Particle production from ee to AA 
and search for the QCD Critical Point with PHENIX

Máté Csanád (Eötvös University, Budapest) 
for the PHENIX Collaboration
and for Roy L. et al (the authors of arXiv:1601.06001)

54th International School of Subnuclear Physics, Erice, Sicily, 2016

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Particle production mechanisms from ee to AA

- A+A(B) collisions: frequently described with thermo/hydrodynamics

- Model ingredients: macroscopic variables (temperature, entropy)
  see e.g. W. Kittel and E. A. DeWolf, Soft Multihadron Dynamics, (World Scientific, 2005)
  or recent PHENIX, PHOBOS, STAR, ALICE, CMS and ATLAS papers

- Microscopic phenomenology used in $e^- + e^+$, $e^\pm + p$, $p(\bar{p}) + p$ or $p + A$

- Perturbative gluon exchange, gauge fields, strings, partons
  see e.g. Kharzeev et al., NPA747; Armesto et al., PRL94, Dusling et al., PRD87
  and other references in arXiv:1601.06001

- Similarity in particle production $\iff$ available $E_{\text{eff}}$ for part. production
  Sarkisyan and Sakharov, hep-ph/0410324

\[
\kappa_1 \sqrt{s_{\text{ee}}} \approx \kappa_2 \sqrt{s_{\text{pp}}} \approx \kappa_3 \sqrt{s_{\text{ep}}} \quad \text{with } \kappa_1 \equiv 1
\]  

- Role of quark participant pairs in pp, pA and AA describing initial stage

- What do the measurements tell us?
\[ \langle N_{\text{ch}} \rangle \text{ vs. } \sqrt{s} \text{ scaling in } e^- + e^+, \ p(\bar{p}) + p \text{ and } e^\pm + p \]

- Entropy ansatz: \( S \sim (TR)^3 \), \( dN_{\text{ch}}/d\eta \) and \( \langle N_{\text{ch}} \rangle \sim S \)
- Initial stage variable \( N_{pp} \) number of participant pairs (\( N_{pp} = 1 \) here)
- Global assumption: \( N_{pp}^{1/3} \propto R \)
- Simple result:
  \[ \left[ \langle N_{\text{ch}} \rangle / N_{pp} \right]^{1/3} \sim T \sim \langle p_T \rangle \]
- Scaling versus \( \kappa_n \sqrt{s} \)
- Fit result:
  \[ \langle N_{\text{ch}} \rangle = \left[ b_{\langle N_{\text{ch}} \rangle} + m_{\langle N_{\text{ch}} \rangle} \log(\kappa_n \sqrt{s}) \right]^3 \]
  \[ b_{\langle N_{\text{ch}} \rangle} = 1.22 \pm 0.01 \]
  \[ m_{\langle N_{\text{ch}} \rangle} = 0.775 \pm 0.006 \]

See details and references in Lacey et al., arXiv:1601.06001
Quark participant scaling from pp through pA to AA

- Initial stage size measure: $N_{pp}$
- Use quark participant pairs $N_{qpp}$
- Recall $[(dN_{\text{ch}}/d\eta)/N_{qpp}]^{1/3} \sim T$
- Flat size ($N_{qpp}$) dependence
- Strikingly similar $\sqrt{s_{NN}}$ trends for p+p and A+A(B) collisions
- Common production mechanism?
- Small deviation for $\lesssim 2$ TeV
- Smooth trend over full range
- Details in Lacey et al., arXiv:1601.06001
- When does QGP production start?
- Phases of QCD?
Emergent QCD phenomena

Exploring the QCD phase diagram

- QCD: fundamental theory mostly understood
- Emergent phenomena (phases, nucleons, etc): hard to handle
- Important part of the phase diagram: RHIC energies!
The PHENIX Experiment at RHIC

