Probing Short-Range Correlations of Hadrons

Femtoscopy Analysis of p-Λ pairs in Ag-Ag collisions at 1.58 A GeV with HADES

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Content

1. Introduction – motivation
2. HADES (GSI) detector system
3. RPC / ToF, particle identification / centrality
4. Weak Decay Recognition (Λ data / simulation)
5. Correlation theory / Experimental results
6. Lednicky & Lyuboshitz (LL) analytical model
7. global result comparison
8. Final results minimum bias
9. Summary

Neutron stars (NS) are the remnants of the gravitational collapse of massive stars during supernova event.

- Their masses and radii are of the order of $1 - 2 \, M_\odot$ and $10 - 12 \, \text{km}$, respectively.

- Central densities in the range of $4 - 8$ times the normal nuclear matter saturation density, $\varepsilon_0 \sim 2.7 \times 10^{14} \, \text{g/cm}^3$ ($\rho_0 \sim 0.16 \, \text{fm}^{-3}$)

Best suitable theory takes hyperons into account,

- Hyperons are expected to appear in the core of NS at $\rho \sim 2 - 3 \rho_0$

- Hyperons softens the EoS $\rightarrow$ Reduction on maximum NS mass

- Observation of the NS with $M_\odot > 2M_\odot$ is incompatible with such soft EoS

- Although the existence of hyperons is energetically favorable, their existence makes the EoS softer and is not consistent with the experimental results. This is the essence of the hyperon puzzle.
why hyperons are produced

Neutron (uud, m = 938 MeV)

Λ Hyperon (uus, m = 1115 MeV)

Neutron (uud, m = 938 MeV)

Λ Hyperon (uus, m = 1115 MeV)

Expected evaluation in time

This is how existence of hyperons is energetically favorable.
HADES Spectrometer

- SIS-18 beams: protons (1-4 GeV), nuclei (1-2 AGeV), pions (0.4-2 GeV/c) – secondary beam
- rare probes: (e^+, e^-), strangeness: K^{+/0}, Λ, Ξ^-, φ
- ΔM/M - 2% at ρ / ω
- PID : π/p/K – dE/dx (MDC) and TOF : σ_{tof} ~80 ps (RPC)
- electrons : RICH (hadron blind)
- neutral particles: ECAL

Geometry:

- full azimuthal, polar angles 18° - 85°
HADES Ag-Ag collision

Ag-Ag @ 1.58 A GeV
(march-19 data)

Duration: 430.9 h
Events recorded: $13.64 \times 10^9$
Mean event rate: 8.8 kHz
Data recorded: 333.6 TB

The 15 target segments are determined by a 15-fold Gaussian fit function with a common standard deviation ($\sigma$).
Particle identification

ToF

RPC

https://doi.org/10.21248/gups.68651

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Selected events, Multiplicity

![Histogram of Multiplicity](image)

- 20% - 30%
- 10% - 20%
- 0% - 10%

![Heatmap of Multiplicity vs. M_{\gamma e^+}[MeV/c^2]](image)

- 0% - 10%
- 10% - 20%
- 20% - 30%

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• Distance of closest approach (DCA) between the daughter tracks and the primary vertex,  
  → Dau1VD = > 8 mm  
  → Dau2VD = > 24 mm

• DCA between reconstructed mother track and primary vertex (Mot-VD) = < 5 mm

• Distance between the primary and secondary vertex (VDX) = > 65 mm

• DCA between the two daughter tracks (MTD) = < 6 mm

• Opening angle between the two daughter tracks (A) = > 15°
Reconstructed $\Lambda$ signal

$(\pi^- + p \rightarrow \Lambda)$

$\frac{S}{S+B} = 89.80\%$

$\sigma = (2.2873 \pm 0.01)\text{ MeV}/c^2$

$\mu = (1115.02 \pm 0.01)\text{ MeV}/c^2$

Ag+Ag $\sqrt{s_{NN}} = 2.55\text{ GeV}$

0 - 30% most central

$V_0$ reconstruction: $p + \pi^- \rightarrow \Lambda$

- Signal+Background
- Background (Event Mixing)
- Signal
- Gauss fit

Counts

Mass [MeV/c]

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Strategy of analysis

\[ C^{ab}(P, q) = \frac{\mathcal{P}(\vec{P}_a, \vec{P}_b)}{\mathcal{P}(\vec{P}_a)\mathcal{P}(\vec{P}_b)} = \int d^3r' S_p(r')|\phi(q, r')|^2 \]

Method 1:
- Lednicky Model: Correlation formula as a function of the $\Lambda p$ scattering length and source radii $r_0$.
- Scan and extract strong interacting parameters ($f_0, d_0$) and source radii ($r_0$).

Method 2:
- SMASH simulation for particle correlation
- CRAB Afterburner to account for the Final State Interaction among the emitted particles.
p-Λ correlation in AgAg collision at 1.58 A GeV

For all centrality classes estimated purity for pΛ: 90% - 92% ± 3% (data) (<400 MeV/c)

HADES preliminary work in progress
Result: $p - \Lambda$ correlation

$C(k^*)$

$Ag+Ag \sqrt{s_{NN}}=2.55 \text{ GeV} \ 0-30\%$

HADES work in progress

$p-\Lambda$ correlation

$(0 < y < 1.4, 0 < pT < 1.5)$

HADES preliminary

work in progress

Centrality

- 0 - 10%
- 10 - 20%
- 20 - 30%

HADES preliminary

work in progress
The normalized pair separation distribution (source function) $S(r^*)$ is assumed to be Gaussian,

$$S(r^*) = (2\sqrt{\pi}r_0)^{-3} e^{-\frac{r^*^2}{4r_0^2}}$$

The correlated function can be calculated analytically by averaging $\Psi^s$ over the total spin $S$ and the distribution of the relative distances $S(r^*)$.

$$C(k^*) = 1 + \sum_S \rho_s \left[ \frac{1}{2} \left| \frac{f^S(k^*)}{r_0} \right|^2 \left( 1 - \frac{d_0^S}{2\sqrt{\pi}r_0} \right) + \frac{2\Re f^S(k^*)}{\sqrt{\pi}r_0} F_1(Qr_0) - \frac{3f^S(k^*)}{r_0} F_2(Qr_0) \right]$$

with $F_1(z) = \int_0^z dx e^{x^2 - z^2} / z$ and $F_2(z) = \left( 1 - e^{-z^2} \right) / z$

Decomposition for spin channels:

$$C(k^*) = \frac{1}{4} (1 + \lambda C(k^*, s = 0)) + \frac{3}{4} (1 + \lambda C(k^*, s = 1))$$

Parameters: $f_{0s}, d_{0s}, f_{0t}, d_{0t}$

<table>
<thead>
<tr>
<th>Model</th>
<th>$f_0^{N=0}$ (fm)</th>
<th>$f_0^{N=1}$ (fm)</th>
<th>$d_0^{N=0}$ (fm)</th>
<th>$d_0^{N=1}$ (fm)</th>
<th>$n_\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND [77]</td>
<td>1.77</td>
<td>2.06</td>
<td>3.78</td>
<td>3.18</td>
<td>1.1</td>
</tr>
<tr>
<td>NF [78]</td>
<td>2.18</td>
<td>1.93</td>
<td>3.19</td>
<td>3.358</td>
<td>1.1</td>
</tr>
<tr>
<td>NSC89 [79]</td>
<td>2.73</td>
<td>1.48</td>
<td>2.87</td>
<td>3.04</td>
<td>0.9</td>
</tr>
<tr>
<td>a</td>
<td>0.71</td>
<td>2.18</td>
<td>5.86</td>
<td>2.76</td>
<td>1.0</td>
</tr>
<tr>
<td>b</td>
<td>0.9</td>
<td>2.13</td>
<td>4.92</td>
<td>2.84</td>
<td>1.0</td>
</tr>
<tr>
<td>c</td>
<td>1.2</td>
<td>2.08</td>
<td>4.11</td>
<td>2.92</td>
<td>1.0</td>
</tr>
<tr>
<td>d</td>
<td>1.71</td>
<td>1.95</td>
<td>3.46</td>
<td>3.08</td>
<td>1.0</td>
</tr>
<tr>
<td>e</td>
<td>2.1</td>
<td>1.86</td>
<td>3.19</td>
<td>3.19</td>
<td>1.1</td>
</tr>
<tr>
<td>f</td>
<td>2.51</td>
<td>1.75</td>
<td>3.03</td>
<td>3.32</td>
<td>1.0</td>
</tr>
<tr>
<td>ESC08 [81]</td>
<td>2.7</td>
<td>1.65</td>
<td>2.97</td>
<td>3.63</td>
<td>0.9</td>
</tr>
<tr>
<td>χEFT</td>
<td>[0.01, 5.0]</td>
<td>[0.01, 2.0]</td>
<td>[0.01, 5.0]</td>
<td>[0.01, 2.0]</td>
<td>[0.01, 5.0]</td>
</tr>
<tr>
<td>Jülich</td>
<td>1.56</td>
<td>1.59</td>
<td>1.43</td>
<td>3.16</td>
<td>1.0</td>
</tr>
<tr>
<td>J04 [83]</td>
<td>2.56</td>
<td>1.66</td>
<td>2.75</td>
<td>2.93</td>
<td>1.4</td>
</tr>
<tr>
<td>J04c [83]</td>
<td>2.66</td>
<td>1.57</td>
<td>2.67</td>
<td>3.08</td>
<td>1.1</td>
</tr>
</tbody>
</table>

HADES results

<table>
<thead>
<tr>
<th>Parameters</th>
<th>p-Nb (LO)</th>
<th>p-Nb (NLO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{0s}$</td>
<td>1.91 fm</td>
<td>2.91 fm</td>
</tr>
<tr>
<td>$d_{0s}$</td>
<td>1.40 fm</td>
<td>2.78 fm</td>
</tr>
<tr>
<td>$f_{0t}$</td>
<td>1.23 fm</td>
<td>1.54 fm</td>
</tr>
<tr>
<td>$d_{0t}$</td>
<td>2.13 fm</td>
<td>2.72 fm</td>
</tr>
<tr>
<td>$r_0$</td>
<td>1.71±0.10</td>
<td>1.62±0.02</td>
</tr>
</tbody>
</table>
How do we formulate this model?

Principle ways of generate the theoretical correlation function.

1. The Lednicky-Luboshitz semi-analytical model (utilized in CorrfitCumac codes) provides an immediate correlation function value but may be computationally intensive due to integral calculations.

2. The first fitter employs ROOT minimizers, offering precise statistical uncertainty estimation, but it operates on "continuous" maps with limited control over parameter steps.

3. The second fitter, Hal:Minimizer, accommodates "non-continuous" functions, allowing parameters to change in discrete steps. However, it provides only approximate uncertainty estimates.

Special Thanks to Dr. Daniel Wilanek and Prof. Yuri Sinyukov
$f_{0s}, d_{0s}, f_{0t} \text{ and } d_{0t}$ parameters : $\chi^2$ value

Singlet

- Extracted parameters:
  - $f_{0s} = 0.78 \text{ fm}$, $d_{0s} = 0.01 \text{ fm}$

Triplet

- Extracted parameters:
  - $f_{0s} = 1.89 \text{ fm}$, $d_{0s} = 3.76 \text{ fm}$
1. $\lambda$ and $R$ [fm] parameters: $\chi^2$ value
2. Fitted spectra with extracted parameters
Parameters scan and Plot: $r_0$ vs $A^{1/3}$

Strong interacting parameters

Hades Ag+Ag prediction
Hades Ag+Ag result

HADES preliminary work in progress

Slope: 0.42
Intercept: 0.312
Result: $p - \Lambda$ correlation:

- Centrality classes: 0-10\%, 10-20\%, 20-30\%

- $r_0 = 2.6 \pm 0.39$
- $r_0 = 2.16 \pm 0.33$
- $r_0 = 1.81 \pm 0.34$

- Systematic Uncertainty:
  - 0 - 10 \%: 15.30 \%
  - 10 - 20 \%: 15.49 \%
  - 20 - 30 \%: 19.00 \%
Result: \( p - \Lambda \) correlation:
kT bins: 0-400, 400-800, 800-1200 [MeV/c]

<table>
<thead>
<tr>
<th>kT region</th>
<th>Systematic Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 400</td>
<td>19 %</td>
</tr>
<tr>
<td>400 - 800</td>
<td>15 %</td>
</tr>
<tr>
<td>800 - 1200</td>
<td>22 %</td>
</tr>
</tbody>
</table>
Resolution effects

- pΛ correlation SMASH model
- smash model with no resolution
- smash model with resolution

- Resolution effects

- HADES preliminary work in progress
- Ag+Ag \( \sqrt{s_{NN}} = 2.55 \text{ GeV} \) 0-30%
- HADES work in progress

- HADES preliminary work in progress

- Smash model + LL weights + Resolution

- \( r = 2.24^{+0.12}_{-0.11} \)
- \( \lambda = 0.74 \)

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Summary

1. The correlation signals in Ag-Ag collision is extracted: $p-\Lambda$, ✔
2. Resolution effects ($\theta, \phi, p$) studies are performed, fits are available for MC ✔
3. Systematics studies are performed ✔
4. Detector effects, purity determination and model interference are studied ✔

2nd stage: (towards strong parameters)
5. Use Lednicky and Lyuboshitz (LL) analytical model
   - source radii (R), ✔
   - extract strong interaction parameters ✔
   - Uncertainties ✔ ($\chi^2$ method done ✔, ALICE bootstrap technique under progress .....)

6. adding proton and lambda resolution resolution to smash model with LL weights ✔
7. Few cross-checks needed to lock obtain parameters: resolution ✔, check $mT/pT$ ✔ scaling, rechecks centrality results, acceptance check.

What’s next? (new ideas to explore)
8. physics behind heavier hydrogen (deuteron) interaction with lambda (d–\Lambda) will be interesting.
9. also opportunity to work with new HADES (p-p collision)- data for femtoscopy studies........
Thank you

for any specific detail please mail: narendra.rathod@pw.edu.pl
Result: STAR and LHC data

RHIC: Au+Au @ 200 GeV and STAR: LHC Pb+Pb @ 2.76 TeV: Testing fitting procedure
Armenteros-Podolanski plots

Geometrical definition of the Armenteros-Podolanski variables

Example: $\Lambda \rightarrow p + \pi^-$

$P_T$ vs $\alpha = \frac{p_+^- - p_+^+}{p_+^+ + p_+^-}$

Simulation

HADES: Low energies

Additional boost to daughter particles

TVector3 beta (0., 0., 0.99);

Corrected

Entries 62147
Mean x 0.6719
Mean y 88.79

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**Proton resolution**

Reconstructed (+ ID check) proton momentum deviation

Reconstructed (+ ID check) proton \( \theta \) deviation

Reconstructed (+ ID check) proton \( \phi \) deviation

---

**Linear**

**Polynomial 4**

**Polynomial 6**

- \( p_\text{s1} \)
- \( p_\text{s2} \)
- \( p_\text{s3} \)
- \( \text{mf} \)

*Best fit: \( p_\text{s3} \)*

---

**Sigma**

**Theta(\( \theta \))**

*Best fit: \( p_\text{s2} \)*

---

**Sigma**

**Phi(\( \phi \))**

*Best fit: \( p_\text{s2} \)*

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Lambda resolution

Reconstructed (+ ID check) Lambda (p) deviation

Reconstructed (+ ID check) Lambda (θ) deviation

Reconstructed (+ ID check) proton φ deviation

Linear
Polynomial 4
Polynomial 6
ps1
ps2
ps3
mf

Best fit : pol6

Best fit : ps2

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Result - II

- Experimental raw spectra
- Model effect
- Detector effects + model
- Exp + corrected (detector+model)
- Exp + corrected + purity : final spectra

Graphs showing:
- $p - \Lambda$ correlation signal (centrality: 0% - 10%)
- $p - \Lambda$ correlation signal (centrality: 10% - 20%)
- $p - \Lambda$ correlation signal (centrality: 20% - 30%)

HADES Preliminary
Armenteros-Podolanski plots

HADES:
Low energies

Entries 62147
Mean x 0.6513
Mean y 89.57

Additional boost to daughter particles
TVector3 beta (0., 0., 0.99);

Corrected

Simulation

Entries 62147
Mean x 0.6719
Mean y 88.79
$\Delta \theta$ vs $\Delta \phi$ distribution

RPC results

ToF results

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How correlations are obtain?

1. Source
   - Analytical
     - Weights
     - Transport model

2. Potential
   - Numerical solution for Schrodinger equation
     - Exact solution
     - Wave function

Correlation function

https://indico.mitp.uni-mainz.de/event/191/contributions/3148/attachments/2450/2649/VMS_BORMIO2020_final.pdf

https://doi.org/10.1103/PhysRevLett.83.3138

V_{Usmani} = V_C - \left( \bar{V} - \frac{1}{4} V_{\sigma \Lambda} \cdot \vec{\sigma}_p \right) T^2_{\pi},

V_C = W_C \left( 1 + \exp \left( \frac{r - R}{d} \right) \right)^{-1}.
Lednicky & Lyuboshitz analytical model

\[ C(k^*) = \left\langle |\Psi_{-k^*}^S(r^*)|^2 \right\rangle, \]

where the wave function \( \Psi^S \) represents the approximate stationary solution of the scattering problem

\[ \Psi_{-k^*}^S(r^*) = e^{-ik^* \cdot r^*} + \frac{f^S(k^*)}{r^*} e^{ik^* \cdot r^*}. \]

The effective range approximation for the scattering amplitude is

\[ f^S(k^*) = \left( \frac{1}{f_0^S} + \frac{1}{2} d_0^S k^* - i k^* \right)^{-1}, \]

where \( f_0^S \) is the scattering length and \( d_0^S \) is the effective radius for a given total spin \( S = 1 \) or \( S = 0 \).

The particle is assumed to be unpolarized (the polarization \( P = 0 \) ):

- singlet state \( \rho_0 = \frac{1}{4} (1 - P^2) \) and triplet state \( \rho_1 = \frac{3}{4} (1 - P^2) \).
Energy-loss correction

Reconstructed (+ ID check) proton momentum deviation

Reconstructed (+ ID check) proton momentum deviation

Reconstructed (+ ID check) pion momentum deviation

Reconstructed (+ ID check) pion momentum deviation

Proton

Pion
Systematics check (few of them)

**PID variation**

- Signal: 360501
- Signal: 563105
- Signal: 628352

**Mass cut variation**

- Lambda (p + π⁻ → Λ) signal
- Signal: 360501
- Signal: 563105
- Signal: 628352

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Thank you