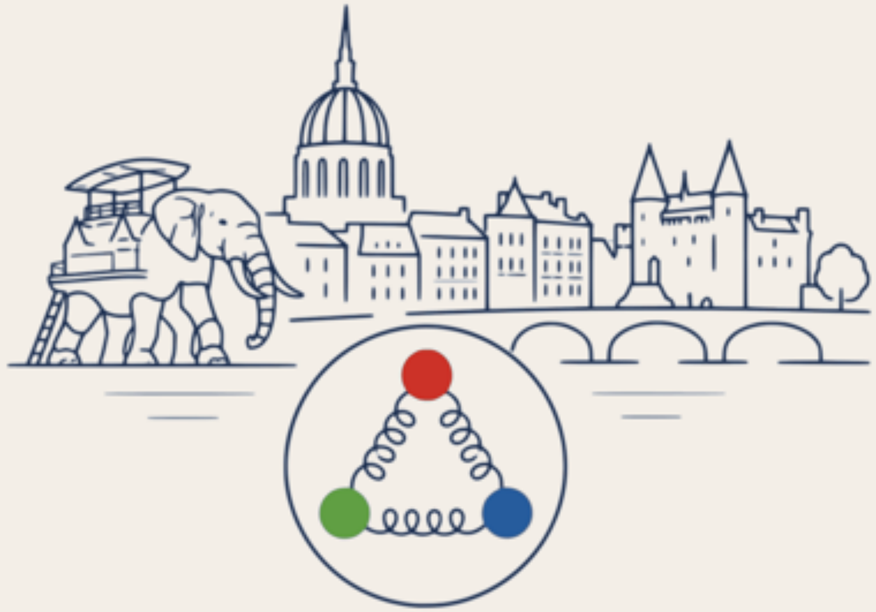
Heavy-ion data match finite-temperature lattice QCD

Jean-Yves Ollitrault

based on 2603.09647
with Mubarak Alqahtani & Tribhuban Parida

ASSEMBLÉE GÉNÉRALE DU GDR QCD

SUBATECH · 7–9 OCTOBRE 2026



GDR QCD 2026

– NANTES –

HADRON–2030

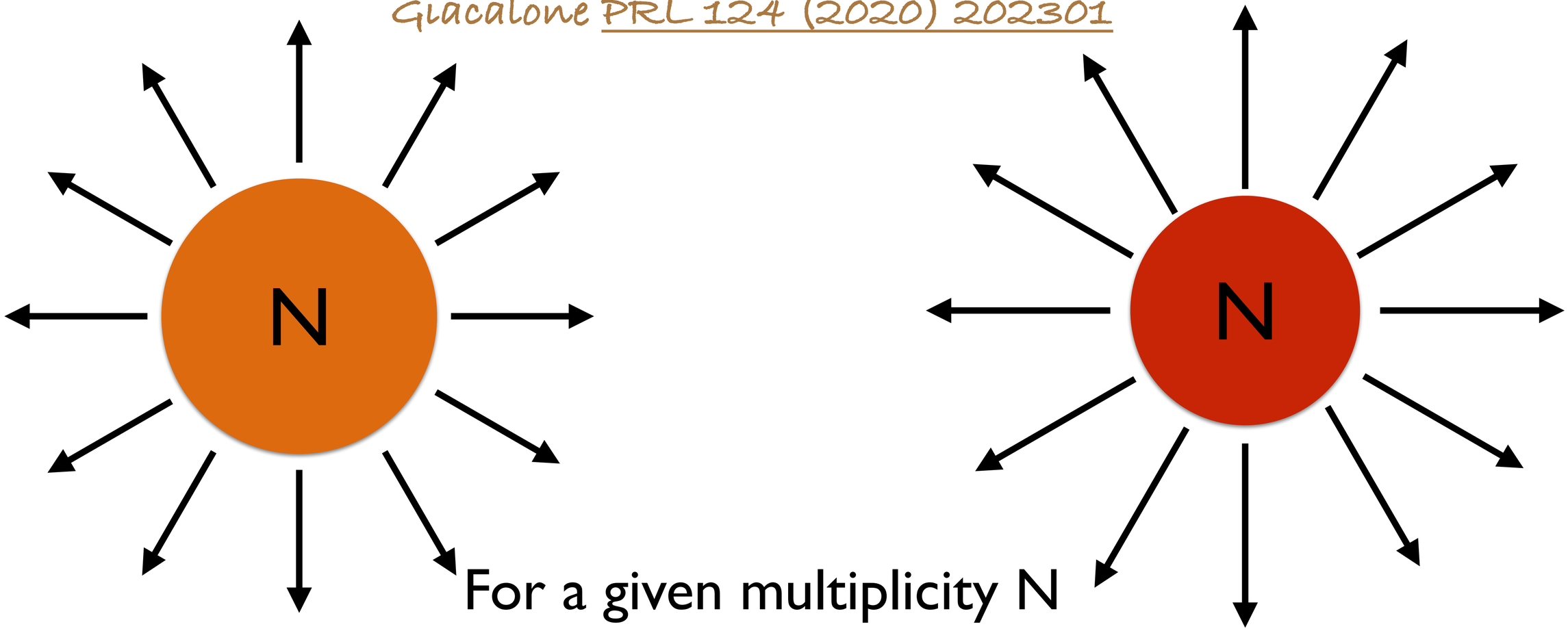
Heavy ions versus elementary particles: a change of paradigm

- Scattering theory and particle production are traditionally formulated in momentum space, without any reference to the actual volume in which particles are produced.
- There is ample evidence that Pb+Pb collisions at the LHC create a thermalized system (quark-gluon plasma, QGP).
- The momentum distribution depends on the temperature, which is related to the density through the equation of state.
- For a given number of produced particles (collision multiplicity) the momentum distribution depends on the volume.

