$\Lambda_c \to \Sigma\pi\pi$ resonant decays in Belle data

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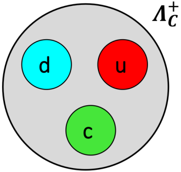
Physics of Λ_c



- Lightest charmed baryon
- Outstanding importance for understanding of higher resonances
- A lot of hadronic modes haven't been measured yet

Λ_c^+ $I(J^P) = 0(1/2)^+$

$\Gamma(\Lambda_c \to p^+ K^- \pi^+)/\Gamma_{total}$

$5.84 \pm 0.27 \pm 0.23$	BES3	2016
$6.84 \pm 0.24^{+0.21}_{-0.27}$	Belle	2014

$\Gamma(\Lambda_c \to p^+ K^+ \pi^-)/\Gamma_{total}$ $[10^{-3}]$

$2.35 \pm 0.27 \pm 21$	Belle	2016

$\Lambda_c \to K^+ \pi^+ p \pi^0$, s. f. $\Lambda_c \to \phi p \pi^0$

arXiv:1707.00089 Belle 2017.

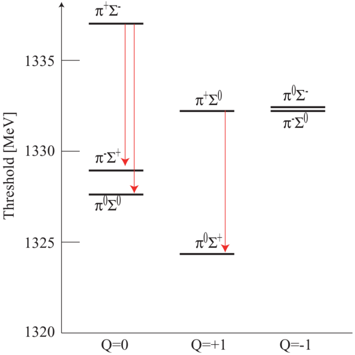
Motivation: $\Sigma\pi$ Scattering Lengths

- Original Motivation: Measure the $\Sigma\pi$ scattering lengths based on "Cabibbo's method", T. Hyodo and M. Oka, Phys. Rev. C84, 035201 (2011)
- **Further goals**: Measure the $\mathcal{B}(\Sigma\pi\pi)$ relative to $pK^-\pi^+$.
- **Further goals**: int. resonances.

Visible decay modes at Belle:

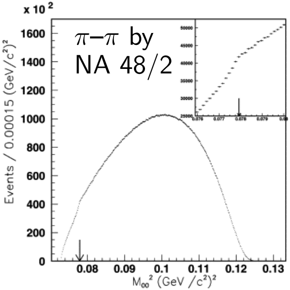
$$\Lambda_c \rightarrow \Sigma^+\pi^-\pi^+(4.57 \pm 0.29\%)^*$$
$$\Lambda_c \rightarrow \Sigma^0\pi^+\pi^0(2.3 \pm 0.9\%)^*$$
$$\Lambda_c \rightarrow \Sigma^+\pi^0\pi^0(\text{unknown})$$

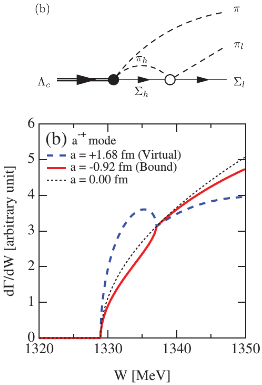
Energy difference of $\Sigma\pi$ under final state charge exchange.



* C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016).

Motivation: $\Sigma\pi$ Scattering Lengths





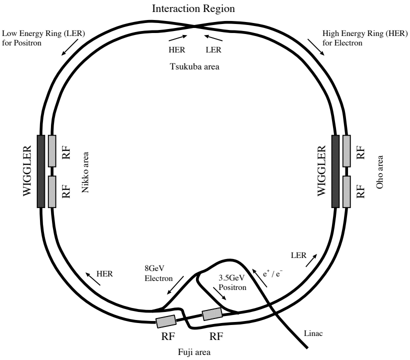
Another Motivation

I=1 suppressed production of $\Lambda(1405)$ at low mass, $\Lambda(1670)$

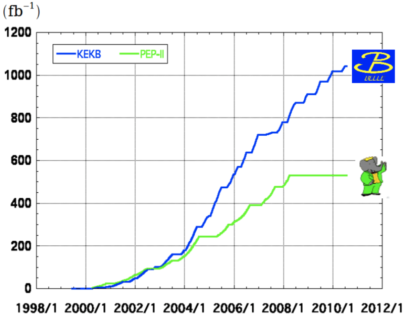
K. Miyahara, T. Hyodo, E. Oset, Phys. Rev. C. 92, 055204 (2015)

