HUGS 2022

Thermodynamic approach to Quark-Gluon Plasma

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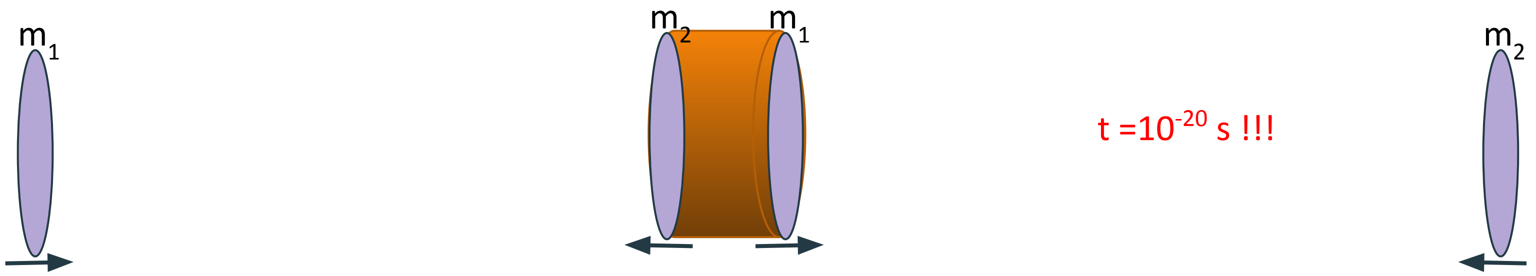
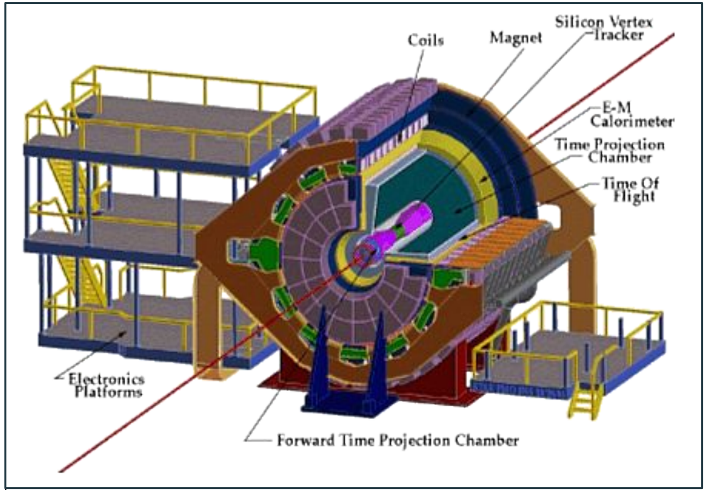
Relativistic Heavy-Ion Collisions

- ❖ Heavy Atoms like Pb/Au/Cu.
- ❖ Stripped off of their electrons → Ions (Heavy-Ion).
- ❖ Accelerated to speed of light.
- ❖ Collide them with each other to form "Little Bangs".
- ❖ Study the aftermath by specialized detector systems around the collision.

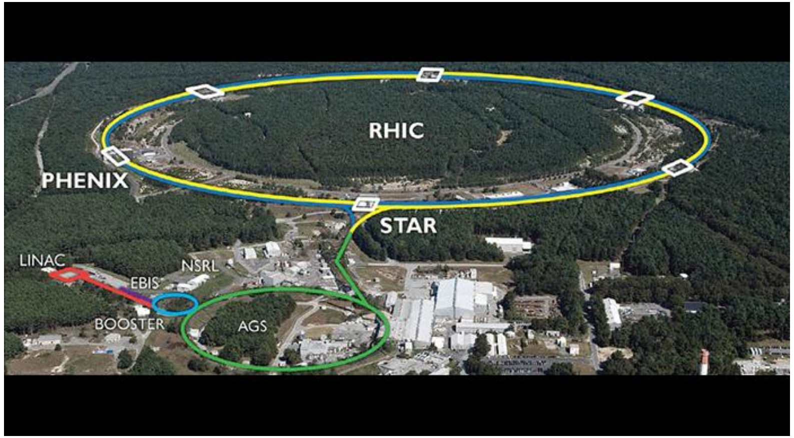


RHIC: STAR Experiment

- STAR: Solenoidal Tracker At RHIC.
- Heavy ion collisions of Au,Cu and d.
- Energy range from 3 GeV - 200 GeV ($\sqrt{s_{NN}}$).



