The 21st International Conference
on Hadron Spectroscopy and Structure

Measurement of Branching Fraction of $\Lambda_c^+ \to p K_S^0 \pi^0$ at Belle

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On behalf of Belle & Belle II Collaborations

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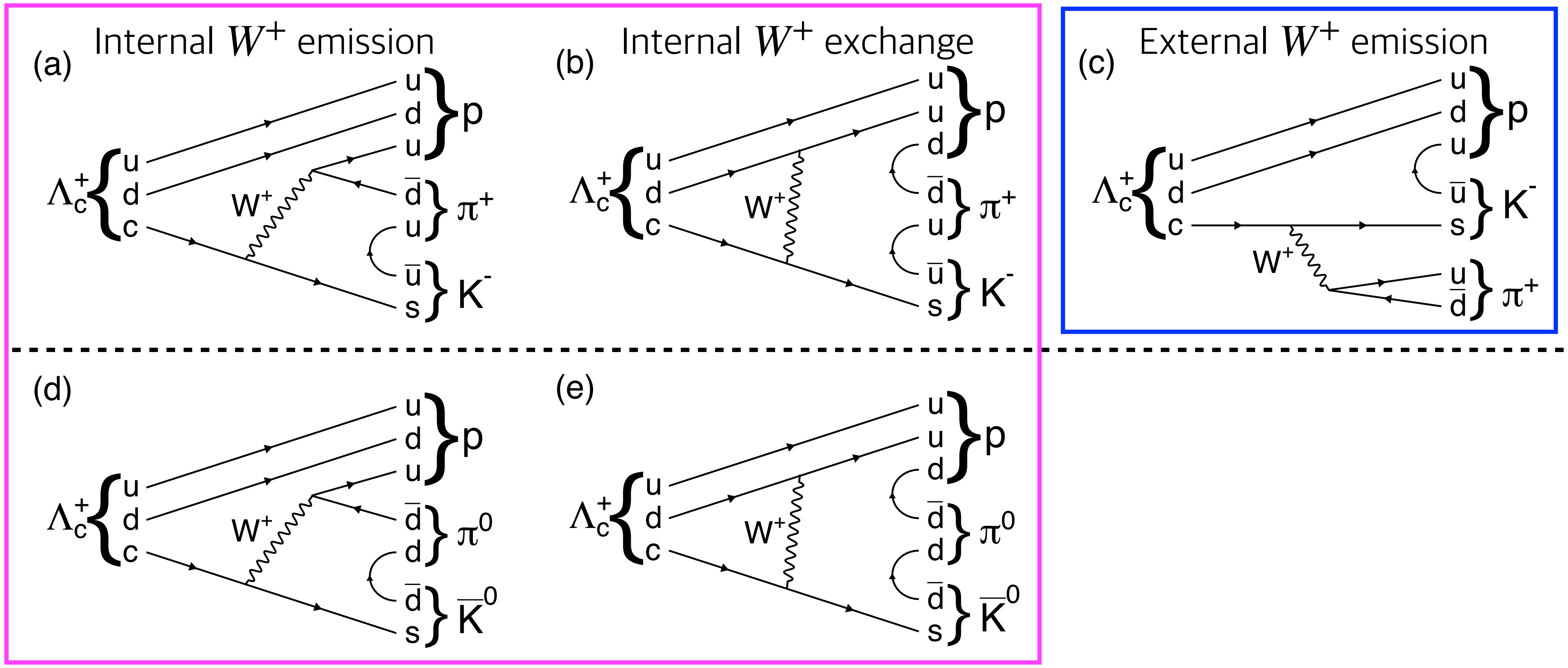
Overview

Presentation about paper (submitted to PRD)
Please find arXiv:2503.04371

- **Motivation**
- **Branching ratio measurement**
  - ➡ Reconstruction and Efficiency
  - ➡ Yield Extraction
  - ➡ Relative and absolute Branching Ratios
- **Intermediate structures**
  - ➡ Dalitz plots
  - ➡ Two particle mass projections
- **Summary**

Physics analysis motivation



$\Lambda_c^+ \to pK^-\pi^+$

$\Lambda_c^+ \to pK_S^0\pi^0$

- $\Lambda_c^+ \to N\bar{K}\pi$ decays are good playground testing the isospin properties.
- Λ_c^+ decays result in a final state with $I = I_3 = 1$ ($c \to su\bar{d}$ transition, $\Delta S = 1$)
  - ➡ Isospin symmetry: $\sqrt{2}\mathscr{A}(p\bar{K}^0\pi^0) + \mathscr{A}(pK^-\pi^+) + \mathscr{A}(n\bar{K}^0\pi^+) = 0 \to$ amplitude and phase

[1] PRD **93** 056008 (2016)
[2] PRL **118**, 112001 (2017)
[3] PRD **98**, 116015 (2018)
[4] PRD **98**, 073003 (2018)

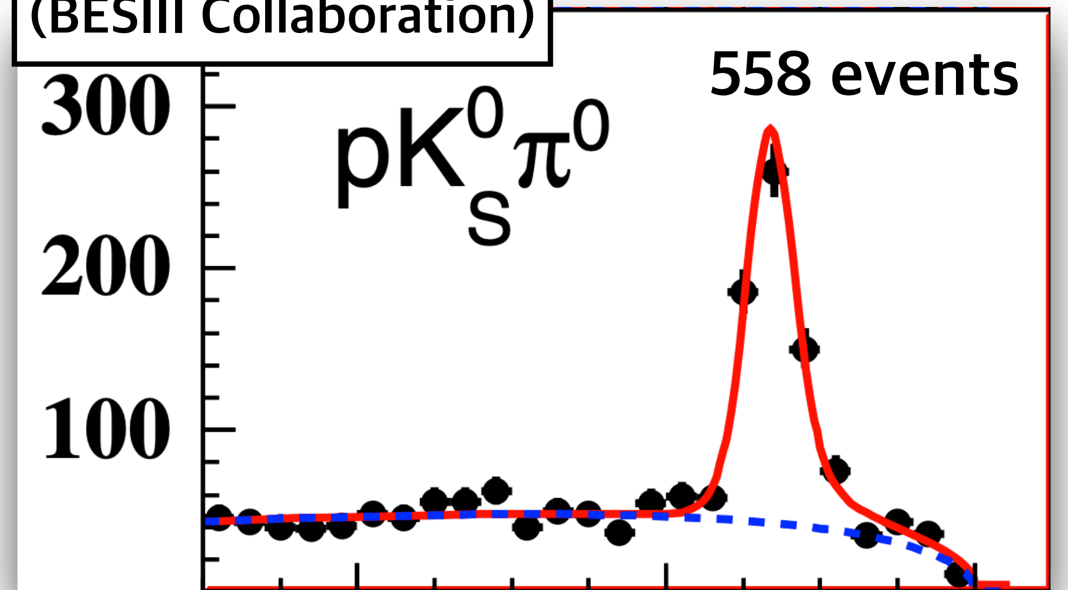
- (a), (b) , (d), (e) are color-suppressed, (c) is color-allowed
  - ➡ Direct π^+ emission leaves the ud in the Λ_c^+ as a spectator, uds cluster is pure $I = 0$.
  - ➡ If direct π^+ emission(c) is dominant, $\Lambda_c^+ \to \Lambda\pi^+$ is favored over $\Lambda_c^+ \to \Sigma^0\pi^+$. However, in experiment results, they are comparable. How about Λ^* and Σ^*?

[5] PRC **92**, 055204 (2015)
[6] PRD **118**, 034027 (2019)

Physics analysis motivation

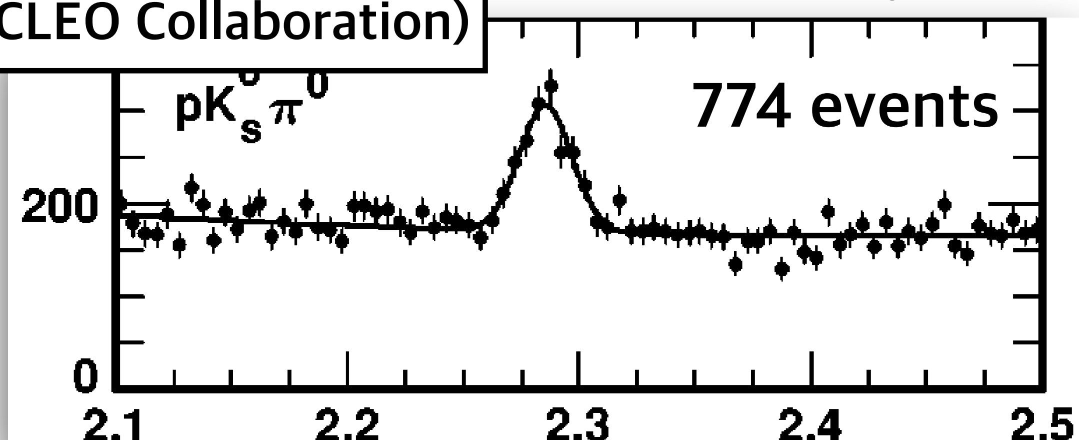
PRL **116**, 052001
(BESIII Collaboration)

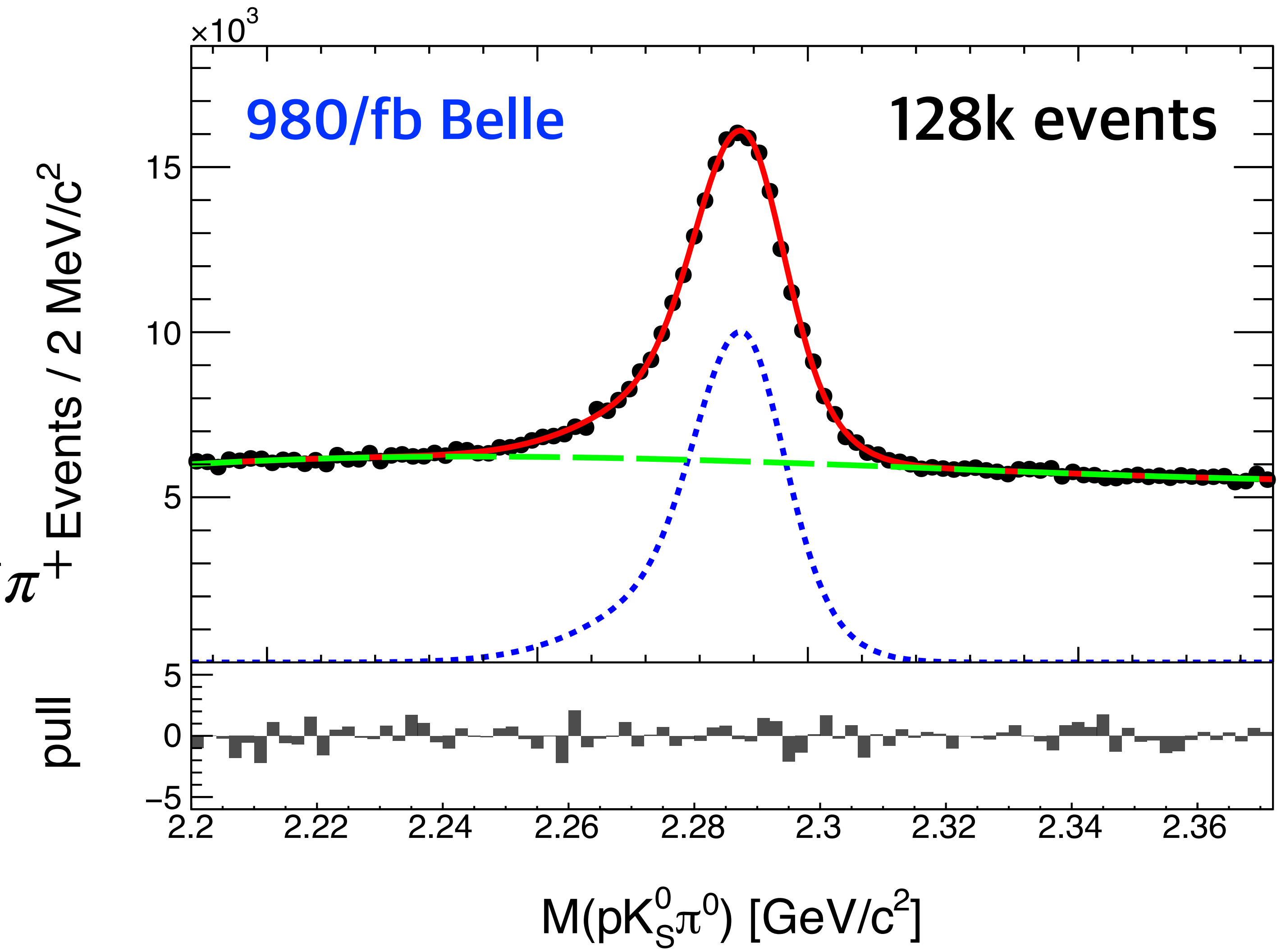
Absolute



PRD **57**, 4467
(CLEO Collaboration)

Relative to $\Lambda_c^+ \to pK^-\pi^+$





- **Update of the** $\Gamma(\Lambda_c^+ \to pK^0_S\pi^0)/\Gamma(\Lambda_c^+ \to pK^-\pi^+)$ **with x100 statistics than previous reports**
- First investigation of intermediate resonances in the $\Lambda_c^+ \to pK^0_S\pi^0$ decay

