Beam Energy Scan at RHIC & z-Scaling

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Contents

- Introduction
- BES at RHIC
- $z$-Scaling (ideas, definitions, properties,...)
- Self-similarity of hadron production in $pp$ & AA
- Energy loss in $pp$ & AA
- Signatures of phase transition & Critical Point
- Conclusions
“Scaling” and “Universality” are concepts developed to understanding critical phenomena. Scaling means that systems near the critical points exhibiting self-similar properties are invariant under transformation of a scale. According to universality, quite different systems behave in a remarkably similar fashion near the respective critical points. Critical exponents are defined only by symmetry of interactions and dimension of the space.

H.Stanley, G.Barenblatt,…

Dense, strongly-coupled matter and an almost perfect liquid with partonic collectivity has been created in HIC at RHIC.


Phase structure of QCD matter is experimentally studied at SPS, RHIC and LHC
The phase diagram of water is established:

- Phases (ice I-XV, liquid, vapor)
- Phase boundaries
- Phase transitions
- Triple Point (16)
- Critical Point (2)

The phase diagram of strongly interacting nuclear matter is under study:

- Phases - ?
- Phase boundaries - ?
- Phase transitions - ?
- Triple Point - ?
- Critical Point - ?
Discontinuity and Smearing near a Critical Point

Heat capacity $\text{H}_2\text{O}$

\[
c_v = -T(\partial^2 G / \partial T^2)_V
\]

$G$ - Gibbs potential

\[
\varepsilon \equiv (T - T_c)/T_c
\]

$\varepsilon$ - scaled temperature

\[
c_v \sim |\varepsilon|^{-\alpha}
\]

$\alpha$ - critical exponent

- Discontinuity of heat capacity near a Critical Point
- Impurities smear the region of localization of a Critical Point
- Region with small energy loss is of most preferable for search for localization of a Critical Point

Nuclear matter at RHIC

New extreme conditions are reached in heavy ion collisions:
- high multiplicity density \( (dN_{\text{ch}}/d\eta \approx 700) \)
- high energy density \( (\varepsilon_{\text{Bj}} \approx 4-5 \text{ GeV/fm}^3) \)
- various types of particles (\( \pi, K, \ldots, \Omega, \ldots \) )
- light nuclei, hypernuclei
The Relativistic Heavy Ion Collider

- 3.83 km circumference
- Two separated rings
- 120 bunches/ring
- 106 ns bunch crossing time
- A+A, p+A, p+p
- Maximum Beam Energy:
  - 500 GeV for p+p
  - 200A GeV for Au+Au
- Luminosity
  - Au+Au: $2 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$
  - p+p: $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- Beam polarizations
  - P=70%

Nucleus-nucleus collisions (AuAu, CuCu, dAu, CuAu, UU, … $\sqrt{s_{NN}}=7.7$-200 GeV)
Polarized proton-proton collisions

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The Solenoid Ttracker At RHIC (STAR)

TPC: full azimuthal coverage
-1.3<\eta<1.3
Uniform acceptance for all beam energies
ToF: full azimuthal coverage
-0.9<\eta<0.9
Low material budget in the tracking volume
STAR Detector

MRPC ToF Barrel
BBC
FPD
pp2pp'
DAQ1000
HLT
HFT
MTD
EMC Barrel
EMC End Cap
FMS
pp2pp'
computing
COMPLETE
Ongoing
R&D
STAR Beam Energy Scan at RHIC

Motivation

- Search for phase transition and critical point of strongly interacting matter
  - Elliptic & directed flow $v_2$, $v_1$
  - Azimuthally-sensitive femtoscopy
  - Fluctuation measures: $<K/\pi>$, $<p/\pi>$, $<p_T>$, $<N_{ch}>$...
- Search for turn-off of new phenomena seen at higher RHIC energies
  - Constituent-quark-number scaling of $v_2$
  - Hadron suppression $R_{AA}$ & $R_{CP}$
  - Ridge ($\Delta\phi$-$\Delta\eta$ correlations)
  - Local parity violation

STAR Collaboration:

An Experimental Exploration of the QCD Phase Diagram: The Search for the Critical Point and the Onset of Deconfinement

arXiv:1007.2613v1 [nucl-ex]
Beam Energy Scan Program at STAR

Central Au+Au @ 7.7 GeV event in STAR TPC

Central Au+Au @ 200 GeV event in STAR TPC

RHIC Beam Energy Scan with Au+Au:
(collider mode)
\[ \sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, 62, 130, 200 \text{ GeV} \]
AuAu Beam Energy Scan at RHIC

Multiplicity distribution

\[ \frac{1}{N_{\text{evts}}} dN/d\eta \]

Uncorrected \( dN/d\eta \) for \(|\eta|<0.5\)

<table>
<thead>
<tr>
<th>( \sqrt{s_{\text{NN}}} ) (GeV)</th>
<th>( \mu_B ) (MeV)</th>
<th>MB Events in Millions</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>550</td>
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<tr>
<td>27</td>
<td>151</td>
<td>70.4</td>
</tr>
<tr>
<td>39</td>
<td>112</td>
<td>130.4</td>
</tr>
</tbody>
</table>

Identified Particle Acceptance at STAR

Homogeneous acceptance for all energies.