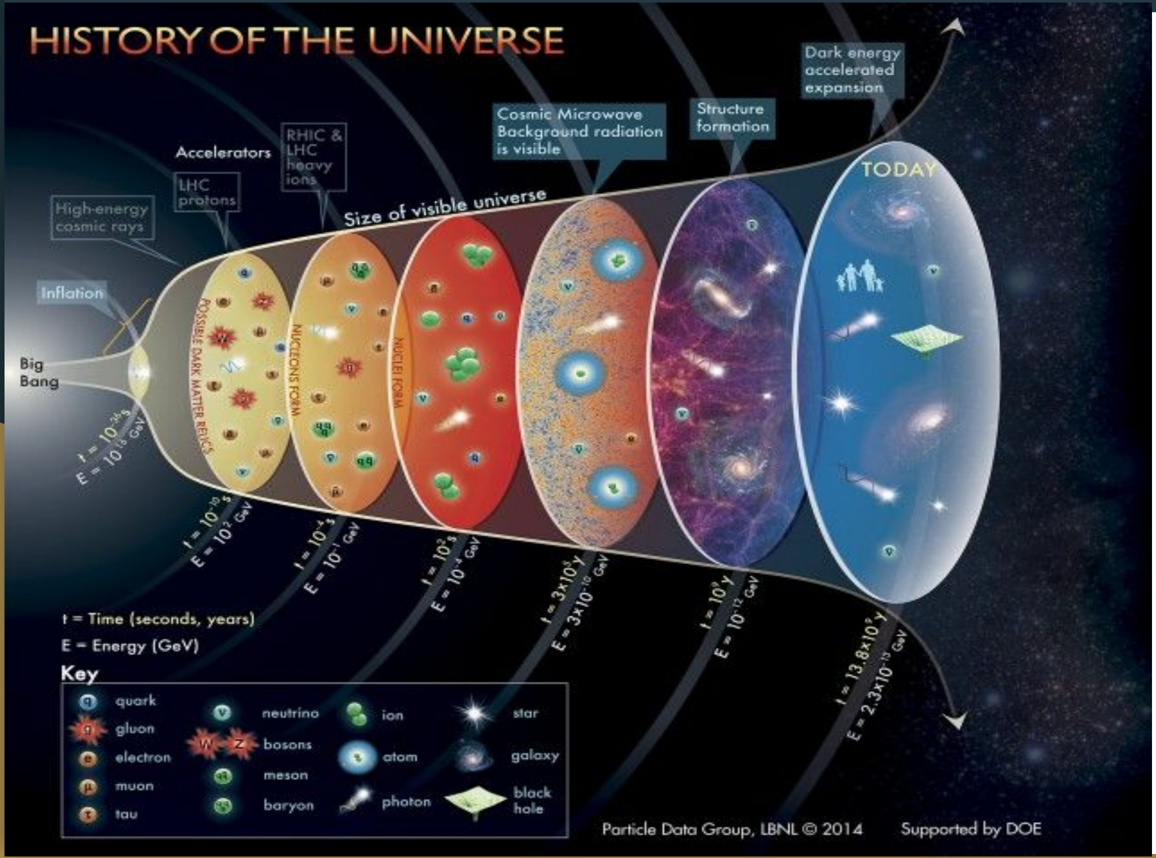
https://www.star.bnl.gov



https://www.star.bnl.gov

- Located at Brookhaven National Laboratory (BNL).
- Long Island, New York, USA.

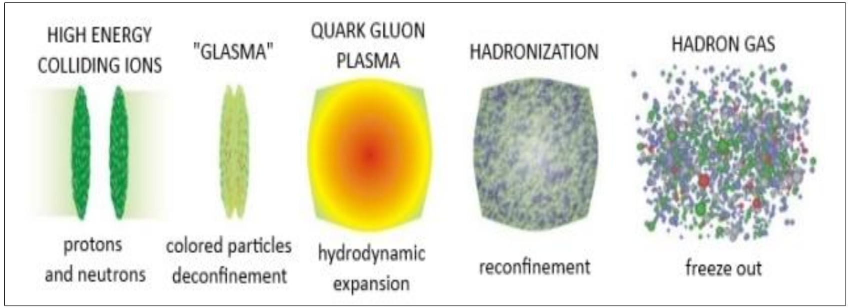
What is our Mission ?



- ❖ Probe to look back into the past.
- ❖ What happened micro seconds after the Big Bang?
- ❖ Constraints on the Standard Model.
- ❖ Establish the existence of a phase (state) of deconfined and chirally symmetric matter.
- ❖ Determine state variables.
- ❖ Predict new Particles?

Confinement and Deconfinement of Hadrons

- ❖ Hadrons are composite objects made of quarks and gluons. q-q interactions become weaker as the inter-quark distance becomes shorter (asymptotic freedom). The system behaves like free quarks and gluons.

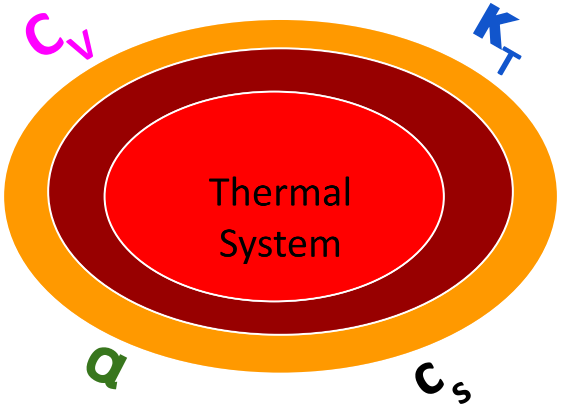


arXiv:1207.7028

- ❖ The deconfined state of hadronic matter is called Quark-Gluon Plasma (QGP).
- ❖ QGP a thermalised, or near to thermalised state of quarks and gluons, where quarks and gluons are free to move over a nuclear volume.
- ❖ With QCD the only strongly interacting theory in the Standard Model, mapping the transition region of its phase diagram is a scientific goal of the highest order.

QGP as a Thermal System

- With the advent of Heavy-Ion Experiments, each collision produced thousands of particles. So a single collision can be approximated to a thermodynamic state.
- In particular we can establish a well defined temperature and study its fluctuations.
- Hence if the collision is to be identified as a thermal system we can experimentally determine important state variables of the system.



Statistical Hadronization Models

- ❖ The Hadron gas can be approximated as non-interacting ground state hadrons and their heavier resonances.
- ❖ We can calculate a partition function involving all known species and calculate macroscopic quantities from it .
- ❖ Such a model can describe quantitatively the yield of most particles, including multi-strange ones, has in fact been indicated by fits to average particle abundances at AGS, SPS and RHIC energies.

- ❖ Models give no information on how and when the system reaches equilibrium.
- ❖ Model makes no predictions of dynamical quantities.
- ❖ A completely phenomenological description.
- ❖ Hence we need Quantum Chromodynamics, a fundamental theory on first principles and Lattice QCD, a non-perturbative approach to QCD.

