Phenomenology of the Quark-Gluon Plasma

Rajeev S. Bhalerao

Indian Institute of Science Education & Research (IISER)
Pune, India

The Myriad Colorful Ways of Understanding Extreme QCD Matter

ICTS, Bangalore, 12 April 2019

IISER PUNE

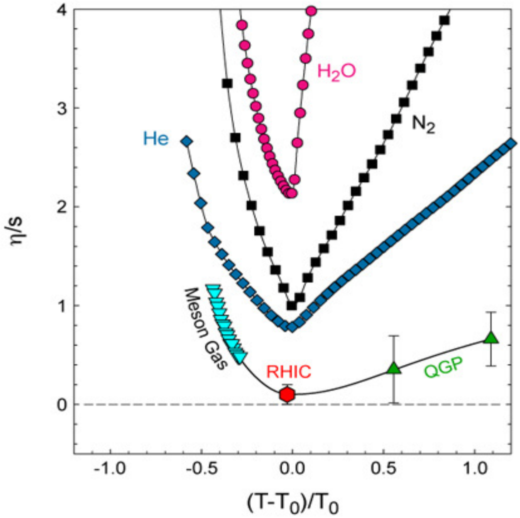
Quark-Gluon Plasma is

the smallest, hottest, densest, and most perfect

fluid ever produced in the laboratory

- Life-time: $\sim 4 \times 10^{-23}$ sec
- Smallest: $R \sim 10$ fm
- Hottest: $T \sim 200$ MeV $\sim 2 \times 10^{12}$ K
  (T at the core of the sun $\sim 1.6 \times 10^{7}$ K)
- Densest: several GeV/fm^3 $\gg$ nuclear density
- Most perfect: Even more so than liquid helium

Meaning of “the Most Perfect Fluid” ..... Fig : Roy Lacey



Constant-pressure (P_{crit}) curves

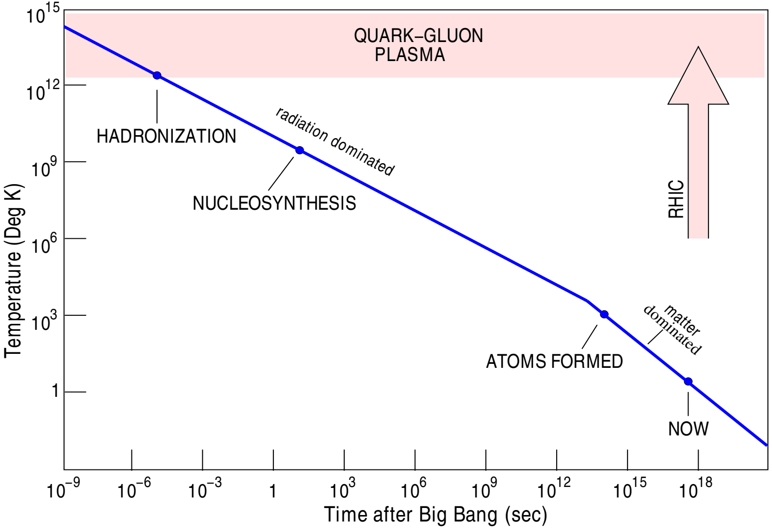
Meson gas: χPT (50 % error not shown)

QGP: LGT calc. of Nakamura & Sakai

Small η/s has been seen also in some ultracold trapped atomic systems

Liquids & gases behave differently. QCD: Liquid cools into a gas !!

Recreating the "Early Universe" in the Lab



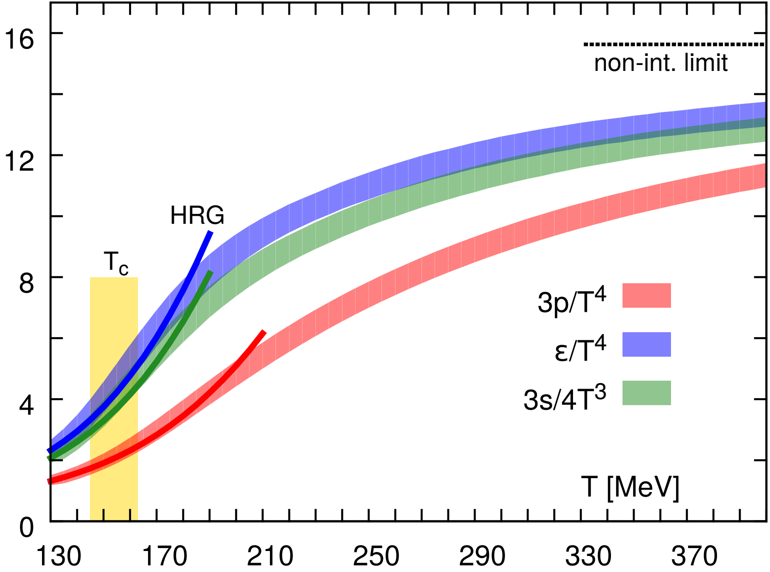
Temperature history of the universe

Fundamental Questions

This interdisciplinary field addresses some fundamental questions regarding QCD:

- Nature of equilibration processes in QCD
- Collectivity (especially in small systems) as an emergent phenomenon in QCD
- How to experimentally probe the physical degrees of freedom relevant in the QCD transition region

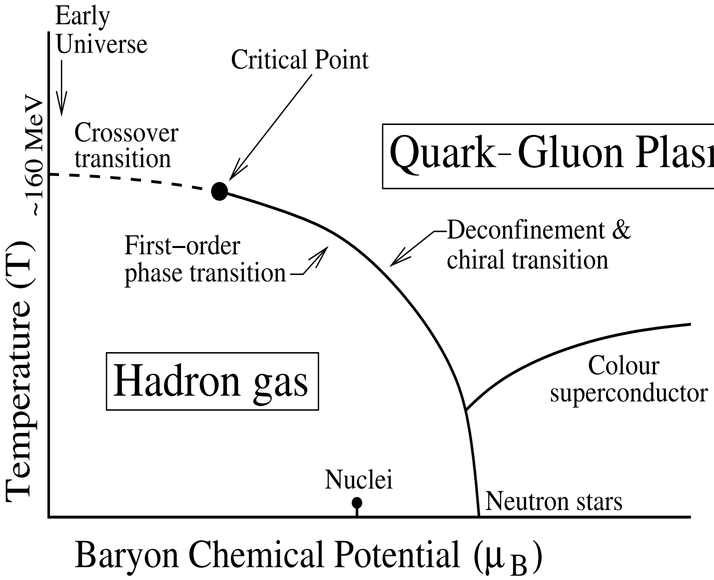
Lattice QCD Results for EOS ... HotQCD Collab 2014



Lattice QCD Results for EOS (contd.)

