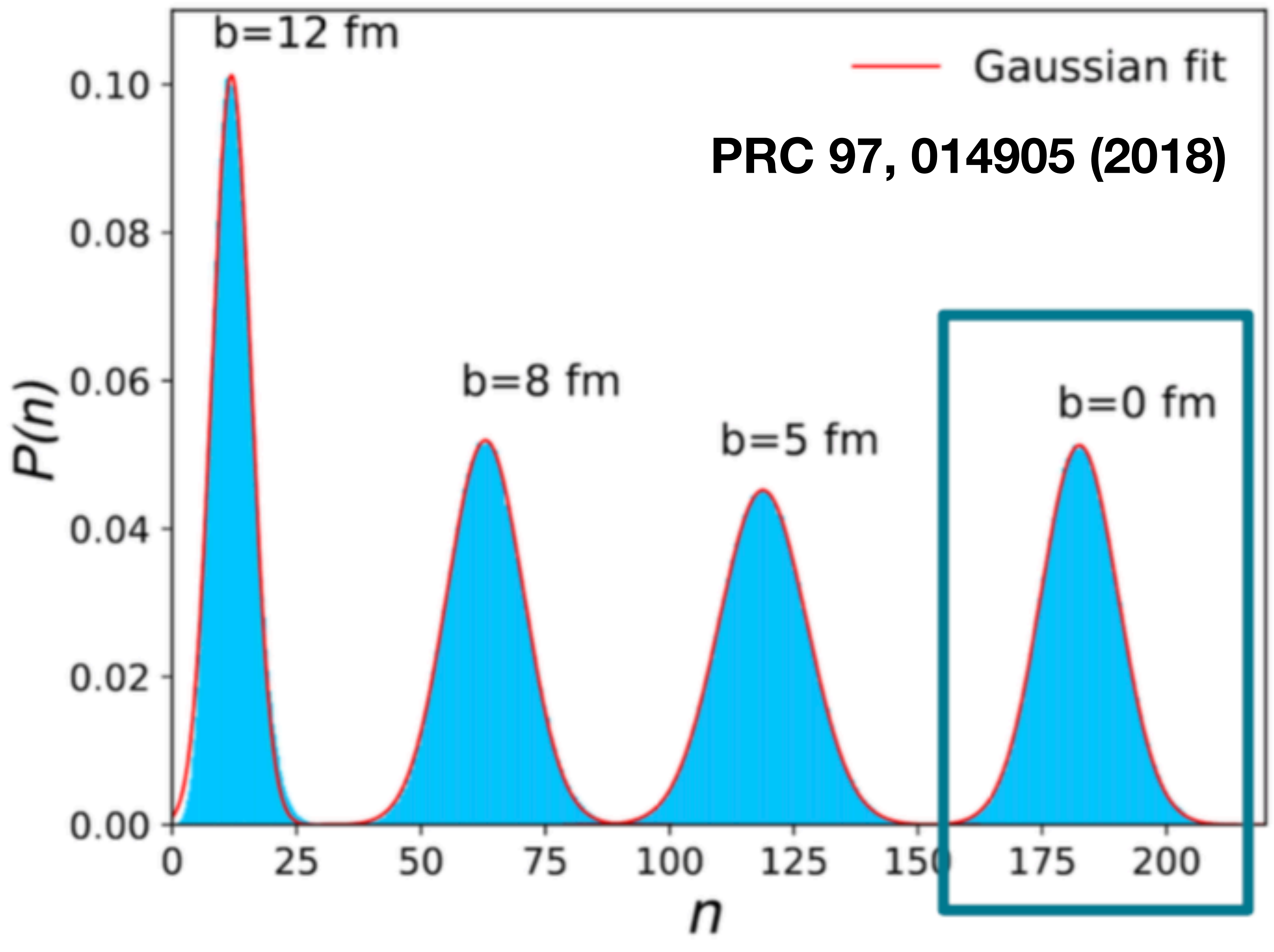


Effect of Multiplicity fluctuations

- Spread of multiplicities produced at a given b
- Cannot directly isolate events with exactly b=0
- Must account for the effects of a distribution of initial b at given N_{ch}



