Study of Ξ^* and other Hyperons at Belle/Belle II

Mizuki Sumihama

Gifu University / Osaka University RCNP

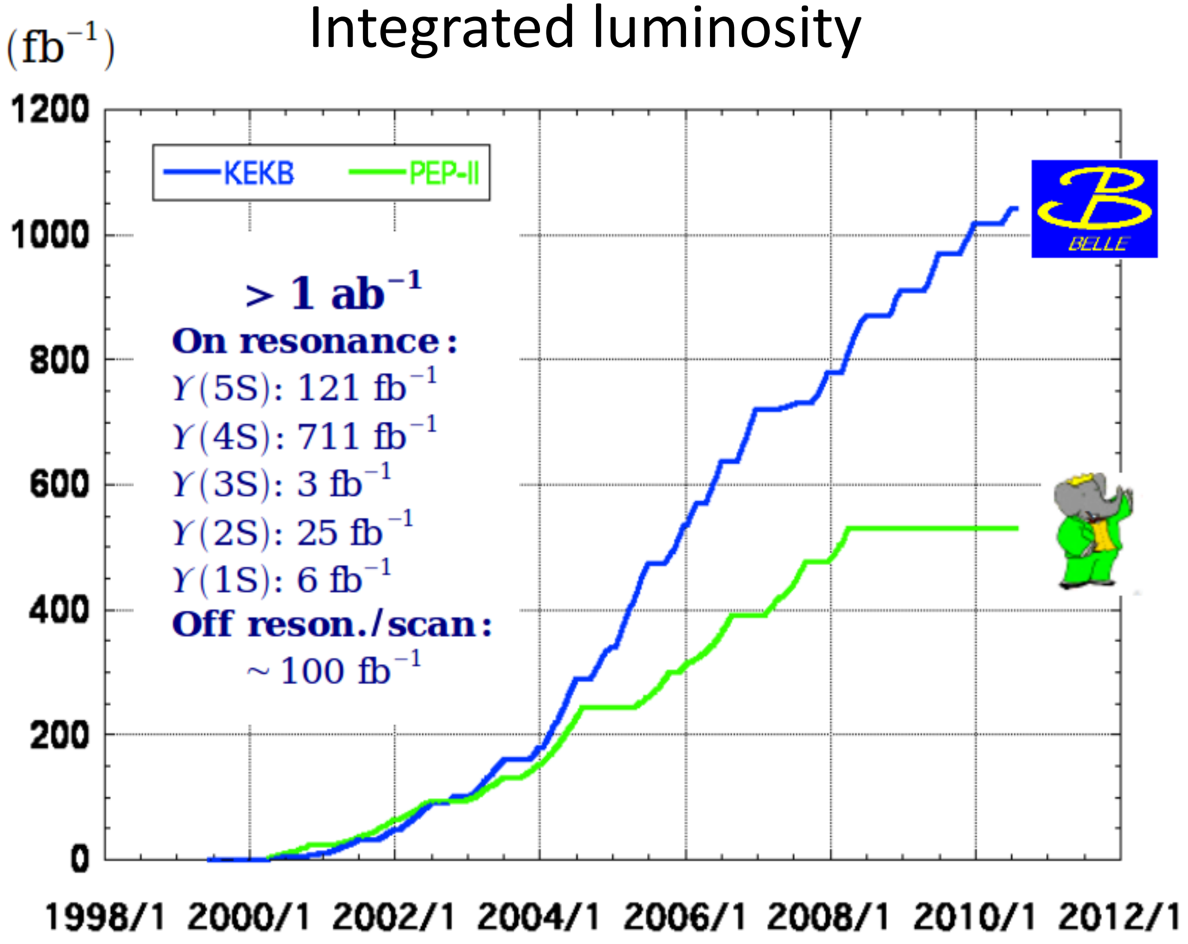
for the Belle/BelleII collaborations

1. Introduction to Belle and Belle II Experiments
2. Experimental Results of Ξ^* and $\Lambda_c(2625)^+$
3. Summary of the Talk

Belle experiment

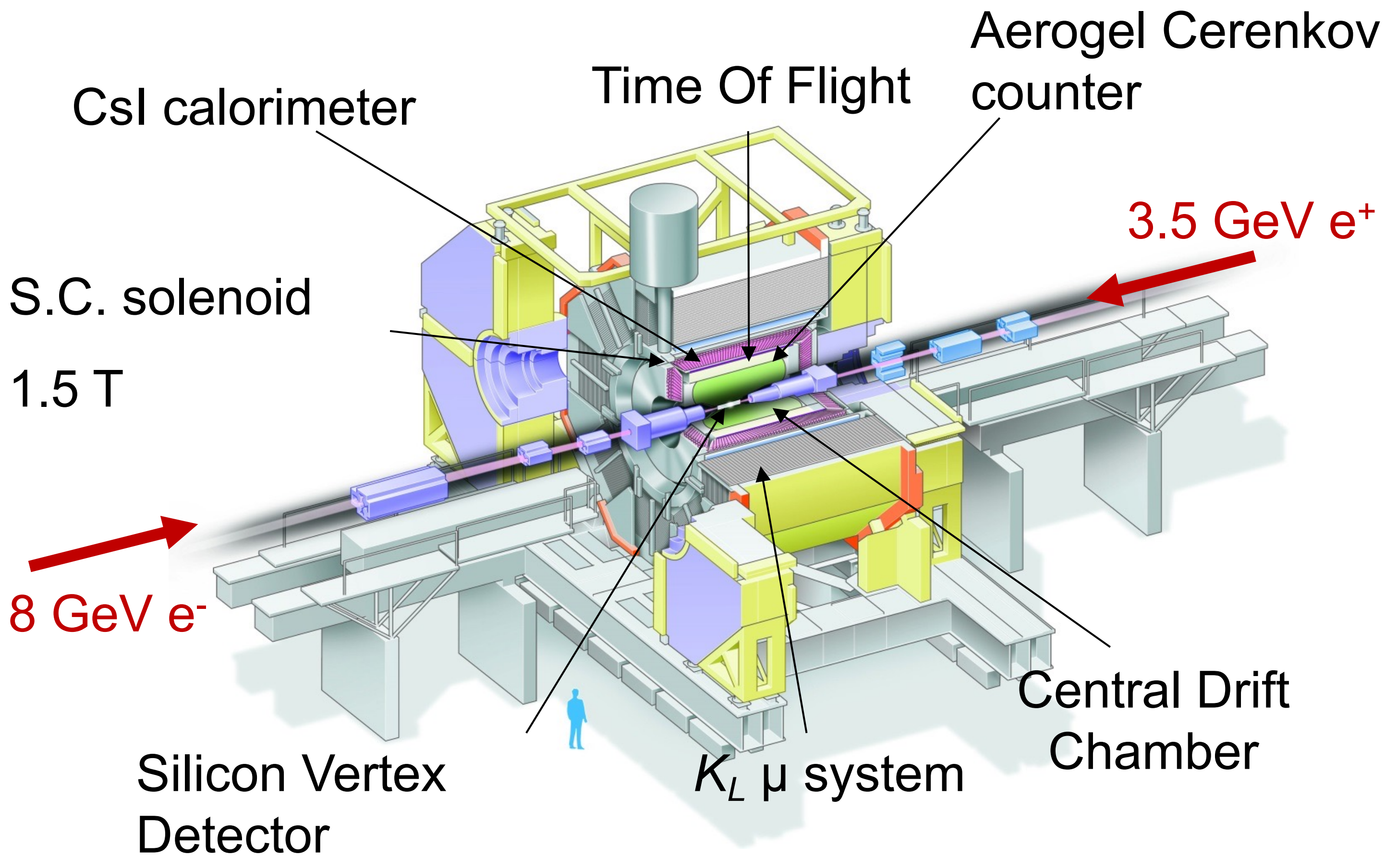
- Belle experiment is the experiment at KEK B factory with Belle detector dedicated for the CP violation physics of B mesons.
- Data acquisition was finished in June 2010 (running 1999-2010).
- $\sqrt{s}\sim 10.6\ GeV$
- $1\ ab^{-1}$ integrated luminosity
- A lot of hadrons → hadron physics

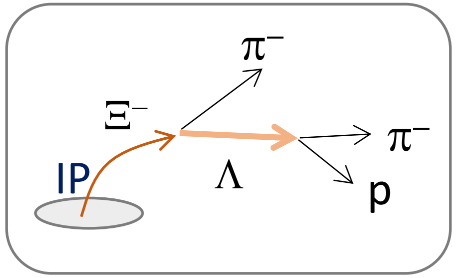
Integrated luminosity



Year

Belle detector





$c\tau_\Lambda = 7.98\ cm$
$c\tau_{\Xi^-} = 4.91\ cm$

Long lifetime

Detect charged particle($e^\pm\ \mu^\pm\ \pi^\pm\ K^\pm$ p) and γ

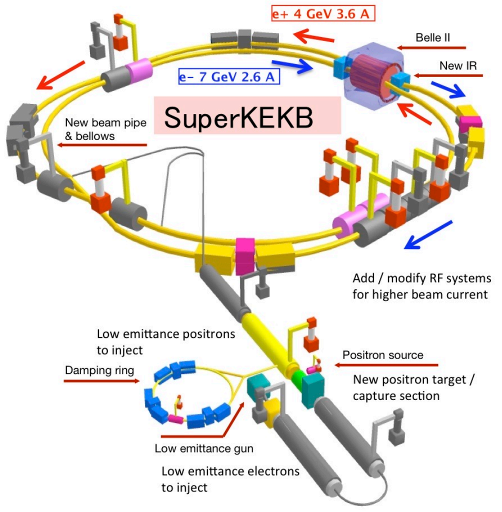
Belle → Belle II experiment

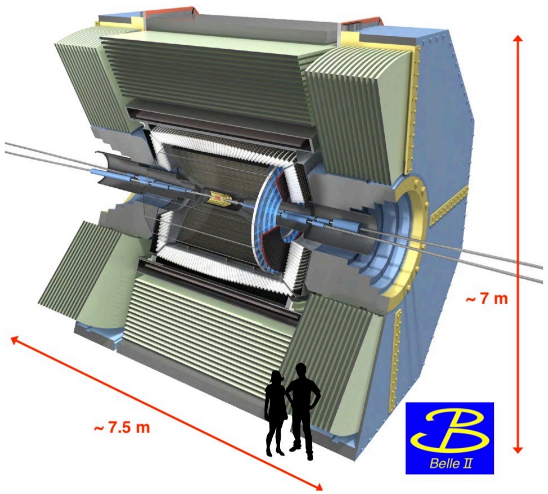
- Belle II experiment
  KEKB -> SuperKEKB (accelerator)
  Belle detector -> Belle II detector

