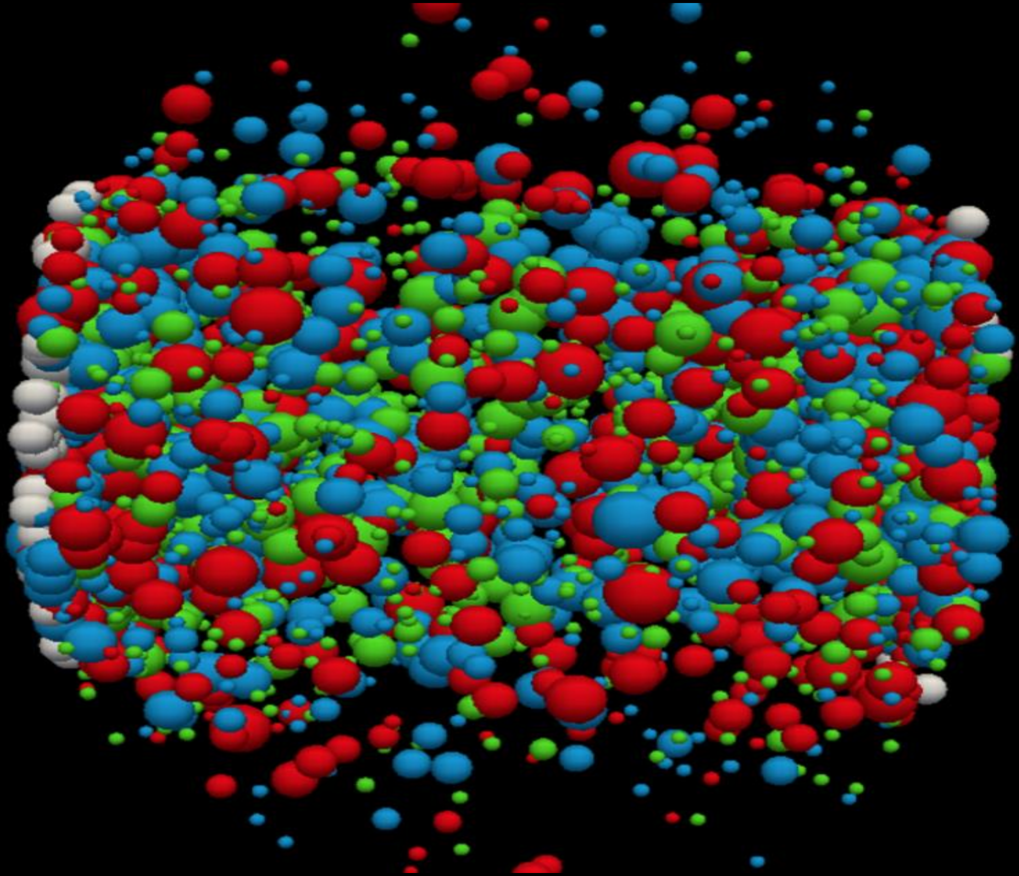
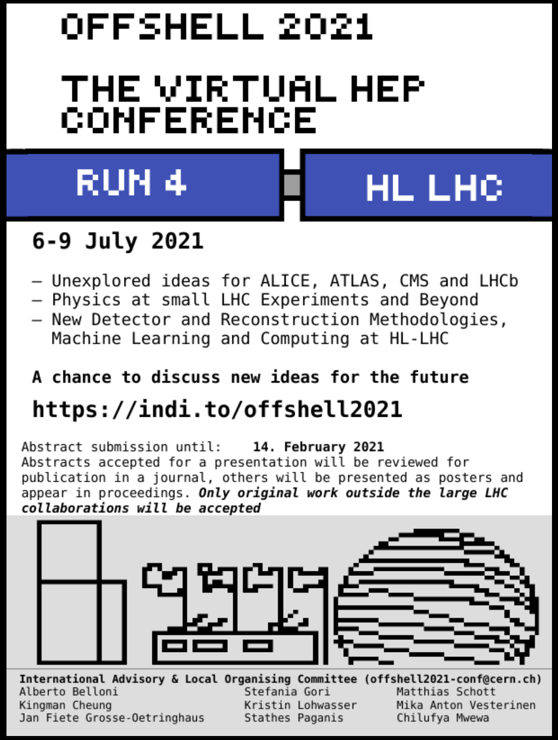
Thermodynamics of the 'Little Bang'

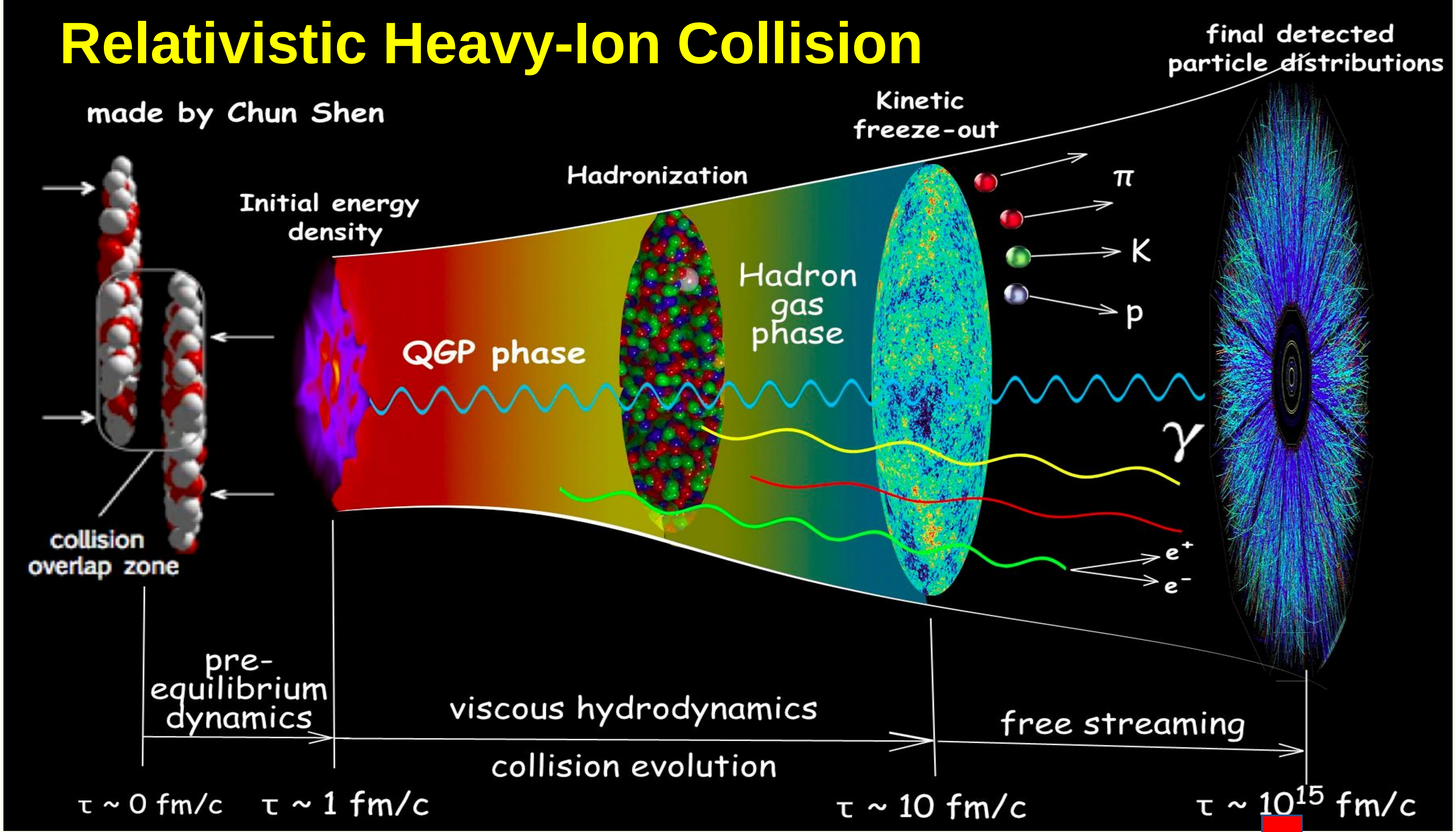




Presenter: Tapan Nayak, NISER(India) and CERN

in collaboration with

- Sumit Basu, Lund University, Sweden
- Claude Pruneau, Wayne State University, USA



Initial State Fluctuations

Thermal Fluctuations

Hadronization

Measurement (Fluctuation-Correlation)

Properties of Nuclear Matter — Experimental Perspective

Extensive variables: depend on the system size: energy, volume, or particle number, entropy ….
Intensive variable: does not depend on system size.

- Applicability of thermodynamics ..
- Basic Observables:

  Temperature, pressure, volume, entropy density, and energy density, ..
- Observables/Properties of interest (pertaining to the properties of nuclear matter)

  Properties defining/determined by the equation of state (EOS) of the QGP matter, including response functions such as the heat capacity, the isothermal compressibility, as well as the speed of sound.
- Accessing thermodynamic properties of the system

  EOS: thermodynamic equation relating variables which describe the state of matter under a given set of physical conditions.

  In heavy-ion collisions after thermalization the system evolves hydrodynamically and its behavior depends on the EOS: connecting energy density, pressure, volume, temperature ….

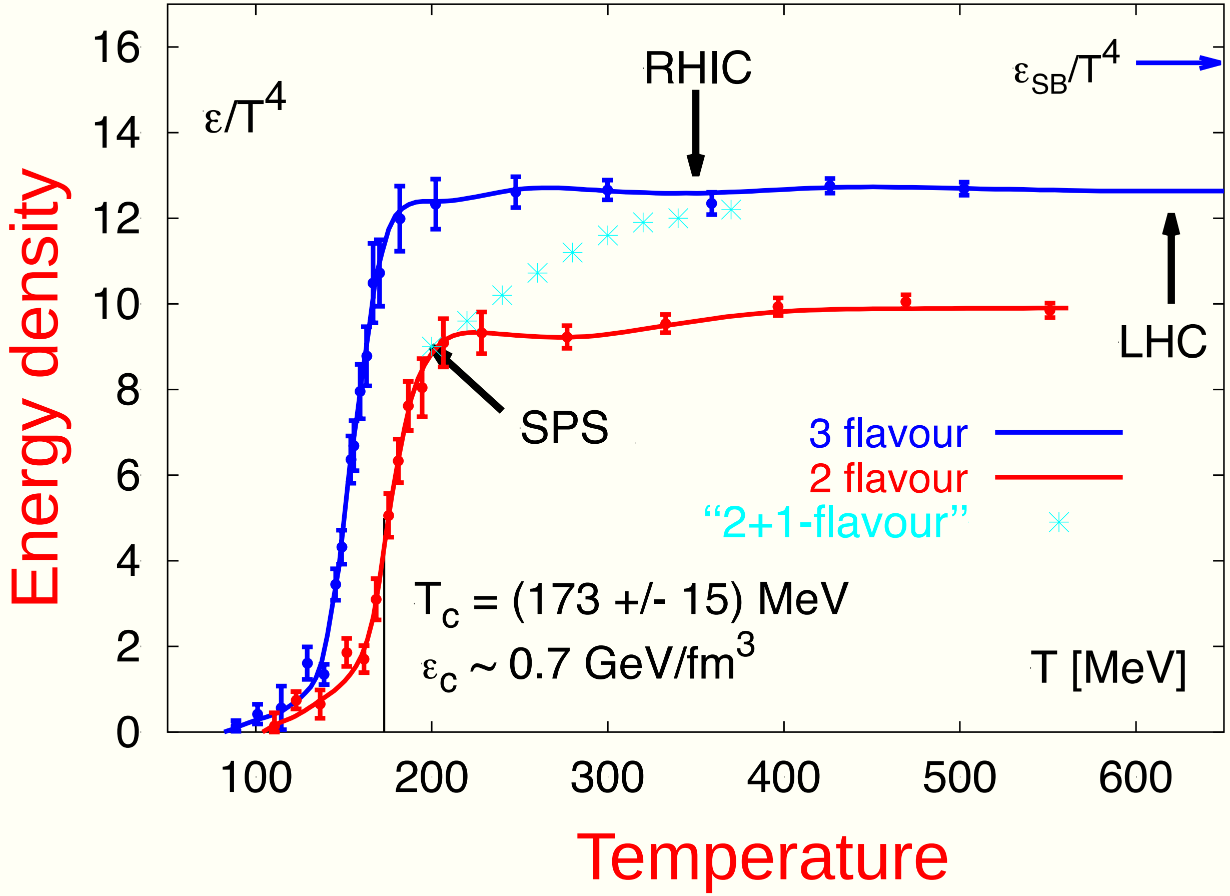
For today: WILL CONCENTRATE ON ACCESSING TEMPERATURE AND FLUCTUATION IN TEMPERATURE.

Talk Outline

- ✦ Properties of mesoscopic systems of QCD matter (QGP) predicted by LQCD and phenomenological models
- ✦ Experimental evidence for the applicability of thermodynamics in Heavy-Ion collisions
- ✦ Focus on the specific heat of QCD matter
    - Extract the specific heat based on measurements of temperature ($\langle p_T \rangle$) fluctuations
- ✦ Using p_T fluctuations as a proxy for temperature fluctuations
- ✦ p_T correlations
- ✦ Prior measurements and caveats
- ✦ New ideas and new measurements with ALICE
- ✦ Summary

Properties of Nuclear Matter Predictions/Expectations (I)