Physics analysis motivation

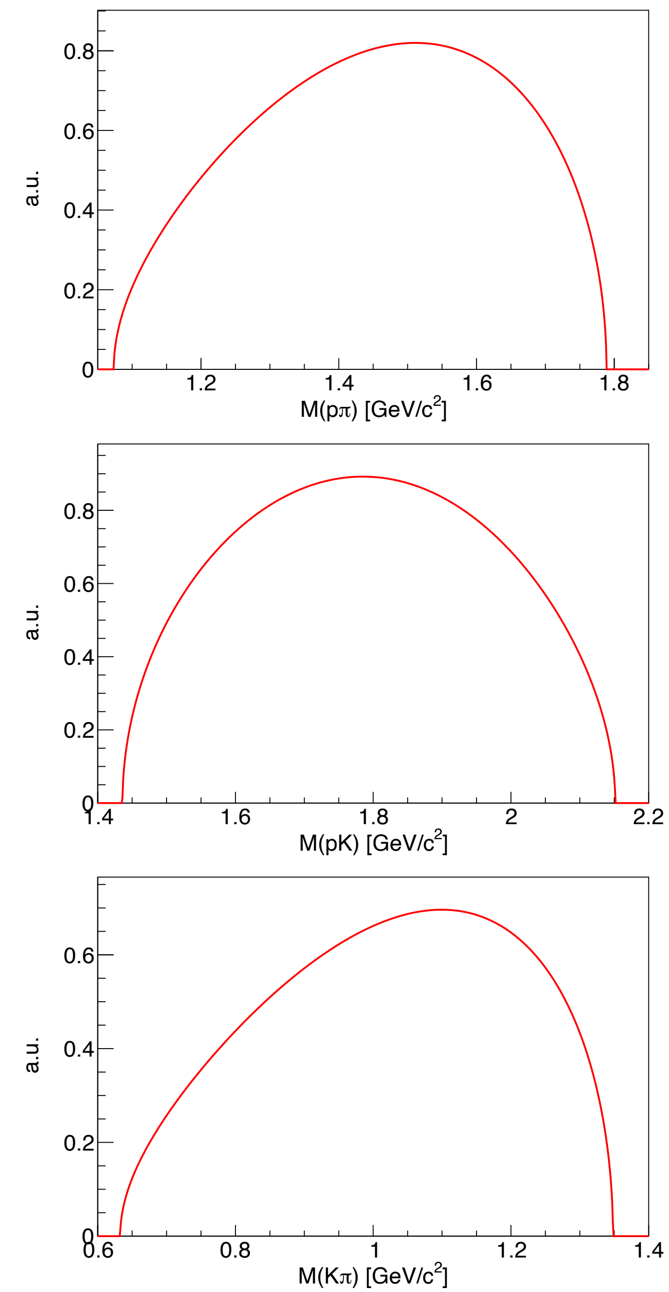
$\Lambda_c^+ \to pK^-\pi^+$

Γ_2	$pK^-\pi^+$		$(6.24 \pm 0.28)\%$
Γ_3	$p\overline{K}_0^*(700)^0$		$(1.9 \pm 0.6) \times 10^{-3}$
Γ_4	$p\overline{K}^*(892)^0$	[1]	$(1.39 \pm 0.07)\%$
Γ_5	$p\overline{K}_0^*(1430)$		$(9.2 \pm 1.8) \times 10^{-3}$
Γ_6	$\Delta(1232)^{++}K^-$		$(1.76 \pm 0.09)\%$
Γ_7	$\Delta(1600)^{++}K^-$		$(2.8 \pm 1.0) \times 10^{-3}$
Γ_8	$\Delta(1700)^{++}K^-$		$(2.4 \pm 0.6) \times 10^{-3}$
Γ_9	$\Lambda(1405)^0\pi^+$		$(4.8 \pm 1.9) \times 10^{-3}$
Γ_{10}	$\Lambda(1520)\pi^+$	[1]	$(1.16 \pm 0.16) \times 10^{-3}$
Γ_{11}	$\Lambda(1600)\pi^+$		$(3.2 \pm 1.2) \times 10^{-3}$
Γ_{12}	$\Lambda(1670)\pi^+$		$(7.4 \pm 2.1) \times 10^{-4}$
Γ_{13}	$\Lambda(1690)\pi^+$		$(7.4 \pm 2.2) \times 10^{-4}$
Γ_{14}	$\Lambda(2000)\pi^+$		$(6.0 \pm 0.7) \times 10^{-3}$
Γ_{15}	$pK^-\pi^+$ nonresonant		$(3.5 \pm 0.4)\%$

$\Lambda_c^+ \to pK_S^0\pi^0$

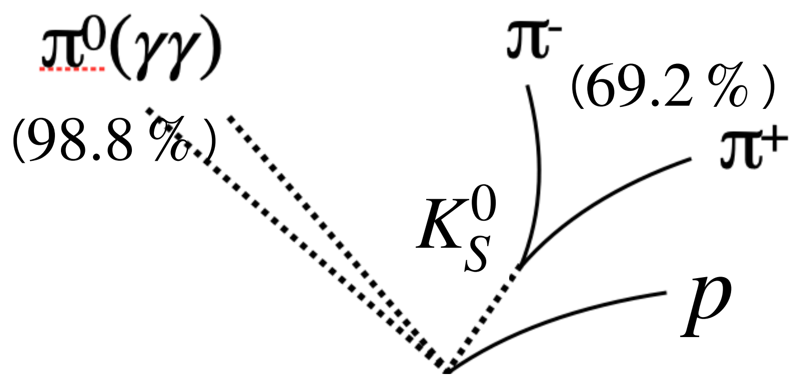
Γ_{16}	$pK_S^0\pi^0$	$(1.96 \pm 0.12)\%$

Allowed phase space of Λ_c^+ decays

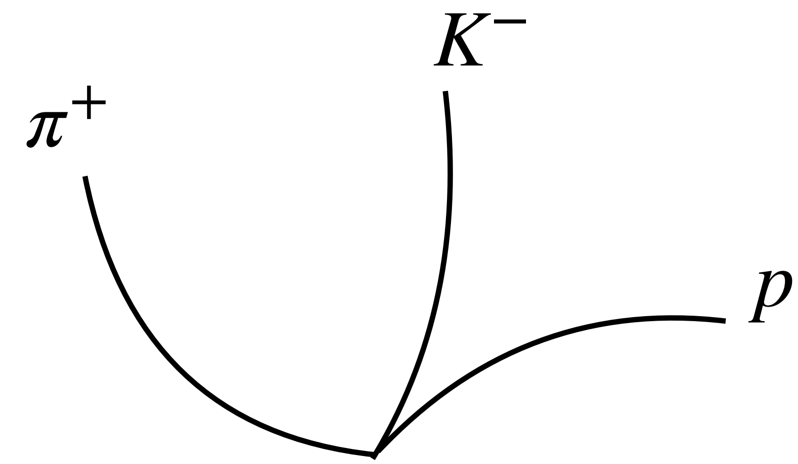


- Update of the $\Gamma(\Lambda_c^+ \to pK_S^0\pi^0)/\Gamma(\Lambda_c^+ \to pK^-\pi^+)$ with x100 statistics than previous reports
- **First investigation of intermediate resonances in the $\Lambda_c^+ \to pK_S^0\pi^0$ decay**

Λ_c^+ Reconstruction



$\Lambda_c^+ \to p K_S^0 \pi^0$

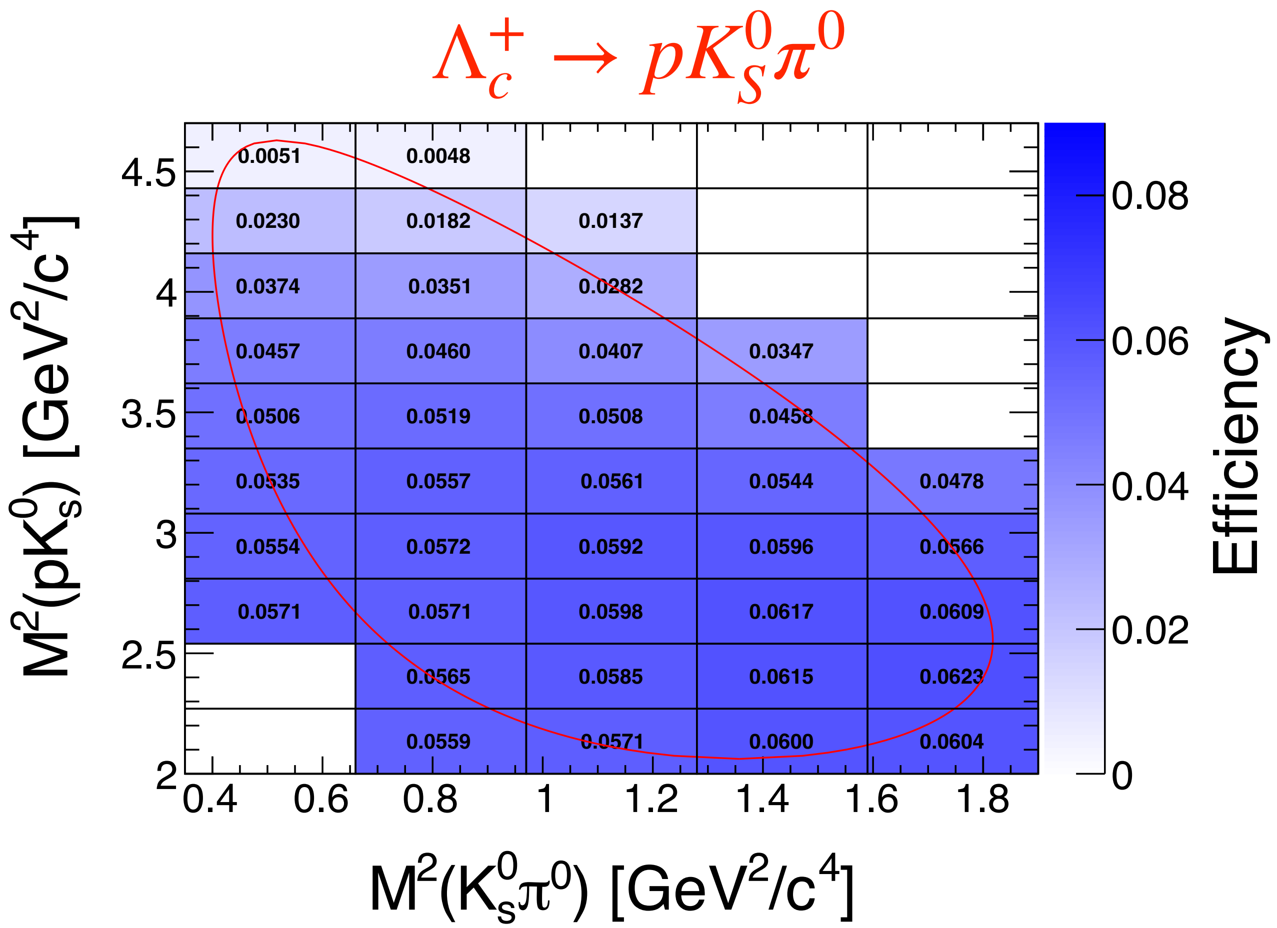


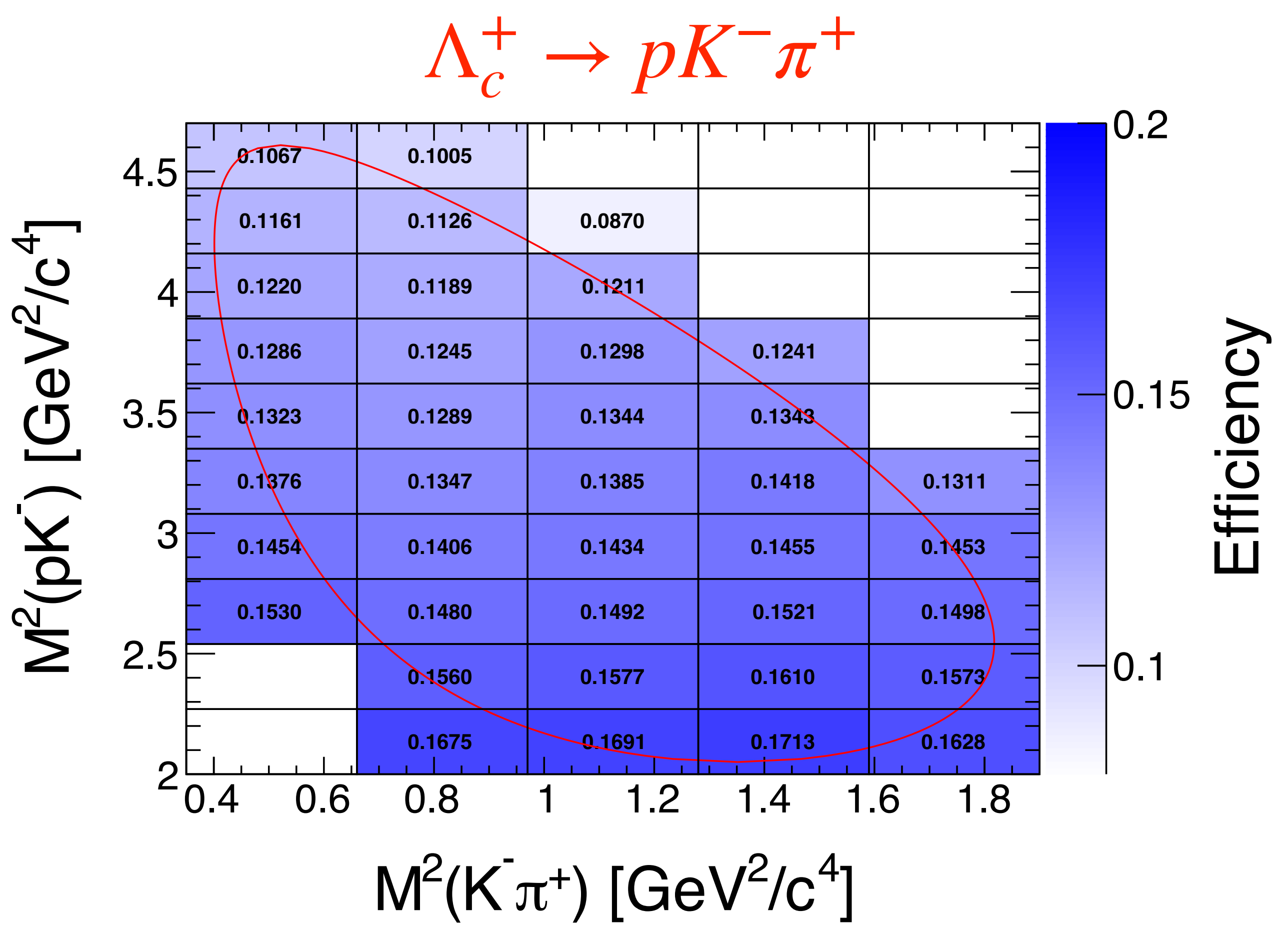
$\Lambda_c^+ \to p K^- \pi^+$

- $\Lambda_c^+ \to p K_S^0 \pi^0$ **(Signal mode)**
  - Λ_c^+: Scaled momentum x_p, vertex fit χ^2
  - p: PID, Impact parameters
  - $\pi^0(\gamma\gamma)$: mass, momentum, E_γ
  - $K_S^0(\pi^+\pi^-)$: Belle standard K_S^0, vertex fit χ^2
- $\Lambda_c^+ \to p K^- \pi^+$ **(Normalization mode)**
  - Λ_c^+: Scaled momentum x_p, vertex fit χ^2
  - p, K^-, π^+: PID, Impact parameters

➡ Selection criteria are optimized to maximize
$FoM = N_{sig}/\sqrt{N_{sig} + N_{bkg}}$ (Statistical significance)