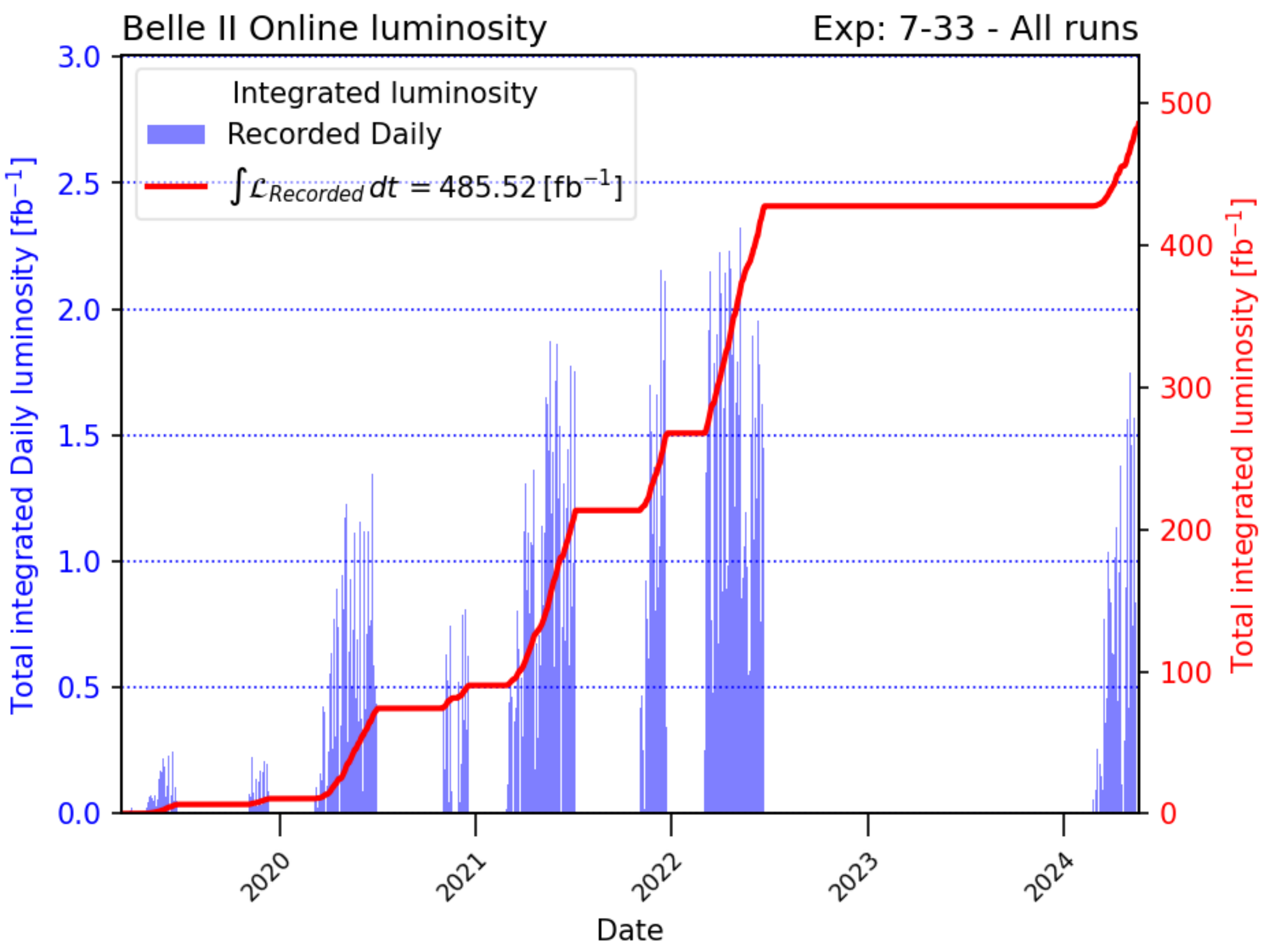
  aiming one order higher luminosity

- Belle II experiment is now running.

  Upgrades in all parts of the detector

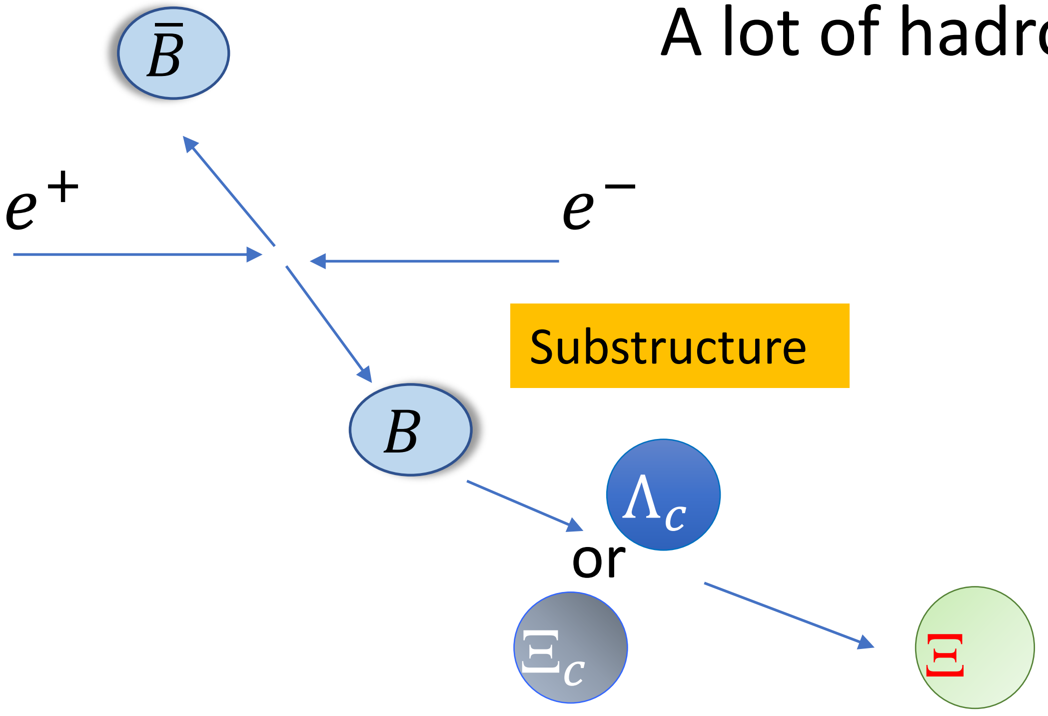


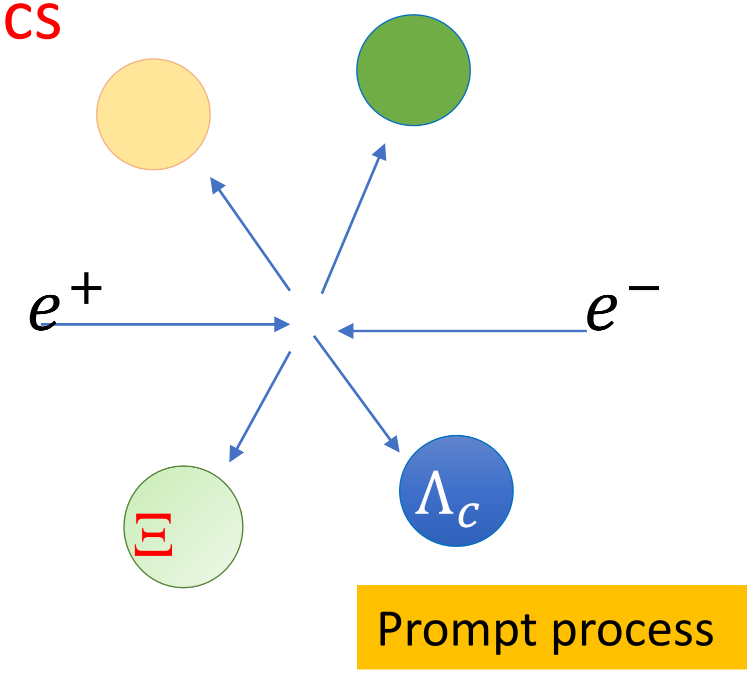




Belle/Belle II experiment

A lot of hadrons → hadron physics





Access to various production/decay processes.

Study charmed and strange baryons as resonant substructures in B meson decays or direct production from e^+e^- collisions.

Ξ^* and cusp structures in Λ_c^+ decay

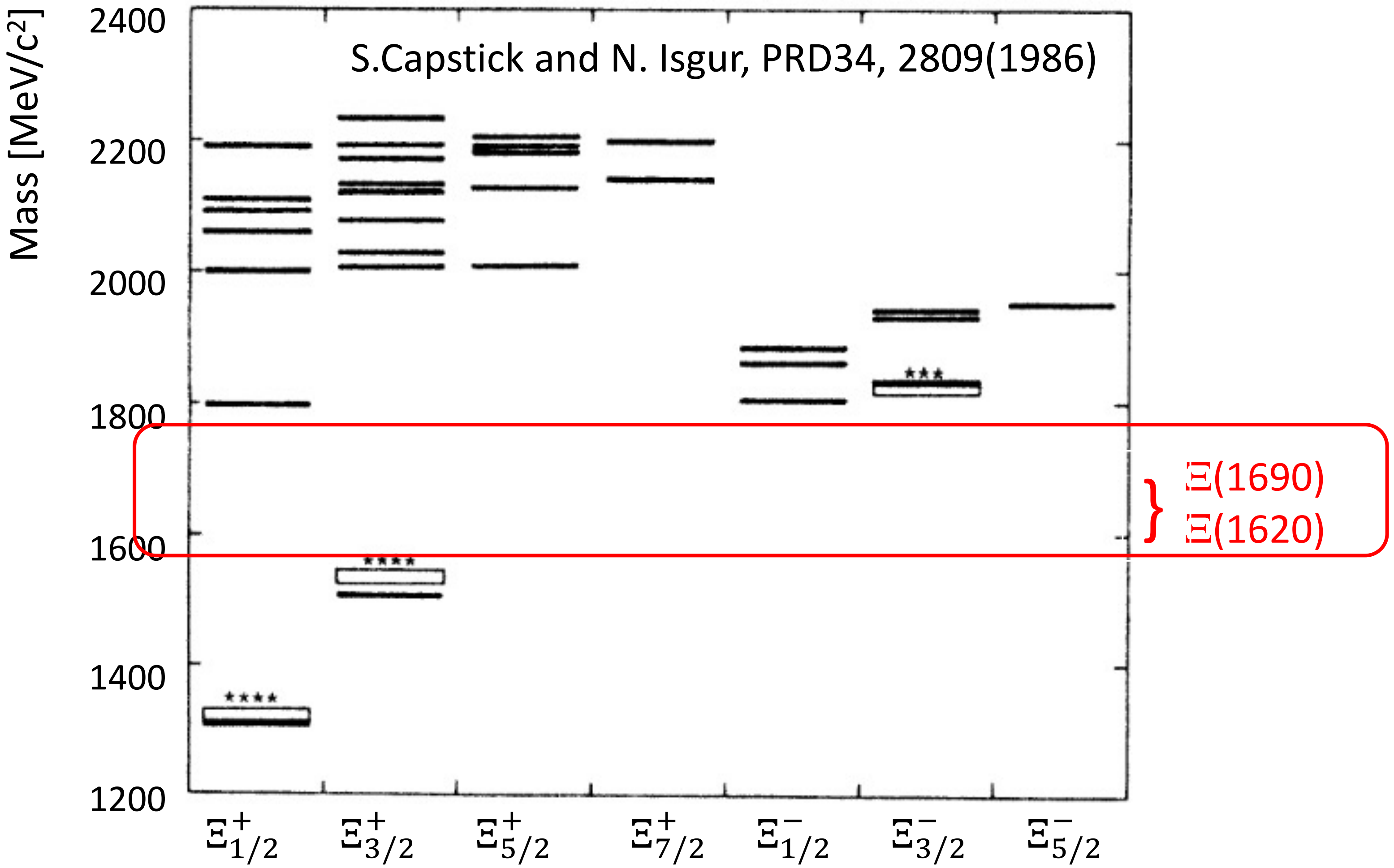
Physics motivation -Status of Ξ^*

Particle Data Group, Phys. Rev. D 110, 030001 (2024)

Particle	J^P	Overall status	$\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
$\Xi(1318)$	1/2+	****					Decays weakly
$\Xi(1530)$	3/2+	****	****				
$\Xi(1620)$		**	**				
$\Xi(1690)$		***	**	***	**		
$\Xi(1820)$	3/2−	***	**	***	**	**	
$\Xi(1950)$		***	**	**		*	
$\Xi(2030)$		***		**	***		
$\Xi(2120)$		*		*			
$\Xi(2250)$		**					3-body decays
$\Xi(2370)$		**					3-body decays
$\Xi(2500)$							3-body decays