Lattice QCD calculations

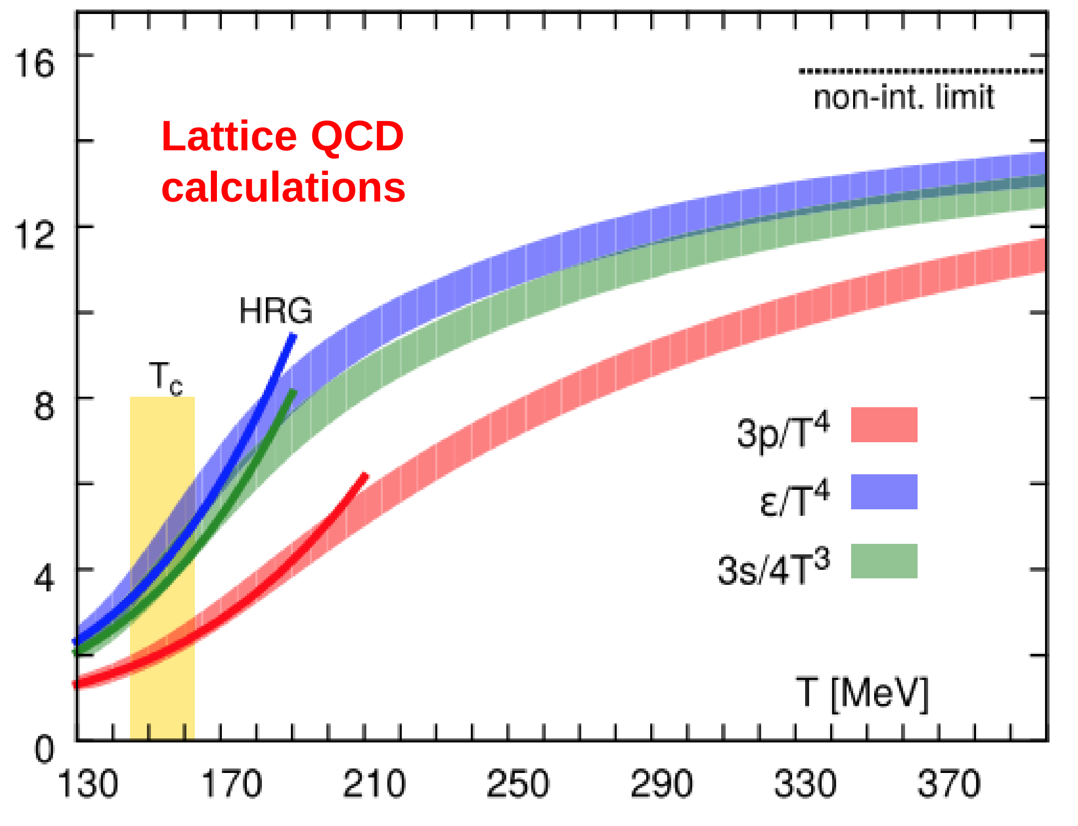


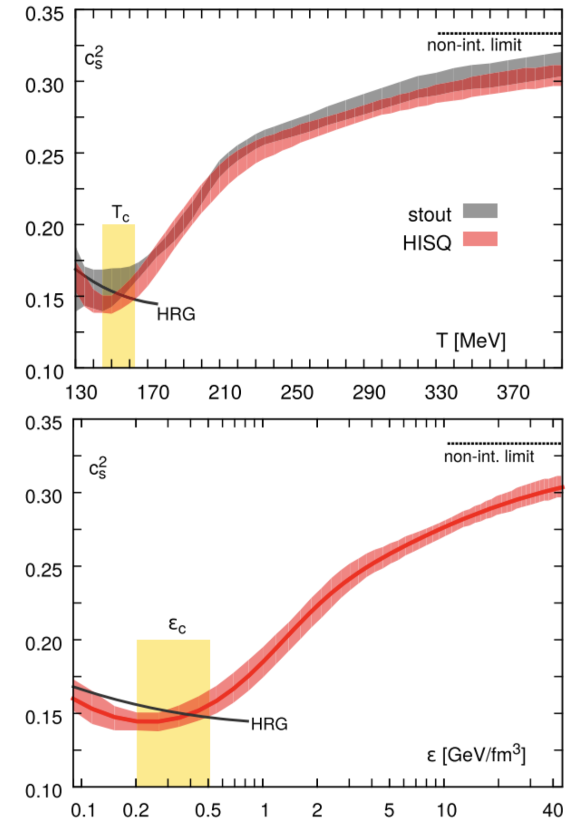
F. Karsch, 2002, Lect. Notes Phys. 583, 209

Lattice QCD: well-established non-perturbative approach to solve QCD.

Properties of Nuclear Matter Predictions/Expectations (II)

HOTQCD Collaboration
Phys. Rev. D90 (2014) , 094503





Lattice Calculations of
- Pressure, energy density, entropy density as a function of *T*
- Speed of sound square as a function of T and energy density.

Pseudo-critical temperature for chiral crossover transition
- T_c = (154 ± 9) MeV
- ε_c ≈ (0.34 ± 0.16) GeV/fm3

- will come back to discussion of speed of sound …

Hydro calculations use the EOS from lattice QCD.

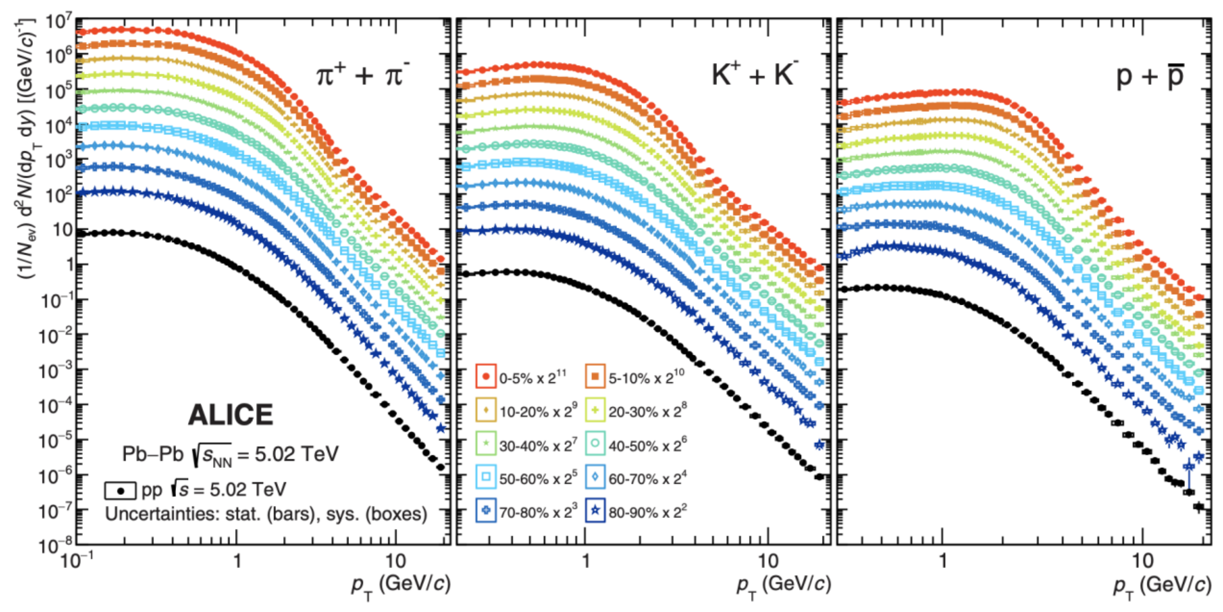
Stefan-Boltzmann limit:

$$\boxed{\varepsilon = g\frac{\pi^2}{30}T^4}$$

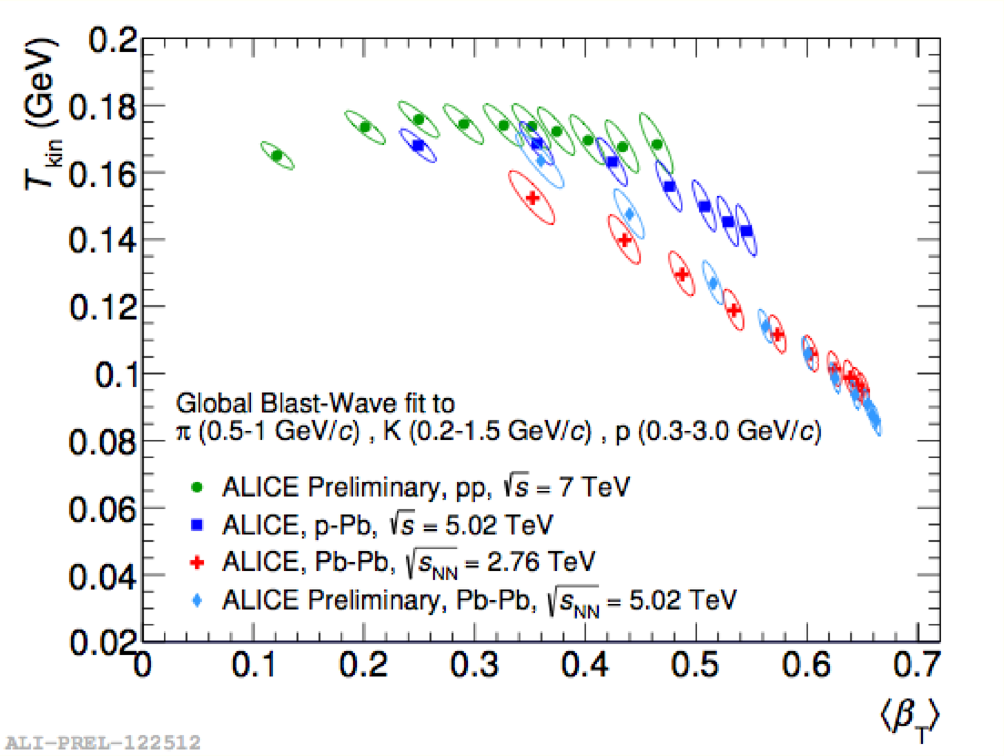
- For hadronic matter, g=3
- For QGP: dof increases by ~10 (8 gluons, 2 quark flavours, 2 antiquarks, 2 spins, 3 colors)

Experimental measurement of temperature and other thermodynamic quantities gives access to the number of degrees of freedom …

Evidence for the production of thermal systems (I)



Evolution of Kinetic freeze-out temperature T_{kin} and radial flow velocity $\langle \beta_T \rangle$



Boltzmann-Gibbs Blast-Wave model:

- Particle production from a thermalized source + a radial flow boost.
- A thermodynamic model with 3 fit parameters: T_{kin}, $\langle \beta_T \rangle$, and n (velocity profile).

$$E\frac{d^3N}{dp^3} \propto \int_0^R m_T I_0\left(\frac{p_T \sinh(\rho)}{T_{kin}}\right) K_1\left(\frac{m_T \cosh(\rho)}{T_{kin}}\right) r\, dr.$$

The velocity profile ρ is given by

$$\rho = \tanh^{-1}\beta_T = \tanh^{-1}\left[\left(\frac{r}{R}\right)^n \beta_s\right],$$

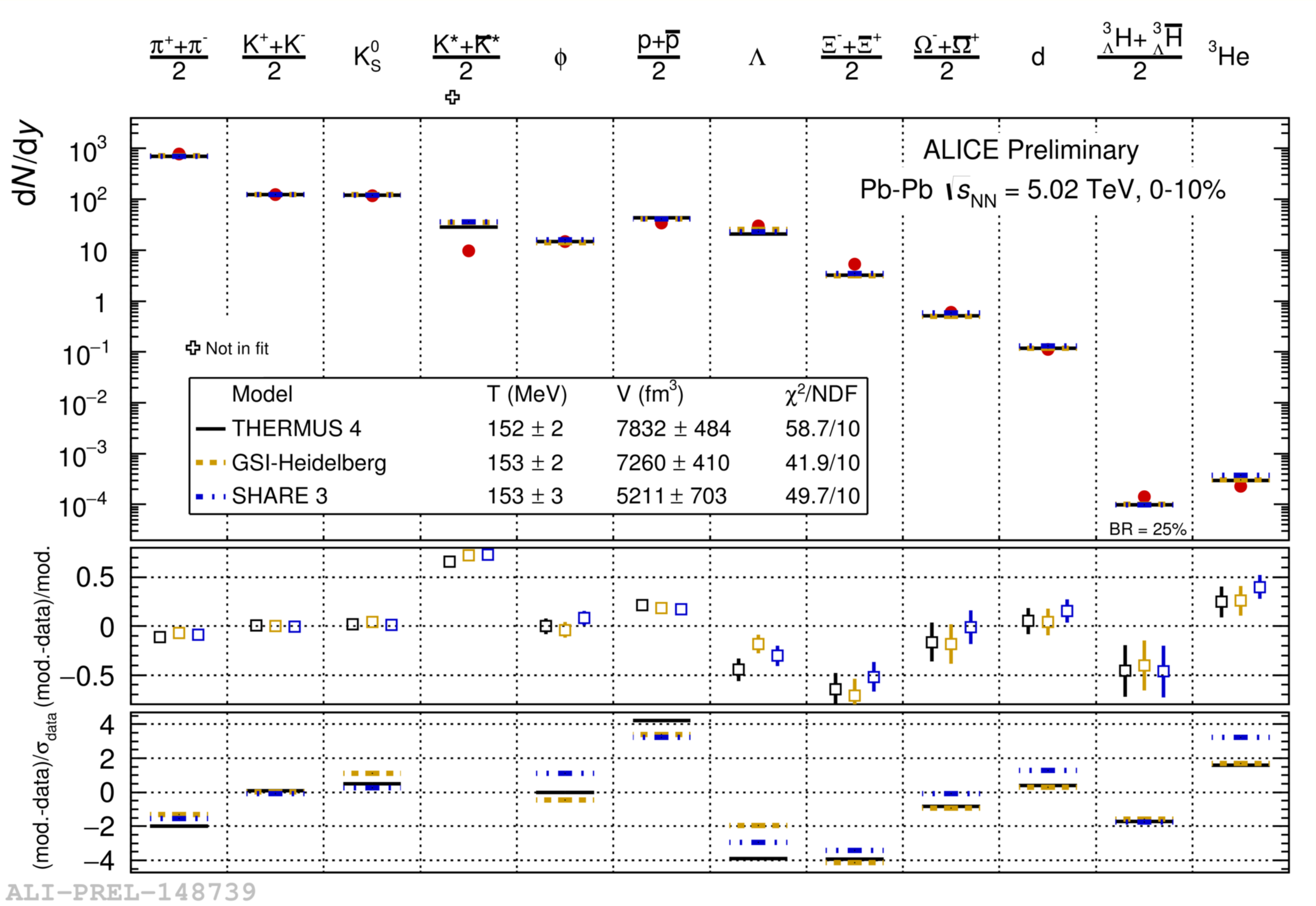
n changes from peripheral to central

Source of radial flow fluctuation

- $\langle \beta_T \rangle$ increases with centrality
- Similar evolution of fit parameters in case of pp and p-Pb collisions
- At similar multiplicities, $\langle \beta_T \rangle$ is larger for smaller systems

Evidence for the production of thermal systems (II)

Particle yields in Pb-Pb at 5.02 TeV



Thermal models:

- At Chemical freeze-out => Particle yields get fixed.
- Abundance is determined by thermodynamic equilibrium:

$$\frac{dN}{dy} \propto \exp\left(\frac{-m}{T_{chem}}\right)$$

Particle yields are well described by statistical models

T_{ch} (Chemical freeze-out temperature) ~153 MeV

Accessing thermodynamics properties w/ fluctuation measurements

- Thermodynamics applicable when dealing with *equilibrated system: equilibrated* in the sense that approximately all available phase space is equally populated.
- Probability of a particular state: P~exp(S), where S is the entropy of the state
- Consequently, temperature fluctuations are expected with probability:

$$P \sim \exp\left[-\frac{C_v(T)}{2}\left(\frac{\Delta T}{T}\right)^2\right] = \exp\left[-\frac{1}{2}\frac{(\Delta T/T)^2}{\sigma_T^2}\right]$$

ΔT deviation of system temperature from mean value

$C_v(T)$ heat capacity of nuclear matter

$C_v = T\frac{\partial S}{\partial T}|N,V$ (Extensive quantity, proportional to volume, V, and/or the number of particles, N)

- So, in principle, a measurement of fluctuations of *T* should yield the heat capacity of nuclear matter.

L. Stodolsky, Phys. Rev. Lett. 75 ž1995. 1044.
E.V. Shuryak, Physics Letters B 423 (1998) 9.

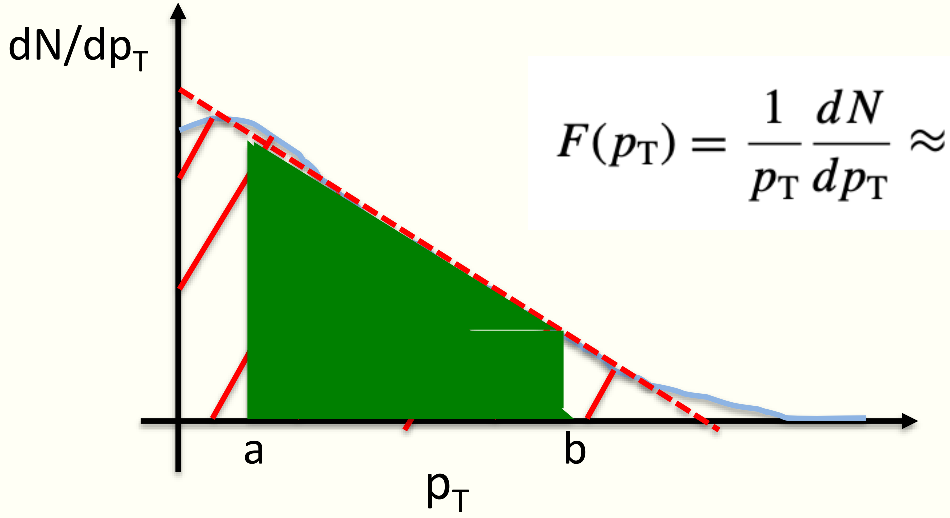
Basic Idea: Measure event-by-event fluctuations of system temperatures. Measure the variance of these fluctuations to assess the heat capacity

Caveat: Measuring the temperature of a single event based e.g., on the p_T distribution does not yield a very good precision.