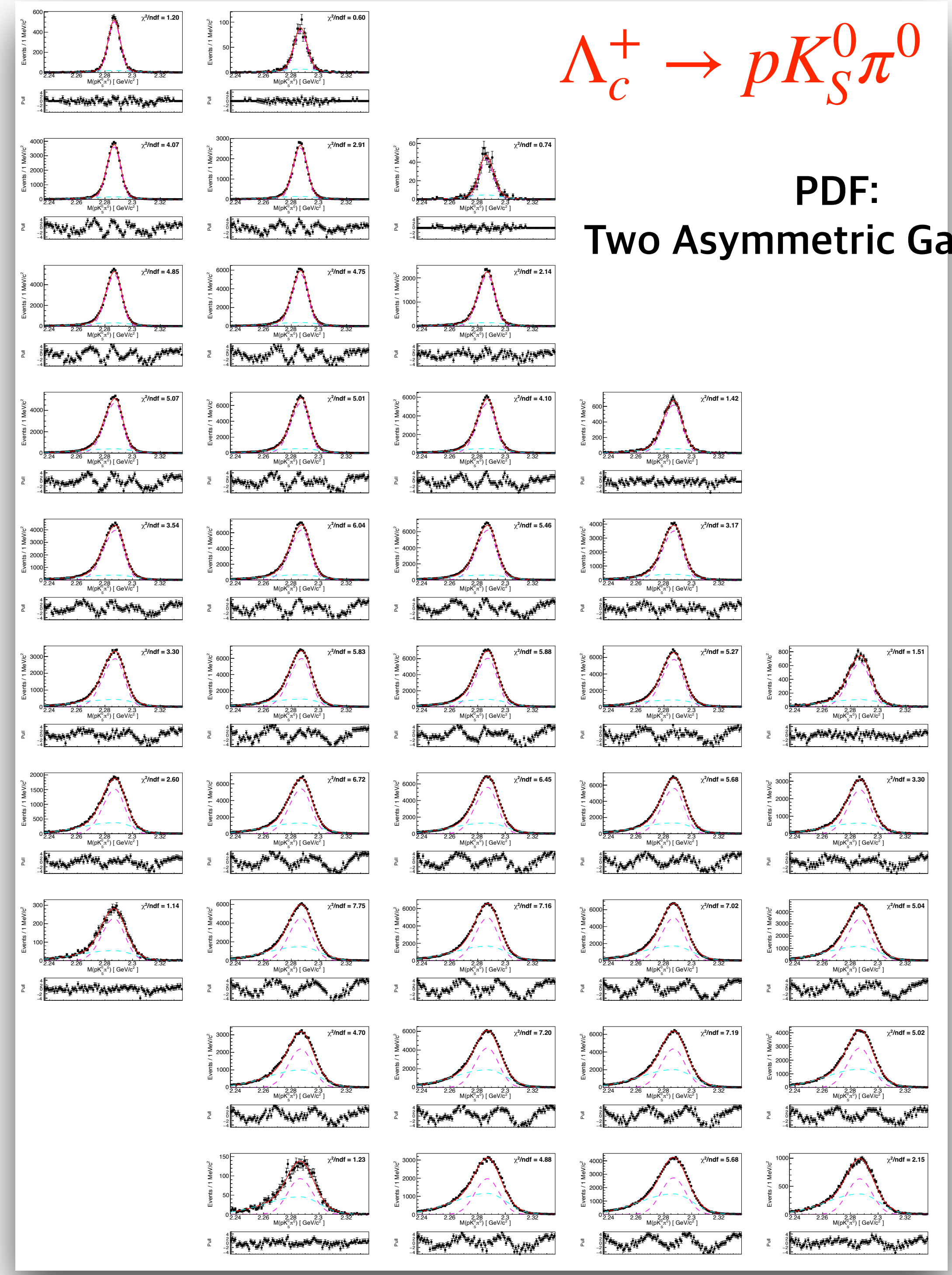
Reconstruction Efficiency

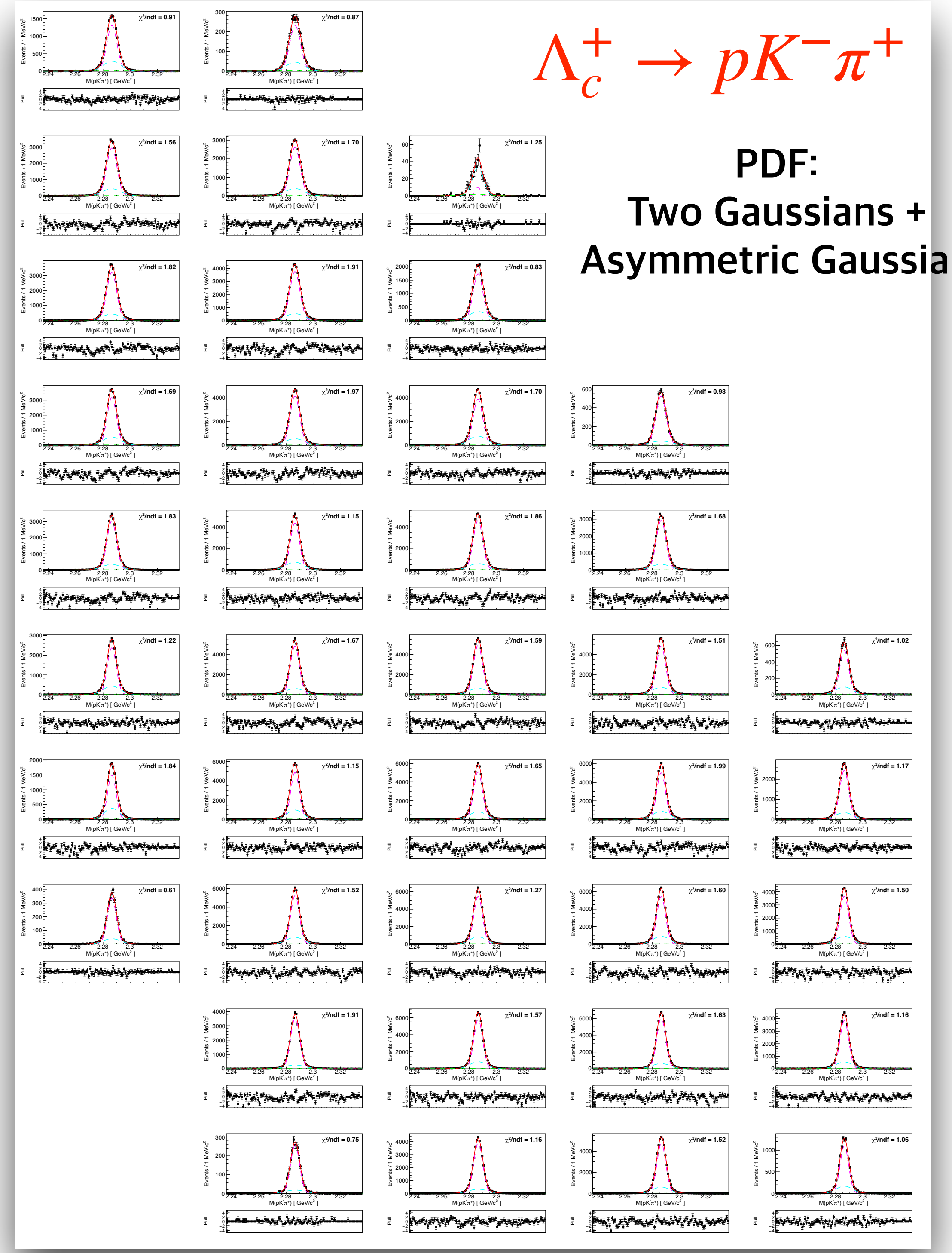




- In order to perform a resonance model-independent efficiency correction
  - ➡ Intermediate resonances are shown in Dalitz plot. (horizontal, vertical, diagonal)
  - ➡ Yield extraction and efficiency correction are performed on **5 × 10 Dalitz bins**

Signal PDF

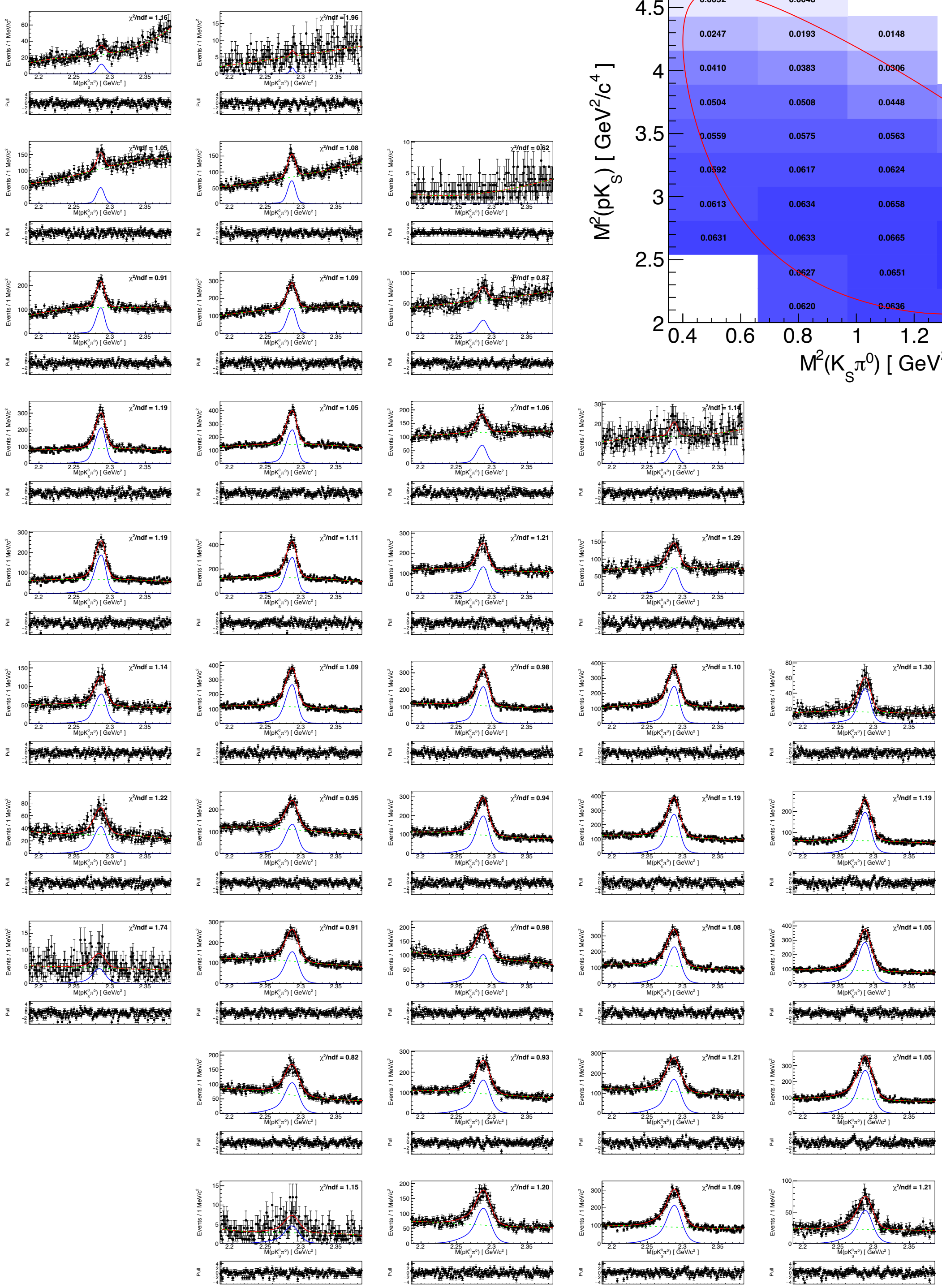


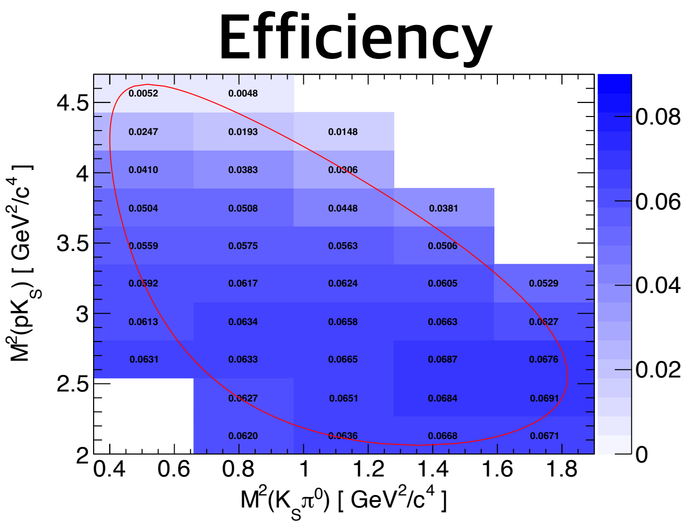


- Signal line shapes are constrained for each bin. Only m_0 and scale parameter σ are floated

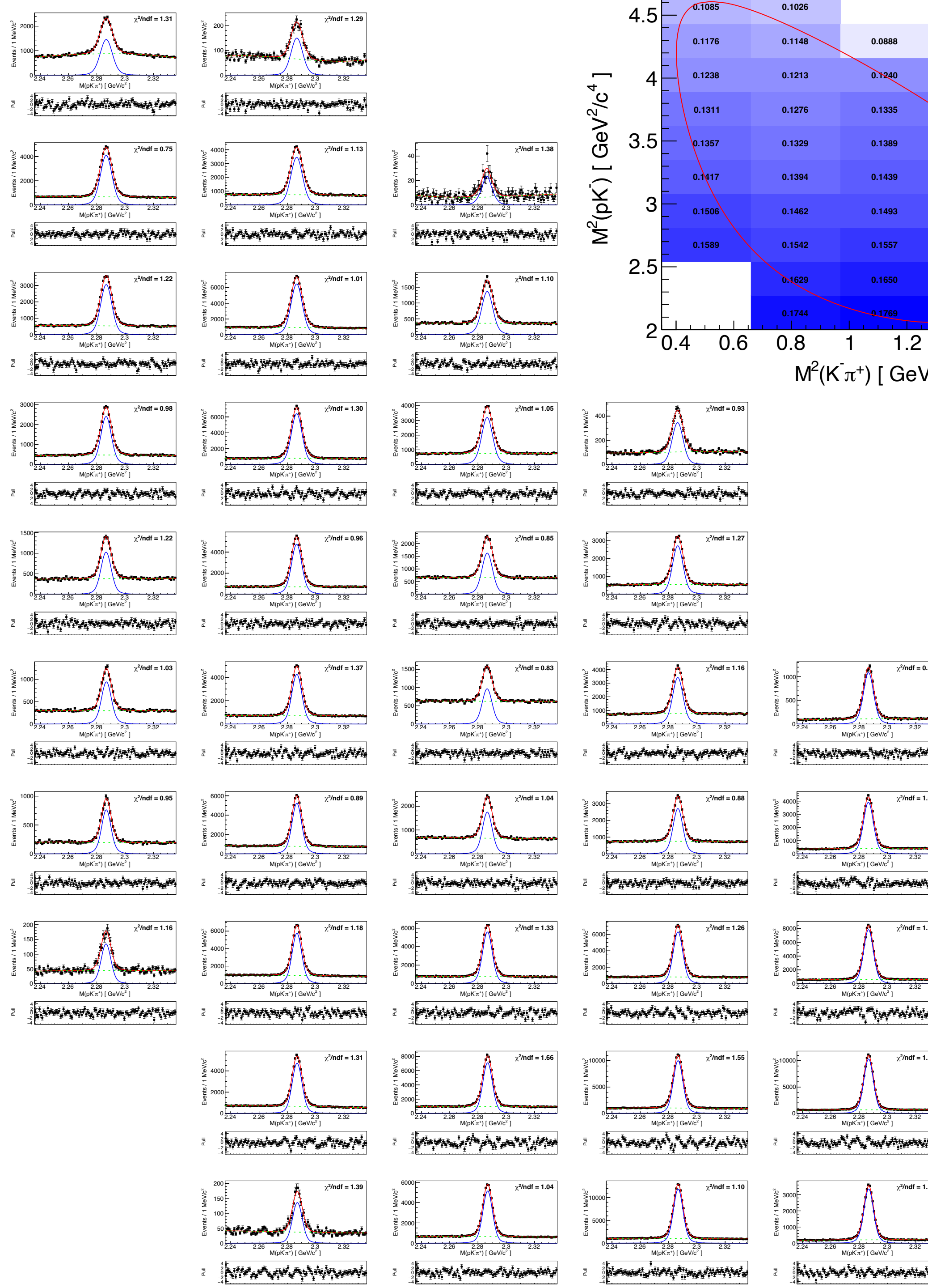
$N(\Lambda_c^+ \to pK_S^0\pi^0)$ and $N(\Lambda_c^+ \to pK^-\pi^+)$ extraction