- First excited states with ½+, ½ - are not identified.
- Important test of our understanding
- Analog of $\Lambda(1405)$ with ½-
- $\Xi(1620)/\Xi(1690)$ are candidates for $½^-$, $½^+$
  → Inconsistent with constituent quark model

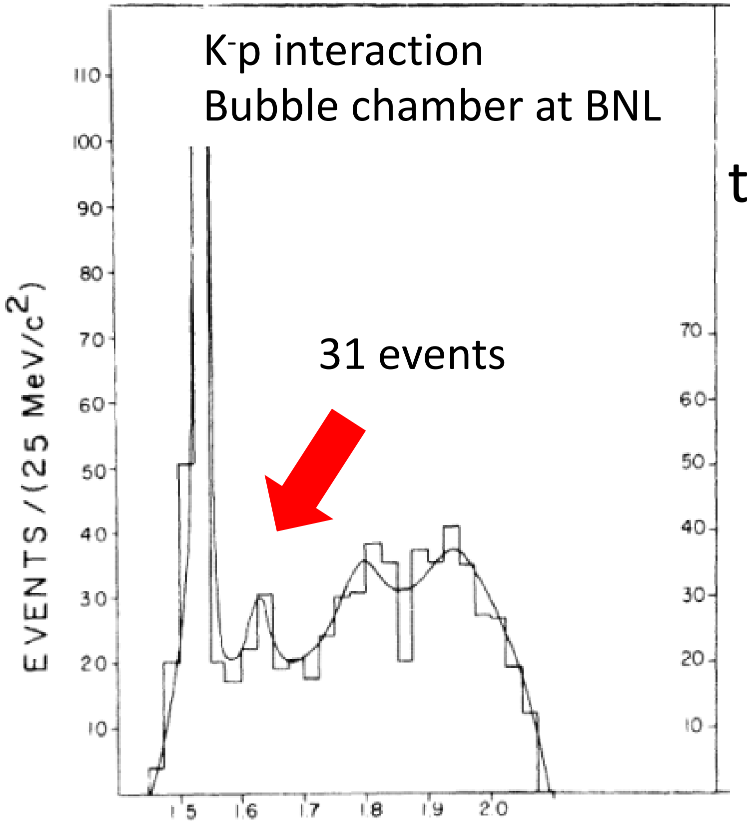
Prediction by constituent QM



- Predicted first excited state in constituent quark model is around 1800 MeV.
- Controversy regarding the theoretical interpretation of Ξ(1690) and Ξ(1620)

Previous experiments on $\Xi(1620)^0/\Xi(1690)^0$

$\Xi(1620)^0$



M(Ξπ)

E. Briefel *et al*. PRD16 2706(1977)

$\Xi(1620)^*$

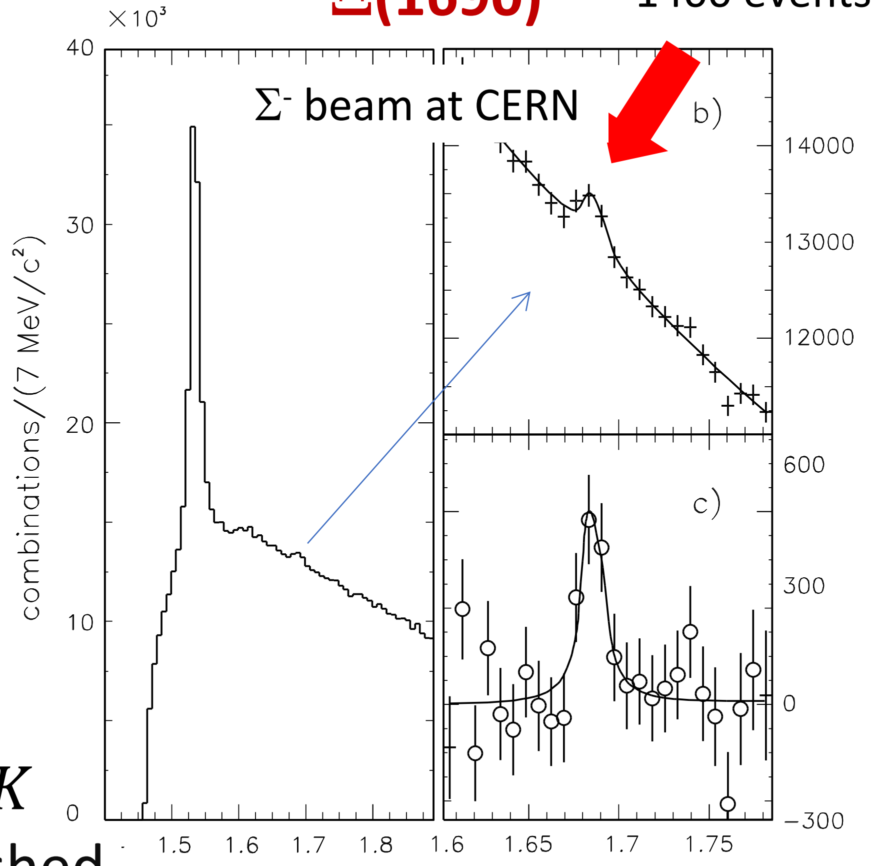
the limited statistics

$\Xi(1690)$ ***

Seen in $\Xi\pi, \Lambda K, \Sigma K$

fairly well-established.

$\Xi(1690)^0$ 1400 events



M(Ξπ)

M.I. Adamovich *et al.* EPJ C5 621 (1998)
WA89 collaboration

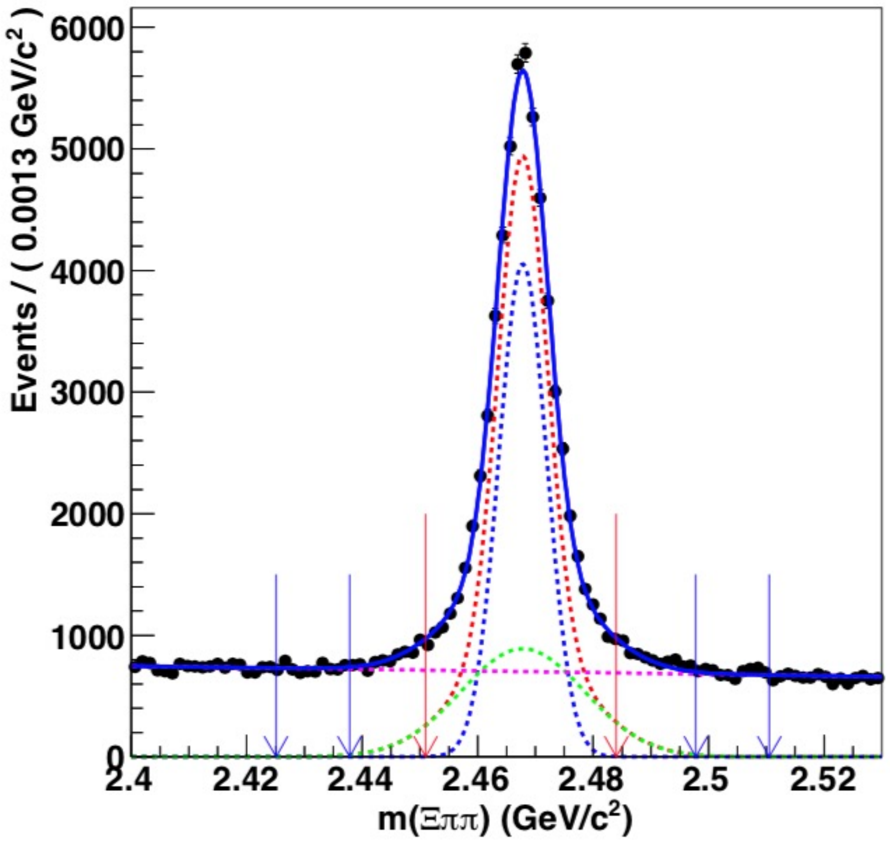
$\Xi(1620)/\Xi(1690)$ in $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ at Belle

PhysRevLett.122.072501

Ξ^{*0} in $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ at Belle experiment

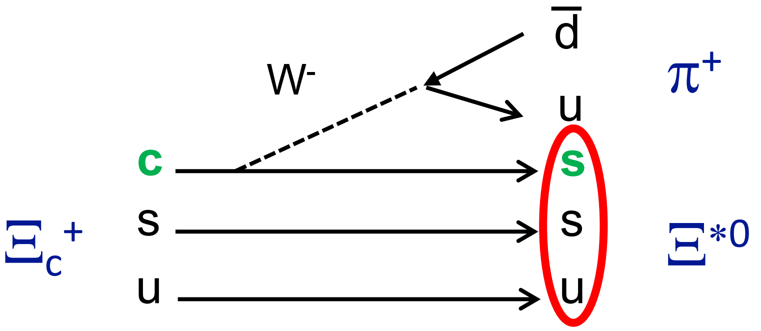
Ξ_c^+

~50,000 events



Charmed baryons have an advantage in finding strange baryons as a substructure in the weak decay of charmed baryons.

