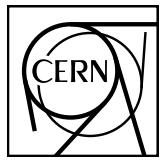


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Lambda-Kaon and Cascade-Kaon Femtoscopy in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ from the LHC ALICE Experiment

Jesse T. Buxton¹

1. Department of Physics, The Ohio State University, Columbus, Ohio, USA

Email: jesse.thomas.buxton@cern.ch

Abstract

We present results from a femtoscopic analysis of Lambda-Kaon correlations in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ by the ALICE experiment at the LHC. All pair combinations of Λ and $\bar{\Lambda}$ with K^+ , K^- and K_S^0 are analyzed. The femtoscopic correlations are the result of strong final-state interactions, and are fit with a parametrization based on a model by R. Lednicky and V. L. 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^+ ($\bar{\Lambda} K^-$) and ΛK^- ($\bar{\Lambda} K^+$) correlations in pairs with low relative momenta ($k^* \lesssim 100 \text{ MeV}$). Additionally, the average of the ΛK^+ ($\bar{\Lambda} K^-$) and ΛK^- ($\bar{\Lambda} K^+$) correlation functions is consistent with our ΛK_S^0 ($\bar{\Lambda} K_S^0$) measurement. The results suggest an effect arising from different quark-antiquark interactions in the pairs, i.e. $s\bar{s}$ in ΛK^+ ($\bar{\Lambda} K^-$) and $u\bar{u}$ in ΛK^- ($\bar{\Lambda} K^+$). To gain further insight into this hypothesis, we currently are conducting a Ξ -K femtoscopic analysis.

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12 1 Introduction

13 We present results from a femtoscopic analysis of Lambda-Kaon correlations in Pb-Pb collisions at $\sqrt{s_{NN}}$
 14 = 2.76 TeV by the ALICE experiment at the LHC. All pair combinations of Λ and $\bar{\Lambda}$ with K^+ , K^- and
 15 K_S^0 are analyzed. The femtoscopic correlations are the result of strong final-state interactions, and are
 16 fit with a parametrization based on a model by R. Lednicky and V. L. Lyuboshitz [1]. This allows us to
 17 both characterize the emission source and measure the scattering parameters for the particle pairs. We
 18 observe a large difference in the Λ - K^+ ($\bar{\Lambda}$ - K^-) and Λ - K^- ($\bar{\Lambda}$ - K^+) correlations in pairs with low relative
 19 momenta ($k^* \lesssim 100$ MeV). Additionally, the average of the Λ - K^+ ($\bar{\Lambda}$ - K^-) and Λ - K^- ($\bar{\Lambda}$ - K^+) correlation
 20 functions is consistent with our Λ - K_S^0 ($\bar{\Lambda}$ - K_S^0) measurement. The results suggest an effect arising from
 21 different quark-antiquark interactions in the pairs, i.e. $s\bar{s}$ in Λ - K^+ ($\bar{\Lambda}$ - K^-) and $u\bar{u}$ in Λ - K^- ($\bar{\Lambda}$ - K^+). To
 22 gain further insight into this hypothesis, we currently are conducting a Ξ -K femtoscopic analysis.

23 2 Data Sample and Software

24 2.1 Data Sample

25 The analysis used “pass 2” reconstructed Pb-Pb data from LHC11h (AOD145). The runlist was selected
 26 from runs with global quality tag “1” in the ALICE Run Condition Table. Approximately 40 million
 27 combined central, semi-central, and minimum bias events were analyzed. Runs from both positive (++)
 28 and negative (--) magnetic field polarity settings were used.

29 Run list: 170593, 170572, 170388, 170387, 170315, 170313, 170312, 170311, 170309, 170308, 170306,
 30 170270, 170269, 170268, 170230, 170228, 170207, 170204, 170203, 170193, 170163, 170159, 170155,
 31 170091, 170089, 170088, 170085, 170084, 170083, 170081, 170040, 170027, 169965, 169923, 169859,
 32 169858, 169855, 169846, 169838, 169837, 169835, 169591, 169590, 169588, 169587, 169586, 169557,
 33 169555, 169554, 169553, 169550, 169515, 169512, 169506, 169504, 169498, 169475, 169420, 169419,
 34 169418, 169417, 169415, 169411, 169238, 169167, 169160, 169156, 169148, 169145, 169144, 169138,
 35 169099, 169094, 169091, 169045, 169044, 169040, 169035, 168992, 168988, 168826, 168777, 168514,
 36 168512, 168511, 168467, 168464, 168460, 168458, 168362, 168361, 168342, 168341, 168325, 168322,
 37 168311, 168310, 168315, 168108, 168107, 168105, 168076, 168069, 167988, 167987, 167985, 167920,
 38 167915

39 Analysis was also performed on the LHC12a17a_fix (AOD149) Monte Carlo HIJING events for certain
 40 checks. THERMINATOR2 was also used for certain aspects, such as transform matrices described feed-
 41 down contributions.

42 2.2 Software

43 The analysis was performed on the PWGCF analysis train using AliRoot v5-08-18-1 and AliPhysics
 44 vAN-20161027-1.

45 The main classes utilized include: AliFemtoVertexMultAnalysis, AliFemtoEventCutEstimators, AliFem-
 46 toESDTrackCutNSigmaFilter, AliFemtoV0TrackCutNSigmaFilter, AliFemtoXiTrackCut, AliFemtoV0PairCut,
 47 AliFemtoV0TrackPairCut, AliFemtoXiTrackPairCut, and AliFemtoAnalysisLambdaKaon. All of these
 48 classes are contained in /AliPhysics/PWGCF/FEMTOSCOPY/AliFemto and .../AliFemtoUser.

49 3 Data Selection

50 3.1 Event Selection and Mixing

51 The events used in this study were selected with the class AliFemtoEventCutEstimators according to the
 52 following criteria:

- 53 – Triggers
- 54 – minimum bias (kMB)
- 55 – central (kCentral)
- 56 – semi-central (kSemiCentral)
- 57 – z-position of reconstructed event vertex must be within 10 cm of the center of the ALICE detector
- 58 – the event must contain at least one particle of each type from the pair of interest
- 59 The event mixing was handled by the AliFemtoVertexMultAnalysis class, which only mixes events with
- 60 like vertex position and centrality. The following criteria were used for event mixing:
- 61 – Number of events to mix = 5
- 62 – Vertex position bin width = 2 cm
- 63 – Centrality bin width = 5
- 64 The AliFemtoEventReaderAODChain class is used to read the events. Event flattening is not currently
- 65 used. FilterBit(7). The centrality is determined by the “V0M” method of AliCentrality, set by calling Al-
- 66 iFemtoEventReaderAOD::SetUseMultiplicity(kCentrality). I utilize the SetPrimaryVertexCorrectionT-
- 67 PCPoints switch, which causes the reader to shift all TPC points to be relative to the event vertex.
- 68 **3.2 K[±] Track Selection**
- 69 Charged kaons are identified using the AliFemtoESDTrackCutNSigmaFilter class. The specific cuts used
- 70 in this analysis are as follows:
- 71 Track Selection:
- 72 – Kinematic range:
- 73 – $0.14 < p_T < 1.5 \text{ GeV}/c$
- 74 – $|\eta| < 0.8$
- 75 – FilterBit(7)
- 76 – TPC tracks
- 77 – Track Quality
- 78 – Minimum number of clusters in the TPC (fminTPCncls) = 80
- 79 – Maximum allowed χ^2/N_{DOF} for ITS clusters = 3.0
- 80 – Maximum allowed χ^2/N_{DOF} for TPC clusters = 4.0
- 81 – Primary Particle Selection:
- 82 – Maximum XY impact parameter = 2.4 cm
- 83 – Maximum Z impact parameter = 3.0 cm
- 84 – Remove particles with any kink labels (fRemoveKinks = true)
- 85 – Maximum allowed sigma to primary vertex (fMaxSigmaToVertex) = 3.0

86 K $^\pm$ Identification:

87 – PID Probabilities:

- 88 – K: > 0.2
- 89 – π : < 0.1
- 90 – μ : < 0.8
- 91 – p: < 0.1

92 – Most probable particle type must be Kaon (fMostProbable=3)

93 – TPC and TOF N $_\sigma$ cuts:

- 94 – $p < 0.4 \text{ GeV}/c$: N $_{\sigma K, \text{TPC}} < 2$
- 95 – $0.4 < p < 0.45 \text{ GeV}/c$: N $_{\sigma K, \text{TPC}} < 1$
- 96 – $0.45 < p < 0.8 \text{ GeV}/c$: N $_{\sigma K, \text{TPC}} < 3 \& N_{\sigma K, \text{TOF}} < 2$
- 97 – $0.8 < p < 1.0 \text{ GeV}/c$: N $_{\sigma K, \text{TPC}} < 3 \& N_{\sigma K, \text{TOF}} < 1.5$
- 98 – $p > 1.0 \text{ GeV}/c$: N $_{\sigma K, \text{TPC}} < 3 \& N_{\sigma K, \text{TOF}} < 1$

99 – Electron Rejection: Reject if N $_{\sigma e^-, \text{TPC}} < 3$

100 – Pion Rejection: Reject if:

- 101 – $p < 0.65 \text{ GeV}/c$
 - 102 * if TOF and TPC available: N $_{\sigma \pi, \text{TPC}} < 3 \& N_{\sigma \pi, \text{TOF}} < 3$
 - 103 * else
 - 104 · $p < 0.5 \text{ GeV}/c$: N $_{\sigma \pi, \text{TPC}} < 3$
 - 105 · $0.5 < p < 0.65 \text{ GeV}/c$: N $_{\sigma \pi, \text{TPC}} < 2$
- 106 – $0.65 < p < 1.5 \text{ GeV}/c$: N $_{\sigma \pi, \text{TPC}} < 5 \& N_{\sigma \pi, \text{TOF}} < 3$
- 107 – $p > 1.5 \text{ GeV}/c$: N $_{\sigma \pi, \text{TPC}} < 5 \& N_{\sigma \pi, \text{TOF}} < 2$

108 The purity of the K $^\pm$ collections was estimated using the MC data, for which the true identity of each
109 reconstructed K $^\pm$ particle is known. Therefore, the purity may be estimated as:

$$\text{Purity}(K^\pm) = \frac{N_{\text{true}}}{N_{\text{reconstructed}}} \quad (1)$$

110 Purity(K $^+$) \approx Purity(K $^-$) \approx 97%

111 3.3 V0 Selection

112 Λ ($\bar{\Lambda}$) and K $_S^0$ are neutral particles which cannot be directly detected, but must instead be reconstructed
113 through detection of their decay products, or daughters. This process is illustrated in Figure 1. In
114 general, particles which are topologically reconstructed in this fashion are called V0 particles. The
115 class AliFemtoV0TrackCutNSigmaFilter (which is an extension of AliFemtoV0TrackCut) is used to
116 reconstruct the V0s.

117 In order to obtain a true and reliable signal, one must ensure good purity of the V0 collection. The purity
118 of the collection is calculated as:

$$\text{Purity} = \frac{\text{Signal}}{\text{Signal} + \text{Background}} \quad (2)$$

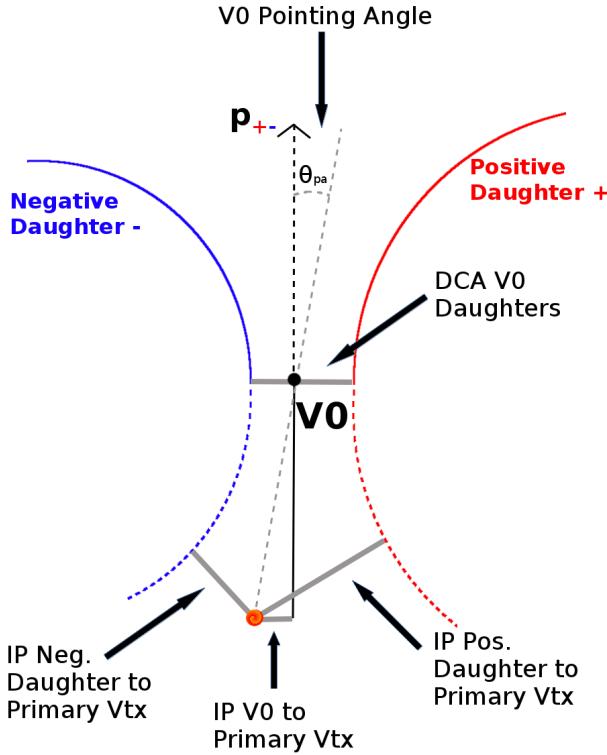


Fig. 1: V0 Reconstruction

119 To obtain both the signal and background, the invariant mass distribution (m_{inv}) of all V0 candidates
 120 must be constructed immediately before the final invariant mass cut. Examples of such distributions can
 121 be found in Figures 3 and 5. It is vital that this distribution be constructed immediately before the final
 122 m_{inv} cut, otherwise it would be impossible to estimate the background. As shown in Figures 3 and 5, the
 123 background is fit (with a polynomial) outside of the peak region of interest to obtain an estimate for the
 124 background within the region. Within the m_{inv} cut limits, the background is the region below the fit while
 125 the signal is the region above the fit.

126 3.3.1 **Λ Reconstruction**

127 The following cuts were used to select good Λ ($\bar{\Lambda}$) candidates:

128 1. Daughter Particle Cuts

129 (a) Cuts Common to Both Daughters

- 130 i. $|\eta| < 0.8$
- 131 ii. SetTPCnclsDaughters(80)
- 132 iii. SetStatusDaughters(AliESDtrack::kTPCrefit)
- 133 iv. DCA πp Daughters < 0.4 cm

134 (b) Pion Specific Daughter Cuts

- 135 i. $p_T > 0.16$ GeV/c
- 136 ii. DCA to prim vertex > 0.3 cm
- 137 iii. TPC and TOF N σ Cuts
 - 138 A. $p < 0.5$ GeV/c : N $\sigma_{\text{TPC}} < 3$
 - 139 B. $p > 0.5$ GeV/c :

- if TOF & TPC available: $N\sigma_{\text{TPC}} < 3$ & $N\sigma_{\text{TOF}} < 3$
- else $N\sigma_{\text{TOF}} < 3$

142 (c) Proton Specific Daughter Cuts

- i. $p_T > 0.5(p)[0.3(\bar{p})] \text{ GeV}/c$
- ii. DCA to prim vertex $> 0.1 \text{ cm}$
- iii. TPC and TOF $N\sigma$ Cuts
 - A. $p < 0.8 \text{ GeV}/c : N\sigma_{\text{TPC}} < 3$
 - B. $p > 0.8 \text{ GeV}/c :$
 - if TOF & TPC available: $N\sigma_{\text{TPC}} < 3$ & $N\sigma_{\text{TOF}} < 3$
 - else $N\sigma_{\text{TOF}} < 3$

150 2. V0 Cuts

- (a) $|\eta| < 0.8$
- (b) $p_T > 0.4 \text{ GeV}/c$
- (c) $|m_{\text{inv}} - m_{\text{PDG}}| < 3.8 \text{ MeV}$
- (d) DCA to prim. vertex $< 0.5 \text{ cm}$
- (e) Cosine of pointing angle > 0.9993
- (f) OnFlyStatus = false
- (g) Decay Length $< 60 \text{ cm}$

155 3. Shared Daughter Cut for V0 Collection

- Iterate through V0 collection to ensure that no daughter is used in more than one V0 candidate

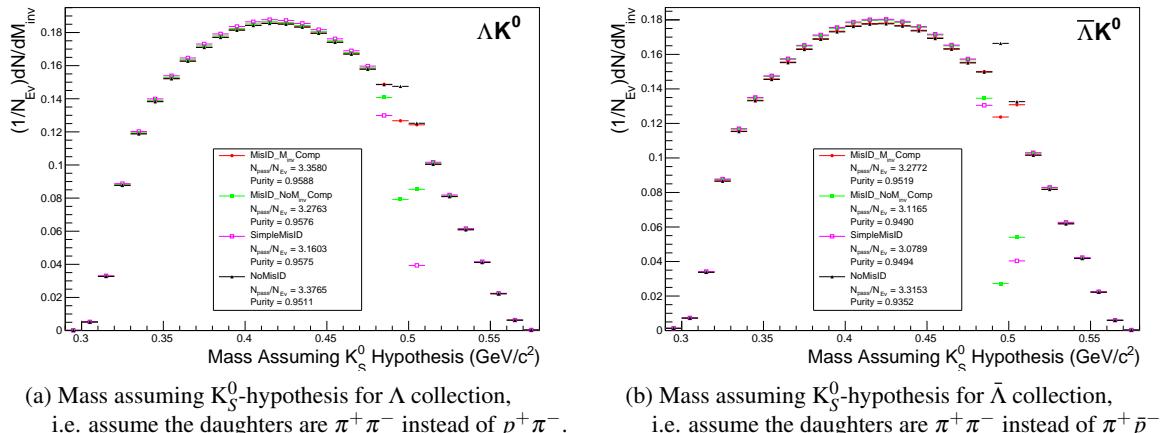


Fig. 2: Mass assuming K_S^0 -hypothesis for V0 candidates passing all Λ (2a) and $\bar{\Lambda}$ (2b) cuts. The “NoMisID” distribution (black triangles) uses the V0 finder without any attempt to remove misidentified K_S^0 . The slight peak in the “NoMisID” distribution around $m_{\text{inv}} = 0.5 \text{ GeV}/c^2$ contains misidentified K_S^0 particles in our $\Lambda(\bar{\Lambda})$ collection. “SimpleMisID” (pink squares) simply cuts out the entire peak, which throws away some good Λ and $\bar{\Lambda}$ particles. “MisID_NoM_{inv}Comp” (green squares) uses the misidentification cut outlined in the text, but does not utilize the invariant mass comparison method. “MisID_M_{inv}Comp” (red circles) utilizes the full misidentification methods, and is currently used for this analysis. “ $N_{\text{pass}}/N_{\text{ev}}$ ” is the total number of $\Lambda(\bar{\Lambda})$ particles found, normalized by the total number of events. The purity of the collection is also listed.

Figure 2a shows the mass assuming K_S^0 hypothesis for the Λ collection, i.e. assume the daughters are $\pi^+\pi^-$ instead of $\pi^+\bar{p}$. Figure 2b is a similar plot, but is for the $\bar{\Lambda}$ collection, i.e. assume the daughters are $\pi^+\pi^-$ instead of $\pi^+\bar{p}$. The K_S^0 contamination is visible, although not profound, in both in the slight peaks around $m_{\text{inv}} = 0.497 \text{ GeV}/c^2$. If one simply cuts out the entire peak, good Λ particles will be lost. Ideally, the Λ selection and K_S^0 misidentification cuts are selected such that the peak is removed from this plot while leaving the distribution continuous. To attempt to remove these K_S^0 contaminations without throwing away good Λ and $\bar{\Lambda}$ particles, the following misidentification cuts are imposed; a $\Lambda(\bar{\Lambda})$ candidate is rejected if all of the following criteria are satisfied:

- $|m_{\text{inv}, K_S^0 \text{ Hypothesis}} - m_{\text{PDG}, K_S^0}| < 9.0 \text{ MeV}/c^2$
- Positive and negative daughters pass π daughter cut implemented for K_S^0 reconstruction
- $|m_{\text{inv}, K_S^0 \text{ Hypothesis}} - m_{\text{PDG}, K_S^0}| < |m_{\text{inv}, \Lambda(\bar{\Lambda}) \text{ Hypothesis}} - m_{\text{PDG}, \Lambda(\bar{\Lambda})}|$

Figure 3 shows the invariant mass (m_{inv}) distribution of all $\Lambda(\bar{\Lambda})$ candidates immediately before the final invariant mass cut. These distributions are used to calculate the collection purities. The Λ and $\bar{\Lambda}$ purities are found to be: $\text{Purity}(\Lambda) \approx \text{Purity}(\bar{\Lambda}) \approx 95\%$.

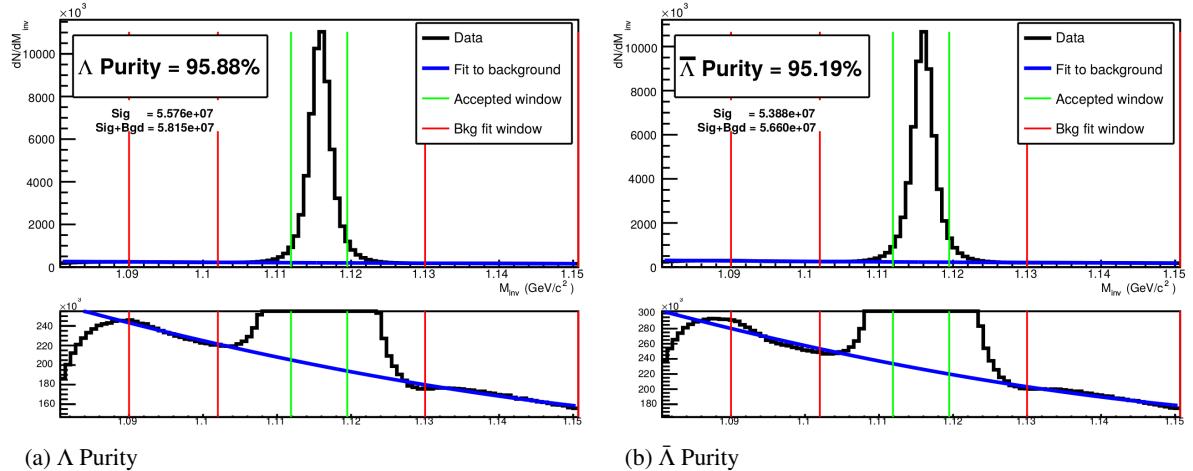


Fig. 3: Invariant mass (m_{inv}) distribution of all Λ (a) and $\bar{\Lambda}$ (b) candidates immediately before the final invariant mass cut. The bottom figures are zoomed to show the background with fit. The vertical green lines represent the m_{inv} cuts used in the analyses, the red vertical lines delineate the region over which the background was fit, and the blue line shows the background fit. These distributions are used to calculate the collection purities, $\text{Purity}(\Lambda) \approx \text{Purity}(\bar{\Lambda}) \approx 95\%$.

3.3.2 K_S^0 Reconstruction

The following cuts were used to select good K_S^0 candidates:

1. Pion Daughter Cuts

- (a) $|\eta| < 0.8$
- (b) SetTPCnclsDaughters(80)
- (c) SetStatusDaughters(AliESDtrack::kTPCrefic)
- (d) DCA $\pi^+\pi^-$ Daughters $< 0.3 \text{ cm}$

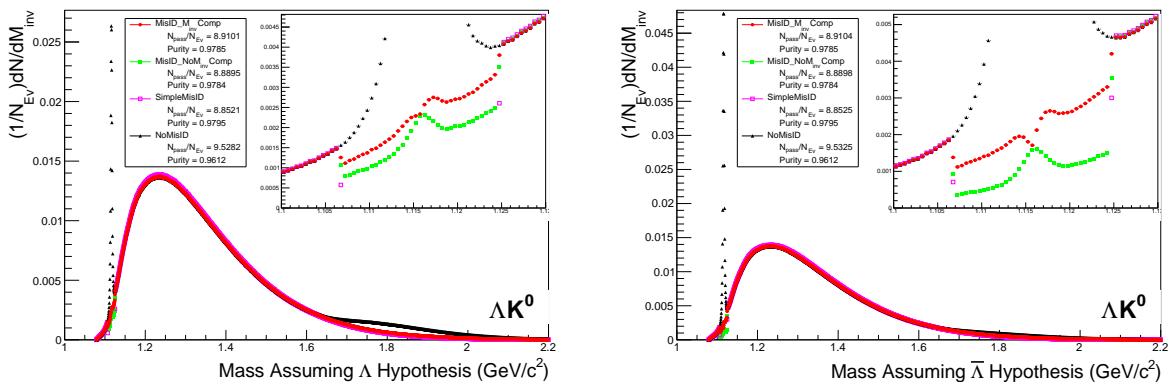
- (e) $p_T > 0.15 \text{ GeV}/c$
(f) DCA to prim vertex $> 0.3 \text{ cm}$
(g) TPC and TOF $N\sigma$ Cuts
i. $p < 0.5 \text{ GeV}/c : N\sigma_{\text{TPC}} < 3$
ii. $p > 0.5 \text{ GeV}/c :$
– if TOF & TPC available: $N\sigma_{\text{TPC}} < 3 \& N\sigma_{\text{TOF}} < 3$
– else $N\sigma_{\text{TOF}} < 3$

2. K_S^0 Cuts

- (a) $|\eta| < 0.8$
(b) $p_T > 0.2 \text{ GeV}/c$
(c) $m_{\text{PDG}} - 13.677 \text{ MeV} < m_{\text{inv}} < m_{\text{PDG}} + 2.0323 \text{ MeV}$
(d) DCA to prim. vertex $< 0.3 \text{ cm}$
(e) Cosine of pointing angle > 0.9993
(f) OnFlyStatus = false
(g) Decay Length $< 30 \text{ cm}$

3. Shared Daughter Cut for V0 Collection

- Iterate through V0 collection to ensure that no daughter is used in more than one V0 candidate



(a) Mass assuming Λ -hypothesis for K_S^0 collection, i.e. assume the daughters are $p^+\pi^-$ instead of $\pi^+\pi^-$.

(b) Mass assuming $\bar{\Lambda}$ -hypothesis for K_S^0 collection, i.e. assume the daughters are $\pi^+\bar{p}^-$ instead of $\pi^+\pi^-$.

Fig. 4: Mass assuming Λ -hypothesis (4a) and $\bar{\Lambda}$ -hypothesis (4b) for K_S^0 collection. The “NoMisID” distribution (black triangles) uses the V0 finder without any attempt to remove misidentified Λ and $\bar{\Lambda}$. The peak in the “NoMisID” distribution around $m_{\text{inv}} = 1.115 \text{ GeV}/c^2$ contains misidentified Λ (4a) and $\bar{\Lambda}$ (4b) particles in our K_S^0 collection. “SimpleMisID” (pink squares) simply cuts out the entire peak, which throws away some good K_S^0 particles. “MisID_NoM_{inv}Comp” (green squares) uses the misidentification cut outlined in the text, but does not utilize the invariant mass comparison method. “MisID_M_{inv}Comp” (red circles) utilizes the full misidentification methods, and is currently used for this analysis. “ $N_{\text{pass}}/N_{\text{ev}}$ ” is the total number of K_S^0 particles found, normalized by the total number of events. The purity of the collection is also listed. Also note, the relative excess of the “NoMisID” distribution around $1.65 < m_{\text{inv}} < 2.1 \text{ GeV}/c^2$ shows misidentified $\bar{\Lambda}$ (4a) and Λ (4b) particles in our K_S^0 collection.

As can be seen in Figure 4, some misidentified Λ and $\bar{\Lambda}$ particles contaminate our K_S^0 sample. Figure 4a shows the mass assuming Λ -hypothesis for the K_S^0 collection, i.e. assume the daughters are $p^+\pi^-$

instead of $\pi^+\pi^-$. Figure 4b is similar, but shows the mass assuming $\bar{\Lambda}$ hypothesis for the collection, i.e. assume the daughters are $\pi^+\bar{p}^-$ instead of $\pi^+\pi^-$. The Λ contamination can be seen in 4a, and the $\bar{\Lambda}$ contamination in 4b, in the peaks around $m_{\text{inv}} = 1.115 \text{ GeV}/c^2$. Additionally, the $\bar{\Lambda}$ contamination is visible in Figure 4a, and the Λ contamination visible in Figure 4b, in the region of excess around $1.65 < m_{\text{inv}} < 2.1 \text{ GeV}/c^2$. This is confirmed as the number of misidentified Λ particles in the sharp peak of Figure 4a (misidentified $\bar{\Lambda}$ particles in the sharp peak of Figure 4b) approximately equals the excess found in the $1.65 < m_{\text{inv}} < 2.1 \text{ GeV}/c^2$ region of Figure 4a (Figure 4b).

The peaks around $m_{\text{inv}} = 1.115 \text{ GeV}/c^2$ in Figure 4 contain both misidentified Λ ($\bar{\Lambda}$) particles and good K_S^0 . If one simply cuts out the entire peak, some good K_S^0 particles will be lost. Ideally, the K_S^0 selection and $\Lambda(\bar{\Lambda})$ misidentification cuts can be selected such that the peak is removed from this plot while leaving the distribution continuous. To attempt to remove these Λ and $\bar{\Lambda}$ contaminations without throwing away good K_S^0 particles, the following misidentification cuts are imposed; a K_S^0 candidate is rejected if all of the following criteria are satisfied (for either Λ or $\bar{\Lambda}$ hypothesis):

- $|m_{\text{inv}, \Lambda(\bar{\Lambda}) \text{ Hypothesis}} - m_{\text{PDG}, \Lambda(\bar{\Lambda})}| < 9.0 \text{ MeV}/c^2$
- Positive daughter passes $p^+(\pi^+)$ daughter cut implemented for $\Lambda(\bar{\Lambda})$ reconstruction
- Negative daughter passes $\pi^-(\bar{p}^-)$ daughter cut implemented by $\Lambda(\bar{\Lambda})$ reconstruction
- $|m_{\text{inv}, \Lambda(\bar{\Lambda}) \text{ Hypothesis}} - m_{\text{PDG}, \Lambda(\bar{\Lambda})}| < |m_{\text{inv}, K_S^0 \text{ Hypothesis}} - m_{\text{PDG}, K_S^0}|$

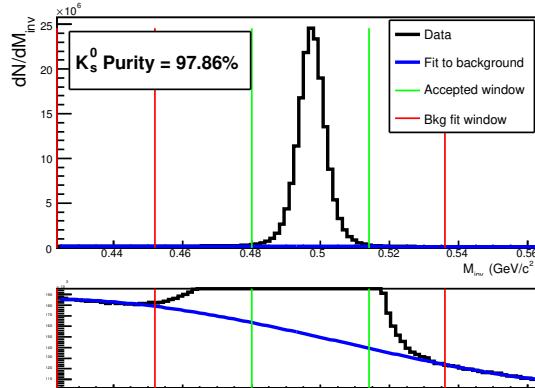


Fig. 5: Invariant mass (m_{inv}) distribution of all K_S^0 candidates immediately before the final invariant mass cut. The bottom figure is zoomed to show the background with fit. The vertical green lines represent the m_{inv} cut used in the analyses, the red vertical lines delineate the region over which the background was fit, and the blue line shows the background fit. This distribution is used to calculate the collection purity, $\text{Purity}(K_S^0) \approx 98\%$.

3.3.3 V0 Purity Background Estimation

As previously stated, the backgrounds in the m_{inv} distributions are fit with a polynomial outside of the final cut region in an attempt to estimate the background within the cut region. As this estimation of the background under the mass peak is vital in our estimation of our V0 purity, it is important for us to ensure that our estimation is accurate. More specifically, it is necessary that we ensure the background is well described by a polynomial fit within the cut region.

To better understand our background, we studied V0 candidates reconstructed with daughters from different events. These mixed-event V0s certainly do not represent real, physical V0s (a single V0 cannot have daughters living in two different events!), but rather represents a large portion of the background creeping into our analysis.

227 The standard AliFemto framework is not equipped to handle this situation, as most are not interested
 228 in these fake-V0s. Therefore, we built the AliFemtoV0PurityBgdEstimator class. In addition to finding
 229 fake-V0s using mixed-event daughters, we also used our AliFemtoV0PurityBgdEstimator class to
 230 find real-V0s using same-event daughters. The purpose here was to compare our simple V0 finder (in
 231 AliFemtoV0PurityBgdEstimator) to the established V0 finder used in standard AliFemto analyses.

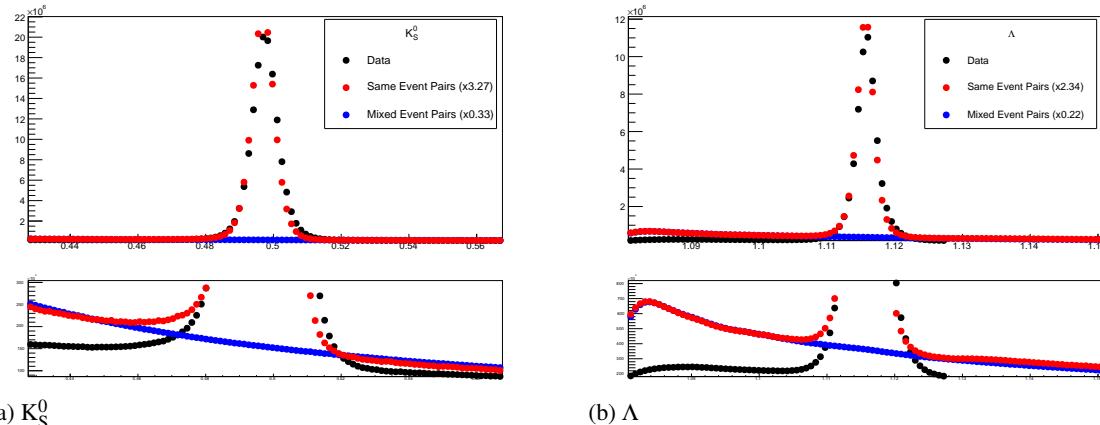


Fig. 6: V0 Purity Background Estimation. The black points, marked "Data", correspond to real V0s found using the standard V0-finder (i.e. the V0s used in my analyses). The red points, marked "Same Event Pairs", show real V0s reconstructed with our personal V0-finder in AliFemtoV0PurityBgdEstimator. These data are scaled by a factor (listed in the legend) to match their *Signal + Background* value in the cut region with that of the data. The blue points, marked "Mixed Event Pairs", show fake-V0s reconstructed with our personal V0-finder using mixed-event daughters. The blue points are scaled by a factor (listed in the legend) to closely match the red points in the side-band region.

Figure 6 shows the results of our study. In the figures, the black points, marked "Data", correspond to V0s found using the standard V0-finder, and to the V0s used in my analyses. The red points show real V0s reconstructed with our personal V0-finder (in AliFemtoV0PurityBgdEstimator) using same-event daughters, and the blue points show fake-V0s reconstructed with our personal V0-finder using mixed-event daughters. Both the red and blue points have been scaled by different factors (listed in the figure's legends) to nicely align all three data on a single plot.

Figure 6 shows that our personal V0-finder does a good, but not perfect, job of matching the shape of the m_{inv} plots obtained from the data. The scale factor listed in the legend reveals that we are only finding 1/3 - 1/2 of the V0s found by the standard V0-finder. These two points are not of concern, as our purpose here was to gain a sense of the broad shape of the background. It is revealed in Fig. 6, when studying the red and blue points, that the background distribution within the mass peak region is simply a smooth connection of the backgrounds outside of the cut region. Therefore, our method of fitting the background outside of the cut region, fitting with a smooth polynomial, and extrapolating to the cut region is justified.

245 3.4 Cascade Reconstruction

246 Our motivation for studying ΞK^\pm systems is to hopefully better understand the striking difference in the
247 ΛK^+ and ΛK^- data at low k^* (Figure 13).

The reconstruction of Ξ particles is one step above V0 reconstruction. V0 particles are topologically reconstructed by searching for the charged daughters' tracks into which they decay. With Ξ particles, we search for the V0 particle and charged daughter into which the Ξ decays. In the case of Ξ^- , we search for the Λ (V0) and π^- (track) daughters. We will refer to this π as the “bachelor π ”.

252 The following cuts were used to select good Ξ^- ($\bar{\Xi}^+$) candidates:

- 253 1. V0 Daughter Reconstruction
- 254 (a) V0 Daughter Particle Cuts
- 255 i. Cuts Common to Both Daughters
- 256 A. $|\eta| < 0.8$
- 257 B. SetTPCnclsDaughters(80)
- 258 C. SetStatusDaughters(AliESDtrack::kTPCrefic)
- 259 D. SetMaxDcaV0Daughters(0.4)
- 260 ii. Pion Specific Daughter Cuts
- 261 A. $p_T > 0.16$
- 262 B. DCA to prim vertex > 0.3
- 263 iii. Proton Specific Daughter Cuts
- 264 A. $p_T > 0.5(p) [0.3(\bar{p})] \text{ GeV}/c$
- 265 B. DCA to prim vertex > 0.1
- 266 (b) V0 Cuts
- 267 i. $|\eta| < 0.8$
- 268 ii. $p_T > 0.4 \text{ GeV}/c$
- 269 iii. $|m_{inv} - m_{PDG}| < 3.8 \text{ MeV}$
- 270 iv. DCA to prim. vertex $> 0.2 \text{ cm}$
- 271 v. Cosine of pointing angle to Ξ decay vertex > 0.9993
- 272 vi. OnFlyStatus = false
- 273 vii. Decay Length $< 60 \text{ cm}$
- 274 viii. The misidentification cuts described in Section 3.3.1 are utilized
- 275 2. Bachelor π Cuts
- 276 (a) $|\eta| < 0.8$
- 277 (b) $p_T < 100 \text{ GeV}/c$
- 278 (c) DCA to prim vertex $> 0.1 \text{ cm}$
- 279 (d) SetTPCnclsDaughters(70)
- 280 (e) SetStatusDaughters(AliESDtrack::kTPCrefic)
- 281 3. Ξ Cuts
- 282 (a) $|\eta| < 0.8$
- 283 (b) $0.8 < p_T < 100 \text{ GeV}/c$
- 284 (c) $|m_{inv} - m_{PDG}| < 3.0 \text{ MeV}$
- 285 (d) DCA to prim. vertex $< 0.3 \text{ cm}$
- 286 (e) Cosine of pointing angle > 0.9992
- 287 4. Shared Daughter Cut for Ξ Collection
- 288 – Iterate through Ξ collection to ensure that no daughter is used in more than one Ξ candidate

289 The purity of our Ξ and $\bar{\Xi}$ collections are calculated just as those of our V0 collections 3.3. Figure 8,
290 which is used to calculate the purity, shows the m_{inv} distribution of our $\Xi(\bar{\Xi})$ candidates just before the
291 final m_{inv} cut. Currently, we have $\text{Purity}(\Xi^-) \approx 90\%$ and $\text{Purity}(\bar{\Xi}^+) \approx 92\%$.

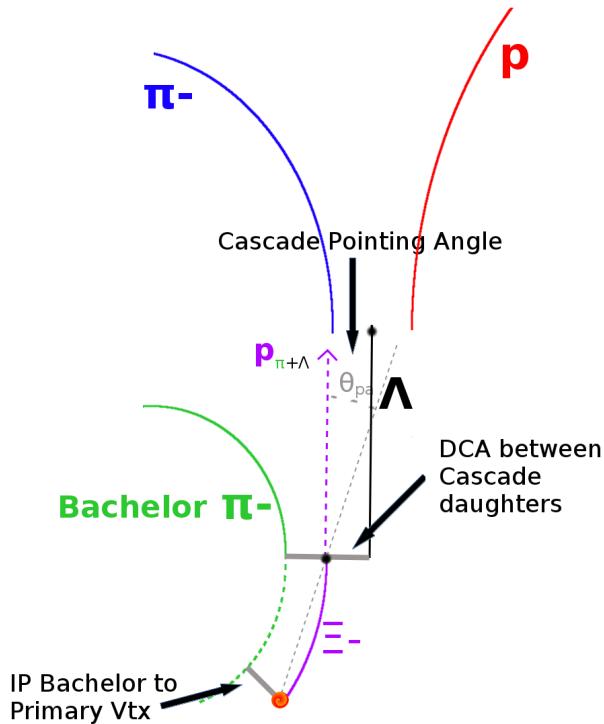


Fig. 7: Ξ Reconstruction

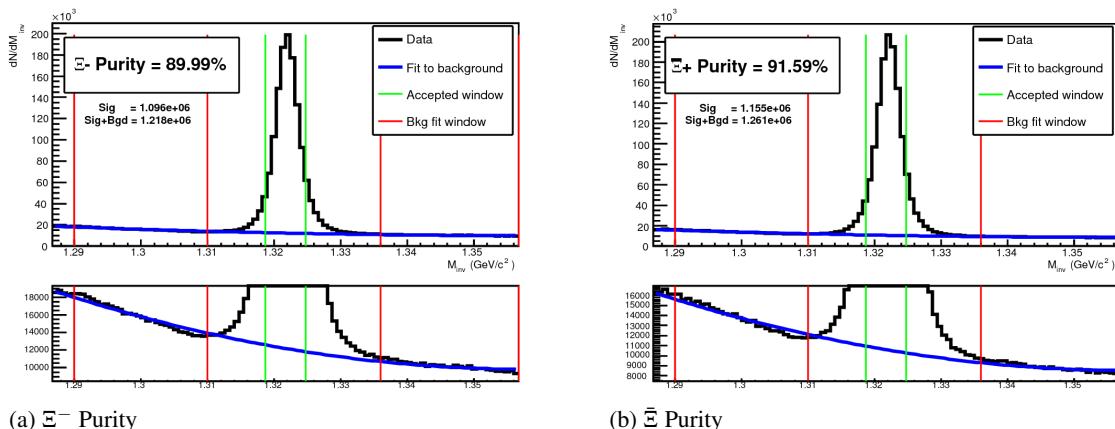


Fig. 8: $\Xi^- (\bar{\Xi}^+)$ Purity 0-10%: Purity(Ξ^-) \approx 90% and Purity($\bar{\Xi}^+$) \approx 92%.

292 3.5 Pair Selection

293 It is important to obtain true particle pairs in the analysis. In particular, contamination from pairs constructed with split or merged tracks, and pairs sharing daughters, can introduce an artificial signal into
294 the correlation function, obscuring the actual physics.
295

296 1. Shared Daughter Cut for Pairs

297 (a) V0-V0 Pairs (i.e. $\Lambda(\bar{\Lambda})K_S^0$ analyses)

- 298 – Remove all pairs which share a daughter
 - 299 – Ex. Λ and K_S^0 particles which share a π^- daughter are not included

300 (b) V0-Track Pairs (i.e. $\Lambda(\bar{\Lambda})K^\pm$ analyses)

- 301 – Remove pairs if Track is also used as a daughter of the V0
 302 – In these analyses, this could only occur if, for instance, a K is misidentified as a π
 303 or p in the V0 reconstruction

304 (c) Ξ -Track Pairs

- 305 – Remove pairs if Track is also used as a daughter of the Ξ
 306 – In these analyses, this could only occur if, for instance, a K is misidentified as a π
 307 or p in the V0 reconstruction, or misidentified as bachelor π .
 308 – Remove pair if bachelor π is also a daughter of the Λ
 309 – This is not a pair cut, but is included here because this cut occurs in the
 310 AliFemtoXiTrackPairCut class

311 2. Average Separation Cuts

- 312 – Used to cut out splitting and merging effects
 313 – The motivation for these cuts can be seen in Figures 9, 10, and 11, in which average separa-
 314 tion correlation functions are presented

315 (a) $\Lambda(\bar{\Lambda})K_S^0$ Analyses

- 316 – Average separation > 6.0 cm for like charge sign daughters
 317 – ex. p daughter of Λ and π^+ daughter of K_S^0
 318 – No cut for unlike-sign daughters

319 (b) $\Lambda(\bar{\Lambda})K^\pm$ Analyses

- 320 – Average Separation > 8.0 cm for daughter of $\Lambda(\bar{\Lambda})$ sharing charge sign of K^\pm
 321 – ex. in ΛK^+ analysis, p daughter of Λ with K^+
 322 – No cut for unlike signs

323 (c) $\Xi(\bar{\Xi})K^\pm$ Analyses

- 324 – Average Separation > 8.0 cm for any daughter of Ξ sharing charge sign of K^\pm
 325 – ex. in $\Xi^- K^-$ analysis, π^- daughter of Λ daughter with K^- , and bachelor π^- daugh-
 326 ter with K^-
 327 – No cut for unlike signs

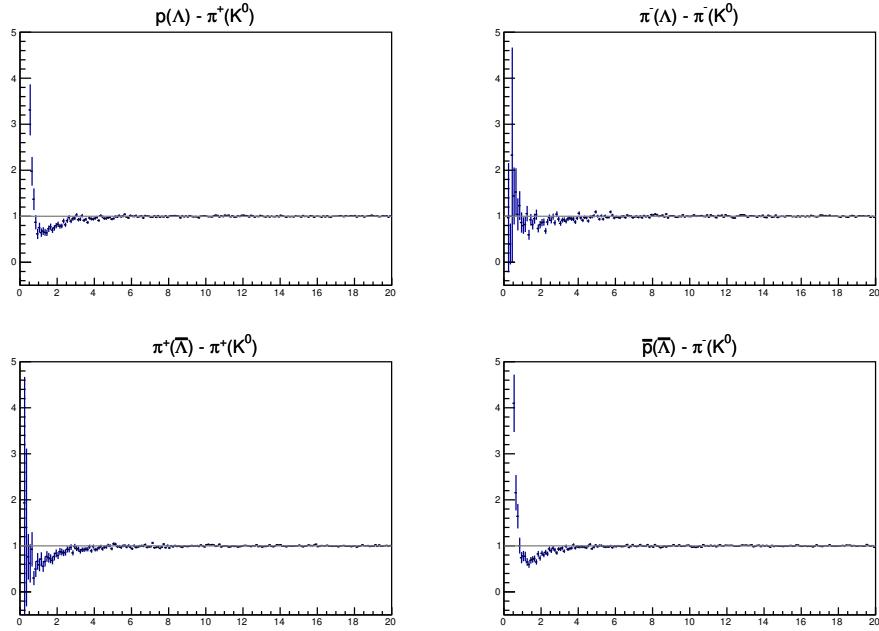


Fig. 9: Average separation (cm) correlation functions of $\Lambda(\bar{\Lambda})$ and K_S^0 Daughters. Only like-sign daughter pairs are shown (the distributions for unlike-signs were found to be flat). The title of each subfigure shows the daughter pair, as well as the mother of each daughter (in “()”), ex. top left is p from Λ with π^+ from K_S^0 .

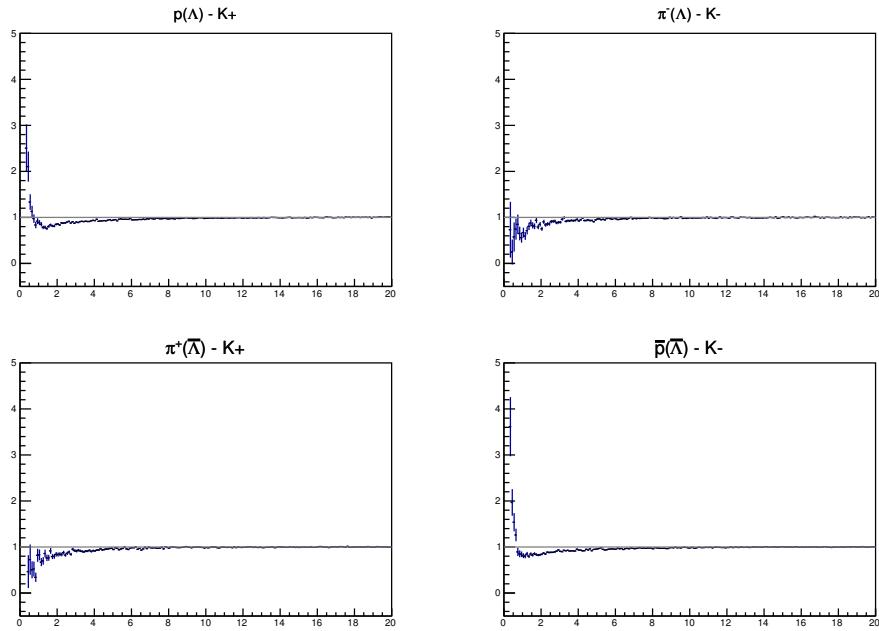


Fig. 10: Average separation (cm) correlation functions of $\Lambda(\bar{\Lambda})$ Daughter and K^\pm . Only like-sign pairs are shown (unlike-signs were flat). In the subfigure titles, the particles in “()” represent the mothers, ex. top left is p from Λ with K^+ .

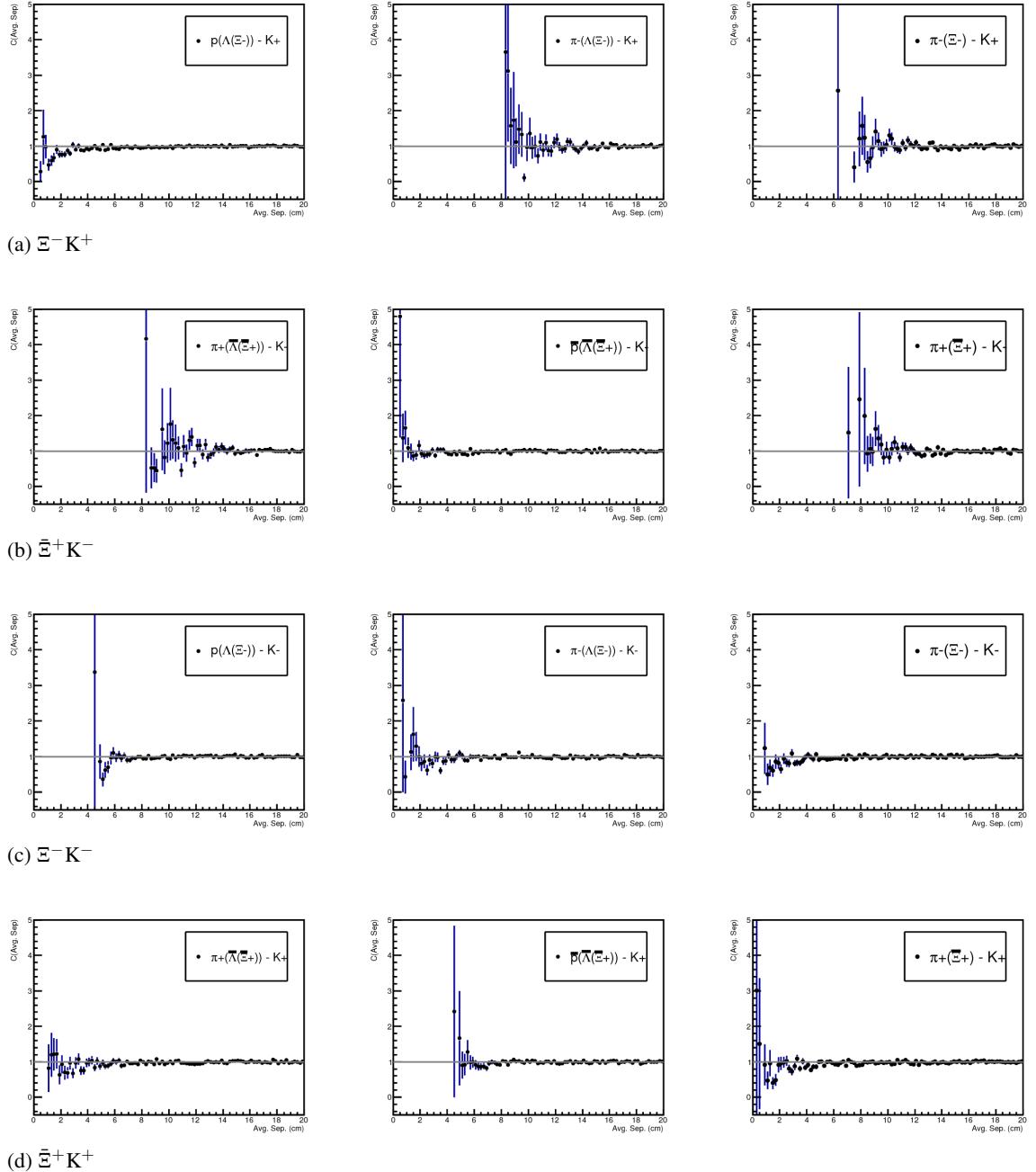


Fig. 11: Average separation (cm) correlation functions of Ξ Daughter and K^\pm . In the subfigure titles, the particles in “()” represent the mothers, ex. top left is p from Λ from Ξ^- with K^+ .

328 **4 Correlation Functions**

329 This analysis studies the momentum correlations of both Λ -K and Ξ -K pairs using the two-particle correlation function, defined as $C(k^*) = A(k^*)/B(k^*)$, where $A(k^*)$ is the signal distribution, $B(k^*)$ is the reference (or background) distribution, and k^* is the momentum of one of the particles in the pair rest frame. In practice, $A(k^*)$ is constructed by binning in k^* pairs from the same event. Ideally, $B(k^*)$ is similar to $A(k^*)$ in all respects excluding the presence of femtoscopic correlations [2]; as such, $B(k^*)$ is used to divide out the phase-space effects, leaving only the femtoscopic effects in the correlation function.

335 This analysis presents correlation functions for three centrality bins (0-10%, 10-30%, and 30-50%),
 336 and is currently pair transverse momentum ($k_T = 0.5|\mathbf{p}_{T,1} + \mathbf{p}_{T,2}|$) integrated (i.e. not binned in k_T).
 337 The correlation functions are constructed separately for the two magnetic field configurations, and are
 338 combined using a weighted average:

$$C_{combined}(k^*) = \frac{\sum_i w_i C_i(k^*)}{\sum_i w_i} \quad (3)$$

339 where the sum runs over the correlation functions to be combined, and the weight, w_i , is the number of
 340 numerator pairs in $C_i(k^*)$. Here, the sum is over the two field configurations.

341 **4.1 Typical Correlation Function Construction**

342 Typically, in practice, $B(k^*)$ is obtained by forming mixed-event pairs, i.e. particles from a given event
 343 are paired with particles from $N_{mix}(= 5)$ other events, and these pairs are then binned in k^* . In forming the
 344 background distribution, it is important to mix only similar events; mixing events with different phase-
 345 spaces can lead to artificial signals in the correlation function. Therefore, in this analysis, we mix events
 346 with primary vertices within 2 cm and centralities within 5% of each other. Also note, a vertex correction
 347 is also applied to each event, which essentially re-centers the primary vertices to $z = 0$.

348 Figures 12a, 12b, 12c show the correlation functions for all centralities studied for $\Lambda K^+(\bar{\Lambda} K^-)$, $\Lambda K^-(\bar{\Lambda} K^+)$,
 349 and $\Lambda(\bar{\Lambda}) K_S^0$, respectively. All were normalized in the range $0.32 < k^* < 0.4$ GeV/c.

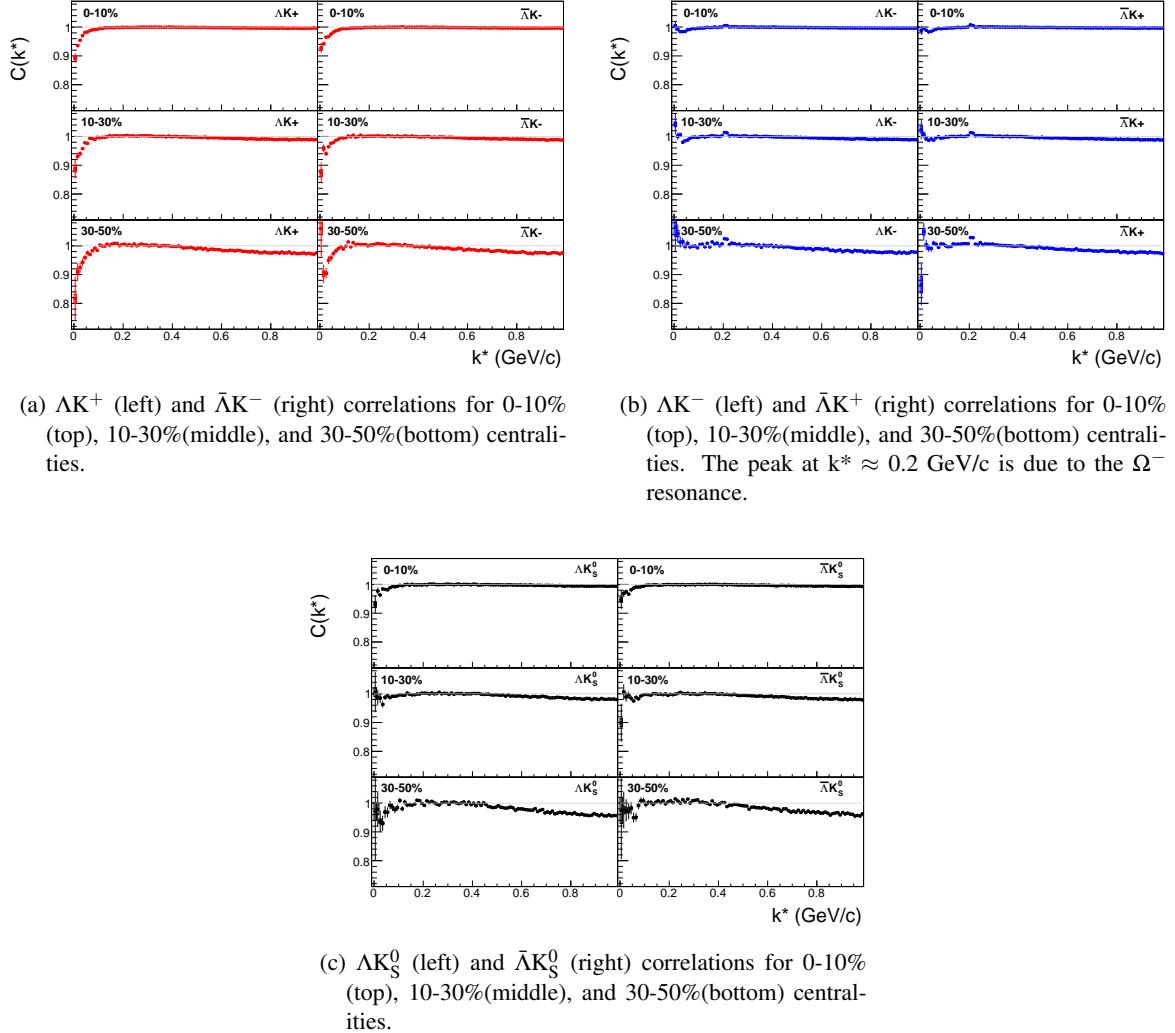


Fig. 12: ΛK and $\bar{\Lambda} K$ correlation functions for 0-10%, 10-30%, and 30-50% centralities. The lines represent the statistical errors, while the boxes represent the systematic errors.

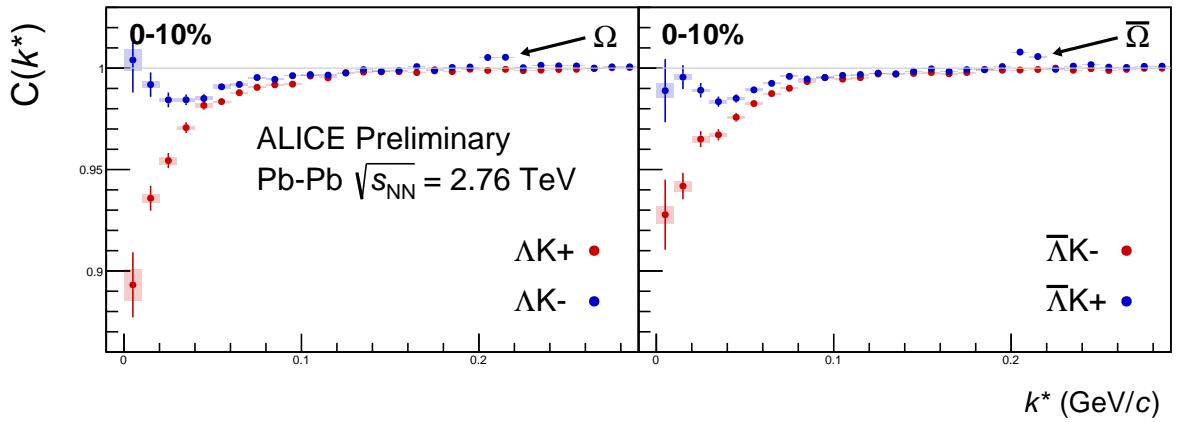


Fig. 13: Correlation Functions: ΛK^+ vs ΛK^- ($\bar{\Lambda} K^+$ vs $\bar{\Lambda} K^-$) for 0-10% centrality. The peak in ΛK^- ($\bar{\Lambda} K^+$) at $k^* \approx 0.2$ GeV/c is due to the Ω^- resonance. The lines represent the statistical errors. (NOTE: This figure is slightly dated, and a new one will be generated which includes both statistical and systematic uncertainties)

350 4.2 Stavinsky Correlation Function Construction

351 The purpose of the Stavinsky method is to rid the correlation functions of the non-femtoscopic back-
352 ground. More specifically, this method is intended to handle background contributions from elliptic
353 flow, and other sources having reflection symmetry in the transverse plane. With the Stavinsky method,
354 mixed-event pairs are not used for the background; instead, same-event suds-pairs, formed by rotating
355 one particle in a real pair by 180° in the transverse plane, as used as a background. This rotation rids
356 the pairs of any femtoscopic correlation, while maintaining correlations due to elliptic flow (and other
357 properly symmetric contributors).

358 The results of correctly implementing such a procedure are shown in Figure 14. The figure shows the
359 Stavinsky method does a very good job of ridding the ΛK^\pm correlations of their non-femtoscopic back-
360 grounds. We also see the procedure does not work as well on the ΛK_S^0 system.

361 Now, one must be somewhat careful when applying this Stavinsky method. We found that, in order to
362 obtain correct results, we had to run our pseudo-pairs through the same pair cuts used in our analyses. In
363 an ideal world, our pair cut would only remove truly bad pairs results from splitting, merging, etc. In the
364 real world, the pair cut always throws out some of the good with the bad. For the pseudo-pairs to form a
365 reliable background, they too must experience the pair cut, and the loss of "good" pairs. We found this
366 issue affected mainly our ΛK^+ & $\bar{\Lambda} K^-$ analysis, as can be seen in Figure 15, which shows both a correct
367 implementation of the Stavinsky method, and an incorrect implementation lacking the additional pair cut
368 on the pseudo-pairs.

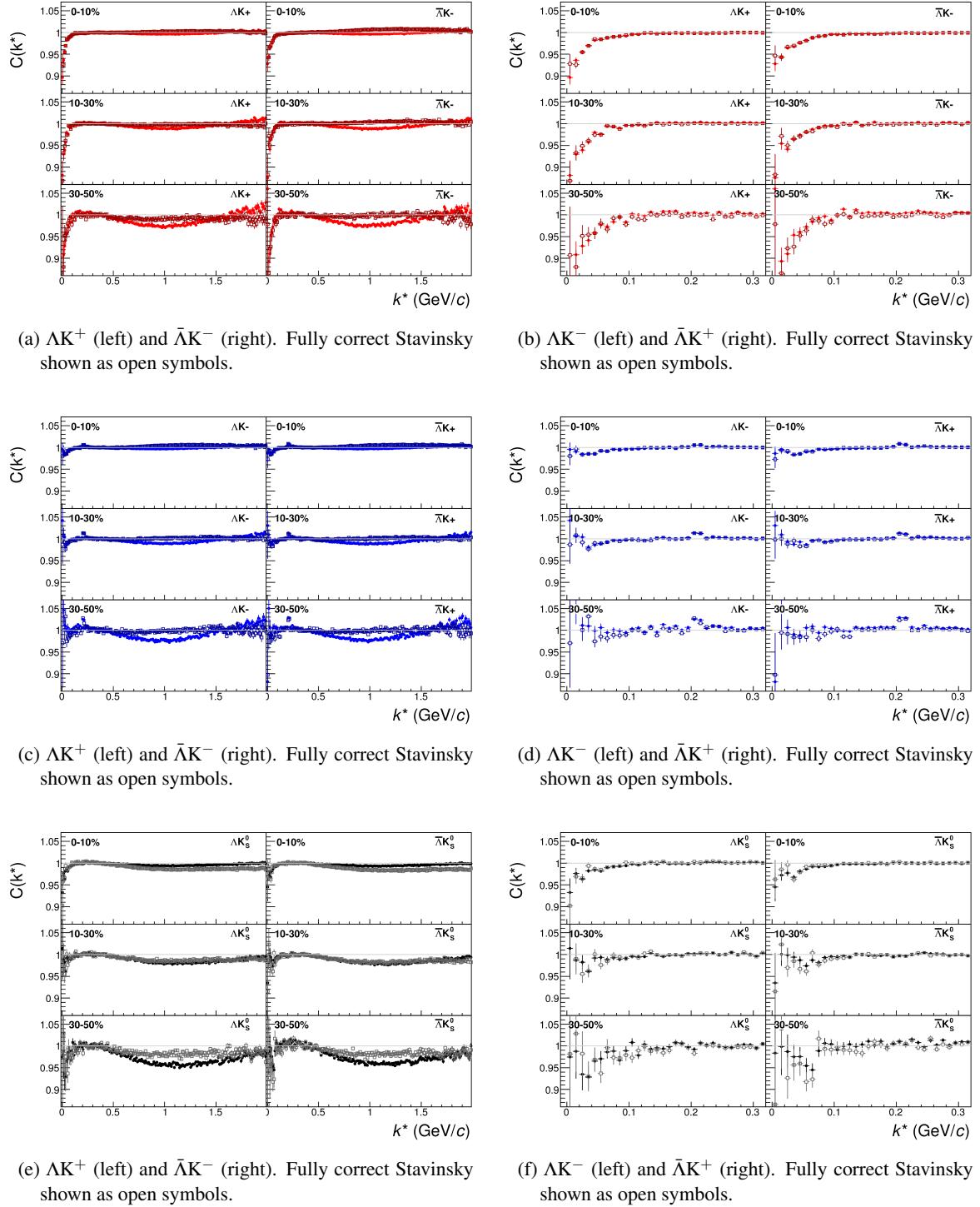
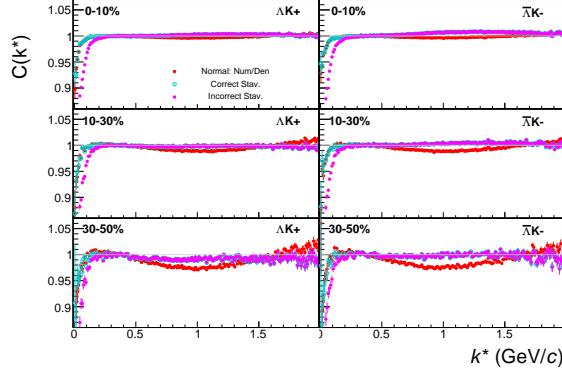
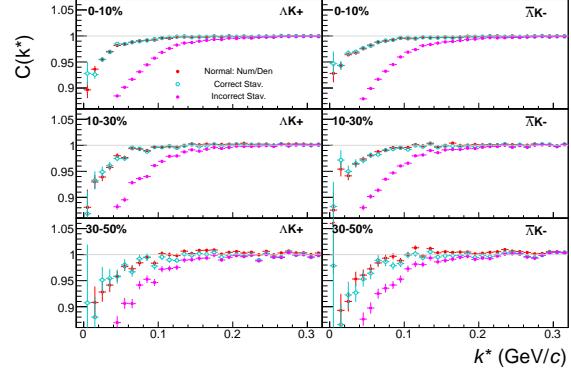


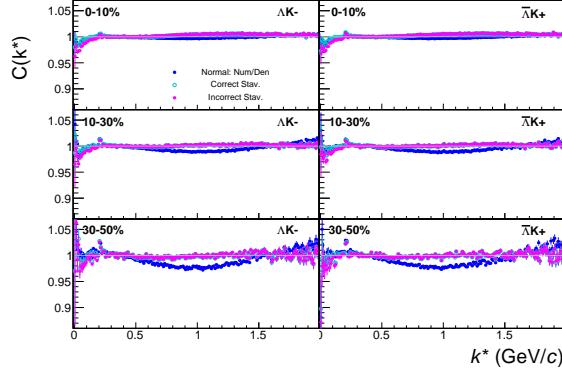
Fig. 14: ΛK and $\bar{\Lambda} K$ correlation functions built using the fully correct Stavinsky method for 0-10%, 10-30%, and 30-50% centralities. In the full correct method, the pseudo-pairs (same-event pairs with one particle rotated by 180° in the transverse plane) are also run through the pair cuts used in the analysis. Closed symbols represent correlations built using the normal mixed-event background, while open symbols represent correlations formed using the Stavinsky same-event pseudo-pairs as a background. Figures in the right column are zoomed-in versions of figures in the left column.



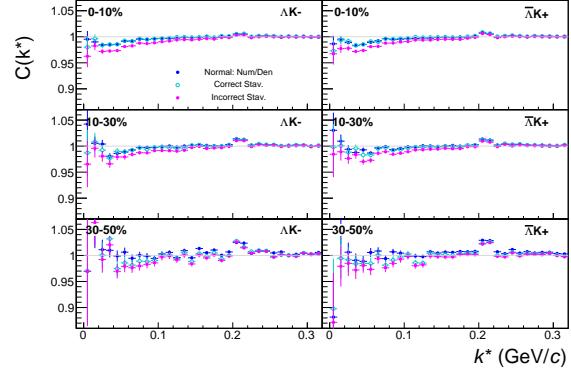
(a) ΛK^+ (left) and $\bar{\Lambda} K^-$ (right). Incorrect Stavinsky shown as open symbols.



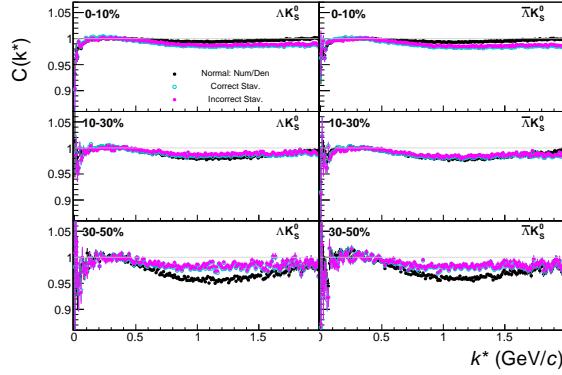
(b) ΛK^- (left) and $\bar{\Lambda} K^+$ (right). Incorrect Stavinsky shown as open symbols.



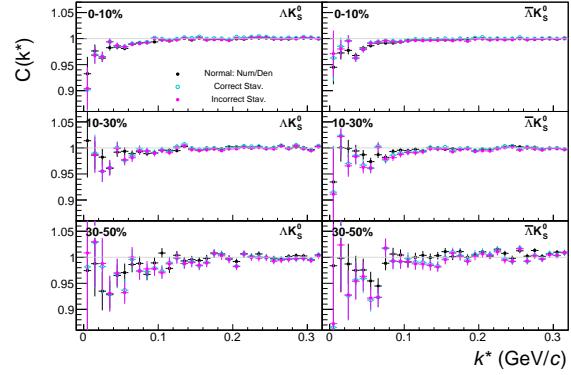
(c) ΛK^+ (left) and $\bar{\Lambda} K^-$ (right). Incorrect Stavinsky shown as open symbols.



(d) ΛK^- (left) and $\bar{\Lambda} K^+$ (right). Incorrect Stavinsky shown as open symbols.



(e) ΛK^+ (left) and $\bar{\Lambda} K^-$ (right). Incorrect Stavinsky shown as open symbols.



(f) ΛK^- (left) and $\bar{\Lambda} K^+$ (right). Incorrect Stavinsky shown as open symbols.

Fig. 15: ΛK and $\bar{\Lambda} \bar{K}$ correlation functions built using the Stavinsky method for 0-10%, 10-30%, and 30-50% centralities. The closed, (red, blue, black) symbols represent correlation functions formed using the normal method with mixed-event background pairs. The open, cyan symbols represent correlation functions formed using the correct Stavinsky method. The closed, magenta symbols represent correlation functions formed using the incorrect Stavinsky method. In the incorrect method, the pseudo-pairs (same-event pairs with one particle rotated by 180° in the transverse plane) are not run through the pair cuts used in the analysis. Figures in the right column are zoomed-in versions of figures in the left column.

369 **5 Fitting**

370 **5.1 Model:** ΛK_S^0 , ΛK^\pm , $\Xi^{ch} K_S^0$

371 The two-particle relative momentum correlation function may be written theoretically by the Koonin-
 372 Pratt equation [3, 4]:

$$C(\mathbf{k}^*) = \int S(\mathbf{r}^*) |\Psi_{\mathbf{k}^*}(\mathbf{r}^*)|^2 d^3 \mathbf{r}^* \quad (4)$$

373 In the absence of Coulomb effects, and assuming a spherically gaussian source of width R , the 1D
 374 femtoscopic correlation function can be calculated analytically using:

$$C(k^*) = 1 + C_{QI}(k^*) + C_{FSI}(k^*) \quad (5)$$

375 C_{QI} describes plane-wave quantum interference:

$$C_{QI}(k^*) = \alpha \exp(-4k^{*2}R^2) \quad (6)$$

376 where $\alpha = (-1)^{2j}/(2j+1)$ for identical particles with spin j , and $\alpha = 0$ for non-identical particles.
 377 Obviously, $\alpha = 0$ for all analyses presented in this note. C_{FSI} describes the s-wave strong final state
 378 interaction between the particles:

$$\begin{aligned} C_{FSI}(k^*) &= (1 + \alpha) \left[\frac{1}{2} \left| \frac{f(k^*)}{R} \right|^2 \left(1 - \frac{d_0}{2\sqrt{\pi}R} \right) + \frac{2\Re f(k^*)}{\sqrt{\pi}R} F_1(2k^*R) - \frac{\Im f(k^*)}{R} F_2(2k^*R) \right] \\ f(k^*) &= \left(\frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - ik^* \right)^{-1}; \quad F_1(z) = \int_0^z \frac{e^{x^2-z^2}}{x} dx; \quad F_2(z) = \frac{1-e^{-z^2}}{z} \end{aligned} \quad (7)$$

379 where R is the source size, $f(k^*)$ is the s-wave scattering amplitude, f_0 is the complex scattering length,
 380 and d_0 is the effective range of the interaction.

381 An additional parameter λ is typically included in the femtoscopic fit function to account for the purity
 382 of the pair sample. In the case of no residual correlations (to be discussed in Section 5.4, the fit function
 383 becomes:

$$C(k^*) = 1 + \lambda [C_{QI}(k^*) + C_{FSI}(k^*)] \quad (8)$$

384 **5.2 Model:** $\Xi^{ch} K^{ch}$

385 The two-particle correlation function may be written as:

$$C(\mathbf{k}^*) = \sum_S \rho_S \int S(\mathbf{r}^*) |\Psi_{\mathbf{k}^*}^S(\mathbf{r}^*)|^2 d^3 \mathbf{r}^* \quad (9)$$

386 where ρ_S is the normalized emission probability of particles in a state with spin S , $S(\mathbf{r}^*)$ is the pair
 387 emission source distribution (assumed to be Gaussian), and $\Psi_{\mathbf{k}^*}^S(\mathbf{r}^*)$ is the two-particle wave-function
 388 including both strong and Coulomb interactions [5]:

$$\Psi_{\mathbf{k}^*}(\mathbf{r}^*) = e^{i\delta_c} \sqrt{A_c(\eta)} [e^{i\mathbf{k}^* \cdot \mathbf{r}^*} F(-i\eta, 1, i\xi) + f_c(k^*) \frac{\tilde{G}(\rho, \eta)}{r^*}] \quad (10)$$

where $\rho = k^*r^*$, $\eta = (k^*a_c)^{-1}$, $\xi = \mathbf{k}^* \cdot \mathbf{r}^* + k^*r^* \equiv \rho(1 + \cos\theta^*)$, and $a_c = (\mu z_1 z_2 e^2)^{-1}$ is the two-particle Bohr radius (including the sign of the interaction). δ_c is the Coulomb s-wave phase shift, $A_c(\eta)$ is the Coulomb penetration factor, $\tilde{G} = \sqrt{A_c}(G_0 + iF_0)$ is a combination of the regular (F_0) and singular (G_0) s-wave Coulomb functions. $f_c(k^*)$ is the s-wave scattering amplitude:

$$f_c(k^*) = \left[\frac{1}{f_0} + \frac{1}{2}d_0k^{*2} - \frac{2}{a_c}h(\eta) - ik^*A_c(\eta) \right]^{-1} \quad (11)$$

where, the “h-function”, $h(\eta)$, is expressed through the digamma function, $\psi(z) = \Gamma'(z)/\Gamma(z)$ as:

$$h(\eta) = 0.5[\psi(i\eta) + \psi(-i\eta) - \ln(\eta^2)] \quad (12)$$

In this case, the λ parameter may be included as:

$$C(\mathbf{k}^*) = (1 - \lambda) + \lambda \sum_S \rho_S \int S(\mathbf{r}^*) |\Psi_{\mathbf{k}^*}^S(\mathbf{r}^*)|^2 d^3\mathbf{r}^* \quad (13)$$

5.3 Momentum Resolution Corrections

Finite track momentum resolution causes the reconstructed momentum of a particle to smear around the true value. This, of course, also holds true for V0 particles. The effect is propagated up to the pairs of interest, which causes the reconstructed relative momentum (k_{Rec}^*) to differ from the true momentum (k_{True}^*). Smearing of the momentum typically will result in a suppression of the signal.

The effect of finite momentum resolution can be investigated using the MC data, for which both the true and reconstructed momenta are available. Figure 16 shows sample k_{True}^* vs. k_{Rec}^* plots for $\Lambda(\bar{\Lambda})K^\pm$ 0-10% analyses; Figure 16a was generated using same-event pairs, while Figure 16b was generated using mixed-event pairs (with $N_{mix} = 5$).

If there are no contaminations in our particle collection, the plots in Figure 16 should be smeared around $k_{True}^* = k_{Rec}^*$; this is mostly true in our analyses. However, there are some interesting features of our results which demonstrate a small (notice the log-scale on the z-axis) contamination in our particle collection. The structure around $k_{Rec}^* = k_{True}^* - 0.15$ is mainly caused by K_S^0 contamination in our $\Lambda(\bar{\Lambda})$ sample. The remaining structure not distributed about $k_{Rec}^* = k_{True}^*$ is due to π and e contamination in our K^\pm sample. These contaminations are more visible in Figure 17, which show k_{Rec}^* vs. k_{True}^* plots (for a small sample of the ΛK^\pm 0-10% central analysis), for which the MC truth (i.e. true, known identity of the particle) was used to eliminate misidentified particles in the $K^+(a)$ and $\Lambda(b)$ collections. (NOTE: This is an old figure and is for a small sample of the data. A new version will be generated shortly. It, nonetheless, demonstrates the point well).

Information gained from looking at k_{Rec}^* vs k_{True}^* can be used to apply corrections to account for the effects of finite momentum resolution on the correlation functions. A typical method (“Ratio” method) involves using the MC HIJING data to build two correlation functions, $C_{Rec}(k^*)$ and $C_{True}(k^*)$, using the generator-level momentum (k_{True}^*) and the measured detector-level momentum (k_{Rec}^*). The data is then corrected by multiplying by the ratio, C_{True}/C_{Rec} , before fitting. This essentially unsmears the data, which that can be compared directly to theoretical predictions and fits. Although this is conceptually simple, there are a couple of big disadvantages to this method. First, HIJING does not incorporate final-state interactions, so weights must be used when building same-event (numerator) distributions. These weights account for the interactions, and, in the absence of Coulomb interactions, can be calculated using Eq. 5. Of course, these weights are valid only for a particular set of fit parameters. Therefore, in the fitting process, during which the fitter explores a large parameter set, the corrections will not remain valid. As such, applying the momentum resolution correction and fitting becomes a long and drawn out iterative

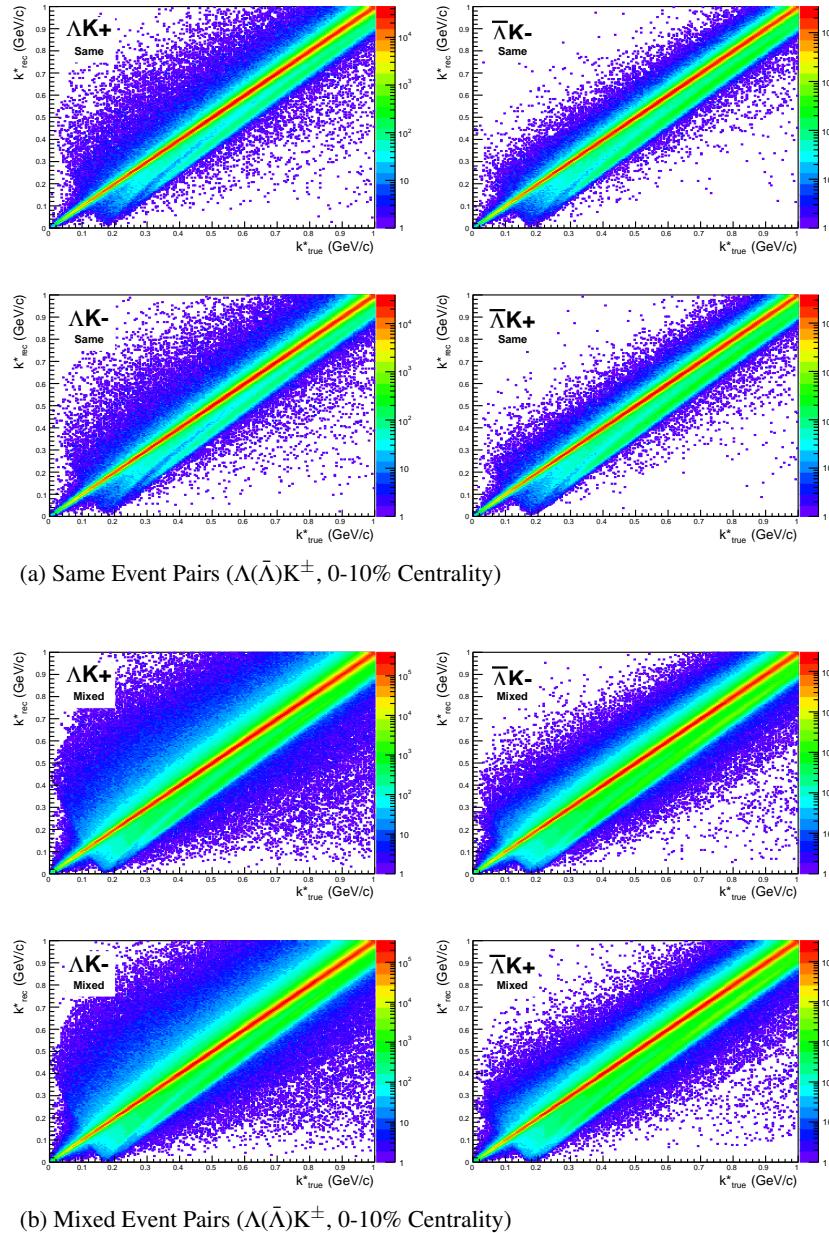
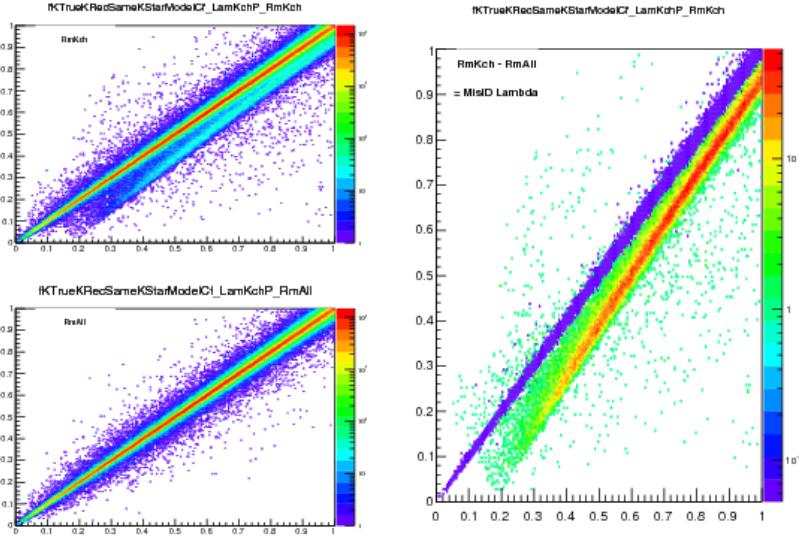
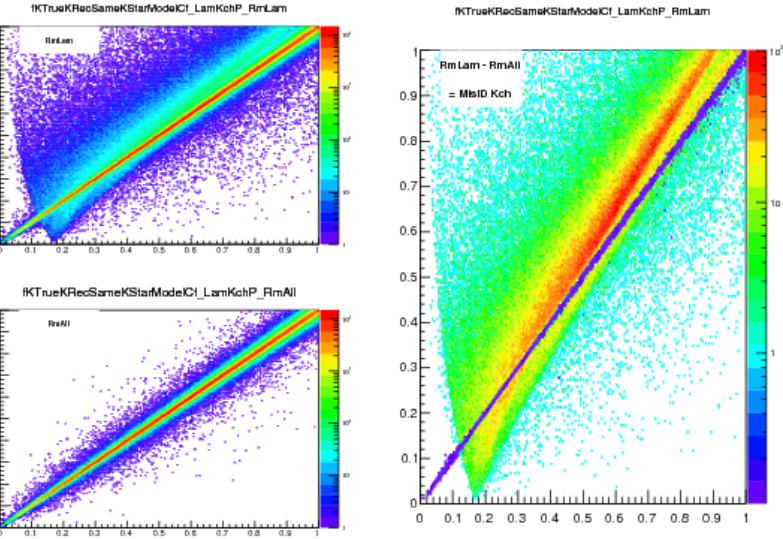


Fig. 16: Sample k_{True}^* vs. k_{Rec}^* plot for $\Lambda(\bar{\Lambda})K^\pm$ 0-10% analyses. The structure which appears around $k_{Rec}^* = k_{True}^* - 0.15$ is mainly caused by K_S^0 contamination in our $\Lambda(\bar{\Lambda})$ sample. The remaining structure not distributed about $k_{Rec}^* = k_{True}^*$ is due to π and e contamination in our K^\pm sample. These contaminations are more clearly visible in Figure 17

process. An initial parameter set is obtained (through fitting without momentum resolution corrections, theoretical models, or a good guess), then the MC data is run over to obtain the correction factor, the data is fit using the correction factor, a refined parameter set is extracted, the MC data is run over again to obtain the new correction factor, etc. This process continues until the parameter set stabilizes. The second issue concerns statistics. With the MC data available on the grid, we were not able to generate the statistics necessary to use the raw C_{True}/C_{Rec} ratio. The ratio was not stable, and when applied to the data, obscured the signal. Attempting to fit the ratio to generate the corrections also proved problematic. However, as HIJING does not include final-state interactions, the same-event and mixed-event pairs are very similar (with the exception of things like energy and momentum conservation, etc). Therefore, one may build the numerator distribution using mixed-event pairs. This corresponds, more or



(a) (Top Left) All misidentified K^+ excluded. (Bottom Left) All misidentified Λ and K^+ excluded. (Right) The difference of (Top Left) - (Bottom Left), which reveals the contamination in our Λ collection. The structure which appears around $k_{Rec}^* = k_{True}^* - 0.15$ is mainly caused by K_S^0 contamination in our $\Lambda(\bar{\Lambda})$ sample.



(b) (Top Left) All misidentified Λ excluded. (Bottom Left) All misidentified Λ and K^- excluded. (Right) The difference of (Top Left) - (Bottom Left), which reveals the contamination in our K^+ collection. The structure not distributed about $k_{Rec}^* = k_{True}^*$ is due to π and e^- contamination in our K^\pm sample.

Fig. 17: Note: This is an old figure and is for a small sample of the data. A new version will be generated shortly.
y-axis = k_{Rec}^* , x-axis = k_{True}^* .

(Left) k_{Rec}^* vs. k_{True}^* plots for a small sample of the ΛK^+ 0-10% central analysis, MC truth was used to eliminate misidentified particles in the K^+ (a) and Λ (b) collections. (Right) The difference of the top left and bottom left plots. Contaminations in our particle collections are clearly visible. Figure (a) demonstrates a K_S^0 contamination in our Λ collection; Figure (b) demonstrates a π and e^- contamination in our K^\pm collection.

436 less, to simply running a the weight generator through the detector framework.

437 A second approach ("Matrix" method) is to use information gained from plots like those in Figure 16,
438 which can be considered response matrices. The reponse matrix describes quantitatively how each k_{Rec}^*

439 bin receives contributions from multiple k_{True}^* bins, and can be used to account for the effects of finite mo-
 440 mentum resolution. With this approach, the resolution correction is applied on-the-fly during the fitting
 441 process by propagating the theoretical (fit) correlation function through the response matrix, according
 442 to:

$$C_{fit}(k_{Rec}^*) = \frac{\sum_{k_{True}^*} M_{k_{Rec}^*, k_{True}^*} C_{fit}(k_{True}^*)}{\sum_{k_{True}^*} M_{k_{Rec}^*, k_{True}^*}} \quad (14)$$

443 where $M_{k_{Rec}^*, k_{True}^*}$ is the response matrix (Figure 16), $C_{fit}(k_{True}^*)$ is the fit binned in k_{True}^* , and the denomi-
 444 nator normalizes the result.

445 Equation 14 describes that, for a given k_{Rec}^* bin, the observed value of $C(k_{Rec}^*)$ is a weighted average of
 446 all $C(k_{True}^*)$ values, where the weights are the normalized number of counts in the $[k_{Rec}^*, k_{True}^*]$ bin. As
 447 seen in Figure 16, overwhelmingly the main contributions comes from the $k_{Rec}^* = k_{True}^*$ bins. Although
 448 the correction is small, it is non-negligible for the low- k^* region of the correlation function.

449 Here, the momentum resolution correction is applied to the fit, not the data. In other words, during
 450 fitting, the theoretical correlation function is smeared just as real data would be, instead of unsmearing
 451 the data. This may not be ideal for the theorist attempting to compare a model to experimental data, but
 452 it leaves the experimental data unadulterated. The current analyses use this second approach to applying
 453 momentum resolution corrections because of two major advantages. First, the MC data must be analyzed
 454 only once, and no assumptions about the fit are needed. Secondly, the momentum resolution correction
 455 is applied on-the-fly by the fitter, delegating the iterative process to a computer instead of the user.

456 The two methods described above, Ratio and Matrix, should reproduce the same results at the parameter
 457 set used to generate the C_{True}/C_{Rec} needed for the Ratio method. Figure 18 shows that the two methods
 458 converge as the binning size is decreased.

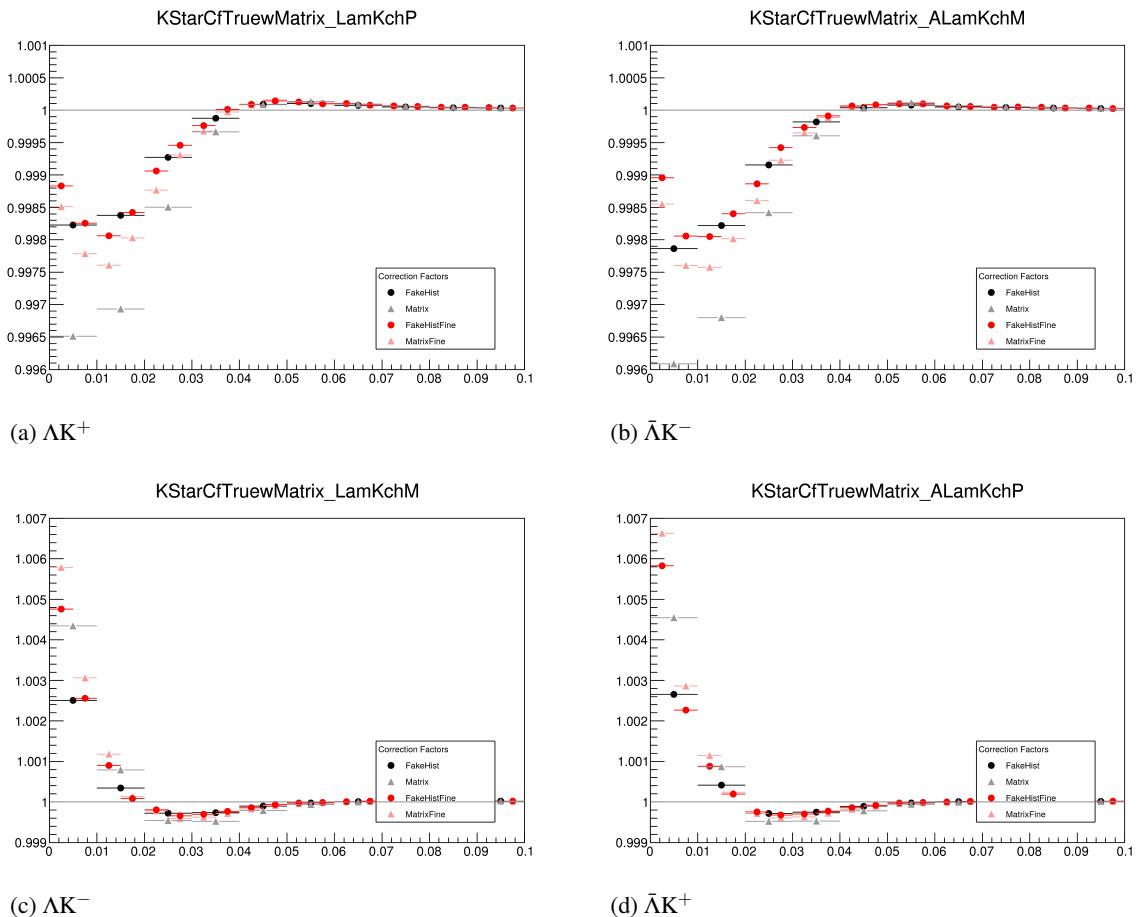


Fig. 18: Comparison of the two methods, Ratio and Matrix, for accounting for momentum resolution effects with HIJING. The Ratio method corresponds to the "FakeHist" histograms (circles), while the Matrix method corresponds to the "Matrix" histograms (triangles). Black shows a coarse binning, while red shows a finer binning.

459 **5.4 Residual Correlations**

460 The purpose of this analysis is study the interaction and scale of the emitting source of the pairs. In
 461 order to obtain correct results, it is important for our particle collections to consist of primary particles.
 462 In practice, this is difficult to achieve for our Λ and $\bar{\Lambda}$ collections. Many of our Λ particles are not
 463 primary, but originate as decay products from other hyperons, including Σ^0 , Ξ^0 , Ξ^- and $\Sigma^{*(+,-,0)}(1385)$.
 464 Additionally, many of our K particles are not primary, but decay from $K^{*(+,-,0)}(892)$ parents. In these
 465 decays, the Λ carries away a momentum very similar to that of its parent. As a result, the correlation
 466 function between a secondary Λ and, for instance, a K^+ will be sensitive to, and dependent upon, the
 467 interaction between the parent of the Λ and the K^+ . In effect, the correlation between the parent of
 468 the Λ and the K^+ (ex. $\Sigma^0 K^+$) will be visible, although smeared out, in the ΛK^+ data; we call this a
 469 residual correlation resulting from feed-down. The contributions from the primary correlation, residual
 470 correlations, and fake pairs on the finally measure data is shown schematically in Figure 19. Residual
 471 correlations are important in an analysis when three criteria are met [6]: i) the parent correlation signal
 472 is large, ii) a large fraction of pairs in the sample originate from the particular parent system, and iii) the
 473 decay momenta are comparable to the expected correlation width in k^* .

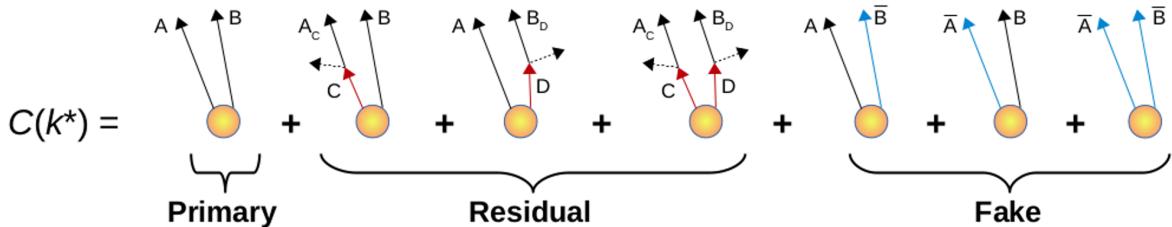


Fig. 19: A schematic representation of the contributions to the finally measured data from the primary correlation, residual correlations, and fake pairs.

474 As it is difficult for us to eliminate these residual correlations in our analyses, we must attempt to account
 475 for them in our fitter. To achieve this, we will simultaneously fit the data for both the primary correlation
 476 function and the residual correlations. For example, in the simple case of a ΛK^+ analysis with residuals
 477 arising solely from $\Sigma^0 K^+$ feed-down:

$$C_{measured}(k_{\Lambda K^+}^*) = 1 + \lambda_{\Lambda K^+}[C_{\Lambda K^+}(k_{\Lambda K^+}^*) - 1] + \lambda_{\Sigma^0 K^+}[C_{\Sigma^0 K^+}(k_{\Lambda K^+}^*) - 1]$$

$$C_{\Sigma^0 K^+}(k_{\Lambda K^+}^*) \equiv \frac{\sum_{k_{\Sigma^0 K^+}^*} C_{\Sigma^0 K^+}(k_{\Sigma^0 K^+}^*) T(k_{\Sigma^0 K^+}^*, k_{\Lambda K^+}^*)}{\sum_{k_{\Sigma^0 K^+}^*} T(k_{\Sigma^0 K^+}^*, k_{\Lambda K^+}^*)} \quad (15)$$

478 $C_{\Sigma^0 K^+}(k_{\Sigma^0 K^+}^*)$ is the $\Sigma^0 K^+$ correlation function from, for instance, Equation 5, and T is the transform
 479 matrix generated with THERMINATOR. The transform matrix is formed for a given parent pair, AB,
 480 by taking all ΛK pairs originating from AB, calculating the relative momentum of the parents (k_{AB}^*)
 481 and daughters ($k_{\Lambda K}^*$), and filling a two-dimensional histogram with the values. The transform matrix
 482 is essentially an unnormalized probability distribution mapping the k^* of the parent pair to that of the
 483 daughter pair when one or both parents decay. An example of such transform matrices can be found in
 484 Figures 20 and 21.

485 The above equation can be easily extended to include feed-down from more sources:

$$\begin{aligned}
C_{measured}(k_{\Lambda K}^*) &= 1 + \lambda_{\Lambda K}[C_{\Lambda K}(k_{\Lambda K}^*) - 1] + \lambda_{\Sigma^0 K}[C_{\Sigma^0 K}(k_{\Lambda K}^*) - 1] + \dots \\
&\quad + \lambda_{P_1 P_2}[C_{P_1 P_2}(k_{\Lambda K}^*) - 1] + \lambda_{other}[C_{other}(k_{\Lambda K}^*) - 1]
\end{aligned}
\tag{16}$$

$$C_{P_1 P_2}(k_{\Lambda K}^*) \equiv \frac{\sum_{k_{P_1 P_2}^*} C_{P_1 P_2}(k_{P_1 P_2}^*) T(k_{P_1 P_2}^*, k_{\Lambda K}^*)}{\sum_{k_{P_1 P_2}^*} T(k_{P_1 P_2}^*, k_{\Lambda K}^*)}$$

486 Or, more compactly:

$$C_{measured}(k_{\Lambda K}^*) = 1 + \sum_i \lambda_i [C_i(k_{\Lambda K}^*) - 1] \tag{17}$$

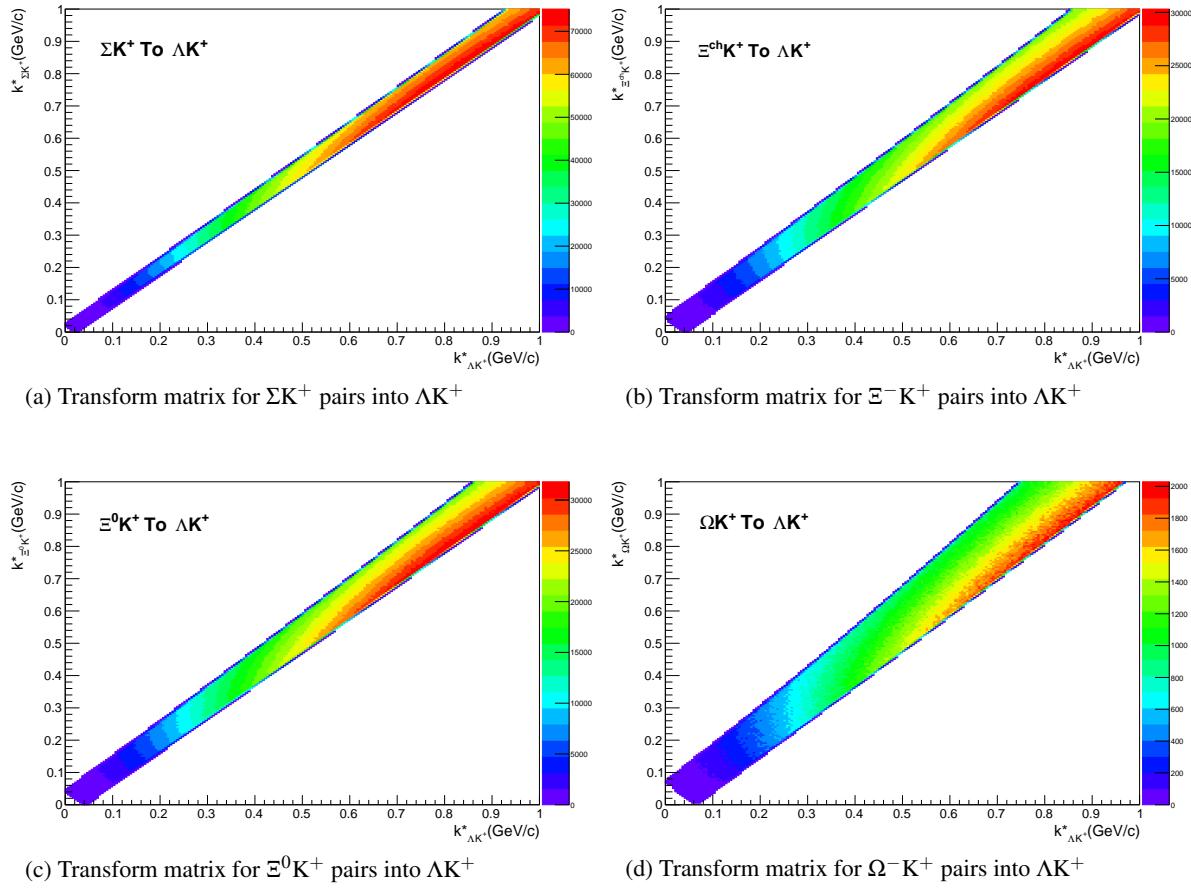


Fig. 20: Transform Matrices generated with THERMINATOR for ΛK^+ Analysis

487 So, in practice, we model the correlation function of the parents, and run the correlation function through
488 the appropriate transform matrix to determine the contribution to the daughter correlation function. A
489 few questions still remain. First, what λ values should be used in the above equation? One option
490 would be to leave all of these λ -parameters free during the fit process. However, this would introduce
491 a huge number of new parameters into the fitter, and would make the fit results less trustworthy. The λ
492 parameters roughly dictate the strength of the parent contribution to the daughter pair. Additionally, as
493 found in [7], the reconstruction efficiency for primary Λ particles is nearly equal to that of Λ particles
494 originating from Σ , Σ^* , Ξ^0 , Ξ^- , and Ω hyperons. Therefore, the λ parameter for parent system AB can

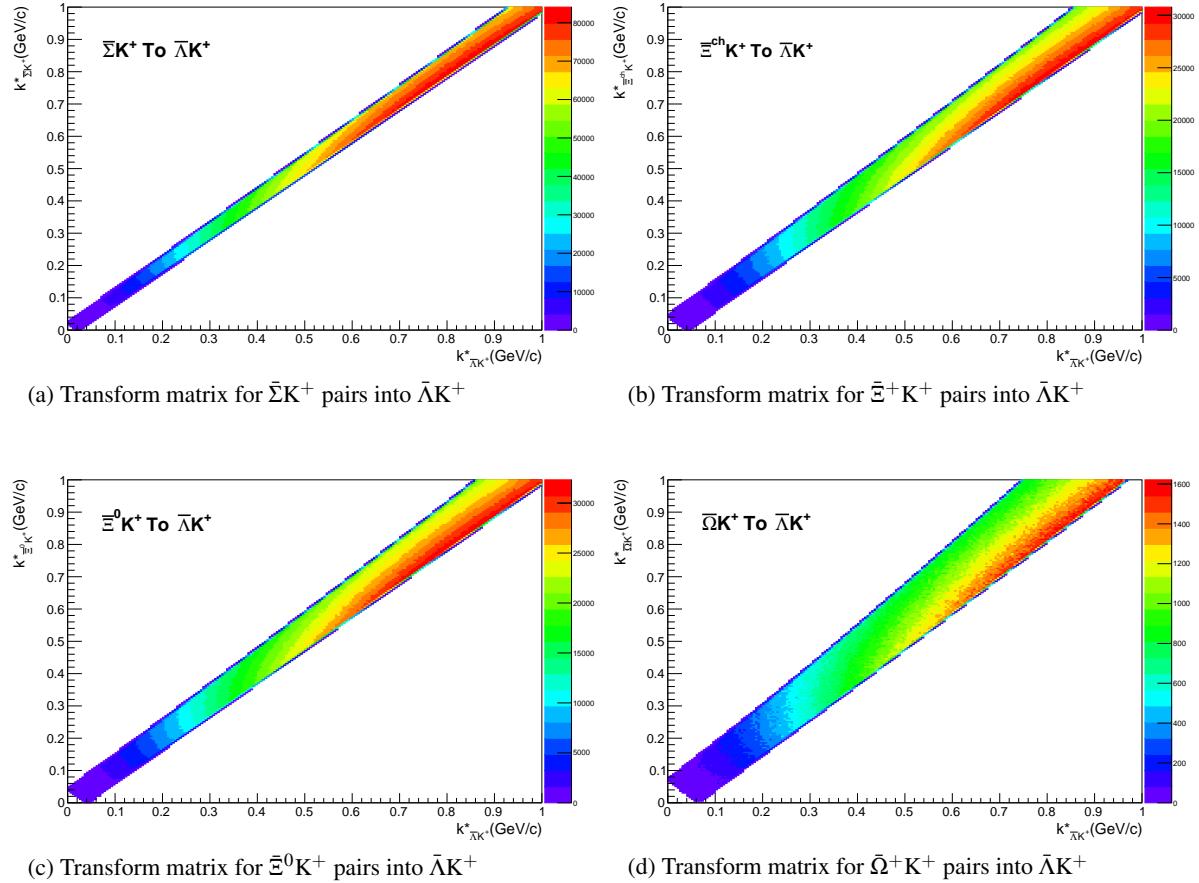


Fig. 21: Transform Matrices generated with THERMINATOR for $\bar{\Lambda}K^+$ Analysis

495 be estimated using THERMINATOR as the total number of ΛK pairs originating from AB (N_{AB}) divided
 496 by the total number of ΛK pairs (N_{Total}):

$$\lambda_{AB} = \frac{N_{AB}}{N_{Total}} \quad (18)$$

497 Now, the remaining question is how do we model the parent correlation functions? In an ideal world, we
 498 would simply look up the parent interaction in some table, and input this into our Lednicky equation (for
 499 the case of one or more charge neutral particle in the pair), or run it through the CoulombFitter machinery
 500 described in Sec. 5.2. Unfortunately, the world in which we live is not perfect, such a table does not
 501 exist, and little is known about the interaction between the residual pairs in this study. One solution
 502 would be to introduce a set of scattering parameters and radii for each residual system. However, as will
 503 be the case of the λ -parameters above, this would introduce a large number of additional fit parameters,
 504 and would make our fitter too unconstrained and would yield untrustworthy results. The second option,
 505 which is adopted in this analysis, is to assume all residual pairs have the same source size as the daughter
 506 pair, and all Coulomb-neutral residual pairs also share the same scattering parameters as the daughter
 507 pair (the case of charged pairs will be described below).

508 Concerning the radii of the residual parent pairs, it was suggested that these should be set to smaller
 509 values. In the interest of minimizing the number of parameters in the fitter, we tested this by introducing
 510 an m_T -scaling of the parent radii. The motivation for this scaling comes from the approximate m_T -scaling
 511 of the radii observed in 45. To achieve this scaling, we assume the radii follow an inverse-square-root

ΛK^+ Residuals		$\bar{\Lambda} K^-$ Residuals	
Pair System	λ value	Pair System	λ value
3 Residuals		3 Residuals	
ΛK^+	0.154	$\bar{\Lambda} K^-$	0.158
$\Sigma^0 K^+$	0.099	$\bar{\Sigma}^0 K^-$	0.102
$\Xi^0 K^+$	0.072	$\bar{\Xi}^0 K^-$	0.067
$\Xi^- K^+$	0.069	$\bar{\Xi}^+ K^-$	0.065
Other	0.558	Other	0.560
Fakes	0.048	Fakes	0.048
10 Residuals		10 Residuals	
ΛK^+	0.154	$\bar{\Lambda} K^-$	0.158
$\Sigma^0 K^+$	0.099	$\bar{\Sigma}^0 K^-$	0.102
$\Xi^0 K^+$	0.072	$\bar{\Xi}^0 K^-$	0.067
$\Xi^- K^+$	0.069	$\bar{\Xi}^+ K^-$	0.065
$\Sigma^{*+} K^+$	0.046	$\bar{\Sigma}^{*-} K^-$	0.046
$\Sigma^{*-} K^+$	0.042	$\bar{\Sigma}^{*+} K^-$	0.045
$\Sigma^{*0} K^+$	0.042	$\bar{\Sigma}^{*0} K^-$	0.040
ΛK^{*0}	0.039	$\bar{\Lambda} \bar{K}^{*0}$	0.041
$\Sigma^0 K^{*0}$	0.035	$\bar{\Sigma}^0 \bar{K}^{*0}$	0.036
$\Xi^0 K^{*0}$	0.025	$\bar{\Xi}^0 \bar{K}^{*0}$	0.024
$\Xi^- K^{*0}$	0.024	$\bar{\Xi}^+ \bar{K}^{*0}$	0.023
Other	0.305	Other	0.305
Fakes	0.048	Fakes	0.048

Table 1: λ values for the individual components of the ΛK^+ (left) and $\bar{\Lambda} K^-$ (right) correlation functions for the case of 3 and 10 residual contributions.

ΛK ⁻ Residuals		ΛK ⁺ Residuals	
Pair System	λ value	Pair System	λ value
3 Residuals		3 Residuals	
ΛK ⁻	0.154	ΛK ⁺	0.158
Σ ⁰ K ⁻	0.099	Σ ⁰ K ⁺	0.103
Ξ ⁰ K ⁻	0.071	Ξ ⁰ K ⁺	0.068
Ξ ⁻ K ⁻	0.068	Ξ ⁺ K ⁺	0.066
Other	0.561	Other	0.557
Fakes	0.048	Fakes	0.048
10 Residuals		10 Residuals	
ΛK ⁻	0.154	ΛK ⁺	0.158
Σ ⁰ K ⁻	0.099	Σ ⁰ K ⁺	0.103
Ξ ⁰ K ⁻	0.071	Ξ ⁰ K ⁺	0.068
Ξ ⁻ K ⁻	0.068	Ξ ⁺ K ⁺	0.066
Σ ^{*+} K ⁻	0.046	Σ ^{*-} K ⁺	0.046
Σ ^{*-} K ⁻	0.041	Σ ^{*+} K ⁺	0.045
Σ ^{*0} K ⁻	0.041	Σ ^{*0} K ⁺	0.041
ΛK ^{*0}	0.039	ΛK ^{*0}	0.041
Σ ⁰ K ^{*0}	0.035	Σ ⁰ K ^{*0}	0.036
Ξ ⁰ K ^{*0}	0.025	Ξ ⁰ K ^{*0}	0.024
Ξ ⁻ K ^{*0}	0.024	Ξ ⁺ K ^{*0}	0.023
Other	0.308	Other	0.301
Fakes	0.048	Fakes	0.048

Table 2: λ values for the individual components of the ΛK^- (left) and $\bar{\Lambda} K^+$ (right) correlation functions for the case of 3 and 10 residual contributions.

ΛK_S^0 Residuals		$\bar{\Lambda} K_S^0$ Residuals	
Pair System	λ value	Pair System	λ value
3 Residuals		3 Residuals	
ΛK_S^0	0.165	$\bar{\Lambda} K_S^0$	0.169
$\Sigma^0 K_S^0$	0.107	$\bar{\Sigma}^0 K_S^0$	0.111
$\Xi^0 K_S^0$	0.077	$\bar{\Xi}^0 K_S^0$	0.073
$\Xi^- K_S^0$	0.075	$\bar{\Xi}^+ K_S^0$	0.071
Other	0.528	Other	0.528
Fakes	0.048	Fakes	0.048
10 Residuals		10 Residuals	
ΛK_S^0	0.165	$\bar{\Lambda} K_S^0$	0.169
$\Sigma^0 K_S^0$	0.107	$\bar{\Sigma}^0 K_S^0$	0.111
$\Xi^0 K_S^0$	0.077	$\bar{\Xi}^0 K_S^0$	0.073
$\Xi^- K_S^0$	0.075	$\bar{\Xi}^+ K_S^0$	0.071
$\Sigma^{*+} K_S^0$	0.050	$\bar{\Sigma}^{*-} K_S^0$	0.050
$\Sigma^{*-} K_S^0$	0.045	$\bar{\Sigma}^{*+} K_S^0$	0.049
$\Sigma^{*0} K_S^0$	0.045	$\bar{\Sigma}^{*0} K_S^0$	0.044
ΛK^{*0}	0.019	$\bar{\Lambda} K^{*0}$	0.020
$\Sigma^0 K^{*0}$	0.017	$\bar{\Sigma}^0 K^{*0}$	0.017
$\Xi^0 K^{*0}$	0.012	$\bar{\Xi}^0 K^{*0}$	0.011
$\Xi^- K^{*0}$	0.012	$\bar{\Xi}^+ K^{*0}$	0.011
Other	0.329	Other	0.326
Fakes	0.048	Fakes	0.048

Table 3: λ values for the individual components of the ΛK_S^0 (left) and $\bar{\Lambda} K_S^0$ (right) correlation functions for the case of 3 and 10 residual contributions.

512 distribution: $R_{AB} = \alpha m_T^{-1/2}$. Then, it follows that we should scale the parent radii as:

$$R_{AB} = R_{\Lambda K} \left(\frac{m_{T,AB}}{m_{T,\Lambda K}} \right)^{-1/2} \quad (19)$$

513 The values for m_T for each pair system was taken from THERMINATOR. As the fitter dances around
 514 parameter space and selects new radii for the ΛK pairs, the radii of the residuals is scaled by the above
 515 factor. In the end, this scaling factor made no significant difference in our fit results, so this complication
 516 is excluded from our final results. Note that this is not surprising, as the most extreme scaling factor
 517 was, in the case of using 10 residual systems, between ΛK^+ with $m_{T,\Lambda K^+} \approx 1.4 \text{ GeV}/c^2$ and $\Xi^- K^{*0}$ with
 518 $m_{T,\Xi^- K^{*0}} \approx 1.8 \text{ GeV}/c^2$, resulting in a scale factor of ≈ 0.9 .

519 Now, as hinted above, accounting for charged residuals adds a complication in that they necessitate the
 520 inclusion of the CoulombFitter into the process. The complication of combining the two fitters is not
 521 troubling, but it increases the fitting time drastically (the parallelization of the CoulombFitter across a
 522 large number of GPU cores, to drastically decrease run-time, is currently underway). We have two so-
 523 lutions to bypass such a large increase in run time. First, we can use our experimental $\Xi^{\text{ch}} K^{\text{ch}}$ data to
 524 represent all charged parent pair system. In this case, there is no need to make any assumption about
 525 scattering parameters or source sizes, as we already have the experimental data. The downside is that,
 526 especially in the 30-50% centrality bin, the error bars on the data are large. Alternatively, we can assume
 527 the strong interaction is negligible in the charged residual, and generate the parent correlation function
 528 given radius and λ parameters. We find in our $\Xi^{\text{ch}} K^{\text{ch}}$ study that a Coulomb-only description of the sys-
 529 tem describes, reasonably well, the broad features of the correlation. The strong interaction is necessary
 530 for the fine details. However, as these correlations are run through a transform matrix, which largely
 531 flattens out and fine details, a Coulomb-only description should be sufficient. In practice, this Coulomb-
 532 only scenario is achieved by first building a large number of Coulomb-only correlations for various radii
 533 and λ parameter values, and interpolating from this grid during the fitting process. We find consistent
 534 results between using the ΞK data and the Coulomb-only interpolation method. When the number of
 535 residual pairs used is increased to 10, so that pairs such as $\Sigma^{*+} K^-$ enter the picture, the Coulomb-only
 536 interpolation method is used. In other words, the ΞK experimental data is only used to model the ΞK
 537 residual contribution, all other charged pairs are treated with the Coulomb-only interpolation method.

538 Two examples of how very different transform matrices can alter a correlation function are shown in
 539 Figures 22 and 23 below. These figures were taken using parameter values obtained from fits to the data.
 540 In the top left corner of the figures, the input correlation function (closed symbols) is shown together
 541 with the output, transformed, correlation function (open symbols). In the bottom left, the transformed
 542 correlation is shown by itself. This is especially helpful when the λ parameter is very small, in which
 543 case the contribution in the top left can look flat, but the zoomed in view in the bottom left shows the
 544 structure. The right two plots in each figure show the transform matrix without (top right) and with
 545 (bottom right) a log-scale on the z-axis. Note, more examples of these transforms can be found in Sec.
 546 9.

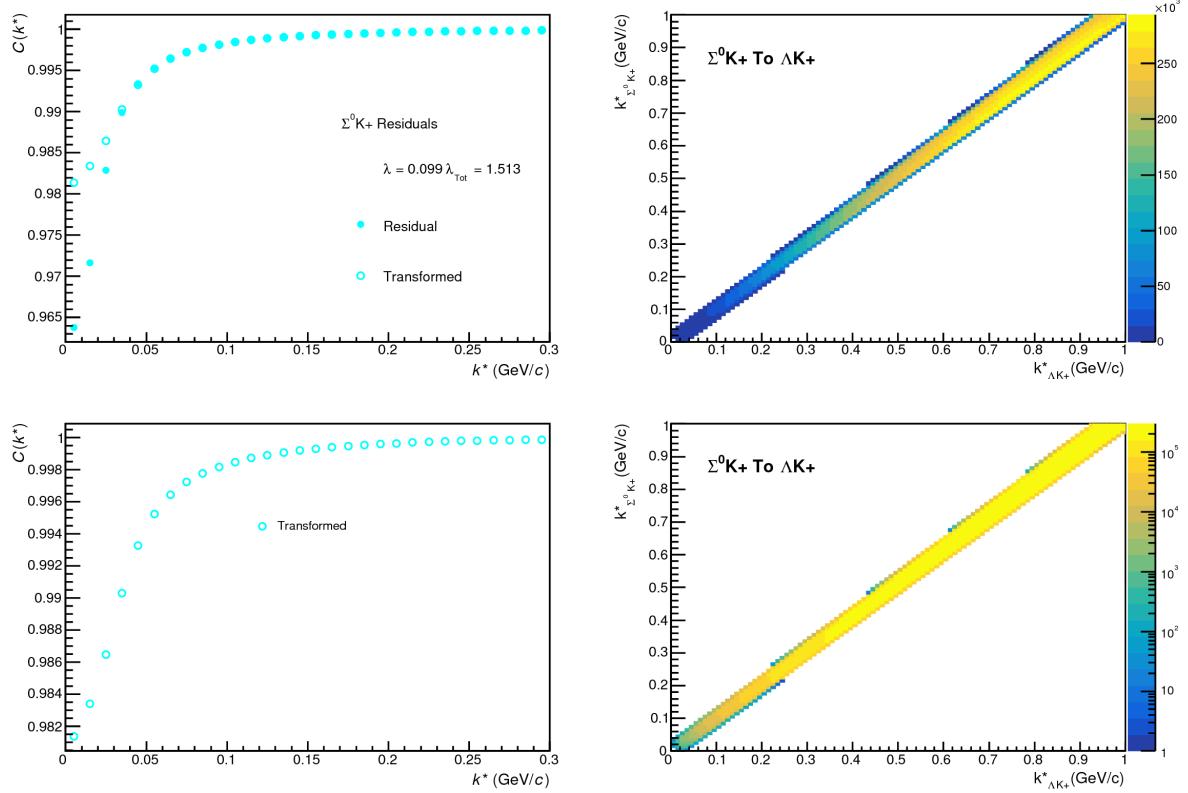


Fig. 22: $\Sigma^0 \text{K}^+$ Transform. These figures were taken using parameter values obtained from fits to the data. In the top left corner of the figures, the input correlation function (closed symbols) is shown together with the output, transformed, correlation function (open symbols). In the bottom left, the transformed correlation is shown by itself. The right two plots in each figure show the transform matrix without (top right) and with (bottom right) a log-scale on the z-axis.

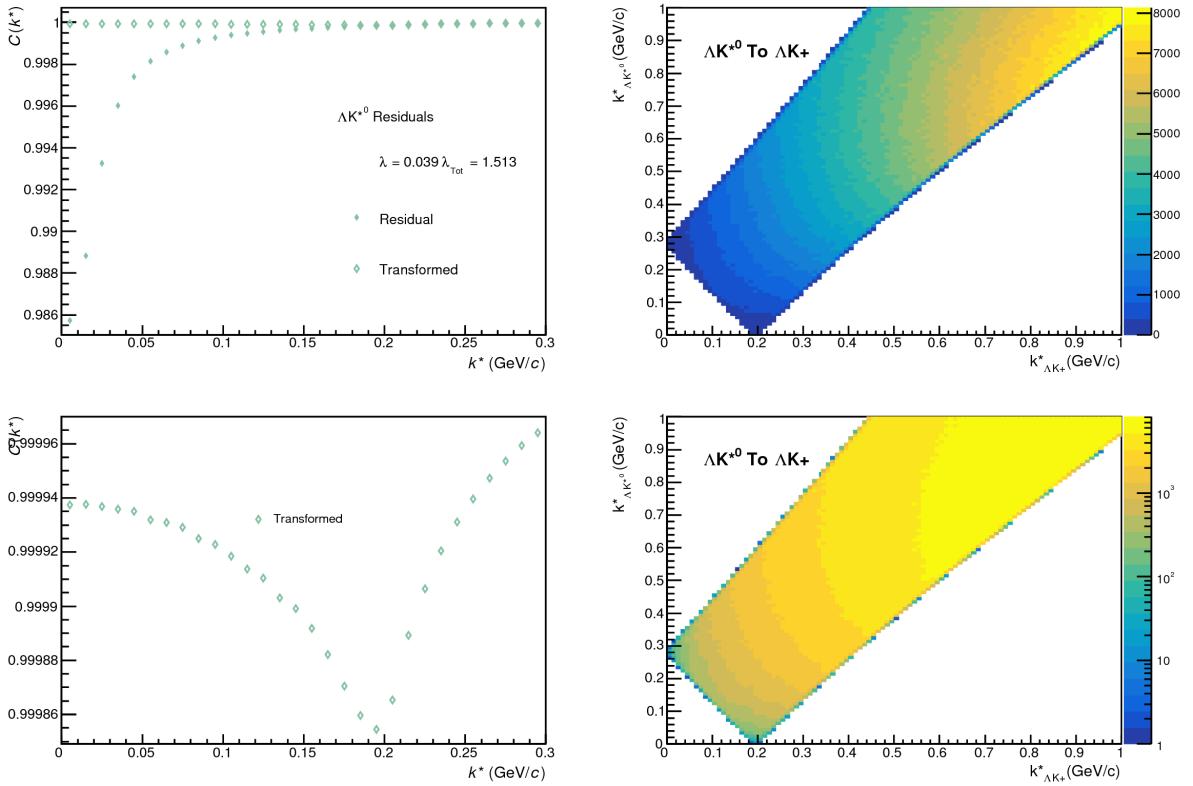
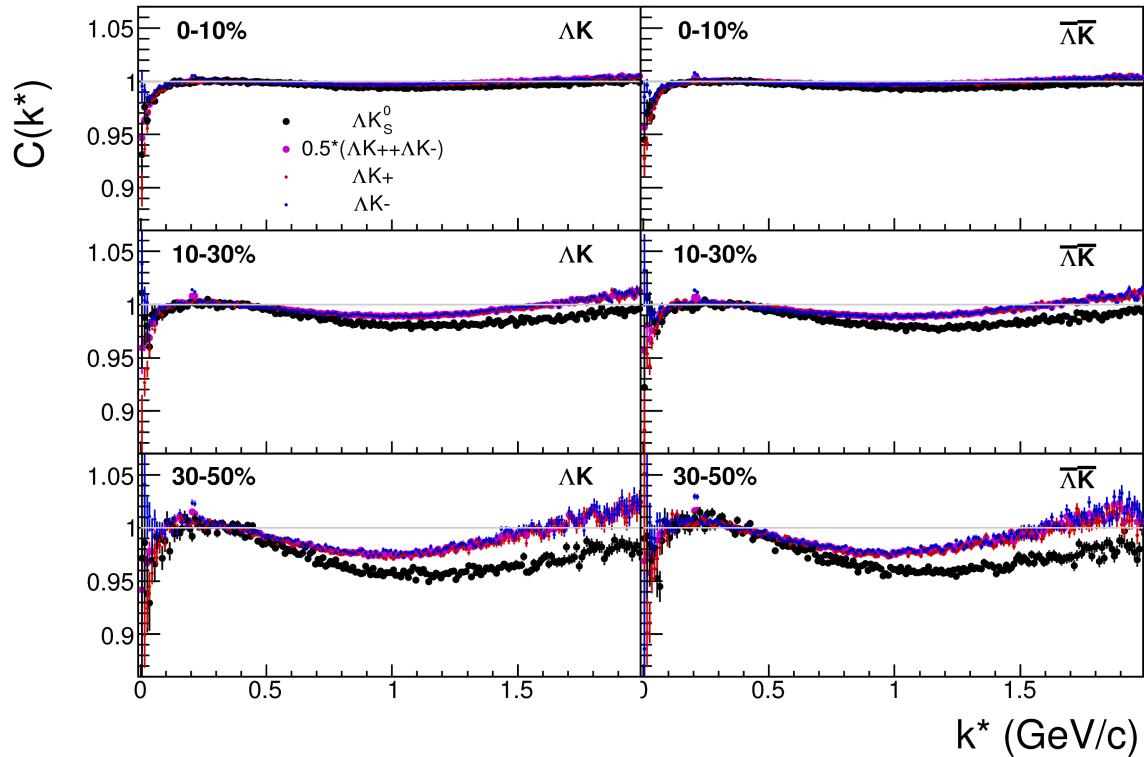


Fig. 23: $\Sigma^0 K^+$ Transform. These figures were taken using parameter values obtained from fits to the data. In the top left corner of the figures, the input correlation function (closed symbols) is shown together with the output, transformed, correlation function (open symbols). In the bottom left, the transformed correlation is shown by itself. The right two plots in each figure show the transform matrix without (top right) and with (bottom right) a log-scale on the z-axis.

547 5.5 Non-Flat Background

548 We observe a significant non-femtoscopic, non-flat, background in all of our correlations at large k^* .
 549 This background increases with decreasing centrality, is the same amongst all ΛK^\pm pairs, and is more
 550 pronounced in the ΛK_S^0 system, as can be seen in Fig. 24.

551 It is important to note that the difference in ΛK^\pm and ΛK_S^0 backgrounds is due mainly to the difference in
 552 kinematic cuts, not due to any interesting physics. In simulation, which do a very good job of matching
 553 the experimental data, when restrictions are imposed on the p_T of the K_S^0 to more closely match the K^\pm
 554 cuts, the backgrounds align.



555 **Fig. 24:** Compare backgrounds

556 It is suggested that this background effect is due primarily to particle collimation associated with elliptic
 557 flow [8]. More specifically, these backgrounds result from mixing events with unlike event-plane angles
 558 (Ψ_{EP}). As explained in [8], when elliptic flow is present, all particles are more likely to be emitted
 559 in a specific direction (in-plane), as opposed to a perpendicular direction. Therefore, the difference in
 560 momenta for pairs of particles tends to be smaller, compared to the case of no flow. In the case of mixed-
 561 event pairs, the two events used do not share an event-plane, and therefore this is no collimation effect
 562 in the pairs from flow. As a result, pairs with larger momentum are more likely when mixed-events are
 563 used, and the correlation function will be observed below unity. In general, a dip below unity, at a given
 564 k^* , means it is more probable to find a pair at that k^* when the daughters are taken from mixed-events, as
 compared to when they are taken from the same event.

565 This same reasoning suggests that the background should lead to an enhancement at low- k^* . The en-
 566 hancement at high- k^* ($k^* \gtrsim 1.5$ GeV/c) does not result from the collective flow of the system. We are not
 567 certain what causes this enhancement, but typical suspects are jet-like correlations and resonance decays.

568 We can split our correlation functions into three main regions. First, the low- k^* region ($k^* \lesssim 0.3$ GeV/c)
 569 contains the femtoscopic correlations, as well as a likely enhancement from the background. The

intermediate- k^* region ($0.3 \lesssim k^* \gtrsim 1.5$ GeV/c) contains a suppression from the background. Finally, the high- k^* region ($k^* \gtrsim 1.5$ GeV/c) contains an enhancement with unknown origin.

THERMINATOR 2 simulation has been shown to reproduce the background features in a π K analysis [8]. As the background effect can be attributed mainly to elliptic flow, which is a global feature of the system, we suspected THERMINATOR 2 could also, at least qualitatively, describe our backgrounds. After ensuring each simulated event received a random event-plane angle (Ψ_{EP})¹, we found THERMINATOR 2 did a good job of describing our data qualitatively, and, in some cases, quantitatively. Figure 25 shows the THERMINATOR 2 simulation (gold) together with experimental data (red, blue, or black). The figure also shows a 6th-order polynomial fit to the simulation (gold), as well as the fit polynomial scaled to match the data (red, blue, black).

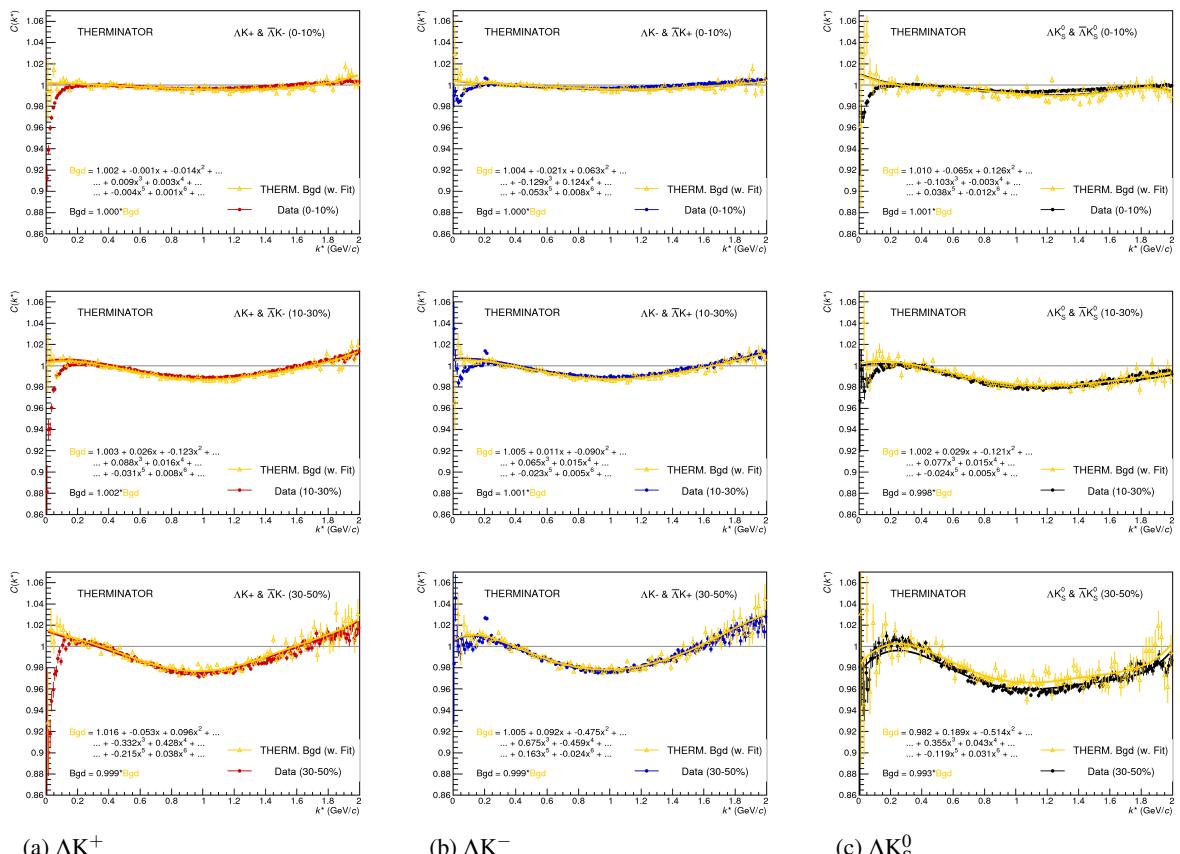


Fig. 25: THERMINATOR 2 simulation (gold) together with experimental data (red, blue, or black). The left column shows results for ΛK^+ (25a), middle for ΛK^- (25b), and right for ΛK_0^S (25c). A 6th-order polynomial fit to the simulation is shown as a solid gold line, and whose fit parameters are printed on the lower left of each plot. This polynomial is scaled to match the experimental data; the value of this scale is printed in the lower left corner of each plot. The polynomial fit with scale factor applied is drawn in a color matching the experimental data (red, blue, black).

Figure 26 shows three different correlation function generated using THERMINATOR 2 simulation ("Cf w/o Bgd (A)", "Cf w. Bgd (B)", "Bgd(C")", as well as two histograms describing the relation between the three ("Ratio (B/C)", "1+Diff(B-C)"). Cf w/o Bgd (A)" shows a correlation function with a femtosopic correlation, but without background. When THERMINATOR 2 is run without randomizing event planes, and therefore having all events share a common event plane, no non-flat background is observed, as

¹default was for all events to share a common event plane

expected. The femtoscopic correlation effect was introduced by assuming scattering parameters for the system, and weighting the numerators appropriately. The second correlation, "Cf w. Bgd (B)", shows a correlation function with both a femtoscopic correlation and a background (most closely matches our situation in experiment). To generate the background, each event was given a random event-plane angle, as is given to us in experiment. To generate the femtoscopic correlation, the same numerator weighting procedure was used. Finally, "Bgd (C)", shows a correlation function with a non-femtoscopic background, but no femtoscopic correlation, i.e. background only. This is generated just as "Cf w. Bgd (B)", with randomized event planes, but unit weights are used when filling the numerators, so no femtoscopic effects are included.

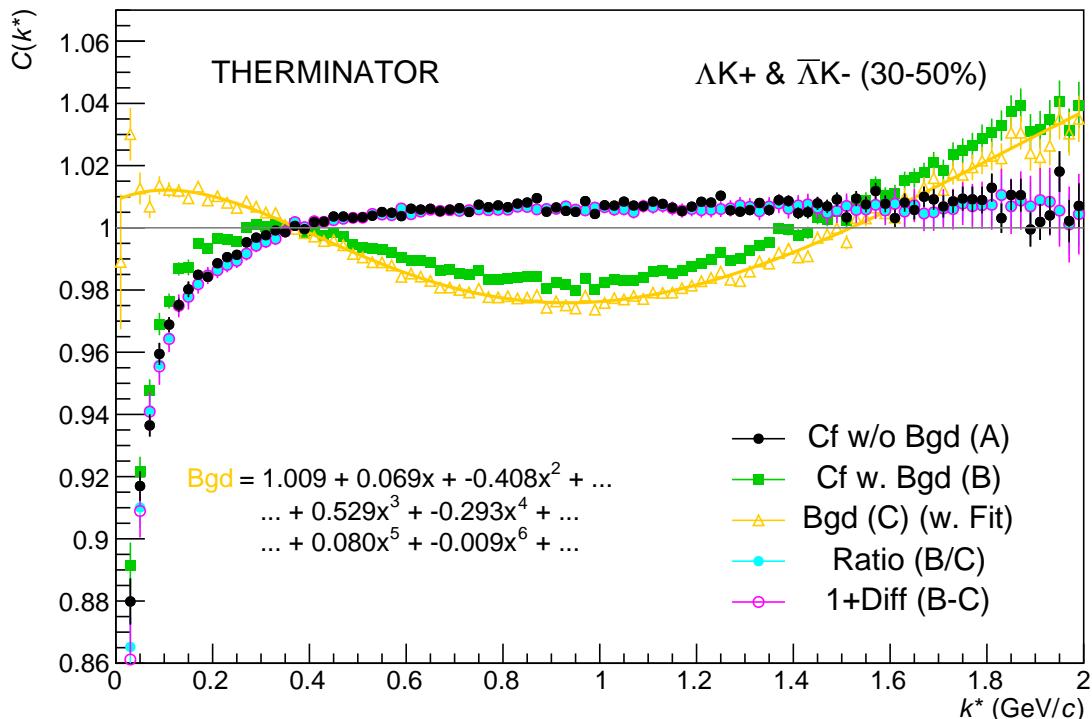


Fig. 26: Correlation with background decomposition with THERMINATOR. "Cf w/o Bgd (A)" shows a correlation function with a femtoscopic correlation, but without background. "Cf w. Bgd (B)", shows a correlation function with both a femtoscopic correlation and a background (most closely matches our situation in experiment). "Bgd (C)", shows a correlation function with a non-femtoscopic background, but no femtoscopic correlation, i.e. background only.

The main point of Fig. 26 is that the black points match the blue (and purple) points; or, equivalently:

$$C_{fw/oBgd} = \frac{C_{fw.Bgd}}{Bgd} \rightarrow C_{theory} = \frac{C_{exp}}{F_{Bgd}} \rightarrow C_{exp} = C_{theory} \cdot F_{Bgd} \quad (20)$$

As shown and described in Fig 26 and Eq. 20, THERMINATOR 2 simulation shows the non-femtoscopic background affects the correlation function as a separable scale factor. We expect this behavior to be roughly the same in the experimental data.

Figure 27 demonstrates the use of the Stavinsky method with THERMINATOR 2. In the figure, unit weights were used for all numerators, so no femtoscopic signal is included, only background effects. The black points show an ideal, experimentally unreachable, situation of aligning all of the event-plane

601 angles. With THERMINATOR 2, when the event-planes are aligned, the background signal is killed. The
 602 green points show the experimental situation of random event-plane angles. The purple points shown the
 603 affect of applying the Stavinsky method to the case of random event-planes. The figure shows that this
 604 method effectively kills the non-flat background (i.e. the procedure takes the green points to the purple).
 605 Finally, the blue points show the effect of applying the Stavinsky method when all of the event-planes
 606 are aligned. This shows that the Stavinsky method does not introduce any signal to an already flat
 607 background.

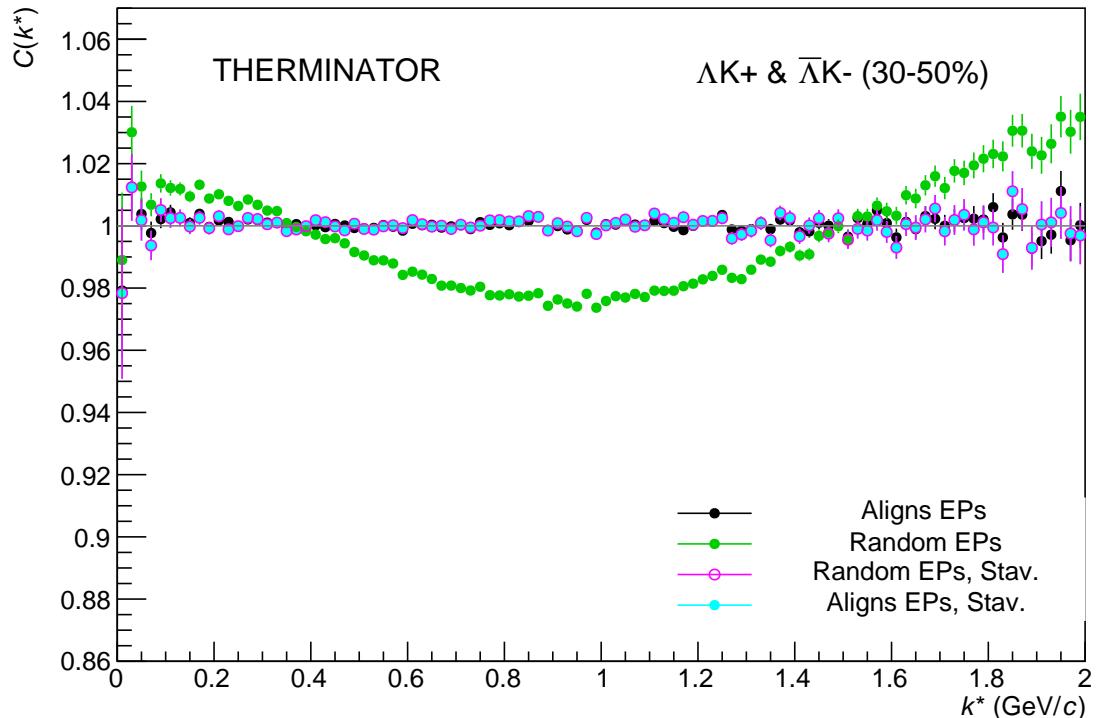


Fig. 27: The use of the Stavinsky method with THERMINATOR 2. Unit weights were used for all numerators, so no femtoscopic signal is included, only background effects. The black points show an ideal, experimentally unreachable, situation of aligning all of the event-plane angles. The green points show the experimental situation of random event-plane angles. The purple points shown the affect of applying the Stavinsky method to the case of random event-planes. Finally, the blue points show the effect of applying the Stavinsky method when all of the event-planes are aligned.

608 5.6 LednickyFitter

609 The code developed to fit the data is called “LednickyFitter”, and utilizes the ROOT TMinuit implemen-
 610 tation of the MINUIT fitting package. In short, given a function with a number of parameters, the fitter
 611 explores the parameter space searching for the minimum of the equation. In this implementation, the
 612 function to be minimized should represent the difference between the measure and theoretical corre-
 613 lation functions. However, a simple χ^2 test is inappropriate for fitting correlation functions, as the ratio
 614 two Poisson distributions does not result in a Poisson distribution. Instead, a log-likelihood fit function
 615 of the following form is used [2]:

$$\chi_{PML}^2 = -2 \left[A \ln \left(\frac{C(A+B)}{A(C+1)} \right) + B \ln \left(\frac{A+B}{B(C+1)} \right) \right] \quad (21)$$

616 where A is the experimental signal distribution (numerator), B is the experimental background distribution
617 (denominator), and C is the theoretical fit correlation function.

618 The LednickyFitter uses Equations 5 – 7 to build the theoretical fit, and Equation 21 as the statistic
619 quantifying the quality of the fit. The parameters to be varied by MINUIT are: λ , R , f_0 ($\mathbb{R}f_0$ and $\mathbb{I}f_0$
620 separately), d_0 , and normalization N . The fitter currently includes methods to correct for momentum
621 resolution and a non-flat background. These corrections are applied to the fit function, the data is never
622 touched. The fitter is able to share parameters between different analyses and fit all simultaneously.

623 In a typical fit, a given pair is fit with its conjugate (ex. ΛK^+ with $\bar{\Lambda} K^-$) across all centralities (0-10%,
624 10-30%, 30-50%), for a total of 6 simultaneous analyses. Each analysis has a unique λ and normalization
625 parameter. The radii are shared between analyses of like centrality, as these should have similar source
626 sizes. The scattering parameters ($\mathbb{R}f_0$, $\mathbb{I}f_0$, d_0) are shared amongst all.

627 In the case of fitting with residuals, the λ_{Fit} parameter serves as an overall normalization shared by all
628 contributors, such that Eqn 17 becomes:

$$\begin{aligned} C_{measured}(k_{\Lambda K}^*) &= 1 + \sum_i \lambda'_i [C_i(k_{\Lambda K}^*) - 1] \\ \lambda'_i &= \lambda_{Fit} \lambda_i \\ \sum_i \lambda'_i &= \lambda_{Fit} \sum_i \lambda_i = \lambda_{Fit} \end{aligned} \quad (22)$$

629 where λ_i is obtained from THERMINATOR, as explained in Section 5.4, and whose values are presented
630 in Tables 1 through 3. For Coulomb-neutral pairs, such as ΛK , $\Sigma^0 K$, and $\Xi^0 K$, $C_i(k_{\Lambda K}^*)$ is calculated from
631 Eqn. 5, with the help of Eqn. 7. For those residual pairs which include a Coulomb interaction, $C_i(k_{\Lambda K}^*)$
632 is either calculated using the CoulombFitter method (Sections 5.2 and 5.7) with no strong interaction, or
633 by using the $\Xi^{ch} K^{ch}$ data directly. Unless otherwise stated, the $\Xi^{ch} K^{ch}$ residual contribution is modeled
634 using the experimental $\Xi^{ch} K^{ch}$ data, and all other charged contributors (ex. $\Sigma^{*ch} K^{ch}$) are modeled using
635 the CoulombFitter technique with no strong interaction contribution.

636 To summarize, the complete fit function is constructed as follows:

637 1. The uncorrected correlation function, $C'_{Fit}(k_{True}^*)$, is constructed using Eq. 22 (with the help of
638 Eqns. 5 and 7, as well as Secs. 5.2 and 5.7)

- 639 – in the case of no residual contributions included in the fit, $\lambda_i = \lambda_{\Lambda K}$ in Eq. 22 is set equal to
- 640 1. Then, the extracted λ_{Fit} parameter should be roughly equal to the pair purity.
- 641 – when residuals are included, the λ_i values are presented in Tables 1 through 3.

642 2. The correlation function is corrected to account for momentum resolution effects using Eq. 14

$$C'_{fit}(k_{Rec}^*) = \frac{\sum_{k_{True}^*} M_{k_{Rec}^*, k_{True}^*} C'_{fit}(k_{True}^*)}{\sum_{k_{True}^*} M_{k_{Rec}^*, k_{True}^*}}$$

644 3. Finally, the non-flat background correction is applied, and the final fit function is obtained

$$C_{Fit}(k_{Rec}^*) = C'_{Fit}(k_{Rec}^*) * F_{Bgd}(k_{Rec}^*)$$

646 Figures 30, 31, and 32 (34, 35, and 36, or 40, 41, and 42), in Section 7, show experimental data with fits
647 for all studied centralities for ΛK_S^0 with $\bar{\Lambda} K_S^0$, ΛK^+ with $\bar{\Lambda} K^-$, and ΛK^- with $\bar{\Lambda} K^+$, respectively. In the

648 figures, the black solid line represents the “raw” fit, i.e. not corrected for momentum resolution effects
 649 nor non-flat background. The green line shows the fit to the non-flat background. The purple points
 650 show the fit after momentum resolution, non-flat background, and residual correlations (if applicable)
 651 corrections have been applied. The initial values of the parameters is listed, as well as the final fit values
 652 with uncertainties.

653 5.7 Coulomb Fitter

654 When fitting the $\Xi^-(\bar{\Xi}^+)K^\pm$ results, it is necessary to include both strong and Coulomb effects. In this
 655 case, Equation 5 is no longer valid, and, in fact, there is no analytical form with which to fit. Therefore,
 656 we must begin with the wave function describing the pair interaction, and simulate many particle pairs
 657 to obtain a theoretical fit correlation function. The code developed to achieve this functionality is called
 658 “CoulombFitter”. Currently, in order to generate the statistics needed for a stable fit, we find that $\sim 10^4$
 659 simulated pairs per 10 MeV bin are necessary. Unfortunately, the nature of this process means that the
 660 “CoulombFitter” takes much longer to run than the “LednickyFitter” of Section 5.1.

661 Unfortunately, with this analysis, we are not sensitive to, and therefore not able to distinguish between,
 662 the iso-spin singlet and triplet states. We proceed with our analysis, but the results must be interpreted
 663 as iso-spin averaged scattering parameters.

664 As stated before, to generate a fit correlation function, we must simulate a large number of pairs, calculate
 665 the wave-function, and average Ψ^2 over all pairs in a given k^* bin. Essentially, we calculate Equation 9
 666 by hand:

$$\begin{aligned} C(\mathbf{k}^*) &= \sum_S \rho_S \int S(\mathbf{r}^*) |\Psi_{\mathbf{k}^*}^S(\mathbf{r}^*)|^2 d^3\mathbf{r}^* \\ &\longrightarrow C(|\mathbf{k}^*|) \equiv C(k^*) = \sum_S \rho_S \langle |\Psi^S(\mathbf{k}_i^*, \mathbf{r}_i^*)|^2 \rangle_i \\ &\longrightarrow C(k^*) = \lambda \sum_S \rho_S \langle |\Psi^S(\mathbf{k}_i^*, \mathbf{r}_i^*)|^2 \rangle_i + (1 - \lambda) \end{aligned} \quad (23)$$

667 where $\langle \rangle_i$ represents an average over all pairs in a given k^* bin.

668 In summary, for a given k^* bin, we must draw $N_{pairs} \sim 10^4$ pairs, and for each pair:

669 1. Draw a random \mathbf{r}^* vector according to our Gaussian source distribution $S(\mathbf{r}^*)$

670 2. Draw a random \mathbf{k}^* vector satisfying the $|\mathbf{k}^*|$ restriction of the bin

671 – We draw from real k^* vectors obtained from the data

672 – However, we find that drawing from a distribution flat in k^* gives similar results

673 3. Construct the wave-function Ψ

674 After all pairs for a given k^* bin are simulated and wave-functions obtained, the results are averaged to
 675 give the fit result.

676 Construction of the wave-functions, Equation 10, involves a number of complex functions not included
 677 in standard C++ or ROOT libraries (namely, $h(\eta)$, $\tilde{G}(\rho, \eta)$), and $F(-i\eta, 1, i\xi)$. These functions were
 678 even difficult to find and implement from elsewhere. Our solution was to embed a Mathematica kernel
 679 into our C++ code to evaluate these functions. However, having Mathematica work on-the-fly with the
 680 fitter was far too time consuming (fitter would have taken day, maybe weeks to finish). Our solution
 681 was to use Mathematica to create matrices representing these functions for different parameter values.

682 During fitting, these matrices were then interpolated and the results used to build the wave-functions.
 683 This method decreased the running time dramatically, and we are not able to generate results in under \sim
 684 1 hour. This process will be explained in more detail in future versions of the note.

685 6 Systematic Errors

686 In order to understand my systematic uncertainties, the analysis code was run many times using slightly
 687 different values for a number of important cuts, and the results were compared.

688 In order to quantify the systematic errors on the data, all correlation functions built using all varied cut
 689 values were bin-by-bin averaged, and the resulting variance of each bin was taken as the systematic error.
 690 The cuts which were utilized in this study are presented in Sections 6.1.1 (ΛK_S^0) and 6.2.1 (ΛK^\pm).

691 Similarly, the fit parameters extracted from all of these correlation functions were averaged, and the
 692 resulting variances were taken as the systematic errors for the fit parameters. As with the systematic
 693 errors on the data, this was performed for all varied cut values. Additionally, a systematic analysis was
 694 done on our fit method (which, for now, just includes our choice of fit range). These two sources of
 695 uncertainty were combined in quadrature to obtain the final systematic uncertainties on the extracted fit
 696 parameters.

697 6.1 Systematic Errors: ΛK_S^0

698 6.1.1 Particle and Pair Cuts

699 The cuts included in the systematic study, as well as the values used in the variations, are listed below.
 700 Note, the central value corresponds to that used in the analysis.

ΛK_S^0 systematics	
DCA $\Lambda(\bar{\Lambda})$	4, 5, 6 mm
DCA K_S^0	2, 3, 4 mm
DCA $\Lambda(\bar{\Lambda})$ Daughters	3, 4, 5 mm
DCA K_S^0 Daughters	2, 3, 4 mm
$\Lambda(\bar{\Lambda})$ Cosine of Pointing Angle	0.9992, 0.9993, 0.9994
K_S^0 Cosine of Pointing Angle	0.9992, 0.9993, 0.9994
DCA to Primary Vertex of $p(\bar{p})$ Daughter of $\Lambda(\bar{\Lambda})$	0.5, 1, 2 mm
DCA to Primary Vertex of $\pi^-(\pi^+)$ Daughter of $\Lambda(\bar{\Lambda})$	2, 3, 4 mm
DCA to Primary Vertex of π^+ Daughter of K_S^0	2, 3, 4 mm
DCA to Primary Vertex of π^- Daughter of K_S^0	2, 3, 4 mm
Average Separation of Like-Charge Daughters	5, 6, 7 cm

Table 4: ΛK_S^0 systematics

701 6.1.2 Non-Flat Background

702 We fit our non-flat background with a linear function. To study the contribution of this choice to our sys-
 703 tematic errors, we also fit with a quadratic and Gaussian form. The resulting uncertainties are combined
 704 with the uncertainties arising from our particle cuts.

705 6.1.3 Fit Range

706 Our choice of k^* fit range was varied by $\pm 25\%$. The resulting uncertainties in the extracted parameter
 707 sets were combined with our uncertainties arising from our particle and pair cuts.

708 **6.2 Systematic Errors: ΛK^\pm**

709 **6.2.1 Particle and Pair Cuts**

710 The cuts included in the systematic study, as well as the values used in the variations, are listed below.
 711 Note, the central value corresponds to that used in the analysis.

ΛK^\pm systematics	
DCA $\Lambda(\bar{\Lambda})$	4, 5, 6 mm
DCA $\Lambda(\bar{\Lambda})$ Daughters	3, 4, 5 mm
$\Lambda(\bar{\Lambda})$ Cosine of Pointing Angle	0.9992, 0.9993, 0.9994
DCA to Primary Vertex of $p(\bar{p})$ Daughter of $\Lambda(\bar{\Lambda})$	0.5, 1, 2 mm
DCA to Primary Vertex of $\pi^-(\pi^+)$ Daughter of $\Lambda(\bar{\Lambda})$	2, 3, 4 mm
Average Separation of $\Lambda(\bar{\Lambda})$ Daughter with Same Charge as K^\pm	7, 8, 9 cm
Max. DCA to Primary Vertex in Transverse Plane of K^\pm	1.92, 2.4, 2.88
Max. DCA to Primary Vertex in Longitudinal Direction of K^\pm	2.4, 3.0, 3.6

Table 5: ΛK^\pm systematics

712 **6.2.2 Non-Flat Background**

713 We fit our non-flat background with a linear function. To study the contribution of this choice to our sys-
 714 tematic errors, we also fit with a quadratic and Gaussian form. The resulting uncertainties are combined
 715 with the uncertainties arising from our particle cuts.

716 **6.2.3 Fit Range**

717 Our choice of k^* fit range was varied by $\pm 25\%$. The resulting uncertainties in the extracted parameter
 718 sets were combined with our uncertainties arising from our particle and pair cuts.

719 **6.3 Systematic Errors: ΞK^\pm**

720 **6.3.1 Particle and Pair Cuts**

721 The cuts included in the systematic study, as well as the values used in the variations, are listed below.
 722 Note, the central value corresponds to that used in the analysis.

723 **7 Results and Discussion**

724 **7.1 Results: ΛK_S^0 and ΛK^\pm**

725 NOTE: The fit results need to be updated. I was not sure how we wanted to handle the non-flat back-
 726 ground (THERMINATOR 2 simulation with polynomial fit, linear fit to the data, Stavinsky method to
 727 rid date of background), so I did not yet inset the final figures. With the exception of the following figure
 728 (Fig. 28), the results shown use a linear form of the non-flat background fit to the data, and $\Lambda K^+(\bar{\Lambda} K^-)$
 729 radii are not shared with $\Lambda K^-(\bar{\Lambda} K^+)$. In Figure 28, we show extracted fit parameters for the case of
 730 $\Lambda K^+(\bar{\Lambda} K^-)$ sharing radii with $\Lambda K^-(\bar{\Lambda} K^+)$. The figure shows results for three different treatments of
 731 the non-femtoscopic background: a polynomial fit to THERMINATOR 2 simulation to model the back-
 732 ground (circles), a linear fit to the data to model the background (squares), and the Stavinsky method
 733 (crosses).

734 I first collect all of the summary results, and will show the actual fits to the data in Sections 7.1.1, 7.1.2,
 735 and 7.1.3. In the first of the summary plots, we show the extracted scattering parameters in the form of a

$\Xi^- K^\pm$ systematics

$\Xi^- K^\pm$ systematics	
Max. DCA $\Xi(\bar{\Xi})$	2, 3, 4 mm
Max. DCA $\Xi(\bar{\Xi})$ Daughters	2, 3, 4 mm
Min. $\Xi(\bar{\Xi})$ Cosine of Pointing Angle to Primary Vertex	0.9991, 0.9992, 0.9993
Min. $\Lambda(\bar{\Lambda})$ Cosine of Pointing Angle to $\Xi(\bar{\Xi})$ Decay Vertex	0.9992, 0.9993, 0.9994
Min. DCA Bachelor π	0.5, 1, 2 mm
Min. DCA $\Lambda(\bar{\Lambda})$	1, 2, 3 mm
Max. DCA $\Lambda(\bar{\Lambda})$ Daughters	3, 4, 5 mm
Min. DCA to Primary Vertex of $p(\bar{p})$ Daughter of $\Lambda(\bar{\Lambda})$	0.5, 1, 2 mm
Min. DCA to Primary Vertex of $\pi^-(\pi^+)$ Daughter of $\Lambda(\bar{\Lambda})$	2, 3, 4 mm
Min. Average Separation of $\Lambda(\bar{\Lambda})$ Daughter and K^\pm with like charge	7, 8, 9 cm
Min. Average Separation of Bachelor π and K^\pm with like charge	7, 8, 9 cm
Max. DCA to Primary Vertex in Transverse Plane of K^\pm	1.92, 2.4, 2.88
Max. DCA to Primary Vertex in Longitudinal Direction of K^\pm	2.4, 3.0, 3.6

Table 6: $\Xi^- K^\pm$ systematics

736 Im[f₀] vs Re[f₀] plot, which includes the d₀ values to the right side. The next three summary plots show
 737 the λ vs. Radius parameters. The first group of plots shows: 1) results without any residual correlations
 738 included in the fit (marked as "QM 2017"), 2) results with 10 residual pairs included, and 3) results
 739 with 3 residual pairs included. The second group of plots also includes the case where we fixed the d₀
 740 parameter to zero.

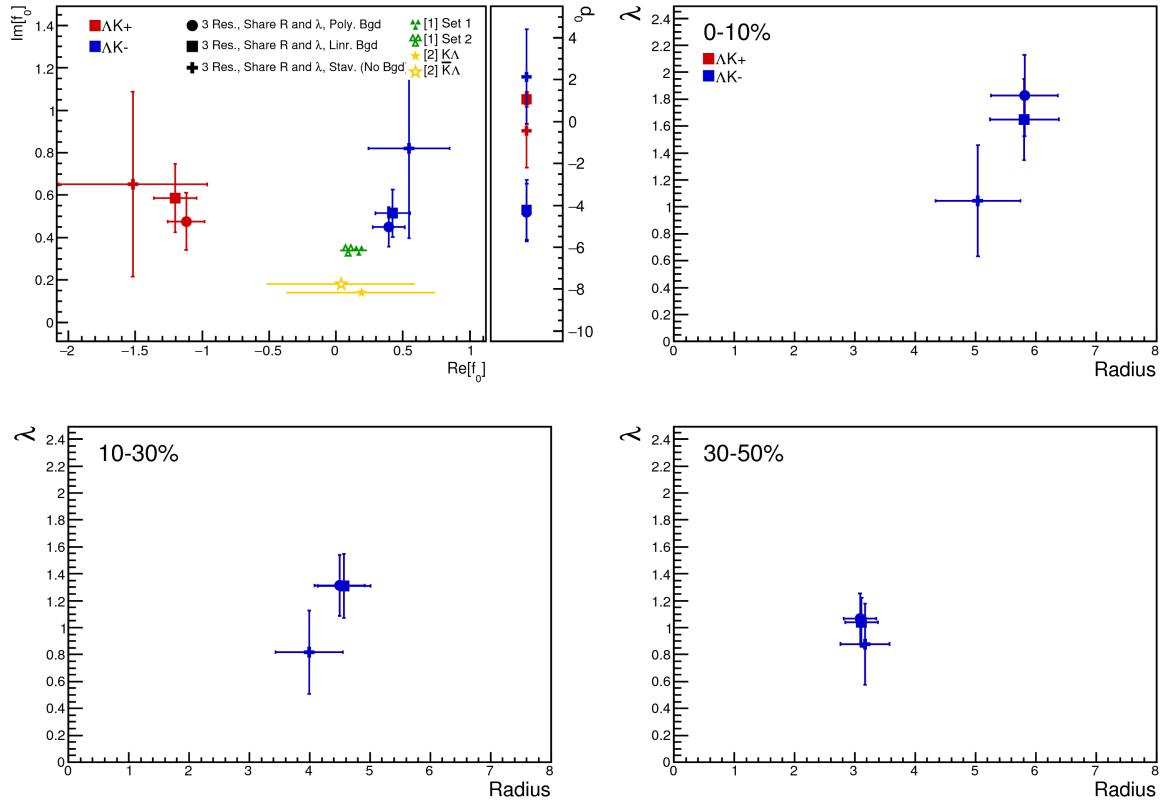


Fig. 28: Extracted fit results for all of our $\Lambda(\bar{\Lambda})K^\pm$ systems across all studied centrality bins (0-10%, 10-30%, 30-50%). The $\Lambda K^+(\bar{\Lambda} K^-)$ and $\Lambda K^-(\bar{\Lambda} K^+)$ systems share both a radius and a λ parameter for each centrality bin (i.e. 3 total radius parameters, 3 total λ parameters). The figure shows results for three different treatments of the non-femtoscopic background: a polynomial fit to THERMINATOR 2 simulation to model the background (circles), a linear fit to the data to model the background (squares), and the Stavinsky method (crosses). Note, ΛK^+ on the plot is shorthand for ΛK^+ and $\bar{\Lambda} K^- (\Lambda K^+(\bar{\Lambda} K^-))$, and similar for the others. The green [9] and yellow [10] points show theoretical predictions made using chiral perturbation theory.

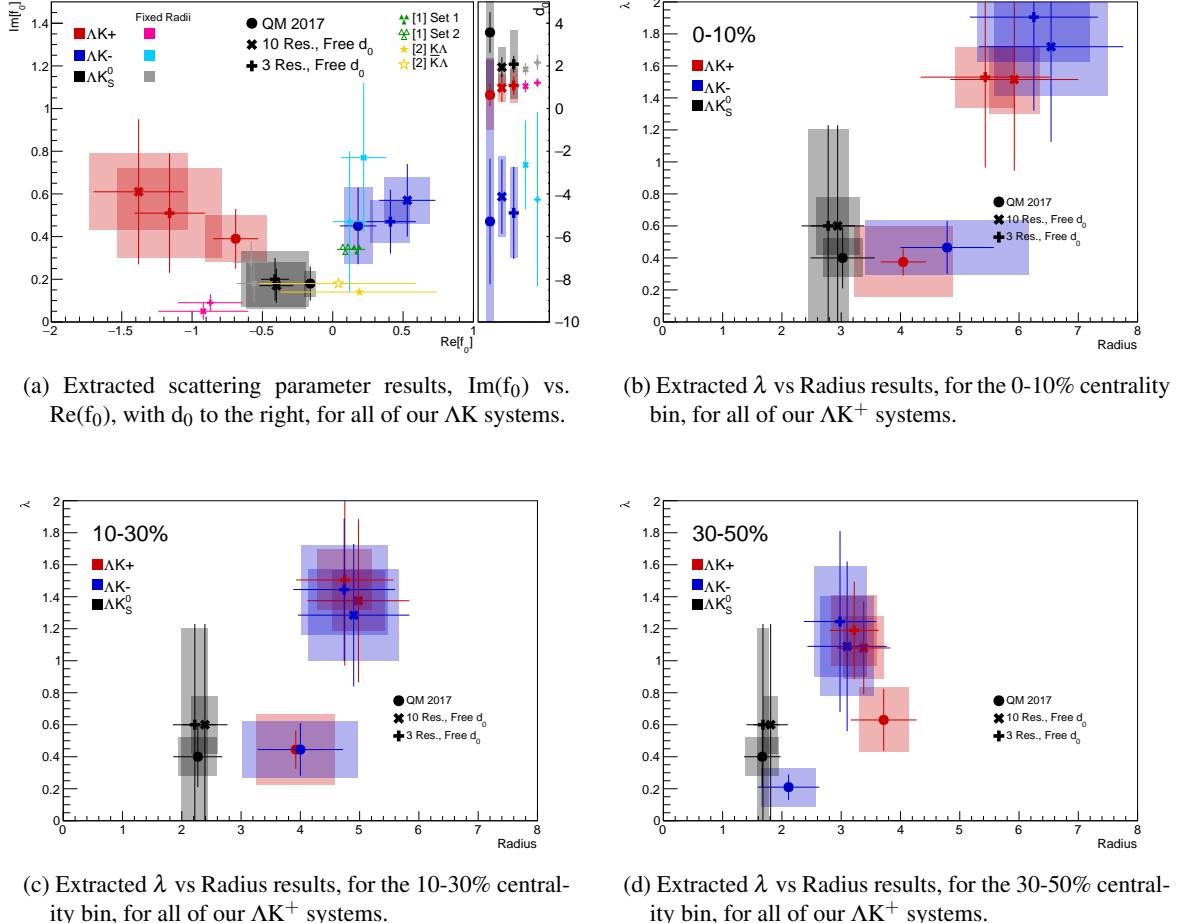


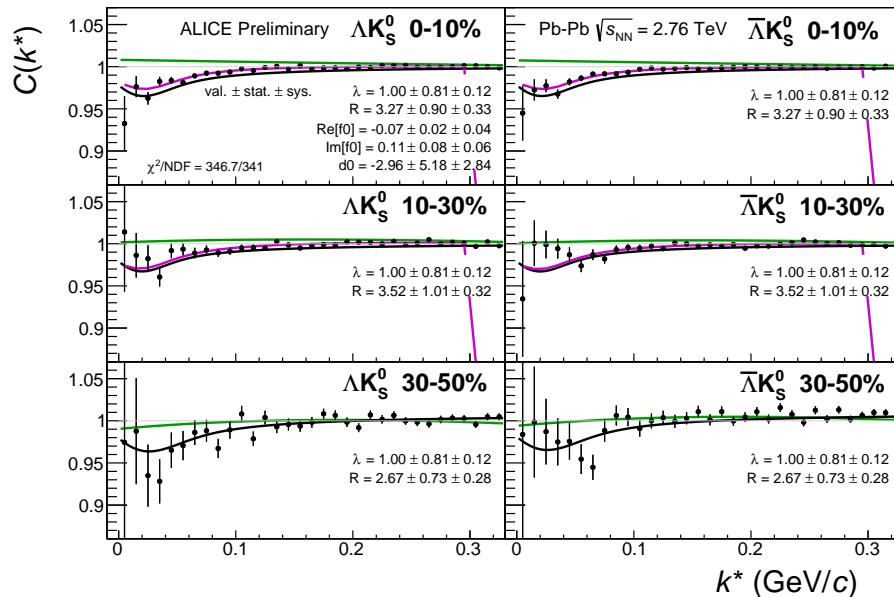
Fig. 29: Extracted fit results for all of our ΛK systems across all studied centrality bins (0-10%, 10-30%, 30-50%). The plots show results including no residuals (circles), 10 residual pairs (X), and 3 residual pairs (+). Note, ΛK^+ on the plot is shorthand for ΛK^+ and $\bar{\Lambda} K^-$, and similar for the others. In Fig. 29a, the lighter color markers (pink, sky blue, gray) show the extracted parameters when we fix the radii to roughly align with the m_T -scaling plot (Fig. 33). Additionally, the green [9] and yellow [10] points show theoretical predictions made using chiral perturbation theory.

741 **7.1.1 Results: ΛK_S^0 and ΛK^\pm : No Residual Correlations Included in Fit**

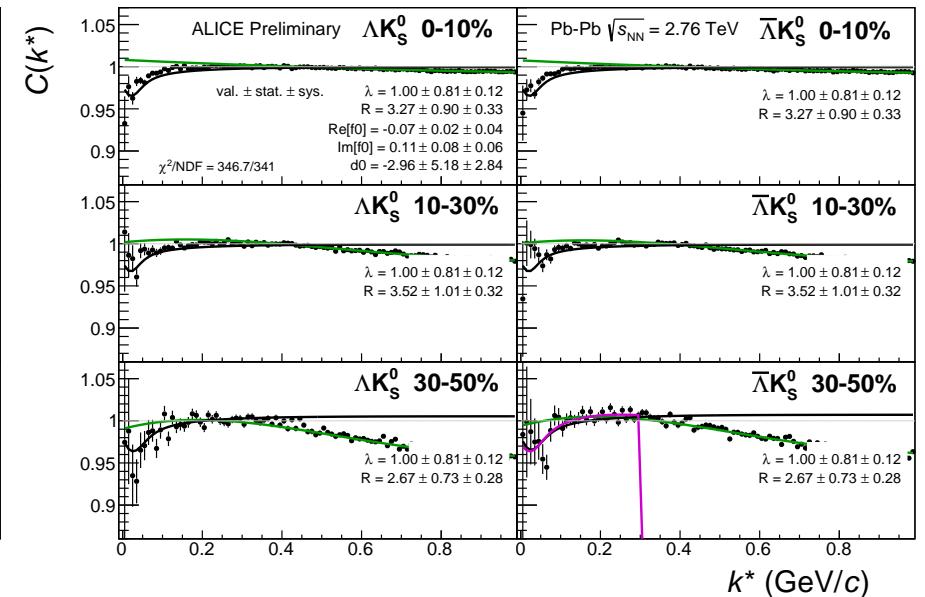
742 Figures 30, 31, and 32 (Section 7) show experimental data with fits for all studied centralities for ΛK_S^0
743 with $\bar{\Lambda} K_S^0$, ΛK^+ with $\bar{\Lambda} K^-$, and ΛK^- with $\bar{\Lambda} K^+$, respectively. The parameter sets extracted from the fits
744 can be found in Tables 7 and 8. All correlation functions were normalized in the range $0.32 < k^* < 0.40$
745 GeV/c, and fit in the range $0.0 < k^* < 0.30$ GeV/c. For the ΛK^- and $\bar{\Lambda} K^+$ analyses, the region 0.19
746 $< k^* < 0.23$ GeV/c was excluded from the fit to exclude the bump caused by the Ω^- resonance. The
747 non-flat background was fit with a linear form from $0.6 < k^* < 0.9$ GeV/c. The theoretical fit function
748 was then multiplied by this background during the fitting process.

749 In the figures (30, 31, and 32), the black solid line represents the “raw” fit, i.e. not corrected for momen-
750 tum resolution effects nor non-flat background. The green line shows the fit to the non-flat background.
751 The purple points show the fit after momentum resolution and non-flat background corrections have been
752 applied. The initial values of the parameters is listed, as well as the final fit values with uncertainties.

753 For the ΛK_S^0 fits without residuals, λ was restricted to [0.4, 0.6].

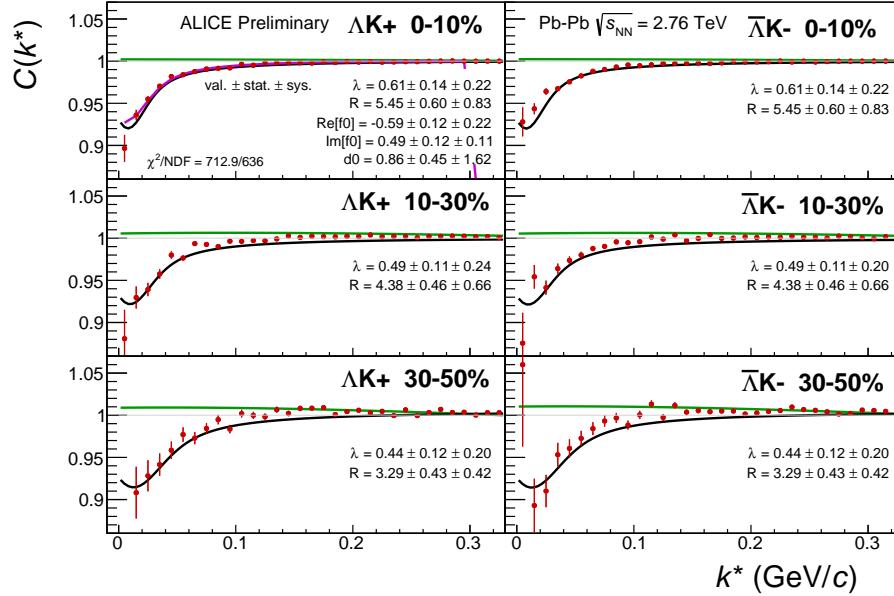


(a) Signal region view ($k^* \lesssim 0.3$ GeV/c)

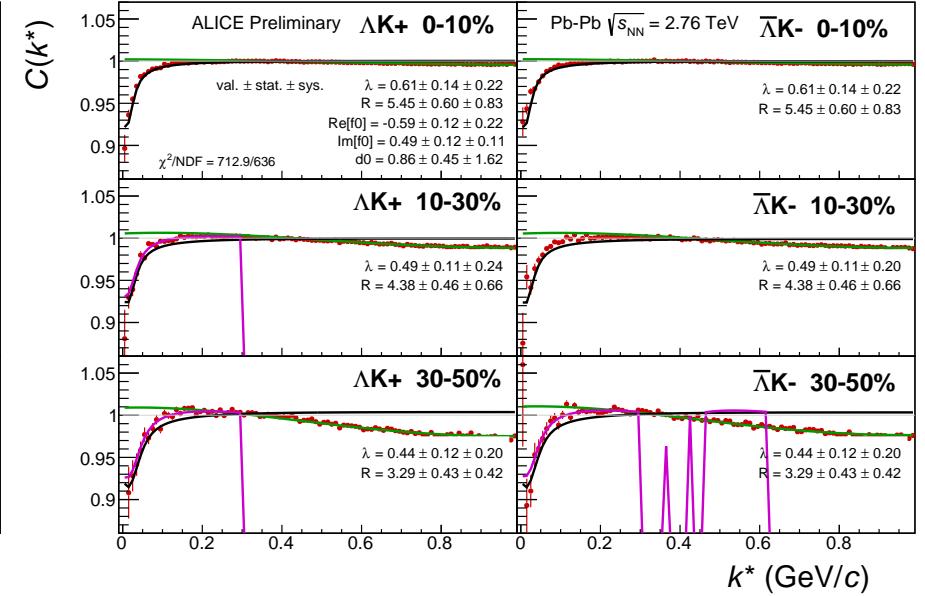


(b) Wide view ($k^* \lesssim 1.0$ GeV/c)

Fig. 30: Fits, with NO residual correlations included, to the ΛK_S^0 (left) and $\bar{\Lambda} K_S^0$ (right) data for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom). The lines represent the statistical errors, while the boxes represent the systematic errors. Each has unique λ and normalization parameters. The radii are shared amongst like centralities; the scattering parameters ($\text{Re}[f_0]$, $\text{Im}[f_0]$, d_0) are shared amongst all. The black solid line represents the “raw” fit, i.e. not corrected for momentum resolution effects nor non-flat background. The green line shows the fit to the non-flat background. The purple points show the fit after momentum resolution and non-flat background corrections have been applied. The initial values of the parameters is listed, as well as the final fit values with uncertainties. Here, R was restricted to [2.,10.] and Λ was restricted to [0.1,0.8].

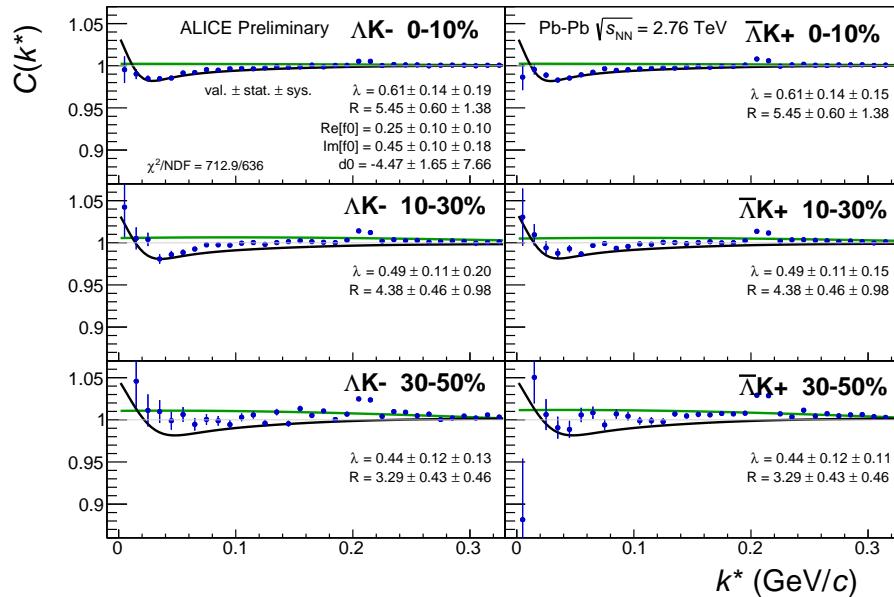


(a) Signal region view ($k^* \lesssim 0.3 \text{ GeV}/c$)

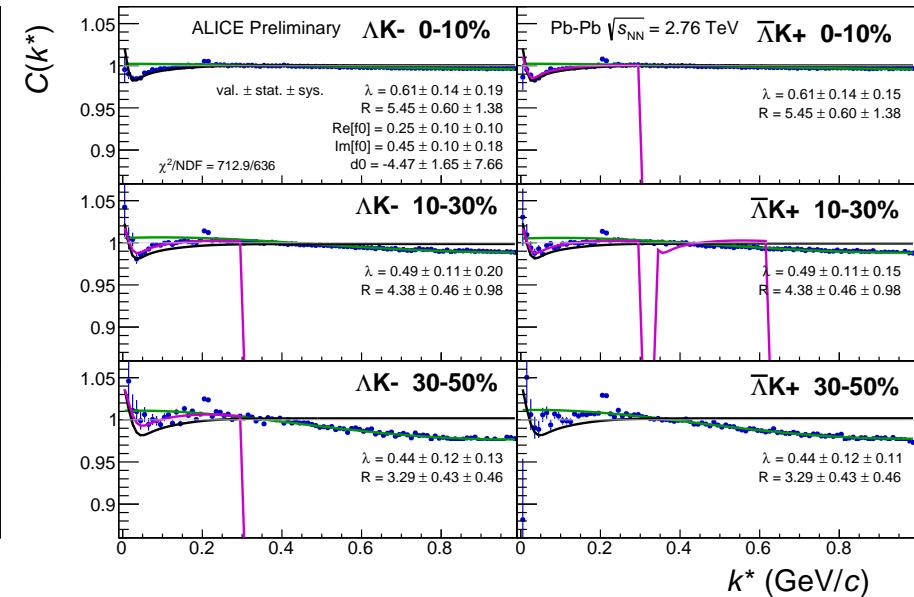


(b) Wide view ($k^* \lesssim 1.0 \text{ GeV}/c$)

Fig. 31: Fits to the ΛK^+ (left) and $\bar{\Lambda}K^-$ (right) data for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom). The lines represent the statistical errors, while the boxes represent the systematic errors. Each has unique λ and normalization parameters. The radii are shared amongst like centralities; the scattering parameters ($\text{Re}[f_0]$, $\text{Im}[f_0]$, d_0) are shared amongst all. The black solid line represents the “raw” fit, i.e. not corrected for momentum resolution effects nor non-flat background. The green line shows the fit to the non-flat background. The purple points show the fit after momentum resolution and non-flat background corrections have been applied. The initial values of the parameters is listed, as well as the final fit values with uncertainties.



(a) Signal region view ($k^* \lesssim 0.3 \text{ GeV}/c$)



(b) Wide view ($k^* \lesssim 1.0 \text{ GeV}/c$)

Fig. 32: Fits, with NO residual correlations included, to the ΛK^- (left) with $\bar{\Lambda} K^+$ (right) data for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom). The lines represent the statistical errors, while the boxes represent the systematic errors. Each has unique λ and normalization parameters. The radii are shared amongst like centralities; the scattering parameters ($R f_0, I f_0, d_0$) are shared amongst all. The black solid line represents the “raw” fit, i.e. not corrected for momentum resolution effects nor non-flat background. The green line shows the fit to the non-flat background. The purple points show the fit after momentum resolution and non-flat background corrections have been applied. The initial values of the parameters is listed, as well as the final fit values with uncertainties.

Fit Results $\Lambda(\bar{\Lambda})K_S^0$					
Pair Type	Centrality	Fit Parameters			
		λ	R	$\mathbb{R}f_0$	$\mathbb{I}f_0$
ΛK_S^0	0-10%	0.400 ± 0.187 (stat.) ± 0.116 (sys.)	3.024 ± 0.541 (stat.) ± 0.329 (sys.)	-0.157 ± 0.031 (stat.) ± 0.043 (sys.)	0.176 ± 0.077 (stat.) ± 0.059 (sys.)
	10-30%		2.270 ± 0.413 (stat.) ± 0.324 (sys.)		
	30-50%		1.669 ± 0.307 (stat.) ± 0.280 (sys.)		
$\bar{\Lambda} K_S^0$	0-10%	0.400 ± 0.187 (stat.) ± 0.116 (sys.)	3.024 ± 0.541 (stat.) ± 0.329 (sys.)	3.566 ± 0.947 (stat.) ± 2.836 (sys.)	
	10-30%		2.270 ± 0.413 (stat.) ± 0.324 (sys.)		
	30-50%		1.669 ± 0.307 (stat.) ± 0.280 (sys.)		

Table 7: Fit Results $\Lambda(\bar{\Lambda})K_S^0$, with NO residual correlations included. Each pair is fit simultaneously with its conjugate (ie. ΛK_S^0 with $\bar{\Lambda} K_S^0$) across all centralities (0-10%, 10-30%, 30-50%), for a total of 6 simultaneous analyses in the fit. Each analysis has a unique λ and normalization parameter. The radii are shared between analyses of like centrality, as these should have similar source sizes. The scattering parameters ($\mathbb{R}f_0$, $\mathbb{I}f_0$, d_0) are shared amongst all. The fit is done on the data with only statistical error bars. The errors marked as “stat.” are those returned by MINUIT. The errors marked as “sys.” are those which result from my systematic analysis (as outlined in Section 6).

Fit Results $\Lambda(\bar{\Lambda})K^\pm$					
Pair Type	Centrality	Fit Parameters			
		λ	R	$\mathbb{R}f_0$	$\mathbb{I}f_0$
ΛK^+	0-10%	0.379 ± 0.085 (stat.) ± 0.220 (sys.)	4.045 ± 0.381 (stat.) ± 0.830 (sys.)	-0.687 ± 0.160 (stat.) ± 0.223 (sys.)	0.391 ± 0.143 (stat.) ± 0.111 (sys.)
	10-30%	0.485 ± 0.129 (stat.) ± 0.241 (sys.)	3.923 ± 0.454 (stat.) ± 0.663 (sys.)		
	30-50%	0.639 ± 0.195 (stat.) ± 0.204 (sys.)	3.717 ± 0.554 (stat.) ± 0.420 (sys.)		
$\bar{\Lambda} K^-$	0-10%	0.371 ± 0.083 (stat.) ± 0.217 (sys.)	4.045 ± 0.381 (stat.) ± 0.830 (sys.)	0.639 ± 0.534 (stat.) ± 1.621 (sys.)	
	10-30%	0.411 ± 0.111 (stat.) ± 0.201 (sys.)	3.923 ± 0.454 (stat.) ± 0.663 (sys.)		
	30-50%	0.616 ± 0.192 (stat.) ± 0.203 (sys.)	3.717 ± 0.554 (stat.) ± 0.420 (sys.)		
ΛK^-	0-10%	0.453 ± 0.162 (stat.) ± 0.186 (sys.)	4.787 ± 0.788 (stat.) ± 1.375 (sys.)	0.453 ± 0.181 (stat.) ± 0.184 (sys.)	-5.292 ± 2.895 (stat.) ± 7.658 (sys.)
	10-30%	0.395 ± 0.149 (stat.) ± 0.198 (sys.)	4.001 ± 0.719 (stat.) ± 0.978 (sys.)		
	30-50%	0.199 ± 0.077 (stat.) ± 0.132 (sys.)	2.112 ± 0.517 (stat.) ± 0.457 (sys.)		
$\bar{\Lambda} K^+$	0-10%	0.479 ± 0.170 (stat.) ± 0.152 (sys.)	4.787 ± 0.788 (stat.) ± 1.375 (sys.)		
	10-30%	0.491 ± 0.179 (stat.) ± 0.148 (sys.)	4.001 ± 0.719 (stat.) ± 0.978 (sys.)		
	30-50%	0.224 ± 0.083 (stat.) ± 0.106 (sys.)	2.112 ± 0.517 (stat.) ± 0.457 (sys.)		

Table 8: Fit Results $\Lambda(\bar{\Lambda})K^\pm$, with NO residual correlations included. Each pair is fit simultaneously with its conjugate (ie. ΛK^+ with $\bar{\Lambda} K^-$ and ΛK^- with $\bar{\Lambda} K^+$) across all centralities (0-10%, 10-30%, 30-50%), for a total of 6 simultaneous analyses in the fit. Each analysis has a unique λ and normalization parameter. The radii are shared between analyses of like centrality, as these should have similar source sizes. The scattering parameters ($\mathbb{R}f_0$, $\mathbb{I}f_0$, d_0) are shared amongst all. The fit is done on the data with only statistical error bars. The errors marked as “stat.” are those returned by MINUIT. The errors marked as “sys.” are those which result from my systematic analysis (as outlined in Section 6).

754 Figure 33 shows extracted R_{inv} parameters as a function of transverse mass (m_T) for various pair systems
 755 over several centralities. The published ALICE data [11] is shown with transparent, open symbols. The
 756 new ΛK results are shown with opaque, filled symbols. The radii show an increasing size with increas-
 757 ing centrality, as is expected from the simple geometric picture of the collisions. The radii decrease
 758 in size with increasing m_T , and we see an approximate scaling of the radii with transverse mass, as is
 759 expected in the presence of collective flow in the system.

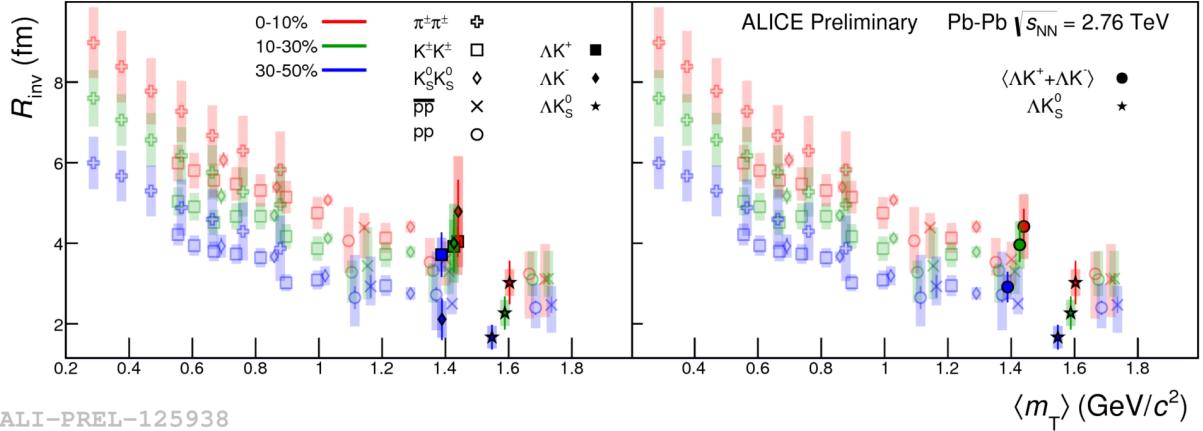


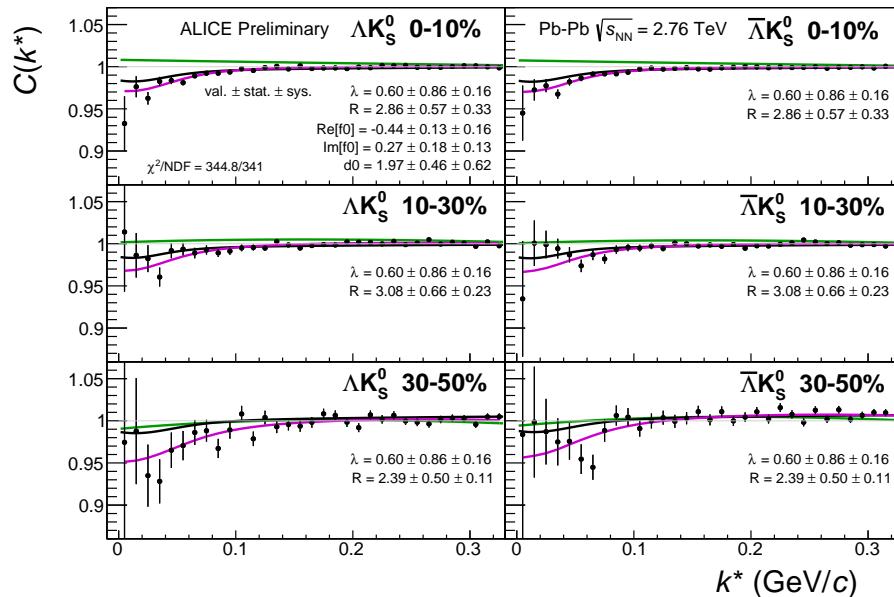
Fig. 33: No residual correlations in ΛK fits. Extracted fit R_{inv} parameters as a function of pair transverse mass (m_T) for various pair systems over several centralities. The ALICE published data [11] is shown with transparent, open symbols. The new ΛK results are shown with opaque, filled symbols. In the left, the ΛK^+ (with its conjugate pair) results are shown separately from the ΛK^- (with its conjugate pair) results. In the right, all ΛK^\pm results are averaged.

760 **7.1.2 Results: ΛK_S^0 and ΛK^\pm : 3 Residual Correlations Included in Fit**

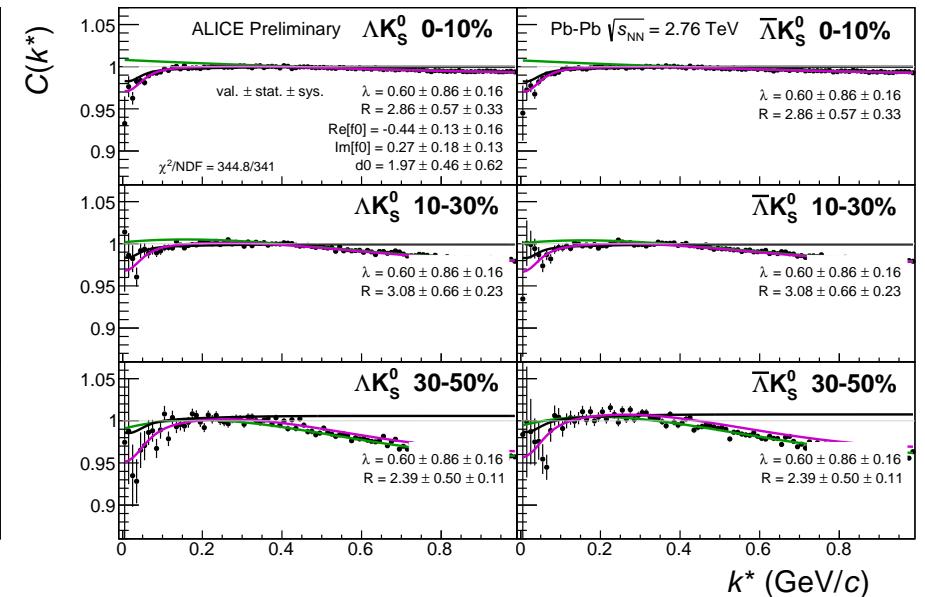
761 Figures 34, 35, and 36 (Section 7) show experimental data with fits for all studied centralities for ΛK_S^0
762 with $\bar{\Lambda} K_S^0$, ΛK^+ with $\bar{\Lambda} K^-$, and ΛK^- with $\bar{\Lambda} K^+$, respectively. The parameter sets extracted from the fits
763 can be found in Tables 9 and 10. All correlation functions were normalized in the range $0.32 < k^* <$
764 0.40 GeV/c , and fit in the range $0.0 < k^* < 0.30 \text{ GeV/c}$. For the ΛK^- and $\bar{\Lambda} K^+$ analyses, the region 0.19
765 $< k^* < 0.23 \text{ GeV/c}$ was excluded from the fit to exclude the bump caused by the Ω^- resonance. The
766 non-flat background was fit with a linear form from $0.6 < k^* < 0.9 \text{ GeV/c}$. The theoretical fit function
767 was then multiplied by this background during the fitting process.

768 In the figures (34, 35, and 36), the black solid line represents the “raw” fit, i.e. not corrected for momen-
769 tum resolution effects nor non-flat background. The green line shows the fit to the non-flat background.
770 The purple points show the fit after momentum resolution and non-flat background corrections have been
771 applied. The initial values of the parameters is listed, as well as the final fit values with uncertainties.

772 For the ΛK_S^0 fits without residuals, λ was restricted to [0.4, 0.6].

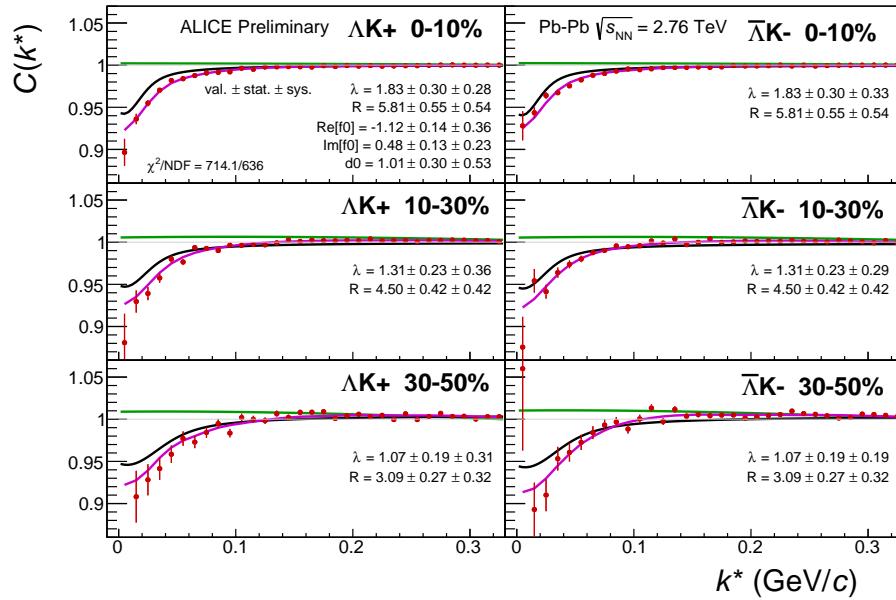


(a) Signal region view ($k^* \lesssim 0.3 \text{ GeV}/c$)

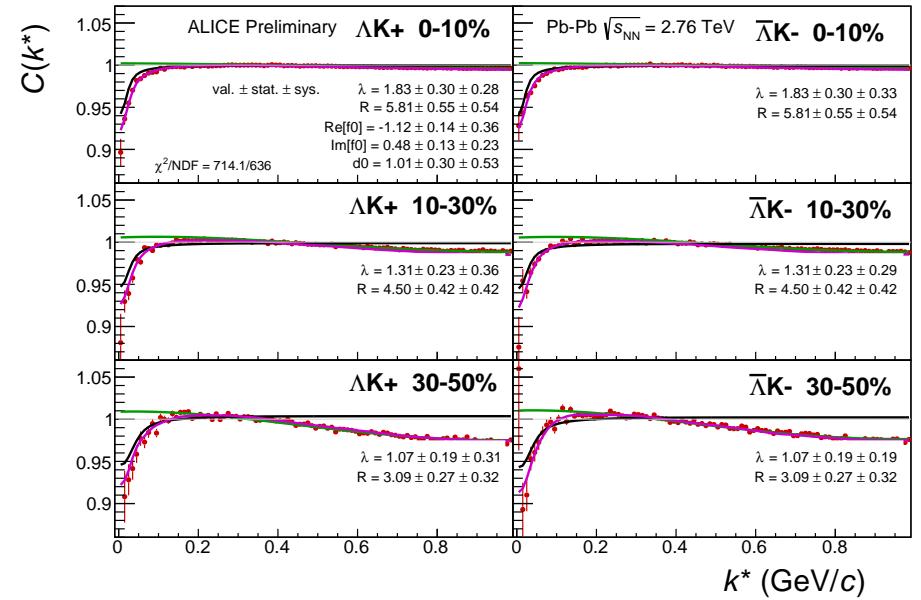


(b) Wide view ($k^* \lesssim 1.0 \text{ GeV}/c$)

Fig. 34: Fits, with 3 residual correlations included, to the ΛK_S^0 (left) and $\bar{\Lambda} K_S^0$ (right) data for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom). The lines represent the statistical errors, while the boxes represent the systematic errors. Each has unique λ and normalization parameters. The radii are shared amongst like centralities; the scattering parameters ($\mathbb{R}f_0$, $\mathbb{I}f_0$, d_0) are shared amongst all. The black solid line represents the “raw” fit, i.e. not corrected for momentum resolution effects nor non-flat background. The green line shows the fit to the non-flat background. The purple points show the fit after momentum resolution and non-flat background corrections have been applied. The initial values of the parameters is listed, as well as the final fit values with uncertainties. Here, R was restricted to [2.,10.] and λ was restricted to [0.1,0.8].

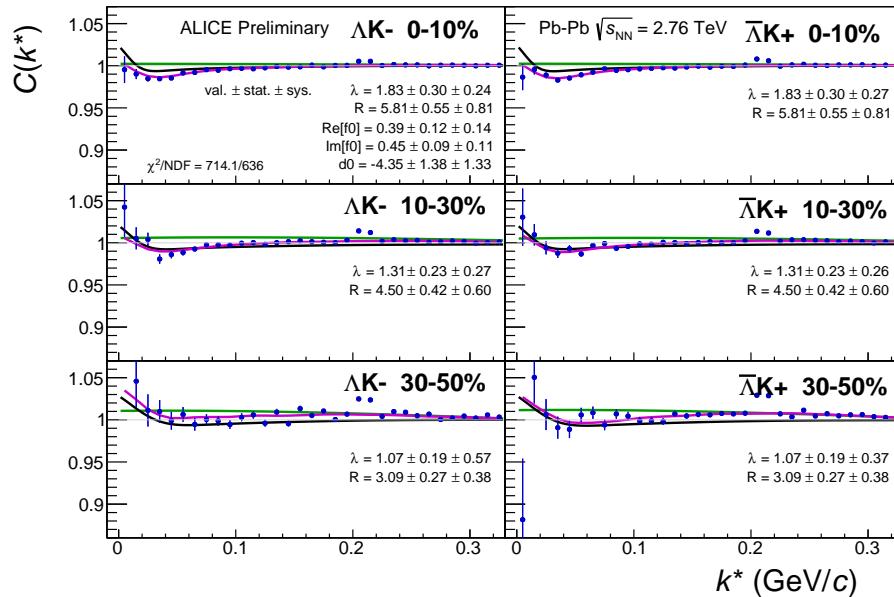


(a) Signal region view ($k^* \lesssim 0.3 \text{ GeV}/c$)

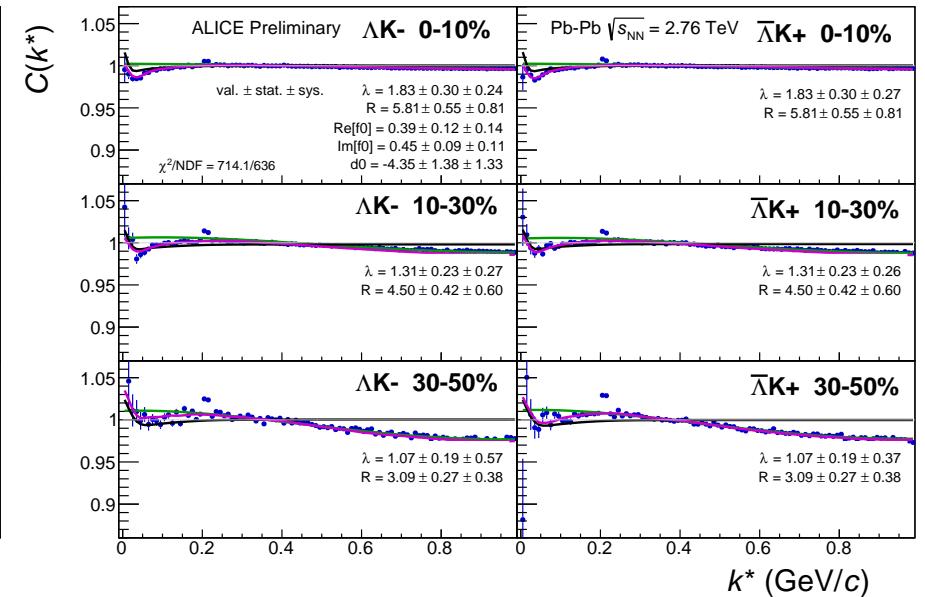


(b) Wide view ($k^* \lesssim 1.0 \text{ GeV}/c$)

Fig. 35: Fits, with 3 residual correlations included, to the ΛK^+ (left) and $\bar{\Lambda} K^-$ (right) data for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom). The lines represent the statistical errors, while the boxes represent the systematic errors. Each has unique λ and normalization parameters. The radii are shared amongst like centralities; the scattering parameters ($\text{Re}[f_0]$, $\text{Im}[f_0]$, d_0) are shared amongst all. The black solid line represents the “raw” fit, i.e. not corrected for momentum resolution effects nor non-flat background. The green line shows the fit to the non-flat background. The purple points show the fit after momentum resolution and non-flat background corrections have been applied. The initial values of the parameters is listed, as well as the final fit values with uncertainties.



(a) Signal region view ($k^* \lesssim 0.3$ GeV/c)



(b) Wide view ($k^* \lesssim 1.0$ GeV/c)

Fig. 36: Fits, with 3 residual correlations included, to the ΛK^- (left) with $\bar{\Lambda} K^+$ (right) data for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom). The lines represent the statistical errors, while the boxes represent the systematic errors. Each has unique λ and normalization parameters. The radii are shared amongst like centralities; the scattering parameters ($\mathbb{R} f_0, \mathbb{I} f_0, d_0$) are shared amongst all. The black solid line represents the “raw” fit, i.e. not corrected for momentum resolution effects nor non-flat background. The green line shows the fit to the non-flat background. The purple points show the fit after momentum resolution and non-flat background corrections have been applied. The initial values of the parameters is listed, as well as the final fit values with uncertainties.

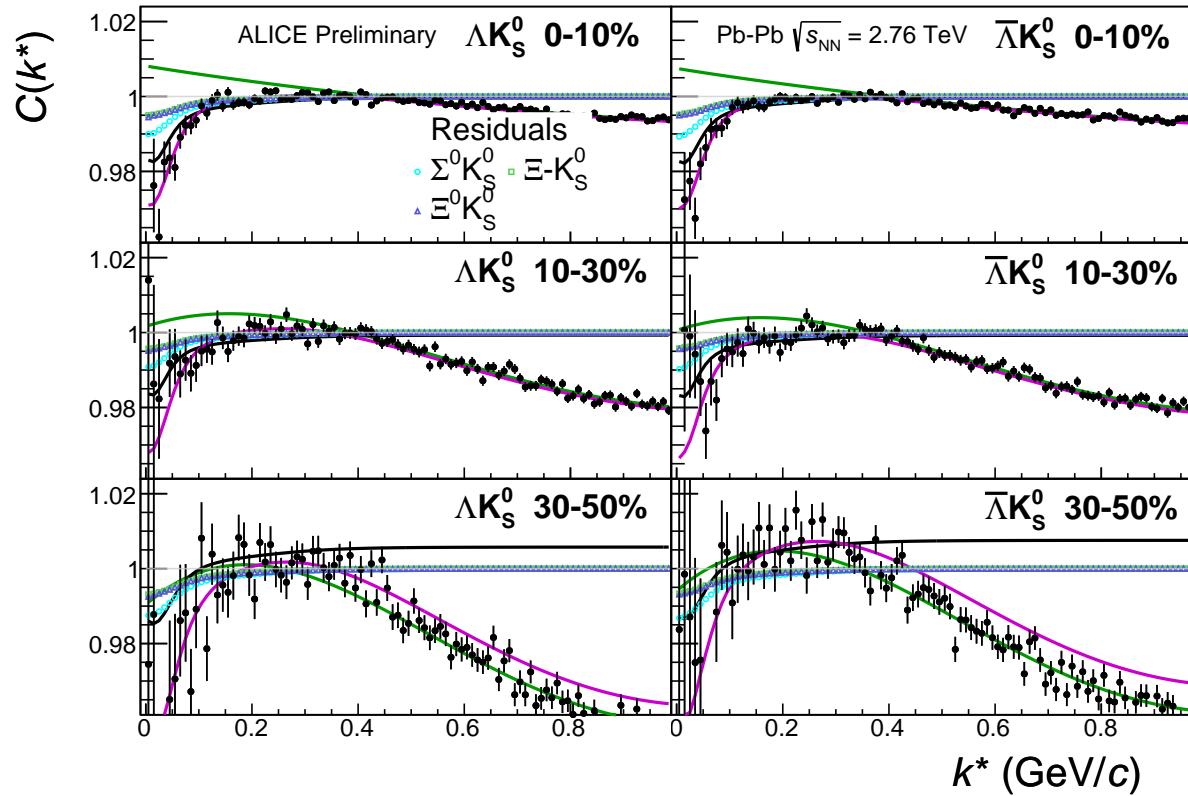
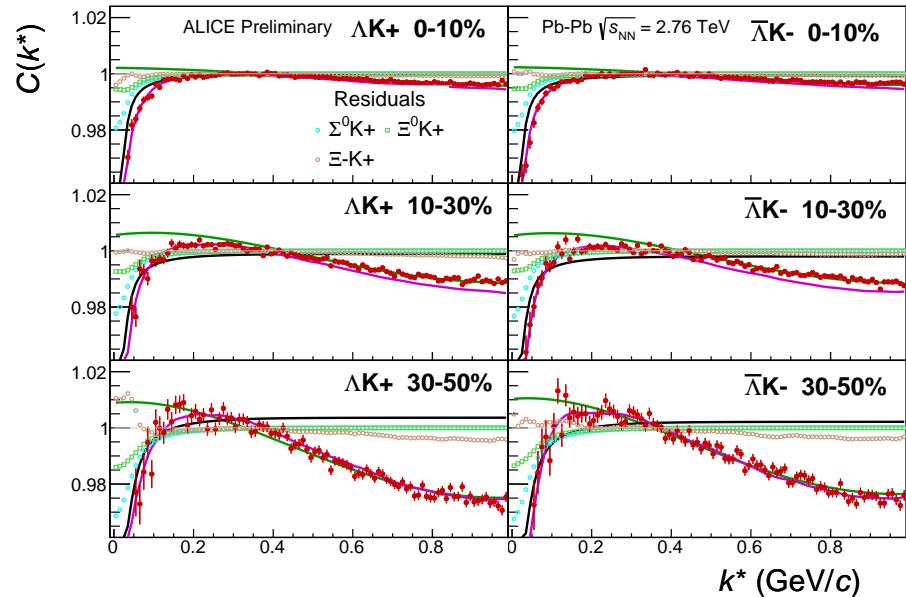
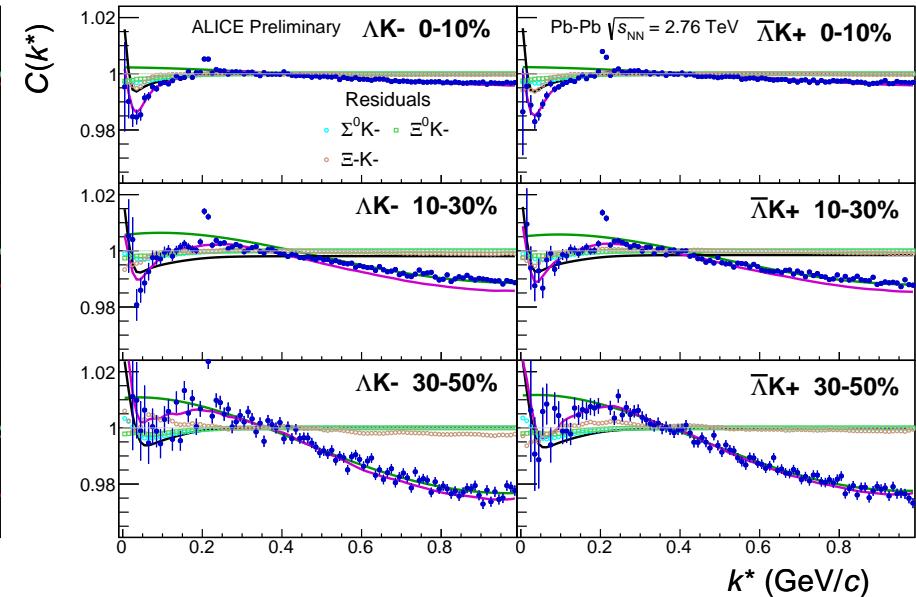


Fig. 37: Fits, with 3 residual correlations included and shown, to the ΛK_S^0 (left) and $\bar{\Lambda} K_S^0$ (right) data for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom). The three parent pairs used for the residual correction to the ΛK_S^0 ($\bar{\Lambda} K_S^0$) fit are $\Sigma^0 K_S^0$, $\Xi^0 K_S^0$, and $\Xi^- K_S^0$ ($\bar{\Sigma}^0 K_S^0$, $\bar{\Xi}^0 K_S^0$, and $\bar{\Xi}^+ K_S^0$).



(a) ΛK^+ ($\bar{\Lambda} K^-$) fits with residual contributions shown for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom)



(b) ΛK^- ($\bar{\Lambda} K^+$) fits with residual contributions shown for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom)

Fig. 38: Fits, with 3 residual correlations included and shown, to the ΛK^+ & $\bar{\Lambda} K^-$ (left) and ΛK^- & $\bar{\Lambda} K^+$ (right) data for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom). The three parent pairs used for the residual correction to the ΛK^+ ($\bar{\Lambda} K^-$) fit are $\Sigma^0 K^+$, $\Xi^0 K^+$, and $\Xi^- K^-$ ($\bar{\Sigma}^0 K^-$, $\bar{\Xi}^0 K^-$, and $\bar{\Xi}^+ K^-$).

Fit Results $\Lambda(\bar{\Lambda})K_S^0$						
System	Centrality	Fit Parameters				
		λ	R	$\mathbb{R}f_0$	$\mathbb{I}f_0$	d_0
$\Lambda K_S^0 \& \bar{\Lambda} K_S^0$	0-10%	$0.60 \pm 0.63 \text{ (stat.)} \pm 0.16 \text{ (sys.)}$	$2.78 \pm 0.45 \text{ (stat.)} \pm 0.33 \text{ (sys.)}$	$-0.41 \pm 0.10 \text{ (stat.)} \pm 0.16 \text{ (sys.)}$	$0.20 \pm 0.10 \text{ (stat.)} \pm 0.13 \text{ (sys.)}$	$2.08 \pm 0.39 \text{ (stat.)} \pm 0.62 \text{ (sys.)}$
	10-30%		$2.22 \pm 0.37 \text{ (stat.)} \pm 0.23 \text{ (sys.)}$			
	30-50%		$1.68 \pm 0.28 \text{ (stat.)} \pm 0.11 \text{ (sys.)}$			

Table 9: Fit Results $\Lambda(\bar{\Lambda})K_S^0$, with 3 residual correlations included. Each pair is fit simultaneously with its conjugate (ie. ΛK_S^0 with $\bar{\Lambda} K_S^0$) across all centralities (0-10%, 10-30%, 30-50%), for a total of 6 simultaneous analyses in the fit. Each analysis has a unique λ and normalization parameter. The radii are shared between analyses of like centrality, as these should have similar source sizes. The scattering parameters ($\mathbb{R}f_0$, $\mathbb{I}f_0$, d_0) are shared amongst all. The fit is done on the data with only statistical error bars. The errors marked as “stat.” are those returned by MINUIT. The errors marked as “sys.” are those which result from my systematic analysis (as outlined in Section 6).

Fit Results $\Lambda(\bar{\Lambda})K^\pm$							
System	Centrality	Pair Type	Fit Parameters				
			λ	R	$\mathbb{R}f_0$	$\mathbb{I}f_0$	
$\Lambda K^+ \& \bar{\Lambda} K^-$	0-10%	ΛK^+ $\bar{\Lambda} K^-$	$1.37 \pm 0.56 \text{ (stat.)} \pm 0.28 \text{ (sys.)}$ $1.39 \pm 0.57 \text{ (stat.)} \pm 0.33 \text{ (sys.)}$	$4.90 \pm 1.09 \text{ (stat.)} \pm 0.54 \text{ (sys.)}$	$-1.13 \pm 0.25 \text{ (stat.)} \pm 0.36 \text{ (sys.)}$	$0.36 \pm 0.28 \text{ (stat.)} \pm 0.23 \text{ (sys.)}$	$1.09 \pm 0.43 \text{ (stat.)} \pm 0.53 \text{ (sys.)}$
	10-30%	ΛK^+ $\bar{\Lambda} K^-$	$1.70 \pm 0.58 \text{ (stat.)} \pm 0.36 \text{ (sys.)}$ $1.51 \pm 0.49 \text{ (stat.)} \pm 0.29 \text{ (sys.)}$	$4.78 \pm 0.82 \text{ (stat.)} \pm 0.42 \text{ (sys.)}$			
	30-50%	ΛK^+ $\bar{\Lambda} K^-$	$1.30 \pm 0.31 \text{ (stat.)} \pm 0.31 \text{ (sys.)}$ $1.18 \pm 0.30 \text{ (stat.)} \pm 0.19 \text{ (sys.)}$	$3.24 \pm 0.41 \text{ (stat.)} \pm 0.32 \text{ (sys.)}$			
$\Lambda K^- \& \bar{\Lambda} K^+$	0-10%	ΛK^- $\bar{\Lambda} K^+$	$1.58 \pm 0.60 \text{ (stat.)} \pm 0.24 \text{ (sys.)}$ $1.60 \pm 0.57 \text{ (stat.)} \pm 0.27 \text{ (sys.)}$	$4.11 \pm 1.08 \text{ (stat.)} \pm 0.81 \text{ (sys.)}$	$0.15 \pm 0.18 \text{ (stat.)} \pm 0.14 \text{ (sys.)}$	$0.30 \pm 0.15 \text{ (stat.)} \pm 0.11 \text{ (sys.)}$	$2.07 \pm 2.16 \text{ (stat.)} \pm 1.33 \text{ (sys.)}$
	10-30%	ΛK^- $\bar{\Lambda} K^+$	$1.08 \pm 0.43 \text{ (stat.)} \pm 0.27 \text{ (sys.)}$ $1.10 \pm 0.46 \text{ (stat.)} \pm 0.26 \text{ (sys.)}$	$3.05 \pm 0.86 \text{ (stat.)} \pm 0.60 \text{ (sys.)}$			
	30-50%	ΛK^- $\bar{\Lambda} K^+$	$1.27 \pm 0.82 \text{ (stat.)} \pm 0.57 \text{ (sys.)}$ $0.83 \pm 0.31 \text{ (stat.)} \pm 0.37 \text{ (sys.)}$	$1.98 \pm 0.61 \text{ (stat.)} \pm 0.38 \text{ (sys.)}$			

Table 10: Fit Results $\Lambda(\bar{\Lambda})K^\pm$, with 3 residual correlations included. Each pair is fit simultaneously with its conjugate (ie. ΛK^+ with $\bar{\Lambda} K^-$ and ΛK^- with $\bar{\Lambda} K^+$) across all centralities (0-10%, 10-30%, 30-50%), for a total of 6 simultaneous analyses in the fit. Each analysis has a unique λ and normalization parameter. The radii are shared between analyses of like centrality, as these should have similar source sizes. The scattering parameters ($\mathbb{R}f_0$, $\mathbb{I}f_0$, d_0) are shared amongst all. The fit is done on the data with only statistical error bars. The errors marked as “stat.” are those returned by MINUIT. The errors marked as “sys.” are those which result from my systematic analysis (as outlined in Section 6).

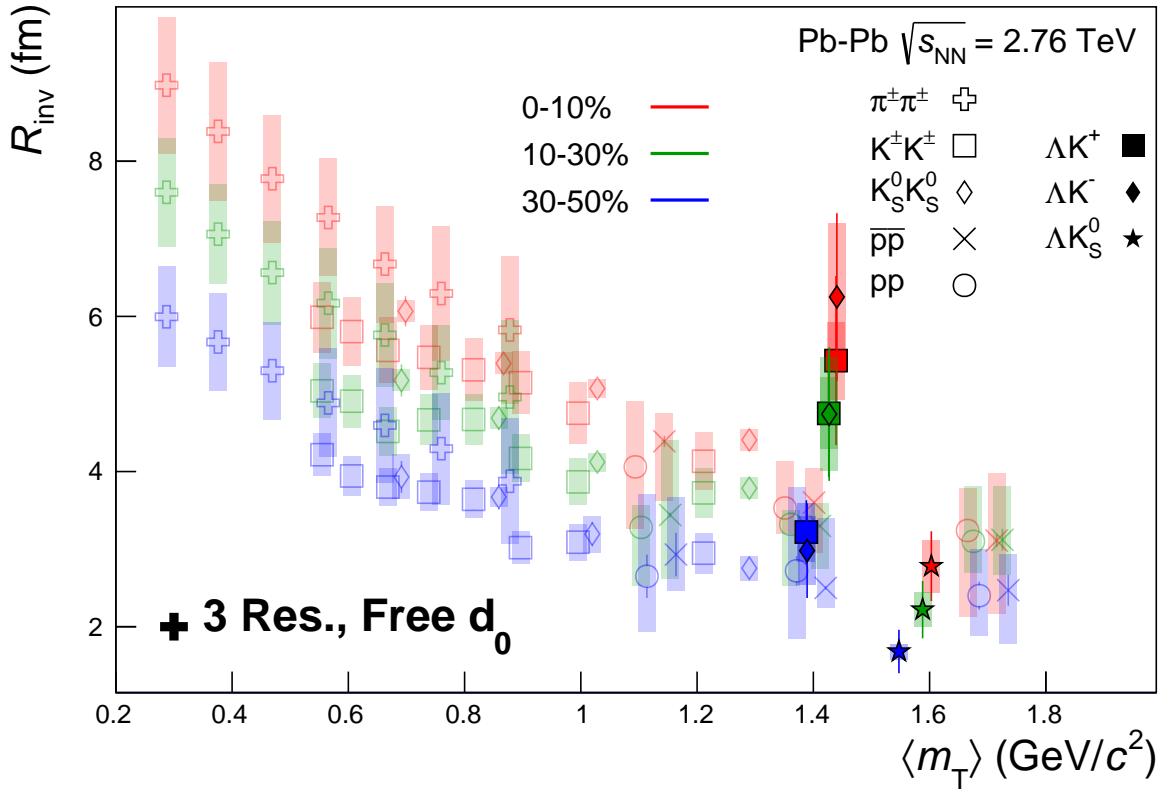


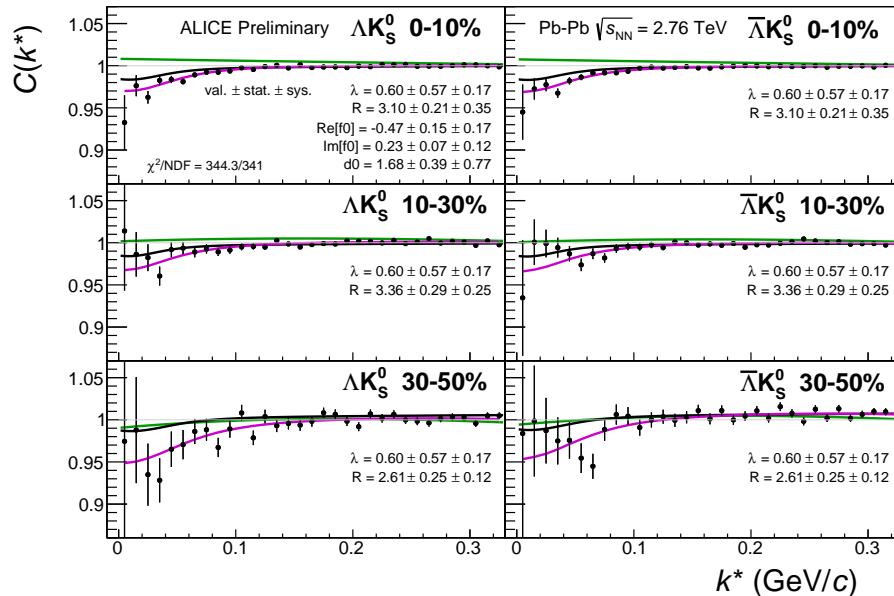
Fig. 39: 3 residual correlations in ΛK fits. Extracted fit R_{inv} parameters as a function of pair transverse mass (m_T) for various pair systems over several centralities. The ALICE published data [11] is shown with transparent, open symbols. The new ΛK results are shown with opaque, filled symbols. In the left, the ΛK^+ (with it's conjugate pair) results are shown separately from the ΛK^- (with it's conjugate pair) results. In the right, all ΛK^\pm results are averaged.

773 **7.1.3 Results: ΛK_S^0 and ΛK^\pm : 10 Residual Correlations Included in Fit**

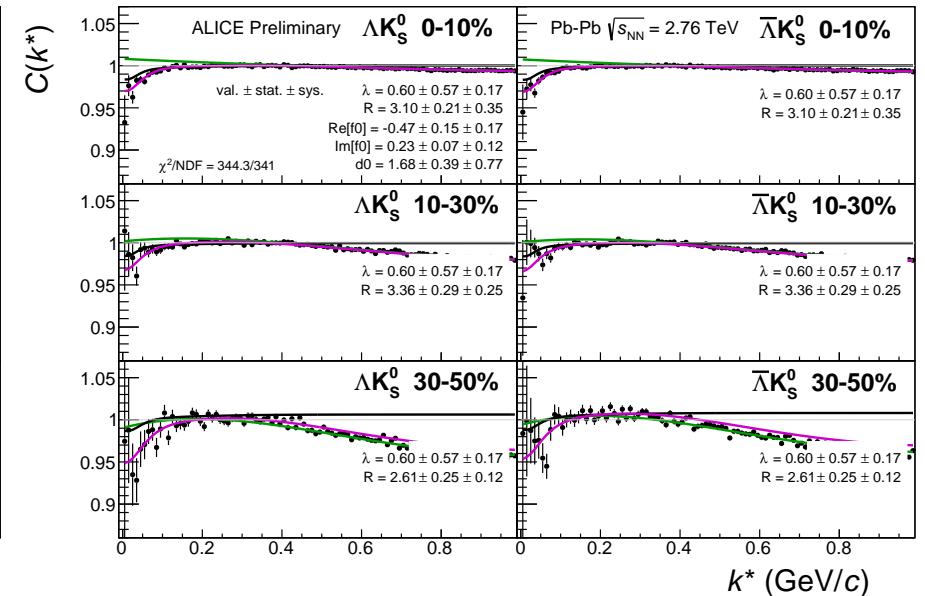
774 Figures 40, 41, and 42 (Section 7) show experimental data with fits for all studied centralities for ΛK_S^0
775 with $\bar{\Lambda} K_S^0$, ΛK^+ with $\bar{\Lambda} K^-$, and ΛK^- with $\bar{\Lambda} K^+$, respectively. The parameter sets extracted from the fits
776 can be found in Tables 11 and 12. All correlation functions were normalized in the range $0.32 < k^* <$
777 0.40 GeV/c , and fit in the range $0.0 < k^* < 0.30 \text{ GeV/c}$. For the ΛK^- and $\bar{\Lambda} K^+$ analyses, the region 0.19
778 $< k^* < 0.23 \text{ GeV/c}$ was excluded from the fit to exclude the bump caused by the Ω^- resonance. The
779 non-flat background was fit with a linear form from $0.6 < k^* < 0.9 \text{ GeV/c}$. The theoretical fit function
780 was then multiplied by this background during the fitting process.

781 In the figures (40, 41, and 42), the black solid line represents the “raw” fit, i.e. not corrected for momen-
782 tum resolution effects nor non-flat background. The green line shows the fit to the non-flat background.
783 The purple points show the fit after momentum resolution and non-flat background corrections have been
784 applied. The initial values of the parameters is listed, as well as the final fit values with uncertainties.

785 For the ΛK_S^0 fits without residuals, λ was restricted to [0.4, 0.6].

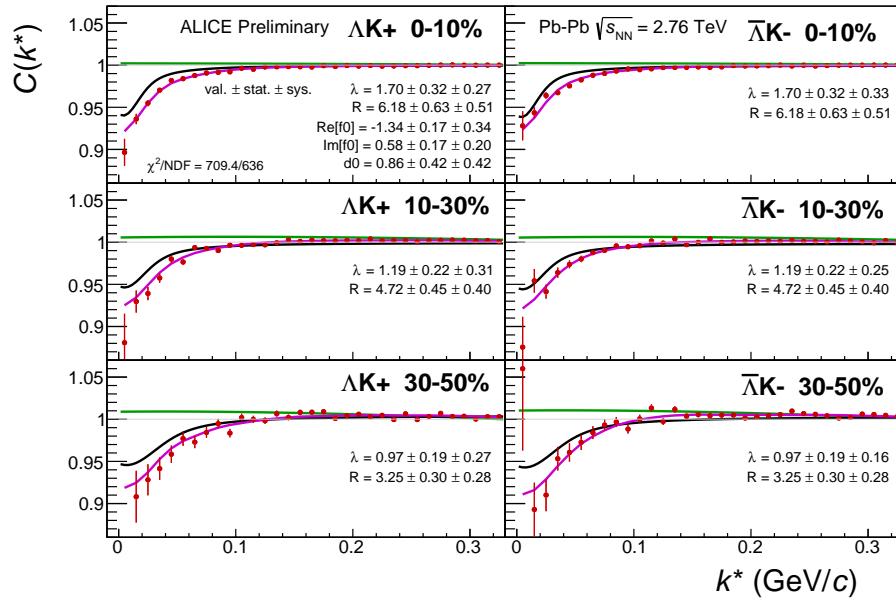


(a) Signal region view ($k^* \lesssim 0.3$ GeV/c)

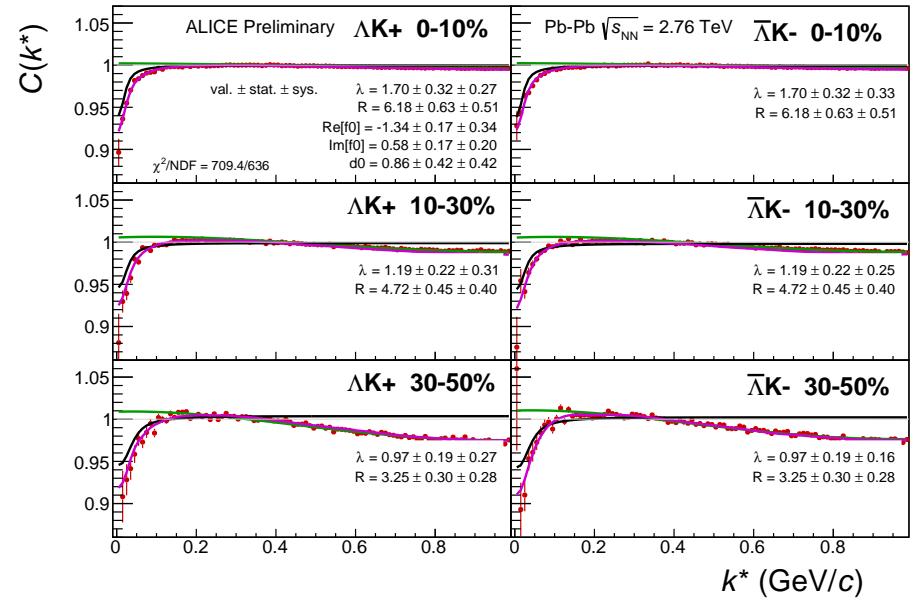


(b) Wide view ($k^* \lesssim 1.0$ GeV/c)

Fig. 40: Fits, with 10 residual correlations included, to the ΛK_s^0 (left) and $\bar{\Lambda} K_s^0$ (right) data for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom). The lines represent the statistical errors, while the boxes represent the systematic errors. Each has unique λ and normalization parameters. The radii are shared amongst like centralities; the scattering parameters ($\text{Re}[f_0]$, $\text{Im}[f_0]$, d_0) are shared amongst all. The black solid line represents the “raw” fit, i.e. not corrected for momentum resolution effects nor non-flat background. The green line shows the fit to the non-flat background. The purple points show the fit after momentum resolution and non-flat background corrections have been applied. The initial values of the parameters is listed, as well as the final fit values with uncertainties. Here, R was restricted to [2.,10.] and Λ was restricted to [0.1,0.8].

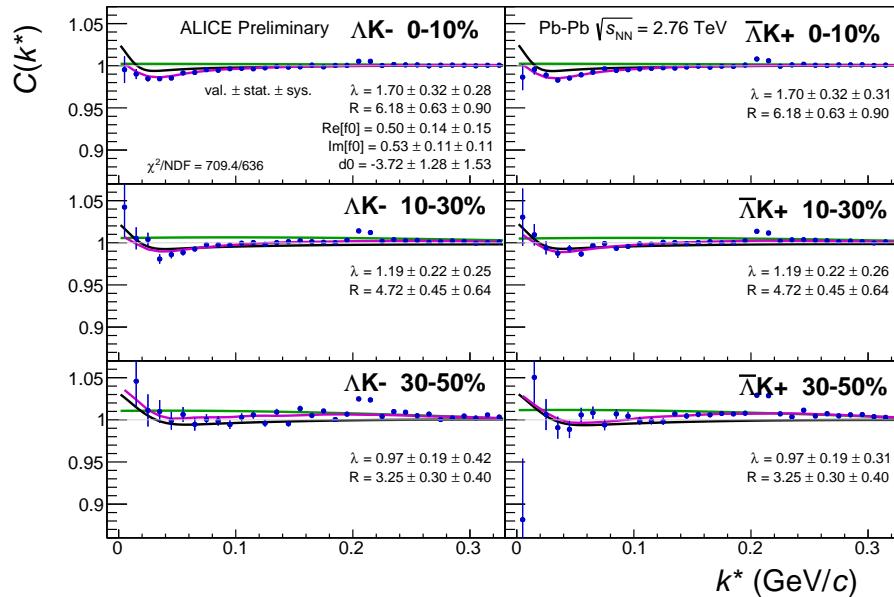


(a) Signal region view ($k^* \lesssim 0.3 \text{ GeV}/c$)

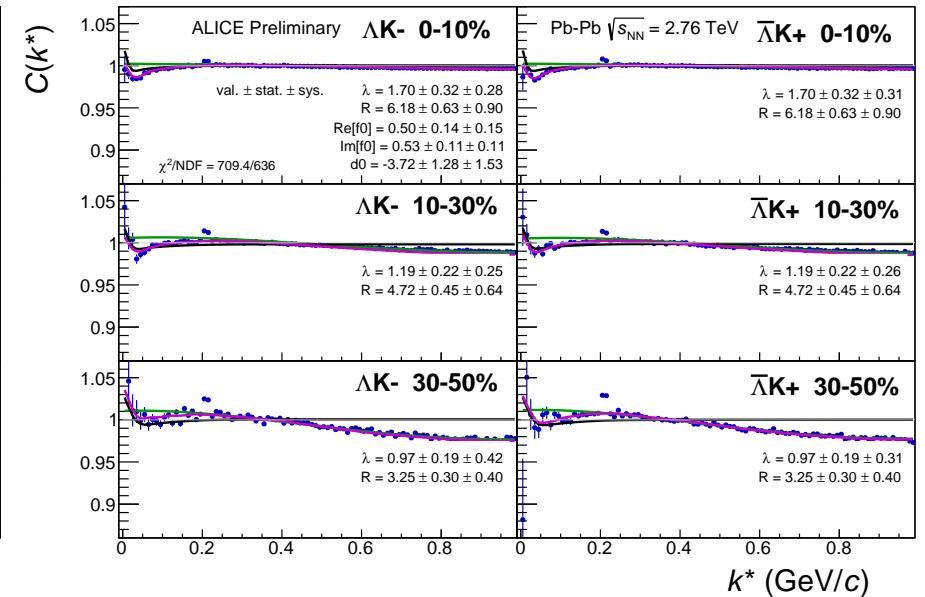


(b) Wide view ($k^* \lesssim 1.0 \text{ GeV}/c$)

Fig. 41: Fits, with 10 residual correlations included, to the ΔK^+ (left) and $\bar{\Delta} K^-$ (right) data for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom). The lines represent the statistical errors, while the boxes represent the systematic errors. Each has unique λ and normalization parameters. The radii are shared amongst like centralities; the scattering parameters ($\text{Re}[f_0], \text{Im}[f_0], d_0$) are shared amongst all. The black solid line represents the “raw” fit, i.e. not corrected for momentum resolution effects nor non-flat background. The green line shows the fit to the non-flat background. The purple points show the fit after momentum resolution and non-flat background corrections have been applied. The initial values of the parameters is listed, as well as the final fit values with uncertainties.



(a) Signal region view ($k^* \lesssim 0.3 \text{ GeV}/c$)



(b) Wide view ($k^* \lesssim 1.0 \text{ GeV}/c$)

Fig. 42: Fits, with 10 residual correlations included, to the ΛK^- (left) with $\bar{\Lambda} K^+$ (right) data for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom). The lines represent the statistical errors, while the boxes represent the systematic errors. Each has unique λ and normalization parameters. The radii are shared amongst like centralities; the scattering parameters ($Re[f_0]$, $Im[f_0]$, d_0) are shared amongst all. The black solid line represents the “raw” fit, i.e. not corrected for momentum resolution effects nor non-flat background. The green line shows the fit to the non-flat background. The purple points show the fit after momentum resolution and non-flat background corrections have been applied. The initial values of the parameters is listed, as well as the final fit values with uncertainties.

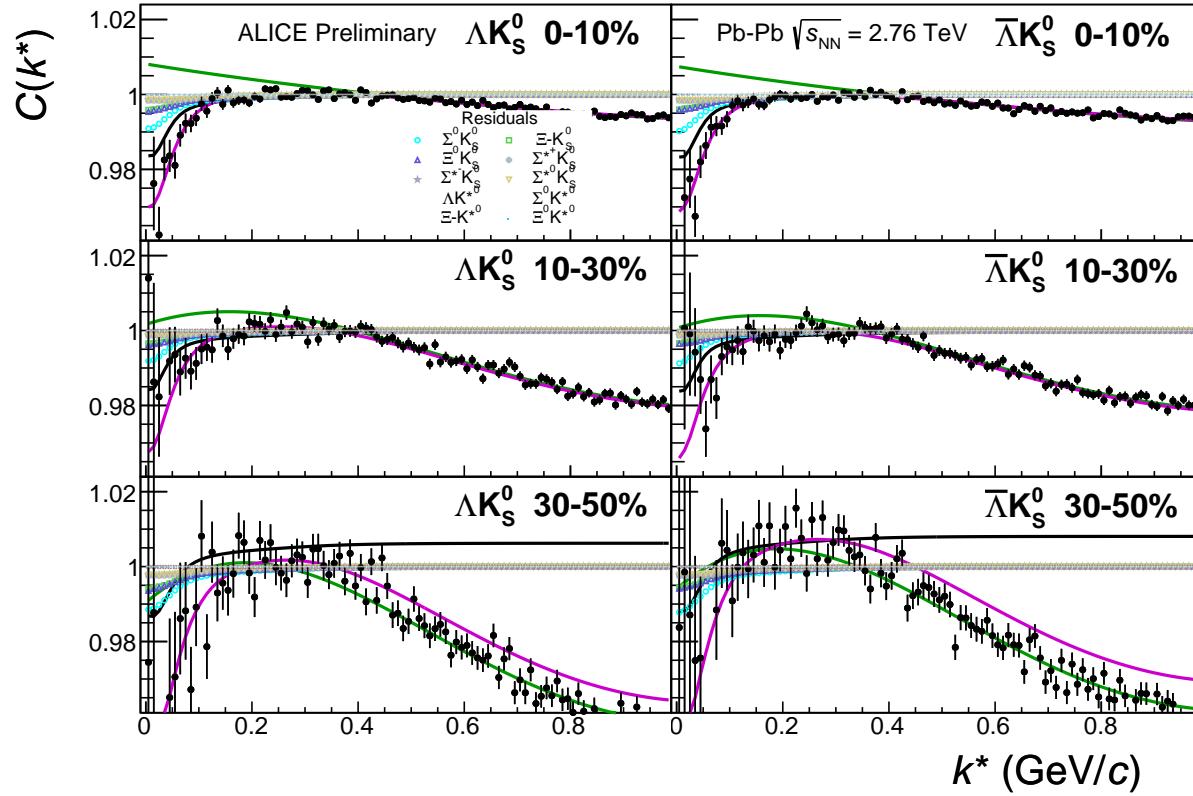
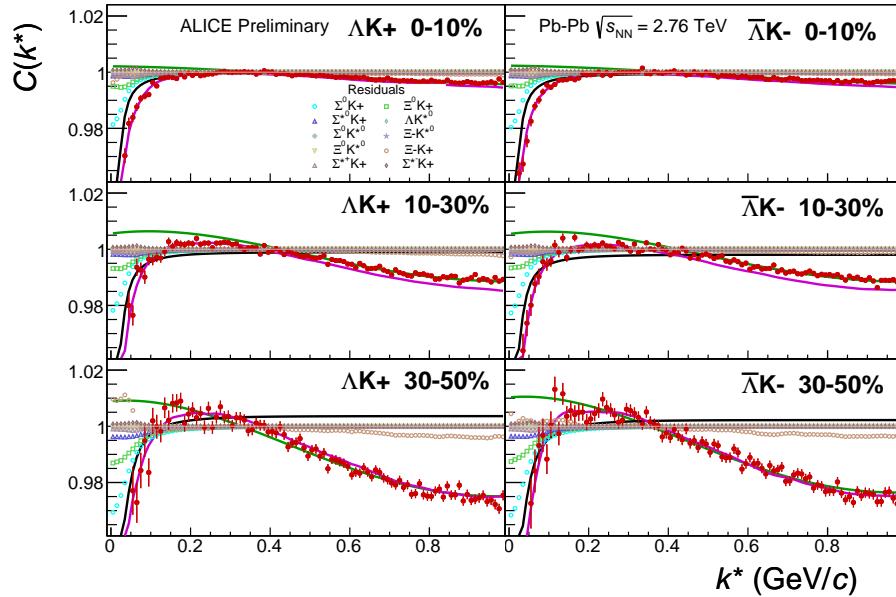
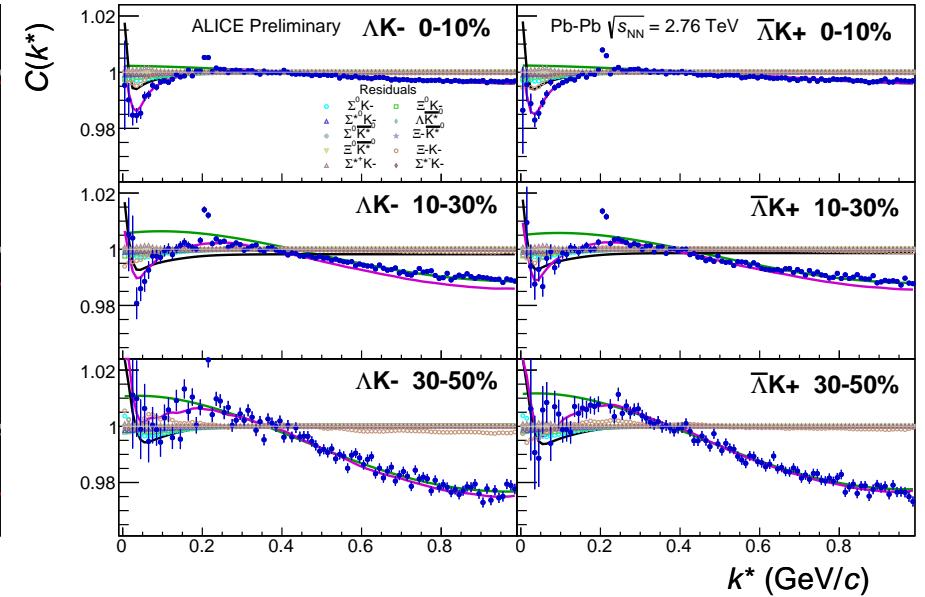


Fig. 43: Fits, with 10 residual correlations included and shown, to the ΛK_S^0 (left) and $\bar{\Lambda} K_S^0$ (right) data for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom). The ten parent pairs used for the residual correction to the ΛK_S^0 ($\bar{\Lambda} K_S^0$) fit are $\Sigma^0 K_S^0$, $\Xi^0 K_S^0$, $\Xi^- K_S^0$, $\Sigma^{*(+,-,0)} K_S^0$, ΛK^{*0} , $\Sigma^0 K^{*0}$, $\Xi^0 K^{*0}$, and $\Xi^- K^{*0}$ ($\bar{\Sigma}^0 K_S^0$, $\bar{\Xi}^0 K_S^0$, $\bar{\Xi}^+ K_S^0$, $\bar{\Sigma}^{*(+,-,0)} K_S^0$, $\bar{\Lambda} \bar{K}^{*0}$, $\bar{\Sigma}^0 \bar{K}^{*0}$, $\bar{\Xi}^0 \bar{K}^{*0}$, and $\bar{\Xi}^+ \bar{K}^{*0}$).



(a) $\Lambda K^+(\bar{\Lambda}K^-)$ fits with residual contributions shown for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom)



(b) $\Lambda K^-(\bar{\Lambda}K^+)$ fits with residual contributions shown for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom)

Fig. 44: Fits, with 10 residual correlations included and shown, to the ΛK^+ & $\bar{\Lambda}K^-$ (left) and ΛK^- & $\bar{\Lambda}K^+$ (right) data for the centralities 0-10% (top), 10-30% (middle), and 30-50% (bottom). The ten parent pairs used for the residual correction to the $\Lambda K^+(\bar{\Lambda}K^-)$ fit are $\Sigma^0 K^+$, $\Xi^0 K^+$, $\Xi^- K^+$, $\Sigma^{*(+,-,0)} K^+$, ΛK^{*0} , $\Sigma^0 K^{*0}$, $\Xi^0 K^{*0}$, and $\Xi^- K^{*0}$ ($\Sigma^0 K^-$, $\Xi^0 K^-$, $\Xi^+ K^-$, $\Sigma^{*(-,+,-,0)} K^-$, $\bar{\Lambda}K^{*0}$, $\Sigma^0 \bar{K}^{*0}$, $\Xi^0 \bar{K}^{*0}$, and $\Xi^- \bar{K}^{*0}$).

Fit Results $\Lambda(\bar{\Lambda})K_S^0$					
Pair Type	Centrality	Fit Parameters			
		λ	R	$\mathbb{R}f_0$	$\mathbb{I}f_0$
ΛK_S^0	0-10%	$0.60 \pm 0.63 \text{ (stat.)} \pm 0.17 \text{ (sys.)}$	$2.94 \pm 0.45 \text{ (stat.)} \pm 0.35 \text{ (sys.)}$	$-0.40 \pm 0.12 \text{ (stat.)} \pm 0.17 \text{ (sys.)}$	$1.94 \pm 0.47 \text{ (stat.)} \pm 0.77 \text{ (sys.)}$
	10-30%		$2.39 \pm 0.38 \text{ (stat.)} \pm 0.25 \text{ (sys.)}$		
	30-50%		$1.81 \pm 0.29 \text{ (stat.)} \pm 0.12 \text{ (sys.)}$		
$\bar{\Lambda} K_S^0$	0-10%	$0.60 \pm 0.63 \text{ (stat.)} \pm 0.17 \text{ (sys.)}$	$2.94 \pm 0.45 \text{ (stat.)} \pm 0.35 \text{ (sys.)}$	$0.17 \pm 0.08 \text{ (stat.)} \pm 0.12 \text{ (sys.)}$	$1.94 \pm 0.47 \text{ (stat.)} \pm 0.77 \text{ (sys.)}$
	10-30%		$2.39 \pm 0.38 \text{ (stat.)} \pm 0.25 \text{ (sys.)}$		
	30-50%		$1.81 \pm 0.29 \text{ (stat.)} \pm 0.12 \text{ (sys.)}$		

Table 11: Fit Results $\Lambda(\bar{\Lambda})K_S^0$, with 10 residual correlations included. Each pair is fit simultaneously with its conjugate (ie. ΛK_S^0 with $\bar{\Lambda} K_S^0$) across all centralities (0-10%, 10-30%, 30-50%), for a total of 6 simultaneous analyses in the fit. Each analysis has a unique λ and normalization parameter. The radii are shared between analyses of like centrality, as these should have similar source sizes. The scattering parameters ($\mathbb{R}f_0$, $\mathbb{I}f_0$, d_0) are shared amongst all. The fit is done on the data with only statistical error bars. The errors marked as “stat.” are those returned by MINUIT. The errors marked as “sys.” are those which result from my systematic analysis (as outlined in Section 6).

Fit Results $\Lambda(\bar{\Lambda})K^\pm$						
Pair Type	Centrality	Fit Parameters				
		λ	R	$\mathbb{R}f_0$	$\mathbb{I}f_0$	d_0
ΛK^+	0-10%	1.51 ± 0.56 (stat.) ± 0.27 (sys.)	5.92 ± 1.08 (stat.) ± 0.51 (sys.)	-1.38 ± 0.32 (stat.) ± 0.34 (sys.)	0.61 ± 0.34 (stat.) ± 0.20 (sys.)	0.97 ± 0.66 (stat.) ± 0.42 (sys.)
	10-30%	1.47 ± 0.55 (stat.) ± 0.31 (sys.)	4.98 ± 0.86 (stat.) ± 0.40 (sys.)			
	30-50%	1.10 ± 0.30 (stat.) ± 0.27 (sys.)	3.38 ± 0.45 (stat.) ± 0.28 (sys.)			
$\bar{\Lambda} K^-$	0-10%	1.52 ± 0.58 (stat.) ± 0.33 (sys.)	5.92 ± 1.08 (stat.) ± 0.51 (sys.)	0.53 ± 0.20 (stat.) ± 0.15 (sys.)	0.57 ± 0.17 (stat.) ± 0.11 (sys.)	-4.13 ± 1.74 (stat.) ± 1.53 (sys.)
	10-30%	1.28 ± 0.47 (stat.) ± 0.25 (sys.)	4.98 ± 0.86 (stat.) ± 0.40 (sys.)			
	30-50%	1.06 ± 0.28 (stat.) ± 0.16 (sys.)	3.38 ± 0.45 (stat.) ± 0.28 (sys.)			
ΛK^-	0-10%	1.72 ± 0.61 (stat.) ± 0.28 (sys.)	6.54 ± 1.22 (stat.) ± 0.90 (sys.)	0.53 ± 0.20 (stat.) ± 0.15 (sys.)	0.57 ± 0.17 (stat.) ± 0.11 (sys.)	-4.13 ± 1.74 (stat.) ± 1.53 (sys.)
	10-30%	1.24 ± 0.43 (stat.) ± 0.25 (sys.)	4.90 ± 0.94 (stat.) ± 0.64 (sys.)			
	30-50%	1.34 ± 0.75 (stat.) ± 0.42 (sys.)	3.10 ± 0.67 (stat.) ± 0.40 (sys.)			
$\bar{\Lambda} K^+$	0-10%	1.72 ± 0.58 (stat.) ± 0.31 (sys.)	6.54 ± 1.22 (stat.) ± 0.90 (sys.)	0.53 ± 0.20 (stat.) ± 0.15 (sys.)	0.57 ± 0.17 (stat.) ± 0.11 (sys.)	-4.13 ± 1.74 (stat.) ± 1.53 (sys.)
	10-30%	1.33 ± 0.46 (stat.) ± 0.26 (sys.)	4.90 ± 0.94 (stat.) ± 0.64 (sys.)			
	30-50%	0.84 ± 0.31 (stat.) ± 0.31 (sys.)	3.10 ± 0.67 (stat.) ± 0.40 (sys.)			

Table 12: Fit Results $\Lambda(\bar{\Lambda})K^\pm$, with 10 residual correlations included.. Each pair is fit simultaneously with its conjugate (ie. ΛK^+ with $\bar{\Lambda} K^-$ and ΛK^- with $\bar{\Lambda} K^+$) across all centralities (0-10%, 10-30%, 30-50%), for a total of 6 simultaneous analyses in the fit. Each analysis has a unique λ and normalization parameter. The radii are shared between analyses of like centrality, as these should have similar source sizes. The scattering parameters ($\mathbb{R}f_0$, $\mathbb{I}f_0$, d_0) are shared amongst all. The fit is done on the data with only statistical error bars. The errors marked as “stat.” are those returned by MINUIT. The errors marked as “sys.” are those which result from my systematic analysis (as outlined in Section 6).

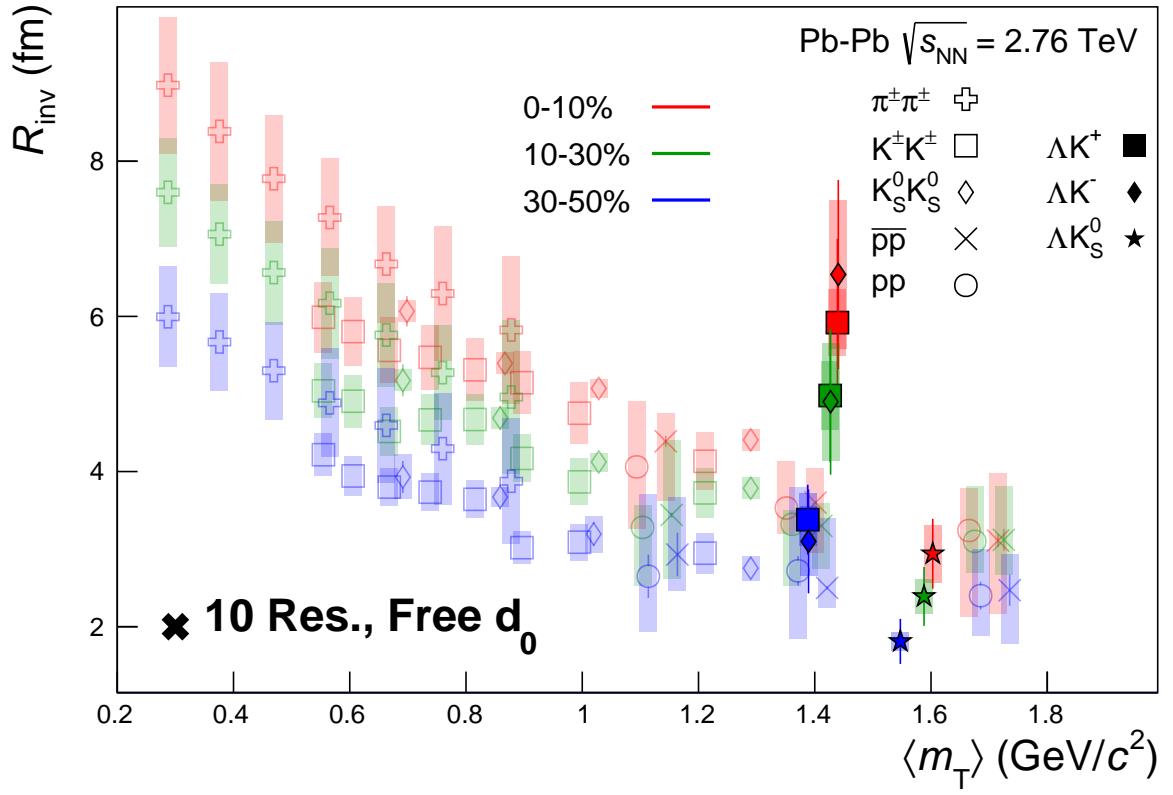


Fig. 45: 10 residual correlations in ΛK fits. Extracted fit R_{inv} parameters as a function of pair transverse mass (m_T) for various pair systems over several centralities. The ALICE published data [11] is shown with transparent, open symbols. The new ΛK results are shown with opaque, filled symbols. In the left, the ΛK^+ (with its conjugate pair) results are shown separately from the ΛK^- (with its conjugate pair) results. In the right, all ΛK^\pm results are averaged.

786 **7.1.4 Results: ΛK_S^0 and ΛK^\pm : Fit Method Comparisons**

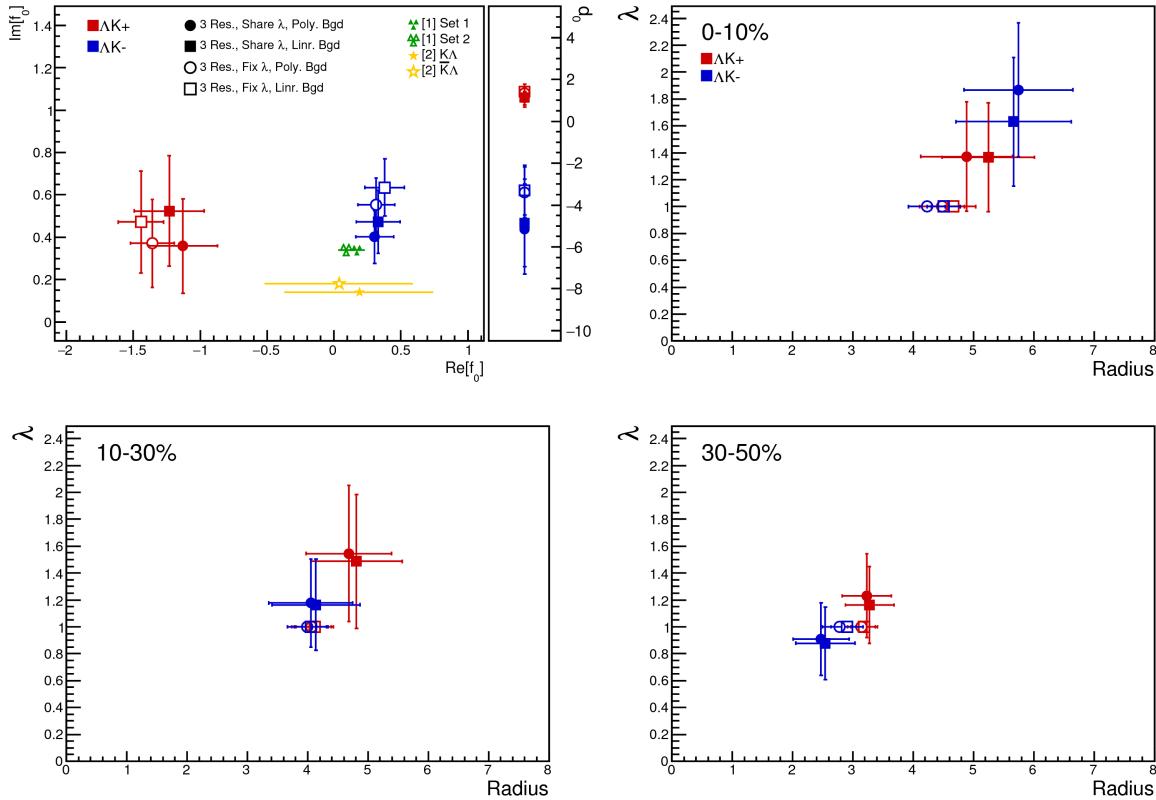


Fig. 46: Compare Fit Parameters: Free vs fixed λ

787 **7.2 Results: ΞK^\pm**

788 Even without any fits to the data, the fact that the $\Xi^- K^+$ data dips below unity (Fig. 50) is exciting, as
 789 this cannot occur purely from a Coulomb interaction. We hope that this dip signifies that we are able to
 790 peer through the overwhelming contribution from the Coulomb interaction to see the effects arising from
 791 the strong interaction.

792 Figure 51 demonstrates graphically, that the $\Xi^- K^+$ results cannot be described by solely the Coulomb
 793 interaction. In this figure, we present the data along with a Coulomb-only band. The Coulomb-only
 794 band is spanned by two Coulomb-only curves, whose parameters are given in the figure. The Coulomb-
 795 only curves were generated using a technique identical to the generation of the fit function, described
 796 in Sec. 5.2, except, of course, with the nuclear scattering parameters all set to zero. The Coulomb-only
 797 curves change monotonically with varying λ or vary in radius parameters, therefore, any curves built with
 798 parameter sets intermediate to those used in the Coulomb-only band will be contained in the band.

799 Including the strong interaction into the simulation can change, sometimes dramatically, the resulting
 800 correlation function, as shown in Figure 52. In the figure, the solid line represents a Coulomb-only curve,
 801 i.e. a simulated correlation function with the strong interaction turned off. The dashed lines represent a
 802 full simulation, including both the strong and Coulomb interactions. The two dashed lines differ only in
 803 the real part of the assumed scattering length: positive in Set 1, and negative in Set 2. In the top figure,
 804 for the $\Xi^- K^+$ simulation, we see that parameter set 2, with a negative real part of the scattering length,
 805 causes the simulated curve to dip below unity, as is seen in the data. If there is a parallel to be drawn
 806 between this analysis and the ΛK analysis, we expect to see similar effects in the ΛK^+ system and the
 807 $\Xi^- K^+$ systems. In these systems, we could have an $s\bar{s}$ annihilation picture. Or, another possible way of

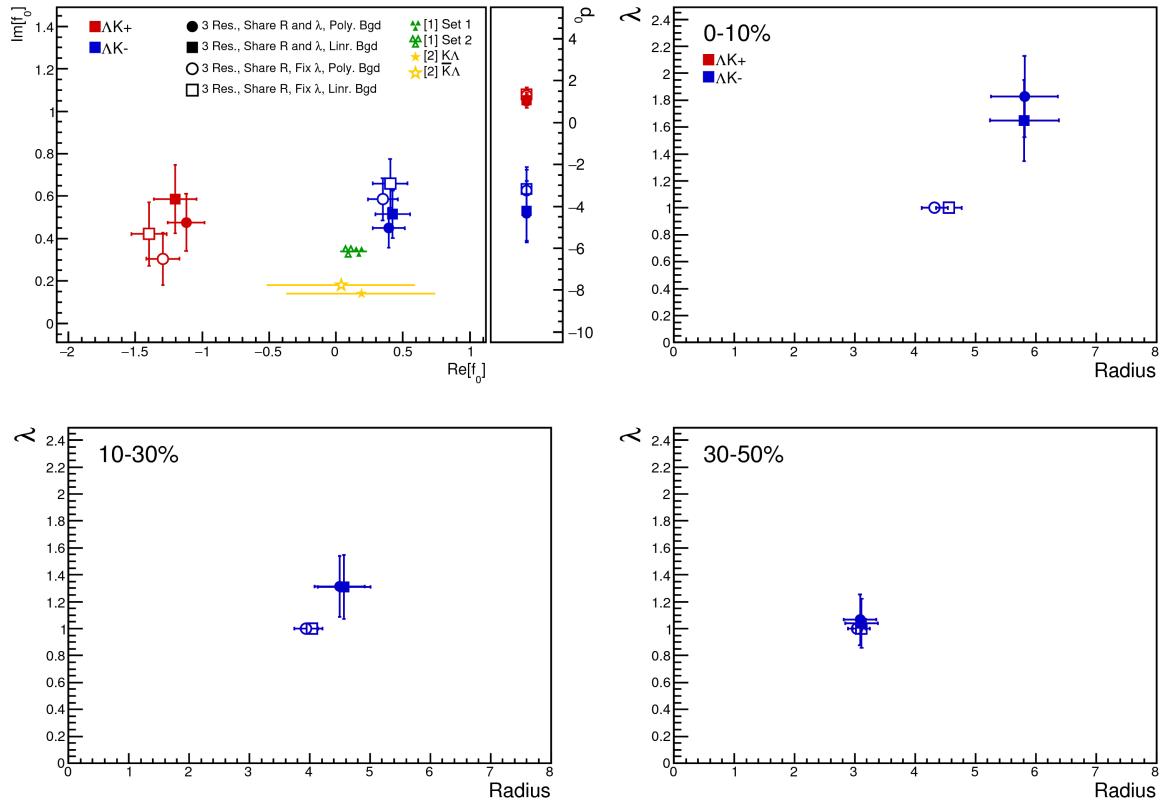


Fig. 47: Compare Fit Parameters: Free vs fixed λ (sharing radii)

thinking about these systems is in terms of net strangeness. The ΛK^+ system has $S=0$, while the ΛK^- has $S=-2$. The $\Xi^- K^+$ has $S=-1$, while the $\Xi^- K^-$ has $S=-3$.

The author was asked to perform a global Coulomb-only fit to the data, to ensure that the system truly could not be described simply by the Coulomb interaction. In other words, in the fit, the strong force was turned off, and the $\Xi^- K^+$, $\bar{\Xi}^+ K^-$, $\Xi^- K^-$, $\bar{\Xi}^+ K^+$ systems all share one sinlge radius parameter, while the pair and conjugate pair systems share a λ parameter. The results of this fit are shown in Figures 53 and 54. In Fig. 53, there was a lower limit of 0.1 fm placed on the radius parameter, and the radius parameter was initialized to 3 fm (as seems reasonable, when considering the transverse mass of the system and looking at Fig. 45). As is shown in the results, the radius parameter reached this unrealistic lower bound of 0.1 fm. In Fig. 54, the parameters were all unbounded, and the radius parameter was initialized to 10 fm. In this case, the radius parameters reamins high, and ends at an unrealistic value of 10.84 fm. In both cases, the λ parameters are too low. From these figures, we conclude that a global Coulomb-only fit is not suitable for the data.

Although the global Coulomb-only fit failed, it is possible that a Coulomb-only fit performed on $\Xi^- K^+$ and $\bar{\Xi}^+ K^-$ separately from $\Xi^- K^-$ and $\bar{\Xi}^+ K^+$ could be suitable. The result of such fits are shown in Figures 55 and 56. Figure 55, shows that the fit is not able to describe the dip in the $\Xi^- K^+$ data below unity. Of course, this is obviously true for an attractive Coulomb-only fit. The radius parameter of 8.43 fm extracted from this fit is unrealistically large. In Figure 56 shows the Coulomb-only fit can described the $\Xi^- K^-$ data reasonable well; although the extracted radius of 3.73 fm is somewhat larger than expected.

8 To Do

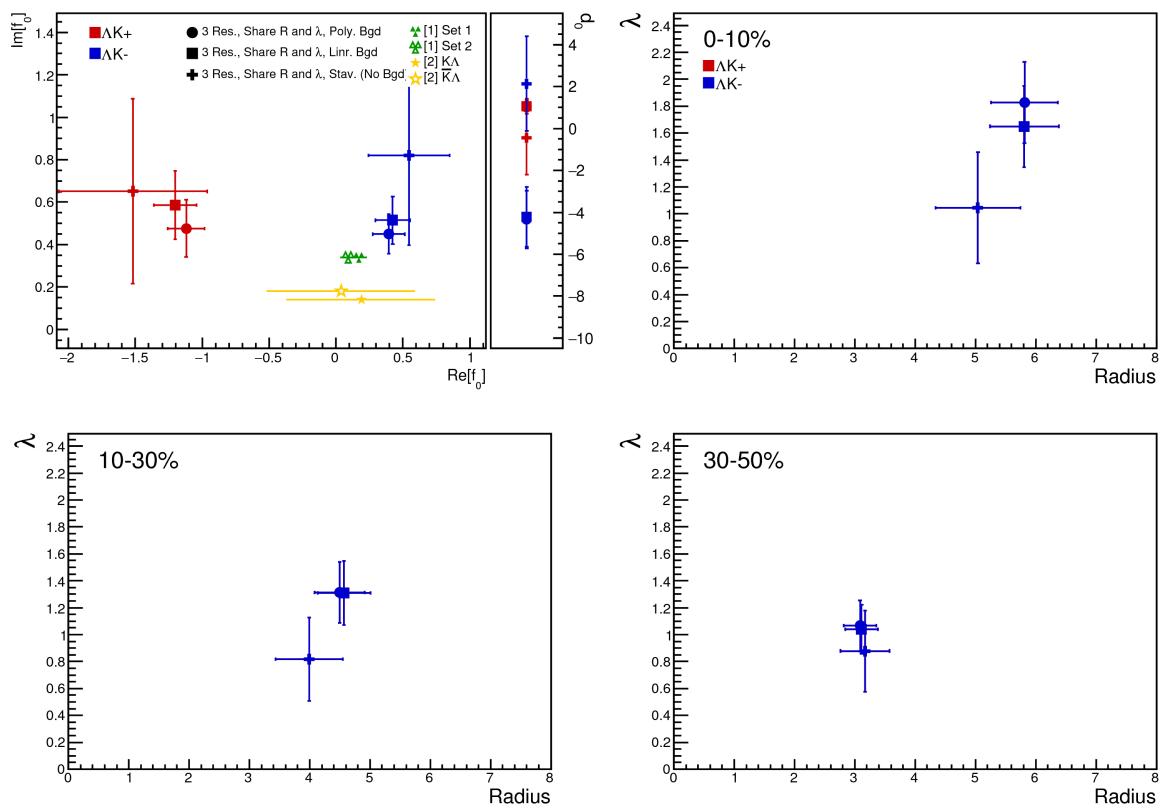


Fig. 48: Compare Fit Parameters: Background methods (sharing radii)

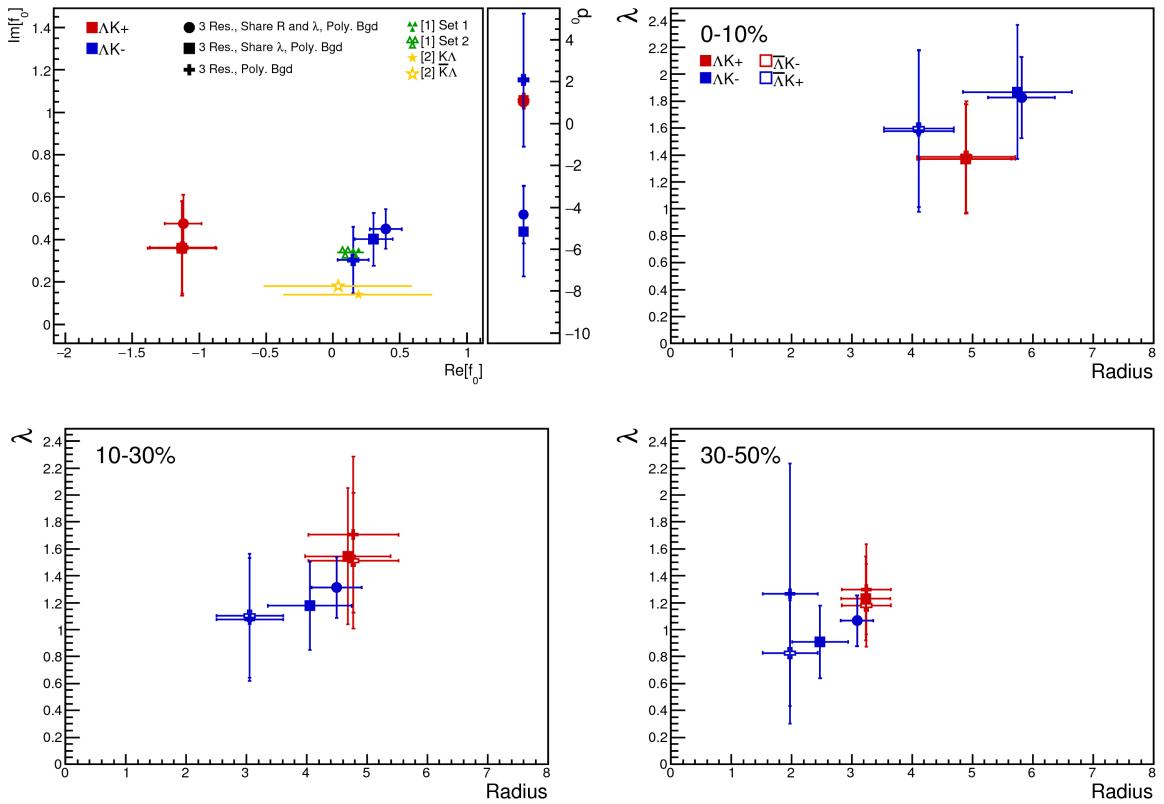
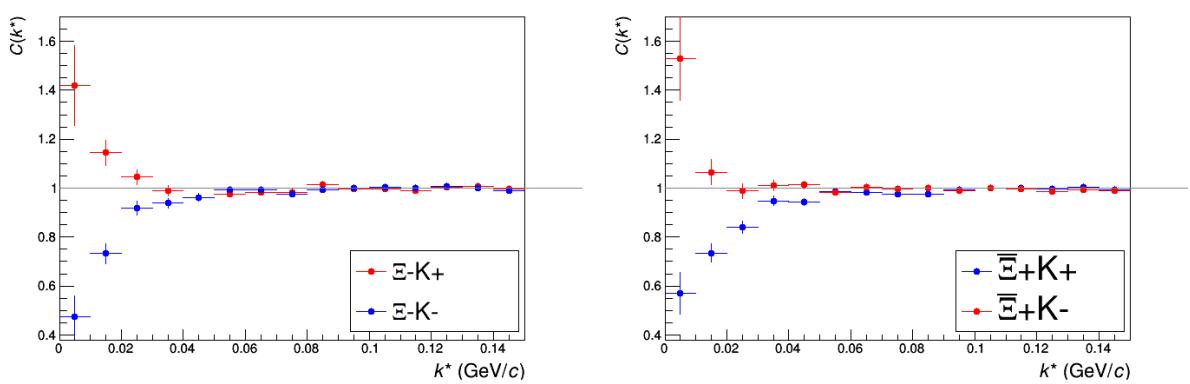


Fig. 49: Compare Fit Parameters: Shared vs. Separate Radii


 Fig. 50: ΞK^\pm Results for 0-10% Centrality. (Left) $\Xi^- K^+$ and $\Xi^- K^-$ (Right) $\Xi^+ K^+$ and $\Xi^+ K^-$

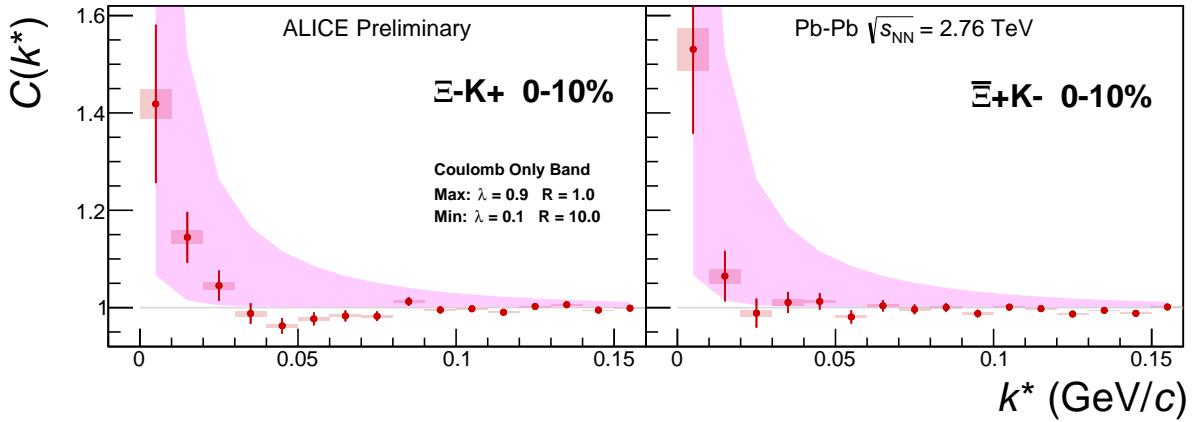
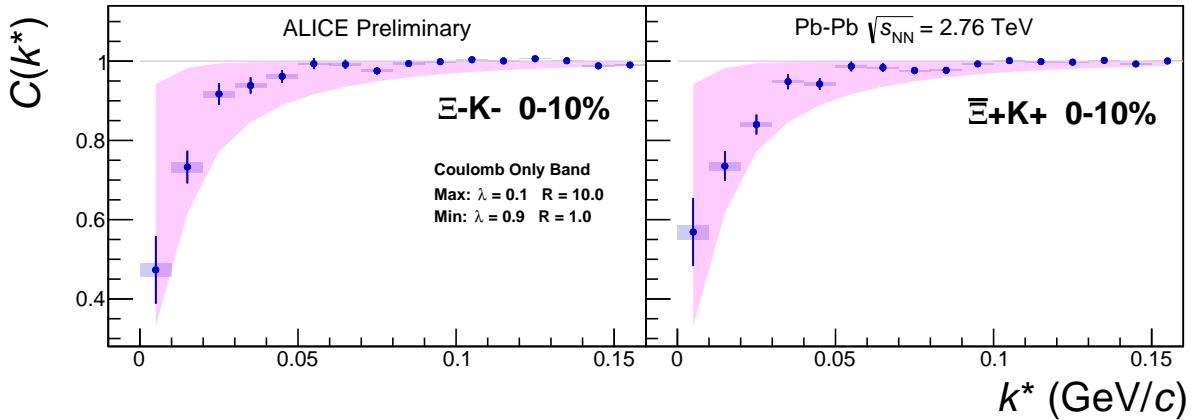
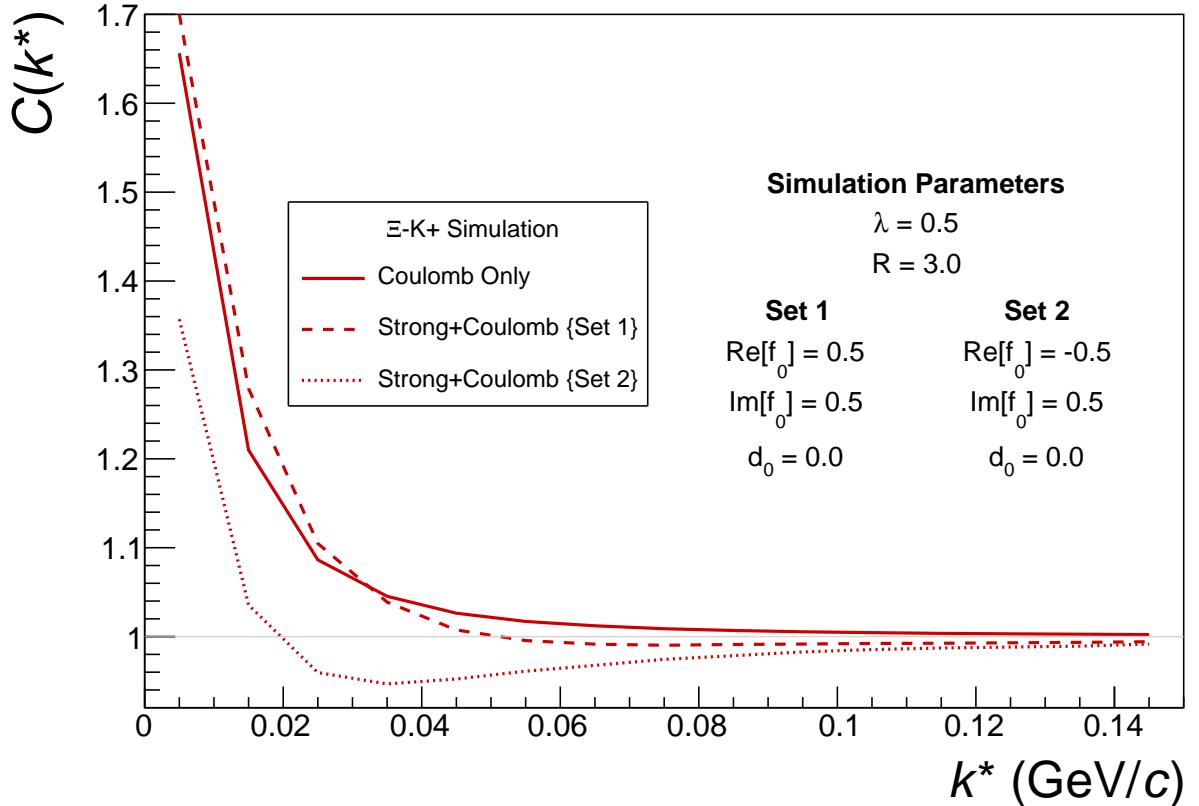
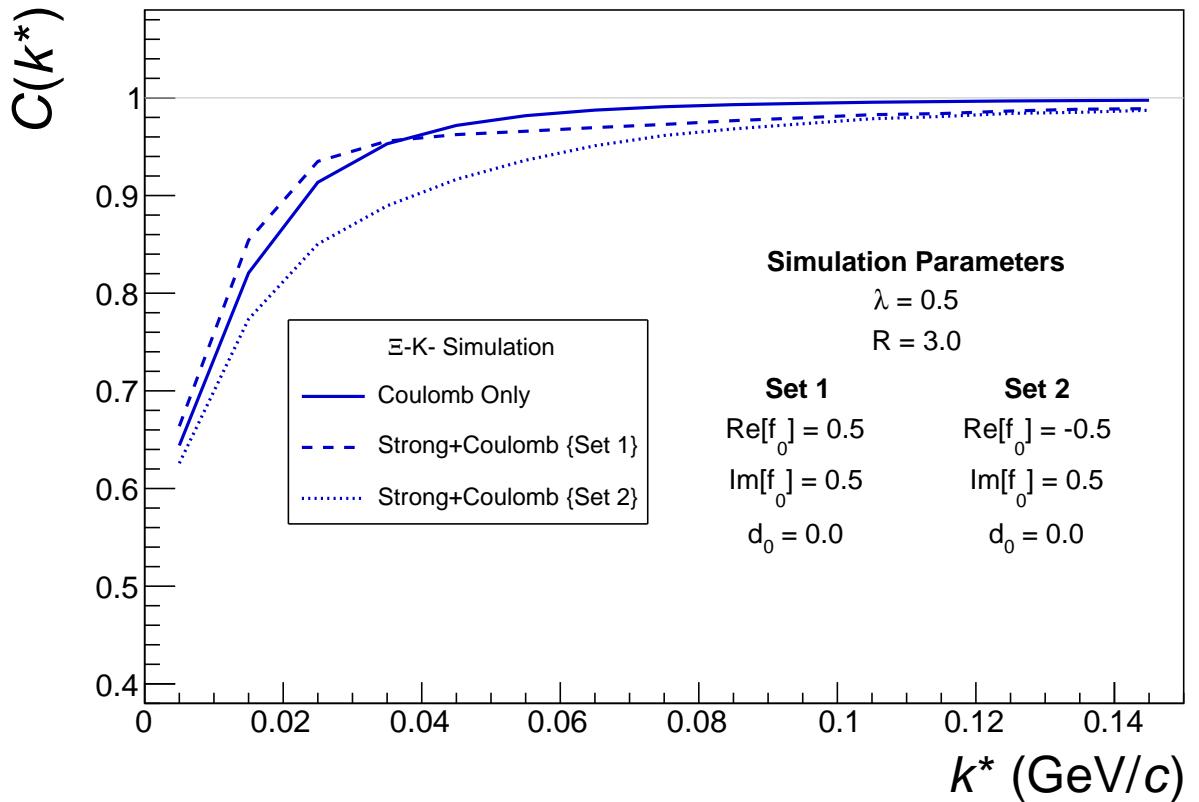
(a) (Left) ΞK^+ and (Right) $\Xi\bar{\text{K}}^-$ (b) (Left) ΞK^- and (Right) $\Xi\bar{\text{K}}^+$

Fig. 51: ΞK^\pm data with Coulomb-only bands for the 0-10% centrality bin. The Coulomb-only bands span two sets of Coulomb-only curves: (1) $\lambda = 0.9$, R = 1.0 fm and (2) $\lambda = 0.1$, R = 10.0 fm. The Coulomb-only curves are simulated correlation functions for the respective pair system assuming only a Coulomb interaction, i.e. ignoring the strong interaction. The Coulomb-only curves change monotonically with varying λ and varying R, therefore, any intermediate parameter set will fall within this Coulomb-only band.



(a) ΞK^+ and $\bar{\Xi} K^-$ simulation



(b) ΞK^- and $\bar{\Xi} K^+$ simulation

Fig. 52: Effect on the Coulomb-only curve of including the strong interaction for ΞK^\pm systems. The solid line represents a Coulomb-only curve, i.e. a simulated correlation function with the strong interaction turned off. The dashed lines represent a full simulation, including both the strong and Coulomb interactions. The two dashed lines differ only in the real part of the assumed scattering length: positive in Set 1, and negative in Set 2.

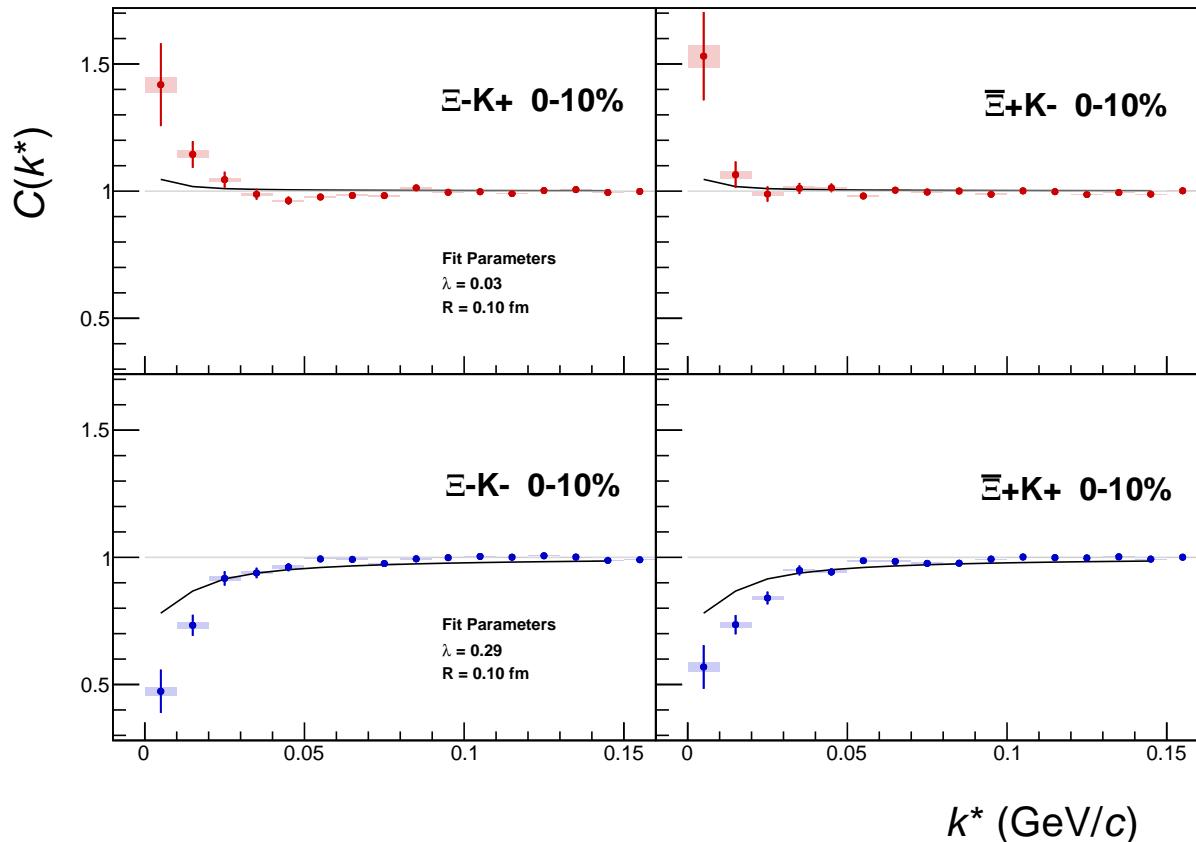


Fig. 53: ΞK^\pm Global Coulomb-only fit (Set 1) for 0-10% centrality. In this fit, there was a lower limit of 0.1 fm placed on the radius parameter, and the radius parameter was initialized to 3 fm (as seems reasonable, when considering the transverse mass of the system and looking at Fig. 45). As is shown in the results, the radius parameter reached this unrealistic lower bound of 0.1 fm. Also, the extracted λ parameters are too low.

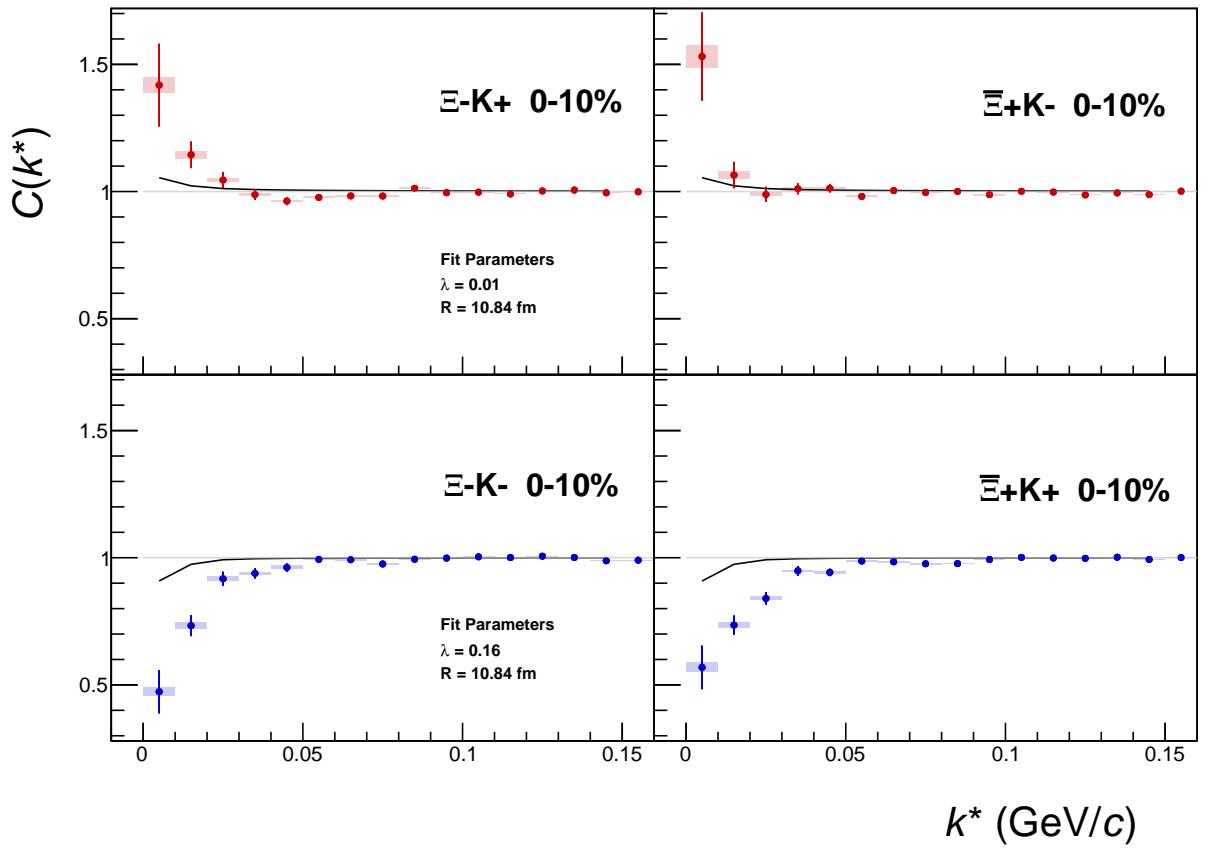


Fig. 54: ΞK^\pm Global Coulomb-only fit (Set 2) for 0-10% centrality. In this fit, the parameters were all unbounded, and the radius parameter was initialized to 10 fm. In this case, the radius parameters remain high, and ends at an unrealistic value of 10.84 fm. Also, the extracted λ parameters are too low.

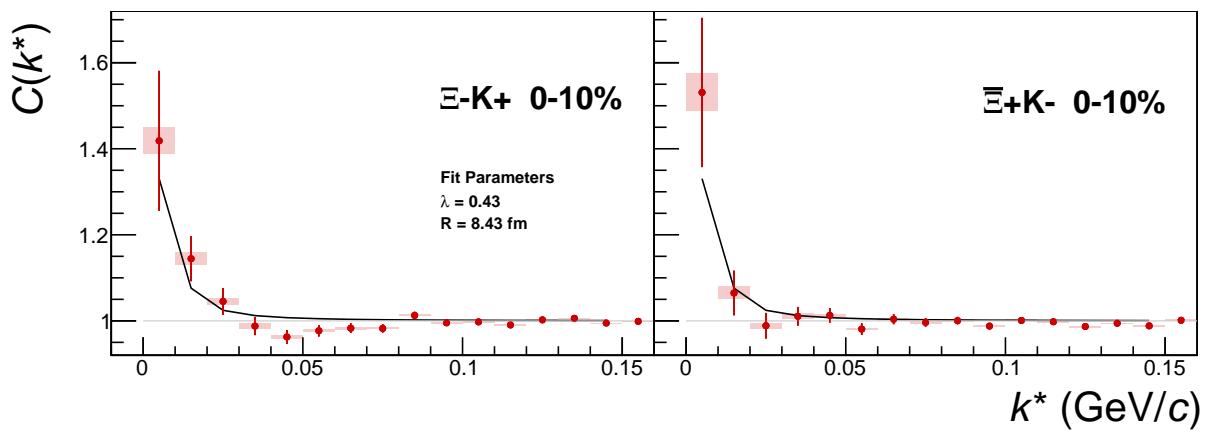


Fig. 55: $\Xi^-\text{K}^+$ Coulomb-only fit for 0-10% centrality

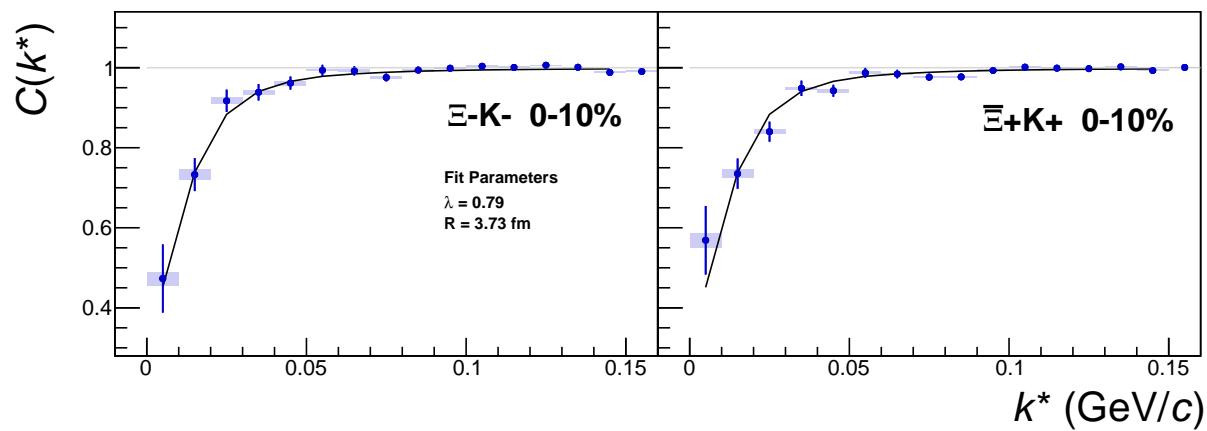


Fig. 56: $\Xi^- \text{K}^-$ Coulomb-only fit for 0-10% centrality

829

9 Additional Figures

 830

9.1 Residuals

 831

9.1.1 ΛK^+ Residuals

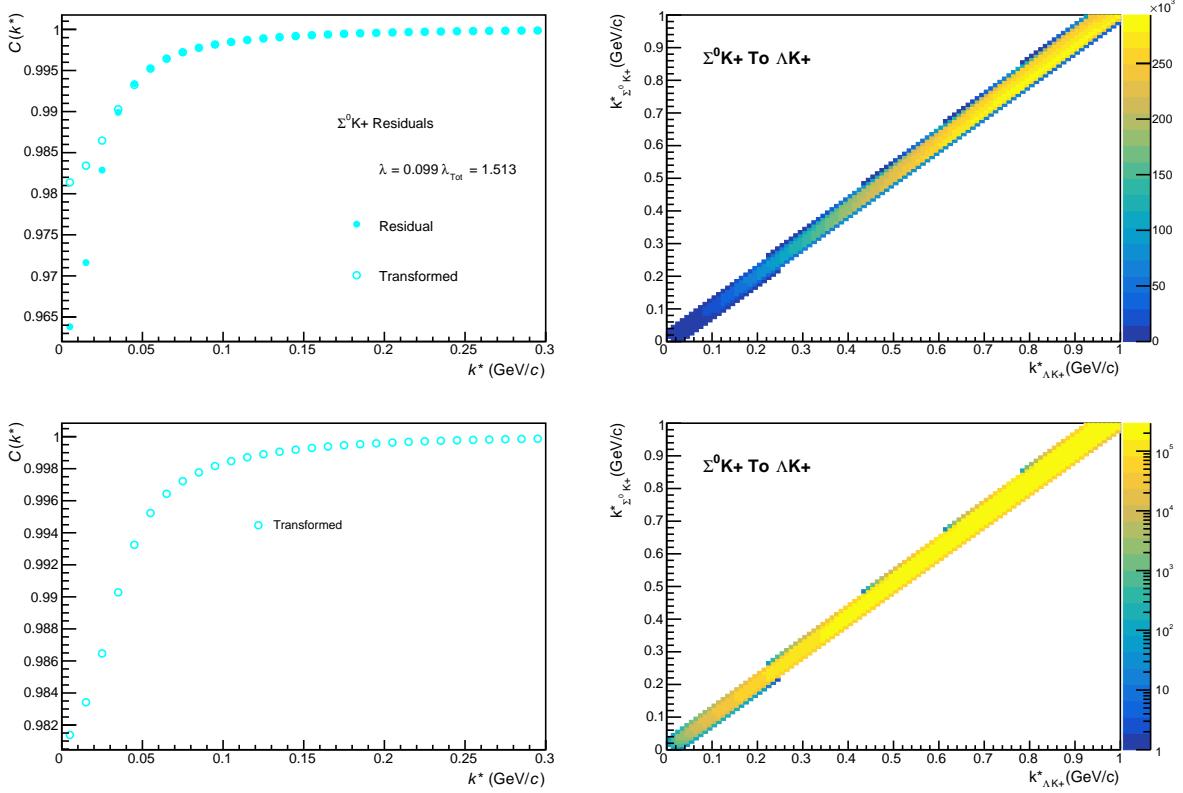


Fig. 57: Residuals: $\Sigma^0 K^+$ to ΛK^+ (0-10% Centrality)

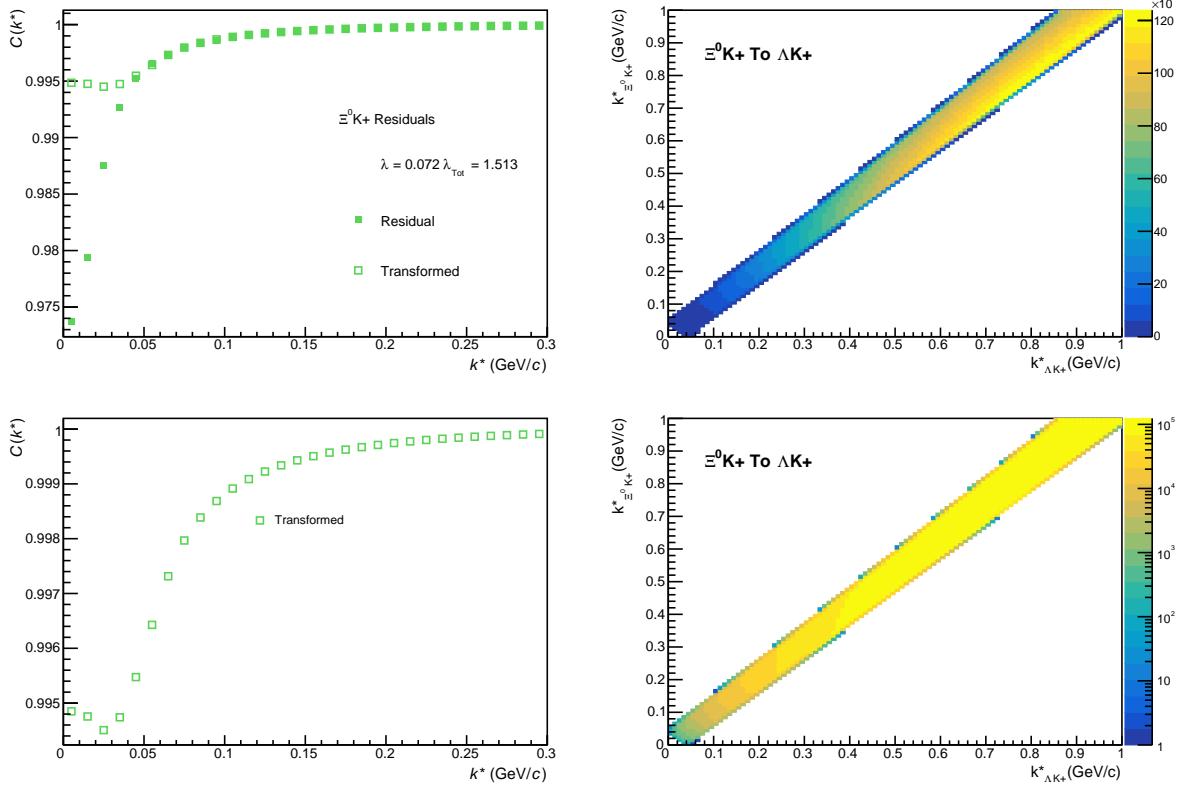


Fig. 58: Residuals: $\Xi^0 \text{K}^+$ to ΛK^+ (0-10% Centrality)

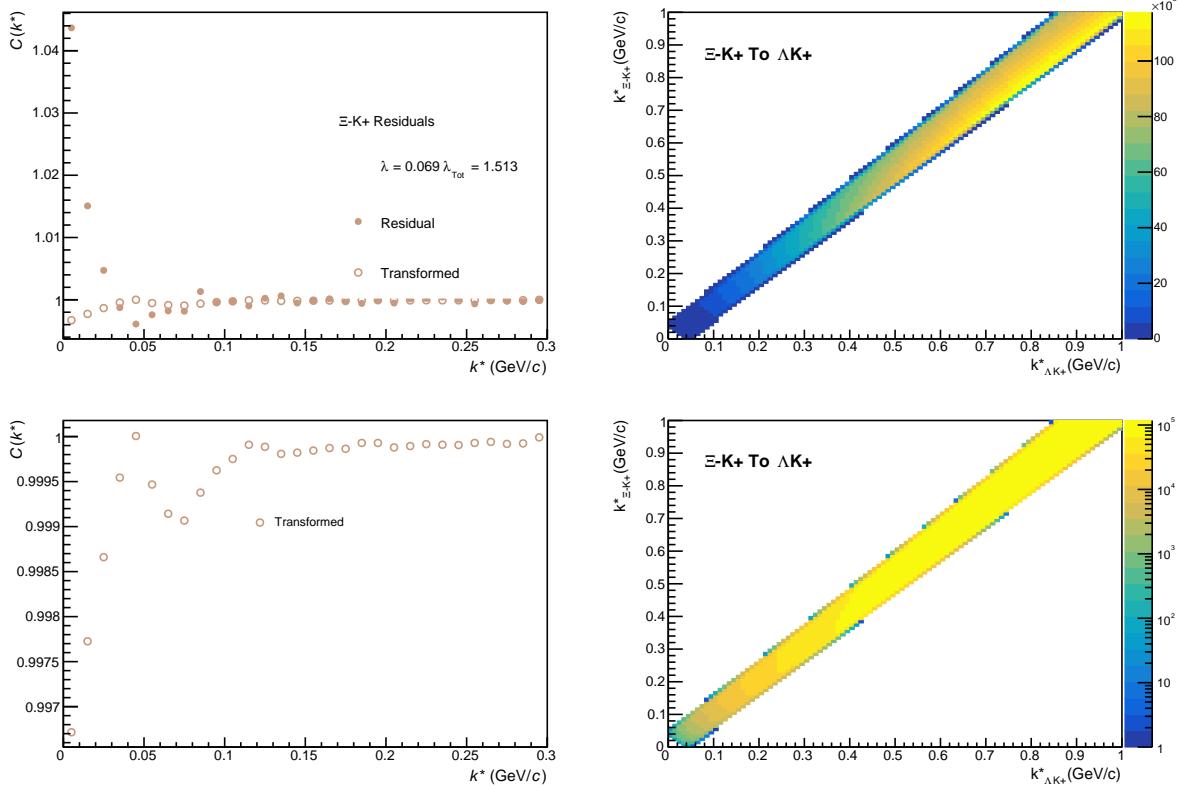


Fig. 59: Residuals: $\Xi^- \text{K}^+$ to ΛK^+ (0-10% Centrality)

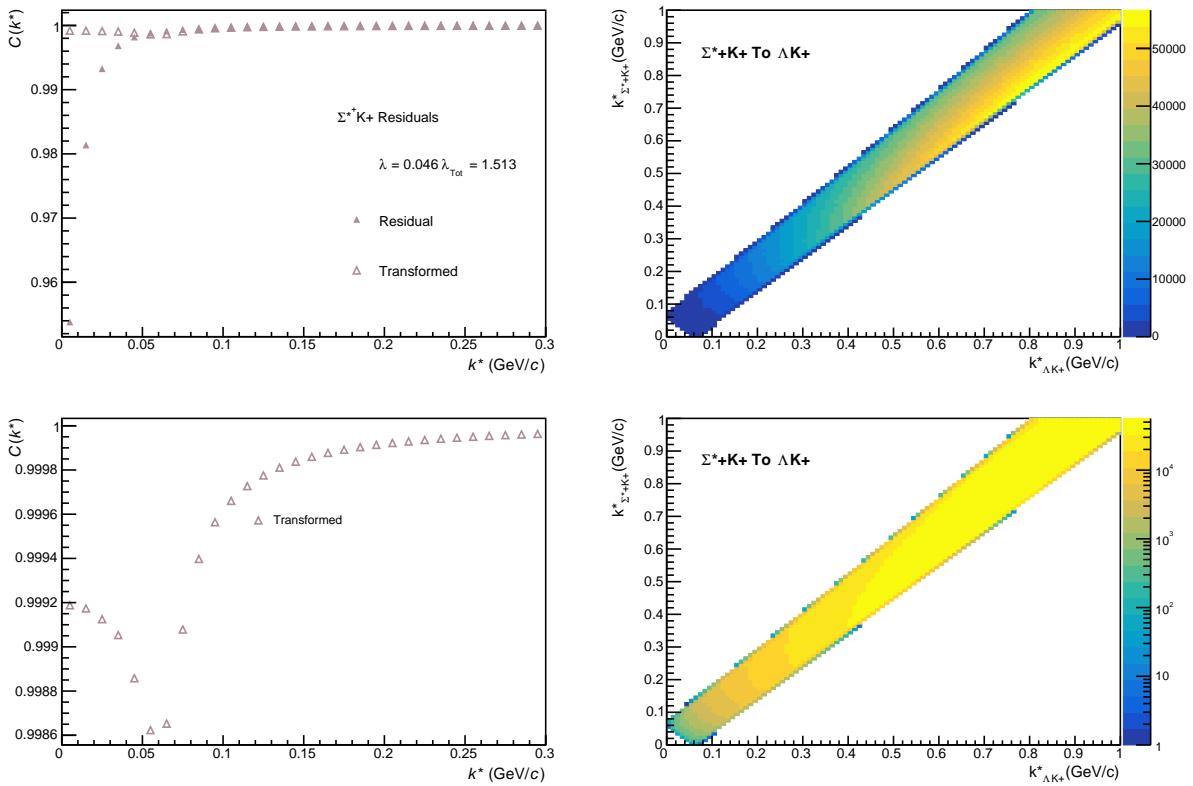


Fig. 60: Residuals: $\Sigma^{*+} K^+$ to ΛK^+ (0-10% Centrality)

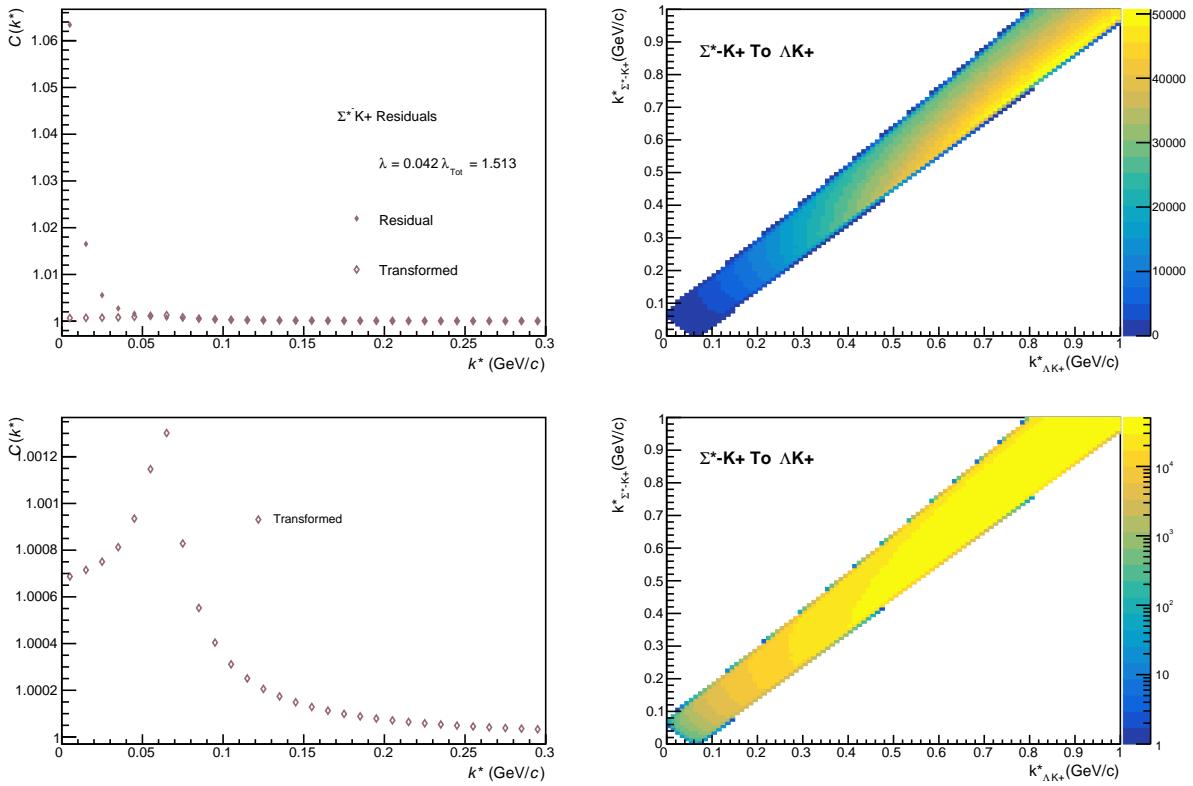


Fig. 61: Residuals: $\Sigma^{*-} K^+$ to ΛK^+ (0-10% Centrality)

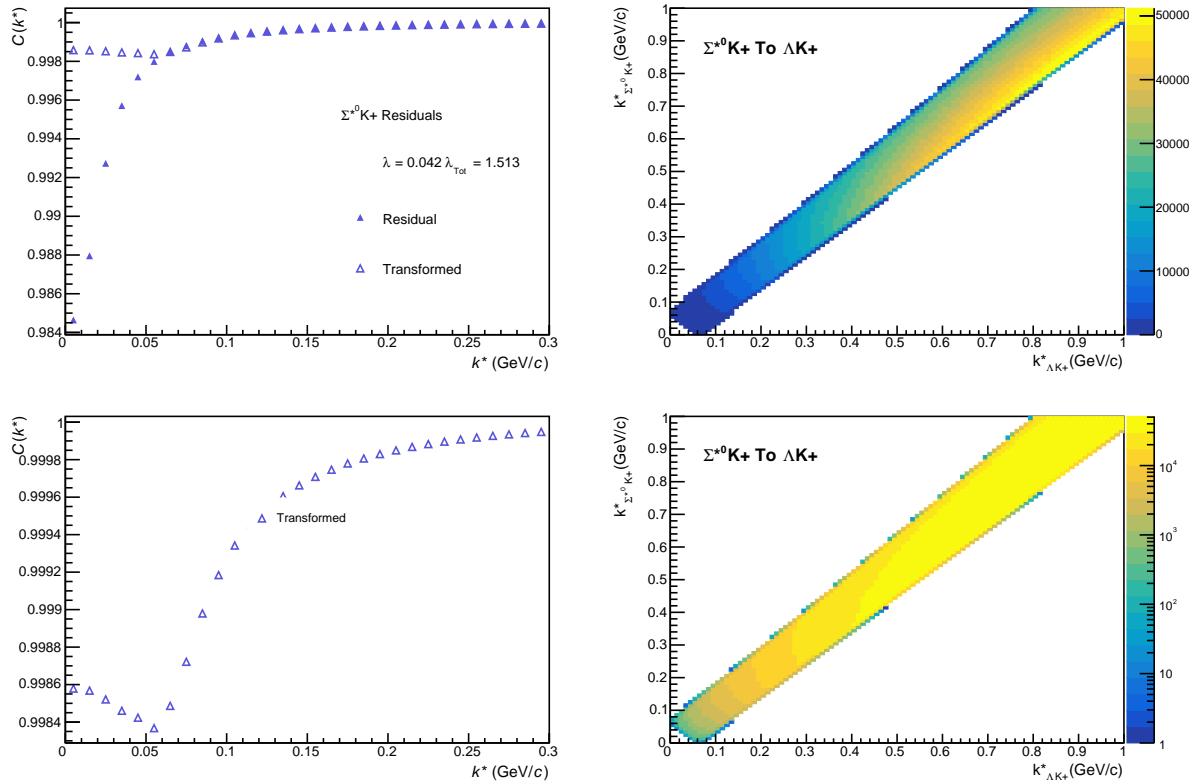


Fig. 62: Residuals: $\Sigma^{*0} \text{K}^+$ to ΛK^+ (0-10% Centrality)

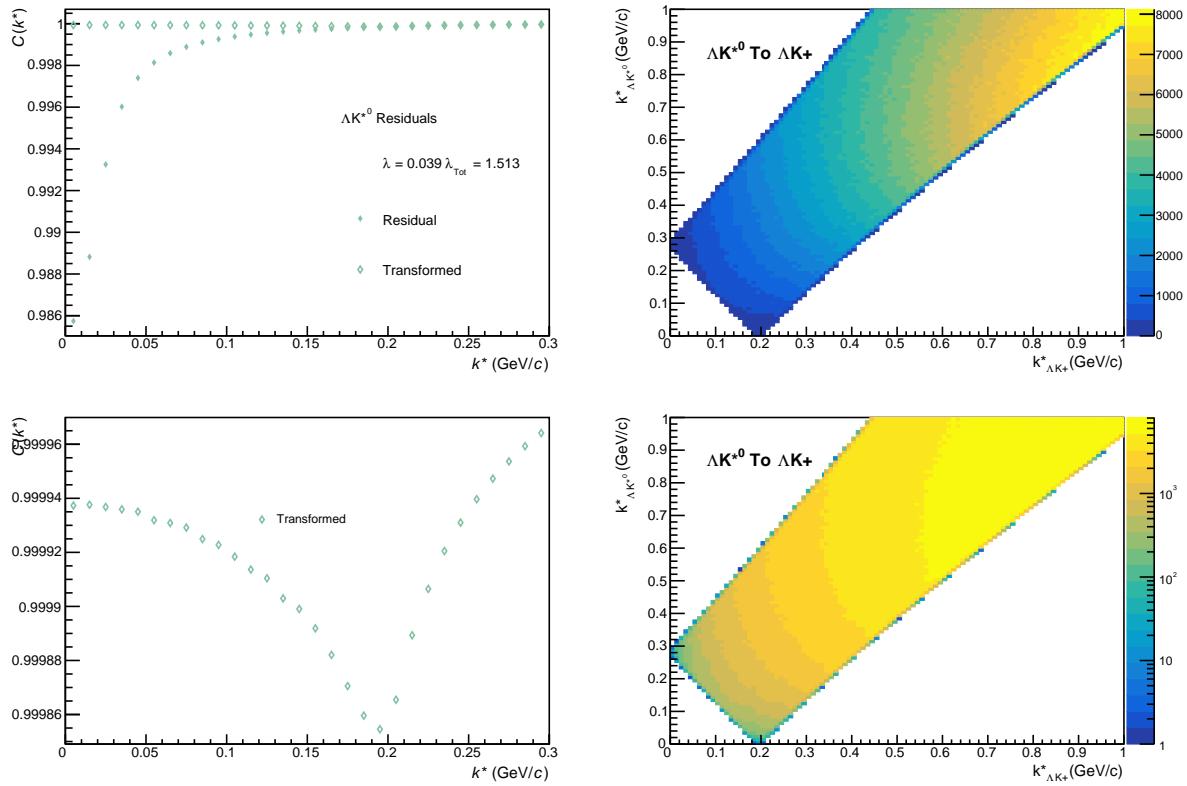
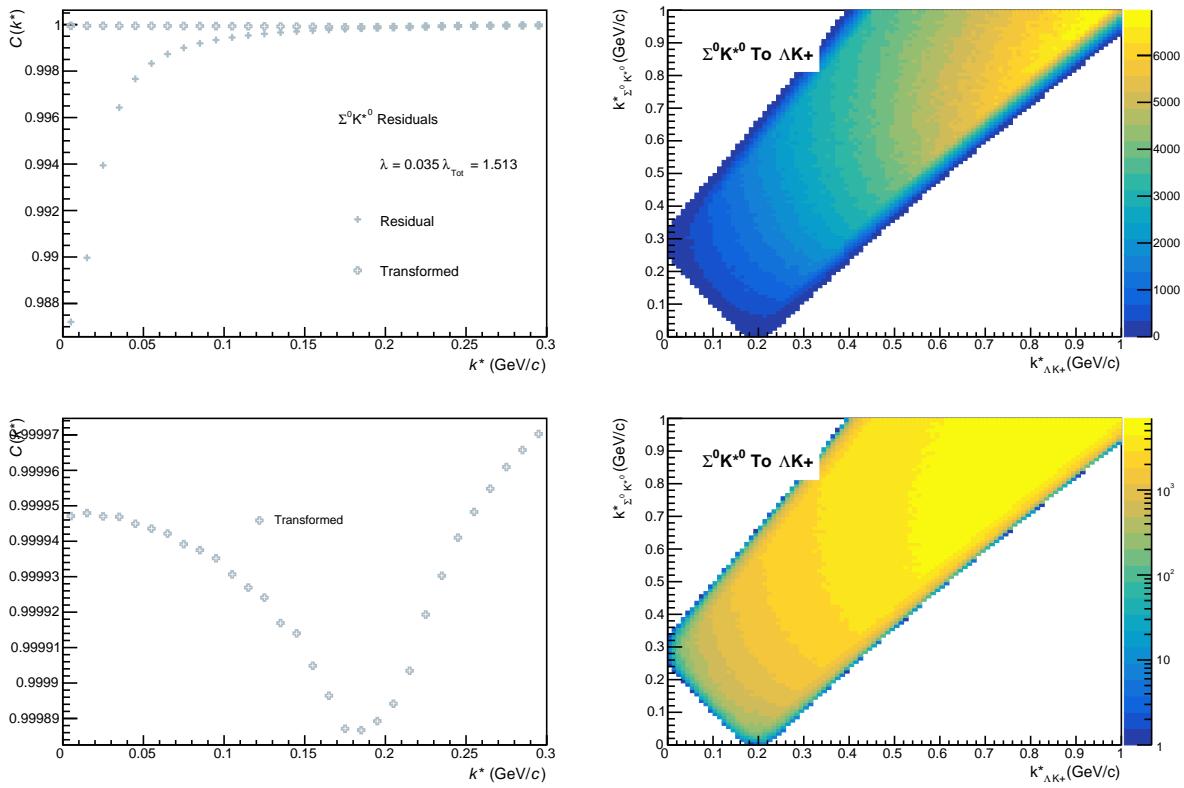
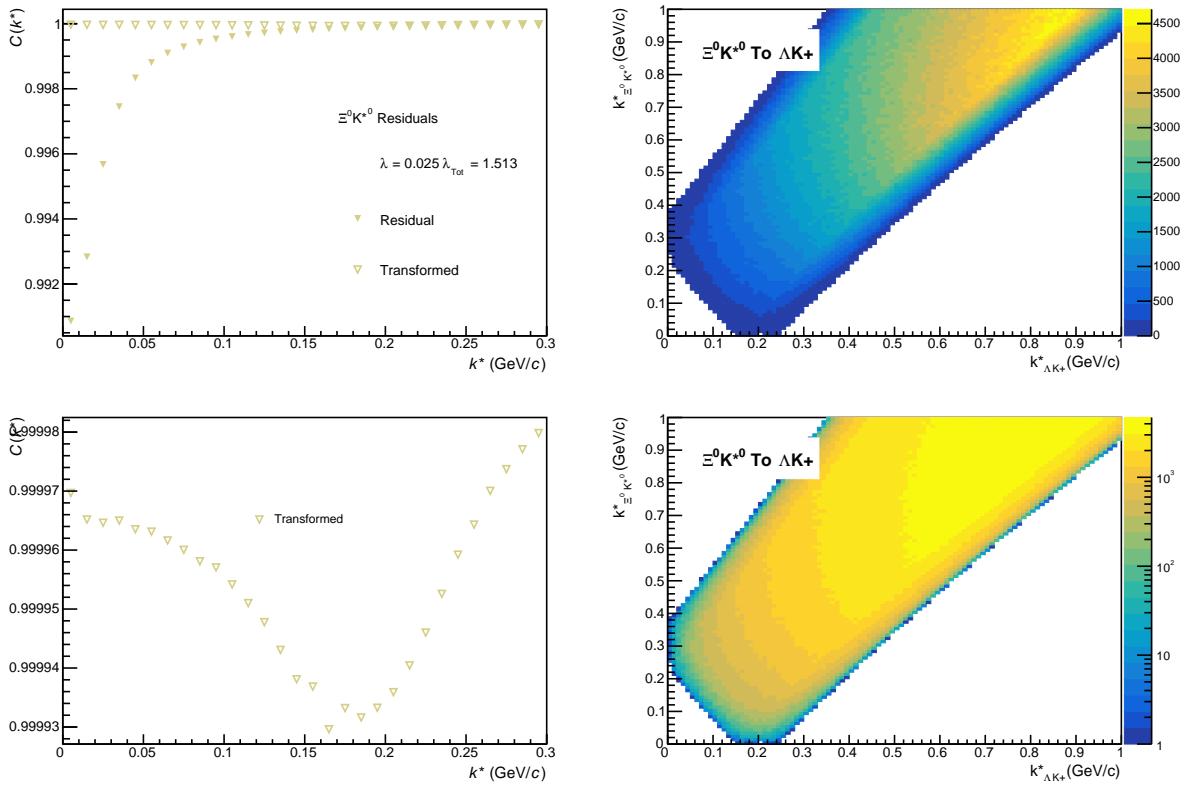


Fig. 63: Residuals: ΛK^{*0} to ΛK^+ (0-10% Centrality)


Fig. 64: Residuals: $\Sigma^0 K^{*0}$ to ΛK^+ (0-10% Centrality)

Fig. 65: Residuals: $\Xi^0 K^{*0}$ to ΛK^+ (0-10% Centrality)

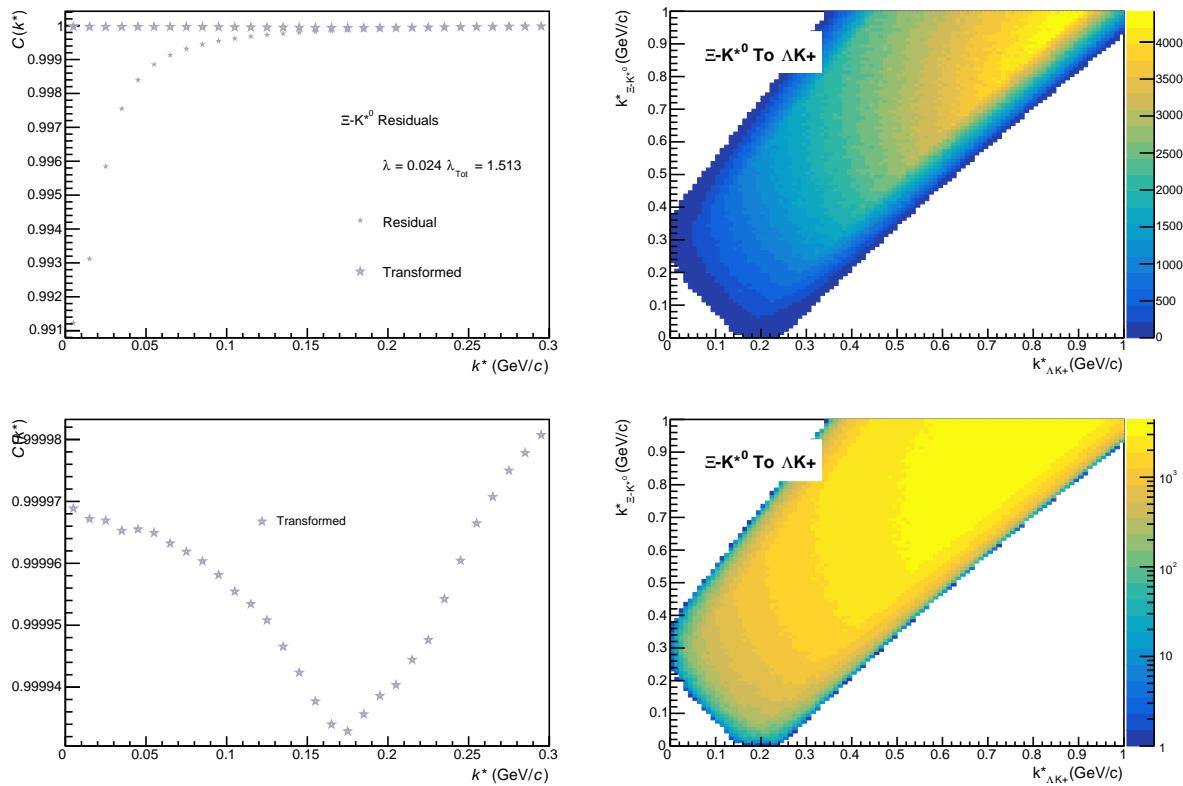
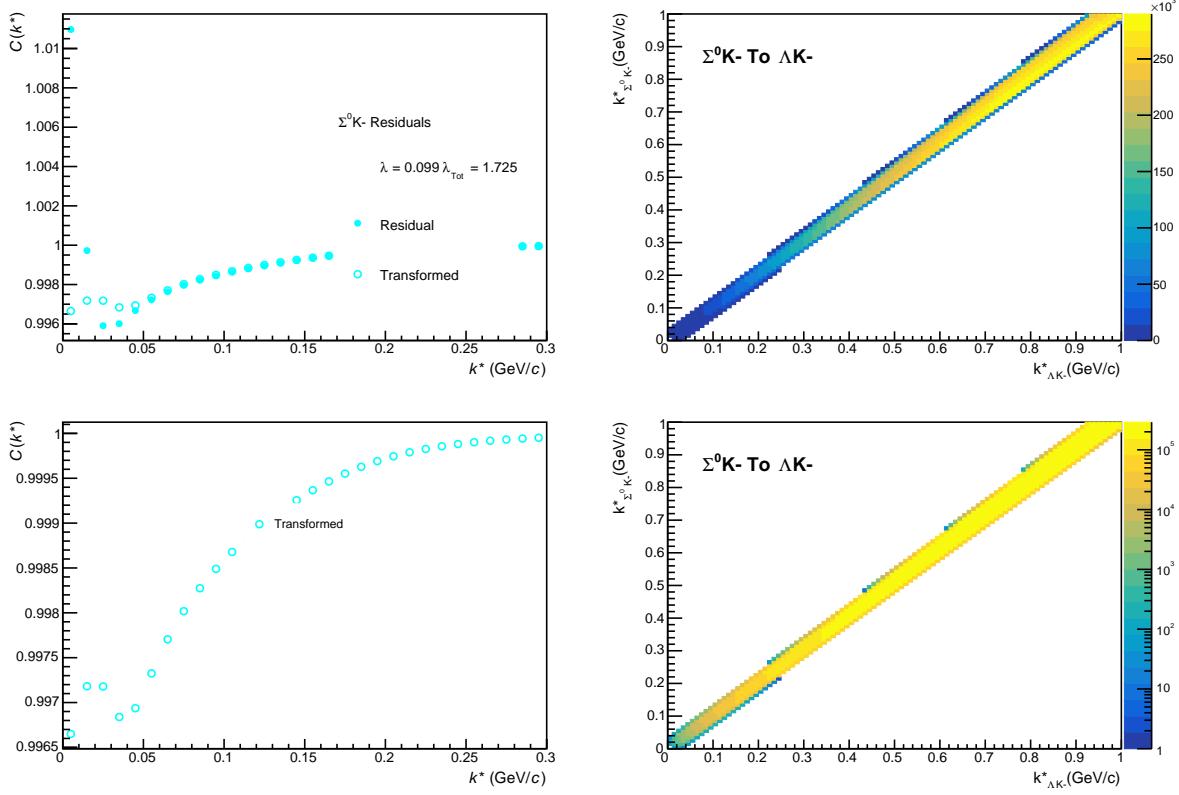


Fig. 66: Residuals: $\Xi^- K^{*0}$ to ΛK^+ (0-10% Centrality)

832 **9.1.2 ΛK^- Residuals**

Fig. 67: Residuals: $\Sigma^0 K^-$ to ΛK^- (0-10% Centrality)

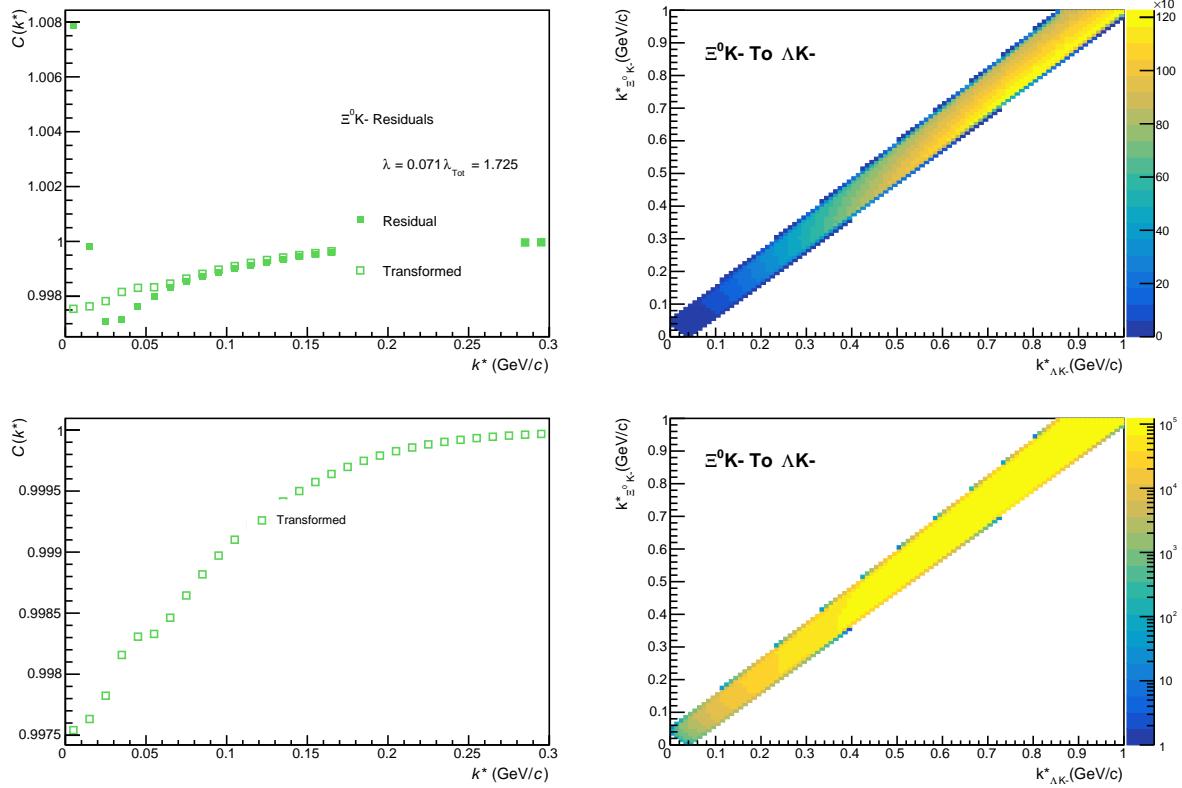


Fig. 68: Residuals: $\Xi^0 \text{K}^-$ to ΛK^- (0-10% Centrality)

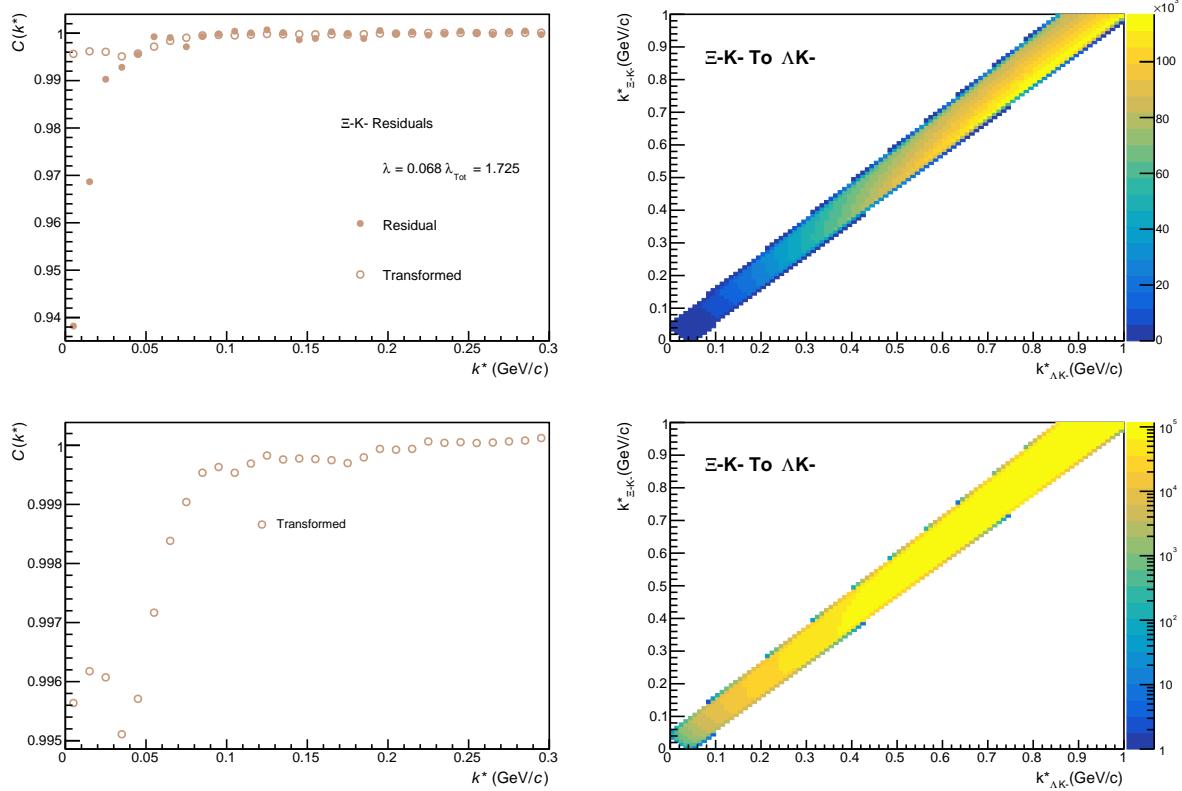
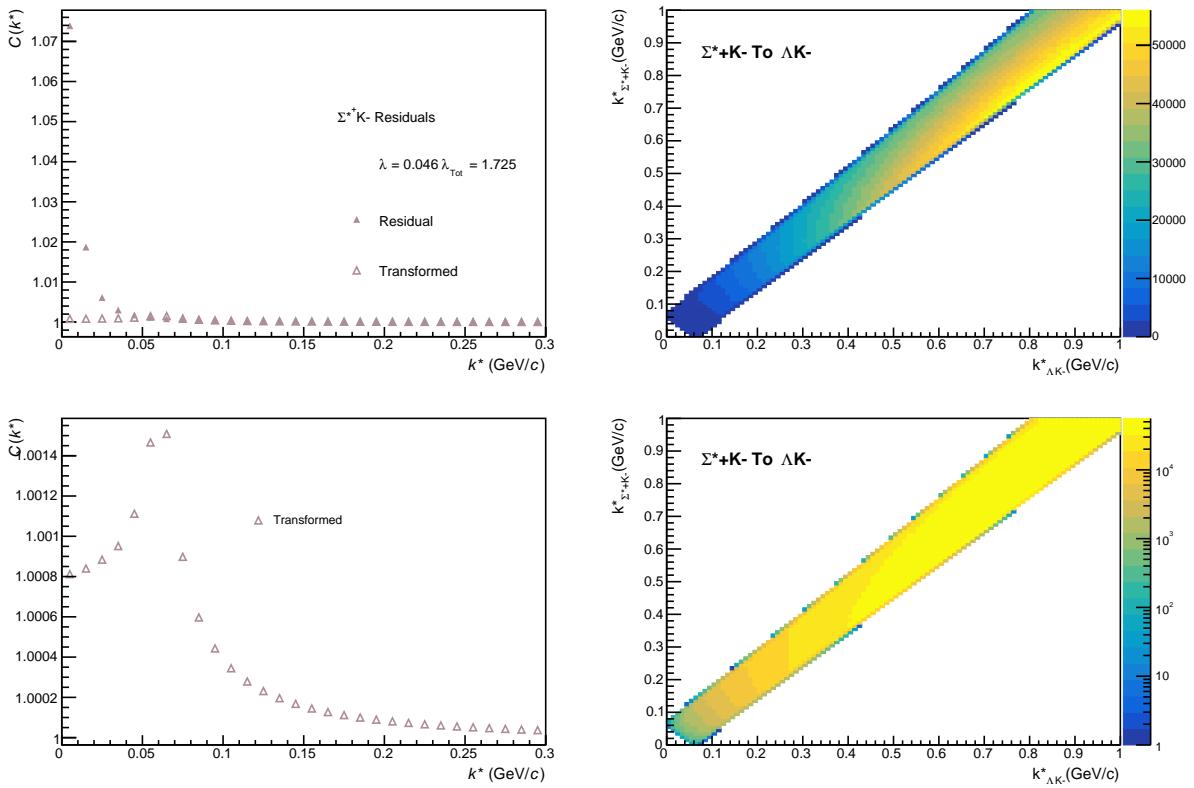
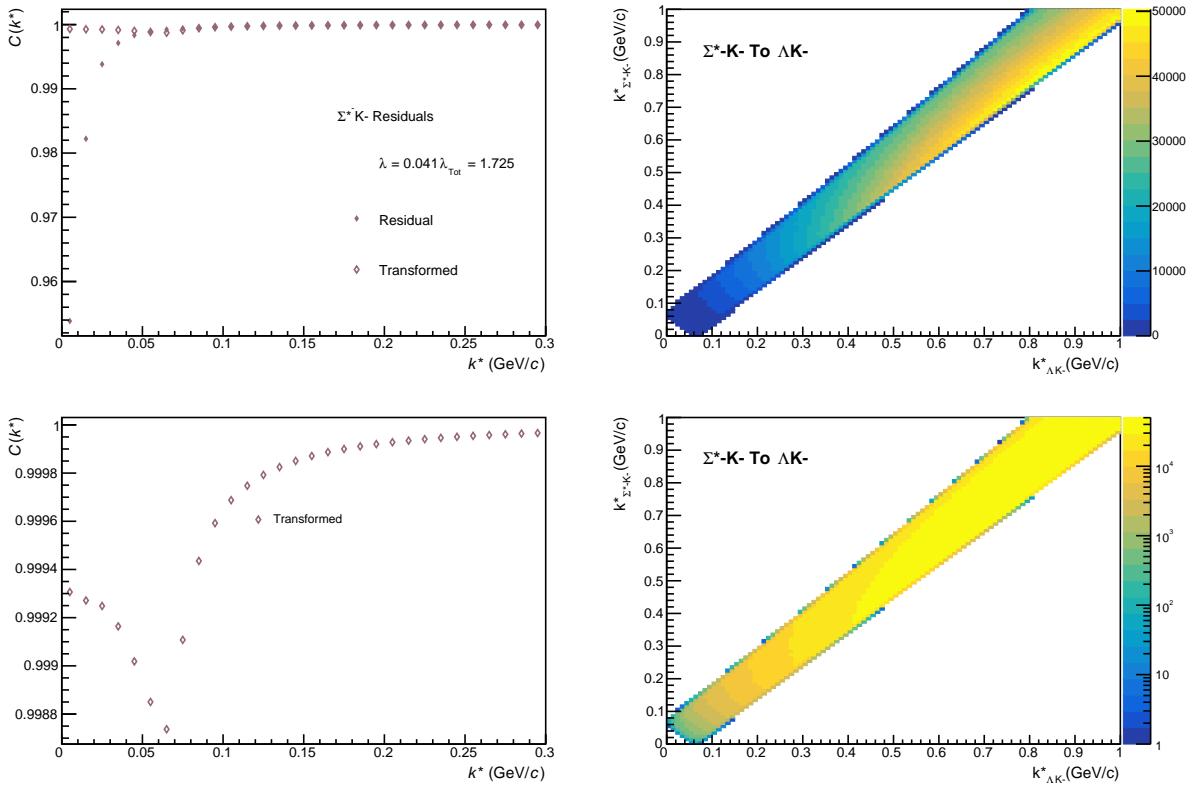


Fig. 69: Residuals: $\Xi^- \text{K}^-$ to ΛK^- (0-10% Centrality)


Fig. 70: Residuals: $\Sigma^{*+} K^-$ to ΛK^- (0-10% Centrality)

Fig. 71: Residuals: $\Sigma^{*-} K^-$ to ΛK^- (0-10% Centrality)

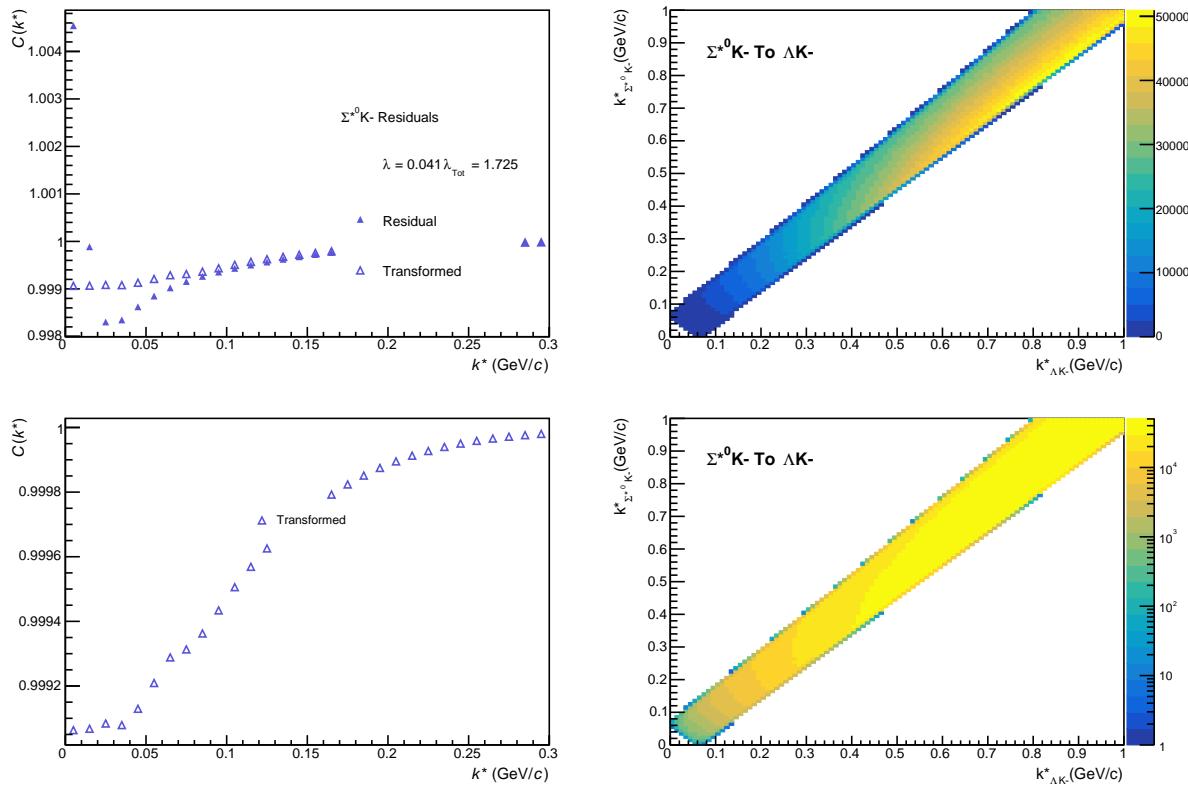


Fig. 72: Residuals: $\Sigma^0 \text{K}^-$ to ΛK^- (0-10% Centrality)

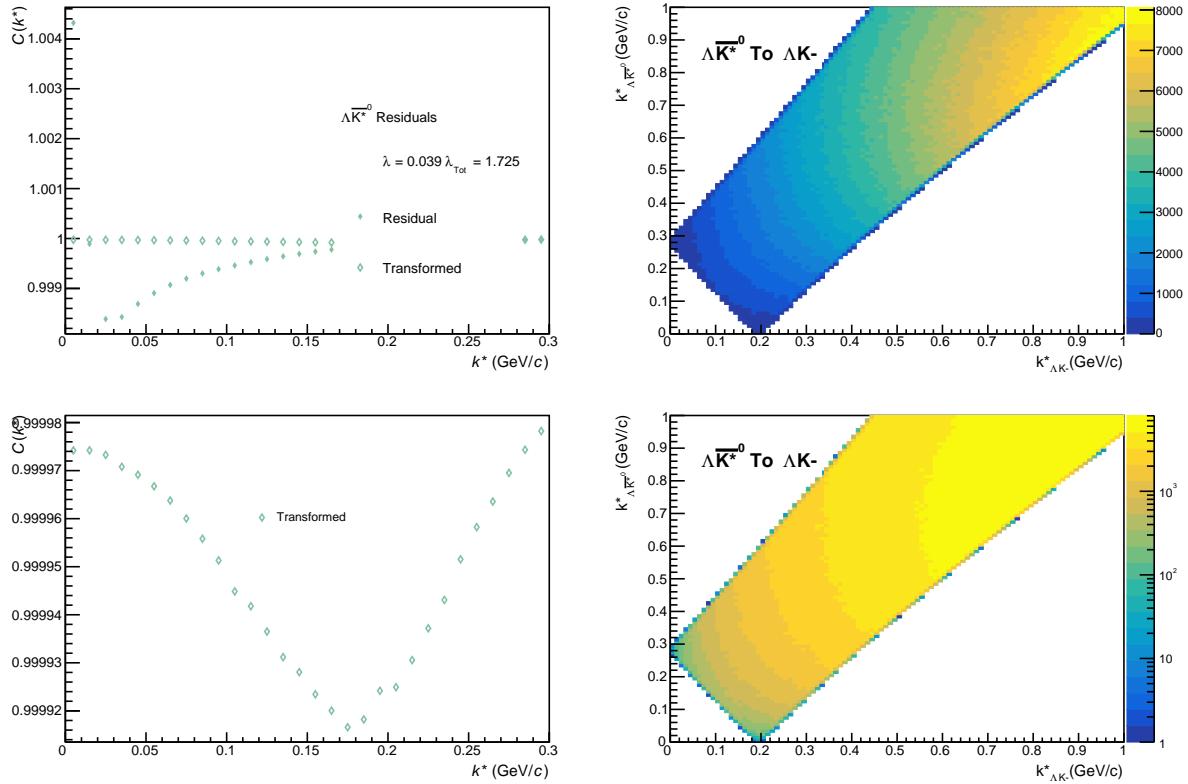
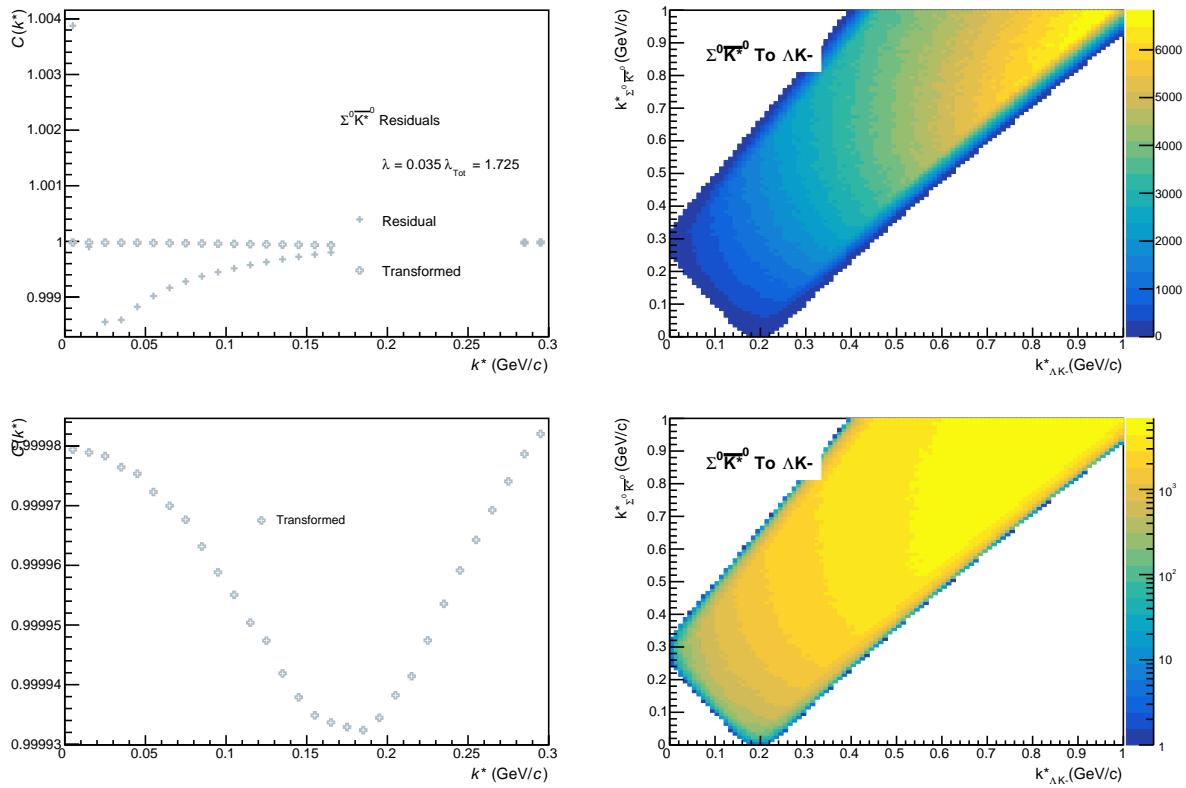
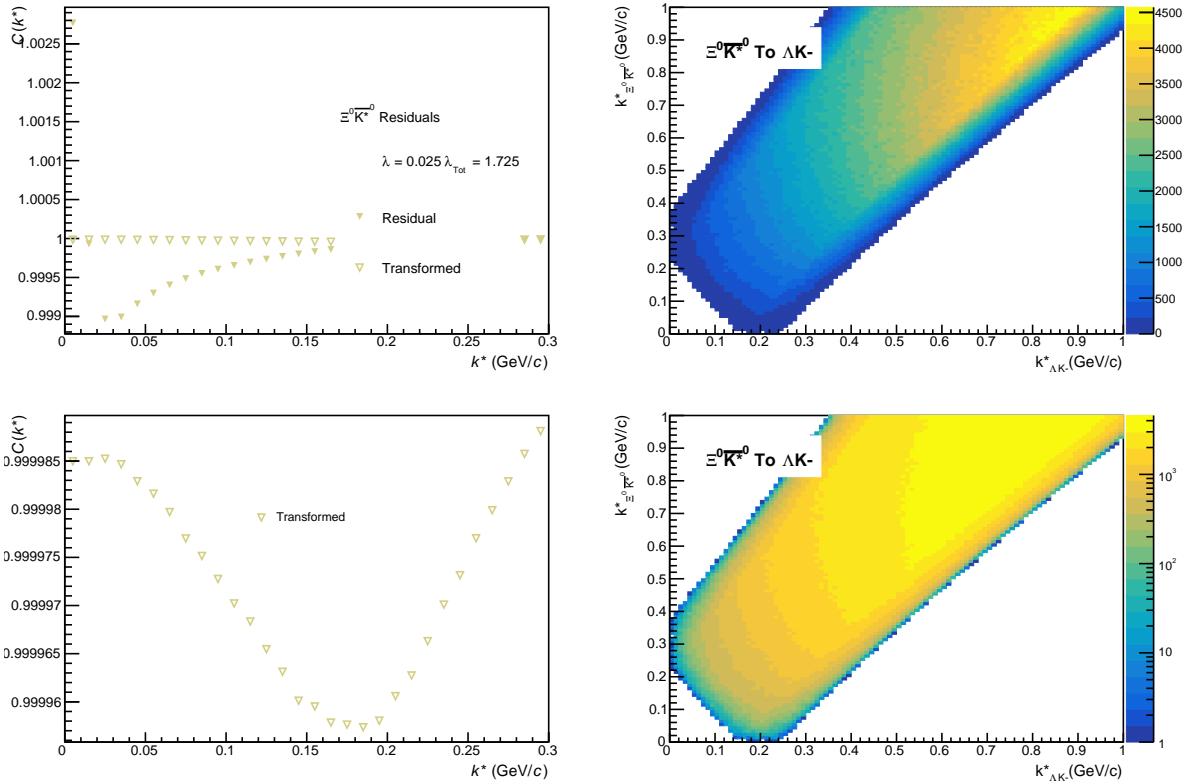


Fig. 73: Residuals: $\Lambda \bar{K}^0$ to ΛK^- (0-10% Centrality)


Fig. 74: Residuals: $\Sigma^0 \bar{K}^{*0}$ to ΛK^- (0-10% Centrality)

Fig. 75: Residuals: $\Xi^0 \bar{K}^{*0}$ to ΛK^- (0-10% Centrality)

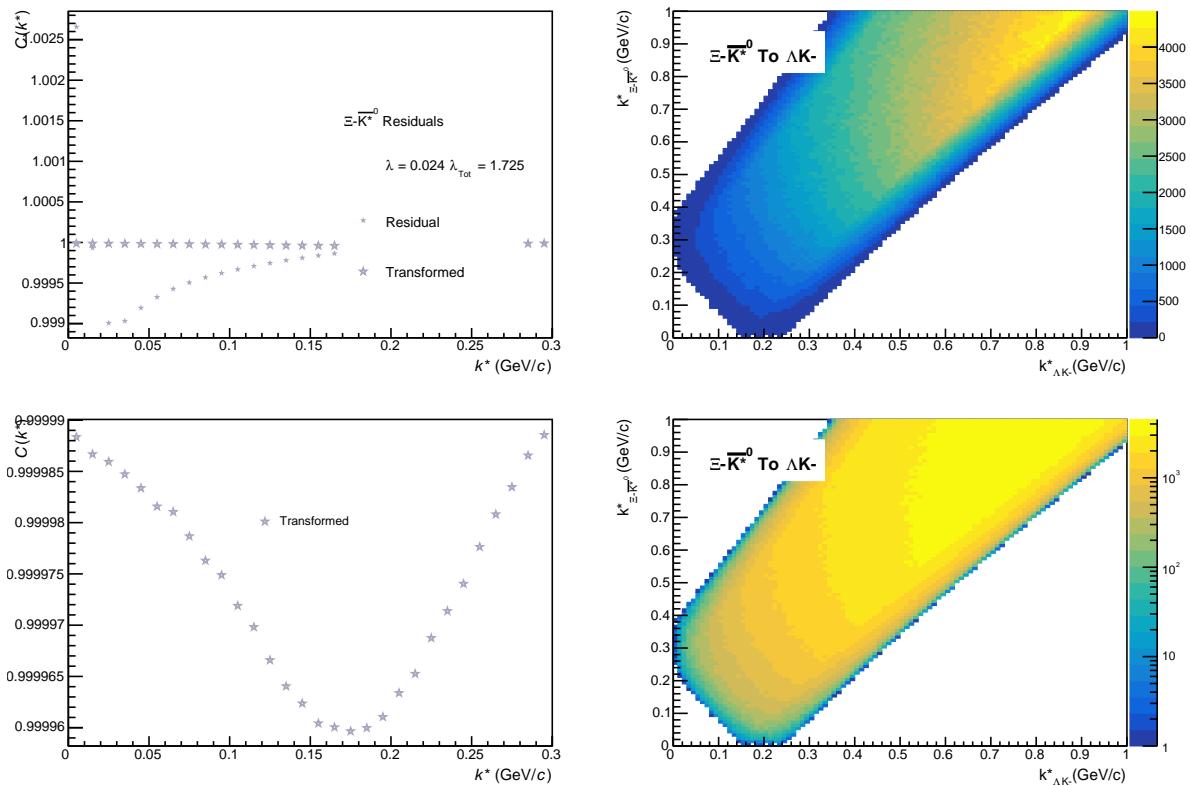


Fig. 76: Residuals: $\Xi^- \bar{K}^{*0}$ to ΛK^- (0-10% Centrality)

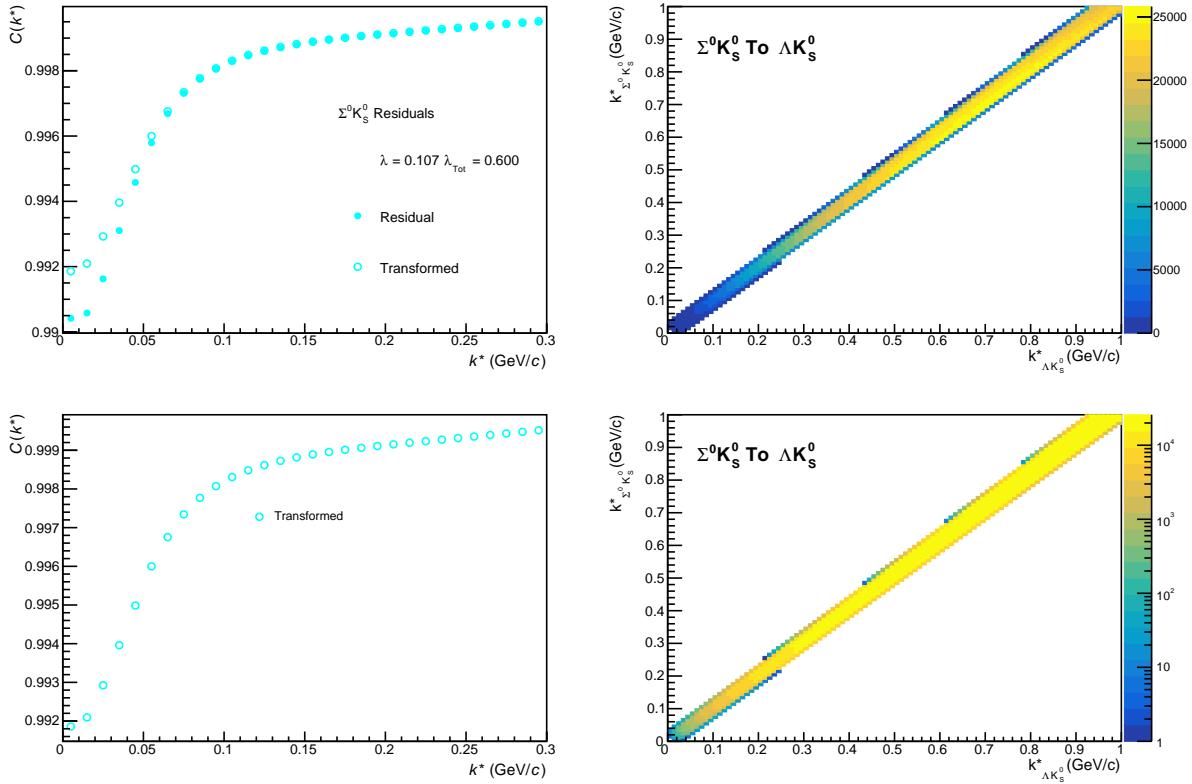
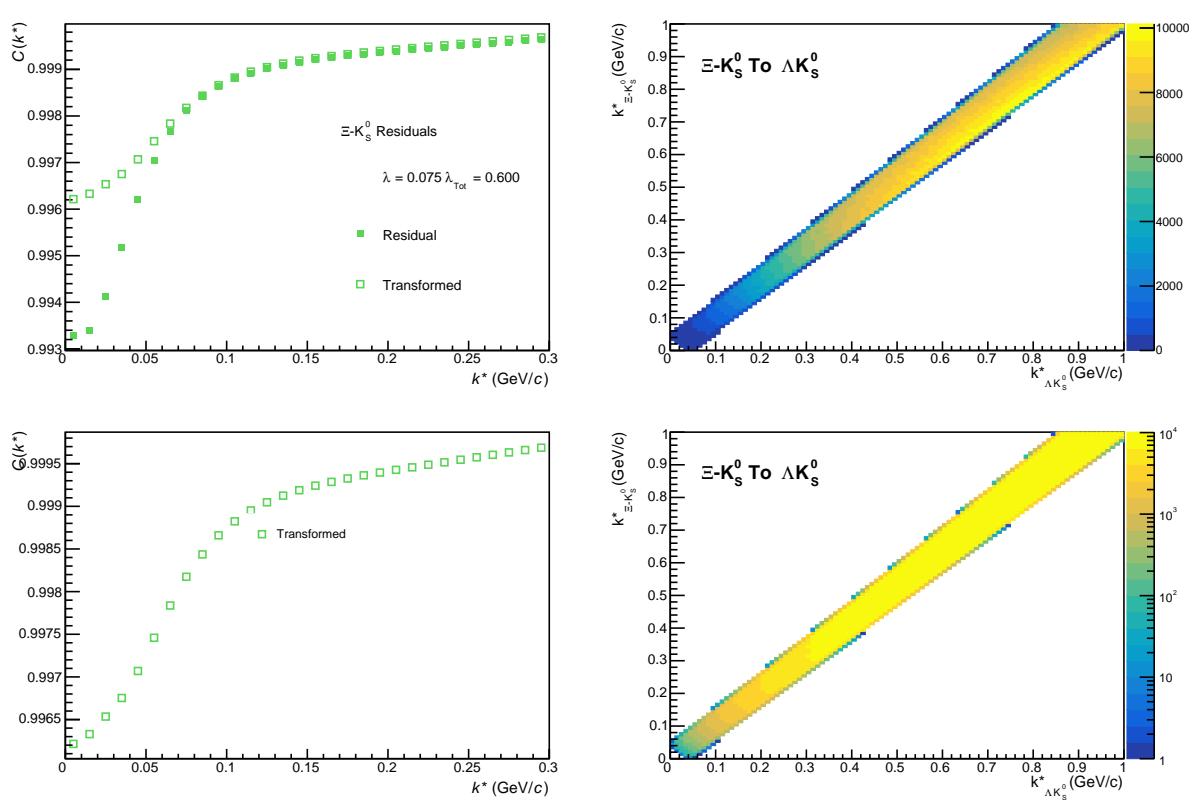
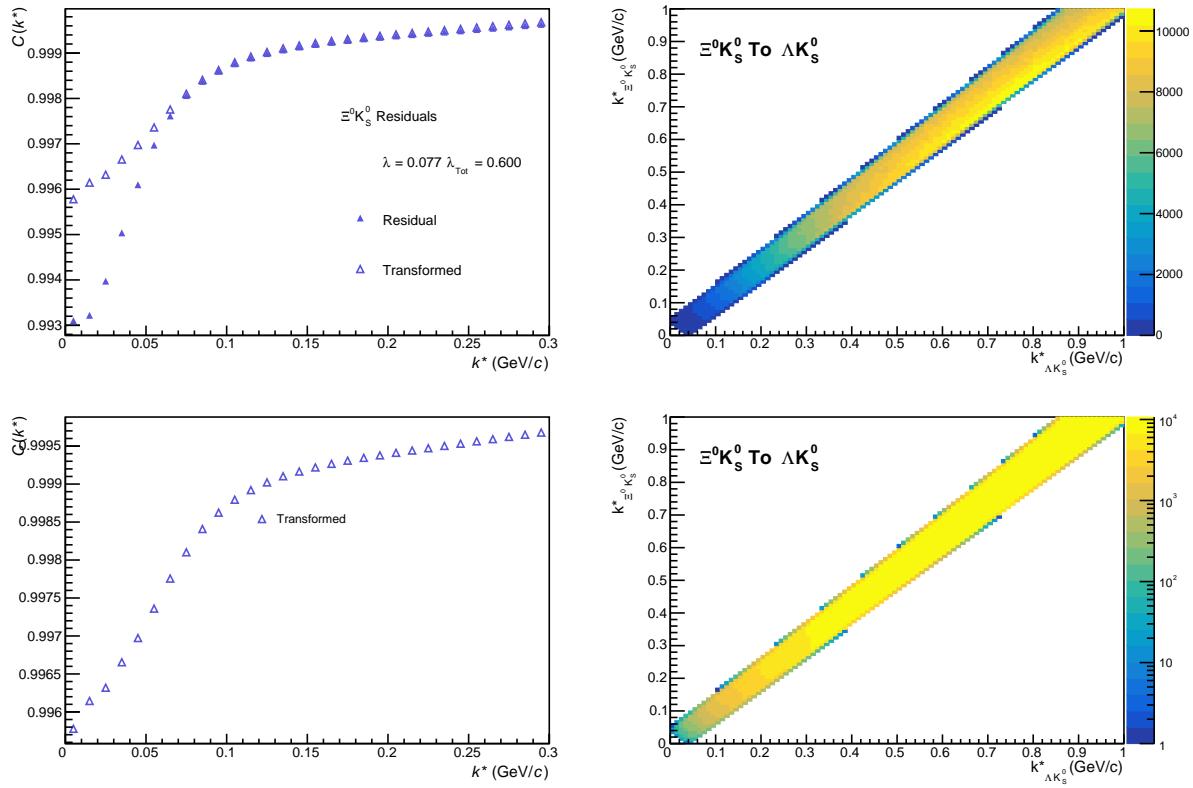
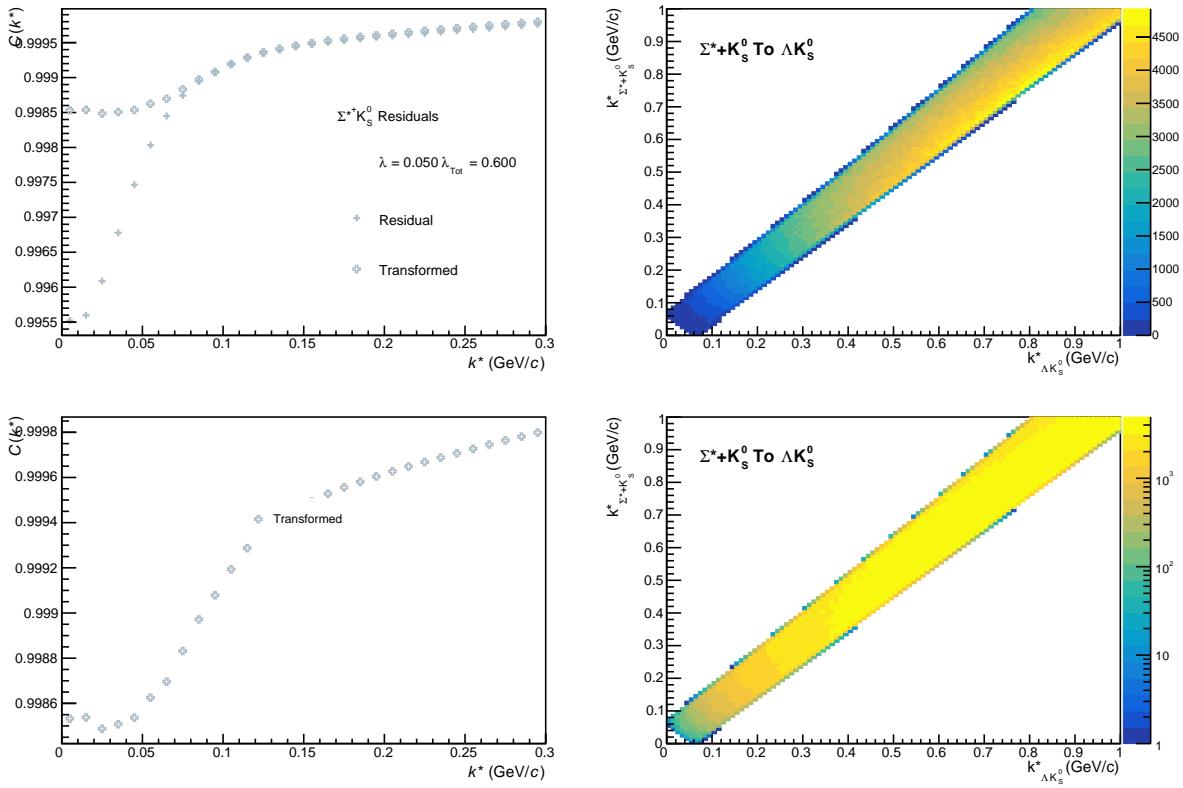
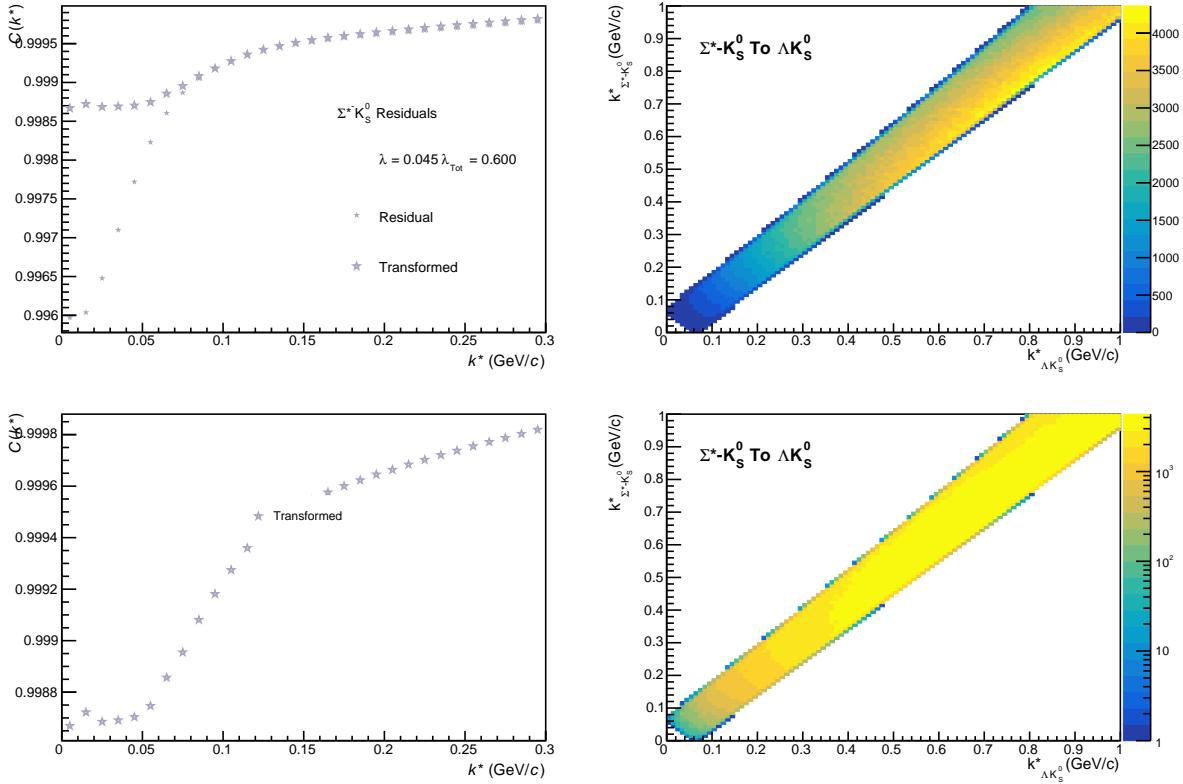
833 9.1.3 ΛK_S^0 Residuals


Fig. 77: Residuals: $\Sigma^0 K_s^0$ to ΛK_s^0 (0-10% Centrality)




Fig. 80: Residuals: $\Sigma^* + K_s^0 \rightarrow \Lambda K_s^0$ (0-10% Centrality)

Fig. 81: Residuals: $\Sigma^* - K_s^0 \rightarrow \Lambda K_s^0$ (0-10% Centrality)

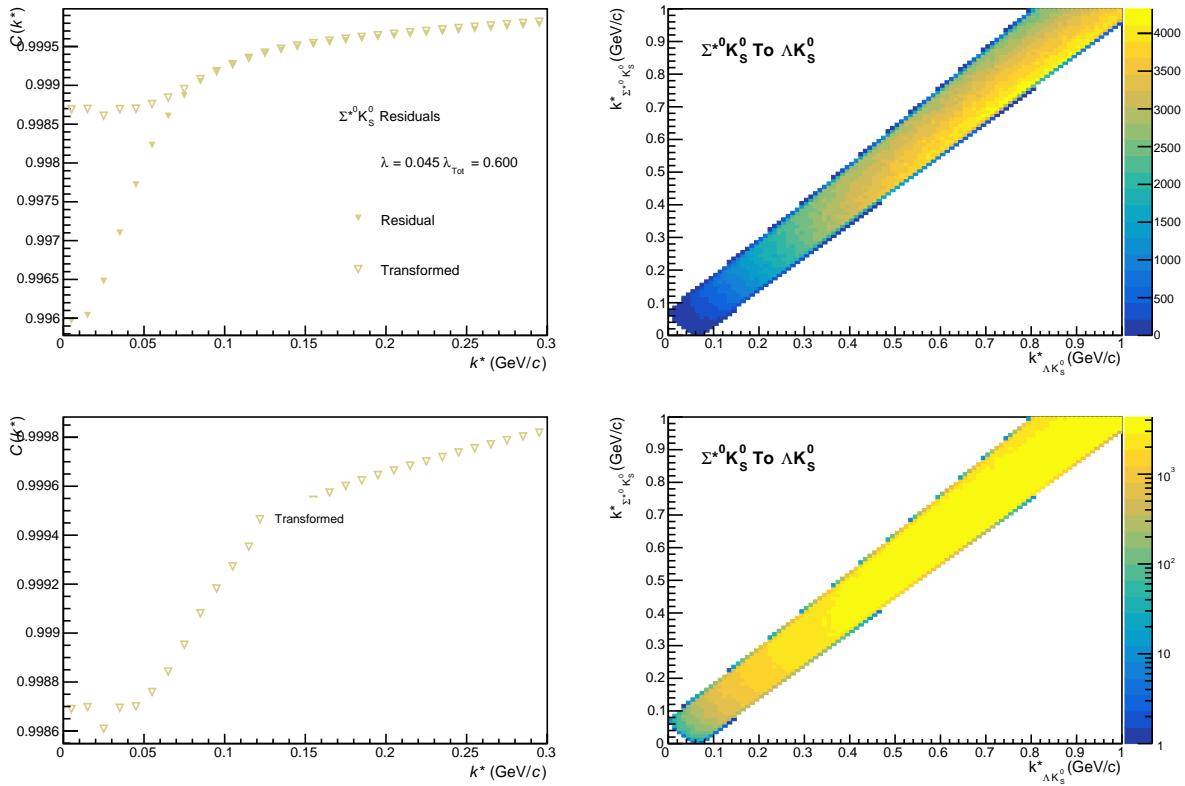


Fig. 82: Residuals: $\Sigma^{*0} K_S^0$ to ΛK_S^0 (0-10% Centrality)

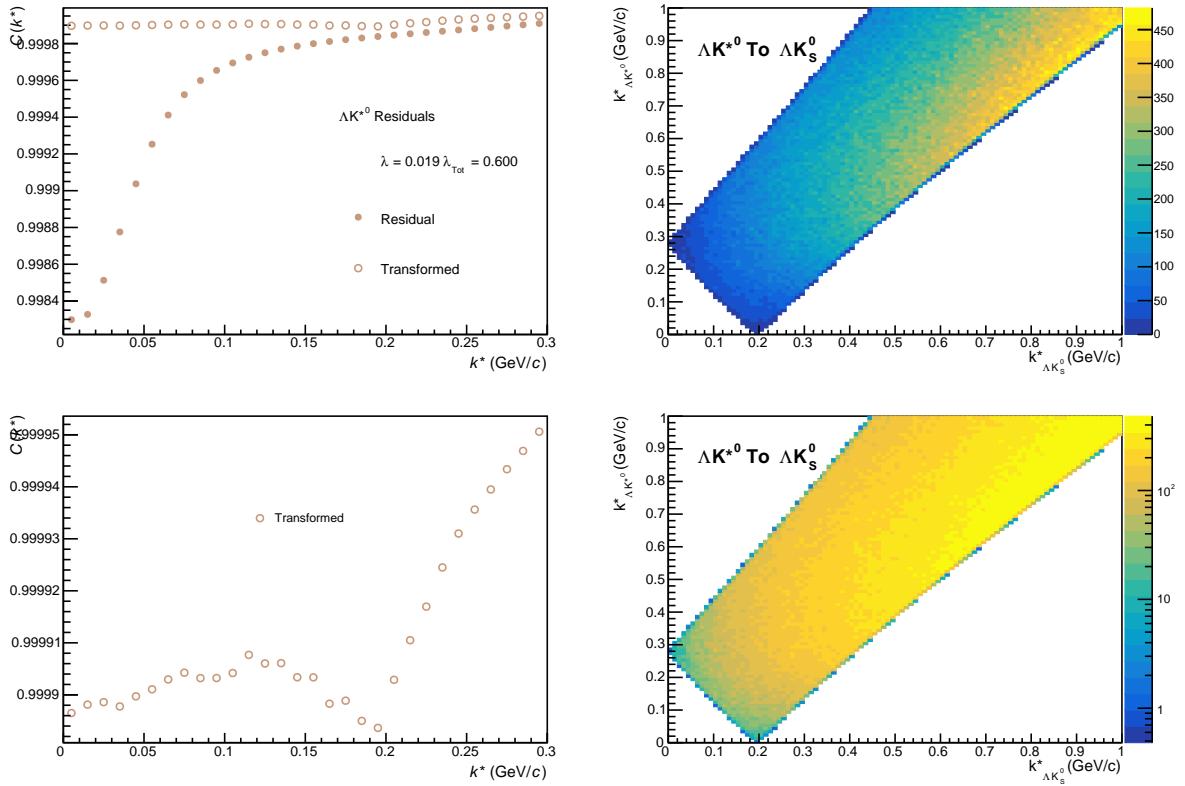
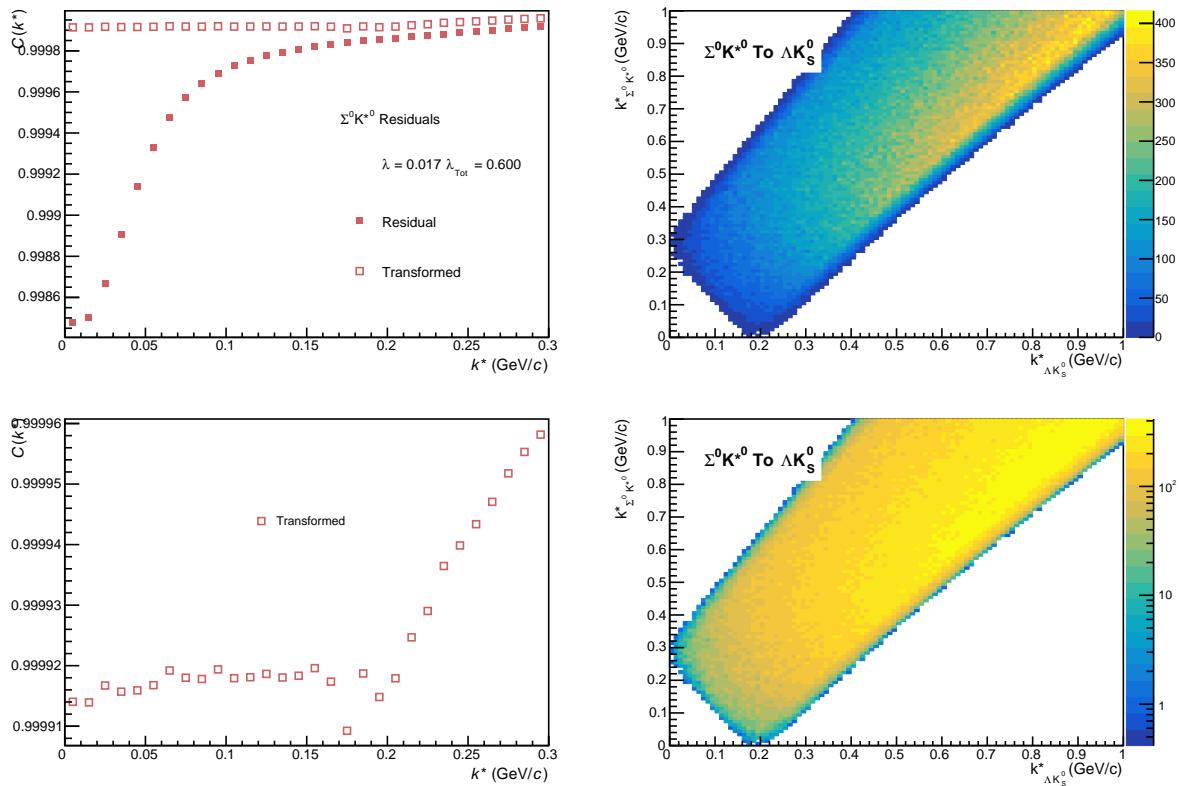
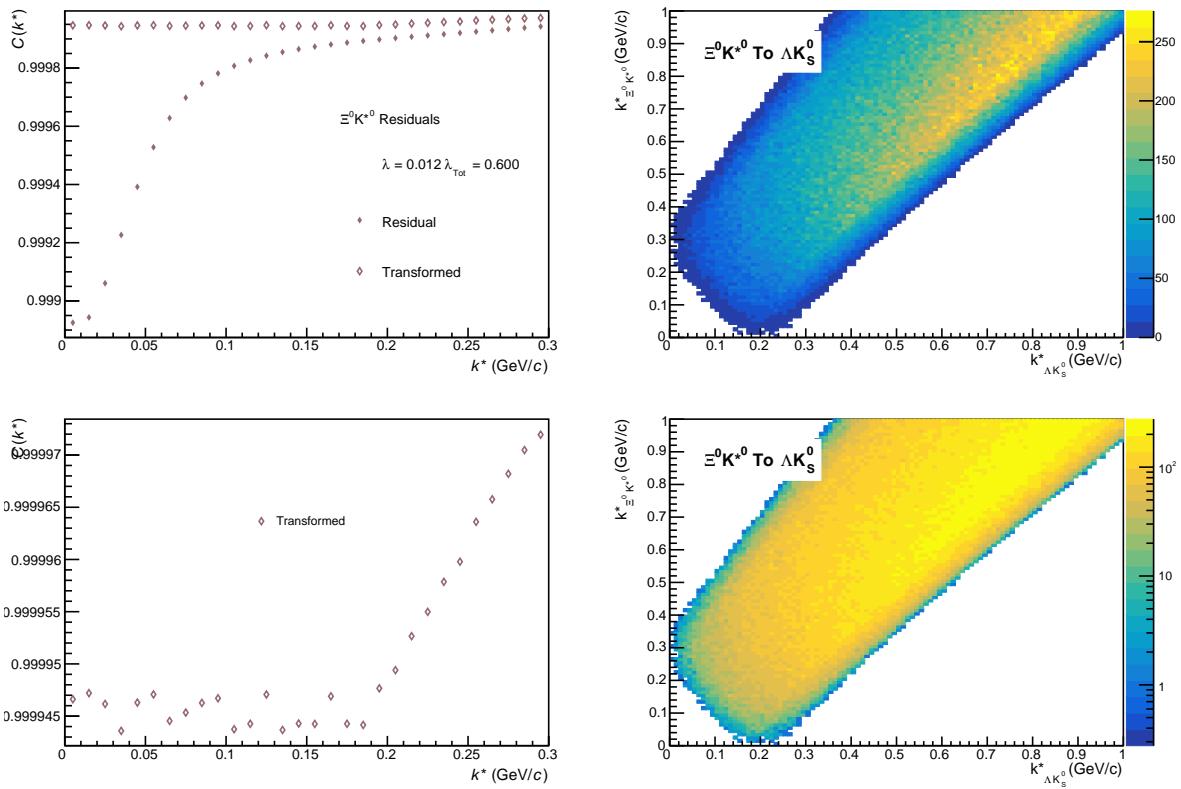


Fig. 83: Residuals: ΔK^{*0} to ΛK_S^0 (0-10% Centrality)


Fig. 84: Residuals: $\Sigma^0 K^{*0}$ to ΛK_S^0 (0-10% Centrality)

Fig. 85: Residuals: $\Xi^0 K^{*0}$ to ΛK_S^0 (0-10% Centrality)

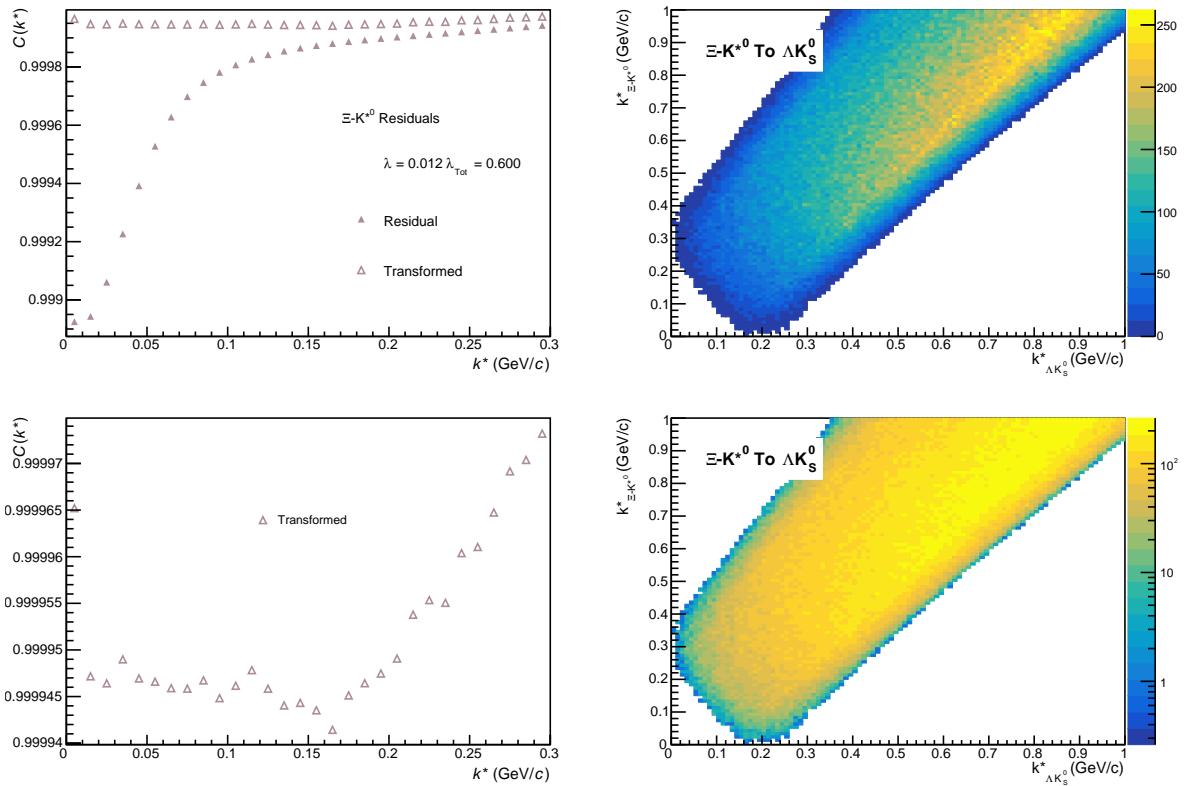


Fig. 86: Residuals: $\Xi^- K^{*0}$ to ΛK_s^0 (0-10% Centrality)

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