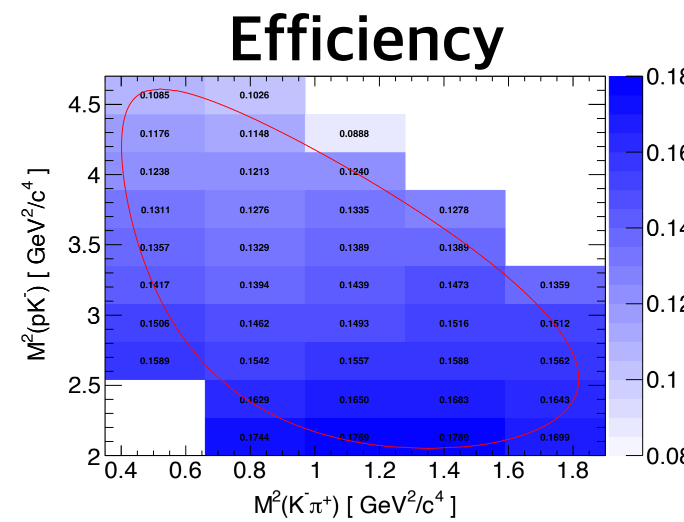
$\Lambda_c^+ \to pK_S^0\pi^0$





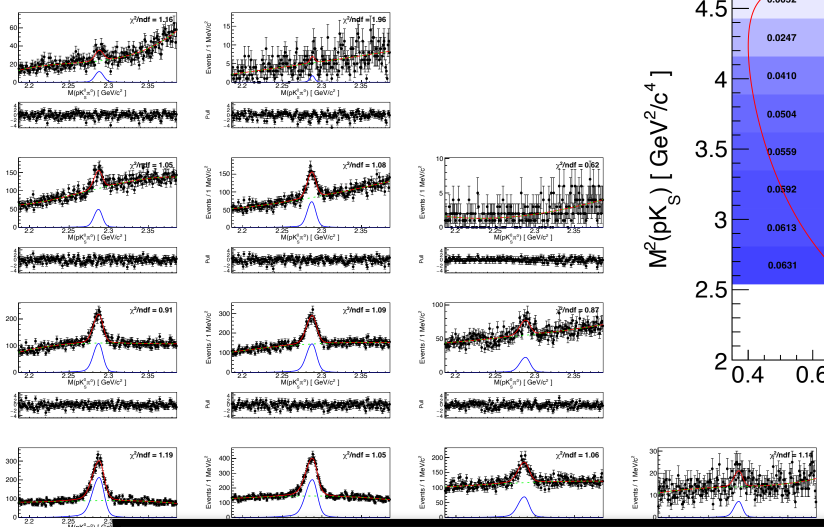
$\Lambda_c^+ \to pK^-\pi^+$

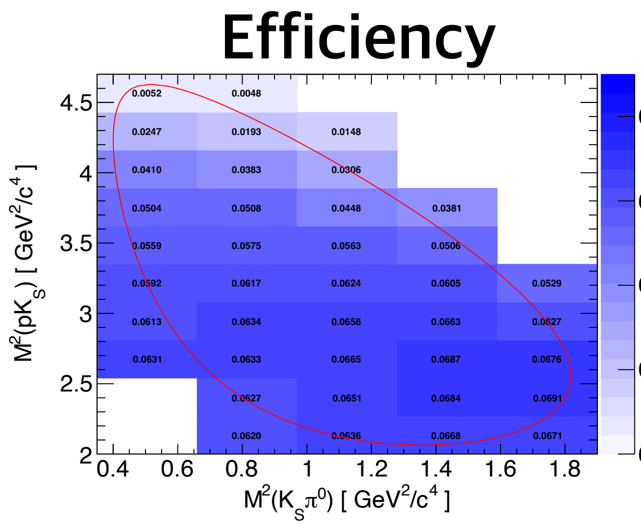




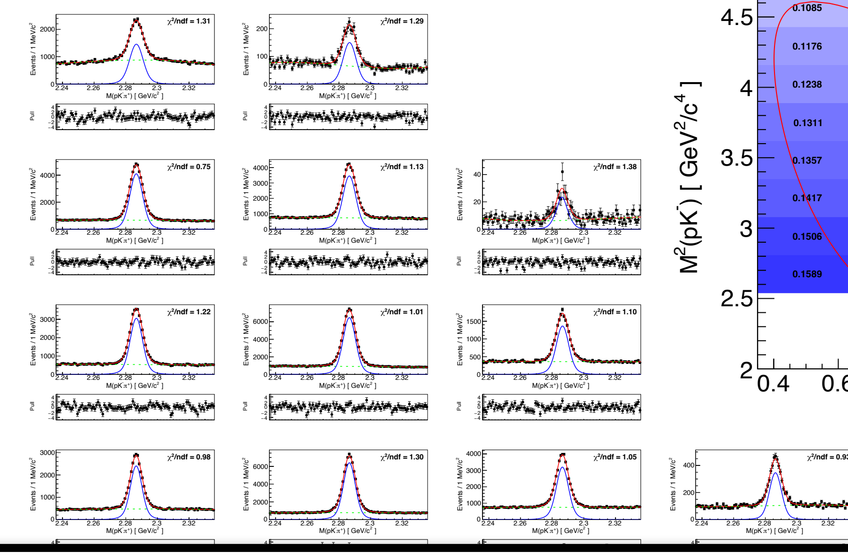
Relative and Absolute BFs

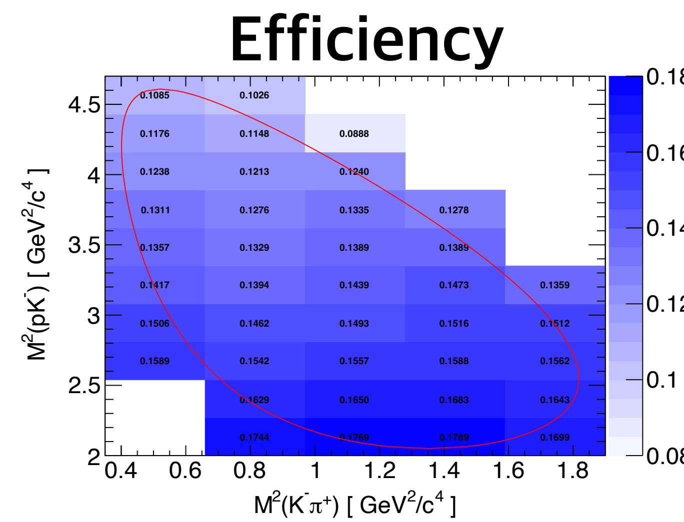
$\Lambda_c^+ \to pK_S^0\pi^0$





$\Lambda_c^+ \to pK^-\pi^+$





$$\frac{\Gamma(\Lambda_c^+ \to pK_S^0\pi^0)}{\Gamma(\Lambda_c^+ \to pK^-\pi^+)} = \frac{y^{corr}(\Lambda_c^+ \to pK_S^0\pi^0)}{y^{corr}(\Lambda_c^+ \to pK^-\pi^+) \times B(\pi^0 \to \gamma\gamma) \times B(K_S^0 \to \pi^+\pi^-)}$$

This Work

$\Gamma(\Lambda_c^+ \to pK_S^0\pi^0)/\Gamma(\Lambda_c^+ \to pK^-\pi^+)$ **= 0.339 ± 0.002(stat.) ± 0.009(syst.)**

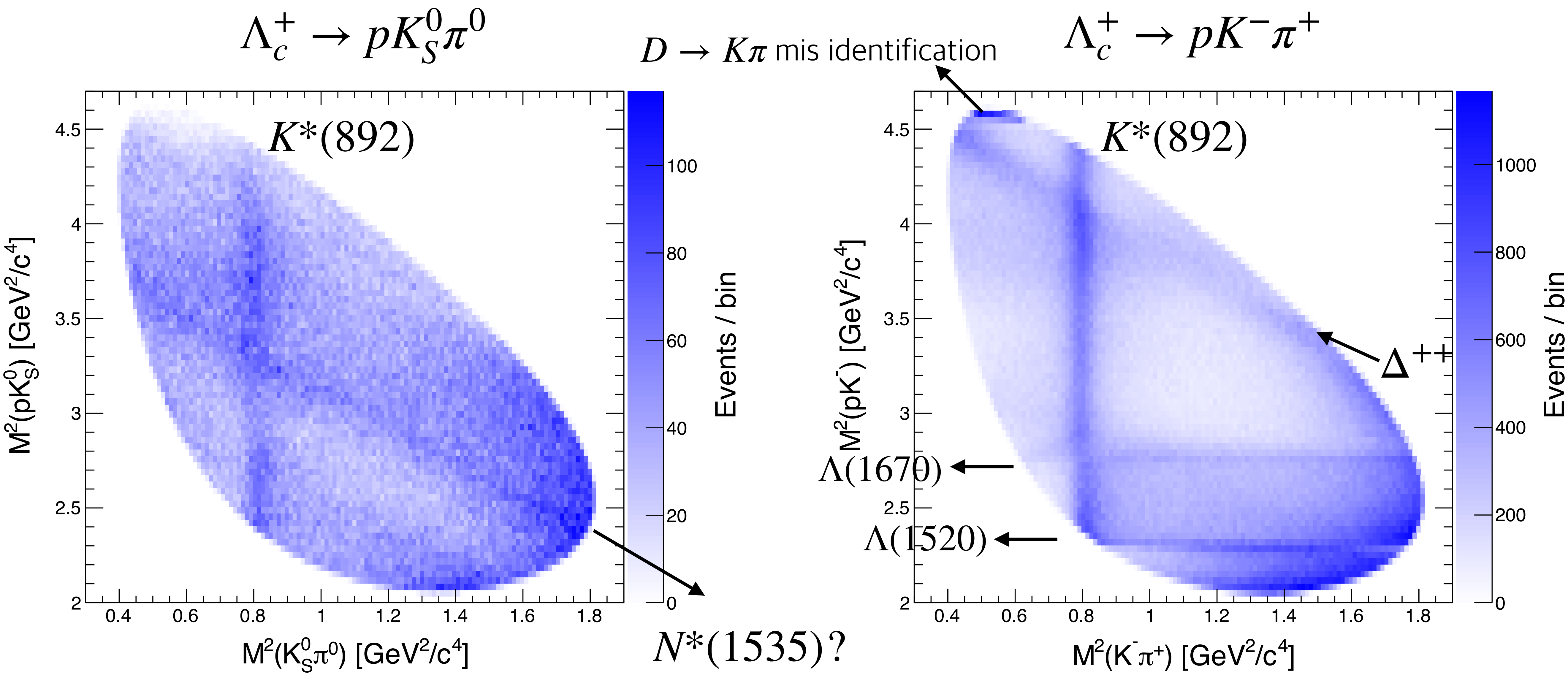
$\mathscr{B}(\Lambda_c^+ \to pK_S^0\pi^0)$ **= 2.12 ± 0.01(stat.) ± 0.05(syst.) ± 0.10(norm PDG2024) (%)**

Fivefold improvement than previous measurement (CLEO),

Threefold improvement than BESIII

Dalitz plots

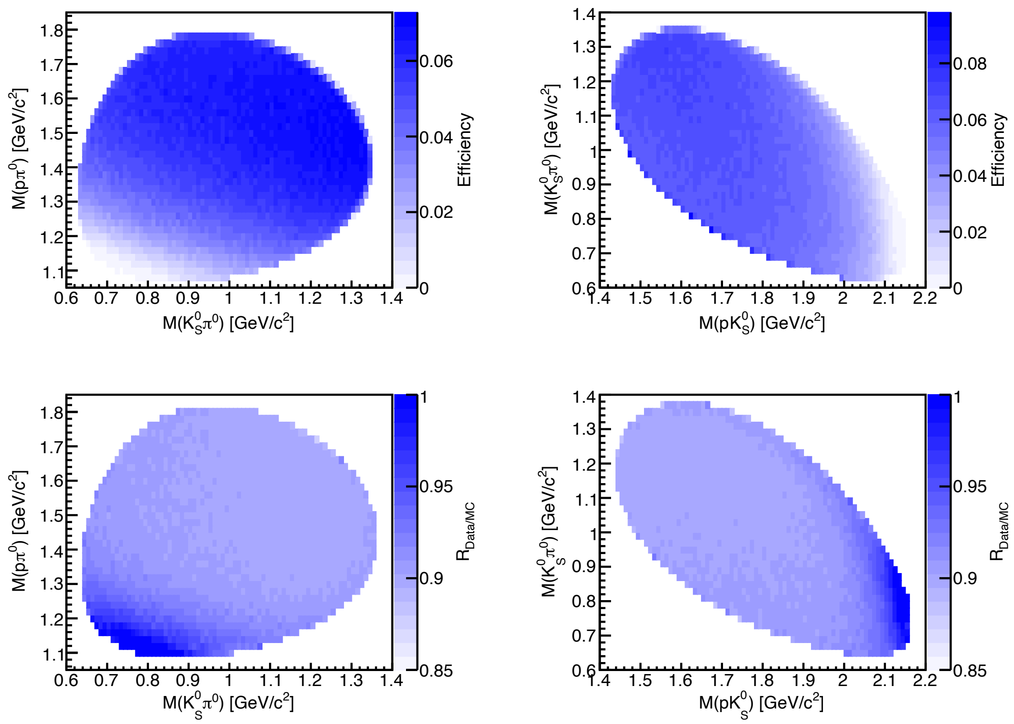
Possible resonances	$pK^-\pi^+$	$pK_S^0\pi^0$
pK	Λ, Σ^0	Σ^+
$p\pi$	Δ^{++}	Δ^+, N^+
$K\pi$	$\bar{K}^{*0}$	