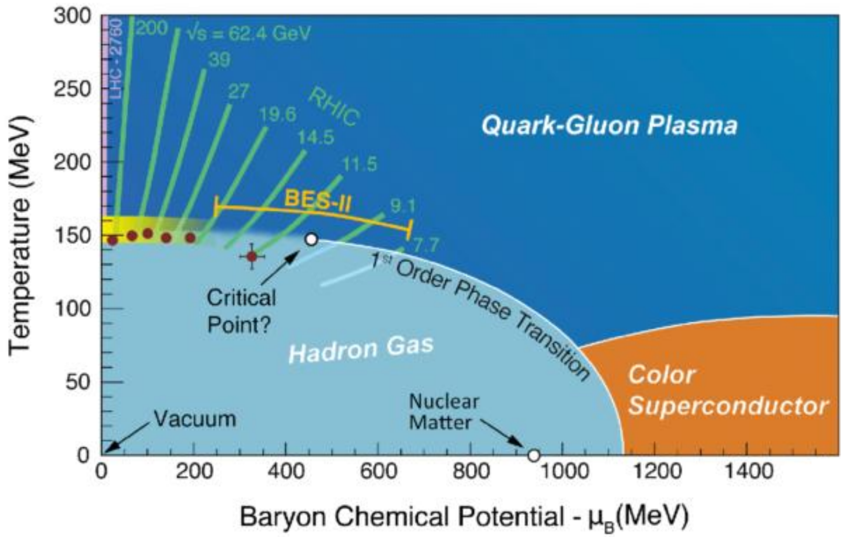
Objective

- ❖ Lattice QCD calculations show that the QCD transition is an analytical crossover at $\mu_B \cong 0$, involves a rapid change as opposed to a discontinuous jump .

- ❖ On the other hand QCD inspired phenomenological models predict a first order phase transition at high μ_B.

- ❖ The point where the doping of matter over antimatter becomes large enough to instigate a first order phase transition is referred to as the QCD critical point.

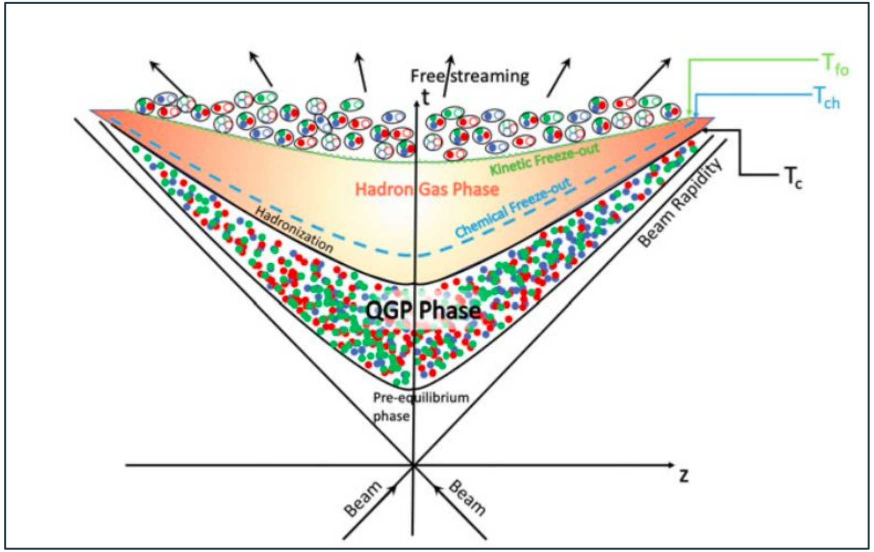
- ❖ This suggests the possible existence of a QCD critical point where the first order transition terminates.



arXiv:2108.13867

What do we measure in these Experiments?

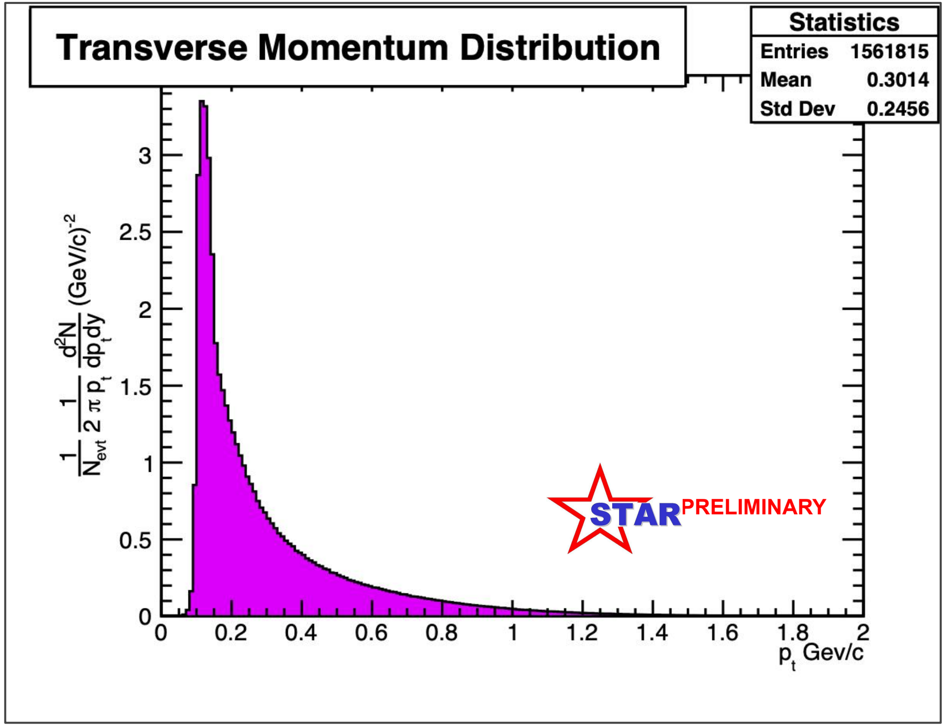
- **Spectra** : Distribution of particle momenta.
- **Yield**: Count of particle numbers. (Multiplicity)
- After the chemical freeze-out (T_{ch}), the yield is fixed.
- After the kinetic freeze-out (T_{kin}), the spectra are fixed.



https://doi.org/10.1007/978-3-030-67235-5_6

Spectra

- Transverse Momentum p_T is defined as $\sqrt{(p_x^2 + p_y^2)}$.
- Fluctuations in temperature are obtained from the fluctuations in transverse momentum.
- Temperature is found by applying fits to the spectra under different formalisms.



