Temperature Fluctuations

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Outline

Event-by-Event Fluctuations in:

- Global Event Temperature
- Local Temperatures in $\eta-\phi$ bins

Motivated by:

- CMBR, Event-by-event Hydrodynamic Calculations
- Calculation of heat capacity

Event-by-Event Temperature Fluctuations

Two sources of fluctuations:

- Quantum fluctuations occurring at fast time scales
- Thermodynamic fluctuations which occur after elapse of sufficient time after the collision.

- Initial state fluctuations arise because of internal structures of the colliding nuclei and fluctuations in initial energy densities, and appear as event-by-event fluctuations in the energy density or temperature.
- Thermodynamic fluctuations originate from local thermal fluctuations of energy density and event-by-event variation in the freeze-out conditions.

Fluctuations in temperature are related to the heat capacity of the system:

$$\frac{1}{C_V} = \frac{\sigma_T^2}{\langle T\rangle^2}$$

Heat Capacity Using Event-by-Event Temperature Fluctuations

$$\frac{1}{C_V} = \frac{\sigma_T^2}{\langle T \rangle^2}$$

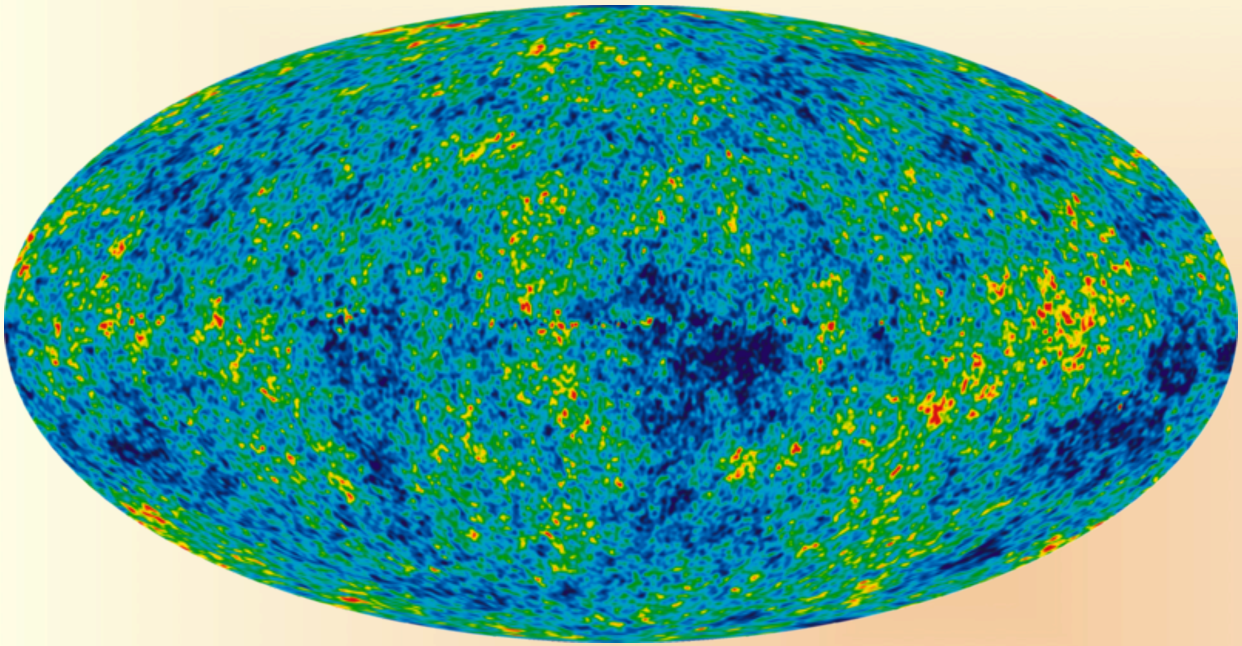
Landau and Lifschitz,
Course of Theoretical Physics, Statistical Physics Vol. 5

- Fluctuations in temperature may arise due to fluctuations in energy or entropy or finite particle number, and can be calculated using fluctuations of transverse momentum (p_T).
- p_T fluctuations have been studied extensively by NA49, STAR, PHENIX, ALICE experiments.
- Stephanov, Rajagopal and Shuryak (Phy. Rev. D, Vol. 60, 114028) have shown that p_T fluctuations are not appropriate measure of temperature fluctuations. Extraction of heat capacity from pT correlations are not like temperature fluctuation or even energy fluctuation …
- To circumvent this limitation, a new approach by assigning a temperature to an event and estimating event-by-event fluctuations.

LOCAL TEMPERATURE FLUCTUATIONS

(EVENT – BY – EVENT)

CMBR: Fluctuation Analysis



Cosmic Microwave Background Radiation (CMBR) by WMAP: shows Temperature fluctuation spectrum of the Big Bang at age 380,000 yrs.

Temperature anisotropies are analyzed using Spherical harmonics:

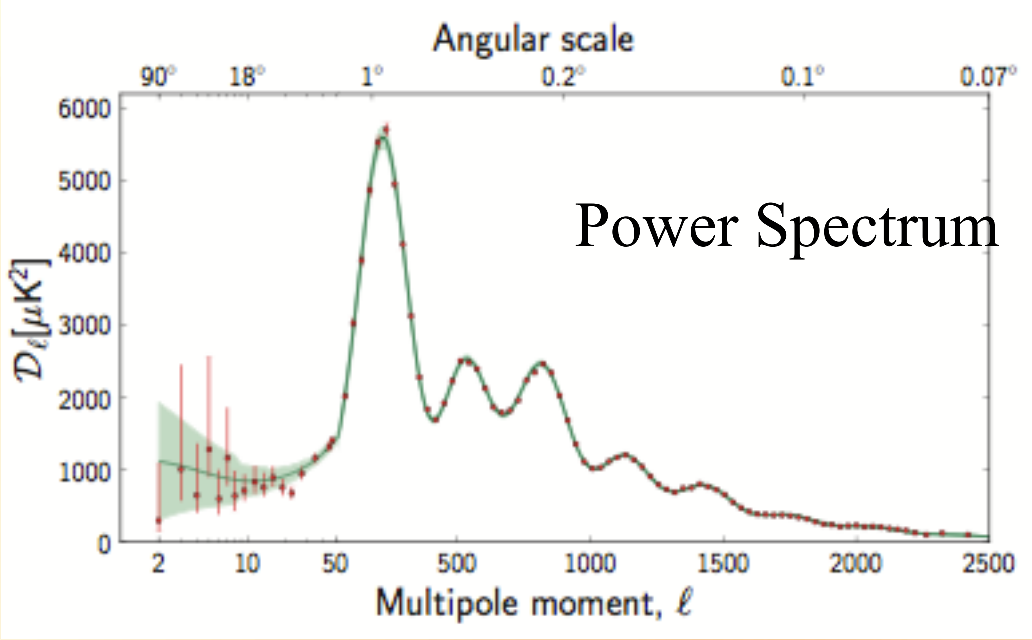
$$\frac{\Delta T}{T}(\theta,\phi) = a_{lm} Y_{lm}(\theta,\varphi)$$

Average values of these expansions coefficients are zero due to overall isotropy of the universe:

$$< a_{lm} >= 0$$

But standard deviations of the coefficients are non-zero and contain crucial information:

$$C_l =<| a_{lm} |^2 >$$

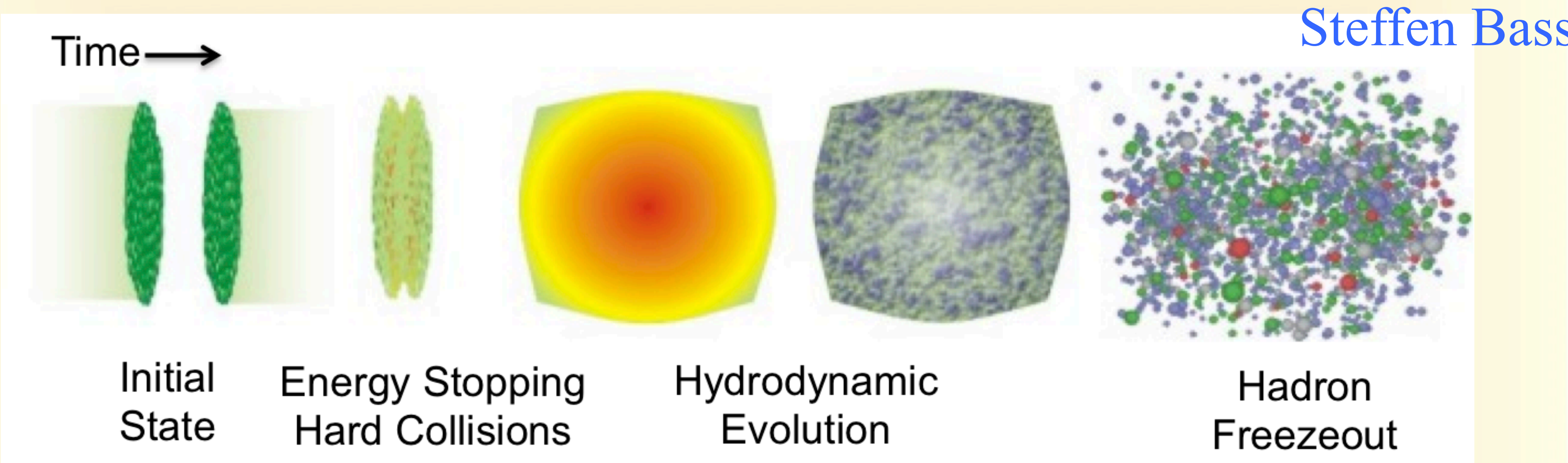


WMAP observations: Astrophys.J.Suppl. 170:377,2007

Vital information regarding the Universe has been obtained by Analyzing the temperature fluctuations:

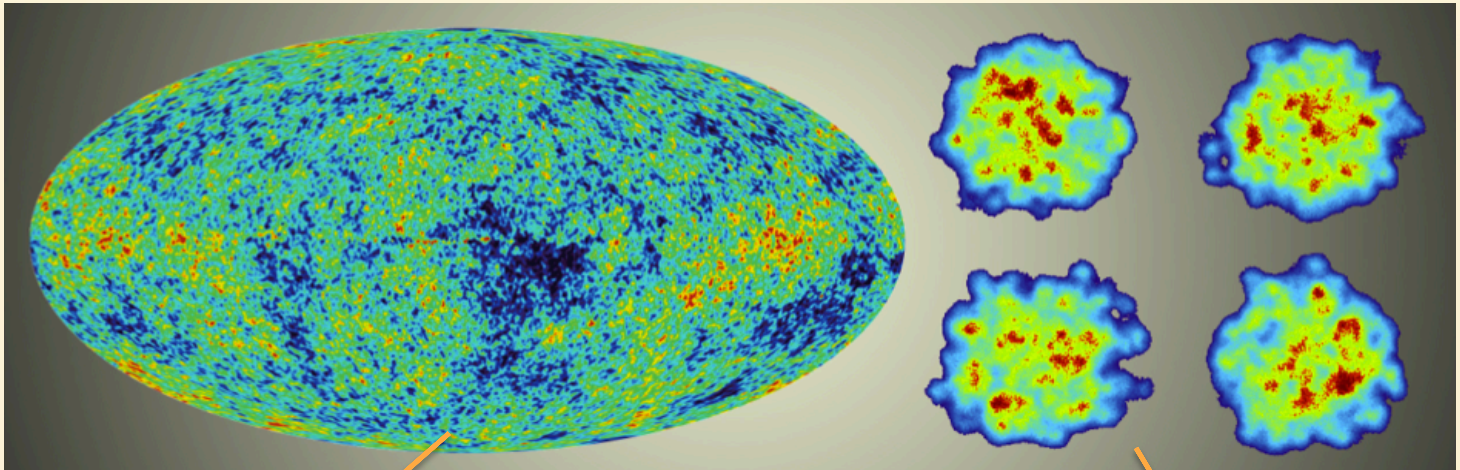
- Age of the Universe: 13.8 Billion years with 1% error
- First stars: 200 million years after Big Bang
- Light from WMAP picture from 379,000 years after Big Bang
- Content of the Universe: 4% atoms, 23% Dark Matter, 73% Dark Energy
- Expansion rate, Hubble constant with 5% error: H_0 = 71km/sec/Mpc
- New evidence for inflation
- ….

Time Evolution of Heavy-Ion Collisions



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

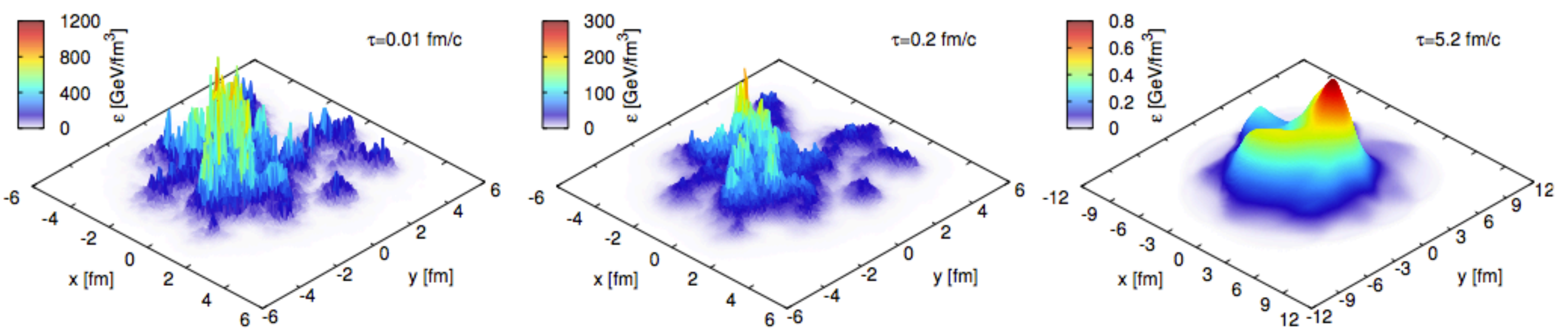
Uli Heinz, arXiv:1304.3634v1 [nucl-th] 11 Apr 2013



WMAP

Pb-Pb collisions at the LHC after 0.2

IP Glasma: Schenke, Tribedy and Venugopalan PRL 108 252301 (2012)



IP Glasma: Transverse energy density profiles for semiperipheral Au+Au collision at different times (0.01fm/c, 0.2fm/c and 5.2 fm/c)

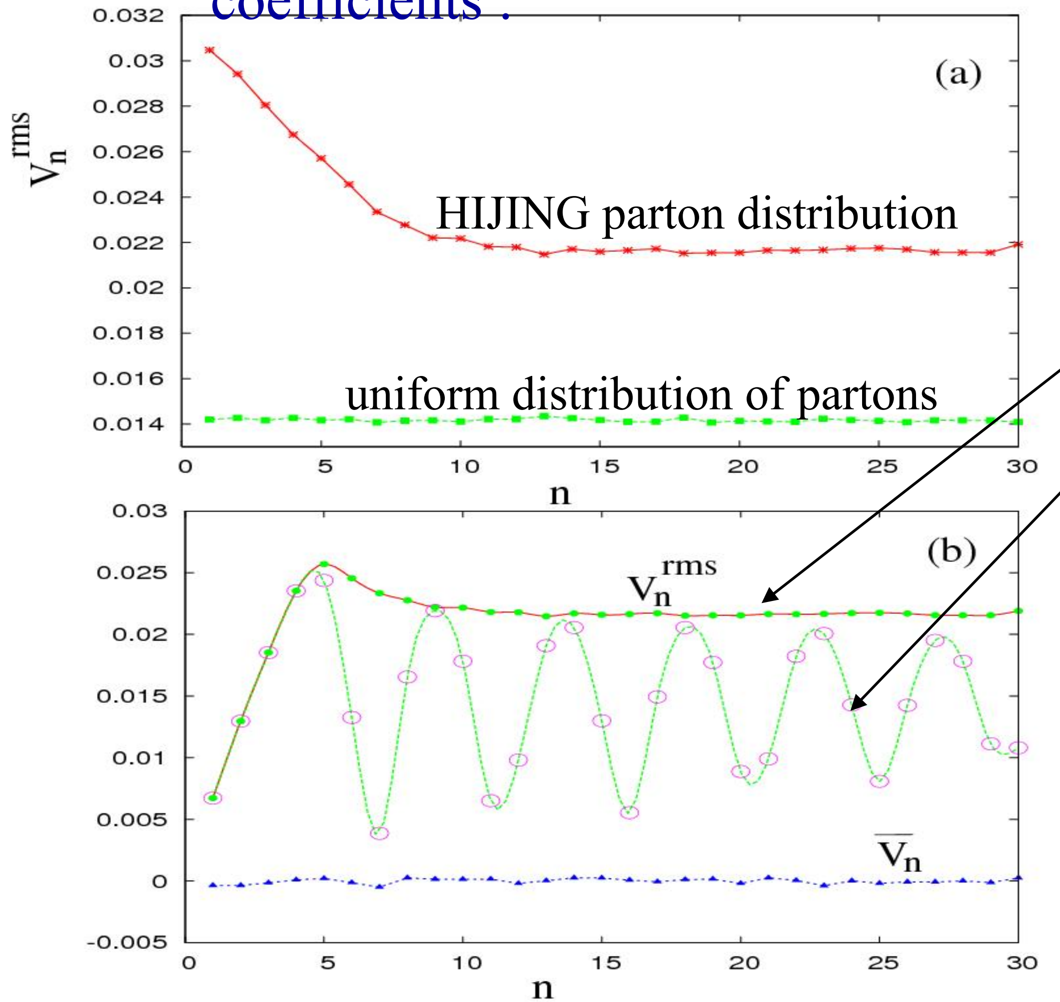
Acoustic peaks in CMBR and Heavy Ion collisions

A.P. Mishra, R.K. Mohapatra, P.S. Saumia, and A.M. Srivastava:
Phys.Rev.C, 77,064902, 2008 & Phys.Rev.C, 81,034903, 2010.

