Revealing QCD thermodynamics in ultra-relativistic nuclear collisions

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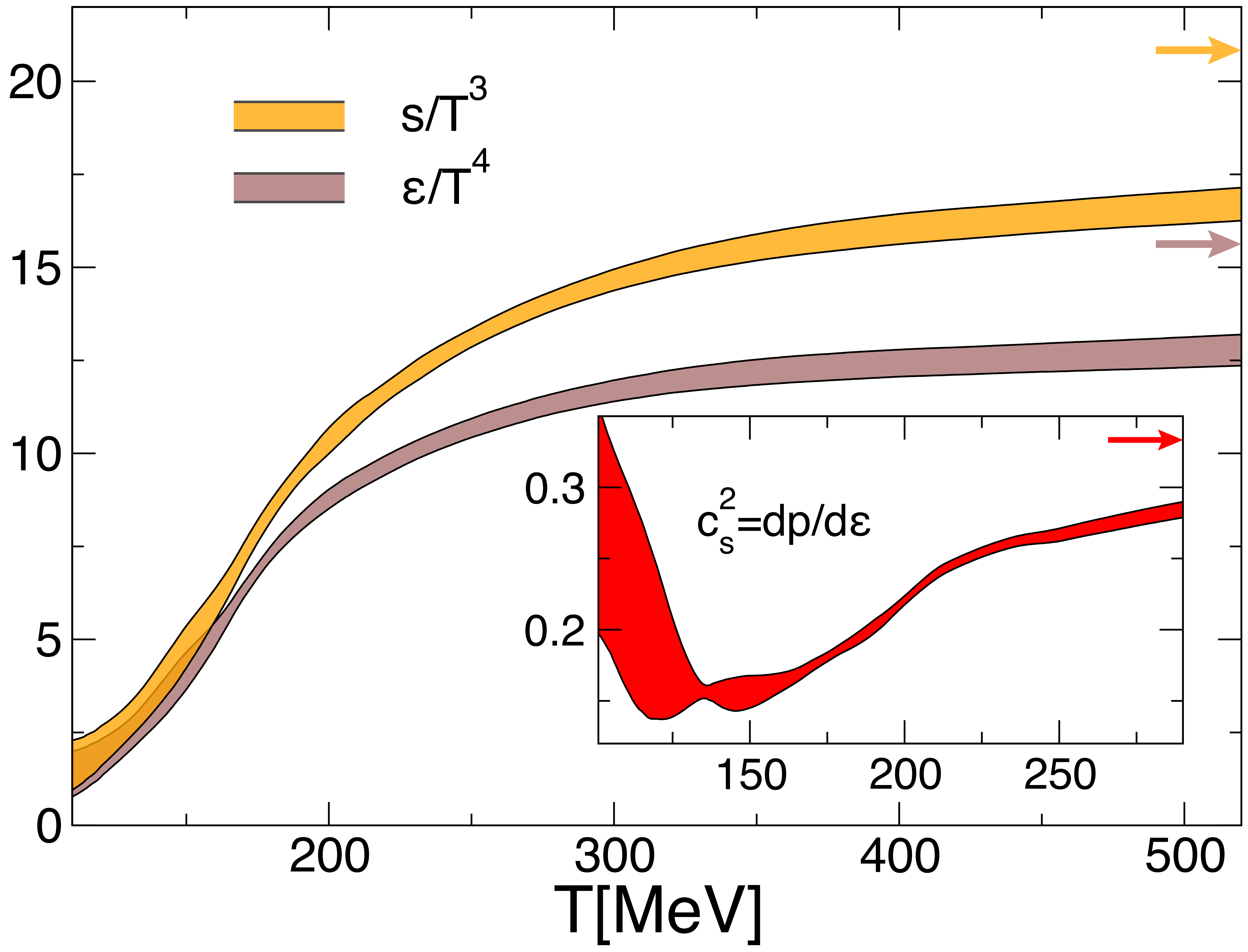
Based on 1908.09728, 1909.11609, in collaboration with Fernando Gardim, Giuliano Giacalone, Matt Luzum

Can we measure the equation of state of QCD in heavy ion collisions?



Borsanyi et al, 1309.5258

The equation of state is accurately calculated in lattice QCD.

Can we confirm some of these results with heavy-ion data ?

Heavy Ion Collisions: The Big Picture, and the Big Questions

Wit Busza,[1] Krishna Rajagopal,[1,2] and Wilke van der Schee[2,3]

Annual Review of Nuclear and Particle Science, 1802.04801

5. Can we obtain an experimental determination, even indirectly, of the temperature of the matter produced in a heavy ion collision at a time at which we can also determine its energy density? If we could, we could obtain an experimental determination of the number of thermodynamic degrees of freedom, the quantity whose increase reflects the liberation of color above the crossover in the QCD phase diagram.

This talk: Yes we can!!

Why this is difficult

The temperature in a Pb-Pb collision depends on space and time:
Larger in the center, smaller near the edges.
Larger at the beginning, smaller at the end of the evolution

In a hydrodynamic calculation, the temperature typically varies from 400 MeV down to 150 MeV.

I will show that the relation between multiplicity and mean p_t is determined by a narrow range of temperature, around 220 MeV at LHC run 2.

Effective temperature, effective volume

We define the effective temperature, T_{eff}, and the effective volume, V_{eff}, of the quark-gluon plasma, as those of a uniform fluid at rest which would have the same energy E and entropy S as the fluid at freeze-out.

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

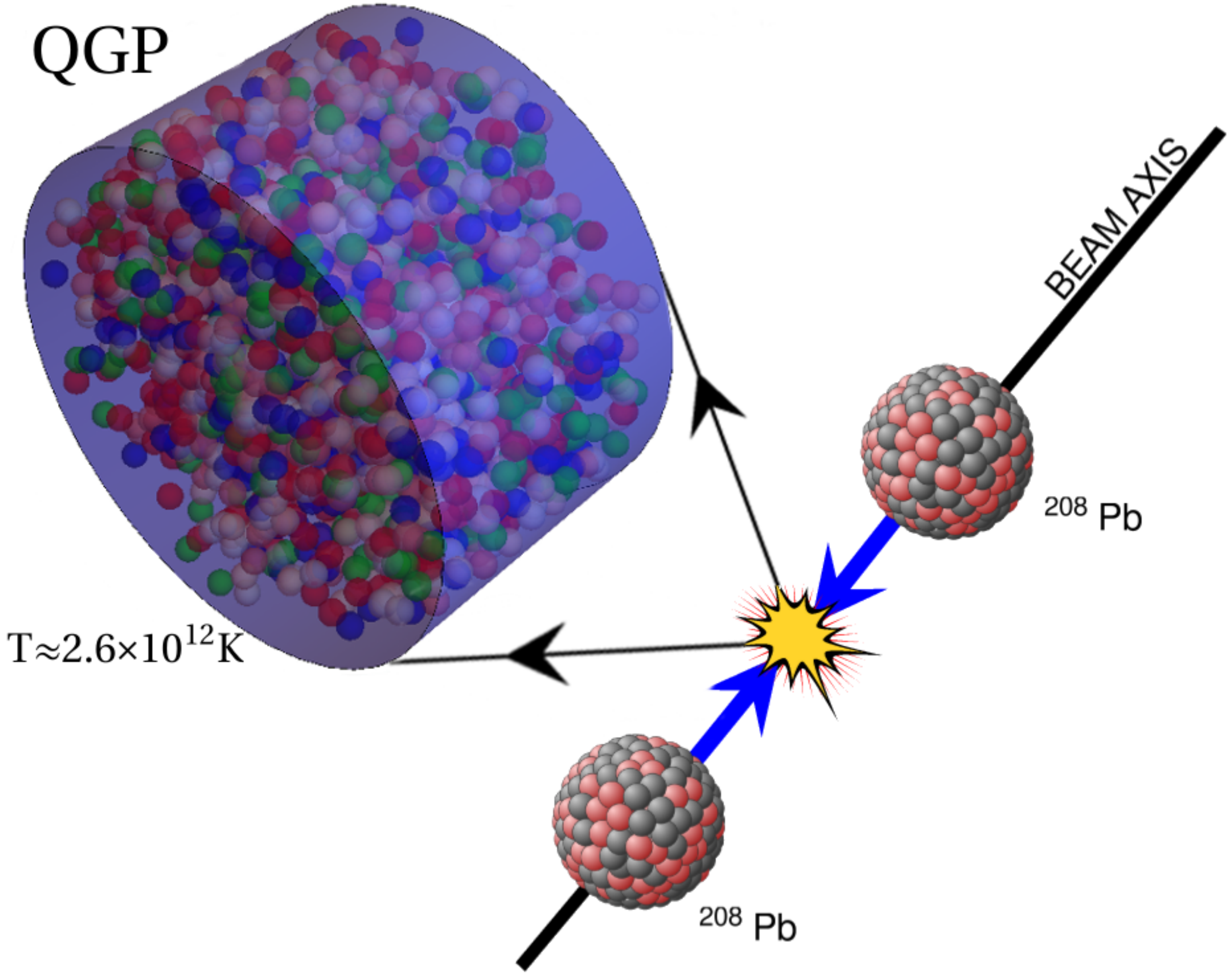
$$S = \int_{\text{f.o.}} s u^\mu d\sigma_\mu = s(T_{\text{eff}}) V_{\text{eff}},$$

I will show that T_{eff} and $s(T_{eff})$ can be obtained from experiment.

Effective temperature, effective volume

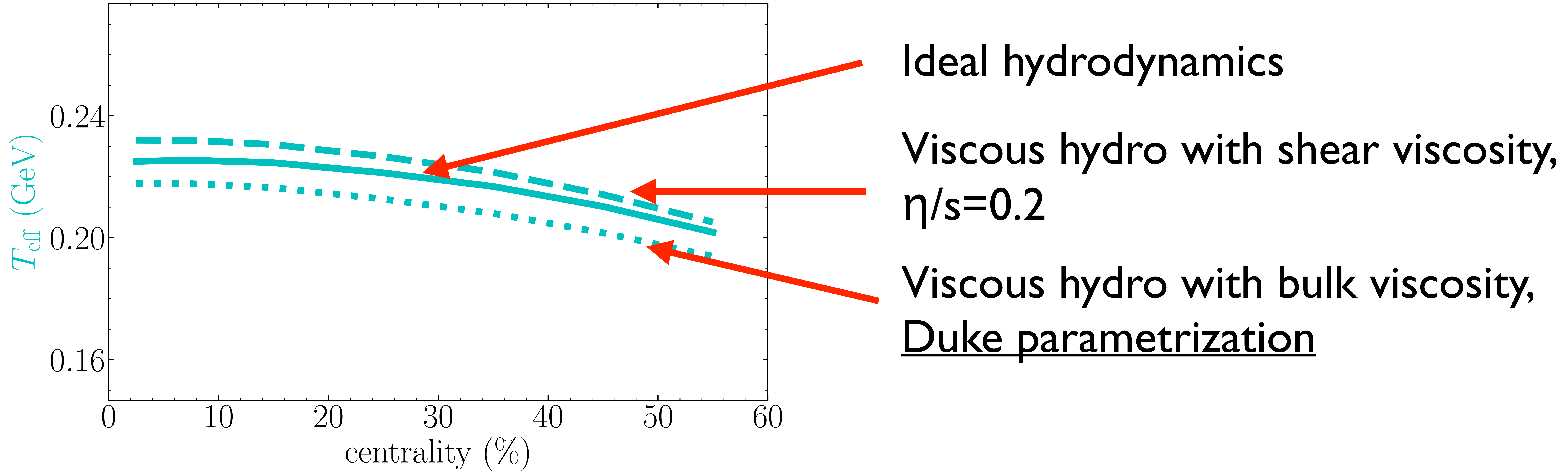
Put the total energy and entropy contained in the system (just before it transforms into hadrons) into a uniform cylinder.