Size-flow transmutation

Bozek Broniowski PRC 96 (2017) 014904

Giacalone PRL 124 (2020) 202301



For a given multiplicity N

smaller radius R implies hotter: larger momentum per particle $[p_T]$

Hydrodynamics

- = The standard description of particle production in heavy-ion collisions. Equation of state (of QCD) enters hydro equations.
- A quark-gluon plasma is formed shortly after the collision at a very high temperature, $T \approx 400 - 500$ MeV
- It behaves as a fluid which expands into the vacuum and cools down until it hadronizes at temperature $T \simeq 155$ MeV
- Temperature depends on space and time: Solving hydrodynamic equations requires the QCD equation of state in a broad range of temperatures $155 < T < 500$ MeV
- It seems counter-intuitive that one could constrain the equation of state at a specific temperature using heavy-ion data.

Effective hydrodynamics

Gardim Giacalone Luzum JYO Nature Physics 16 (2020) 615

- Counter-intuitive but true.
- At early times $t \ll R$, expansion is purely longitudinal, volume $\propto t$, entropy S is conserved, entropy density $s \propto 1/t$ irrespective of equation of state.
- Equation of state only matters when transverse expansion builds up, at times $t \sim R$, which determines the value of $[p_T]$.
- The temperature then is in the range $200 < T < 250$ MeV.

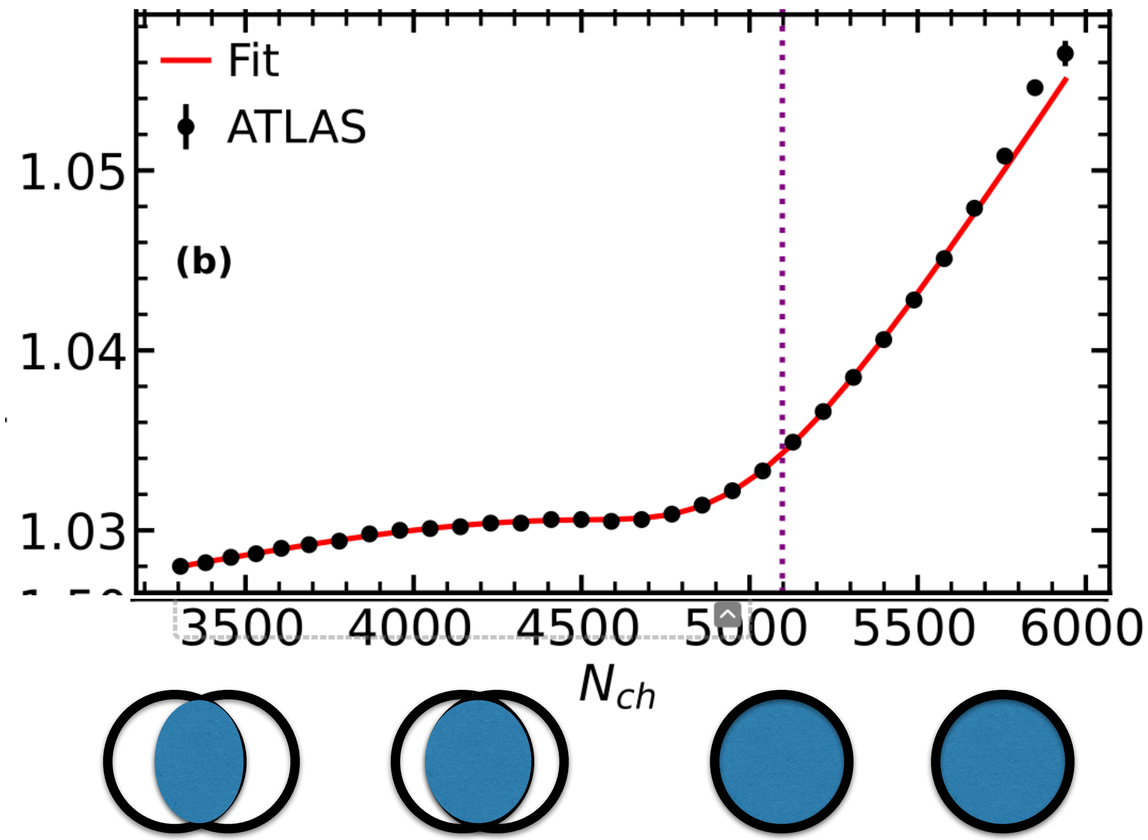
Effective hydrodynamics

Gardim Giacalone Luzum JYO Nature Physics 16 (2020) 615

- Numerical hydrodynamic simulations show that the only temperature that matters is an *effective* temperature $T_{eff} \simeq [p_T]/3 \simeq 220$ MeV at current LHC energy.
- The corresponding entropy density is $s(T_{eff}) \propto S/R^3$ (proportionality factor depends somewhat on details, but scaling law is extremely robust, as it follows from dimensional analysis).
- Entropy proportional to multiplicity $S \approx 6.7\, N_{ch}$, with universal proportionality factor (hadronization at $T \simeq 155$ MeV)
- These 3 equations are the key for relating the QCD equation of state to heavy-ion data.

