Amplitude analysis of $\Xi_c^0 \to \Lambda^0 K^- \pi^+$

Belle II Explorer

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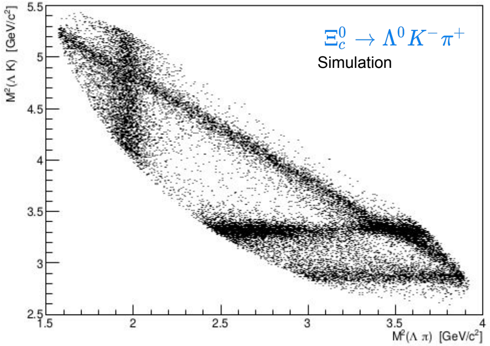
Motivation

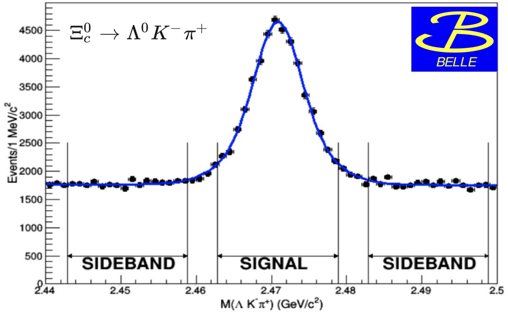
- Belle observed decays of Λ, $\Xi_c^{\ 0}$, $\Xi_c^{\ +}$ and Ω_c but few have been subjected to a full amplitude analysis
    - Shed light on the existence of hyperon resonances
    - Quark structure of candidate exotic states may be better understood through the hadronic decays of charmed baryons via charm-to-strange quark transitions



Potential resonant substructure:

$\Xi(1690)^- \to \Lambda^0 K^-$
$\Xi(1820)^- \to \Lambda^0 K^-$
$\Sigma(1385)^+ \to \Lambda^0 \pi^+$
$\overline{K^*}(892)^0 \to K^- \pi^+$

$\Xi(1690)^-$ and $\Xi(1820)^-$ are relatively poorly understood, 3-star states in the PDG



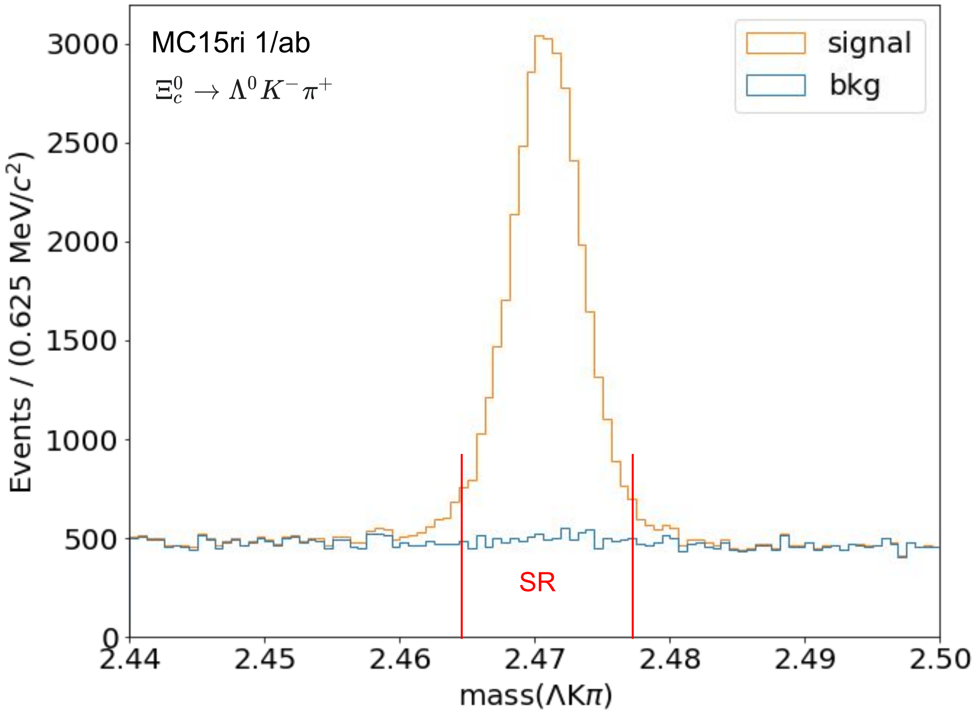
- Charmed baryon decays display rich substructure of hyperon resonances
    - Belle studies of $\Xi(1620)^0$ and $\Xi(1690)^0$ in $\Xi_c^{\ +} \to (\Xi^- \pi^+)\pi^+$
    - Additional analyses looking for $\Xi(1690)^0$ in $\Lambda_c^{\ +}$ decays
    - Amplitude analysis of $\Xi_c^{\ 0} \to \Xi^0\ (K^- K^+)$
    - Here we are studying $\Xi_c^{\ 0} \to \Lambda^0 K^- \pi^+$

Sample and selection criteria

Sample: MC15ri 1/ab
release: light-2212-foldex

Cuts

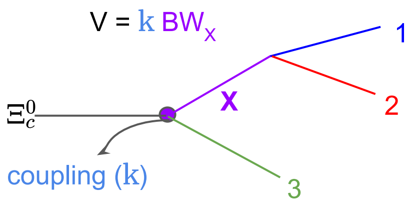
- Xic_CMS_p > 2.8
- For tracks:
  - thetaInCDCAcceptance
  - nCDCHits > 20
  - dr < 1 and abs(dz) < 4 (prompt only)
- For proton decaying from Lambda:
  - protonID > 0.5
- Treefit chiProb > 0.001
- Binary K/π ID > 0.3 (kaons)
- Binary π/K ID > 0.2 (pions)
- Kaon pt > 0.4
- Pion pt > 0.1
- Λ^0 flight significance > 10
- Trinary (K/π & p) ID > 0.3 (kaons)



Signal Region = 2.465 - 2.477 (12 MeV window) (5σ)

Accepted signal = 26,659
Remaining background in SR = 10,200
S/B in SR = 2.61 (Purity = 72.3%)

Amplitude model



- Construct the amplitude as a piece describing the coupling and propagator and a piece describing the decay:

$$U^{M,\lambda_\Lambda}(\vec{x}) = \langle \Lambda K^+ \pi^- | H | \Xi_c \rangle = \sum_{j_X,\lambda_X} T_{j_x,\lambda_X} \Theta_J^{M,\lambda_X}(\theta_X, \phi_X) \times g_{j_X,\lambda_X} \Phi_{j_X}^{\lambda_X,\lambda_\Lambda}(\theta_\Lambda, \phi_\Lambda)$$

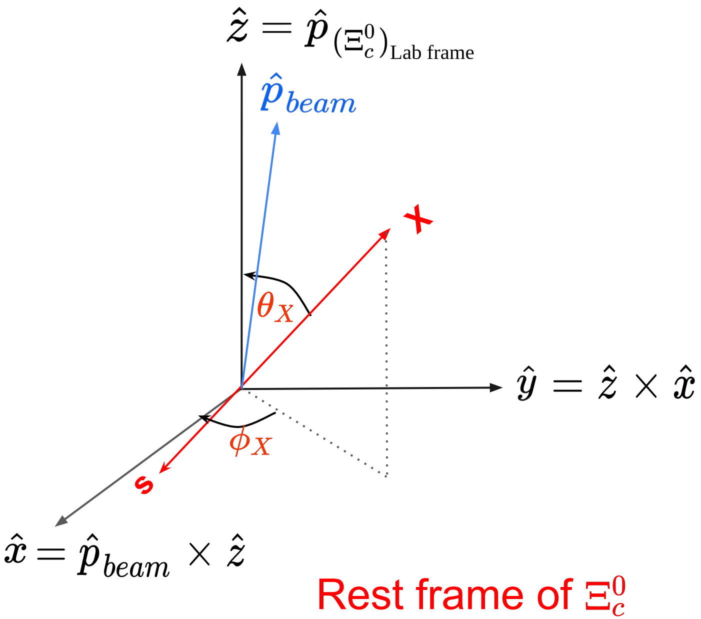
- Then treat the coupling as a free parameter, so the amplitude becomes

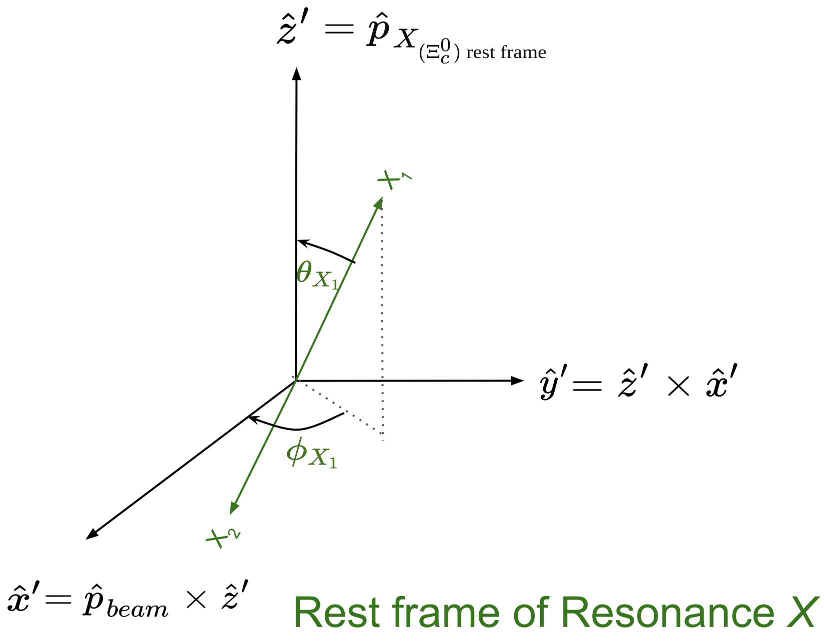
$$U^{M,\lambda_\Lambda}(\vec{x}) = \sum_{j_X,\lambda_X} V_{j_X,\lambda_X} A_{j_X,\lambda_X}^{M,\lambda_\Lambda}(\vec{x})$$

$$V_{j_X,\lambda_X} = k_{j_X,\lambda_X} BW_{j_X,\lambda_X}$$

$$A^{M,\lambda_\Lambda}(\vec{x}) = \sum_{j_X,\lambda_X} N_J D^j_{M,\lambda_X}(\phi_X, \theta_X, 0) N_{j_X} D^{j_x}_{\lambda_X,\lambda_\Lambda}(\phi_\Lambda, \theta_\Lambda, 0)$$

Angular distribution





$$A^{M,\lambda_\Lambda}(\vec{x}) = \sum_{j_X,\lambda_X} N_J D^j_{M,\lambda_X-\lambda_s}(\phi_X,\theta_X,0) N_{j_X} D^{j_X}_{\lambda_X,\lambda_{X1}}(\phi_{X1},\theta_{X1},0)$$

Wigner D-function representing the decay of mother particle and resonant particle

Fitting results: Toy model

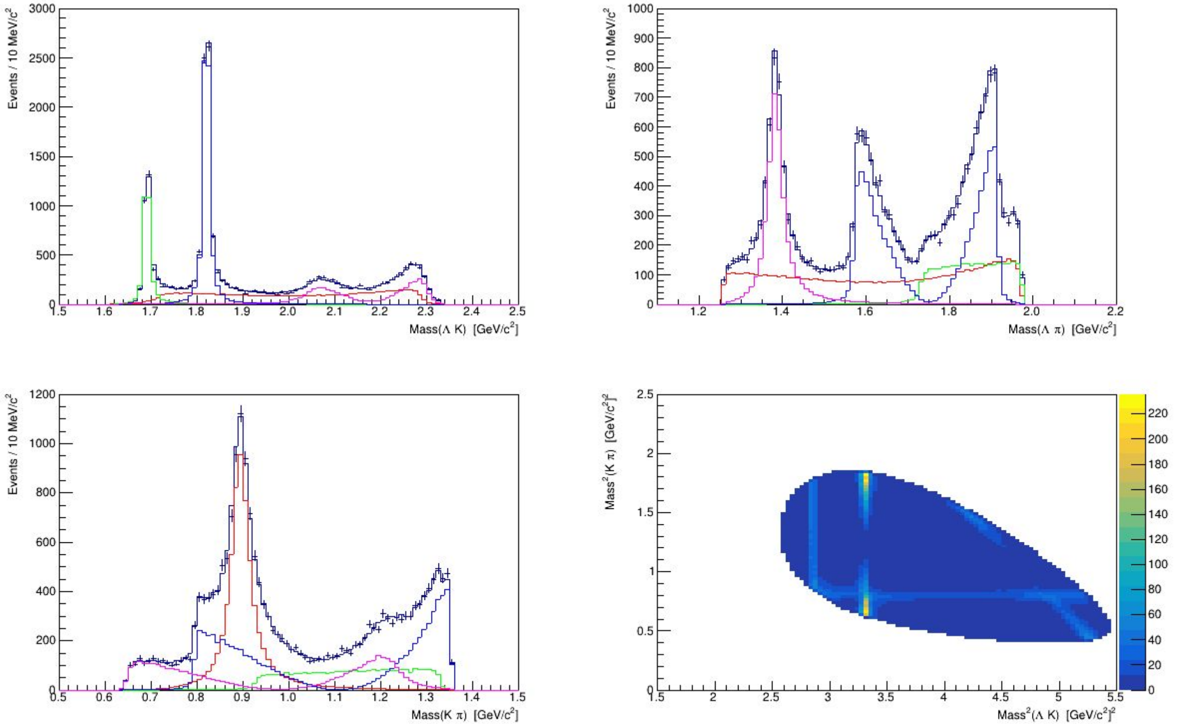
Generated amplitude	Fitted amplitude
$\bar{K}^*(892)^0$ = 1.0, 0	1.0, 0
$\Xi(1690)^-$ = 0.8, 0	0.8141, -0.0478
$\Xi(1820)^-$ = 1.0, 0.5	1.0063, 0.5042
$\Sigma(1385)^+$ = 1.0, -0.5	0.9917, -0.5219

Sample generated and fitted by AmpTools

$\Xi(1690)^-$
M = 1.690 GeV/c^2
W = 0.01 GeV
J = 1/2

$\Xi(1820)^-$
M = 1.820 GeV/c^2
W = 0.01 GeV
J = 3/2

$\bar{K}^*(892)$
M = 0.8947 GeV/c^2
W = 0.0445 GeV
J = 1



-2ln(L) = -412021.3178

$\Sigma(1385)^-$
M = 1.3833 GeV/c^2
W = 0.0385 GeV
J = 3/2

Fitting results: Toy model

Generated amplitude	Fitted amplitude
$\bar{K}^*(892)^0$ = 1.0, 0	1.0, 0
$\Xi(1690)^-$ = 0.8, 0	0.1717, -0.8295
$\Xi(1820)^-$ = 1.0, 0.5	0.7502, -0.3169
$\Sigma(1385)^+$ = 1.0, -0.5	0.7771, -0.7114

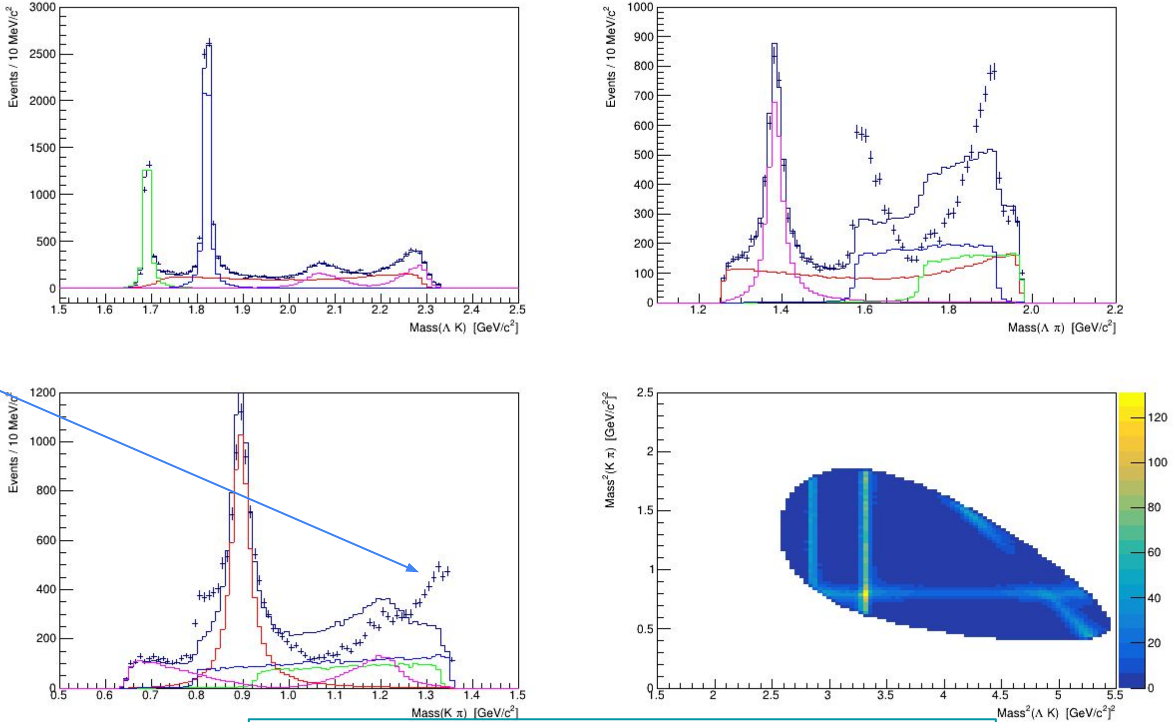
Testing alternate hypothesis:

Sample generated and fitted by AmpTools

$\Xi(1690)^-$
M = 1.690 GeV/c^2
W = 0.01 GeV
J = 1/2

$\Xi(1820)^-$
M = 1.820 GeV/c^2
W = 0.01 GeV
J = 1/2 **wrong!**

$\bar{K}^*(892)$
M = 0.8947 GeV/c^2
W = 0.0445 GeV
J = 1



-2ln(L) = -404073.9963
Much worse!

$\Sigma(1385)^-$
M = 1.3833 GeV/c^2
W = 0.0385 GeV
J = 3/2

AmpTools can extract correct parameters

Fitting result: basf2 reconstructed sample

Sample: Four resonances with equal weight (25%)

Fit fraction per amplitude

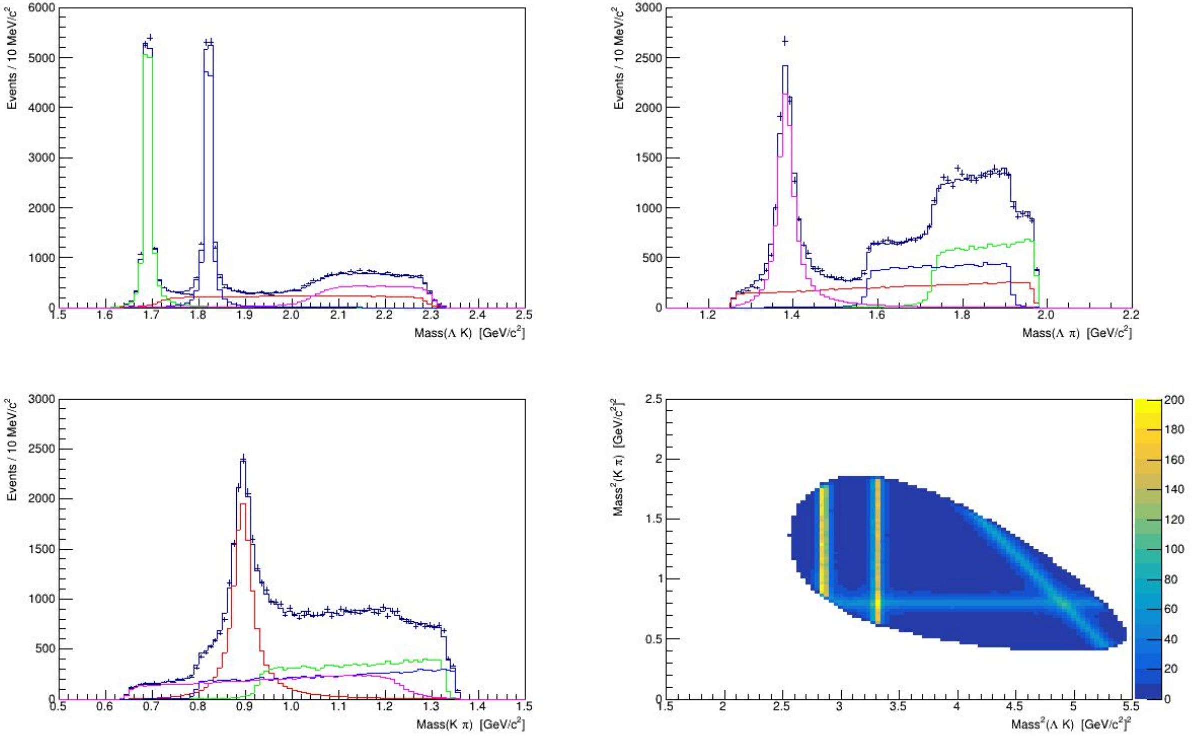
$\bar{K}^*(892)^0$ = 0.2427 ± 0.0031
$\Xi(1690)^-$ = 0.2619 ± 0.0027
$\Xi(1820)^-$ = 0.2442 ± 0.0028
$\Sigma(1385)^+$ = 0.2137 ± 0.0024

-2ln(L) = -1151795.8079

Spin of resonances while fitting:

$\bar{K}^*(892)^0$ = 0
$\Xi(1690)^-$ = 1/2
$\Xi(1820)^-$ = 1/2
$\Sigma(1385)^+$ = 1/2

- Mass and width of each resonance fixed



Bootstrap to check uncertainties

*Requires larger statistics sample (pending), but uncertainties underestimated (~few percent)

AmpTools uncertainties computed from matrix of second derivatives and **may not be reliable in all cases**

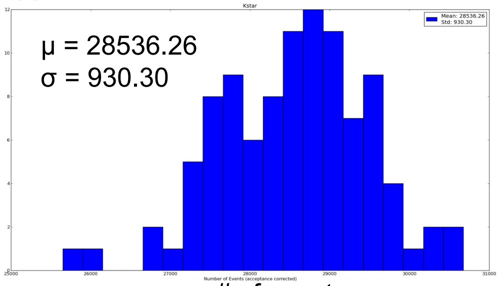
To test: bootstrap (from large sample), **compare the standard deviation of the fitted parameter with uncertainties from nominal fit**

Initial test

- Bootstrap 10,373 events (comparable to expectations in data) from a sample of 29,973 signal events

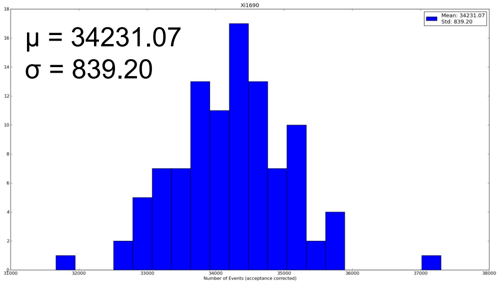
- Mass and width of resonances = fixed
- Constrain K* amplitude to be real
- Free parameters: 7 (real/imag amps)

$\overline{K}$*



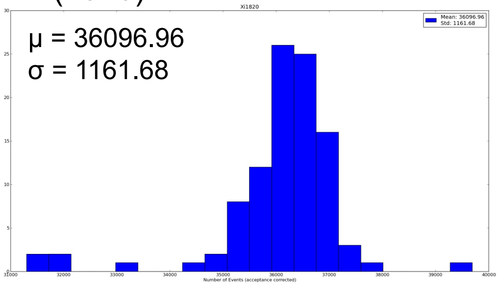
# of events

Xi*(1690)



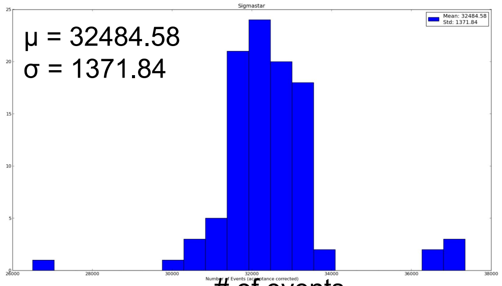
# of events

Xi*(1820)



# of events

Σ*



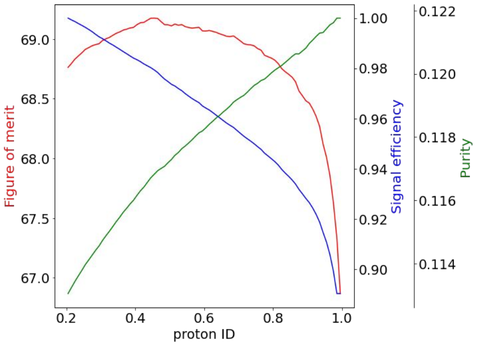
# of events

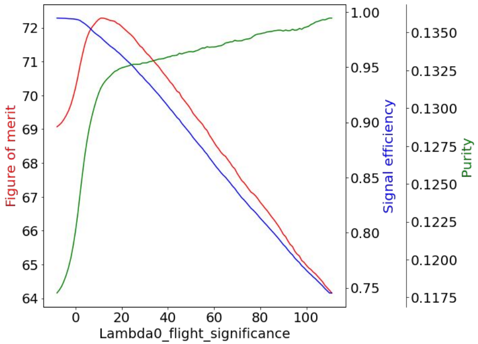
Next steps and plans

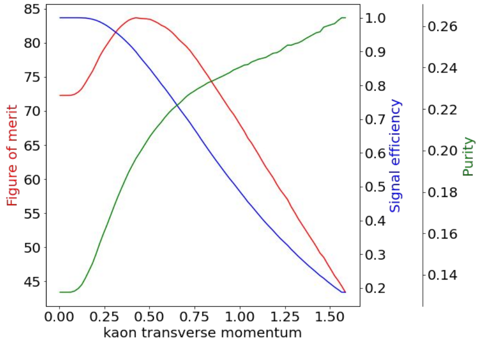
- Ongoing: Amplitude analysis of $\Lambda_c^+ \to p K \pi$ to check the fitting model (by comparing with the result from LHCb)
- Fine tune fitting method to find global minimum by randomizing the parameters
- Finalize check on uncertainties by bootstrapping from a larger sample
- Study the helicity angles of K* distribution and finalize the model to be used for fitting.
- Before looking Data: Final steps of fitting method include adding and removing amplitudes and checking their significance
- Systematic studies

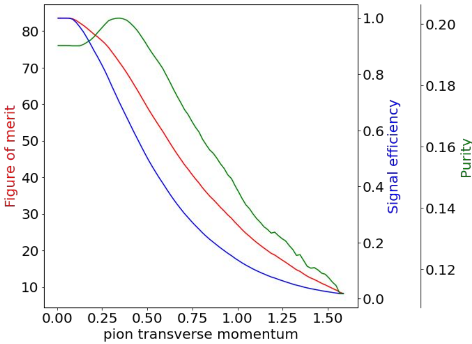
Extra slides

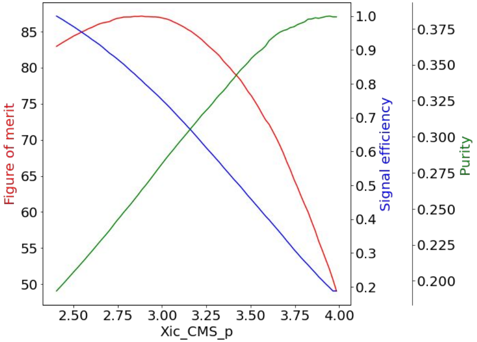
FOM optimization

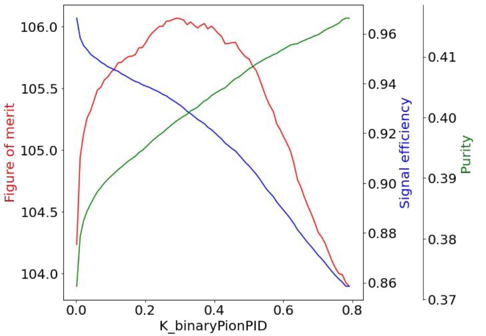


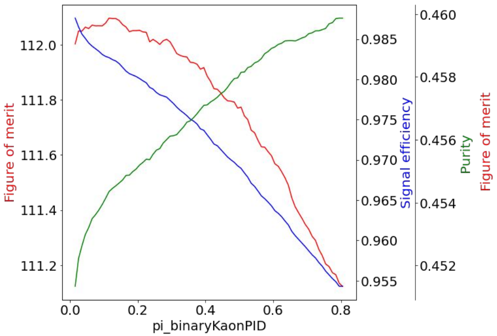


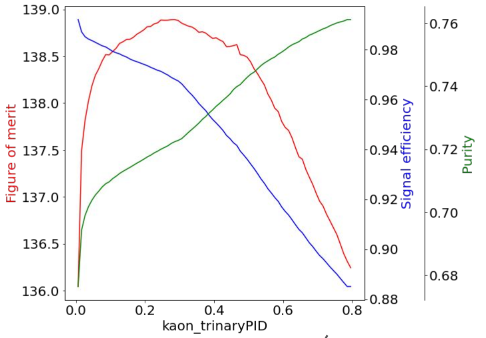


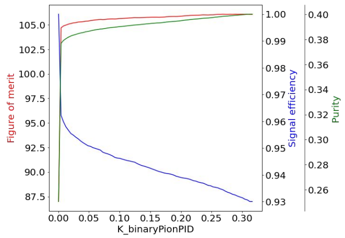






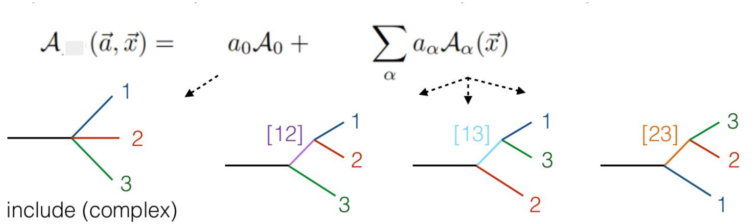






Final Purity ~ 72%

Theoretical background

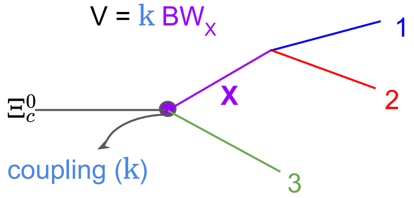


Often include (complex) non-resonant term

- amplitude for $\Xi_c^0 \to \Lambda^0 K^- \pi^+$: $U^{M,\lambda_\Lambda}(\vec{x}) = <\Lambda K^- \pi^+ | H | \Xi_c^0>$

- can be parameterized as: $U^{M,\lambda_\Lambda}(\vec{x}) = \sum_{j_X,\lambda_X} V_{j_X,\lambda_X} \, A^{M,\lambda_\Lambda}_{j_X,\lambda_X}(\vec{x})$

$V_{j_X,\lambda_X} = k_{j_X,\lambda_X} BW_{j_X,\lambda_X}$ describes the propagator of the intermediate state and its coupling to Ξ_c^0 and $A^{M,\lambda_\Lambda}_{j_X,\lambda_X}$ describes the angular distribution of final-state particles.



- The density of events at $\vec{x}$ is given by the intensity: $I(\vec{x}) = \sum_{M,\lambda_\Lambda} |U^{M,\lambda_\Lambda}(\vec{x})|^2$

- To extract the couplings, k_{j_X,λ_X} ,an unbinned maximum likelihood fit is performed on $\Lambda^0 K^- \pi^+$ invariant mass.

- The probability to find an event in the detector at some location in phase space, $\vec{x}$, is given by

$$f(x_i|\vec{\zeta}) = \frac{\eta(\vec{x})\, I(\vec{x}|\vec{\zeta})}{\int \eta(\vec{x})\, I(\vec{x}|\vec{\zeta})\, dx}$$

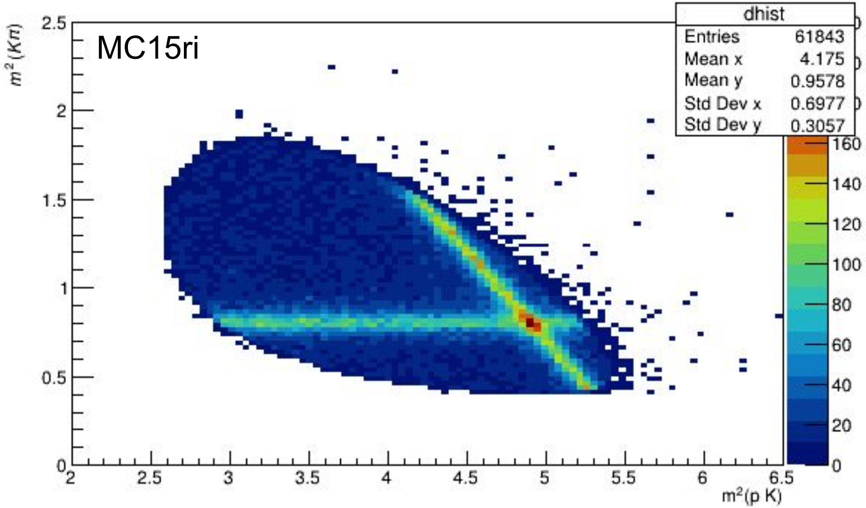
, $\eta(\vec{x})$ is the efficiency of the detector to find an event at $\vec{x}$

- The propagator is described by a Breit-Wigner function and the coupling is set as a free parameter in an unbinned, maximum likelihood fit to the data. The number and type of intermediate states is varied until an optimal solution is found. Any remaining backgrounds are accounted using background samples added to the data set with negative weights.