Effective temperature and volume are those of this cylinder.



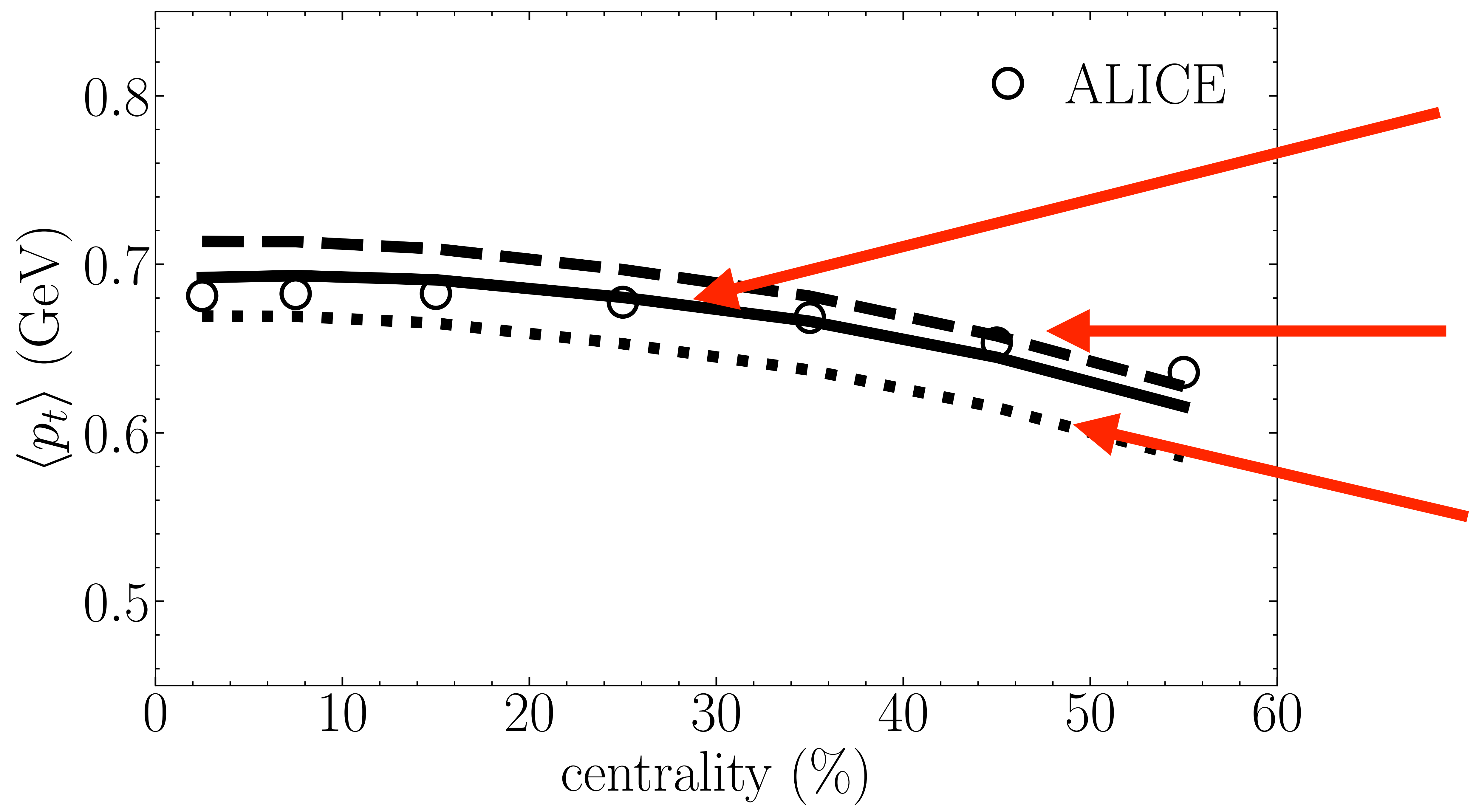
Value of T_{eff} in Pb+Pb collisions at 5.02 TeV

Hydrodynamic calculations using the MUSIC code, initial temperature tuned to reproduce the charged multiplicity measured by ALICE for each centrality.



Can we relate T_{eff} to observables?

We compute the mean transverse momentum of charged hadrons at freeze-out



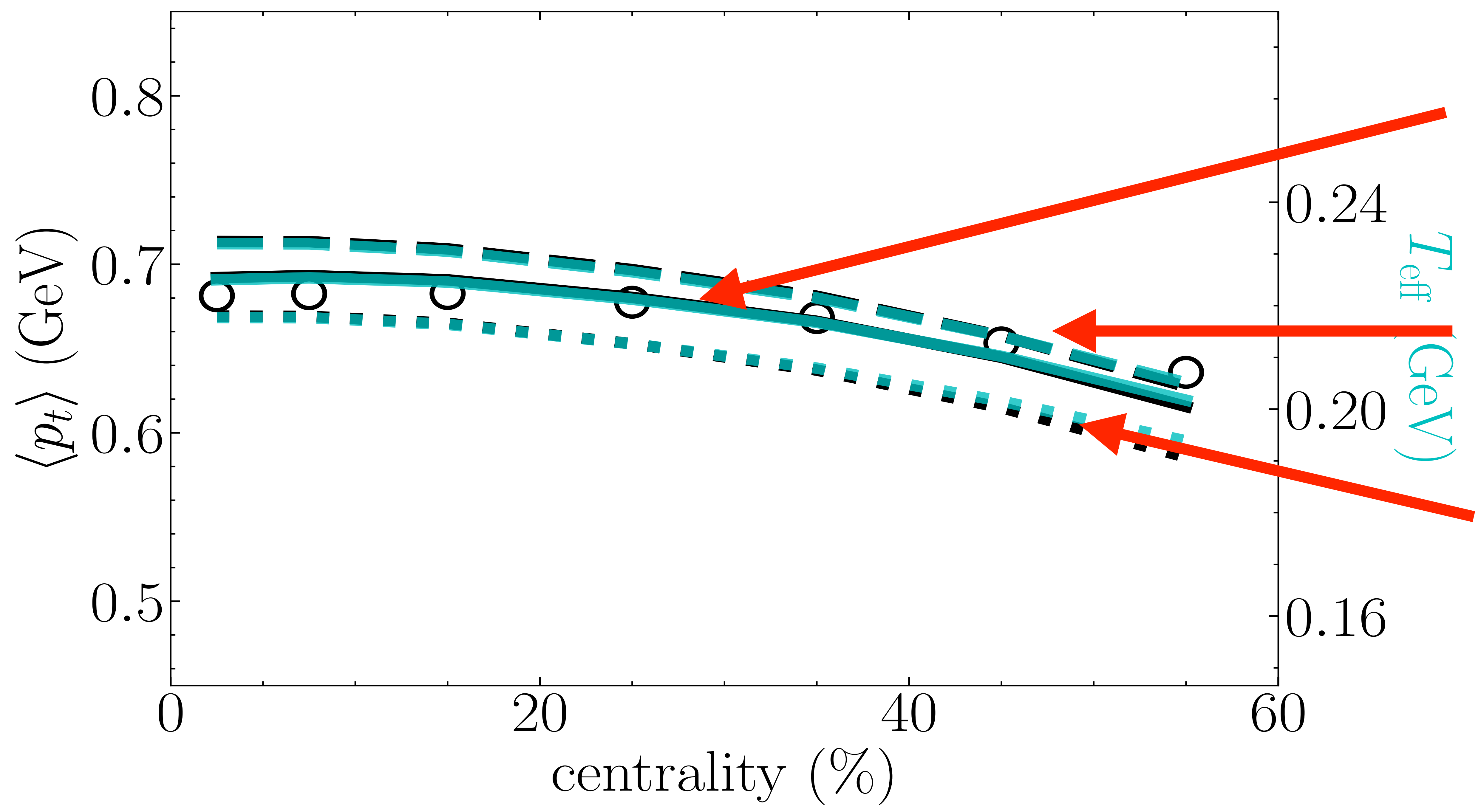
Ideal hydrodynamics

Viscous hydro with shear viscosity, $\eta/s=0.2$

Viscous hydro with bulk viscosity, Duke parametrization

And the miracle occurs!

$\langle p_t \rangle = 3.07\, T_{eff}$ for all centralities, irrespective of bulk and shear viscosity!



Ideal hydrodynamics

Viscous hydro with shear viscosity, η/s=0.2

Viscous hydro with bulk viscosity, Duke parametrization

Interpretation

In a massless ideal gas, the energy per particle is $3T$

$<p_t>$ is essentially the energy per particle, somewhat smaller because of longitudinal motion.

For massive particles, $<p_t>$ is somewhat larger

Eventually, $<p_t>$ ends up being very close to $3T_{eff}$ in a hydrodynamic calculation, irrespective of details of the hydrodynamic model, provided that freeze-out is realistic.

Value of T_{eff} in central 5.02 TeV Pb+Pb collisions

Extraction from data is straightforward.
ALICE measures $\langle p_t \rangle$ = 681 MeV in 0-5% centrality bin.

This implies $T_{eff} = \langle p_t \rangle / 3.07 = 222 \pm 9$ MeV,

where the error is estimated by varying the freeze-out temperature.

Next step: entropy density at T_{eff}

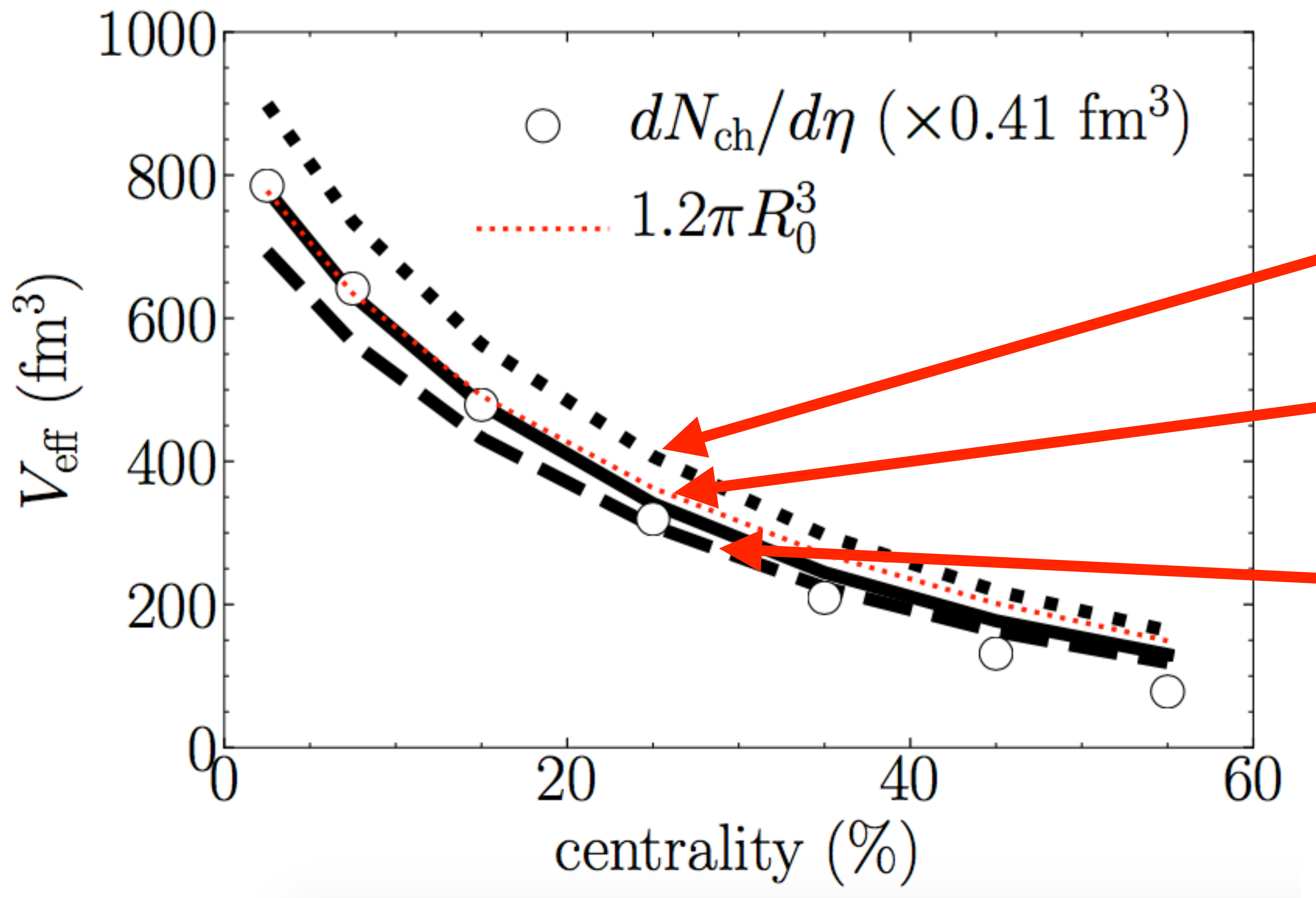
Entropy density = S/V_{eff}

S =entropy *at freeze-out*, by definition of V_{eff} and T_{eff}
S/N_{ch} = 6.7 ± 0.8 after resonance decays,
N_{ch} is measured, therefore, S is known

Hanus, Mazeliauskas Reygers, 1908.02792

Effective volume V_{eff} cannot be extracted from data.
Comes from a hydrodynamic calculation.

Estimating the effective volume



Viscous hydro with bulk viscosity, <u>Duke parametrization</u>

Ideal hydrodynamics

Viscous hydro with shear viscosity, $\eta/s=0.2$

V_{eff} is proportional to R_0^3, where R_0 = initial transverse size

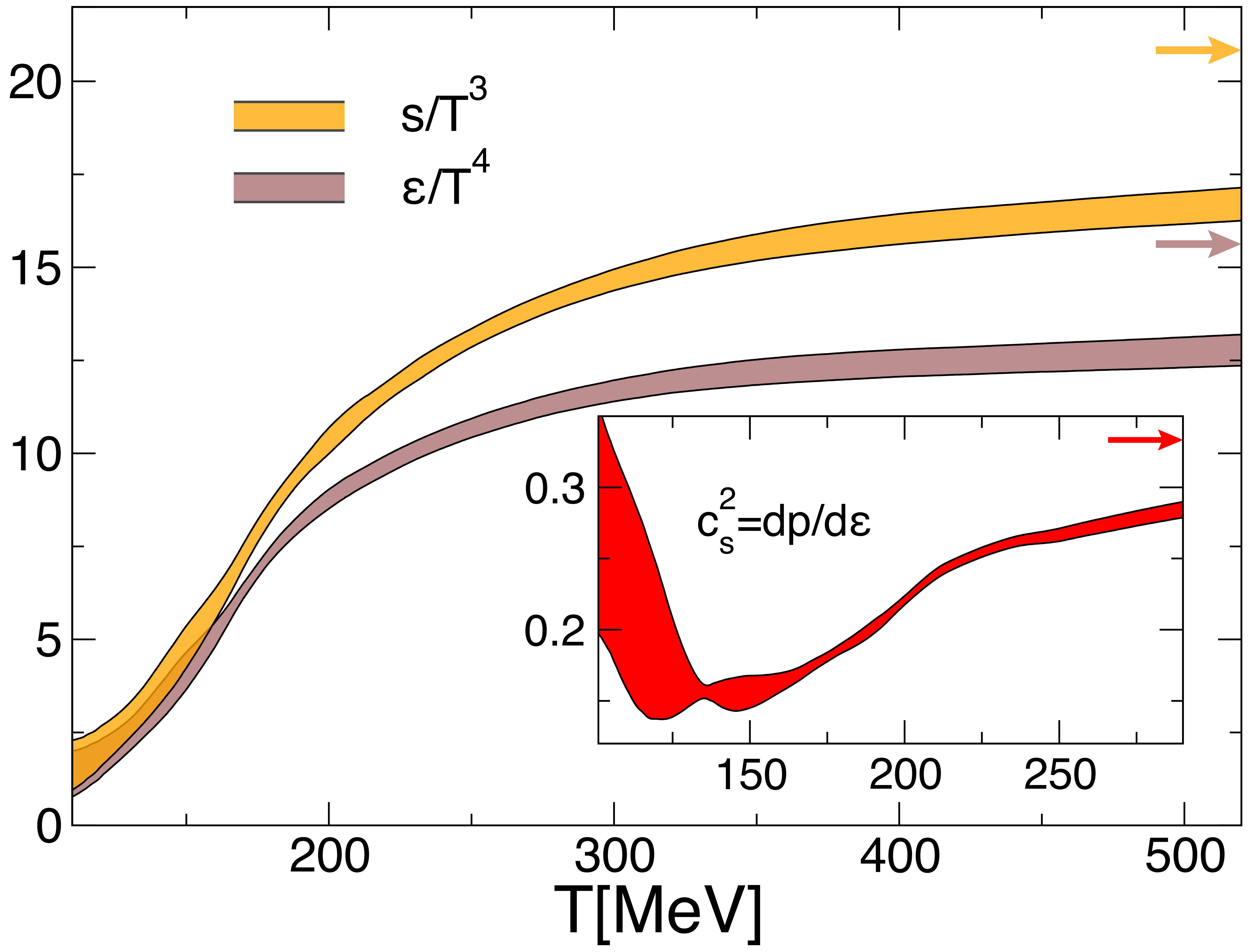
Entropy density at T_{eff}

We obtain $S/V_{eff} = s(T_{eff}) = 20 \pm 5\ fm^{-3}$.

error : 40% from initial size R_0, which depends on the model of initial conditions

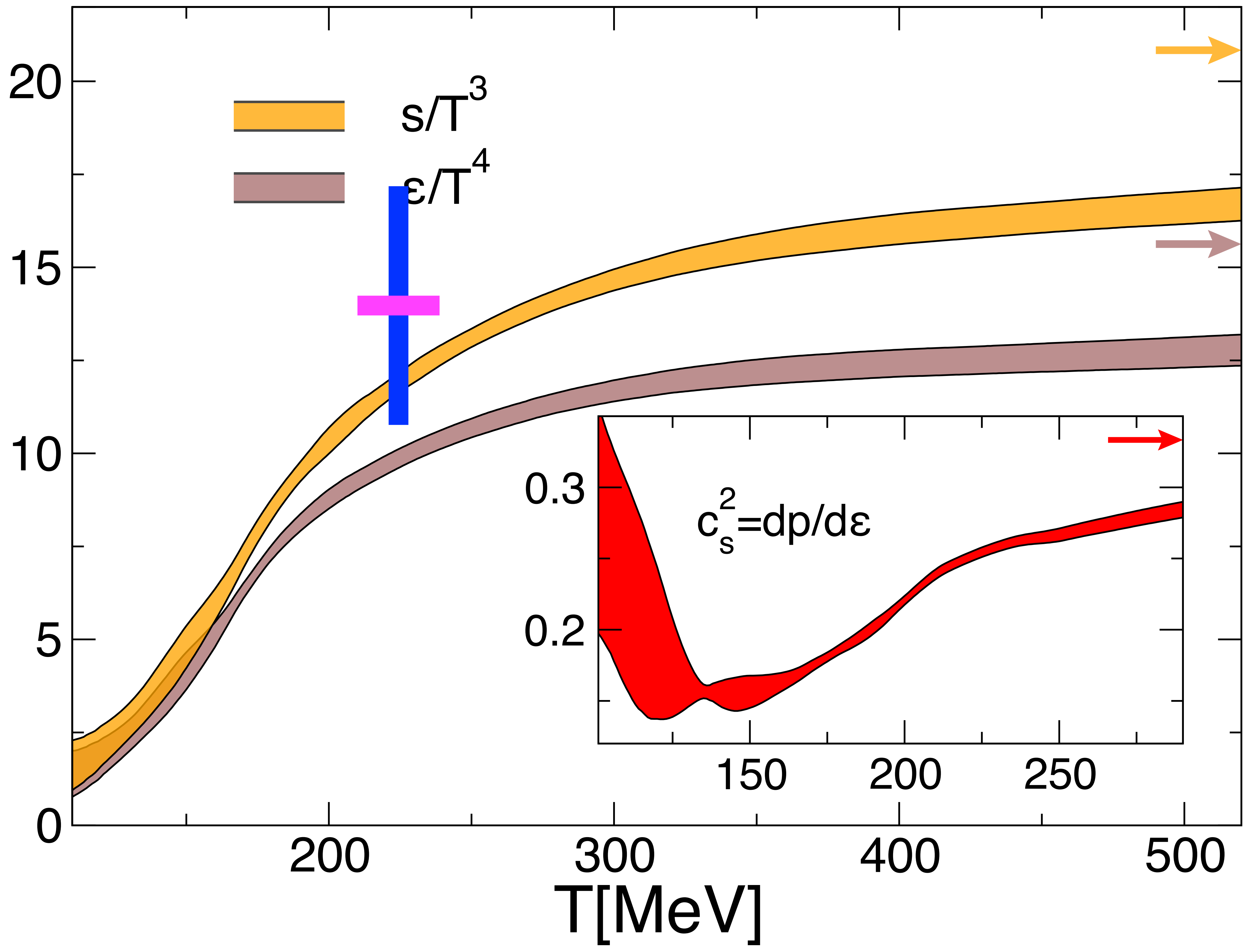
60% from transport coefficients, which modify V_{eff} / R_0^3