Multiplicity fluctuation correction

- Spread of multiplicities produced at a given b
- Cannot directly isolate events with exactly b=0
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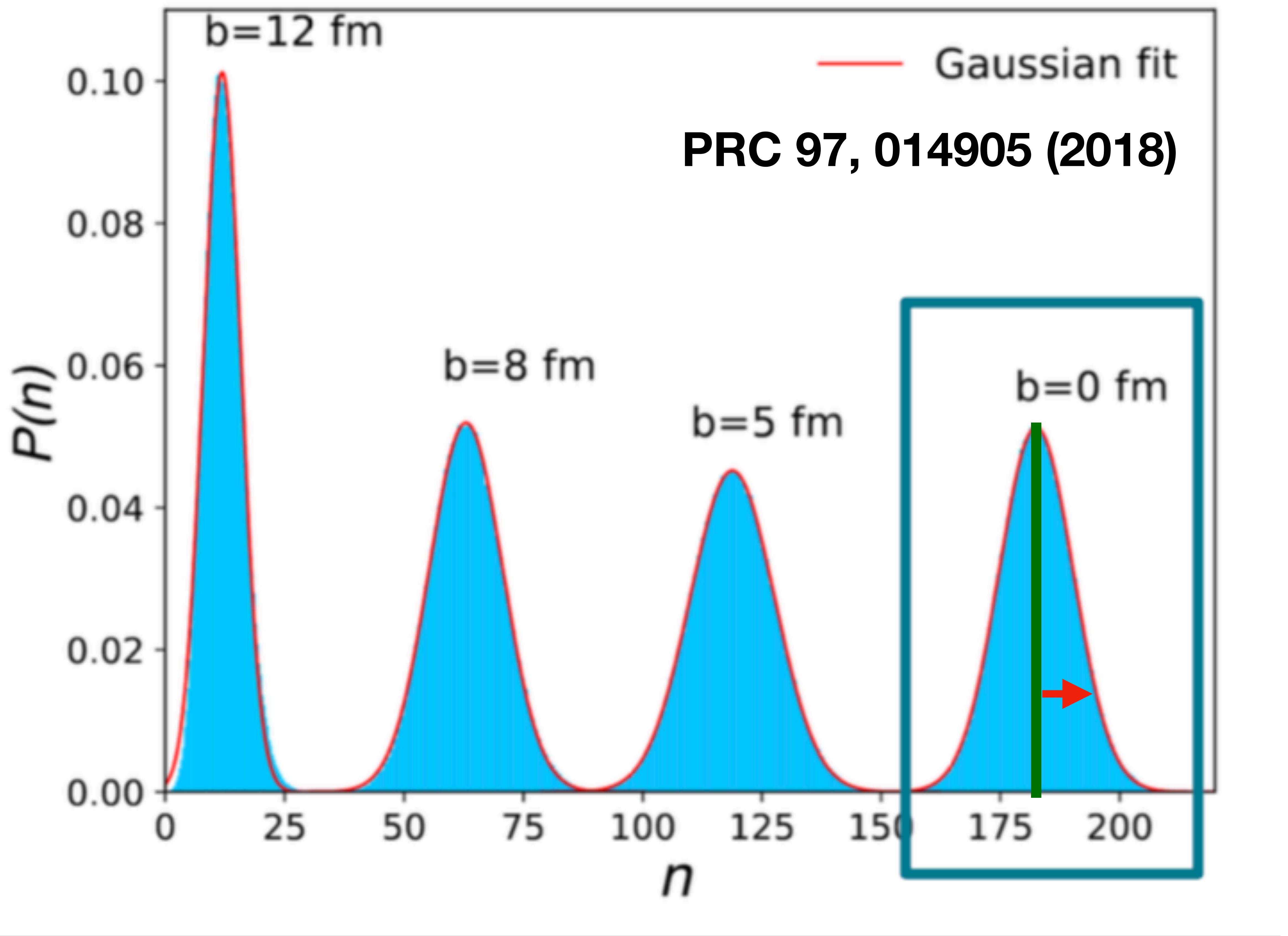


$$\langle p_T \rangle^{\text{norm}} = \left(\frac{N_{\text{ch}}^{\text{norm}}}{\langle \overline{N_{\text{ch}}^{\text{knee}}} | N_{\text{ch}}^{\text{norm}} \rangle} \right)^{c_s^2}$$

