Subjects

- Phase diagram of nuclear matter
- Global observables and the initial state
- Hydrodynamical flow
- Partonic energy loss in the medium
- Provocative ideas
The phase diagram of nuclear matter

Dan Cebra
Misha Stephanov
Swagato Mukherjee
Rajan Gupta
Grzegorz Stefanek
Lattice: QCD transition at $\mu_B = 0$ a crossover. More in talks by S. Mukherjee and R. Gupta.

Models (and lattice) suggest the transition becomes 1

Can we observe the critical point in heavy ion collisions?

Lattice groups agree on critical temperature

Theoretical searches for the critical point
• Since the original design of RHIC (1985), running at lower energies has been envisioned.


• In 2009 the RHIC PAC approved a series of six energies to search for the turn-off of QGP signatures, the critical point, and evidence of a first order phase transition.

• The scan was completed during the 2010 and 2011 run periods.
Using the particle ratios from the $\pi$, $K$, and $p$ and a thermal model, we can determine our location on the phase diagram.
• rapid changes in energy dependence of hadron production properties provide evidence for the phase transition

• the LHC and RHIC BES points confirm NA49 measurements and trends

Data:
NA49: C.Alt et al., PRC 77, 024903 (2008)
and
A.Rustamov, arXiv:1201.4520

Theoretical predictions:
M.Gazdzicki, M.Gorenstein, APP B30, 2705 (99)

Evidence for the onset of deconfinement in Pb+Pb collisions at $\sqrt{s_{NN}} \approx 8$ GeV
Conclusions

- The RHIC facility has successfully completed a *phase I* beam energy scan.

- Charged particle spectra allow determination of a location on the phase diagram.

- Clear evidence of turn-off of QGP signatures
  - Constituent quark scaling of flow
  - High $p_T$ suppression
  - Chiral magnetic effect anisotropies

- Some evidence for first order phase transition
  - The magnitude of the elliptic flow
  - The directed flow
  - The azimuthal HBT

- Searches for critical point signatures
  - Particle ratio fluctuations (K/$\pi$ etc.)
  - Skew and Kurtosis of conserved quantities
Take home messages

• Theory:
  • Agreement on critical temperature from Lattice
  • Searches for critical point

• Experiment:
  • Unprecedented wealth of data
  • Some evidence for the critical point… but not yet conclusive
  • RHIC & SPS data agree
Global observables and the initial condition

Bjoern Schenke
David Silvermyr
Magdelena Malek
Sooraj Radhakrishnan
IP-Glasma: Initial energy density

Initial energy density at $\tau = 0$:

$$\varepsilon(\tau = 0) = \frac{2}{g^2 a^4} (N_c - \text{Re} \, \text{tr} \, U_\square) + \frac{1}{a^4} \text{tr} \, E_\eta^2$$

with the longitudinal magnetic and electric energy density.

The plaquette is given by

$$U^j_\square = U^x_j \, U^y_{j+x} \, U^{x\dagger}_j \, U^{y\dagger}_j$$

arbitrary units

Björn Schenke (BNL)
Flow and initial density fluctuations

\[ \Rightarrow \quad \frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} n \cos(n(\phi - \Psi_n)) \]

\[ \nu_n = \langle \cos(n(\phi - \Psi_n)) \rangle \]

\[ \epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi) \rangle^2 + \langle r^n \sin(n\phi) \rangle^2}}{\langle r^n \rangle} \]

- Collective pressure driven expansion. Initial spatial asymmetry \( \rightarrow \) final momentum space anisotropy
- The flow signal is sensitive to initial geometry and dynamics of the medium \( \rightarrow \) equation of state, transport coefficients: shear viscosity

**Event Plane Analysis**

- EP direction:
  \[ \tan(n\Psi_n) = \frac{\sum_i w_i \cos(n\phi_i)}{\sum_i w_i \sin(n\phi_i)} \]
- Correlate EP with tracks
  \[ \nu_n = \langle \cos(n(\phi - \Psi_n)) \rangle \]
- Resolution correction \( \nu_n^{\text{actual}} = \nu_n / R \);
  \[ R \approx \langle \sqrt{2 \cos(\Psi_a - \Psi_b)} \rangle \]
- Ensure rapidity gap to reduce jet correlations

Sooraj Radhakrishnan
\( \sim 2.1 \text{ TeV at } \eta = 0; \text{ at least 3 times larger than at RHIC} \)