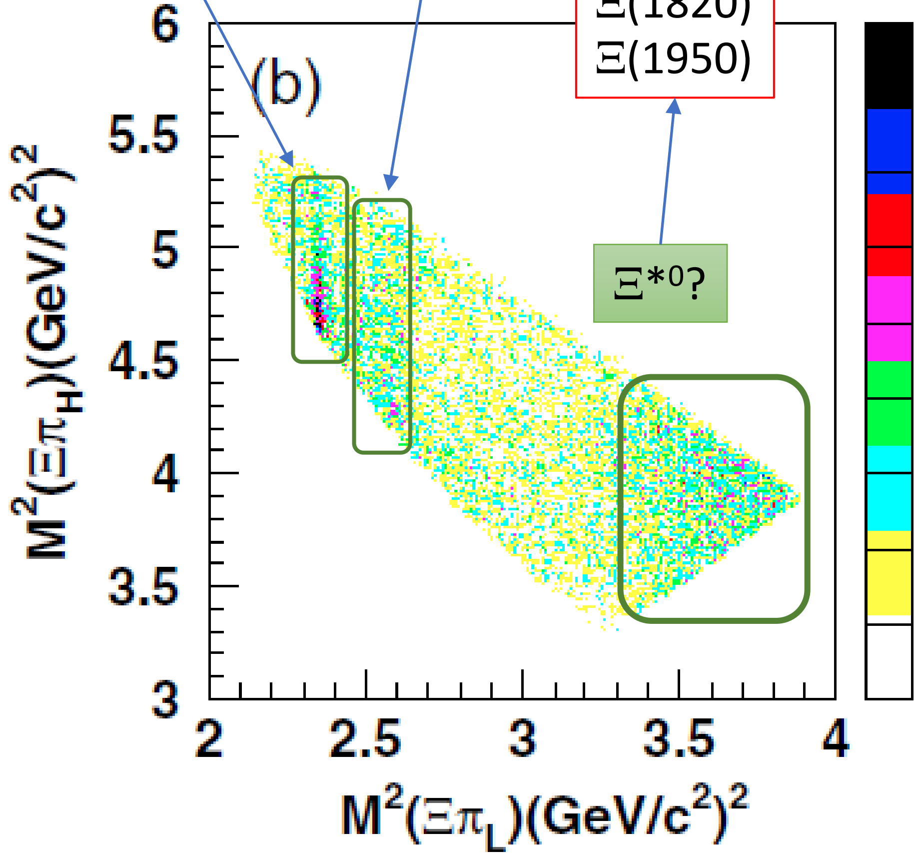
All data sample, 980 fb^{-1}

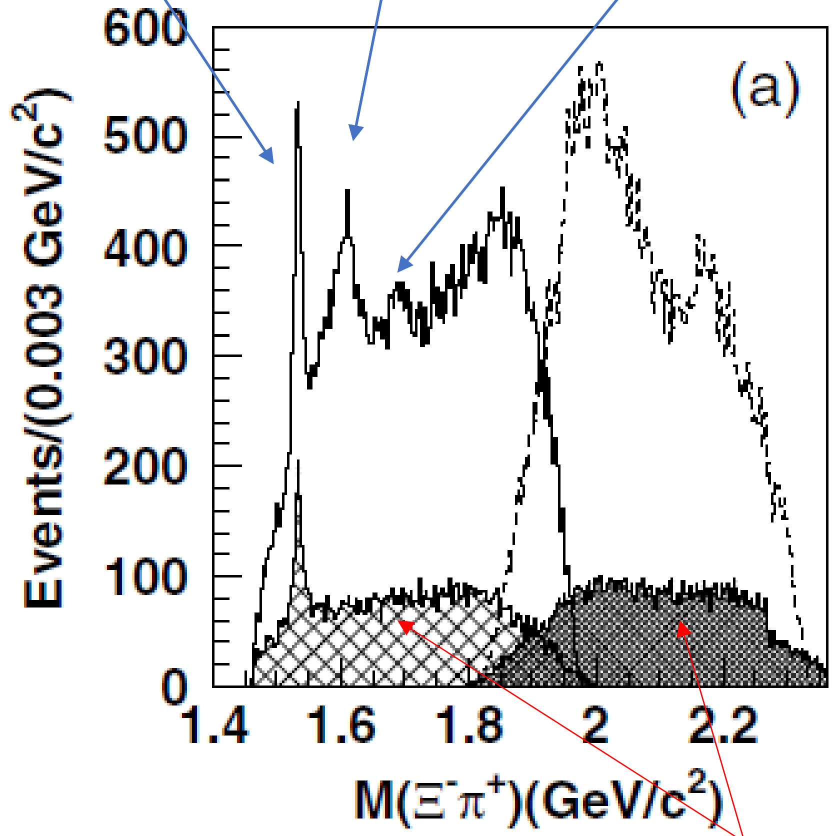


$$\Xi_c^+ \rightarrow \Xi^{*0}\pi^+$$
$$\rightarrow \Xi^-\pi^+\pi^+$$
$$\rightarrow \Lambda\pi^-\pi^+\pi^+$$
$$\rightarrow p\pi^-\pi^-\pi^+\pi^+$$

The best condition due to a good efficiency and momentum resolution of charged particles

Dalitz plot and M($\Xi^-\pi^+$) of $\Xi_c^+ \rightarrow \Xi^-\pi_L^+\pi_H^+$

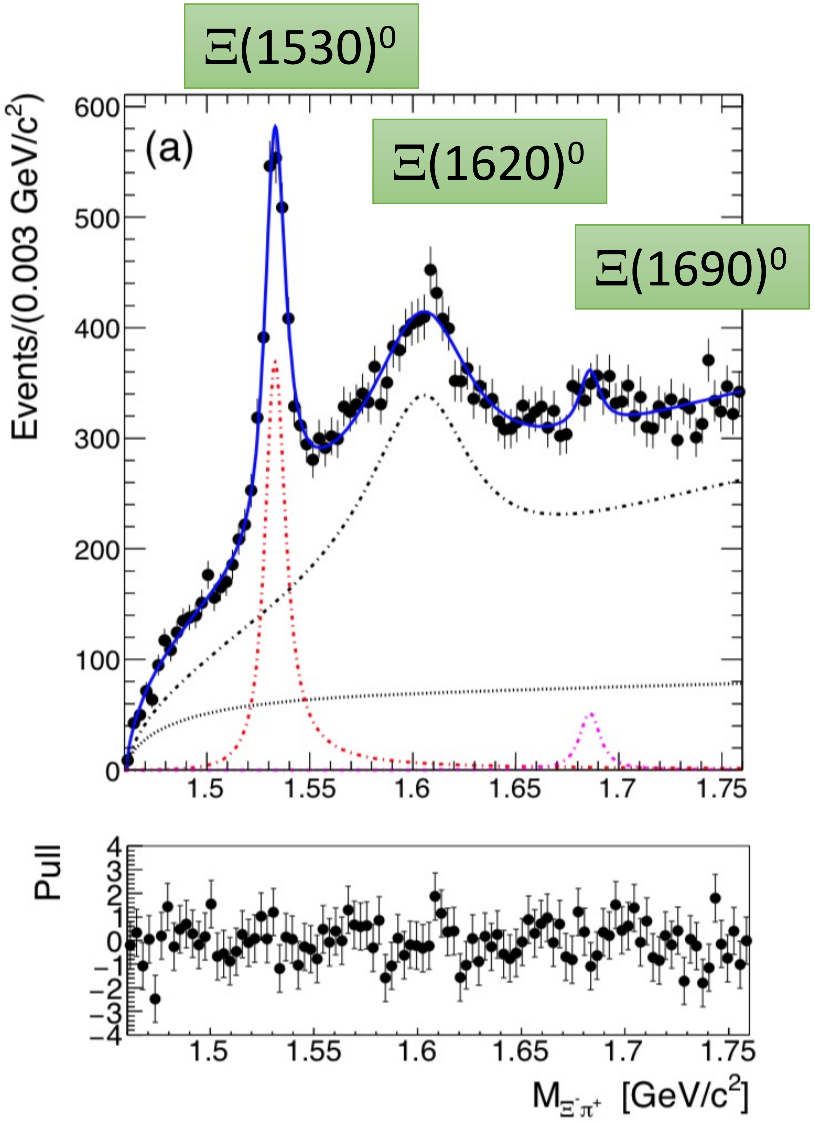




No prompt process?

Ξ_c^+ sideband events

Invariant mass spectrum $\Xi^- \pi_L^+$



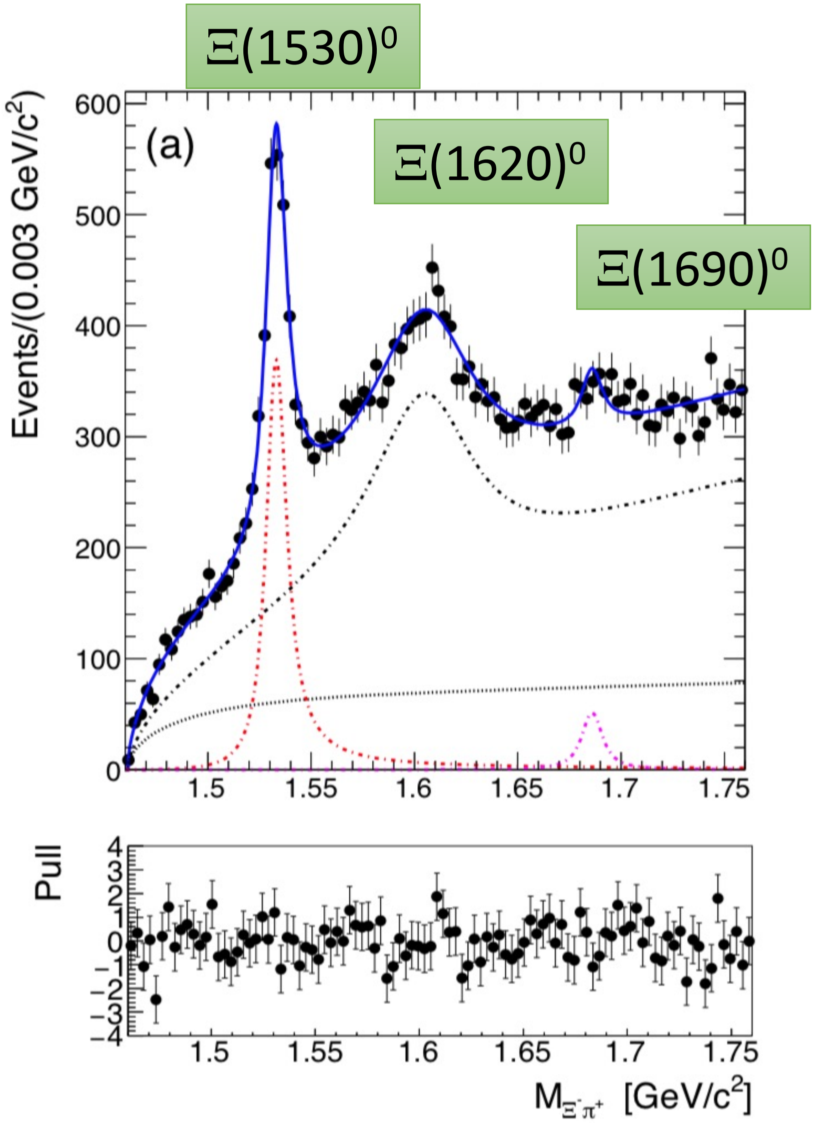
Determination of mass and width of $\Xi(1620)^0$

✓ Fitting function:

- Ξ(1530) -relativistic P-wave Breit-Wigner
- Ξ(1620) -relativistic S-wave Breit-Wigner convoluted with Gaussian
- Ξ(1690) -relativistic S-wave Breit-Wigner convoluted with Gaussian (fixed mass/width)
- Nonresonant- S-wave 3 body decay (phase space)
- Combinatorial background (sideband events)

Interference between Ξ(1620) and nonresonant

Invariant mass spectrum $\Xi^- \pi_L^+$

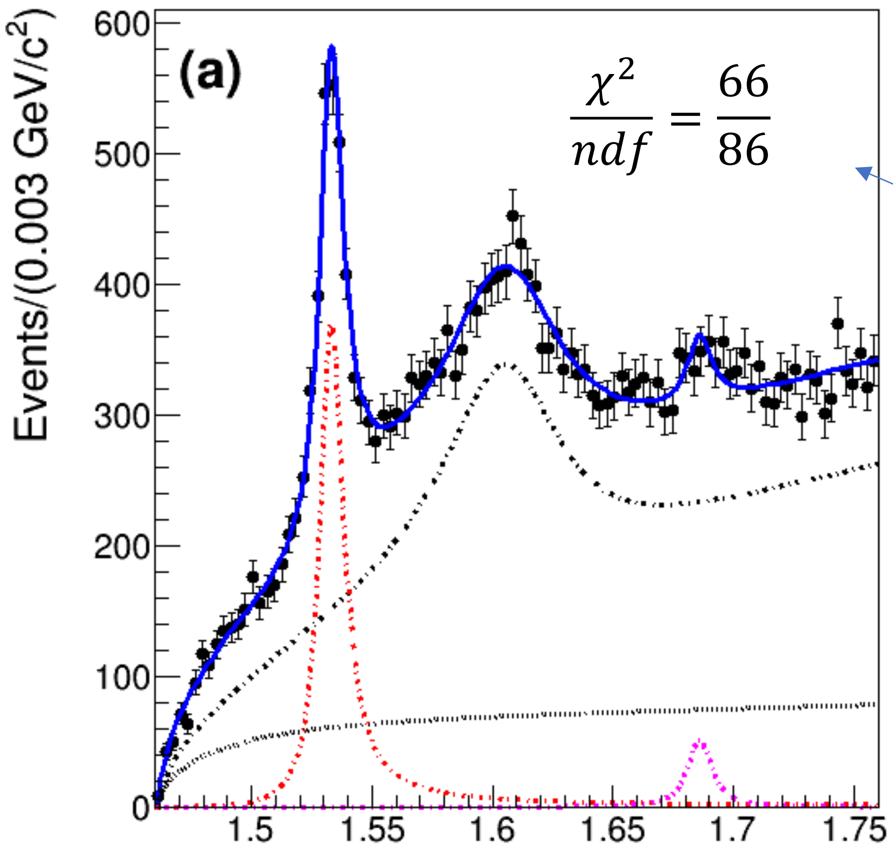


Determination of mass and width of Ξ(1620)⁰

- Mass:
  $1610.4 \pm 6.0(stat.)^{+6.1}_{-4.2}(syst.)\ MeV/c^2$
- Width:
  $59.9 \pm 4.8(stat.)^{+2.8}_{-7.1}(syst.)\ MeV$
  - ✓ Consistent with previous experiments
  - ✓ Much more precise
  - ✓ Large width
- Significance
  25σ for $\Xi(1620)^0$, 4.0σ for $\Xi(1690)^0$