Comparison with lattice QCD



Entropy density

Comparison with lattice QCD



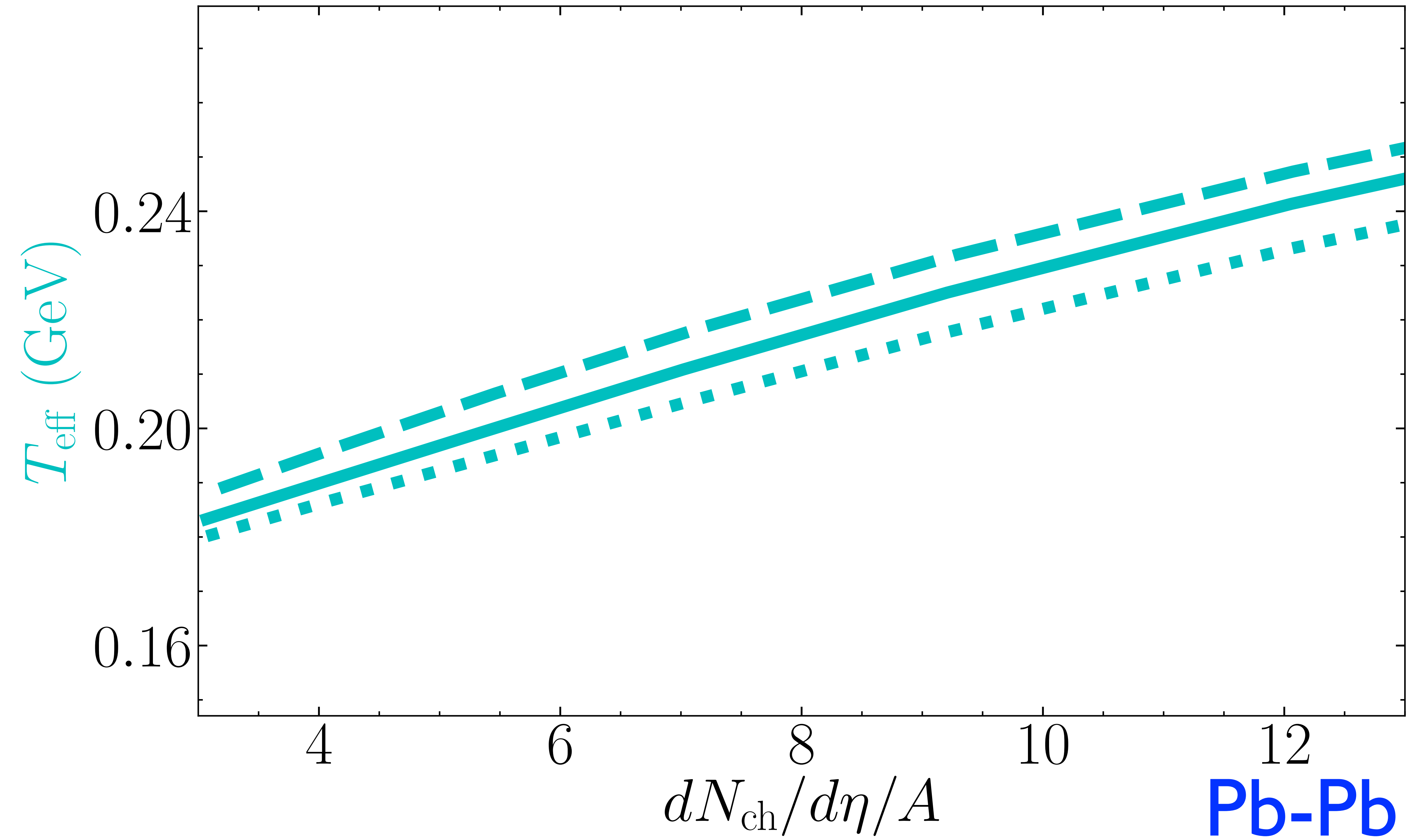
T_{eff}=222 ± 9 MeV

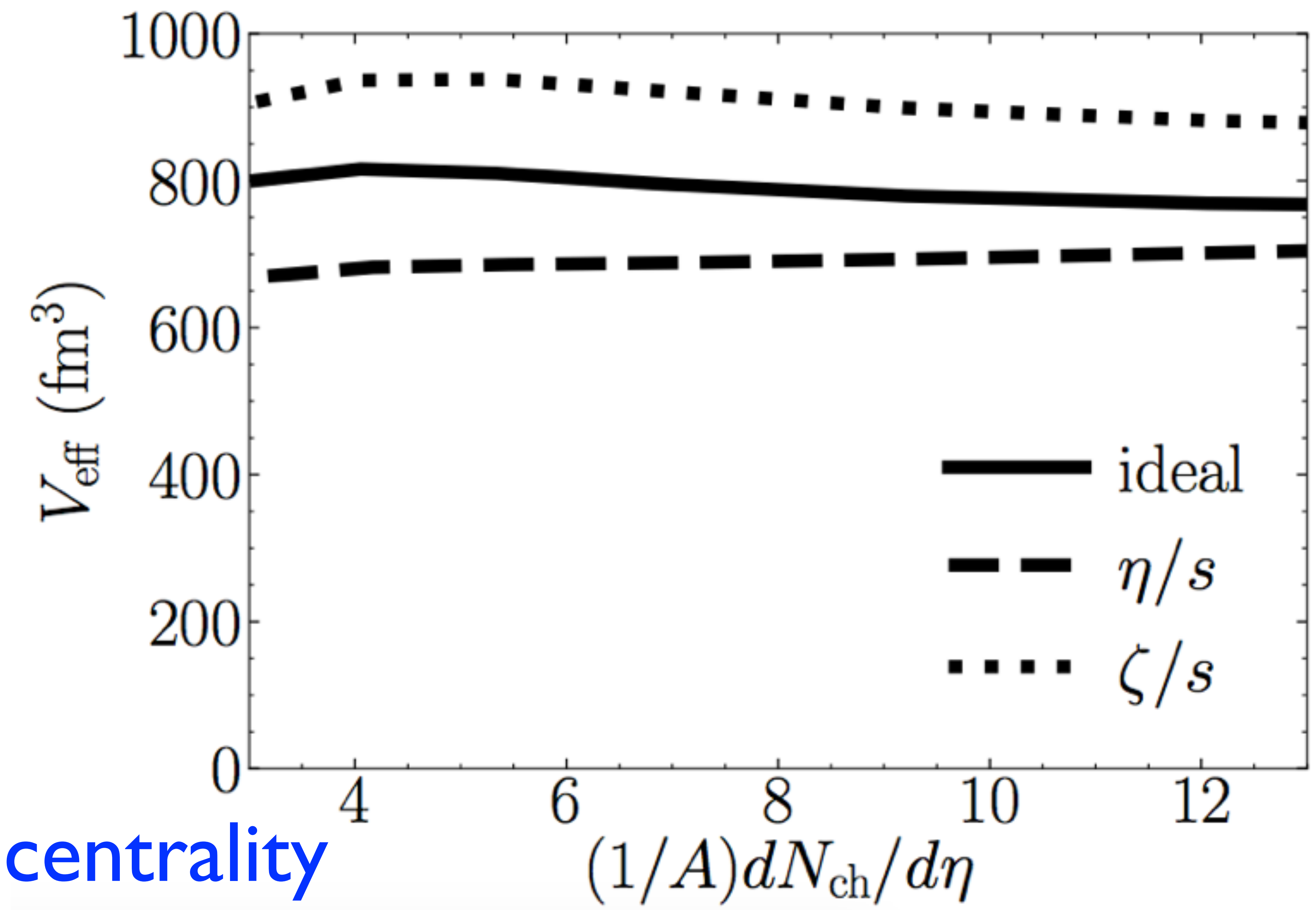
$s(T_{eff})/T_{eff}^3$ = 14 ± 3.5

compatible with lattice.

Confirms large number of degrees of freedom, implying that color is liberated: ***deconfinement observed!***

