Λ K Femtoscopy in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the LHC ALICE Experiment

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We present our femtoscopic analysis of ΛK correlations in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from ALICE. The femtoscopic correlations result from strong final-state interactions, and are fit with a parametrization based on a model by Lednicky and Lyuboshitz [1]. This allows us to both characterize the emission source and measure the scattering parameters for the particle pairs. We observe a large difference in the ΛK+ and ΛK- correlations in pairs with low relative momenta. This might suggest an effect arising from different quark-antiquark interactions between the pairs ($s\bar{s}$ in ΛK+ and $u\bar{u}$ in ΛK-), or from different net strangeness for each system. To investigate further, we conduct a ΞK analysis, for which preliminary results are shown.

1. Introduction

- Femtoscopic analysis of ΛK correlations
  - Result of strong final-state interactions
- Study the ΛK interactions
  - Scattering parameters never before measured
- Characterize the ΛK pair emission regions
  - Obey transverse mass (m_T) scaling
    - Signature of hydrodynamic flow
- Investigate striking difference of ΛK+ and ΛK- systems at small relative momenta (k^*)
  - Effect arising from $s\bar{s}$ annihilation compared to $u\bar{u}$?
  - Or S=0 ΛK+ system has more interaction channels than S=-2 ΛK-?

$\Lambda = uds$

$\overline{\Lambda} = \overline{uds}$

$K^+ = u\bar{s}$

$K^- = \bar{u}s$

$K^0_S = \frac{1}{\sqrt{2}}(d\bar{s} + s\bar{d})$

2. Femtoscopy (1 fm = 10^{-15} m)

- Space-time characterization of particle-emitting sources on femtometer (10^{-15} m) scale
- Direct measurement of times/positions of fireball impossible
  - Extremely small size and lifetime
- Momentum difference of emitted particles is measurable
  - Connected to the time and space properties
- Exploit measured two-particle (or higher) momentum correlations of hadrons to probe freeze-out structure of dynamic matter created in collisions
  - Most direct link to size and lifetime
  - Sensitive to quantum statistics, strong and Coulomb interactions
  - Allows for measurements of nuclear scattering parameters
    - For some pairs, difficult, if not impossible, to measure otherwise

3. Formalism

- Theory [2,3]:

$$C(k^*) = \int S(\boldsymbol{r}^*)\,|\Psi_{\boldsymbol{k}^*}(\boldsymbol{r}^*)|^2\, d^3\boldsymbol{r}^*$$

  - S($\boldsymbol{r}^*$) : source distribution
  - $\Psi_{k^*}(\boldsymbol{r}^*)$: two-particle wave-function
  - k* : momentum of one particle in the pair rest frame

- Experiment:

$$C(k^*) = \frac{A(k^*)}{B(k^*)}$$

  - A(k*) : signal distribution (same-event)
  - B(k*) : background distribution (mixed events)

- Quantum statistics (QS) and strong final-state interactions (FSI)
  - Lednicky and Lyuboshitz formulation [1]
  - ΛK systems

$$C(k^*) = 1 + \lambda\left[\alpha \exp\left(-4k^{*2}R^2\right) + C_{FSI}(k^*)\right]$$

$$C_{FSI} = (1+\alpha)\left[\frac{1}{2}\left|\frac{f(k^*)}{R}\right|^2\left(1 - \frac{d_0}{2\sqrt{\pi}R}\right) + \frac{2\Re f(k^*)}{\sqrt{\pi}R}F_1(2k^*R) - \frac{\Im f(k^*)}{R}F_2(2k^*R)\right]$$

$$f(k^*) = \left(\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - ik^*\right)^{-1} \qquad F_1(z) = \int_0^z dx\, \frac{e^{x^2 - z^2}}{z} \qquad F_2(z) = \frac{1 - e^{-z^2}}{z}$$

  - λ – rough estimate of primary pair fraction
  - R – source size
  - f_0 – complex scattering length
  - d_0 – effective range of interaction

- Non-identical particles ➡ $\alpha = 0$ ➡ $C(k^*) = 1 + \lambda\left[C_{FSI}(k^*)\right]$