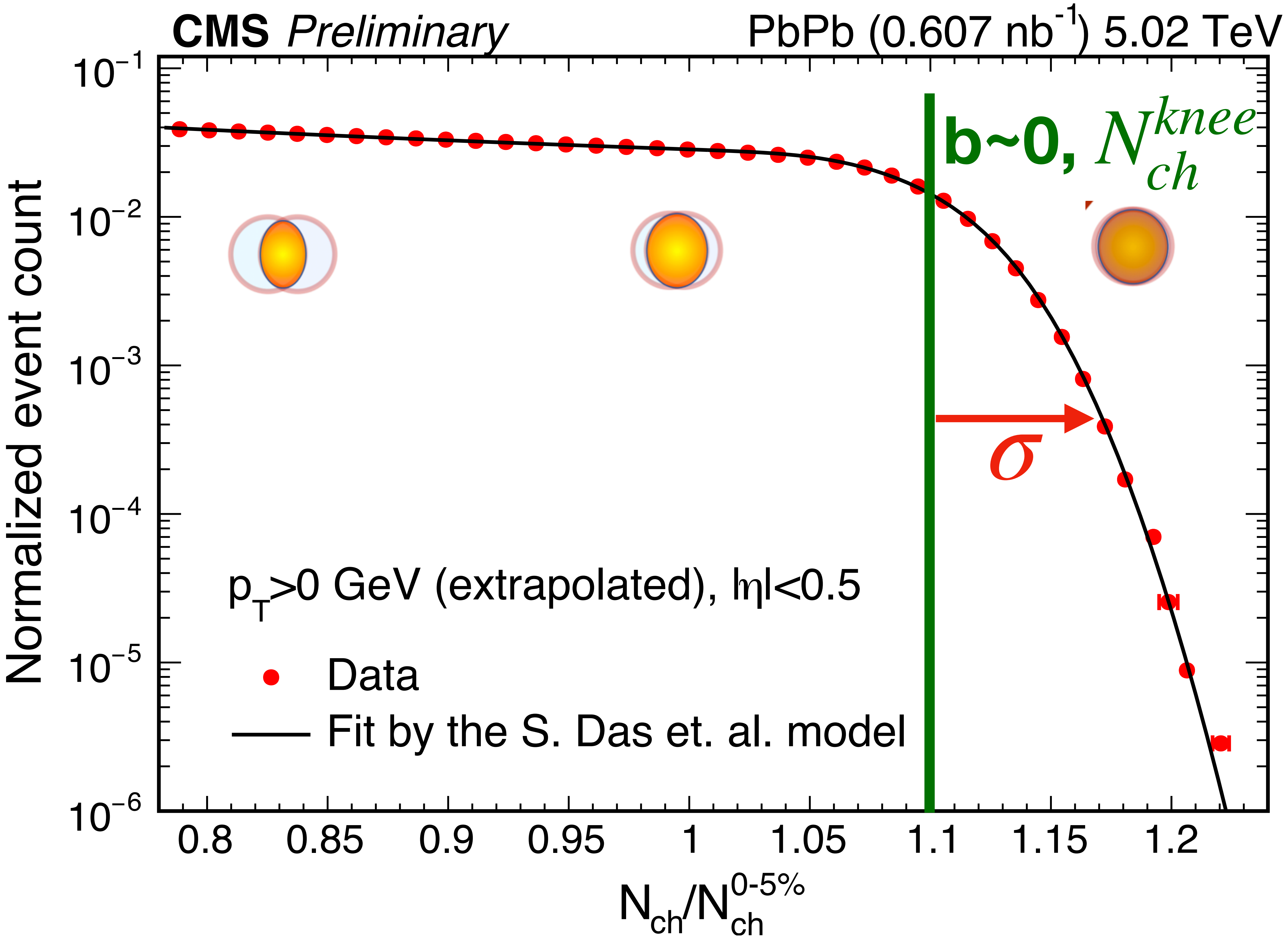
$$\langle \overline{N_{\text{ch}}^{\text{knee}}} | N_{\text{ch}}^{\text{norm}} \rangle = N_{\text{ch}}^{\text{norm}} - \sigma \sqrt{\frac{2}{\pi}} \frac{\exp\left(- \frac{(N_{\text{ch}}^{\text{norm}} - \overline{N_{\text{ch}}^{\text{knee}}})^2}{2\sigma^2} \right)}{\text{erfc}\left(\frac{N_{\text{ch}}^{\text{norm}}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

2 Free parameters: σ, N_{ch}^{knee}

From PLB 809 (2020) 135749

Constraining with N_{ch} distribution

- **Spread of multiplicities produced at a given b**
- **Cannot directly isolate events with exactly b=0 by cutting on N_{ch}**
- **Must account for the effects of a distribution of initial b at given N_{ch}**