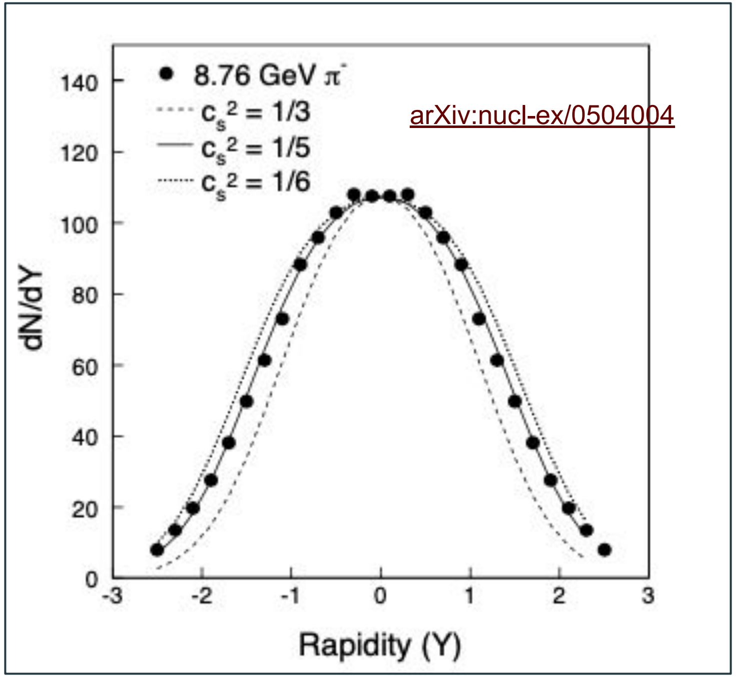
- $\sqrt{s_{NN}}$ = 3 GeV Au+Au collisions.

Yields

❖ Multiplicity: Particle yields.

❖ Fluctuations can be studied for identified particles or charged particles.

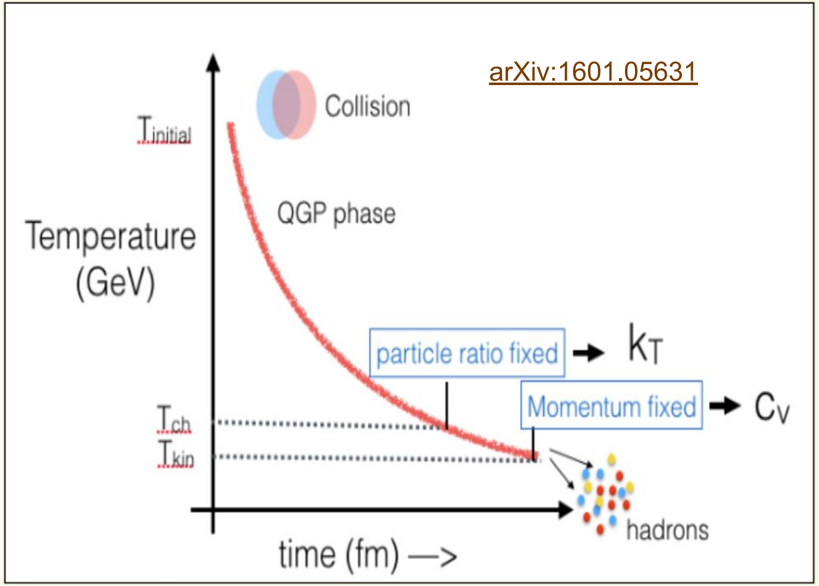
❖ Multiplicity fluctuations are associated to conserved charges :
  ➢ Electric Charge
  ➢ Baryon Number
  ➢ Strangeness



❖ Yield distributions

Fluctuations

- Fluctuations quantify proximity to critical point.
- Yield fluctuations → Conserved quantum numbers.
- Spectra fluctuations → Temperature
- Ratios of cumulants, thermodynamic functions are calculated to quantify these fluctuations.



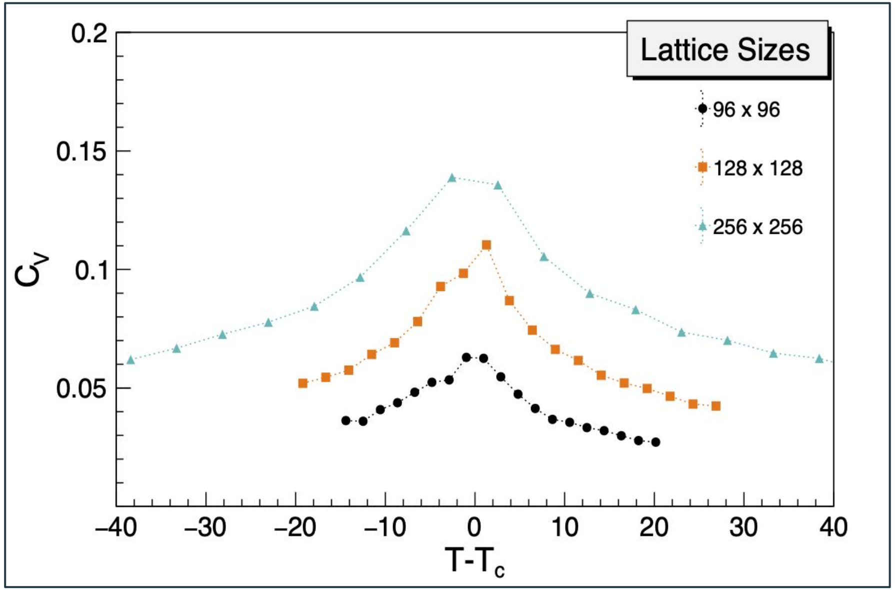
- Temperature Vs time

Why Specific Heat C_V ?

- For a system undergoing phase transition, C_v is expected to diverge at the critical point.

- Thus the variation of thermal fluctuations with temperature can be effectively used to probe the critical point.

- In the 2D Ising Model we can see the divergence of C_v as we change the temperature of the system.



- Simulations from 2D Ising Model for C_v.

Why Specific Heat C_V ?