Variation of $\langle p_T \rangle$ with N_{ch}

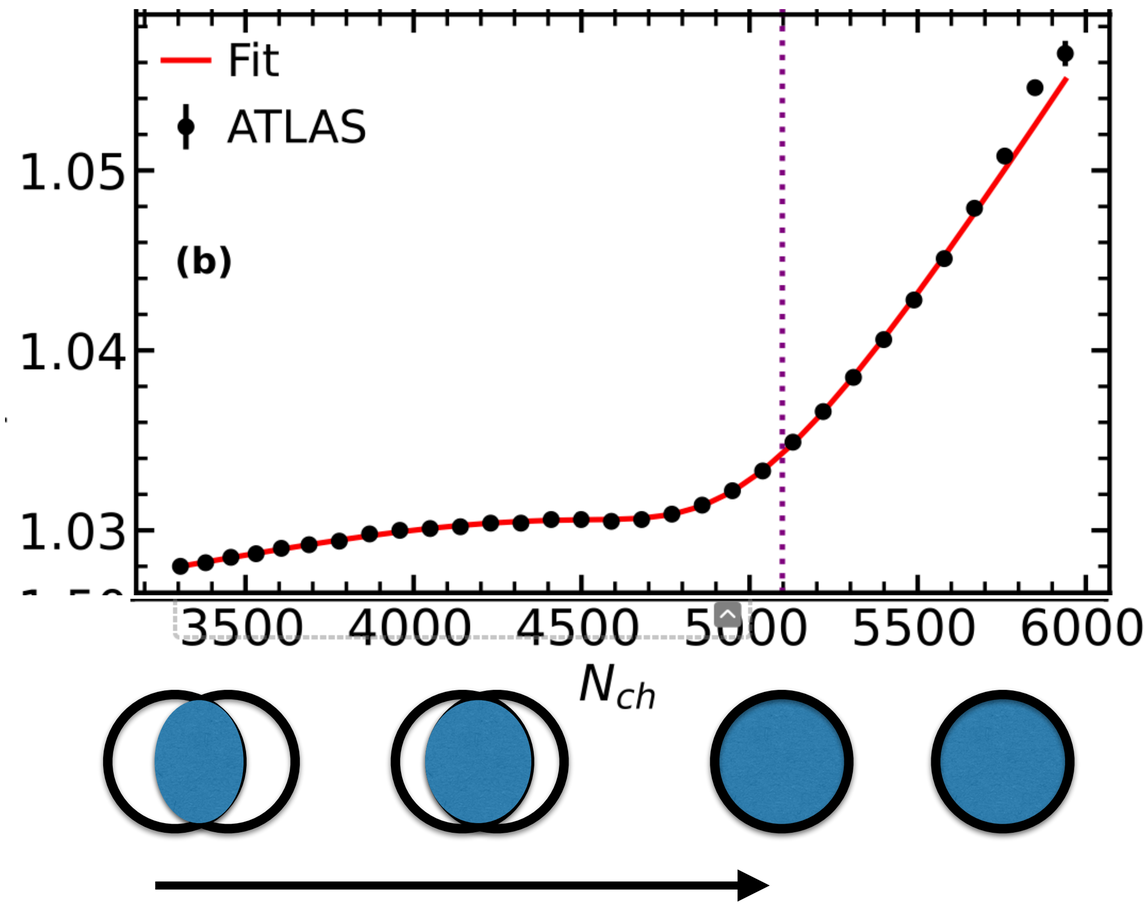
ATLAS 2407.06413



- How do we understand these data on the basis of
- $T_{eff} \simeq \langle p_T \rangle / 3$
- $s(T_{eff}) \propto N_{ch}/R^3$?