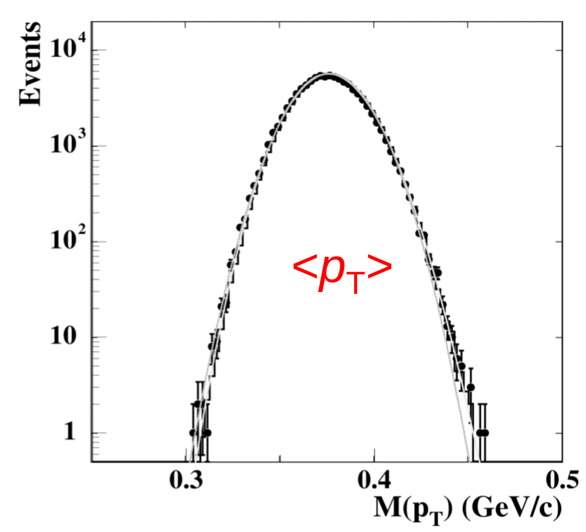
Accessing the heat capacity …

Cleymans et al. PRC 73 (2006) 034905
STAR Collaboration PRC 79 (2009) 034909
ALICE Collaboration PRD 88 (2013) 044910
Sumit Basu et al. PRC 94 (2016) 044901

Using p_T fluctuations as a proxy for temperature fluctuations

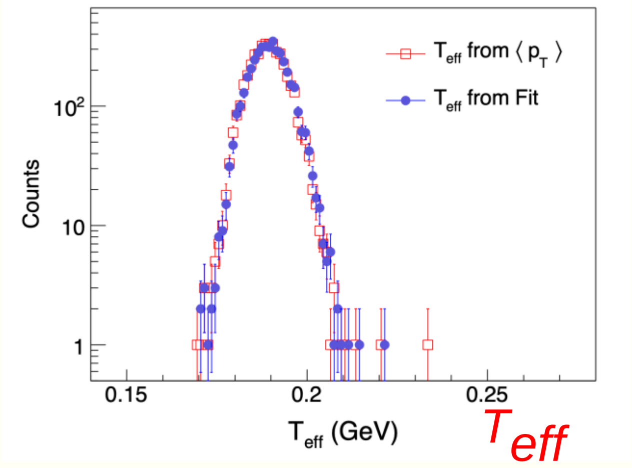


$$F(p_\mathrm{T}) = \frac{1}{p_\mathrm{T}}\frac{dN}{dp_\mathrm{T}} \approx Ae^{-p_\mathrm{T}/T_\mathrm{eff}}$$



$$\langle p_T\rangle = \frac{\int_0^\infty p_T^2 F(p_T)dp_T}{\int_0^\infty p_T F(p_T)dp_T} = \frac{2T_\mathrm{eff}^2 + 2m_0T_\mathrm{eff} + m_0^2}{m_0 + T_\mathrm{eff}}$$

$$\langle p_T\rangle = \frac{\int_a^b p_T^2 F(p_T)dp_T}{\int_a^b p_T F(p_T)dp_T} = 2T_\mathrm{eff} + \frac{a^2e^{-a/T_\mathrm{eff}} - b^2e^{-b/T_\mathrm{eff}}}{(a+T_\mathrm{eff})e^{-a/T_\mathrm{eff}} - (b+T_\mathrm{eff})e^{-b/T_\mathrm{eff}}}$$

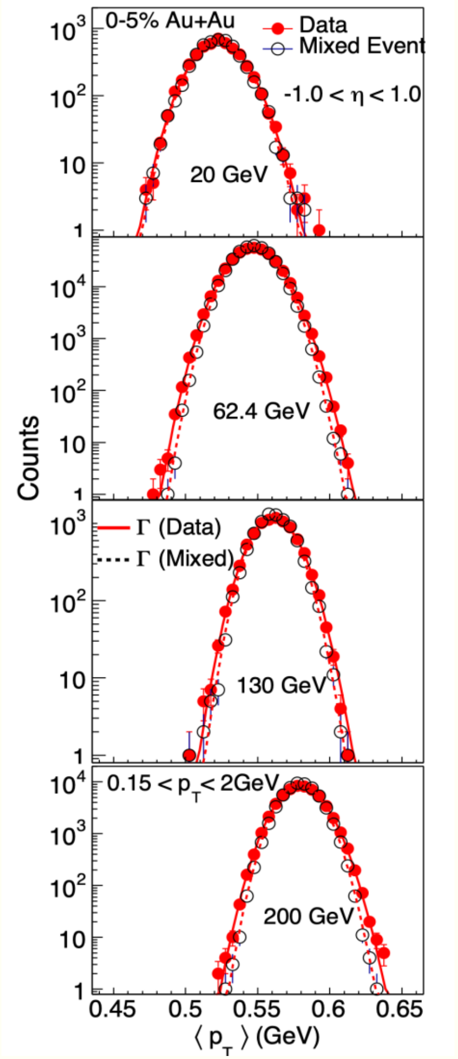


Accessing the heat capacity …

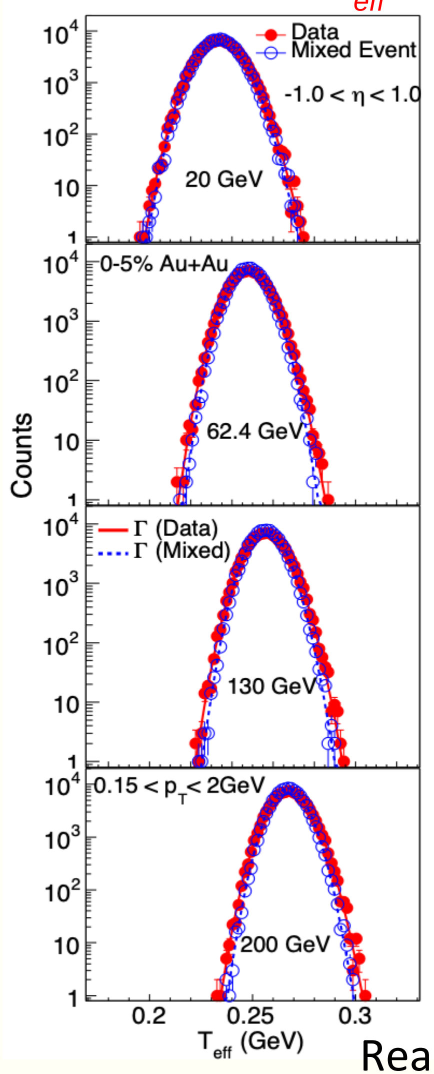
Using p_T fluctuations as a proxy for temperature fluctuations

$\langle p_T \rangle$

STAR, Phys. Rev. C 72 (2005)



T_{eff}



Phys.Rev. C94 (2016) S. Basu et al.

Distributions of $\langle p_T \rangle$ and T_{eff}

$\langle p_T \rangle$ distribution can be described by the gamma Function:

M.J. Tannenbaum, PLB 498 (2001) 29

$$f(x) = f_\Gamma(x,a,b) = \frac{b}{\Gamma(a)}(bx)^{a-1}e^{-bx}$$

Fits of the $\langle p_T \rangle$ distribution gives *a* and *b*, from which we obtain:

- Mean and std: $$\mu = \frac{a}{b} = \langle p_T \rangle; \quad \sigma = \frac{\sqrt{a}}{b}.$$
- Skewness and Kurtosis $$s = \frac{2}{\sqrt{a}}; \quad \kappa = \frac{6}{a}$$

Real and mixed events: $(\Delta T_{\rm eff})^2 = (\Delta T_{\rm eff}^{dyn})^2 + (\Delta T_{\rm eff}^{stat})^2$

Subtracting the width of mixed events, we obtain the dynamic fluctuation.

Estimates of the specific heat (c_V) from STAR measurements

Heat capacity:

$$\boxed{C = \left(\frac{\partial E}{\partial T}\right)_v} \Rightarrow \quad \frac{1}{C} = \frac{(\langle T^2\rangle - \langle T\rangle^2)}{\langle T\rangle^2}$$

T_{eff} has contributions from thermal (T_{kin}) and collective motion in the transverse direction ($\langle \beta_T \rangle$): radial flow

$$T_{\text{eff}} = T_{\text{kin}} + f(\beta_T)$$

Neglecting fluctuation in β_T:

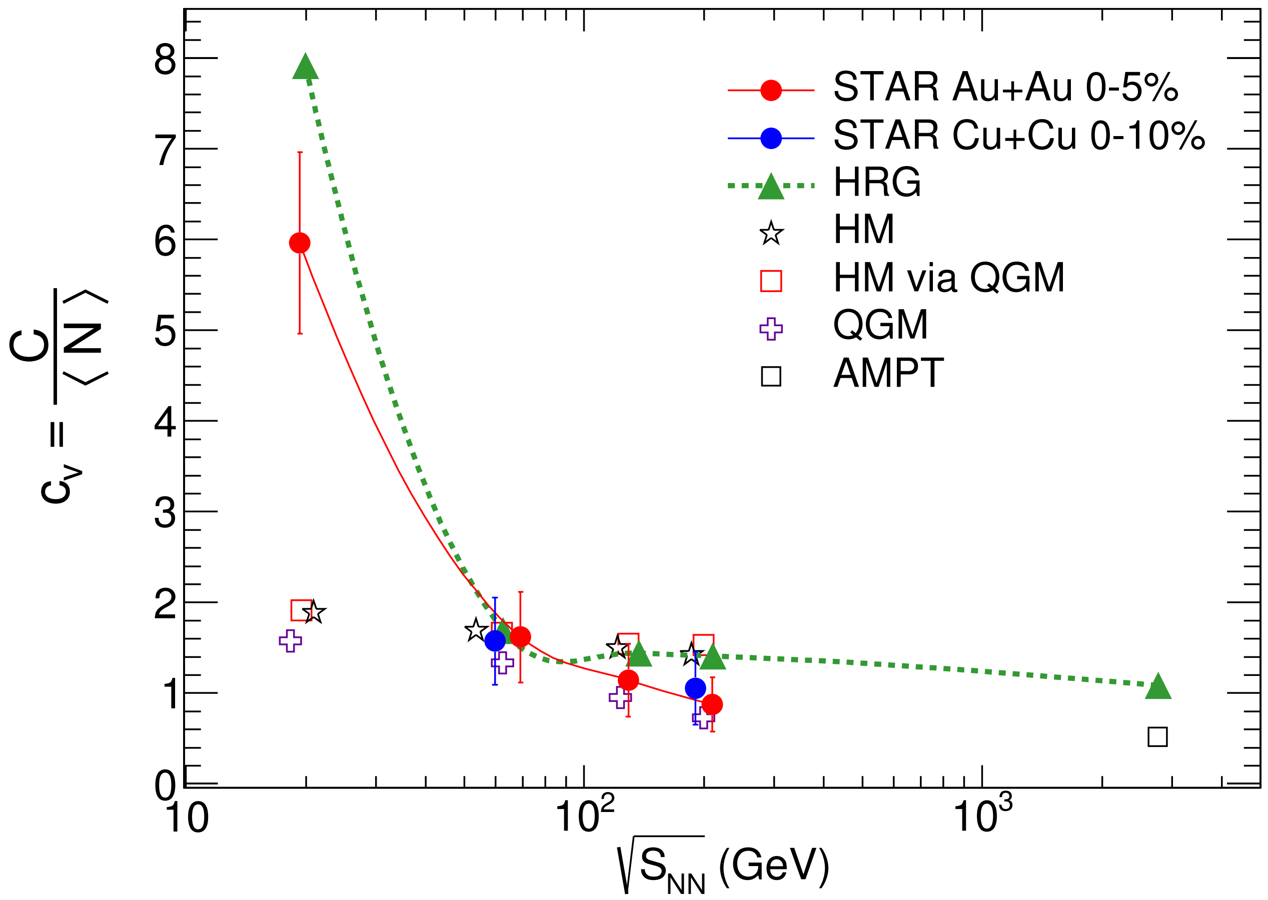
$$\frac{1}{C} = \frac{(\Delta T_{\text{eff}})^2}{\langle T_{\text{kin}}\rangle^2}$$

$$(\Delta T_{\text{eff}})^2 = (\Delta T_{\text{eff}}^{dyn})^2 + (\Delta T_{\text{eff}}^{stat})^2$$

$(\Delta T_{\text{eff}}^{dyn})^2$: obtained by subtraction of width of the mixed event

$$\frac{1}{C} = \frac{(\Delta T_{\text{eff}}^{dyn})^2}{\langle T_{\text{kin}}\rangle^2}.$$

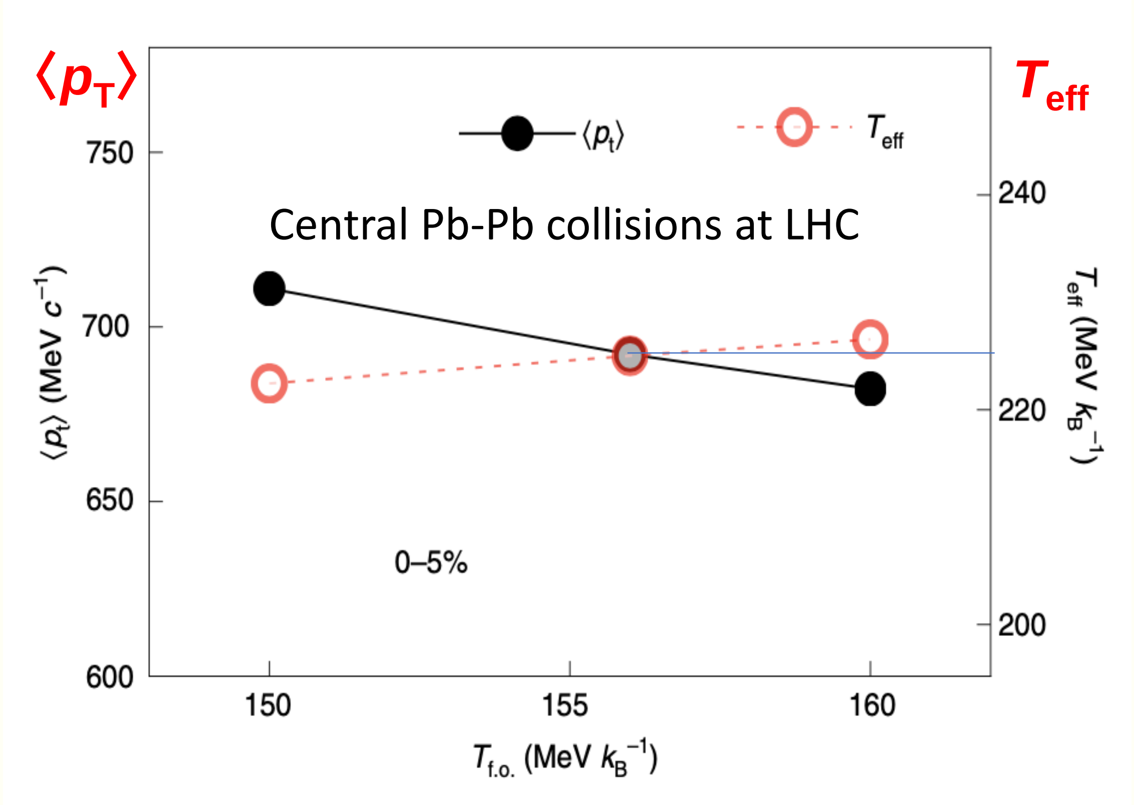
Phys.Rev. C94 (2016)
S. Basu, S. Chatterjee, R. Chatterjee, B. Nandi TN



Specific heat: $c_V = \frac{C}{\langle N \rangle} = \frac{C}{VT^3}$

Thermodynamics of hot strong-interaction

Nature Physics Letters 2020
Gardim, Giacalone, Luzum and Ollitraut



Variation of $\langle p_T \rangle$ and T_{eff} as a function of the freeze-out temperature in ideal hydrodynamic simulations

QGP, modelled as a massless ideal gas with Boltzmann statistics, has a particle density $n = gT^3/\pi^2$

From experimental data, $g \approx 30$
=> This large number shows that the colour degrees of freedom are active.

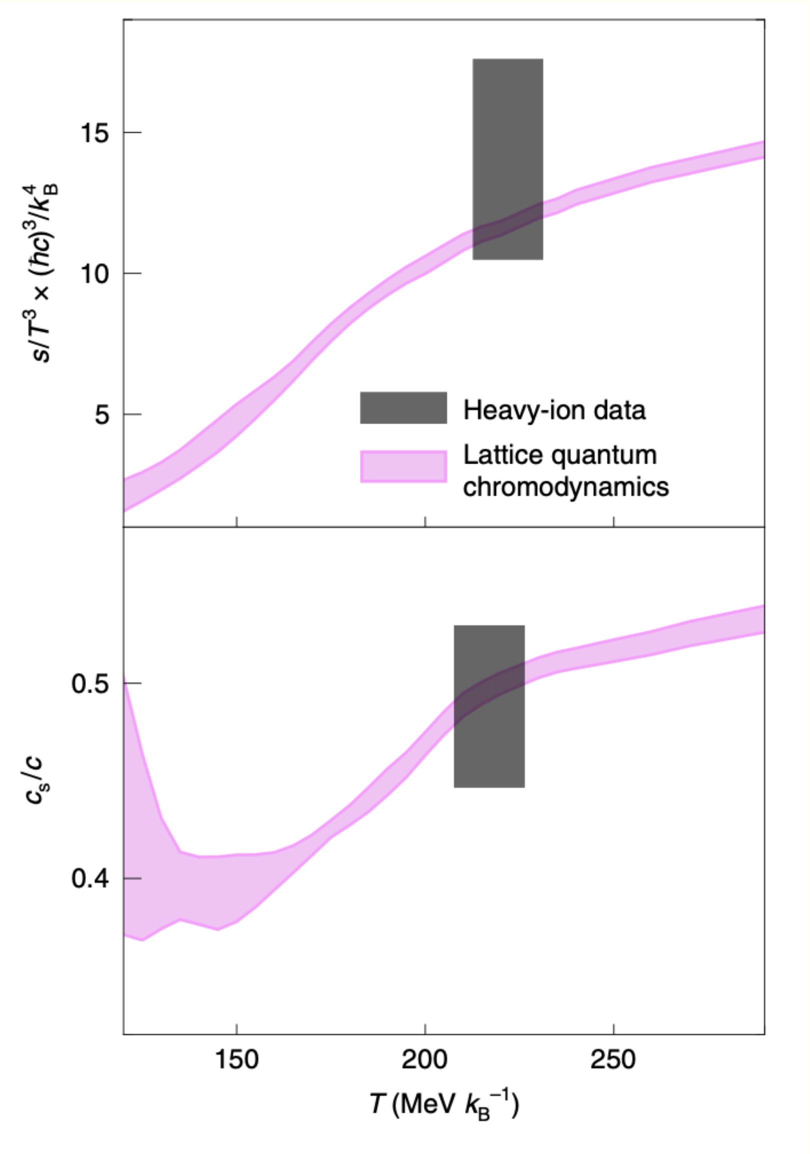
Entropy density:

$$s(T_{\rm eff}) = \frac{1}{V_{\rm eff}} \frac{S}{N_{\rm ch}} \frac{dN_{\rm ch}}{dy}$$

$$s(T_{\rm eff}) = 20 \pm 5\ \mathrm{fm}^{-3}$$

$$s(T_{\rm eff})/T_{\rm eff}^3 = 14 \pm 3.5$$

$\langle p_T \rangle$ distribution and Speed of sound



Nature Physics Letters 2020
Gardim, Giacalone, Luzum and Ollitraut

Entropy density:

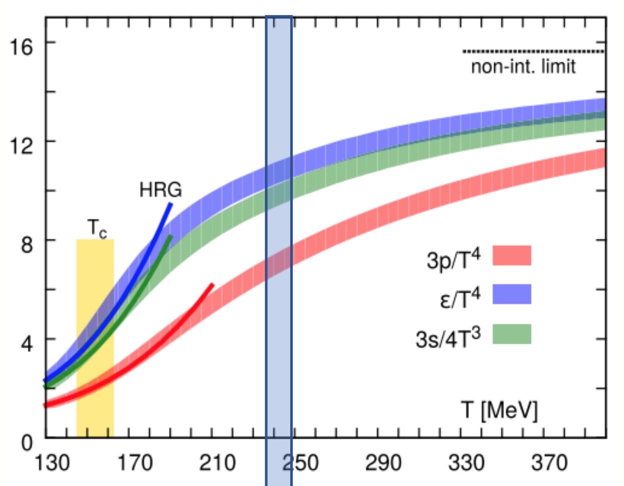
$$s(T_{\rm eff})/T_{\rm eff}^3 = 14 \pm 3.5$$

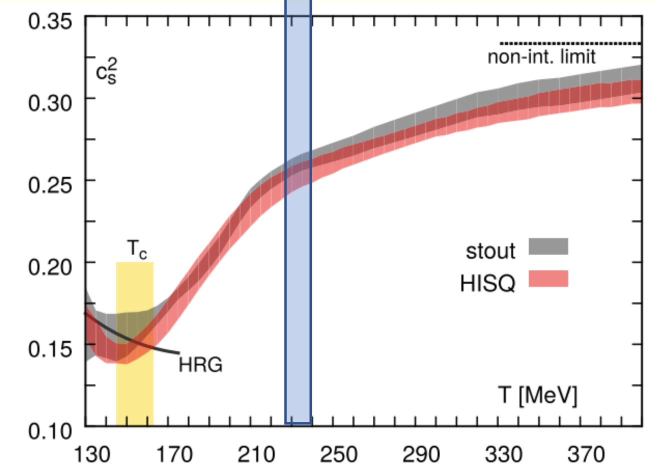
Speed of sound:

the velocity at which a compression wave travels in a fluid

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

$$c_s^2(T_{\rm eff}) = 0.24 \pm 0.04$$





HOTQCD Collaboration
Phys. Rev. D90 (2014) , 094503

Skewness of $\langle p_T \rangle$ distribution

Phys. Rev. C 103, 024910 (2021)
Giacalone, Gardim, Norohna-Hostler, and Ollitraut

Skewness of $\langle p_T \rangle$ distribution is proposed as a fine probe of hydrodynamic behavior

Mean:

$$\langle\langle p_t \rangle\rangle \equiv \left\langle \frac{\sum_{i=1}^{N_{\mathrm{ch}}} p_i}{N_{\mathrm{ch}}} \right\rangle$$

Variance:

$$\langle \Delta p_i \Delta p_j \rangle \equiv \left\langle \frac{\sum_{i,j\neq i} (p_i - \langle\langle p_t \rangle\rangle)(p_j - \langle\langle p_t \rangle\rangle)}{N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)} \right\rangle$$

Skewness:

$$\langle \Delta p_i \Delta p_j \Delta p_k \rangle \equiv \left\langle \frac{\sum_{i,j\neq i,k\neq i,j} (p_i - \langle\langle p_t \rangle\rangle)(p_j - \langle\langle p_t \rangle\rangle)(p_k - \langle\langle p_t \rangle\rangle)}{N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)(N_{\mathrm{ch}}-2)} \right\rangle$$

- $\langle p_T \rangle$ fluctuations result from fluctuations of the energy of the fluid when the hydrodynamic expansion starts.
- Hydrodynamics predicts that the $\langle p_T \rangle$ fluctuations have positive skew.

Higher-order cumulants would serve as detailed probes of QCD thermodynamics at higher temperatures, achieved during the early stages of the collision.

Run3 – Run4 data needed

Transverse Momentum correlations

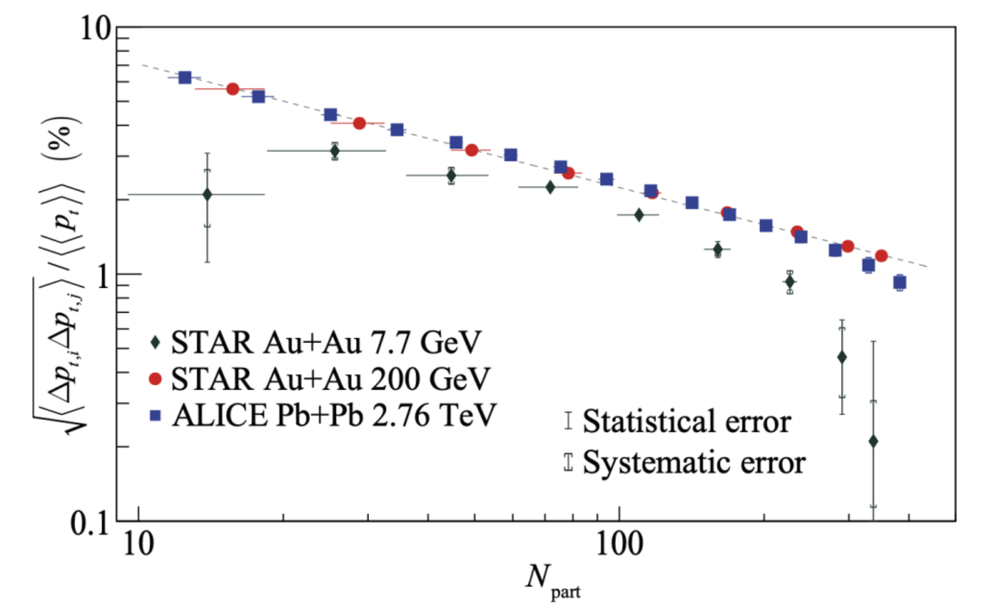
Eur. Phys. J. C (2014) 74
ALICE Collaboration

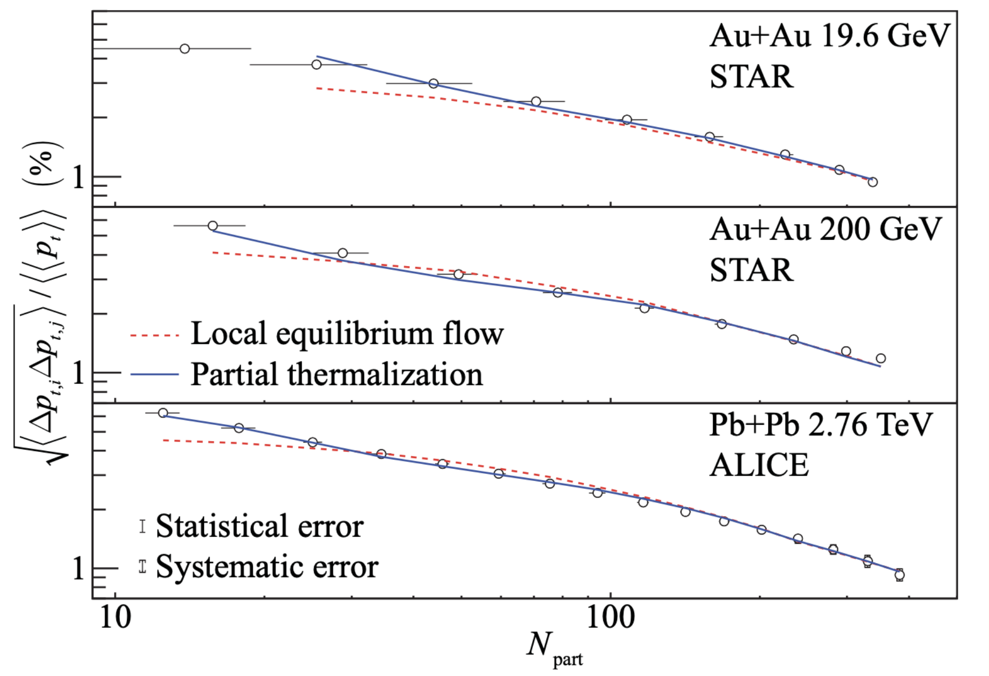
Phys. Rev. C **99** (2019)
STAR Collaboration

$$c_k = \sum_{i=1}^{N_{\mathrm{ch},k}} \sum_{j=i+1}^{N_{\mathrm{ch},k}} (p_{\mathrm{T},i} - \langle p_{\mathrm{T}} \rangle) \cdot (p_{\mathrm{T},j} - \langle p_{\mathrm{T}} \rangle)$$

$$C = \langle \Delta p_{\mathrm{T},i}, \Delta p_{\mathrm{T},j} \rangle = \frac{1}{\sum_{k=1}^{n_{\mathrm{ev}}} N_{\mathrm{ch},k}^{\mathrm{pairs}}} \sum_{k=1}^{n_{\mathrm{ev}}} \sum_{i=1}^{N_{\mathrm{ch},k}} \sum_{j=i+1}^{N_{\mathrm{ch},k}} (p_{\mathrm{T},i} - \langle p_{\mathrm{T}} \rangle) \cdot (p_{\mathrm{T},j} - \langle p_{\mathrm{T}} \rangle)$$
$$= \frac{1}{\sum_{k=1}^{n_{\mathrm{ev}}} N_{\mathrm{ch},k}^{\mathrm{pairs}}} \sum_{k=1}^{n_{\mathrm{ev}}} c_k \,.$$

Centrality Dependence of p_{T} correlations





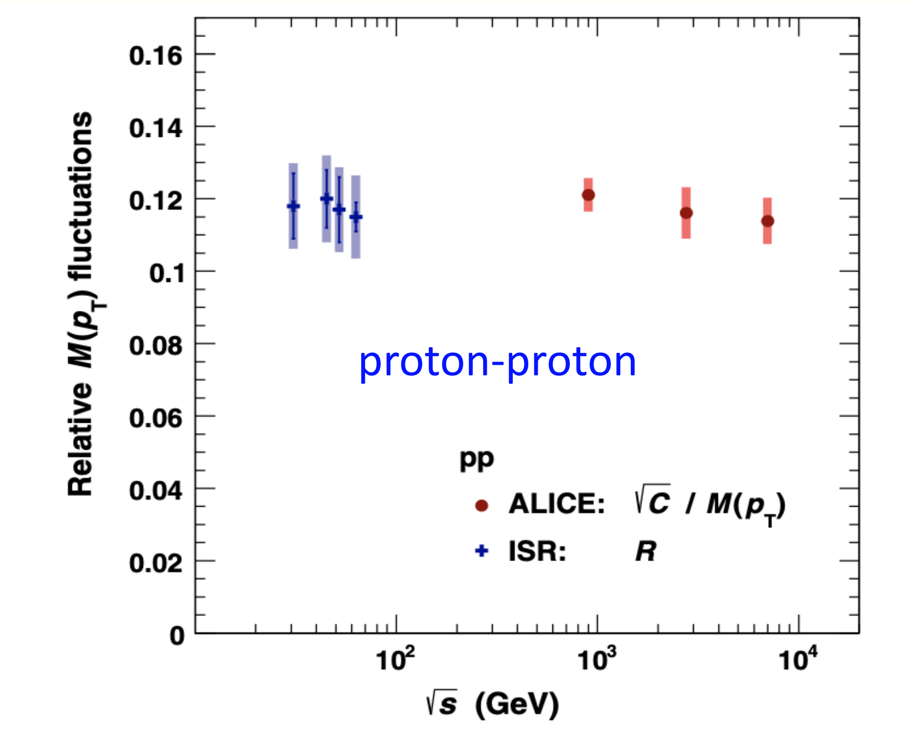
For most peripheral collisions: the two-particle $\langle p_{\mathrm{T}} \rangle$ correlations show evidence of incomplete thermalization when compared with the Boltzmann-Langevin model

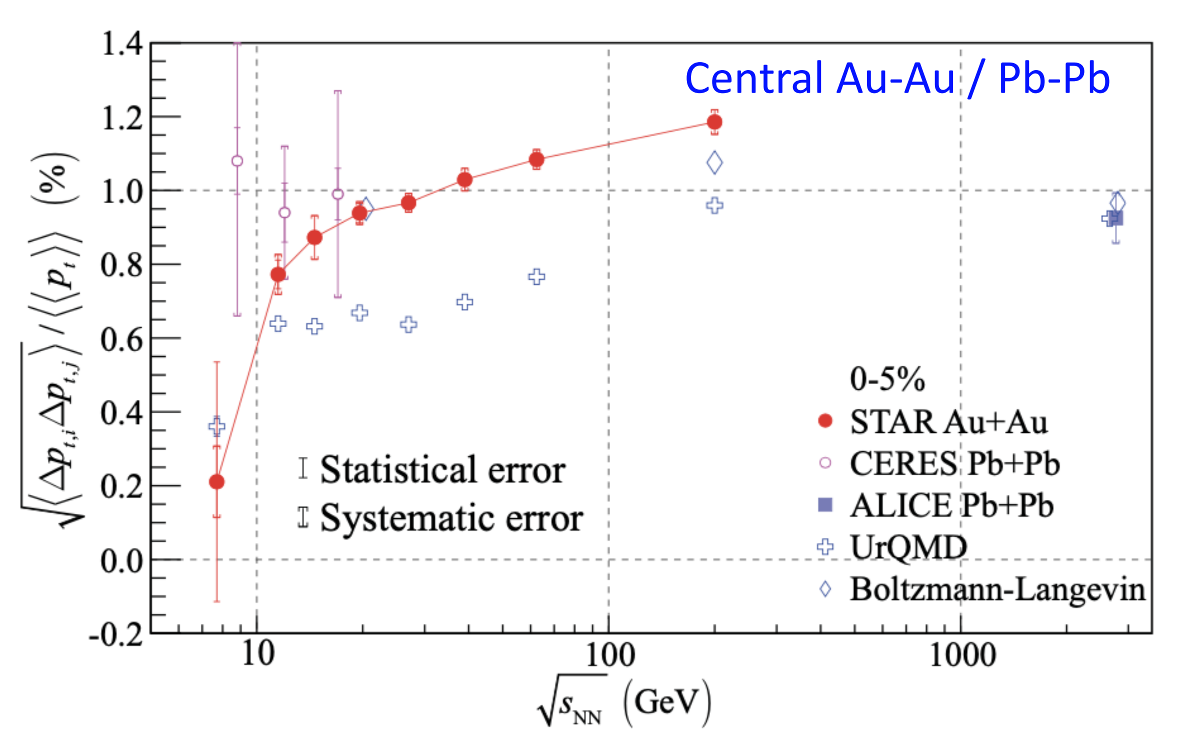
Evolution of p_T correlations w/ beam energy

Phys. Rev. C 99 (2019) 044918
STAR Collaboration

Eur. Phys. J. C (2014) 74:3077
ALICE Collaboration

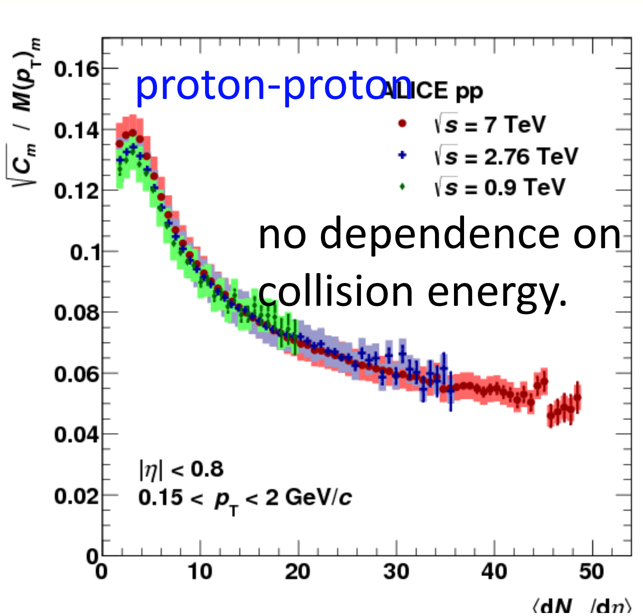
Collision energy Dependence of p_T correlations



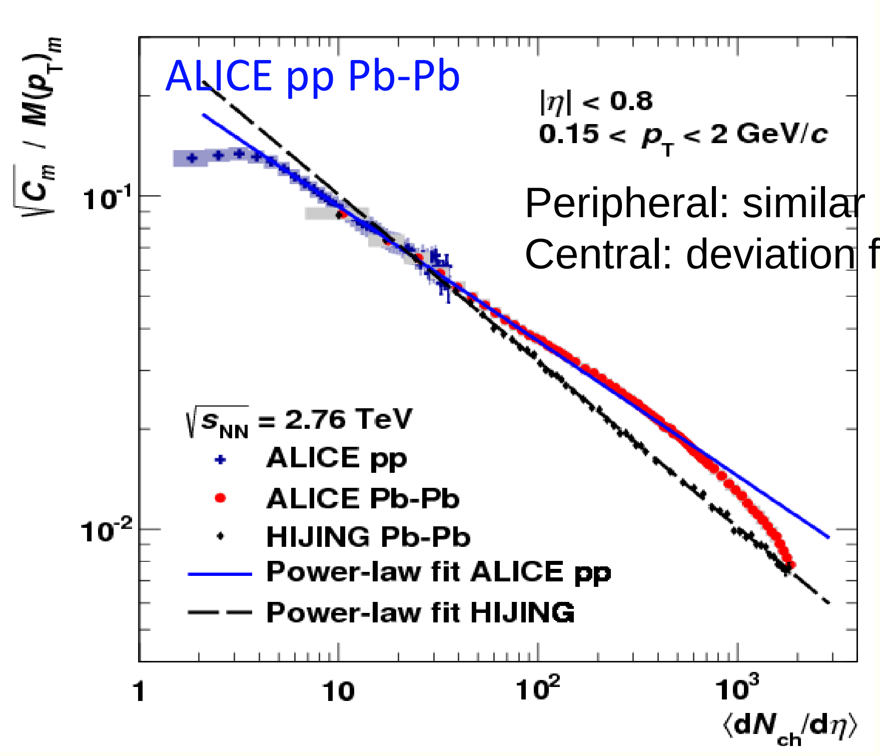


- The relative dynamical correlations increase with collision energy up to 200 GeV.
- For Pb+Pb collisions at 2.76 TeV, it is lower than that of Au+Au collisions at 200 GeV.

Relative dynamical correlations

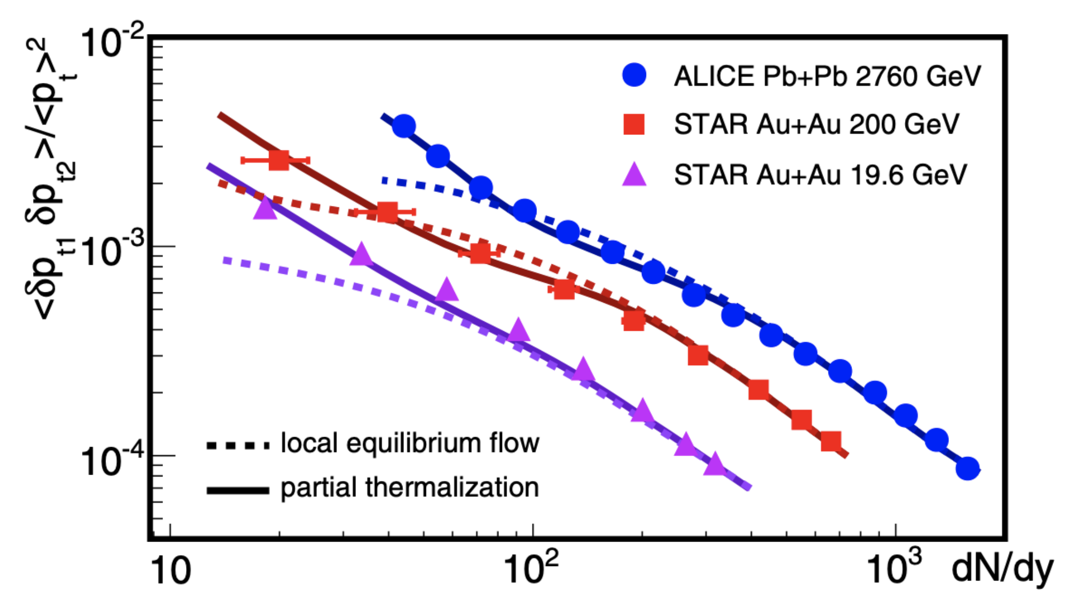


Eur. Phys. J. C (2014) 74:3077
ALICE Collaboration



Peripheral: similar multiplicity to pp.
Central: deviation from the trend

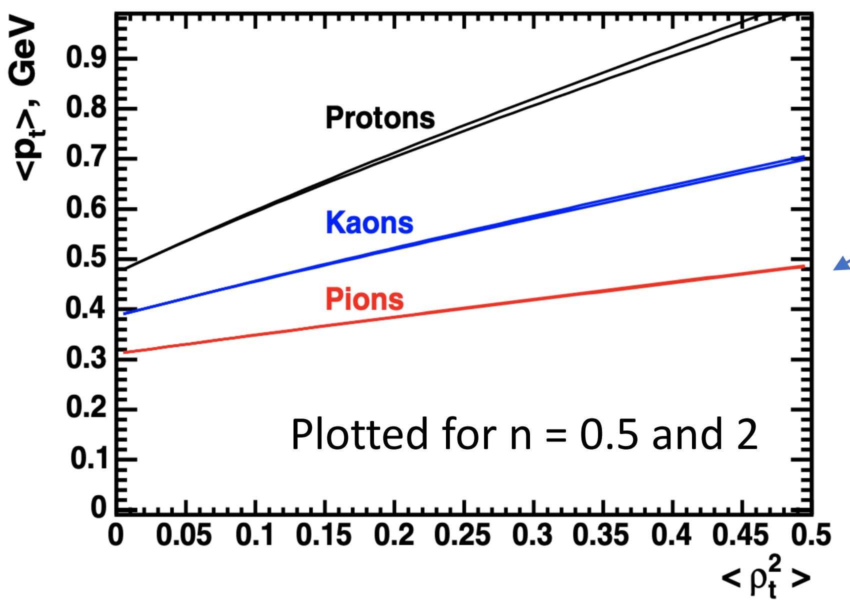
Boltzmann-Langevin approach to pre-equilibrium correlations in nuclear collisions: theoretical and phenomenological tools for studying non-equilibrium aspects of correlation measurements by Sean Gavin et al., PRC 95 (2017)

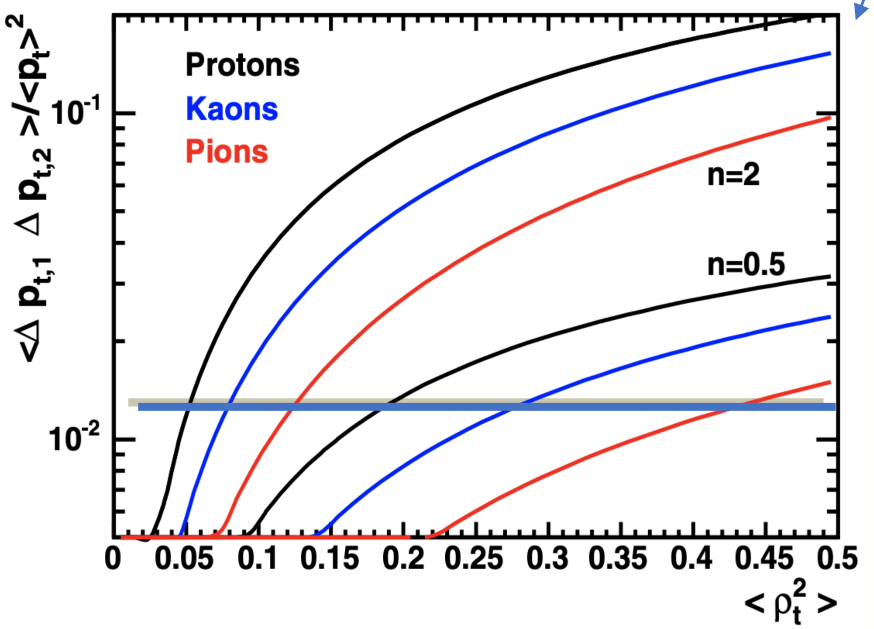


- The first traces of thermalization emerges in peripheral collisions, becoming more significant with increasing centrality as the system lifetime increases.
- Peripheral collisions show a systematic discrepancy with local equilibrium flow.

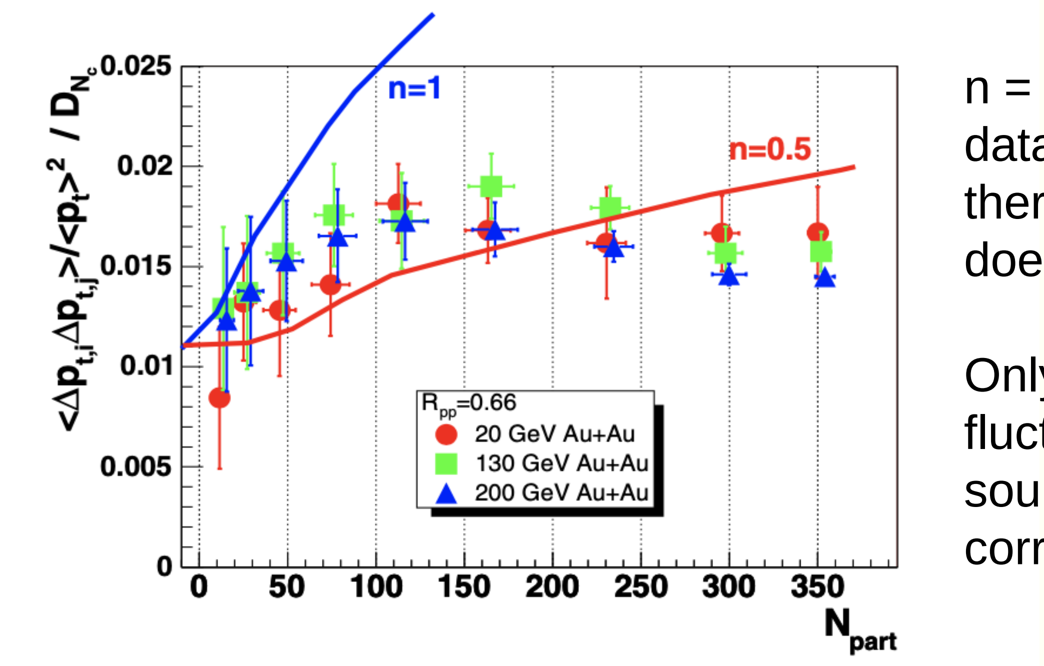
Effect of radial flow on p_T fluctuation

2006 J. Phys.: Conf. Ser. **50** 013
Sergei A Voloshin





- p_T correlations measure the variance in collective transverse expansion velocity => more sensitive to the actual velocity profile (n).
- $\langle p_T \rangle$ depends very weakly on the actual profile.
- On the other hand, the correlations are drastically different for the two velocity profiles (n) values studied.



n = 0.5 describes the data. n=1 (ideal thermodynamics) does not).

Only radial flow fluctuation is not the source of this correlation.

Sensitivity could be explored going in going to higher order $\Delta p_T \Delta p_T$ correlations.

Run3 – Run4 data needed

Two-particle differential p_T correlations

Phys. Rev. C 100 (2019) 044903
ALICE Collaboration

Integral correlations have been discussed earlier – now to differential ..

$$\rho_1(\eta,\varphi) = \frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\eta\mathrm{d}\varphi},$$
$$\rho_2(\eta_1,\varphi_1,\eta_2,\varphi_2) = \frac{1}{\sigma}\frac{\mathrm{d}^4\sigma}{\mathrm{d}\eta_1\mathrm{d}\varphi_1\mathrm{d}\eta_2\mathrm{d}\varphi_2}$$

Single and two particle number densities

Two-particle "number" correlations:

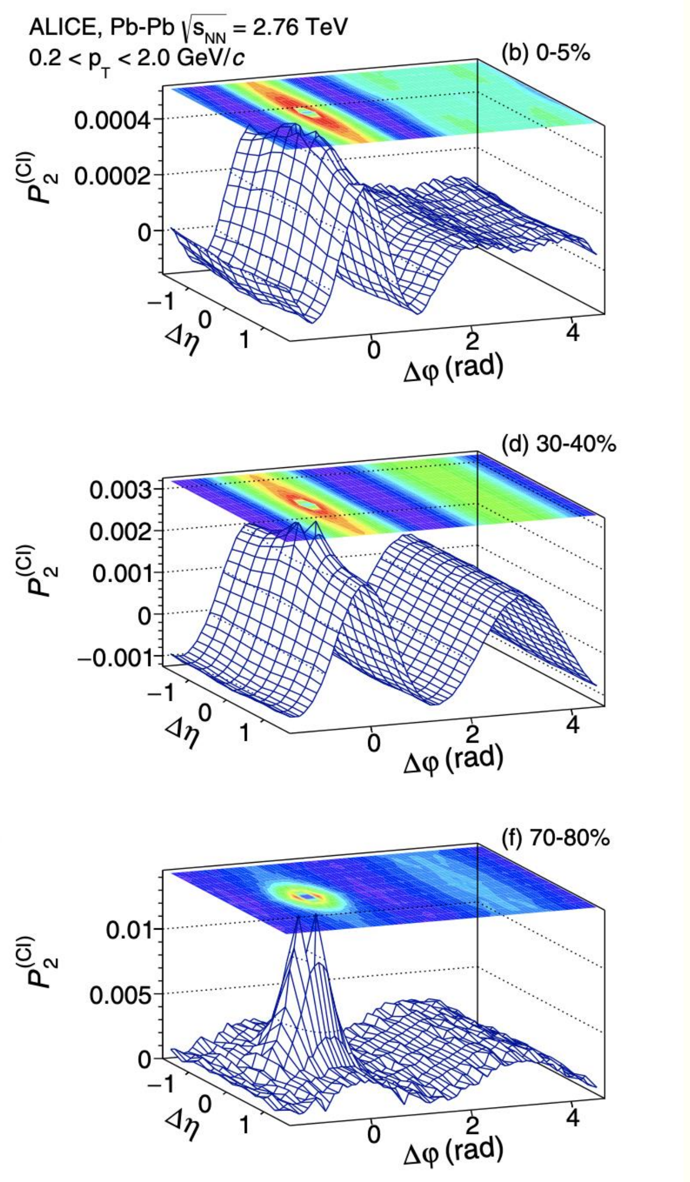
$$R_2(\eta_1,\varphi_1,\eta_2,\varphi_2) = \frac{\rho_2(\eta_1,\varphi_1,\eta_2,\varphi_2)}{\rho_1(\eta_1,\varphi_1)\rho_1(\eta_2,\varphi_2)} - 1,$$

Differential correlator:

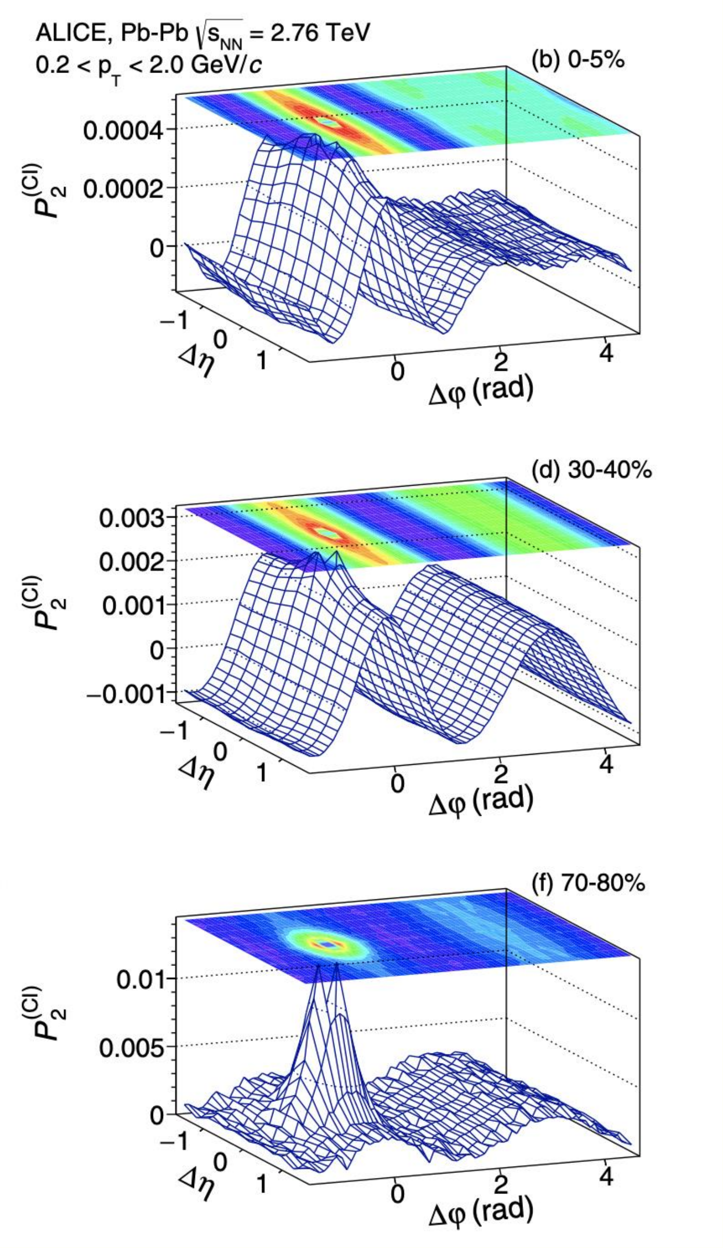
$$\langle\Delta p_T\Delta p_T\rangle(\eta_1,\varphi_1,\eta_2,\varphi_2) = \frac{\int_{p_{T,\min}}^{p_{T,\max}} dp_{T,1}dp_{T,2}\rho_2(\vec{p}_1,\vec{p}_2)\Delta p_{T,1}\Delta p_{T,2}}{\int_{p_{T,\min}}^{p_{T,\max}} dp_{T,1}dp_{T,2}\rho_2(\vec{p}_1,\vec{p}_2)}$$

Normalized p_T correlator:

$$P_2(\eta_1,\varphi_1,\eta_2,\varphi_2) = \frac{\langle\Delta p_T\Delta p_T\rangle(\eta_1,\varphi_1,\eta_2,\varphi_2)}{\langle p_T\rangle^2}.$$



Phys. Rev. C 100 (2019) 044903
ALICE Collaboration



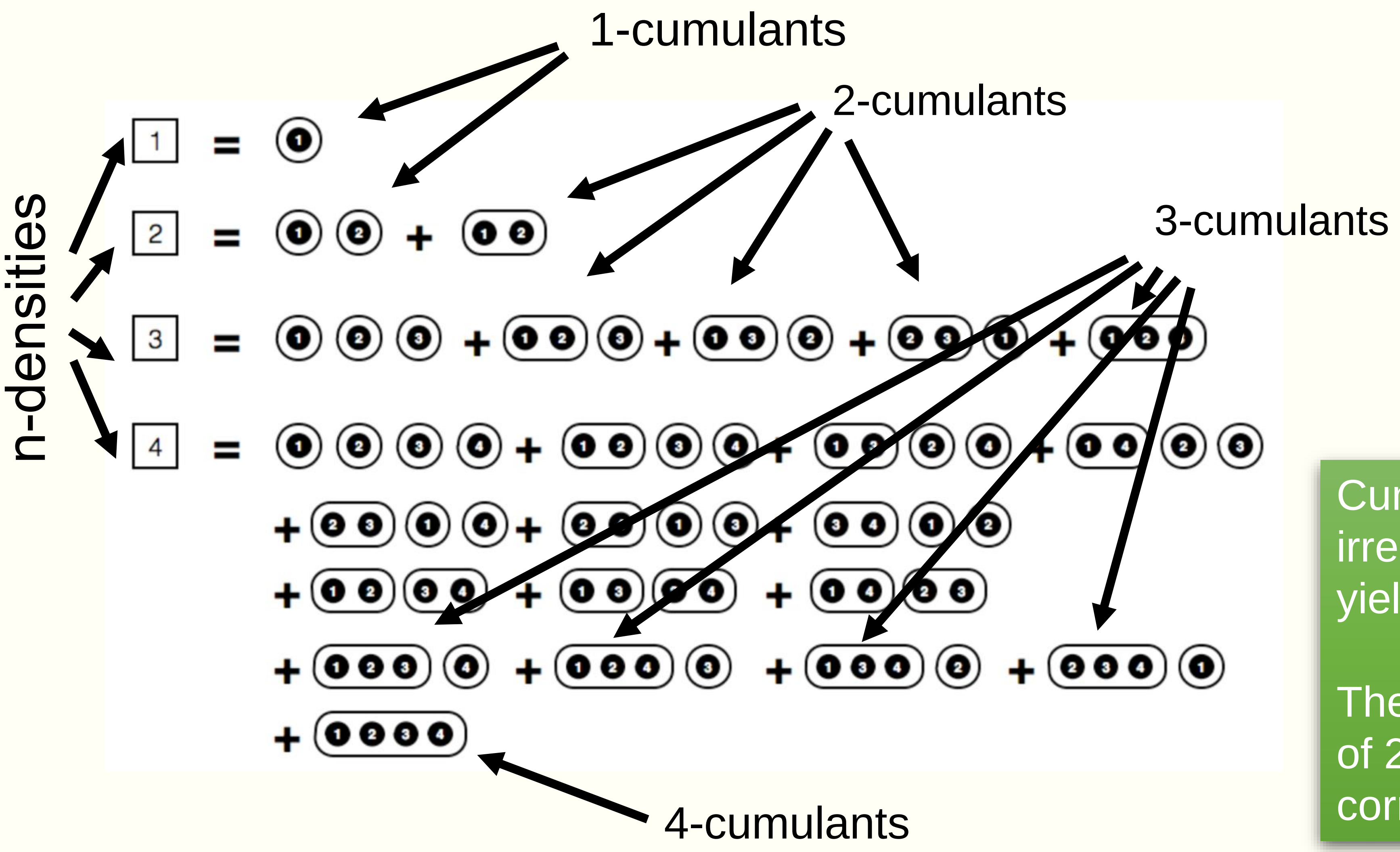
- Differential p_T correlation functions sensitive to **collective flow effects** — i.e., correlation w.r.t. reaction plane in mid- to central collisions.
- **Two-particle correlations** domination peripheral collisions and are relative strong in mid to central collisions.
- Integrating over $\Delta\phi$ and $\Delta\eta$ gives the integral correlator $\langle \Delta p_T \Delta p_T \rangle$
  - $\cos n\Delta\phi$ terms vanish in the integral
  - Sensitivity to temperature fluctuations remains
  - But correlation strength determined largely from the near-side peak, i.e, two-particle correlations — which have "nothing" to do with temperature fluctuations.

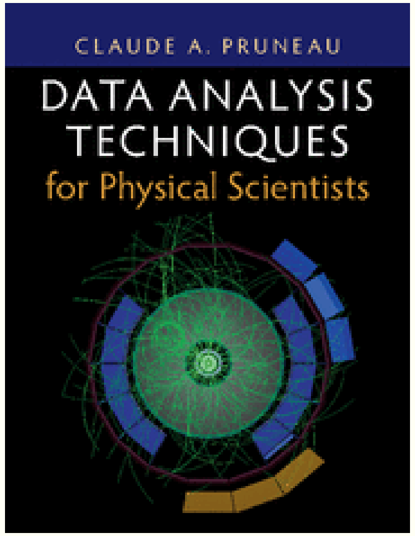
Obvious: need to suppress two-particle correlations (aka non flow effects)

Not possible to understand with current dataset.
Need to go for 3- or 4-particle correlations.

Run3 – Run4 data needed

N-particle densities are functions of n-particle cumulants.





Cumulants amount to irreducible particle correlated yields.

They are genuine indicators of 2-, 3-, 4-, etc particle correlations.

Experimentally, cumulants are obtained (recursively) from N-particle densities.

m-cumulants

1-density

2-density

3-density

2-density

1-density

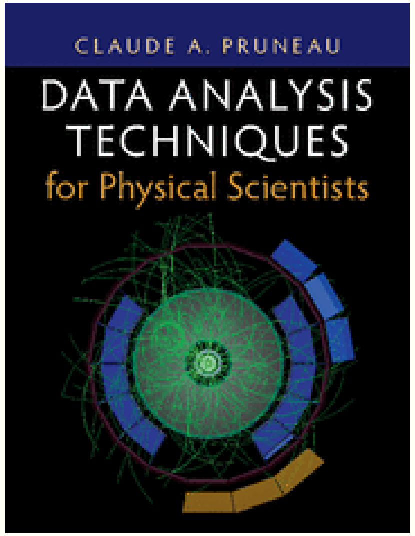
4-density

$$C_1 = \boxed{1}$$

$$C_{12} = \boxed{2_{12}} - \boxed{1_1}\,\boxed{1_2}$$

$$C_{123} = \boxed{3_{123}} - \boxed{2_{12}}\,\boxed{1_3} - \boxed{2_{13}}\,\boxed{1_2} - \boxed{2_{23}}\,\boxed{1_1} + 2\,\boxed{1_1}\,\boxed{1_2}\,\boxed{1_3}$$

$$\begin{aligned} C_{1234} = {} & \boxed{4_{1234}} - \boxed{3_{123}}\,\boxed{1_4} - \boxed{3_{124}}\,\boxed{1_3} - \boxed{3_{134}}\,\boxed{1_2} - \boxed{3_{234}}\,\boxed{1_1} \\ & - \boxed{2_{12}}\,\boxed{2_{34}} - \boxed{2_{13}}\,\boxed{2_{24}} - \boxed{2_{14}}\,\boxed{2_{23}} \\ & + 2\,\boxed{2_{12}}\,\boxed{1_3}\,\boxed{1_4} + 2\,\boxed{2_{13}}\,\boxed{1_2}\,\boxed{1_4} + 2\,\boxed{2_{14}}\,\boxed{1_2}\,\boxed{1_3} \\ & + 2\,\boxed{2_{23}}\,\boxed{1_1}\,\boxed{1_4} + 2\,\boxed{2_{24}}\,\boxed{1_1}\,\boxed{1_3} + 2\,\boxed{2_{34}}\,\boxed{1_1}\,\boxed{1_2} \\ & - 6\,\boxed{1_1}\,\boxed{1_2}\,\boxed{1_3}\,\boxed{1_4} \end{aligned}$$



Cumulants amount to irreducible particle correlated yields.

They are genuine indicators of 2-, 3-, 4-, etc particle correlations.

p_T correlations are computed in a similar fashion but one includes an explicit dependence on p_T

Mean p_T: $$\langle p_T \rangle \equiv \frac{\int_\Omega p_T \rho_1(p_{T,1}) dp_T}{\int_\Omega \rho_1(p_{T,1}) dp_T}$$

Deviates: $$\Delta p_T = p_T - \langle p_T \rangle$$

2nd order: $$C_2^{pT} \equiv \langle \Delta p_T \Delta p_T \rangle \equiv \frac{\int_\Omega \Delta p_{T,1} \Delta p_{T,2} \rho_2(p_{T,1}, p_{T,2}) dp_{T,1} dp_{T,2}}{\int_\Omega \rho_2(p_{T,1}, p_{T,2}) dp_{T,1} dp_{T,2}} \propto \int_\Omega p_{T,1} p_{T,2} C_2(p_{T,1}, p_{T,2}) dp_{T,1} dp_{T,2}$$

3rd order: $$C_3^{pT} \equiv \langle \Delta p_T \Delta p_T \Delta p_T \rangle \propto \int_\Omega p_{T,1} p_{T,2} p_{T,3} C_3(p_{T,1}, p_{T,2} p_{T,3}) dp_{T,1} dp_{T,2} dp_{T,2}$$

4th order: $$C_4^{pT} \equiv \int_\Omega p_{T,1} p_{T,2} p_{T,3} p_{T,4} C_4(p_{T,1}, p_{T,2} p_{T,3} p_{T,4}) dp_{T,1} dp_{T,2} dp_{T,3} dp_{T,4}$$
$$= \langle \Delta p_{T,1} \Delta p_{T,2} \Delta p_{T,3} \Delta p_{T,4} \rangle - 3\langle \Delta p_{T,1} \Delta p_{T,2}$$

$$C_4^{pT} = \langle \Delta p_{T,1} \Delta p_{T,2} \Delta p_{T,3} \Delta p_{T,4} \rangle - 3\langle \Delta p_{T,1} \Delta p_{T,2} \rangle^2$$

And similarly for higher orders…

High order p_T correlations

4th order: $$C_4^{pT} = \langle \Delta p_{T,1} \Delta p_{T,2} \Delta p_{T,3} \Delta p_{T,4} \rangle - 3\langle \Delta p_{T,1} \Delta p_{T,2} \rangle^2$$

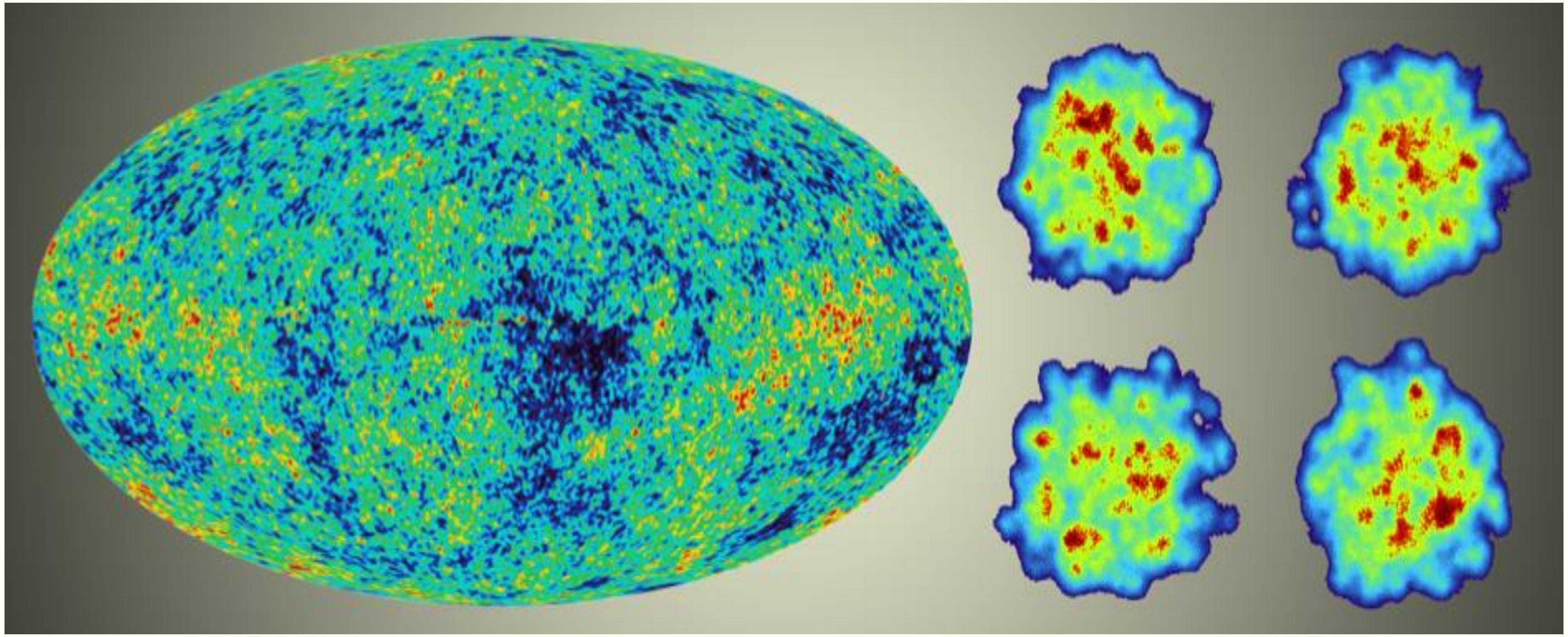
- As in the context of flow measurements, higher cumulants suppress “non-flow” effects — i.e., 2-particle correlations contributions.
- With no explicit dependence on cos($\Delta\phi$), **anisotropic flow does not contribute** to these correlators.
- These correlators are thus sensitive to **temperature fluctuations as well as fluctuations of the radial flow profile**.

C_n^{pT} cumulants are thus nominally sensitive to the temperature fluctuations and the stiffness of the equation of state.

Run3 – Run4 data needed

Fluctuations in the Little Bang

Uli Heinz, arXiv:1304.3634v1 [nucl-th] 11 Apr 2013

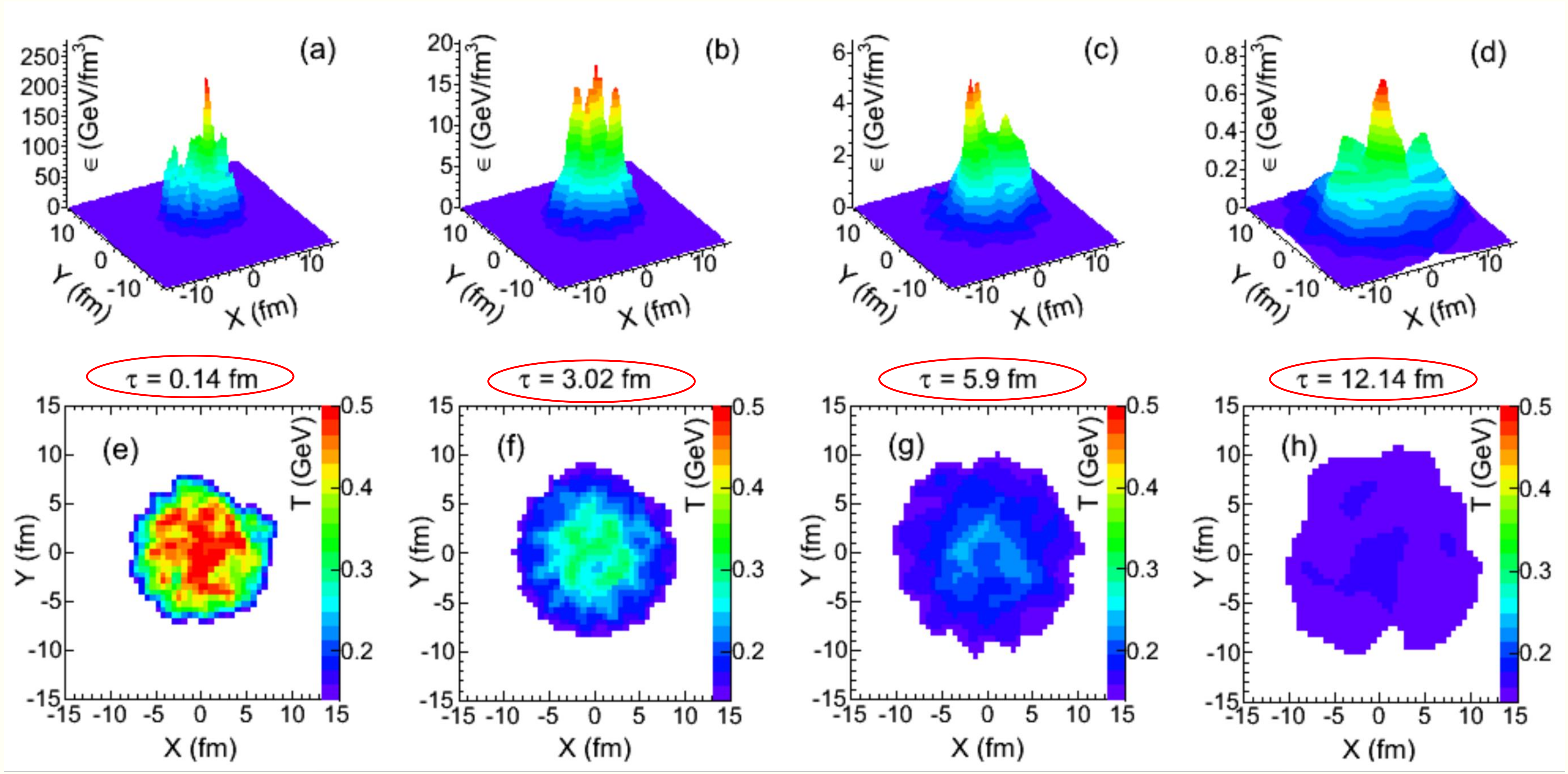


WMAP **Heavy-ion Collisions**

- Hadrons detected by the experiment are mostly emitted at the freeze-out
- Similar to the CMBR which carry information at the surface of last scattering in the Universe, these hadrons may provide information about the earlier stages (hadronization) of the reaction in heavy-ion collision.

Hydrodynamic simulation of central Pb-Pb at 2.76 TeV

arXiv:1504.04502 [nucl-ex]
Sumit Basu, TN et al.



Evolution of Energy Density and temperature

Evolution of Energy Density and temperature

arXiv:1504.04502 [nucl-ex]
Sumit Basu, TN et al.

Taking the average over the X-Y bins in every event, we obtain:

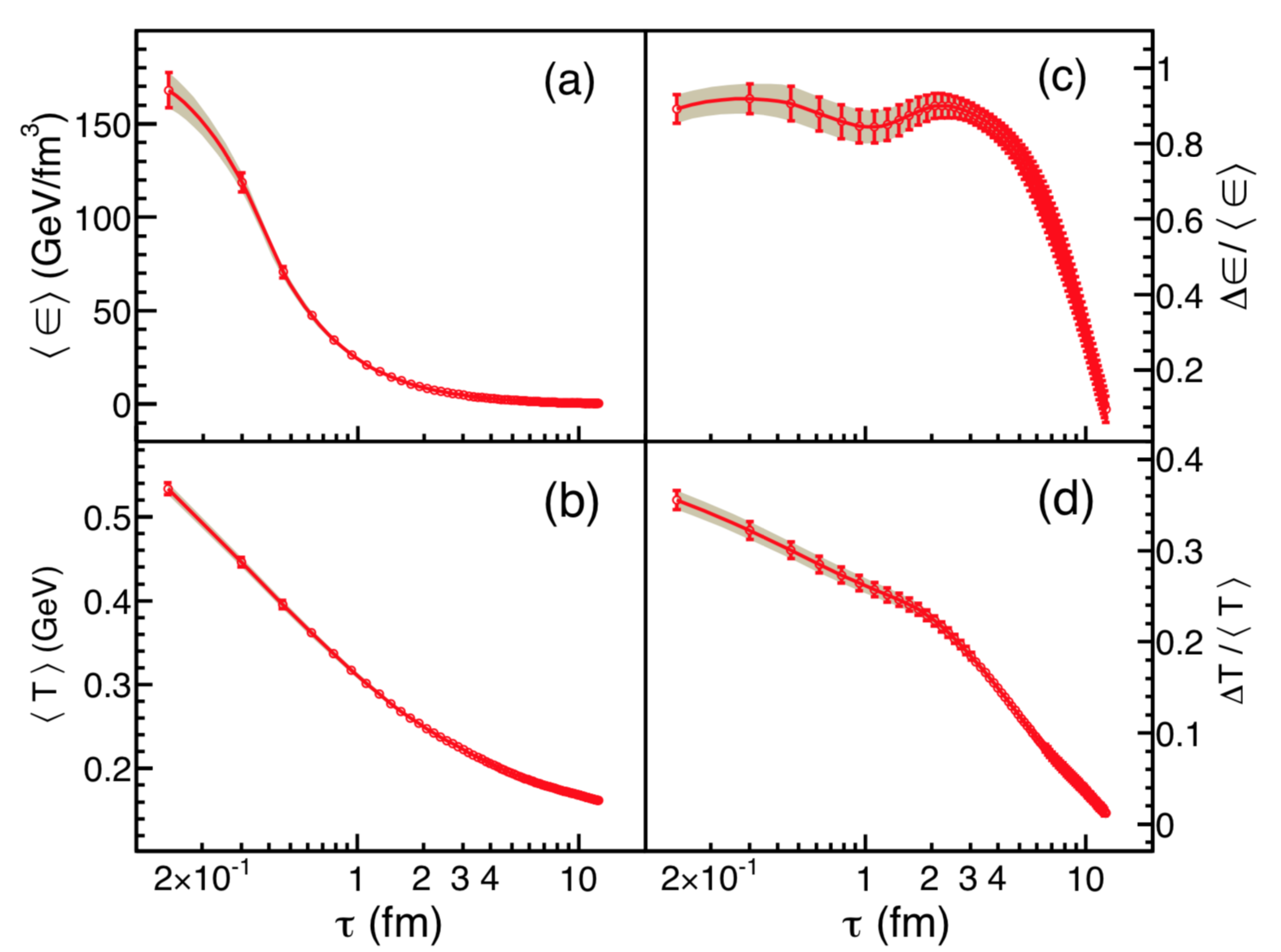
Time evolution of:

(a) average energy density

(b) average temperature

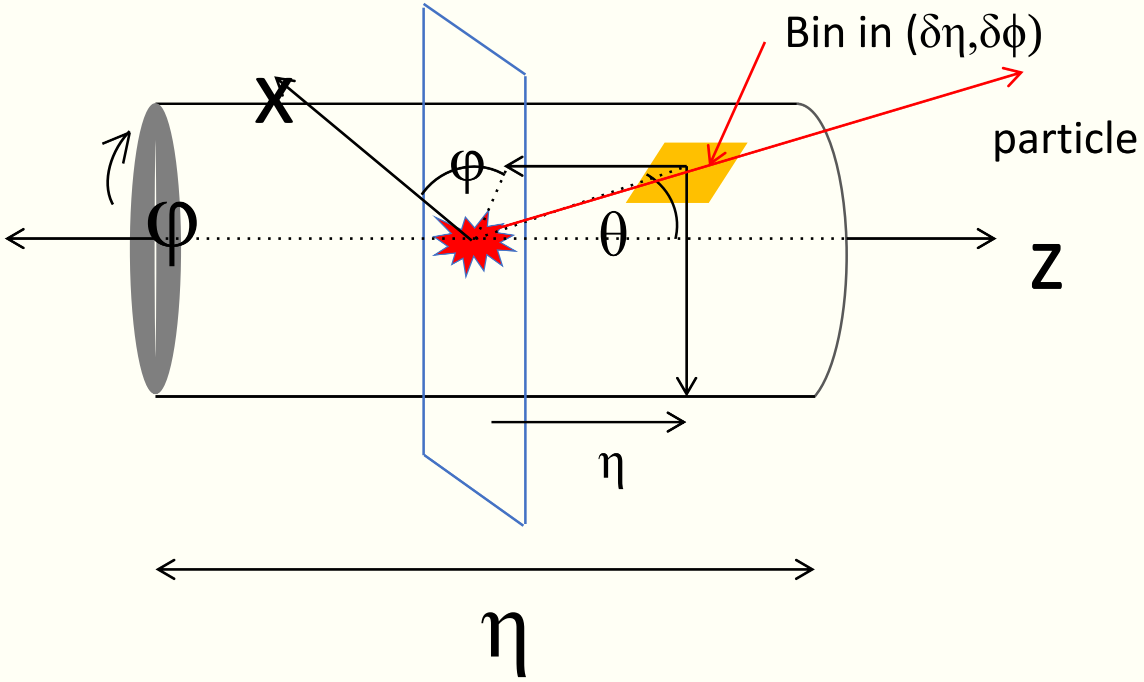
(c) fluctuations in energy density,

(d) fluctuations in temperature

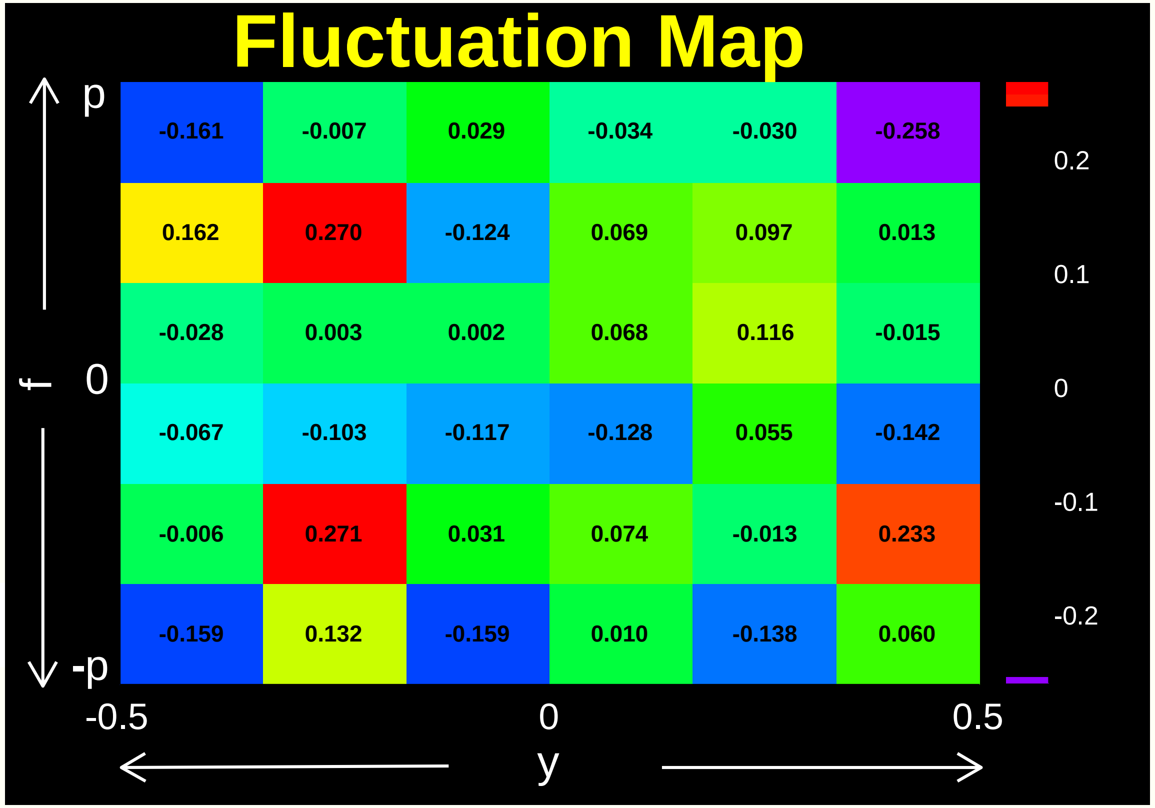


Local Fluctuation

arXiv:1504.04502 [nucl-ex]
Sumit Basu, TN et al.



SINGLE Event



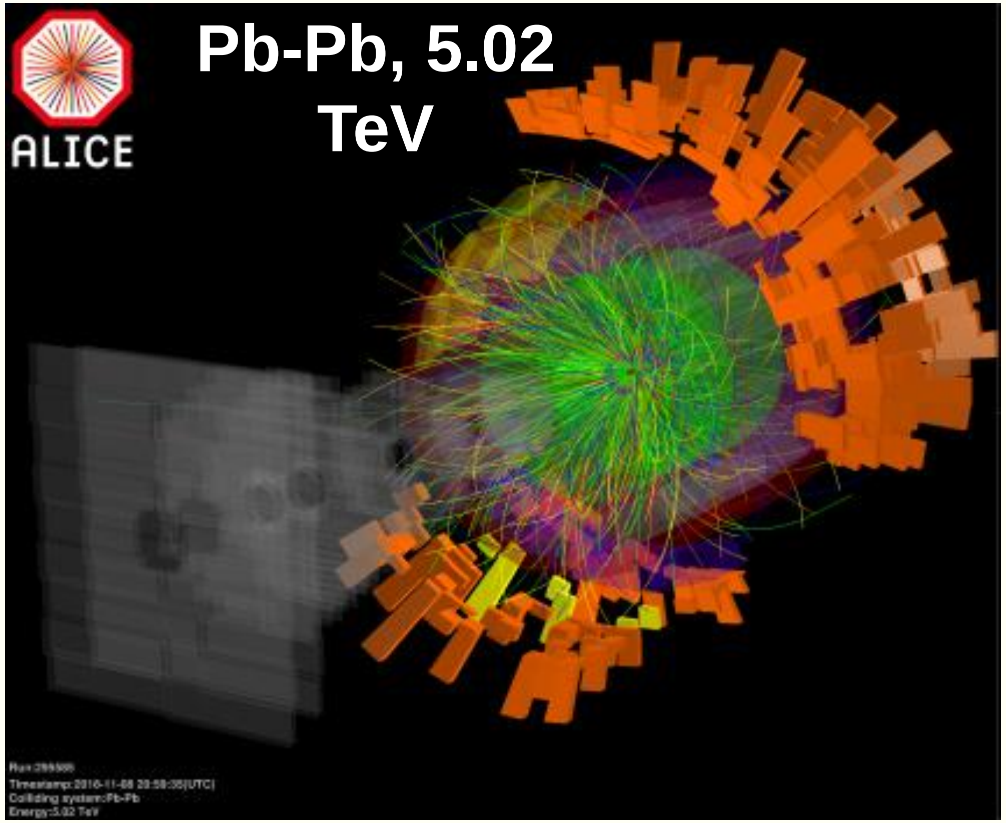
- For each event and each bin: obtain $\langle p_T \rangle$ and extrapolate to T_{eff}
- Obtain event $\langle p_T \rangle$ and extrapolate T_{eff}
- Bin-to-bin fluctuation map is constructed taking the difference of T_{eff} of the bin from T_{eff} of the event.

  - Need large acceptance detectors
  - Novel method to map the Heavy-ion collisions
  - Need a strong connection to theory to derive early stage fluctuations.

Run3 – Run4 data needed

ALICE at CERN LHC

- Excellent track and vertex reconstruction capabilities in high multiplicity environment
- Particle identification over a wide momentum range



Run 1 + Run 2

System	Years	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011	2.76	~75 mb^{-1}
Pb-Pb	2015, 2018	5.02	~1 nb^{-1}
Xe-Xe	2017	5.44	~0.3 mb^{-1}
p-Pb	2013, 2016	5.02, 8.16	~18 nb^{-1} , ~25 nb^{-1}
pp	2009-2013, 2015-2018	0.9, 2.76, 7, 8, 5.02, 13	>25 pb^{-1}

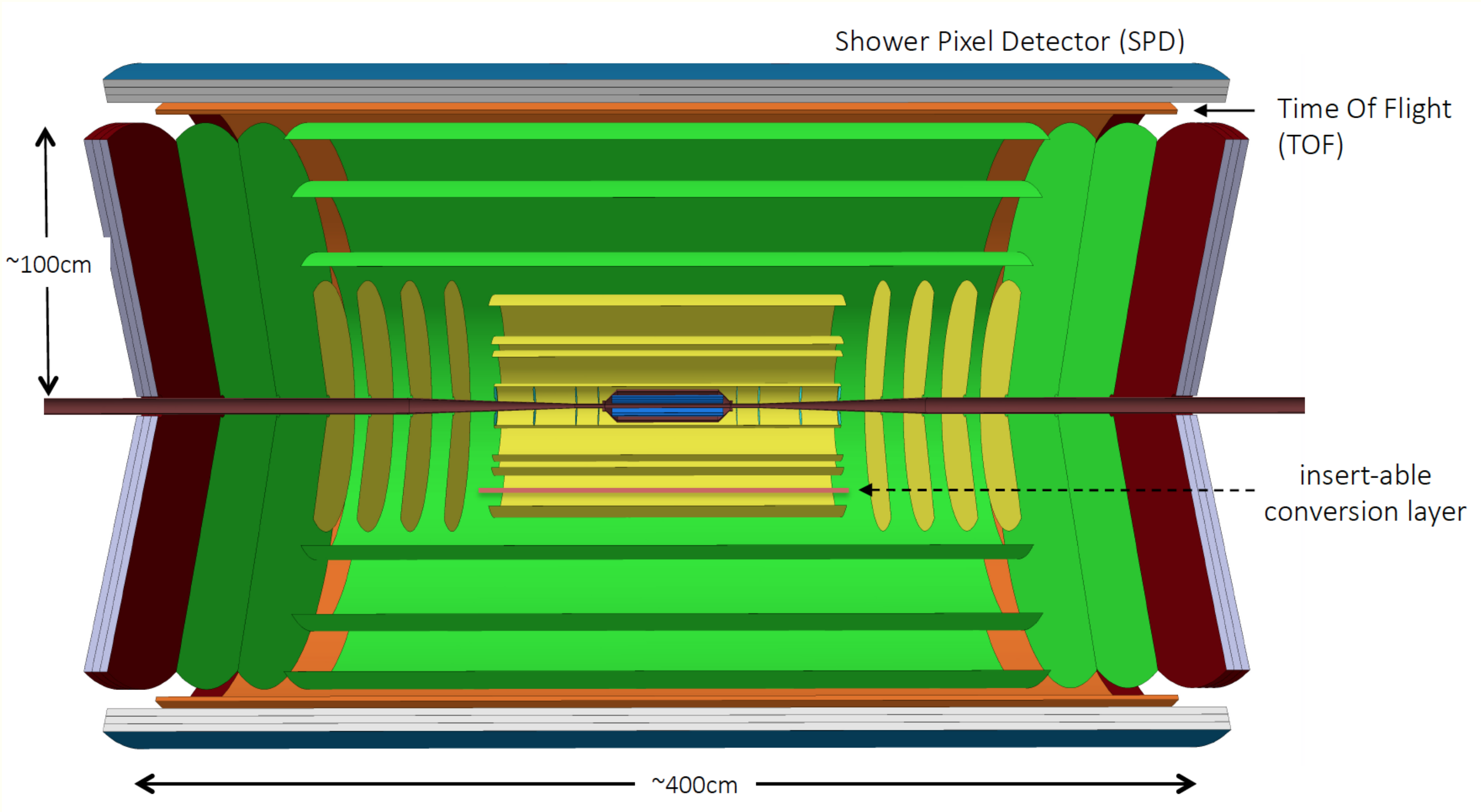
- During LS2: ALICE has gone through major upgradation and added new components to: ITS, TPC, MFT, FIT and the readout and data acquisition systems.
- The interaction rate of lead ions during the LHC Run 3 is foreseen to reach around 50 kHz, corresponding to an instantaneous luminosity of 6×10^{27} cm^{-2} s^{-1}.
- ALICE will accumulate a data sample 100 times larger than what has been taken in Run 1 + Run 2.

Run3 – Run4

Large minimum bias data sample with no event pileup.

A "New ALICE" from LHC Run-5 (2032 ..)

https://arxiv.org/abs/1902.01211



CMOS imaging technologies: high-precision spatial and time resolution + FoCal (Forward Calorimeters)

LHC Run-5:

- Tracker: ~10 tracking barrel layers
- Hadron ID: TOF: outer silicon layers
- Electron ID: pre-shower
- Conversion photons

Low p_T down to ~20 MeV/c
Extended rapidity coverage: up to 8 rapidity units

Ideal detector for thermodynamics

$\Rightarrow$ Correlation and Fluctuation

Summary

Extracting thermodynamics:

- temperature, energy density
- Freeze-out temperatures from particle spectra, particle ratios

- Extraction of specific heat from temperature (mean transverse momentum) fluctuations
- Extraction of speed of sound
- Higher momens of $\langle p_T \rangle$ distributions

- $\Delta p_T \Delta p_T$ correlations -> traces of early stage thermalization
- Effect of radial flow and radial flow fluctuation
- Higher order cumulants

- Local temperatures and its fluctuation over small phase bins

- LHC data from Run3, Run4 and beyond will be needed for getting a better understanding of the thermodynamics of hot and dense matter formed in relativistic heavy-ion collisions and thus the early universe thermodynamics.