- (2+1)-flavour QCD; almost physical quark masses; $N_\tau = 6, 8, 10, 12$; continuum extrapolated results
- Horizontal line : Stephan-Boltzmann limit for ε
- Vertical band: crossover region 154 ± 9 MeV
- $T \simeq 154$ MeV: increase in entropy due to the release of partonic degrees of freedom
- p rises less rapidly than ϵ
- High-T limit: $\epsilon = 3p$
- HRG: Hadron Resonance Gas

QCD Phase Diagram (schematic)



THE BIG IDEA

- MAP OUT THE QCD PHASE DIAGRAM QUALITATIVELY and QUANTITATIVELY
- STUDY QCD NON-EQLBM (TRANSPORT) PROPERTIES
- TEST NON-PERT-QCD PREDICTIONS

RELATIVISTIC HEAVY-ION COLLISIONS IS THE ONLY AVAILABLE LABORATORY TOOL

Various Stages

- Collision of two Lorentz-contracted nuclei (or two CGC plates)
- Deposition of kinetic energy & formation of a fireball (or Glasma)
- Liberation of partons from the strong chromofields (or Decoherence)
- Approx. local thermalization of partons: Formation of QGP
- Hydrodynamic expansion, cooling, dilution. QCD EoS.
- Particlization — Kinetic theory
- Chemical freezeout: inelastic processes stop
- Kinetic freezeout: elastic scatterings stop. Free streaming.
- Detection of particles — Extraction of QGP properties

Wealth of Data

- Initial-State Variables: beam energy, beam species, centrality of collision
- Final-State Variables: particle species, transverse momentum, rapidity or pseudo-rapidity
- Observables (differential or integrated): charged particle multiplicity, p_T spectra, anisotropic transverse flows for $n = 1 - 7$, strangeness enhancement, J/ψ suppression, Υ suppression, BE correlations, jet quenching, 2-,3- and multi-particle correlations, γ and $\ell\ell$ spectra, ...

Any model has to agree with this body of data

HOW TO SIMULATE THE

ENTIRE COLLISION HISTORY?

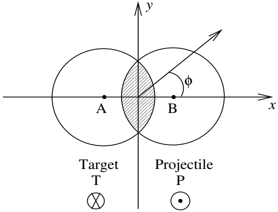
THREE MAIN STAGES AS DESCRIBED ABOVE

STAGE I ...

Stage I: From Collision to Formation of QGP

Also called the preeqlbm or prehydrodynamization stage

Old Outdated Approach



- Shaded area: overlap of two (smooth) Woods-Saxon distributions
- Initial energy (or entropy) density $\epsilon(x, y)$: Smooth
- Hydro evolution assuming smooth initial conditions

However, the reality is not so simple.

Initial geometry is not smooth.

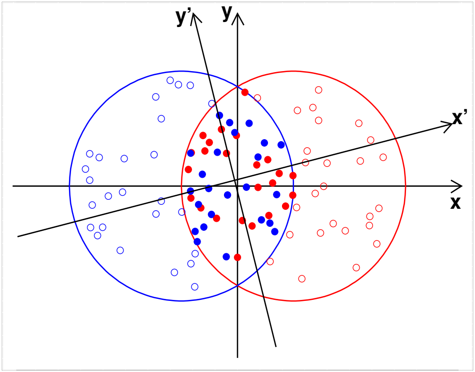
Why?

Event-to-event fluctuations in initial geometry

Basic idea: AA collision time-scale is so short that each incoming nucleus sees nucleons/partons in the other nucleus in a frozen configuration.

E-to-E fluctuations in no. of particles, their positions (& hence in collision points), apart from quantum fluctuations in soft, (semi)hard interactions result in fluctuations in the shape & orientation of the overlap zone. Resulting initial $\epsilon(x, y)$ lumpy with hot spots.

Event-to-event fluctuations in nucleon/parton positions



“Snapshot” of positions at the instant of collision. Due to e-to-e fluctuations, the overlap zone is shifted & tilted w.r.t. the (x, y) frame. $x'y'$: principal axes of inertia.

Modern Approaches

- Monte Carlo Glauber model
- Trento model
- CGC-inspired models: MC-KLN, IP-Glasma, EKRT
- ADS/CFT holography inspired models
- AMPT (A Multi-Phase Transport) Model
- UrQMD cascade model, etc.

A Typical Event (at the end of Stage I)

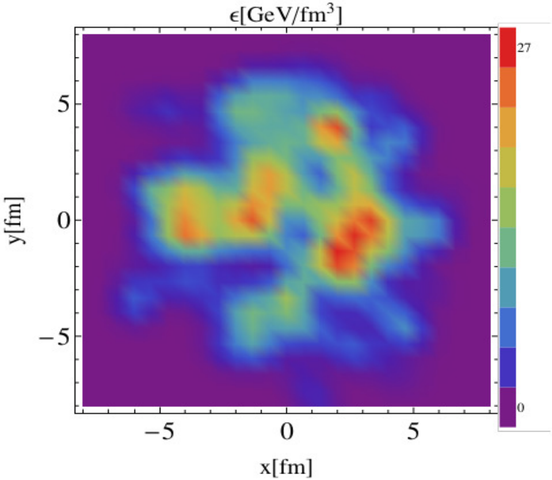


Fig. from Ollitrault & Gardim, 1210.8345

Energy density in the transverse plane at $z = 0$ in a simulated random central Pb-Pb collision at 2.76 TeV.

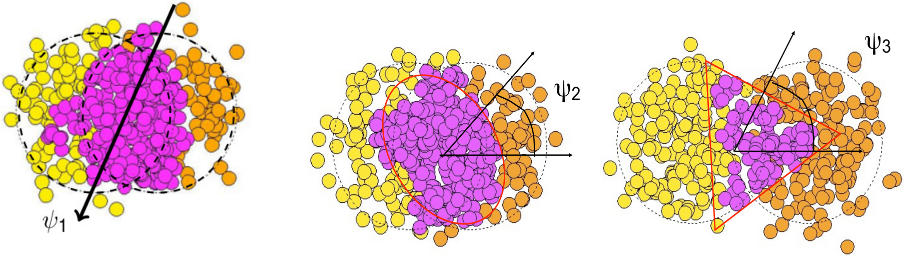
Characterization of the State at the End of Stage I

This is also the "initial" state for Stage II.