Asymmetric shape of mass peak

w/ interference
between $\Xi(1620)$ *and* s-wave nonresonant

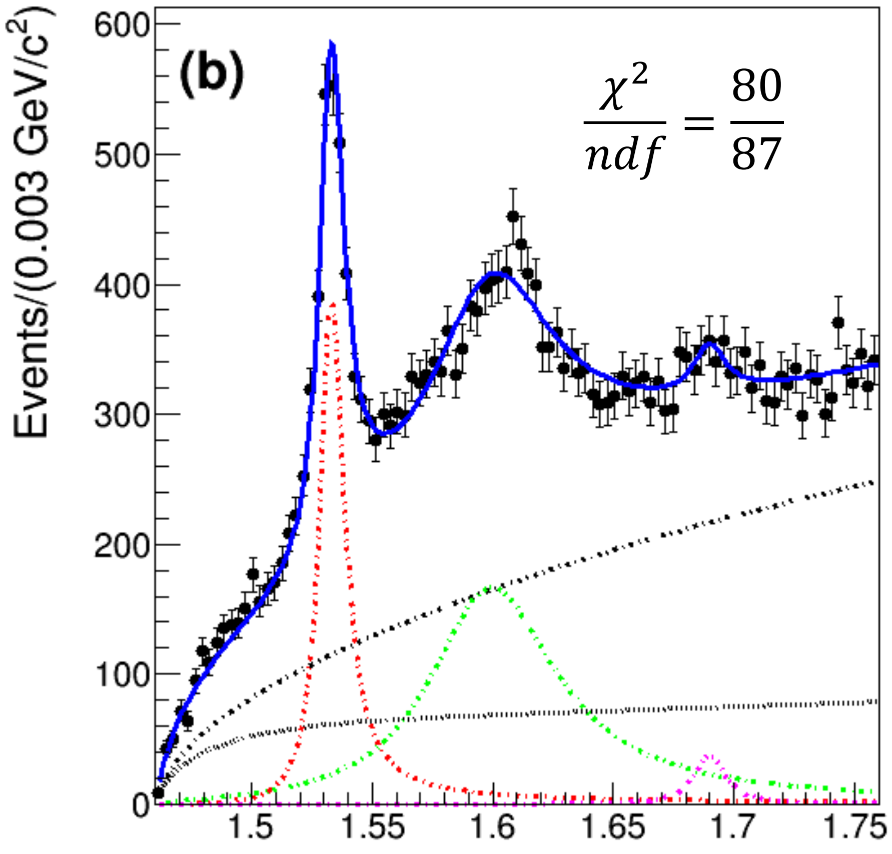


$$\frac{\chi^2}{ndf} = \frac{66}{86}$$

$M(\Xi^-\pi^+)\ GeV/c^2$

Better fit

w/o interference

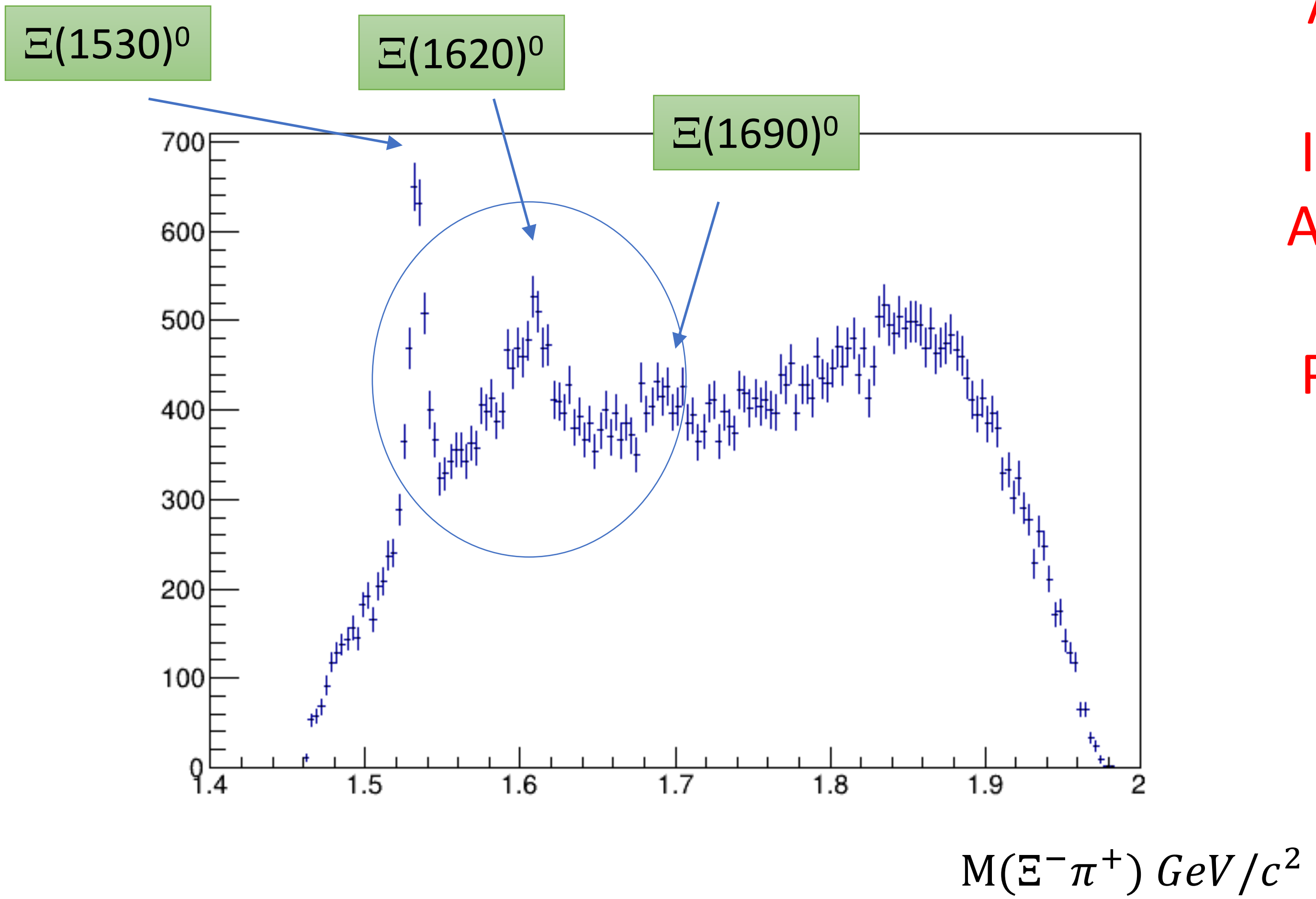


$$\frac{\chi^2}{ndf} = \frac{80}{87}$$

$M(\Xi^-\pi^+)\ GeV/c^2$

Is this a resonance?

Is interference the best explanation for the asymmetric shape?



"Asymmetric shape"

Interference?

Another possibility?

Peak is near $K\Lambda$ threshold.

$1620 \sim M(K\Lambda)$

Resonance or cusp?

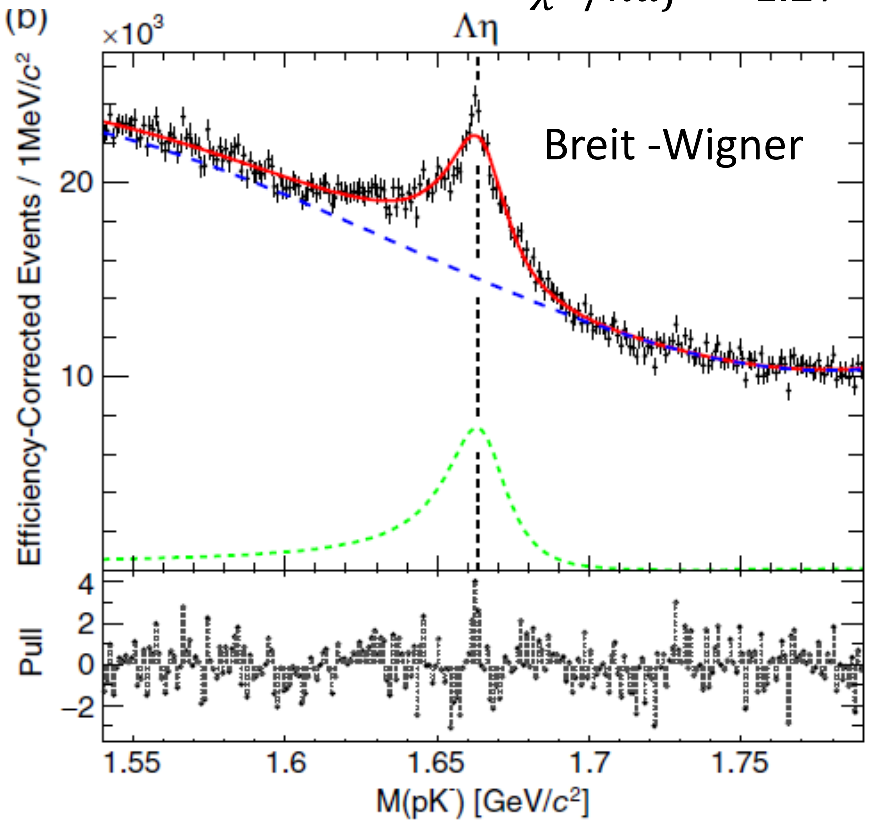
PHYS. REV. D 108, L031104 (2023)