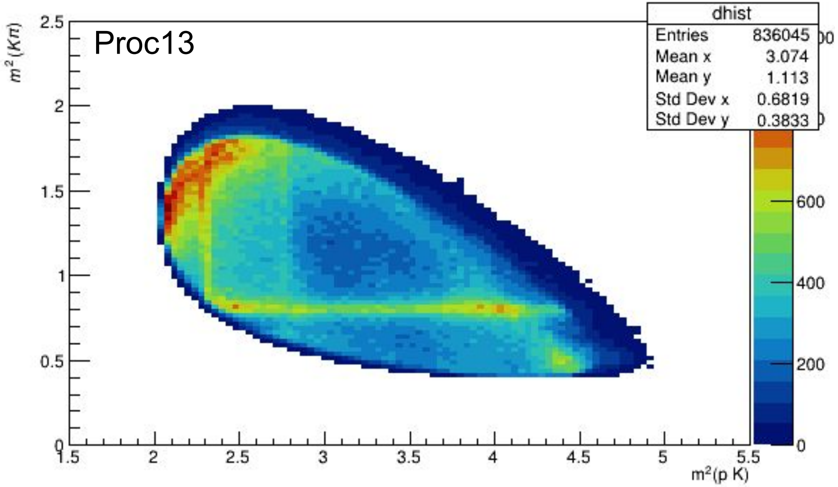
$$L(\vec{\zeta}) = \prod_{i=1}^{N_{data}} f(\vec{x_i}|\vec{\zeta}) \prod_{j=1}^{N_{MC}^{bkg}} f(\vec{x_i}|\vec{\zeta})^{-w_j}$$

Dalitz plots

Dalitz plot: $\Xi_c^0 \rightarrow \Lambda K \pi$



Dalitz plots: $\Lambda_c^+ \rightarrow p K \pi$

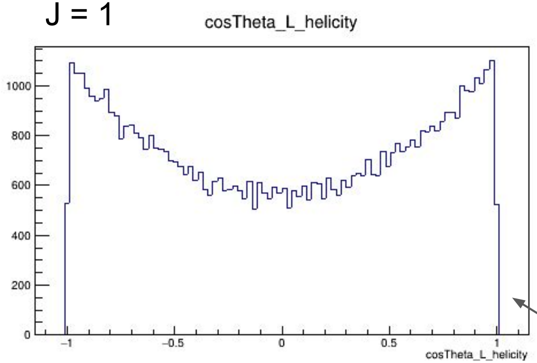


Helicity angles of K*

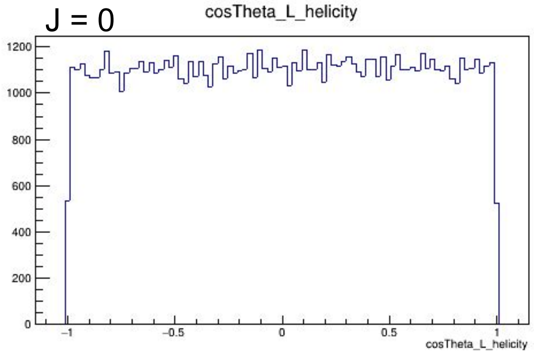
K* being a vector, J = 1

Toy sample by AmpTools

J = 1

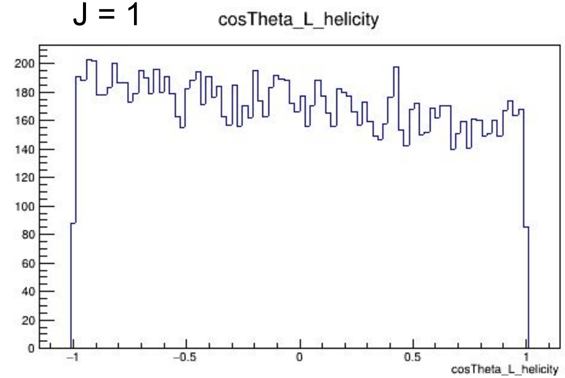


J = 0



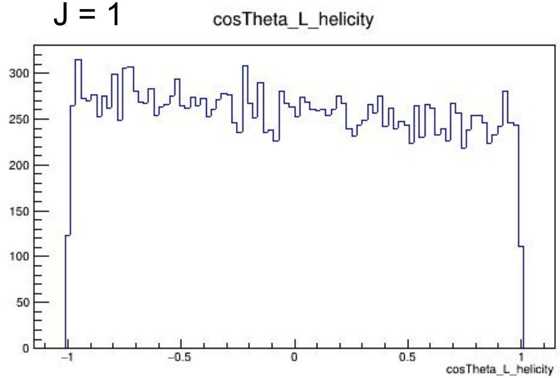
Signal MC by basf2

J = 1



Generic MC by basf2

J = 1



- Expected curved helicity angle
- basf2 generated sample have almost flat distribution (study going on: might be helpful to address fitting fractions)