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Flow of nuclear matter

Collectivity of partonic degrees of freedom
Number-of- Constituent Quark Scaling

STAR: PRL 95, 122301 (2005)
PHENIX: PRL 98, 162301 (2007)
Directed \((v_1)\) & Elliptic \((v_2)\) flow in AuAu collisions

Coordinate-Space Anisotropy

Momentum-Space Anisotropy

Fourier expansion of the momenta distribution

\[
E \frac{d^3N}{d^3p} \propto \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos n(\phi - \Psi_r) \right)
\]

\[v_n = \langle \cos n(\phi - \Psi_r) \rangle\]

\[\phi = \tan^{-1}\left( \frac{P_y}{P_x} \right)\]

- \(v_1 (y)\) sensitive to baryon transport, space momentum correlations and QGP formation.
- \(v_2\) provides the possibility to gain information about the degree of thermalization of the hot, dense medium.
- The breaking of \(v_2\) number of quark scaling will indicate a transition from partonic to hadronic degrees of freedom.

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Flow vs. energy, centrality, particle mass

$v_2$ of light nuclei scaled to the number of constituent quarks (NCQ) of their constituent nucleons, are consistent with NCQ scaled $v_2$ of baryons and mesons

NCQ scaling holds good for $v_2$ of light nuclei in Au+Au 39 GeV

C.Jena, CPOD 2011, November 7-11, Wuhan, China
BES @ NCQ scaling of $v_2$

Scaled elliptic flow vs. scaled kinetic energy

- Universal trend for most of particles
- $\phi$ meson $v_2$ indicates strange quark collectivity becomes weaker with decreasing beam energy
- Difference of $v_2(p_T)$ between particles and antiparticles.

AuAu @ 7.7, 11.5, 19.6, 27, 39

S.Shi, CPOD, November 7-11, 2011, Wuhan, China
H.Masui, Moriond QCD and High Energy Interactions, March 10-17, 2012
Spectra

probing QCD phase diagram
with identified particles: $\pi^{+/-}$, $K^{+/-}$ and $\overline{p}/p$
in STAR BES-I
**π⁺⁻, K⁺⁻ and ℓ⁻/ℓ⁺ spectra in AuAu**

**Au+Au @ 39 GeV**

- BES spectra obtained with TPC and TOF:
  - Consistent with dE/dx in overlapping range
$\pi^{+/−}$, $K^{+/−}$ spectra in AuAu

Spectra of identified particle up to 1.5 GeV/c.

L. Kumar ICPAQGP, 2010

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Spectra

probing QCD phase diagram
with identified strange particles: $\varphi$, $K_S^0$, $\Lambda$, $\Xi$, $\Omega$
in STAR BES-I
Spectra from $\varphi \rightarrow K^+K^-$ decay channel

Transverse momentum spectra are well described by the Levy function with parameters $T$ & $n$

$$
\frac{1}{2\pi p_T} \frac{d^2 N}{dp_T dy} = \frac{dN/dy}{2nT(nT+m(n-2))} \left(1 + \frac{\sqrt{p_T^2 + m^2 - m}}{nT}\right)^{-n}
$$
Spectra of $K_S^0$, $\Lambda$, $\Xi$ particles & AuAu, 7.7 GeV

$\sqrt{s}=7.7$ GeV

$\Lambda$ spectra are weak decay feed-down corrected:
- $\sim 11\%$ for $\Lambda$
- $\sim 35\%$ for anti-$\Lambda$

Spectra vs. collision energy, centrality, transverse momentum
Spectra of $K_S^0$, $\Lambda$, $\Xi$ particles & AuAu, 11.5 GeV

$\sqrt{s}=11.5$ GeV

$\Lambda$ spectra are weak decay feed-down corrected:

$\sim 15\%$ for $\Lambda$

$\sim 27\%$ for anti-$\Lambda$

Spectra vs. collision energy, centrality, transverse momentum
Spectra of $K_S^0$, $\Lambda$, $\Xi$ particles & AuAu, 39 GeV

$\sqrt{s}=39$ GeV

$\Lambda$ spectra are weak decay feed-down corrected:
~ 20% for $\Lambda$
~ 25% for anti-$\Lambda$

Spectra vs. collision energy, centrality, transverse momentum

X.Zhu, CPOD 2011, November 7-11, 2011, China

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Spectra of strange baryons $\Omega$, $\bar{\Omega}$

Strangeness vs. energy, centrality,…
Dependence of signature of phase transition near a Critical Point over a range $\sqrt{s_{NN}} = 7.7$-39 GeV on flavor.