Peak at $\Lambda\eta$ threshold in pK^- of $\Lambda_c^+ \to pK^-\pi^+$

All data sample, 980 fb^{-1}

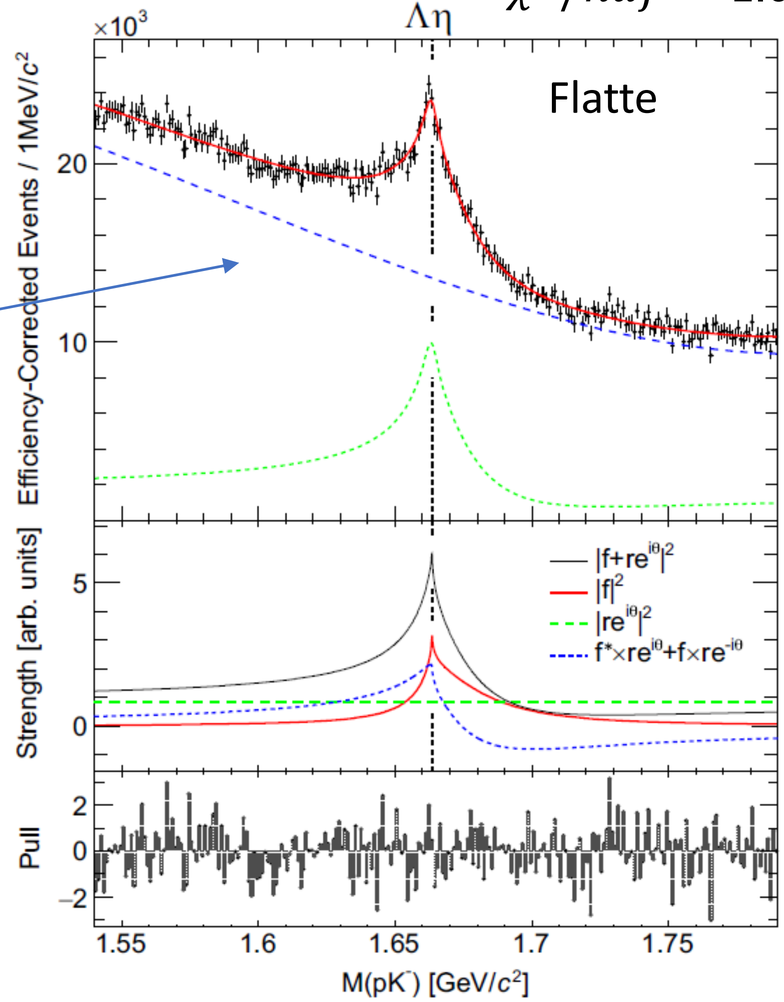
Breit-Wigner as Resonance

$\chi^2/ndf = 1.27$



Flatte function as Cusp

$\chi^2/ndf = 1.06$



Best fit

Threshold cusp

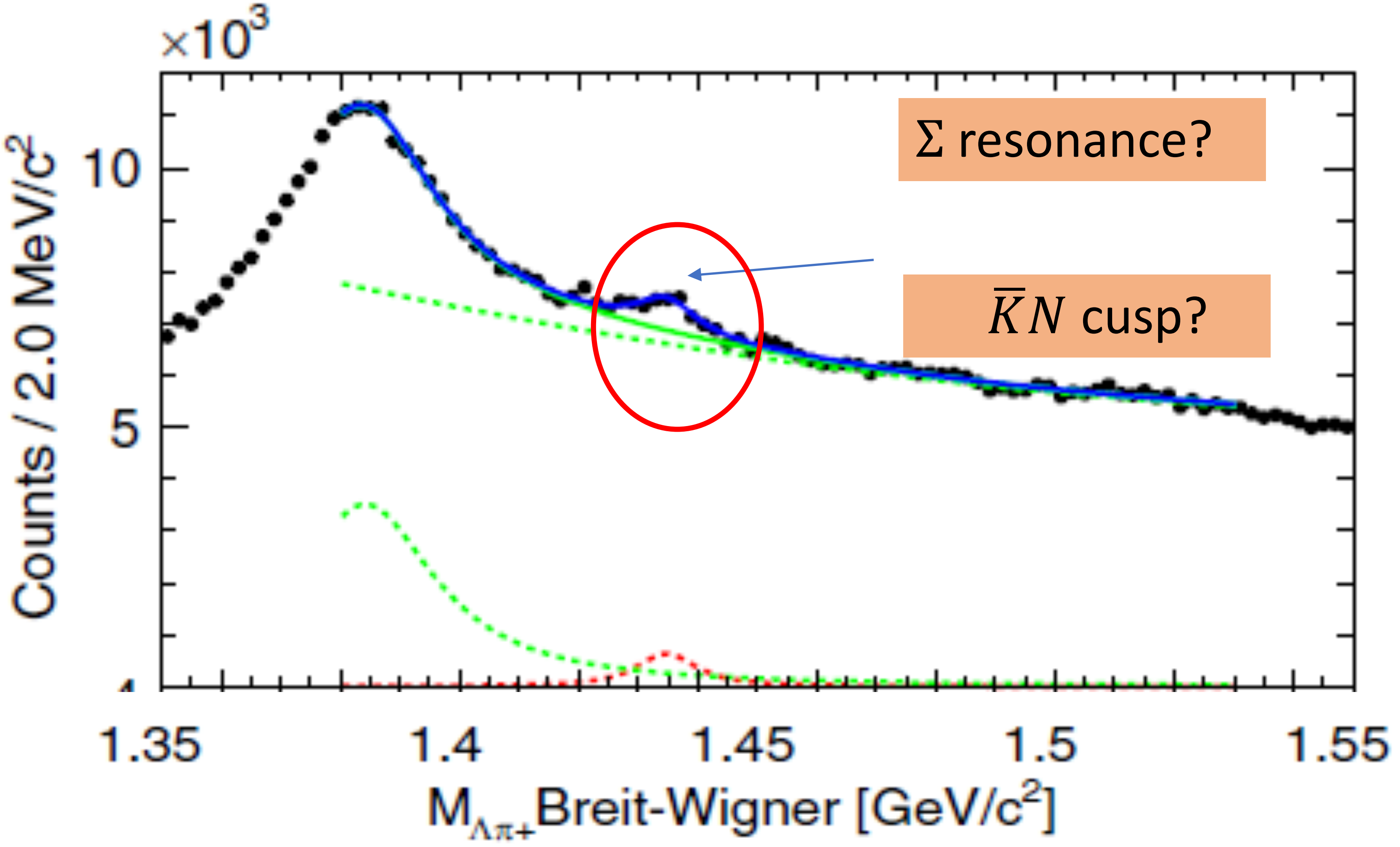
Flatte function

PHYSICAL REVIEW LETTERS 130, 151903 (2023)

Signal in $M(\Lambda\pi^{\pm})$ in $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$

All data sample, 980 fb^{-1}

$\Lambda_c^+ \to \Sigma^*\pi^+\pi^-$

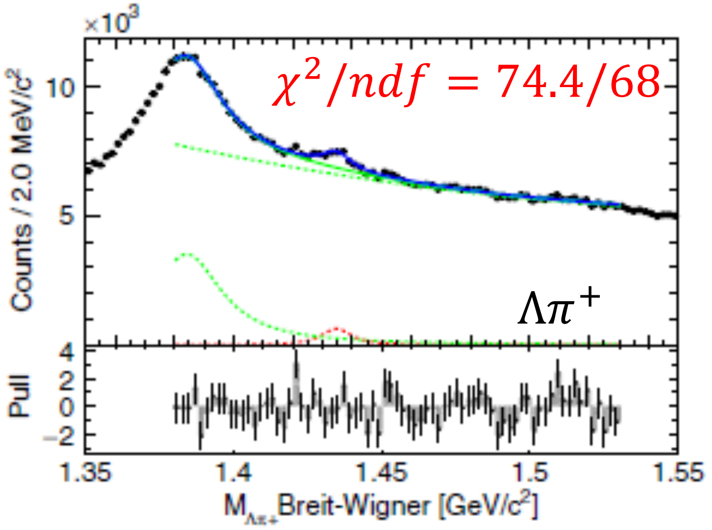


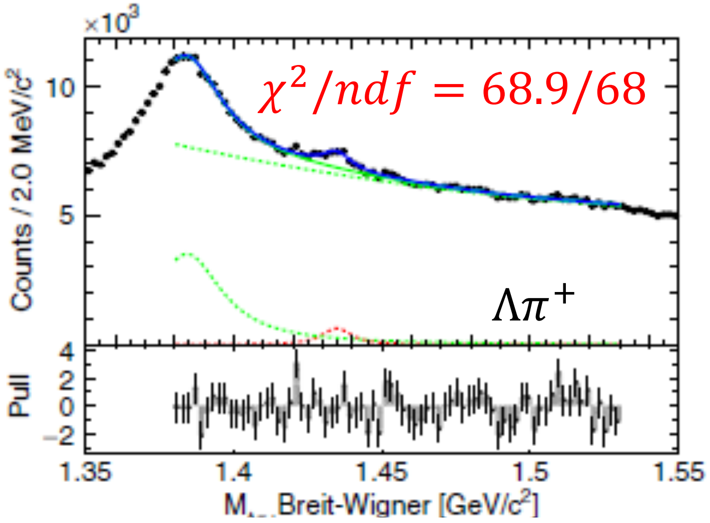
Test
with Breit-wigner function
and

with Dalitz model

PHYSICAL REVIEW LETTERS 130, 151903 (2023)

Signal in $M(\Lambda\pi^{\pm})$ in $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$

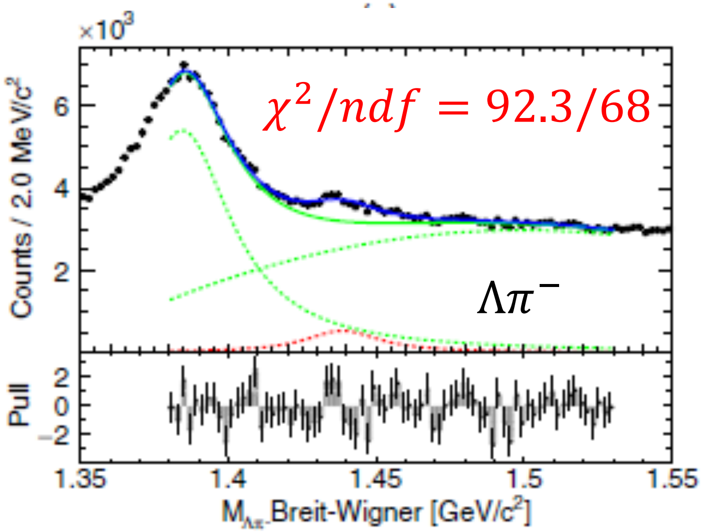


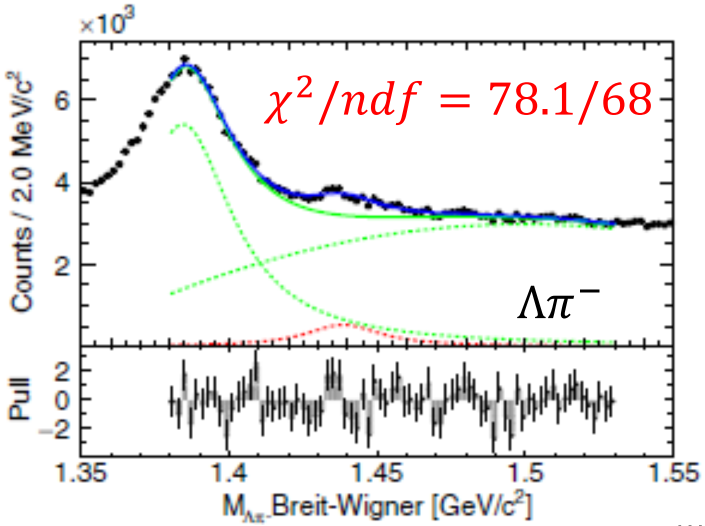


Σ resonance

$\bar{K}N$ cusp

Not discriminate





Theoretical calculations

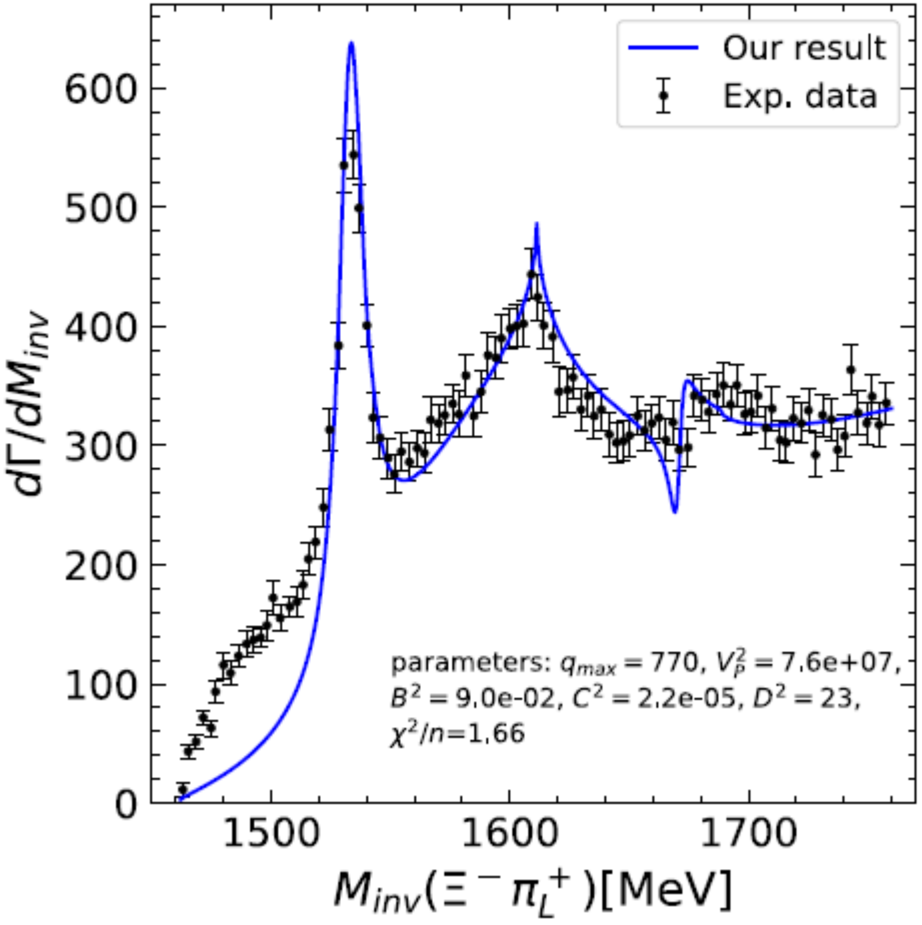
Eur. Phys. J. C (2023) 83:954

Some studies can generate both Ξ(1620) and Ξ(1690).

