Proton-Proton and Lambda-proton correlations in p+Nb reactions at 3.5 GeV

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Excellence Cluster Universe
• What is a particle correlator?

• Proton-proton correlations
  Corrections and results from comparison with models

• Lambda-proton correlations
  Use of proton-proton results to investigate the interaction of $\Lambda p$ pairs
Introduction

Theoretical correlation function:

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

Source function:
Distribution of relative distance between the particle pairs (in CMS)

Wavefunction of particle pair:
Includes the interactions

Experimental correlation function:

\[ C(k) = \frac{A(k)}{B(k)} \]

- Same: relative momentum dist. of particles in the same event
- Mixed: particles from different events (not correlated)
- Normalized to unity: \( C(k > 100 \text{ MeV}/c) \equiv 1 \)
Introduction

Strategy of analysis:

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

1. Understand the emission profile of the pNb system

2. Use the information of point 1 to investigate particle interactions which are not well known

region of homogeneity == „Source“

\[ S_P(r) \]
Method

Benchmark Channel

Investigated Channel

\[ C^{pp}(P, q) = \int d^3 r' S(r') |\varphi(q, r')|^2 \]

Method 1:
- Known Interaction
- Assumption that the source is Gaussian \((R_0)\)
- Calculation of the Correlation Function and comparison to the Data

Method 2:
- UrQMD Simulation for particle production
- CRAB Afterburner to account for the Final State Interaction among the emitted particles.
Method

Benchmark Channel

Investigated Channel

\[ C^{\text{pp}}(P, q) = \int d^3 r' S(r') |\varphi(q, r')|^2 \]

Method 1:
- Known Interaction
- **Assumption that the source is Gaussian** \((R_0)\)
- Calculation of the Correlation Function and comparison to the Data

Check that the same assumption about the source is valid

Method 2:
- UrQMD Simulation for particle production
- CRAB Afterburner to account for the Final State Interaction among the emitted particles.

Take the UrQMD 'prediction for the \(\Lambda p\) Source
Method

Benchmark Channel

Investigated Channel

\[ C^{pp}(P, q) = \int d^3r' S(r') |\phi(q, r')|^2 \]

Method 1:
- Known Interaction
- Assumption that the source is Gaussian (R₀)
- Calculation of the Correlation Function and comparison to the Data

Method 1:
- Lednicky Model: Correlation Formula as a function of the Λp scattering length and source Radius R₀.
- Test different scattering length

Method 2:
- UrQMD Simulation for particle production
- CRAB Afterburner to account for the Final State Interaction among the emitted particles.

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1. Understand the emission profile of the pNb system

region of homogeneity == "Source"

\[ S_P(r) \]
Information about the source – proton proton correlation function:
Proton-proton correlation function **without** any corrections:

**Strong interaction**

**Coulomb interact. + Quantum statistic**

**Should be flat for large momenta ...**

Coulomb interact. + Quantum statistic
Information about the source — proton-proton correlation function:
Proton-proton correlation function **without** any corrections:

**PRELIMINARY**

Should be flat for large momenta ...

.. unfortunately *not* the case
Correlation Function

Information about the source – proton-proton correlation function:

**Corrections**

Reject pairs which are too close together

Correct for finite momentum resolution

Correct for long range correlations

\[ |\Delta \phi| > 3 \times 0.039 \text{ rad} \]

\[ |\Delta \Theta| > 3 \times 0.015 \text{ rad} \]

![Graph](image)

\[
\frac{C_{\text{real}}(k)}{C_{\text{measured}}(k)} = \frac{C_{\text{ideal}}(k)}{C_{\text{smeared}}(k)}
\]

\[
C(k) \equiv \frac{C_{\text{raw}}(k)}{C_{\text{UrQMD}}(k)}
\]
Information about the source – proton-proton correlation function:

**Corrections**

Reject pairs which are too close together

\[ |\Delta \phi| > 3 \times 0.039 \text{ rad} \]
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\[ \frac{C_{\text{real}}(k)}{C_{\text{measured}}(k)} = \frac{C_{\text{ideal}}(k)}{C_{\text{smeared}}(k)} \]