Variation of $\langle p_T \rangle$ with N_{ch}

ATLAS 2407.06413

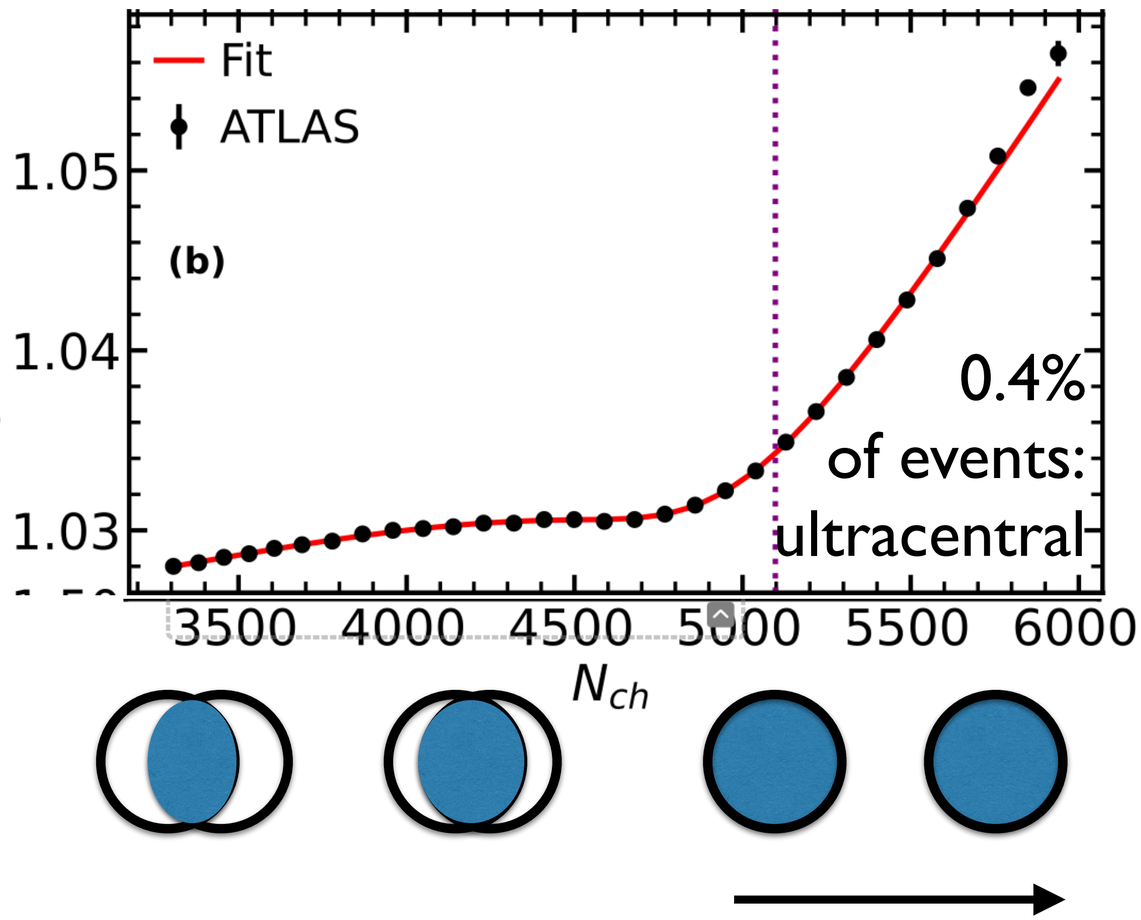


- How do we understand these data on the basis of
- $T_{eff} \simeq \langle p_T \rangle / 3$
- $s(T_{eff}) \propto N_{ch}/R^3$?

R increases, $N_{ch}/R^3 \sim$ constant

Variation of $\langle p_T \rangle$ with N_{ch}

ATLAS 2407.06413



- How do we understand these data on the basis of
- $T_{eff} \simeq \langle p_T \rangle / 3$
- $s(T_{eff}) \propto N_{ch}/R^3$?
- $$\frac{d \ln \langle p_T \rangle}{d \ln N_{ch}} = \frac{d \ln T}{d \ln s} = c_s^2(T_{eff})$$