- BRAHMS data described by Landau hydro; Gaussian with \( \sigma = \sqrt{\ln \gamma} \)
- for \(|\eta| < 5.2\) and centrality 0-2.5\%: \( dE_T/d\eta \) consistent with a Gaussian with \( \sigma_\eta = 3.6 \pm 0.1 \)
- for \( \tau_0 = 1 \text{ fm/c and } R = 7.1 \text{ fm} \): energy density of \( \approx 15 \text{ GeV/fm}^3 \)
- for central events total transverse energy per pair of participating nucleons is \( 92 \pm 6 \text{ GeV} \)

\[ \text{arXiv:1205.2488v1 [nucl-ex]} \]
dNch/d\eta

N.B.: Approx. same centrality dependence at 7.7 GeV as at 2.76 TeV!
[note: no RHIC average here, just PHENIX..]
Also for transverse energy:
Approx. same centrality dependence at 7.7 GeV as at 2.76 TeV!
Take home messages

- Theory:
  - Fluctuations in initial state energy density are very important

- Experiment:
  - Energy densities reached at the LHC several times the critical energy density
  - Same dependence of particle multiplicity, transverse energy produced on system size independent of collision energy

- Outlook
  - Advances in calculations will allow us to distinguish between different proposed initial states
Flow

Energy density, $b = 9.3 \text{ fm}$
$t = 1.000 \text{ fm/c}$

Huichao Song
Michael Strickland
ShinIchi Esumi
Monika Sharma
Ramiro Debbe
Perfect Fluid and Hydrodynamics

ALICE preliminary
Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
Centrality 20-40%

Hydro
CGC, $\eta/s=0.20$
VISHNU VISH2+1

Flow coefficient $v_2$

$\pi$, $K$, $p$, $\Xi$, $\Omega$

2005 – RHIC Discovery of QGP as nearly perfect fluid

2011 – LHC energy density increase more than x2.6
perfect fluidity persists

Jamie Nagle
$v_2(p_T)$, $<v_2>$ comparison between RHIC and LHC

similar hydro properties  $<v_2>$ still increases with $<p_T>$
QGP viscosity from $\nu_2 / \varepsilon - (1/ S)dN / dy$

**MC-KLN**

(Par. Plan)

**MC-Glauber**

(Par. Plan)

$$1 \times (1/4\pi) \leq \eta / s \leq 3 \times (1/4\pi)$$

$\eta / s = 0.16 - 0.24$ for MC-KLN initial conditions

$\eta / s = 0.08 - 0.16$ for MC-Glauber initial conditions

H. Song, S. Bass, U. Heinz, T. Hirano, and C. Shen,
Identified particle $v_2$ and $(m_T-m_0)/n_{\text{quark}}$ scaling
--- including strangeness/heavy baryons ---

Scaling does not work as good as at RHIC
CMS $\pi^0 v2$ results compared to PHENIX $\pi^0 v2$

- Results agree despite a factor of $\sim 14$ increase in $\sqrt{s}$
- Same as observed for inclusive charged particles
- Systematic errors not shown on PHENIX results
All harmonics show the same behavior as when extracted from different bins of transverse momentum; They all increase in value to a maximum at $\sim$3-4 GeV/c and then drop into a long tail at high $p_T$. The ordering of the harmonics by magnitude is the same at all centralities except at the very central events.
A short summary

- $\nu_2$ is sensitive to $\eta/s$

Extraction $\eta/s$ from elliptic flow data using viscous hydro + UrQMD indicates:

$$1 \times \left(\frac{1}{4\pi}\right) \leq \eta/s \leq 3 \times \left(\frac{1}{4\pi}\right)$$

Similar averaged QGP viscosity at RHIC and LHC energies

- Relatively larger uncertainties are from initial geometry
  
  \begin{align*}
  \text{MC-Glauber:} & \quad \eta/s = (1 - 2) \times \left(\frac{1}{4\pi}\right) \\
  \text{MC-KLN:} & \quad \eta/s = (2 - 3) \times \left(\frac{1}{4\pi}\right)
  \end{align*}

- Relatively smaller uncertainties are from initial flow, bulk viscosity, single short hydro vs. e-by-e simulations …

Huichao Song
The perfect fluid

\[ \frac{\eta}{S} \approx 0 \]
The not-so-perfect fluid

\[ \frac{\eta}{S} \gg 0 \]
Entropy Production

2nd order approximation

Exact solution

$\tau_0 = 0.25 \phi \mu / \chi$
$T_0 = 600 \text{ MeV}$
$T_f = 150 \text{ MeV}$

$\tau_0 = 0.25 \phi \mu / \chi$
$T_0 = 400 \text{ MeV}$
$T_f = 150 \text{ MeV}$
Take home messages

• Theory:
  • Hydrodynamical flow is a powerful tool to understand the properties of the medium (i.e., $\eta/S$, $T$)...
  • ...provided we take all relevant effects into account

• Experiment:
  • Extensive experimental data over a wide range of momenta, particle type

• Outlook
  • Upcoming U+U, Cu+Au results from RHIC valuable for distinguishing models
Jets and energy loss


ATLAS

Guang-you Qin
Sevil Salur
Jinfeng Liao
Di-lun Yang
Ramiro Debbe

Christine Nattrass (University of Tennessee at Knoxville), CIPANP 2012
Tomographic probes

Diagnosing QCD medium: (simplified idea) pass a QCD-sensitive probe through it, then look for any modifications due to the medium.