Correct for long range correlations

\[ C(k) \equiv C_{\text{raw}}(k)/C_{\text{UrQMD}}(k) \]
Information about the source – proton proton correlation function:

Proton-proton correlation function corrected for all efficiencies:

\[ C(k) \]

\[ k \text{ [MeV/c]} \]
Correlation Function

Information about the source – proton-proton correlation function:

Extract source size: \( C^{ab}(k) = N \int d^3r' S_P(r') |\phi(k, r')|^2 \)

Potential used for strong interaction:

\( R_G = 2.016 \pm 0.010 \text{ fm} \)
\( N = 1.005 \pm 0.002 \)


\[ \frac{d^2w}{d\rho^2} + \left[ 1 - \frac{2\eta}{\rho} - \frac{l(l+1)}{\rho^2} - \frac{2\mu}{k^2} V(\rho) \right] = 0 \]

\( S(r) \sim \exp(-r^2/4R_G^2) \)

\[ R_G = 2.016 \pm 0.010^{+0.039}_{-0.027} \text{ fm} \]
Interaction

Source comparison to transport theory (same potential used than for the fit):

In one dimension:

Calculation of UrQMD correlation function with help of CRAB

\[ \text{Exp} \]

\[ \text{UrQMD+CRAB} \]

\[ p_z > 0, \Theta \in [15^\circ, 85^\circ] \]

UrQMD gives a good source description for protons
Interaction

Source comparison to transport theory (same potential used than for the fit):

In three dimensions:

\[ C(k_{out}) \]

\[ C(k_{side}) \]

\[ C(k_{long}) \]

\[ \begin{align*}
  \text{Exp} \\
  \text{UrQMD+CRAB} & \quad p_z > 0, \Theta \in [15^\circ, 85^\circ]
\end{align*} \]
Interaction

Strategy of analysis:

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

1. Understand the emission profile of the pNb system

2. Use the information of point 1 to investigate particle interactions of not well known type
Select $\Lambda'$s with large purity – different cut combinations to investigate systematics:

$\Lambda \rightarrow p\pi^-$

Purity $\equiv \frac{S}{S+B}(2\sigma)$

- $\alpha_{id,re} < 0.1$
- VerDistA > 7 mm
- VerDistB > 15 mm
- VerDistX > 52 mm
- MTD < 10 mm

$N(\Lambda) = 356486$
$\sigma = 3.0 \text{ MeV/c}^2$
$S/B = 6.2$
Purity = 86.1%
Select $\Lambda'$ with large purity – different cut combinations to investigate systematics:

\[ \text{Purity} \equiv \frac{S}{S+B}(2\sigma) \]

- $\alpha_{id, re} < 0.1$
- $\text{VerDistA} > 7$ mm
- $\text{VerDistB} > 25$ mm
- $\text{VerDistX} > 57$ mm
- $\text{MTD} < 10$ mm

$N(\Lambda) = 278773$
$\sigma = 3.1$ MeV/c\(^2\)
$S/B = 8.6$
Purity = 89.6 %
Select $\Lambda^{' S}$ with large purity – different cut combinations to investigate systematics:

\[
\Lambda \rightarrow p\pi^-
\]

Purity \( \equiv \frac{S}{S+B}(2\sigma) \)

\( \alpha_{id,re} < 0.1 \)
\( \text{VerDistA} > 10 \text{ mm} \)
\( \text{VerDistB} > 28 \text{ mm} \)
\( \text{VerDistX} > 61 \text{ mm} \)
\( \text{MTD} < 10 \text{ mm} \)

\( N(\Lambda) = 177893 \)
\( \sigma = 3.2 \text{ MeV/c}^2 \)
\( S/B = 12.3 \)
\( \text{Purity} = 92.5 \% \)
Interaction

Again corrections: Influence of finite momentum resolution:

The momentum resolution suppresses slightly the correlation signal
Again corrections: Influence of close track efficiency:

Topology for correlated pairs:
Again corrections: Influence of close track efficiency:

Topology for correlated pairs:
Again corrections: Influence of close track efficiency:

Topology for correlated pairs:

Minimum opening angle
Again corrections: Influence of close track efficiency:

\[ C(k) \Lambda p \]

(GiBUU Sim)

- No CT cut
- \( \angle(p_{\text{prim}}, p_\Lambda) > 0.105 \text{ rad} \)
Apply corrections – investigate systematics:

Lednicky’s model:

\[
C(k) = 1 + \sum_S \rho_S \left[ \frac{1}{2} f^{S}(k) \frac{f^{S}(k)}{R_{G}^{\Lambda p}} \right]^2 \left( 1 - \frac{d_0^S}{2\sqrt{\pi} R_{G}^{\Lambda p}} \right) + 2 \frac{\mathcal{R} f^{S}(k)}{\sqrt{\pi} R_{G}^{\Lambda p}} F_1(Q R_{G}^{\Lambda p}) - \frac{\mathcal{I} f^{S}(k)}{R_{G}^{\Lambda p}} F_2(Q R_{G}^{\Lambda p}) \right]
\]
Apply corrections – investigate systematics:

**Correlation function after application of all corrections**

\[
C(k) = 1 + \sum_S \rho_S \left[ \frac{1}{2} \left( \frac{f^S(k)}{R_G^{A_p}} \right)^2 \left( 1 - \frac{d^S}{\sqrt{2} R_G^{A_p}} \right) + \frac{R f^S(k)}{\sqrt{2} R_G^{A_p}} F_1(Q R_G^{A_p}) - \frac{L f^S(k)}{R_G^{A_p}} F_2(Q R_G^{A_p}) \right]
\]

Can we use the pp measurement to fix it?
Source comparison from transport theory:
Improved UrQMD for the scattering part of Lambdas

\[ \sigma_{\Lambda p} \approx 37 \text{ mb} \]

Improvement for low energies necessary
Interaction

Source comparison from transport theory:
Improved UrQMD for the scattering part of Lambdas

Will also affect dN/dy spectra in pNb
Source extraction from transport theory (UrQMD) - LCMS:

\[ C^{ab}(k) = \int d^3r' S_P(r') |\phi(k, r')|^2 \quad k < 30 \text{ MeV/c} \]

Proton-Proton

\[ \sim \exp\left(-\frac{r^2}{2\sigma^2}\right) \]
Interaction

Source extraction from transport theory (UrQMD) - LCMS:

\[ C^{ab}(k') = \int d^3r' S_P(r') |\phi(k, r')|^2 \quad k < 30 \text{ MeV/c} \]

\[ \sim \exp\left(-r^2/2\sigma^2\right) \]
Interaction

Source extraction from transport theory (UrQMD) - LCMS:

\[ C^{ab}(k') = \int d^3 r' S_P(r') |\phi(k, r')|^2 \quad k < 30 \text{ MeV/c} \]

\[ \Lambda p \]

\[ R_{\text{inv}} = \sqrt{\frac{R_{\text{out}}^*}{3}} \quad R_{\text{inv}}^{pp} = 3.175 \text{ fm} \]

\[ R_{\text{inv}}^{\Lambda p} = 2.655 \text{ fm} \quad \text{RF} = 1.196 \]
Interaction

Correlation function after application of all corrections

Lednicky’s model:

\[ C(k) = 1 + \sum_S \rho_S \left[ \frac{1}{2} \left| \frac{f^S(k)}{R_G^{\Lambda p}} \right|^2 \left( 1 - \frac{d_0^S}{2 \sqrt{F_1(Q R_G^{\Lambda p})}} \right) + 2 \frac{R f^S(k)}{\sqrt{F_1(Q R_G^{\Lambda p})}} F_1(Q R_G^{\Lambda p}) - \frac{T f^S(k)}{R_G^{\Lambda p}} F_2(Q R_G^{\Lambda p}) \right] \]