- RHIC collisions: versatile in energy, 5-500 GeV/nucleon
- Versatile in colliding nuclei: p, d, Cu, Au, Al, He, U
- Tracking via Drift Chambers & Pad Chambers
- PID via time of flight from TOF & EMCal
- Momentum resolution: $\delta p/p \approx 1.3\% \oplus 1.2\% \times p$ GeV/c
- Charged pion ID from $p \approx 0.18$ to 2 GeV/c
The RHIC Beam Energy Scan

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- p+p
- Au+Au
- d+Au
- Cu+Cu
- U+U
- Cu+Au
- He+Au
- p+Au
- p+Al

Introduction to Bose-Einstein correlations

- In case of free bosons, momentum correlation function:
  \[ C_2(q) \simeq 1 + \left| \frac{\tilde{S}(q)}{\tilde{S}(0)} \right|^2 \], \( \tilde{S}(q) = \int S(x)e^{iqx}d^4x, \quad q = p_1 - p_2 \)  

- Final state interactions distort the simple Bose-Einstein picture
- Coulomb interaction important, handled via two-particle wave function
- Resonance pions: Halo around primordial Core
- Halo part unresolvable

Lévy shaped source and the Critical Point

- Lévy distributed source and resulting correlation function:

\[
S(r)_{\alpha, R} = \frac{1}{(2\pi)^3} \int d^3 q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha} \Rightarrow C_2(q) = 1 + \lambda \cdot e^{-(R|q|)^\alpha} \tag{3}
\]

- Parameters: $\lambda, R, \alpha$, may depend on average pair momentum
- Related to anomalous diffusion or generalized random walk
- $\alpha = 2$: Gauss, $\alpha = 1$: Cauchy; power-law tail for $\alpha < 2$
- Levy index $\alpha$ identified with critical exponent $\eta$
  - Spatial correlation function $\propto r^{-(d-2+\eta)} \rightarrow$ critical $\eta$ exponent
  - Symmetric stable distributions (Lévy) $\rightarrow$ spatial corr. $\propto r^{-1-\alpha}$
- QCD universality class $\leftrightarrow$ 3D Ising
- 3D Ising: $\eta = 0.03631(3)$, Random field 3D Ising: $\eta = 0.50 \pm 0.05$
- Change in $\alpha \leftrightarrow$ proximity of CEP
- Motivation for precise Levy HBT
Example correlation function measurement result

Measured in 31 $m_T^2 = m^2 + p_T^2$ bins for $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs

MinBias Au+Au @ $\sqrt{s_{NN}} = 200$ GeV, $\pi^+\pi^+$, $p_T = 0.2-0.22$ GeV/c

$\lambda = 0.72 \pm 0.02$
$R = 8.74$ fm $\pm 0.24$ fm
$\alpha = 1.16 \pm 0.03$
$\epsilon = -0.102 \pm 0.005$
$N = 1.0095 \pm 0.0005$
$\chi^2/NDF = 93/97$
conf. level = 0.5909

Physical parameters: $R, \lambda, \alpha$; measured versus pair $m_T$
Example correlation function measurement result

Measured in 31 $m_T^2 = m^2 + p_T^2$ bins for $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs

Physical parameters: $R, \lambda, \alpha$; measured versus pair $m_T$
Levy scale parameter $R$ versus pair $m_T$

- Similar decreasing trend as usual Gaussian HBT radii
- Hydro behaviour: $1/R^2 \sim m_T$, not incompatible
- Interesting, since simple hydro would mean $\alpha = 2$
Correlation strength $\lambda$ versus pair $m_T$

- From the Core-Halo model: $\lambda = \left(\frac{N_C}{N_C + N_H}\right)^2$
- Large and correlated systematic uncertainties
- Observed decrease at small $m_T \rightarrow$ increase of halo fraction
- May be interesting physics in $\lambda$, strange speculations:
  - Resonance effects, chiral symmetry restoration?
  - Partially coherent pion production?
  - Aharanov-Bohm effect?
Levy exponent $\alpha$ versus pair $m_T$

- Far from Gaussian ($\alpha = 2$) and Cauchy/exponential ($\alpha = 1$)
- Also far from 3D Ising value at CEP ($\alpha \leq 0.5$)
- More or less constant (at least within systematic errors)
- Although the constant fit is statistically not acceptable
- Motivation to do fits with fixed $\alpha = 1.134$
Newly discovered scaling parameter $\hat{R}$