These two resonances are generated dynamically from the interaction in coupled channels of $\pi\Xi, \overline{K}\Lambda, \overline{K}\Sigma, \eta\Xi$ within the chiral unitary approach.

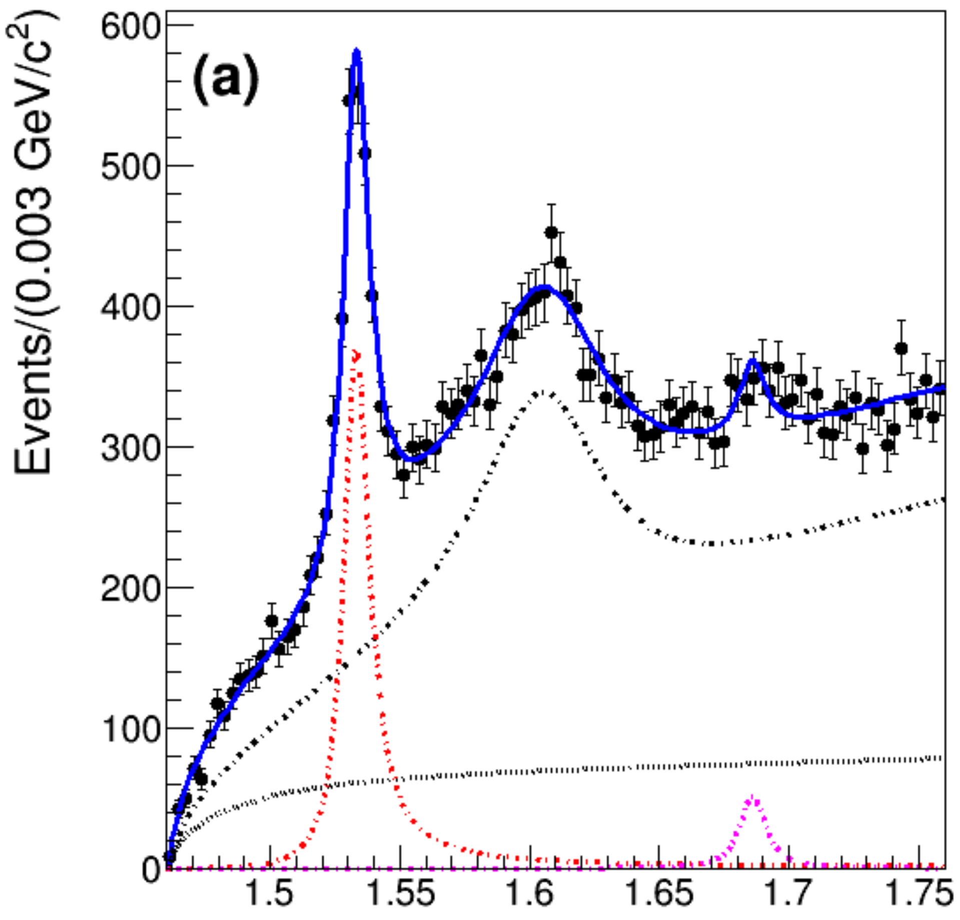
Some studies mention the $\overline{K}N$ threshold effect.

The threshold cusp effect can distort the mass distribution and should be taken into account to determine the pole position.



PhysRevLett.122.072501

$M(\Xi^-\pi^+)$ in $\Xi_c^+ \to \Xi^-\pi_L^+\pi_H^+$



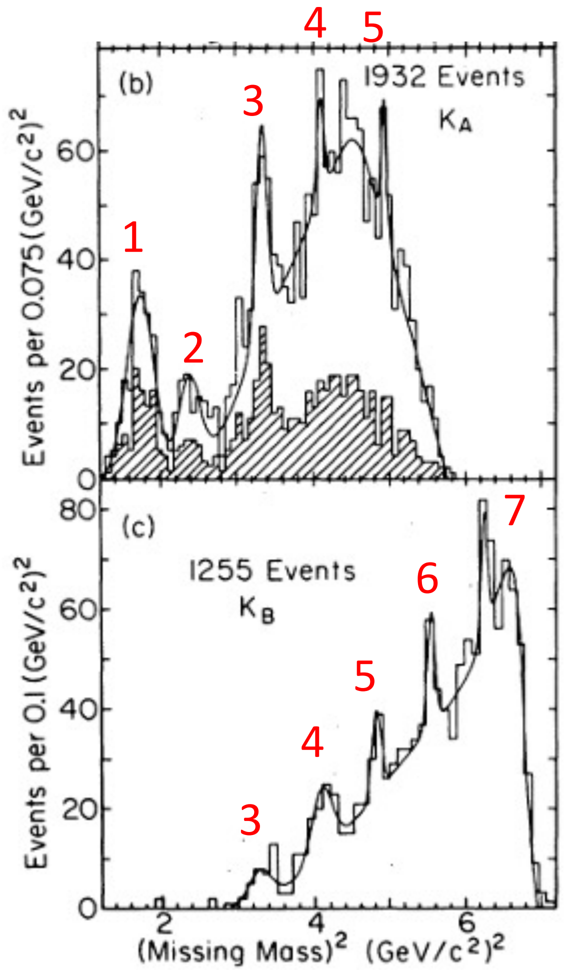
$M(\Xi^-\pi^+)\ GeV/c^2$

Asymmetric shape
➔ We need further study
Including a threshold cusp.

Ξ^* in missing mass

PRL 51.951 (1983) BNL

$K^- p \rightarrow K^+ X$

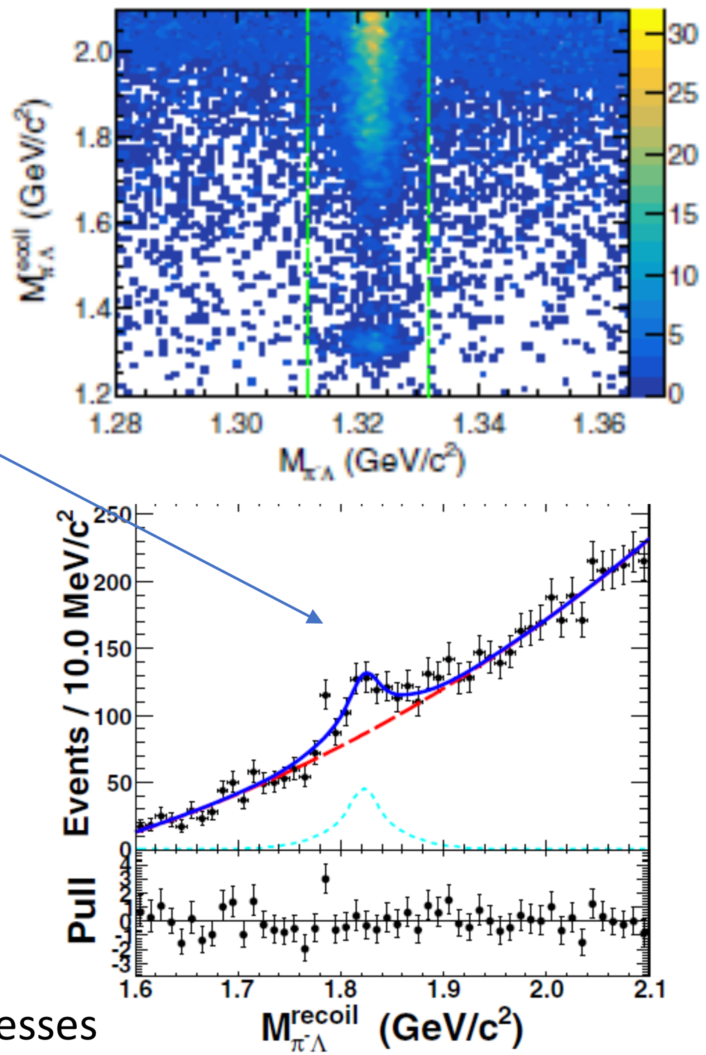


	Particle	J^P	Overall status
1	$\Xi(1318)$	$1/2+$	****
2	$\Xi(1530)$	$3/2+$	****
➡	$\Xi(1620)$		**
➡	$\Xi(1690)$		***
3	$\Xi(1820)$	$3/2-$	***
➡	$\Xi(1950)$		***
4	$\Xi(2030)$		***
➡	$\Xi(2120)$		*
5	$\Xi(2250)$		**
6	$\Xi(2370)$		**
7	$\Xi(2500)$		*