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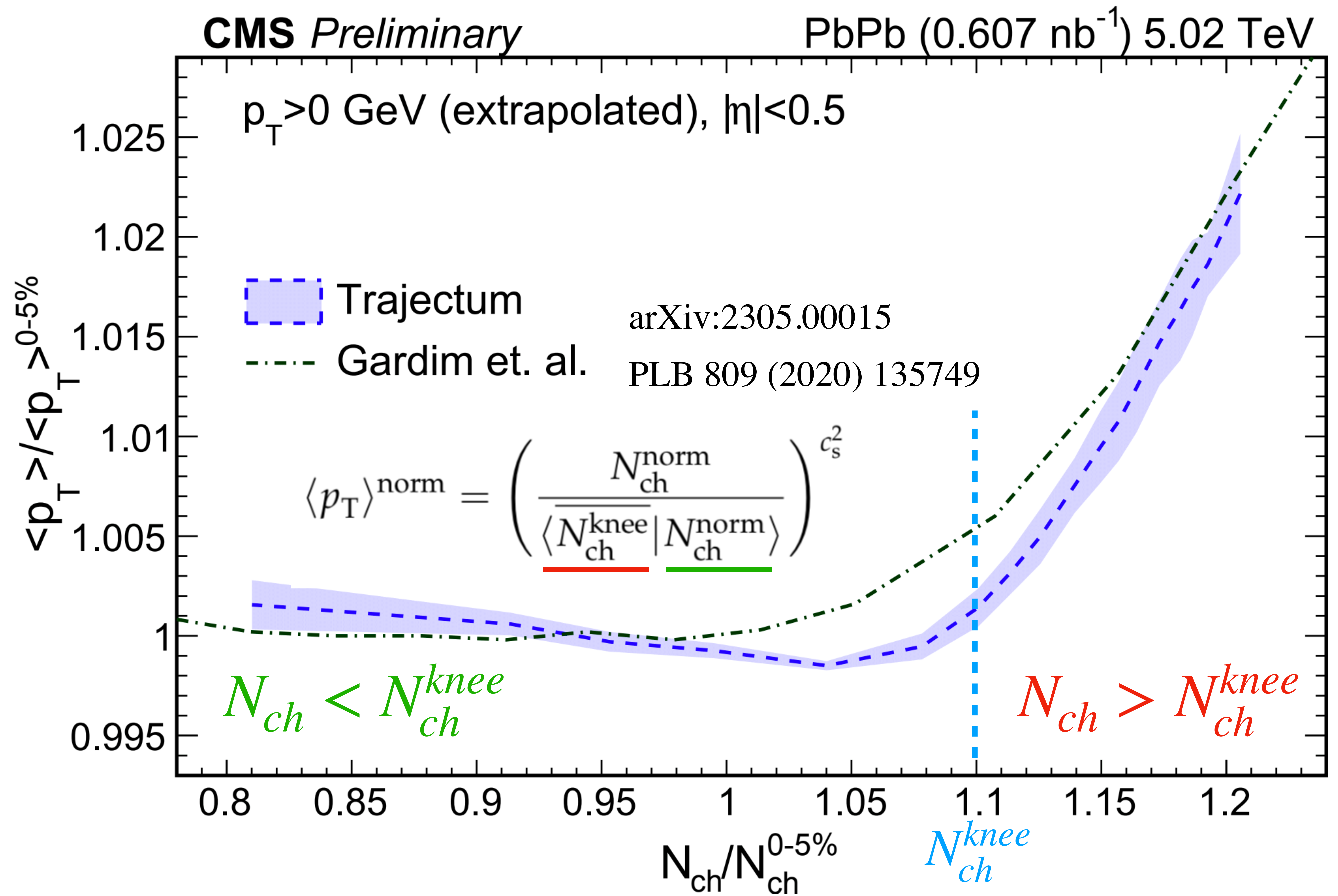
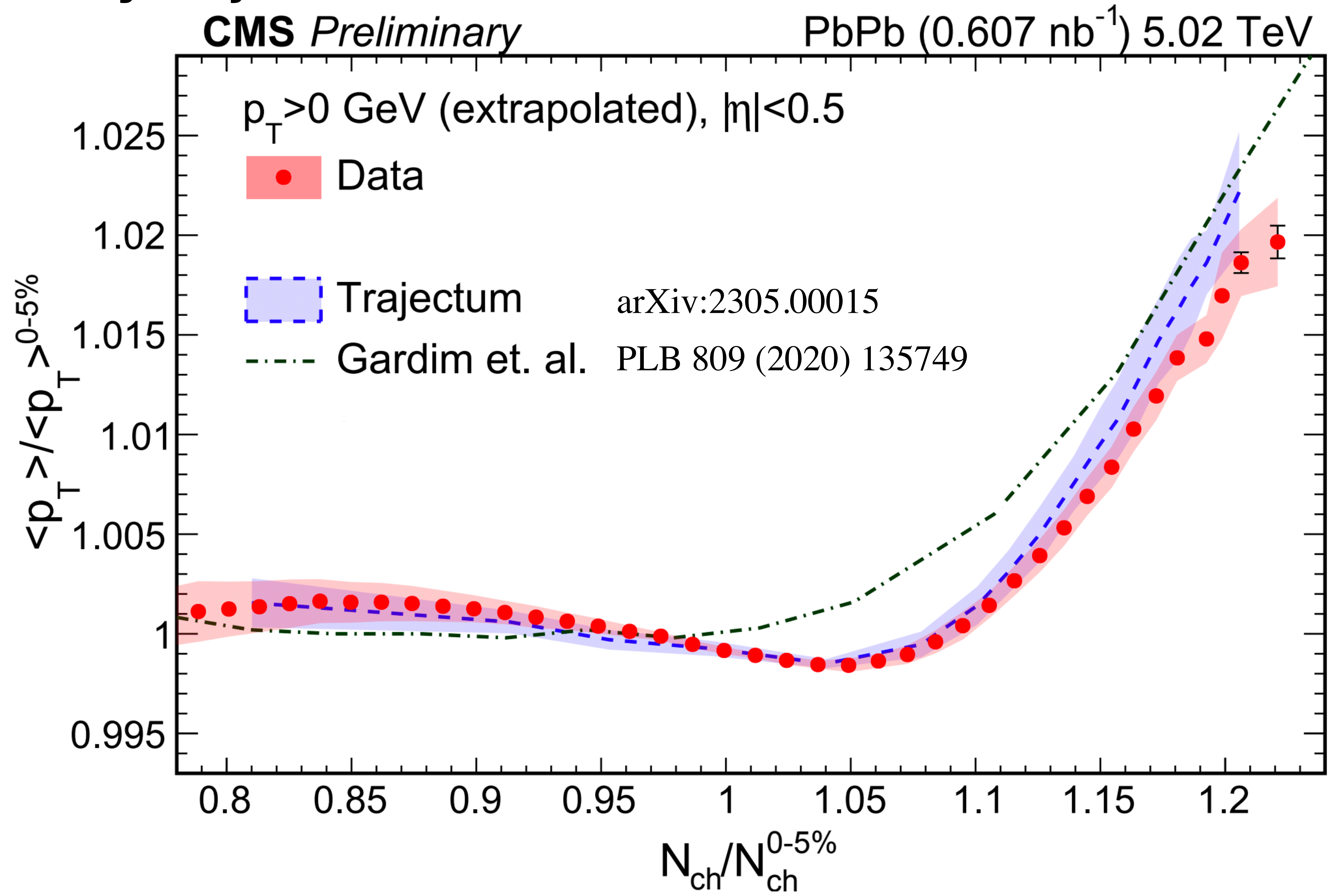
Reminder of hydro predictions