F. Zhao, APS, DNP, 2011, October 26-29, East Lansing, USA

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Charged hadron spectra in AuAu & 7.7-62.4 GeV

Central

Peripheral

 Peripheral spectra show stronger dependence on beam energy
Nuclear modification factor $R_{CP}$ & AuAu, 7.7-200 GeV

- Lower energies strongly enhancement
- Suppression for $\sqrt{s_{NN}} \geq 39$ GeV
- Ratio for $h^-$ & $h^+$ vs. $p_T$ & $\sqrt{s_{NN}}$
- Feed-down corrections

Expectation of BES:
Large suppression at $\sqrt{s_{NN}} = 200$ GeV is attributed for QGP
Smaller and shorter-lived QGP at lower beam energy
Nuclear modification factor $R_{CP}$ & AuAu, 7.7-39 GeV

STAR results from the RHIC Beam Energy Scan-I

Identified particles

The QCD signature turned off?

L. Kumar (for the STAR Collaboration)
Nuclear Physics A 904–905 (2013) 256–263
Thermo and Blast Wave Models

Phase diagram of nuclear matter

- Higher $T_{ch}$ lower chemical potential $\mu_B$
- Higher centrality higher $T_{ch}$ and $\mu_B$

- Higher $T_{kin}$ lower average flow velocity $\langle \beta \rangle$ and vice versa
- Higher centrality lower $T_{kin}$ and larger $\langle \beta \rangle$

L. Kumar (for the STAR Collaboration)
STAR Beam Energy Scan Phase I - completed

- signatures for a phase transition
- signatures for a critical point
- boundary of phase diagram

Almost equidistant steps in $T_{ch}$–$\mu_B$ plane

AuAu @ 7.7, 11.5, 19.6, 27, 39 and 39 GeV + 62 & 200 GeV

<table>
<thead>
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<tr>
<td>62.4</td>
<td>73</td>
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<tr>
<td>200</td>
<td>24</td>
<td>&gt;500</td>
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</tbody>
</table>
z-Scaling

Self-similarity of hadron production
Universality of flavour formation
Power law in soft and hard regions
Inclusive cross sections of $\pi^-$, $K^-$, $\bar{p}$, $\Lambda$ in pp collisions

FNAL:
PRD 75 (1979) 764

ISR:
NPB 100 (1975) 237
PLB 64 (1976) 111
NPB 116 (1976) 77
(low $p_T$)
NPB 56 (1973) 333
(small angles)

STAR:
PLB 616 (2005) 8
PLB 637 (2006) 161
PRC 75 (2007) 064901

Scaling – “collapse” of data points onto a single curve.
Scaled particle yield ($\Psi$) vs. scaled variable ($z$).
Universality classes – hadron species ($\varepsilon_F$, $\alpha_F$).

- Energy & angular independence
- Flavor independence ($\pi$, $K$, $\bar{p}$, $\Lambda$)
- Saturation for $z < 0.1$
- Power law $\Psi(z) \sim z^{-\beta}$ for high $z > 4$

MT & I. Zborovsky
T. Dedovich
J. Mod. Phys. 3, 815 (2012)
Goals in $z$-scaling approach

Development of $z$-scaling approach for description of hadron production in inclusive reactions to search for signatures of new state of nuclear matter (phase transitions, critical point, …).

Analysis of $AA$ experimental data obtained at RHIC & SPS to verify properties of $z$-scaling observed in $pp$ & $p\bar{p}$ collisions at U70, ISR, S$p\bar{p}$S, SPS and Tevatron.

Estimation of constituent energy loss in central $AA$ collisions vs. collision energy, centrality, transverse momentum over the range $\sqrt{s_{NN}} = 7.7-200$ GeV.

Search for irregularities in dependence of “specific heat” $c$, fractal dimensions $\delta, \varepsilon$ on $\sqrt{s_{NN}}$, centrality and $p_T$. 
Principles: locality, self-similarity, fractality

Locality: collisions of hadrons and nuclei are expressed via interactions of their constituents (partons, quarks and gluons,...).

Self-similarity: interactions of the constituents are mutually similar.

Fractality: the self-similarity over a wide scale range.