Belle and B-Factories

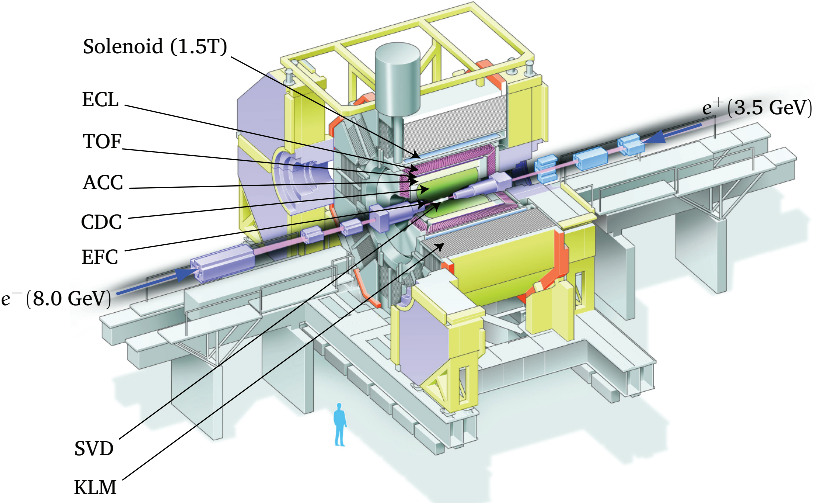
Belle is the detector at the KEKB asymmetric e^+(3.5 GeV)e^-(8 GeV) collider.



Originally constructed for the study of CP violation. Its world record integrated luminosity of 1 ab^{-1} offers many opportunities for hadron physics.



The Belle detector



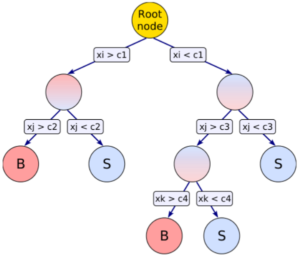
Selection and sample

Production processes

$$e^+e^- \rightarrow c\bar{c} \rightarrow \Lambda_c + X$$
$$e^+e^- \rightarrow c\bar{c} \rightarrow X' \rightarrow \Lambda_c + X$$

$$\Sigma^+ \rightarrow p\pi^0 \ (51.57 \pm 0.30)\%$$
$$\Sigma^0 \rightarrow \Lambda^0\gamma \ (100)\%$$
$$\Lambda^0 \rightarrow p\pi^- \ (63.9 \pm 0.5)\%$$

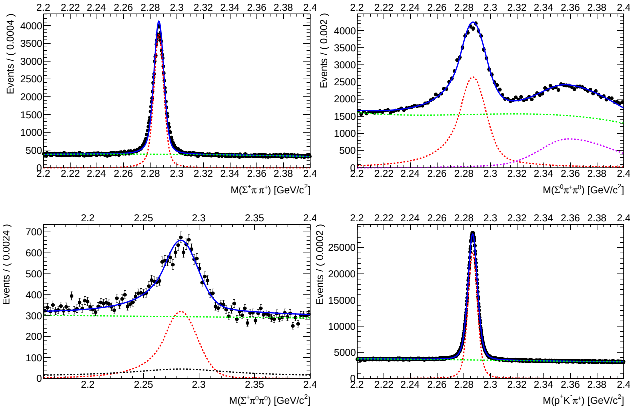
Selection with BDT



BDT input variables

Among others: p/p_{max}, the χ^2 of the vertex constrained fit, the cluster energy and direction of detected photons in the ECL

Invariant mass parameterization



MC studies

Shape determination
Consistency tests
Model uncertainty

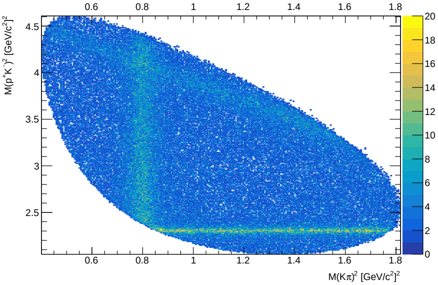
Λ_c in 711 fb^{-1} at $\Upsilon(4S)$

Final state	Yield
$\Sigma^+\pi^-\pi^+$	$100,208 \pm 369$
$\Sigma^+\pi^0\pi^0$	$5,951 \pm 261$
$\Sigma^0\pi^+\pi^0$	$46,995 \pm 413$
$p^+K^-\pi^+$	$1,182,781 \pm 1,351$