- QS, strong, and Coulomb FSI [4]
  - No analytic form → integrate by hand, or simulate pairs
  - $\Xi^{ch}K^{ch}$ systems

$$\Psi_{-\boldsymbol{k}^*}(\boldsymbol{r}^*) = e^{i\delta_c}\sqrt{A_c(\eta)}\left[e^{i\boldsymbol{k}^*\cdot\boldsymbol{r}^*}F(-i\eta, 1, i\xi) + f_c(k^*)\frac{\tilde{G}(\rho,\eta)}{r^*}\right]$$

$$f_c(k^*) = \left[\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - \frac{2}{a_c}h(\eta) - ik^* A_c(\eta)\right]$$

  - F = confluent hypergeometric function
  - G = $\sqrt{A_c}(G_0 + iF_0)$
    - regular (F_0) and singular (G_0) s-wave Coulomb functions
  - a_c = two-particle Bohr radius
  - δ_c = Coulomb s-wave shift
  - A_c = Coulomb penetration factor
  - $\rho = k^*r^*$; $\eta = (k^*a_c)^{-1}$; $\xi = \boldsymbol{k}^*\cdot\boldsymbol{r}^* + k^*r^*$

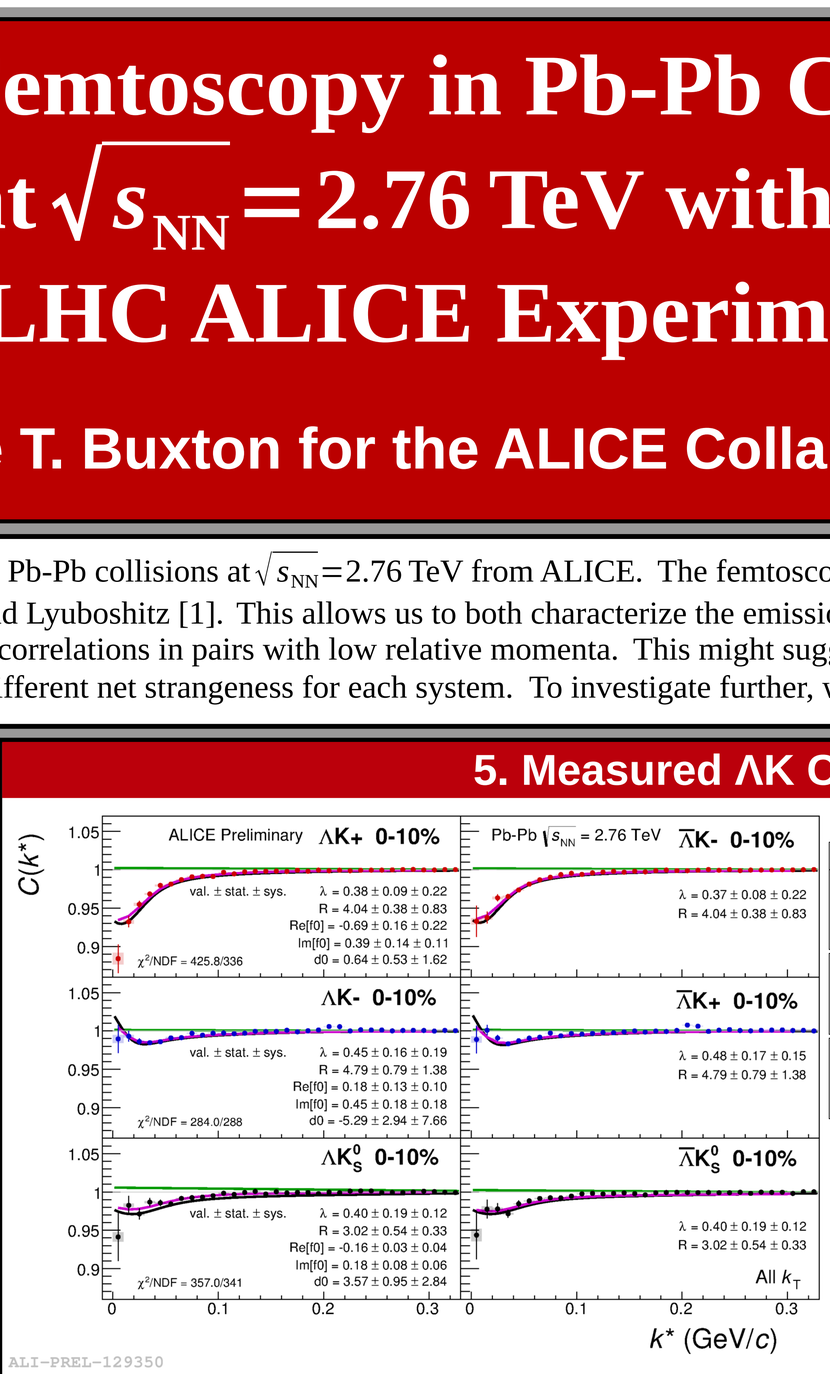
4. Ask me about!

- Residual correlations from feed-down
  - ex. $\Sigma^0K \to \Lambda K$, $\Xi^{0(ch)}K \to \Lambda K$, $\Omega^{ch}K \to \Lambda K$, etc.
- New treatment of non-flat background
  - Model with THERMINATOR
  - Attempt to eradicate with particle rotation method

References

[1] R. Lednicky and V. L. Lyuboshitz. *Sov. J. Nucl. Phys.* 35:770 (1982)
[2] S. Koonin. *Phys. Lett. B* 70:43 (1977)
[3] S. Pratt, T. Csörgő, and J. Zimányi. *Phys. Rev. C* 42:2646 (1990)
[4] R. Lednicky. *Phys. Part. Nucl.* 40:307 (2009)
[5] J Adam et al. [ALICE Collaboration] *Phys. Rev. C* 92:054908 (2015)

5. Measured ΛK Correlations with Fits



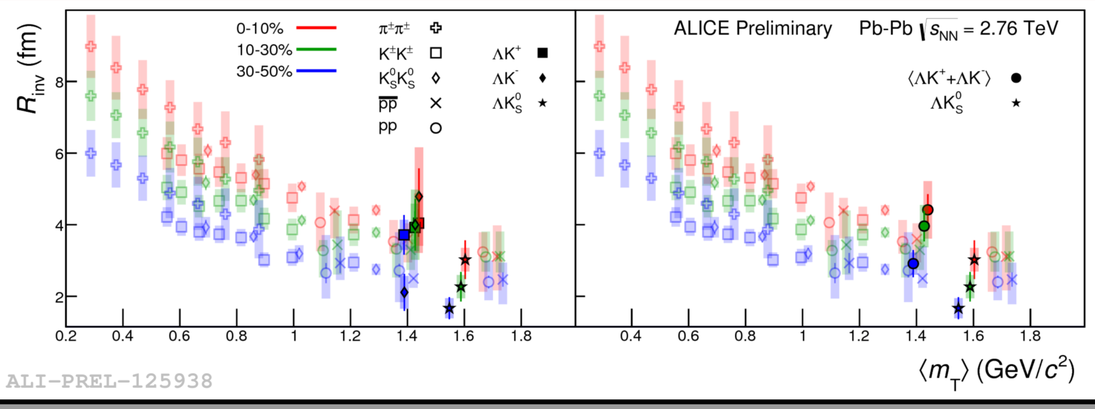
Fit Parameters (value ± statistical error ± systematic error)

Pair Type	Centrality	R	$\Re f_0$	$\Im f_0$	d_0
ΛK^+ & $\bar{\Lambda}K^-$	0-10%	4.04 ± 0.38 ± 0.83			
	10-30%	3.92 ± 0.45 ± 0.66	-0.69 ± 0.16 ± 0.22	0.39 ± 0.14 ± 0.11	0.64 ± 0.53 ± 1.62
	30-50%	3.72 ± 0.55 ± 0.42			
ΛK^- & $\bar{\Lambda}K^+$	0-10%	4.79 ± 0.79 ± 1.38			
	10-30%	4.00 ± 0.72 ± 0.98	0.18 ± 0.13 ± 0.10	0.45 ± 0.18 ± 0.18	-5.29 ± 2.94 ± 7.66
	30-50%	2.11 ± 0.52 ± 0.46			
ΛK^0_S & $\bar{\Lambda}K^0_S$	0-10%	3.02 ± 0.54 ± 0.33			
	10-30%	2.27 ± 0.41 ± 0.32	-0.16 ± 0.03 ± 0.04	0.18 ± 0.08 ± 0.06	3.57 ± 0.95 ± 2.84
	30-50%	1.67 ± 0.30 ± 0.28			

- For a given pair and conjugate:
  - Radii shared amongst like centralities
    - Only 0-10% shown in figure
  - Scattering parameters (f_0, d_0) shared amongst all
  - Each correlation function has a unique normalization parameter
- ΛK^{ch} analyses
  - Each correlation has a unique λ parameter
- ΛK^0_S analyses
  - All share a single λ parameter to aid in the fitting process

Green = fit to non-flat, non-femtoscopic, background
Black = "raw", uncorrected, fit
Magenta = final fit; momentum resolution and non-flat background corrections applied

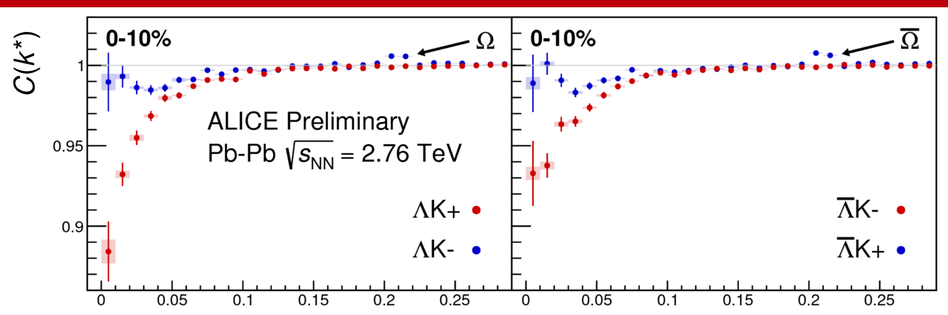
6. m_T Scaling of Radii



R_{inv} parameters vs m_T for (preliminary) ΛK pairs with ALICE results [5] for $\pi^{ch}\pi^{ch}$, $K^{ch}K^{ch}$, $K^0_SK^0_S$, pp, and $\bar{p}\bar{p}$. ΛK+ (with ΛK-) and ΛK- (with ΛK+) are shown separately in the left, and averaged in the right. Statistical (lines) and systematic (boxes) uncertainties are shown.

$$m_T^2 = \left(\frac{m_{inv}}{2}\right)^2 + \left(\frac{1}{2}\left|\boldsymbol{p}_{T,1} + \boldsymbol{p}_{T,2}\right|\right)^2$$

7. ΛK+ vs. ΛK-



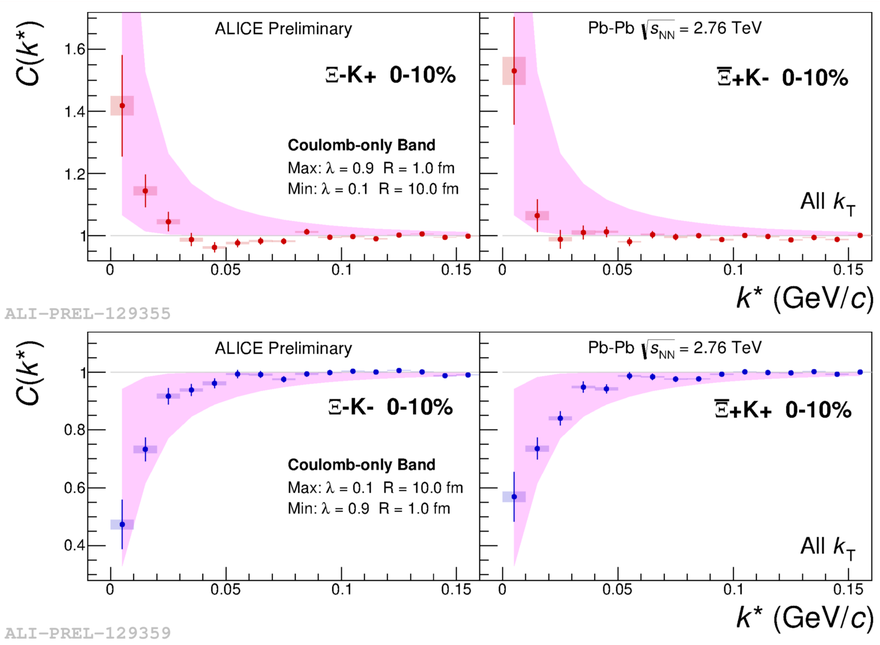
Sample correlation functions for the 0-10% centrality bin. (Left) ΛK+ with ΛK-; (Right) $\bar{\Lambda}$K- with $\bar{\Lambda}$K+.

- ΛK+ shows greater suppression at low k^* compared to ΛK-
  - Effect arising from $s\bar{s}$ annihilation compared to $u\bar{u}$?
  - Or S=0 ΛK+ system has more interaction channels than S=-2 ΛK-?
- Ξ^0K^{ch} ideal to further probe $s\bar{s}$ vs. $u\bar{u}$
  - Impossible: $\Xi^0 \to \Lambda\pi^0$
- $\Xi^{ch}K^{ch}$ is next best option

$\Xi^0 = uss$

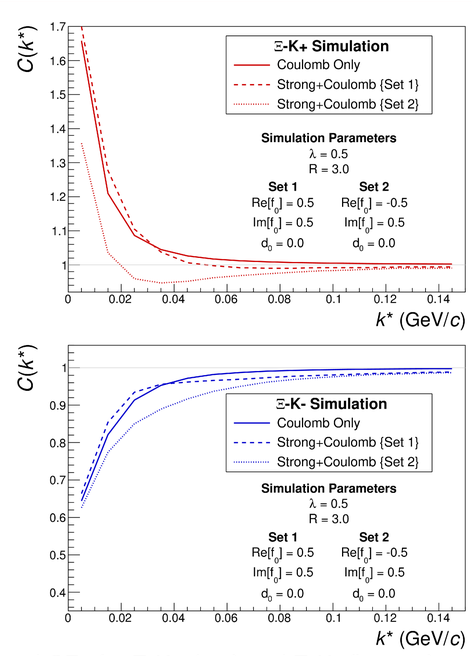
$\Xi^- = dss$

8. $\Xi^{ch}K^{ch}$ Data vs. Coulomb-only Simulation



$\Xi^{ch}K^{ch}$ correlation functions for 0-10% centrality. **Magenta** band is spanned by two Coulomb-only simulated CFs, with λ and R values listed (curves from intermediate values are within band). The Ξ-K+ data (top left) cannot be described by Coulomb-only picture. Is the dip below unity the strong force showing itself?

9. Effect of Strong Interaction



Simulated CFs for Ξ-K+ (top) and Ξ-K- (bottom) systems. Solid lines represent Coulomb-only simulations, and dashed lines also include the strong interaction. Two sets of scattering parameters are shown.

10. Summary

- ΛK femtoscopic analysis presented for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
- First measurement of ΛK scattering parameters
- Source radii extracted for 0-10%, 10-30% and 30-50% centralities
  - Follow approximate m_T-scaling observed in other systems
- Striking difference in ΛK+ and ΛK- correlations observed at low k^*
- Preliminary results shown for $\Xi^{ch}K^{ch}$ system
  - Hope to gain insight to difference in ΛK+ and ΛK-
  - Ξ-K+ cannot be described by a Coulomb-only picture

11. Outlook

- Finish ΛK analysis and publication
  - Finalize treatment of non-flat background
    - Model with THERMINATOR
    - or build background from same-event pairs, by rotating one particle by 180° in the transverse plane
- Continue work on $\Xi^{ch}K^{ch}$ analysis
  - Fitter greatly complicated by Coulomb interaction
- Use $\Xi^{ch}K^{ch}$ analysis to help ΛK by either
  - (a) removing all Λ's from Ξ^{ch} before fitting, or
  - (b) using $\Xi^{ch}K^{ch}$ data to quantify feed-down