Varying the collision energy

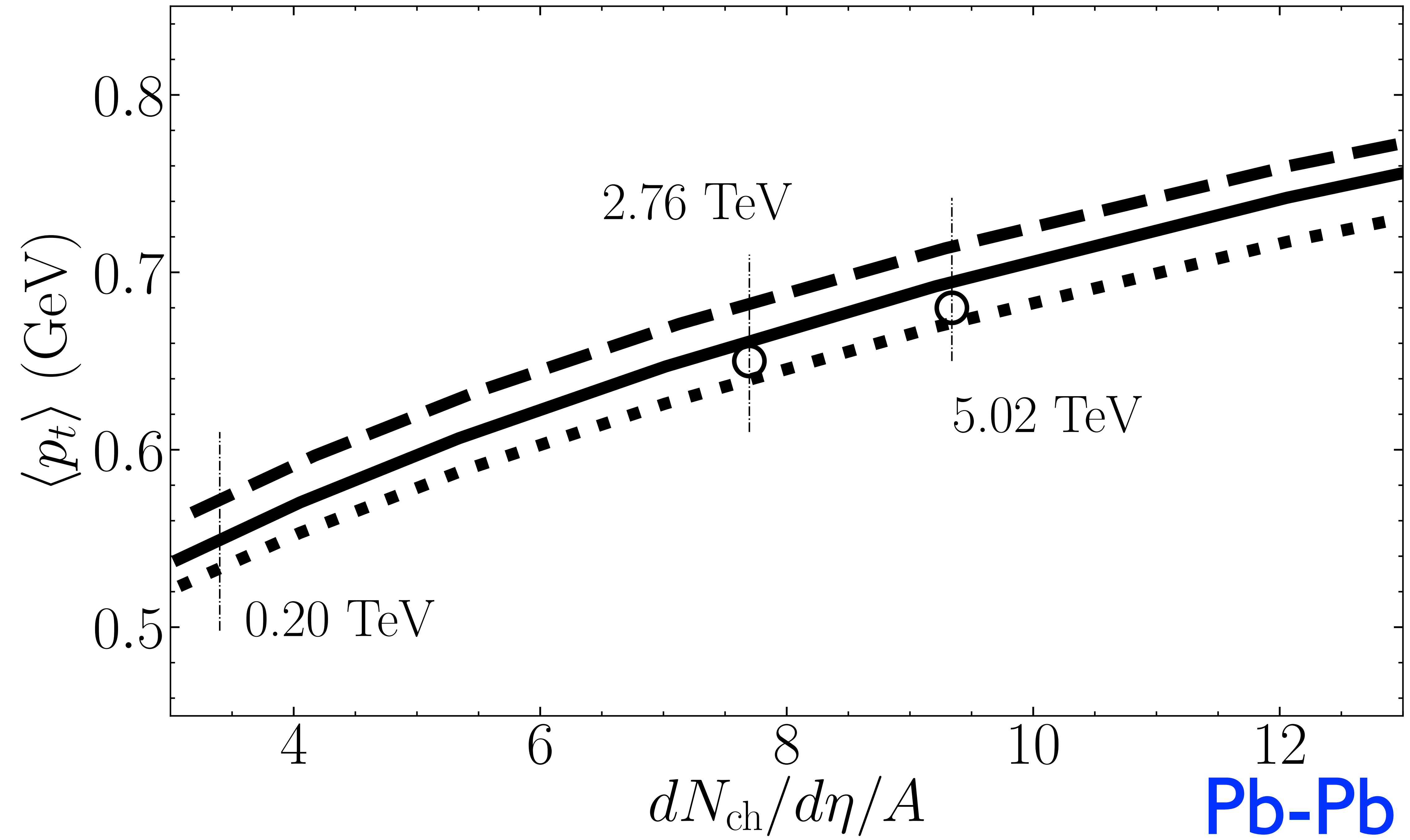


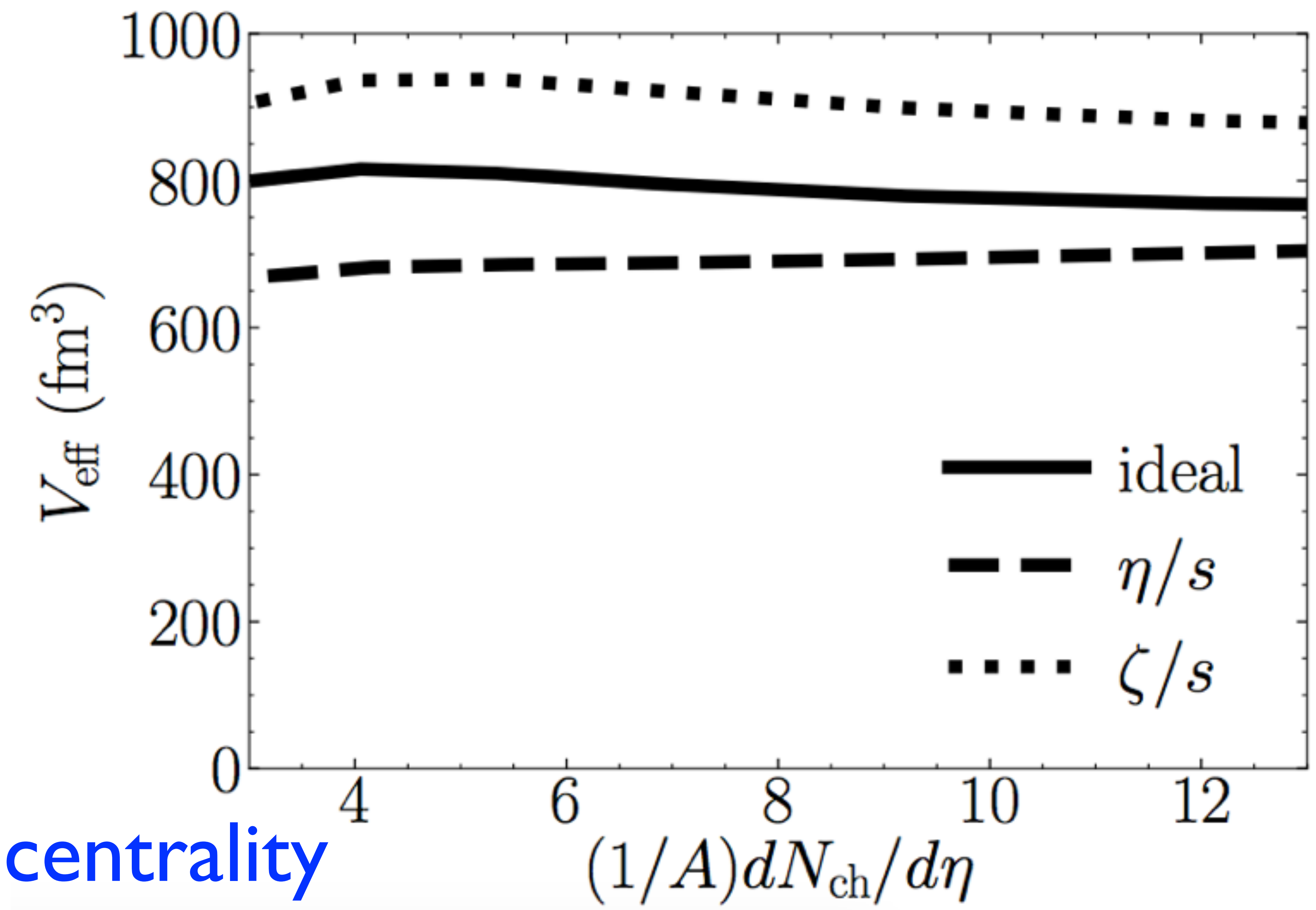


Pb-Pb 0-5% centrality

As sqrt(s) increases, $T_{\rm eff}$ increases, $V_{\rm eff}$ remains constant.
Increasing energy amounts to heating the system at constant volume.