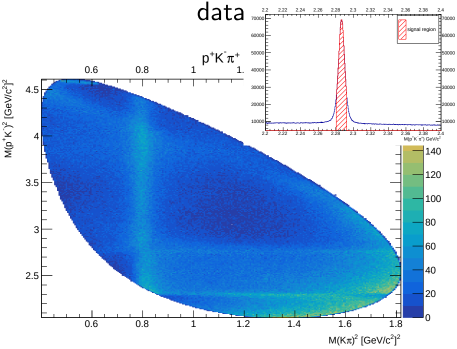
Signal: red, background: green, self-crossfeed: black, $\Lambda^0\pi^+\pi^0 + \gamma$: violet

$p^+K^-\pi^+$ PDG 2016 MC vs data

PDG 2016 MC



data



Standard Belle MC insufficient. (More Dalitz plots later)

Model independent extraction of signal yield

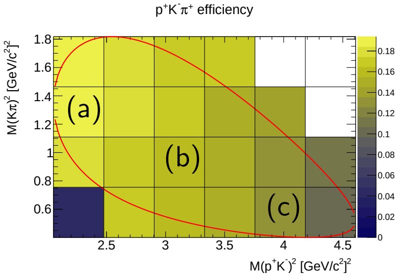
$p^+K^-\pi^+$

Efficiency Corrected yield

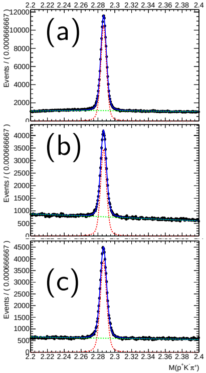
$$y^{corr}_{data} = \sum_i^n \frac{y_i}{\epsilon_i}, \quad \frac{y^{corr}_{PDG}}{y^{corr}_{data}} = 1.05$$

21 bins, ϵ_i^{min}=0.1, ϵ_i^{max}=0.19

Comp. with 75 bins → Syst.



$p^+K^-\pi^+$ mass distribution

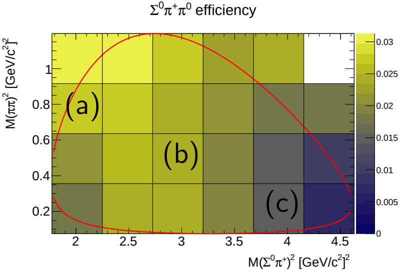


Model independent extraction of signal yield

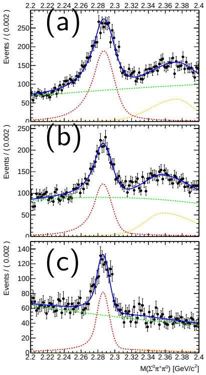
$\Sigma^0\pi^+\pi^0$

Varying $\Lambda^0\pi^+\pi^0 + \gamma$ background

23 bins, ϵ_i^{min}=0.007, ϵ_i^{max}=0.03
Comp. with 83 bins $\rightarrow$ Syst.

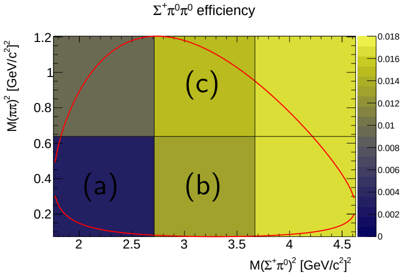


$\Sigma^0\pi^+\pi^0$ mass distribution

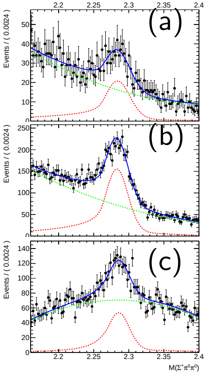


Model independent extraction of signal yield
$\Sigma^+\pi^0\pi^0$

Reduced binning due to lacking statistics.
6 bins, ϵ_i^{min}=0.003, ϵ_i^{max}=0.017
Comp. with one bin $\rightarrow$ Syst.



$\Sigma^+\pi^0\pi^0$ mass distribution



Systematic Errors

Systematic studies

π^0:	$\tau^- \to \pi^- \pi^0 \nu_\tau$	Λ^0:	$B \to \Lambda \bar{\Lambda} K^+$
K π:	$D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$	PDF:	toy MC

Source	$\Delta y(\Sigma^+\pi^+\pi^-)$	$\Delta y(\Sigma^+\pi^0\pi^0)$	$\Delta y(\Sigma^0\pi^+\pi^0)$	$\Delta y(pK\pi)$
Pdf Model	1.3	3.1	1.84	1.04
Dalitz structure	0.3	2.4	0.7	0
Proton identification	0.42	0.39	0.39	0.47
K π identification	2.2		3.1	1.64
Tracking	0	0	0	0.7
Λ identification			2.68	
π^0 identification	2.44	6.8	2.27	
MC statistics	0.1	0.6	0.3	0
$\mathcal{B}_{\mathrm{PDG}}$	0.3	0.3	0.5	
Total	4.38	8.02	5.15	2.64

$\mathcal{B}(\Sigma\pi\pi)$ Results submitted to PRD

Errors are in order stat., sys. and ($\mathcal{B}(pK\pi)$).

Final state	$\mathcal{B}(\Sigma\pi\pi)/\mathcal{B}(pK\pi)$	$\mathcal{B}(\Sigma\pi\pi)$ [%] [1]	$\mathcal{B}_{PDG}(\Sigma\pi\pi)$ [%]
$\Sigma^+\pi^+\pi^-$	$0.706 \pm 0.003 \pm 0.036$	$4.48 \pm 0.02 \pm 0.23 \pm 0.23$	4.57 ± 0.29
$\Sigma^0\pi^+\pi^0$	$0.491 \pm 0.005 \pm 0.028$	$3.12 \pm 0.03 \pm 0.18 \pm 0.16$	2.3 ± 0.9
$\Sigma^+\pi^0\pi^0$	$0.198 \pm 0.006 \pm 0.017$	$1.26 \pm 0.04 \pm 0.11 \pm 0.07$	-

$\mathcal{B}(\Sigma^+\pi^+\pi^-)$ is compatible with the current world average,
$\mathcal{B}(\Sigma^0\pi^+\pi^0)$ is the most precise measurement to date and
$\mathcal{B}(\Sigma^+\pi^0\pi^0)$ is measured for the first time
(min $-ln\mathcal{L} = -509,532$ vs. $-54,768.3$ for only background).

Current status

Belle publication 500: `https://arxiv.org/abs/1802.03421`
Currently working on the response to the referee report.

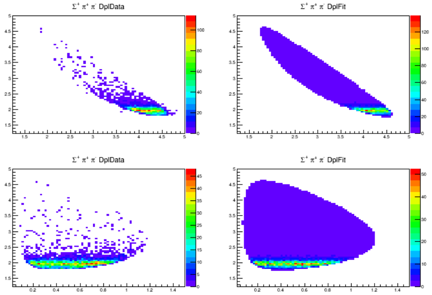
[1] Using $\mathcal{B}(pK\pi) == 6.35 \pm 0.33$

PAWIAN

A partial wave analysis software framework

Pawian

- In development for the Panda experiment
- based on Isobar model
- Already used in BES3 collaboration.
- **Supports coupled channel analysis.**
- Relatively untested for Baryons and “isolated resonances“.



Left data, right fit result.

Pawian algorithm

Event based maximum likelihood fit

$$-\ln \mathscr{L} \approx -\sum_{i=1}^{n_{data}} \ln(w(\boldsymbol{\tau_i}, \boldsymbol{\alpha}) \cdot Q_i) + \left(\sum_{i=1}^{n_{data}} Q_i\right) \cdot \ln\left(\frac{\sum_{j=1}^{n_{MC}} w(\boldsymbol{\tau_j}, \boldsymbol{\alpha})}{n_{MC}}\right) + \frac{1}{2} \cdot \left(\sum_{i=1}^{n_{data}} Q_i\right) \cdot \left(\frac{\sum_{j=1}^{n_{MC}} w(\boldsymbol{\tau_j}, \boldsymbol{\alpha})}{n_{MC}} - 1\right)^2$$

n_{data} : number of reconstructed data events

n_{MC} : number of reconstructed phase space distributed Monte Carlo events

Q_i : event weight

$w(\tau, \alpha)$: transition probability (cross section)

Pawian algorithm

Differential cross section or event weight with $X \rightarrow \Sigma^{+} \pi^{-}$

$$w \propto \sum_{M_{\Lambda_c}=-1/2}^{1/2} P_{M_{\Lambda_c}} \sum_{\lambda_{\Sigma^+}=-1/2}^{1/2} |A^{J_{\Lambda_c},M_{\Lambda_c}}_{\lambda_X,\lambda_{\pi^+}} A^{J_X,\lambda_X}_{\lambda_{\Sigma^+},\lambda_{\pi^-}} F_l(m_x)|^2$$

$\sum_{M_{\Lambda_c}=-1/2}^{1/2} \sum_{\lambda_{\Sigma^+}=-1/2}^{1/2}$: incoherent sum over the spin projections of all initial and final state particles

$P_{M_{\Lambda_c}}$: polarization of the Λ_c related to the quantization axis (fit parameter)

$A^{J_{\Lambda_c},M_{\Lambda_c}}_{\lambda_X,\lambda_{\pi^+}=0}$: production amplitude for the resonance $X \rightarrow \Sigma^{+} \pi^{-}$

$A^{J_X,\lambda_X}_{\lambda_{\Sigma^+},\lambda_{\pi^-}=0}$: decay amplitude for the resonance $X \rightarrow \Sigma^{+} \pi^{-}$

$F_l(m_x)$: dynamics of the resonance X
description by e.g. Breit-Wigner or K-matrix formalism 6
in general depending on orbital momentum l due to barrier factors

Pawian algorithm

production amplitude for the resonance X

$$A^{J_{\Lambda_c},M_{\Lambda_c}}_{\lambda_X,0} = F^{\Lambda_c}_{\lambda_X\ 0} \cdot d^{J_{\Lambda_c}}_{M_{\Lambda_c}\ X}(cos\Theta^{\Lambda_c}_X)$$

$F^{\Lambda_c}_{\lambda_X\ 0}$: complex fit parameter (helicity amplitude)

$d^{J_{\Lambda_c}}_{M_{\Lambda_c}\ X}(cos\Theta^{\Lambda_c}_X)$: Wigner-d function (reference system of Λ_c not known and thus no ϕ information available)

Pawian algorithm

decay amplitude for the resonance X

$$A^{J_X,\lambda_X}_{\lambda_{\Sigma^+},\lambda_{\pi^-}} = F^X_{\lambda_{\Sigma^+}\,0} \cdot D^{J_X}_{\lambda_X\,\lambda_{\Sigma^+}}(cos\Theta^X_{\Sigma^+}, \phi^X_{\Sigma^+})$$

$D^{J_X}_{\lambda_X\,\lambda_{\Sigma^+}}(cos\Theta^X_{\Sigma^+}, \phi^X_{\Sigma^+})$

Wigner-D function (here also ϕ information available)

Parity conservation (strong decay):

$$F^X_{\lambda_{\Sigma^+}\,0} = \eta_\Sigma \eta_\pi (-1)^{J^X - J^{\Sigma^+} - J^{\pi^-}} F^X_{-\lambda_{\Sigma^+}\,0}$$

Transformation of the helicity amplitude $F^X_{\lambda_{\Sigma^+}\,0}$ into the ls-schema

$$F^X_{\lambda_{\Sigma^+}\,0} = \sum_{ls} \alpha^X_{ls}\; CG(l,0,s,\lambda_\Sigma \,|\, s,\lambda_\Sigma)\; CG(J^\Sigma,\lambda_\Sigma,0,0 \,|\, s,\lambda_\Sigma)$$

α^X_{ls} : new fit parameter

Advantage: l-dependent parametrization for a better description of the dynamics $F_l(m_x)$

PWA?

