

$\Lambda\bar{\Lambda}$ Femtoscopy in Pb-Pb collisions at 2.76 TeV

**Update:
Non-femtoscopic
background, TERMINATOR,
Stavinsky method, etc.**

Outline

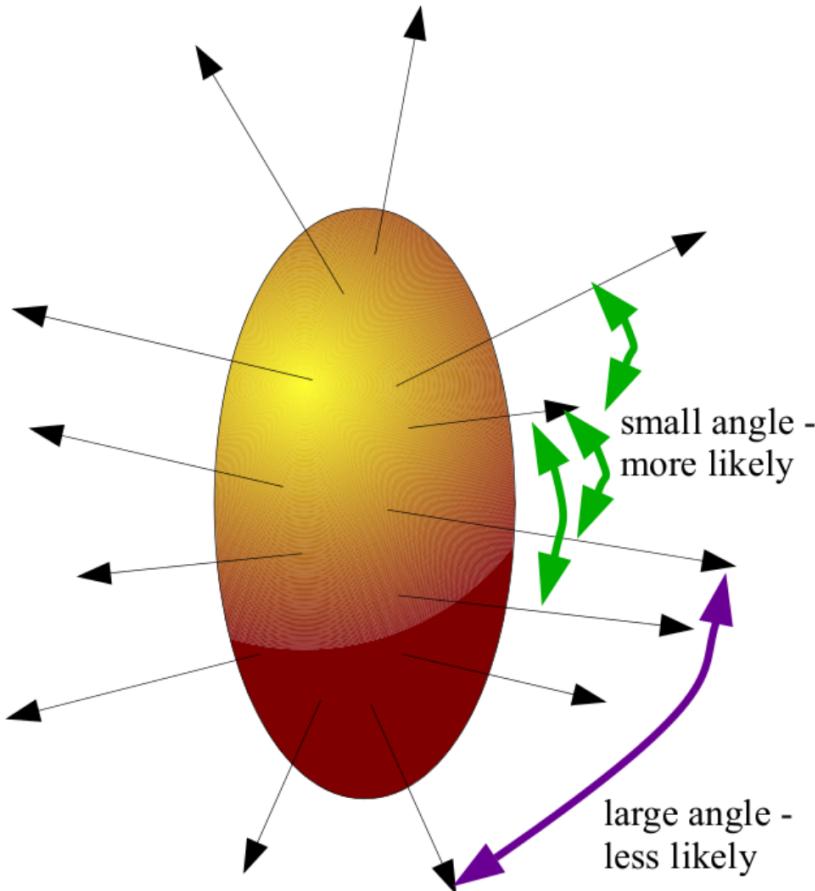
- Significant non-femtoscopic, non-flat background observed in all Cfs at large k^*
 - Increases with decreasing centrality
 - Same amongst all ΛK^{ch} pairs
 - More pronounced for ΛK_s^0 system
- Suggested effect is due primarily to particle collimation associated with elliptic flow
 - Background results from mixing events with unlike event-plane (EP) angles
 - A Kisiel, *Acta Physica Polonica B*, 48
- How does the background behave at low k^* ?
 - How should we handle this contribution in the fit?

Main Points

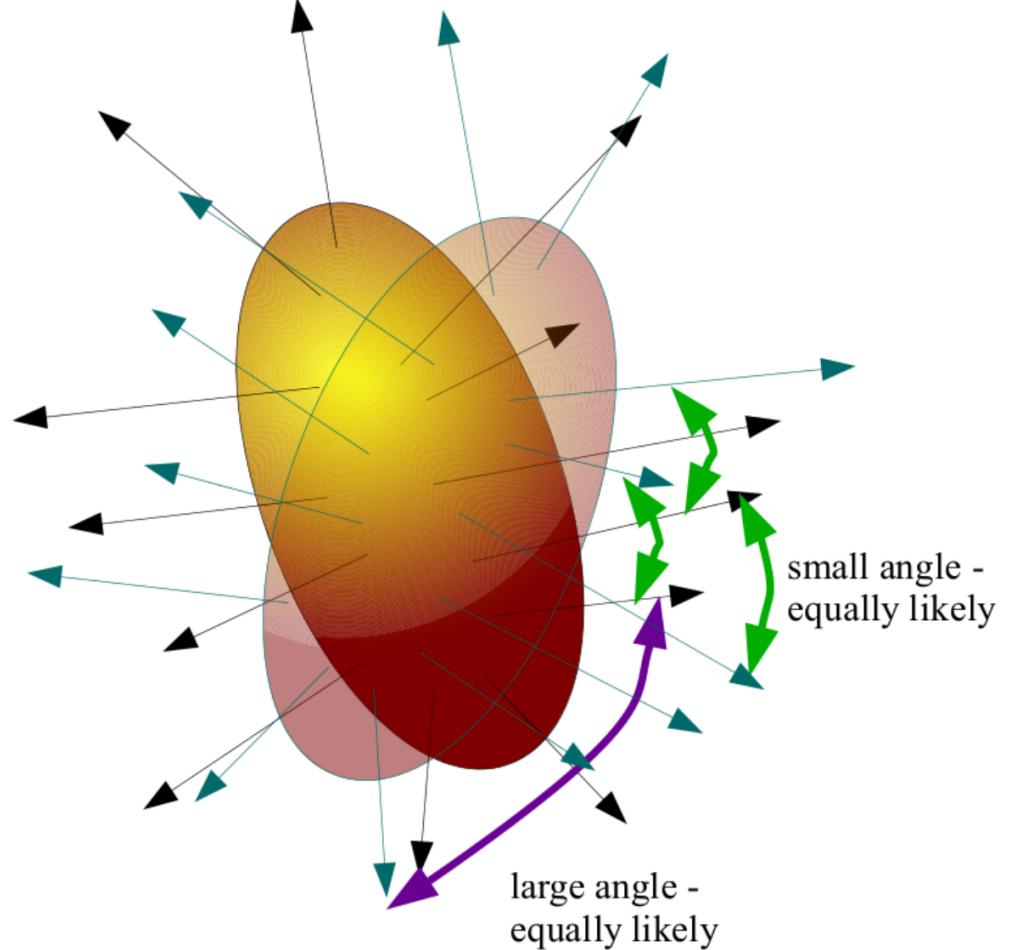
- TERMINATOR does a good job of matching the observed backgrounds
- Stavinsky method does a good job of ridding the experimental data of the backgrounds

Background from elliptic flow

- Same event (signal)

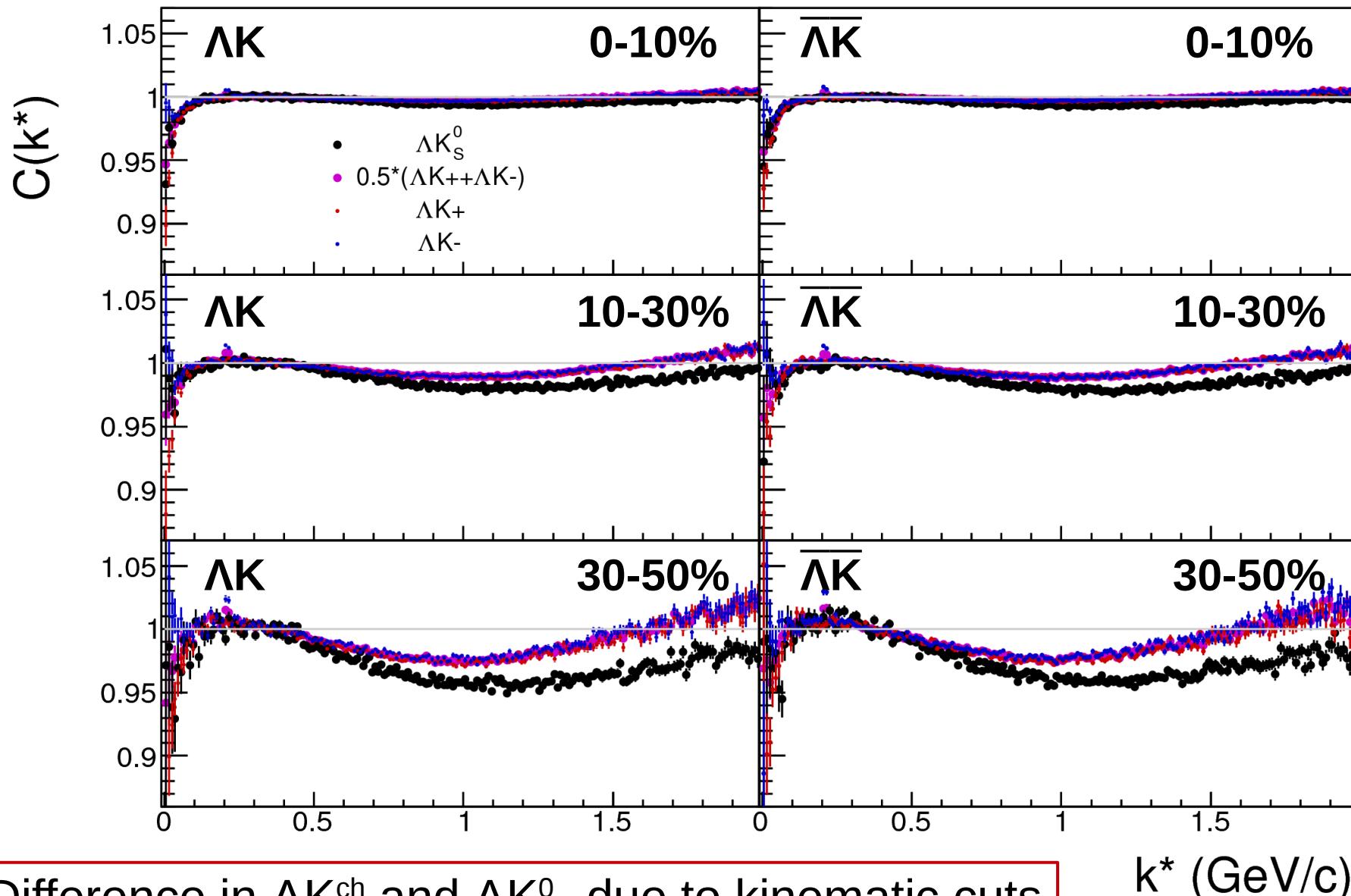


- Mixed events (background)



- In “mixed” sample large- k^* pair are relatively enhanced (resulting in negative correlation function slope)

All Cfs out to large k^*



➤ Difference in ΛK^{ch} and ΛK^0_s due to kinematic cuts

$k^* (\text{GeV}/c)$

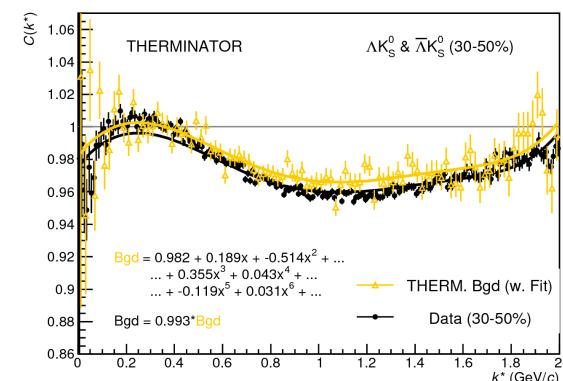
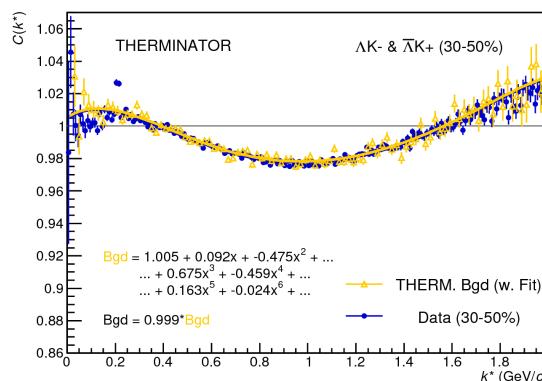
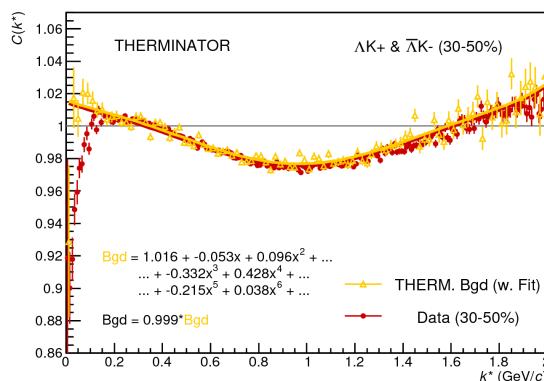
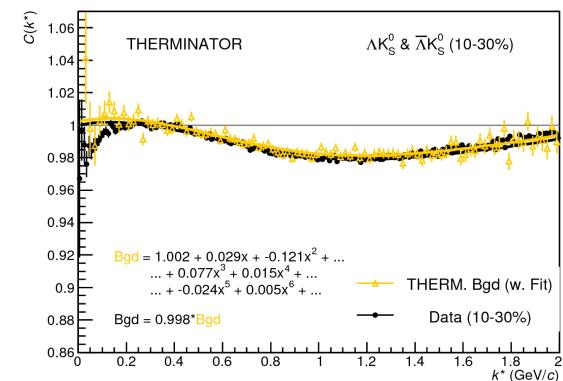
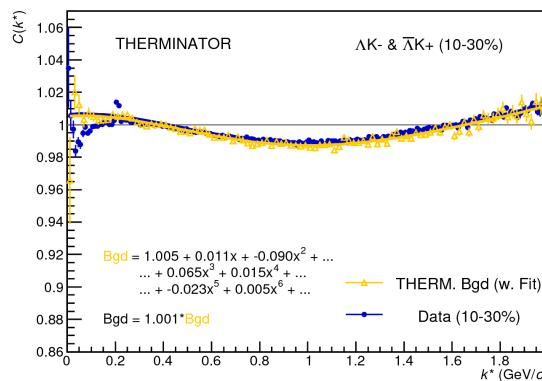
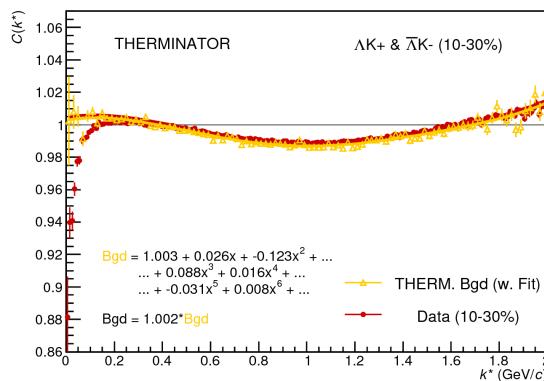
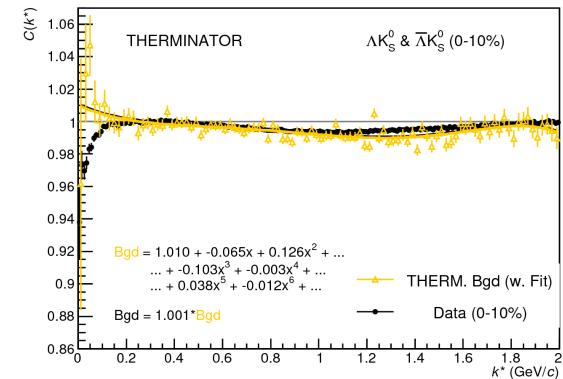
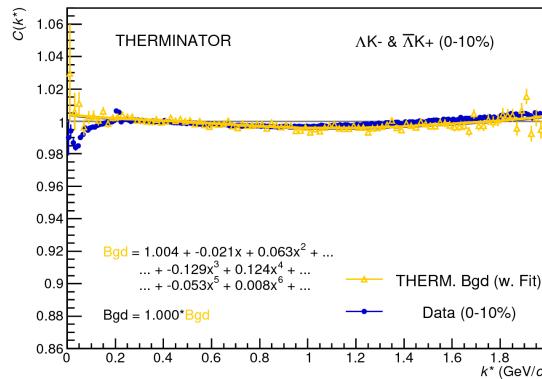
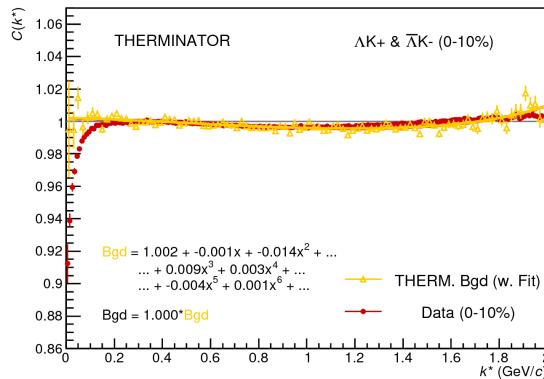
Background Treatment

- **Ideal world (1):** rotate events to align EP angles
 - Not applicable: azimuthal angle acceptance not perfectly uniform and finite EP resolution
- **Ideal world (2):** bin events in EP angle, and only mix events within a given bin
 - Not applicable: finite EP resolution
 - Slight decrease in background observed when using EP bin size = $\pi/8$ (**BACKUP s.32**)
 - No additional reduction observed when using bin size = $\pi/16$
- **Real world:**
 - (a) account for the background in our fit
 - THERMINATOR model or linear fit
 - (b) eliminate background (Stavinsky method)

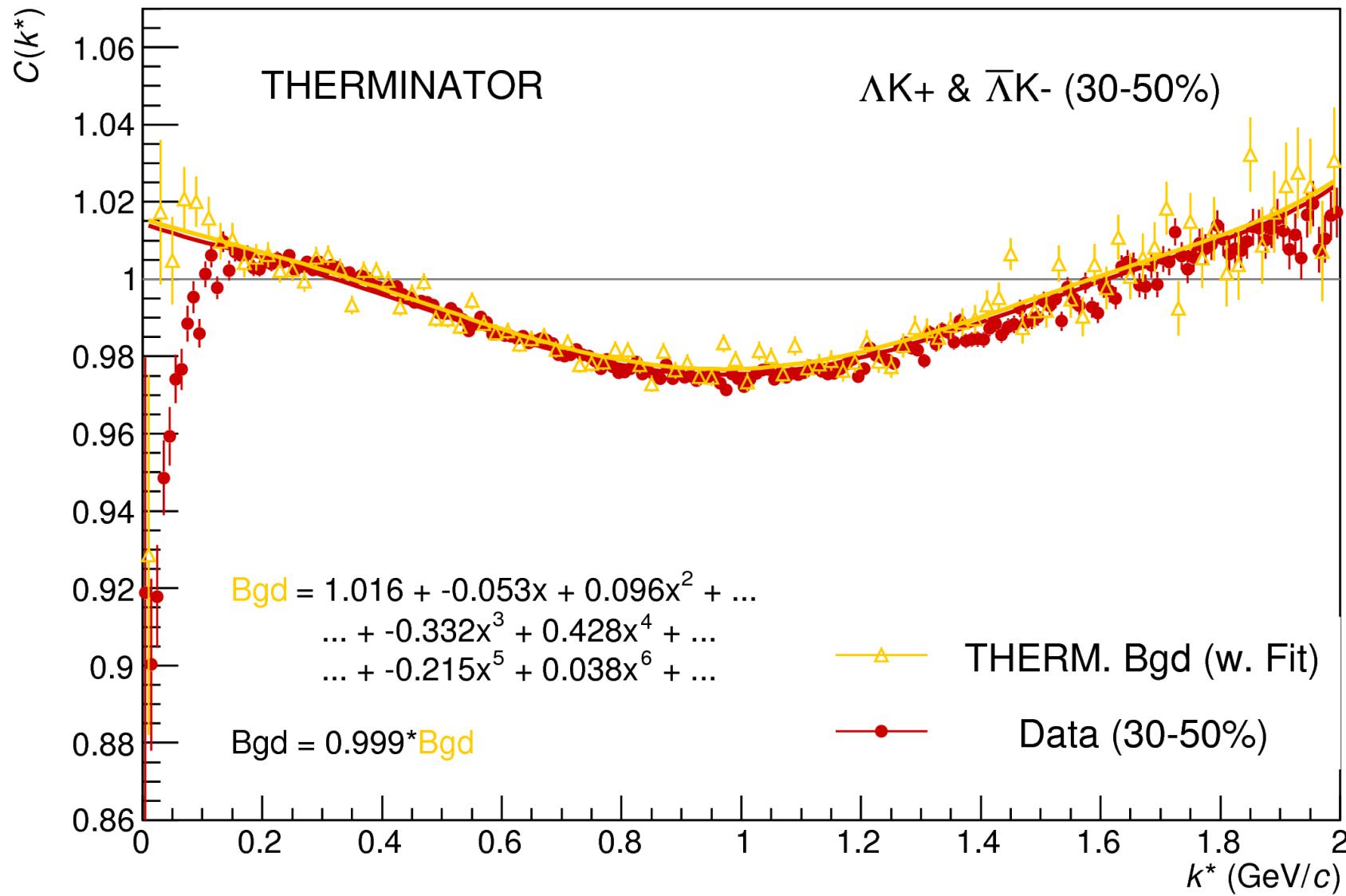
Background with **THERMINATOR**

- By default, all $\Psi_{EP} = 0^\circ$
 - i.e. all EPs aligned, and no background observed
- Remedy: Rotate events by a random angle to simulate experiment
 - i.e. rotate momenta and positions of all particles in an event by a common, random, angle
- After rotation THERMINATOR matches data background very well

THERM vs Data (ALL)

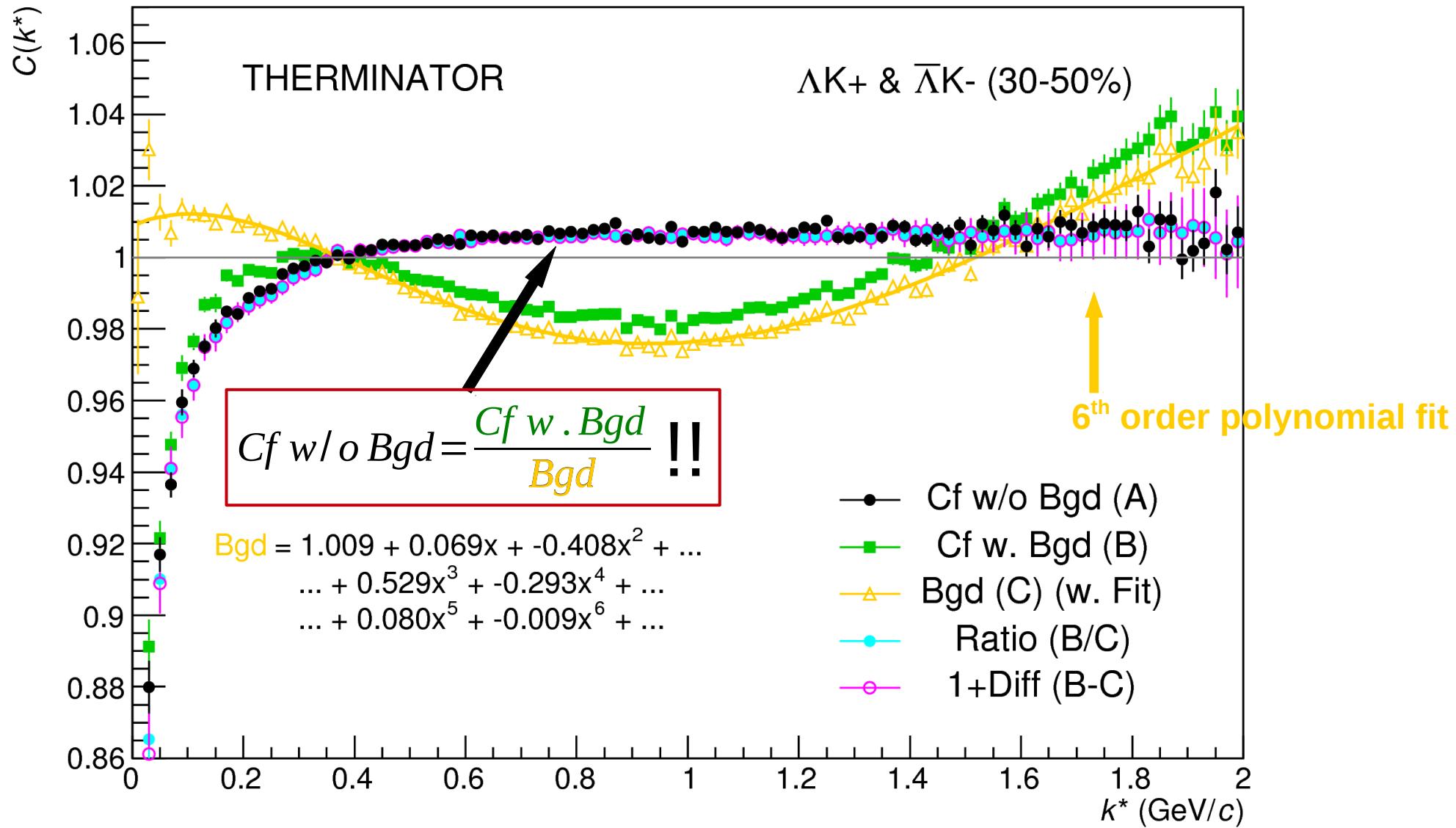


THERM vs Data ($\Lambda K+$ 30-50%)



THERMINATOR

Simulation Only: Interaction achieved by assuming scattering parameters, and weighting the numerators in the simulation



- From the previous slide:

$$Cf_{w/o\,Bgd} = \frac{Cf_w \cdot Bgd}{Bgd} \quad \rightarrow \quad Cf_{th} = \frac{Cf_{exp}}{F_{Bgd}} \quad \rightarrow \quad Cf_{exp} = Cf_{th} \cdot F_{Bgd}$$

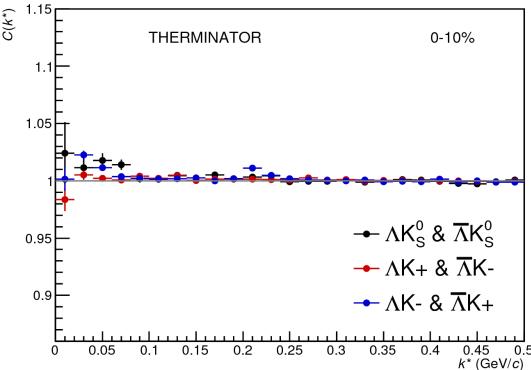
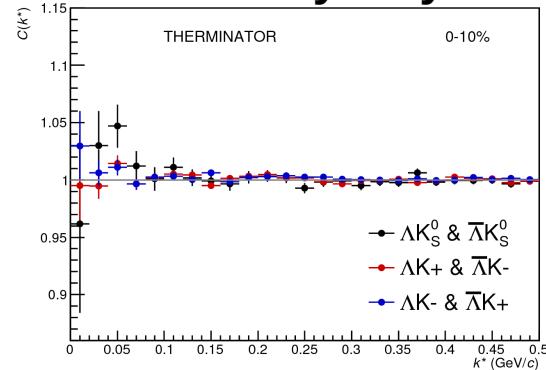
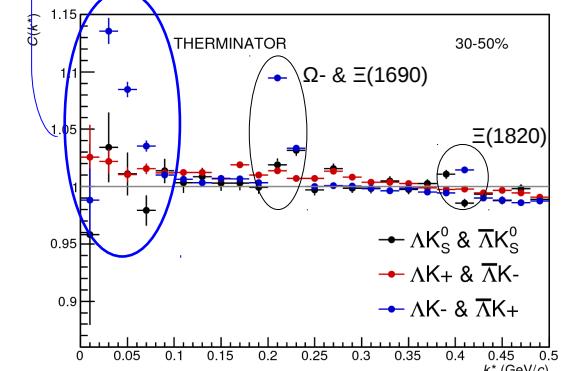
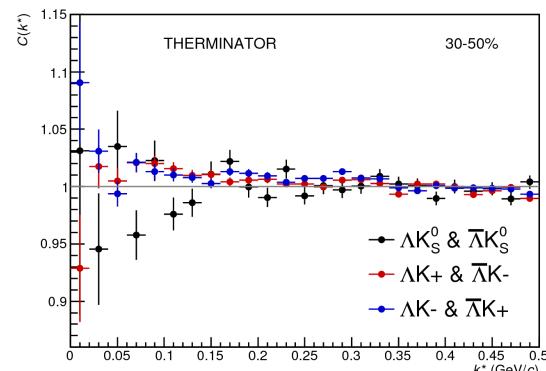
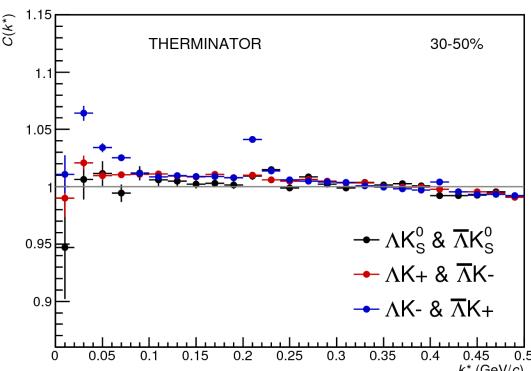
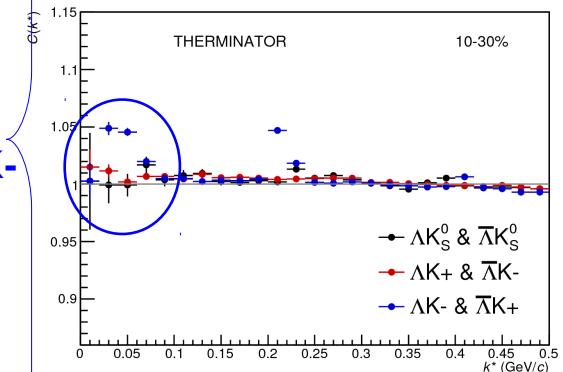
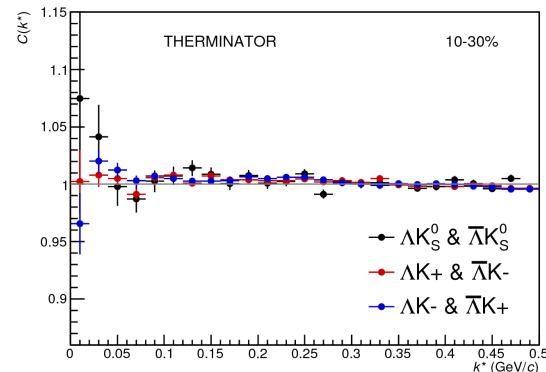
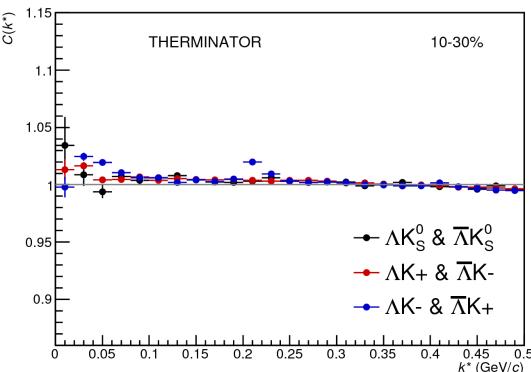
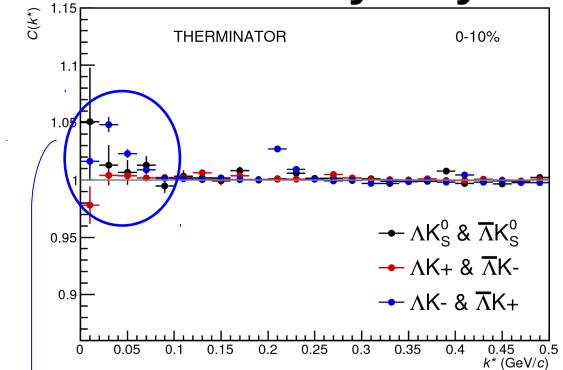
- Proposed fit solution

- (1) Generate THERMINATOR events needed to build backgrounds for all centrality bins
- (2) Before fit: Fit the THERMINATOR background, over all k^* (0-2 GeV/c) to obtain F_{bgd}
 - Adam, in paper, suggests 6th order polynomial
- (3) Scale F_{bgd} to match data
- (4) Keep F_{bgd} constant while fitting over the signal region

THERMINATOR Question

- **Full**
 - no discrimination in origin on Λ or K in pair
- **PrimaryOnly**
 - both particles must be identified as primary by THERMINATOR
- **SecondaryOnly**
 - both particles must NOT be identified as primary by THERMINATOR
- **Who cares?**
 - In ΛK^0_S and ΛK^+ cases, the background looks roughly the same regardless of subset used
 - For ΛK^- case, background at low- k^* looks very different between PrimaryOnly and SecondaryOnly
 - ➔ Large enhancement at low- k^* when using SecondaryOnly subset
 - ➔ Effect leaks somewhat into Full set

Subset Comparisons: TERMINATOR Backgrounds

Full

PrimaryOnly

SecondaryOnly


Enhancement
at low- k^* in ΛK^-

Any ideas what
causes this?

Stavinsky Method

Stavinsky Method

- Do not use mixed-event pairs for background
- Instead, use same-event pairs with one particle rotated by 180° in the transverse plane
 - Rid pairs of any femtoscopic correlations
 - Maintains correlations due to **elliptic flow (v_2)**
 - Due to symmetry of the flow
 - Does not eliminate contributions from higher order flow
- In figures/slides, numerators built with this method identified as Num_{Stav}

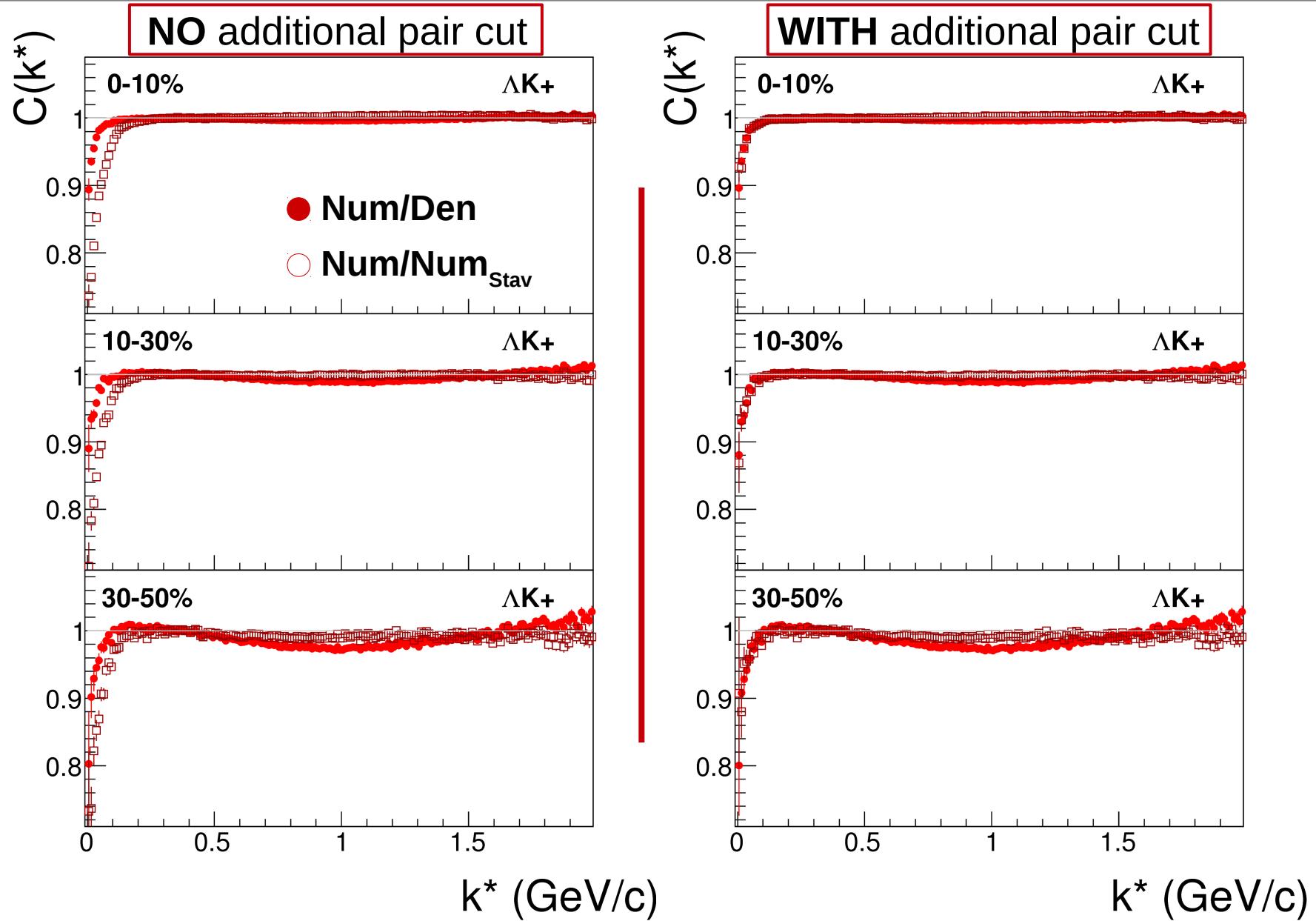
Issue

- For ΛK^+ especially, at low- k^* , same-event Num_{Stav} distribution looks very different from mixed-event Den distribution (**BACKUP s.33**)
 - Expect high- k^* behavior to differ, as we hope this method will eradicate non-flat background
- Not much difference for ΛK^- or ΛK^0_s (**BACKUP s.34-35**)
- ΛK^+ and ΛK^- Den distributions look very different (**BACKUP s.36**)
 - Initially, very surprising, and maybe even troubling
- This difference, and issue, is due to the pair cut
 - Average separation cut
- When pair cut is turned off
 - ΛK^+ and ΛK^- Den distributions look the same (**BACKUP s.37**)
 - ΛK^+ Num_{Stav} agrees with Den at low- k^* (**BACKUP s.38**)

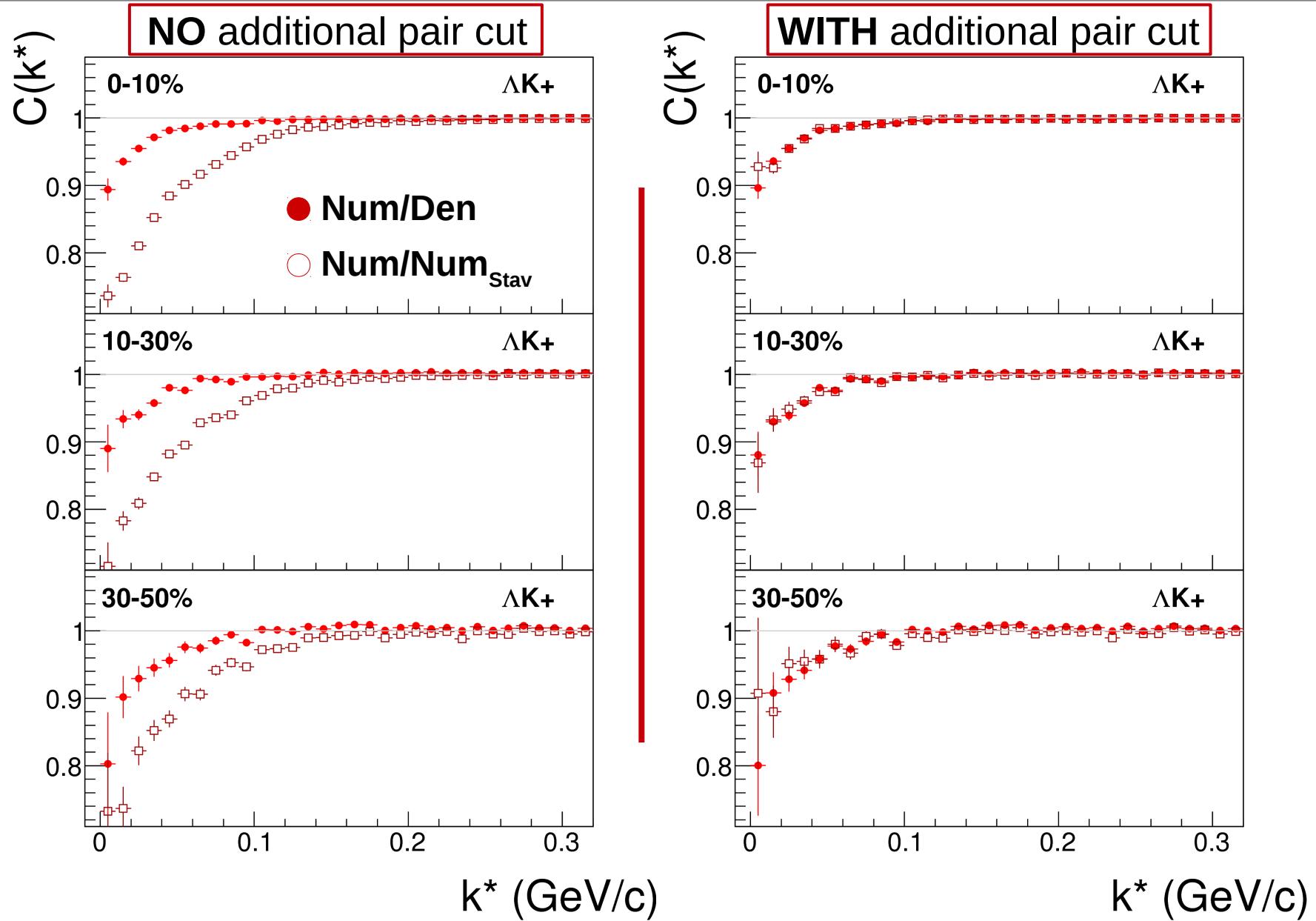
Solution

- When using the Stavinsky method, after particle in pair is rotated, the new pseudo-pair should be run through the pair cut used in the analysis
 - **Ideal world:** pair cut only remove truly bad pairs resulting from splitting and merging effects
 - **Real world:** pair cut throws out some of the good with the bad
 - For pseudo-pairs, also need to include this loss of “good” pairs → must also use pair cut
- Achieved by simply rotating nominal TPC points of tracks by 180° in transverse plane
- Without doing this, the Stavinsky method differs greatly from usual Num/Den method
- After implementing, the two methods agree at low- k^*
 - $\Lambda K + \text{Num}_{\text{Stav}}$ agrees with Den at low- k^* (**BACKUP s.39**)

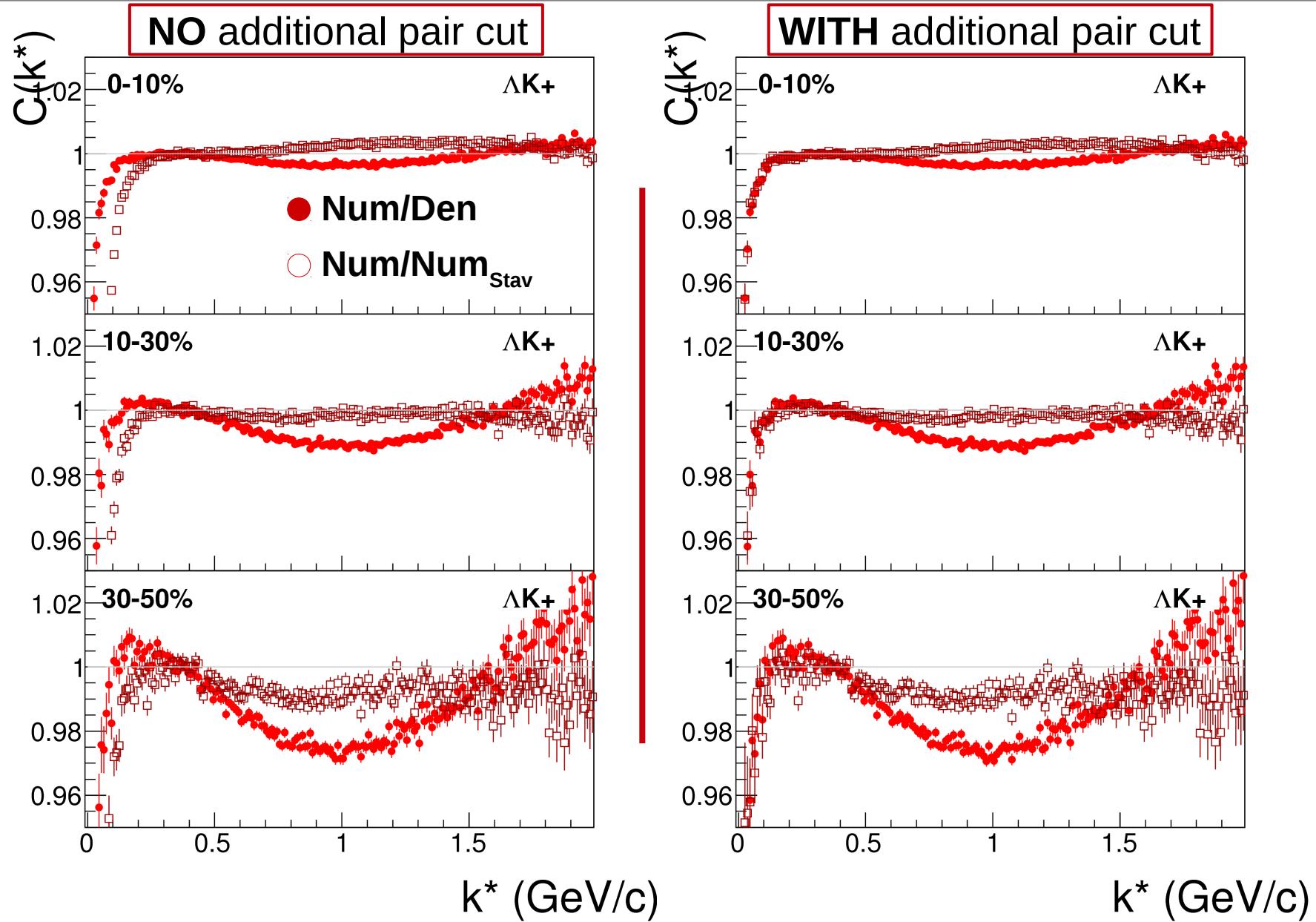
Effect of Additional Pair Cut



Effect of Additional Pair Cut

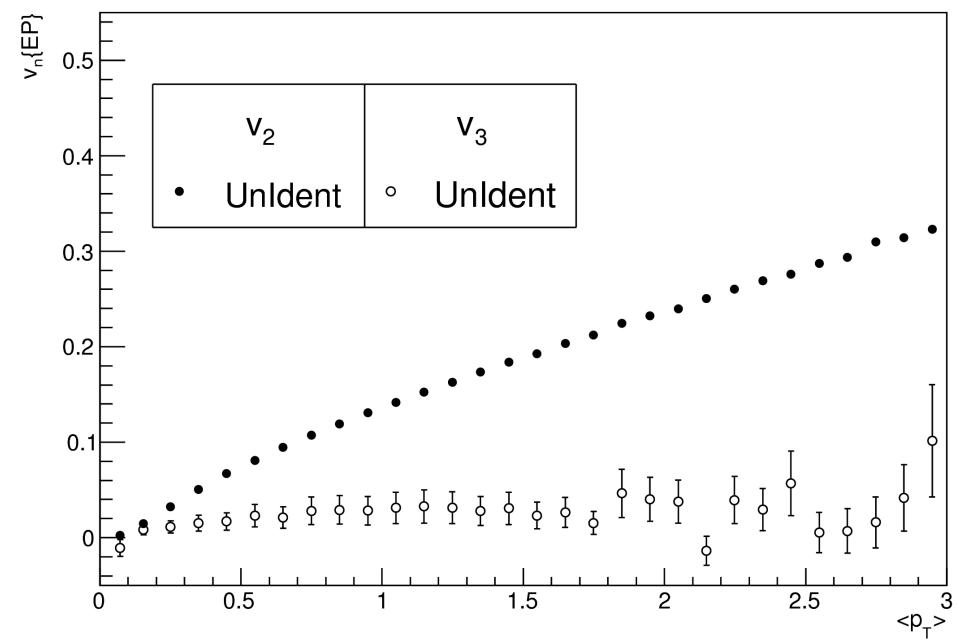
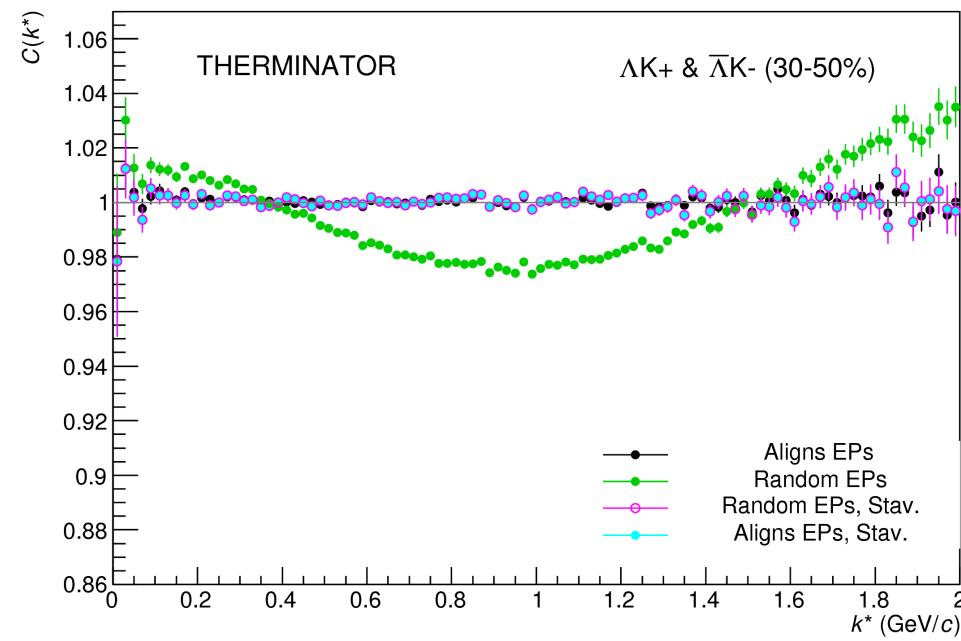


Effect of Additional Pair Cut



Stav. Method with THERM

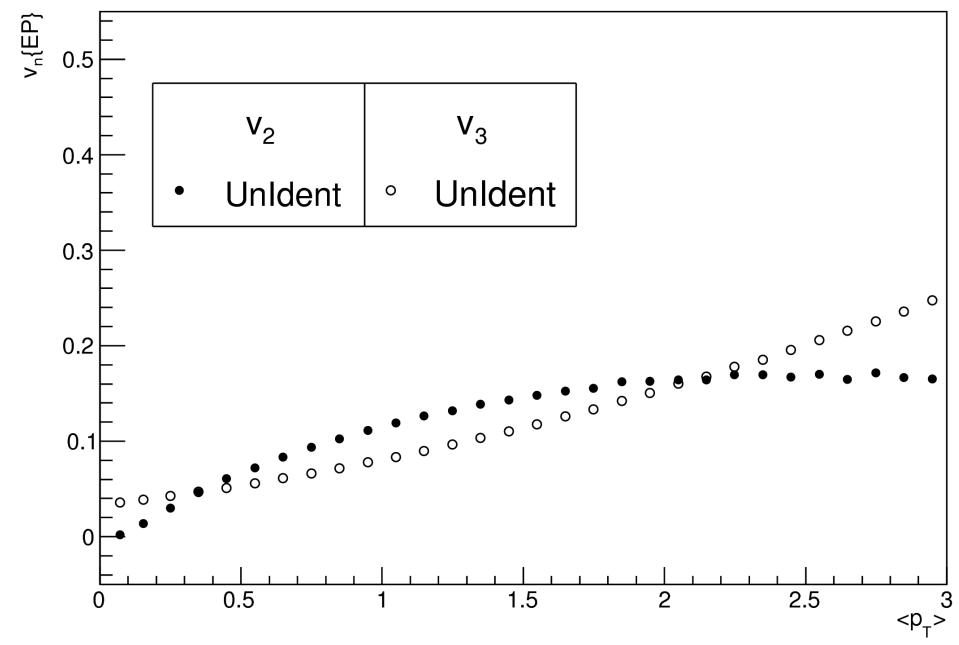
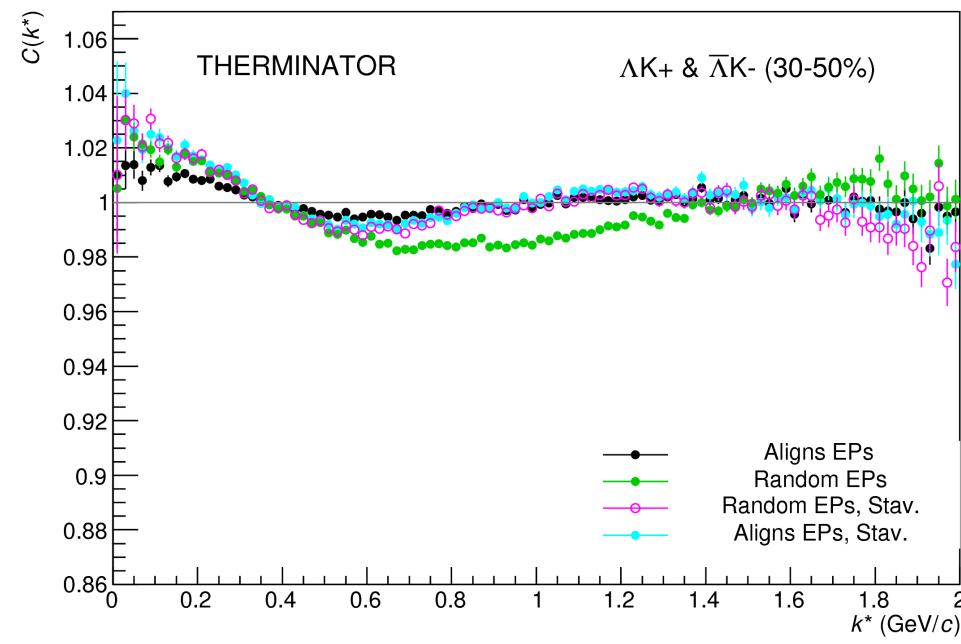
- No v_3 present in THERMINATOR simulation
- EP = Ψ_2



THERM: v_3 added

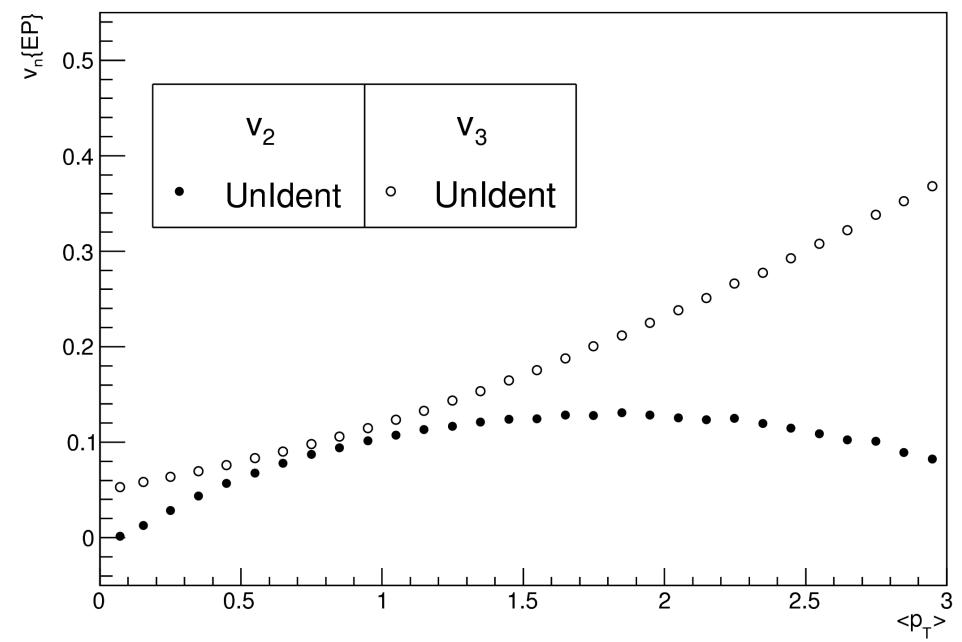
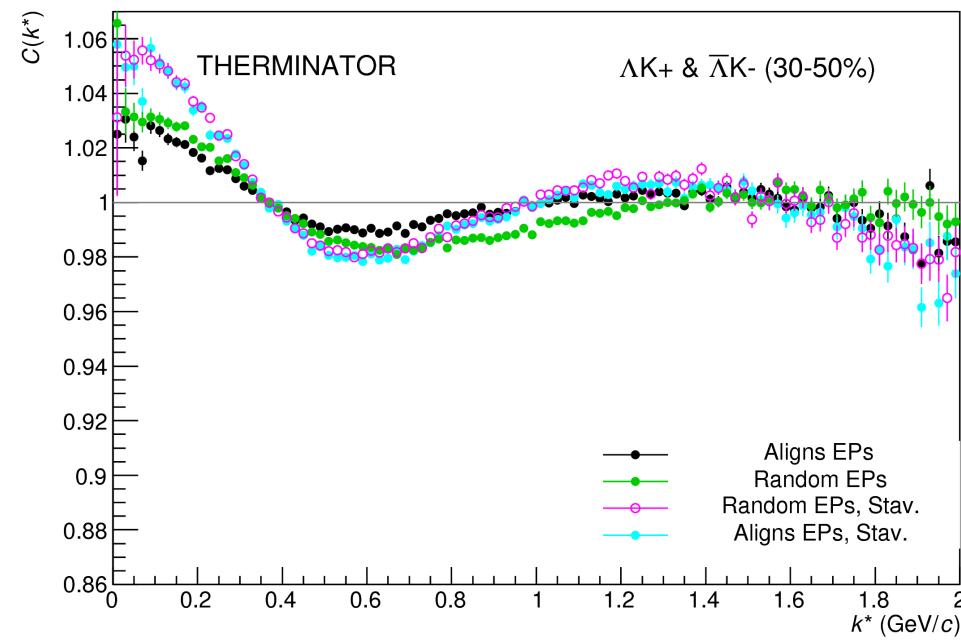
→ Artificially add v_3 signal

→ EP = Ψ_2



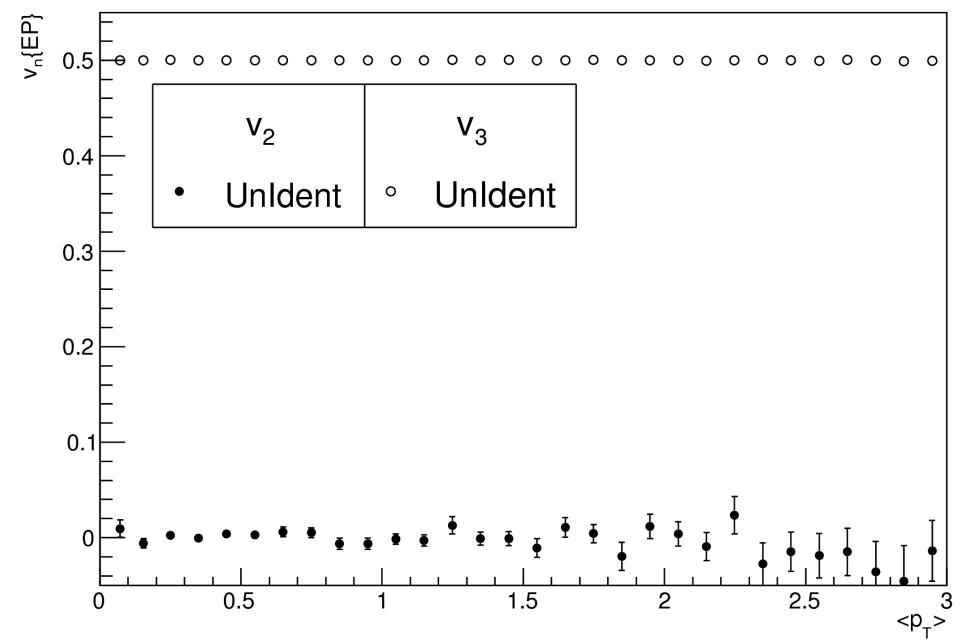
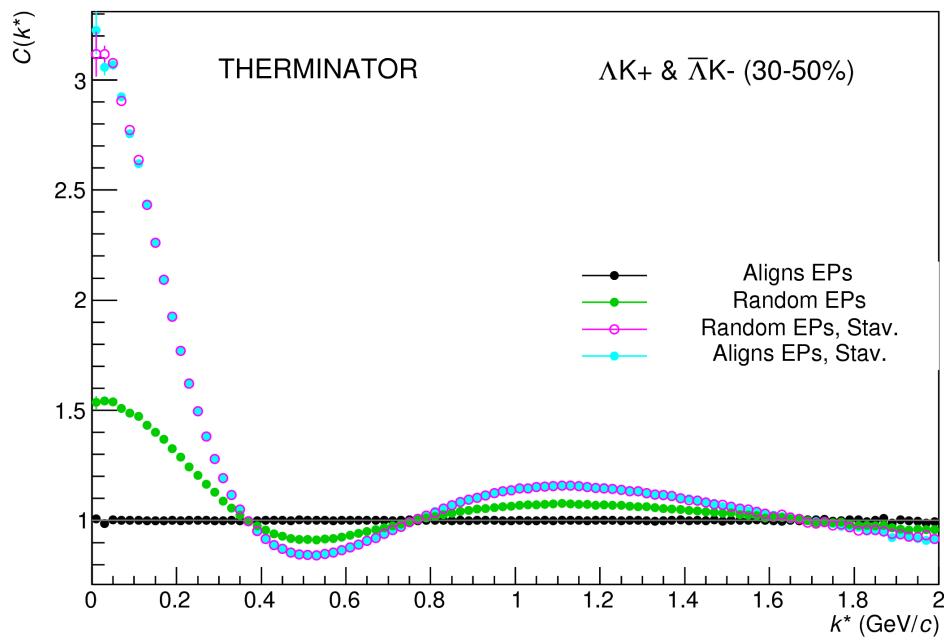
THERM: More v_3 added

- Artificially add MORE v_3 signal
- EP = Ψ_2



THERM: No v_2 , all v_3

- Convert ENTIRE v_2 signal to v_3
- EP = Ψ_3



New Dual Fitter

- Old, single fitter
 - Fit pair with conjugate across all centralities
 - Ex: ΛK^+ with $\bar{\Lambda} K^-$ across (0-10%, 10-30%, 30-50%)
 - All share: $Re[f_0]$, $Im[f_0]$, d_0
 - Like centralities share: R
 - Unique to each: Norm, λ
- New, Dual Fitter
 - Combine all $\Lambda(\bar{\Lambda})K^{ch}$ analyses
 - Radii shared amongst all
 - Possible to share single λ for given centrality bin across all four analyses, ΛK^+ , $\bar{\Lambda} K^-$, ΛK^- , $\bar{\Lambda} K^+$

Comparing Fit Methods

Parameter sharing

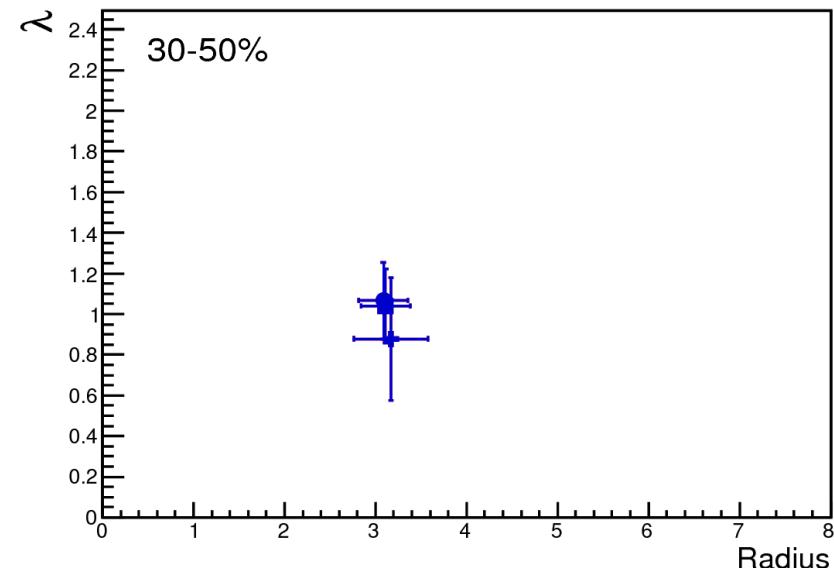
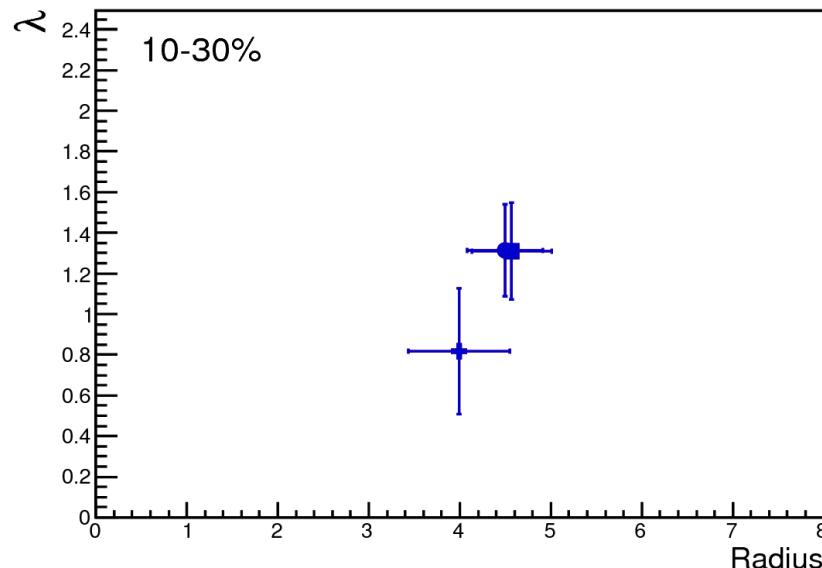
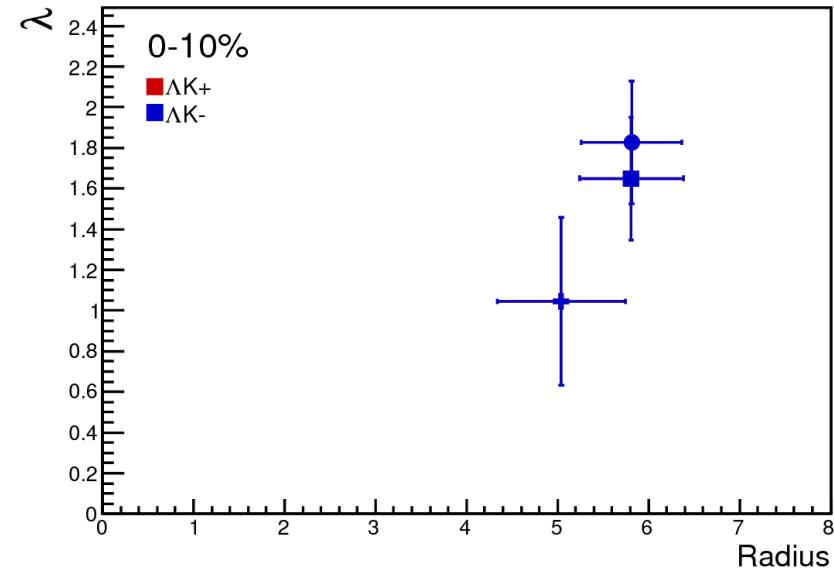
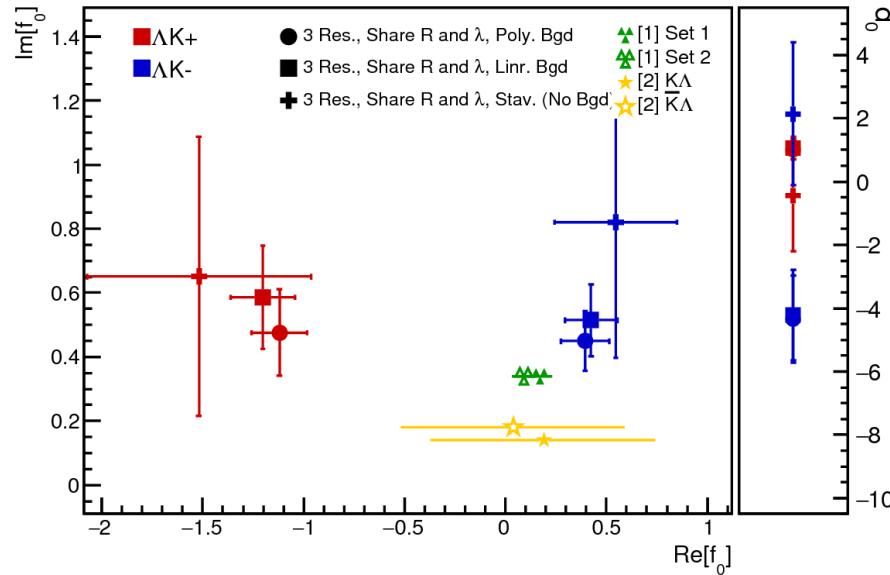
- Shared R
 - Share radii between ΛK^+ (with $\bar{\Lambda} K^-$) and ΛK^- (with $\bar{\Lambda} K^+$) for like centralities
 - Shared $\lambda \rightarrow$ share single λ for each centrality across all [ΛK^+ , $\bar{\Lambda} K^-$, ΛK^- , $\bar{\Lambda} K^+$]
→ 3 total λ parameters
 - Shared λ_{Conj} → share λ for each centrality amongst only pair and conjugate
 - ex. λ_1 for ΛK^+ (with $\bar{\Lambda} K^-$) in 0-10% centrality, λ_2 for ΛK^+ (with $\bar{\Lambda} K^-$) in 0-10% centrality, etc
 - 6 total λ parameters
- Separate R
 - ΛK^+ (with $\bar{\Lambda} K^-$) radii unique from ΛK^- (with $\bar{\Lambda} K^+$)
 - Shared $\lambda \rightarrow$ share λ for each centrality across pair and conjugate (ex. single λ for ΛK^+ with $\bar{\Lambda} K^-$ in 0-10% centrality bin)
 - Separate $\lambda \rightarrow$ each analysis gets unique λ parameter

Background treatments

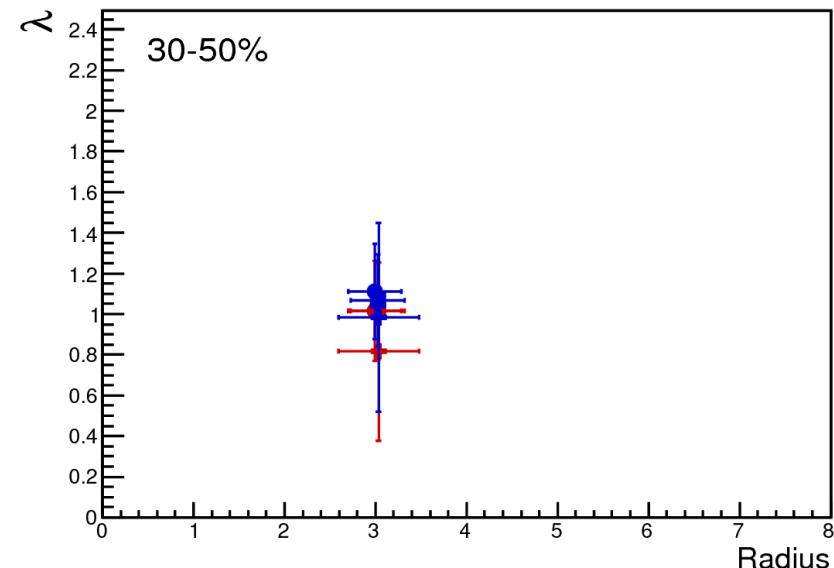
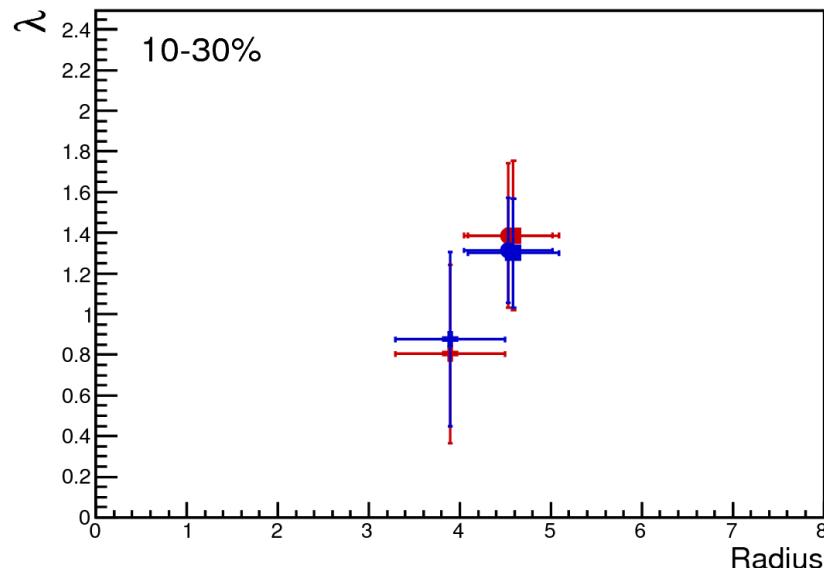
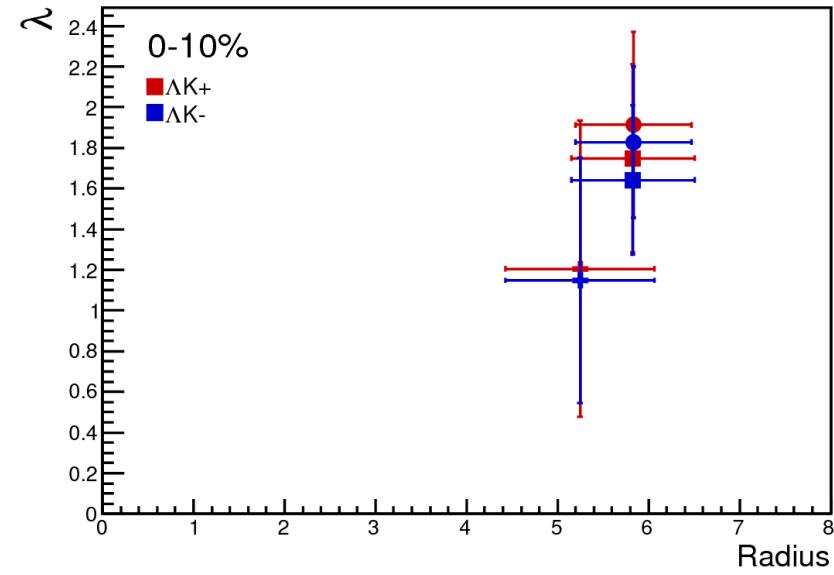
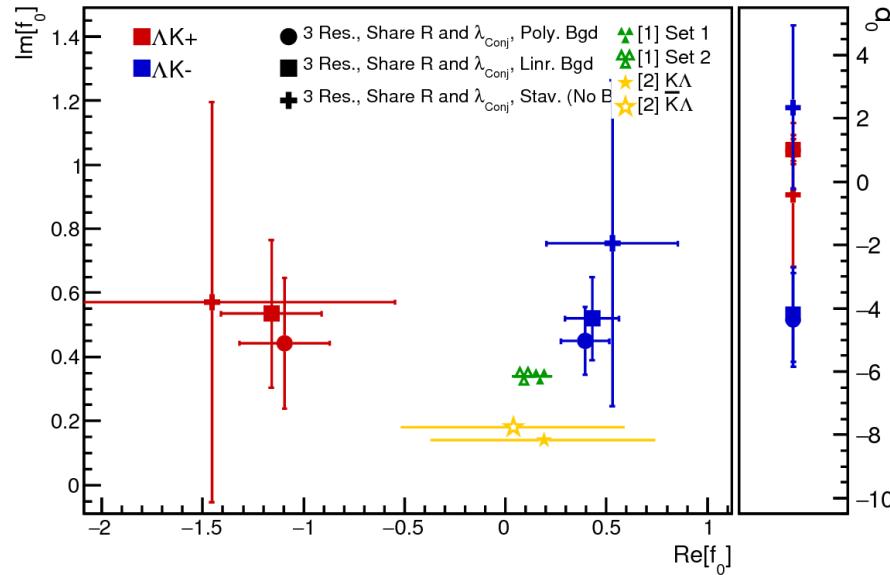
- Poly. Bgd
 - Use THERMINATOR2 to model background with 6th-order polynomial
 - Scale to match data
 - Apply background as scale factor to fit
- Lin. Bgd
 - Use a linear form to model the background
 - Fit background to data, outside of signal region ($0.6 < k^* < 0.9$ GeV/c)
 - Apply background as scale factor to fit
- Stav. (No Bgd)
 - Use Stavinsky method
 - Assume no background in correlations and fit

Compare Background Treatments

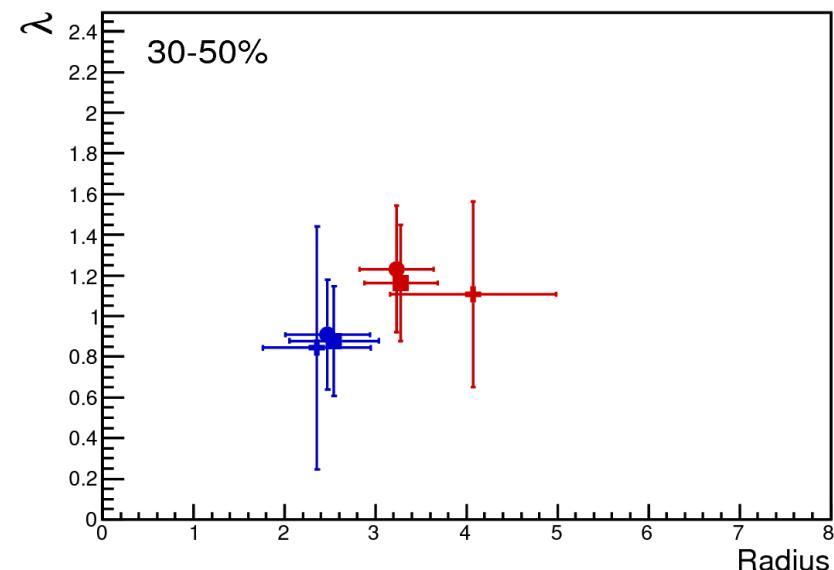
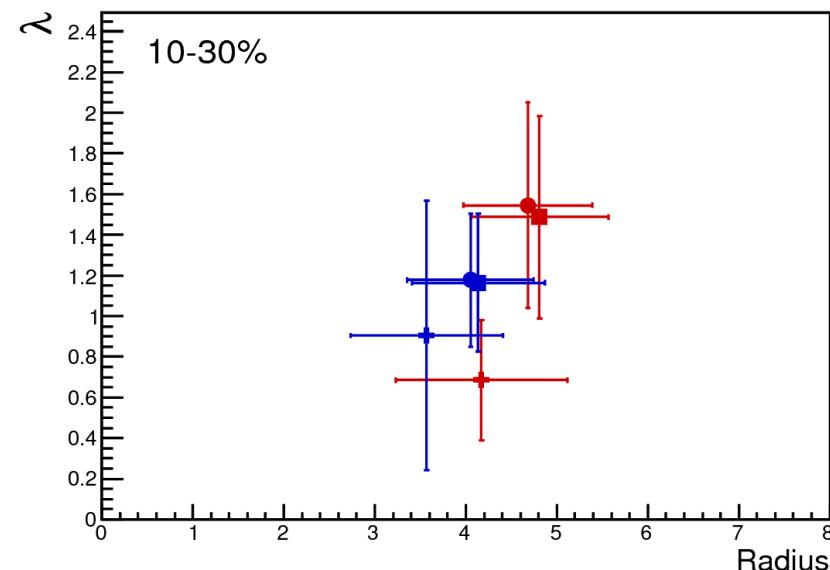
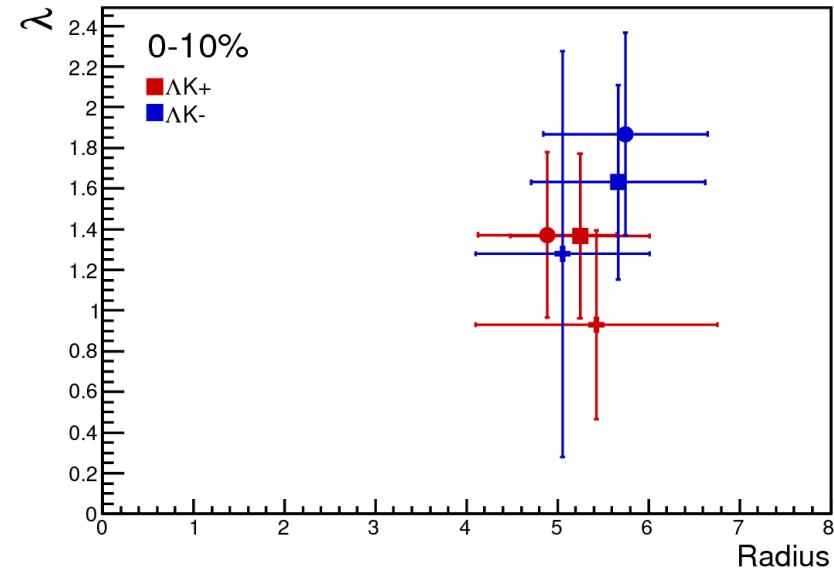
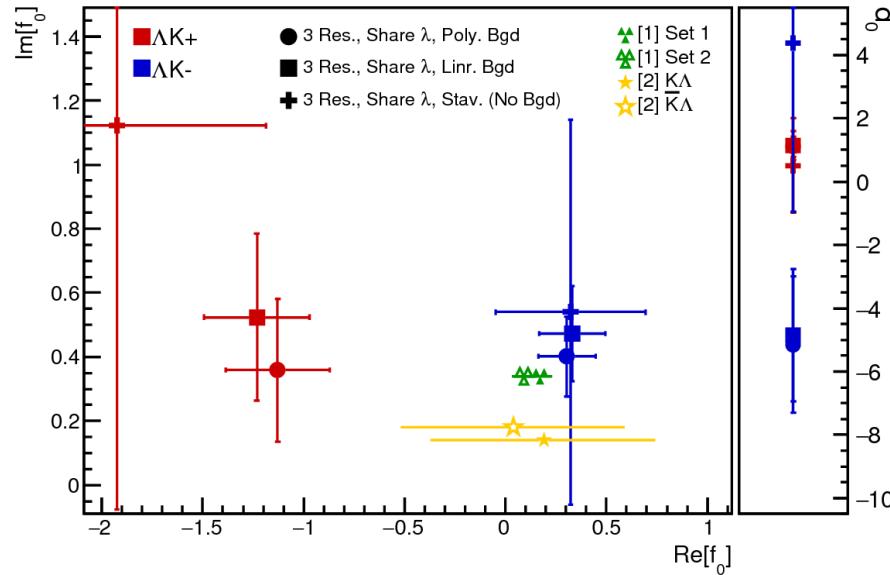
Shared R, shared λ



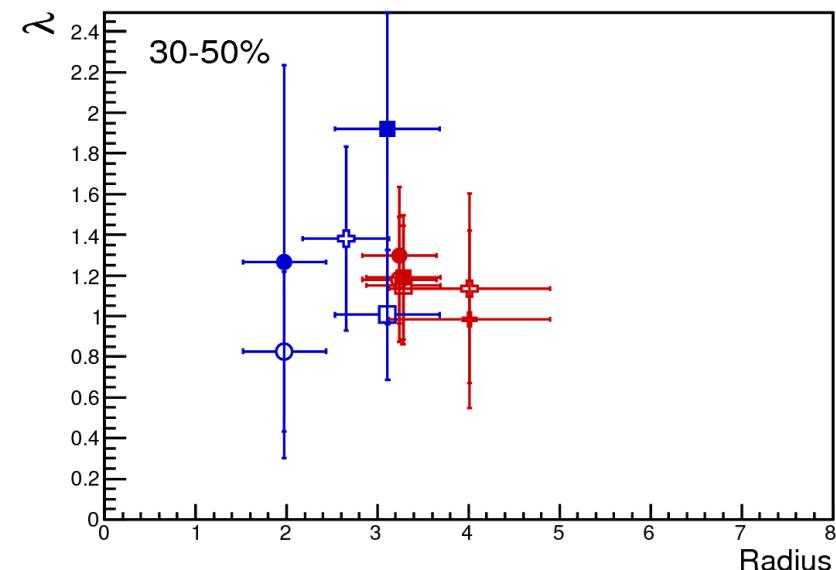
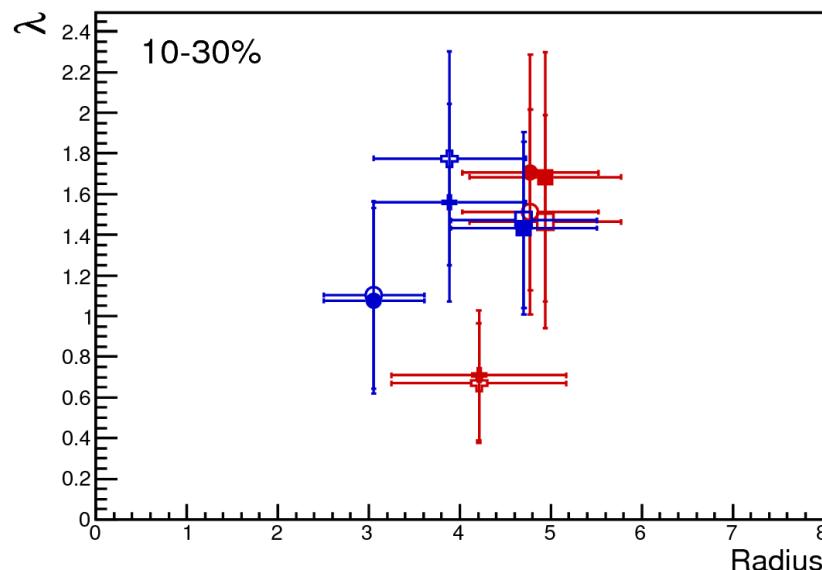
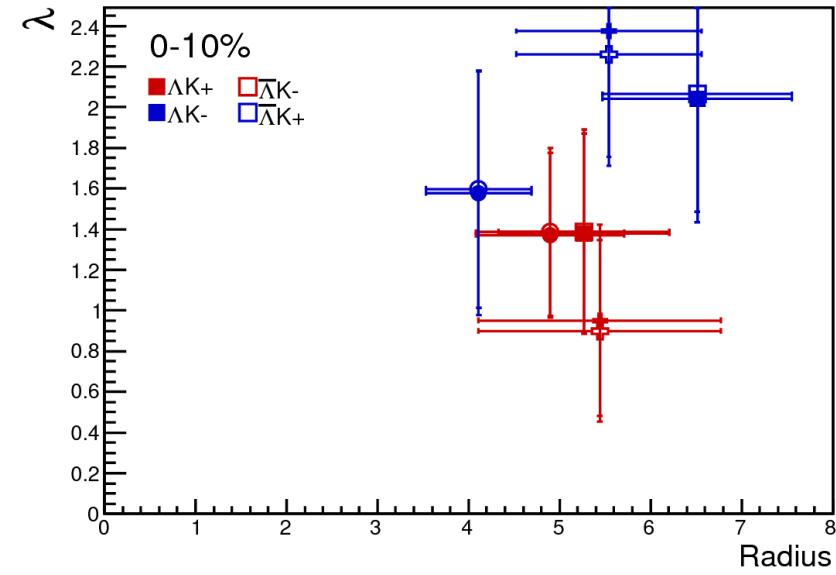
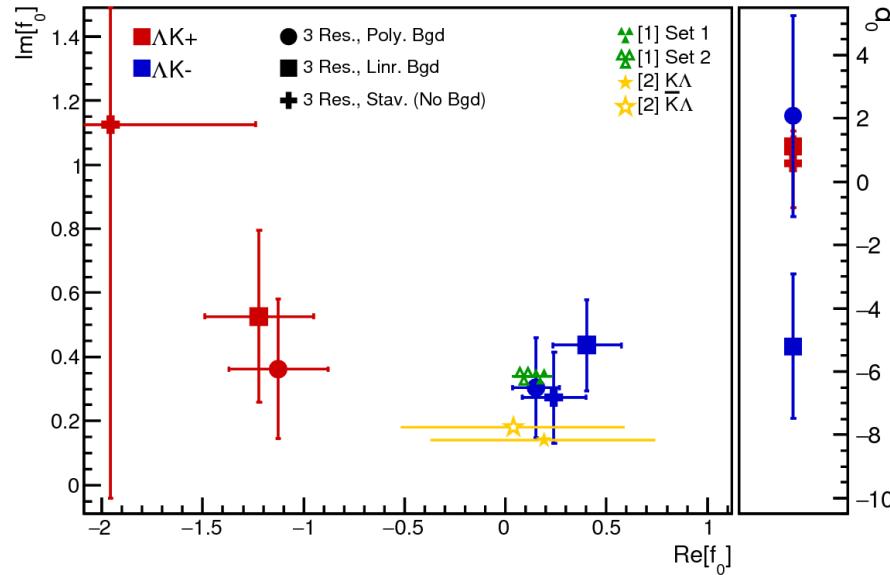
Shared R, shared λ_{Conj}



Separate R, shared λ

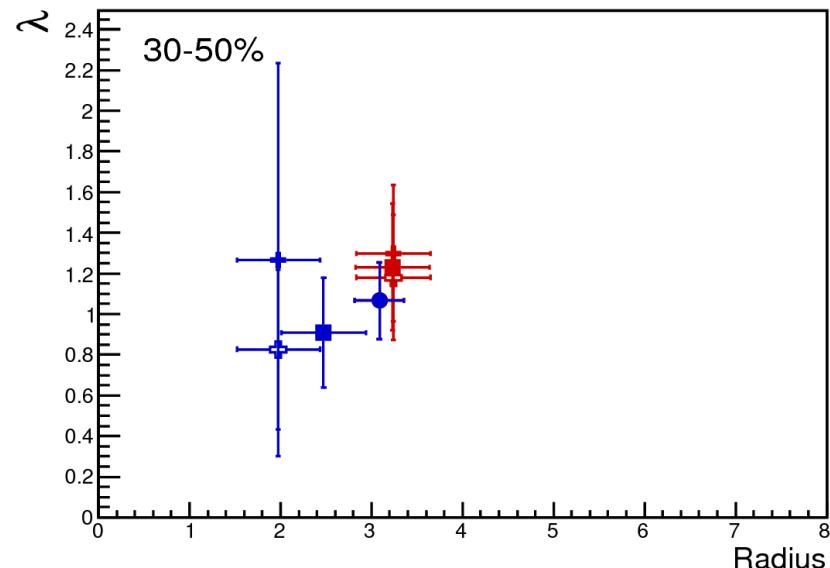
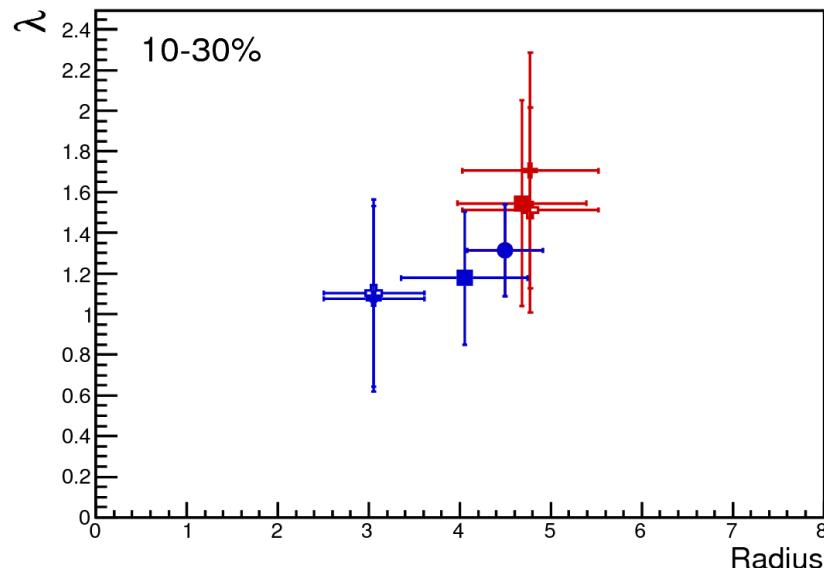
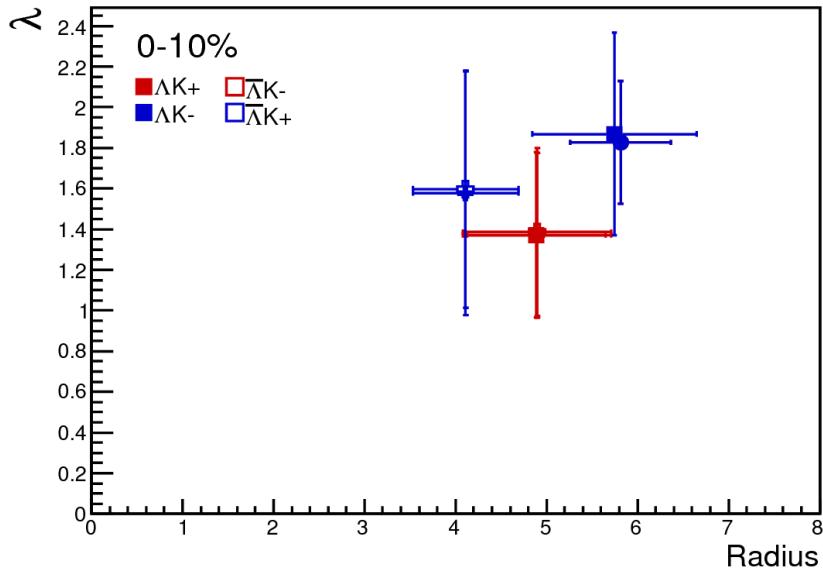
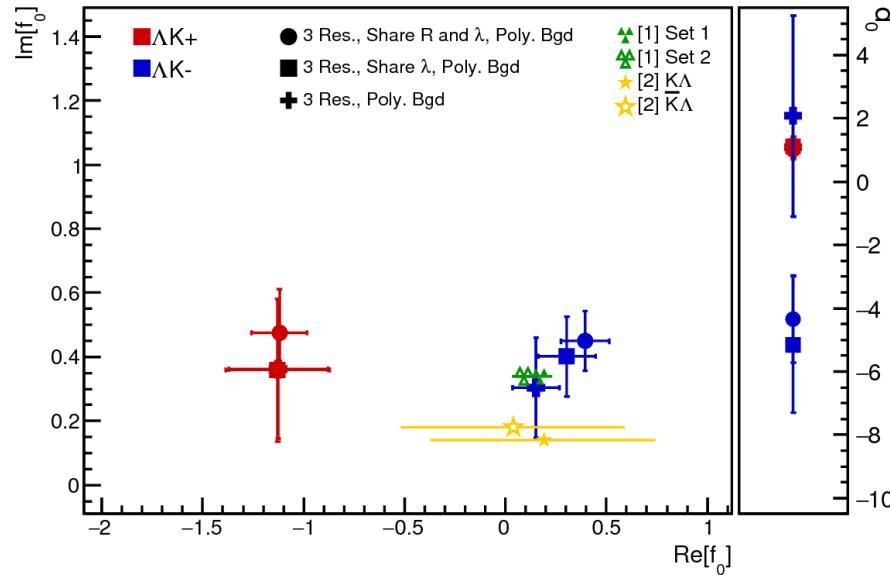


Separate R, separate λ



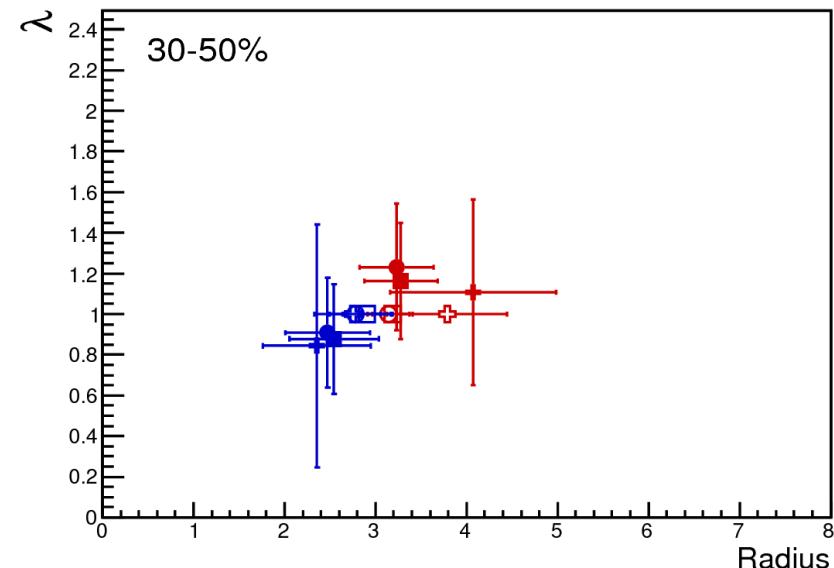
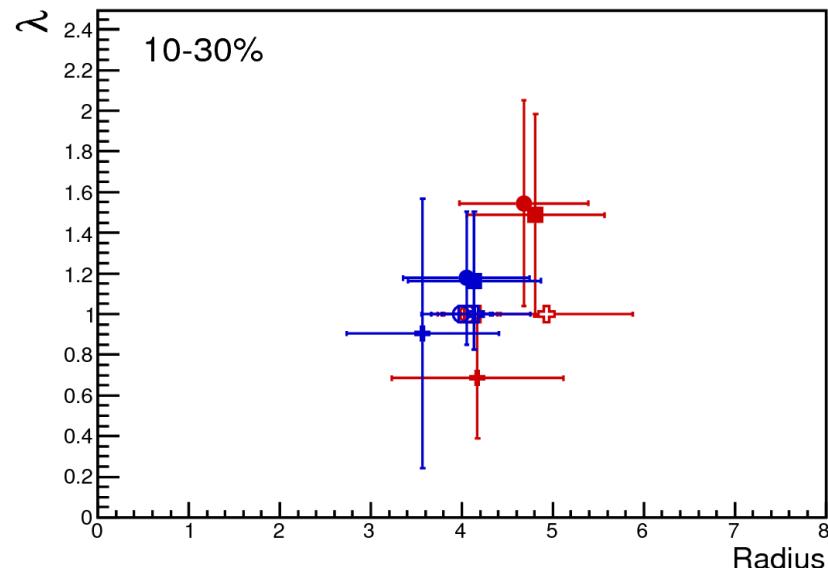
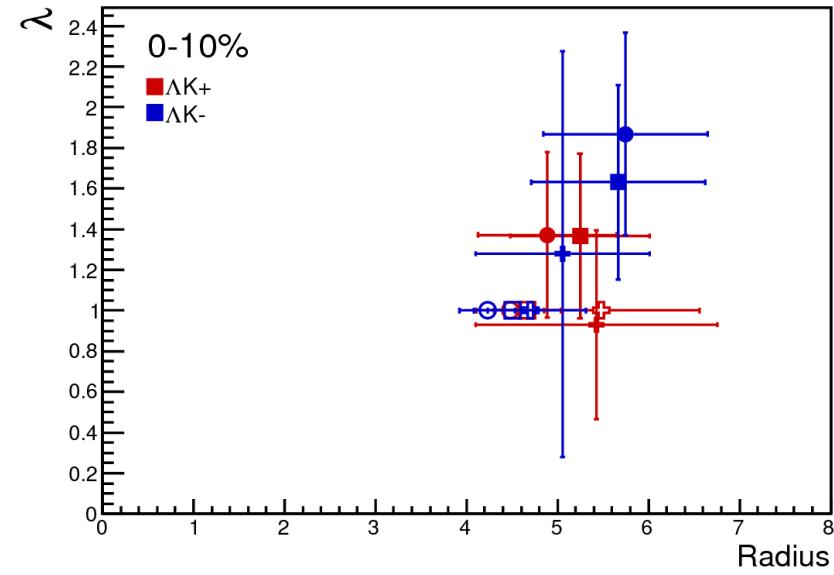
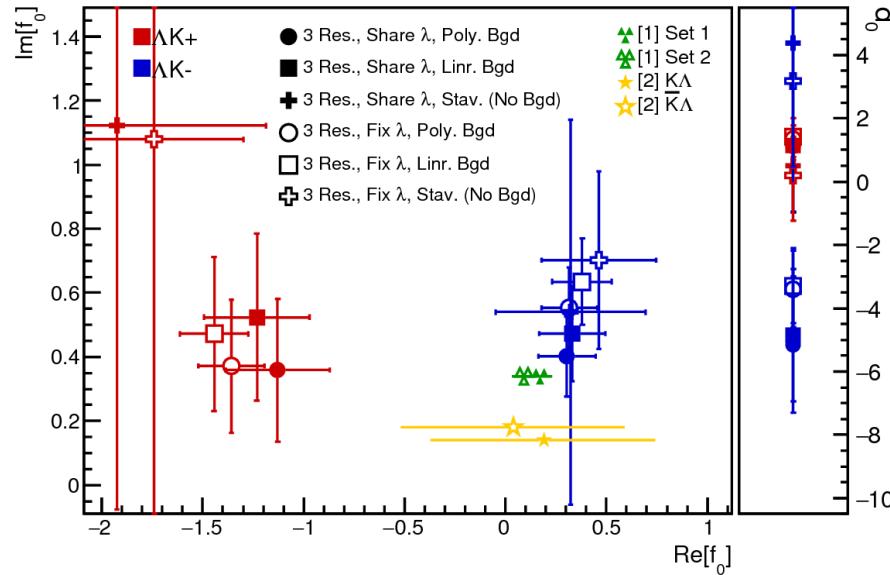
Compare Parameter Sharing

Separate vs Shared R

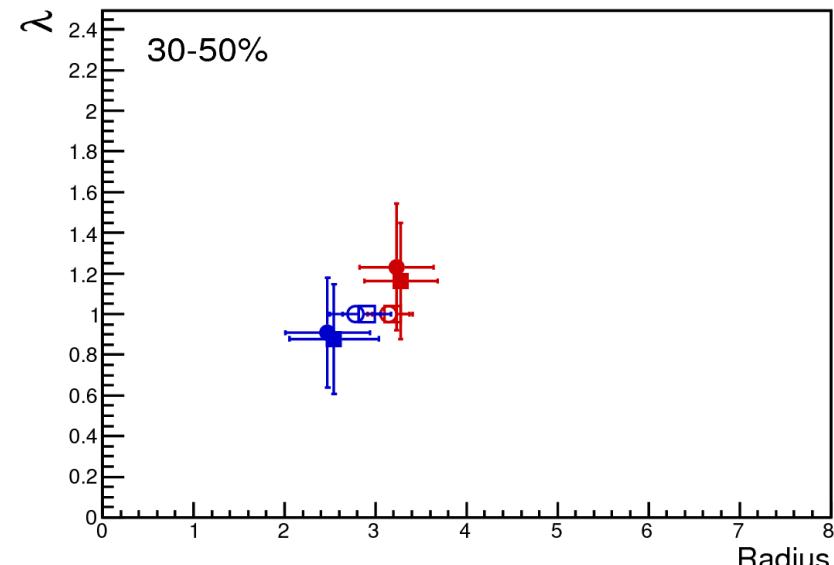
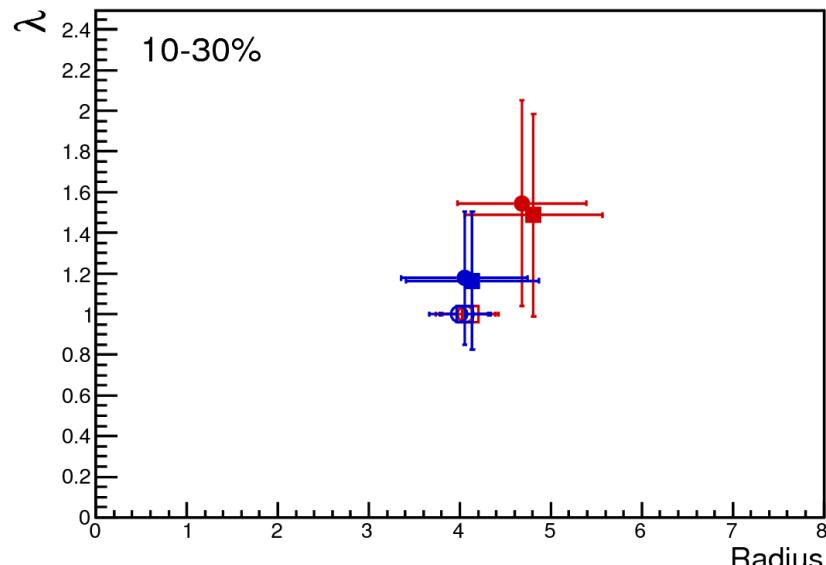
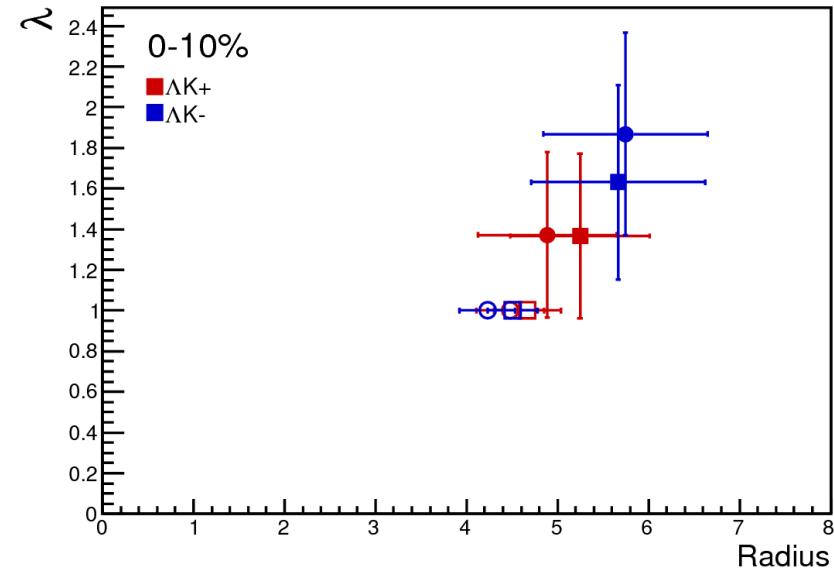
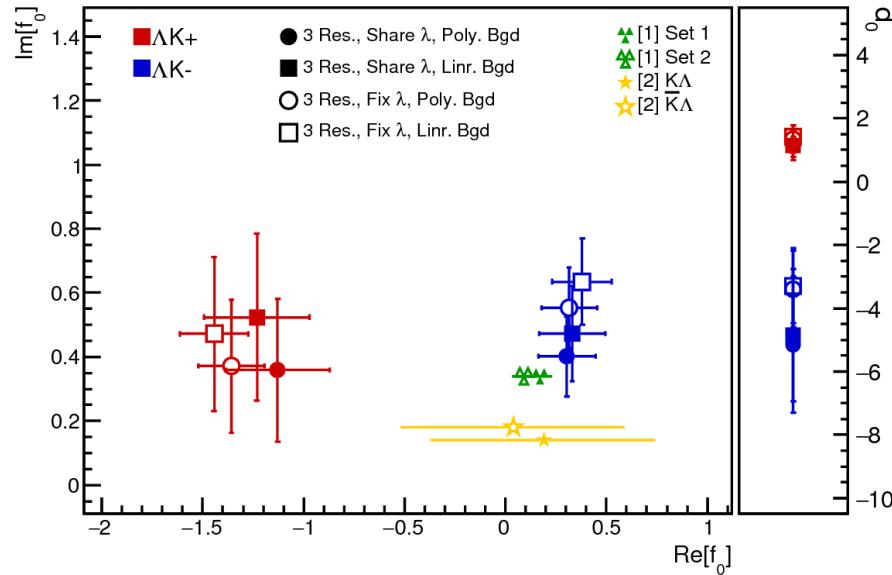


Free vs. Fixed λ

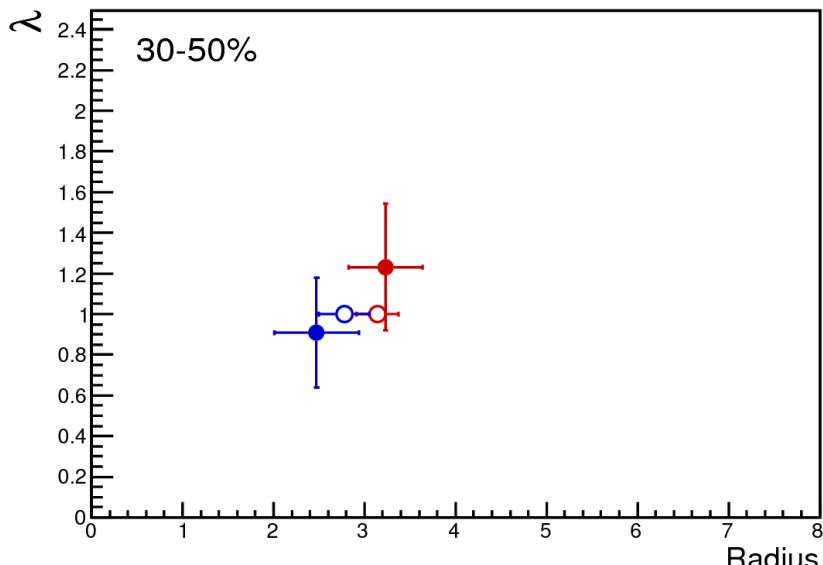
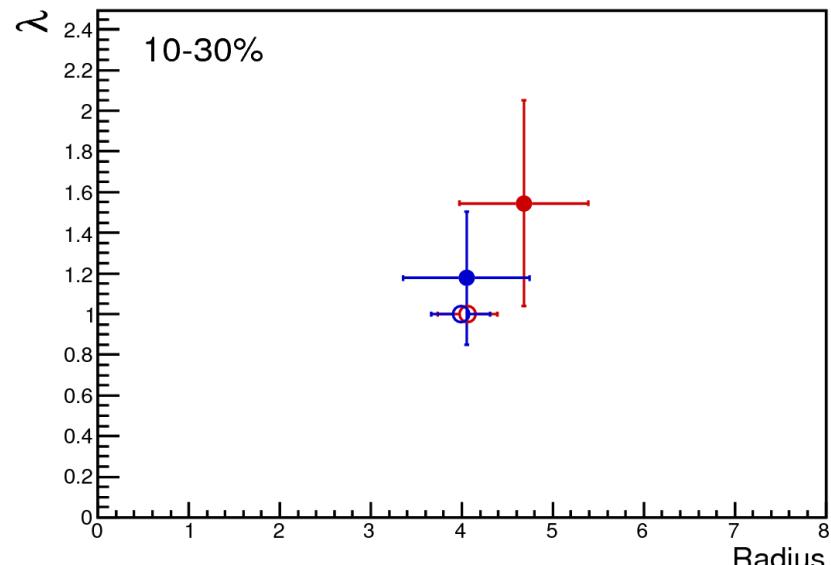
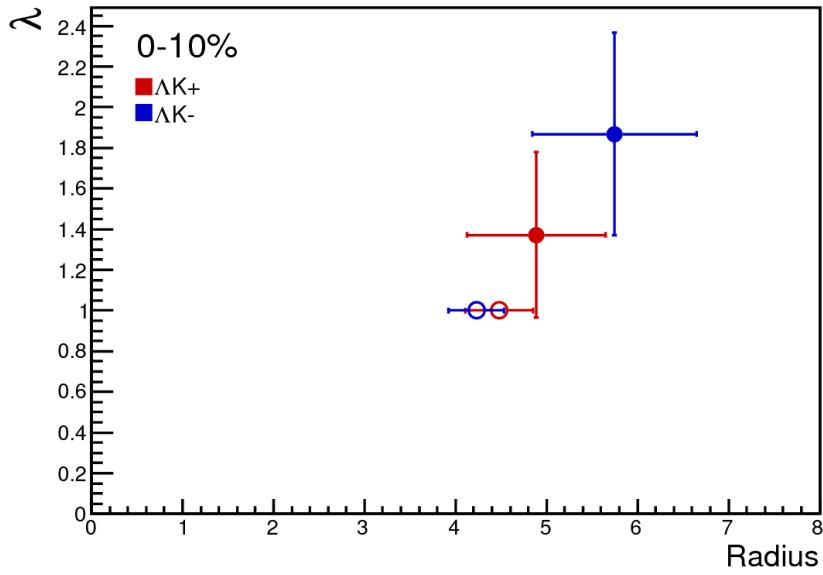
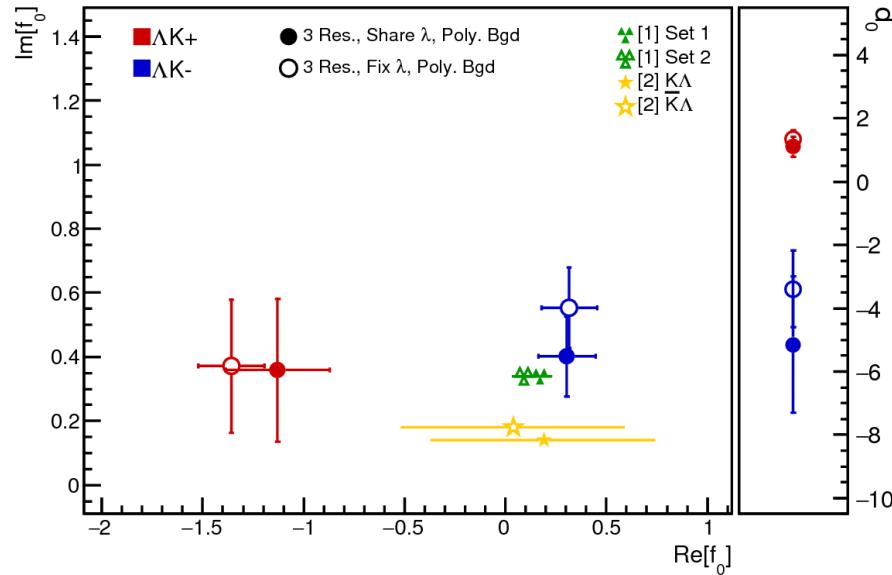
Separate R, shared λ



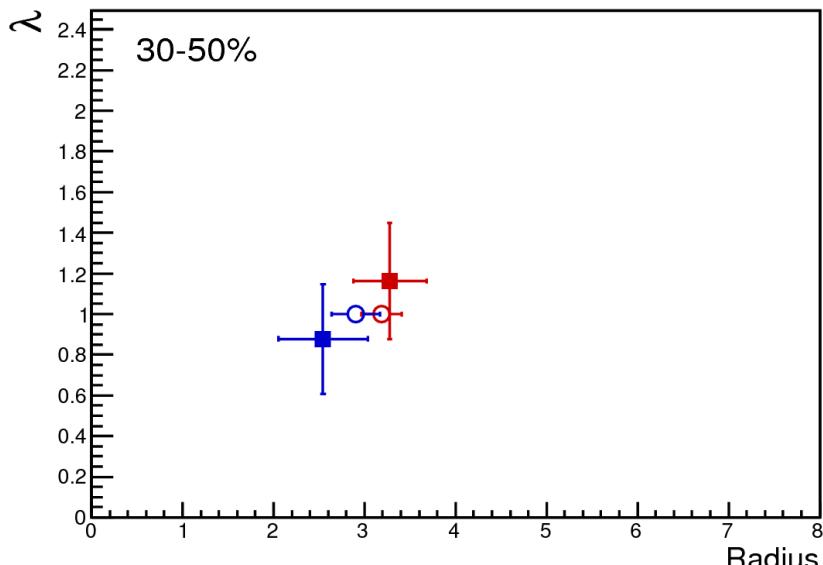
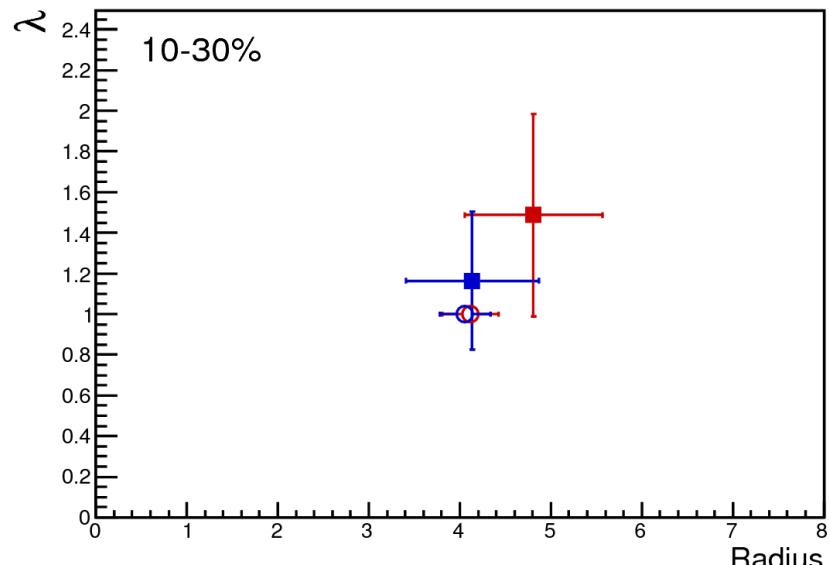
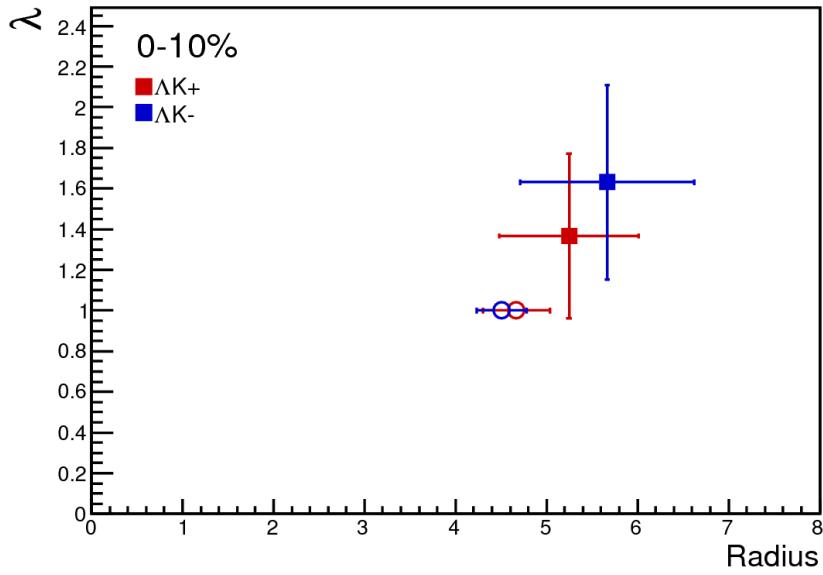
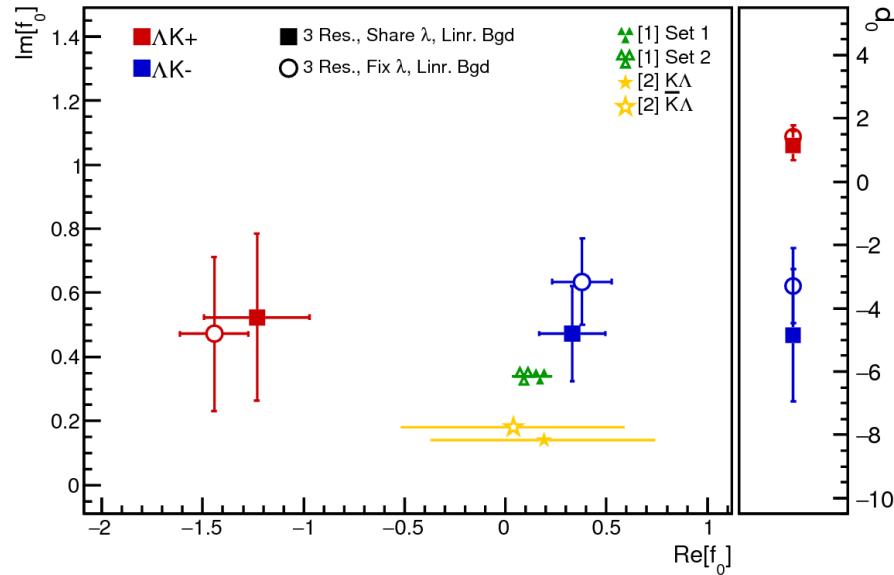
Separate R, shared λ



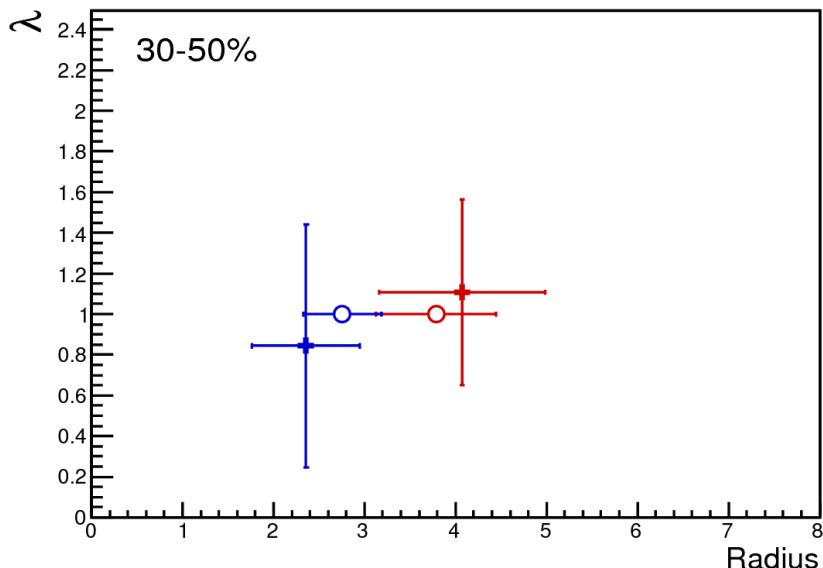
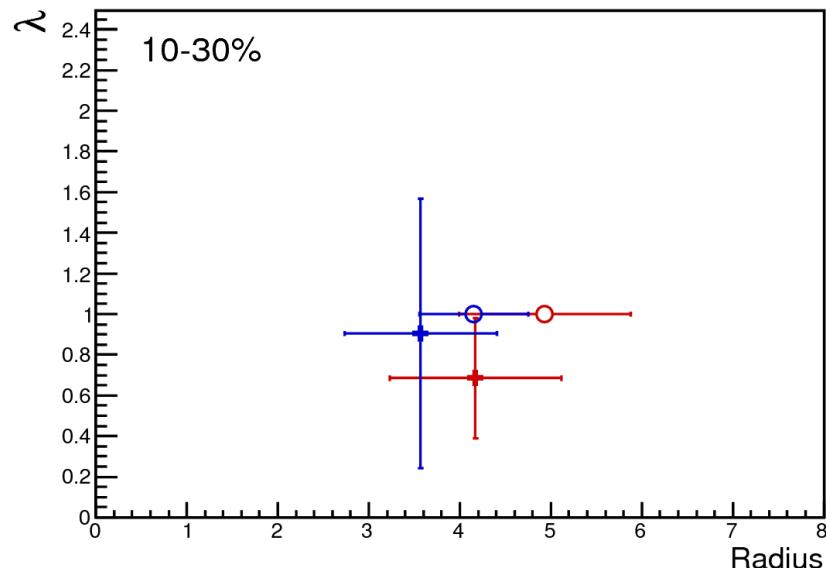
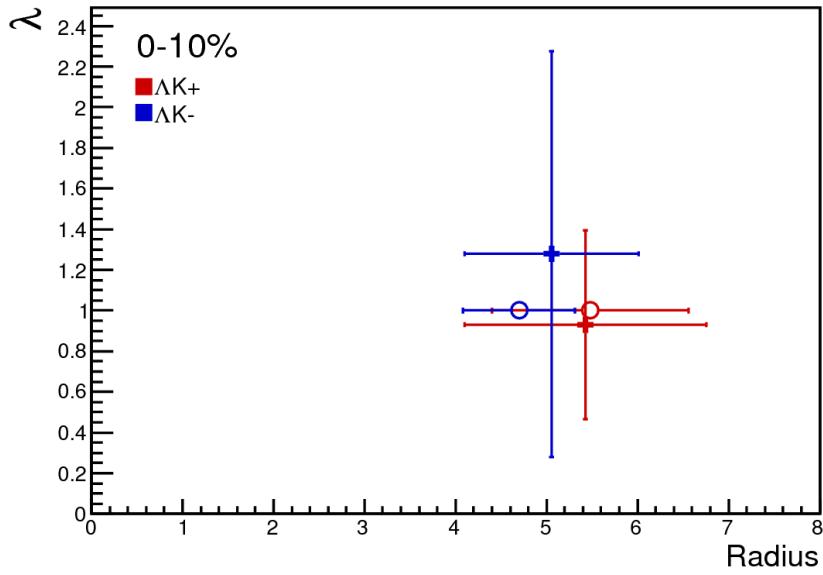
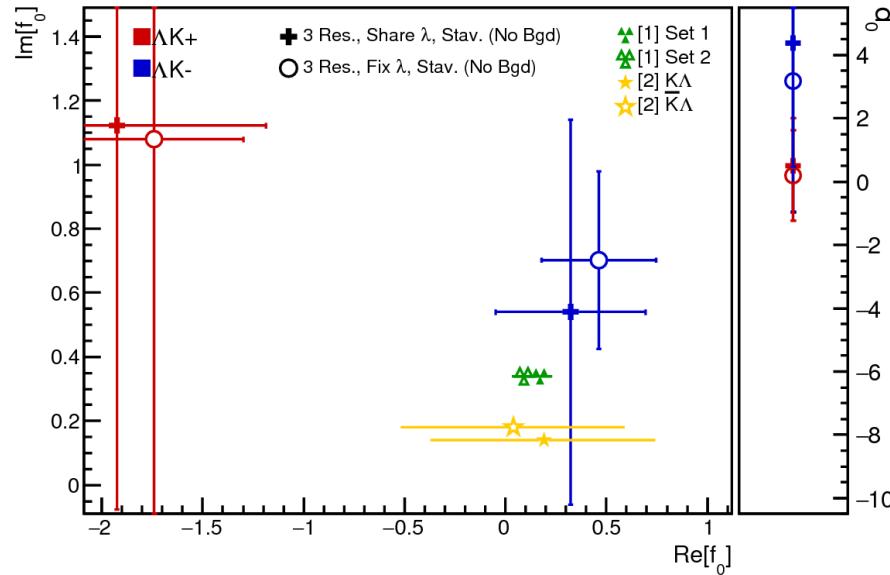
Separate R, shared λ (Poly. Bgd.)



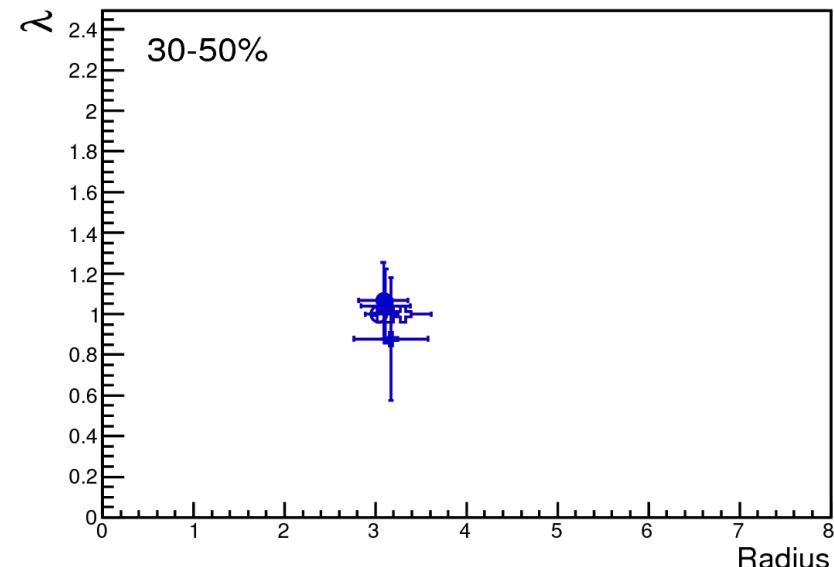
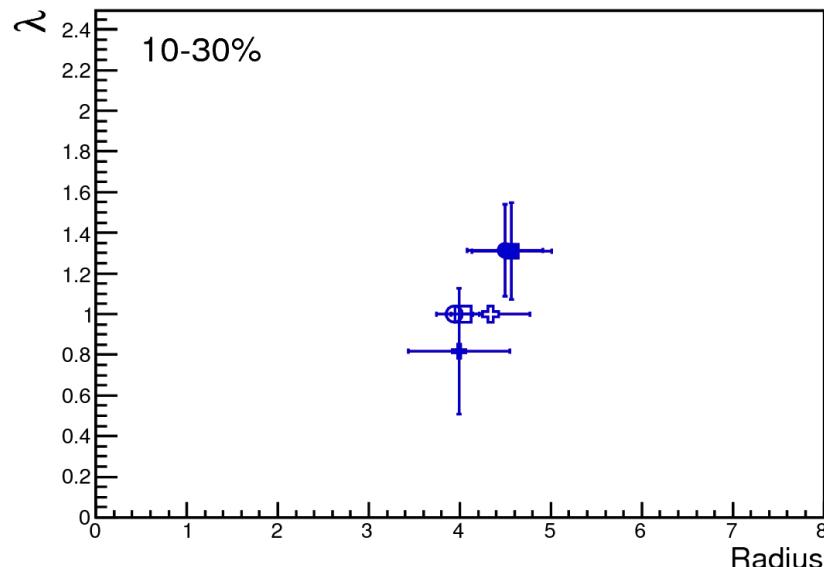
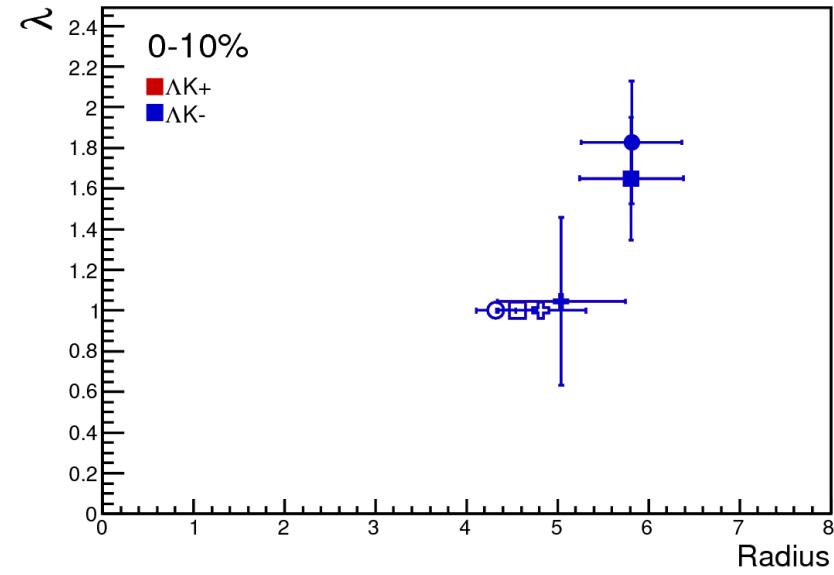
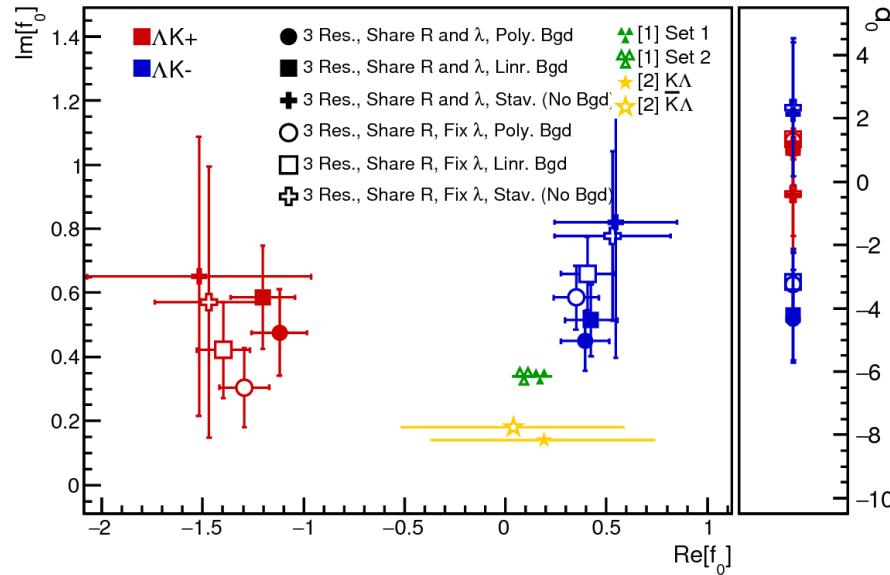
Separate R, shared λ (Linr. Bgd.)



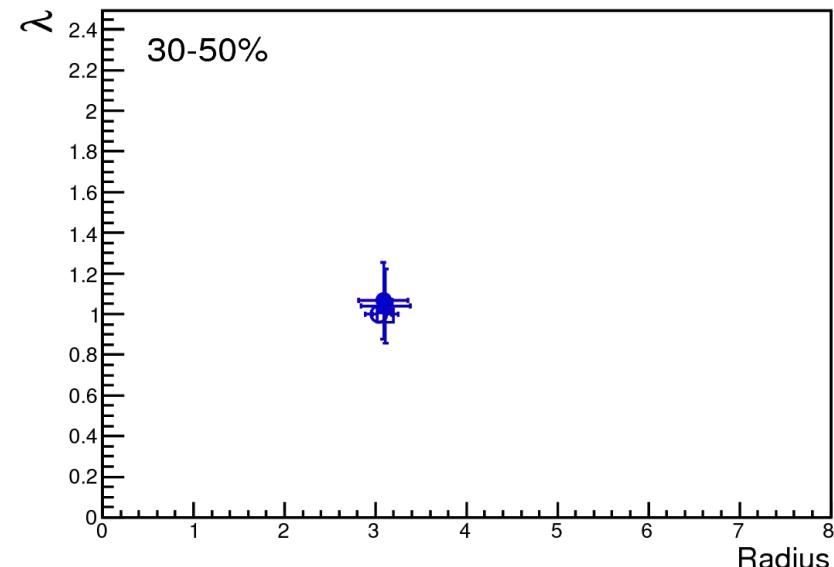
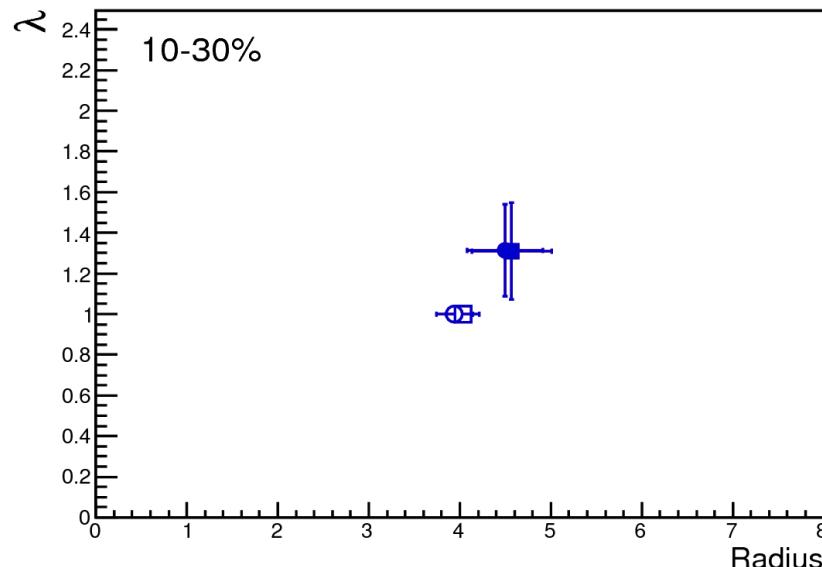
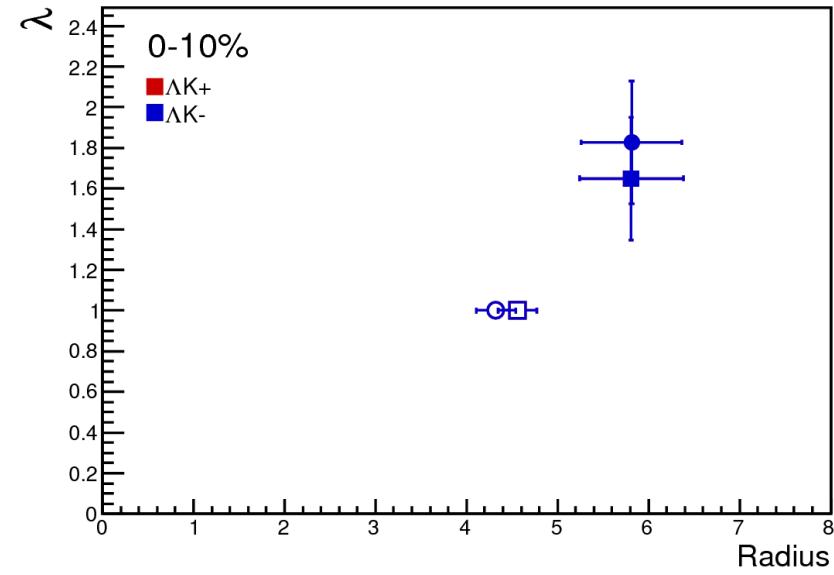
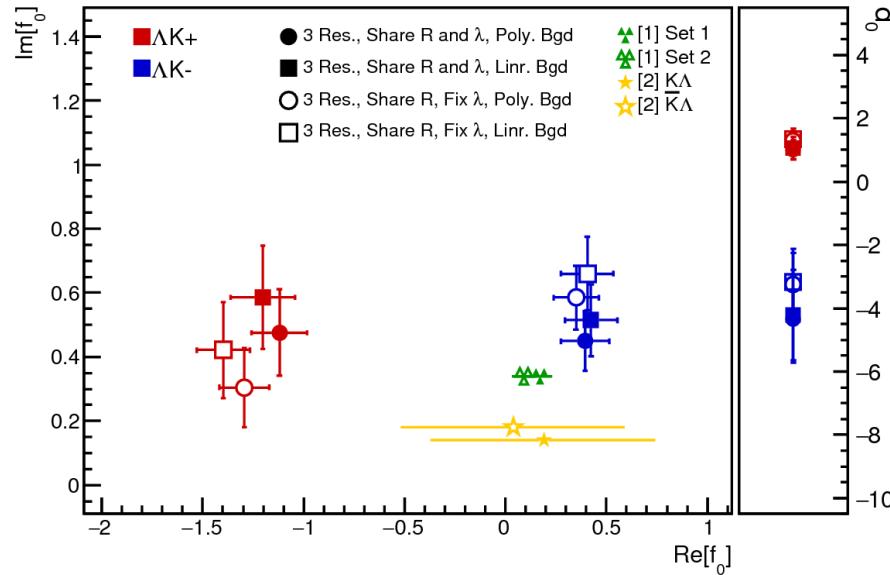
Separate R, shared λ (Stav.)



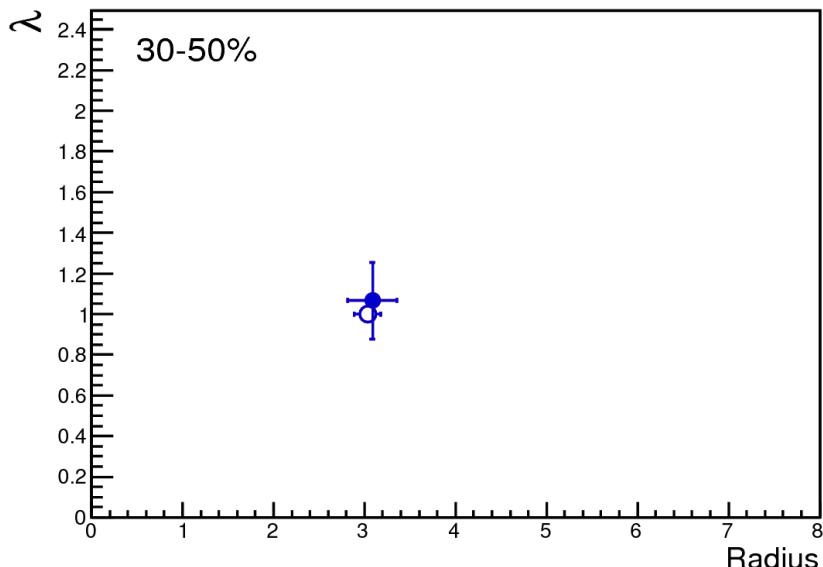
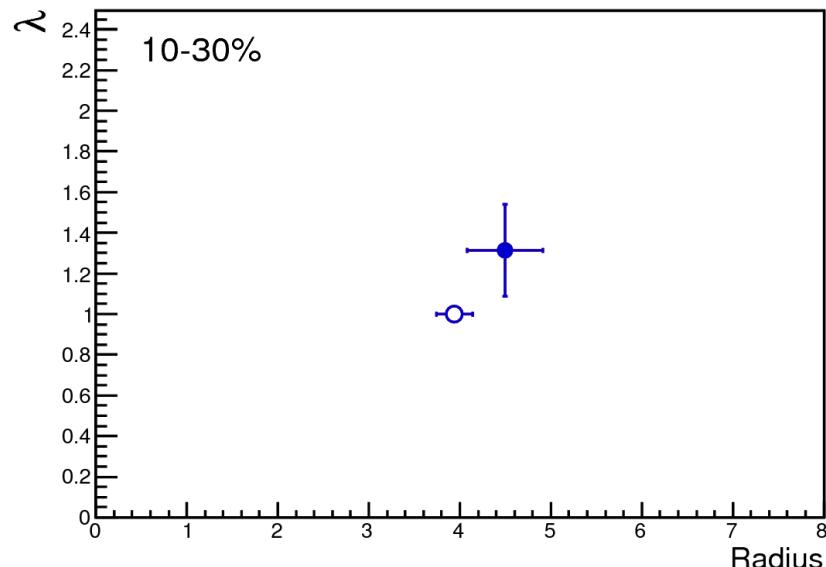
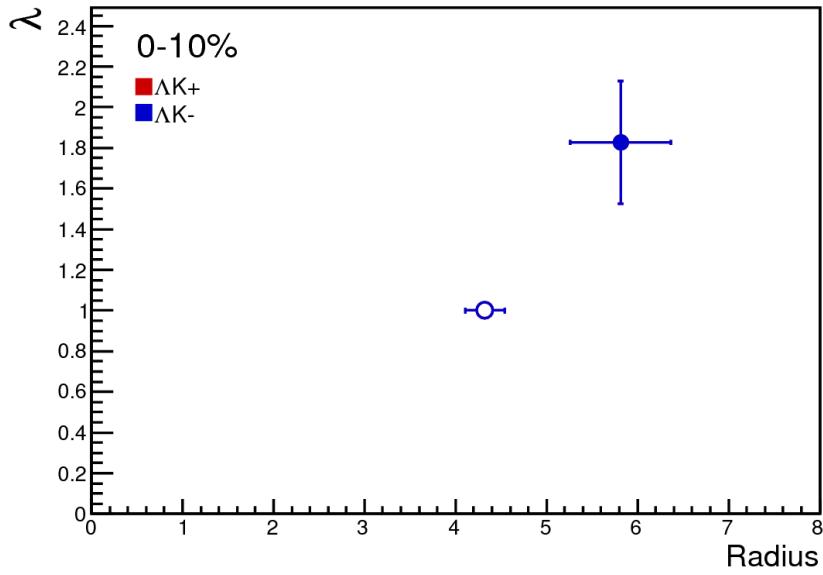
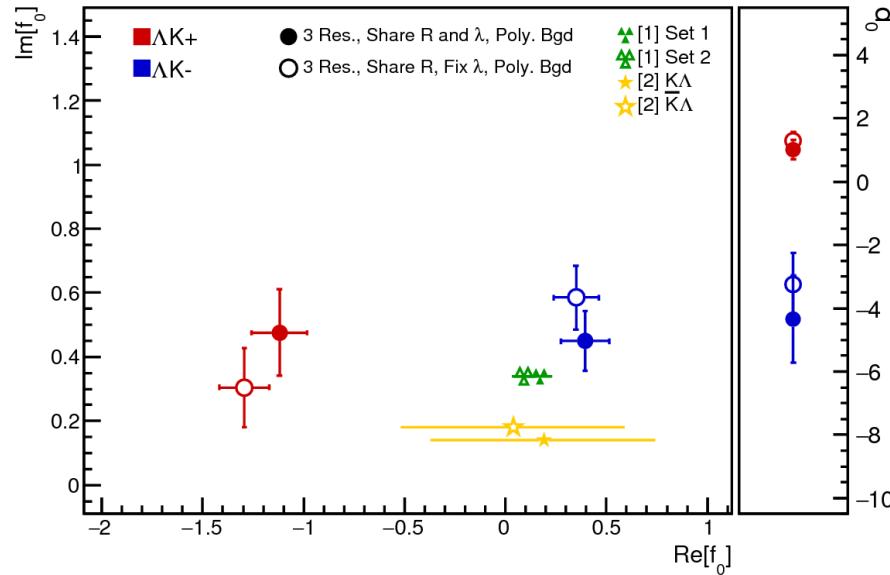
Shared R, shared λ



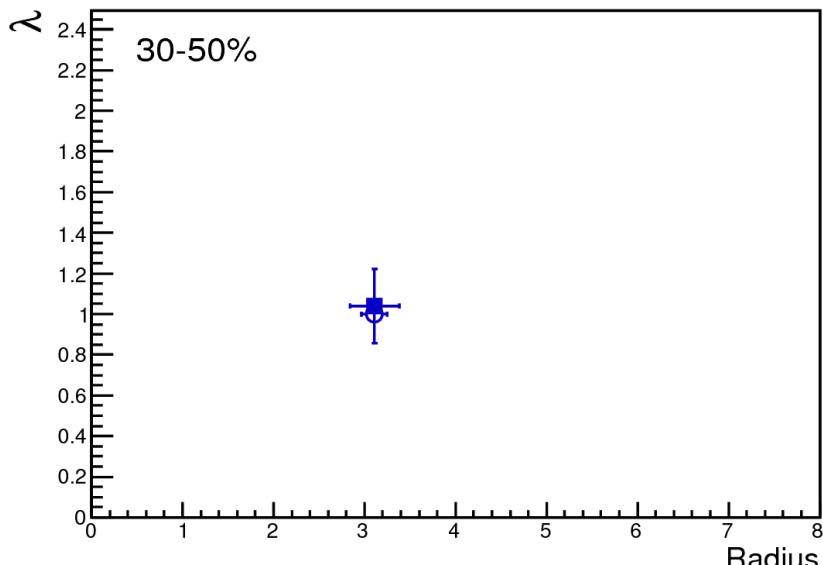
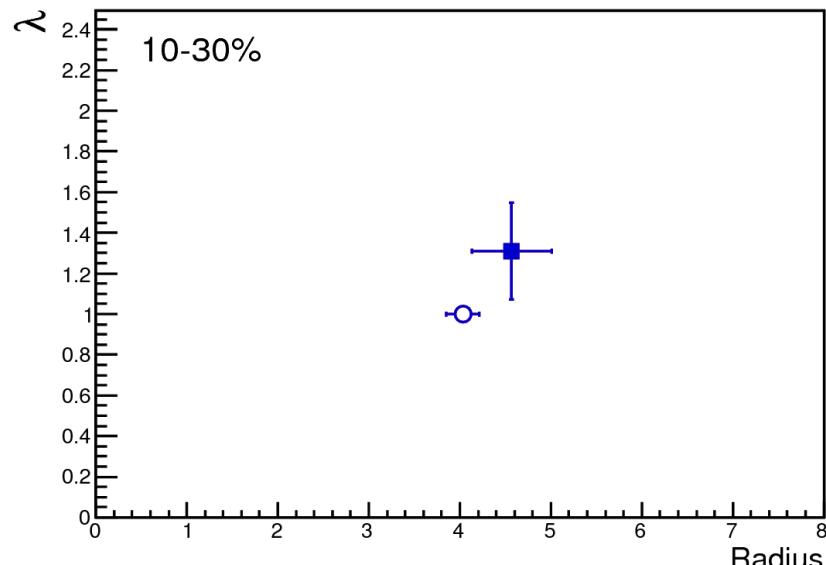
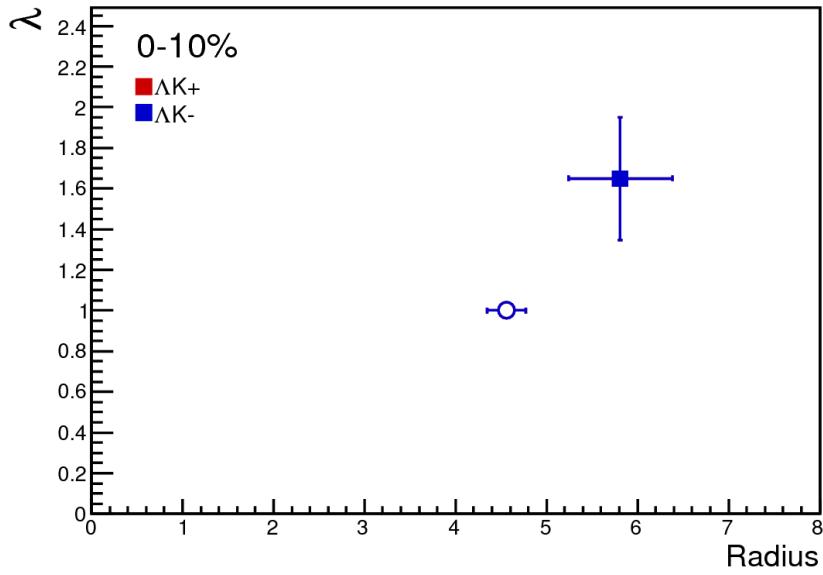
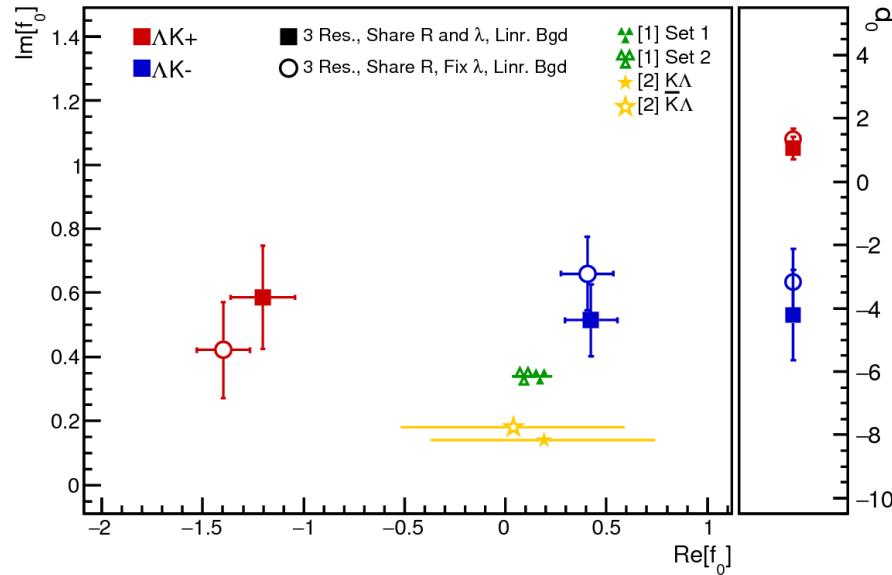
Shared R, shared λ



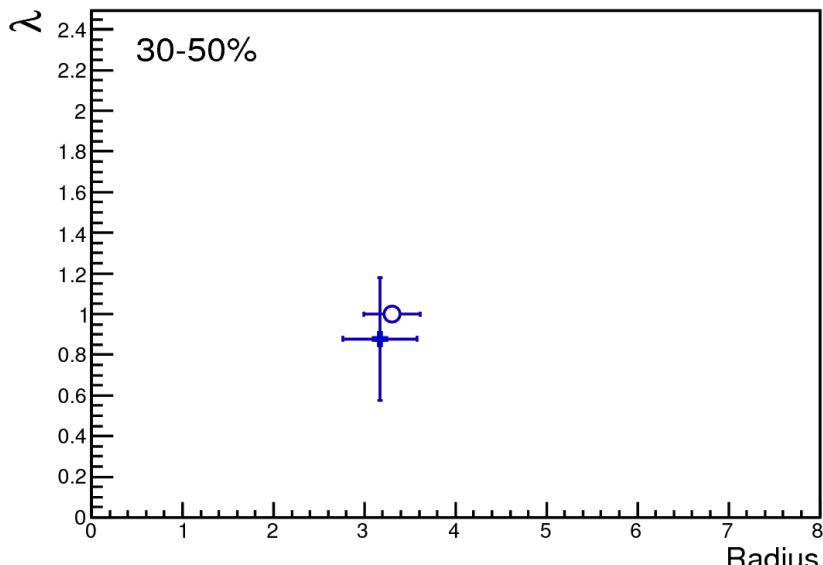
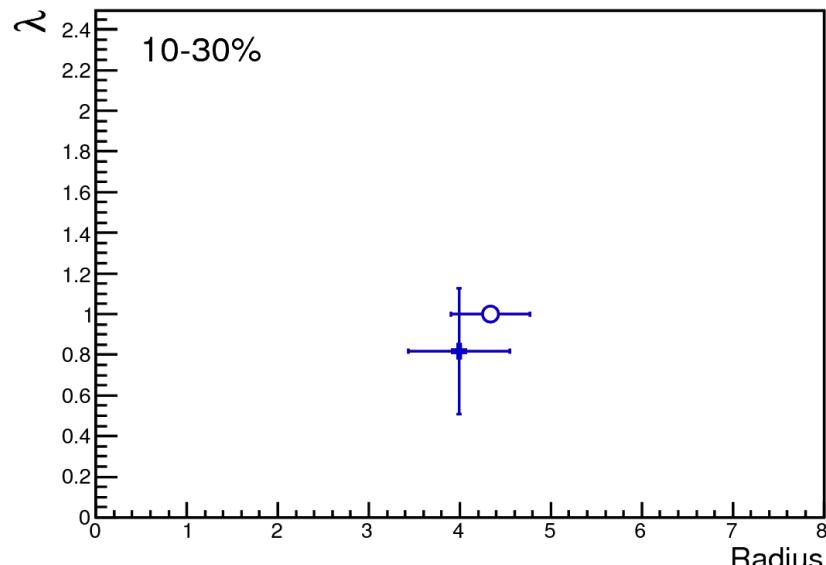
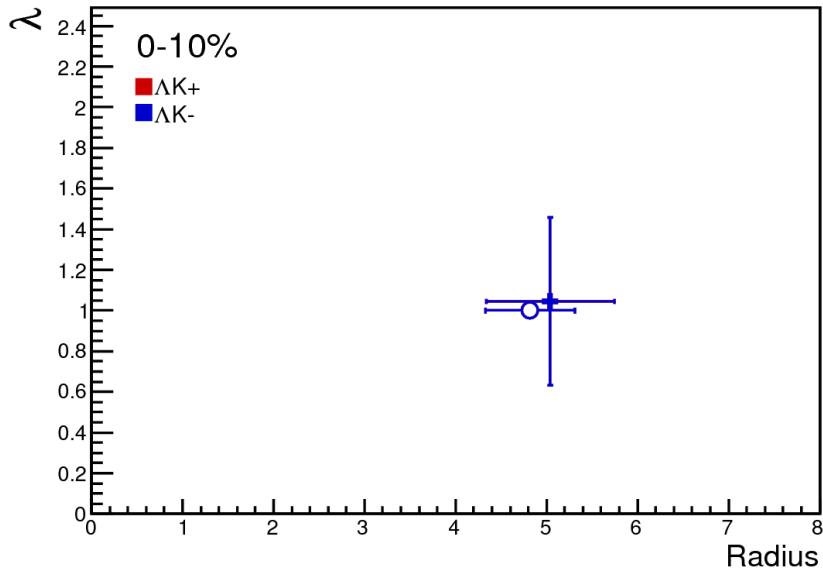
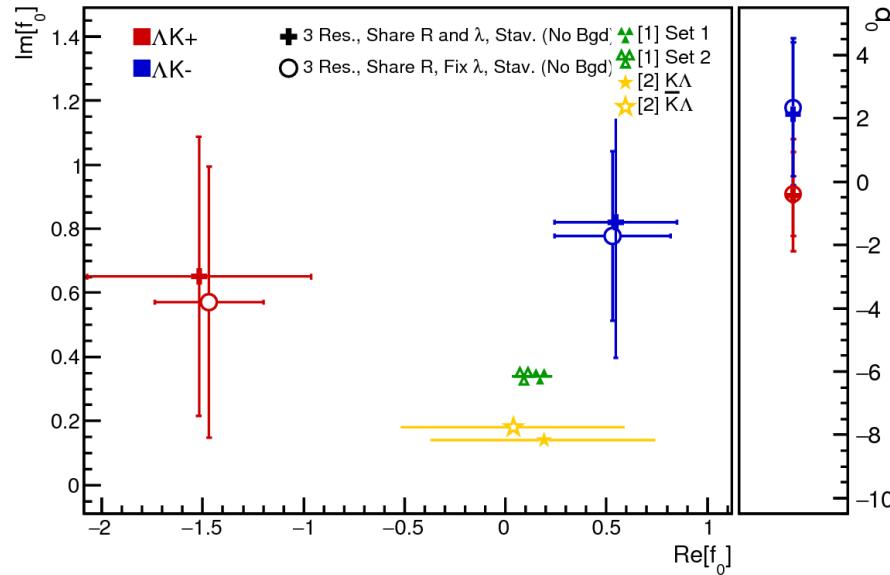
Shared R, shared λ (Poly. Bgd.)



Shared R, shared λ (Linr. Bgd.)



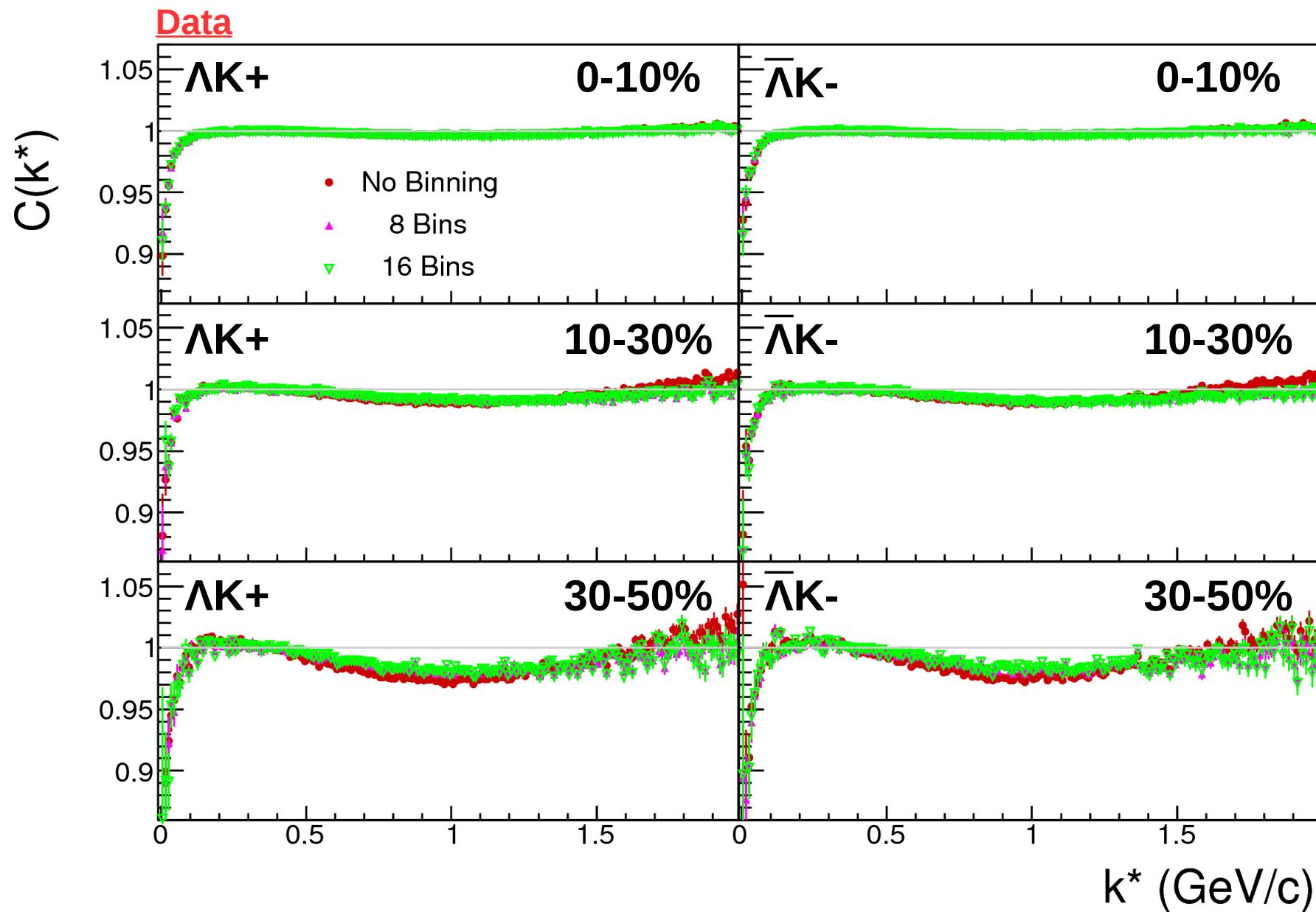
Shared R, shared λ (Stav.)

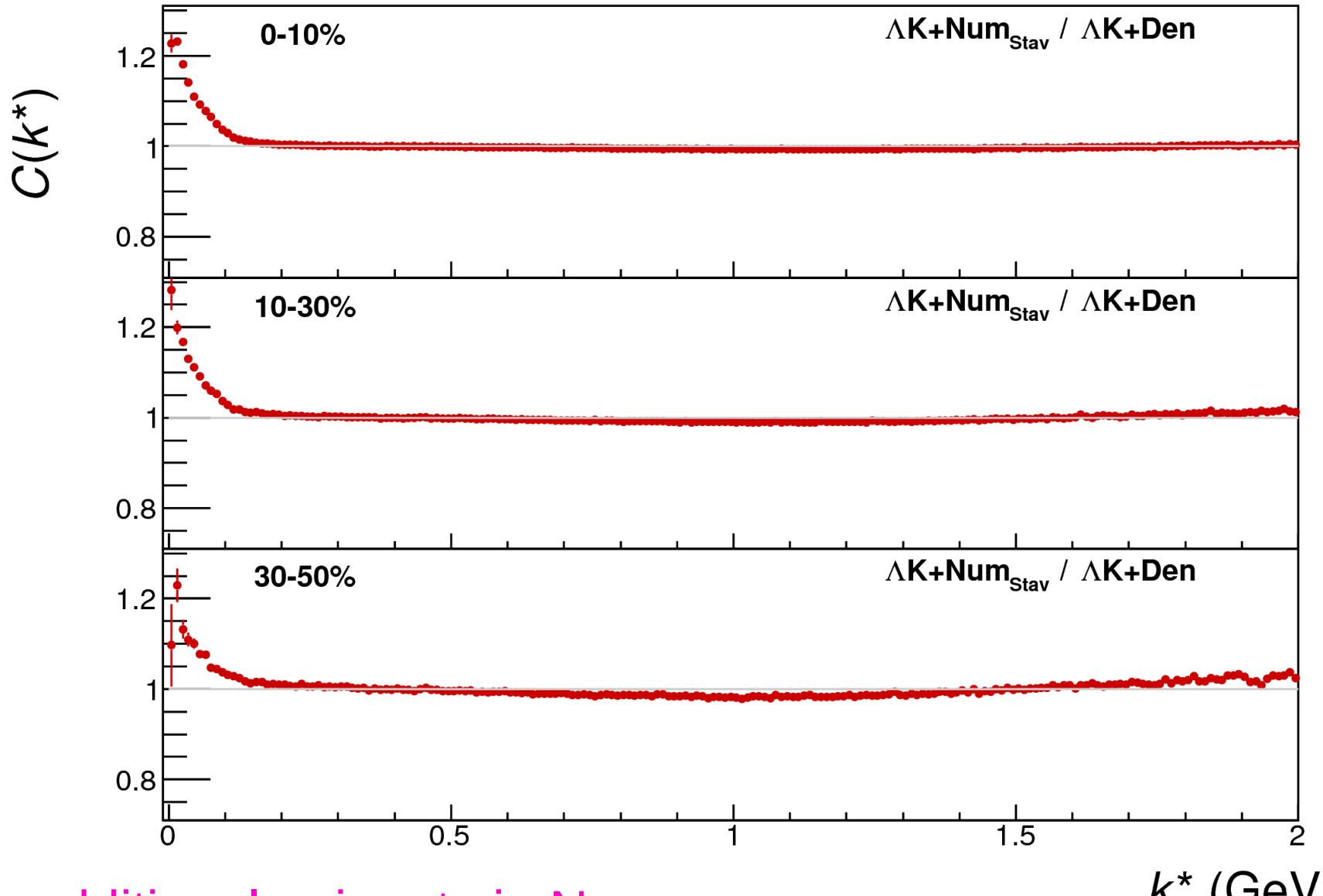


Compare Parameter Sharing

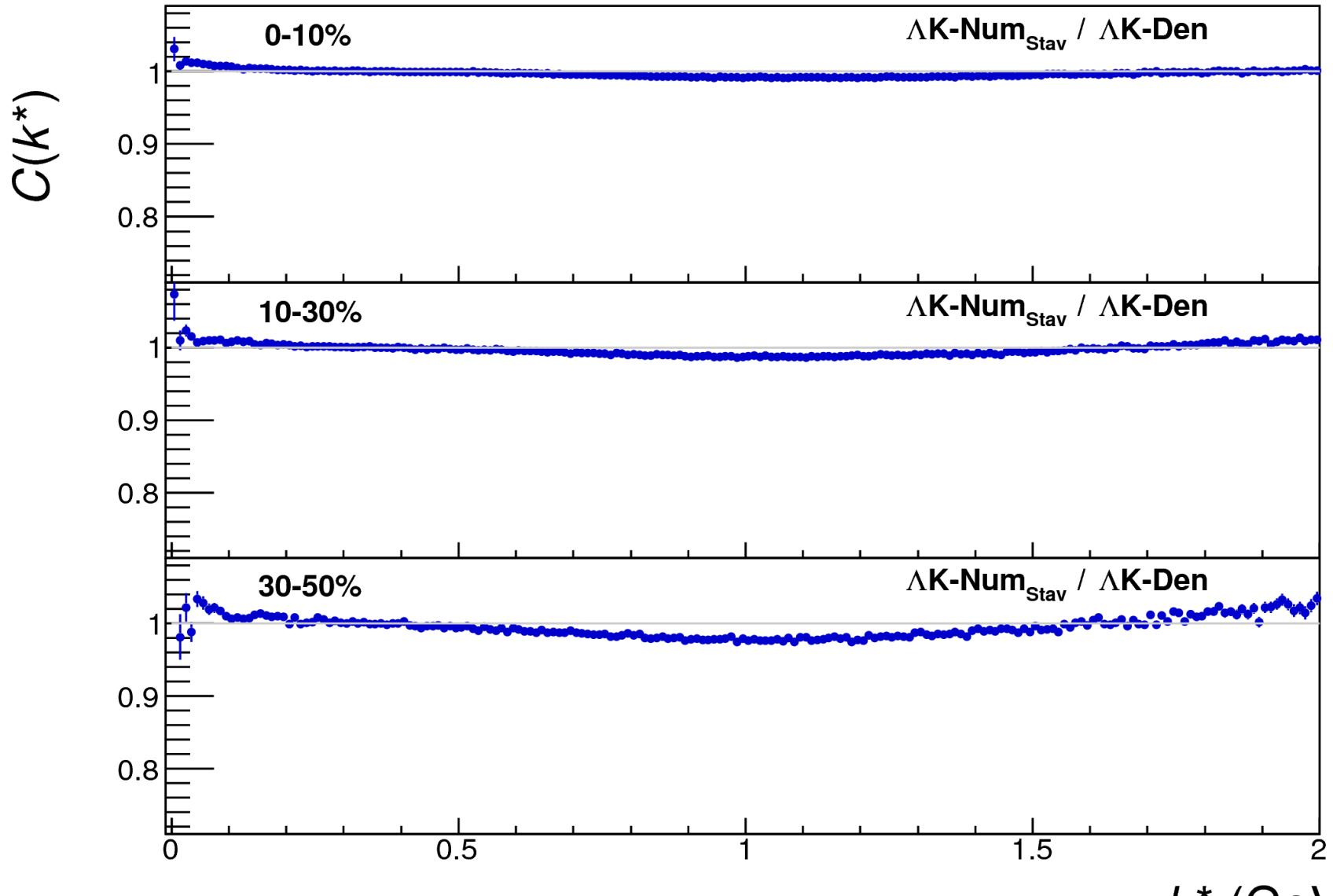
BACKUP

Binning Events in EP Angle

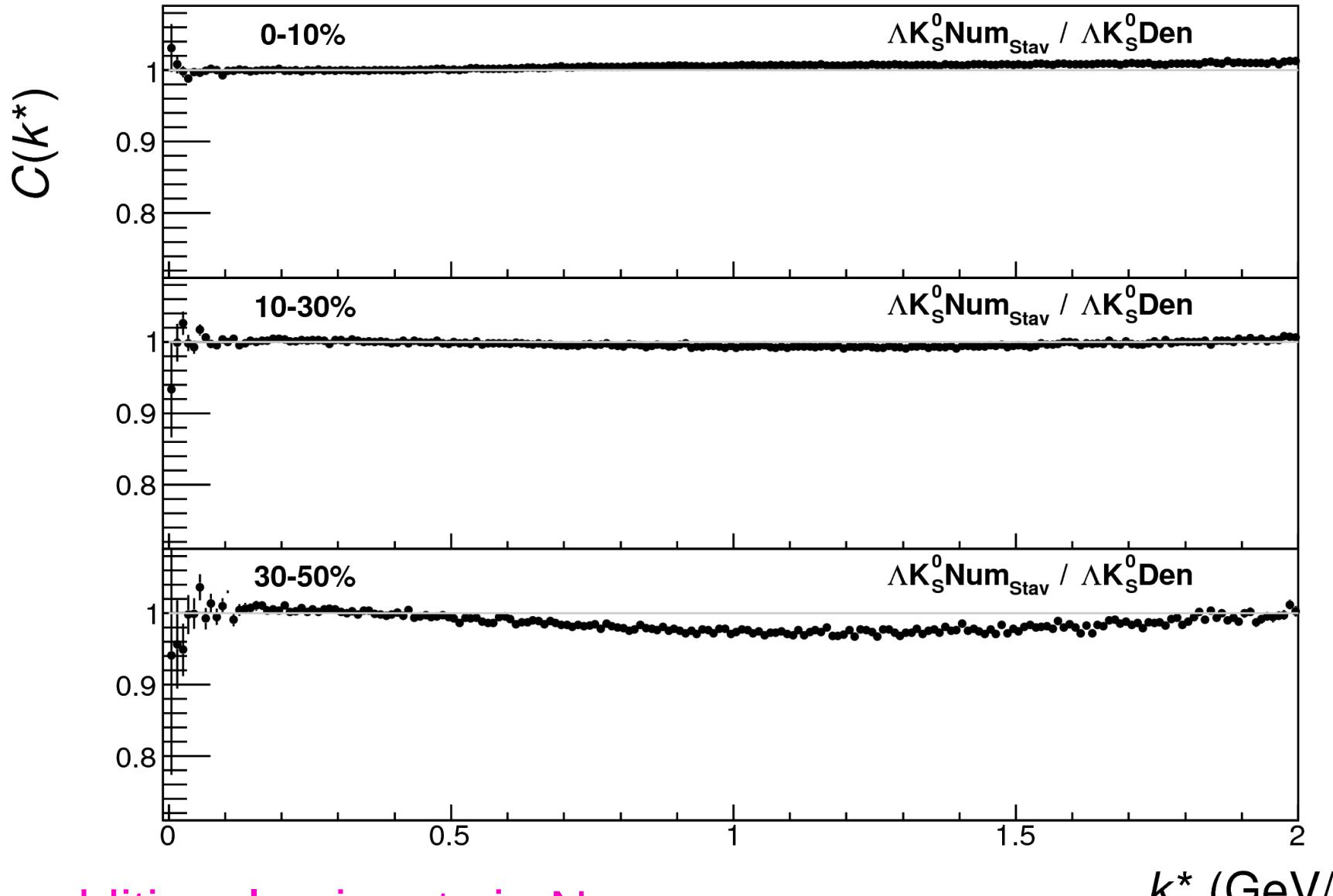




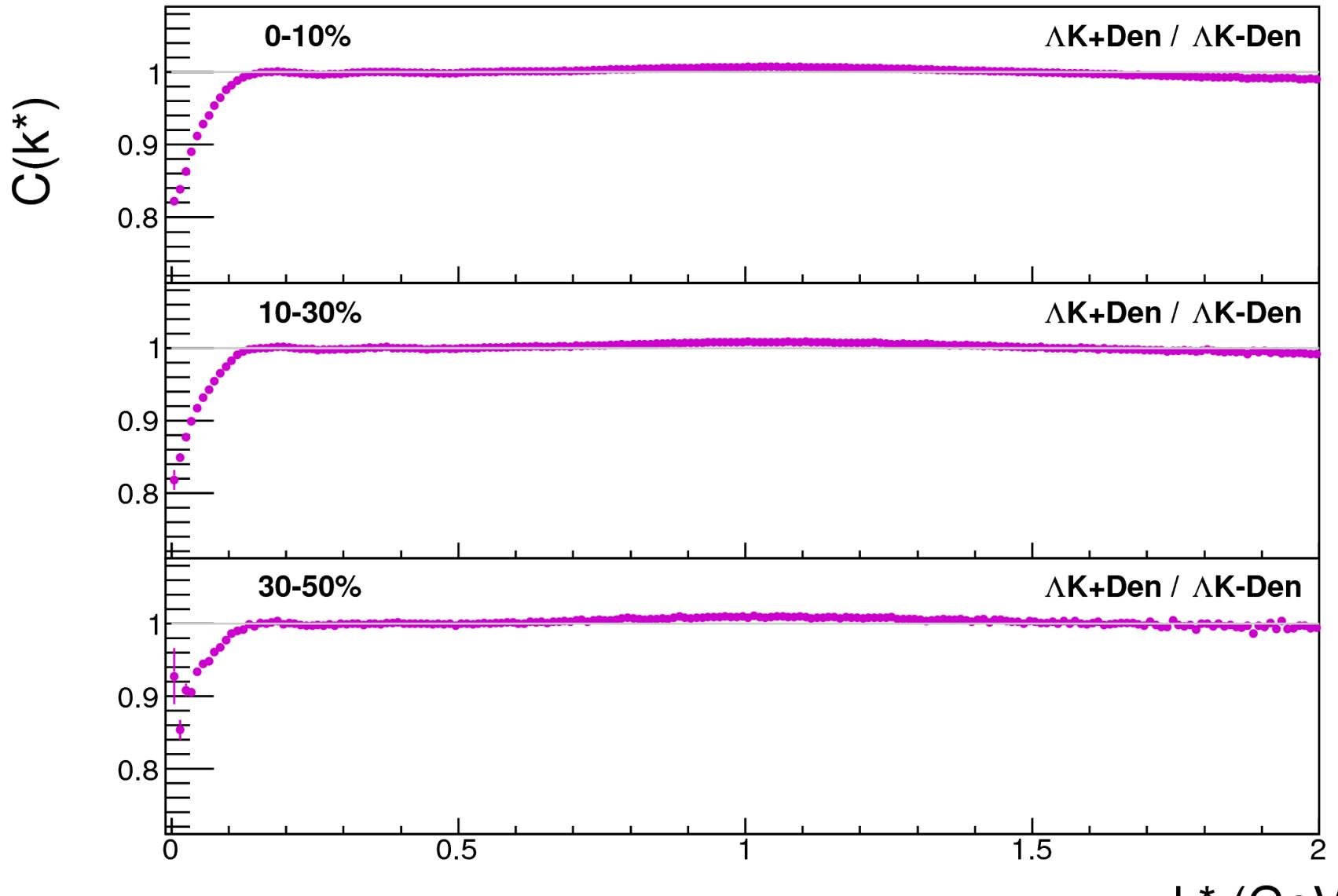
No additional pair cuts in Num_{Stav}



No additional pair cuts in Num_{Stav}

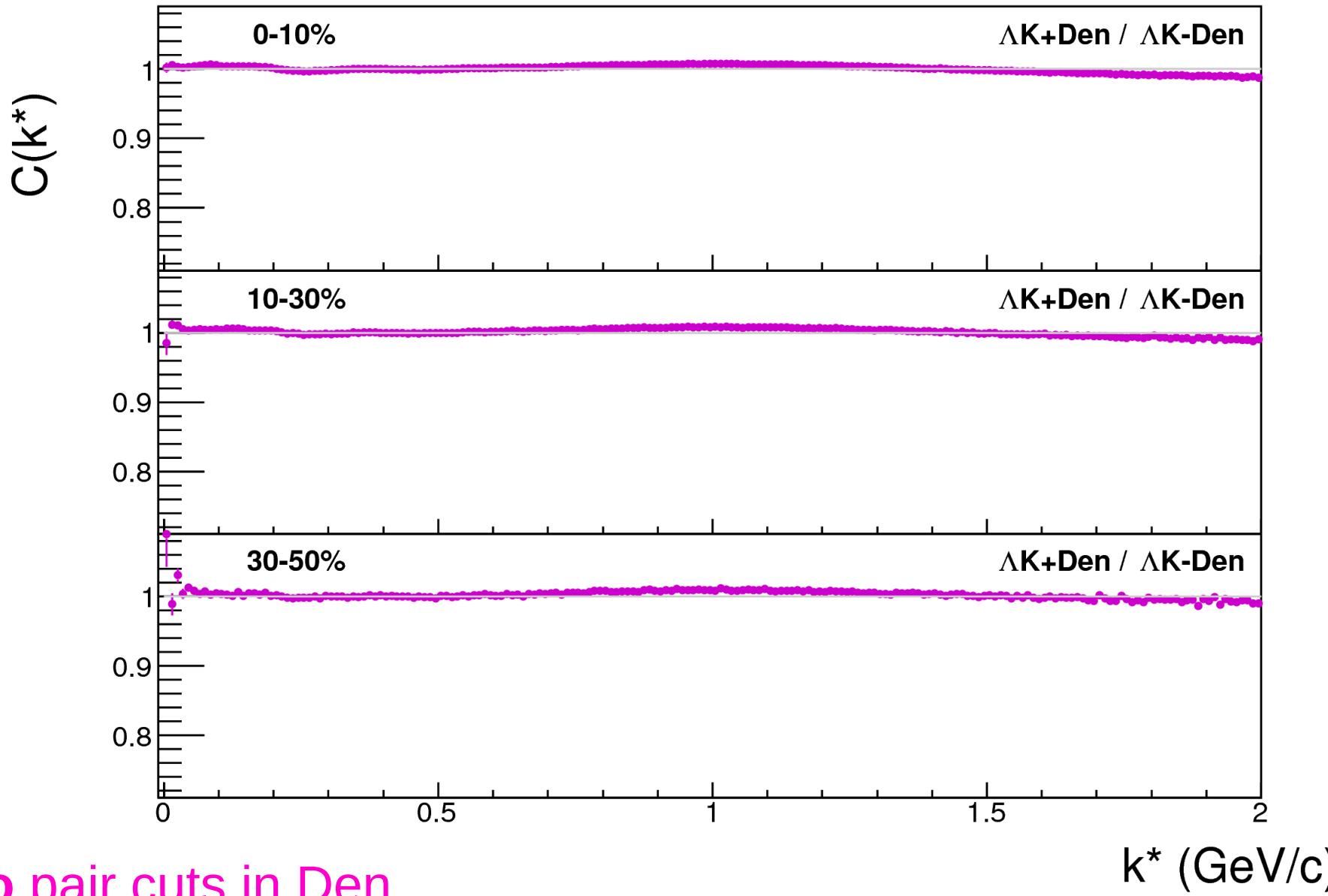


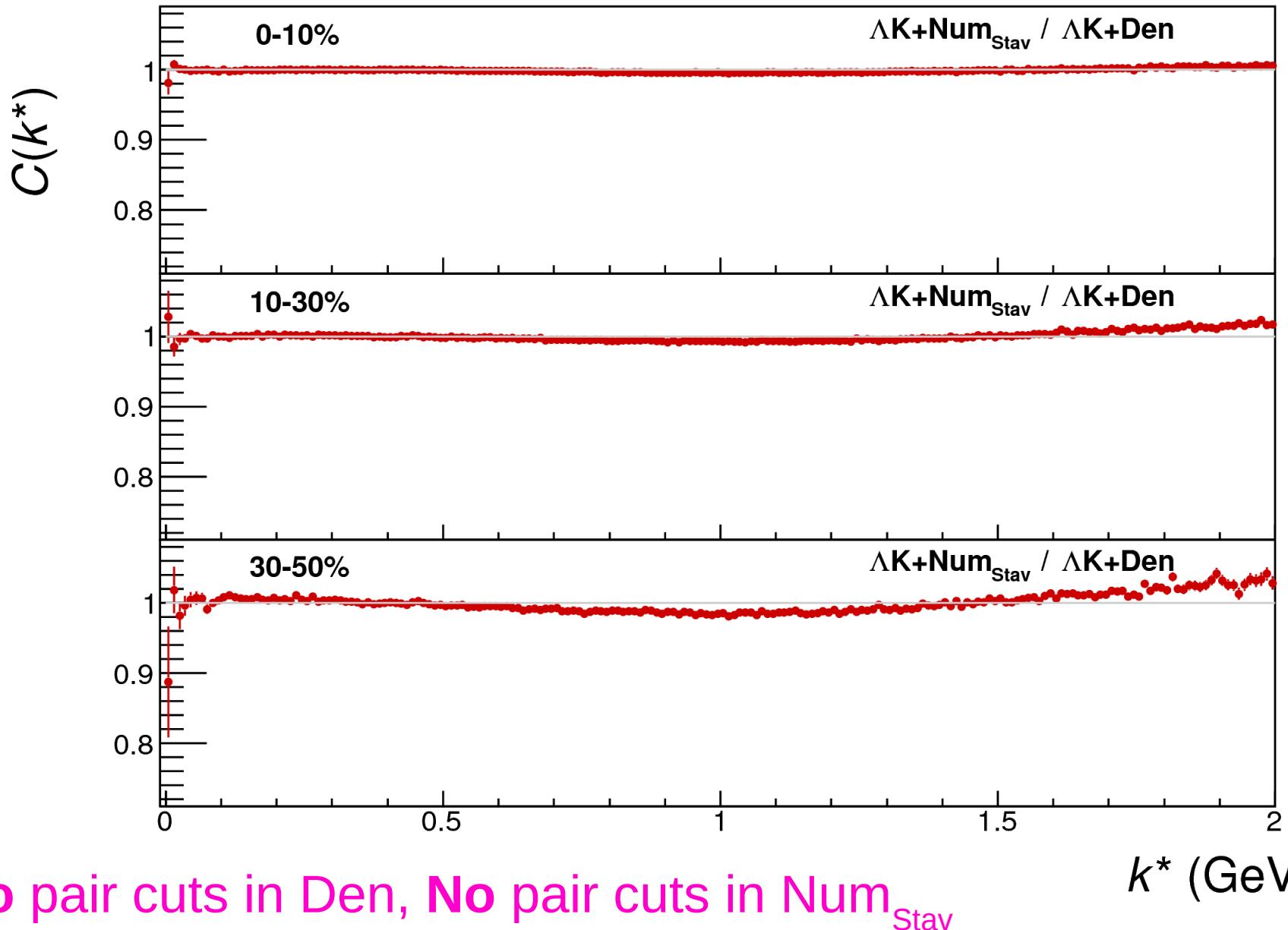
No additional pair cuts in Num_{Stav}

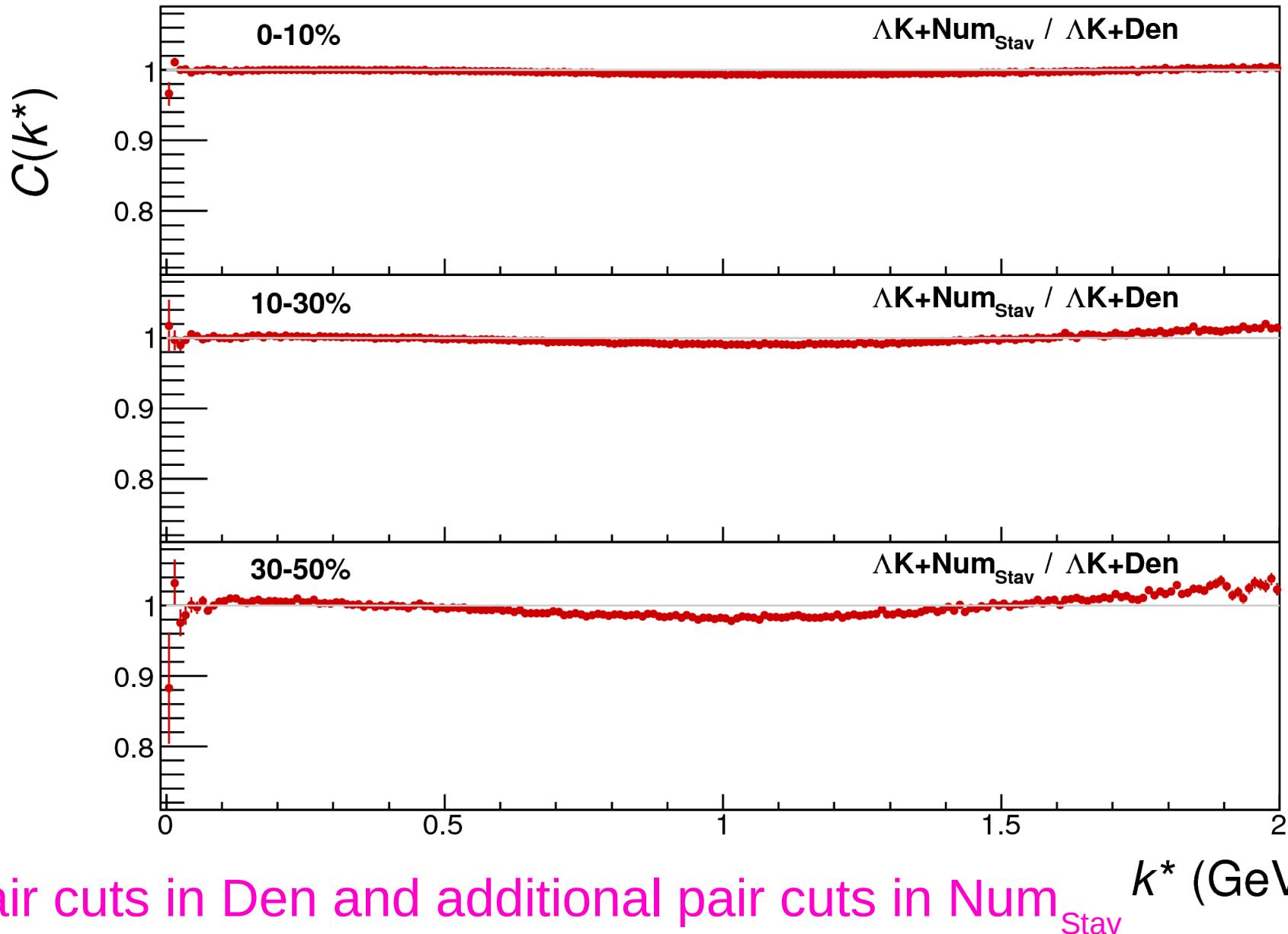


Normal pair cuts implemented in Den

$k^* (\text{GeV}/c)$







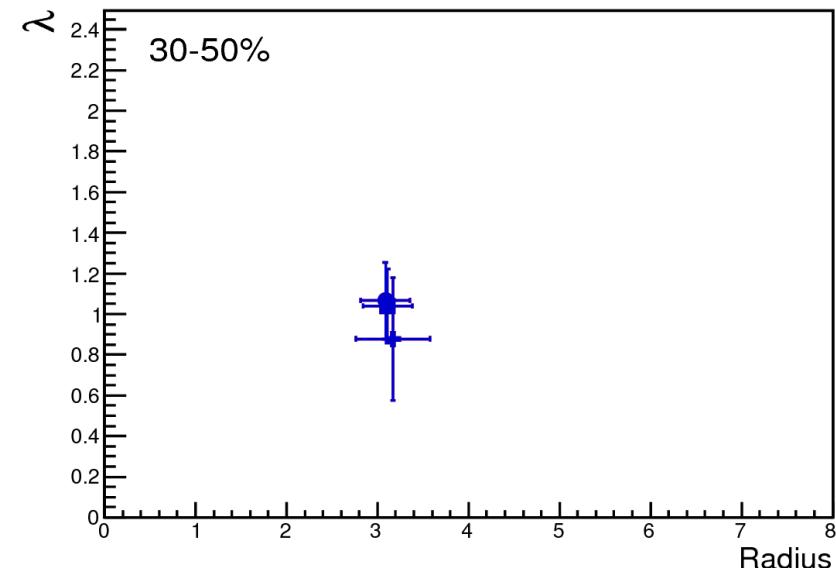
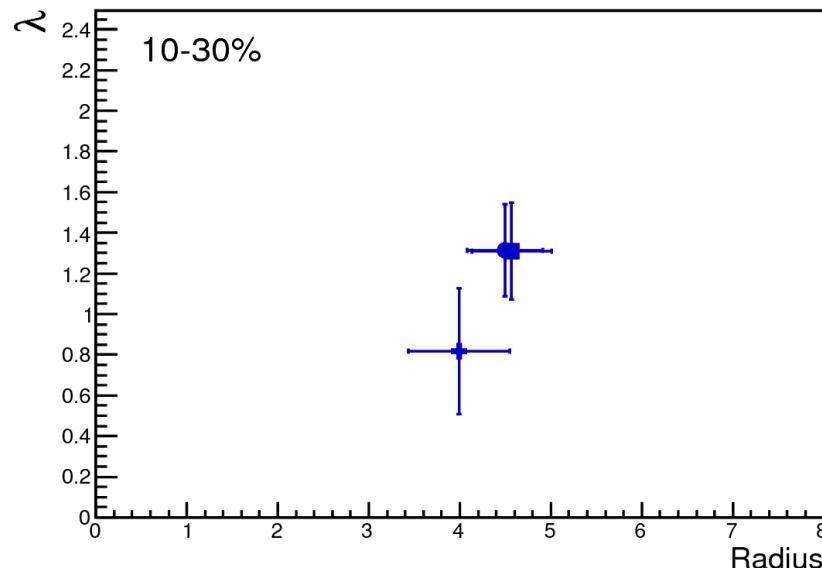
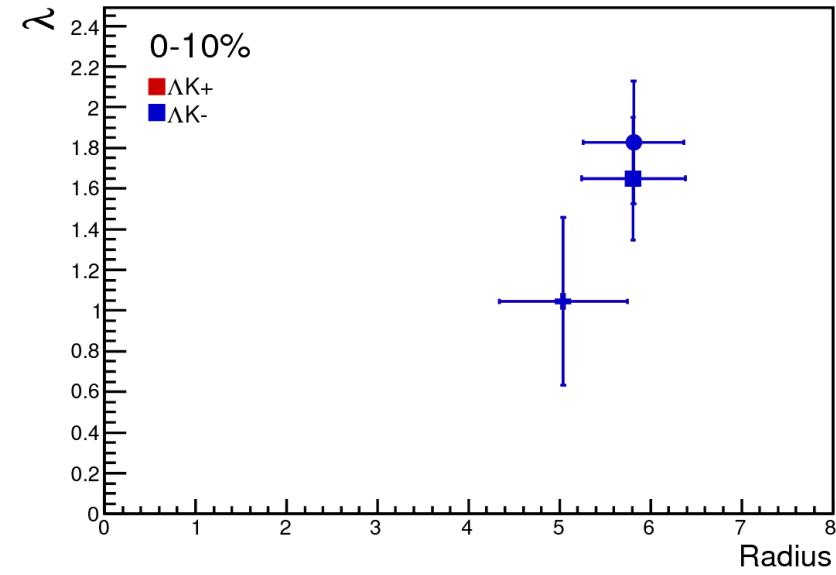
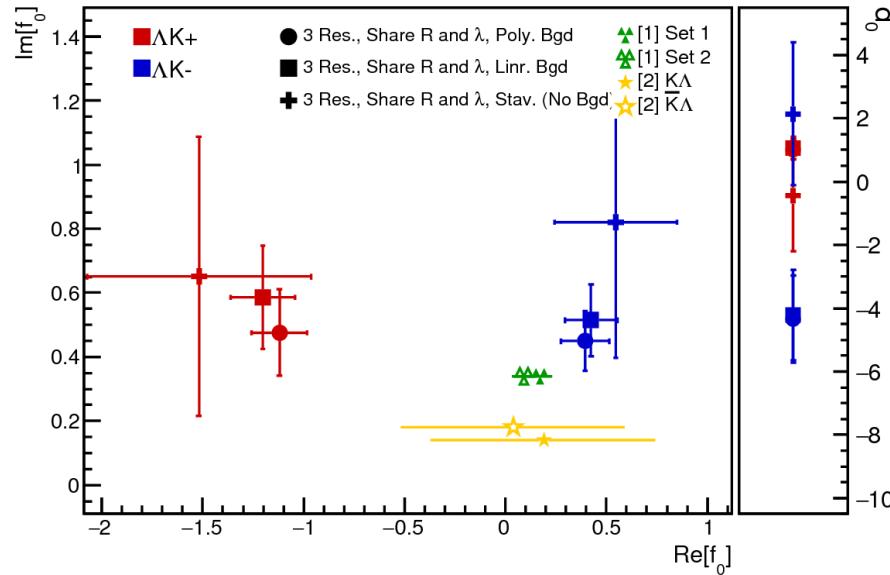
Fit Results: Parameter Plots and Tables

- Shared radii and shared, single, λ parameter for each centrality
- Poly. Bgd
 - Use THERMINATOR to model background with 6th-order polynomial
 - Scale model fit to data
 - Apply background as scale factor to fit
- Lin. Bgd
 - Use a linear form to model the background
 - Fit background to data, outside of signal region ($0.6 < k^* < 0.9$ GeV/c)
 - Apply background as scale factor to fit
- Stav.(No Bgd)
 - Use Stavinsky method
 - Assume no background in correlations

Centrality	System	Parameter	Methods		
			Poly. Bgd	Lin. Bgd	Stav.(No Bgd)
0-10%	ΛK^+	λ			
	$\bar{\Lambda} K^-$		1.83	1.65	1.05
	ΛK^-				
	$\bar{\Lambda} K^+$				
10-30%	$\Lambda K^+ & \bar{\Lambda} K^-$	R	5.81	5.81	5.04
	$\Lambda K^- & \bar{\Lambda} K^+$				
	ΛK^+		1.31	1.31	0.82
	$\bar{\Lambda} K^-$				
30-50%	ΛK^-	λ			
	$\bar{\Lambda} K^+$				
	$\Lambda K^+ & \bar{\Lambda} K^-$		4.50	4.57	3.99
	$\Lambda K^- & \bar{\Lambda} K^+$				
	ΛK^+	R	1.07	1.04	0.88
	$\bar{\Lambda} K^-$				
	ΛK^-				
	$\bar{\Lambda} K^+$				
	$\Lambda K^+ & \bar{\Lambda} K^-$	$\mathbb{R} f_0$	-1.12	-1.20	-1.52
	$\Lambda K^- & \bar{\Lambda} K^+$		0.48	0.59	0.65
	ΛK^+		1.01	1.07	-0.44
	$\bar{\Lambda} K^-$				
	$\Lambda K^+ & \bar{\Lambda} K^-$	$\mathbb{I} f_0$	0.39	0.42	0.55
	$\Lambda K^- & \bar{\Lambda} K^+$		0.45	0.51	0.82
	ΛK^+		-4.35	-4.22	2.14
	$\bar{\Lambda} K^-$				

Fits in BACKUP slides

Shared R, shared λ

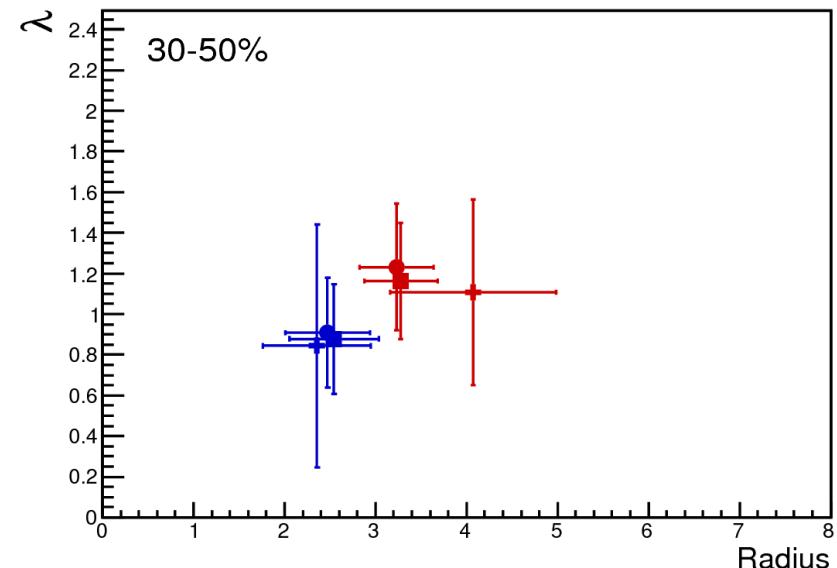
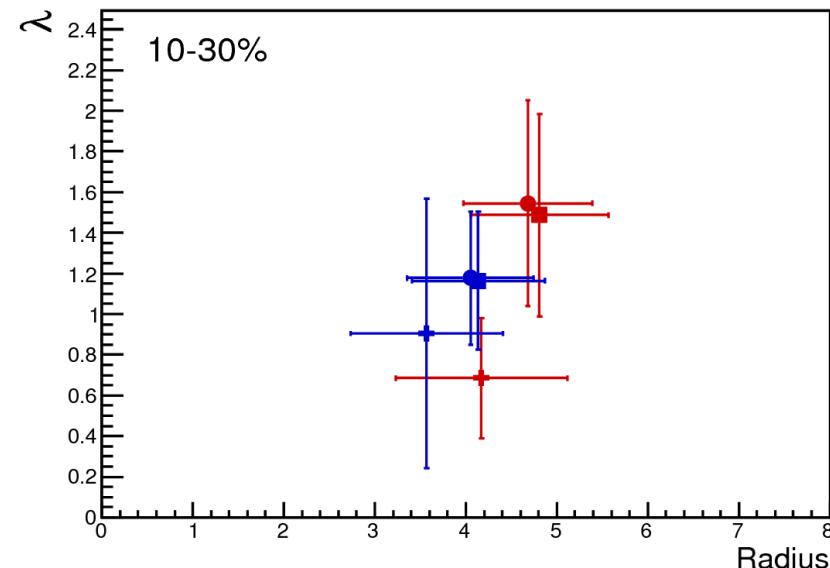
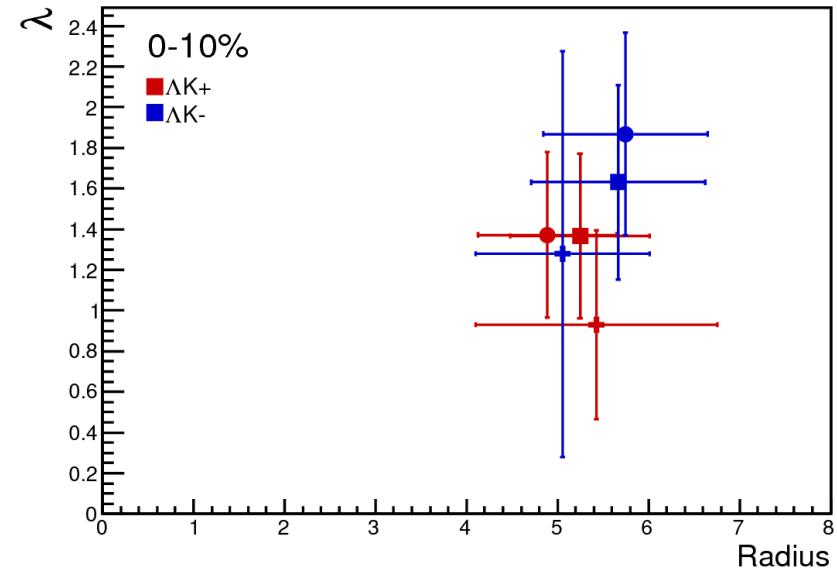
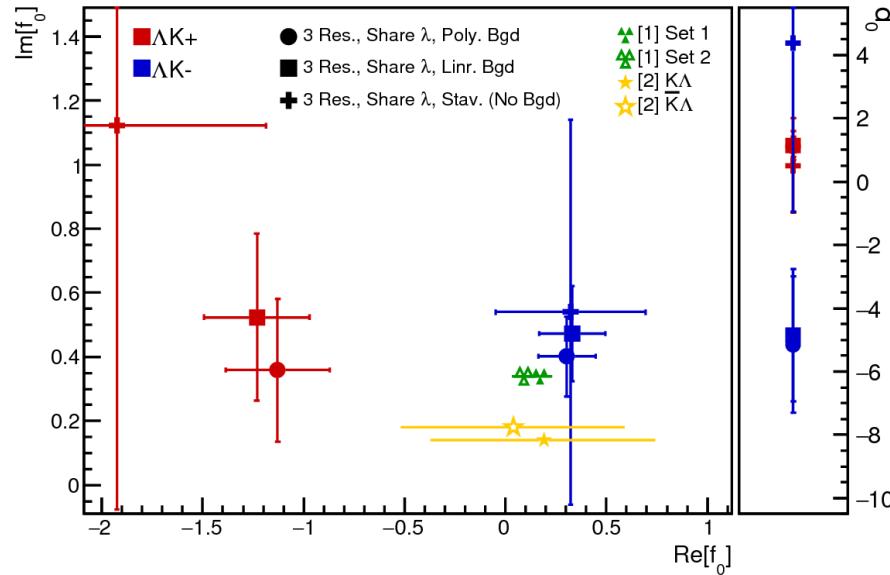


- Separate radii and shared λ parameter for pair & conjugate for each centrality
- Poly. Bgd
 - Use THERMINATOR to model background with 6th-order polynomial
 - Scale model fit to data
 - Apply background as scale factor to fit
- Lin. Bgd
 - Use a linear form to model the background
 - Fit background to data, outside of signal region ($0.6 < k^* < 0.9$ GeV/c)
 - Apply background as scale factor to fit
- Stav.(No Bgd)
 - Use Stavinsky method
 - Assume no background in correlations

Centrality	System	Parameter	Methods		
			Poly. Bgd	Lin. Bgd	Stav.(No Bgd)
0-10%	ΛK^+ $\bar{\Lambda} K^-$	λ	1.37	1.37	0.93
	ΛK^- $\bar{\Lambda} K^+$	λ	1.87	1.63	1.28
	$\Lambda K^+ & \bar{\Lambda} K^-$	R	4.89	5.25	5.43
	$\Lambda K^- & \bar{\Lambda} K^+$	R	5.75	5.67	5.06
10-30%	ΛK^+ $\bar{\Lambda} K^-$	λ	1.54	1.49	0.68
	ΛK^- $\bar{\Lambda} K^+$	λ	1.18	1.16	0.90
	$\Lambda K^+ & \bar{\Lambda} K^-$	R	4.68	4.81	4.17
	$\Lambda K^- & \bar{\Lambda} K^+$	R	4.05	4.14	3.57
30-50%	ΛK^+ $\bar{\Lambda} K^-$	λ	1.23	1.16	1.11
	ΛK^- $\bar{\Lambda} K^+$	λ	0.91	0.88	0.84
	$\Lambda K^+ & \bar{\Lambda} K^-$	R	3.23	3.28	4.07
	$\Lambda K^- & \bar{\Lambda} K^+$	R	2.47	2.54	2.36
	$\Lambda K^+ & \bar{\Lambda} K^-$	$\mathbb{R}f_0$	-1.13	-1.23	-1.92
		$\mathbb{I}f_0$	0.36	0.52	1.12
		d_0	1.11	1.14	0.51
	$\Lambda K^- & \bar{\Lambda} K^+$	$\mathbb{R}f_0$	0.30	0.33	0.32
		$\mathbb{I}f_0$	0.40	0.47	0.54
		d_0	-5.15	-4.85	4.36

Fits in BACKUP slides

Separate R, shared λ



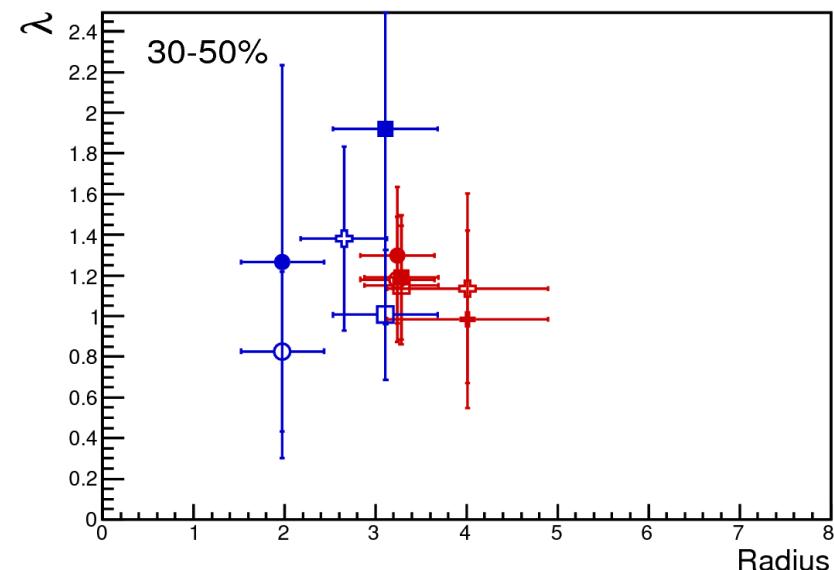
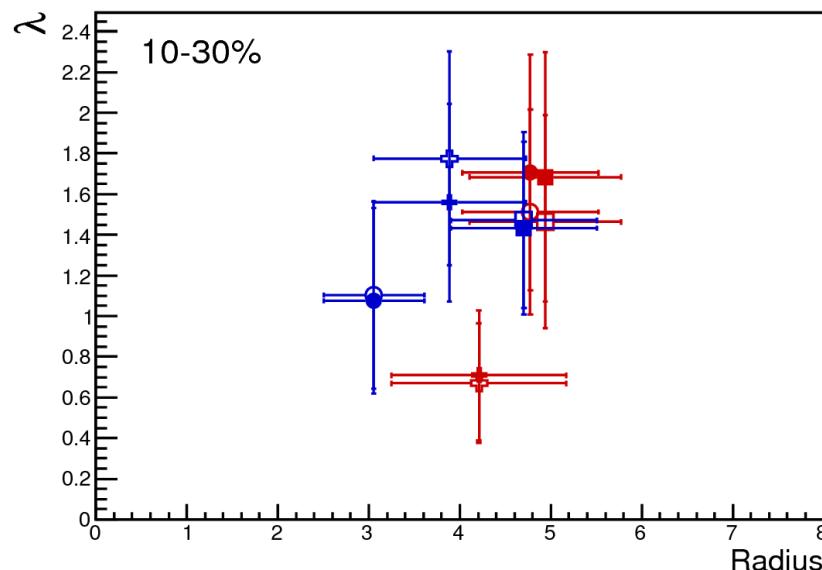
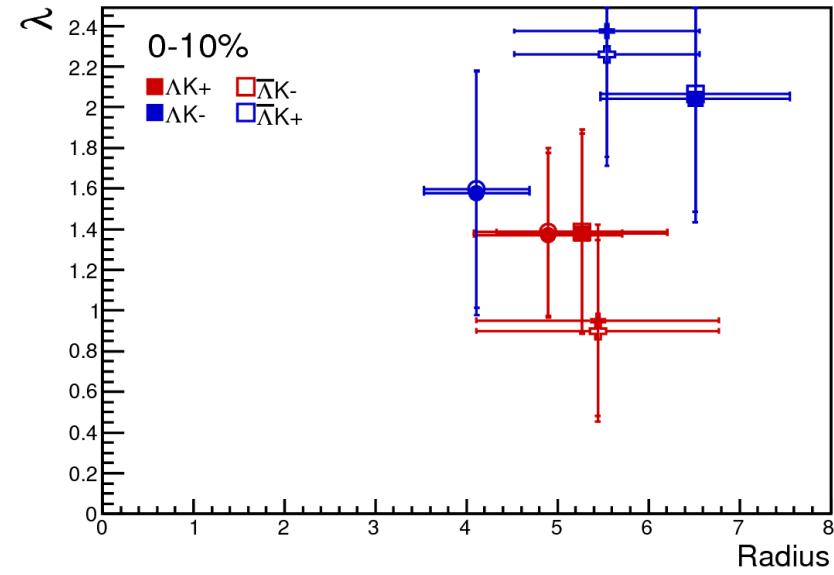
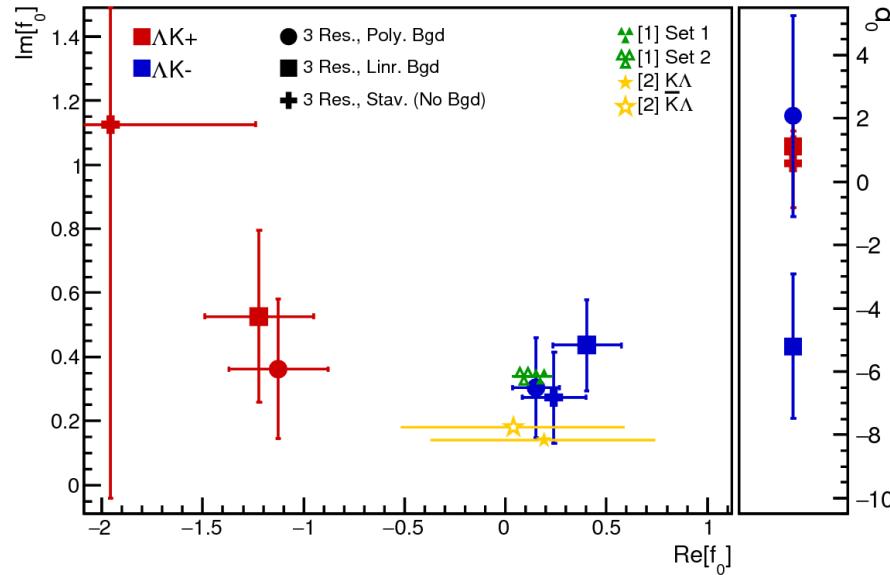
Comparing Bgd Treatments

- Separate radii and unique λ parameter for all
- Poly. Bgd
 - Use THERMINATOR to model background with 6th-order polynomial
 - Scale model fit to data
 - Apply background as scale factor to fit
- Lin. Bgd
 - Use a linear form to model the background
 - Fit background to data, outside of signal region ($0.6 < k^* < 0.9$ GeV/c)
 - Apply background as scale factor to fit
- Stav.(No Bgd)
 - Use Stavinsky method
 - Assume no background in correlations

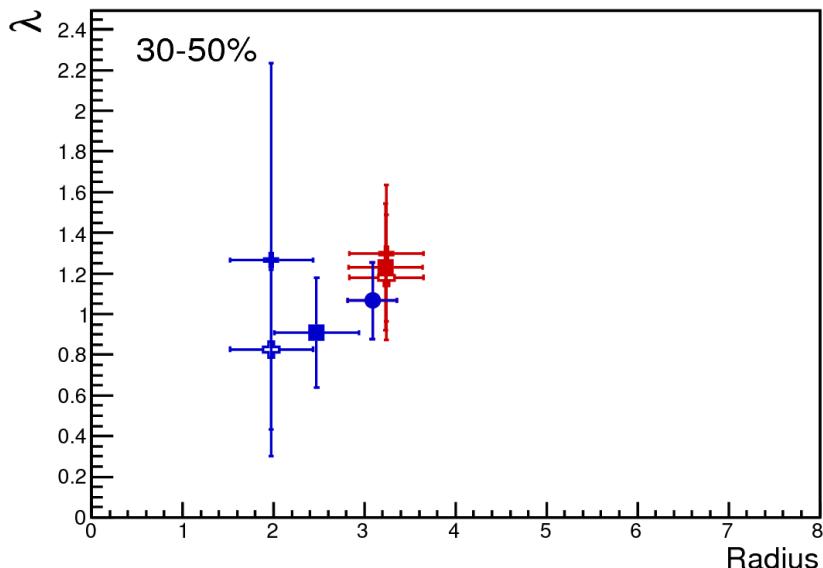
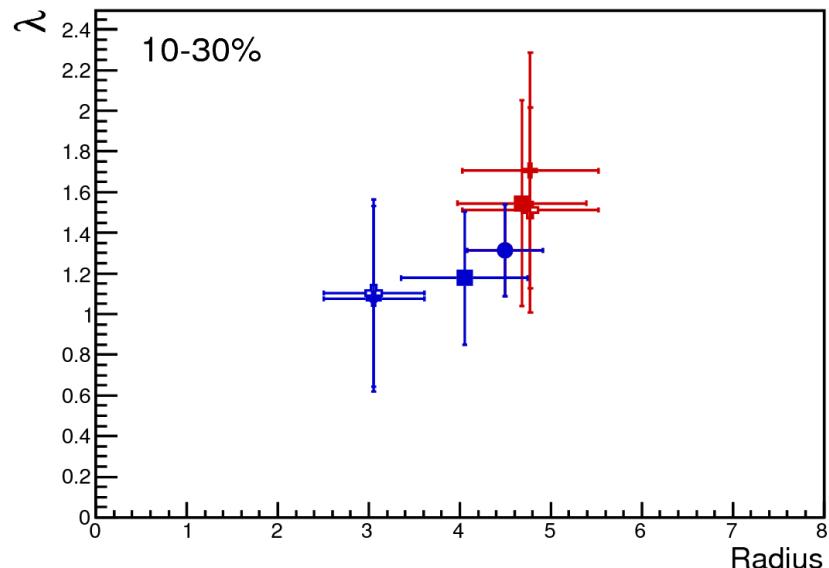
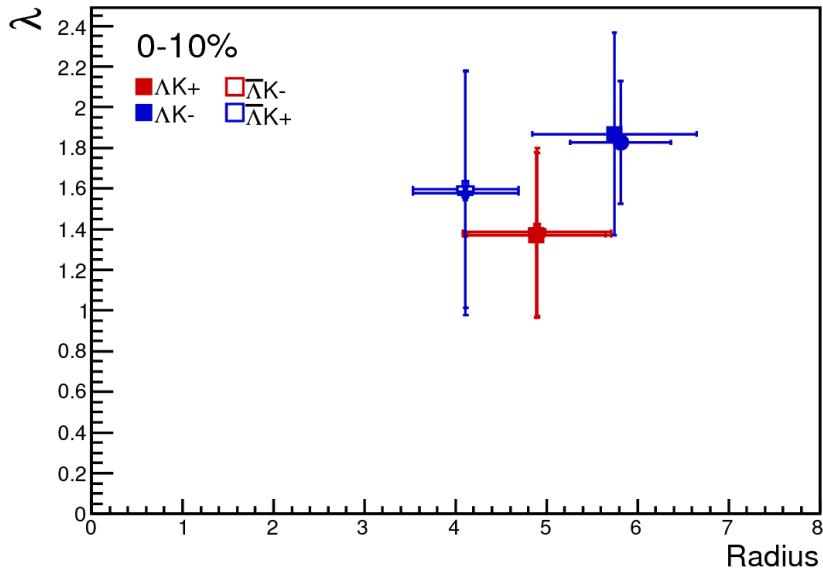
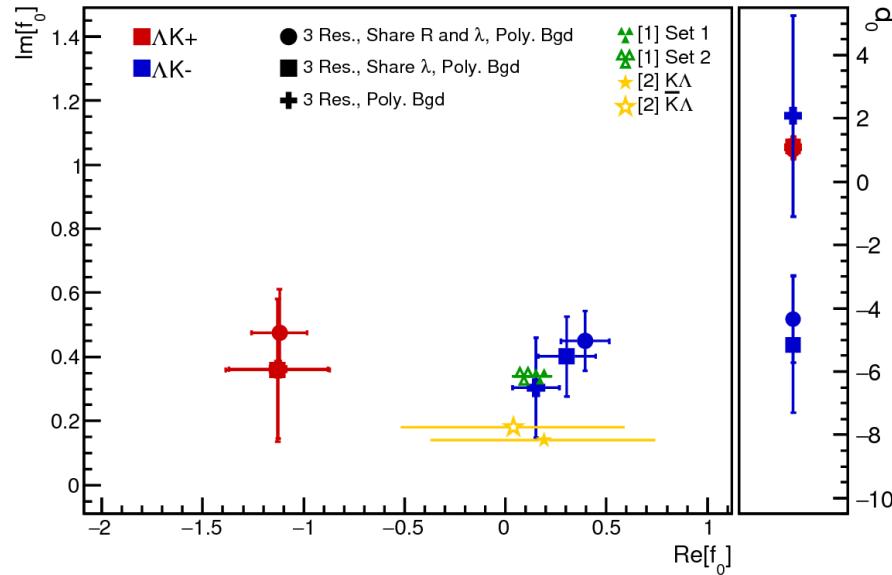
Centrality	System	Parameter	Methods		
			Poly. Bgd	Lin. Bgd	Stav.(No Bgd)
0-10%	ΛK^+	λ	1.37	1.38	0.95
	$\bar{\Lambda} K^-$	λ	1.39	1.39	0.90
	ΛK^-	λ	1.58	2.04	2.38
	$\bar{\Lambda} K^+$	λ	1.60	2.07	2.26
	$\Lambda K^+ & \bar{\Lambda} K^-$	R	4.90	5.27	5.44
	$\Lambda K^- & \bar{\Lambda} K^+$	R	4.11	6.51	5.54
10-30%	ΛK^+	λ	1.70	1.68	0.71
	$\bar{\Lambda} K^-$	λ	1.51	1.46	0.67
	ΛK^-	λ	1.08	1.43	1.56
	$\bar{\Lambda} K^+$	λ	1.10	1.47	1.77
	$\Lambda K^+ & \bar{\Lambda} K^-$	R	4.78	4.94	4.21
	$\Lambda K^- & \bar{\Lambda} K^+$	R	3.05	4.70	3.89
30-50%	ΛK^+	λ	1.30	1.19	0.98
	$\bar{\Lambda} K^-$	λ	1.18	1.15	1.14
	ΛK^-	λ	1.27	1.92	4.14
	$\bar{\Lambda} K^+$	λ	0.83	1.01	1.38
	$\Lambda K^+ & \bar{\Lambda} K^-$	R	3.24	3.28	4.01
	$\Lambda K^- & \bar{\Lambda} K^+$	R	1.98	3.11	2.65
	$\Lambda K^+ & \bar{\Lambda} K^-$	$\mathbb{R}f_0$	-1.13	-1.22	-1.96
		$\mathbb{I}f_0$	0.36	0.53	1.13
		d_0	1.09	1.12	0.58
	$\Lambda K^- & \bar{\Lambda} K^+$	$\mathbb{R}f_0$	0.15	0.40	0.24
		$\mathbb{I}f_0$	0.30	0.44	0.27
		d_0	2.07	-5.20	6.28

Fits in BACKUP slides

Separate R, separate λ



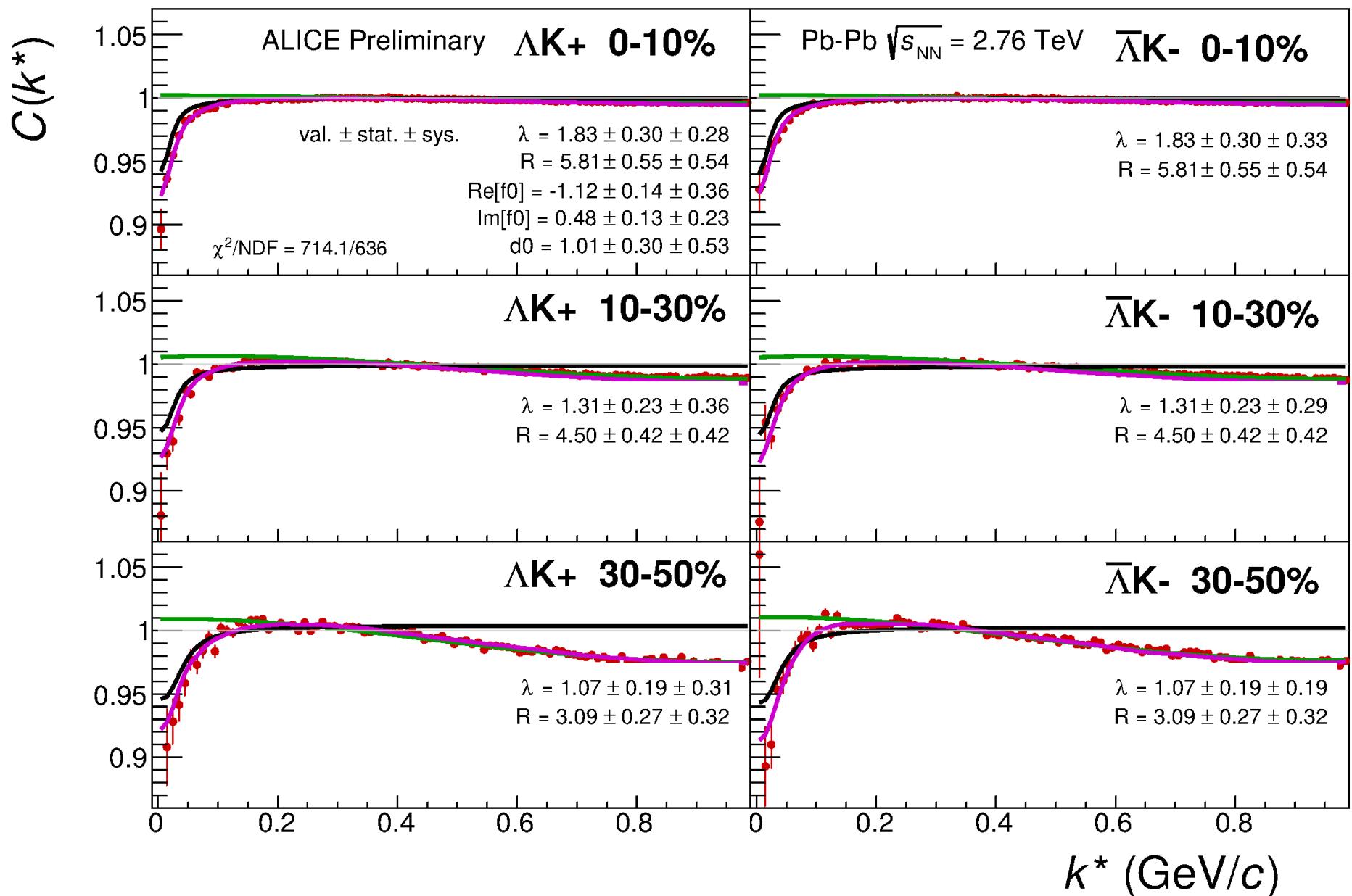
Separate vs Shared R

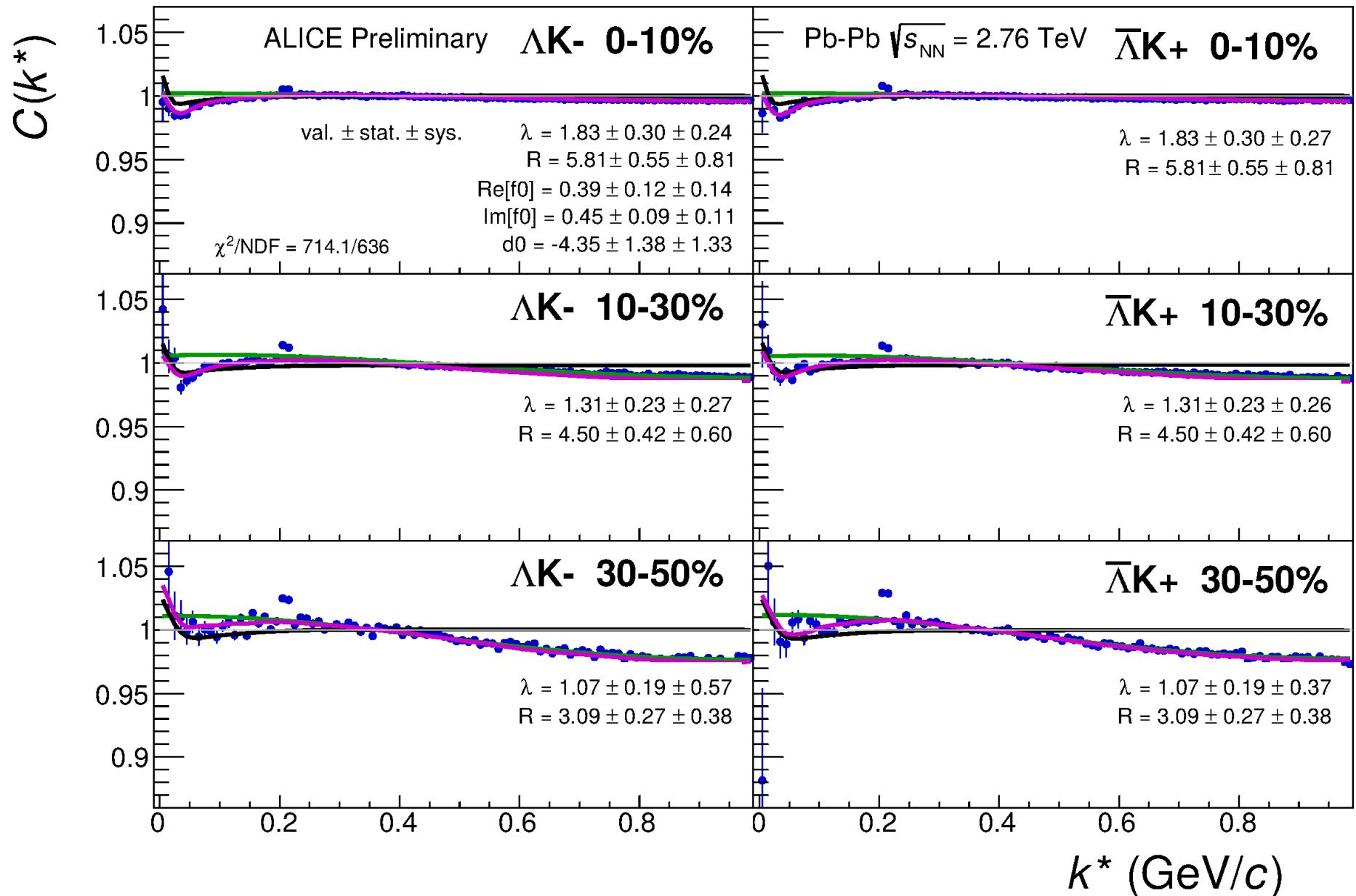


Fit Results: Separate Radii, separate λ

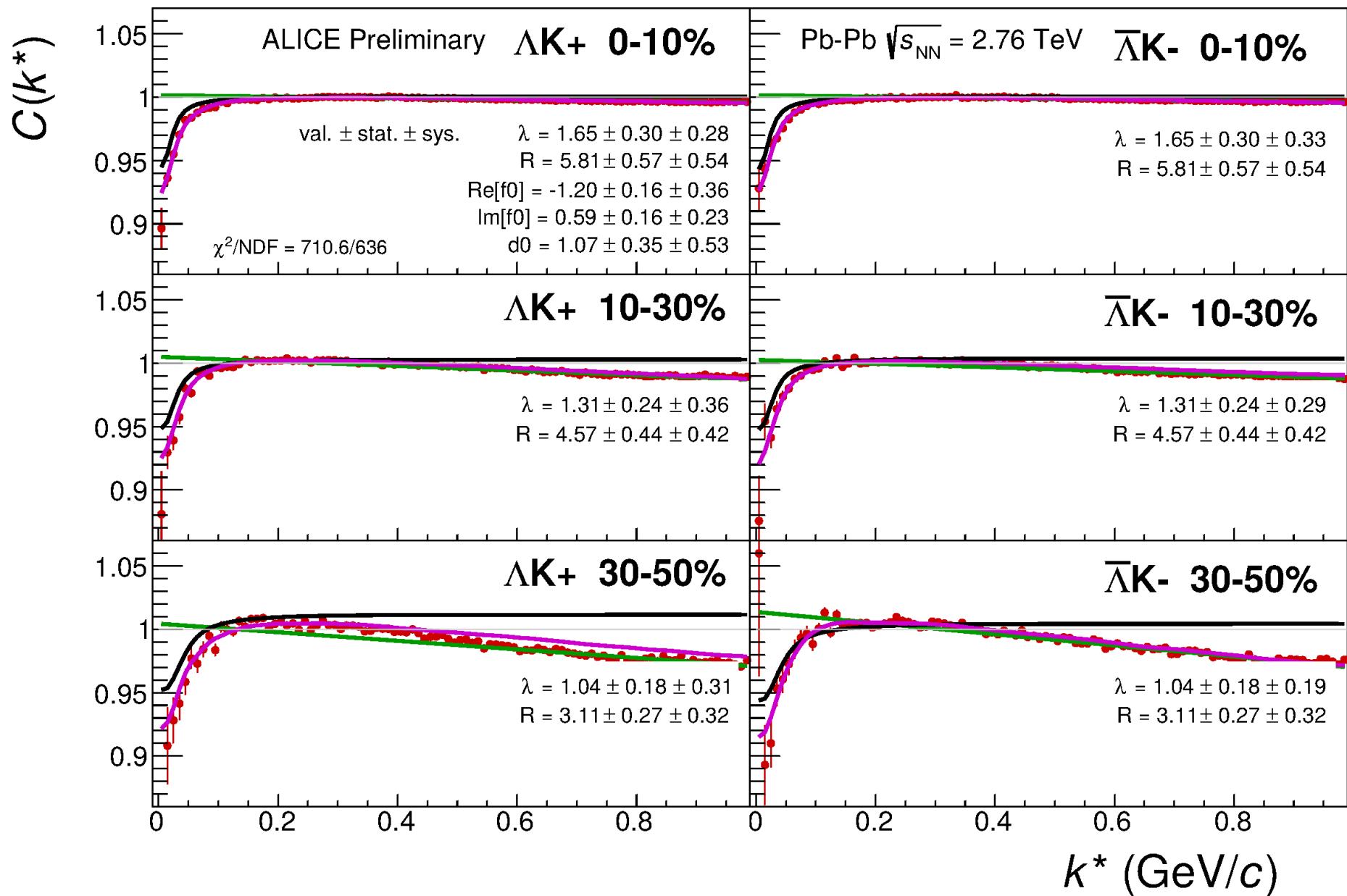
Fit Results: Shared Radii, shared λ

Share R, share λ , Poly. Bgd

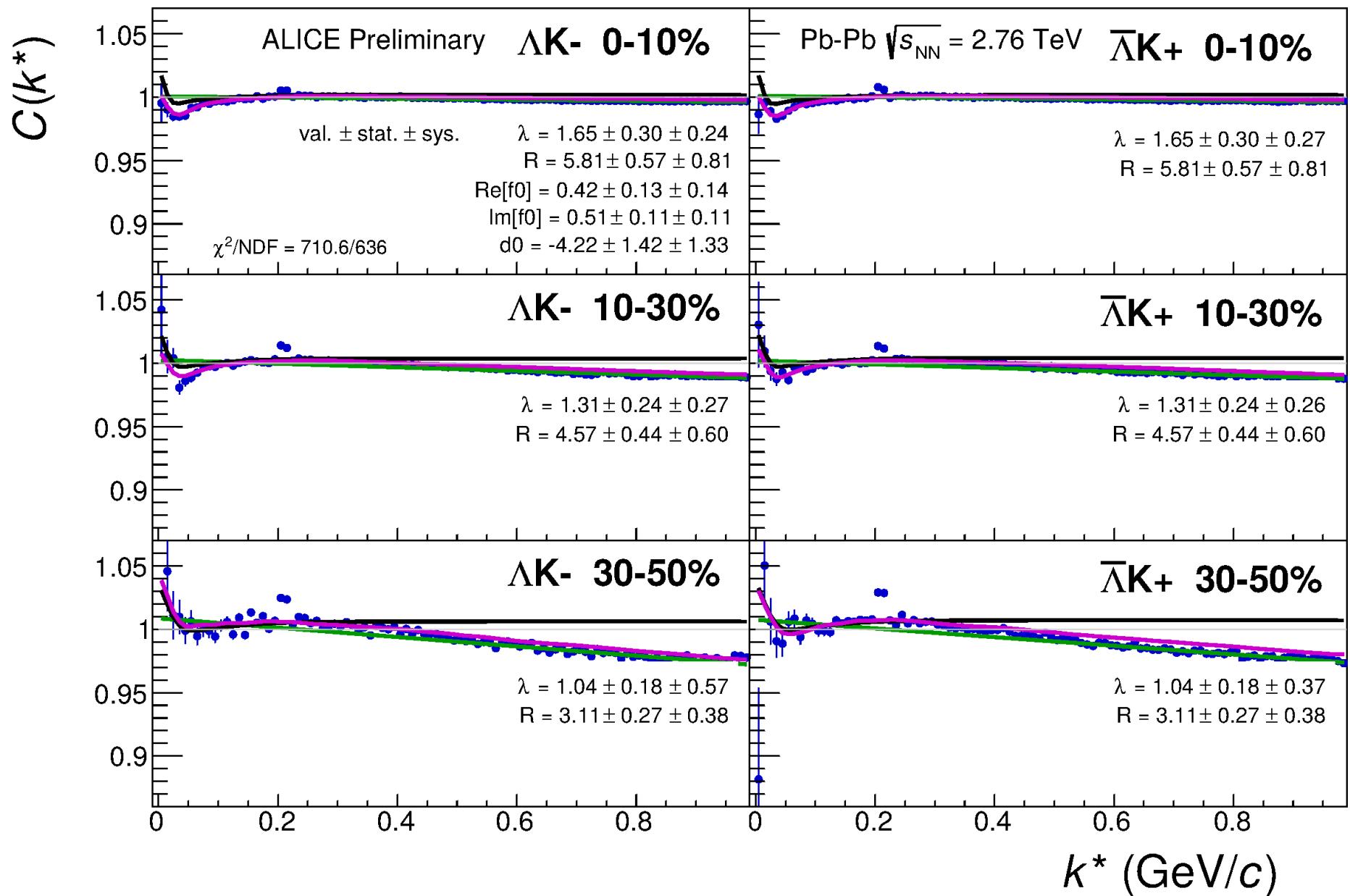




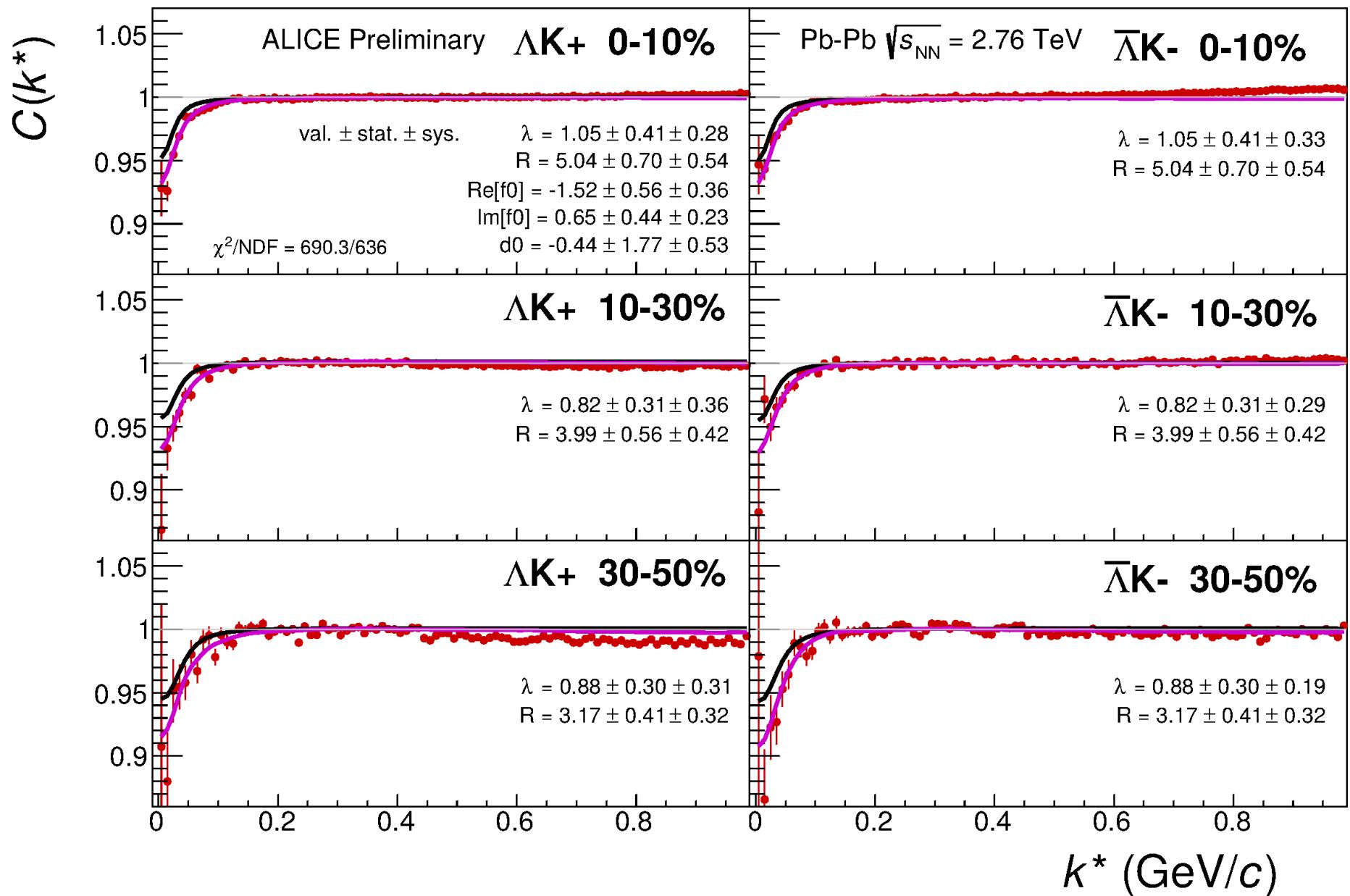
Share R, share λ , Lin. Bgd



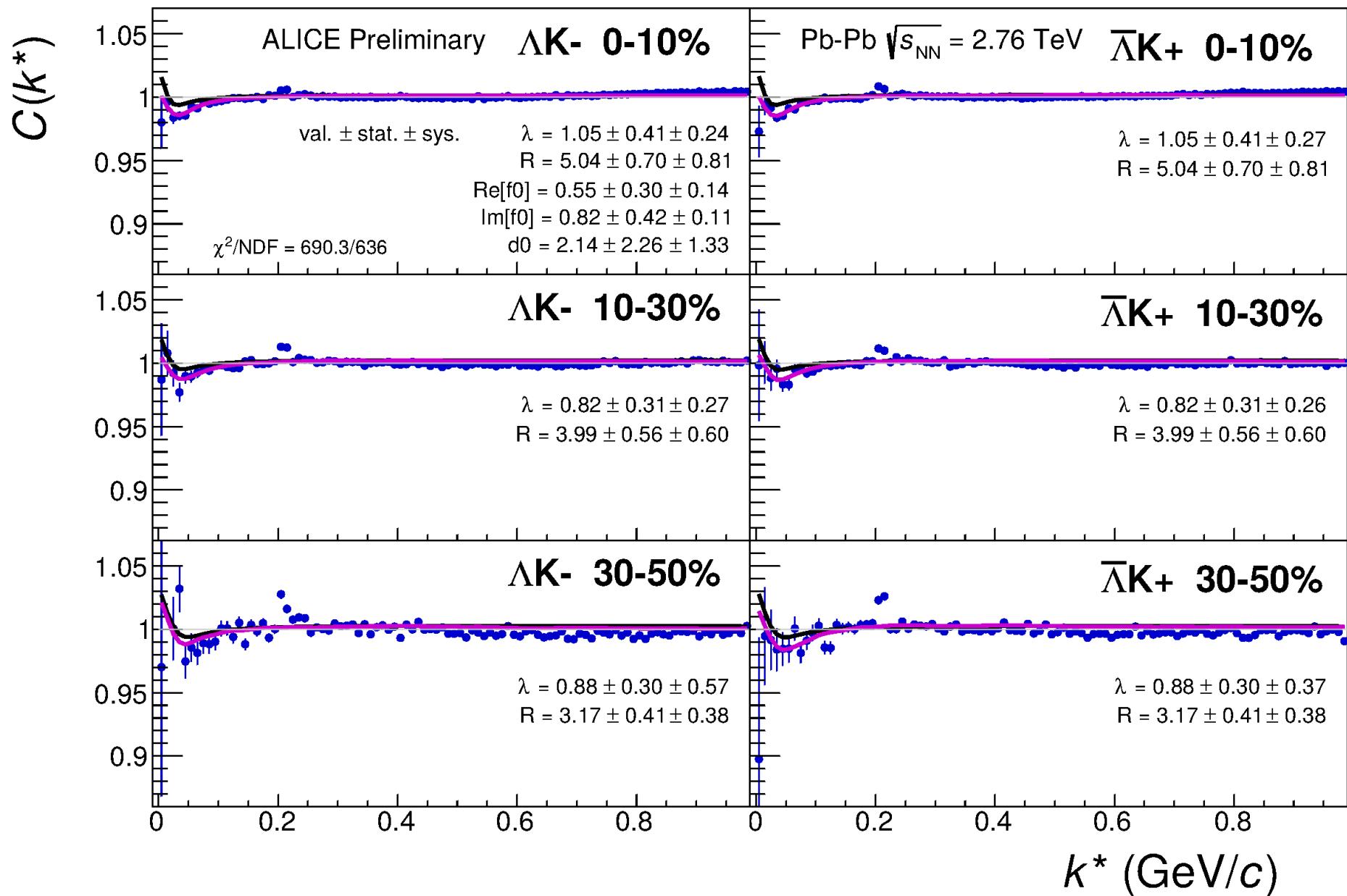
Share R, share λ , Lin. Bgd



Share R, share λ , Stav.(No Bgd)

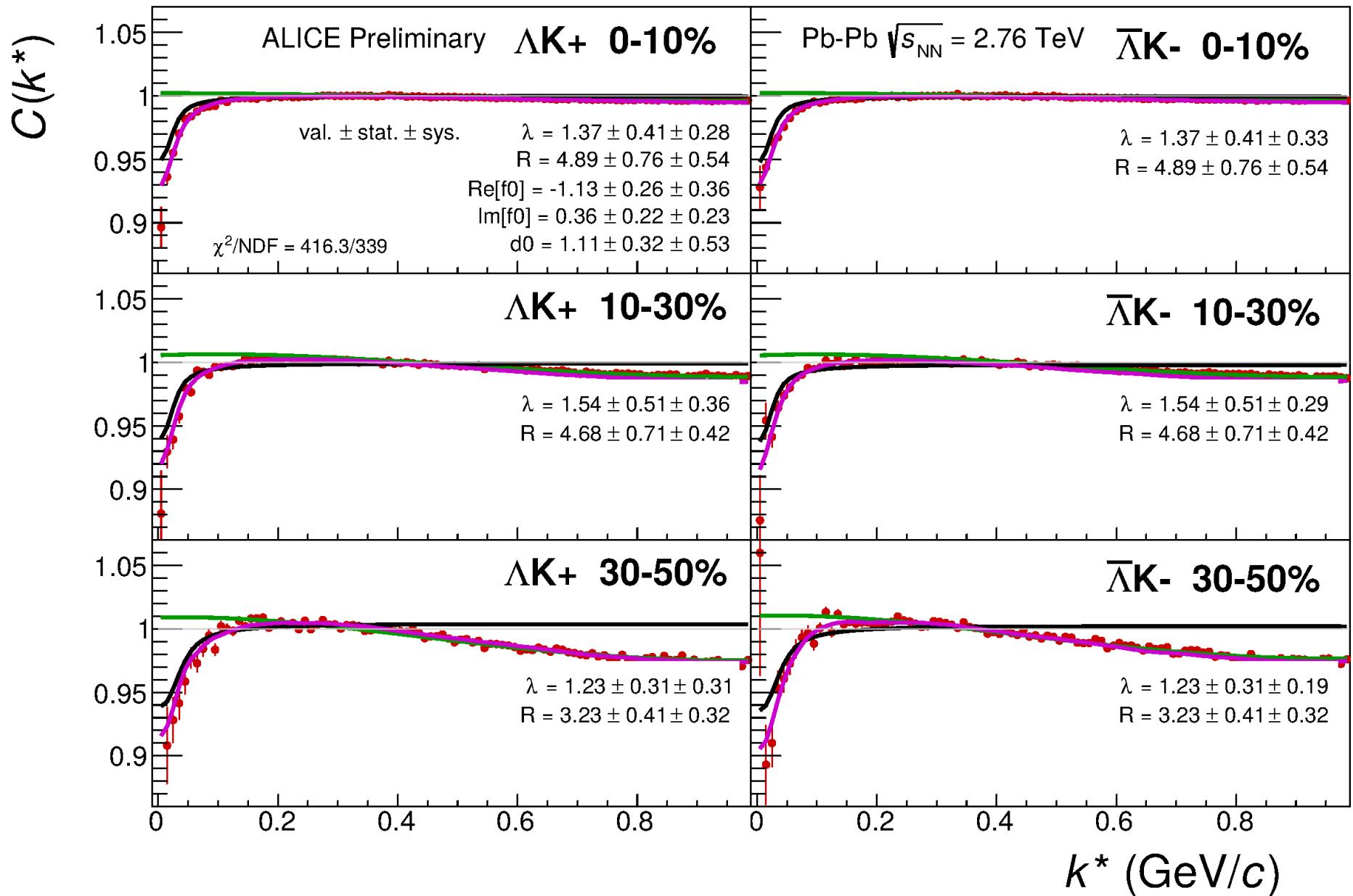


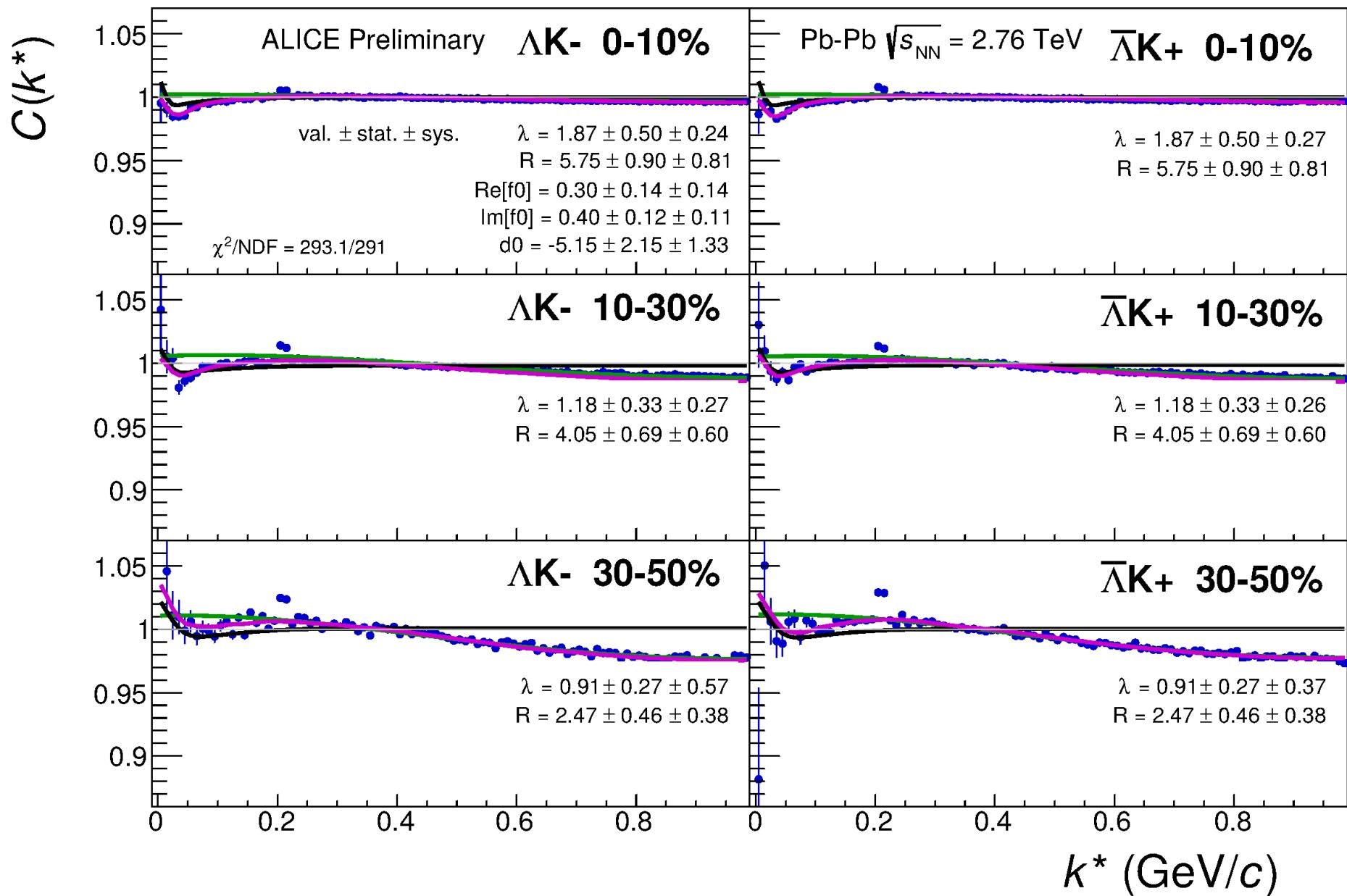
Share R, share λ , Stav.(No Bgd)

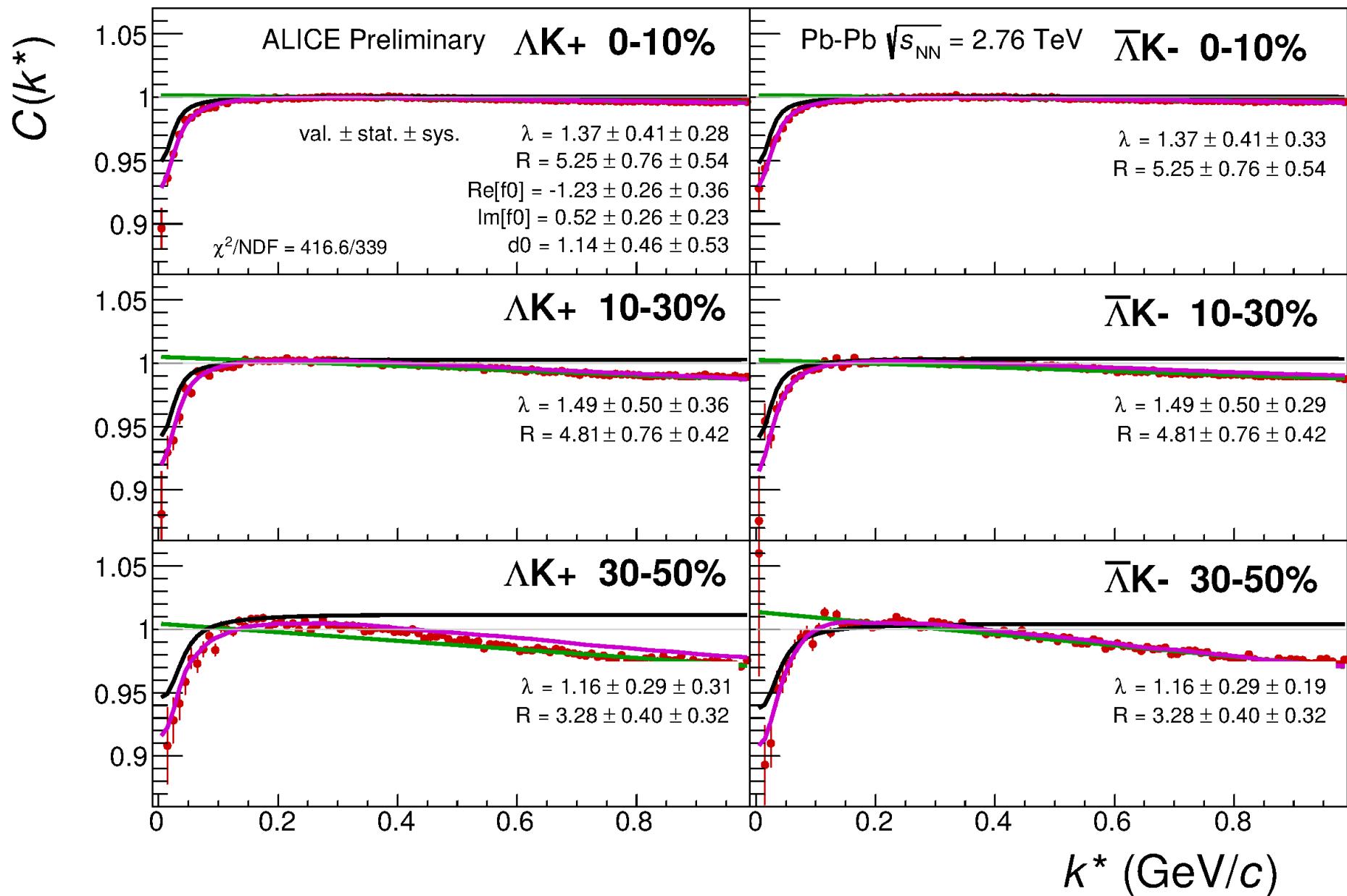


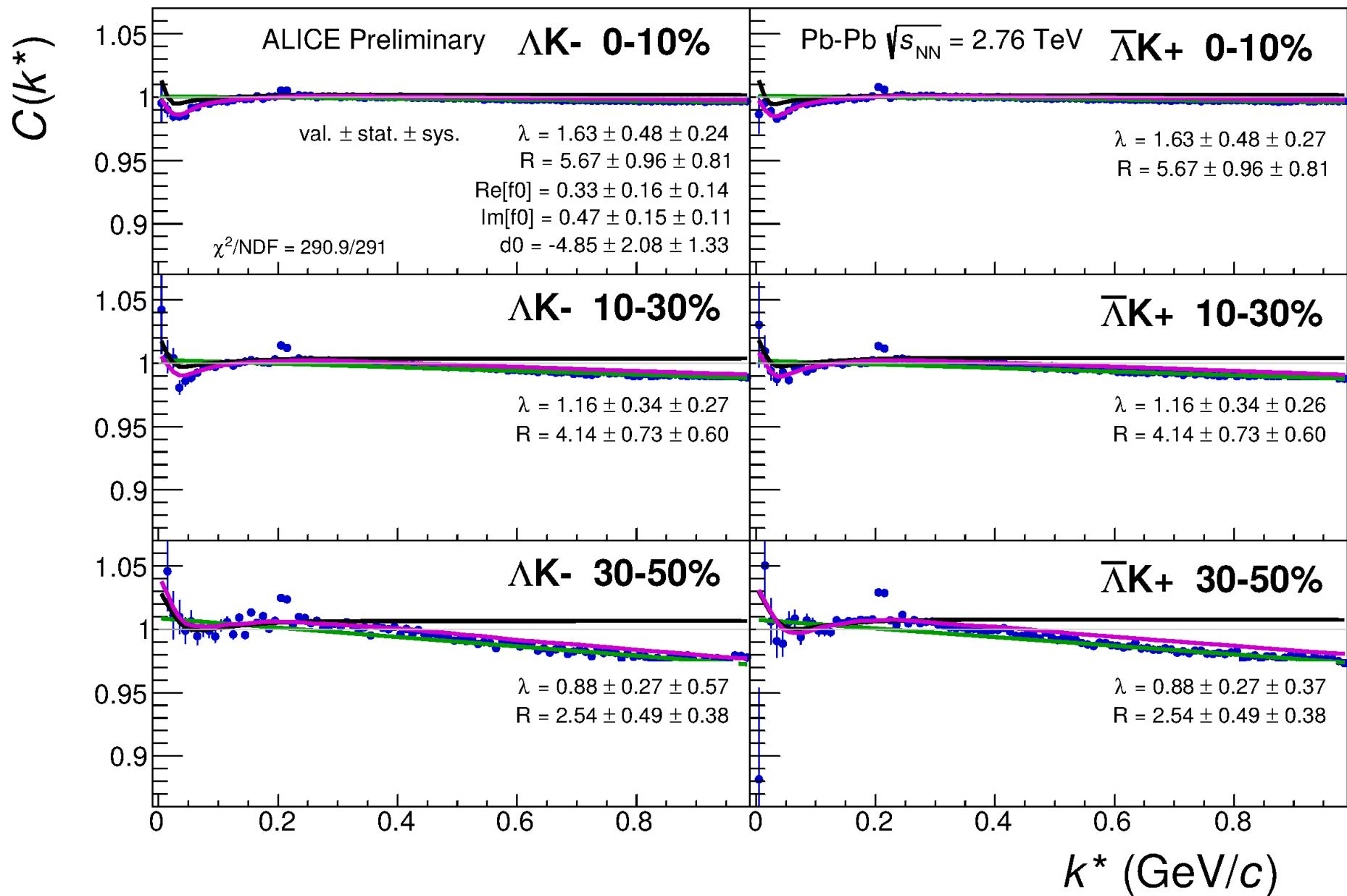
Fit Results: Separate Radii, shared λ

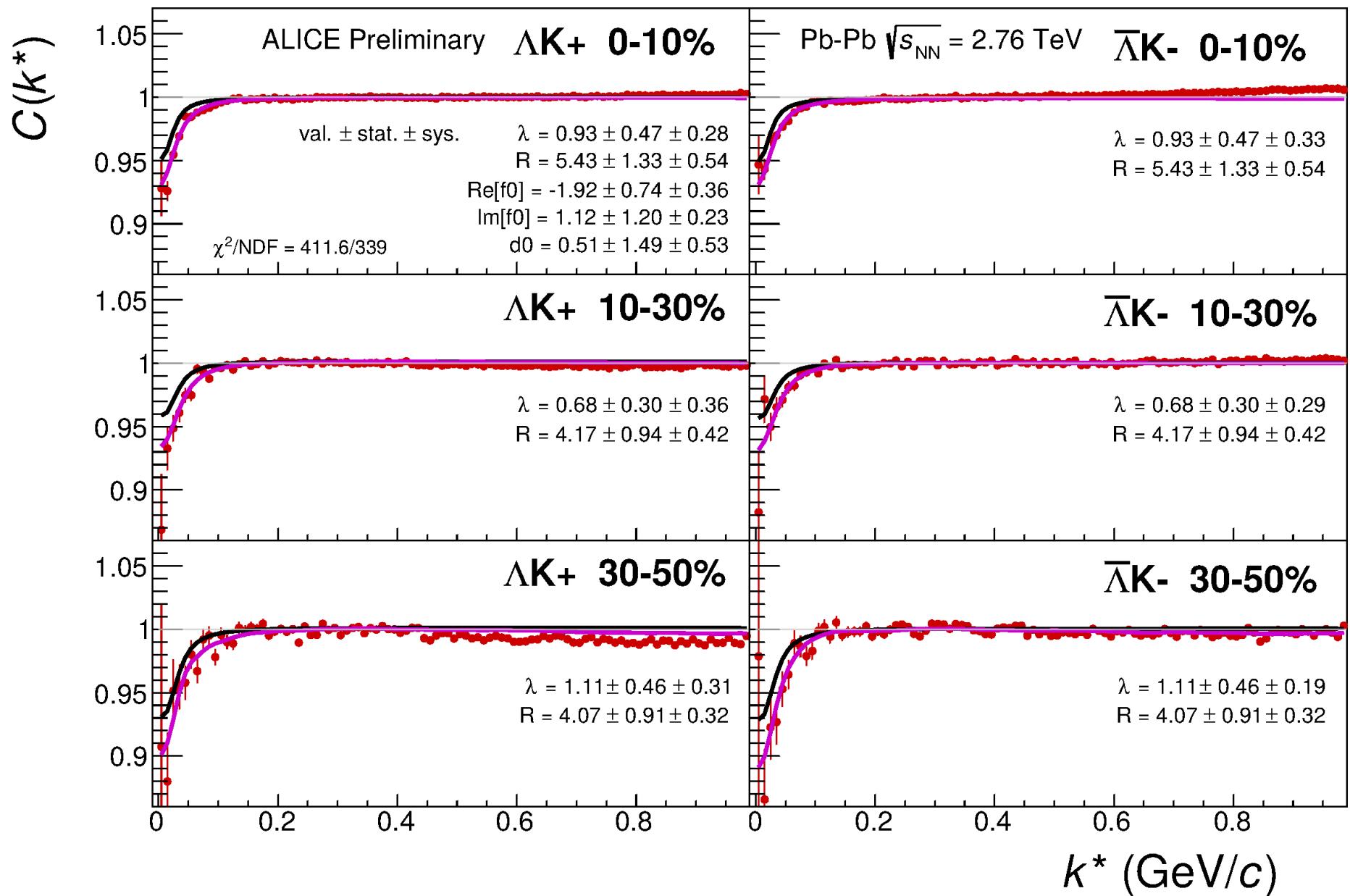
Sep. R, share λ , Poly. Bgd



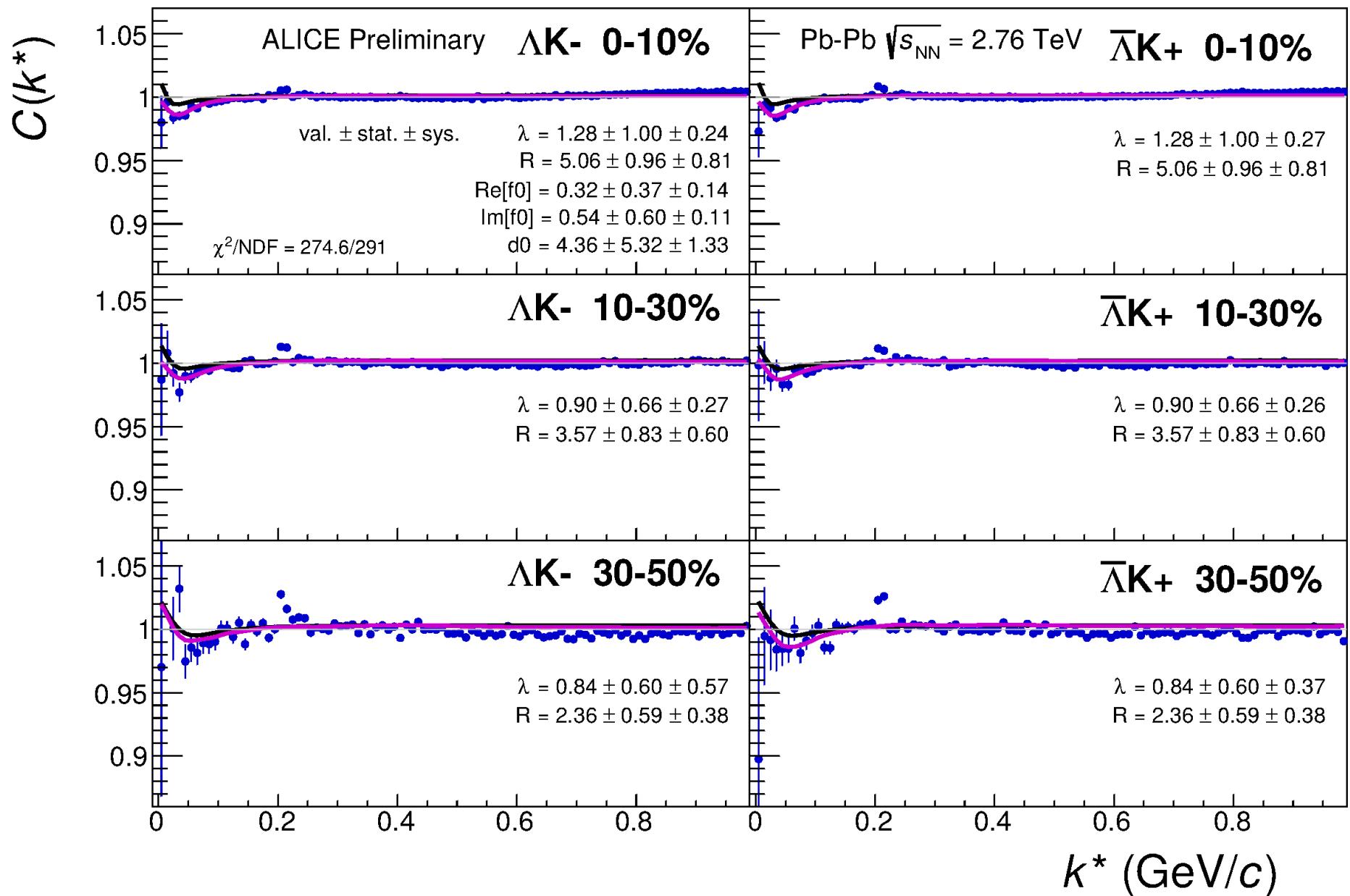




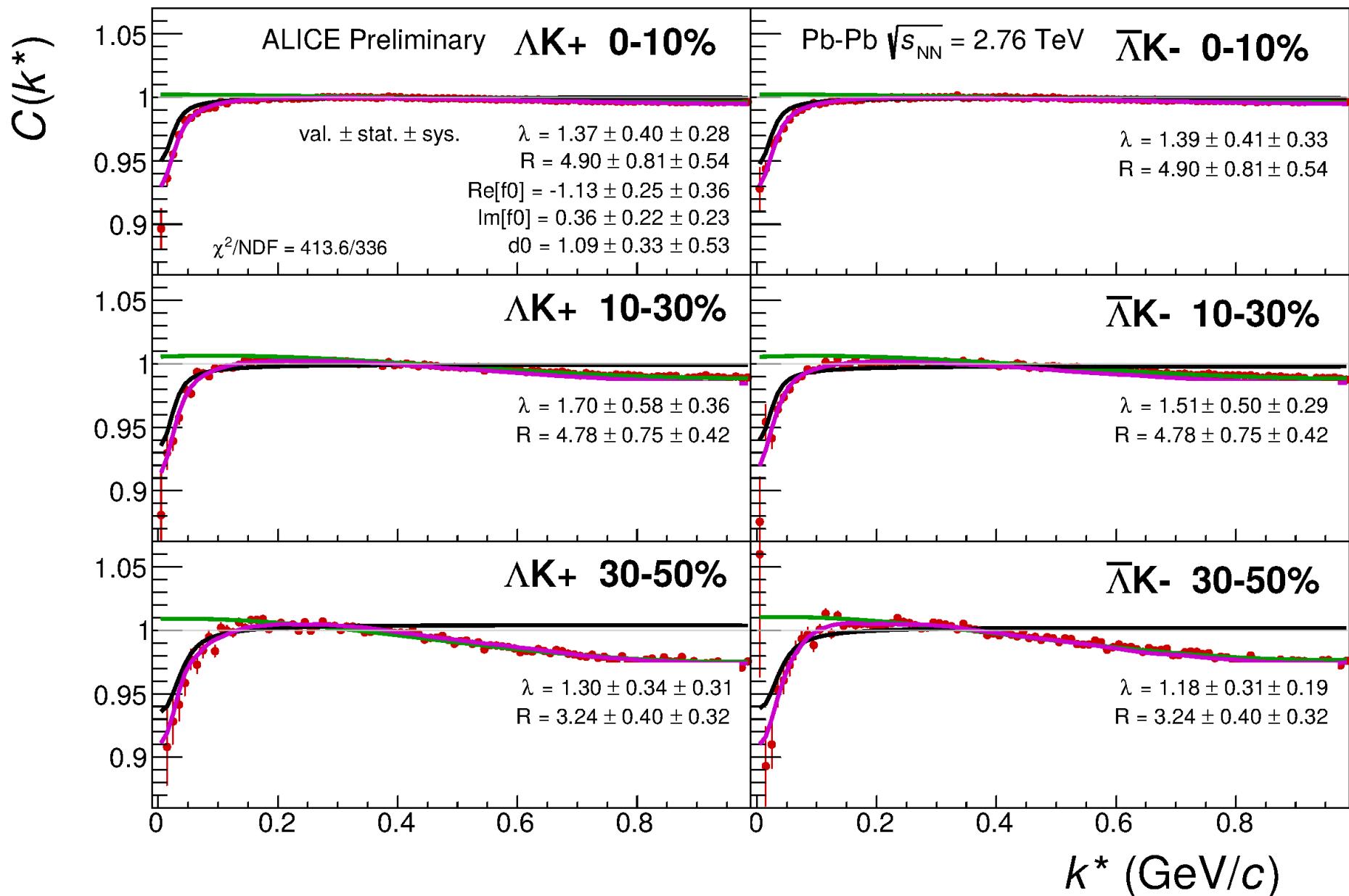


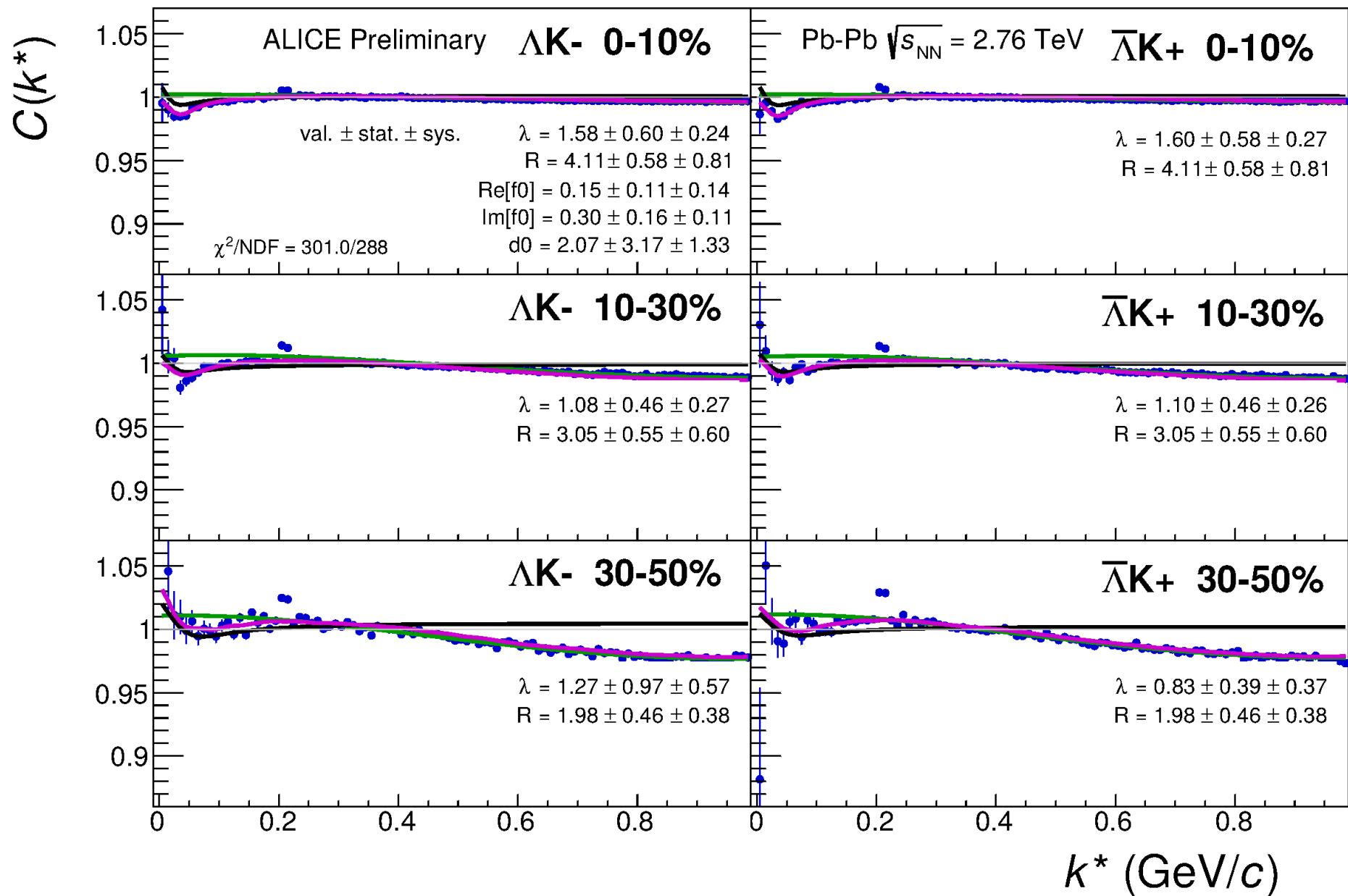


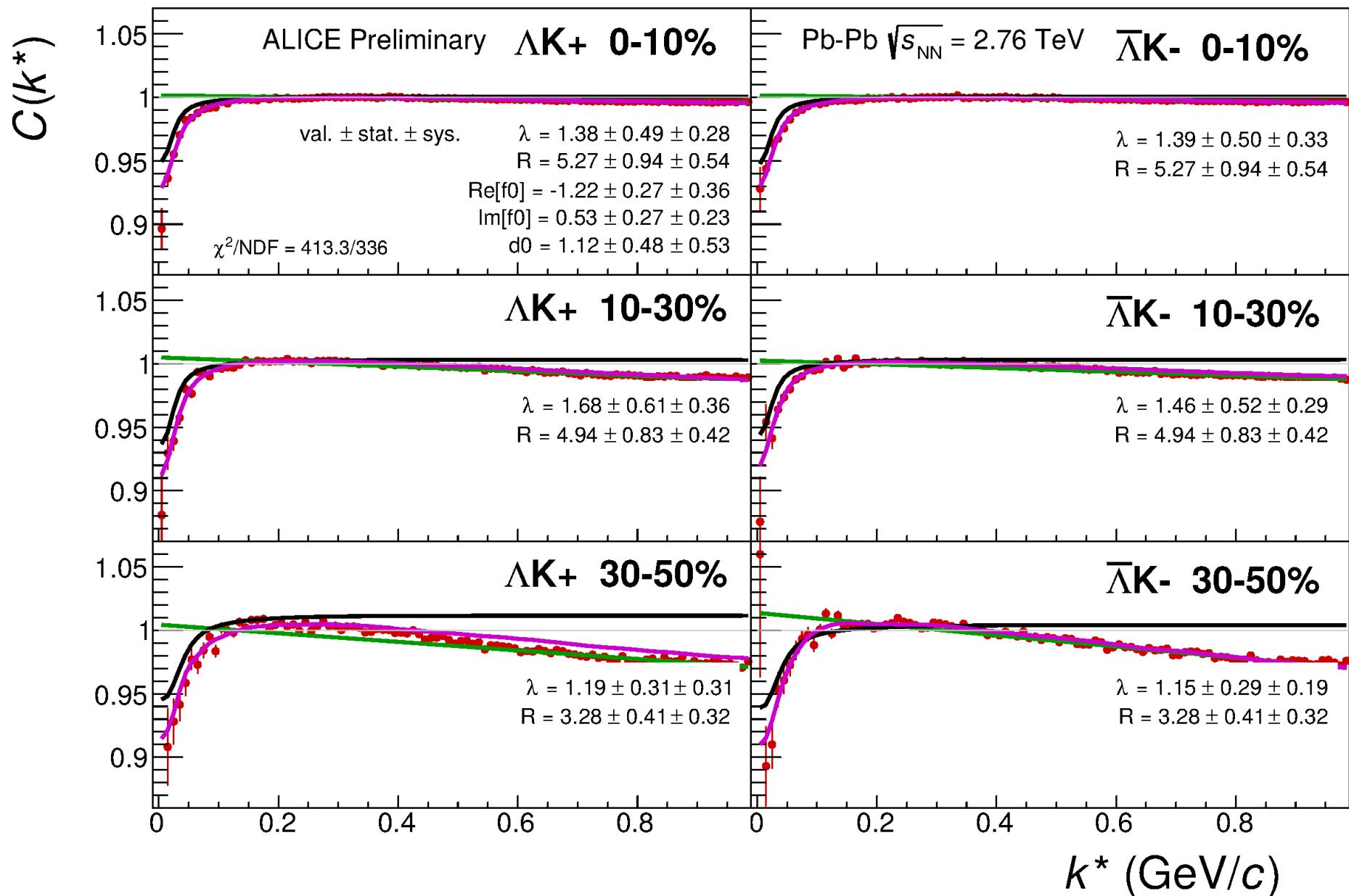
Sep. R, share λ , Stav.(No Bgd)

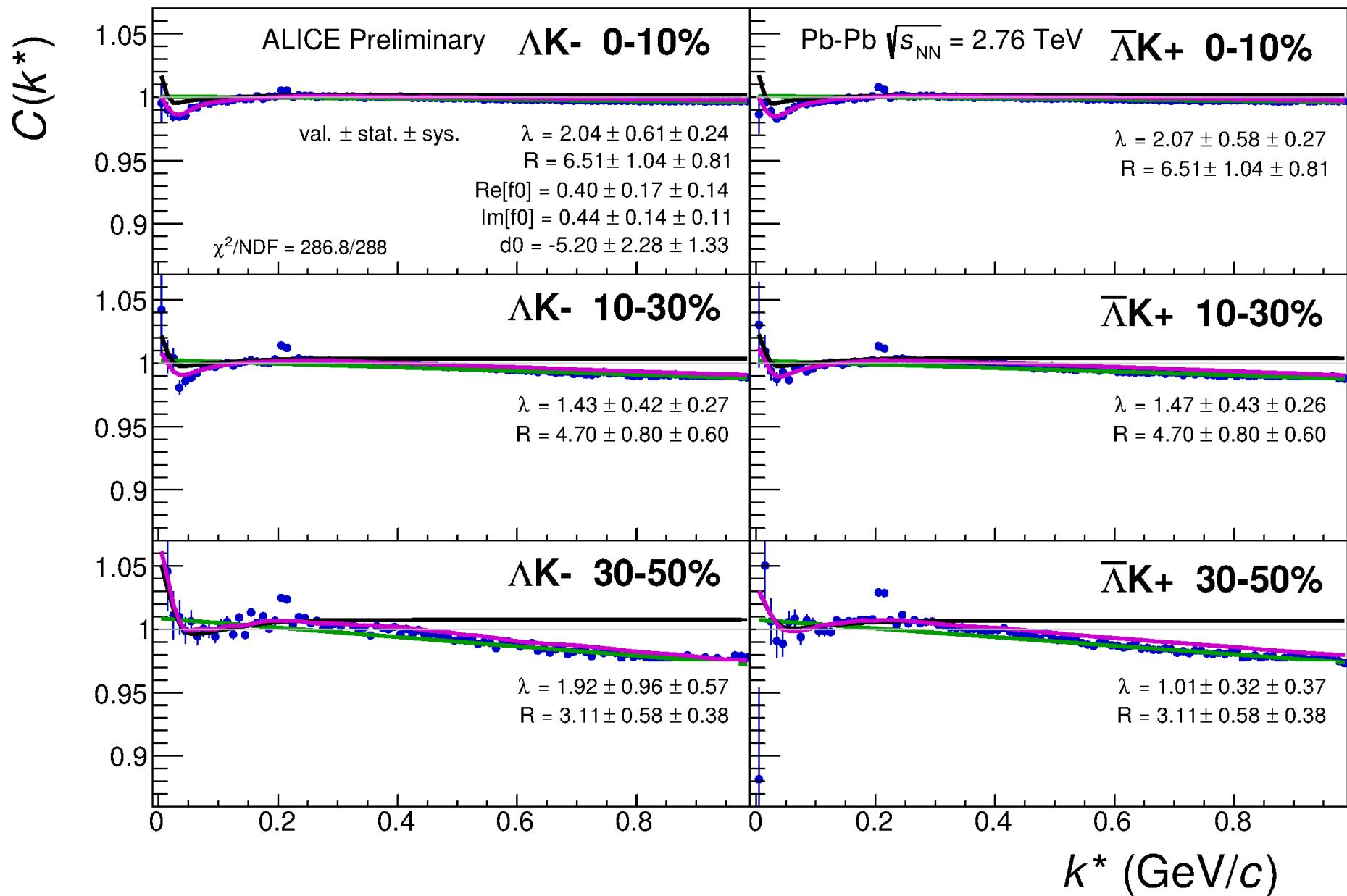


Fit Results: Separate Radii, separate λ

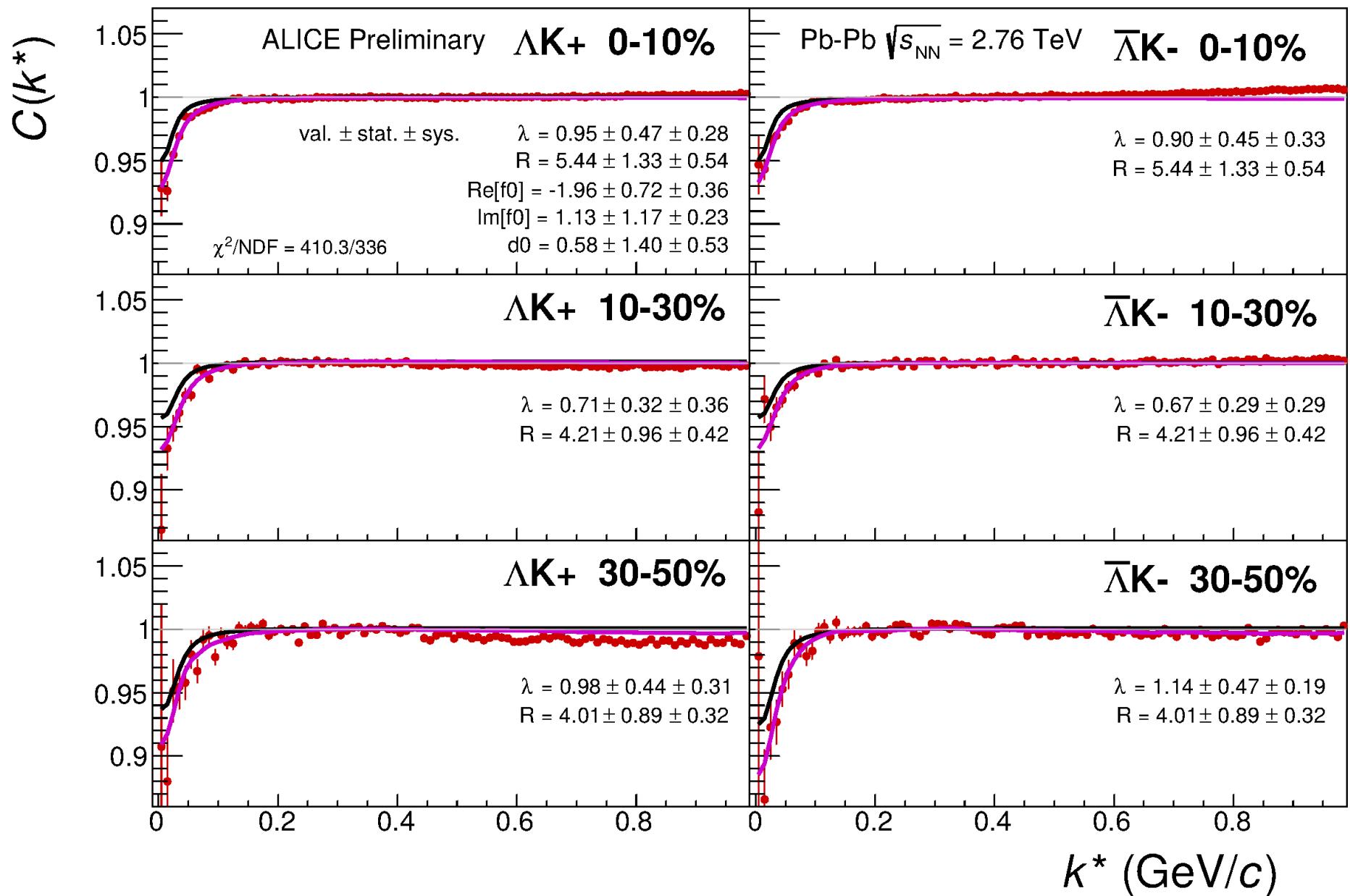








Sep. R, sep. λ , Stav.(No Bgd)



Sep. R, sep. λ , Stav.(No Bgd)