Speed of Sound in QGP

- **Slope of data matches models closely!**
- **'Dip' predicted by Trajectum also in the data!**



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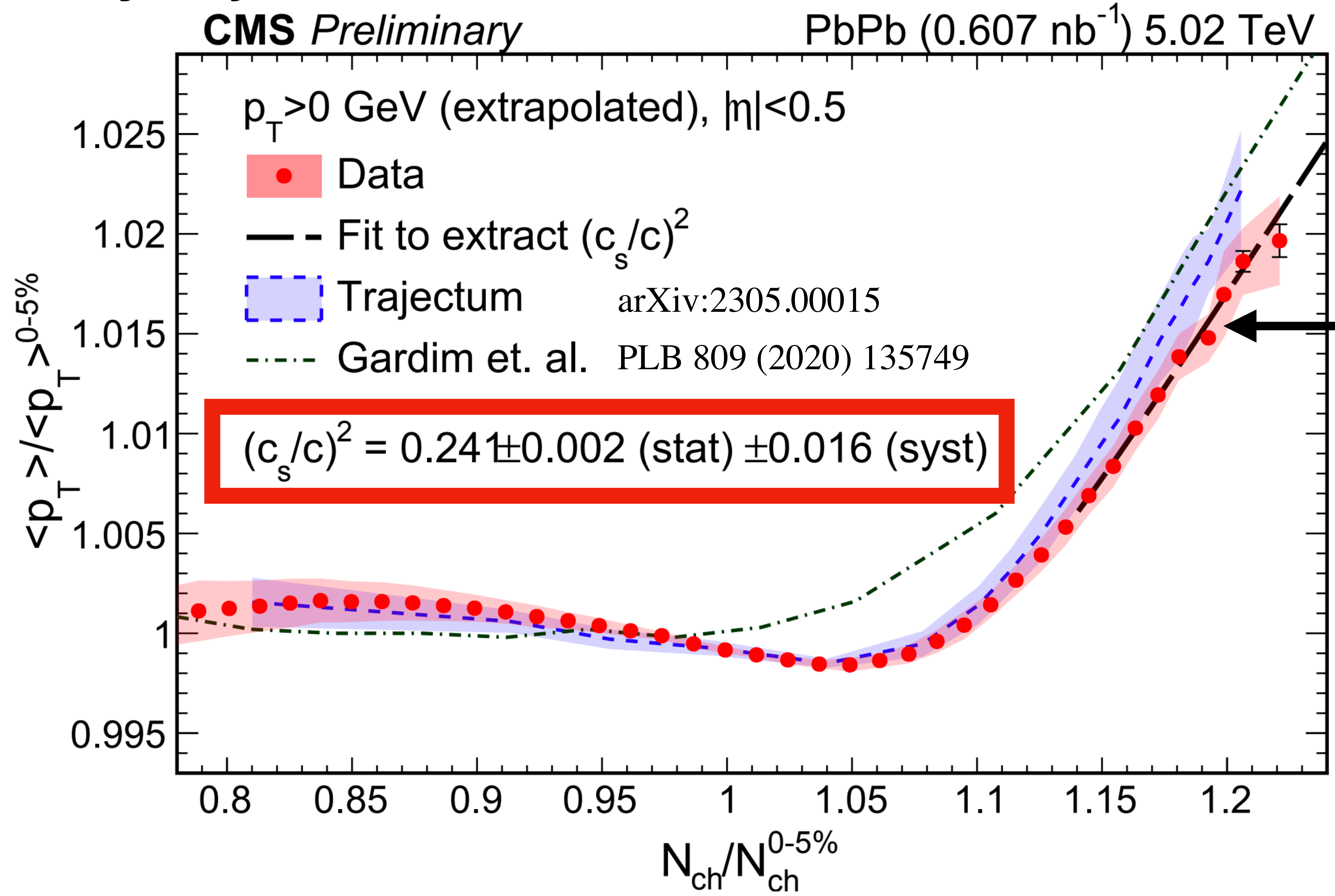