Hypothesis of \( z \)-scaling:

Inclusive particle distributions can be described in terms of constituent sub-processes and parameters characterizing bulk properties of the system.

\[
\frac{Ed^3\sigma}{dp^3} \quad \text{Scaled inclusive cross section of particles depends in a self-similar way on a single scaling variable } z.
\]
Locality of hadron interactions

Constituent subprocess

\((x_1M_1) + (x_2M_2) \Rightarrow (m_1/y_a) + (x_1M_1 + x_2M_2 + m_2/y_b)\)

Kinematical condition (4-momentum conservation law):

\((x_1P_1 + x_2P_2 - p/y_a)^2 = M_X^2\)

Recoil mass: \(M_X = x_1M_1 + x_2M_2 + m_2/y_b\)
$z$ as self-similarity parameter

$z = z_0 \cdot \Omega^{-1}$

$z_0 = \frac{s_{\perp}^{1/2}}{(dN_{\text{ch}}/d\eta|_0)^c m}$

- $\Omega^{-1}$ is the minimal resolution at which a constituent subprocess can be singled out of the inclusive reaction
- $s_{\perp}^{1/2}$ is the transverse kinetic energy of the subprocess consumed on production of $m_1$ & $m_2$
- $dN_{\text{ch}}/d\eta|_0$ is the multiplicity density of charged particles at $\eta = 0$
- $c$ is a parameter interpreted as a “specific heat” of created medium
- $m$ is an arbitrary constant (fixed at the value of nucleon mass)
Fractality is reflected in the definition of \( z \)

\[
z = z_0 \Omega^{-1}
\]

\[
\Omega = (1 - x_1)^\delta_1 (1 - x_2)^\delta_2 (1 - y_a)^\varepsilon_a (1 - y_b)^\varepsilon_b
\]

\( \Omega \) is relative number of the configurations containing the sub-process with fractions \( x_1, x_2, y_a, y_b \) of the corresponding 4-momenta

\( \delta_1, \delta_2, \varepsilon_a, \varepsilon_b \) characterize fractal structure of the colliding objects and fragmentation process, respectively

\( \Omega^{-1}(x_1, x_2, y_a, y_b) \) characterizes resolution at which a constituent sub-process can be singled out of the inclusive reaction

\[
\left. z(\Omega) \right|_{\Omega^{-1} \to \infty} \to \infty
\]

The fractal measure \( z \) diverges as the resolution \( \Omega^{-1} \) increases.
Momentum fractions $x_1$, $x_2$, $y_a$, $y_b$

**Principle of minimal resolution:** The momentum fractions $x_1$, $x_2$ and $y_a$, $y_b$ are determined in a way to minimize the resolution $\Omega^{-1}$ of the fractal measure $z$ with respect to all constituent sub-processes taking into account 4-momentum conservation:

$$\Omega = (1 - x_1)^\delta_1 (1 - x_2)^\delta_2 (1 - y_a)^\varepsilon_a (1 - y_b)^\varepsilon_b$$

$$\begin{align*}
\frac{\partial \Omega}{\partial x_1} \bigg|_{y_a = y_a(x_1, x_2, y_b)} &= 0 \\
\frac{\partial \Omega}{\partial x_2} \bigg|_{y_a = y_a(x_1, x_2, y_b)} &= 0 \\
\frac{\partial \Omega}{\partial y_b} \bigg|_{y_a = y_a(x_1, x_2, y_b)} &= 0
\end{align*}$$

**Momentum conservation law**

$$(x_1 p_1 + x_2 p_2 - p/y_a)^2 = M_X^2$$

**Recoil mass**

$$M_X = x_1 M_1 + x_2 M_2 + m_2/y_b$$
The scaling function $\Psi(z)$ is probability density to produce an inclusive particle with the corresponding $z$. 

$$\Psi(z) = \frac{\pi}{(dN/d\eta) \cdot \sigma_{\text{inel}}} \cdot J^{-1} \cdot E \frac{d^3\sigma}{dp^3}$$

$$\int_0^\infty \Psi(z) dz = 1$$

$z \rightarrow \alpha_F z$, \hspace{1em} $\Psi \rightarrow \alpha_F^{-1} \Psi$

$\int E \frac{d^3\sigma}{dp^3} dy d^2p_{\perp} = \sigma_{\text{inel}} \cdot N$

- $\sigma_{\text{in}}$ - inelastic cross section
- $N$ - average multiplicity of the corresponding hadron species
- $dN/d\eta$ - pseudorapidity multiplicity density at angle $\theta$ ($\eta$)
- $J(z,\eta;p_T^2,y)$ - Jacobian
- $Ed^3\sigma/dp^3$ - inclusive cross section
Properties of $\Psi(z)$ in $pp$ & $\bar{p}p$ collisions

- Energy independence of $\Psi(z)$ ($s^{1/2} > 20$ GeV)
- Angular independence of $\Psi(z)$ ($\theta_{cms}=3^0-90^0$)
- Multiplicity independence of $\Psi(z)$ ($dN_{ch}/d\eta=1.5-26$)
- Power law, $\Psi(z) \sim z^{-\beta}$, at high $z$ ($z > 4$)
- Flavor independence of $\Psi(z)$ ($\pi,K,\varphi,\Lambda,...,D,\psi,J/B,\gamma,...,\text{top}$)
- Saturation of $\Psi(z)$ at low $z$ ($z < 0.1$)

These properties reflect self-similarity, locality, and fractality of the hadron interaction at constituent level. It concerns the structure of the colliding objects, interactions of their constituents, and fragmentation process.

M.T. & I.Zborovsky
Phys.At.Nucl. 70,1294(2007)
J.Mod.Phys.3,815(2012)

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z-Scaling & Heavy Ion Collisions

**z-Scaling reflects** self-similarity, locality and fractality of particle production at a constituent level. The variable $z$ is a self-similarity parameter.

New tool in searching for signatures of new state of nuclear matter created in HIC at high energy and high multiplicity density (phase transition, critical point, QGP…)

- Scaling in $pp$ / $\bar{p}p$ collisions is a reference frame for $AA$ collisions.
- Observed scaling features in $AA$ are sensitive characteristics of nuclear matter and signatures of new medium created in HIC.
- Change of parameters of $z$-scaling can indicate a phase transition.

Analysis of experimental data on charged hadrons produced in $AuAu$ collisions at $\sqrt{s_{NN}} = 7.7$-200 GeV at RHIC to search for CP & estimation of particle energy loss.
Self-similarity parameter $z$ in AA collisions

$$z = z_0 \Omega^{-1}$$

$$z_0 = \frac{S_{\perp}^{1/2}}{(dN_{ch}/d\eta|_0)^{c} m_N}$$

$$\Omega = (1 - x_1)^{\delta_{A1}} (1 - x_2)^{\delta_{A2}} (1 - y_a)^{\varepsilon} (1 - y_b)^{\varepsilon}$$

**Ingredients of $z$ characterizing AA collisions:**

- $dN_{ch}/d\eta|_0$ - multiplicity density in AA collisions
- $c$ - “specific heat” in AA collisions
- $\delta_A$ - nucleus fractal dimension
- $\varepsilon$ - fragmentation dimension in AA collisions

These quantities characterize properties of medium created in AA collisions.

**Additivity of fractal dimensions $\delta_A$ in pA collisions:**

consistent with $z$-scaling in pD, pBe, pTi, pW collisions

$$\delta_A = A \delta$$

**Additivity of fractal dimensions $\delta_A$ in AA collisions:**

$$\delta_{A1} = A_1 \delta \quad \& \quad \delta_{A2} = A_2 \delta$$

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Energy scan of spectra in AuAu collisions

\[ \pi^- \text{ in AuAu at 9.2 & 63, 200 GeV} \]

Saturation of \( \Psi(z) \) for \( z < 0.1 \)

Power law for \( z > 4 \)

Centrality dependence of \( \Psi(z) \) at high \( z \)

Fractal dimension \( \varepsilon \) depends on centrality:

\[ \varepsilon_{AuAu} = \varepsilon_0 (dN_{ch}/d\eta) + \varepsilon_{pp} \]
High-$p_T$ Spectra of Charged Hadrons in Au+Au Collisions at $\sqrt{s_{NN}} = 9.2$ GeV in STAR

STAR test Run 2008

Data sample (2008)
~ 4000 events

- High-$p_T$ spectra vs. centrality
- $R_{CP}$ ratio vs. $p_T$
- Energy loss vs. $p_T$, $dN/d\eta$


STAR: PRC 81 (2010) 024911

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Energy loss vs. energy, centrality, $p_T$

$\pi^-$ in AuAu at 9.2 & 200 GeV

- $y_a$ increases with $p_T$ $\Rightarrow$ energy loss decreases with $p_T$
- $y_a$ decreases with centrality $\Rightarrow$ energy loss increases with centrality
- $x_1$ is independent of centrality at 9.2 GeV
- $M_X$ increases with $p_T$, $\sqrt{s_{NN}}$ and centrality

Smaller energy loss $\Rightarrow$ better localization of a Critical Point
Cumulative region ($A_1x_1 > 1$) is most preferable to search for a Critical Point
Momentum fractions $x_1$, $y_a$ & recoil mass $M_X$

**STAR**

$\pi^-$ in AuAu at 62.4 GeV

$M_X = x_1 M_1 + x_2 M_2 + m_2/y_b$

- $p_T$ dependence of $x_1$ is dependent of centrality
- $y_a$ increases with $p_T \Rightarrow$ energy loss decreases with $p_T$
- $y_a$ decreases with centrality $\Rightarrow$ energy loss increases with centrality
- $M_X$ increases with $p_T$, $s^{1/2}$ and centrality

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Momentum fractions $x_1$, $y_a$ & recoil mass $M_X$

**NA49**

**$\pi^{-}$ in PbPb at 17.3 GeV**

$M_X = x_1 M_1 + x_2 M_2 + m_2 / y_b$

- $p_T$ dependence of $x_1$ is dependent of centrality
- $y_a$ increases with $p_T$ $\Rightarrow$ energy loss decreases with $p_T$
- $y_a$ decreases with centrality $\Rightarrow$ energy loss increases with centrality
- $M_X$ increases with $p_T$, $s^{1/2}$ and centrality

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Self-similarity in peripheral \textbf{AuAu} collisions

Charged hadrons in \textbf{pp} & \textbf{AA} @ 63, 130, 200 GeV

- The energy independence of $\Psi(z)$ in peripheral \textbf{AuAu}
- The same shape of $\Psi(z)$ for \textbf{pp} & peripheral \textbf{AuAu}
- “Specific heat” $c_{\text{AuAu}} = 0.11 < c_{\text{pp}} = 0.25$
- The same $\varepsilon$ in \textbf{pp} & peripheral \textbf{AuAu}

\textbf{pp} collisions:
\[ \frac{dN_{\text{ch}}}{d\eta}|_0 \] for non-single-diffractive events

\textbf{AA} collisions:
\[ \frac{dN_{\text{ch}}}{d\eta}|_0 \] for corresponding AA centrality

\begin{itemize}
  \item ISR: NPB 208 (1982) 1
  \item STAR: PRL 89 (2002) 202301; PRL 91 (2003) 172302
  \item PHOBOS: PRL 94 (2005) 082304
\end{itemize}

\[
\begin{align*}
\Psi(z) & \sim s^{1/2} (\text{GeV}) \\
\text{Au+Au} & \rightarrow h^\pm + X \\
\text{p+p} & \rightarrow h^\pm + X
\end{align*}
\]
Fragmentation dimension $\varepsilon_{AA}$ vs. centrality

Charged hadrons in central AuAu collisions at 200 GeV

Centrality dependence (decrease) of $\Psi(z)$ in central AuAu collisions for $\varepsilon_{AuAu} = \varepsilon_{pp}$

- The same $\Psi(z)$ in pp & AuAu for all centralities
- Dimension $\varepsilon_{AuAu}$ depends on multiplicity
- “Specific heat” $c_{AuAu} = 0.11$ for all centralities

Multiplicity dependence of fragmentation process in HIC
Self-similarity in AuAu collisions

Charged hadrons in pp & AuAu @ 62, 130 GeV

- The same $\Psi(z)$ in AuAu & pp for $\varepsilon_{\text{AuAu}}$ is dependent of AuAu multiplicity
- "Specific heat" $c_{\text{AuAu}}=0.11$ (constant with $s^{1/2}$)
- $\varepsilon_0$ increases with $s^{1/2}$: $\varepsilon_0(62\text{GeV})=0.0018 < \varepsilon_0(130\text{GeV})=0.0022 < \varepsilon_0(200\text{GeV})=0.0028$

Restoration of self-similarity in central AuAu collisions
Energy loss $\Delta E/E \sim (1 - y_a)$

- $y_a$ increases with $p_T$ ⇒ energy loss decreases with $p_T$
- $y_a$ decreases with $s^{1/2}$ ⇒ energy loss increases with $s^{1/2}$
- $y_a$ decreases as centrality increases ⇒ energy loss increases with centrality
- $y_b$ is flat with $p_T$ ⇒ week dependence of $M_X$ on $p_T$
- $y_b << y_a$ for $p_T > 1$ GeV/c ⇒ soft (high multiplicity) recoil $M_X$

**PHOBOS**
- $h^\pm$
- $s^{1/2} = 62$ GeV
- $0.2 < \eta < 1.4$
- $40\%$ energy loss $q = 6.6$ GeV
- $55\%$ energy loss $q = 8.8$ GeV
- $75\%$ energy loss $q = 16$ GeV

**STAR**
- $h^\pm$
- $s^{1/2} = 200$ GeV
- $|\eta| < 0.5$
- $65\%$ energy loss $q = 11.4$ GeV
- $75\%$ energy loss $q = 16$ GeV
- $90\%$ energy loss $q = 40$ GeV
Energy scan of spectra in AuAu collisions

Charged hadrons in central AuAu collisions at 200, 130, 62.4, 9.2 GeV

STAR: PRL 89 (2002) 202301
PRL 91 (2003) 172302
arXiv:1004.5582

$\pi$ at SPS & RHIC

MT & I.Zborovskiy

- Energy scan of the spectra: $\sqrt{s_{NN}} = 9 - 200$ GeV
- Centrality dependence of the spectra at high $p_T$
- Power law for all centralities for $p_T > 2$ GeV/c
- Fragmentation ($\varepsilon$) depends on centrality

Change of the parameters $c, \delta, \varepsilon \Rightarrow$ indication on new properties of matter
Discontinuity of the parameters $c, \delta, \varepsilon \Rightarrow$ indication of existence of CP

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Charged hadrons in central AuAu collisions

Spectra in $z$ presentation - two scenarios

I. Large specific heat $c$ & large $\delta$

II. Small specific heat $c$ & small $\delta$

The same $\Psi(z)$ for all centralities & energy (universality)

$\varepsilon_{AuAu}$ depends on multiplicity density

Scenarios of interaction: large / small “specific heat”

Correlation of $c$, $\varepsilon$, $\delta$

Centrality dependence of the spectra constraints $c$

Different scenarios in high-$z$ range ($p_T > 6$ GeV/c)

$z = \frac{S^{1/2}}{(dN_{ch}/d\eta|_0)c m_N} \cdot \Omega^{-1}$

$\Omega = (1 - x_1)^{\delta_A} (1 - x_2)^{\delta_A} (1 - y_a)^{\varepsilon} (1 - y_b)^{\varepsilon}$

$\delta_A = A \delta$
Energy loss in AuAu collisions $\Delta E/E \sim (1-y_a)$

Momentum fractions $y_a, y_b$ in different scenarios

I. Large specific heat $c$ & large $\delta$: $c=0.23, \delta=0.5$
II. Small specific heat $c$ & small $\delta$: $c=0.11, \delta=0.11$

- $y_a$ increases with $p_T$ $\Rightarrow$ energy loss decreases with $p_T$
- $y_a$ decreases with $\sqrt{s_{NN}}$ $\Rightarrow$ energy loss increases with $\sqrt{s_{NN}}$
- $y_a$ decreases as centrality increases $\Rightarrow$ energy loss increases with centrality
- $y_b$ is flat with $p_T$ $\Rightarrow$ weak dependence of $M_X$ on $p_T$
- $y_b << y_a$ for $p_T > 1$ GeV/c $\Rightarrow$ soft (high multiplicity) recoil $M_X$

Energy loss ($c=0.23, \delta=0.5$) $< \text{Energy loss (c=0.11,}\, \delta=0.15$)
Smaller energy loss $\Rightarrow$ better localization of a Critical Point.....
Momentum fraction $x_1 A_1$ in AuAu collisions

Different scenarios

I  Large specific heat $c$ & large $\delta$: $c=0.23$, $\delta=0.5$
II  Small specific heat $c$ & small $\delta$: $c=0.11$, $\delta=0.11$

> Cumulative region at $p_T > 2.5$ GeV/c
> Smaller energy loss
> Not smeared sub-structure

> Cumulative region at $p_T > 1.5$ GeV/c
> Larger energy loss
> Smeared sub-structure

Smaller energy loss $\Rightarrow$ better localization of a Critical Point
Cumulative region ($x_1 A_1 > 1$) is most preferable to search for a Critical Point

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Recoil mass $M_X$

Recoil mass in different scenarios

I. Large specific heat $c$ & large $\delta$: $c=0.23$, $\delta=0.5$
II. Small specific heat $c$ & small $\delta$: $c=0.11$, $\delta=0.11$

$M_X = x_1 M_1 + x_2 M_2 + m/y_b$

- Cumulative region at $p_T > 2.5$ GeV/c
- Smaller energy loss
- Not smeared sub-structure
- Smaller multiplicity in the way-side

$M_X$ increases with $p_T$, $\sqrt{s_{NN}}$, centrality due to decrease of the fraction $y_b$
Constituent energy loss & $z$-scaling

MC UrQMD

Multiplicity dependence of energy loss $\Delta E/E \sim (1-y_a)$

$\Delta E$ – constituent energy loss, $E(q)$ – constituent energy (momentum)

$y_a$ – constituent energy fraction carried away by inclusive particle.

Small energy loss $\rightarrow$ better localization of a Critical Point.

- Energy loss increases with energy and centrality and decreases as transverse momentum $p_T$ increases.

- High-$p_T$ region ($>4$ GeV/c) at $\sqrt{s_{NN}} = 5-40$ GeV is more preferable for search for phase transition and a Critical Point.

20% energy loss
$p_T = 5$ GeV/c
$q \approx 6.3$ GeV/c

30% energy loss
$p_T = 3$ GeV/c
$q \approx 4.3$ GeV/c

50% energy loss
$p_T = 1$ GeV/c
$q \approx 2$. GeV/c

STAR
PRL 91 (2003) 172302
Phys.At.Nucl.74 (2011) 799

z-Scaling
M. Tokarev
I.Zborovsky
PRD 75(2007) 094008
IJMPA 24 (2009) 1417

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Constituent energy loss & z-scaling

**MC UrQMD**

Energy loss $\frac{\Delta E}{E} \sim (1 - y_a)$ vs. $\sqrt{s}$ & $p_T$

- **20% energy loss**
  - $q \approx 5$ GeV/c

- **20% energy loss**
  - $q \approx 7.5$ GeV/c

- **30% energy loss**
  - $q \approx 8.5$ GeV/c

- **35% energy loss**
  - $q \approx 15.3$ GeV/c

- **40% energy loss**
  - $q \approx 16.7$ GeV/c

**Constituent energy loss decreases with $p_T$, increases with $s^{1/2}$ and centrality**

$q$ - momentum of scattered constituent

$p_T$ - transverse momentum of produced hadron

A. Aparin (2012)
Possible signatures of phase transition and Critical Point:

Constituent energy loss is a characteristic of nuclear matter (QGP)

- Smaller energy loss ➔ better localization of a Critical Point
- High-$p_T$ region is most preferable kinematical region to search for a Critical Point.
- Collision energy $\sqrt{s_{NN}}$ should be not so high.

- **Discontinuity** of the parameters:
  - “specific heat”- $c$, fractal dimension – $\delta$
- **Enhancement** of $c-\delta$ correlations
- **Energy loss** is a contamination factor leading to the smearing of the phase transition

↓

Study of high-$p_T$ hadron spectra in AA could give new information on collective phenomena

M.Tokarev
Conclusions

- Some of STAR results from RHIC Beam Energy Scan-I were reviewed.
- Results of analysis of spectra of charged hadrons produced in AuAu collisions at $\sqrt{s_{NN}} = 200, 130, 62.4, 9.2$ GeV in the $z$-scaling approach were presented and discussed.
- We argue that $z$-scaling reflects the self-similarity, locality and fractality of hadron interactions at a constituent level.
- Two microscopic scenarios of hadron production were discussed.
- The constituent energy loss in AuAu collisions in terms of the momentum fractions were estimated. Its dependence on collision energy, centrality, and momentum of produced hadron was discussed.
- Discontinuity of $c, \delta, \varepsilon$ as a possible signatures of phase transition was suggested.
- RHIC data on charged particle spectra at high-$p_T$ from BES-I at $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39$ GeV are keenly awaited.

The obtained results may be of interest in searching for a Critical Point and signatures of phase transition in hadron matter produced at SPS, RHIC, LHC in present and FAIR & NICA in future.
Thank You For Attention!
Back-up Slides
Regularities in high energy interactions

- $x_{\text{Bj}} = -q^2 / 2(Pq)$  
  Bjorken scaling

- $x_F = p_{||}^*/p_{||\text{max}}^*$  
  Feynman scaling

- $n / <n>$  
  Polyakov-Koba-Nielsen-Olesen scaling

- $t, s, u$  
  Matveev-Muradyan-Tavkhelidze-Brodsky-Farrar
  Quark Counting Rules

- These scaling regularities have restricted range of validity.
- Violation of the scaling laws can be indication of new physics.

New regularity - $z$-Scaling
Universal description of inclusive particle cross sections
over a wide kinematical region
(central+fragmentation region, $p_T > 0.5$ GeV/c, $s^{1/2} > 20$ GeV)

$z$-Scaling reveals self-similar properties in hadron, jet
and direct photon production in high energy hadron and nucleus collisions.
Variable $z$ & Entropy $S$

$$z = z_0 \Omega^{-1}$$

$$z_0 = \frac{S_{\perp}^{1/2}}{(dN_{\text{ch}}/d\eta|_0)^c m_N}$$

$$\Omega = (1-x_1)^{\delta_1} (1-x_2)^{\delta_2} (1-y_a)^\varepsilon (1-y_b)^\varepsilon$$

- relative number of such constituent configurations which contain the configuration $\{x_1, x_2, y_a, y_b\}$

**Statistical entropy:**

$$S = \ln W$$

**Thermodynamical entropy for ideal gas:**

$$S = c_V \ln T + R \ln V + S_0$$

$$S = c \cdot \ln (dN_{\text{ch}}/d\eta|_0) + \ln[(1-x_1)^{\delta_1} (1-x_2)^{\delta_2} (1-y_a)^\varepsilon (1-y_b)^\varepsilon] + \ln W_0$$

- $dN_{\text{ch}}/d\eta|_0$ characterizes “temperature” of the colliding system.
- Provided local equilibrium, $dN_{\text{ch}}/d\eta|_0 \sim T^3$ for high temperatures and small $\mu$.
- $c$ has meaning of a “specific heat” of the produced medium.
- Fractional exponents $\delta_1, \delta_2, \varepsilon$ are fractal dimensions in the space of $\{x_1, x_2, y_a, y_b\}$.
- Entropy increases with $dN_{\text{ch}}/d\eta|_0$ and decreases with increasing resolution $\Omega^{-1}$.

Maximal entropy $S \iff$ minimal resolution $\Omega^{-1}$ of the fractal measure $z$
- signatures for a phase transition
- signatures for a critical point
- boundary of phase diagram

BES phase II will start soon (2015-2017)

\[ \sqrt{s_{NN}} = 2.5 - 19.6 \text{ GeV} \]