- Empirically found scaling parameter
- Linear in $m_T$
- Physical interpretation $\rightarrow$ open question

MinBias Au+Au @ $\sqrt{s_{NN}} = 200$ GeV

$1/R = \lambda \cdot (1+\alpha)$
Summary

- Scaling of $N_{\text{ch}}$ from ee to AA data from GeV to TeV $\sqrt{s}$ regions
  - Effective energy notation successful
  - Quark participants emerging
  - Special signatures at special energies?

- Search for the QCD critical point at RHIC

- New measurement method of Levy sources developed with PHENIX
  - Levy exponent $\alpha$ at $\sqrt{s_{NN}} = 200$ GeV far from Gaussian or critical values
  - Correlation strength $\lambda$ hints at interesting physics
  - New empirically found scaling parameter $\hat{R}$
Thank you for your attention!

Let me invite You to the 16th Zimanyi Winter School on Heavy Ion Physics
Budapest, Hungary, Dec. 5 – 9, 2016
http://zimanyischool.kfki.hu/16/
Similarities from \( p+p \) through \( p+A \) to \( A+A(B) \)

- Similar charged particle multiplicities (\( N_{\text{ch}} \))
- Similar pseudorapidity densities (\( dN_{\text{ch}}/d\eta \))
- Azimuthal long range (\(|\Delta \eta| \geq 4\)) angular correlations, “ridge”
- Collective anisotropic flow in \( A+A \) collisions
- Also in \( p+p \), \( p+Pb \), \( d+Au \) and \( He+Au \)

ALICE PLB719, ATLAS PRL110, CMS PLB718, PHENIX PRL114, PHENIX PRL115

Qualitative consistency achieved with hydro
See e.g. Bozek, PRC85, the Buda-Lund model from Csörgő et al., NPA661, JPhysG30, EPJA38, . . .

Common underlying particle production mechanism dominating?
Our framework to capture underlying physics

- Macroscopic entropy \((S)\) ansatz
  \[
  S \sim (TR)^3 \sim \text{const.} \quad \text{\quad (4)}
  \]
  \[
  \frac{dN_{\text{ch}}}{d\eta} \quad \text{and} \quad \langle N_{\text{ch}} \rangle \sim S \quad \text{\quad (5)}
  \]

- Initial stage variable \(N_{\text{pp}}\) number of participant pairs
  - \(N_{\text{pp}} = 1\) for \(e^- + e^+, e^\pm + p\) and \(p(\bar{p}) + p\)
  - Nucleon or quark participant pairs \((N_{npp}, N_{qpp})\) in \(p+A, A+A(B)\)

- Further assumption: \(N_{pp}^{1/3} \propto R \Rightarrow [(dN_{\text{ch}}/d\eta)/N_{pp}]^{1/3} \sim T \sim \langle p_T \rangle\)

- Monte Carlo Glauber calculations performed to obtain \(N_{npp}\) and \(N_{qpp}\).

  Lacey et al. PRC83, Eremin et al. PRC67, Bialas et al. PLB649, Nouicer EPJC49, PHENIX PRC89

- Subset of initial particles become participants by an initial inelastic \(N+N\) or \(q+q\) interaction.

- \(N_{np} = 2N_{npp}\) or \(N_{qp} = 2N_{qpp}\)

- \(N+N\ (q+q)\) cross sections taken from literature Fagundes et al, J. Phys. G40
Nucleon participant scaling in A+A(B) collisions

- All systems:
  \[
  \left[ \frac{dN_{\text{ch}}/d\eta}{N_{\text{npp}}} \right]^{1/3} \sim T 
  \]
  (a): \( \propto \log(dN_{\text{ch}}/d\eta) \sim \log S \)
  (b): \( \propto N_{\text{npp}}^{1/3} \sim R \)

  - Logarithmic S-dependence
  - Linear size dependence
  - (at a given \( \sqrt{s_{NN}} \))
  - \( \langle p_T \rangle \) increases with \( \sqrt{s_{NN}} \) and \( \log(dN_{\text{ch}}/d\eta) \)
  - Pseudorapidity density factorizes into contributions depending on \( \sqrt{s_{NN}} \) and \( N_{\text{npp}}^{1/3} \)

- Slope increases with beam energy

- Lack of sensitivity to system type (Cu+Cu, Cu+Au, Au+Au, U+U), for fixed \( \sqrt{s_{NN}} \).
PHENIX Levy HBT analysis

- Dataset: $\sqrt{s_{NN}} = 200$ GeV Au+Au, min. bias, ~7 billion events
- Goal: detailed shape analysis of two-pion correlation functions
  - Correlation functions measured in fine pair $m_T = \sqrt{m^2 + p_T^2}$ bins
  - Levy source instead of Gaussian $\rightarrow$ better agreement with data
  - Precision measurement of source parameters versus pair $m_T$
  - Result: $\lambda_{\text{Levy}}(m_T), \alpha_{\text{Levy}}(m_T), R_{\text{Levy}}(m_T)$
- Tracking: DCH & PC1, 2$\sigma$ matching cuts in TOF & EMCal
- Particle identification:
  - time-of-flight data from EMCal & TOF, momentum, flight length
  - 2$\sigma$ cuts on $m^2$ distribution
- Pair-cuts:
  - Exclude particles hitting the same tower/slat/strip
  - Customary shaped cuts in $\Delta \varphi - \Delta z$ plane for TOF, EMCal, DCH
### Example correlation functions

MinBias Au+Au @ $\sqrt{s_{NN}} = 200$ GeV, $\pi^+\pi^-$, $p_T = 0.48$-0.5 GeV/c

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$\lambda = 1.14 \pm 0.06$

$R = 6.90 \text{ fm} \pm 0.28 \text{ fm}$

$\alpha = 1.09 \pm 0.03$

$\varepsilon = -0.025 \pm 0.001$

$N = 1.0015 \pm 0.0001$

$\chi^2$/NDF = 295/251

Conf. level = 0.0293

$C_{\text{Levy}}^{0}(\lambda, R, \alpha; |k|) \times N(1+\varepsilon|k|)$

$C_{\text{Levy}}^{0}(\lambda, R, \alpha; |k|) \times N(1+\varepsilon|k|)$

$C_{\text{Levy}}^{0} = (1+\lambda \cdot \exp(-2 \cdot R \cdot |k|^{\alpha})) \times N(1+\varepsilon|k|)$

PHENIX
preliminary

Máté Csanád (Eötvös University) 54th ISSP, Erice, 2016
Example correlation functions

MinBias Au+Au @ $\sqrt{s_{NN}} = 200$ GeV, $\pi^+\pi^+$, $p_T = 0.72-0.74$ GeV/c

- $\lambda = 1.05 \pm 0.09$
- $R = 4.84$ fm $\pm 0.30$ fm
- $\alpha = 1.20 \pm 0.05$
- $\varepsilon = -0.038 \pm 0.000$
- $N = 1.0007 \pm 0.0002$
- $\chi^2/NDF = 413/380$
- conf. level = 0.1180

$C_{\text{Levy}}^C = (1 + \lambda \cdot \exp(-2 \cdot R \cdot |k|^{\alpha})) \times N(1+\varepsilon|k|)$
Levy scale parameter $R$ versus pair $m_T$

- Similar decreasing trend as usual Gaussian HBT radii
- Hydro behaviour: $1/R^2 \sim m_T$, not incompatible
- Hard to say whether the $1/R^2$ scaling is linear or not
Correlation strength $\lambda$ versus pair $m_T$

- From the Core-Halo model: $\lambda = \left( \frac{N_C}{N_C + N_H} \right)^2$
- Large and correlated systematic uncertainties
- Observed decrease at small $m_T \rightarrow$ increase of halo fraction
- Different effects can cause change in $\lambda$, strange speculations
  - Resonance effects, partial chiral symmetry restoration?
  - Partially coherent pion production?
  - Aharanov-Bohm effect?

MinBias Au+Au @ $\sqrt{s_{NN}} = 200$ GeV

\[ \lambda \]

\[ m_T \text{ [GeV/c}^2] \]

\[ \lambda/\lambda_{\text{max}} \]

\[ m_T \text{ [GeV/c}^2] \]
Levy exponent $\alpha$ versus pair $m_T$

- Far from Gaussian ($\alpha = 2$) and Cauchy/exponential ($\alpha = 1$)
- Also far from 3D Ising value at CEP ($\alpha \leq 0.5$)
- More or less constant (at least within systematic errors)
- Although the constant fit is statistically not acceptable
- Motivation to do fits with fixed $\alpha = 1.134$
Levy scale parameter $R$ with fixed $\alpha = 1.134$

- More smooth trend
- Hydro behaviour seems to be more valid
- The linearity of $1/R^2$ holds
Correlation strength $\lambda$ with fixed $\alpha = 1.134$

- More smooth trend
- Smaller systematic errors
Newly discovered scaling parameter $\hat{R}$

- $\alpha = 1.134$ fixed
- Empirically found scaling parameter
- Linear in $m_T$
- Physical interpretation $\rightarrow$ open question
Beam energy & system size dependence of HBT radii

- $\pi^+\pi^+$, $\pi^-\pi^-$ data combined
- Linear $1/\sqrt{m_T}$ scaling of HBT radii
- Interpolation to common $m_T$, PHENIX and STAR consistent
quantities related to emission duration and expansion velocity
non-monotonic patterns
indication of CEP?

More precise mapping and further detailed studies required

Is there any other way to find the critical point?

Maybe Levy exponent $\alpha$!
Generalized random walks

Random walk, step size with infinite variance
Random Walk

Generalized random walk
(Speculative) connection between $\lambda(m_T)$ and $U_A(1)$

- Partial chiral $U_A(1)$ restoration $\Rightarrow$ reduction of the $\eta'$ mass
- Reduced $\eta'$ mass $\Rightarrow$ larger abundance of $\eta'$
- Decay: $\eta' \rightarrow \eta \pi^+ \pi^-$, $\eta \rightarrow \pi^+ \pi^- \pi^0$ (some probability)
- In summary: $U_A(1)$ restoration $\Rightarrow$ larger number of decay pions
- Larger number of decay pions $\Rightarrow$ larger halo, i.e. reduced $\lambda$
- These decay pions have small momentum, as $\eta'$ has no available energy to give them momentum
- $\lambda$ reduces only at small momentum!
- Hole in $\lambda(m_t)$ distribution!
(Speculative) connection: $\lambda(m_T)$ and Aharanov-Bohm

- Mixing of $a \rightarrow A, b \rightarrow B$ and $a \rightarrow B, b \rightarrow A$
- Correlation strength: $\langle |\Psi_2|^2 - 1 \rangle$, with $|\Psi_2|^2 = 1 + \cos(\Delta x \Delta k)$ and $\Delta x = x_1 - x_2, \Delta k = k_1 - k_2$
- Average on local production probability and random phases at emission (c.f. incoherent production); if no random phases, no correlation!
- Observation: closed loop in the above figure
- Particles go through an expanding, fluctuating medium
- Pairs picking up additional random phases $\phi$, $|\Psi_2|^2 = 1 + \cos(\Delta x \Delta k + \phi)$
- Assume $\phi$ distribution of $\exp[-\phi^2/(2\sigma^2)]$, average on possible $\phi$ values
- $\langle |\Psi_2|^2 - 1 \rangle_\phi = \exp[-\sigma^2/2] \cos(\Delta x \Delta k)$
- Correlation strength $\lambda$ reduced by $\exp[-\sigma^2/2]$
- Suppose $\sigma^2 \sim 1/m_T^2 \Rightarrow \text{“hole” in } \lambda(m_T)$
- Idea from Antal Jakovác (Eötvös University)