- Use the two cleanest samples to conduct a coupled channel PWA.
- Start with the single channels to get a base hypothesis.
- Optimize decision criteria, and refine by adding K-Matrix etc.
- For $pK\pi^+$: Last results from 1999 [2]
- No previous results for $\Sigma^+\pi^-\pi^+$

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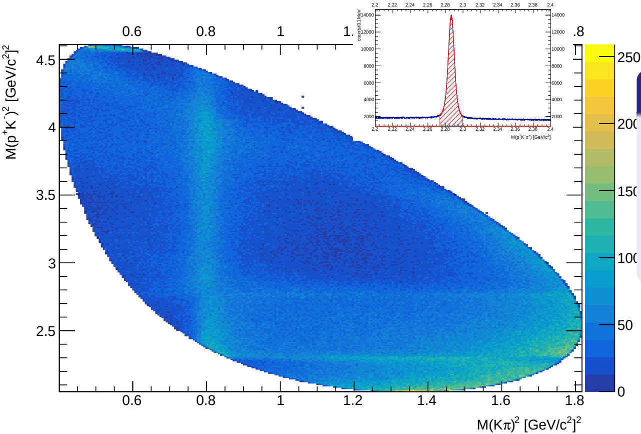
[2] Aitala, E. M., Amato, S., Anjos, J. C., Appel, J. A., Ashery, D., Banerjee, S., Zhang, C. (2000). Multidimensional resonance analysis of $\Lambda_c^+ p^+ K\pi^+$. Physics Letters B, 471(4), 449459. https://doi.org/https://doi.org/10.1016/S0370-2693(99)01397-0

Data sample

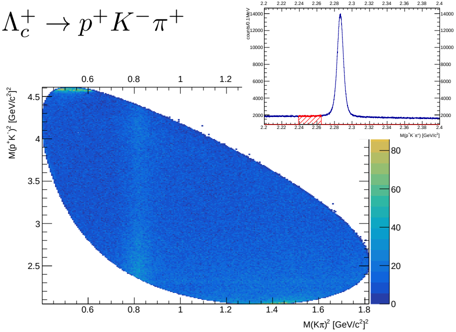
$$\Lambda_c^+ \to p^+ K^- \pi^+$$

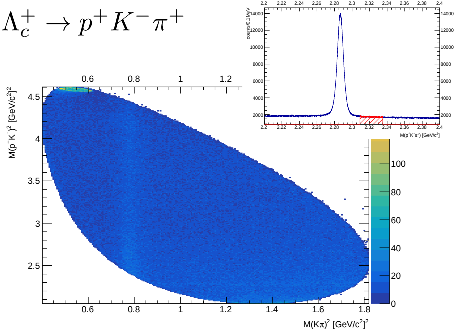


Λ_c in 711 fb^{-1} at Υ(4S)

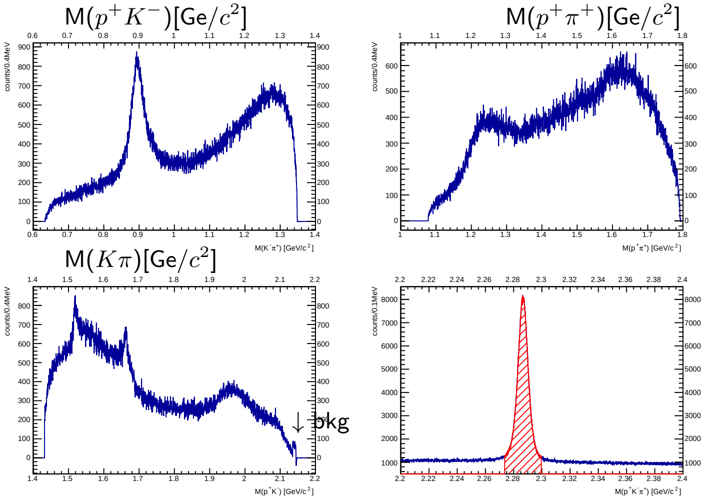
Final state	Yield
$\Sigma^+\pi^-\pi^+$	$100,208 \pm 369$
~~$\Sigma^+\pi^0\pi^0$~~	~~$5,951 \pm 261$~~
~~$\Sigma^0\pi^+\pi^0$~~	~~$46,995 \pm 413$~~
$p^+K^-\pi^+$	$1,182,781 \pm 1,351$

sideband


$\Lambda_c^+ \to p^+ K^- \pi^+$
M(p⁺K⁻)² [GeV/c²]²
M(Kπ)² [GeV/c²]²
M(p⁺K⁻π⁺) [GeV/c²]
counts/0.1MeV


$\Lambda_c^+ \to p^+ K^- \pi^+$
M(p⁺K⁻)² [GeV/c²]²
M(Kπ)² [GeV/c²]²
M(p⁺K⁻π⁺) [GeV/c²]
counts/0.1MeV

Projections (sideband subtracted)



Validation?