Fit slope to get c_s^2

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

Speed of Sound in QGP

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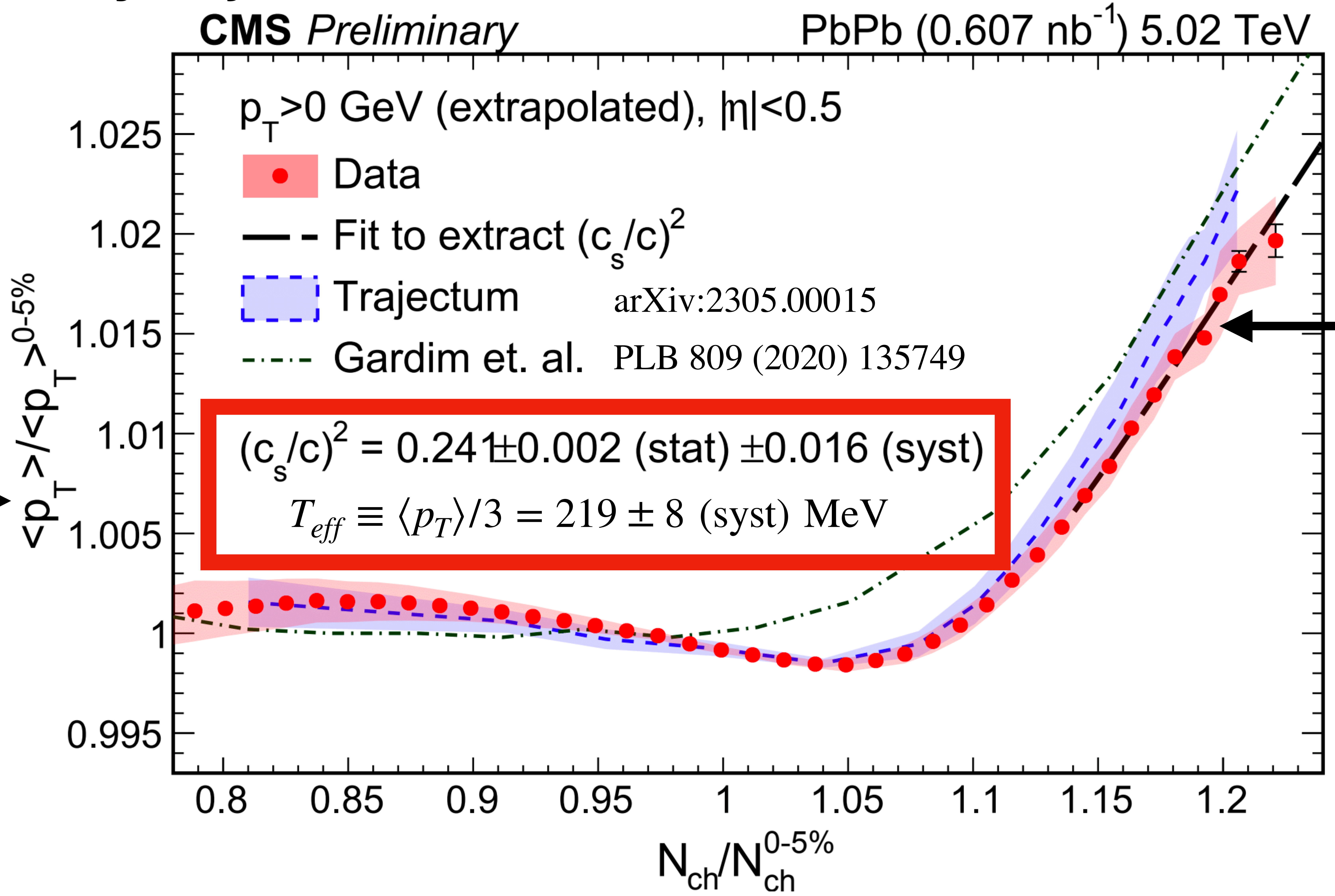
Get T_{eff} from $\langle p_T\rangle/3$



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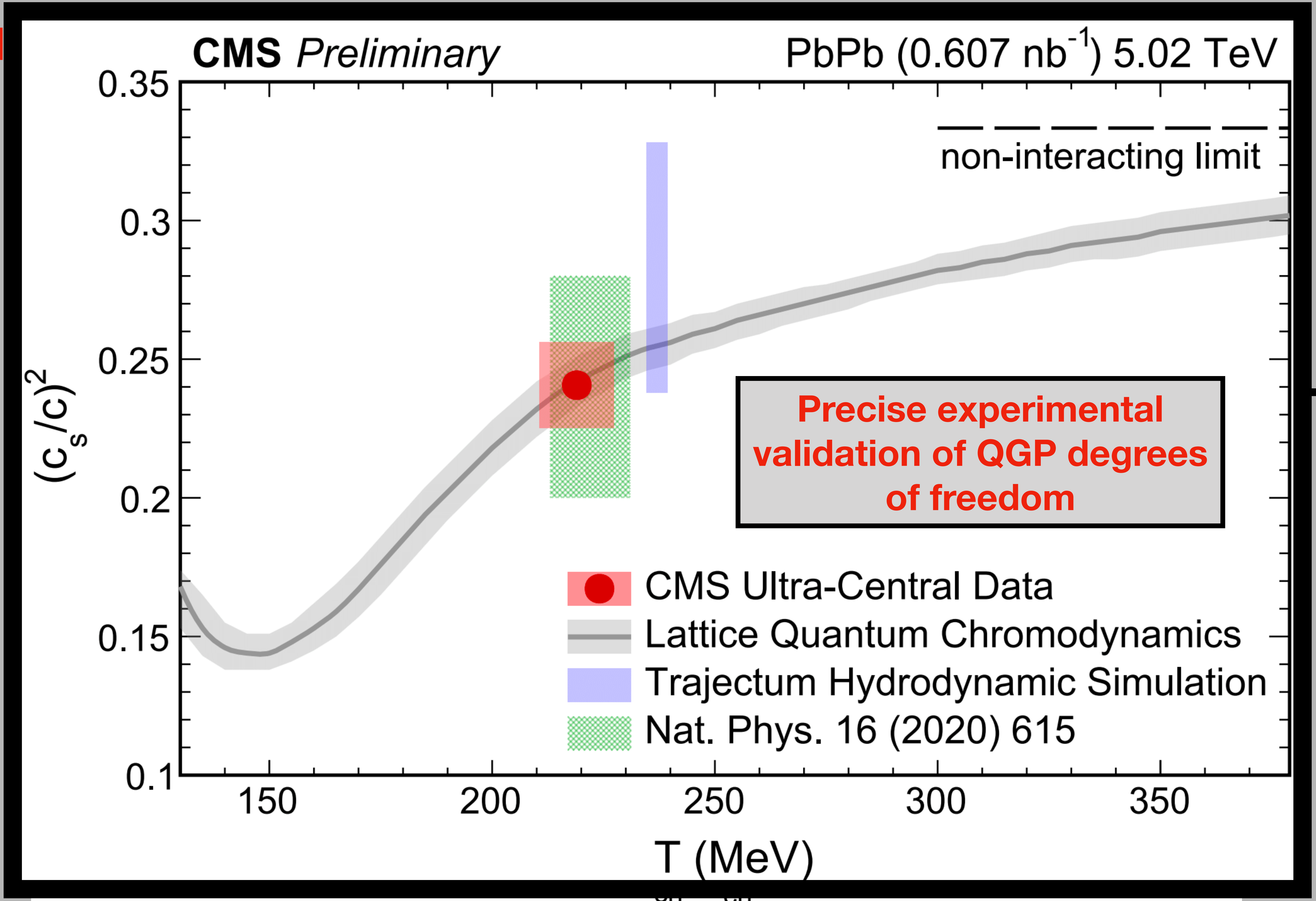
Constraining QCD Equation of State

- **Slope of d**

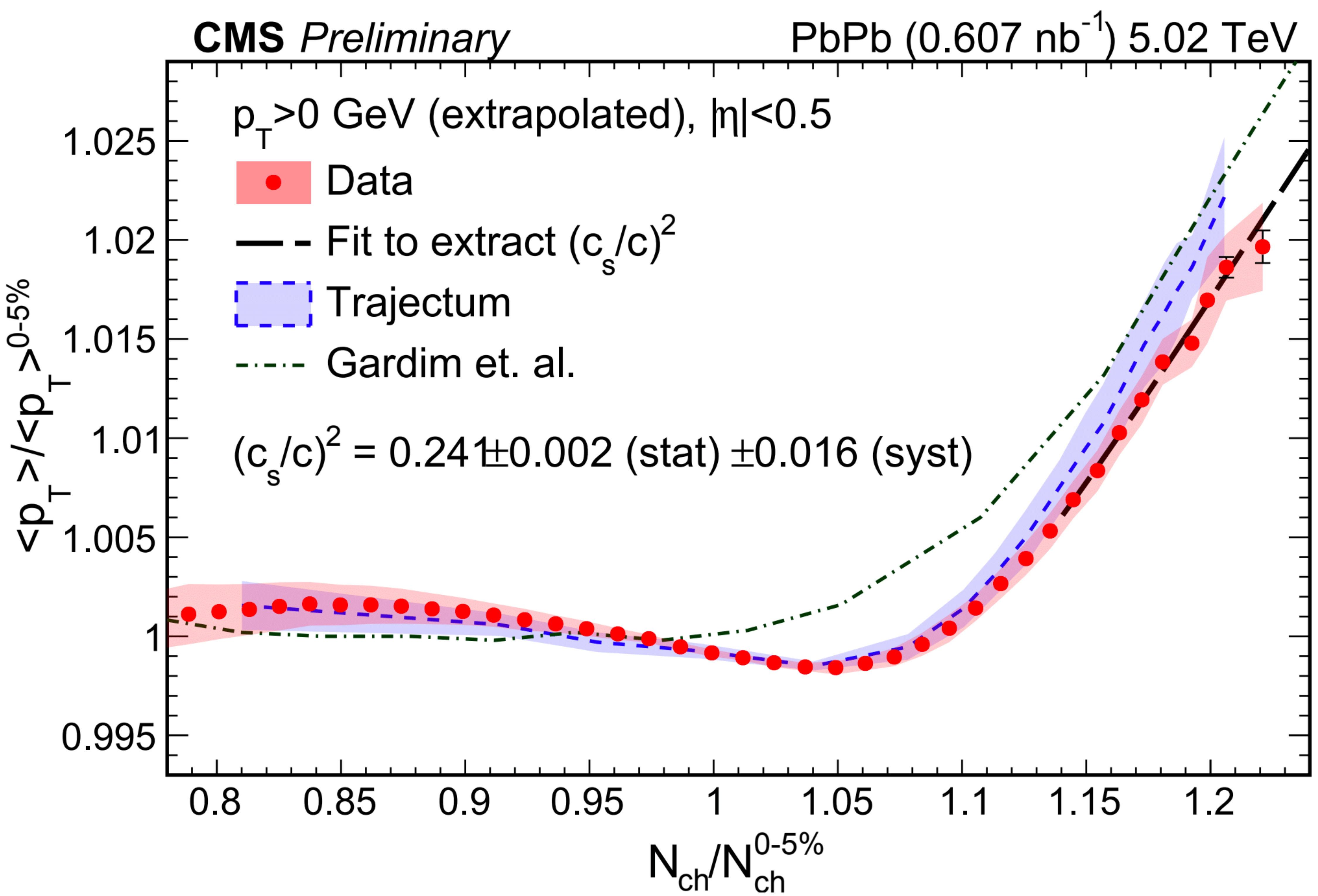


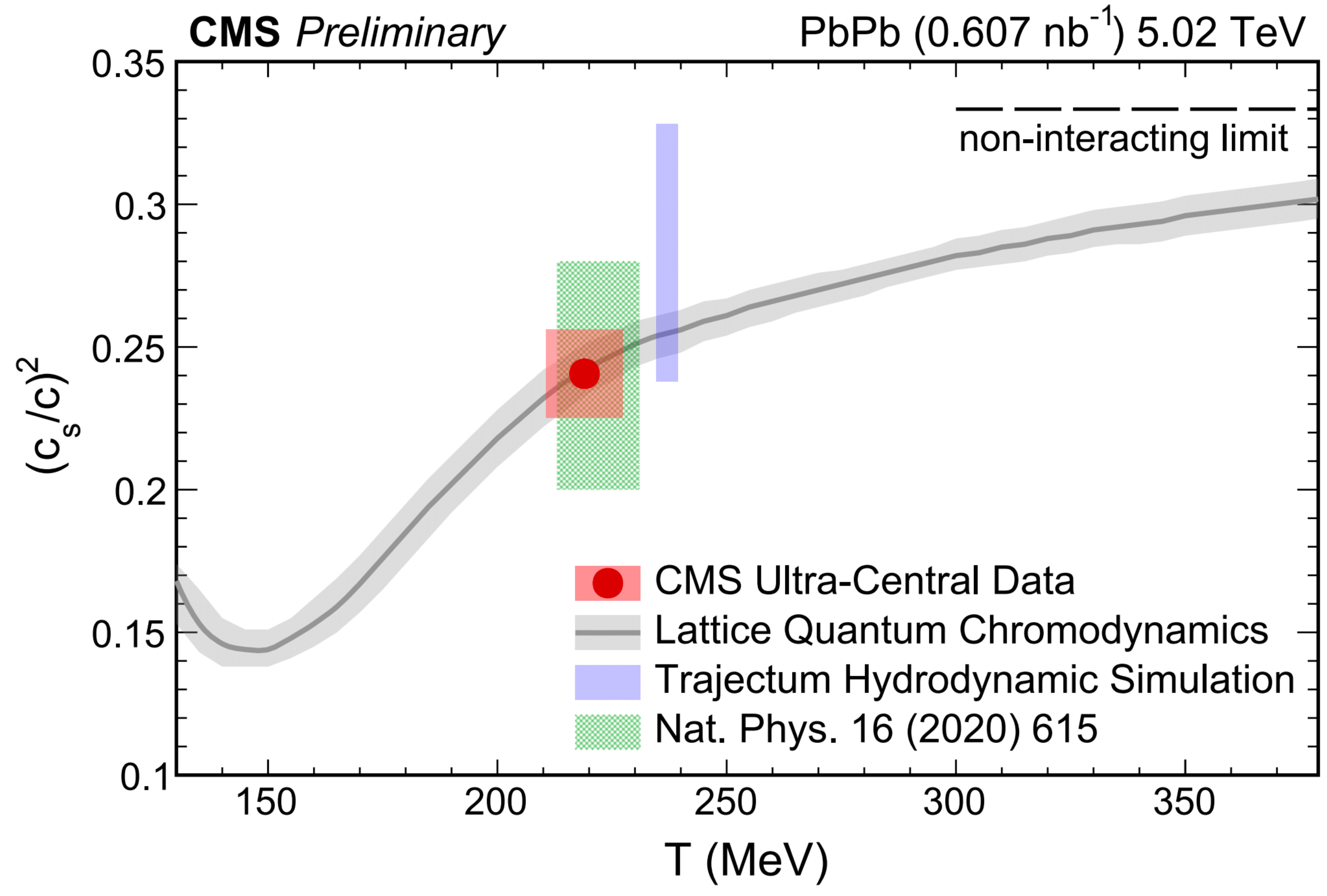
Fit slope to get c_s^2

Summary

- First measurement of the speed of sound in QGP using UCC collisions
- Good agreement with lattice QCD (2+1 flavors)
  - Constrains equation of state - interesting to look at lower T (at RHIC?)
  - Confirms deconfined d.o.f.
- Origin of 'dip' still not understood - fluctuations?

More documentation at:
CMS PAS HIN-23-003





Backup