Eccentricity Σ_n: Characterization of this fluctuating "initial" profile in coord. space in theoretical studies.

- Recall the old definition $\varepsilon_2 \equiv \frac{\{y^2-x^2\}}{\{y^2+x^2\}}$ ... real
- $\Sigma_n \equiv \varepsilon_n e^{in\Phi_n} \equiv -\frac{\{z^n\}}{\{|z|^n\}} = -\frac{\{r^n e^{in\varphi}\}}{\{r^n\}} = -\frac{\int z^n e(z) r\, dr\, d\varphi}{\int |z|^n e(z) r\, dr\, d\varphi}$
- $\{\cdots\}$ = average over the transverse plane in a single event after centering: $\{re^{i\varphi}\} = 0$
- Φ_n: participant-plane angle in the n-th harmonic

First Three Harmonics



Σ_1 Dipole
→ dipolar flow
$v_1(p_T, y)$

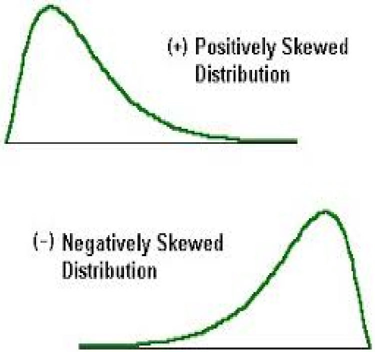
Σ_2 Ellipse
→ elliptic flow
$v_2(p_T, y)$

Σ_3 Triangle
→ triang. flow
$v_3(p_T, y)$

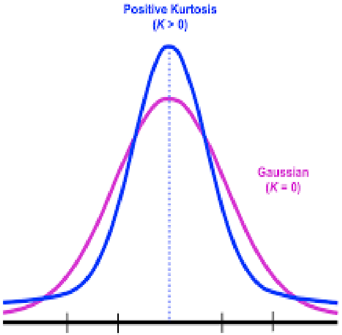
Figure from Luzum, 1107.0592

More Precise Characterization of the Initial State

- Probability distribution $P(\varepsilon_n)$ of eccentricity fluct.
- Measures of non-Gaussian fluct: skewness, kurtosis

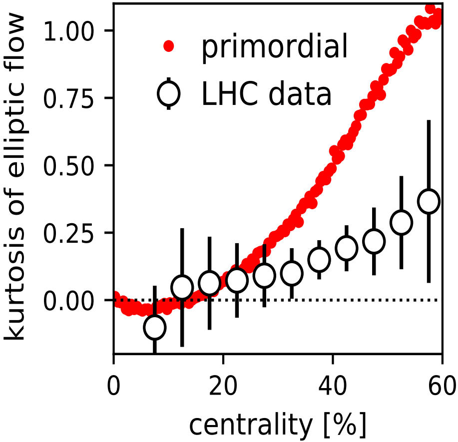


© mvpprograms.com



© mriquestions.com

More Precise Characterization of the Initial State (contd.)



Primordial ↔ Initial-state eccentricity ε_2, LHC data ↔ Final-state elliptic flow v_2. Future high-statistics experiments on v_2 would help constrain $|i\rangle$ models. ··· PR C**99** (2019) 014907, RSB, Giacalone, Ollitrault

Spatial profiles of the energy-momentum tensor $T^{\mu\nu}$ and conserved current N^{μ} at the end of Stage I serve as the initial state for Stage II

HOW TO SIMULATE THE ENTIRE COLLISION HISTORY?

STAGE II ...

Fluid Dynamics

- Loosely speaking, Hydrodynamics
- Effective (macroscopic) theory that describes the slow, long wavelength motion of a fluid (close to local equilibrium)
- Microscopic: Newtonian (many-body) mechanics
- Mesoscopic: Transport/kinetic theory
- Macroscopic in the sense that d.o.f. of constituent particles do not appear in fluid dynamics eqs

- Two length or time scales $\longleftrightarrow$ bulk fluid motion & constituent particle motion
- k: wave no. & ω: freq. of the bulk fluid motion
  ℓ: mfp & τ: mft of the constituent particles
- Hydro regime: $k\ell \ll 1, \;\; \omega\tau \ll 1$
- Transport theory regime: $k\ell \simeq 1, \;\; \omega\tau \simeq 1$
- Nearly free particle regime: $k\ell \gg 1, \;\; \omega\tau \gg 1$
- Powerful technique: initial conditions $\oplus$ EOS $\Rightarrow$ space-time evolution of the matter
- Limitation: applicable at or near 'local' thermodyn. eqlbm only. $(k\ell \ll 1, \;\; \omega\tau \ll 1$ ensures eqlbm)

Fluid Dynamics (contd.)

- Commonly, kinetic theory $\longrightarrow$ fluid dynamics. Microscopic length scale is the mean free path.
- More generally, QFT (where kinetic description may or may not be possible) $\longrightarrow$ fluid dynamics. Microscopic length scale is $1/\text{Temperature}$.
- N.B. Unlike kinetic theory, fluid dynamics is applicable even when there are no known (quasi)particles.

Perfect Fluid (Hypothetical)

- Defn 1: Vanishing coeffs. of shear viscosity (η), bulk viscosity (ζ), thermal conductivity (κ), $\cdots$
- Defn 2: Having at each point a vel. **v**, such that an observer moving with this vel. sees the fluid around him/her as isotropic.
- Equivalent: isotropy $\Leftrightarrow \ell \ll$ observer's length scale
- No internal friction; No heat exchange;
  No energy dissipation
- Motion adiabatic; Isentropic: Entropy conserved
- Thermal eqlbm is strictly maintained

Perfect fluid = Ideal fluid?