Varying the collision energy

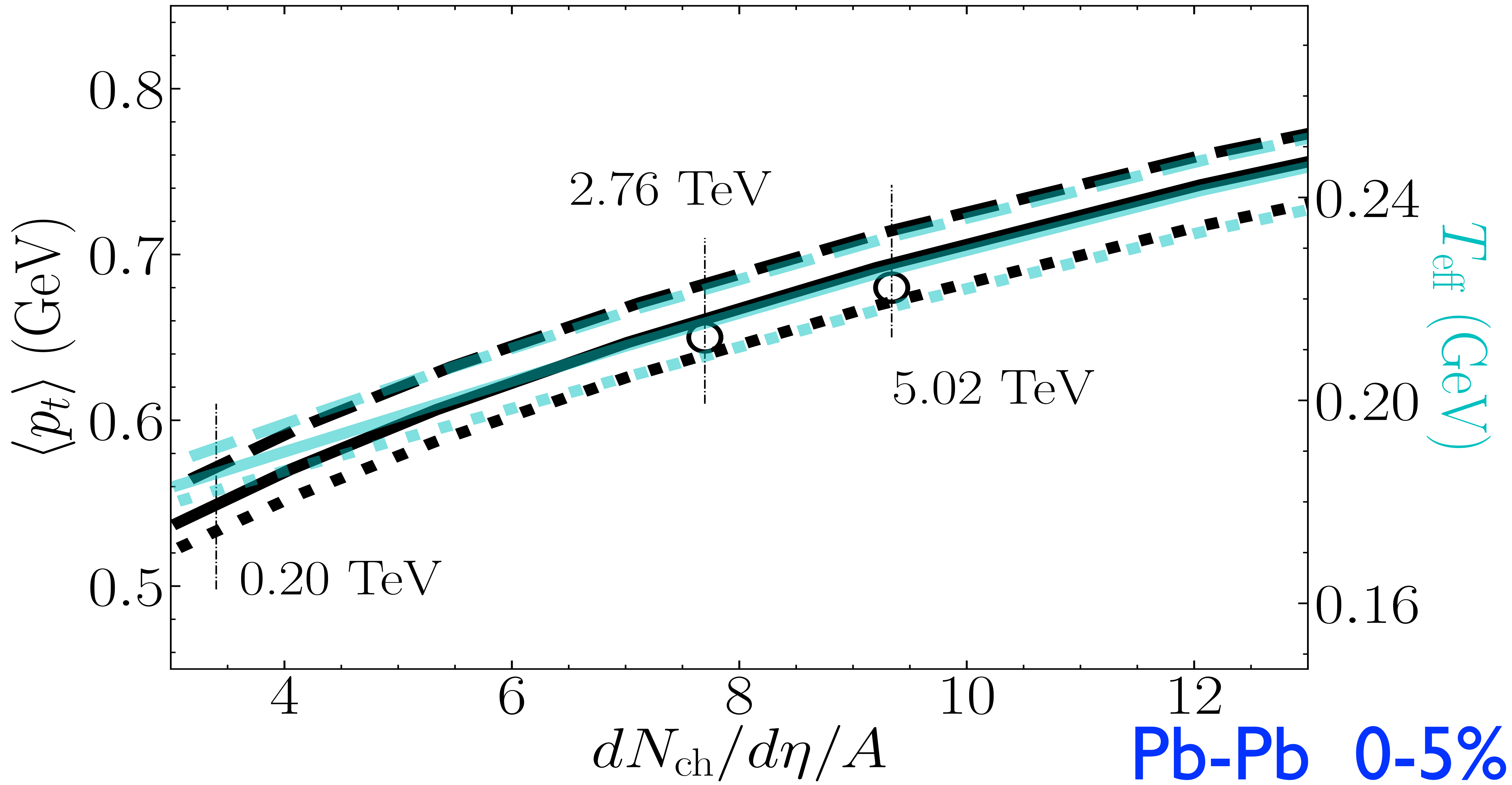




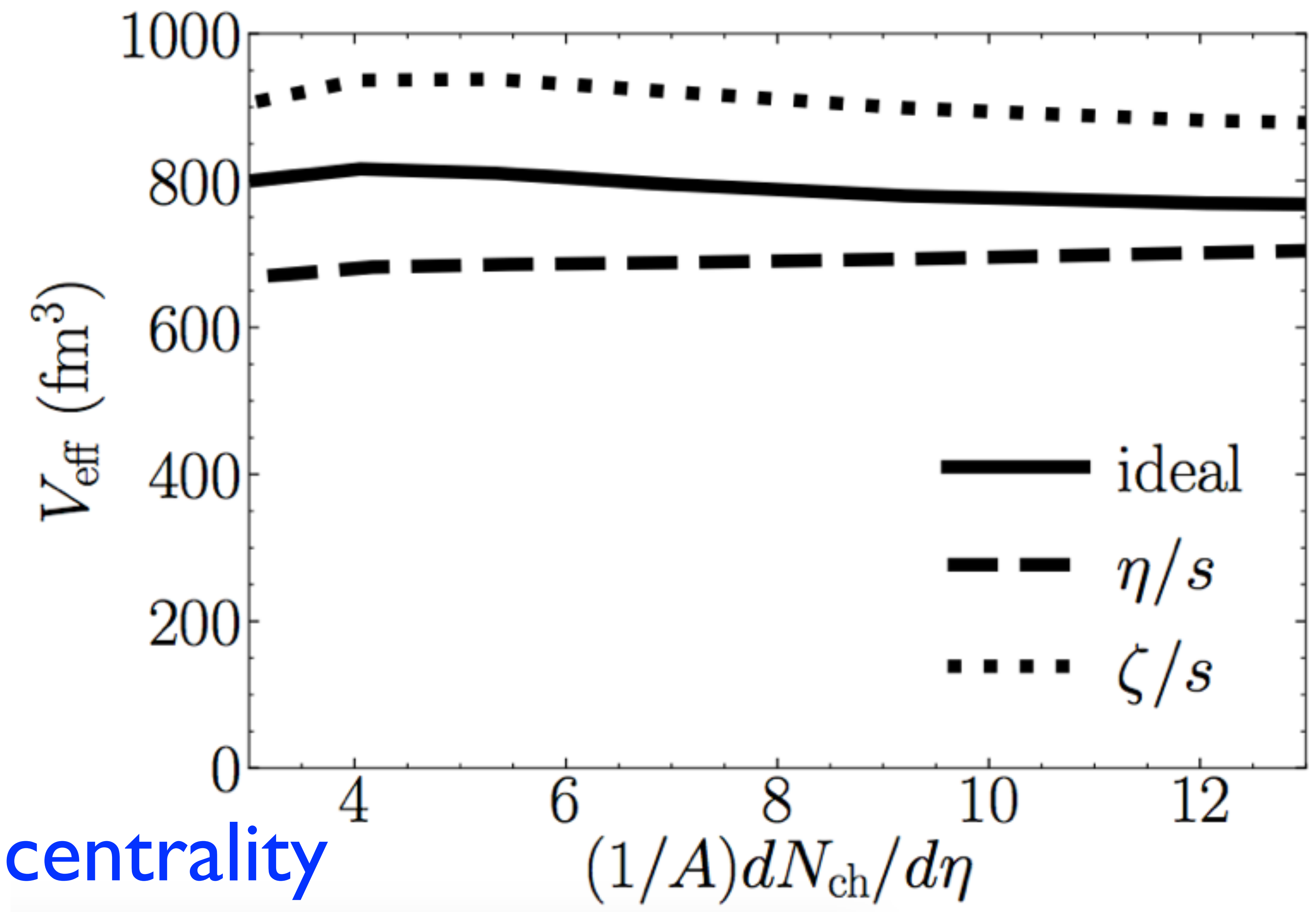
Pb-Pb 0-5% centrality

The variation of <p_t> still closely follows that of T_{eff}

Varying the collision energy

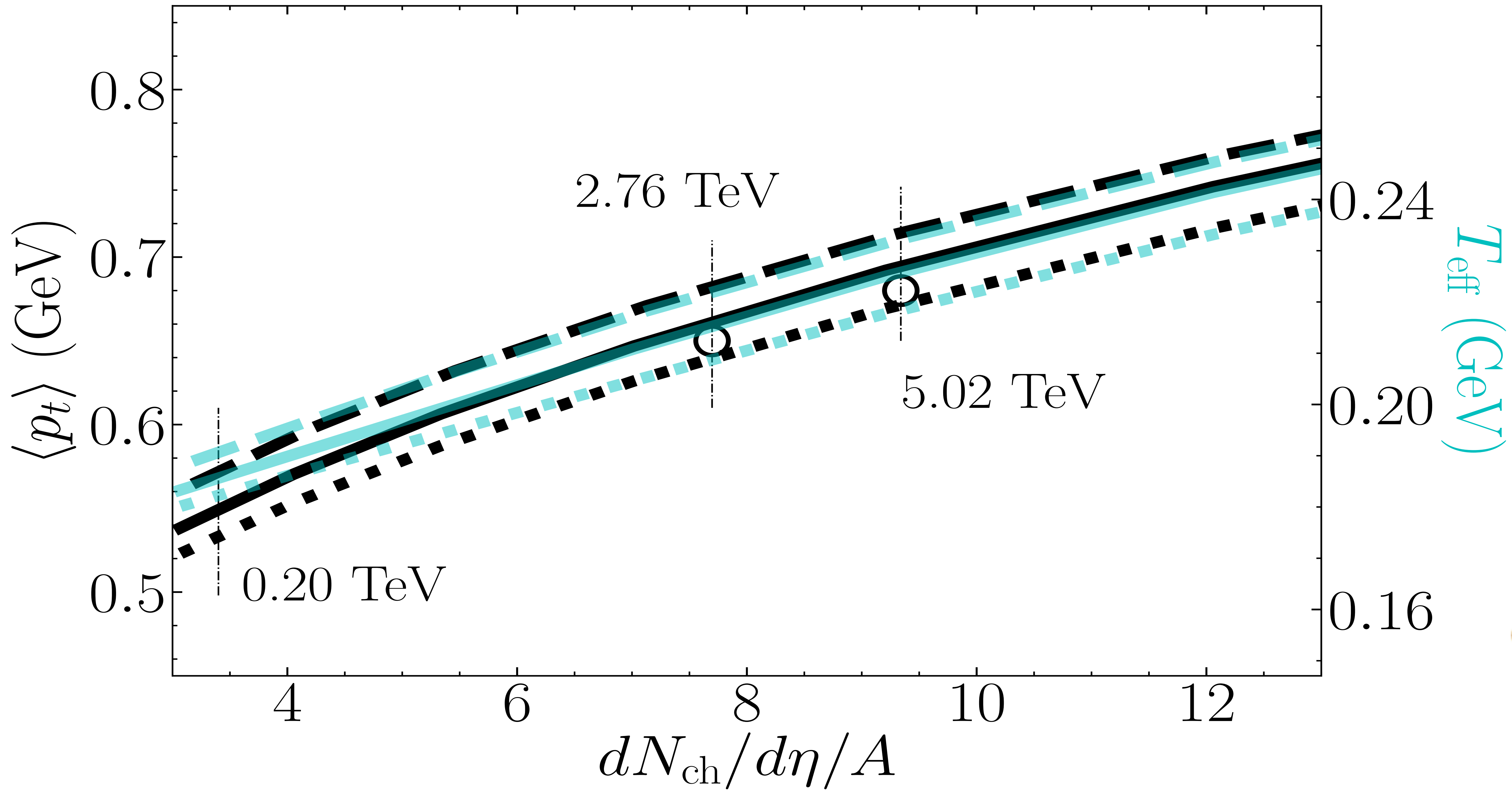


Pb-Pb 0-5% centrality



Deviations from $\langle p_t \rangle = 3.07\, T_{eff}$ are negligible at LHC energy and beyond

Finally: speed of sound c_s in the QGP

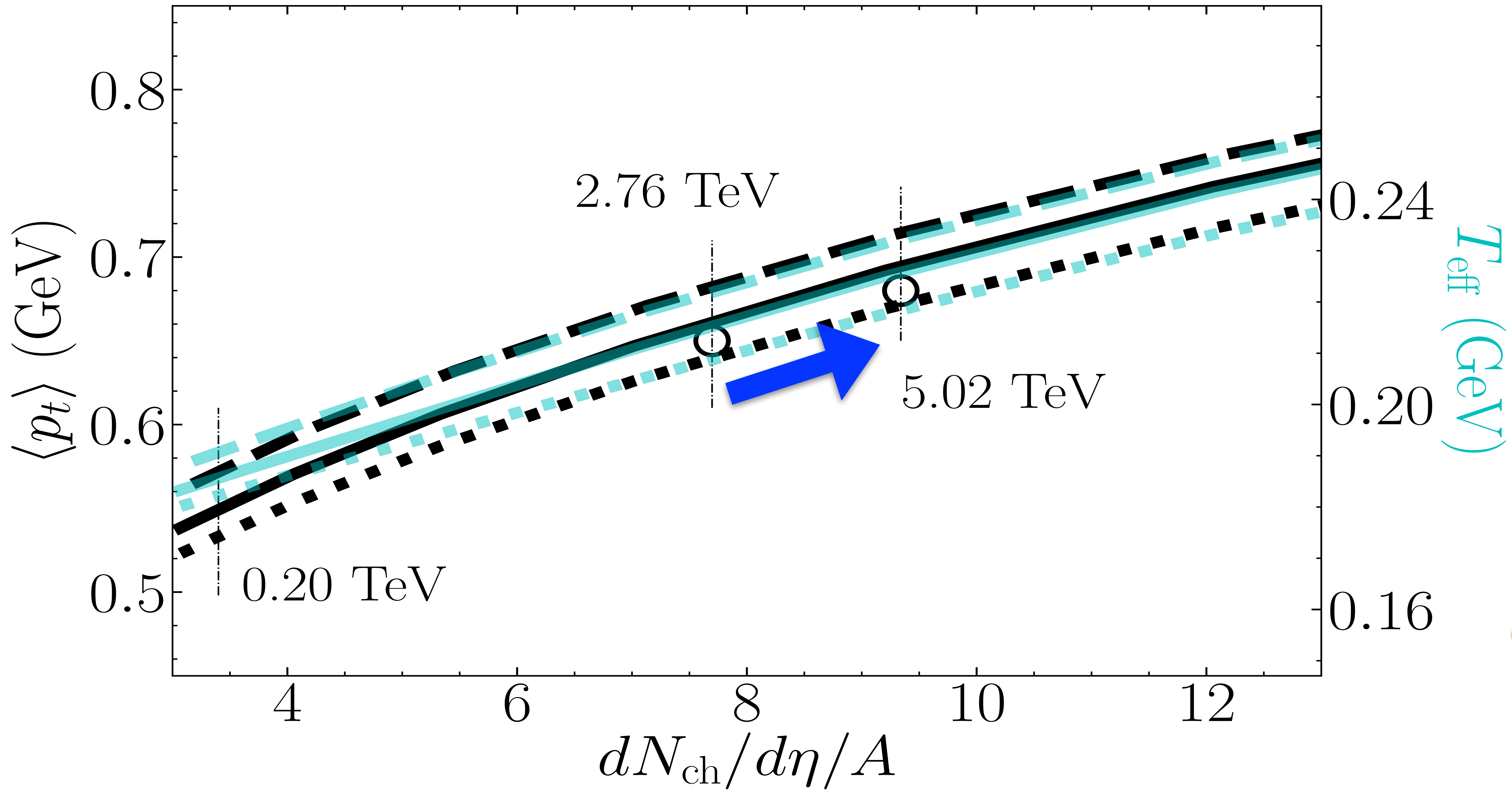


$T_{\rm eff}$ proportional to $\langle p_t \rangle$

$s(T_{\rm eff})$ proportional to $dN_{ch}/d\eta$

$$c_s^2(T_{\rm eff}) \equiv \frac{dP}{d\varepsilon} = \frac{sdT}{Tds}\bigg|_{T_{\rm eff}} = \frac{d\ln\langle p_t\rangle}{d\ln(dN_{\rm ch}/d\eta)}$$

Finally: speed of sound c_s in the QGP



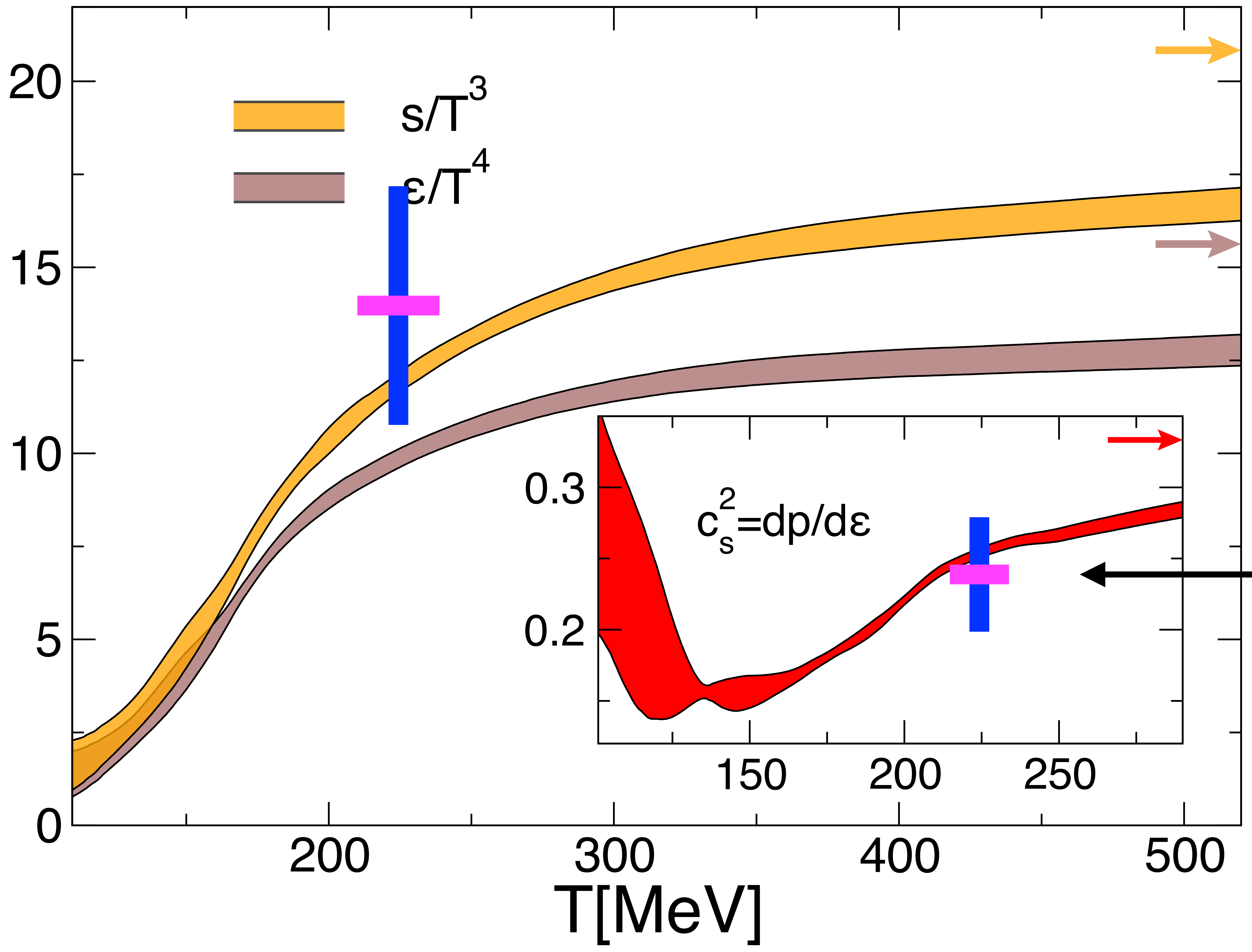
$T_{\rm eff}$ proportional to $\langle p_t \rangle$

$s(T_{\rm eff})$ proportional to $dN_{ch}/d\eta$

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

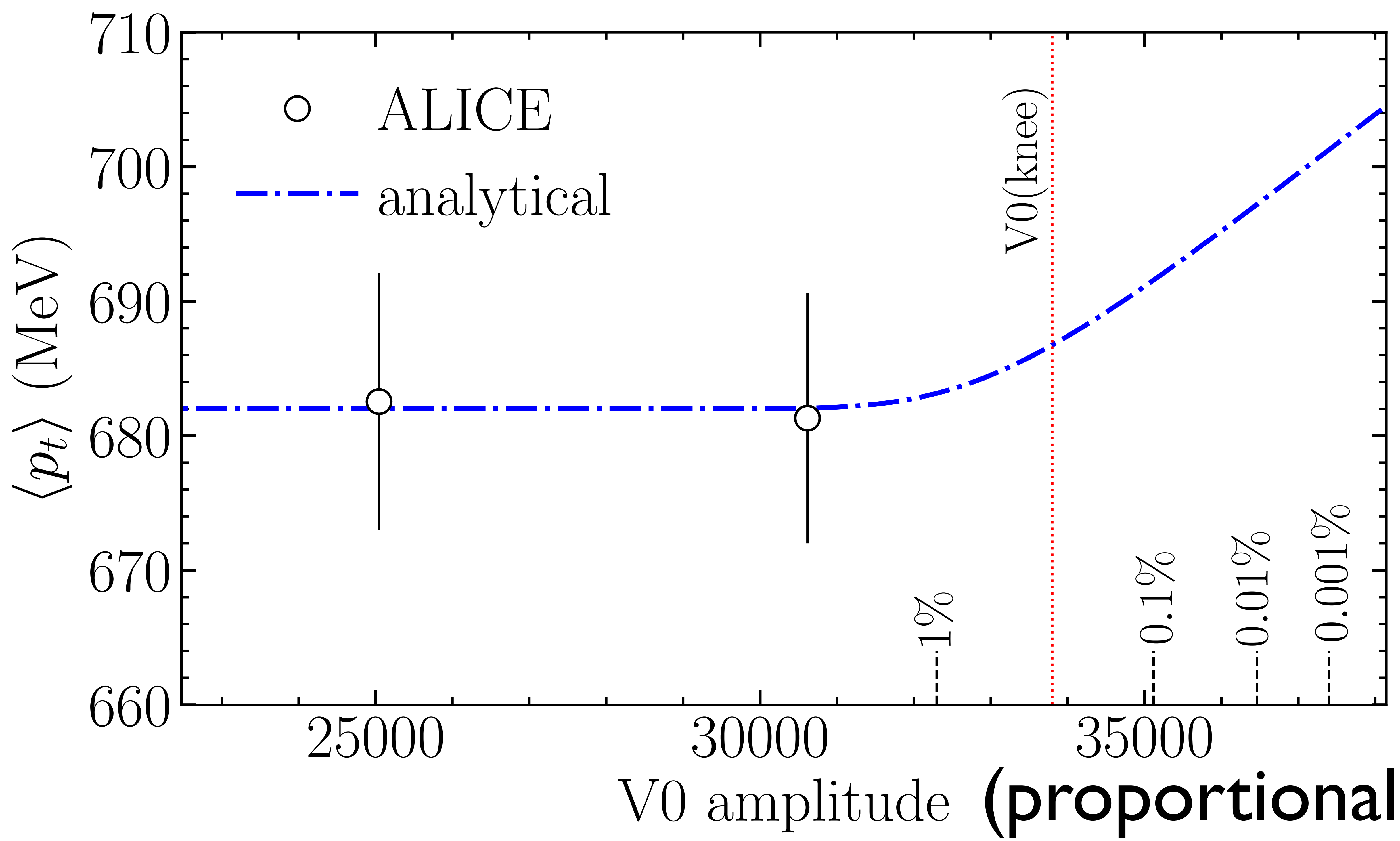
we obtain $c_s^2(T_{\rm eff}) = 0.24 \pm 0.04$ (error from variation of $V_{\rm eff}$)

Comparison with lattice QCD



compatible with lattice

Speed of sound from ultracentral collisions



(proportional to multiplicity)

Alternatively, one can fix sqrt(s) and select ultracentral collisions, with the largest multiplicity

$$c_s^2(T_{\rm eff}) \equiv \frac{dP}{d\varepsilon} = \left.\frac{sdT}{Tds}\right|_{T_{\rm eff}} = \frac{d\ln\langle p_t\rangle}{d\ln(dN_{\rm ch}/d\eta)}$$

We predict an increase of $\langle p_t \rangle$ in ultracentral collisions: also gives access to c_s^2