- Just like for CMBR, one can deduce information about the earlier stages from the properties of hadrons coming from the freeze-out surface.
- Strong similarities in the nature of density fluctuations in the two cases
- Sub-horizon fluctuations in the azimuthal distribution of particle momenta may display oscillatory behaviour, as well as some level of coherence just as for CMBR in the case of inflationary density fluctuations in the universe.
- Flow anisotropies for superhorizon fluctuations should be suppressed by a factor $H_S/\lambda/2$, where H_S is the sound horizon at the freeze-out time and λ is the wavelength of the fluctuation.

RMS values of the flow coefficients :

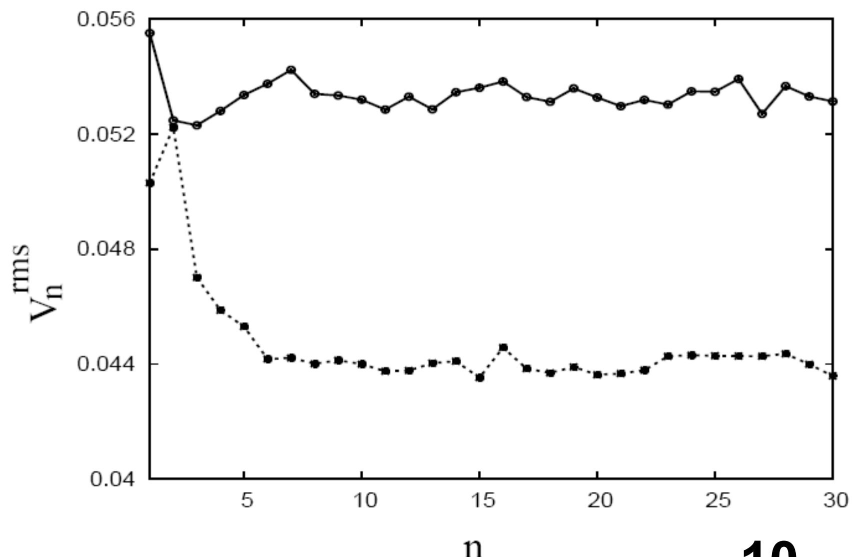
$$V_n^{rms} = \sqrt{< V_n^2 >}$$



Include superhorizon suppression

Include oscillatory factor

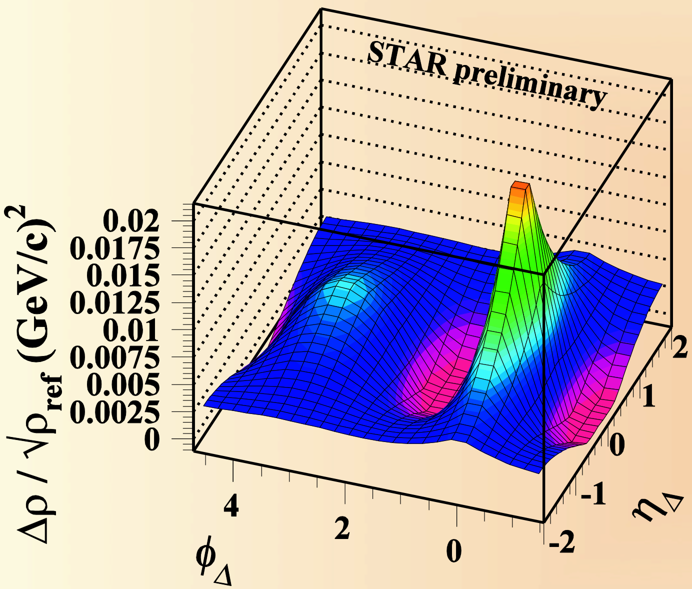
From HIJING final particle momenta.

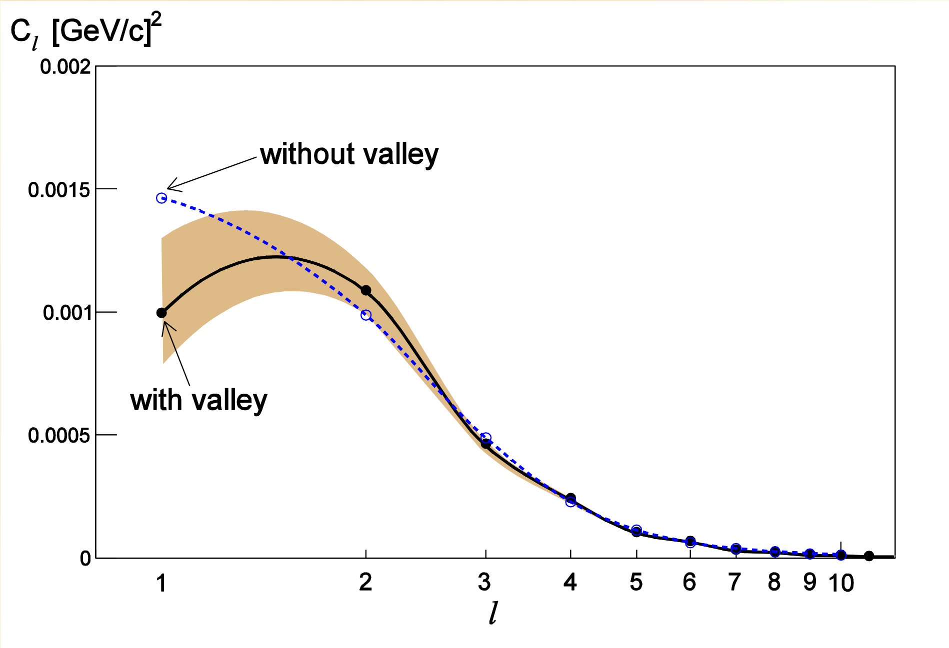


Analyzing Power Spectrum of the Little Bangs

A. Mocsy and P. Sorensen, Nucl. Phys. A855, 241, 2011

- Analysis of the p_T correlation data and extract a power-spectrum





p_T correlations derived from the $\langle p_T \rangle$ fluctuation in Au+Au collisions at 200 GeV

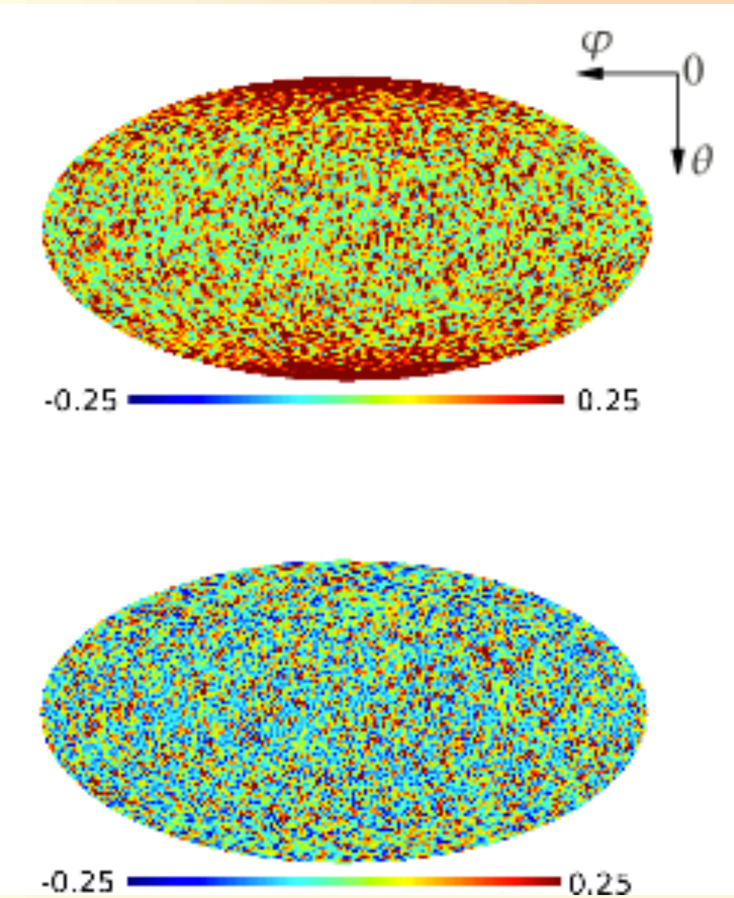
The power spectrum from p_T fluctuations. C_l are calculated at midrapidity with theta=0

Morphology of High Multiplicity Events …

P. Naselsky et. al. arXiv:1204.0387v2 Aug 2012

$$f(\theta,\phi) = \sum_{l=1}^{l_{max}} \sum_{m=-l}^{l} a_{l,m} Y_{l,m}(\theta,\phi)$$

Extends the studies by Srivatava et al. and Sorensen et al.