- Some authors use perfect & ideal interchangeably
- Others define ideal fluid as that which obeys the ideal EoS, $p = nk_B T$ — no collisions — large mfp
- η (measure of the ability to transport momentum over a distance) $\to \infty$
- Paradox: A nearly ideal classical gas has a divergent η & hence is not a perfect fluid

Imperfect fluid

- At least one transport coefficient (η, ζ, κ) nonzero
- Viscous: η and/or ζ nonzero; Inviscid: $\eta = 0 = \zeta$
- Thermal eqlbm is not strictly maintained; Irreversible process; Entropy generated
- Fluid kinetic energy is dissipated as heat
- $P, \rho, \mathbf{v}$ vary appreciably over distances $\sim \mathcal{O}(\ell)$, or over times $\sim \mathcal{O}(\tau)$, or both
- Nonzero space-time gradients of $P, \rho, \mathbf{v}$, unlike the case of a perfect fluid
- Zeroth-, first-, second-order (imperfect) hydrodyn

Zeroth-, First-, Second-Order Hydrodynamics

- Theory formulated as an order-by-order expansion (of viscosity, e.g.) in gradients of velocity **v** or u^μ.
- Zeroth order or Perfect: Euler's equation.
- First order: Navier-Stokes eqs — parabolic — acausal behaviour — rectified in the second-order theory.
- Second order: nonrelativistic case: Burnett eqs, relativistic case: e.g., Israel-Stewart eqs

Basic idea of causal dissipative hydro

- First a simple example of charge diffusion:

$$\begin{aligned} \partial_\mu J^\mu &= 0 && \ldots \text{ Conservation eq.} \\ J_i &= -D\partial_i \rho && \ldots \text{ Constitutive eq. (Fick's law)} \end{aligned}$$

Elimination of J_i gives

$$\partial_0 \rho - D\partial_i^2 \rho = 0 \quad \ldots \text{ Diffusion eq. (parabolic)}$$

Solution: $\rho \sim \exp(-x^2/4Dt)/\sqrt{4\pi Dt}$ ... violates causality

- To restore causality:

$$\begin{aligned} \tau_J \partial_0 J_i + J_i &= -D\partial_i \rho && \ldots \text{ Constitutive eq. (Kelly's law)} \\ \tau_J \partial_0^2 \rho + \partial_0 \rho - D\partial_i^2 \rho &= 0 && \ldots \text{ Diff. eq. (hyperbolic). Telegrapher's eq.} \end{aligned}$$

- If $v^2 \equiv D/\tau_J < 1$, causality is restored.

Basic idea of causal dissipative hydro (contd.)

- Now consider hydro:

$$
\begin{aligned}
\partial_\mu T^{\mu\nu} &= 0 && \ldots \text{ Conservation eq.} \\
\pi^{xy} &= -\eta \partial_x U^y && \ldots \text{ Constitutive eq.} \\
\tau_\pi \partial_t \pi^{xy} + \pi^{xy} &= -\eta \partial_x U^y && \ldots \text{ New Constitutive eq.}
\end{aligned}
$$

- Relativistic Navier-Stokes eq. and Maxwell-Cattaneo law.

- Basic idea is the same. Causality is restored by introducing higher-order terms in the gradient expansion, with a new set of transport coefficients such as τ_π.

- Successful phenomenological extension. Not a first-principle derivation. Not satisfactory.

What are Transport Coefficients?

- Fluid in equilibrium — uniform $T, \; n, \; \Phi, \cdots$ — perturb it — gradients of $T, \; n, \; \Phi, \cdots$ — fluid responds by setting up currents which tend to restore equilibrium — relaxation phenomena

- $\mathbf{Q} = -\kappa \nabla T, \;\; n\mathbf{u} = -D \nabla n, \;\; \mathbf{J} = -\sigma \nabla \Phi = \sigma \mathbf{E}$
  constitutive eqs — they relate fluxes to forces

- Fourier's law, Fick's law, Ohm's law, ...
  Transport of heat, mass, charge, momentum, ...

- Importance: Transport coeffs are of fundamental interest not only because they represent an imp property of the QCD matter, but also because they can be calculated from first principles (e.g., lattice QCD).

Equations to zeroth order

$$\begin{aligned} Dn &= -n\nabla_\mu U^\mu, \\ D\epsilon &= -(\epsilon + p)\nabla_\mu U^\mu, \\ (\epsilon + p)DU^\mu &= \nabla^\mu p. \end{aligned}$$

These get modified in second order. Additionally,

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta + \mathcal{J} + \mathcal{K} + \mathcal{R},$$

$$\tau_n \dot{n}^{\langle\mu\rangle} + n^\mu = \kappa I^\mu + \mathcal{J}^\mu + \mathcal{K}^\mu + \mathcal{R}^\mu,$$

$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + \mathcal{J}^{\mu\nu} + \mathcal{K}^{\mu\nu} + \mathcal{R}^{\mu\nu}.$$

··· Denicol *et al.* **D**85 (2012) 114047

A set of coupled partial differential equations for $n, \ \epsilon, \ (P), \ u^\mu$, and dissipative fluxes $\Pi, \ n^\mu, \ \pi^{\mu\nu}$.

In addition: transport coefficients $(\zeta, \ \kappa, \ \eta)$ & relaxation times $(\tau_\Pi, \ \tau_n, \ \tau_\pi)$, etc. also occur.

HYDRO† PLAYS A CENTRAL ROLE IN UNDERSTANDING THE SOFT SECTOR OF RELATIVISTIC HEAVY-ION COLLISIONS.

† Relativistic, dissipative, causal (second-order) hydrodynamics

Spatial profiles of the temperature T and the

four-velocity u^μ, at the end of Stage II, serve as the

input for Stage III.

HOW TO SIMULATE THE

ENTIRE COLLISION HISTORY?

STAGE III ...

Stage III: From Particlization to Detection

- Fluid $\rightarrow$ particles (hadrons) via some prescription
- Evolution of hadron gas via relativistic kinetic theory
- Free streaming to detectors

The Modern Flow Picture

It is a model in which particles are emitted randomly and independently according to some underlying probability distribution in each event. The azimuthal probability distribution that fluctuates event to event is:

$$P(\phi) = \frac{1}{2\pi} \sum_{n=-\infty}^{+\infty} V_n(p_T, \eta) e^{in\phi} = \frac{1}{2\pi} \sum_{n=-\infty}^{+\infty} v_n e^{in(\phi - \Psi_n)}$$

V_n: (complex) flow in the azimuthal or transverse plane, v_n: magnitude, Ψ_n: event-plane angle. Equivalently,

$$\frac{dN}{d\phi} = \frac{N}{2\pi} \left(1 + \sum_{n=1}^{\infty} 2 v_n \cos n(\phi - \Psi_n) \right)$$