- Specific heat is a thermodynamic quantity characterizing the equation of state of the system.

- $C_V = \left(\frac{\partial E}{\partial T}\right)_V$ Definition from Thermodynamics

- Heat Capacity, C of a system in thermal equilibrium connected to a bath at T can be computed from the event- by-event fluctuations of temperature:

$$\frac{1}{C} = \frac{<T_{kin}^2> - <T_{kin}>^2}{<T_{kin}>^2}$$

arXiv:1601.05631

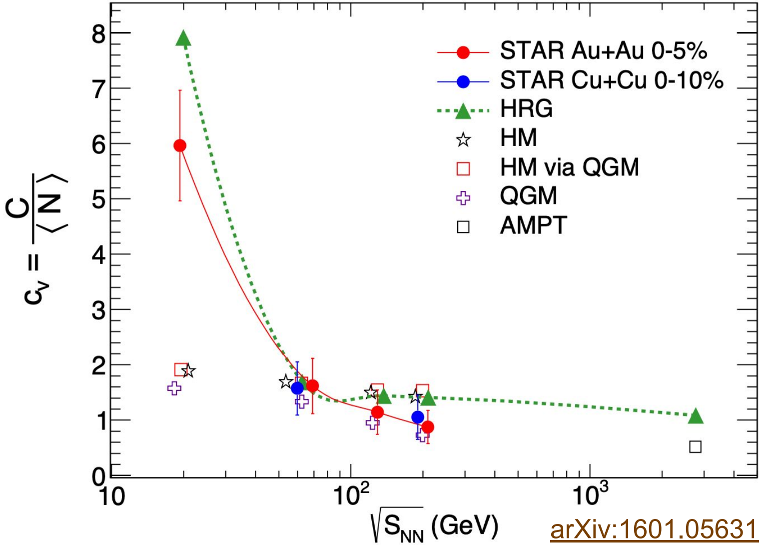
- Temperature fluctuation of the system provides an estimation of C_v.

- Thus, with the measurement of T on an event-by-event basis, it is possible to extract the C_v of the hot and dense strongly interacting matter produced in heavy-ion collisions.

- Assuming complete thermal equilibrium up to the surface of last scattering which is the kinetic freeze-out surface, C_v is then expected to reveal the thermodynamic state of the matter at the moment of kinetic freeze-out.

Progress so far

- STAR has calculated C_v at energies 19.6, 62.4, 130 and 200 GeV.
- The experimental values match the prediction from the HRG Model.
- Monotonic increase coming into effect and the analysis at 3 GeV is critical to understand this trend.
- PACIAE (Event Generator).
- HM : Hadronic Matter.
- QGM : Quark-Gluonic Matter.



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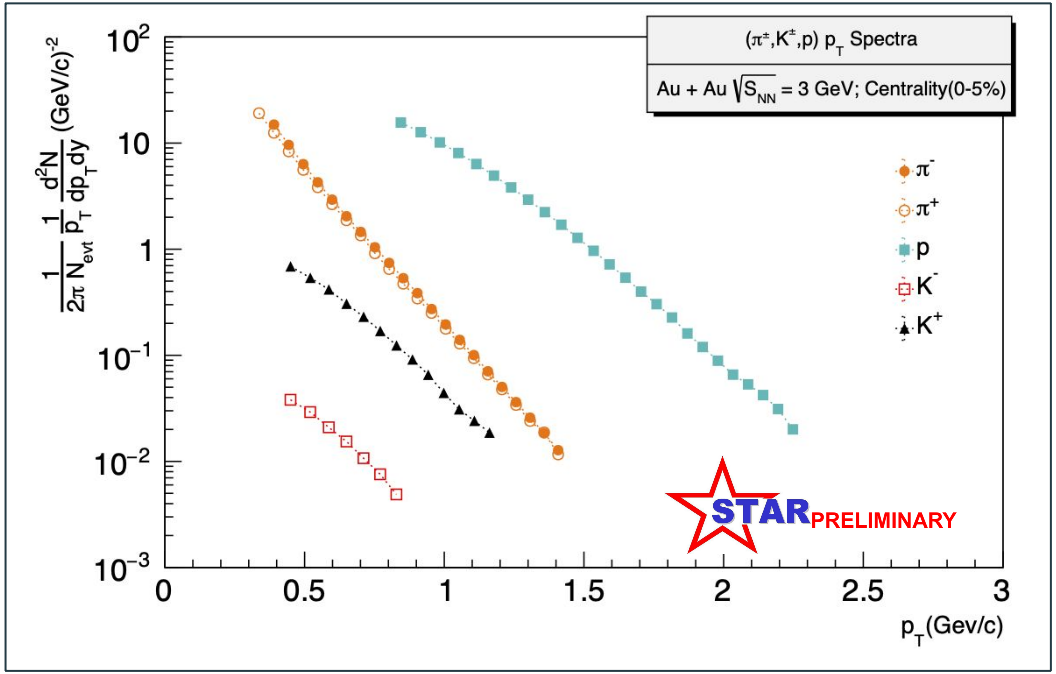
- Specific Heat Vs $\sqrt{s_{NN}}$

Outlook

- Calculation of collective parameters.
- Fluctuations in temperature.
- Baseline calculation from SHM.
- Perform a BES for criticality location.



- Transverse Momentum Distribution at 3 GeV

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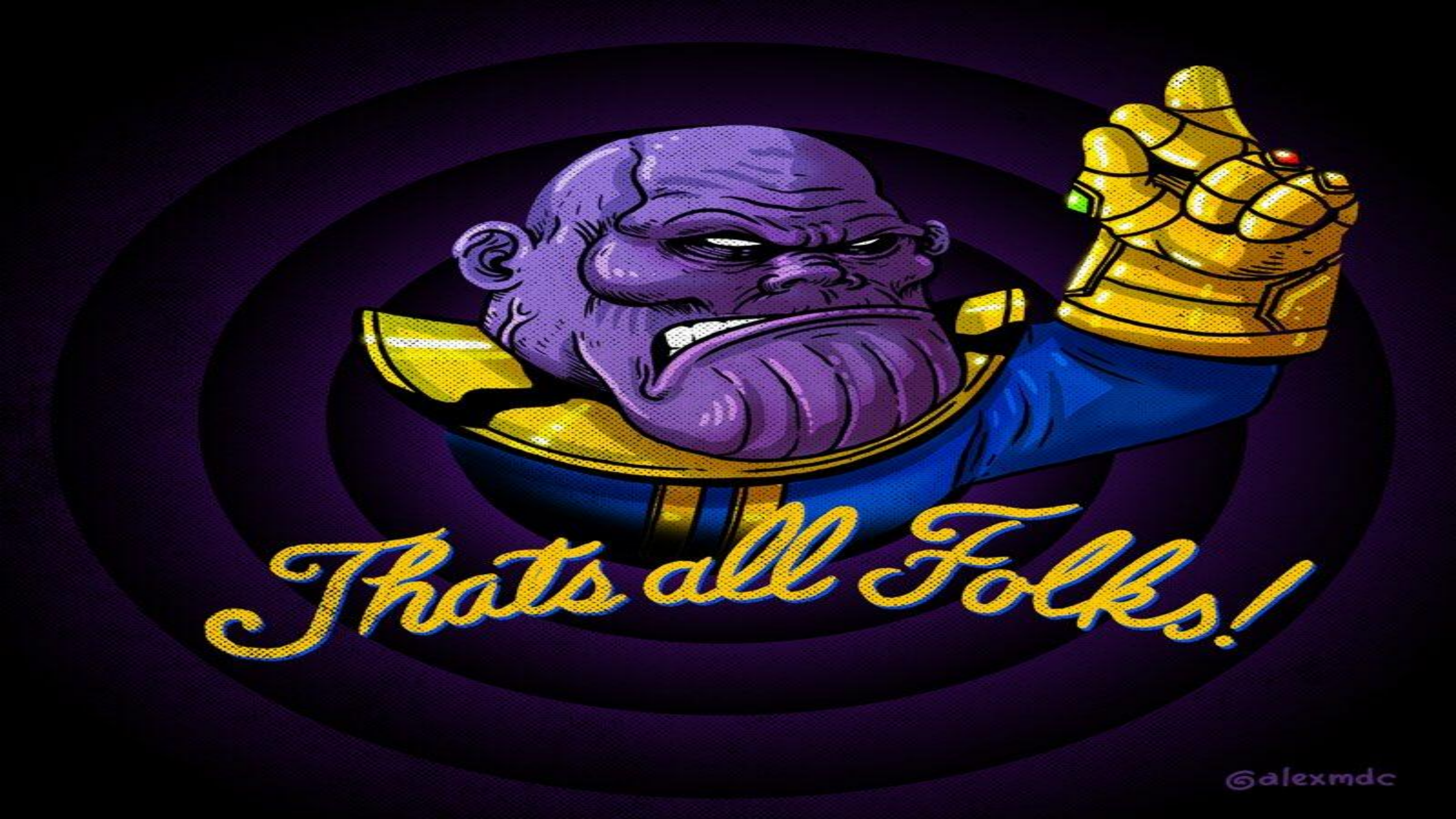
References

- Basu, Sumit, Sandeep Chatterjee, Rupa Chatterjee, Tapan K. Nayak, and Basanta K. Nandi. "Specific heat of matter formed in relativistic nuclear collisions." *Physical Review C* 94, no. 4 (2016): 044901.
- Mukherjee, Maitreyee, Sumit Basu, Arghya Chatterjee, Sandeep Chatterjee, Souvik Priyam Adhya, Sanchari Thakur, and Tapan K. Nayak. "Isothermal compressibility of hadronic matter formed in relativistic nuclear collisions." *Physics Letters B* 784 (2018): 1-5.
- Schnedermann, Ekkard, Josef Sollfrank, and Ulrich Heinz. "Thermal phenomenology of hadrons from 200A GeV S+ S collisions." *Physical Review C* 48, no. 5 (1993): 2462.
- Sahoo, Raghunath. "Relativistic kinematics." *arXiv preprint arXiv:1604.02651* (2016).
- Torrieri, Giorgio, Rene Bellwied, Christina Markert, and Gary Westfall. "Statistical hadronization phenomenology in K/π fluctuations at ultra-relativistic energies." *Journal of Physics G: Nuclear and Particle Physics* 37, no. 9 (2010): 094016.
- Kliemant, Michael, Raghunath Sahoo, Tim Schuster, and Reinhard Stock. "Global properties of nucleus–nucleus collisions." In *The Physics of the Quark-Gluon Plasma*, pp. 23-103. Springer, Berlin, Heidelberg, 2009.


Thats all Folks!
@alexmdc

Questions???

Backup Slides

Why Isothermal Compressibility κ_T ?

- κ_T describes the relative variation of the volume of a system due to a change in the pressure at constant temperature.

$$\kappa_T = \frac{-1}{V}\left(\frac{\partial V}{\partial P}\right)\Big|_{T,<N>}$$

- κ_T is linked to density fluctuations and can be expressed in terms of the second derivative of the free energy with respect to the pressure.

- In a second order phase transition κ_T is expected to show a singularity.

- Under the Grand-Canonical Ensemble Formalism (G.C.E), we have:

- $$\sigma^2 = \frac{k_B T <N>^2}{V}\kappa_T$$

- $$\omega_{ch} = \frac{<N_{ch}^2> - <N_{ch}>^2}{<N_{ch}>}$$

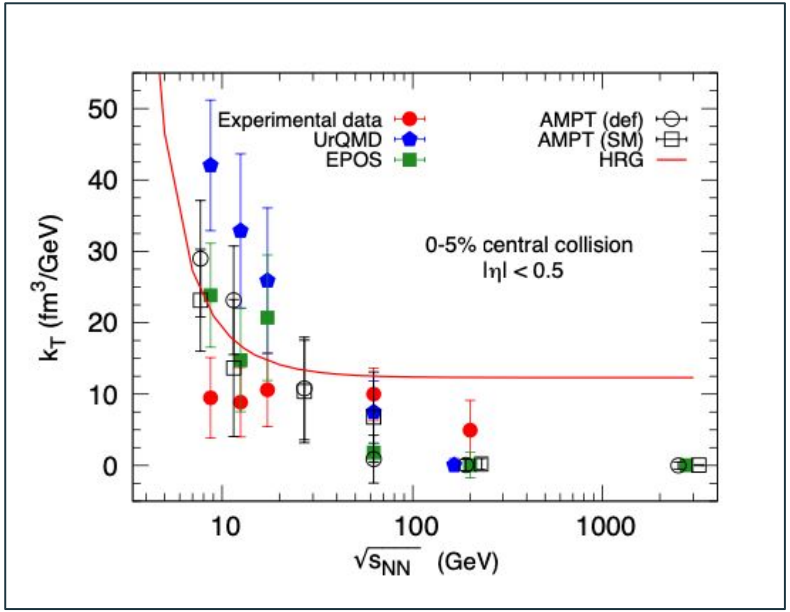
- ω_{ch} Is the scaled variance of the Charged particle yields.

Progress so far

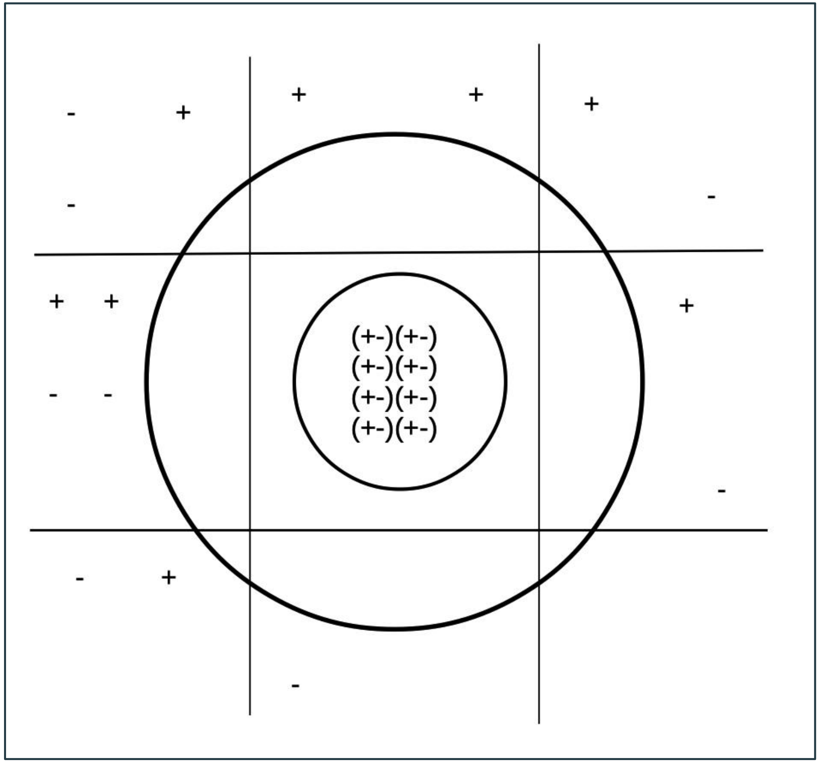
- ❖ Calculations carried out at 7.7, 11.5, 19.6, 62.4 and 200 GeV.

- ❖ A higher value of κ_T at low energies compared to higher energies indicates that the collision system is more compressible at the lower energies.

- ❖ AMPT, UrQMD and EPOS (Event Generators).



❖ Isothermal Compressibility Vs $\sqrt{s_{NN}}$



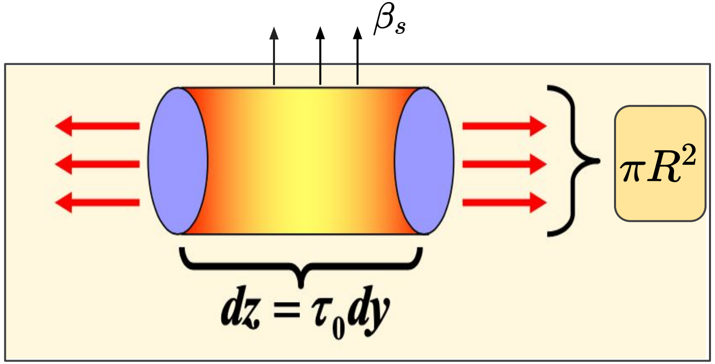
Calculating T_{kin} from the Blast Wave

- ## Blast-Wave formalism:

- The measured p_T spectral shape flattens significantly with increasing particle mass in central Au+Au collisions. This suggests the presence of a collective transverse radial flow field (cylindrical symmetry).

- This p_T distribution is found from the Cooper-Frye equation:

$$E\frac{d^3N}{dp^3} = \int f(x,p)p^{\mu}d\sigma_{\mu}$$



- $E\frac{d^3N}{dp^3} = \frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy}$ (Particle Spectra)