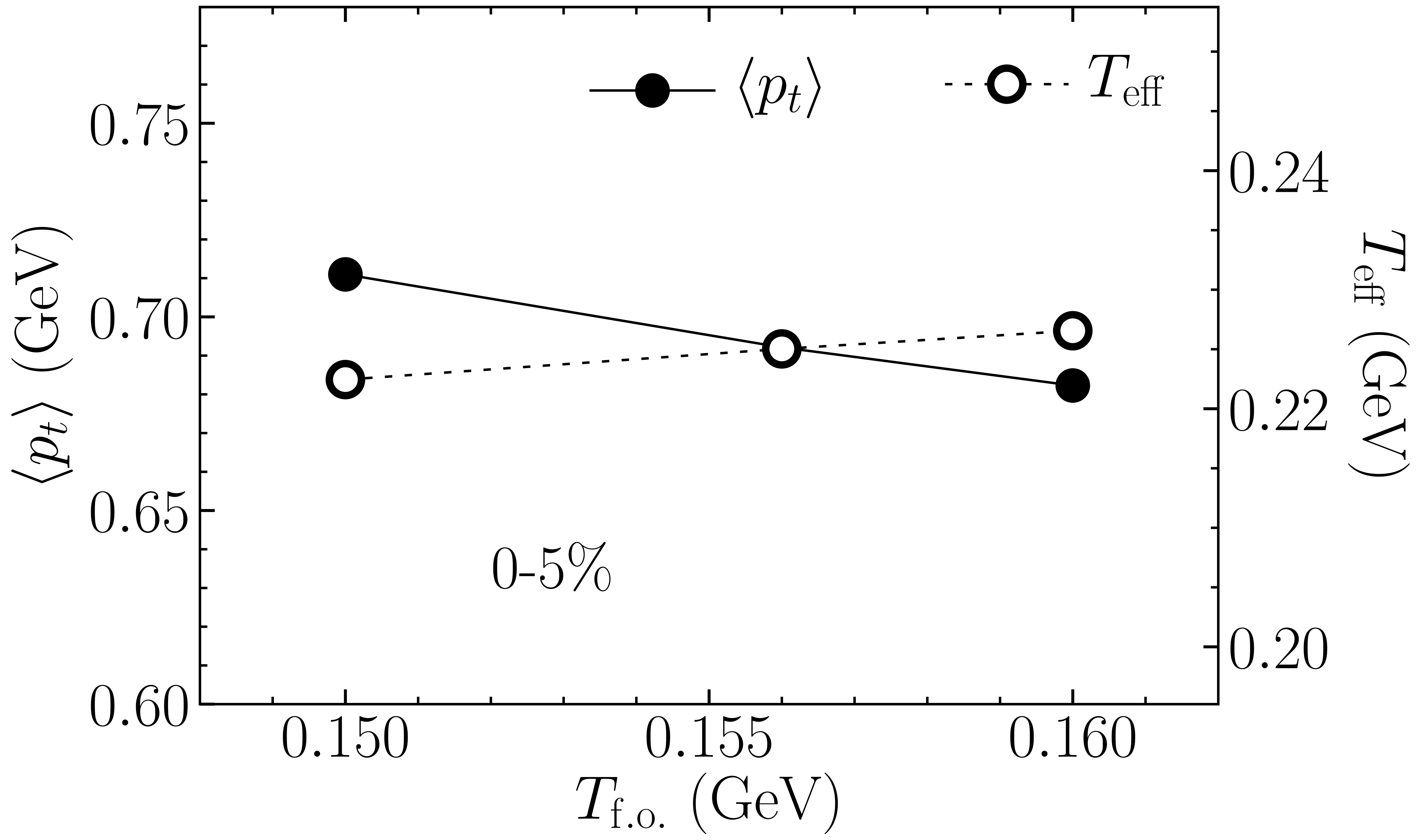
Gardim Giacalone JYO 1909.11609

Summary

- Even though the hydro evolution spans a wide interval of temperatures, only a narrow range matters in practice for $\langle p_t \rangle$ (probably also v_n), corresponding to the time where the transverse expansion develops.
- One can reconstruct the thermodynamics from $\langle p_t \rangle$ and the multiplicity $dN/d\eta$ in this temperature range, 200-220 MeV at LHC.
- Results agree with lattice QCD and clearly confirm that a quark-gluon plasma, where color degrees of freedom are liberated, is produced during the collision.

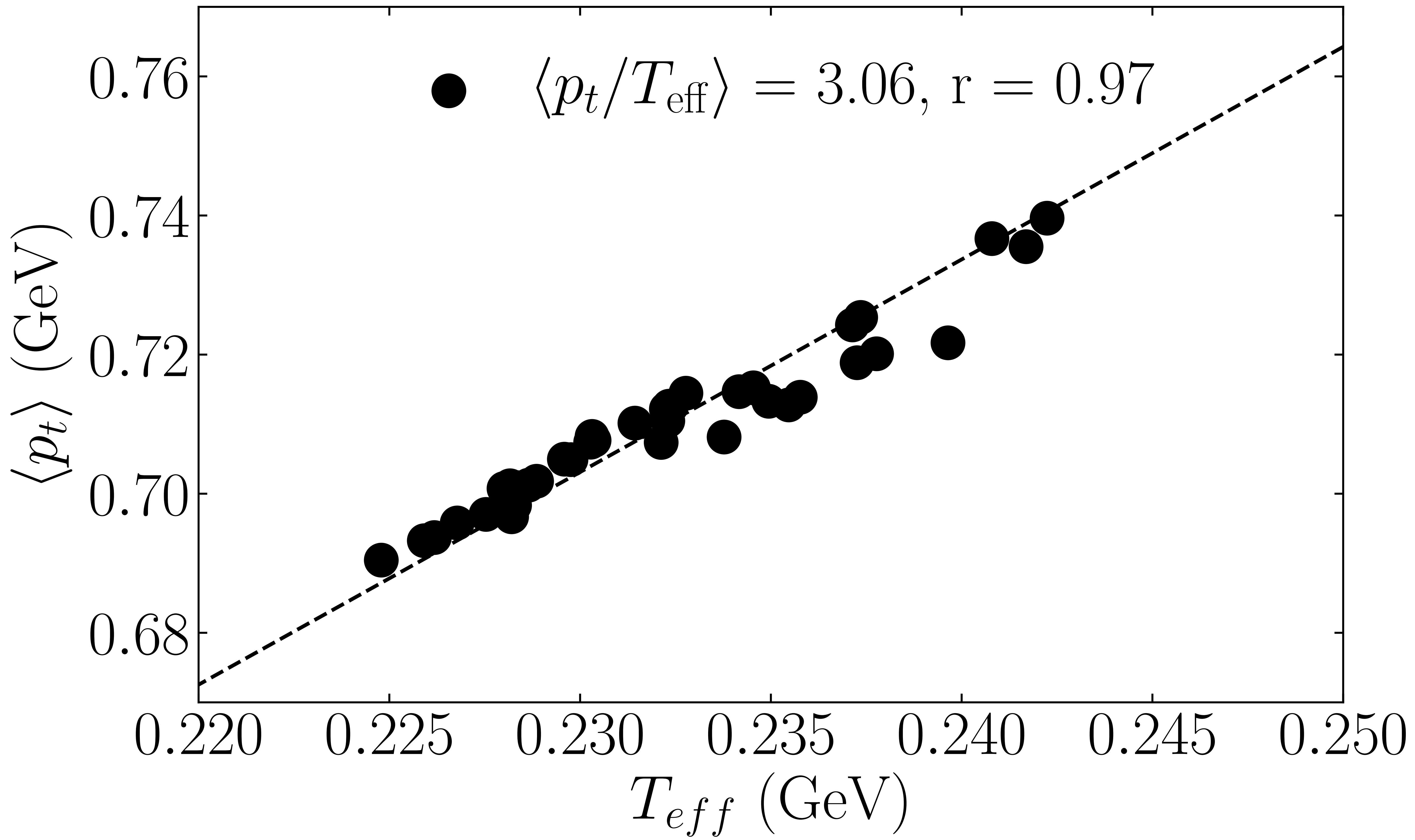
Supplementary material

Varying the freeze-out temperature



This dependence of $\langle p_t \rangle / T_{eff}$ on the freeze-out temperature is the main source of error in the determination of T_{eff} from data.

Event-to-event fluctuations



T_{eff} varies event to event, but the ratio $\langle p_t \rangle / T_{eff}$ is essentially constant.

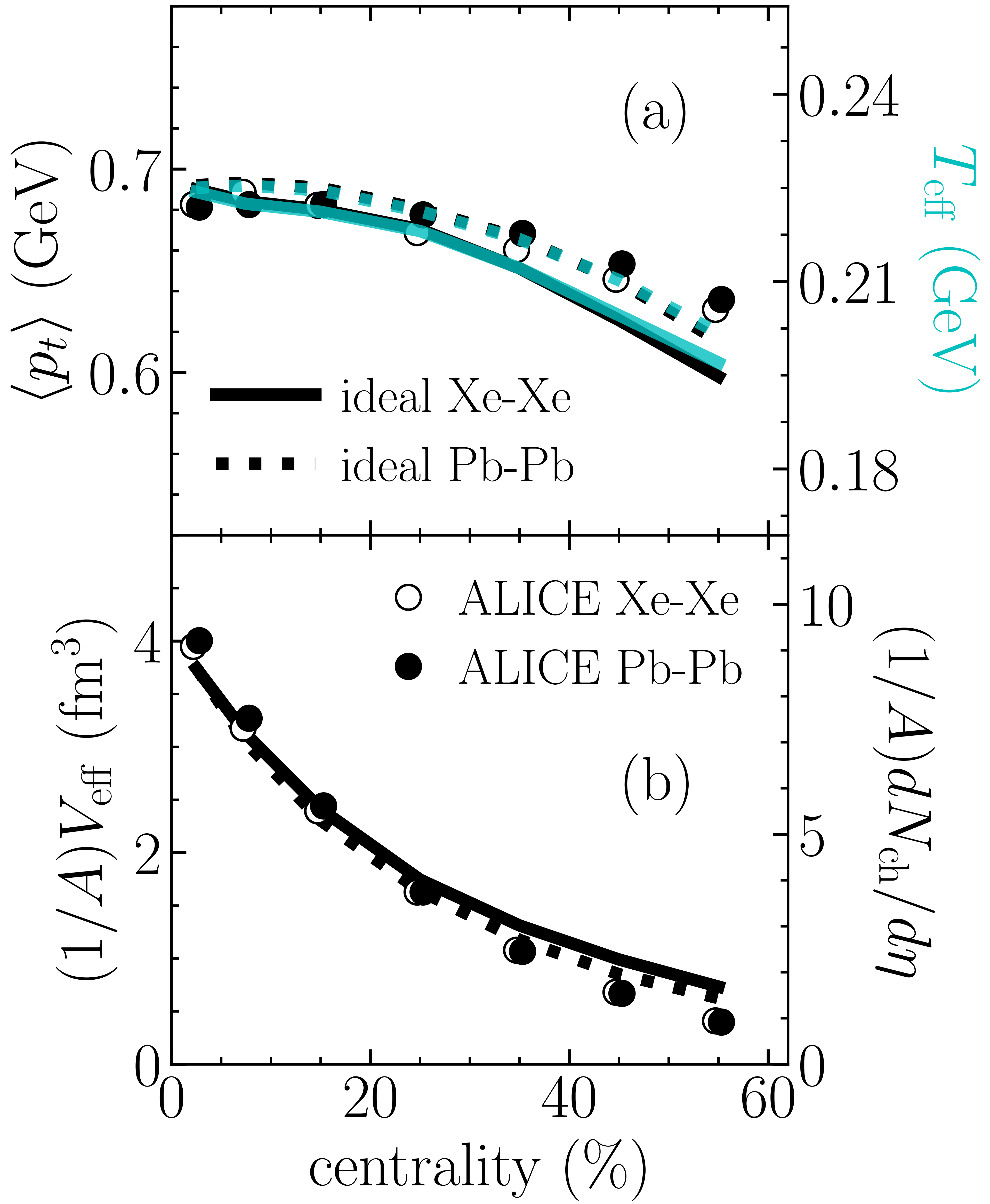
Hence, event-to-event fluctuations do not change the determination of T_{eff} from data

Definition of initial radius R_0

$$(R_0)^2 \equiv \frac{2\int_{\mathbf{r}} |\mathbf{r}|^2 s(\tau_0, \mathbf{r})}{\int_{\mathbf{r}} s(\tau_0, \mathbf{r})}$$

where $s(\tau_0, r)$ is the entropy density profile at the beginning of the hydro evolution, and integration is over the transverse plane.
The factor 2 ensures that one recovers the correct result for a uniform uniform density in a circle of radius R_0.

System-size (in)dependence



In hydro, $\langle p_t \rangle / T_{eff}$ is identical in Pb+Pb and Xe+Xe collisions.

In experiment, $\langle p_t \rangle$ is essentially the same in both systems, therefore T_{eff} is also the same.

V_{eff} and the multiplicity are both proportional to A at a given centrality percentile.