Hard Probes of QGP: Jets, W, Z, photons ...
**Geometric Tomography**

Geometry of nuclei and geometry of collisions play essential roles in jet quenching.

Gyulassy, Vitev, Wang; .......

Same dynamics, different geometry $\rightarrow$ predictable change in exp. outcome with geometry!
Photons

Good agreement data – NLO for both pp & PbPb systems.

No modification of initial state:

Hard scattering processes scale with $<\text{Ncoll}>$ calculated by Glauber model
Suppression in A+A

- No suppression
  - Pions are suppressed
  - Electroweak probes ($\gamma, W, Z$) are unsuppressed
  - B-mesons (secondary $J/\Psi$) are suppressed
  - D-mesons (D0, ±, *) are suppressed

Number of particles in A+A

Number of nucleon-nucleon collisions *

Number of particles in p+p

Suppression

LHC hadrons suppressed by up to factor of ~6 at pT~7 GeV.
Slow rise and plateau at RAA~ 0.5 in pT~40 – 100 GeV
Photon+Jet

Access to the initial parton energy via isolated photon
Access to the final parton energy via jet reconstruction

Photons pass through the medium without interacting so their energy “tags” the original energy of the jet: **Direct measurement of the parton energy loss**!

Jet yields from different centrality events are compared using the ratio:

\[ R_{CP} = \frac{1}{N_{\text{coll}}^{\text{cent}}} \frac{1}{N_{\text{evnt}}^{\text{cent}}} \frac{dN}{dE_T} \]

A factor of 2 suppression is found between central and peripheral events. No cone size R dependence.

Systematic Error:
Bands: Correlated JES, effic., shape, \( R_{\text{coll}} \)
Red Boxes: part. correl. unfolding regularization, JER.
Error bars: sqrt of diagonal of covariant matrix.
Horizontal width, \( N_{\text{part}} \) uncertainty

\( R=0.2 \)
Take home messages

• Theory:
  • Electromagnetic probes described by pQCD. Strong probes require energy loss.

• Experiment:
  • Data in the LHC era allow quantitative determination of energy loss in the medium

• Outlook
  • Many more detailed measurements of jets
Provocative ideas
Scaling of high-$p_T$ $v_2$

\[ R_{AA}^l(p_T, L) \sim \exp \left[ -\frac{2\alpha_s C_F}{\sqrt{\pi}} L \sqrt{\frac{L}{p_T}} \right] \]

$v_2$ follows the $p_T$ dependence observed for jet quenching

Note the expected inversion of the $1/\sqrt{p_T}$ dependence

Roy A. Lacey, Stony Brook University; CIPANP, May 29th - June 3rd, 2012
Scaling of high-pT $v_2$

\[ R_{AA}(p_T, L) \sim \exp \left[ -\frac{2\alpha_s C_F}{\sqrt{\pi}} \frac{L}{\hat{q} \frac{L_i}{p_T}} \right] \]

arXiv:1203.3605

*Combined $\Delta L$ and $1/\sqrt{pT}$ scaling into single universal curve for $v_2$*
Puzzle 2: Why is $v_2(p_T)$ constant?

NB: this means $v_2(p_T)/\langle v_2 \rangle$ independent of $N_{part}, y, \sqrt{s}$
Take home questions

● What causes these empirical scalings?
● Are we measuring the right things?
Summary

- Quantifying the properties of the QGP
- Better understanding of the initial state
- Unprecedented amount of data from RHIC & the LHC to constrain theories
- More to come from data at RHIC & the LHC
Thank you!

Co-convener: Will Horowitz
Plenary speaker: Jamie Nagle
Parallel speakers:
Dan Cebra
Misha Stephanov
Swagato Mukherjee
Rajan Gupta
Grzegorz Stefanek
Bjoern Schenke
David Silvermyr
Magdelena Malek
Sooraj Radhakrishnan
Huichao Song
Michael Strickland
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Monika Sharma
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