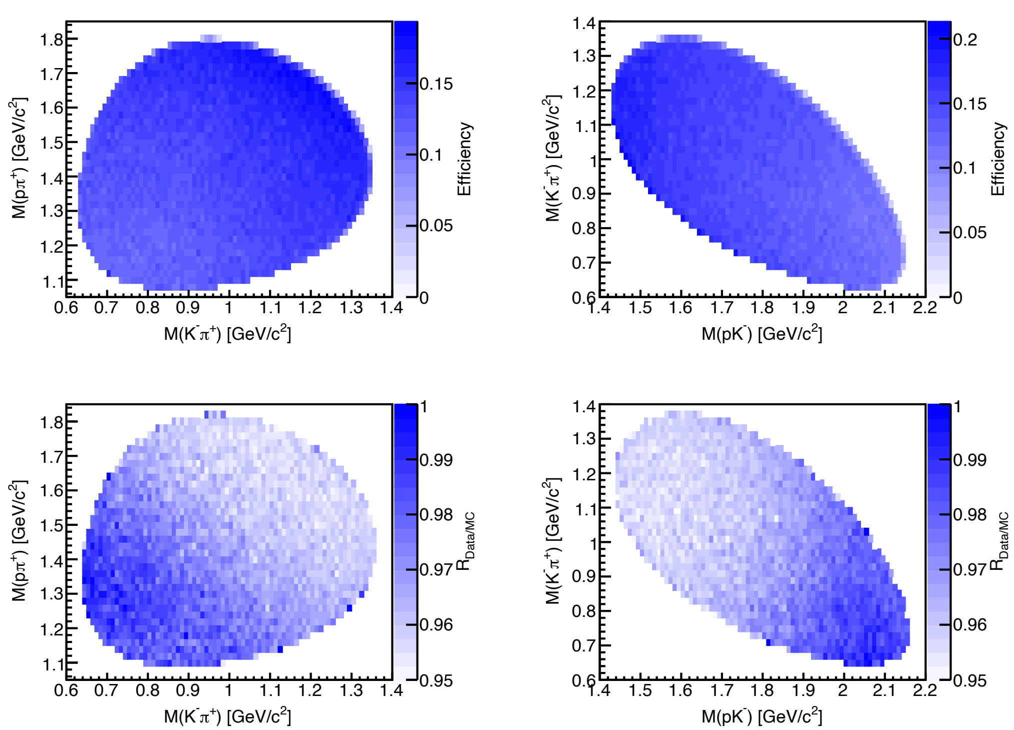
- There is no clear peak structure in the pK_S^0 system (horizontal axis)
- $K^*(892)$ clearly seen and, in the $p\pi^0$ system, a peak appears at 1.5 GeV
- Enhancements are seen in the boundary of the bottom and right side

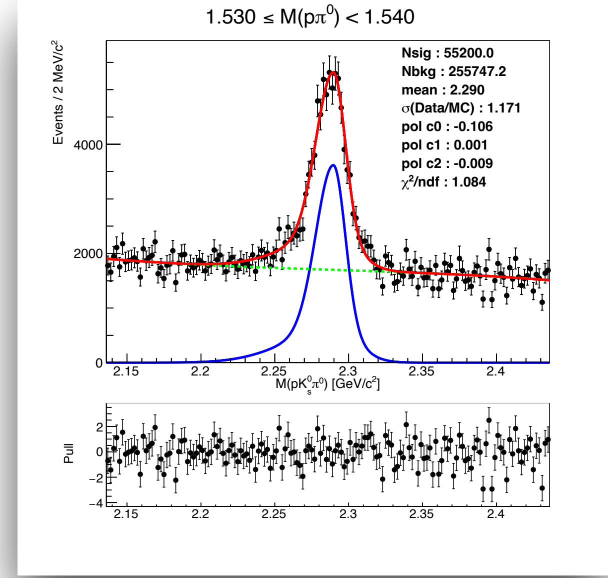
One dimensional mass projections

$\Lambda_c^+ \to pK_S^0\pi^0$



$\Lambda_c^+ \to pK^-\pi^+$





1. We constructed event-by-event **efficiency-corrected $M(\Lambda_c^+)$ histograms** (weighted by $\dfrac{1}{\epsilon_{i,j} \cdot R_{i,j}(Data/MC)}$) for each mass bin $m_{ab,i}$, a, b for daughter particle, i for mass bin of m_{ab}

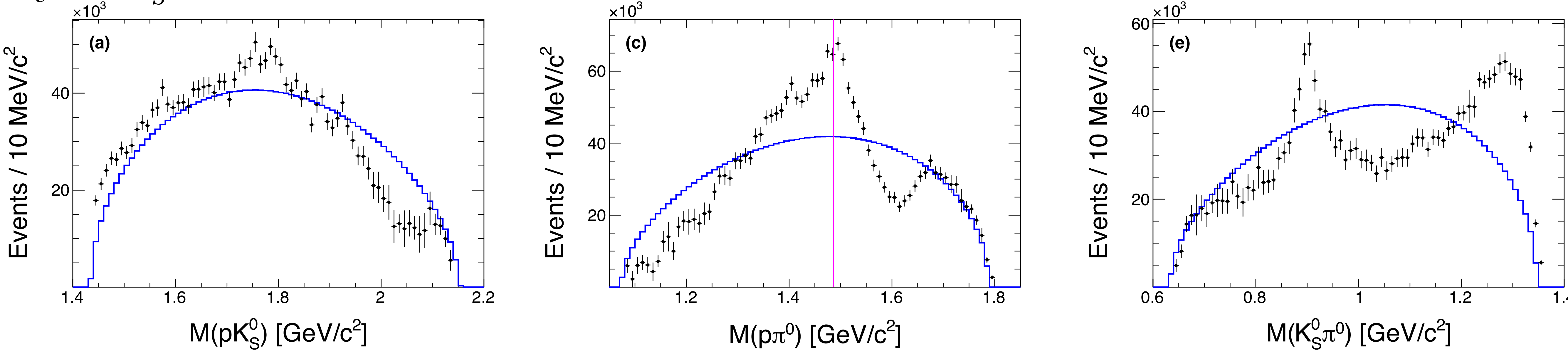
2. Fit and **extract yield for each mass bin $m_{ab,i}$**

3. Similar with BR measurement, Data/MC has been corrected, the same signal PDFs are used, and shape parameters are fixed.
For background PDFs, 3rd order polynomial and Argus function are used depending on mass bin.

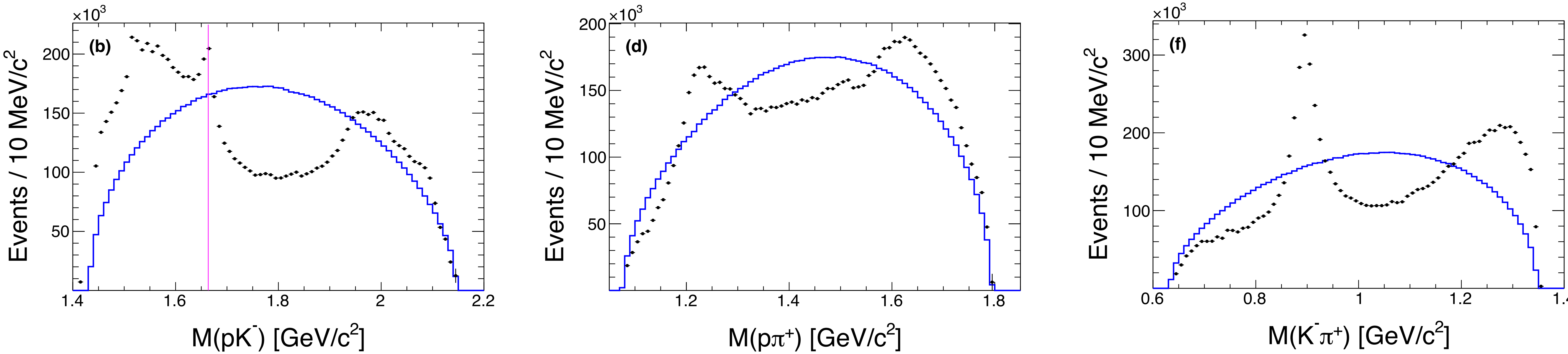
Efficiency corrected mass spectra

$\Lambda_c^+ \to pK_S^0\pi^0$

Blue histograms represent PHSP line shapes

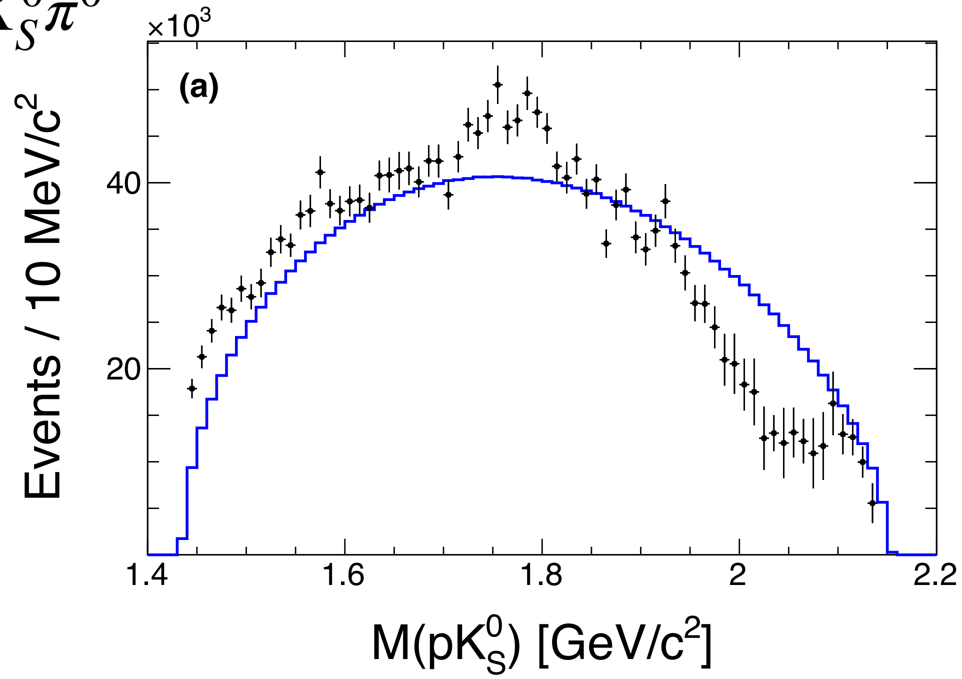


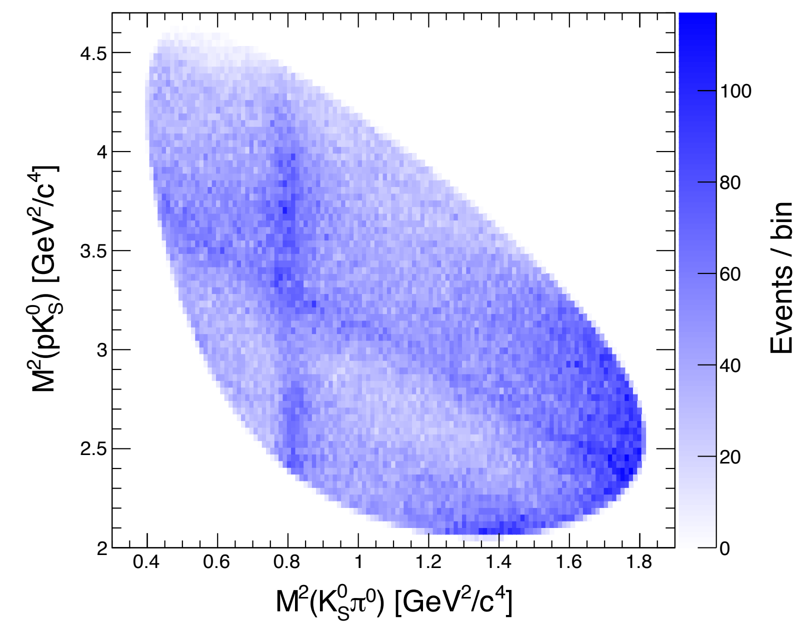
$\Lambda_c^+ \to pK^-\pi^+$

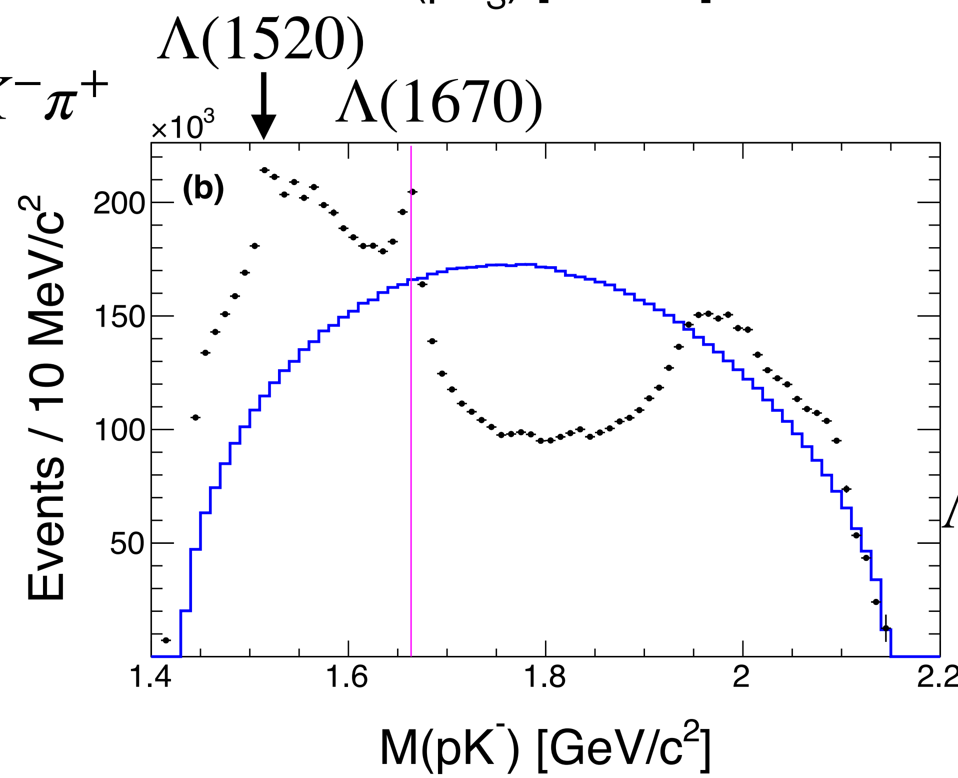


Absence of peak structure in the $M(pK_S^0)$

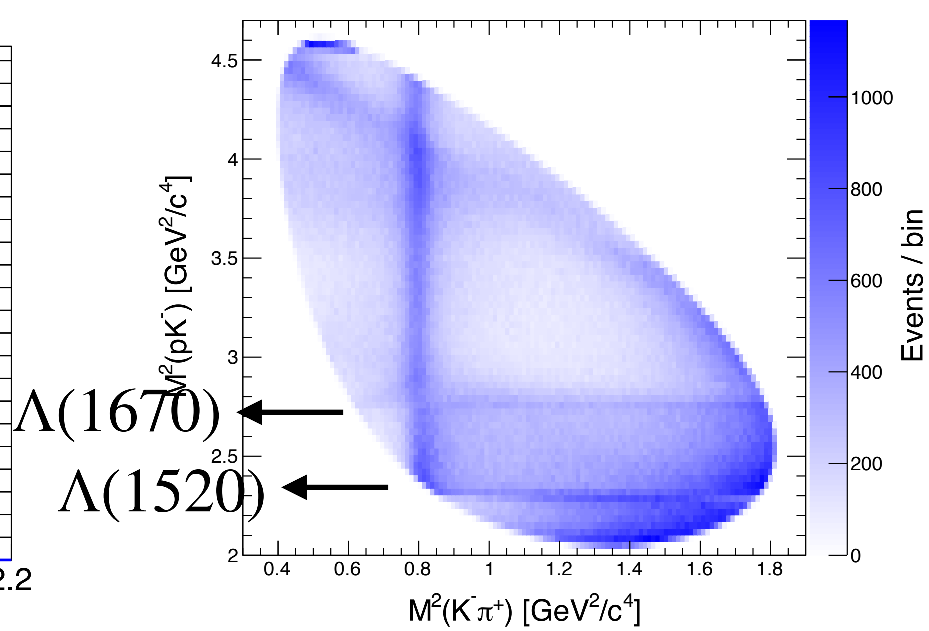
$\Lambda_c^+ \to pK_S^0\pi^0$





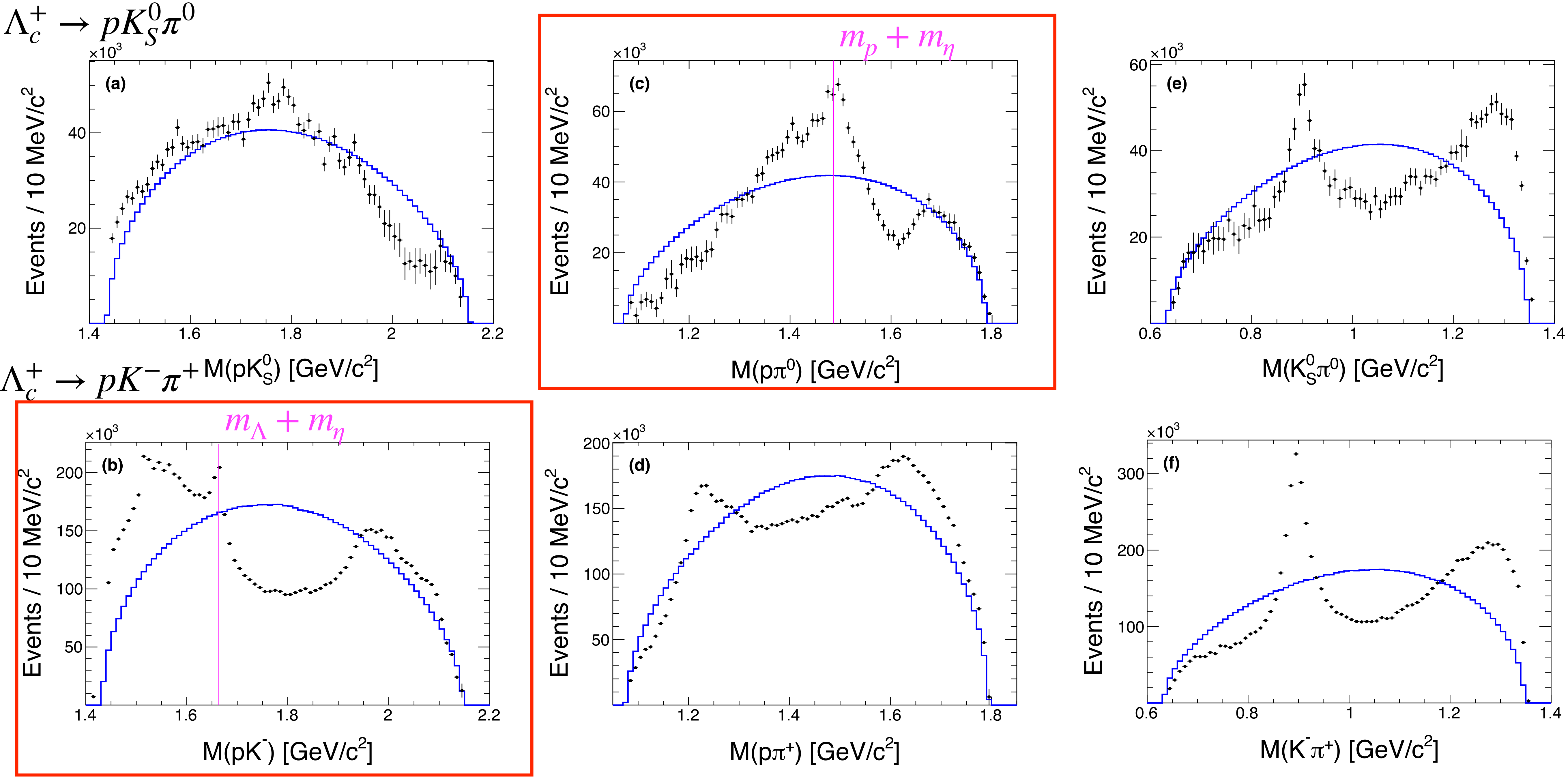


$\Lambda_c^+ \to pK^-\pi^+$



- Compared with Dalitz plots, there is no narrow peak structure (Σ^{*+}) in the $M(pK_S^0)$, while Λ^*s are clearly seen in the $M(pK^-)$

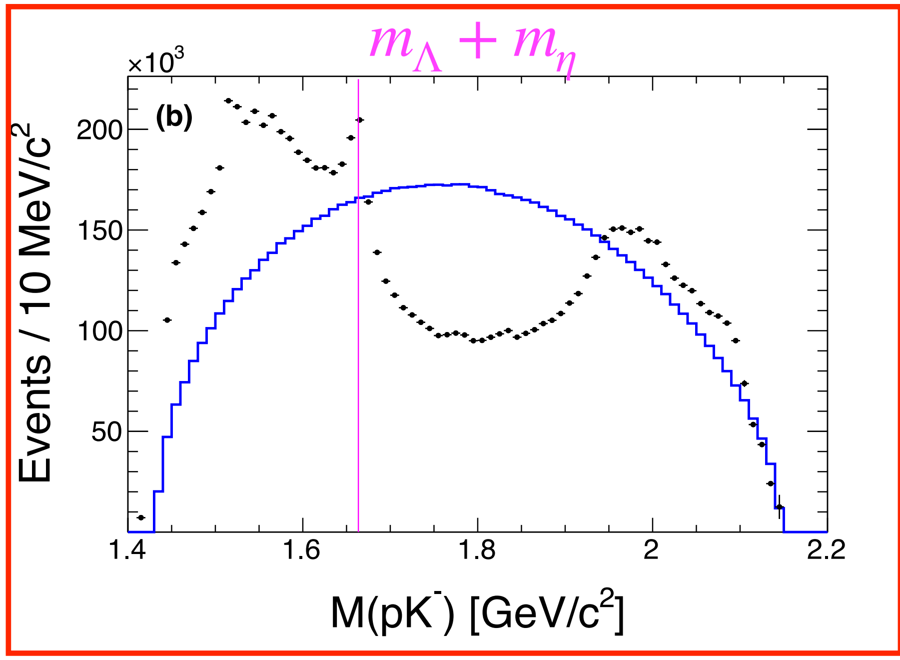
Threshold cusp in $M(p\pi^0)$



- The threshold cups near the $p\eta$ mass threshold enhanced by $N(1535)^+$.
- The same situation with the $\Lambda\eta$ threshold cusp enhanced by $\Lambda(1670)$

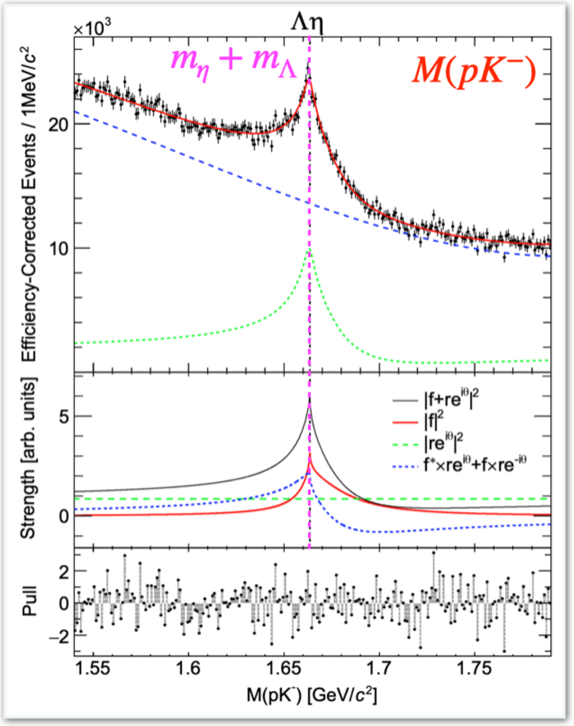
Threshold cusp in $M(p\pi^0)$

$\Lambda_c^+ \to pK^-\pi^+$



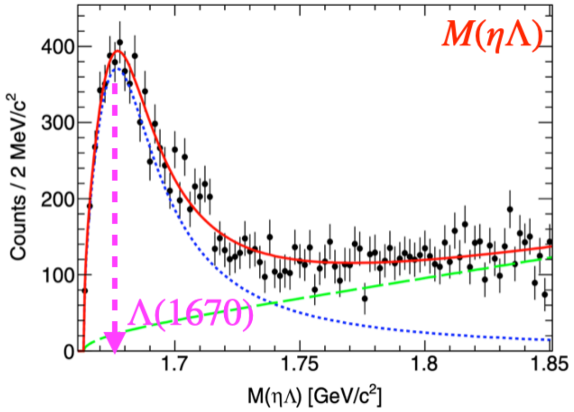
$\Lambda(1670)$ Belle 980/fb, PRD **108**, L031104 (2023)

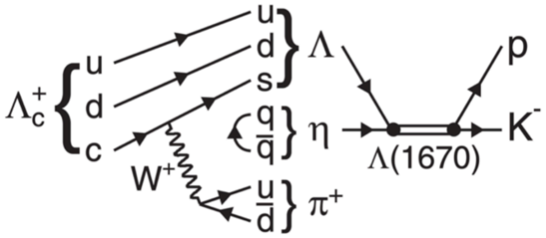
$\Lambda_c^+ \to pK^-\pi^+$



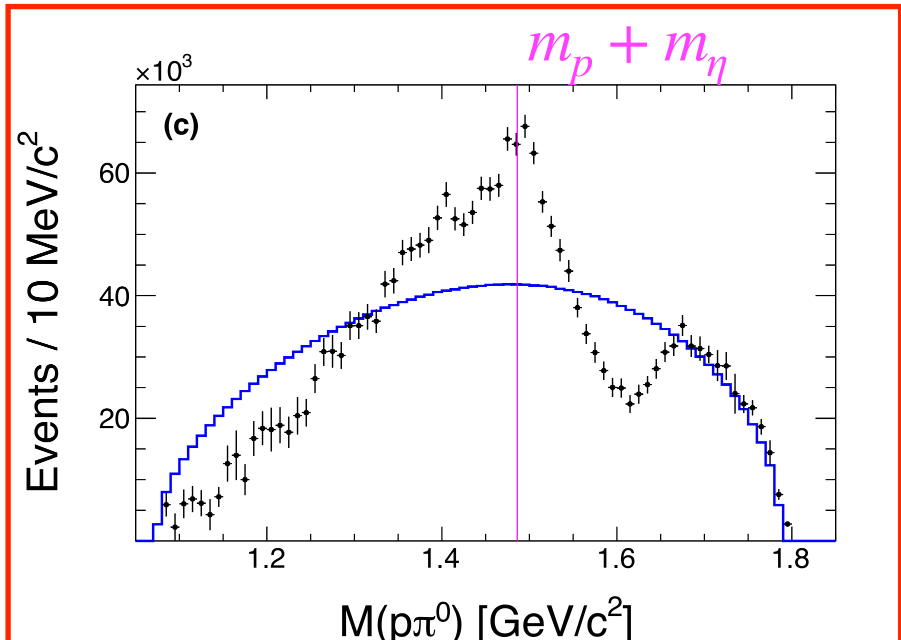
Belle 980/fb, PRD **103**, 052005 (2021)

$\Lambda_c^+ \to \eta\Lambda\pi^+$



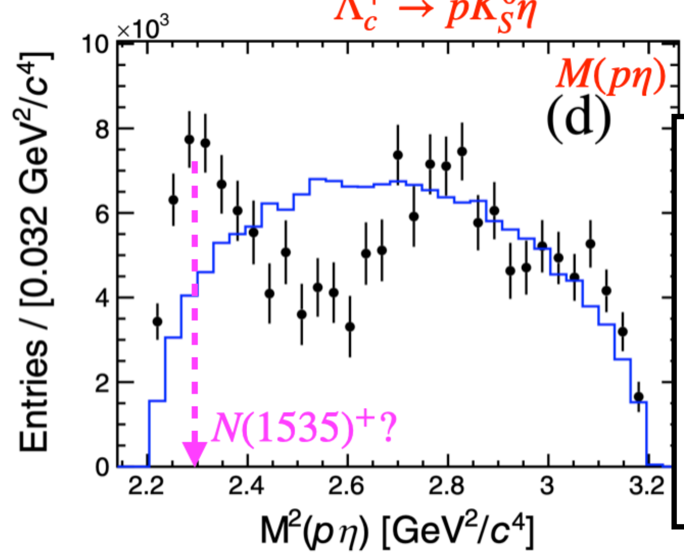


$\Lambda_c^+ \to pK_S^0\pi^0$



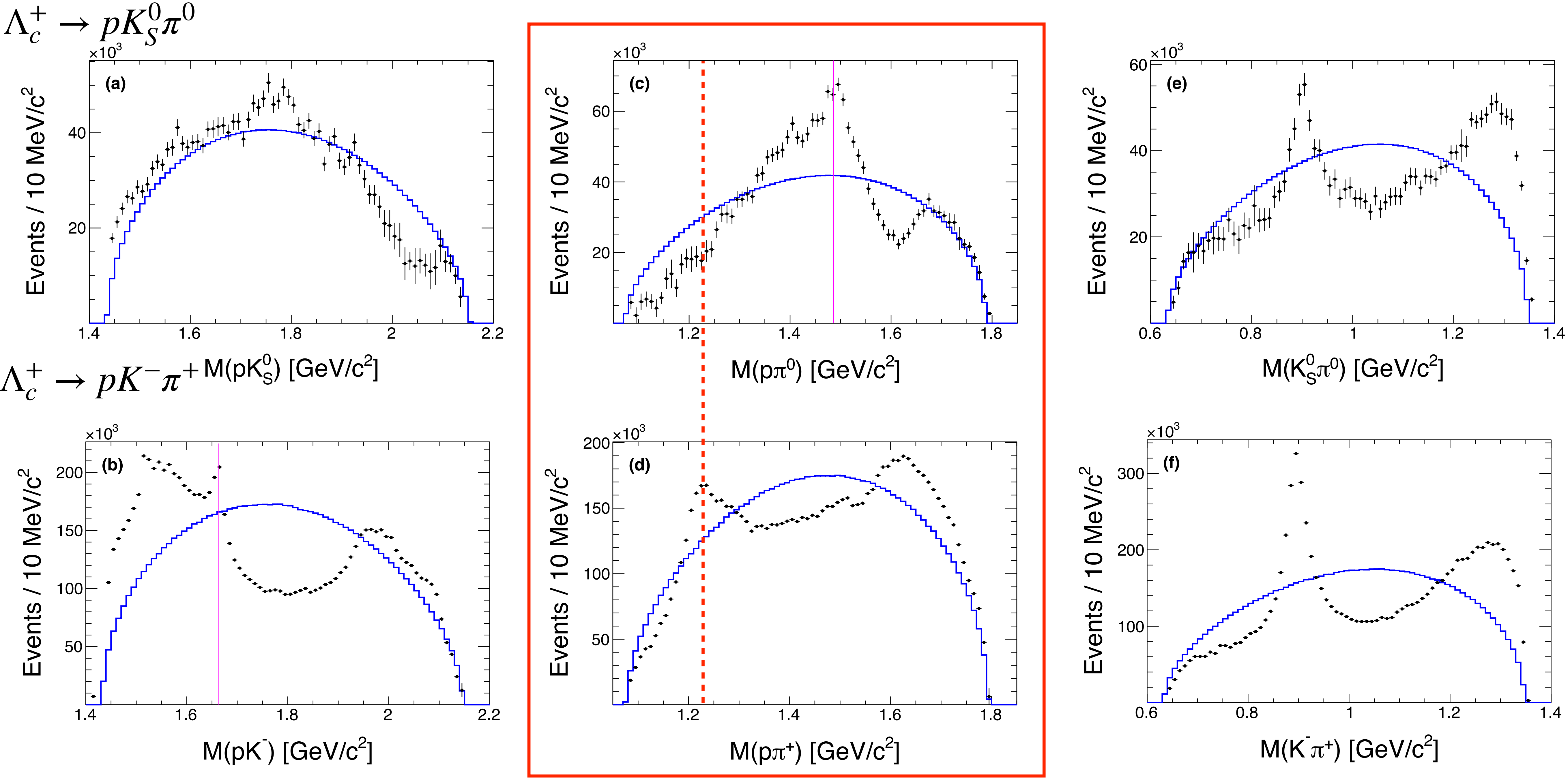
Belle 980/fb, PRD **103**, 032004 (2023)

$\Lambda_c^+ \to pK_S^0\eta$



- $\Lambda(1670)$ observed in $M(\eta\Lambda)$, threshold cusp observed in $M(pK^-)$
- N^* seen in $M(p\eta)$, threshold cusp observed in $M(p\pi^0)$

$\Delta(1232)$ suppression in $M(p\pi^0)$

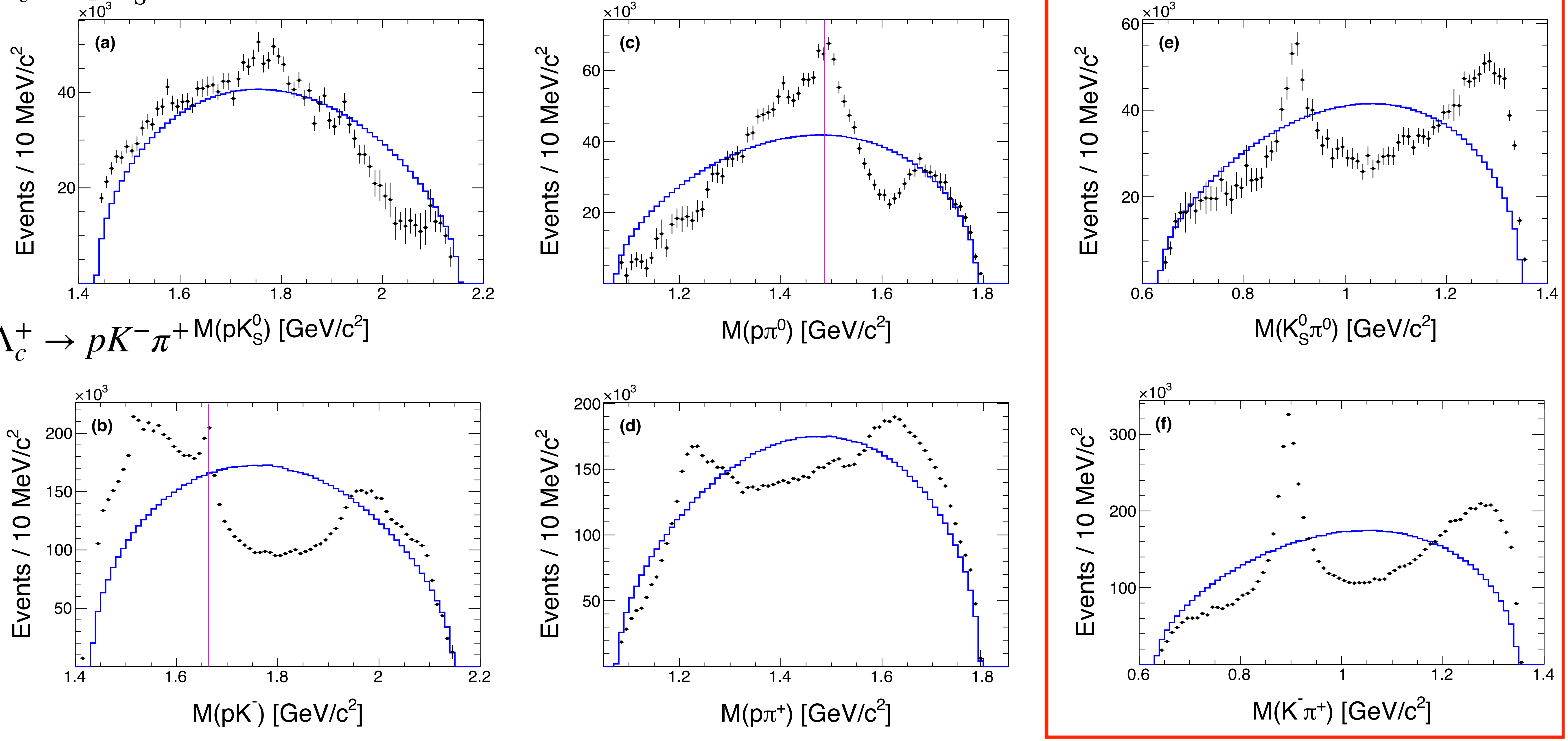


- The $\Delta(1232)$ is not clearly seen in the $M(p\pi^0)$
  - Isospin sum rule $-\mathscr{A}(\Lambda_c^+ \to K^-\Delta^{++}) + \sqrt{3}\mathscr{A}(\Lambda_c^+ \to \bar{K}^0\Delta^+) = 0$ indicates suppression of Δ^+ in the $M(p\pi^0)$

Same line shapes in $K\pi$ systems

$\Lambda_c^+ \to pK_S^0\pi^0$

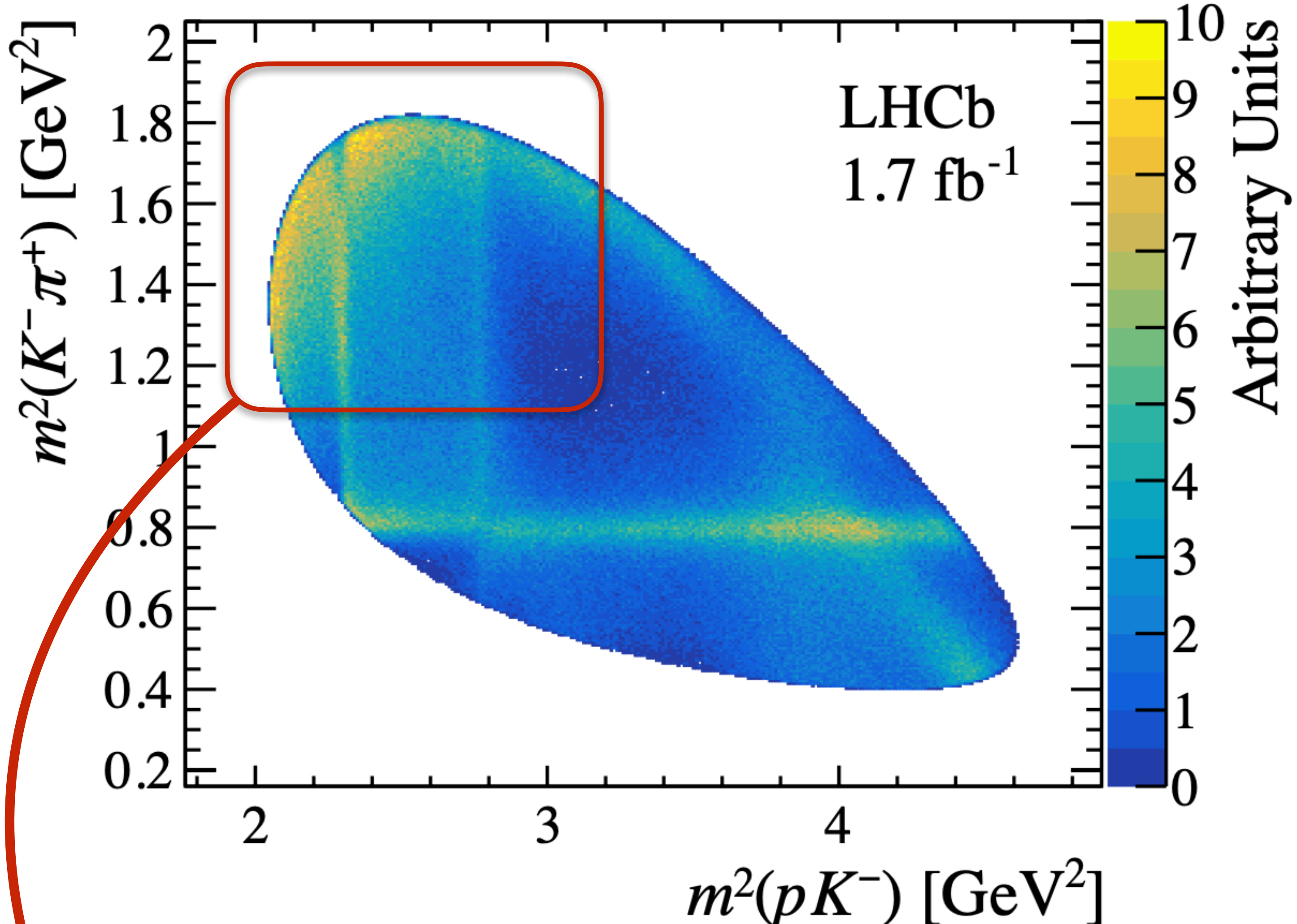
$\Lambda_c^+ \to pK^-\pi^+$

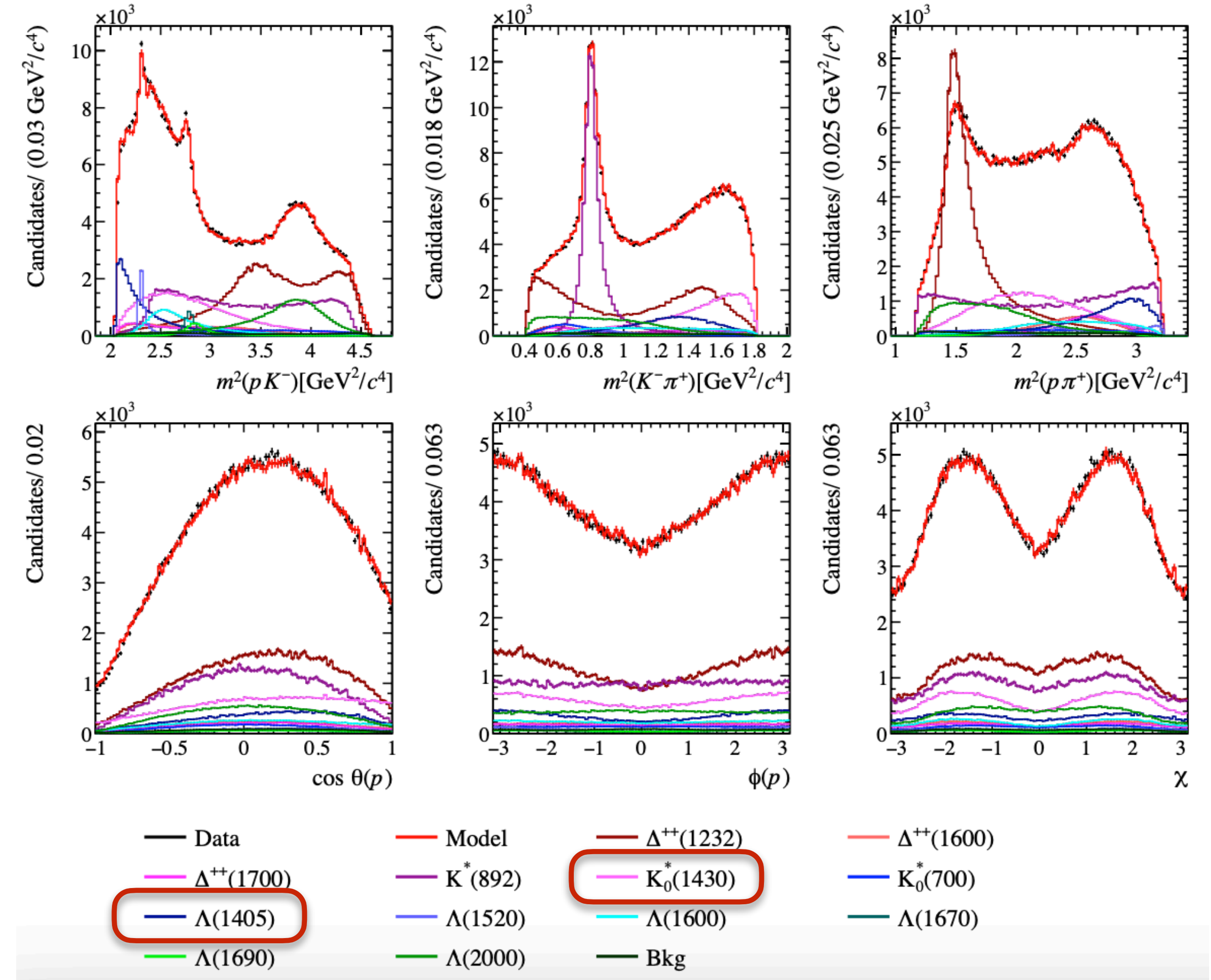


- Same line shapes. $\Lambda_c^+ \to p\bar{K}^{*0}$; $\bar{K}^{*0} \to K^-\pi^+/K_S^0\pi^0$
- $K^*(892)$ and high mass $M(K\pi)$ enhancements are clearly seen

Further analysis: Amplitude analysis

PRD **108**, 012023 (2023)

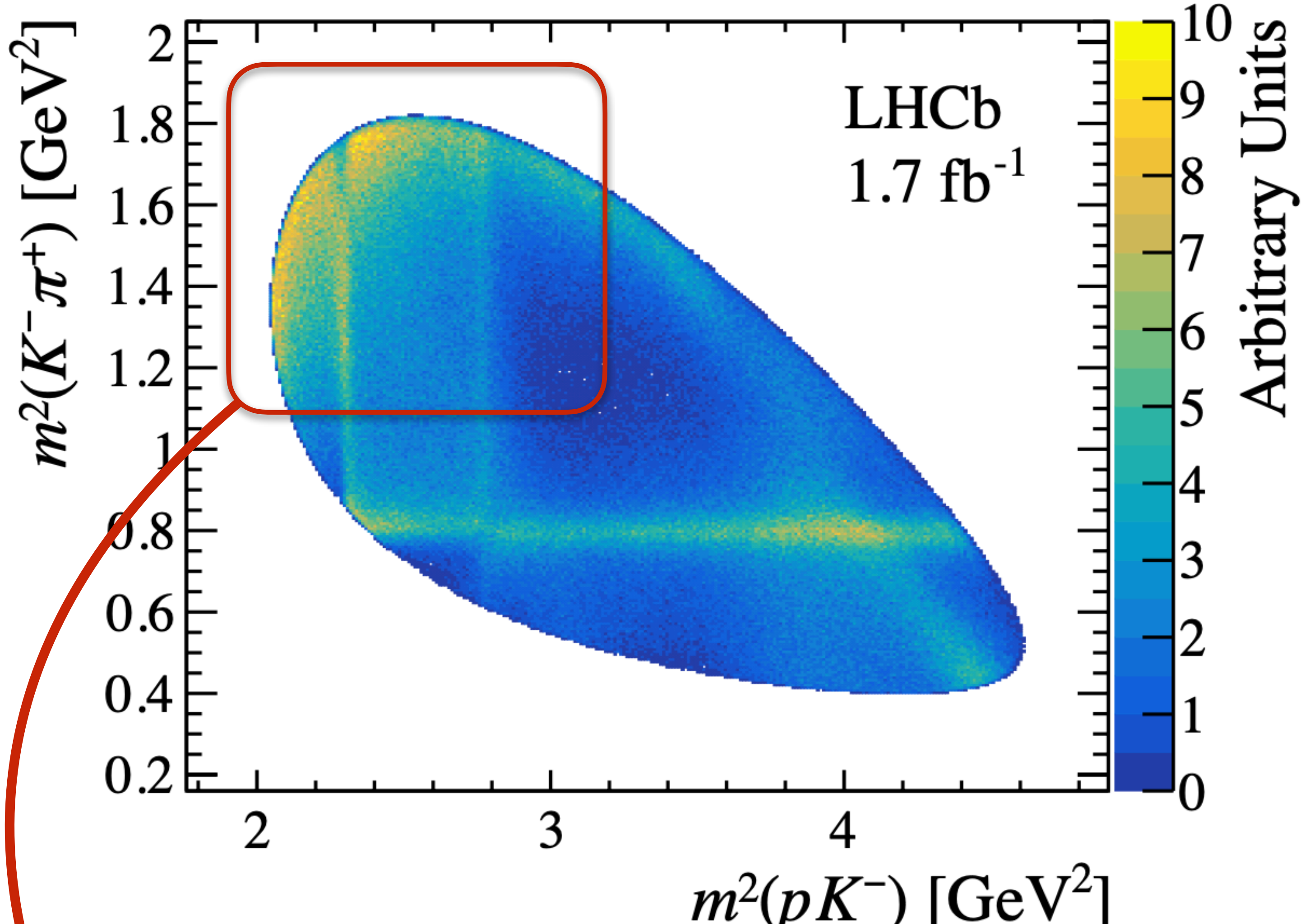


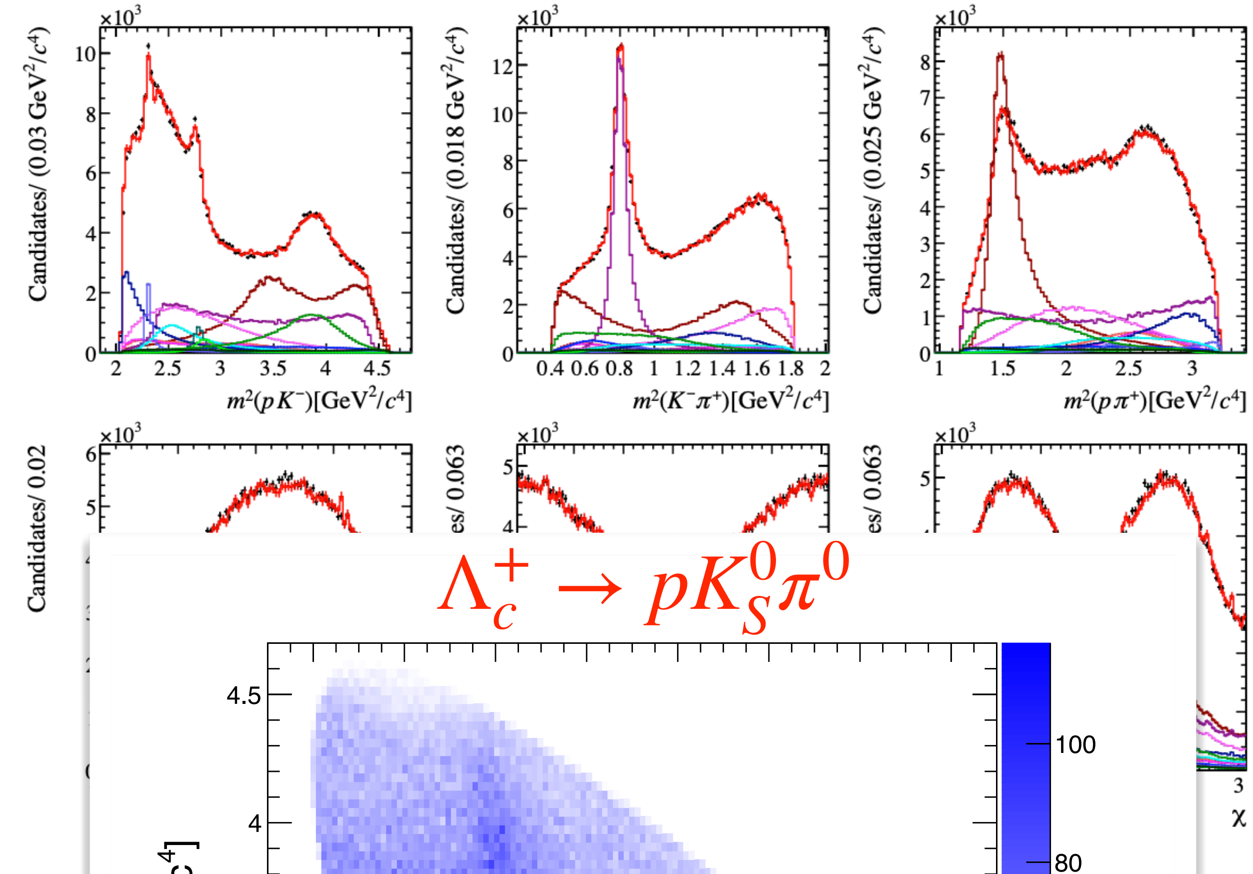


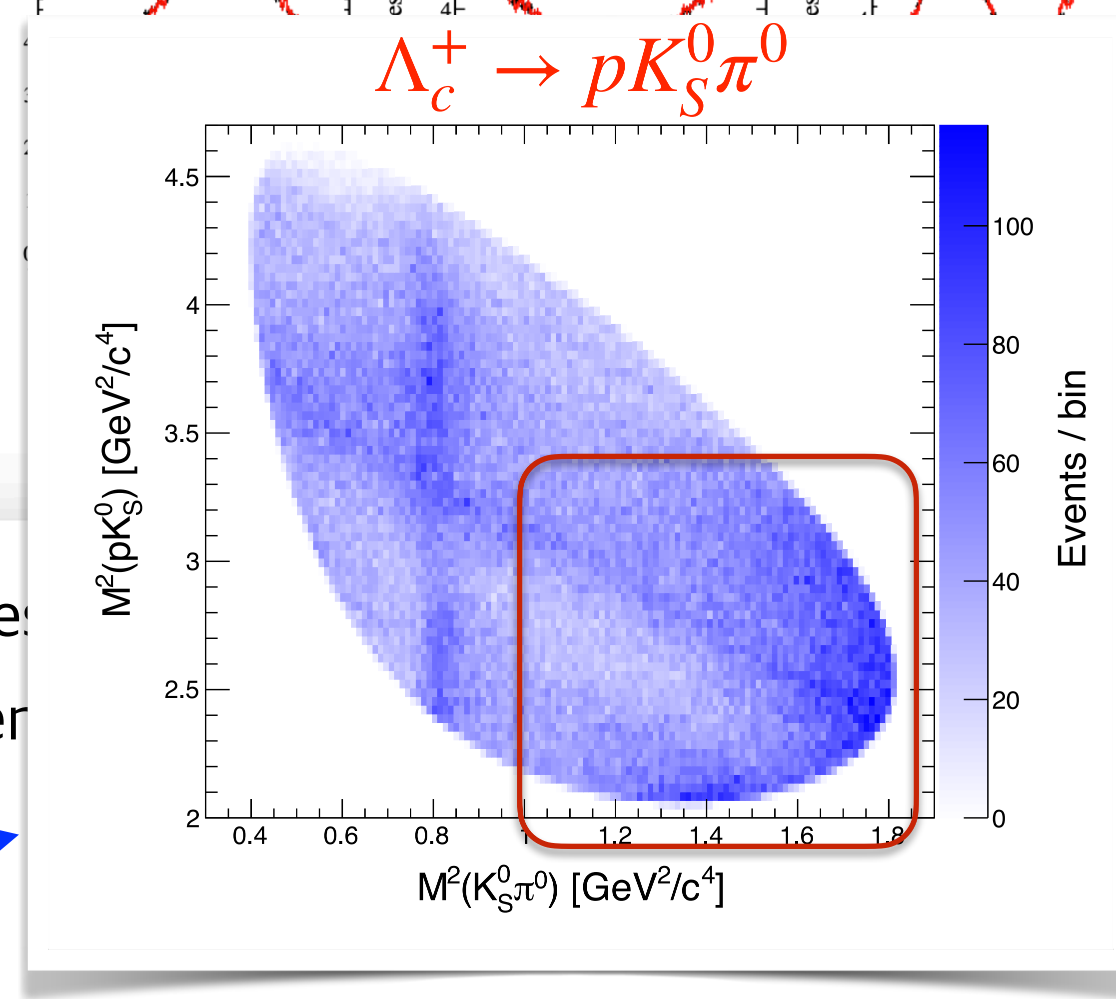
- 400k events of $\Lambda_c^+ \to pK^-\pi^+$ analyzed with 12 resonances using helicity formalism by LHCb
  - High mass $K^-\pi^+$ and low mass pK^- enhancements are explained by the tail parts of $K_0^*(1430)$ and $\Lambda(1405)$

Further analysis: Amplitude analysis

PRD **108**, 012023 (2023)







- 400k events of $\Lambda_c^+ \to pK^-\pi^+$ analyzed with 12 res
b
  - ➡ High mass $K^-\pi^+$ and low mass pK^- enhancemen
the tail parts of $K_0^*(1430)$ and $\Lambda(1405)$
  - ➡ Hint for the $\Lambda_c^+ \to pK_S^0\pi^0$ decay!
$K_0^*(1430)$ and $\Sigma(1385)$?

Summary

- We analyzed $\Lambda_c^+ \to pK_S^0\pi^0$ using the Belle 980/fb data sample.
  - ➡ 130k signal candidates (100 times larger statistics than current PDG)
- We report
  - $\Gamma(\Lambda_c^+ \to pK_S^0\pi^0)/\Gamma(\Lambda_c^+ \to pK^-\pi^+)$ = 0.339 ± 0.002(stat.) ± 0.009(syst.)
  - $\mathscr{B}(\Lambda_c^+ \to pK_S^0\pi^0)$ = 2.12 ± 0.01(stat.) ± 0.05(syst.) ± 0.10(norm.)
- Mass projection spectra (Intermediate resonances)
  - ➡ Absence of Σ^* in the pK_S^0
  - ➡ Possible $p\eta$ threshold cusp in the $p\pi^0$
- Amplitude analysis for the next step analysis
- Paper has been submitted to PRD.
  - ➡ You can find the paper at arXiv:2503.04371

Thank you