Experimentally,

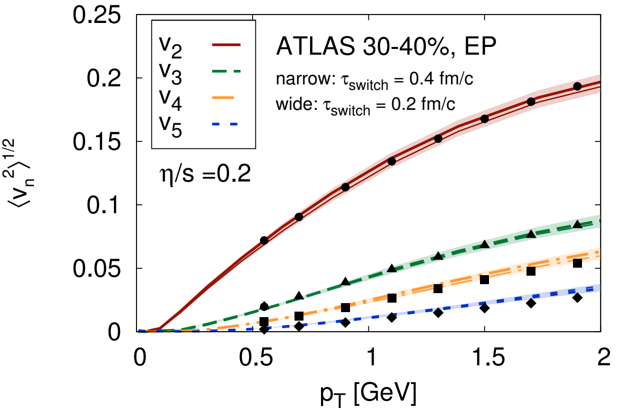
$$V_n \equiv v_n e^{in\Psi_n}(p_T,\eta) = \frac{\int d\phi_p e^{in\phi_p} \frac{dN_{ch}}{p_T dp_T d\eta d\phi_p}}{\int d\phi_p \frac{dN_{ch}}{p_T dp_T d\eta d\phi_p}} = \{e^{in\phi_p}\}$$

$\{\cdots\}$ = average over particle distribution in a single event

- Σ_n characterizes the fluctuating $|i\rangle$ in the coord. space
- V_n characterizes the fluctuating $|f\rangle$ in the mom. space

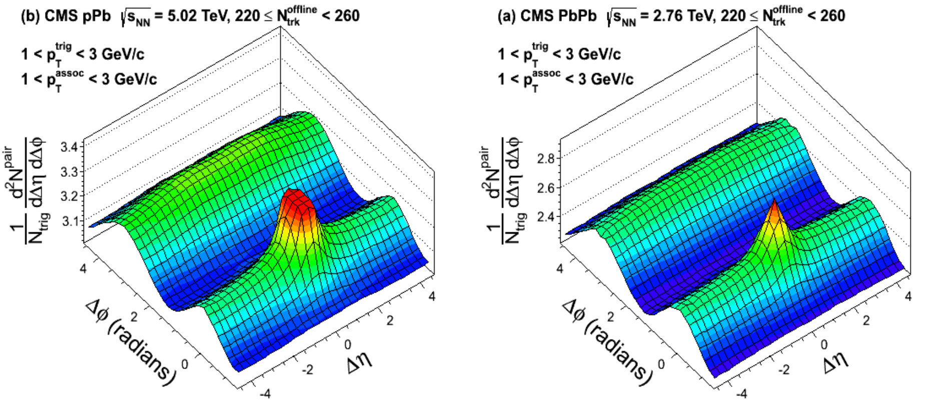
Importance of the Anisotropic or Azimuthal Flow

- Sensitive to the early history of the collision because of the self-quenching expansion.
- Signature of pressure at early times.
- Measure of the degree of thermalization of the quark-gluon matter formed in rhics – (central issue).
- Observation of a "large" elliptic flow at RHIC led to the claim of formation of an almost perfect fluid. Strongly coupled QGP $\Rightarrow$ (local) equilibration of matter.



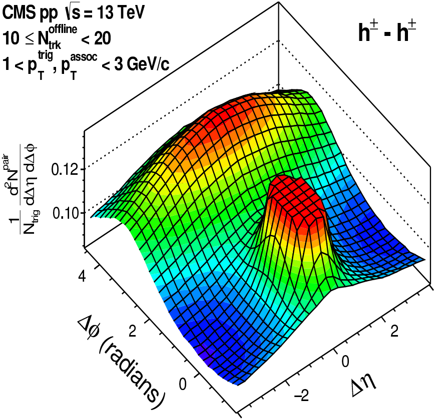
Basic idea: $v_n(perfect\ \ fluid) > v_n(viscous\ \ fluid)$
IF one has a good control on $v_n(perfect\ \ fluid)$, one can adjust η/s to fit the data on v_n, and thus extract η/s

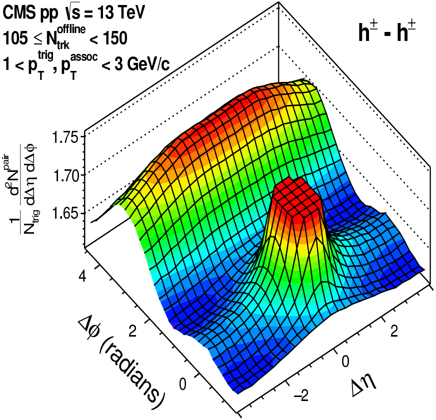
Ridges in *pPb* and *PbPb* collisions at LHC



Phys. Lett. B 724 (2013) 213

CMS Collab, arXiv:1606.06198

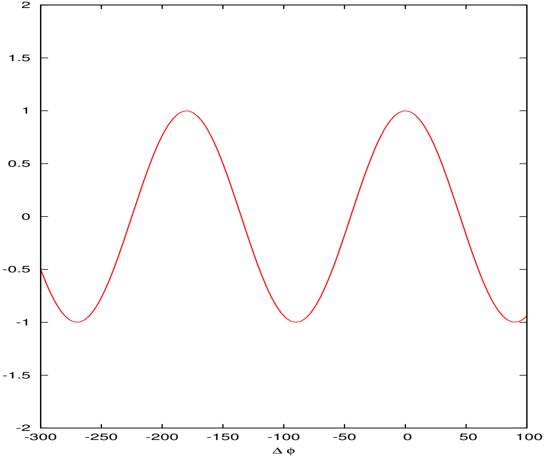




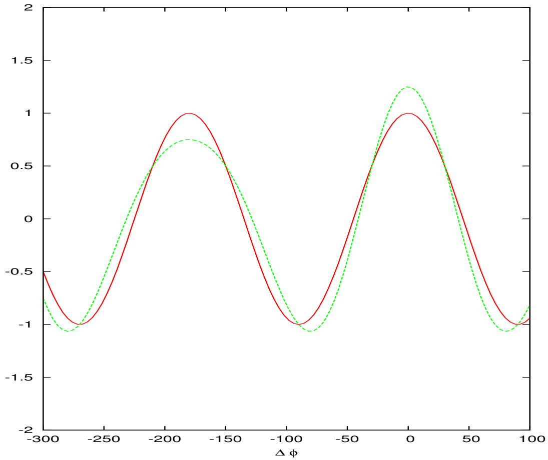
Ridge: One of the key experimental pieces of evidence for the strong collective behaviour comparable to a fluid.

Ridge and Shoulder — Explanation

$\cos(2\Delta\phi)$

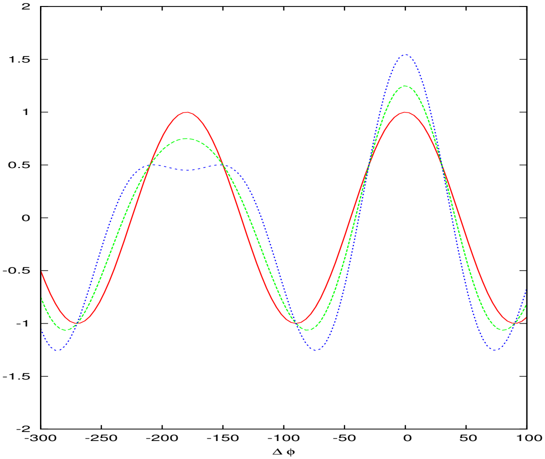


$$\cos(2\Delta\phi) + 0.25\cos(3\Delta\phi)$$



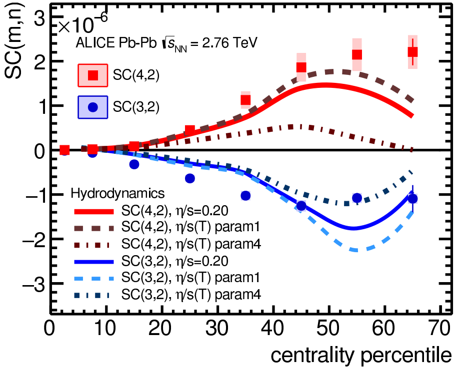
Ridge and Shoulder — Explanation

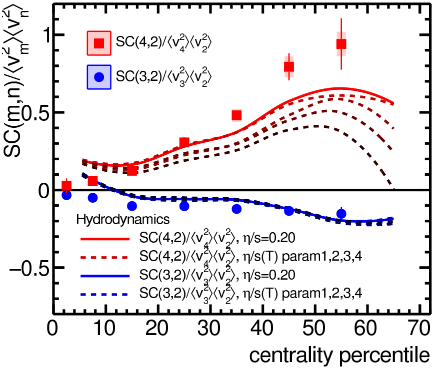
$$\cos(2\Delta\phi) + 0.55\cos(3\Delta\phi)$$



More Precise Characterization of the Final Sate

- Greater precision $\Rightarrow$ Greater discriminating power
- Besides $v_n\{2\}$, $v_n\{4\}$, $v_n\{6\}$, $v_n\{8\}$, ...
- Correlations between magnitudes v_n and v_m
- Correlations between orientation angles Ψ_n and Ψ_m
- Probability distribution $P(v_n)$ of v_n fluct.
- Measures of non-Gaussian fluct: skewness, kurtosis
- $\cdots$





$SC(m,n) =< v_m^2 \; v_n^2 > - < v_m^2 >< v_n^2 >$

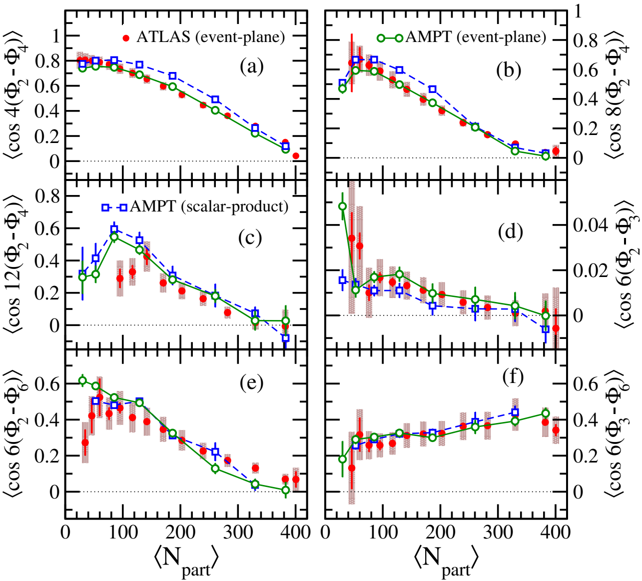
Symmetric Cumulants = Correlations between the amplitudes of anisotropic flow in diff. Fourier harmonics.

Calc by Niemi, Eskola, Paatelainen 1505.02677 [hep-ph]

Event-Plane Correlators

- Pair correlations (or the anisotropic flow v_n extracted from them) are by now reasonably well understood.
- Event-plane correlations: correlations among event planes (Ψ_n) corresponding to different harmonics.
- Represent higher-order correlations, involving at least three particles.
- They bring in a large number of new observables with a promise to provide new, detailed insight into the hydrodynamic response & the initial-state phenomena.
- They open a new direction in heavy-ion physics.
- ATLAS @ LHC (2013): Two- and three-plane correlators. Predictions exist for four-pl correlators.

Two-Event-Plane Correlators ... Pb-Pb, 2.76 TeV, PRC (2013)

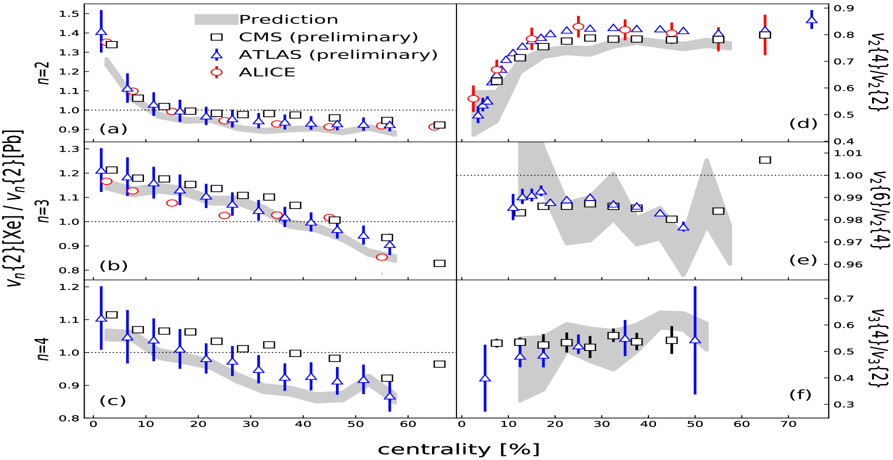


Some Recent Developments $\cdots$

Xe-Xe @ 5.44 TeV

- Why?
- ^{208}Pb: $\sim$ spherical , ^{129}Xe: smaller, non-spherical?
- New interplay bet. nuclear structure & initial state
- Bridges the gap between p-p, p-Pb and Pb-Pb
- Opportunity to test the scaling behaviour in fl. dyn.
- Predictions for $\langle p_T \rangle$, $v_n\{2\}, v_n\{4\}, v_n\{6\}$, $n = 2, 3, 4$ for Xe-Xe as a function of centrality. Comparisons with Pb-Pb data. ... Giacalone *ea.* PRC 97 (2018) 034904

Confronting Hydrodynamic Predictions with Xe-Xe Data



Data: QM2018 and 1805.01832; Fig. from Giacalone *et al.* 1807.05557

- Predictions are largely confirmed. Hence, validation of the standard hydrodynamic picture across both systems.

- A strong indication of a non-spherical ^{129}Xe. Though a deformed shape was expected, this is the first experimental evidence.

- Global Bayesian Analysis with combined Pb-Pb and Xe-Xe flow data with a common parameterization of transport coefficients is desirable.

Confronting state-of-the-art hydrodynamic calculations with the wealth of the flow data

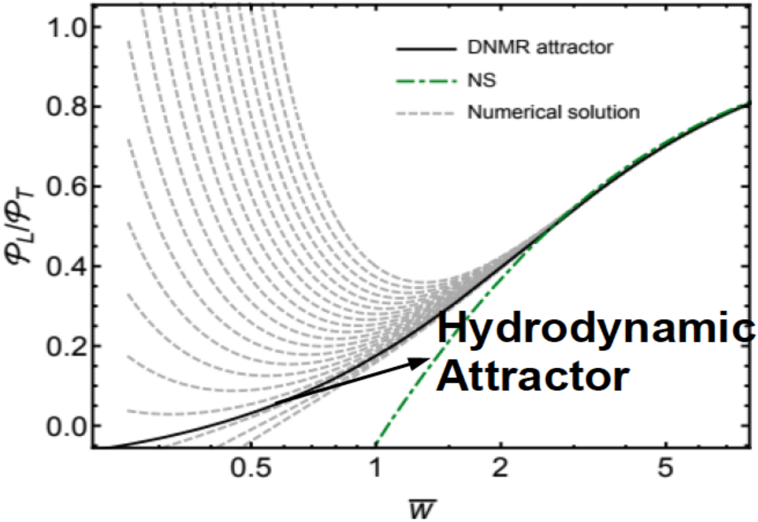
. . .

Model \ Setting	iEBE-VISHNU (I) Ref. [49]	iEBE-VISHNU (II) Ref. [49]	VISH2+1 Ref. [25]	EKRT +Hydro (fixed η/s) Ref. [50]	EKRT +Hydro (param I) Ref. [50]	IP-Glasma + MUSIC + UrQMD Ref. [51]
Initial conditions	T$_R$ENTo	AMPT	AMPT	EKRT	EKRT	IP-Glasma
η/s	η/s(T)	$\eta/s = 0.20$	$\eta/s = 0.16$	$\eta/s = 0.20$	η/s(T)	$\eta/s = 0.095$
ζ/s	ζ/s(T)	$\zeta/s = 0$	$\zeta/s = 0$	ζ/s(T)	ζ/s(T)	ζ/s(T)
Observables						
v_2	✓	✓	✓	✓	✓	✓
v_{3-7}	✓	✓	Δ	✓	✓	✓
$P(v_n)$	✓	✓	Δ	✓	✓	✓
$v_n(p_T)^{ch,PID}$	Δ	✓	N/A	N/A	N/A	Δ
r_n	Δ	Δ	N/A	N/A	N/A	Δ
$SC(m,n)$	Δ	Δ	×	Δ	Δ	N/A
$v_{n,mk}$	✓	✓	N/A	✓	✓	✓
$\rho_{n,mk}$	✓	✓	N/A	✓	✓	✓
$\chi_{n,mk}$	✓	✓	N/A	N/A	N/A	✓
$v_{n,mk}(p_T)^{ch,PID}$	Δ	✓	N/A	N/A	N/A	N/A

Table 1. Current available comparisons of between data and model calculations. Here ✓ (Good), Δ (Not so bad), × (Not good) and N/A (Not available).

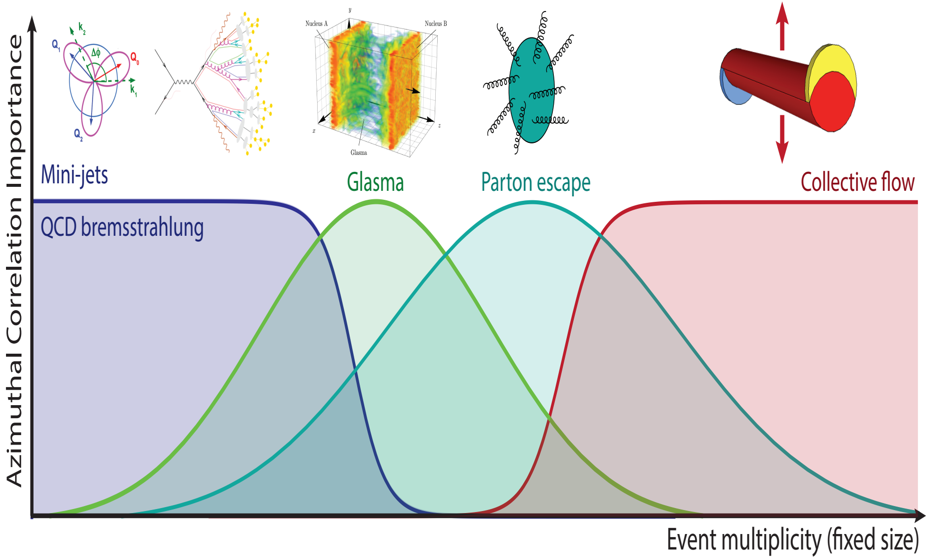
- Dynamics of vorticity and spin
  Motivation: Λ polzn measurement at RHIC
- Non-convergence of the gradient series — resummation
- Aspects of hydrodynamics far from eqlbm
  - Hydrodynamic attractor
  - Anisotropic Hydrodynamics

Hydrodynamic Attractor ... Strickland, Noronha, Denicol, PRD (2018)



Different initial conditions (dashed lines) converge to the hydrodynamic attractor (solid line) even though the system is still far from equilibrium

Various Sources of Anisotropy ... M. Strickland, 1807.0719



Standard Model of URHICs

- Initial state: Glauber model / Colour-Glass Condensate-based model
- Pre-equilibrium evolution: AMPT or classical Yang-Mills eqs
- Intermediate evolution: Rel. 2nd-order hydro $\oplus$ lattice QCD EoS
- End evolution: Rel. Boltzmann dynamics leading to a freeze-out
- Final state: Detailed measurements (single-particle inclusive, two- & multi-particle correlations, etc.) are available.