Theta,Phi distribution of a HIJING event without flow. Mollweide projection: theta runs from north pole to the south pole and phi runs along the equator from centre to left.

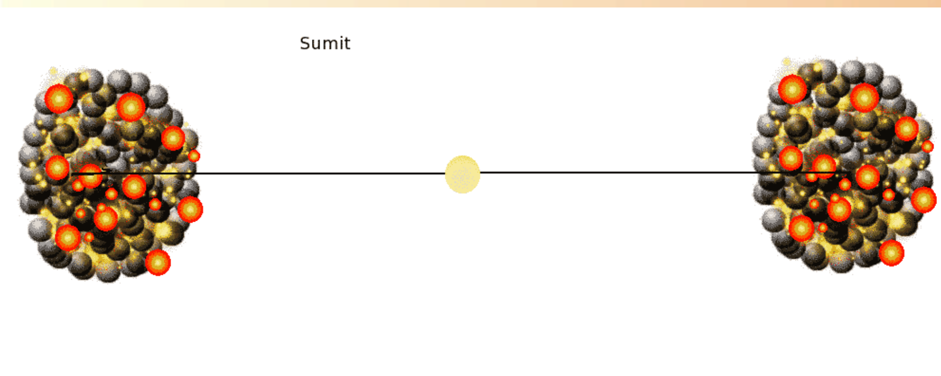
Upper figure: Larger particle densities are found at the poles reflect ing the large number of particles emitted at small angles with respect to the beam direction.
Analysis using Spherical harmonics:

In the bottom panel: m=0 mode is removed to obtain an approximately uniform distribution.

Hydrodynamic Calculation

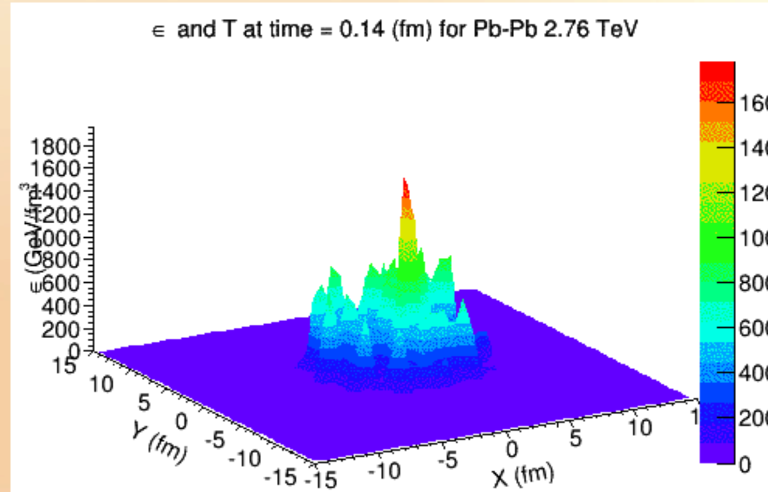
Holopainen, Niemi, Eskola
PRC 83 (2011) 034901

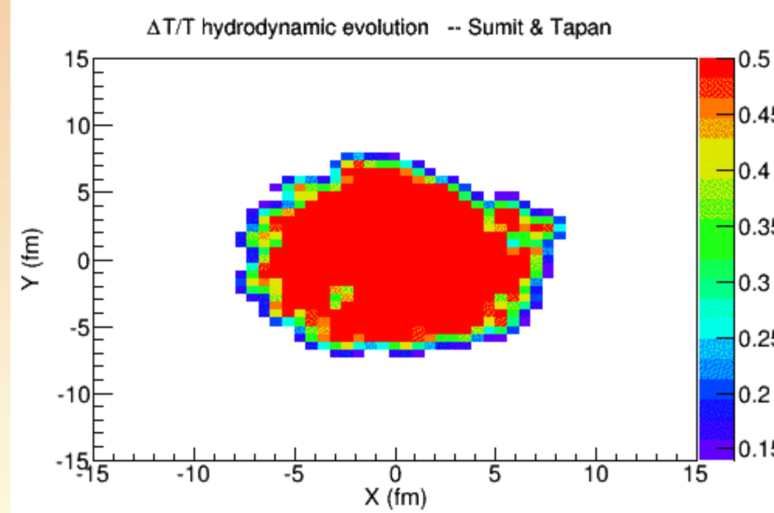
Event-by-event relativistic hydrodynamic calculations:



Hydro calculations by:
Rupa Chatterjee, Sumit Basu

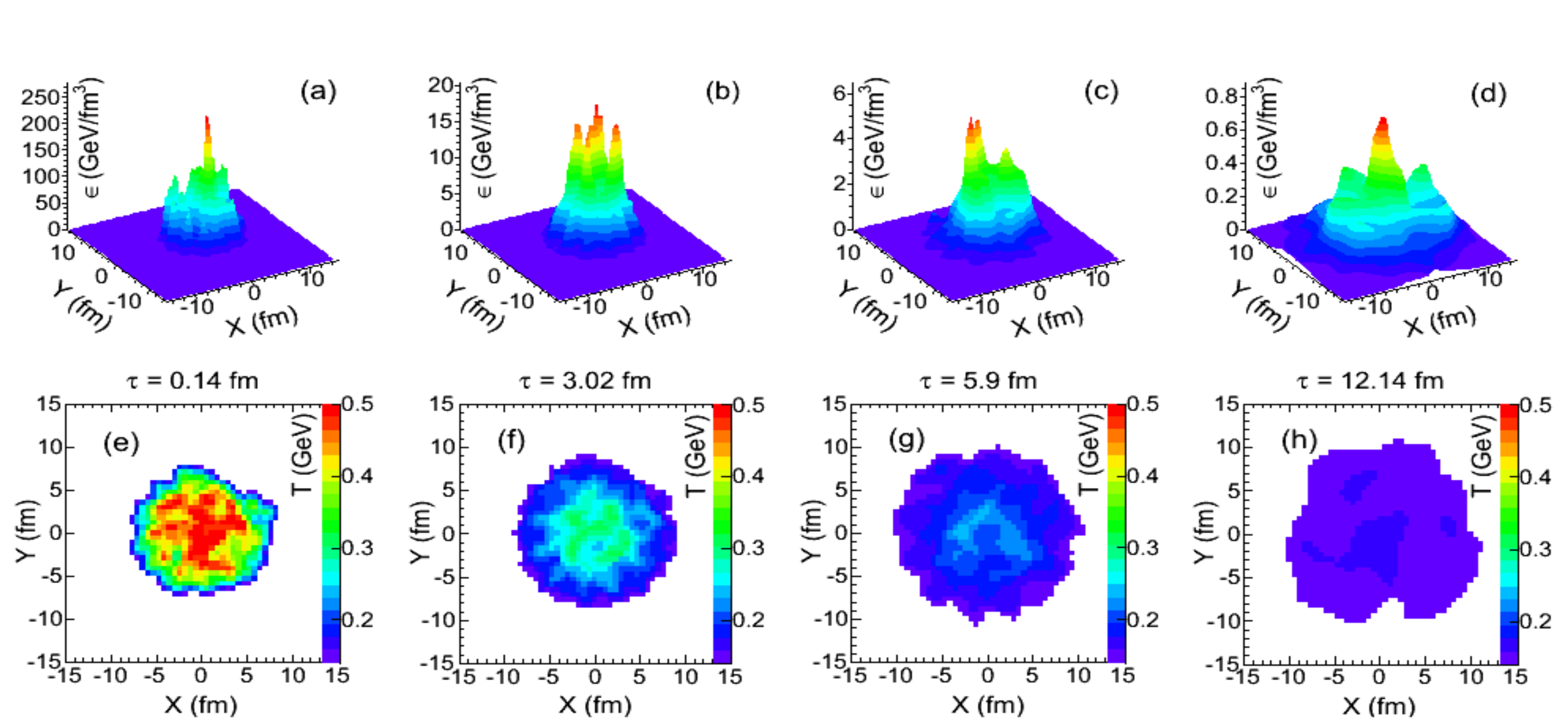
Collision ==> microscopic





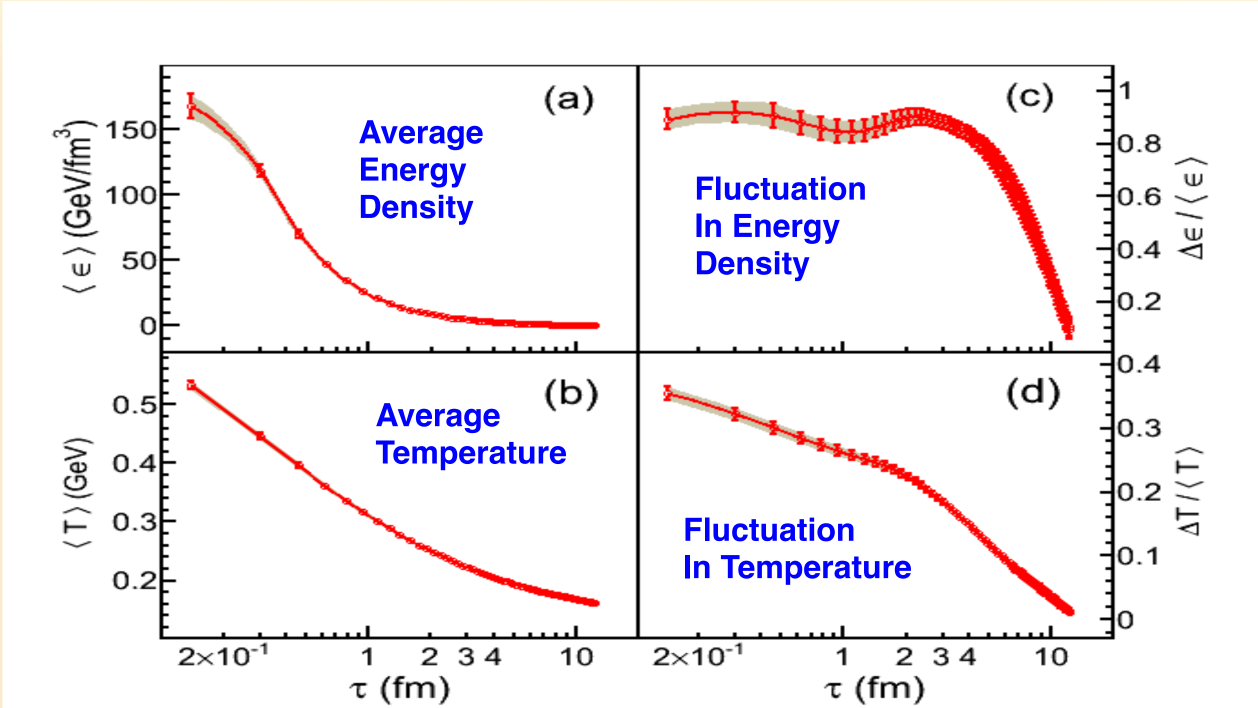
Hydro Calculation:

Energy density and Temperature:



(single event)

Temporal evolution of fluctuation:



Elapsed time →

- At early times, the system is inhomogeneous and quite violent:
  - sharp and pronounced peaks in energy densit & hotspots in temperature
  - Extremely large fluctuations (~90%) in energy density
- With time, the system cools, expands and bin-to-bin variations smoothens
- Energy density drops fast, the fluctuation in energy density remains almost constant up to τ~2.5 fm, then falls rapidly.
- A kink in fluctuation of temperature observed around same time

Methodology for Temperature Calculation

at LHC energy: Pb-Pb collisions at sqrt(s_NN) = 2.76 TeV:

- A large number of particles produced in every collision makes it possible to construct transverse momentum (or even better transverse mass of identified particles) in each event.
- Fitting the m_T distribution of pions with Maxwell-Boltzmann distribution yields the value of the effective temperature.
- This temperature is related to the mean transverse mass $<m_T>$ of pions:

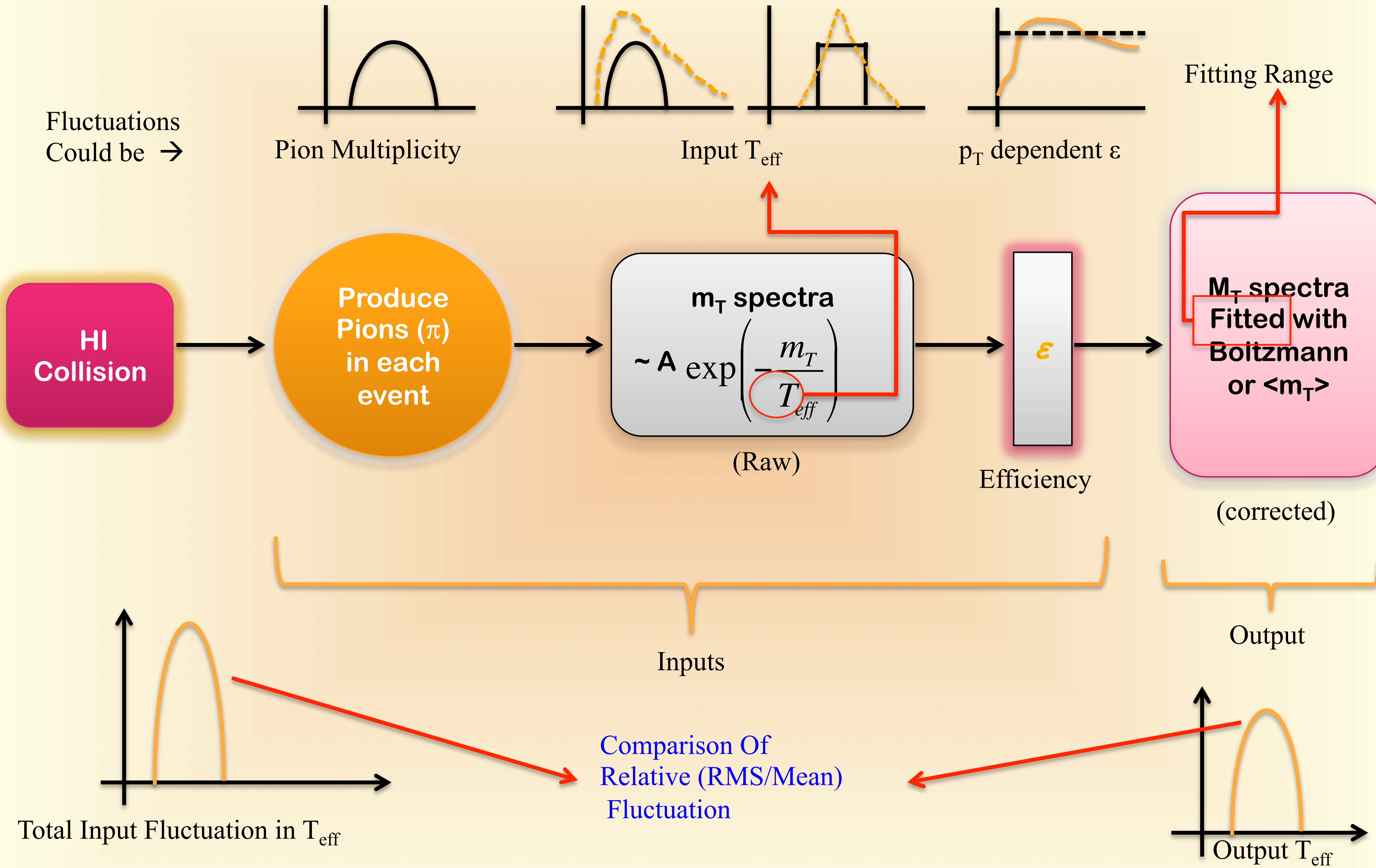
$$\langle m_T \rangle = \frac{2T^2 + 2m_0 T + m_0^2}{m_0 + T},$$

How to Measure Temperature

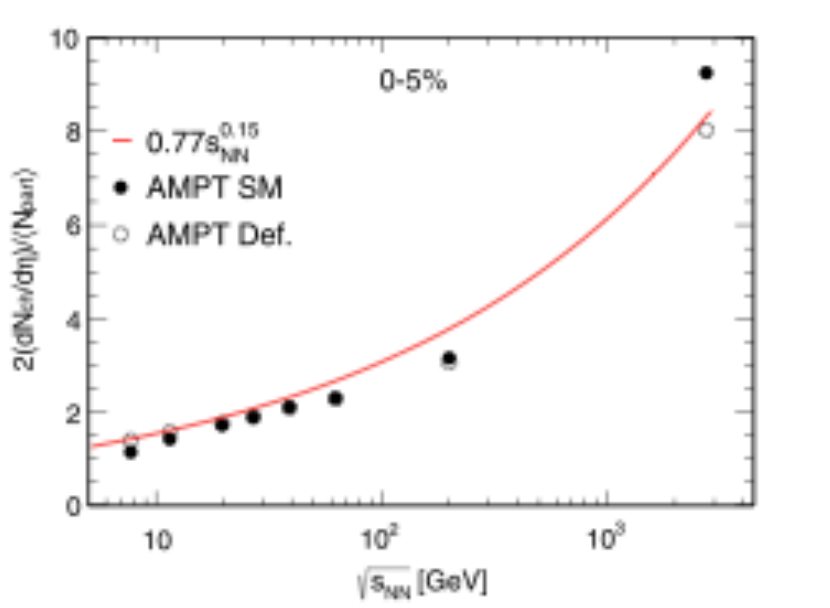
$$\langle m_T \rangle = \frac{2T_{eff}^2 + 2m_0 T_{eff} + m_0^2}{m_0 + T_{eff}} \longrightarrow (1)$$

$$\frac{d\langle m_T \rangle}{dT_{eff}} = 1 + \frac{2T_{eff}}{m_0 + T_{eff}} - 2\left(\frac{T_{eff}}{m_0 + T_{eff}}\right)^2 \longrightarrow (2)$$

Methodology

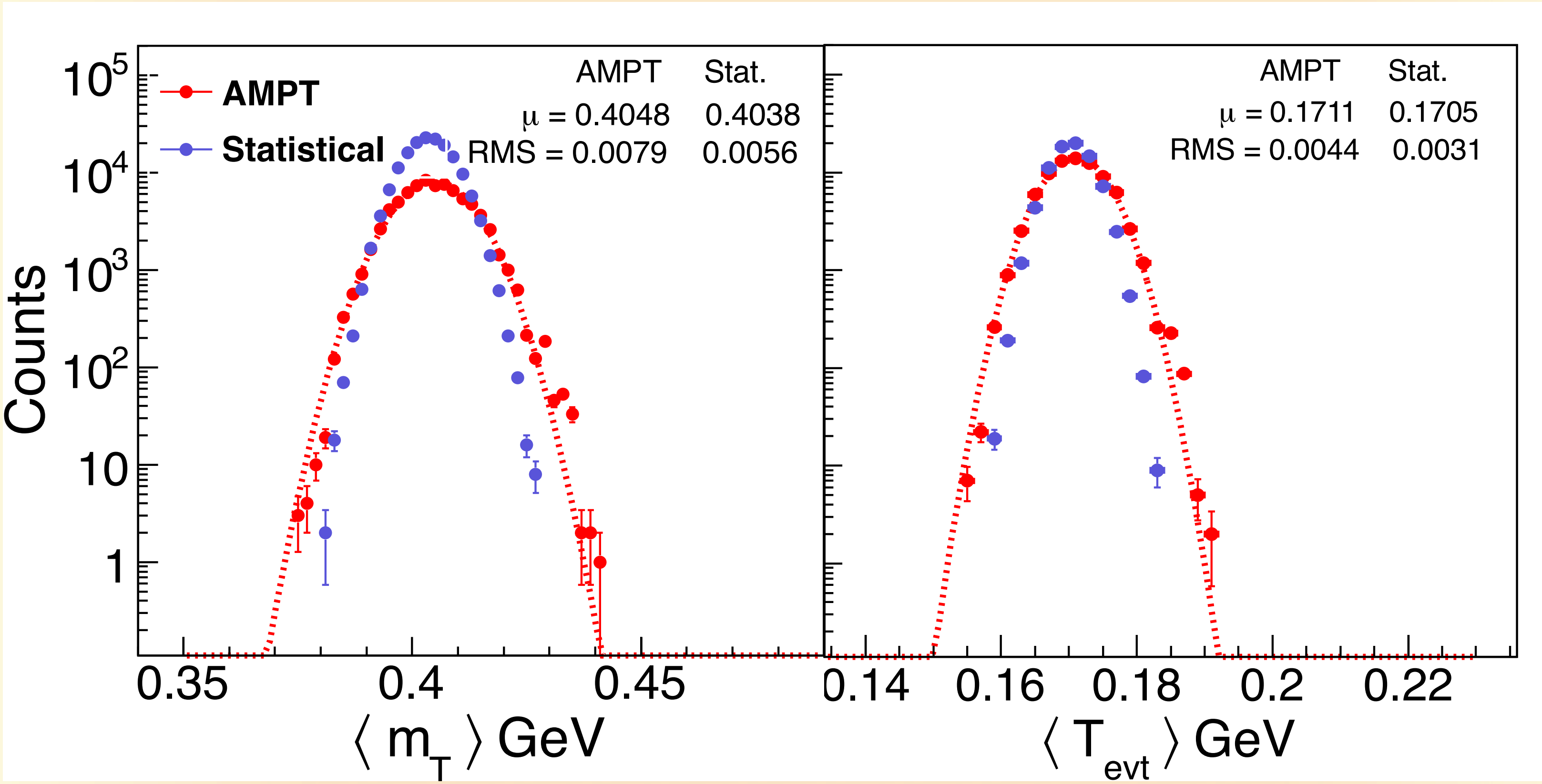


Feasibility using AMPT



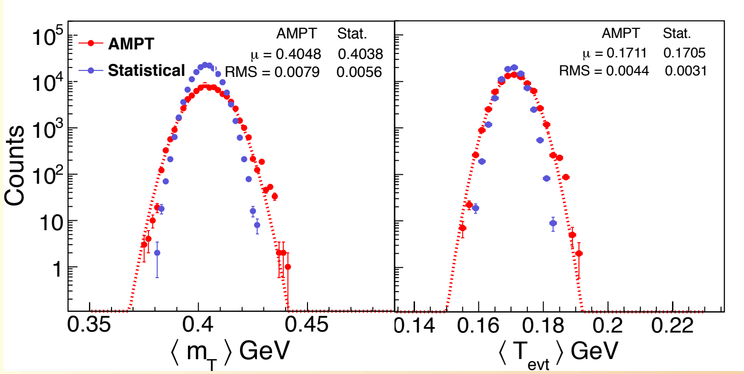
The SM (string melting) mode of AMPT model mimics the experimental conditions at the LHC. AMPT explains majority of the data for multiplicity and flow.

Feasibility using AMPT



Statistical fluctuations to be removed from the total to obtain dynamic fluctuations

Taking out statistical component:



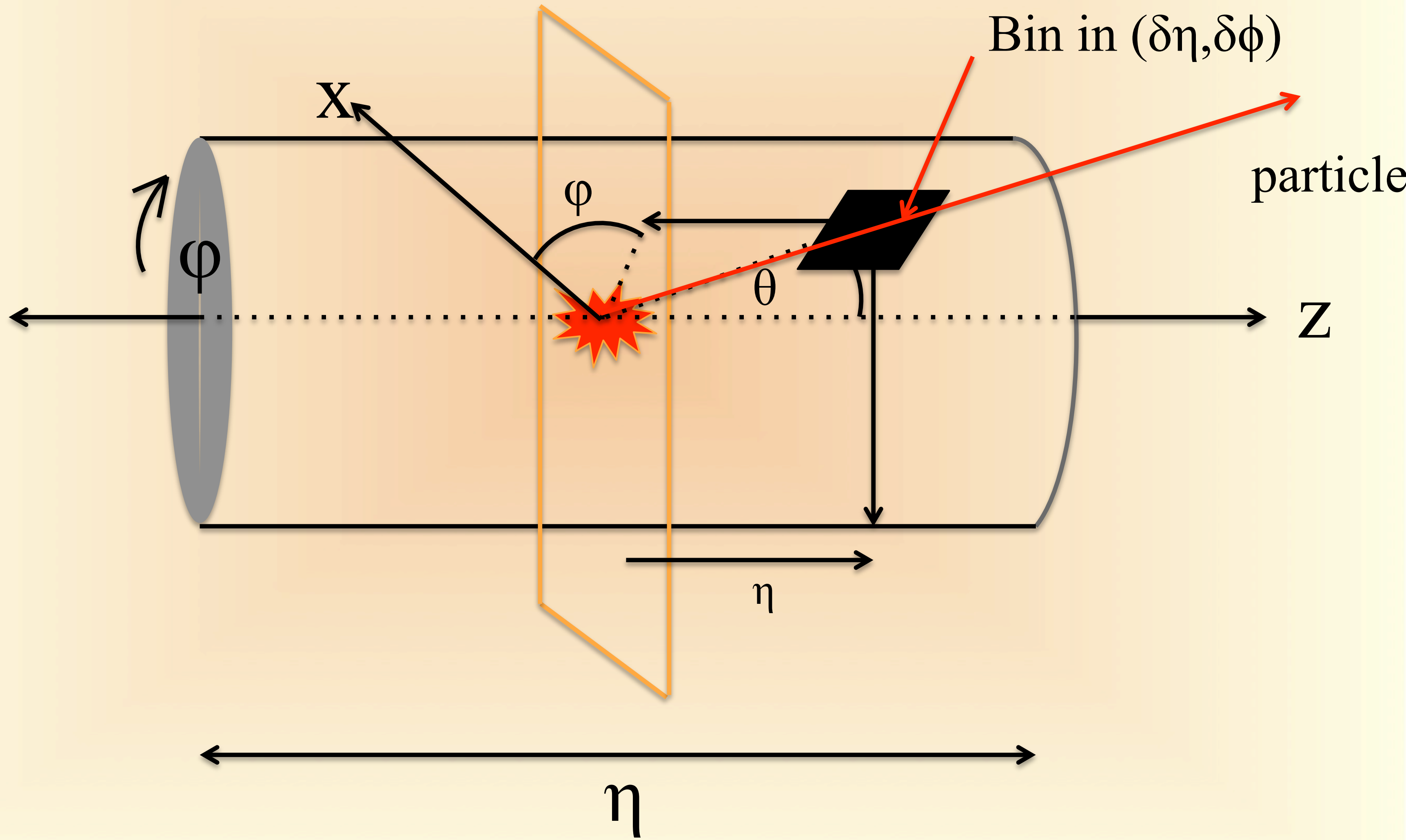
Statistical component of the fluctuation has been estimated by constructing randomly generated synthetic events, keeping the multiplicity and pT distributions similar to those of AMPT.