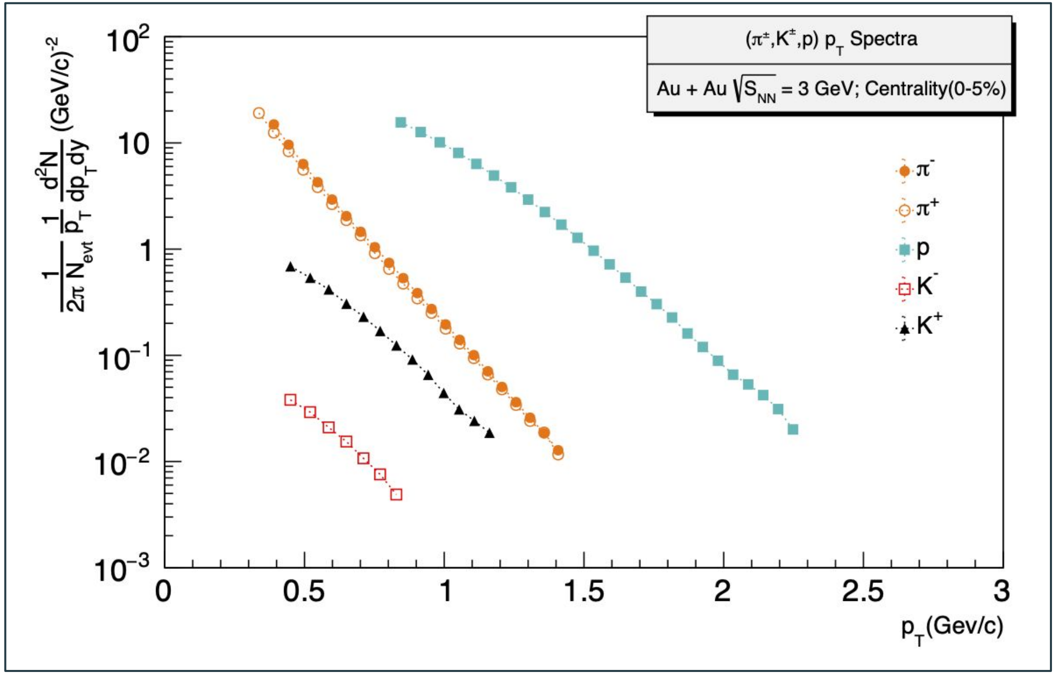
- f(x,p) is the distribution function of the phase space.
- p^{μ} is the momentum 4-vector

- $d\boldsymbol{\sigma}_{\mu}$ is the hypersurface from which the particles are emitted.

Kinetic Freeze-out

❖

$$\frac{\chi^2}{N.D.F.}$$



❖ Combined Blast-Wave Fit

Collision Energy ($\sqrt{s_{NN}}$)

- $\sqrt{s}$ is the total energy in the Center of Mass Frame (CM), invariant mass of the CM.
- Natural units, ħ = c = 1.
- 1eV = 1.60218×10^{-19} J.
- The Collision Energy enables us to reach the desired energy density and temperatures for the system.

$$s = E_{cm}^2 = m_1^2 + m_2^2 + 2(E_1 E_2 + |p_1||p_2|)$$

- Energy of the collision expressed in terms of nucleon- nucleon center of mass energy.
- In the nucleon-nucleon CM frame, two nuclei approach each other with the same velocity.
- The nucleon-nucleon CM energy is denoted by $\sqrt{s_{NN}}$ and is related to the total CM energy by:

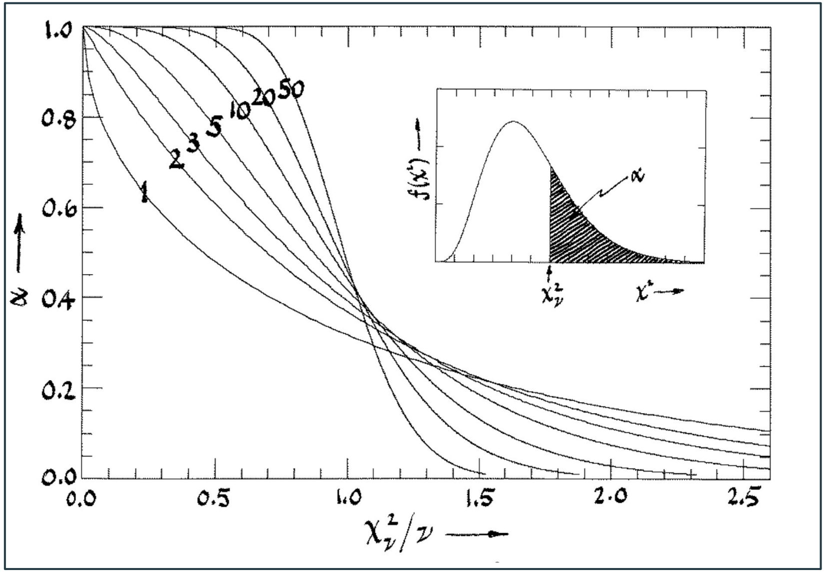
$$\sqrt{s_{NN}} = \frac{\sqrt{s}}{A}$$

- A : Number of Nucleons in the Heavy-Ion

Backup Slides

χ^2 Test for Fitting:

- $\chi^2 = \sum_{i=1}^{\nu} \frac{(x_i - \mu_i)^2}{\sigma_i^2}$
- ν : Number of degrees of freedom (N-r)
- $\chi^2/\nu \cong 1$ (For a good fit).



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transformation betas (NN,lab,pro)     0.0000000  0.9953427 -0.9953427
impact_parameter_real/min/max(fm):    1.25  0.00  3.50  total_cross_section(mbarn):     384.85
equation_of_state:    0  E_lab(GeV/u): 0.2000E+03  sqrt(s)(GeV): 0.1946E+02  p_lab(GeV/u): 0.2009E+03
event#         1 random seed:  1605073721 (auto)   total_time(fm/c):       50 Delta(t)_O(fm/c):       50.000
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op  0    0    0    0    0    0    1    0    1    0    0    0    0    2    1
op  0    0    0    1    1    0    0    0    0    0    0    0    0    1    0
op  0    5    0    0    0    0    0    0    0    0    0    1    0    1    0
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pa 0.2700E+00   0.4900E+00   0.2700E+00   0.1000E+01   0.1600E+01   0.8500E+00   0.1550E+01   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+0
pa 0.9000E+00   0.5000E+02   0.1000E+01   0.1000E+01   0.1000E+01   0.1500E+01   0.1600E+01   0.0000E+00   0.2500E+01   0.1000E+00   0.3000E+0
pa 0.4200E+00   0.1080E+01   0.8000E+00   0.5000E+00   0.0000E+00   0.5500E+00   0.5000E+01   0.8000E+00   0.5000E+00   0.8000E+06   0.1000E+0
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