Aim: To achieve a quantitative understanding of the thermodynamic and transport properties of QGP, e.g., its EoS, transport coeffs, etc.

Major hurdle

Event-by-event fluctuations

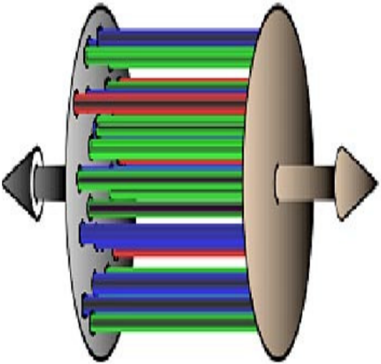
(not just in the initial state)

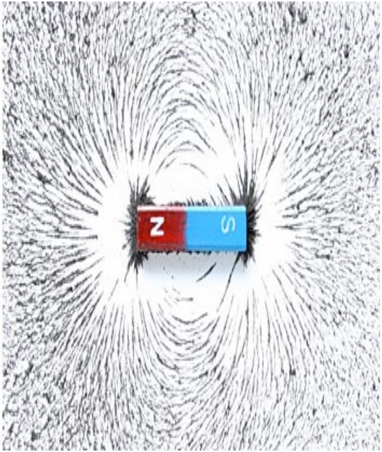
The Big Bang and the Little Bang

Initial quantum fluctuations → Macroscopic fluctuations in the final state.
Aim: To study the (unknown) early state.

Features	Big Bang	Little Bang
Occurrence	Only once	Millions of times
Initial state	Inflation? ($10^{-35}s$)	Glasma? ($10^{-24}s$)
Thermalization	Inflaton E → thermal E	Coherent Glasma →
...	of radiation & matter	$q, \bar{q}, g \rightarrow$ QGP
Expansion	General Relativity	Rel. Dissip. hydro.
Phase transitions	EW and QCD	QCD
Expansion velocity	$v = H_0 r$ (Hubble)	$v_z = z/t$ (Bjorken)
Freezeout/Decoupling	γ : 2.73 K, ν : 1.95 K	$\sim 150, \sim 120$ MeV

The Glasma (initial stage) ..... Fig : Raju Venugopalan





Coloured flux lines produced in *pp* or *AA* collisions just after the collision.
Glasma: Highly excited, coherent, classical field configuration

The Big Bang and the Little Bang (contd.)

Features	Big Bang	Little Bang
Anisotropy observed	Final temp. (CMB)	Final flow profile
Penetrating probes	Photons	Photons, ℓ, jets
Chemical probes	Light nuclei	Various hadron species
Colour shift	Red shift	Blue shift
Parameters (5-10)	Initial density, age, etc.	τ_0, $T_0^{\mu\nu}$, $T_{\rm f.o.}$
Tools	COBE, WMAP, Planck	SPS, RHIC, LHC
Starting years	1989, 2001, 2009	1987, 2000, 2009

Take-Home Message / Open Questions

- All data so far are consistent with the formation of Quark-Gluon Plasma, and we are in the midst of trying to determine its equilibrium and transport properties accurately.
- Data provide a strong support to hydrodynamics as the appropriate effective theory for rhics. But the Standard Model still incomplete.
- Dichotomy between strong and weak coupling descriptions of hot QCD matter.
- How does a weakly-coupled colour-glass condensate become a strongly-coupled fluid?
- Collectivity in small systems. Size of the smallest QCD droplet?
- QCD Phase Diagram still remains largely unknown. Critical Point?
- LHC: High luminosity era. NICA: Fixed target expt. from 2020 CBM@FAIR: Data taking to start in 2022. EIC? So this exciting field is going to remain very active for a decade at least.

Bibliography-1

- Extreme States of Matter in Strong Interaction Physics,
  H. Satz, Lecture Notes in Physics, Vol. 841, Springer, 2012.
- Phenomenology of Ultra-relativistic Heavy-Ion Collisions,
  W. Florkowski, World Scientific, 2010.
- Relativistic Heavy-Ion Physics,
  J. Bartke, World Scientific, 2008.
- Ultra-relativistic Heavy-Ion Collisions,
  R. Vogt, Elsevier Science, 2007.
- Quark-Gluon Plasma,
  K. Yagi, T. Hatsuda & Y. Miake, Cambridge Univ., 2005.
- Hadrons and Quark-Gluon Plasma,
  J. Letessier & J. Rafelski, Cambridge Univ., 2002.

Bibliography-2

- Introduction to High-Energy Heavy-Ion Collisions,
  C.Y. Wong, World Scientific, 1994.
- Introduction to Relativistic Heavy-Ion Collisions,
  L. Csernai, John Wiley, 1994.
- The Physics of the Quark-Gluon Plasma,
  B. Müller, Lecture Notes in Physics, Vol. 225, Springer, 1985.

- Quark-Gluon Plasma, Vols. 3, 4, 5
  R.C. Hwa & X.N. Wong, editors, World Scientific, 2004, 2010, 2016.
- Quark-Gluon Plasma, Vols. 1, 2,
  R.C. Hwa, editor, World Scientific, 1990, 1995.
- The CBM Physics Book: Compressed Baryonic Matter in Lab Expts,
  B. Friman et al. editors, Springer, 2011.

Further reading ...

For a detailed pedagogical introduction to the field of relativistic heavy-ion collisions, see

R.S. Bhalerao,
Lectures given at the First Asia-Europe-Pacific School of High-Energy Physics, Fukuoka, Japan, 14-27 October 2012, published as a CERN Yellow Report (CERN-2014-001) and KEK report (KEK-Proceedings-2013-8), arXiv:1404.3294 [nucl-th].

THANK YOU