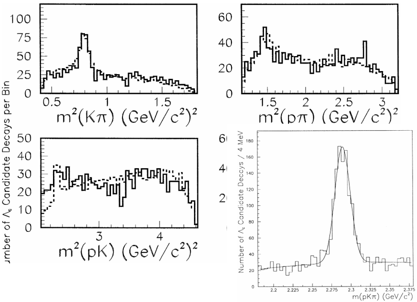
- Apply to $pK\pi$ and compare with E791
- No success with applying their model to Belle data (see next slide).
- Hard to reconcile $\Sigma\pi\pi$ and $pK\pi$ data sets ($\Sigma(1940)^0 \rightarrow p^+K^-$)
- Still very real possibility that there are problems left with the implementation.

E791 $p^+K^-\pi^+$ PWA

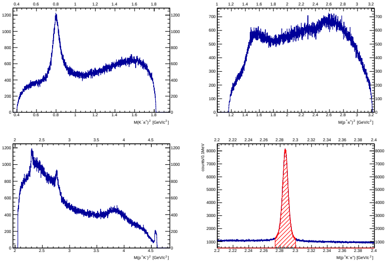
Belle sample compatible?

E791 selection based on proton p_t

$\Lambda_c^+ \to p^+K^-\pi^+$, E791



$\Lambda_c^+ \to p^+K^-\pi^+$, Belle



Plan for 3 months at JAEA

- Measure position width and $\mathcal{BR}$ for $\Lambda(1405)$ from $\Sigma^+\pi^-\pi^+$
  - Directly, from two-body Sigma pi mass
  - ($\mathcal{BR}$) Indirectly, from cutting a region out of the Dalitz plot and fitting the three-body mass
- Σ^* needs to be subtracted from the $\Lambda_c^+ \to \Lambda^0\pi^+\pi^0$ channel.
- Same can be done for $\Lambda(1520)$ from $p^+K^-\pi^+$ and $\Sigma^+\pi^-\pi^+$ if the timing permits

Summery and outlook

- We analyze weak $\Lambda_c \to \Sigma\pi\pi$ decays.
- Branching fractions for $\Sigma^+\pi^+\pi^-$,$\Sigma^+\pi^0\pi^0$ and $\Sigma^0\pi^+\pi^0$ have been measured.
- A variety of resonances appear in the data, including those of longstanding interest like $\Lambda(1405)$.
- Our ultimate plan is to conduct a $pK\pi - \Sigma\pi\pi$ coupled channel analysis utilizing the PAWIAN framework.

Backup

Dalitz (and other) plots

Richard Dalitz (1925 - 2006)

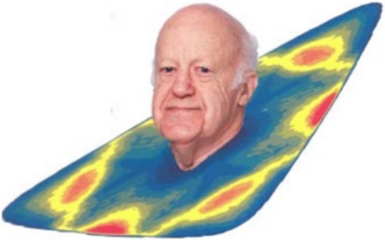
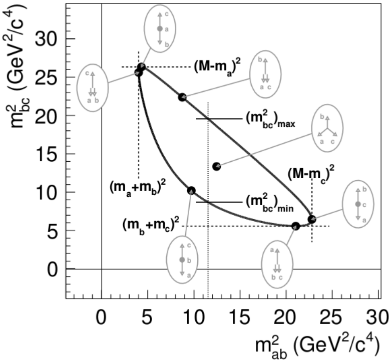


Image credit: Mike Pennington



Initial state

Discussion with Bertram

Initialstate of the inertial system has to be defined in the laboratory system by two 4-vectors[3]

	one projectile	e^+e^- system
E	E_{HER}	$E_{HER} + E_{LER}$
X	$E_{HER} * sin(\theta)$	$E_{HER} * sin(\theta)$
Y	$0.$	$0.$
Z	$E_{HER} * cos(\theta)$	$E_{HER} * cos(\theta) - E_{LER}$

[3] $E_{HER} = 7.9965, E_{LER} = 3.5, \theta = 0.022$

Detector acceptance

- Taken care of by Pawian.
- Needs phasespace distributed signal MC.
- Does not support MC weights.

Reweight MC with PID

- Multiply weights eventwise
- Randomly skip events based on weight
- Randomly save event two times b. o. weight