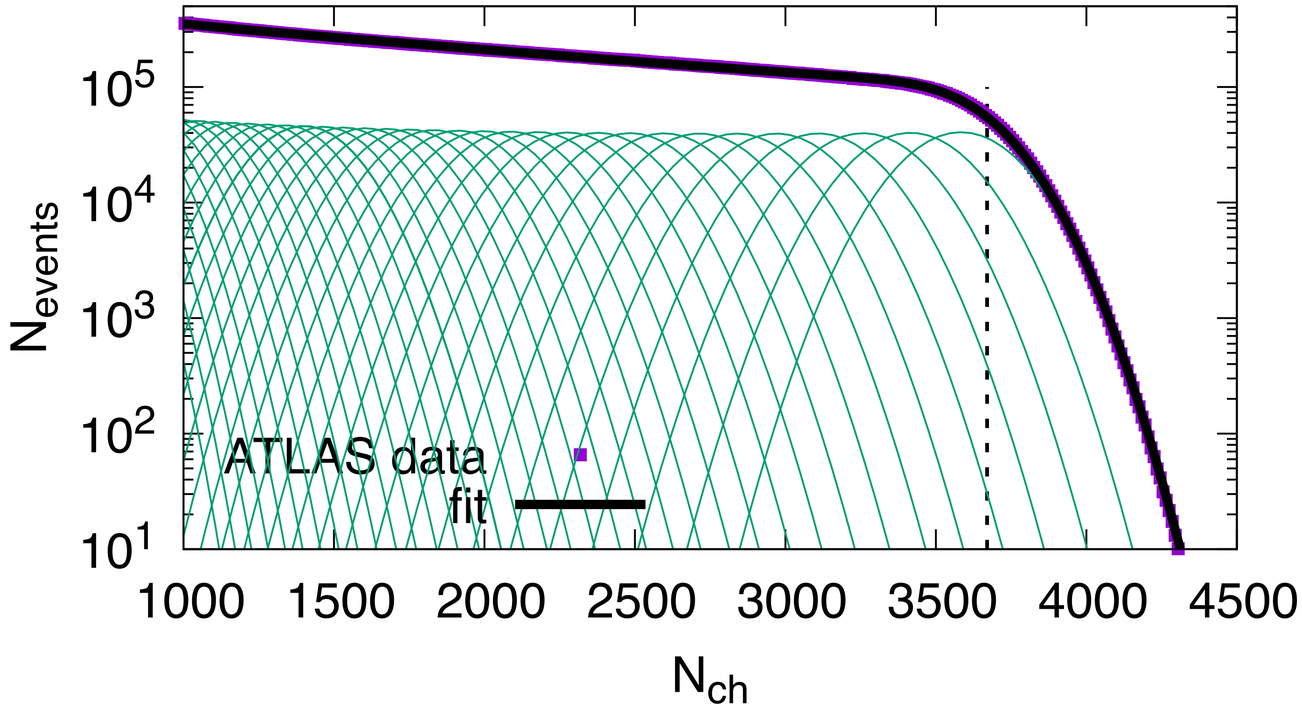
slope = speed of sound at T_{eff}

Gardim Giacalone JYO Phys.Lett.B 809 (2020) 135749

R constant, N_{ch} increases

Method: Reconstructing centrality fluctuations

- It is crucial to control the geometry, in particular that we know the distribution of impact parameter at given N_{ch}.
- Fluctuations of N_{ch} at fixed impact parameter b are Gaussian (because they are small: relative standard deviation is ~3%)
- Fit histogram of N_{ch} as a sum of Gaussians and reconstruct $P(N_{ch}\,|\,b)$
- Bayes' theorem then gives $P(b\,|\,N_{ch})$



Das Giacalone Monard JYO 1708.00081

Technical difficulties (1/2)

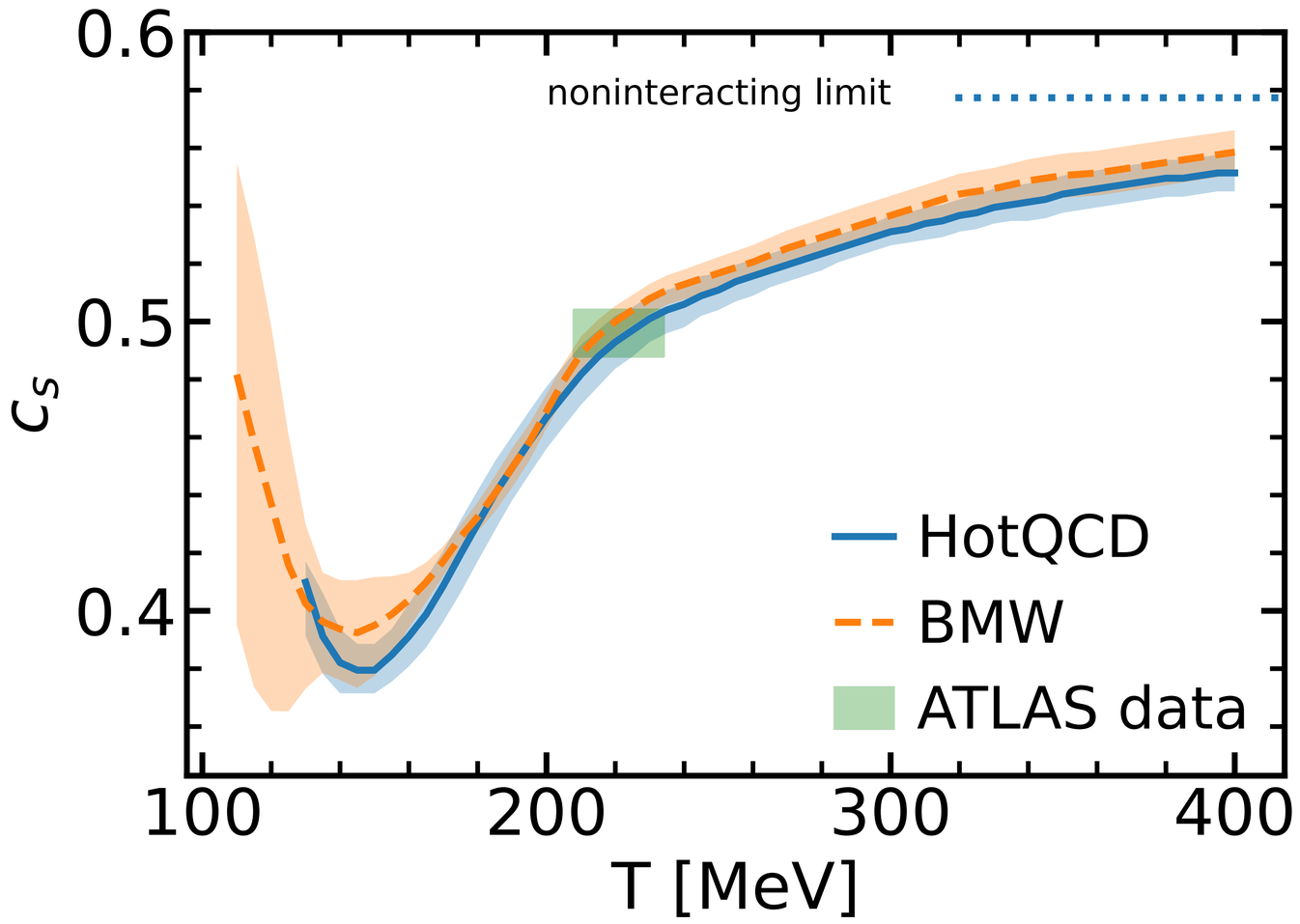
- ATLAS only detects particles with $p_T > 0.5$ GeV/c (~50% missed).
- $\langle p_T \rangle$ of particles with $p_T > 0.5$ GeV/c not trivially related with... $\langle p_T \rangle$
- N_{ch} of particles with $p_T > 0.5$ GeV/c not trivially related with N_{ch}: the fraction of particles detected depends on temperature, i.e., $\langle p_T \rangle$.
- We need to know how a small change in temperature modifies the spectrum. This is a new observable, $v_0(p_T)$, measured for the first time in 2025. We calculate it using hydrodynamics.

Technical difficulties (2/2)



- Hydrodynamics is a continuous description
- In hydro world, hadronization is a shot noise which blurs the smooth image of the fluid.
- The observed multiplicity N_{ch} is proportional to entropy S *up to Poisson fluctuations*, which have no effect on $\langle p_T \rangle$.
- In order to make contact between data and hydro, we need to unfold Poisson fluctuations, i.e., deblur hadronization. We have devised a simple, systematic deblurring method.

Comparison between ATLAS data and lattice QCD



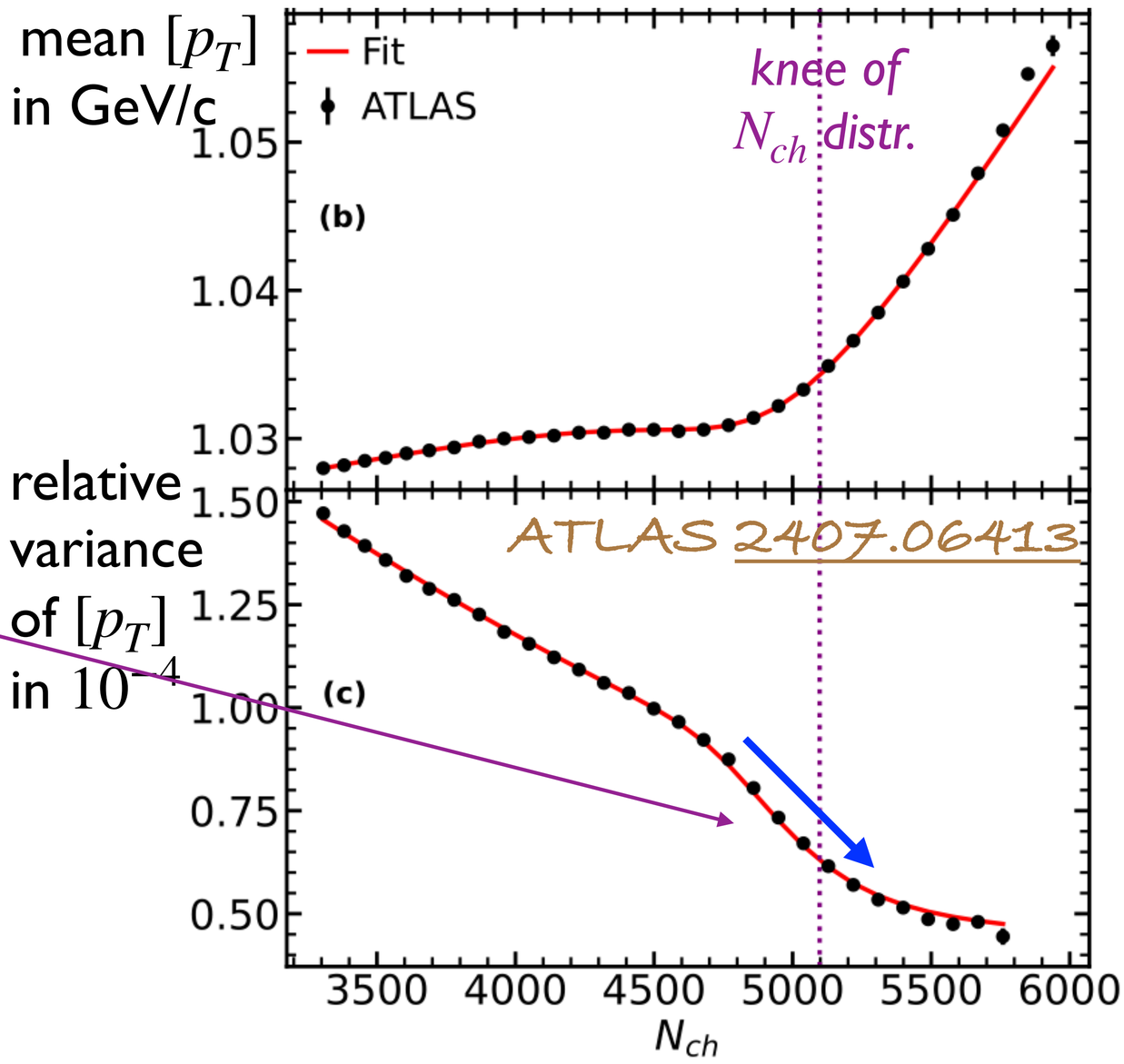
- Perfect agreement: most precise comparison between lattice and data on equation of state
- Value of c_s from fit is very robust
- Largest error is on the effective temperature, at which we measure c_s (can be improved with more hydro simulations)

Other results: event-by-event fluctuations of $[p_T]$

- $[p_T] \approx 3\,T_{\rm eff}$ depends on entropy density $s_{\rm eff} \propto S/R^3 \propto N_{ch}/R^3$
- Fluctuations of $[p_T]$ at fixed N_{ch} induced by size (R^2) fluctuations

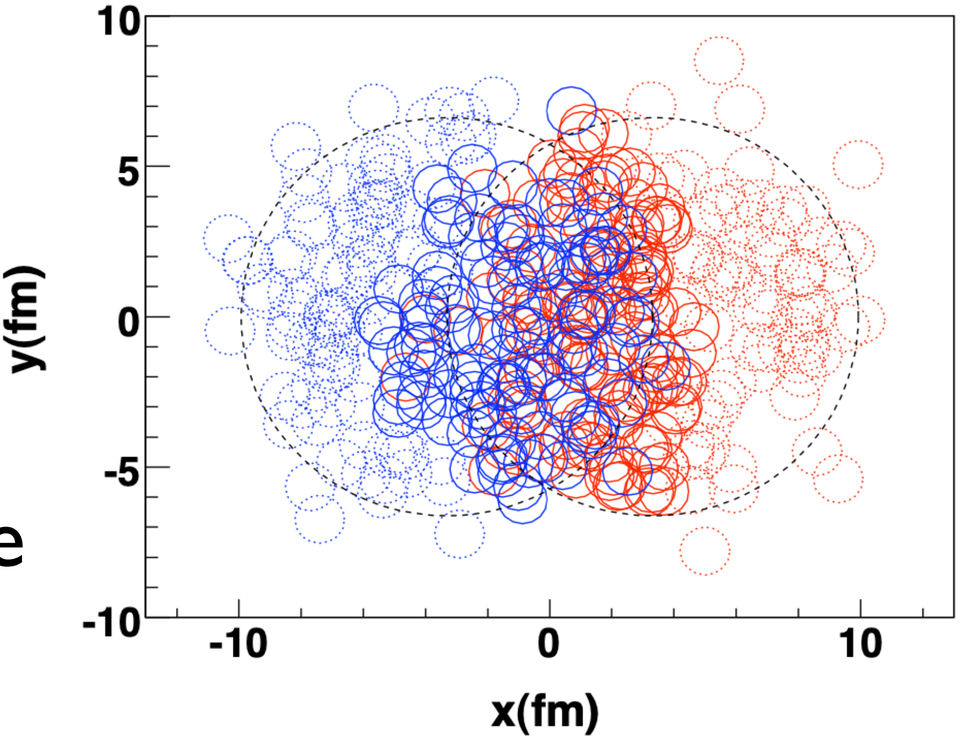
  Broniowski Chojnacki Obara 0907.3216
- The decrease of the variance in ultracentral collisions is explained by the disappearance of b fluctuations: only (quantum) fluctuations of R^2 remain

  Samanta Bhatta Jia Luzum JYO 2303.15323



Sources of quantum fluctuations in heavy-ion collisions

- Mostly fluctuations in positions of nucleons at the time of the collision, determined by the nuclear wavefunction [talk by Giuliano today]
- Gluon production is essentially classical [François yesterday: "Gauge fields behave as classical solutions of Yang-Mills equations"]
- Hydrodynamics is classical too.
- We remove the shot noise from hadronization.



Alver Baker Loizides Steinberg 0805.4411

Observing zero-point fluctuations of ^{208}Pb

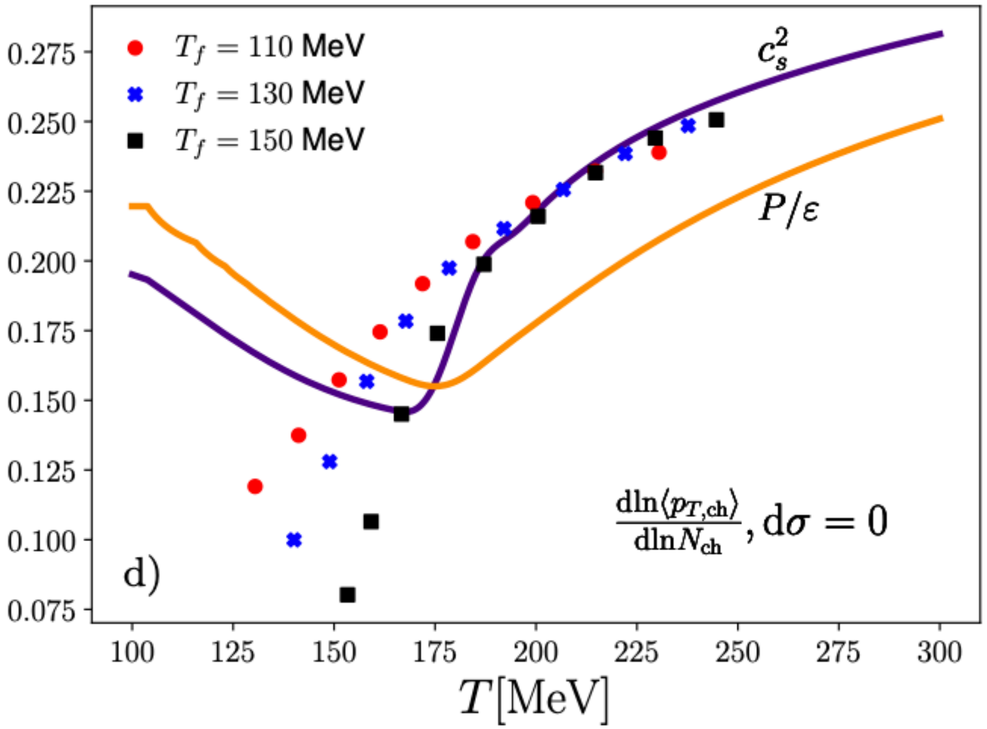
- From ATLAS data on $[p_T]$ fluctuations, we infer a relative std. dev. of R^2 (mean square radius) of $3.09 \pm 0.15\,\%$ at $b = 0$
- Fluctuations of the nuclear radius can be inferred from experiment (giant monopole resonance). The resulting fluctuation of R^2 is $2.81\,\%$, which leaves little room for additional fluctuations.
- Sampling nucleon positions independently (standard "Glauber" modeling) gives too large fluctuations $3.61\,\%$. Size fluctuations are suppressed by the Pauli principle. Heavy-ion physicists need to remember that nuclei are quantum objects.

Blaizot & JYO 2609.24977

Backup

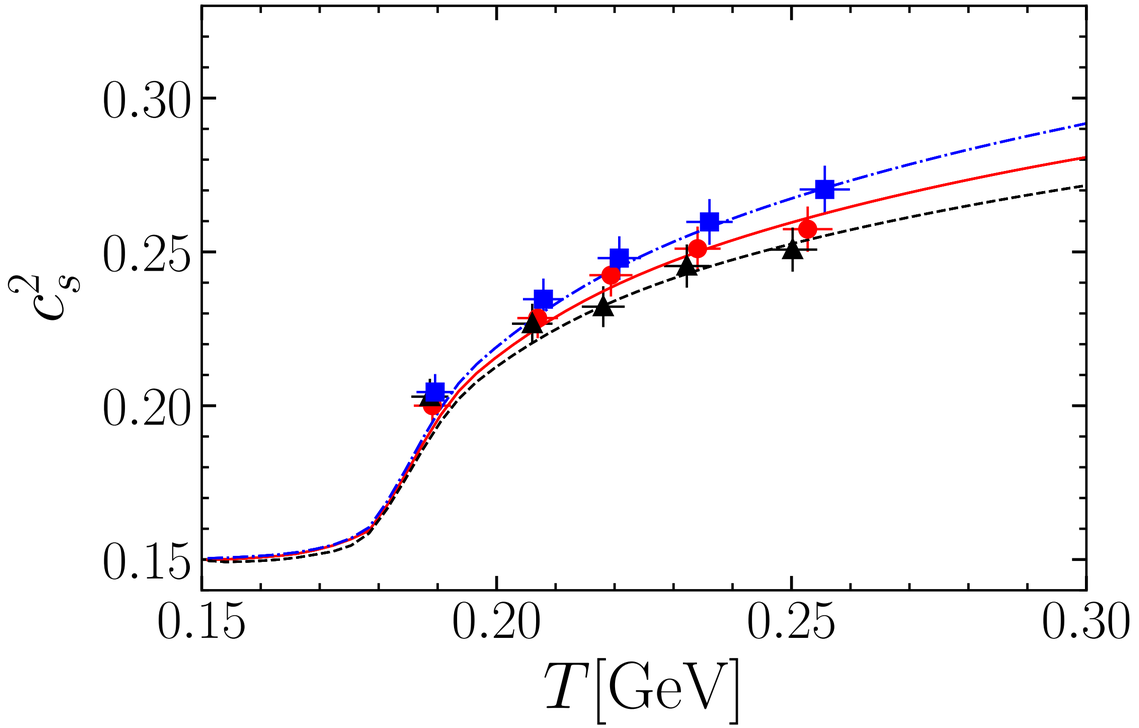
Testing $c_s^2(T_{\rm eff}) = d\ln\langle p_T\rangle / d\ln N_{ch}$ in hydro

Various freeze-out temperatures & energies



Gavassino Hirvonen Paquet Singh SoaresRocha 2503.20765

Various equations of state & energies



Gardim Giannini JYO 2403.06052