INVESTIGATION OF THE TWO-PARTICLE SOURCE FUNCTION AT $\sqrt{S_{NN}} = 2.76$ TeV WITH EPOS

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DAY OF FEMTOSCOPY

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• Two-particle (pair) source: \( D(r, K) = \int S\left( \rho + \frac{r}{2}, K \right) S\left( \rho - \frac{r}{2}, K \right) d^4 \rho \)

• Correlation function: \( C(q, K) = \frac{\int D(r, K) |\Psi_q(r)|^2 d^4r}{\int D(r, K) d^4r} \)

• Experiments – no direct access to pair-source
  • Assume given source shape and wave function
  • Calculate the correlation function
  • Test the assumptions on the measured correlation

• Event generator models (like EPOS) – direct access to pair-source!
LÉVY DISTRIBUTIONS IN HEAVY ION PHYSICS

- Measurements suggest phenomena beyond Gaussian distribution

- Lévy-stable distribution: \( L(r; \alpha, R) = (2\pi)^{-3} \int d^3q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha} \)
  - \( \alpha \): Lévy stability index
  - \( R \): Lévy scale parameter

- 1-D projection: \( L(r; \alpha, R) = (2\pi^2 r)^{-1} \int dq e^{-\frac{1}{2}(qr)^\alpha} \sin(qr)q \)

- Some possible causes:
  - Event averaging (Cimerman et al., Phys.Part.Nucl. 51 (2020) 282)
THE EPOS MODEL

• EPOS = Energy conserving quantum mechanical multiple scattering approach, based on Partons (parton ladders), Off-shell remnants, and Saturation of parton ladders K. Werner et al., PRC82 (2010) 044904, PRC89 (2014) 064903

• Monte-Carlo based phenomenological model

• Stages of the evolution:
  • Initial stage – parton based Gribov-Regge theory
  • Core-corona separation
  • 3+1D viscous hydrodynamic evolution
  • Hadronic rescattering – UrQMD

• Dataset: EPOS3 2.76 TeV PbPb, 800k events
RECONSTRUCTING THE TWO-PARTICLE SOURCE

• Source spherically symmetric in the LCMS (PHENIX coll., *Phys. Rev. Lett.* 93 (2004), 152302)

\[ r_{LCMS} = \left( x_1 - x_2, y_1 - y_2, z_1 - z_2 - \frac{\beta(t_1 - t_2)}{\sqrt{1 - \beta^2}} \right), \quad \beta = \frac{p_{z,1} + p_{z,2}}{E_1 + E_2} \]

• Calculate \( D(r_{LCMS}) \) event-by-event!

• Average transverse momentum \( (k_T) \) classes

• Investigated cases:
  • Pions:
    • CORE, primordial
    • CORE, primordial+decay
    • CORE+CORONA+UrQMD, primordial
    • CORE+CORONA+UrQMD, primordial+decay
  • Kaons: CORE+CORONA+UrQMD, primordial+decay
  • Protons: CORE+CORONA+UrQMD, primordial+decay
LÉVY FITS TO THE TWO-PARTICLE SOURCE

• Event-by-event Lévy fits
• Without decays and UrQMD → close to Gaussian
• After decays or UrQMD → far from Gaussian
• Lévy shape appears in single events!
• Similar fits for kaons and protons
• Only keep fits with CL > 0.1%
Introduction

EPOS model

Analysis details

Results

**7/16 DISTRIBUTION OF THE SOURCE PARAMETERS**

- Collect all fit results in $R$ vs $\alpha$ histograms
- Similar figures for each centrality, $k_T$ and for kaons or protons
- Extract average values $\langle R \rangle$ and $\langle \alpha \rangle$
- Extract standard deviations
- Investigate centrality and $k_T$ dependence
CONTOURS OF THE $R$ VS $\alpha$ DISTRIBUTIONS

- $1\sigma$ contours for all $k_T$ classes
- Ellipses from $\sigma_\alpha$, $\sigma_R$ and $corr_{\alpha,R}$
- Only 2 centralities in one figure for clarity
- $\alpha - R$ anti-correlation
- Illustrates centrality and $k_T$ dependence

EPOS3 CORE+CORONA+UrQMD

Balázs Kórodi, Day of Femtoscopy 2023
PION SOURCE PARAMETERS

- Transverse mass: $m_T = \sqrt{k_T^2 + m^2}$
- Lévy scale parameter ($R$):
  - Larger in central collisions $\rightarrow$ spatial scale
  - Decreases with $m_T$ $\rightarrow$ hydrodynamic scaling
  - Small effect of decay products
- Lévy stability index ($\alpha$):
  - Weak centrality dependence
  - Small decrease with $m_T$
  - Smaller after decays $\rightarrow$ source shape influenced
- Error bands = standard deviation of $R/\alpha \neq$ statistical uncertainty of $\langle R \rangle / \langle \alpha \rangle$
• Similar centrality and $m_T$ dependence
• $\langle R \rangle (2.76 \text{ TeV EPOS}) > \langle R \rangle (200 \text{ GeV EPOS})$
• $\langle R \rangle (2.76 \text{ TeV EPOS}) > R (5.02 \text{ TeV data})$?
**COMPARISON TO DATA AND LOWER ENERGY EPOS**

- Similar centrality and $m_T$ dependence
- $\langle \alpha \rangle (2.76 \text{ TeV EPOS}) < \langle \alpha \rangle (200 \text{ GeV EPOS})$
- $\langle \alpha \rangle (2.76 \text{ TeV EPOS}) < \alpha (5.02 \text{ TeV data})$

*Kincses, Stefaniak, Csanád, Entropy 24 (2022) 308*
• Similar trends

• Hydrodynamics + Gaussian source \( \frac{1}{R^2} \sim m_T \) particle independent scaling

• EPOS \( \rightarrow R \) depends on the particle type

• No universal \( m_T \) scaling in EPOS

• For given species scaling is approximately fulfilled

• Stat. uncertainties smaller than markers
• $R$ vs. $(m_T - m) \rightarrow$ same curve for pions and kaons

• Divide $R$ with one plus the number of valence quarks $\rightarrow$ same curve for protons

• Unknown reasons and interpretation
• $N_{\text{part}}$ : average number of participating nucleons

• $N_{\text{part}}^{1/3} \sim$ one-dimensional initial size

• Approximately linear scaling $\rightarrow$ geometric interpretation

• Super small statistical uncertainties:
  \[ \frac{\sigma_R}{\sqrt{N_{\text{evts}}}} \approx 0.01\% \]
**PION, KAON, PROTON LÉVY STABILITY INDEX**

- Source deviation from Gaussian ($\alpha = 2$)
- In case of anomalous diffusion:
  - Smaller cross-section $\rightarrow$ larger mean free path $\rightarrow$ longer power-law tail $\rightarrow$ smaller $\alpha$
- Prediction: $\alpha_K < \alpha_\pi < \alpha_p$
- Only partially fulfilled!
- Anomalous diffusion cannot be the only reason for the Lévy shape
SUMMARY

• Analysis steps:
  • Event-by-event reconstruction of the two-particle source in EPOS 2.76 TeV PbPb
  • Single event Lévy fits – event-by-event Lévy shape
  • Extract mean Lévy parameters $\langle R \rangle$ and $\langle \alpha \rangle$

• Results:
  • Hydrodynamic-like and geometric scaling of $\langle R \rangle$
  • $\langle \alpha \rangle$ affected by decays
  • Similar trends to experiment, but different magnitudes
  • Particle species dependent $\langle R \rangle$
  • Partially fulfilled predictions of anomalous diffusion

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BACKUP SLIDES
KAON AND PROTON EXAMPLE FIT

EPOS3 single event

10-20% Pb+Pb@\sqrt{s_{NN}} = 2.76 TeV
KK, |n| < 1, \( k_T = 0.48\)\(-0.62 \) GeV/c

\[ D(r_{\text{LCMS}}) \text{ [fm}^{-3} \text{]} \]

- Levy distr. (\( \alpha,2/\alpha R_{r_{\text{LCMS}}} \))
- Gaussian distr. (\( R_{G_{r_{\text{LCMS}}}} \))

- \( k_T = 1.00\)\(-1.40 \) GeV/c

pp, |n| < 1

CORE+CORONA+UrQMD
primordial+decay kaons
\( \alpha = 1.53 \pm 0.02 \)
\( R = (10.45 \pm 0.09) \) fm
\( \chi^2/\text{NDF} = 72/68 \)
conf. lev. = 34.48%\

CORE+CORONA+UrQMD
primordial+decay protons
\( \alpha = 1.70 \pm 0.04 \)
\( R = (13.58 \pm 0.22) \) fm
\( \chi^2/\text{NDF} = 69/59 \)
conf. lev. = 16.88%