UrQMD +pp Fit used to fit \( R_G^{\Lambda p} \)
Interaction

Correlation function after application of all corrections

Lednicky’s model:

\[ C(k) = 1 + \sum_S \rho_S \left[ \frac{1}{2} \left| \frac{f^S(k)}{R^R_G} \right|^2 \left( 1 - \frac{d^S_0}{2\sqrt{\pi} R^R_G k^2} \right) + 2 \frac{R f^S(k)}{\sqrt{\pi} R^R_G} F_1(Q R^R_G) \right. \]

\[ \left. - \frac{I f^S(k)}{R^R_G} F_2(Q R^R_G) \right] \]

Effective Range expansion of the complex scattering amplitude

\[ f^S(k) = \left( 1 - \frac{1}{2 f^S_0 k} - i k \right)^{-1} \]

\[ f^S_0 : \text{Scattering length} \]

\[ d^S_0 : \text{Effective range} \]
Comparison to models:

Correlation function obtained by using the NLO and LO scattering length and effective range results

\[ R_G = 2.016 \pm 0.010^{+0.039}_{-0.027} \text{ fm} \]

\[ R_G^{\Lambda p} = \frac{R_G^{pp}}{R_F} \]

\[ R_F = 1.196 \]

Valid alternative to scattering experiments

Haidenbauer et al. arXiv:1602.08880

\[ \Lambda p \rightarrow \Lambda p \]
Summary

- Correlation function calculated and source size for proton pairs extracted
- Study interaction of Lambda-proton pairs. Comparison to model predictions.
New Measurements

* Factor 10 for $\Lambda$-p correlation (2019)
  p+Nb at 3.7 GeV (3 weeks)
  3 KHz compared to actual 70 kHz
  $3 \times 10^6 = \text{beam intensity}$

* $\Sigma^0$-p correlation with the calorimeter (2019)

50% additional reduction wrt $\Lambda$ (with 6 sectors)
- Evaluate the background to the $\Lambda$p correlation quantitatively
- Measure for the first time the $\Sigma^0$-p scattering length

• Go to 3-body correlation $\Lambda$-p-p: the more the merrier
• $\Xi$-p ?? Simulations are needed
BACKUP
Interaction

Comparison to models:

Question: Effect on source size extraction?

\(C(k)\) vs. \(k\) [MeV/c]

**LO**
- \(R_G = 1.597 \pm 0.019\) fm
- \(a_{1s0} = 1.91\) fm
- \(a_{3s1} = 1.23\) fm
- \(r_{1s0} = 1.40\) fm
- \(r_{3s1} = 2.13\) fm

**NLO**
- \(R_G = 1.626 \pm 0.023\) fm
- \(a_{1s0} = 2.91\) fm
- \(a_{3s1} = 1.54\) fm
- \(r_{1s0} = 2.78\) fm
- \(r_{3s1} = 2.72\) fm

Small on source size
Results from pNb femtoscopy – Correlation function (angle integrated):

Can we model them (LRC)?

Baseline: as a function of pair transverse momentum \( k_T = |p_{1T} + p_{2T}| \)

- \( k_T \in [0, 250] \text{ MeV/c} \)
- \( k_T \in [250, 500] \text{ MeV/c} \)
- \( k_T \in [500, 750] \text{ MeV/c} \)
- \( k_T \in [750, 1000] \text{ MeV/c} \)
- \( k_T \in [1000, 1250] \text{ MeV/c} \)
- \( k_T \in [1250, 1500] \text{ MeV/c} \)

UrQMD
Exp
Systematic errors on pp correlation function – close track efficiency:

Errors from pp source size – Variation of close track efficiency cut (use 35 different cut combinations on $\Delta \phi$, $\Delta \Theta$):

$$R_G = 2.078 \pm 0.010^{+0.016}_{-0.010} \text{ fm}$$
Systematic errors on pp correlation function – momentum resolution:

Use a variation of 10% around the chosen mean source size of 2.2 fm

\[ R_G = 2.078 \pm 0.010 \text{ (stat)}^{+0.016}_{-0.010} \text{ (sys)}^{+0.019}_{-0.022} \text{ fm} \]
Interaction

Comparison to other measurements and to models:

Only effective scattering length measured (no information about spin)
Interaction

Comparison to other measurements and to models:

Interaction

Comparison to other measurements and to models:

Comparison to other measurements and to models: