ΛK Femtoscopy in Pb-Pb collisions at 2.76 TeV

Update:
Non-femtoscopic background, THERMINATOR, Stavinsky method, etc.

Outline

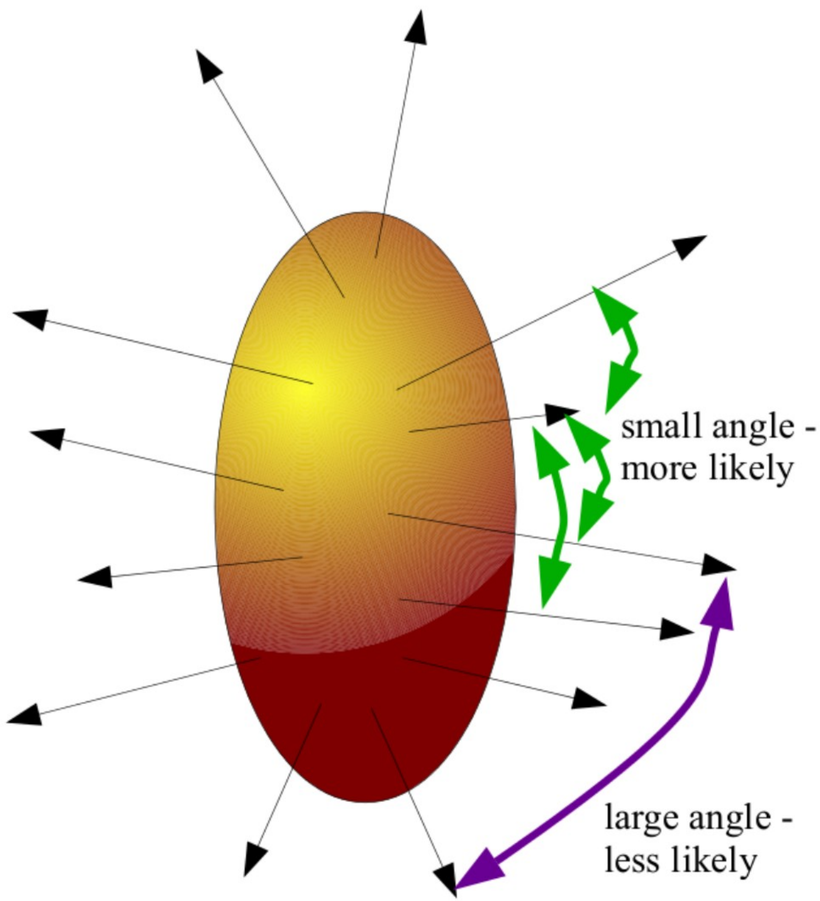
- Significant non-femtoscopic, non-flat background observed in all Cfs at large k^*
  - Increases with decreasing centrality
  - Same amongst all ΛK^{ch} pairs
  - More pronounced for ΛK^0_S system
- Suggested effect is due primarily to particle collimation associated with elliptic flow
  - Background 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

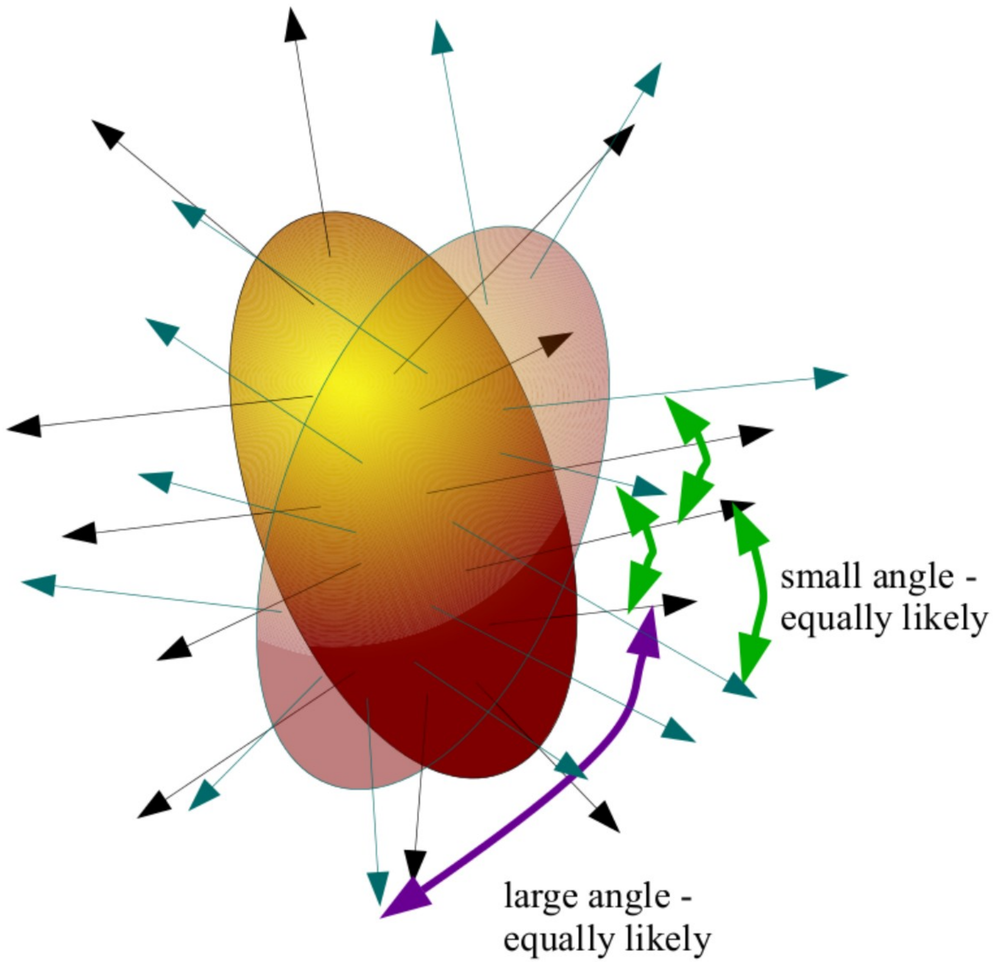
- THERMINATOR does a good job of matching the observed backgrounds
- Stavinsky method does a good job of ridding the experimental data of the backgrounds

Background from elliptic flow

- Same event (signal)

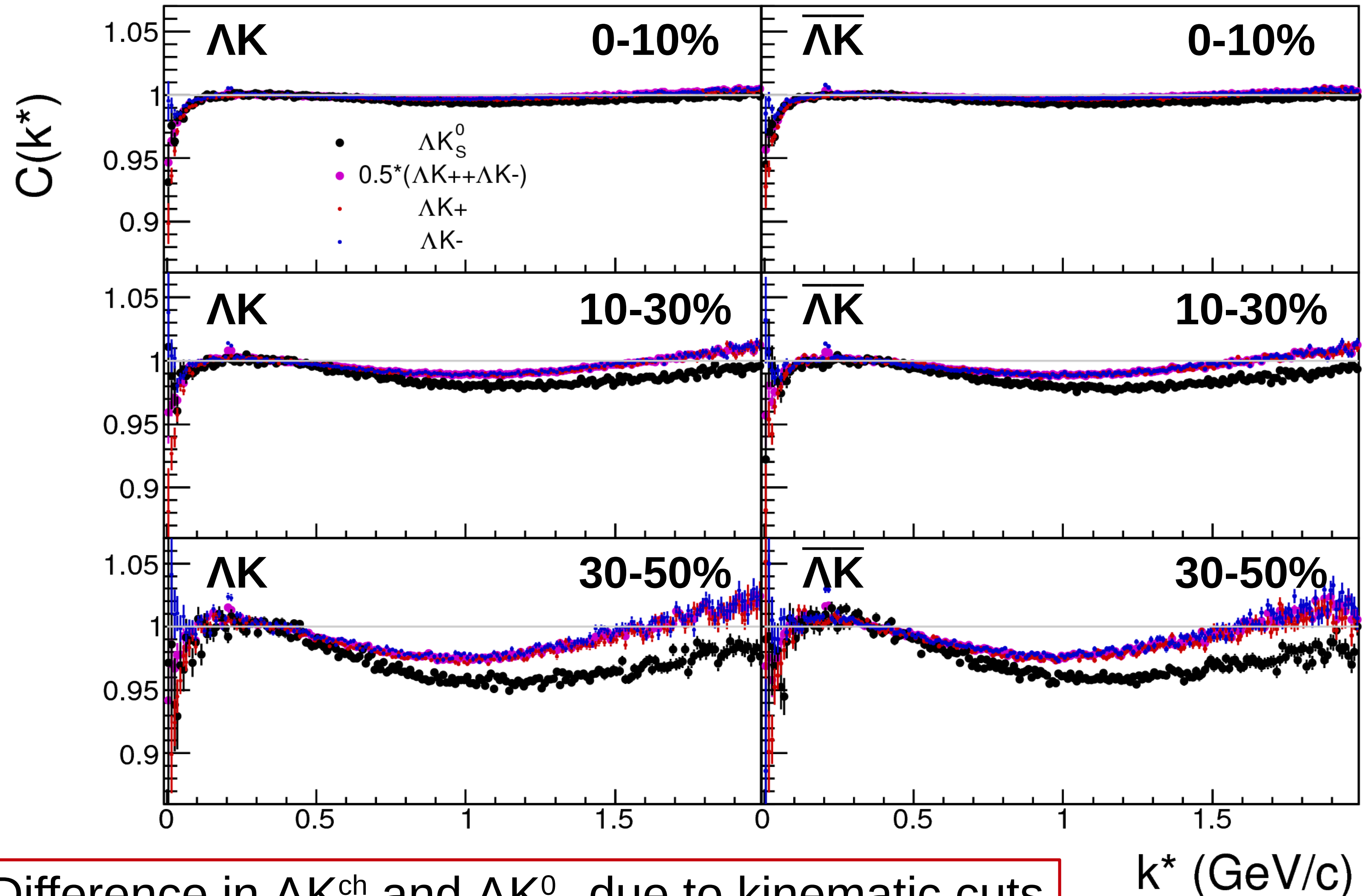


- Mixed events (background)



- 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

Background Treatment

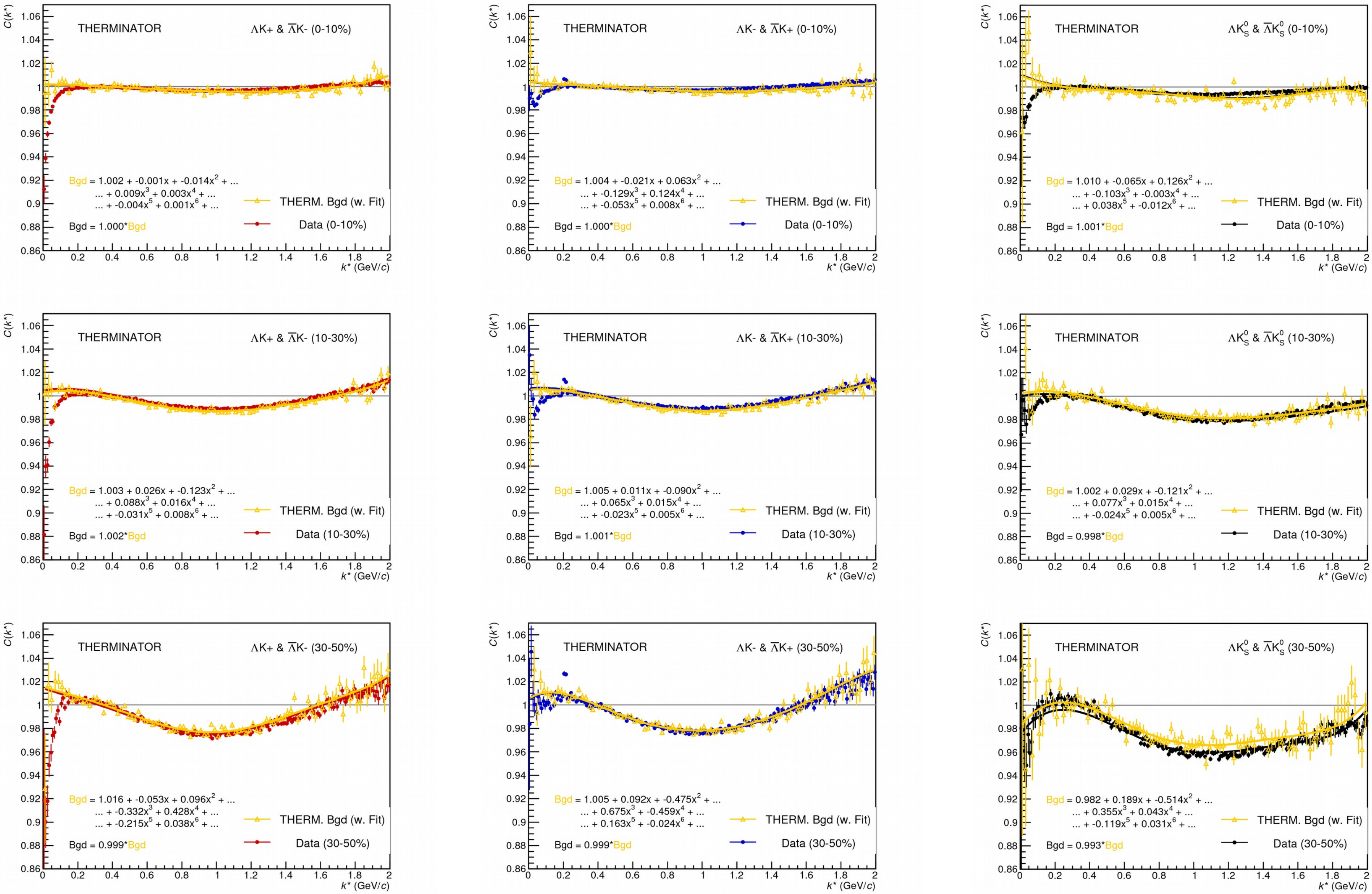
- **Ideal world (1)**: rotate events to align EP angles
  - Not applicable: azimuthal angle acceptance not perfectly uniform and finite EP resolution
- **Ideal world (2)**: bin events in EP angle, and only mix events within a given bin
  - Not applicable: finite EP resolution
  - Slight decrease in background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

Background with THERMINATOR

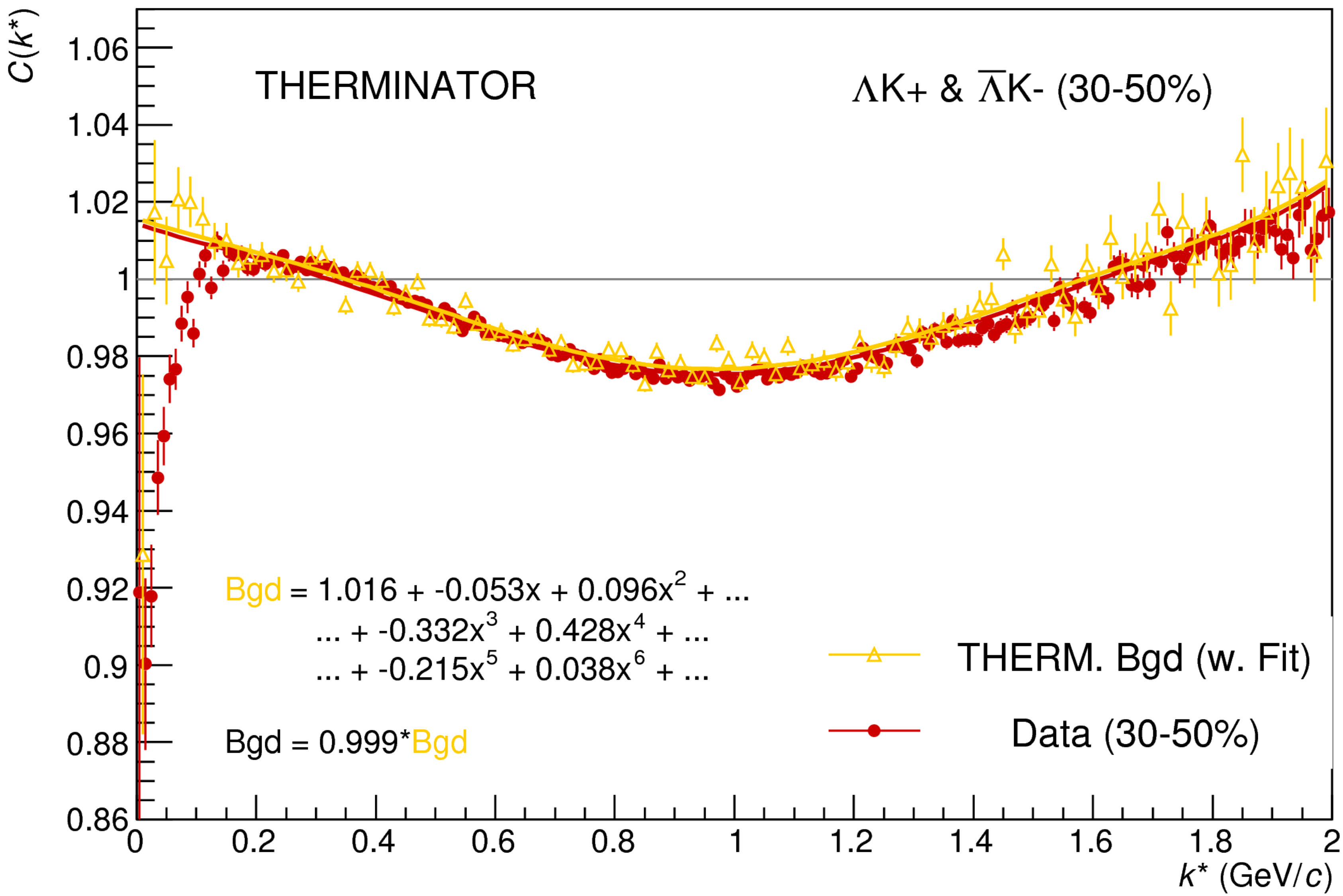
THERMINATOR

- By default, all $\Psi_{EP} = 0°$
  - 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)

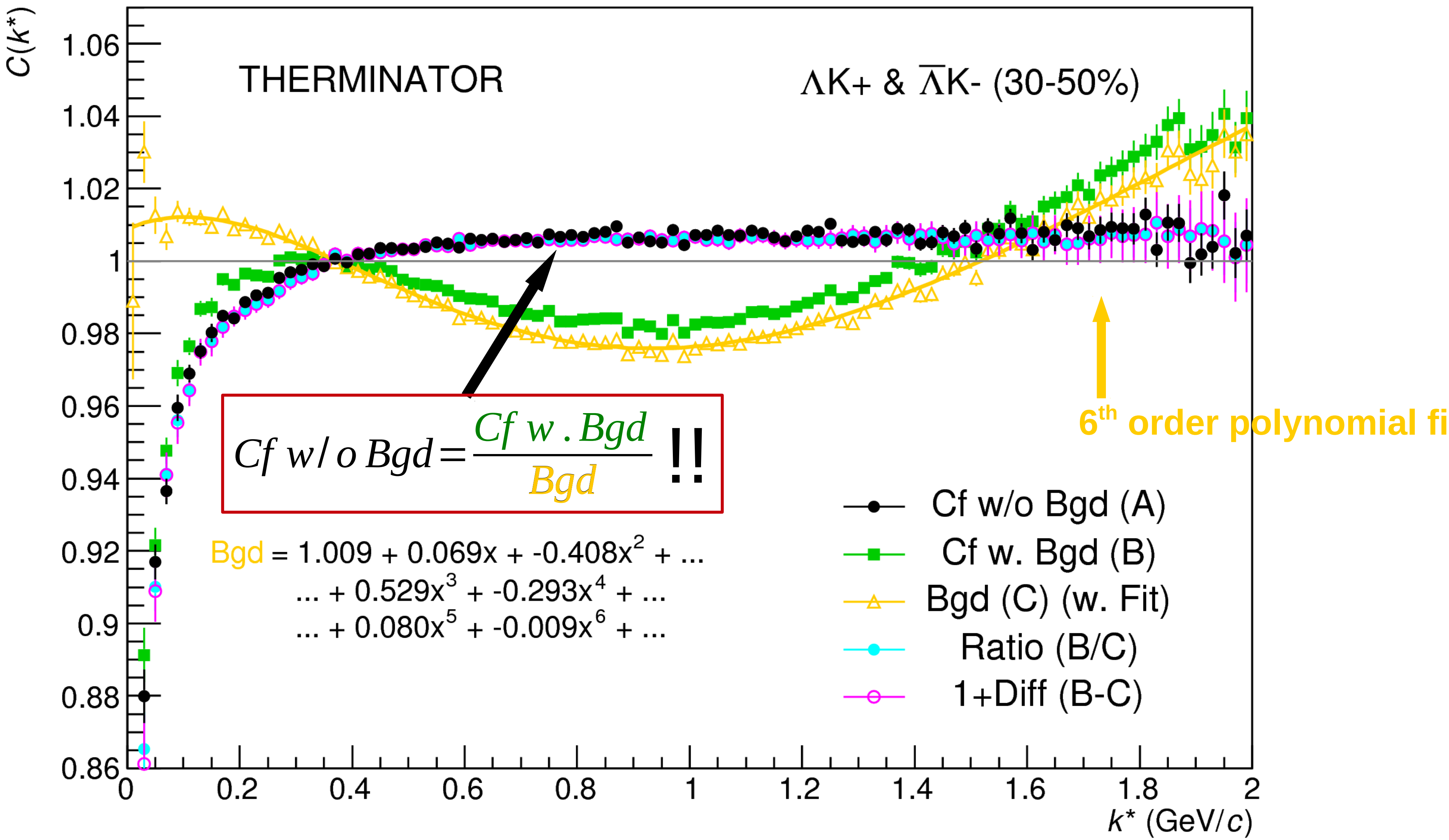


THERM vs Data (ΛK+ 30-50%)



THERMINATOR

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



Quantitative use of THERM

- From the previous slide:

$$Cf\ w/o\ Bgd = \frac{Cf\ w.Bgd}{Bgd} \quad \Rightarrow \quad Cf_{th} = \frac{Cf_{\exp}}{F_{Bgd}} \quad \Rightarrow \quad Cf_{\exp} = Cf_{th} \cdot F_{Bgd}$$

- 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

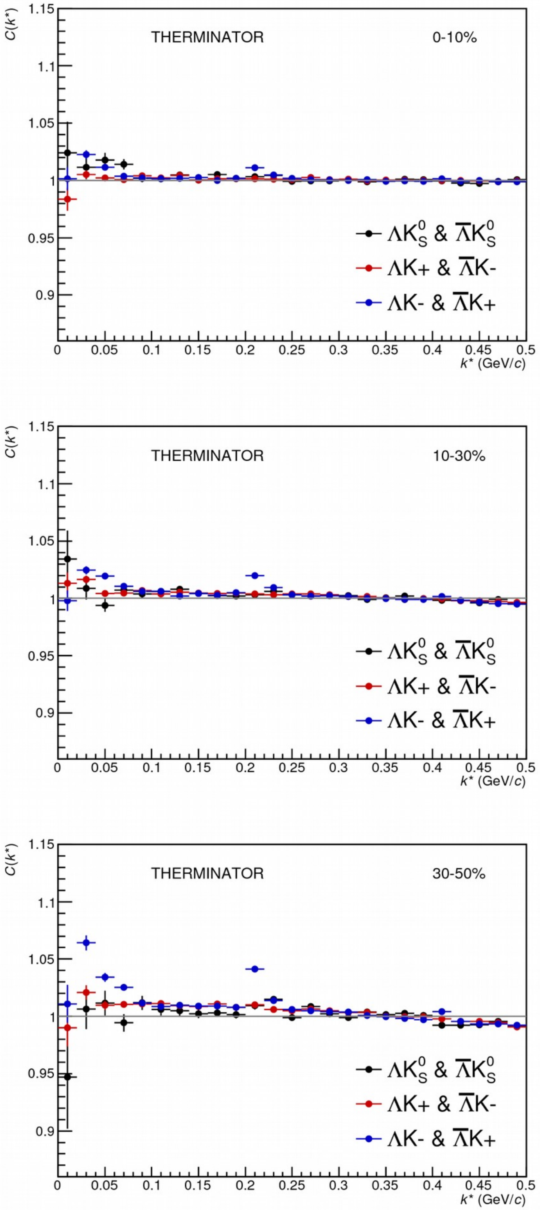
THERMINATOR Question

THERMINATOR

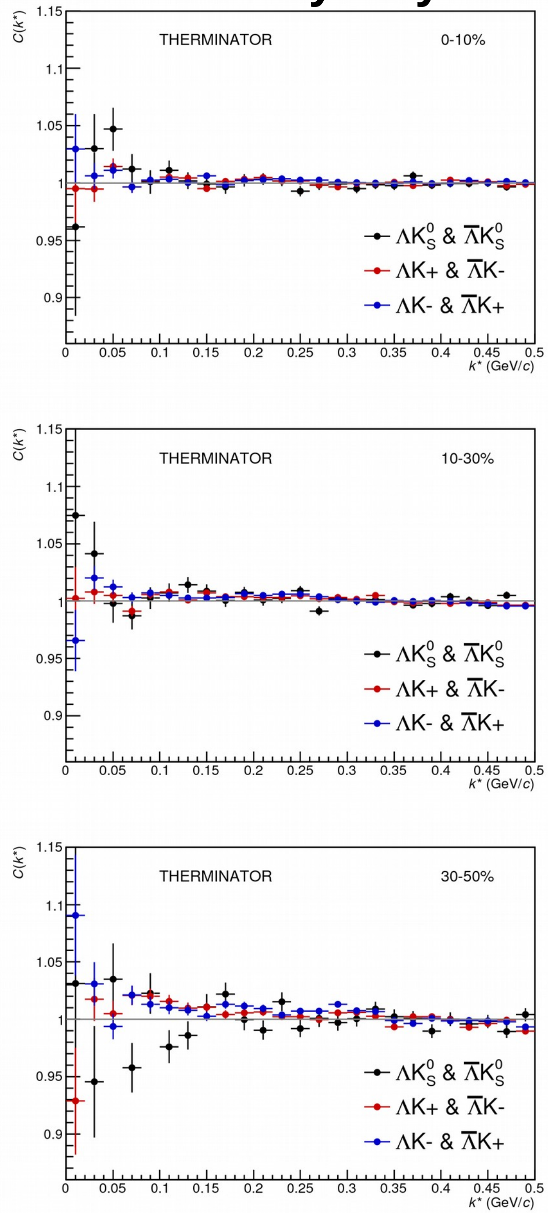
- **Full**
  - no discrimination in origin on Λ or K in pair
- **PrimaryOnly**
  - both particles must be identified as primary by THERMINATOR
- **SecondaryOnly**
  - both particles must NOT be identified as primary by THERMINATOR
- Who cares?
  - In ΛK^0_S and ΛK+ cases, the background looks roughly 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:
THERMINATOR Backgrounds

Full



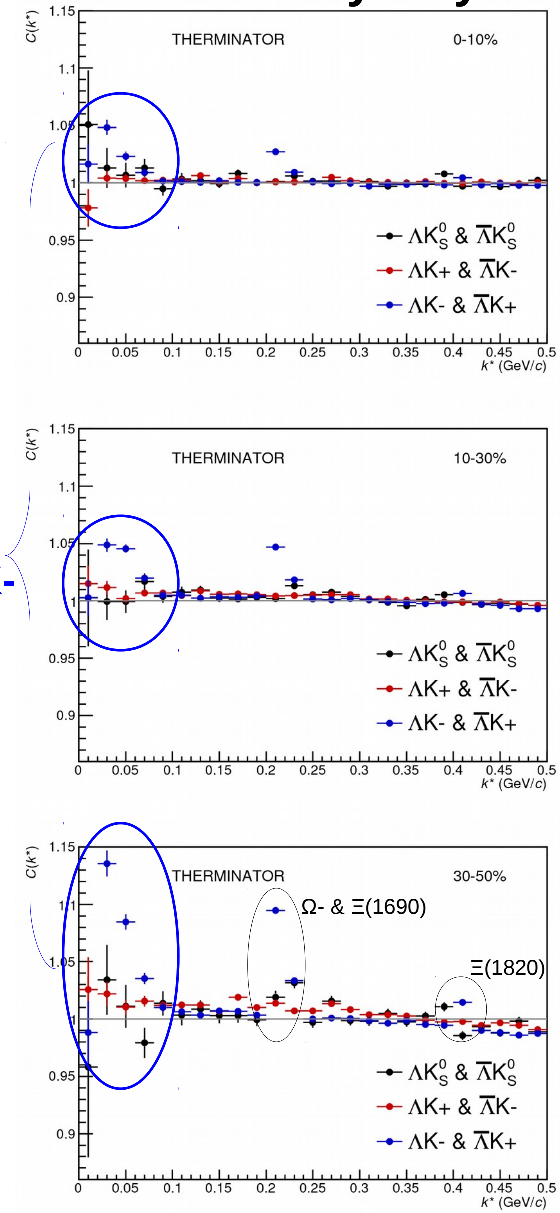
PrimaryOnly



Enhancement at low-k^* in ΛK-

Any ideas what causes this?

SecondaryOnly



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 $\mathrm{Num}_{\mathrm{Stav}}$

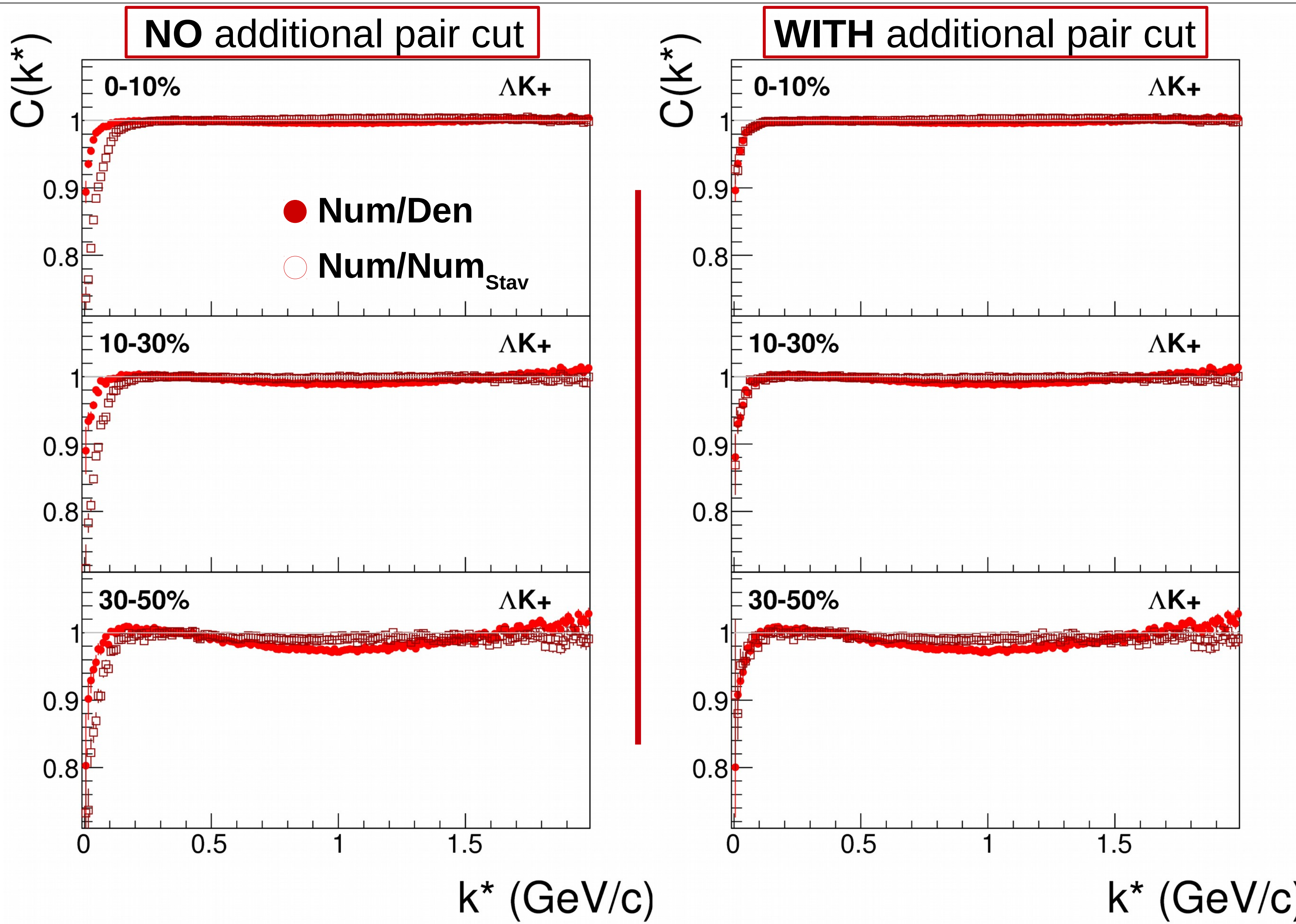
Issue

- For ΛK+ especially, at low-*k**, same-event $\mathrm{Num}_{\mathrm{Stav}}$ 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+ $\mathrm{Num}_{\mathrm{Stav}}$ agrees with Den at low-*k** (**BACKUP s.38**)

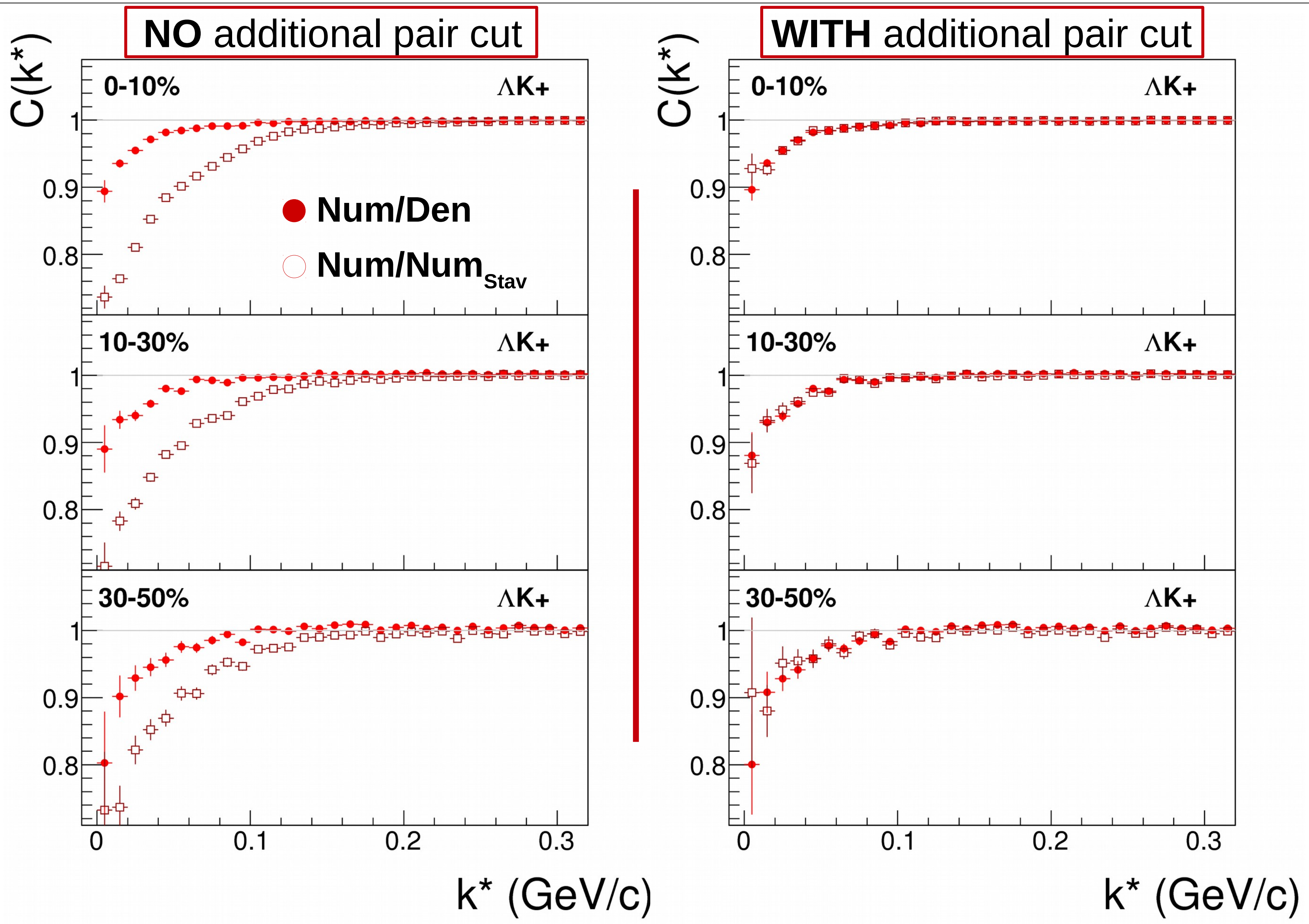
Solution

- 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^*
  - $\Lambda K+$ Num_{Stav} agrees with Den at low-k^* (**BACKUP s.39**)

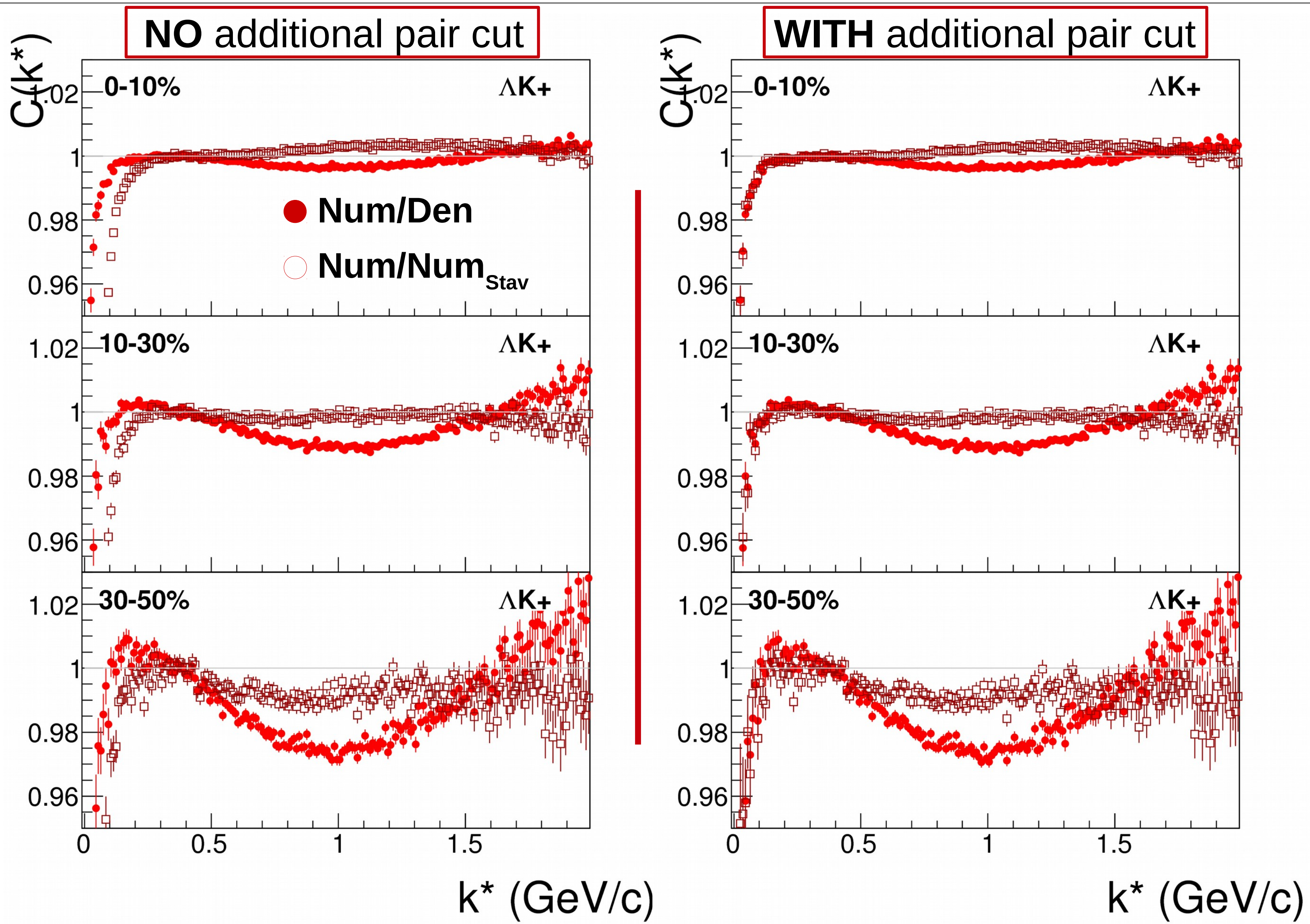
Effect of Additional Pair Cut



Effect of Additional Pair Cut



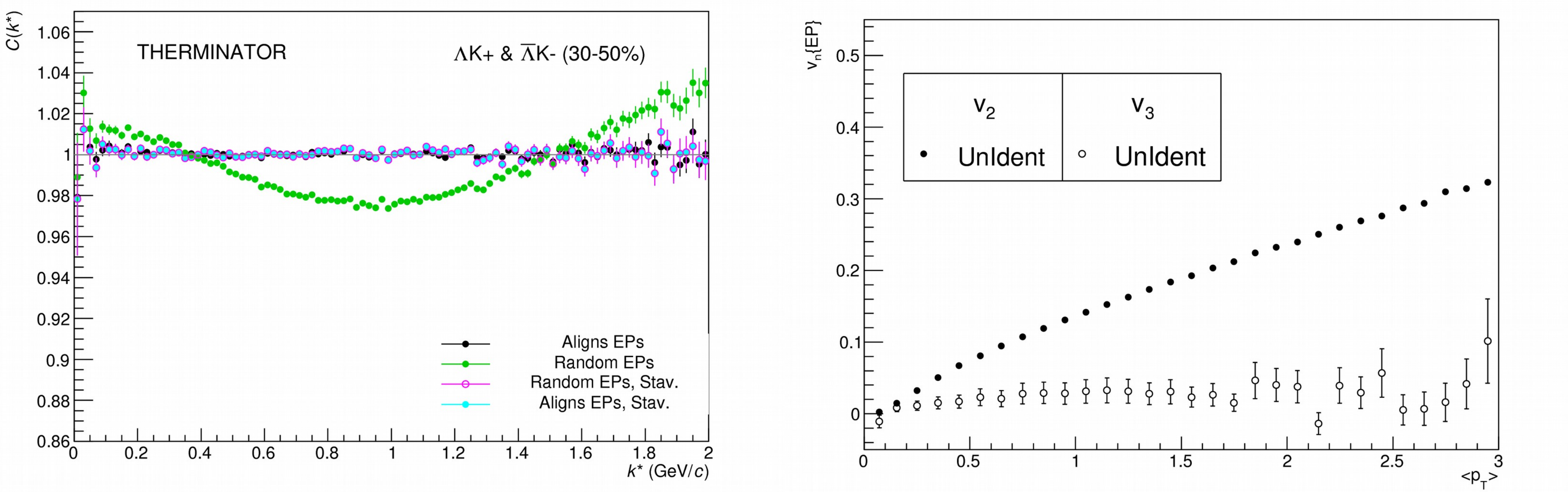
Effect of Additional Pair Cut



Stav. Method with THERM

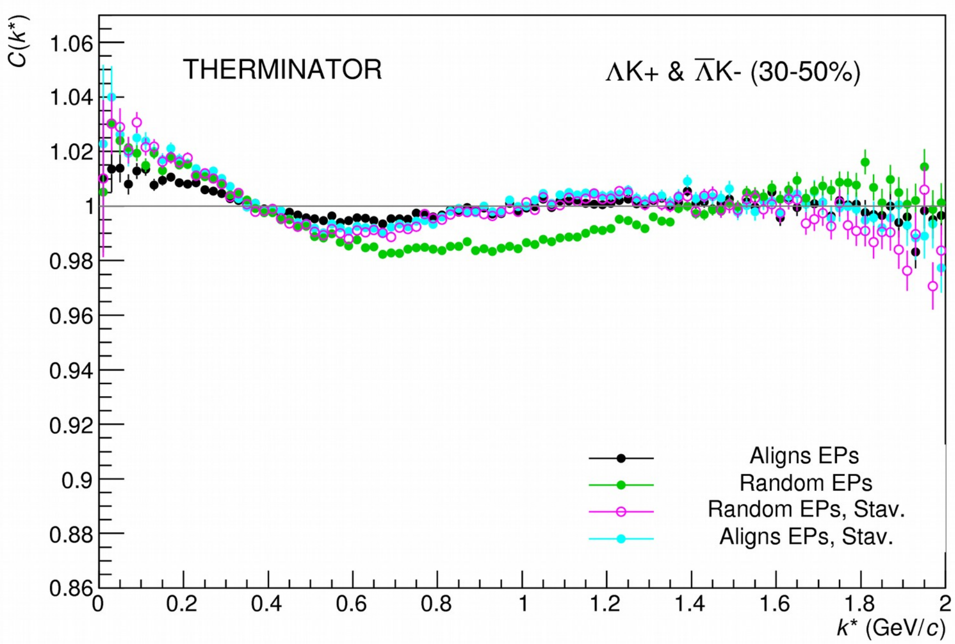
THERM: Normal

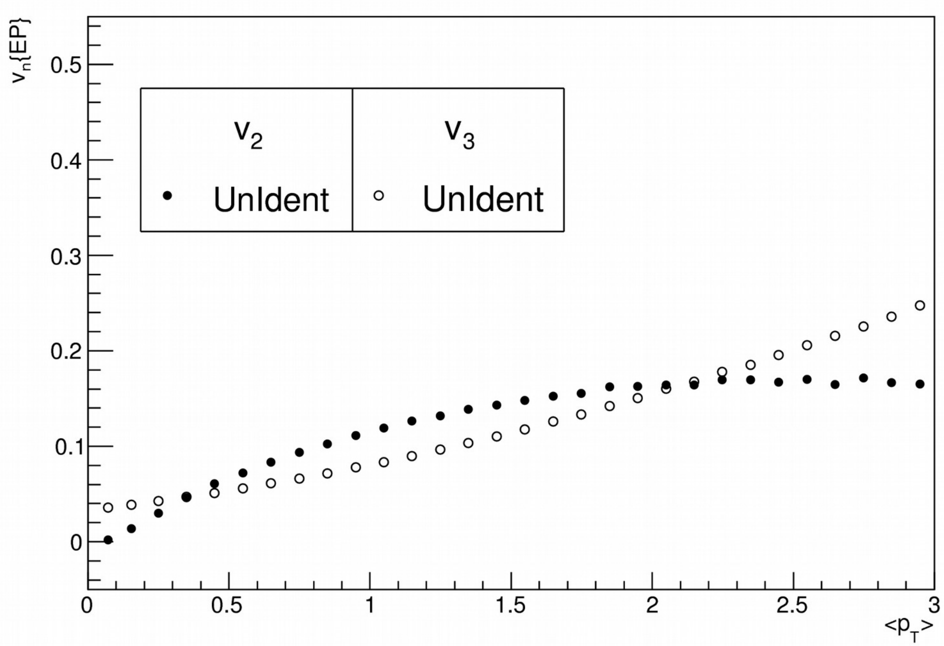
- No v_3 present in THERMINATOR simulation
- $EP = \Psi_2$



THERM: v_3 added

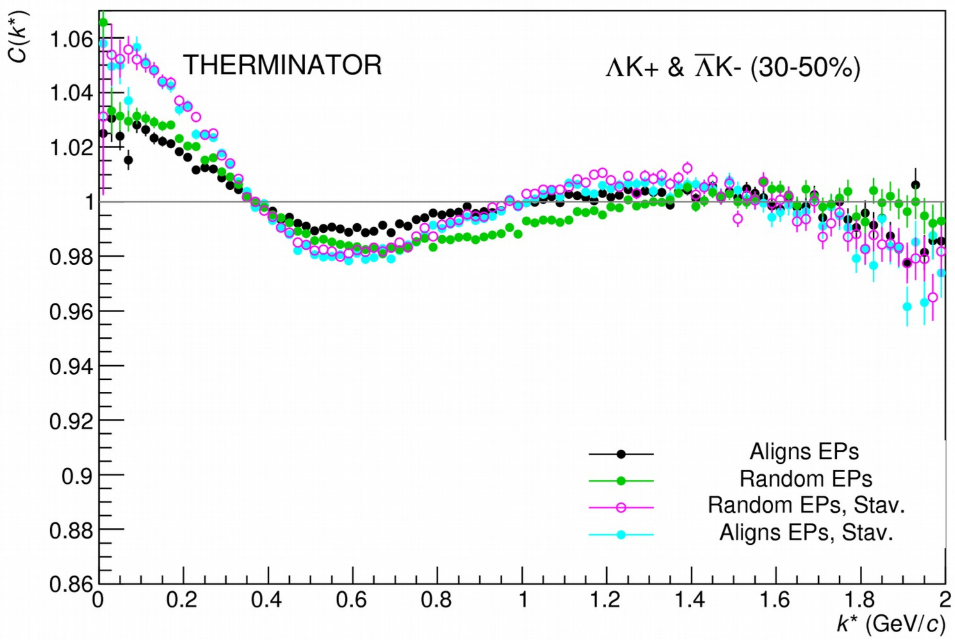
- Artificially add v_3 signal
- EP = Ψ_2

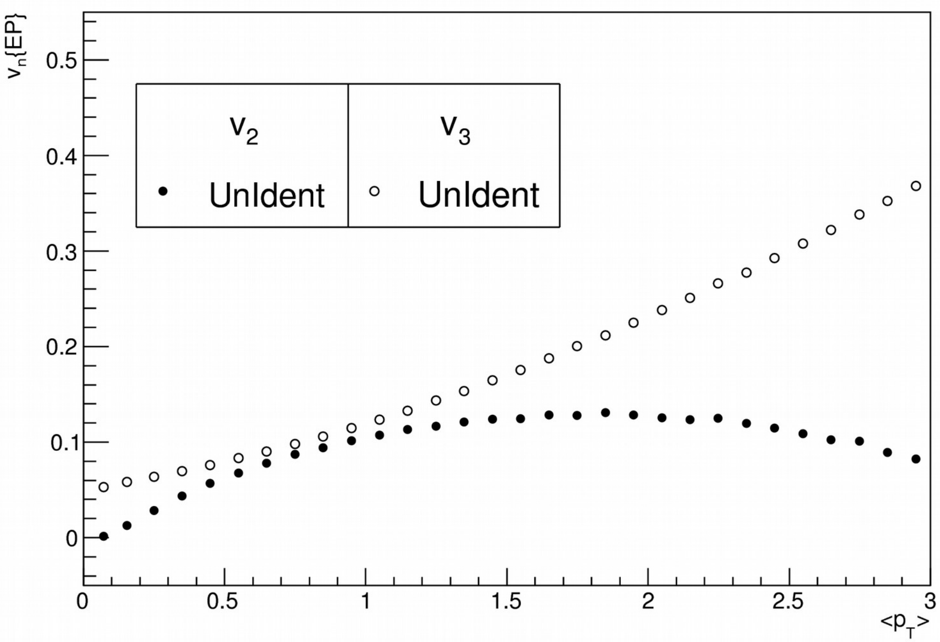




THERM: More v_3 added

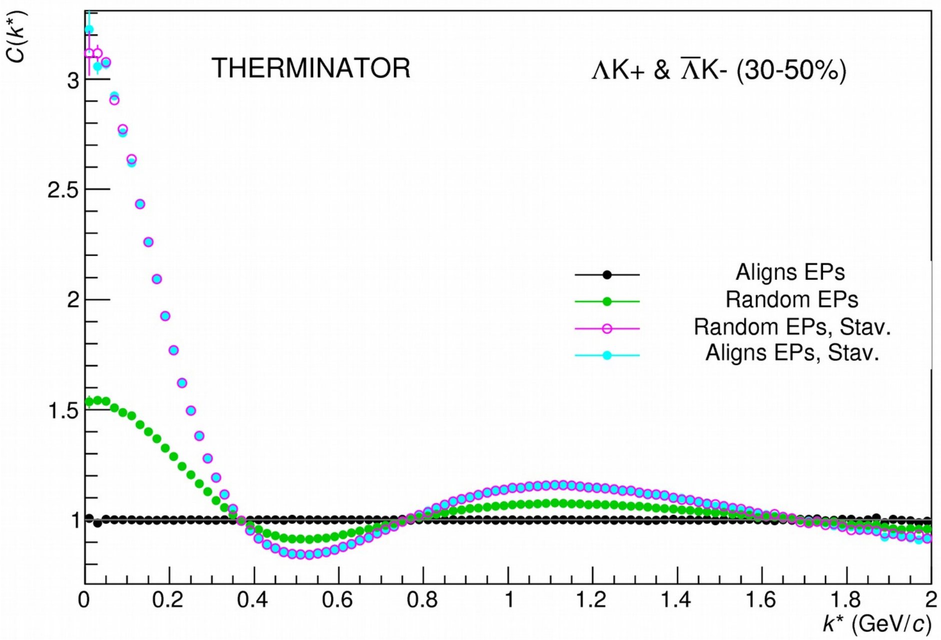
- ➔ Artificially add MORE v_3 signal
- ➔ EP = Ψ_2

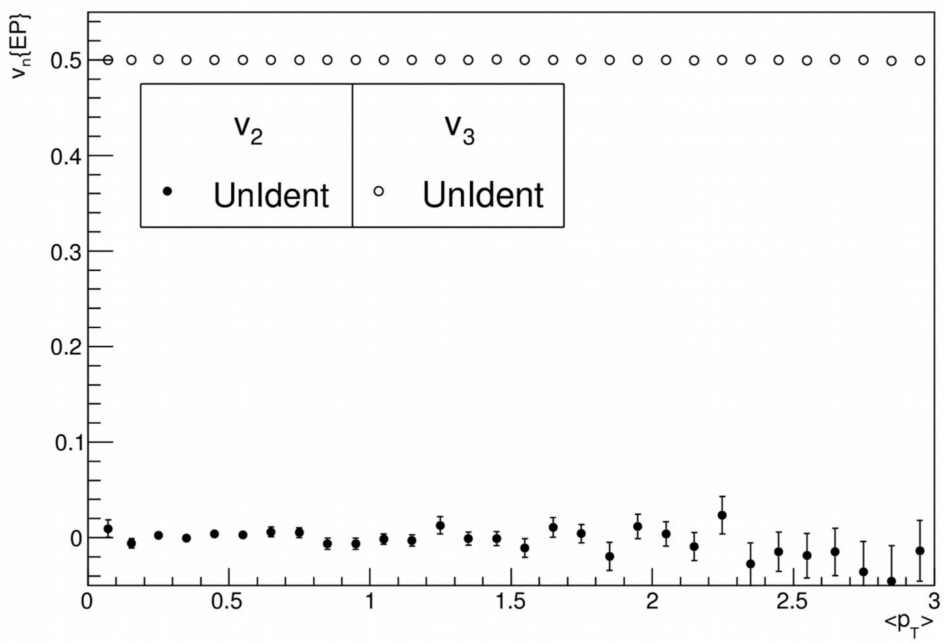




THERM: No v_2, all v_3

- 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 Λ($\bar{\Lambda}$)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

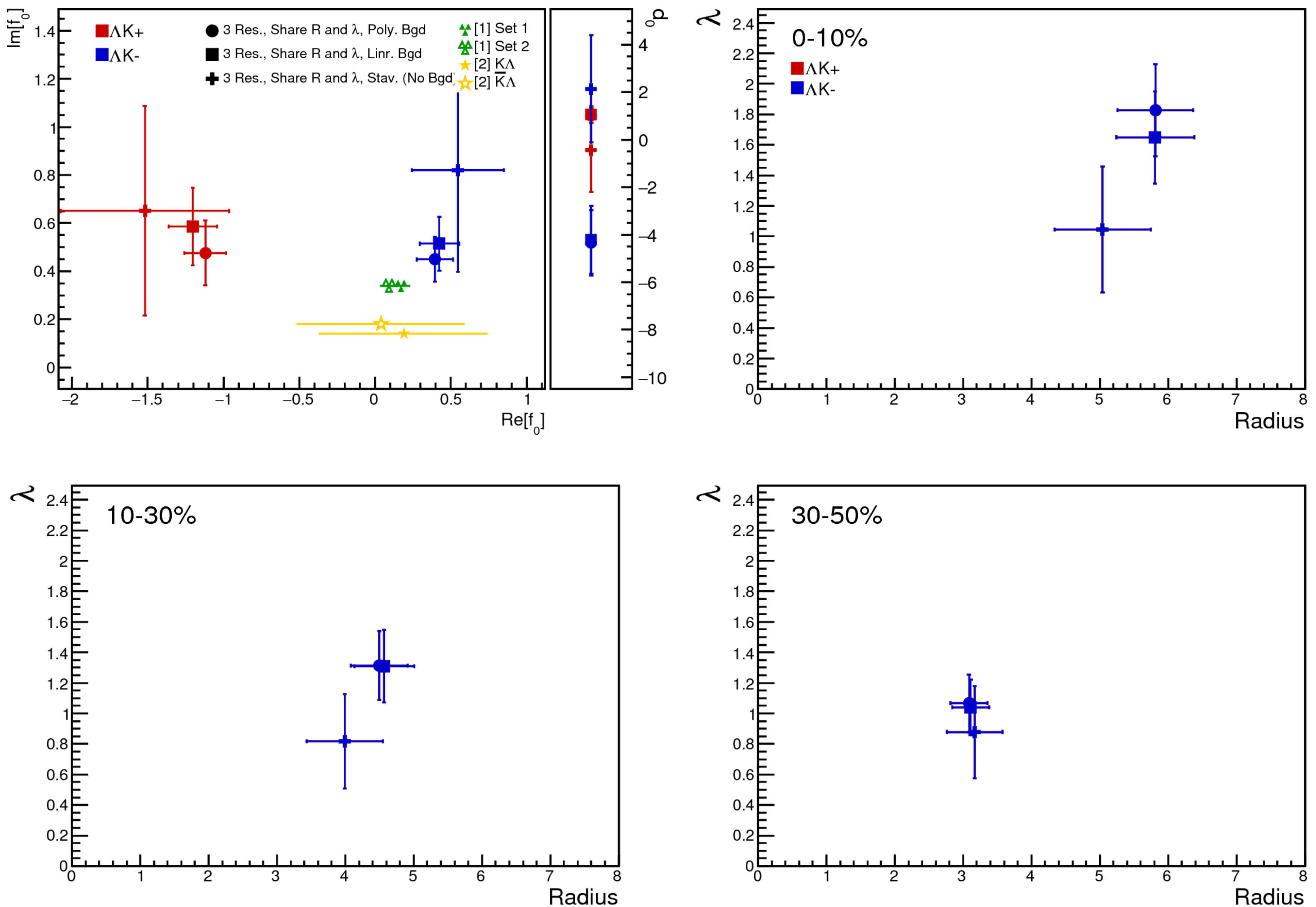
- Shared R
  - Share radii between $\Lambda K+$ (with $\bar{\Lambda}K-$) and $\Lambda K-$ (with $\bar{\Lambda}K+$) for like centralities
  - Shared λ → share single λ for each centrality across all [$\Lambda K+$, $\bar{\Lambda}K-$, $\Lambda K-$, $\bar{\Lambda}K+$]
    - 3 total λ parameters
  - Shared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

Background treatments

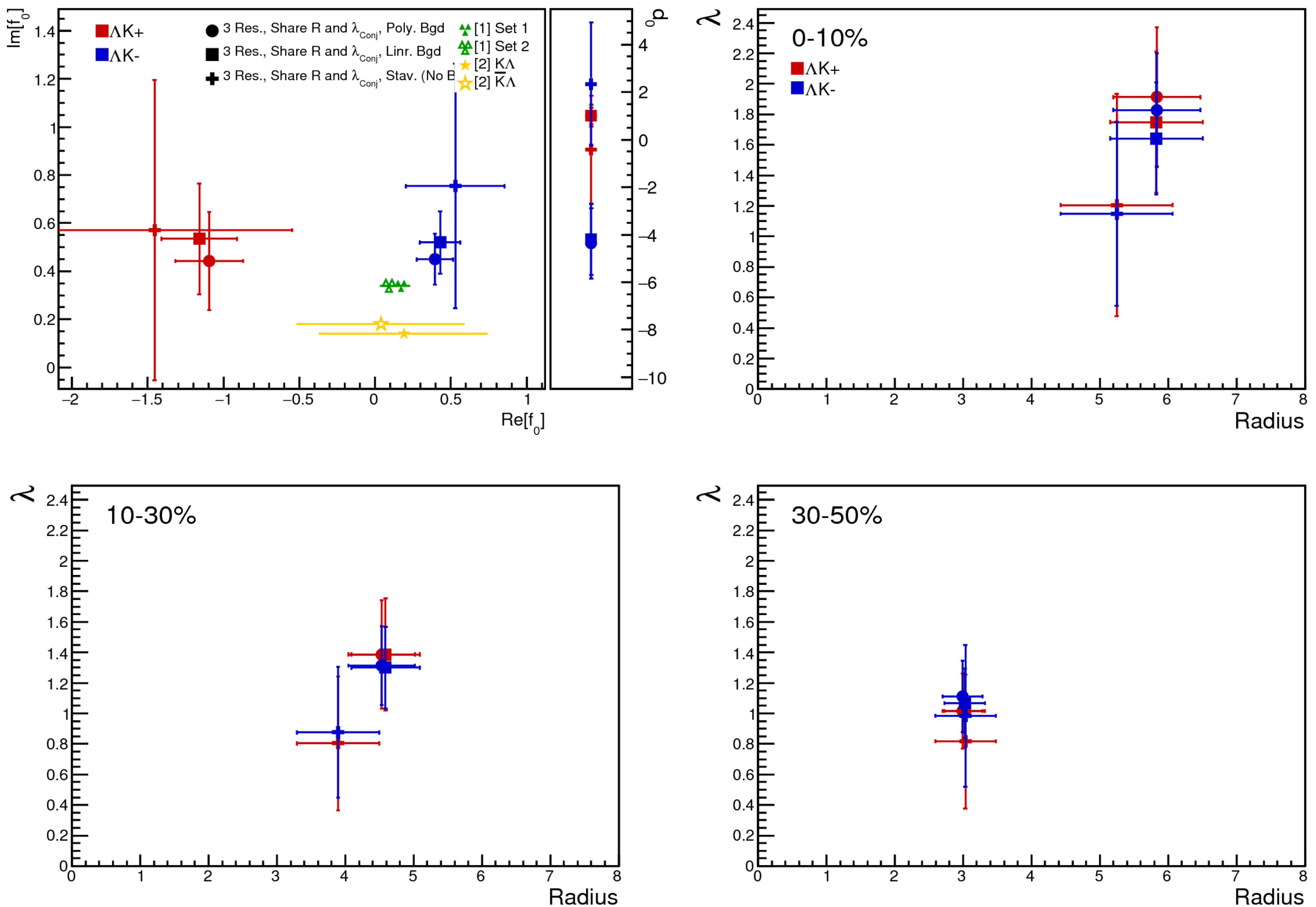
- Poly. Bgd
  - Use THERMINATOR2 to model background with 6^{th}-order polynomial
  - Scale to match data
  - Apply background as scale factor to fit
- Lin. Bgd
  - Use a linear form to model the background
  - Fit background to data, outside of signal region ($0.6 < k^* < 0.9$ GeV/*c*)
  - Apply background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

Compare Background Treatments

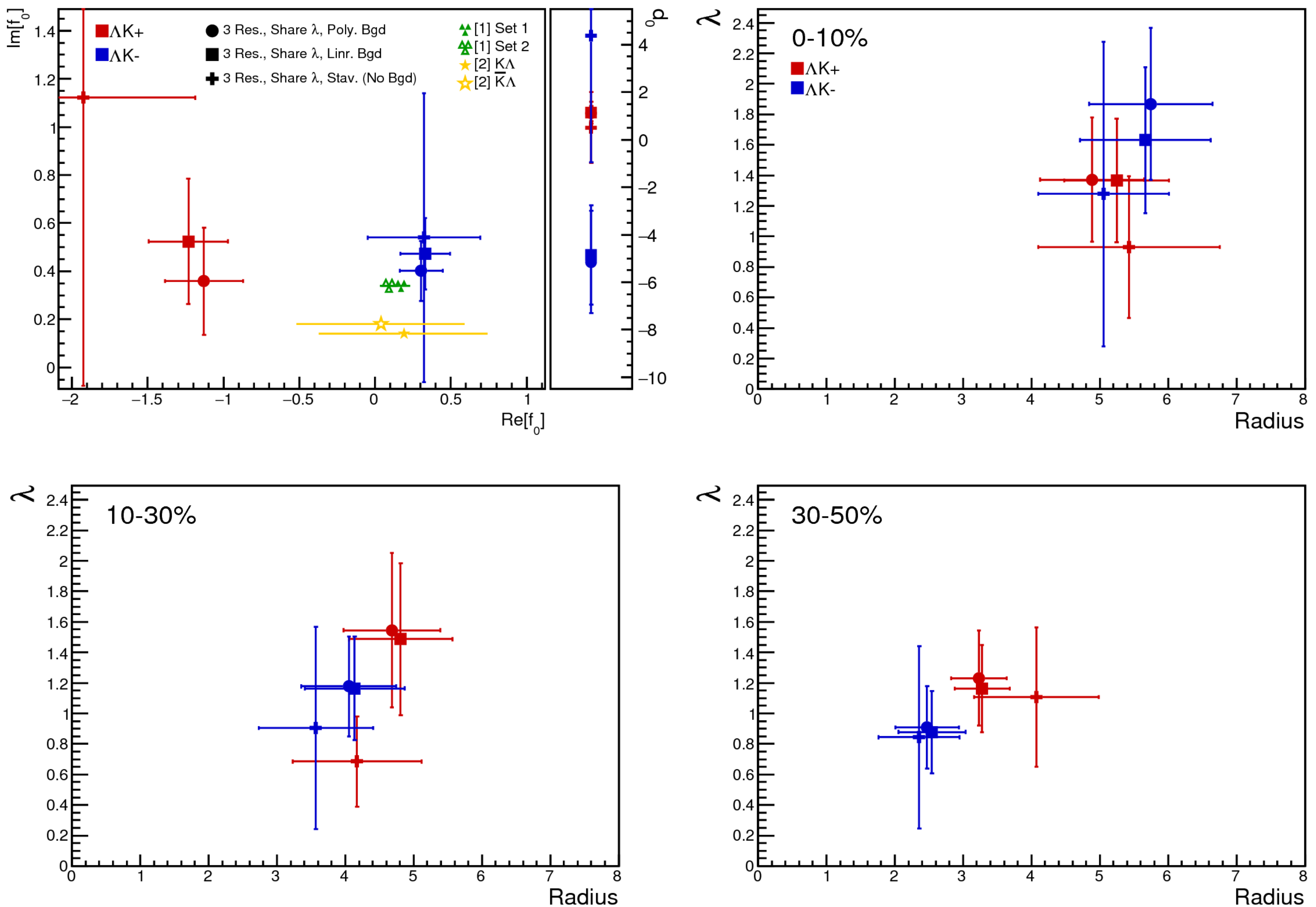
Shared R, shared λ



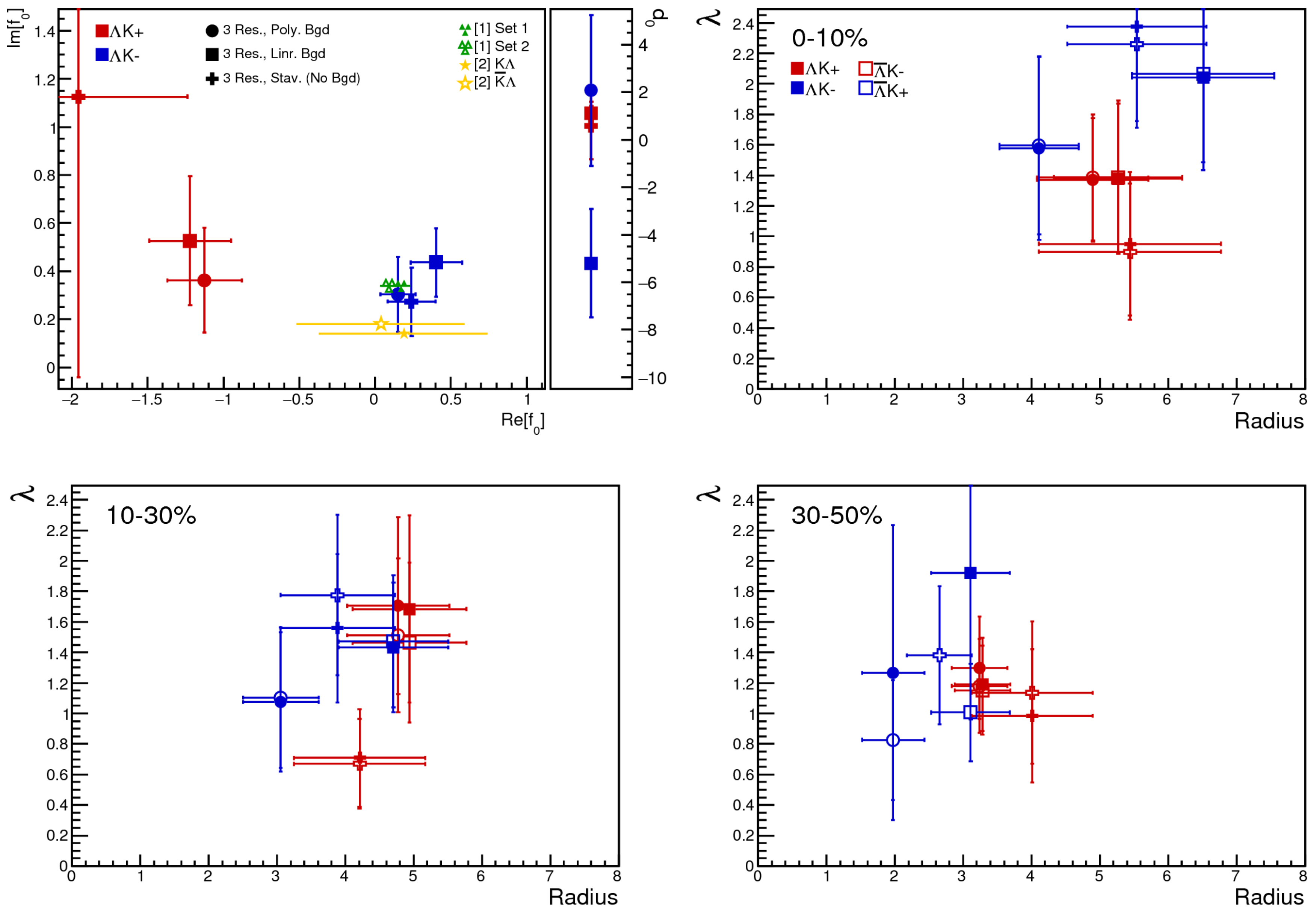
Shared R, shared λ_{Conj}



Separate R, shared λ

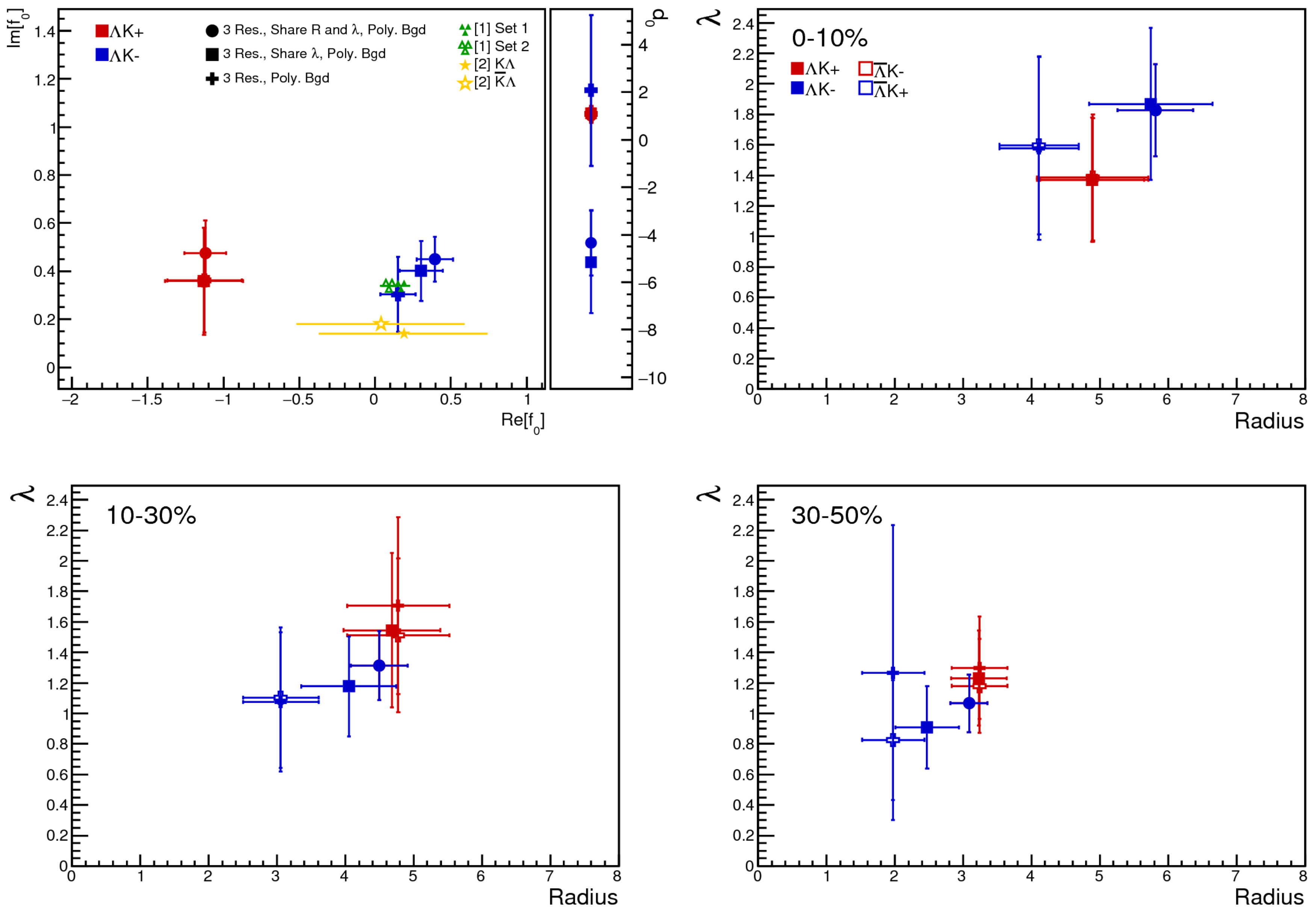


Separate R, separate λ



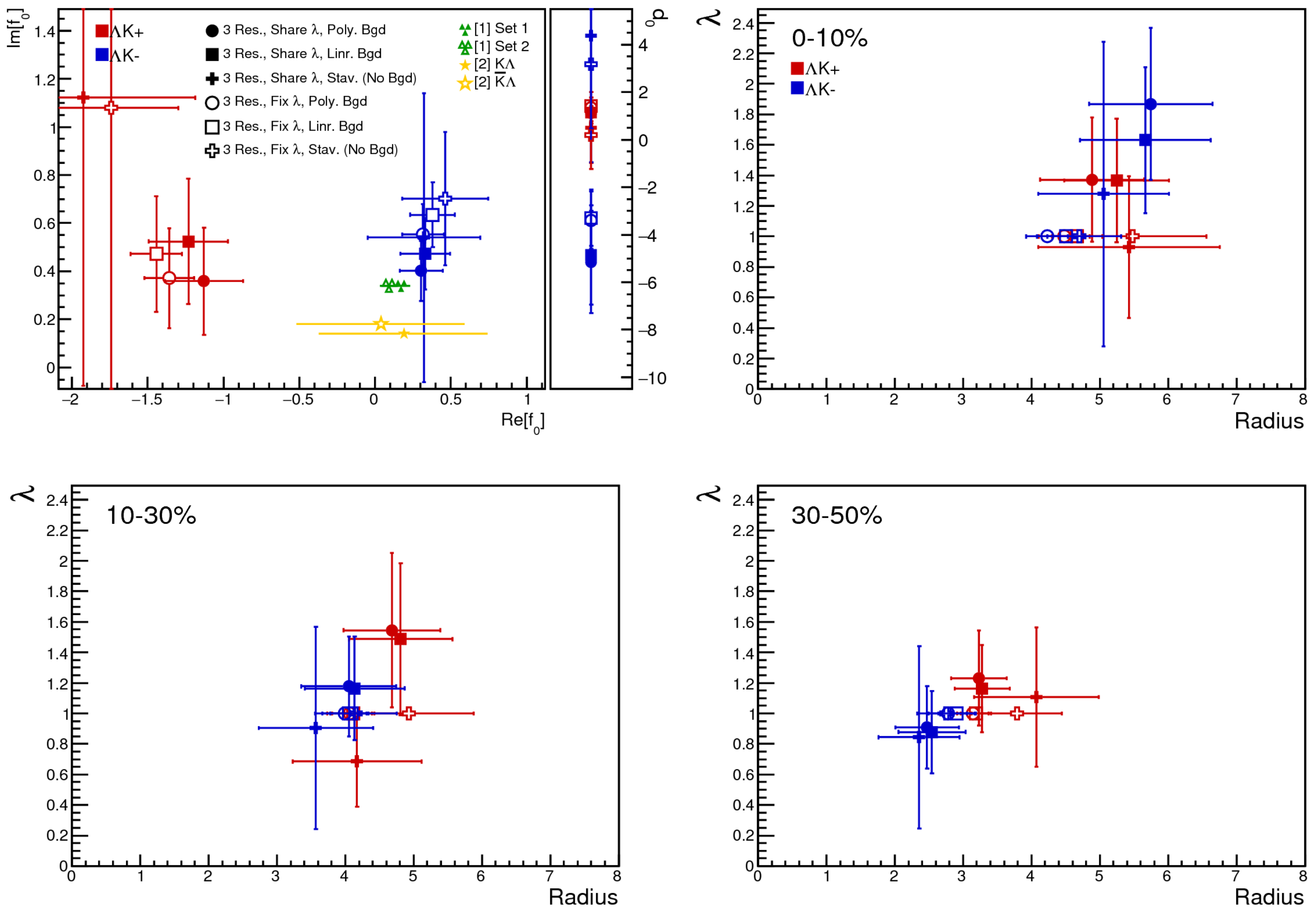
Compare Parameter Sharing

Separate vs Shared R

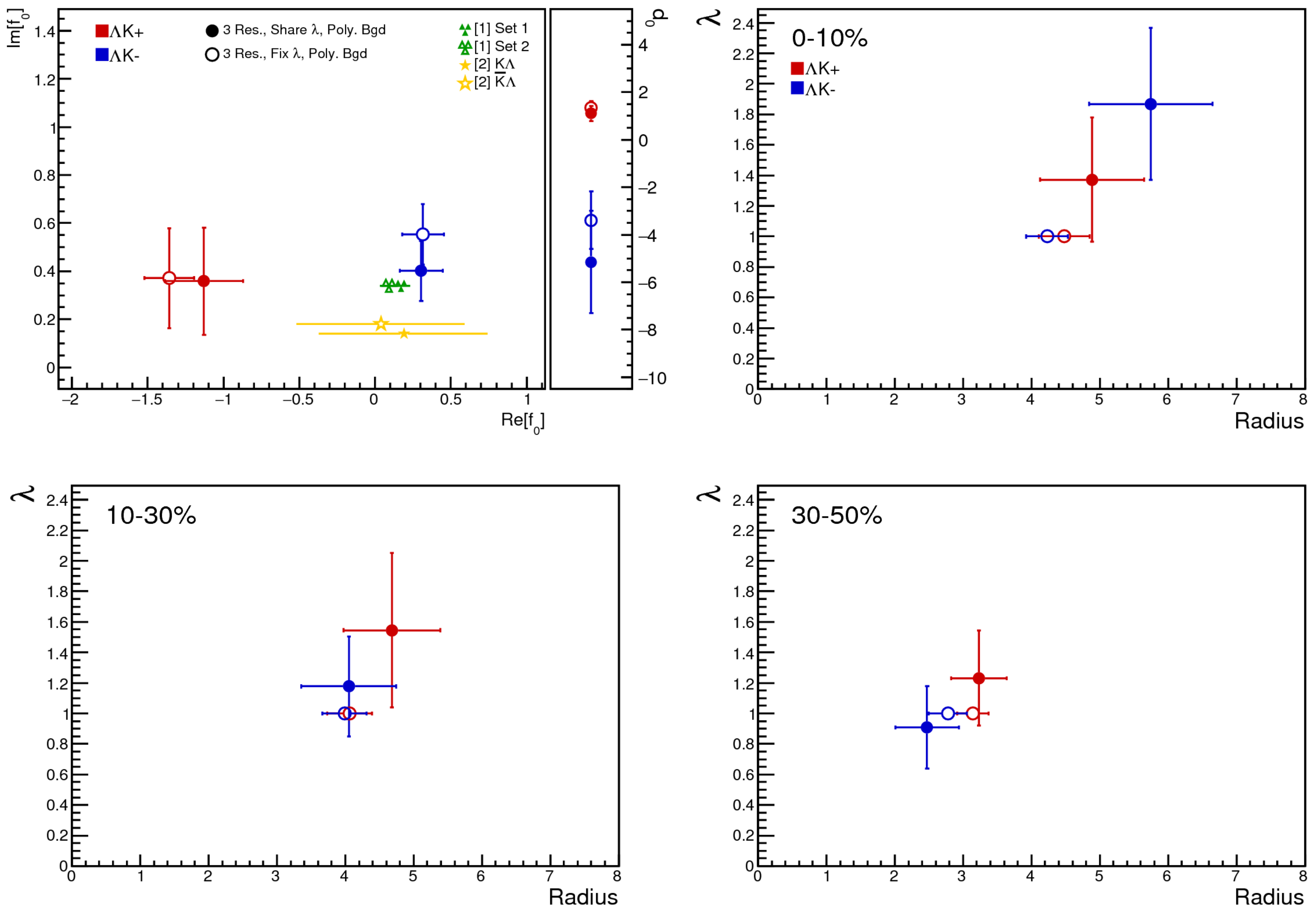


Free vs. Fixed λ

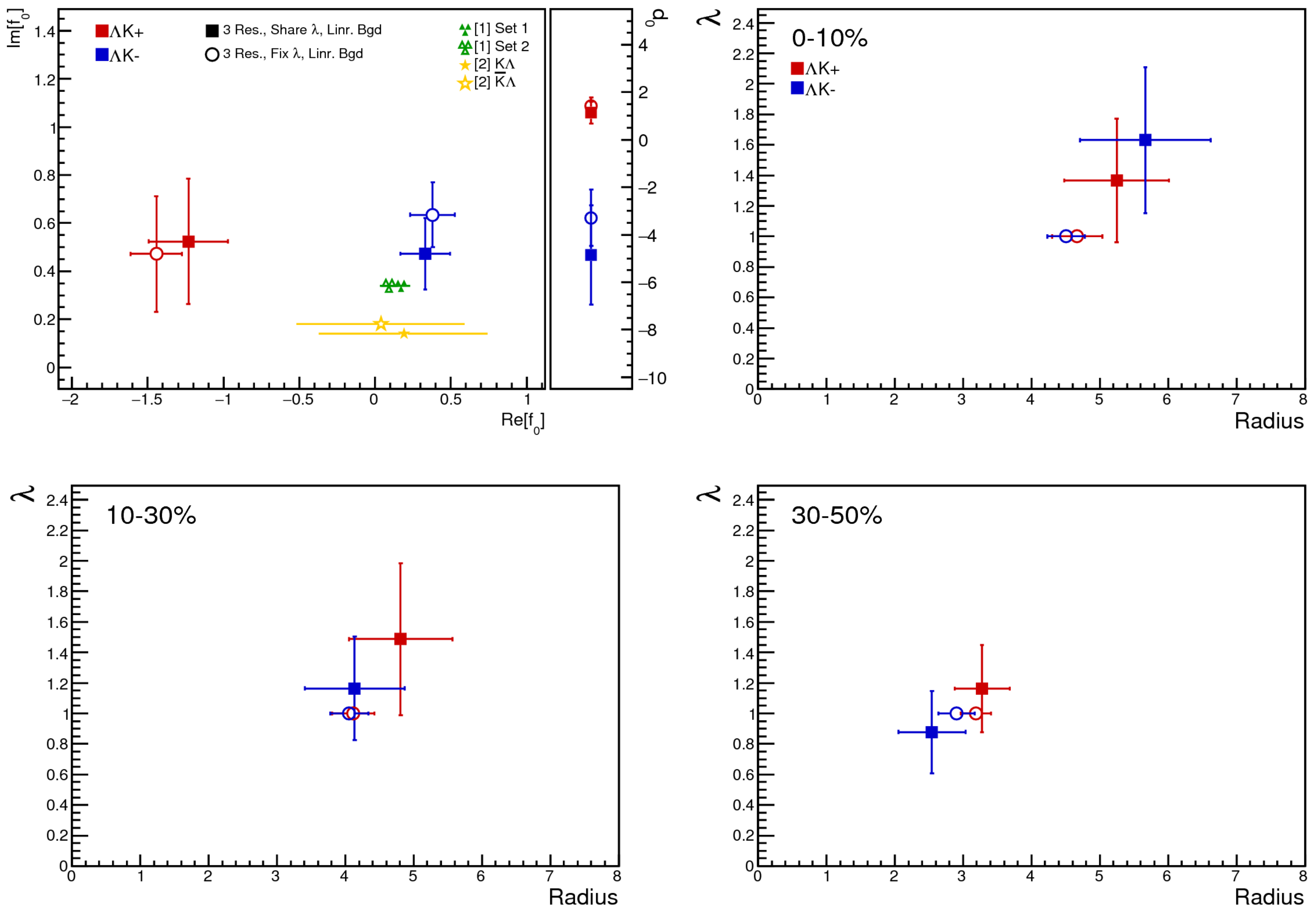
Separate R, shared λ



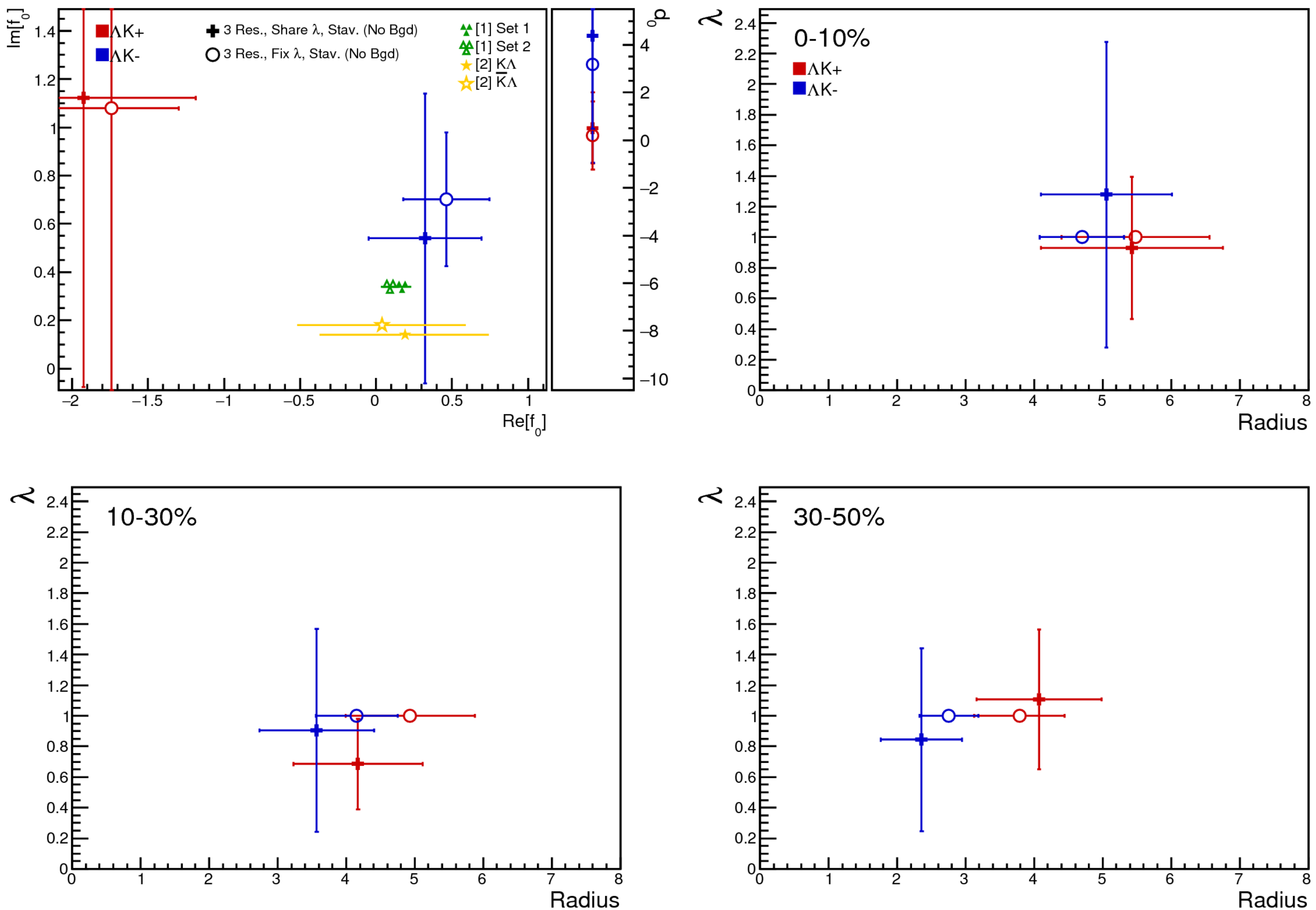
Separate R, shared λ (Poly. Bgd.)



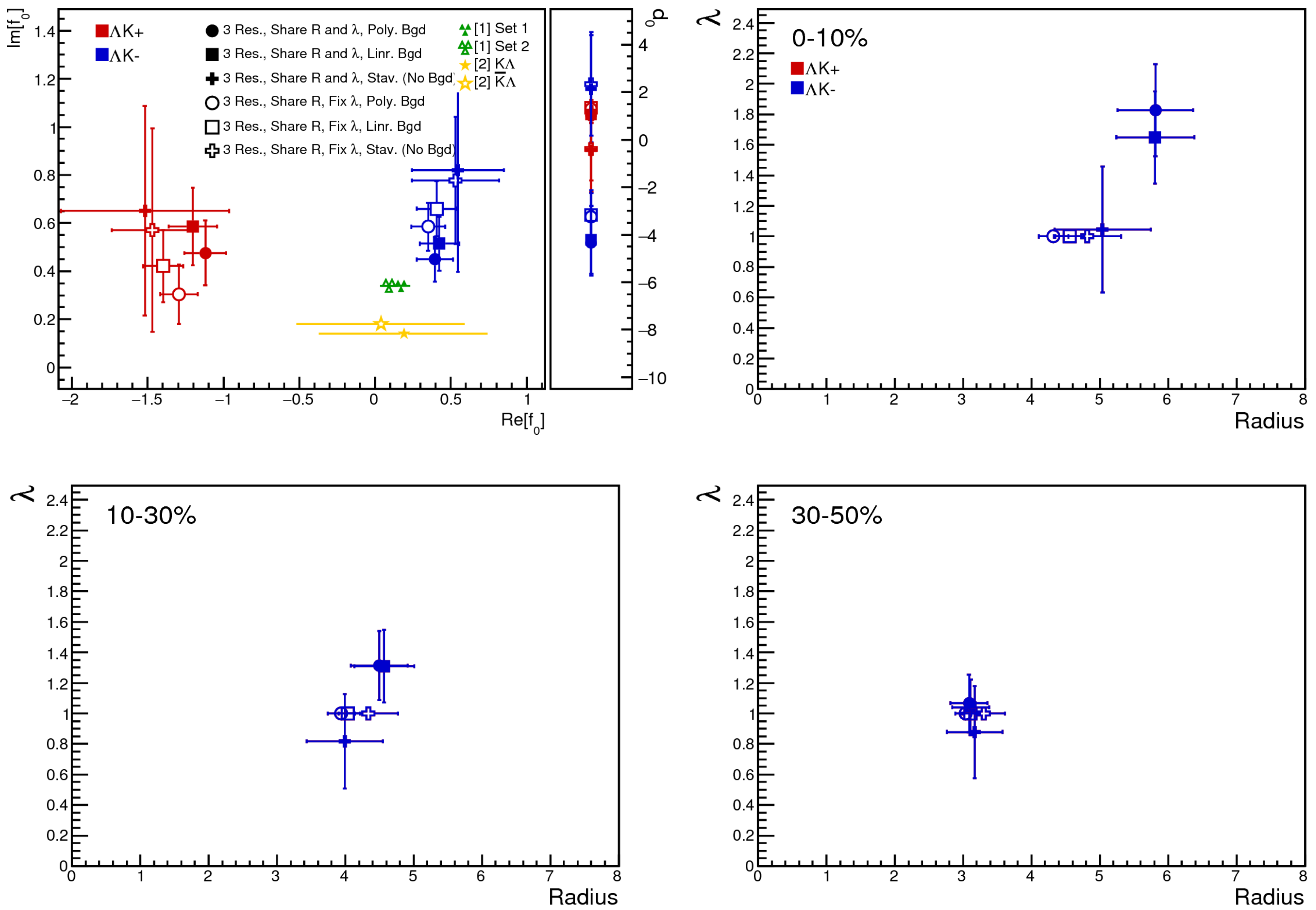
Separate R, shared λ (Linr. Bgd.)



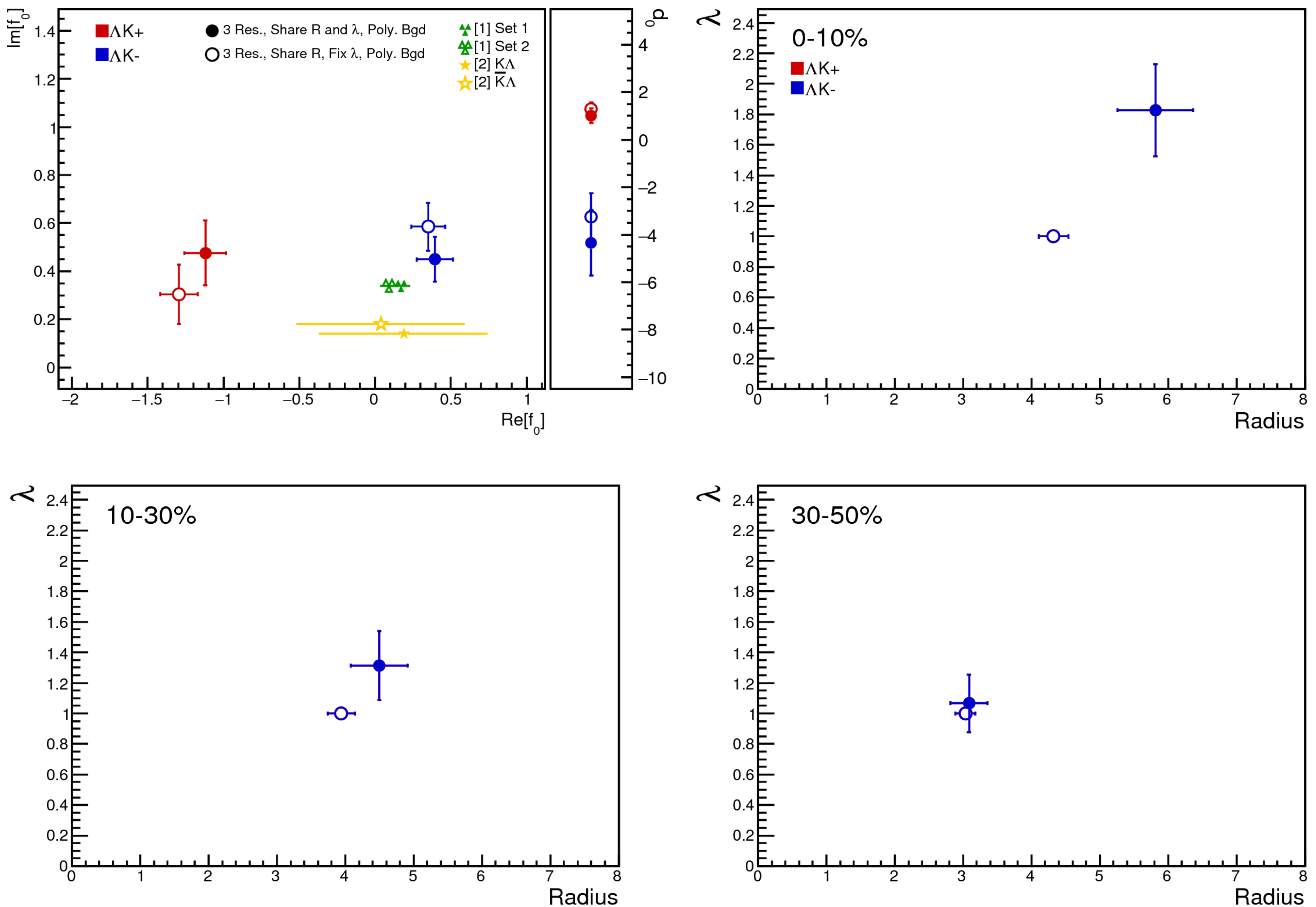
Separate R, shared λ (Stav.)



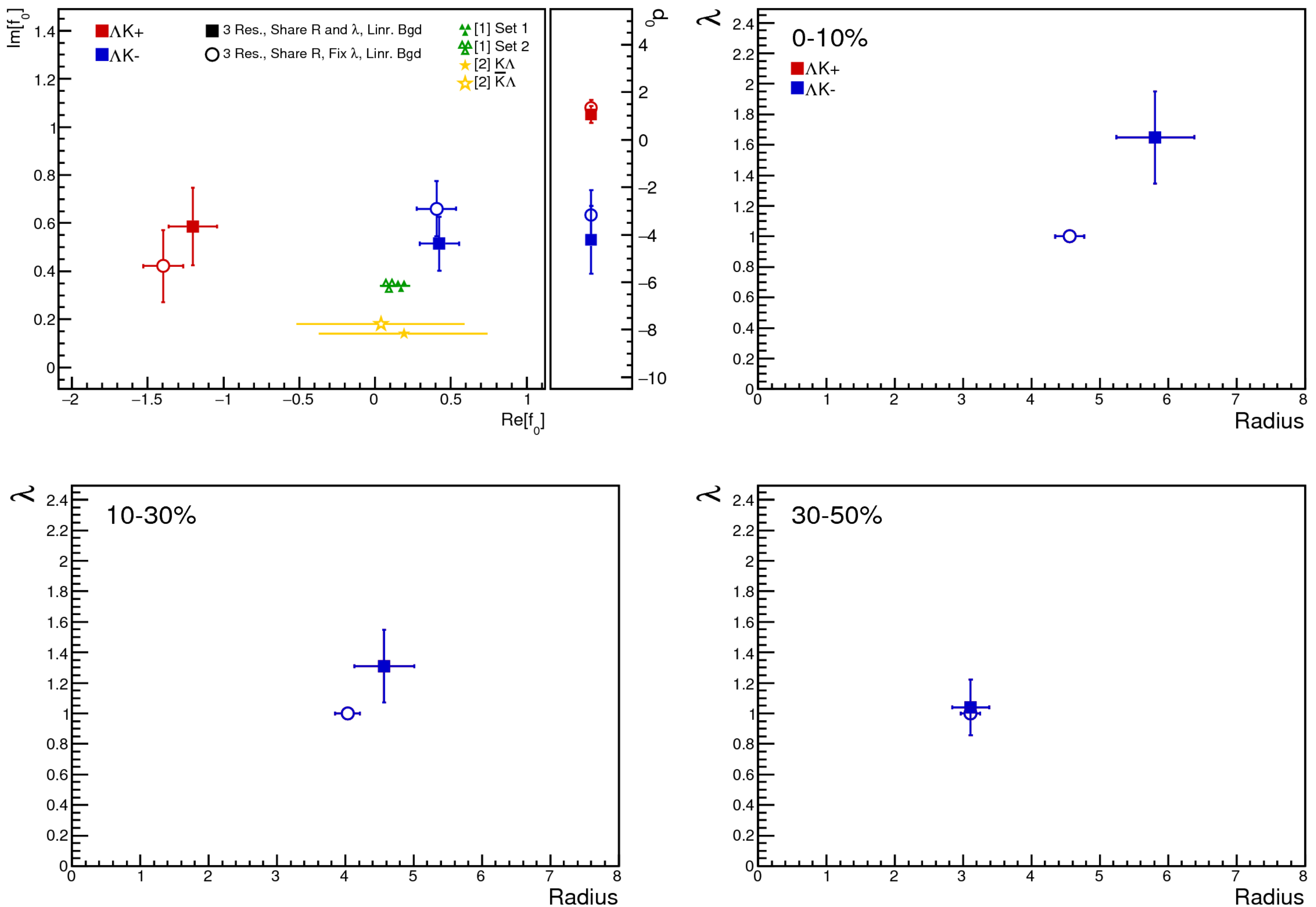
Shared R, shared λ



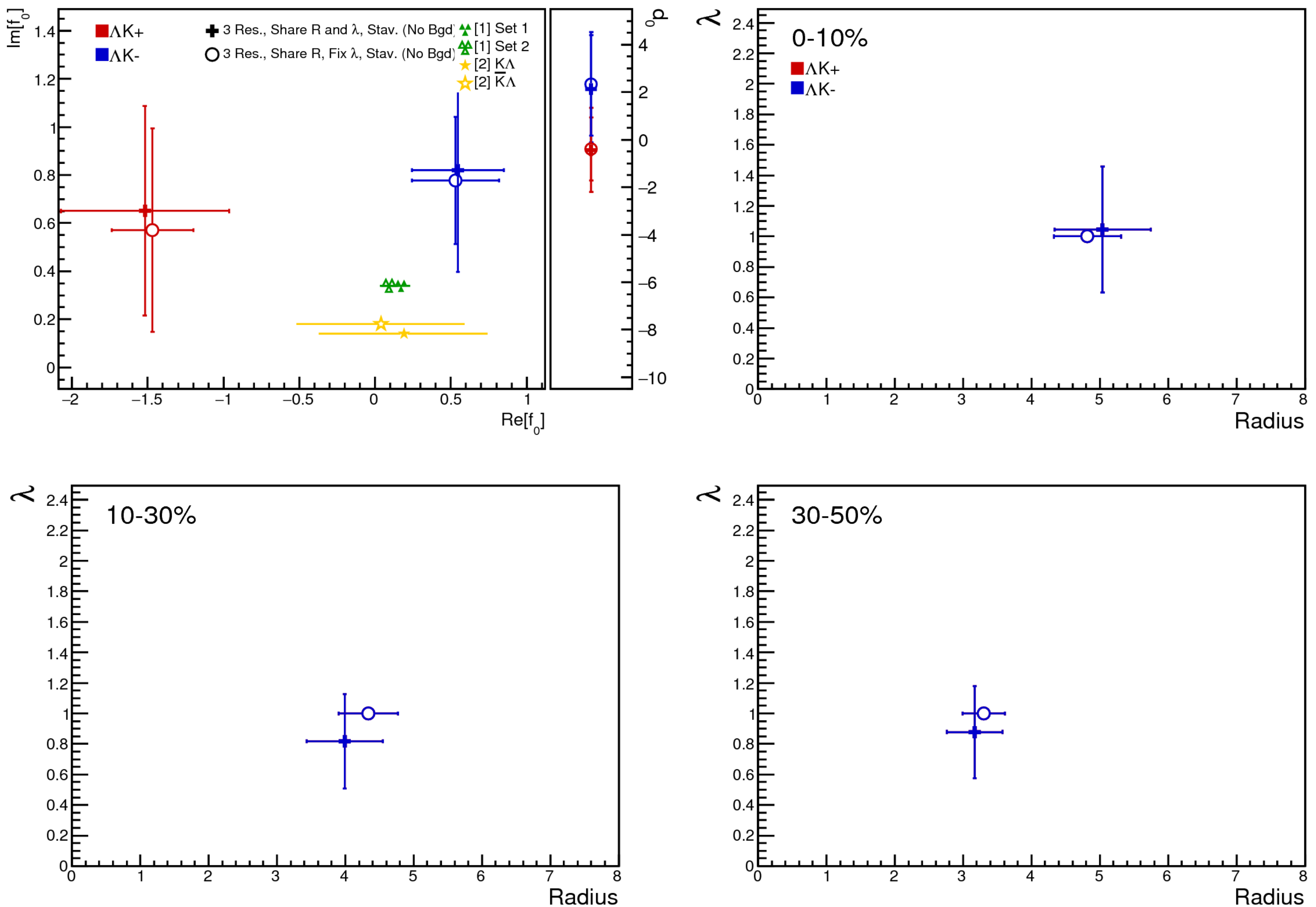
Shared R, shared λ (Poly. Bgd.)



Shared R, shared λ (Linr. Bgd.)



Shared R, shared λ (Stav.)

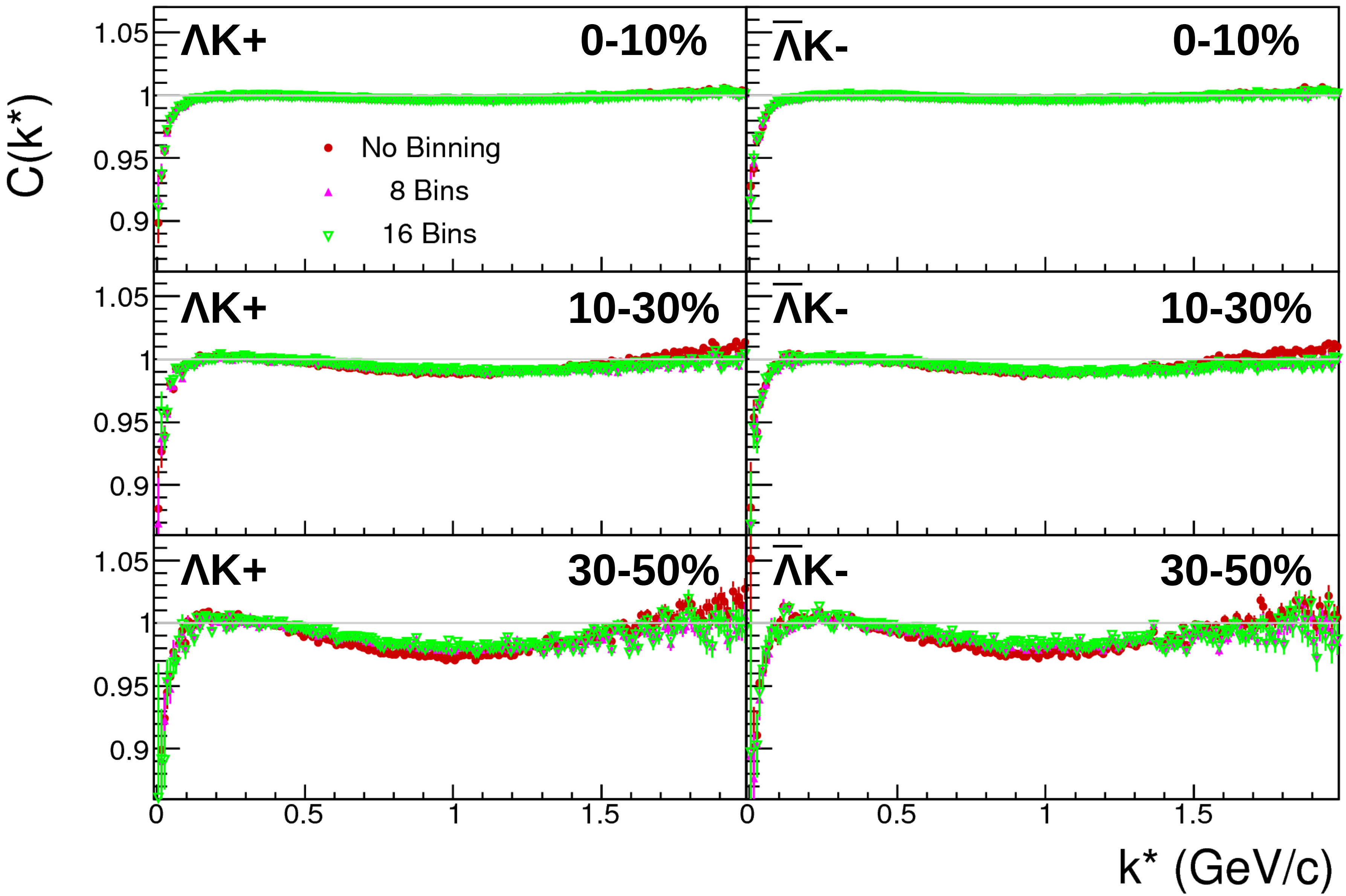


Compare Parameter Sharing

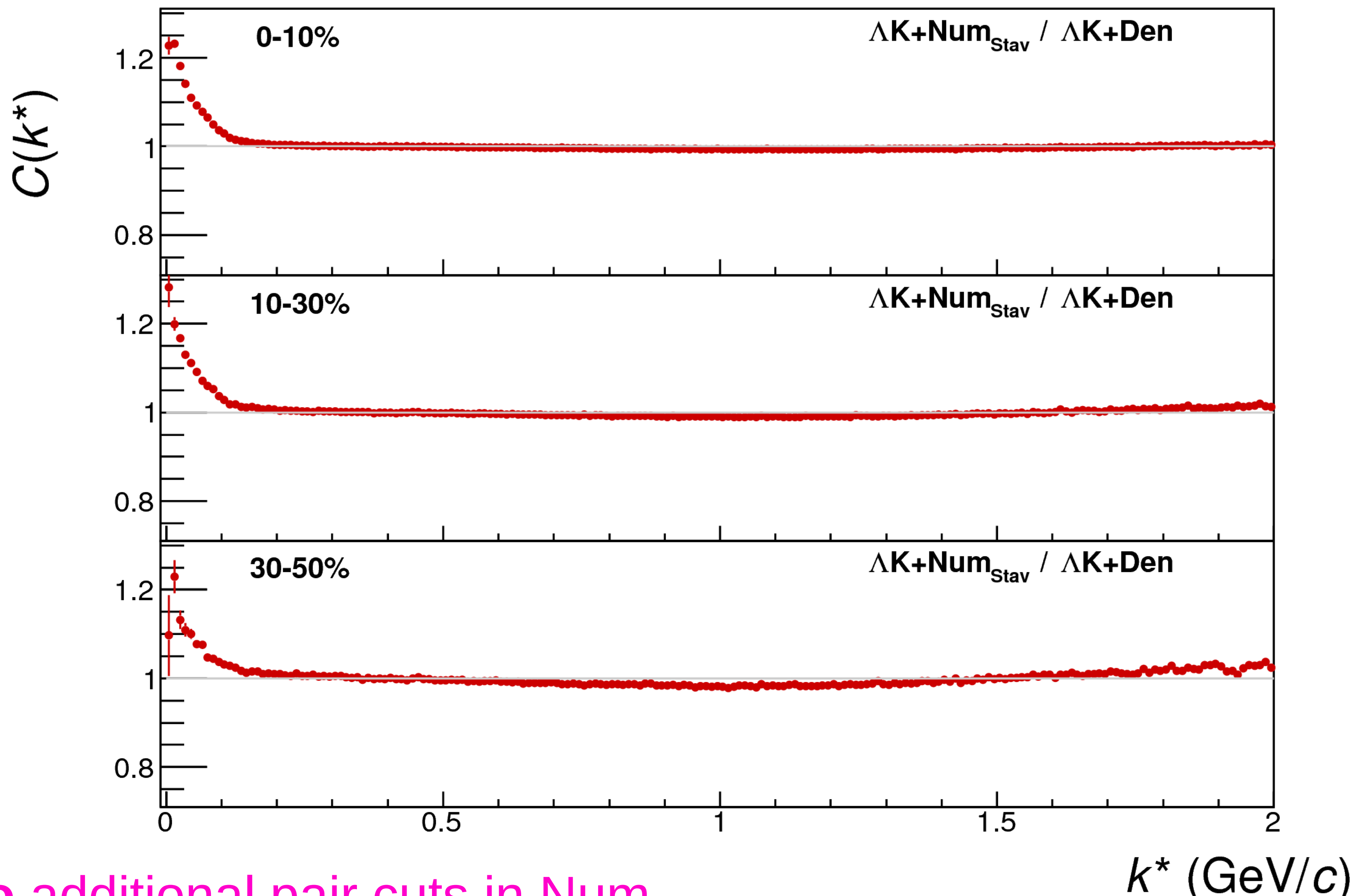
BACKUP

Binning Events in EP Angle

Data

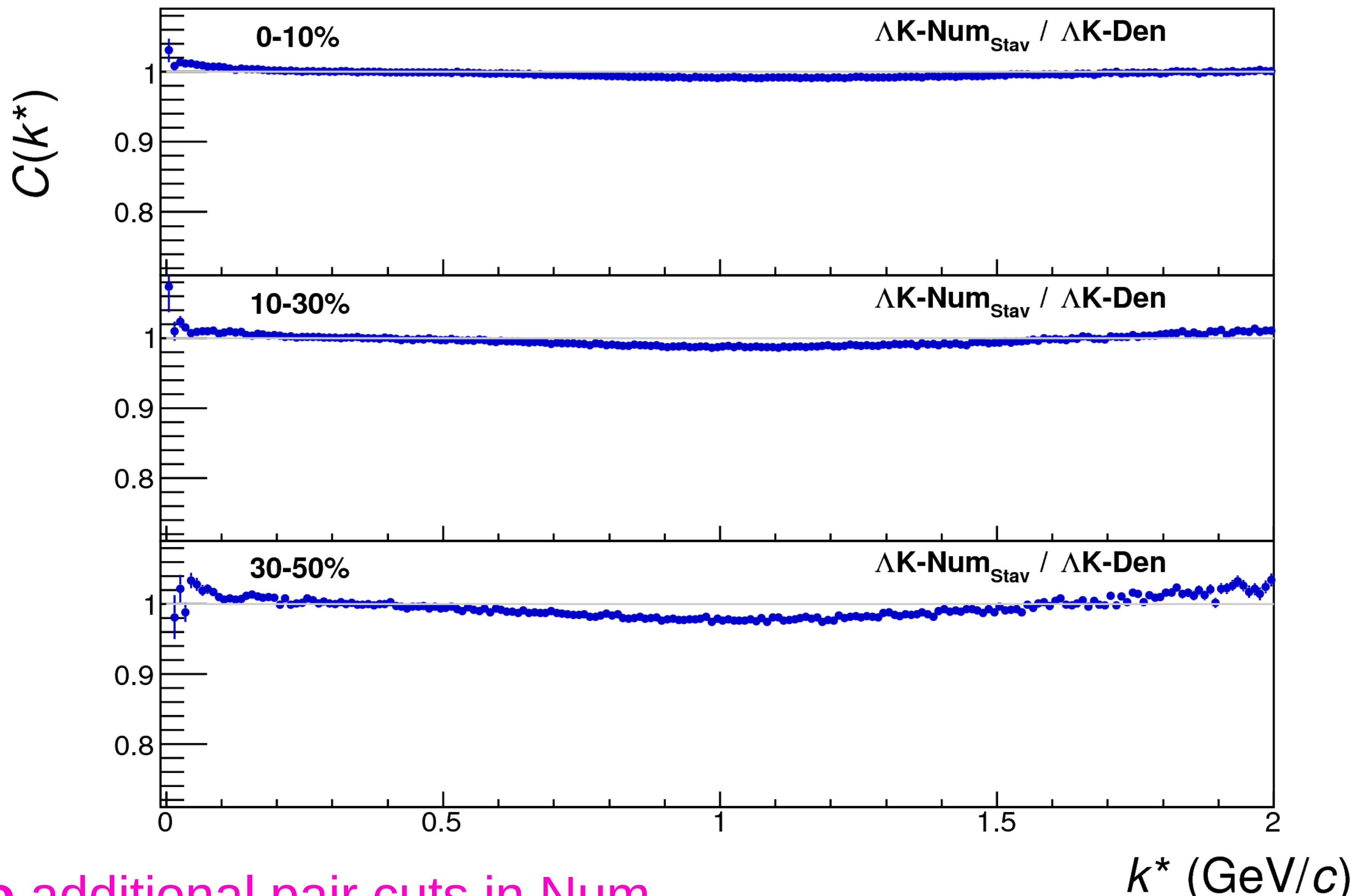


ΛK+ Num$_{Stav}$ / ΛK+ Den



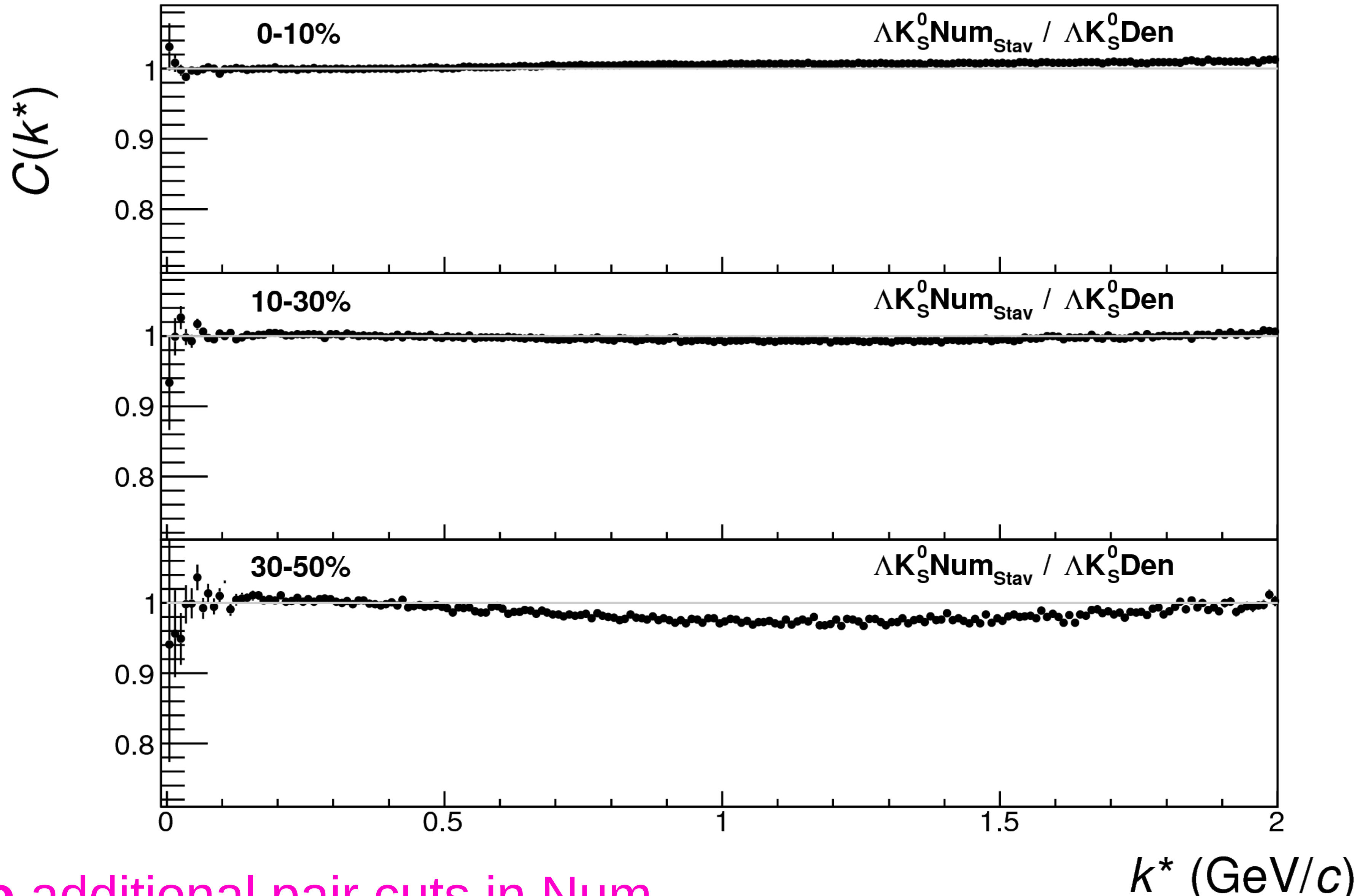
No additional pair cuts in Num$_{Stav}$

ΛK- Num_{Stav} / ΛK- Den



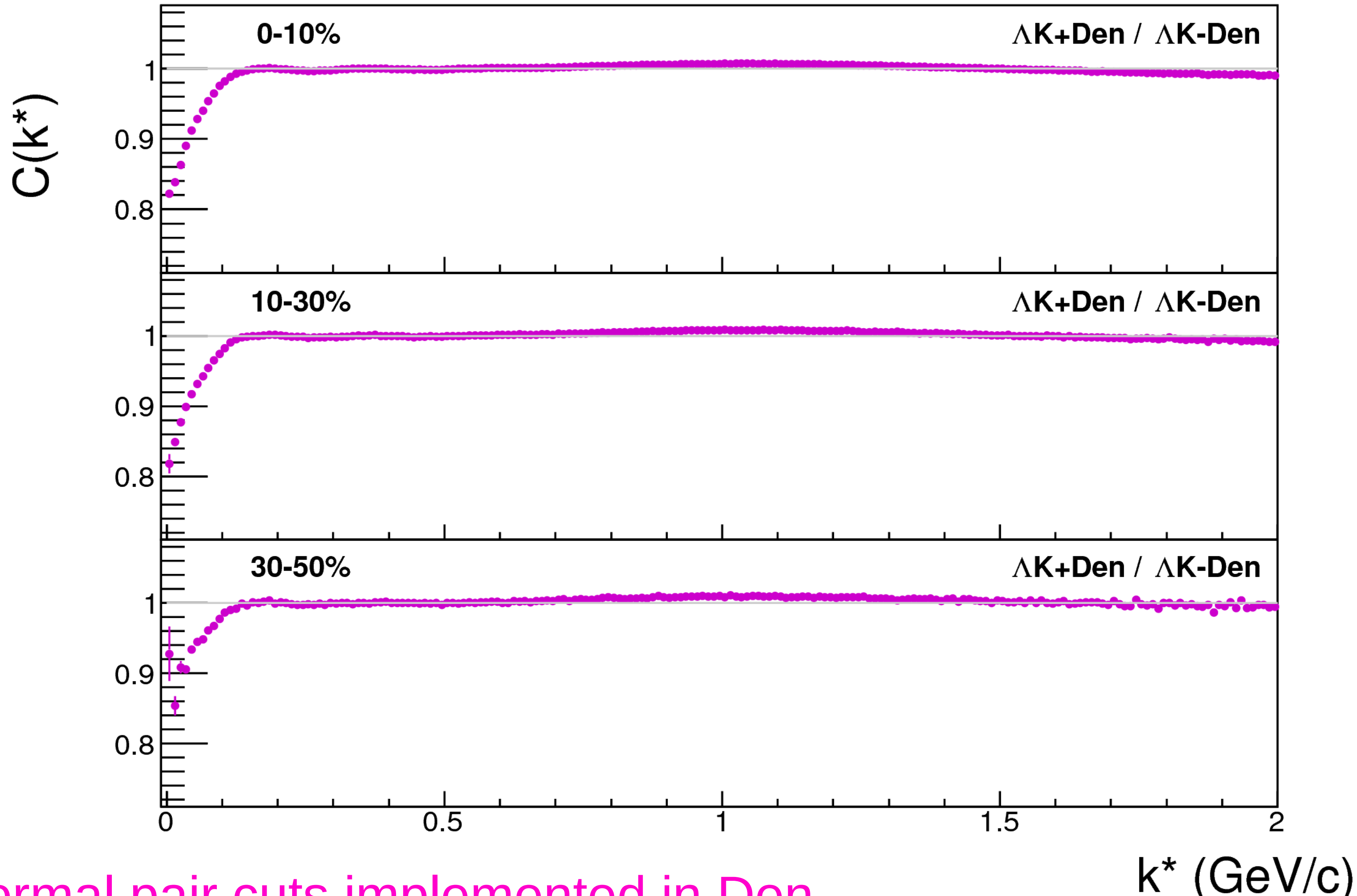
No additional pair cuts in Num_{Stav}

ΛK^0_S Num_{Stav} / ΛK^0_S Den



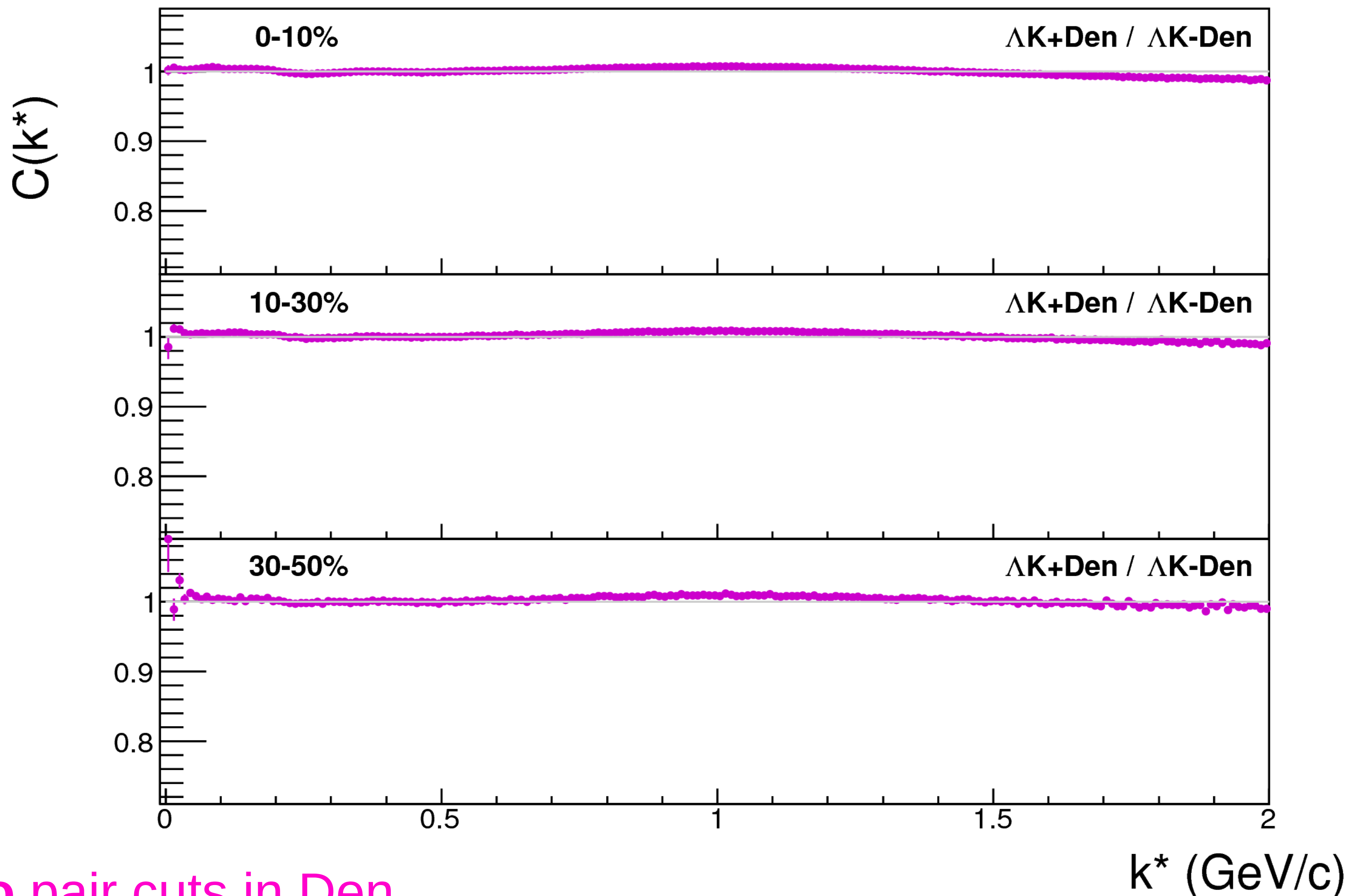
No additional pair cuts in Num_{Stav}

ΛK+ Den / ΛK- Den



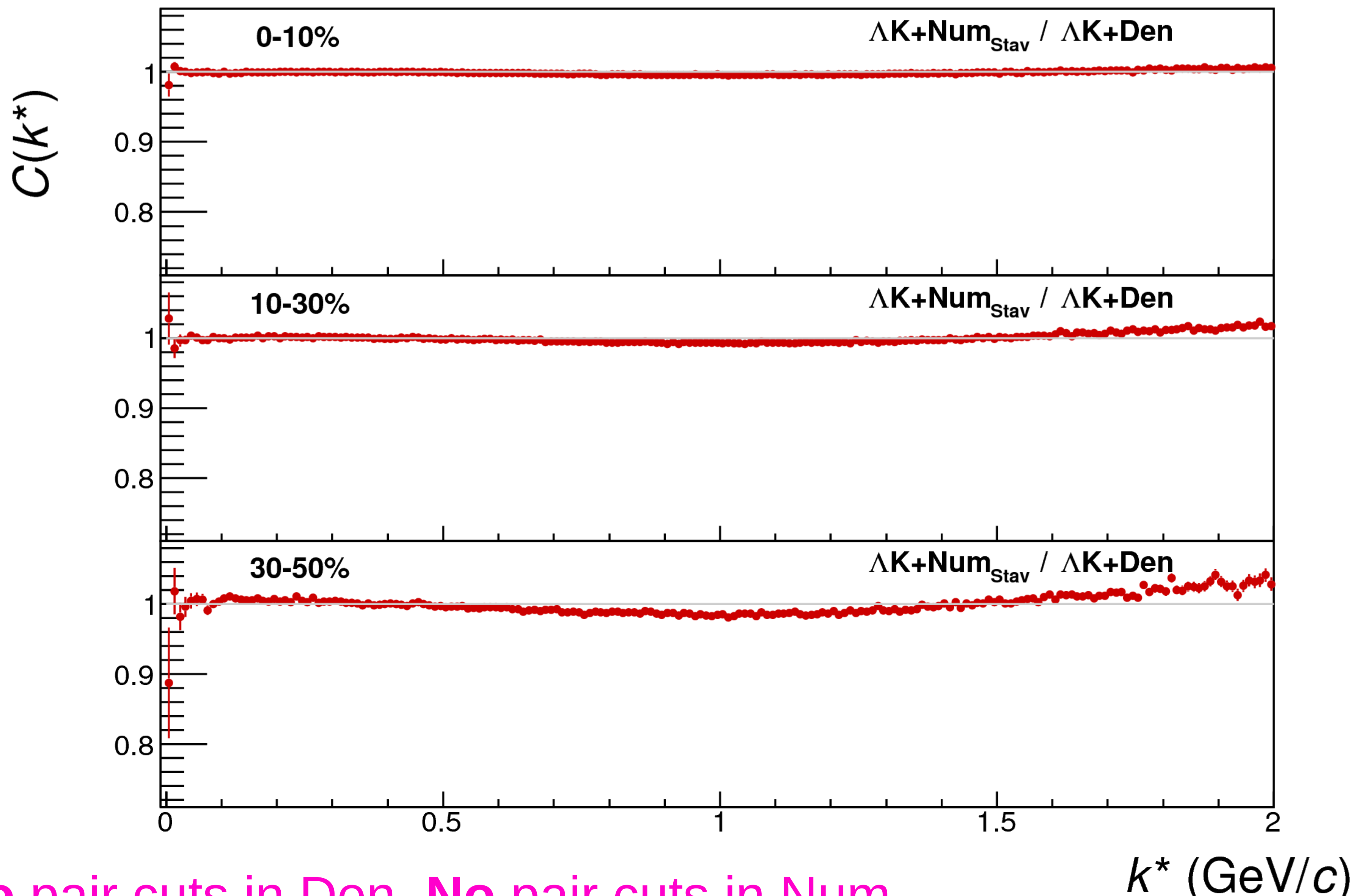
Normal pair cuts implemented in Den

ΛK+ Den / ΛK- Den



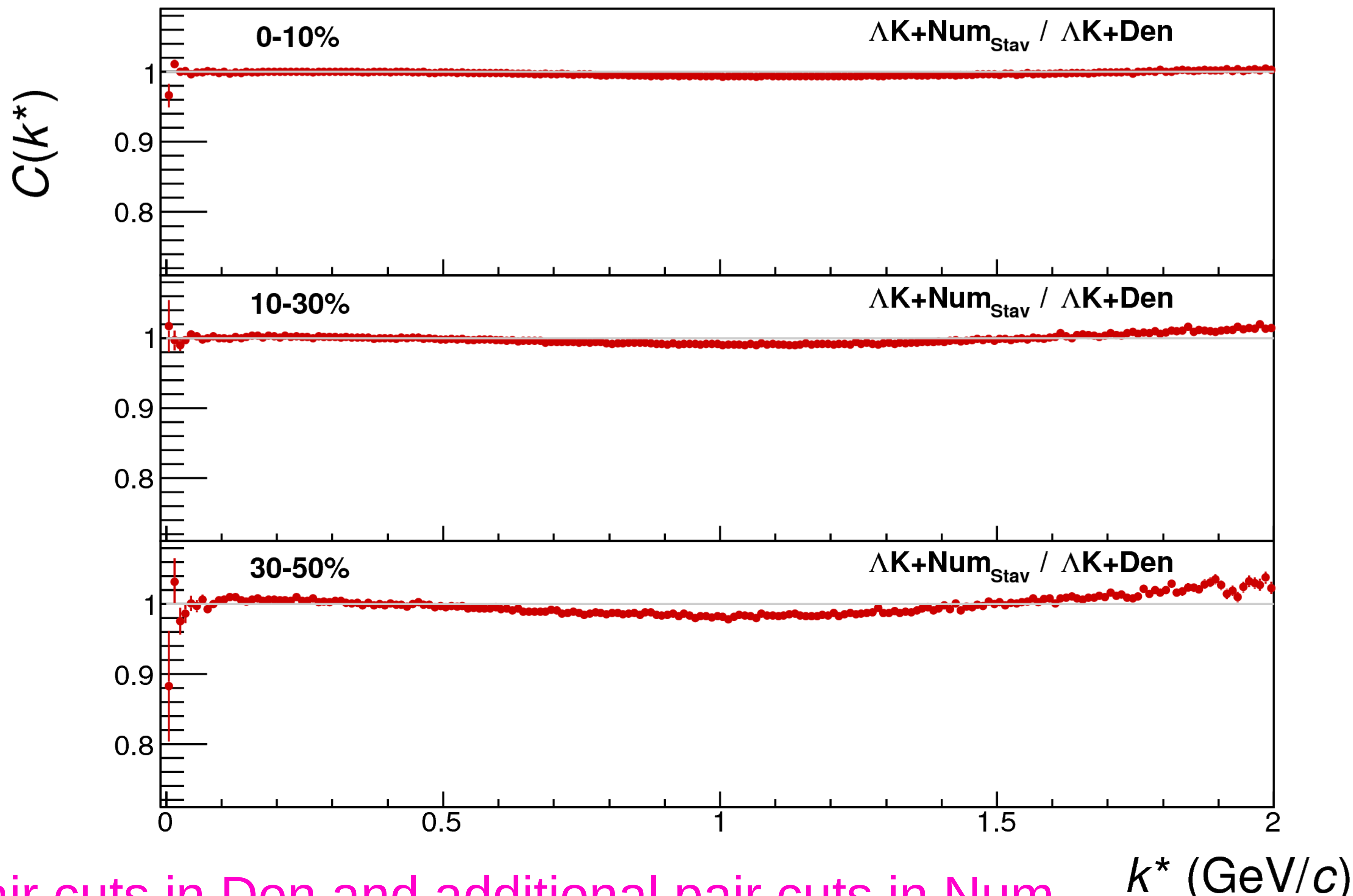
No pair cuts in Den

ΛK+ Num$_{Stav}$ / ΛK+ Den



No pair cuts in Den, **No** pair cuts in Num$_{Stav}$

ΛK+ Num$_{Stav}$ / ΛK+ Den



Pair cuts in Den and additional pair cuts in Num$_{Stav}$

Fit Results:
Parameter Plots and Tables

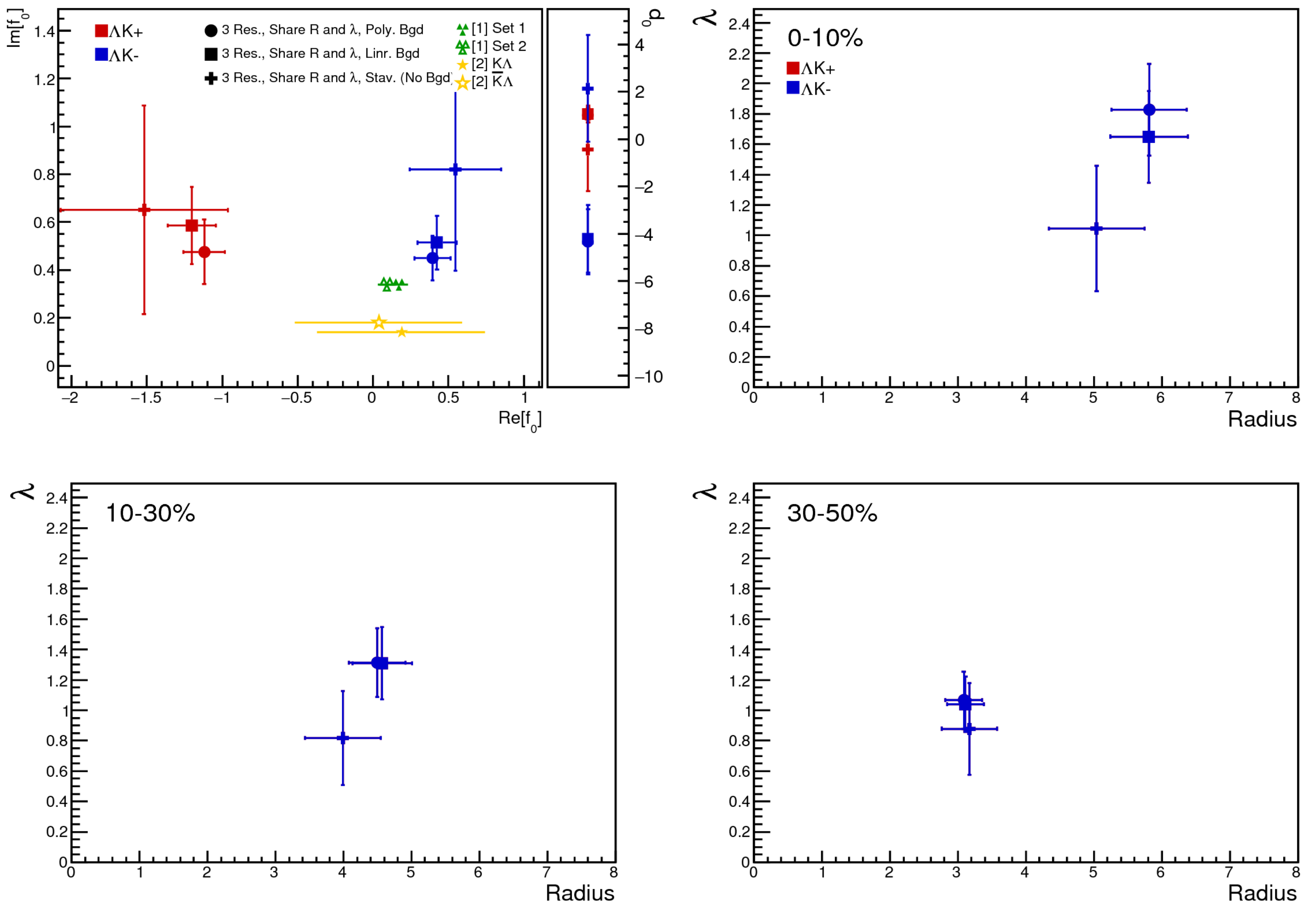
Comparing Bgd Treatments

- **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

Fits in BACKUP slides

Centrality	System	Parameter	Methods		
			Poly. Bgd	Lin. Bgd	Stav.(No Bgd)
0-10%	ΛK^+ $\bar{\Lambda} K^-$ ΛK^- $\bar{\Lambda} K^+$	λ	1.83	1.65	1.05
	ΛK^+ & $\bar{\Lambda} K^-$ ΛK^- & $\bar{\Lambda} K^+$	R	5.81	5.81	5.04
10-30%	ΛK^+ $\bar{\Lambda} K^-$ ΛK^- $\bar{\Lambda} K^+$	λ	1.31	1.31	0.82
	ΛK^+ & $\bar{\Lambda} K^-$ ΛK^- & $\bar{\Lambda} K^+$	R	4.50	4.57	3.99
30-50%	ΛK^+ $\bar{\Lambda} K^-$ ΛK^- $\bar{\Lambda} K^+$	λ	1.07	1.04	0.88
	ΛK^+ & $\bar{\Lambda} K^-$ ΛK^- & $\bar{\Lambda} K^+$	R	3.09	3.11	3.17
	ΛK^+ & $\bar{\Lambda} K^-$	$\mathbb{R} f_0$	-1.12	-1.20	-1.52
		$\mathbb{I} f_0$	0.48	0.59	0.65
		d_0	1.01	1.07	-0.44
	ΛK^- & $\bar{\Lambda} K^+$	$\mathbb{R} f_0$	0.39	0.42	0.55
		$\mathbb{I} f_0$	0.45	0.51	0.82
		d_0	-4.35	-4.22	2.14

Shared R, shared λ



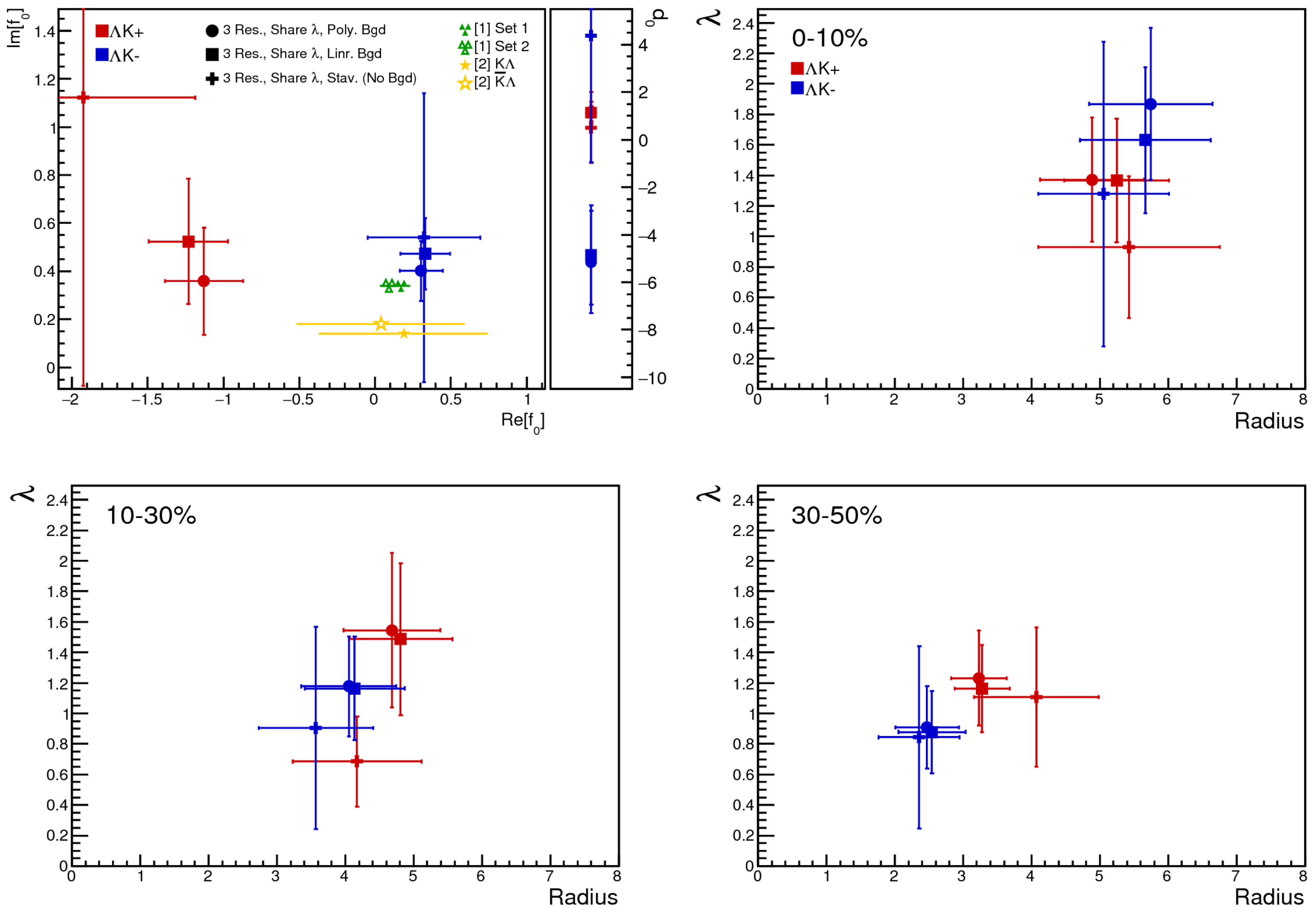
Comparing Bgd Treatments

- **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
	ΛK^+ & $\bar{\Lambda} K^-$	R	4.89	5.25	5.43
	ΛK^- & $\bar{\Lambda} K^+$	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
	ΛK^+ & $\bar{\Lambda} K^-$	R	4.68	4.81	4.17
	ΛK^- & $\bar{\Lambda} K^+$	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
	ΛK^+ & $\bar{\Lambda} K^-$	R	3.23	3.28	4.07
	ΛK^- & $\bar{\Lambda} K^+$	R	2.47	2.54	2.36
	ΛK^+ & $\bar{\Lambda} K^-$	$\mathbb{R} f_0$	-1.13	-1.23	-1.92
		$\mathbb{I} f_0$	0.36	0.52	1.12
		d_0	1.11	1.14	0.51
	ΛK^- & $\bar{\Lambda} K^+$	$\mathbb{R} f_0$	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



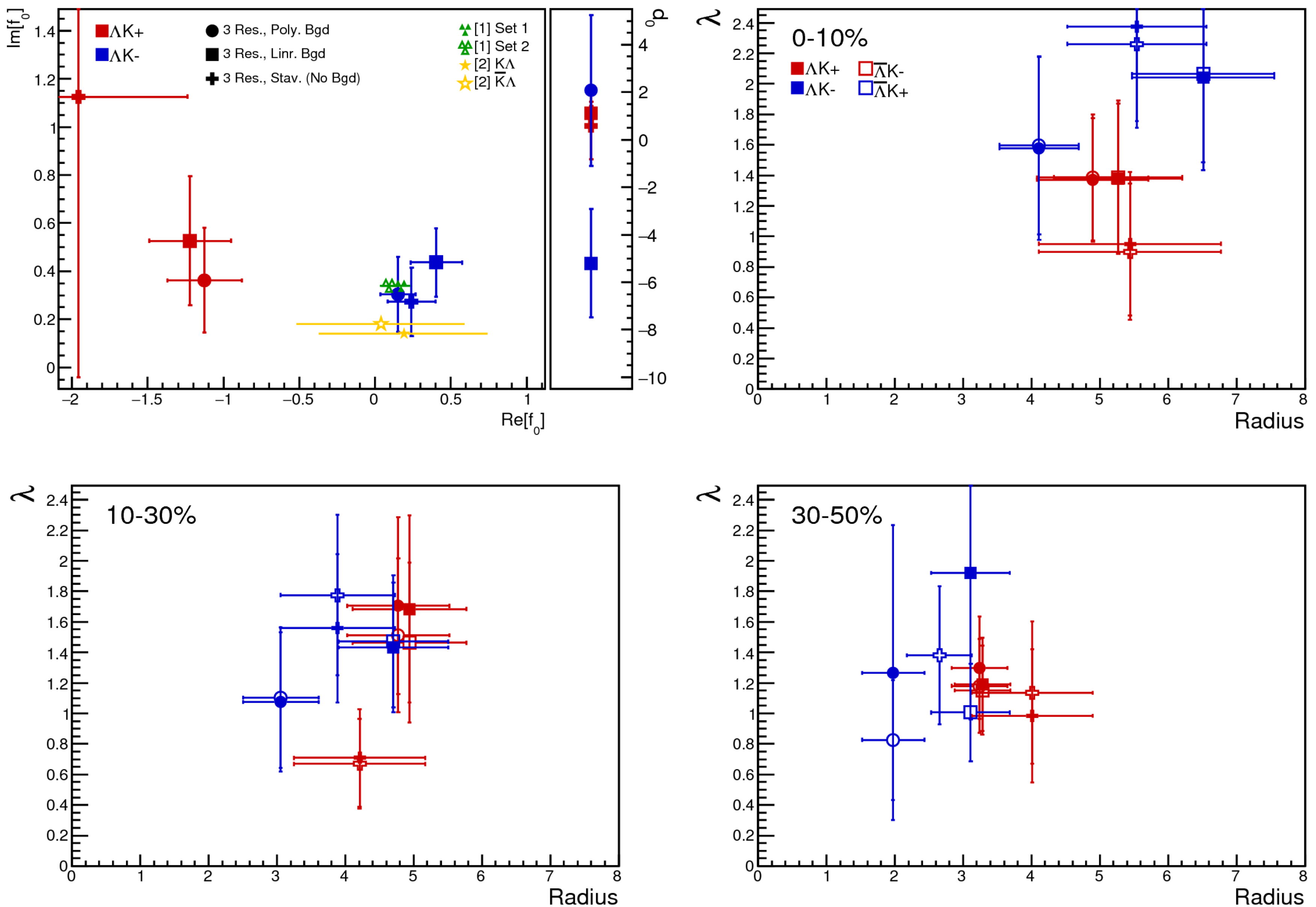
Comparing Bgd Treatments

- **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

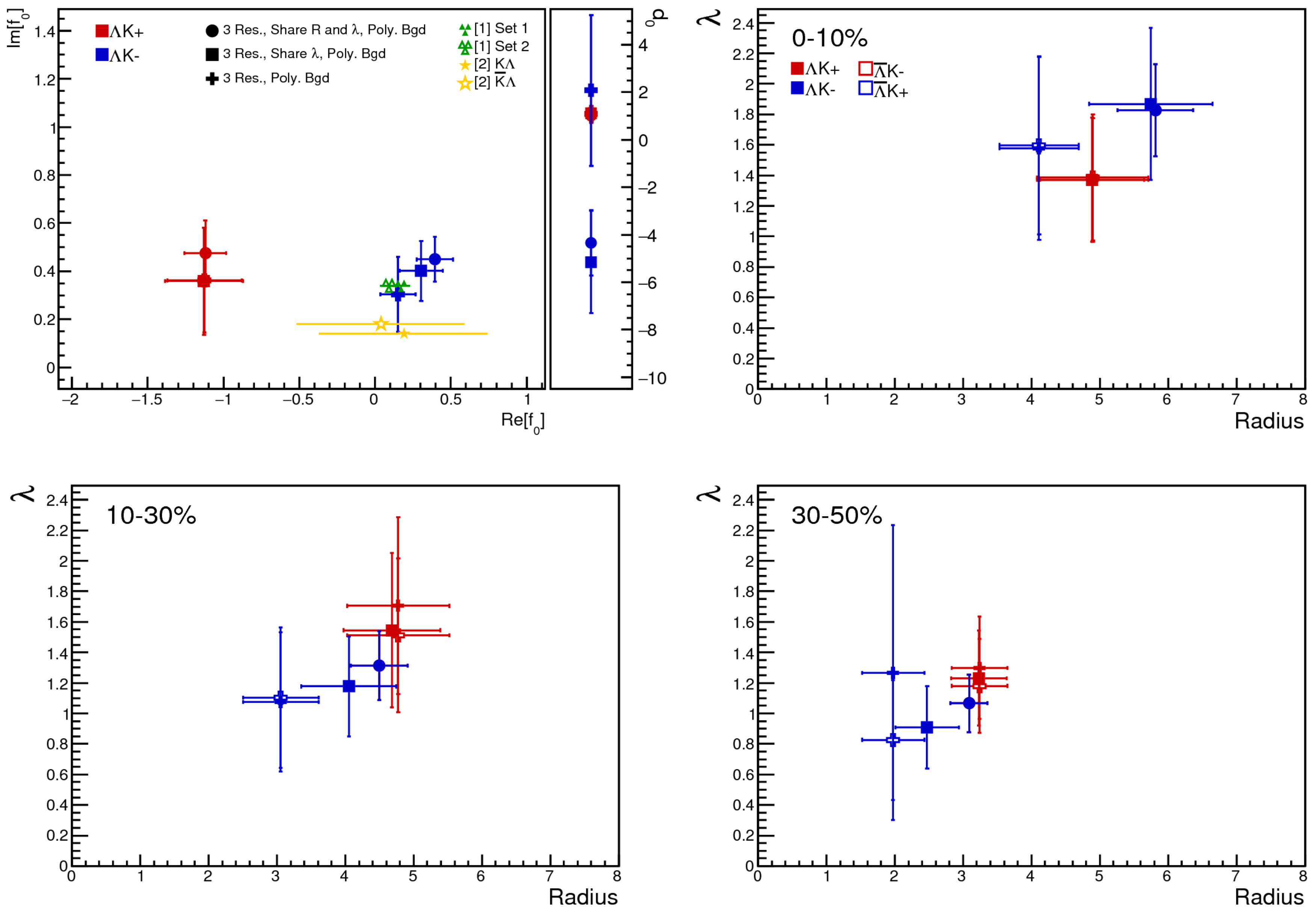
Fits in BACKUP slides

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
	ΛK^+ & $\bar{\Lambda} K^-$	R	4.90	5.27	5.44
	ΛK^- & $\bar{\Lambda} K^+$	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
	ΛK^+ & $\bar{\Lambda} K^-$	R	4.78	4.94	4.21
	ΛK^- & $\bar{\Lambda} K^+$	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
	ΛK^+ & $\bar{\Lambda} K^-$	R	3.24	3.28	4.01
	ΛK^- & $\bar{\Lambda} K^+$	R	1.98	3.11	2.65
	ΛK^+ & $\bar{\Lambda} K^-$	$\mathbb{R}f_0$	-1.13	-1.22	-1.96
		$\mathbb{I}f_0$	0.36	0.53	1.13
		d_0	1.09	1.12	0.58
	ΛK^- & $\bar{\Lambda} K^+$	$\mathbb{R}f_0$	0.15	0.40	0.24
		$\mathbb{I}f_0$	0.30	0.44	0.27
		d_0	2.07	-5.20	6.28

Separate R, separate λ



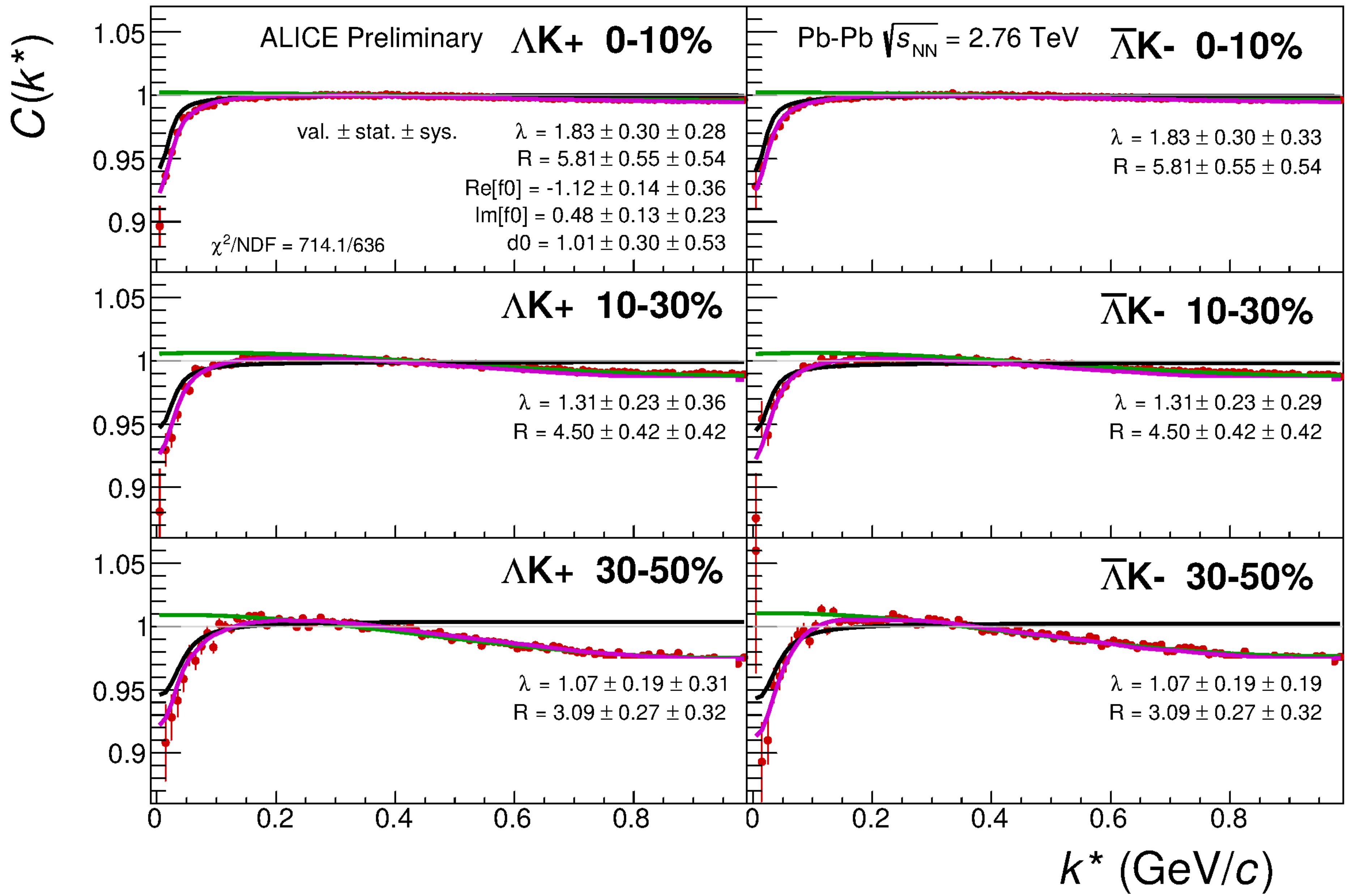
Separate vs Shared R



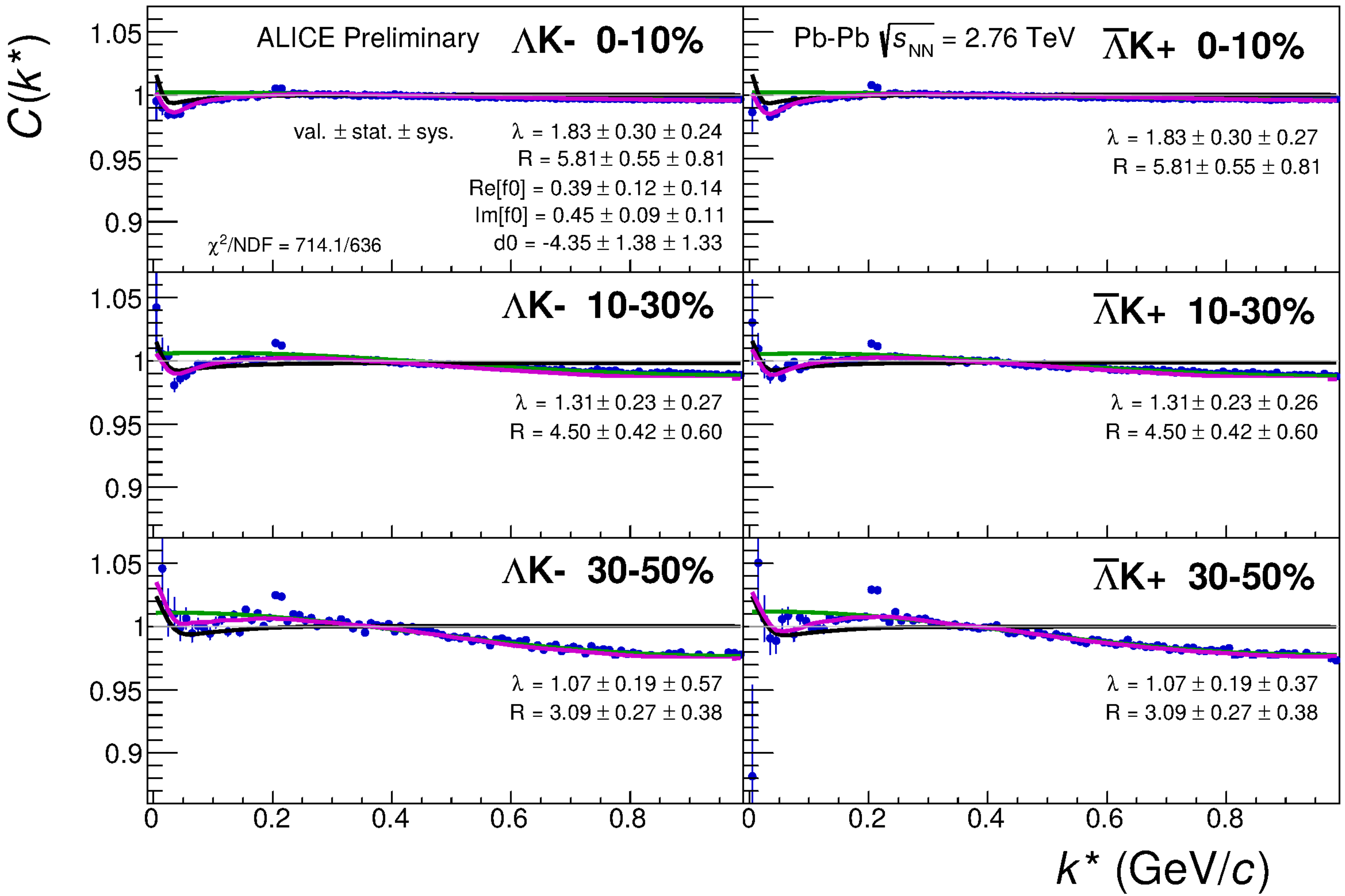
Fit Results:
Separate Radii, separate λ

Fit Results:
Shared Radii, shared λ

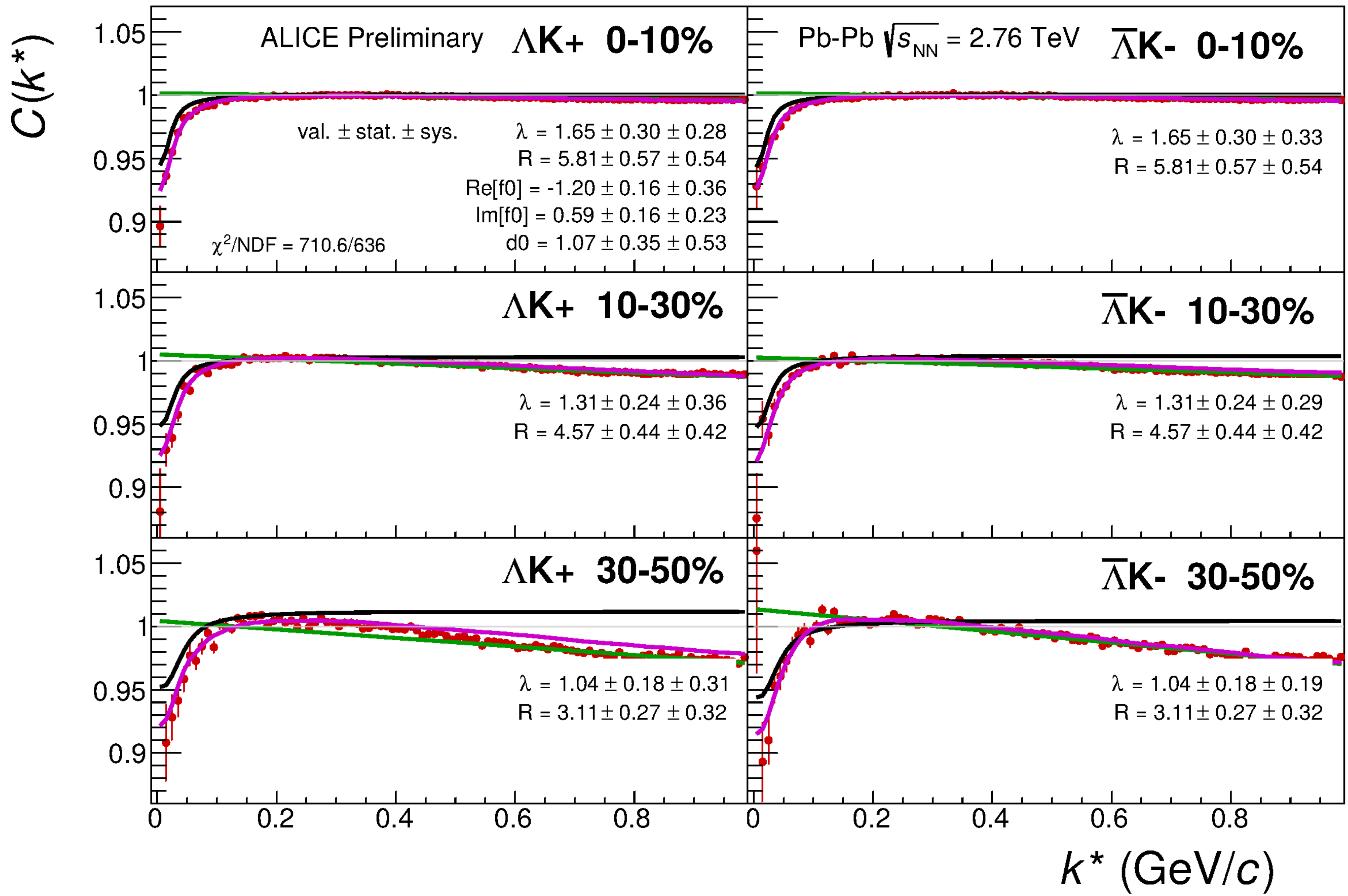
Share R, share λ, Poly. Bgd



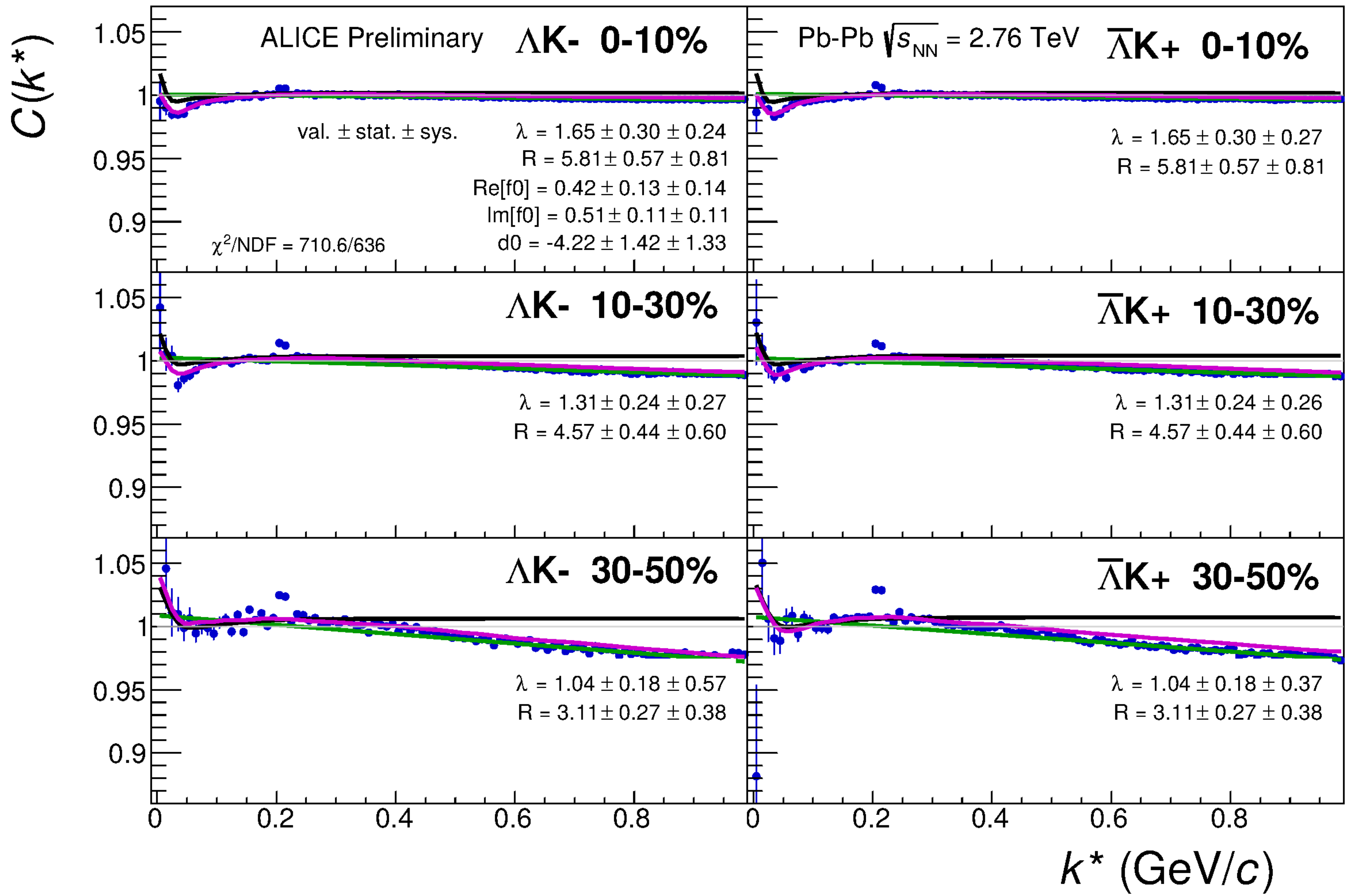
Share R, share λ, Poly. Bgd



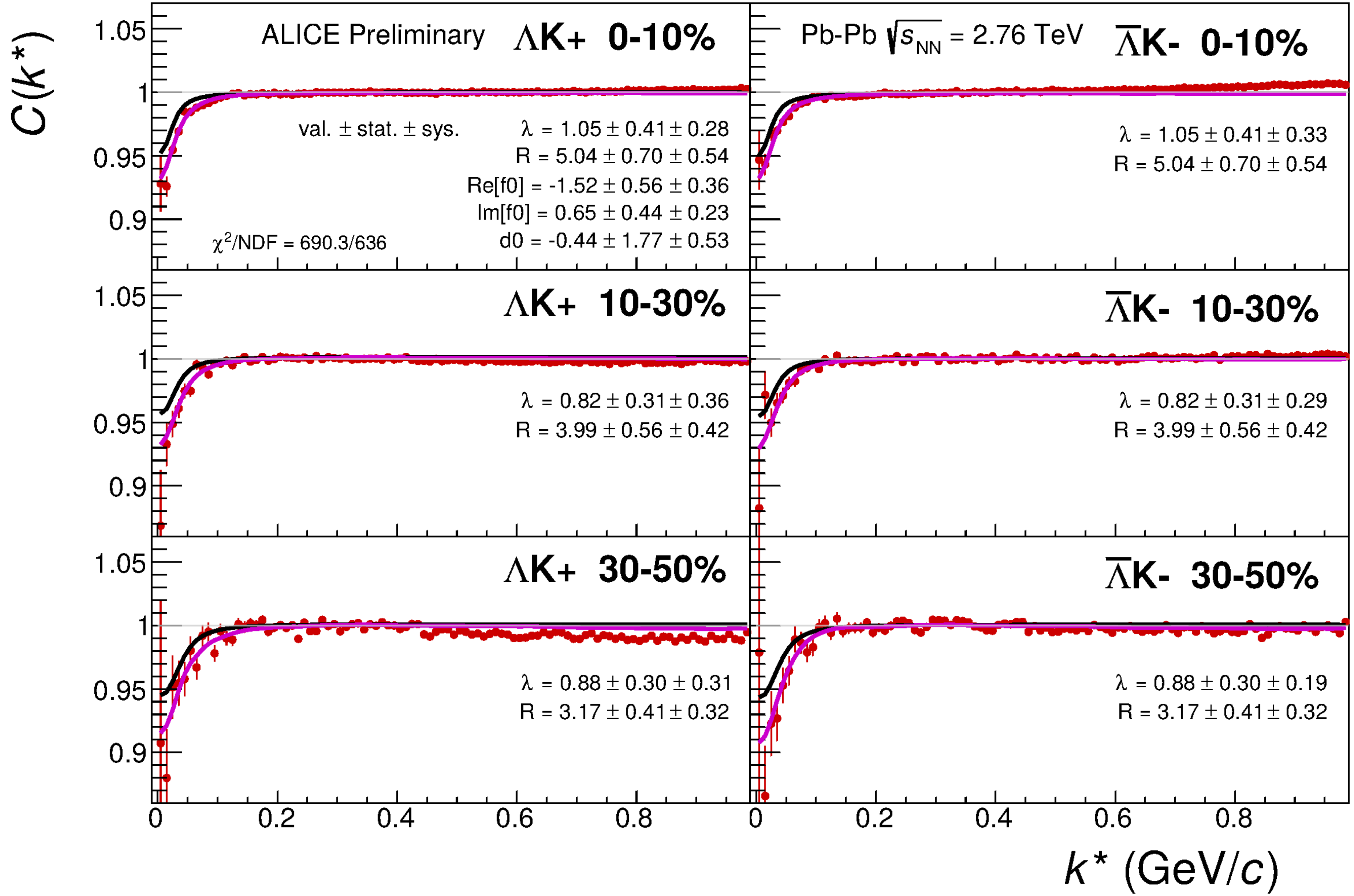
Share R, share λ, Lin. Bgd



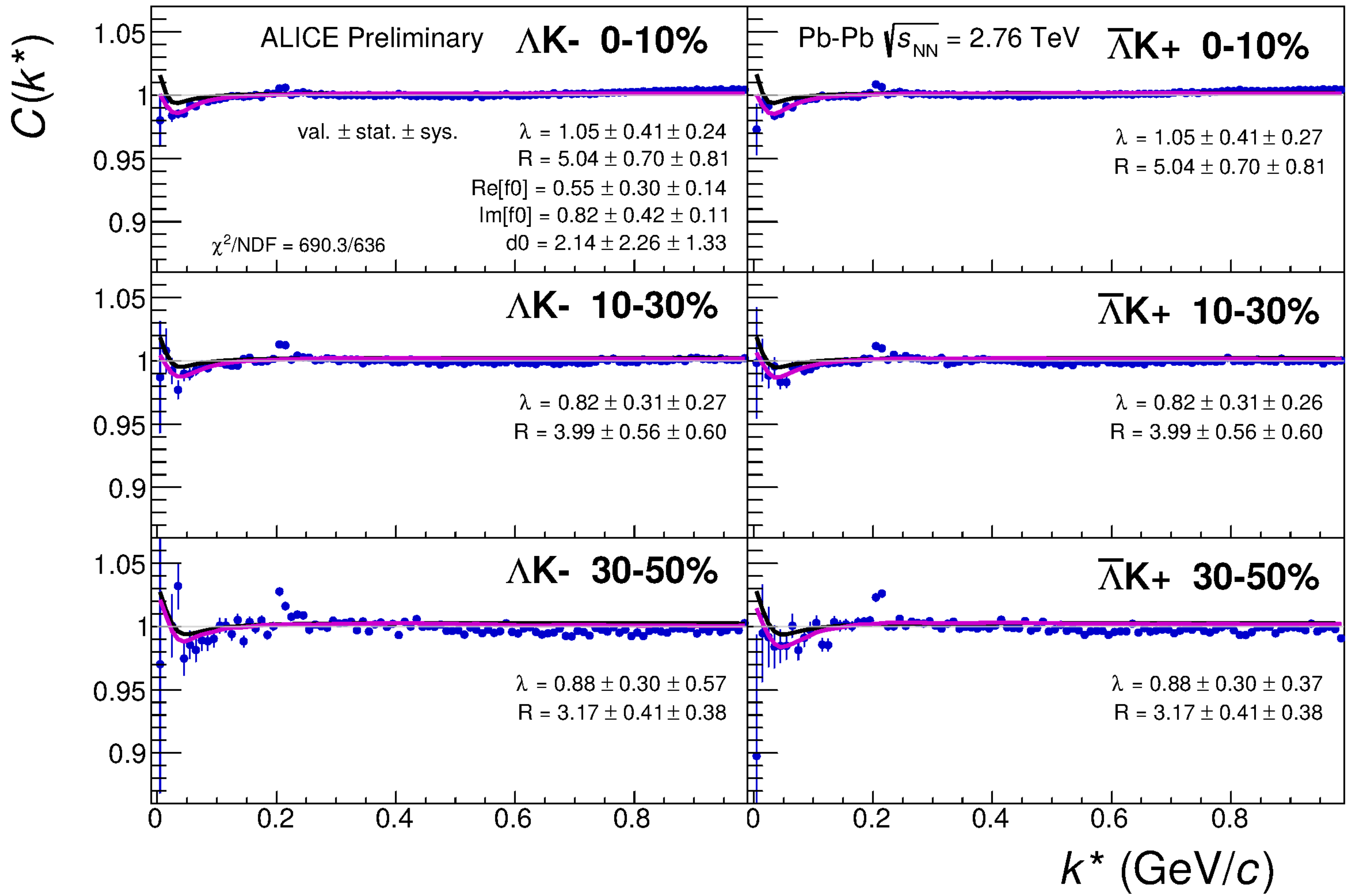
Share R, share λ, Lin. Bgd



Share R, share λ, Stav.(No Bgd)

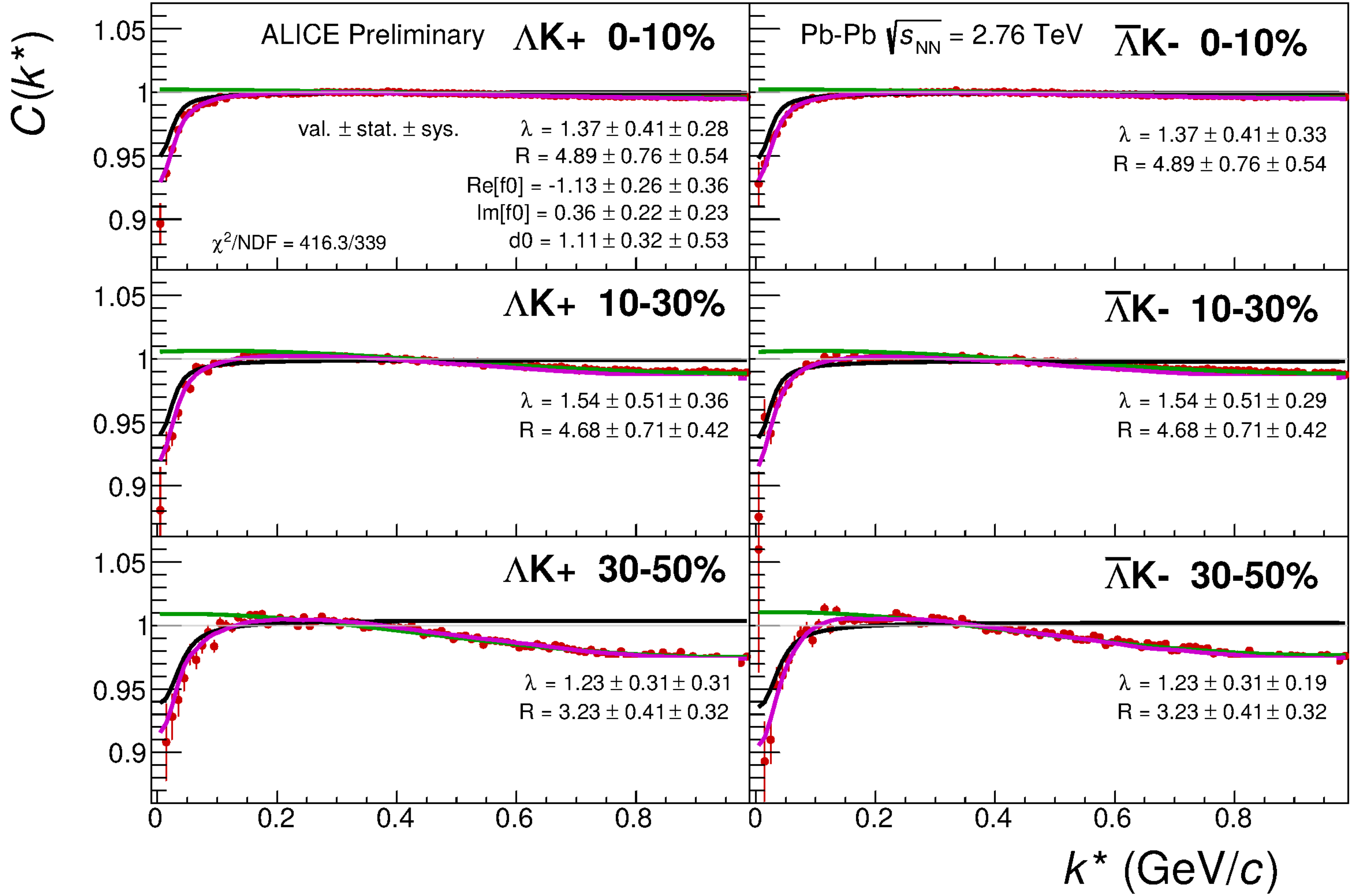


Share R, share λ, Stav.(No Bgd)

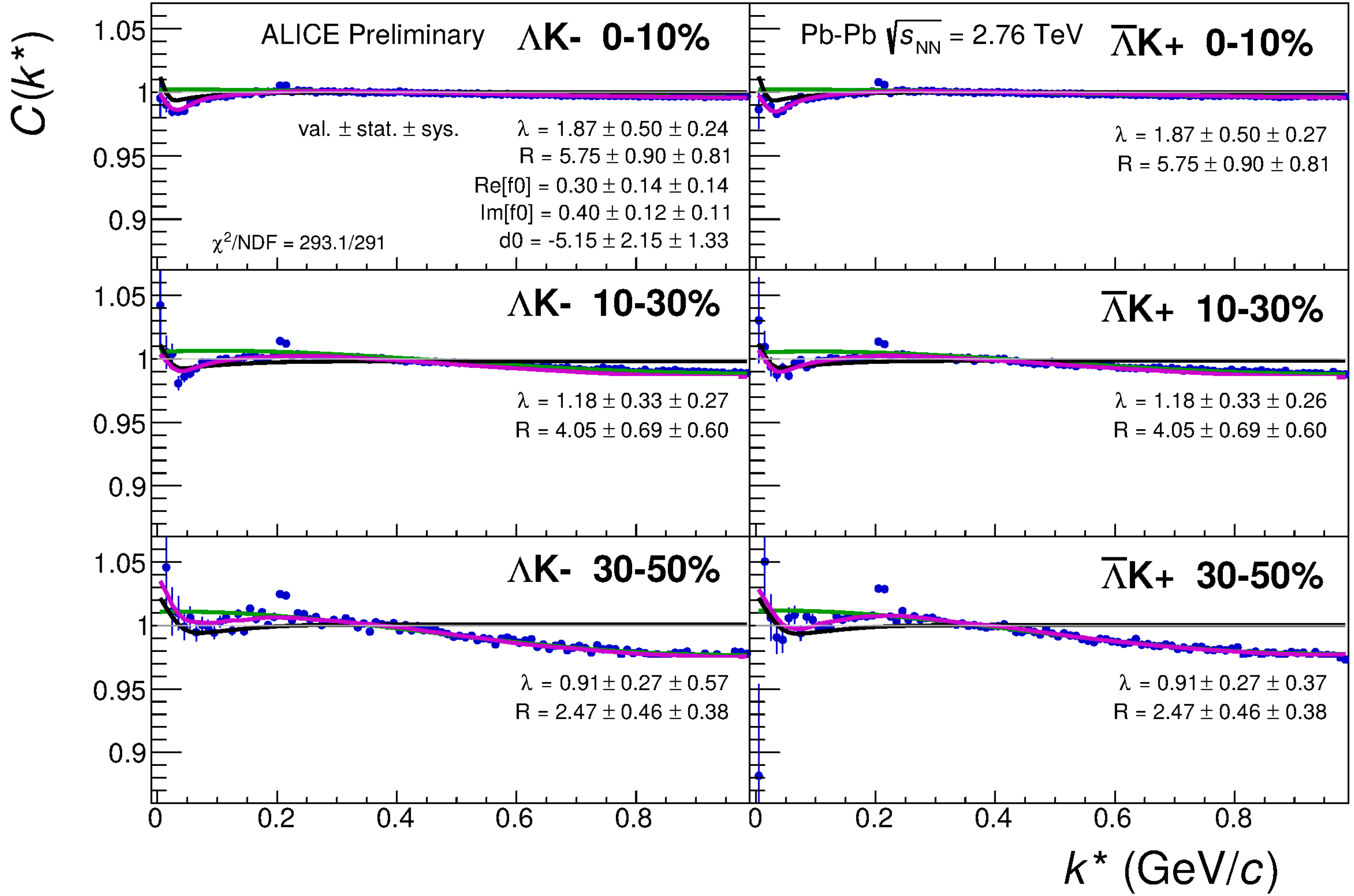


Fit Results:
Separate Radii, shared λ

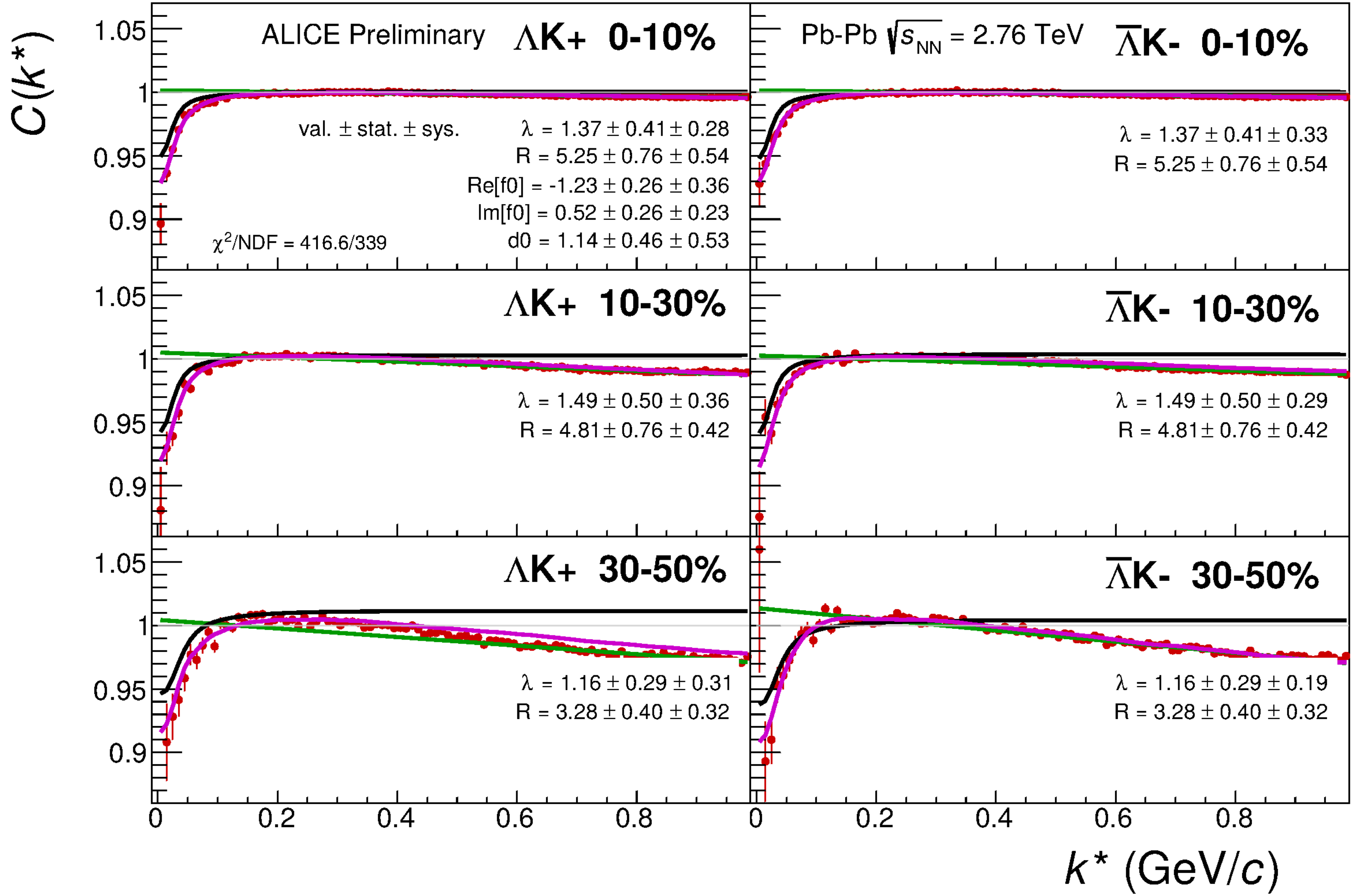
Sep. R, share λ, Poly. Bgd



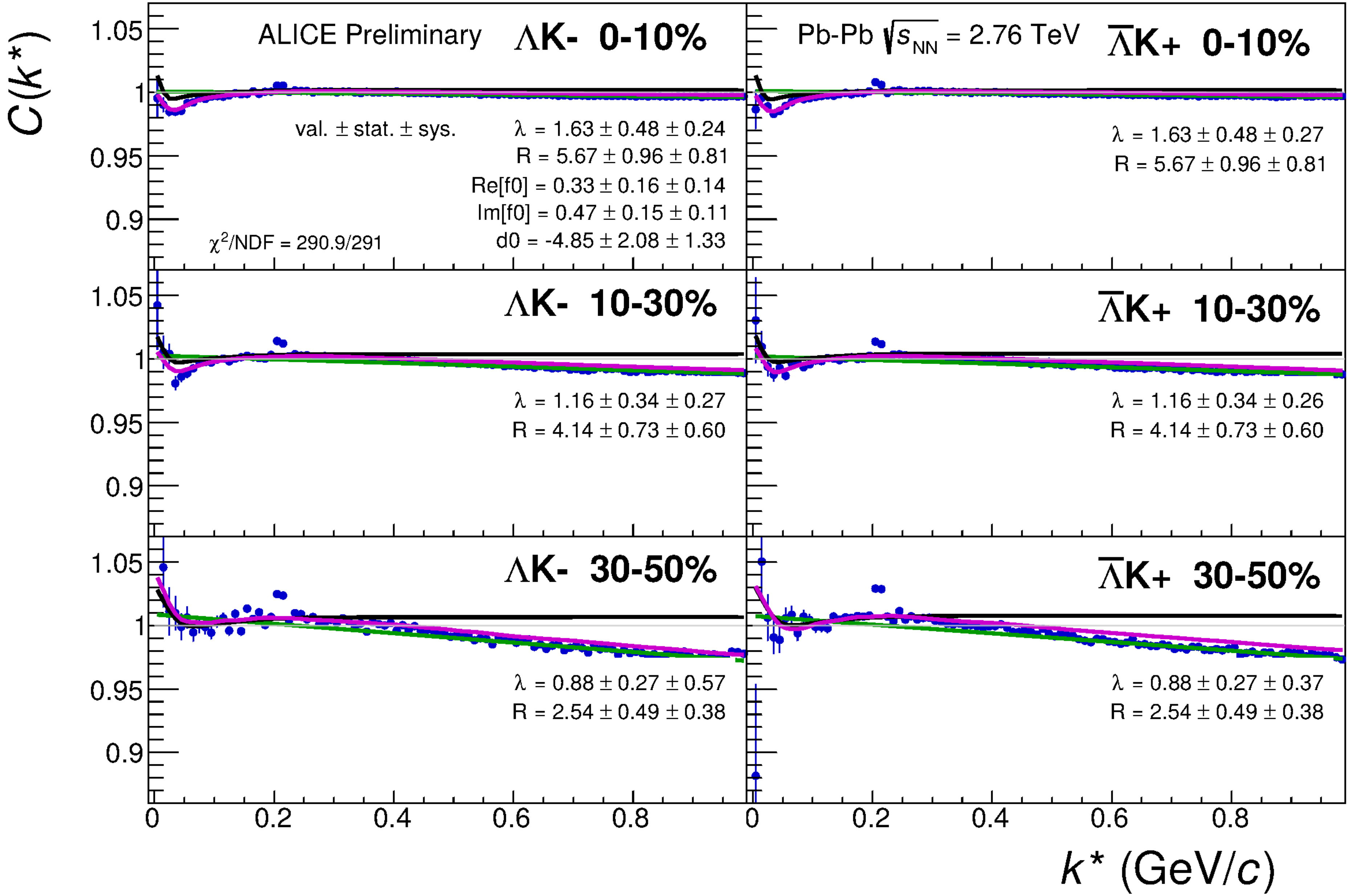
Sep. R, share λ, Poly. Bgd



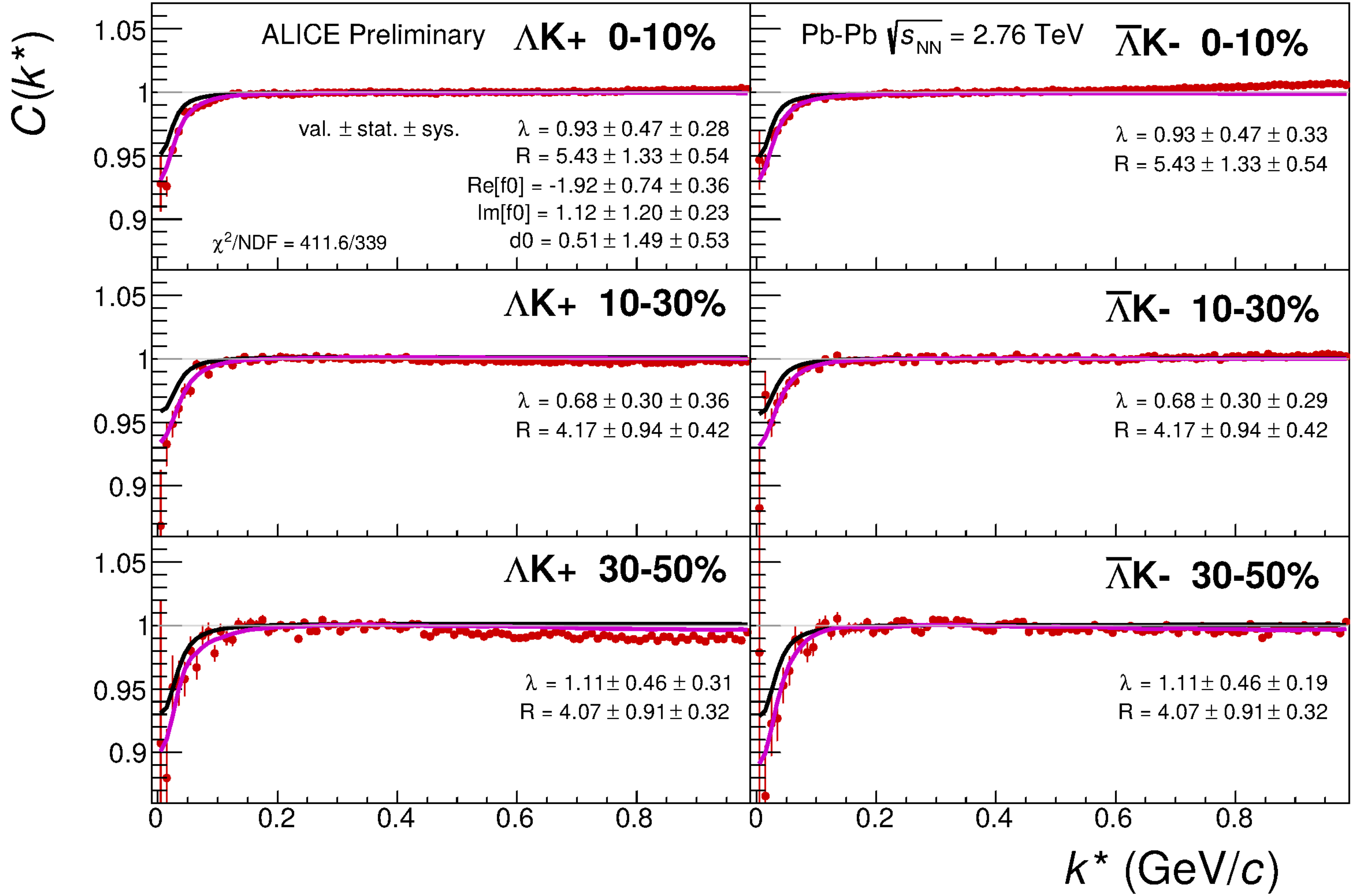
Sep. R, share λ, Lin. Bgd



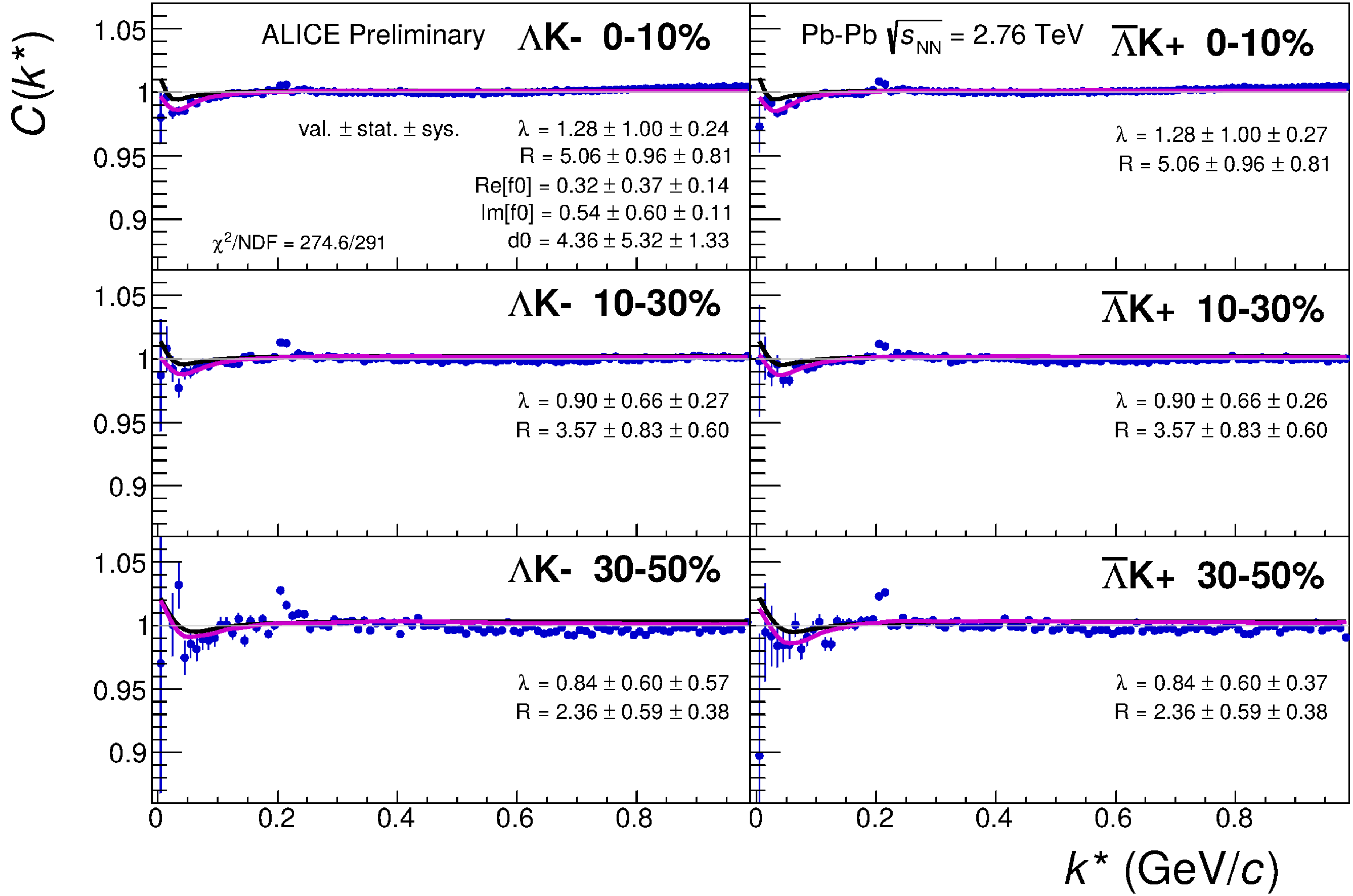
Sep. R, share λ, Lin. Bgd



Sep. R, share λ, Stav.(No Bgd)

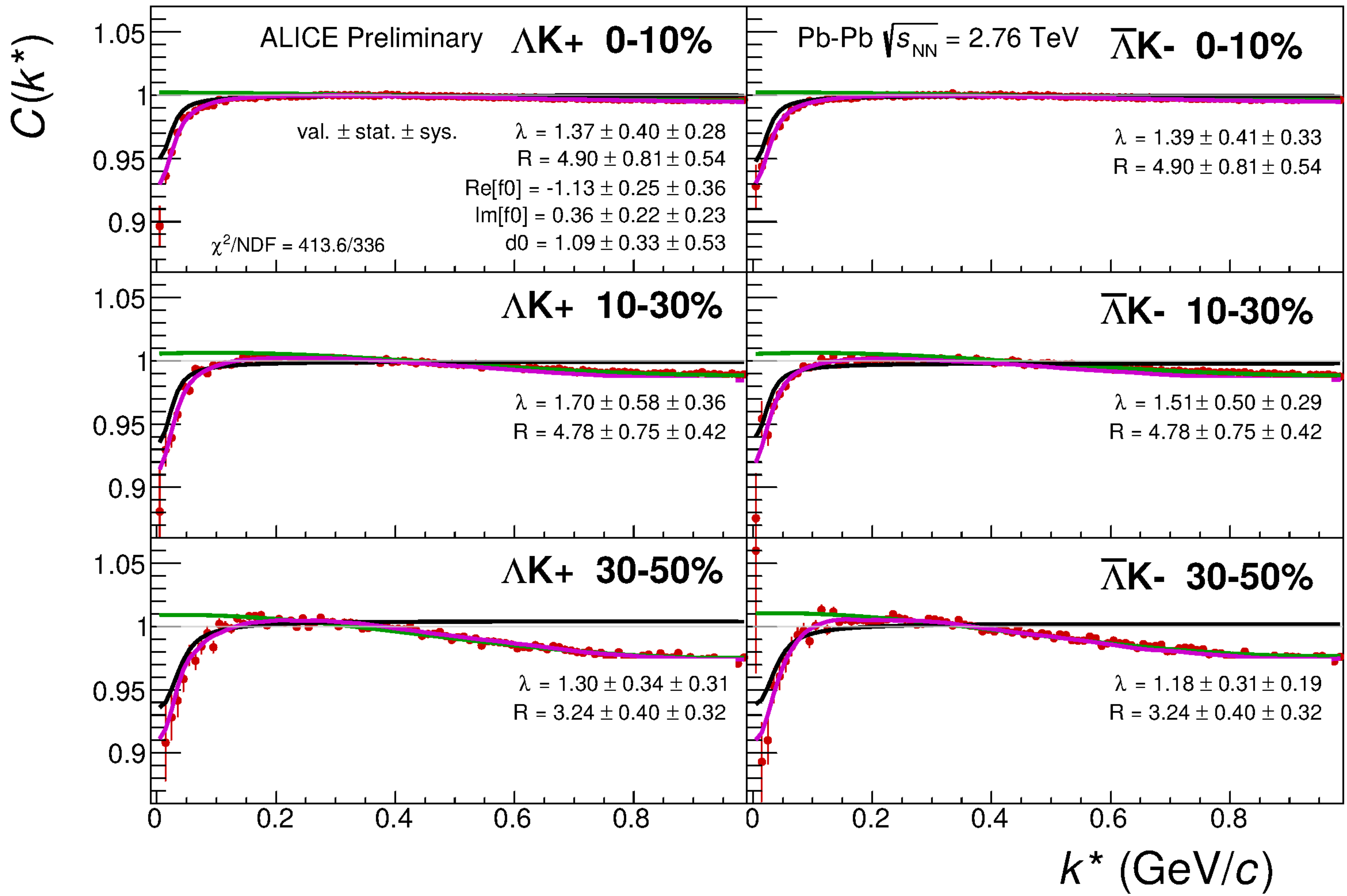


Sep. R, share λ, Stav.(No Bgd)

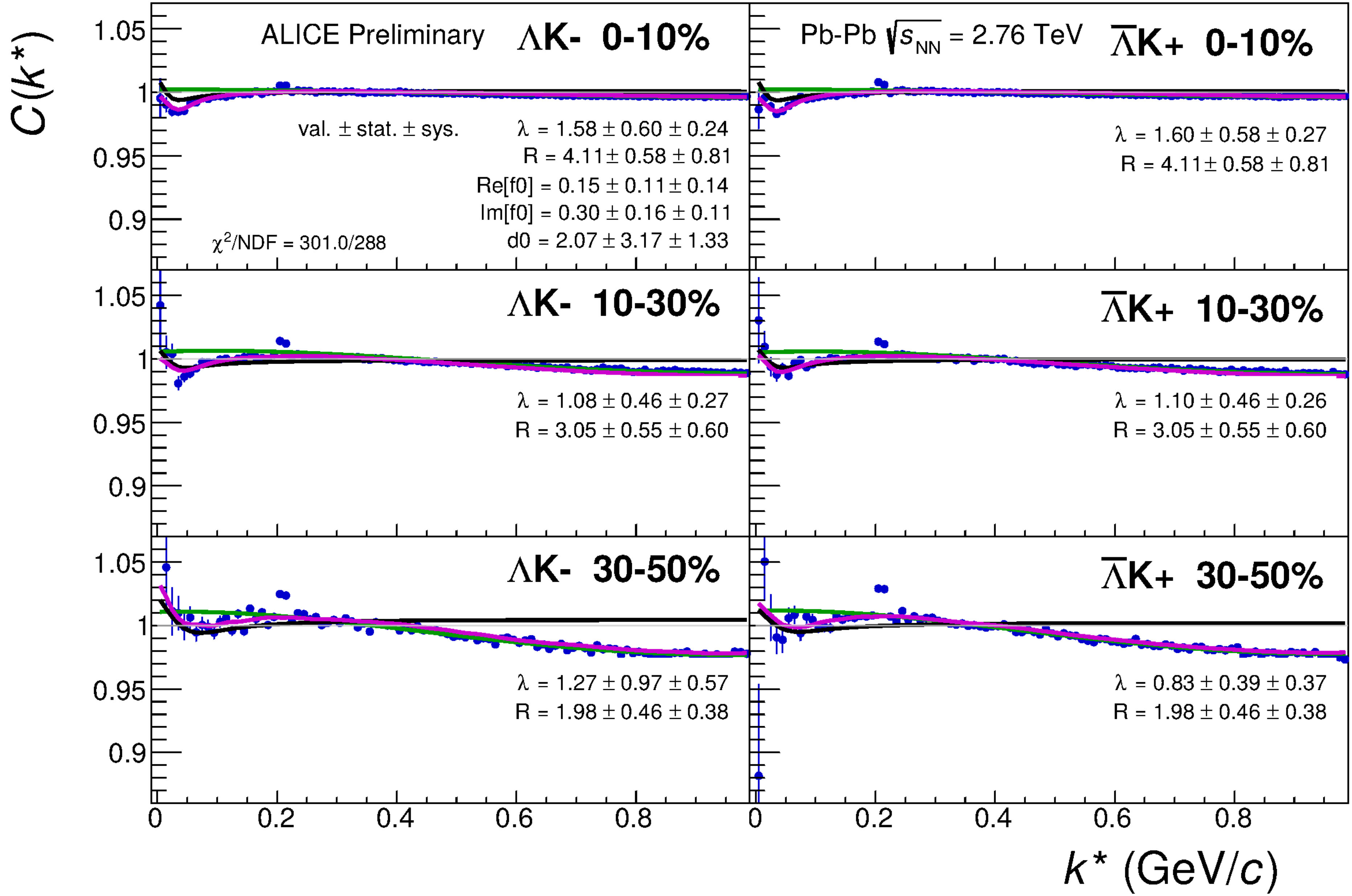


Fit Results:
Separate Radii, separate λ

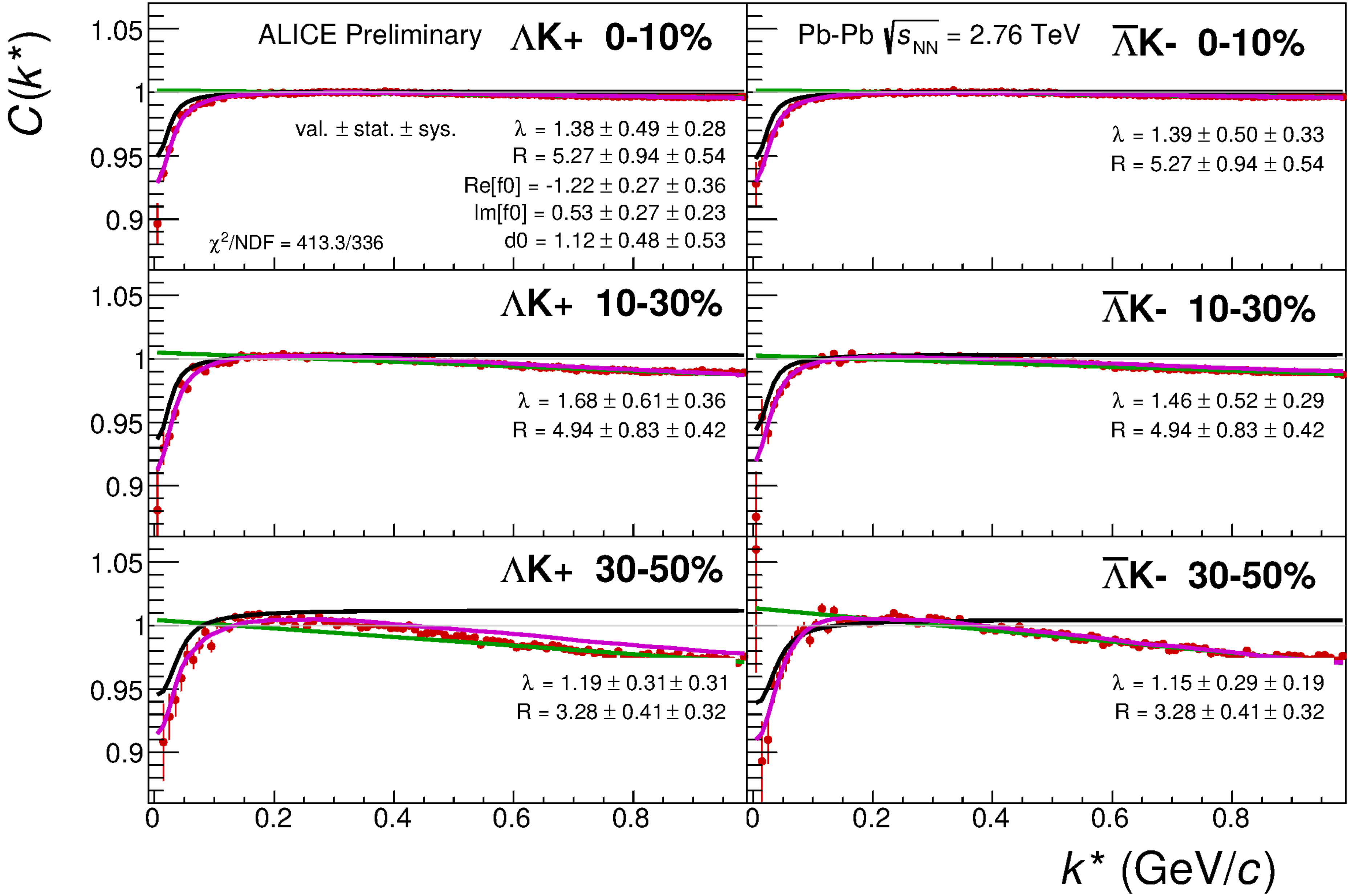
Sep. R, sep. λ, Poly. Bgd



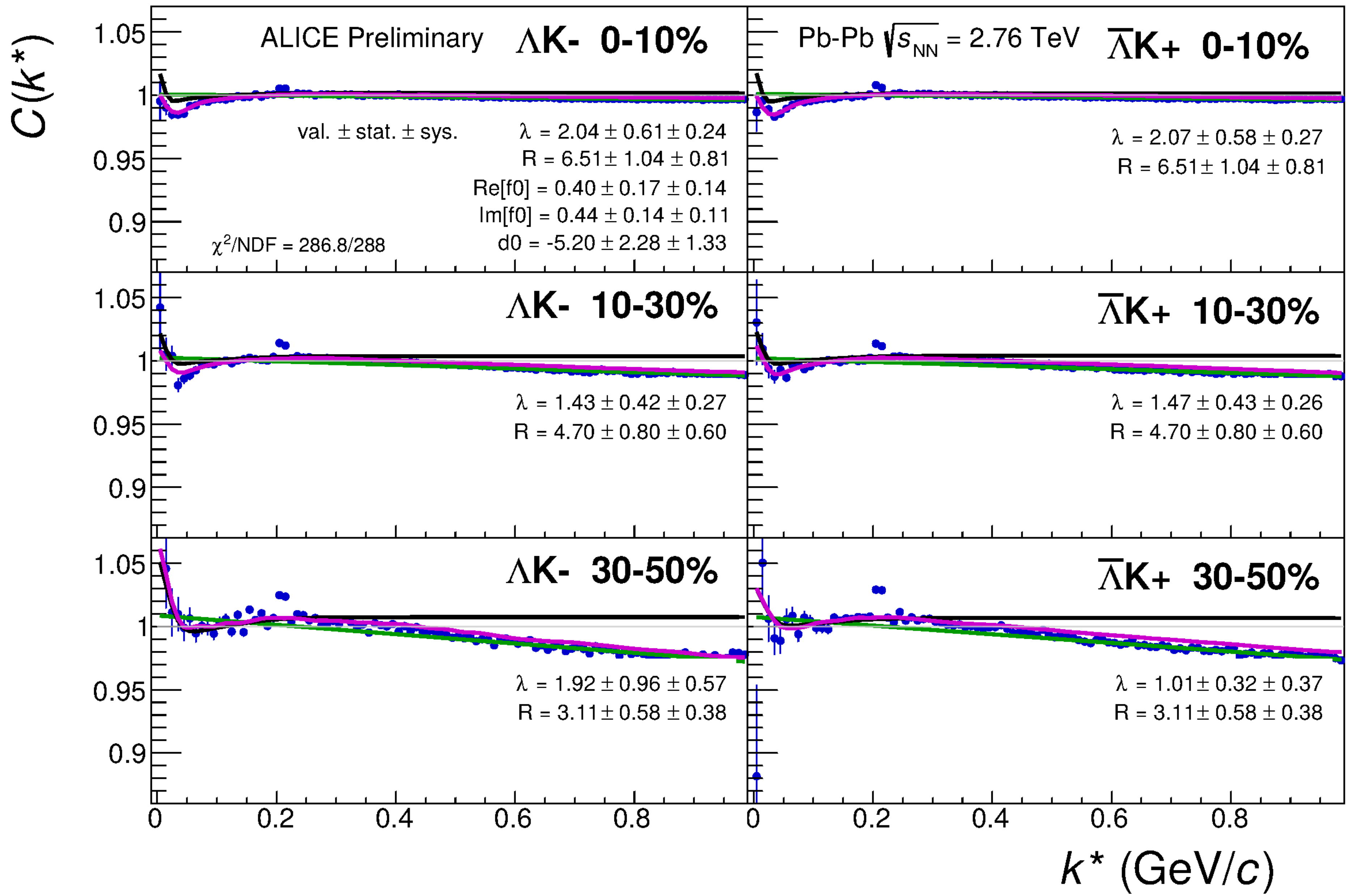
Sep. R, sep. λ, Poly. Bgd



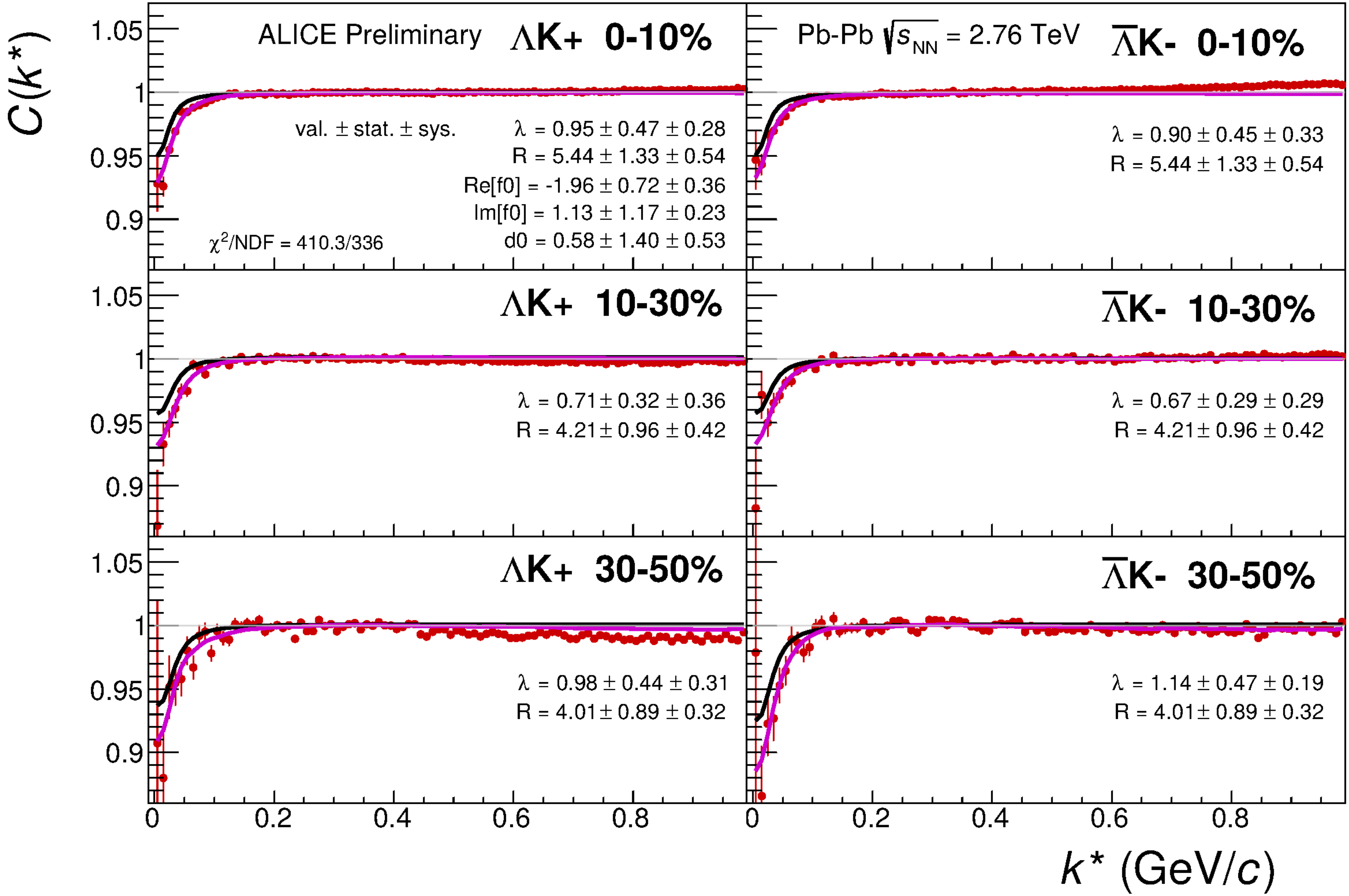
Sep. R, sep. λ, Lin. Bgd



Sep. R, sep. λ, Lin. Bgd



Sep. R, sep. λ, Stav.(No Bgd)



Sep. R, sep. λ, Stav.(No Bgd)