Heat Capacity

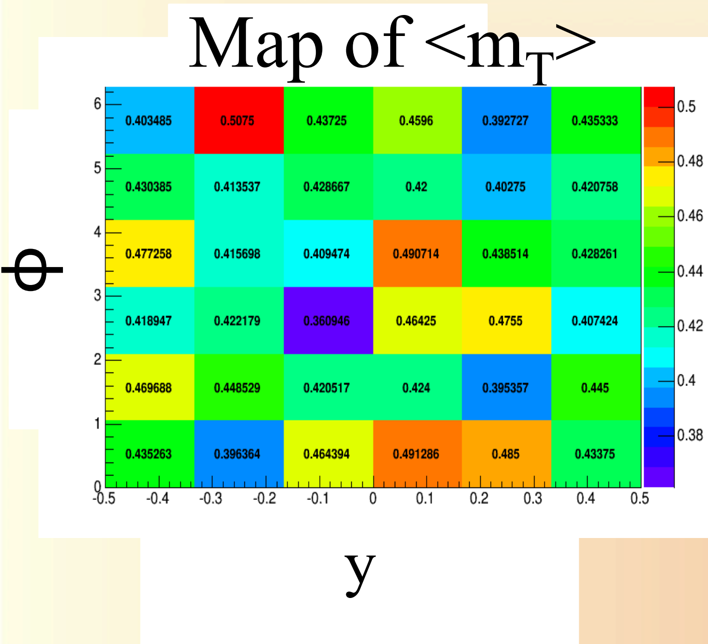
For AMPT events: Dynamical component of Temperature fluctuation: 1.8%.

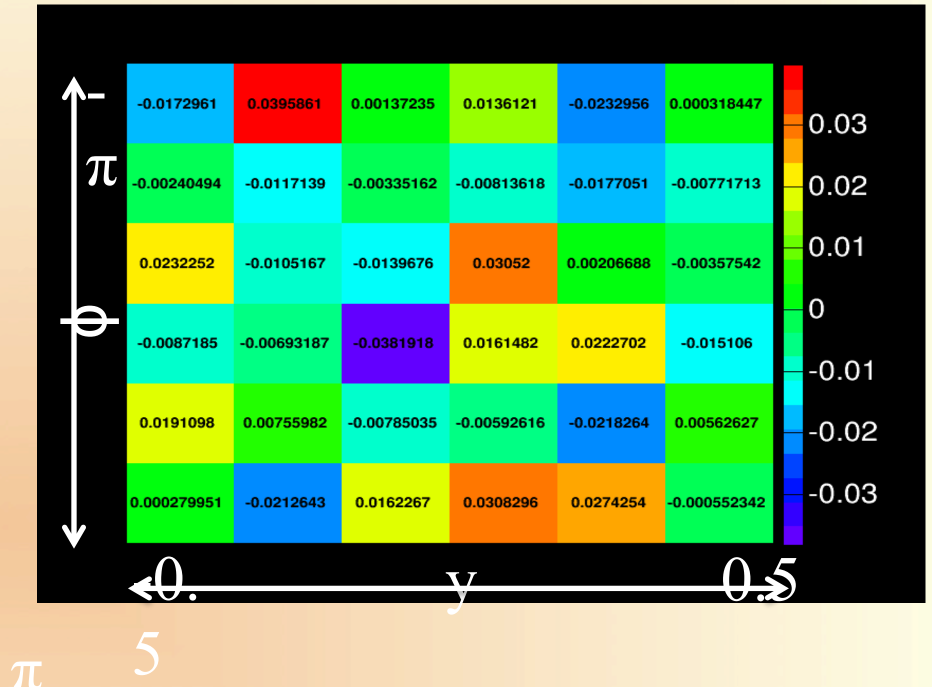
$C_V = 3067.$

Local Fluctuation



Within The Event : Local Fluctuation

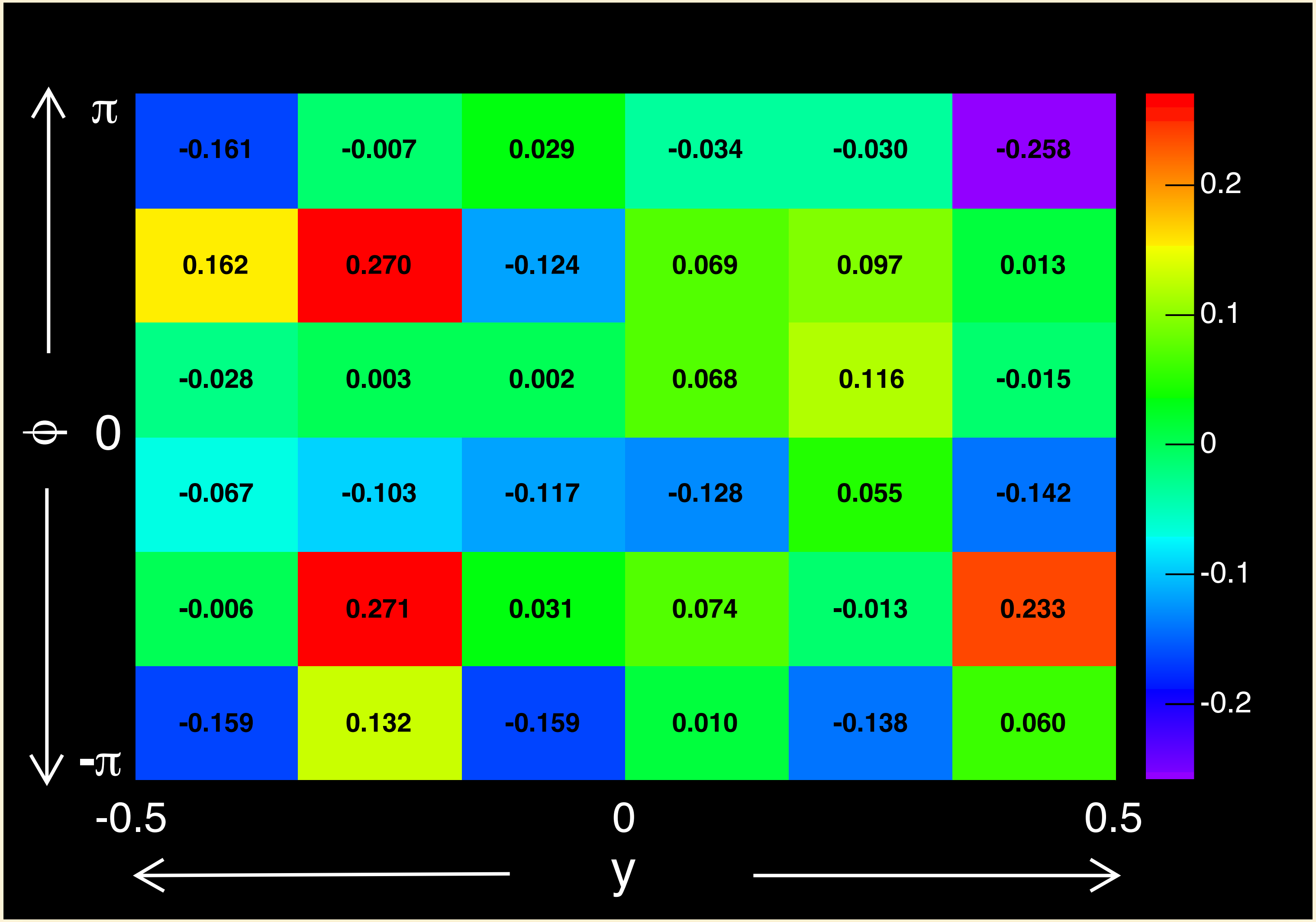




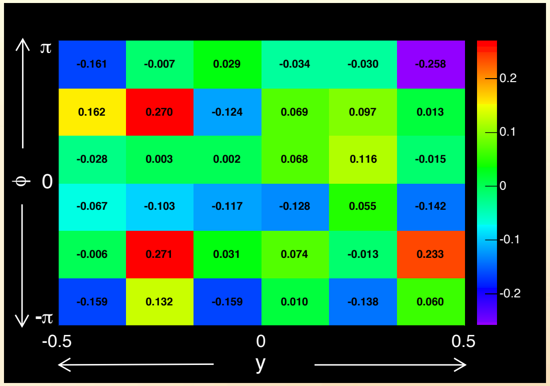
- Get <mT> for each bin => Get Temperature of each bin
- It is checked that the event Temperature is close to mean of bin temperatures in an event.

$$F_{bin} = (T_{bin} - T_{evt})/T_{evt}.$$

Map of the Little Bang



$$F_{\text{bin}} = (T_{\text{bin}} - T_{\text{evt}})/T_{\text{evt}}.$$

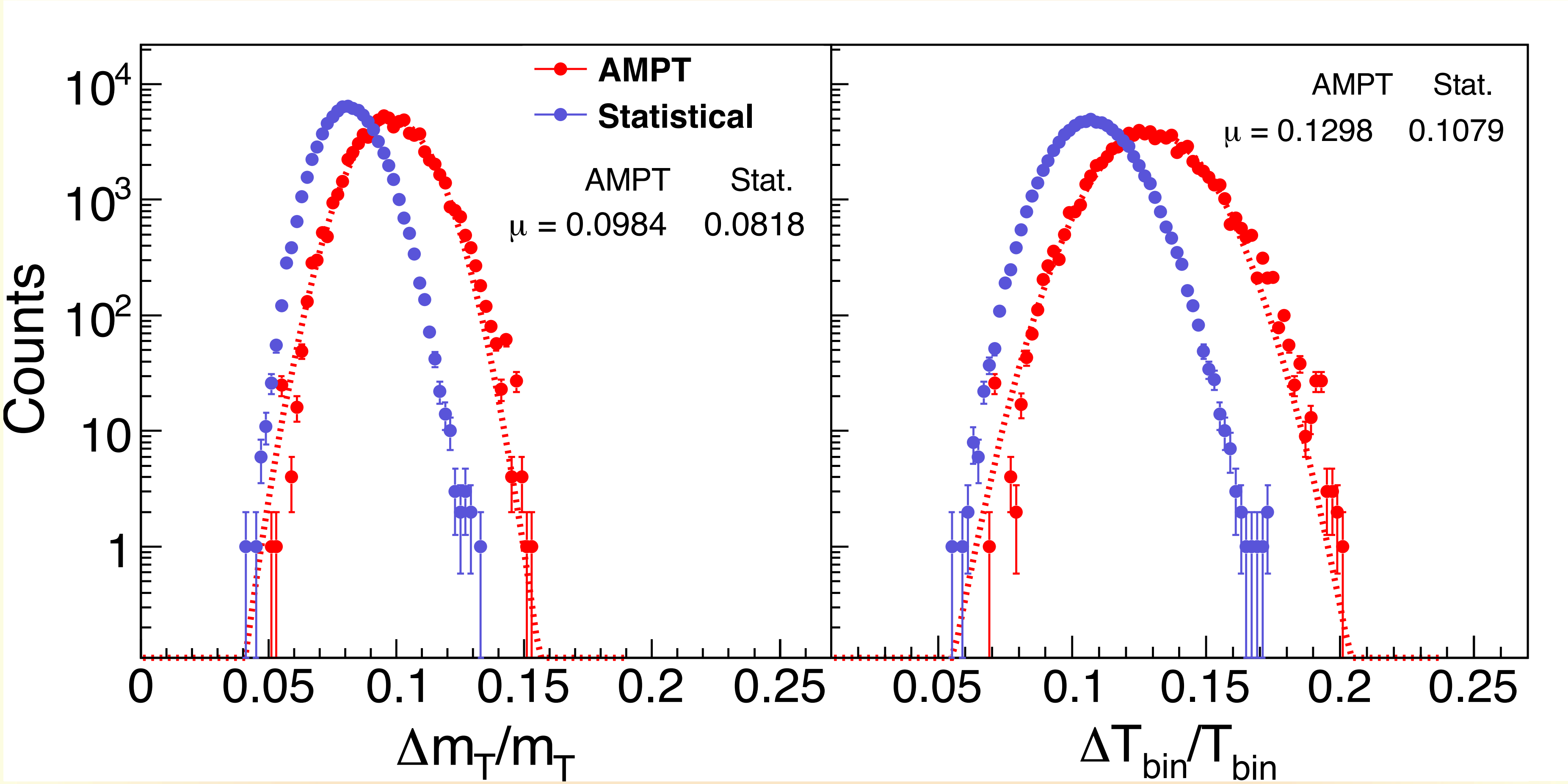


- Get <mT> for each bin => Get Temperature of each bin
- It is checked that the event Temperature is close to mean of bin temperatures in an event.

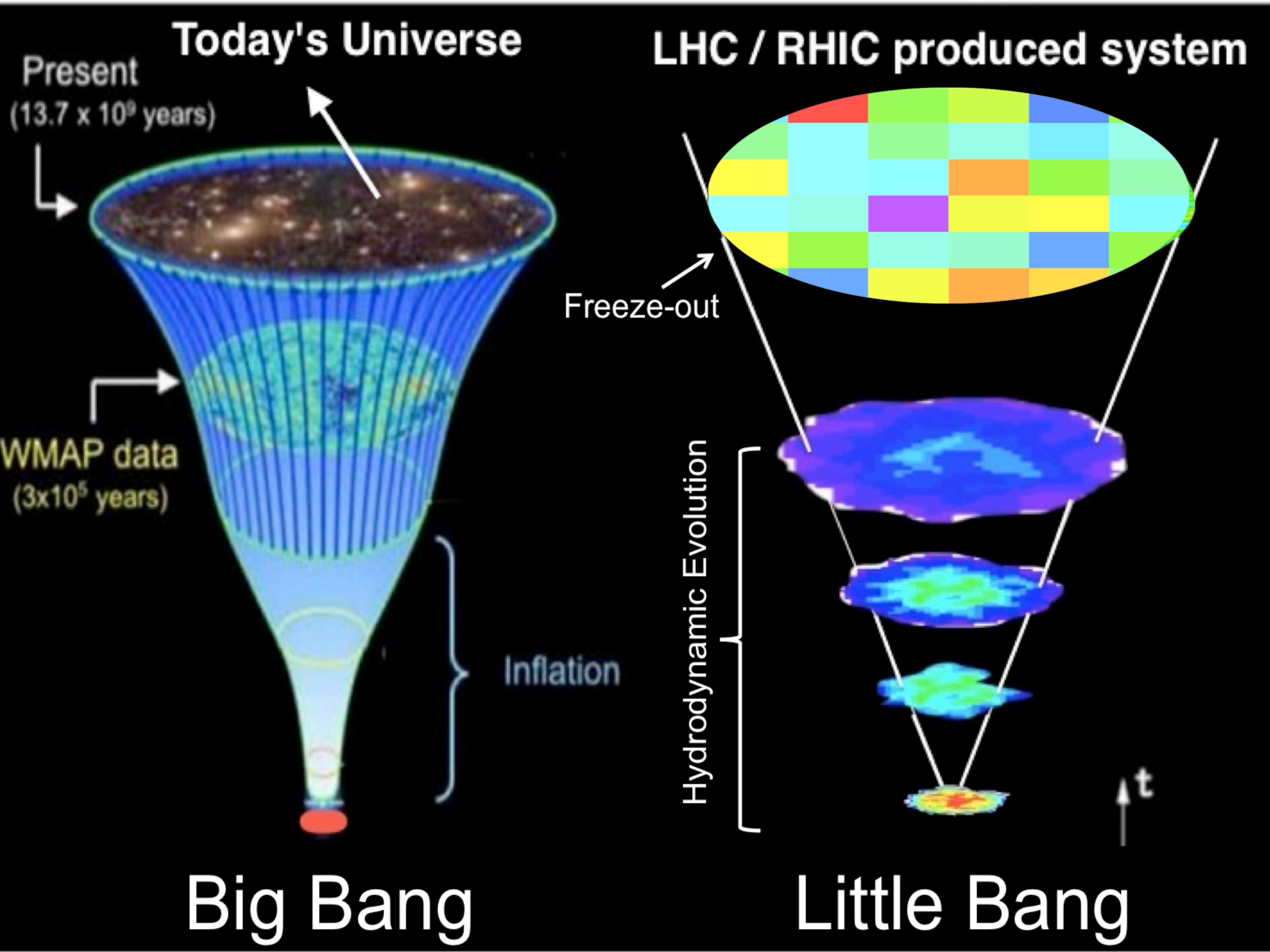
$$F_{\mathrm{bin}} = (T_{\mathrm{bin}} - T_{\mathrm{evt}})/T_{\mathrm{evt}}.$$

- Plot F_{bin} for an event. Mean of this distribution gives the amount of local fluctuation of the event.
- Distribution of event-by-event local temperature for central collisions:

Local Fluctuations Event-by-Event



Local Temperature fluctuation (dynamic component): 10.79%.


Today's Universe
Present
(13.7 x 10⁹ years)
WMAP data
(3x10⁵ years)
Inflation
LHC / RHIC produced system
Freeze-out
Hydrodynamic Evolution
t
Big Bang
Little Bang

Summary

- Heat Capacity calculated from Event-by-Event (EbyE) Temperature Fluctuations:
  - For Central Pb+Pb 2.76 TeV, we get heat capacity of 3067.
  - Prospect for RHIC BES energies to calculate C_V from temperature fluctuations.

- Local temperature fluctuation MAP similar to CMBR:
  - In 6x6 bins, local fluctuation amounts to 7.2%.

=> Opens up new avenues for characterizing heavy-ion collisions.

ALICE: Analysis in progress