Missing??
Broad width / low statistics

PRL 124,032002(2020) BESIII

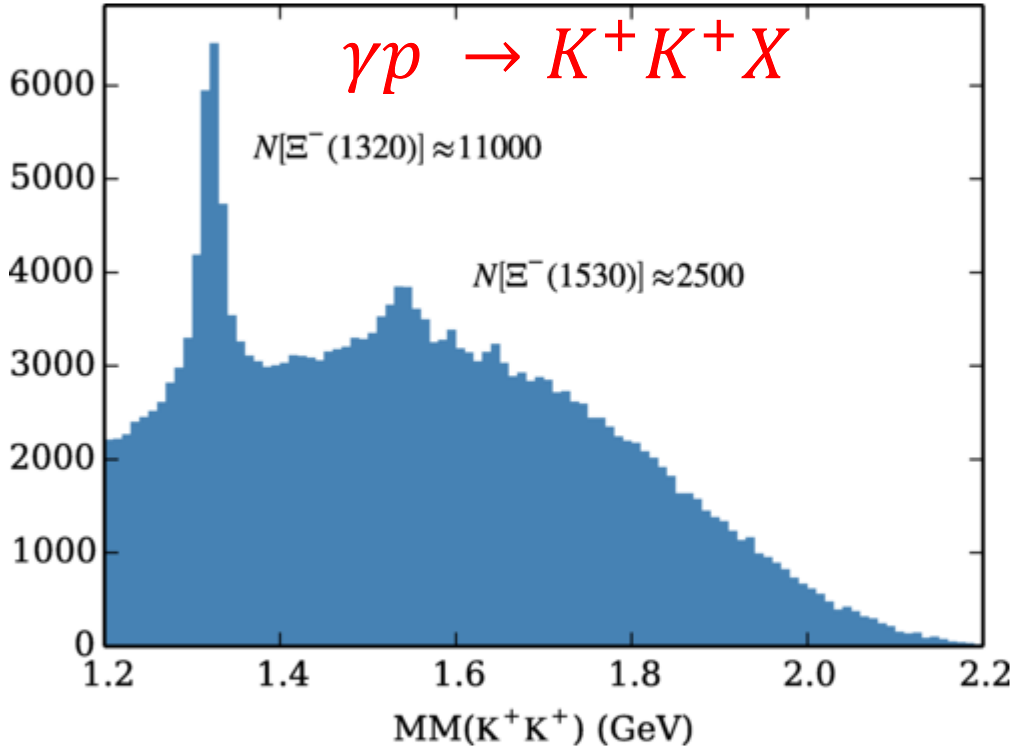
$e^+ e^- \rightarrow \Xi^- \bar{\Xi}^+$



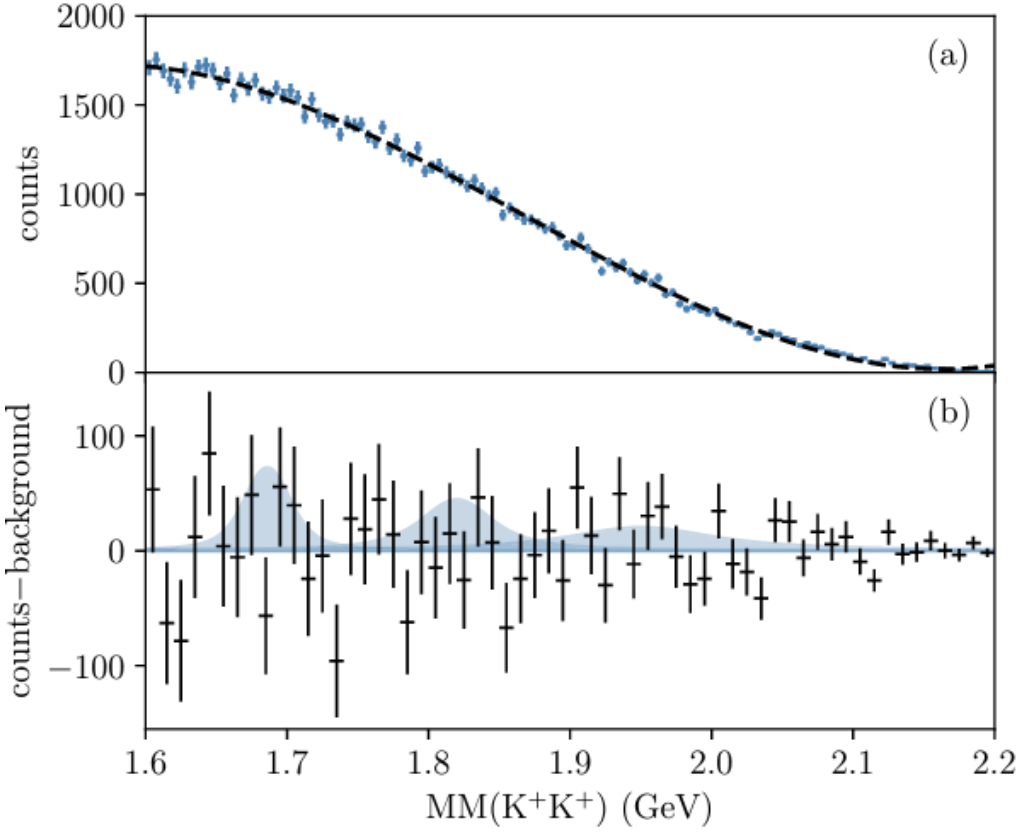
Some resonances might select specific production processes

PRC 98 062201(R)(2018)

Missing mass of photoproduction from CLAS



No evidence for higher mass resonances



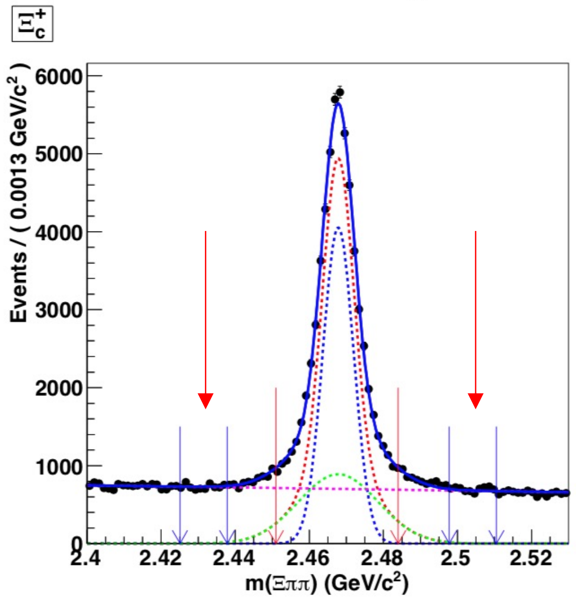
No evidence for higher mass Ξ^*

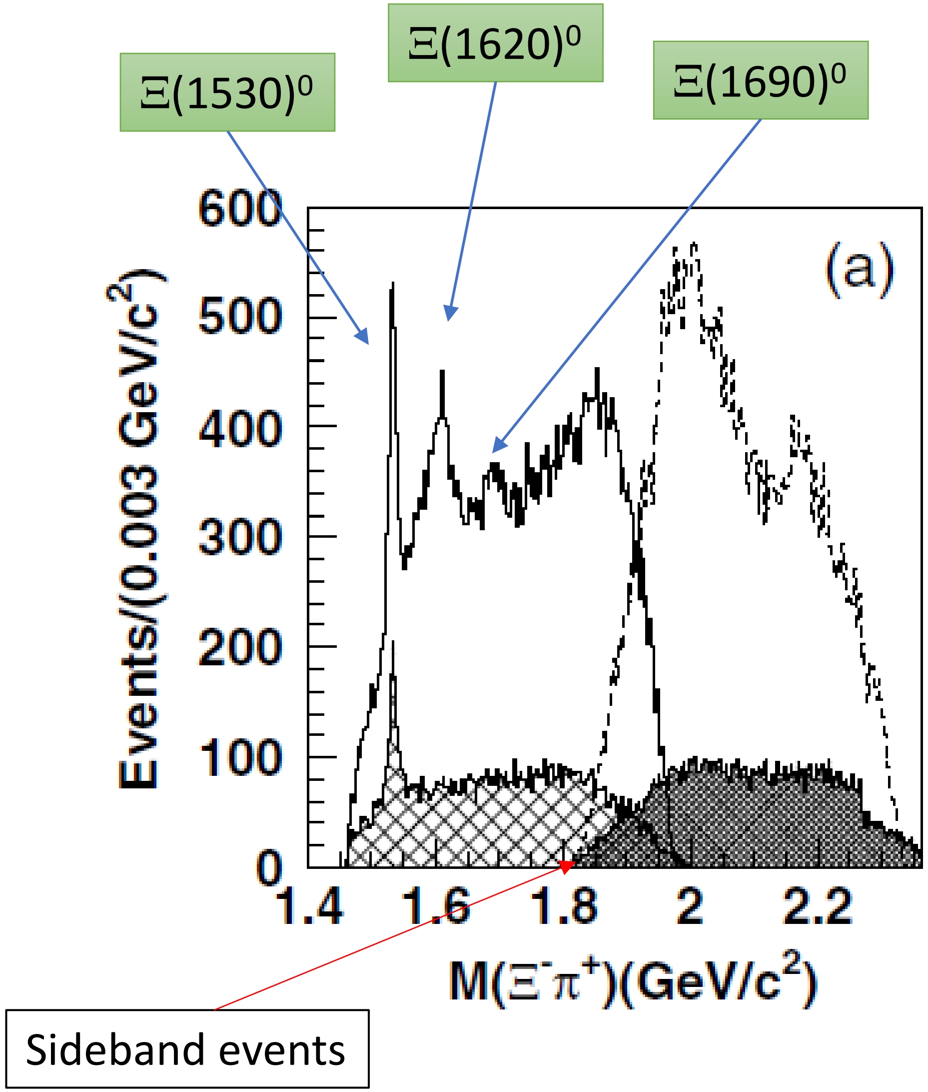
This could be due to limited statistics. Alternatively, heavy resonances might not be producible with photons.

PhysRevLett.122.072501

$M(\Xi^-\pi^+)$ in $\Xi_c^+ \to \Xi^-\pi^+\pi^+$

- Resonance structures are seen in Ξ_c^+ decay.
- Only $\Xi(1530)$ is seen in the sideband spectrum.

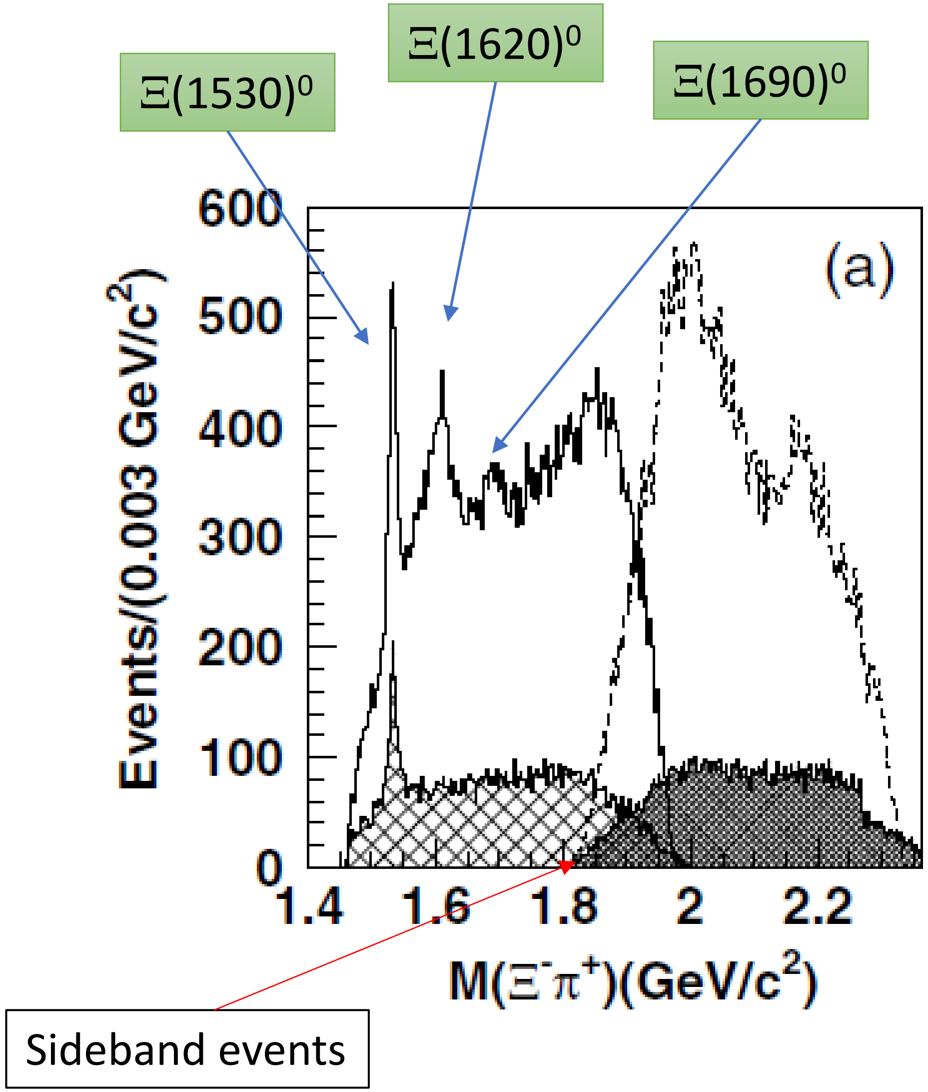




PhysRevLett.122.072501

$M(\Xi^-\pi^+)$ in $\Xi_c^+ \to \Xi^-\pi^+\pi^+$

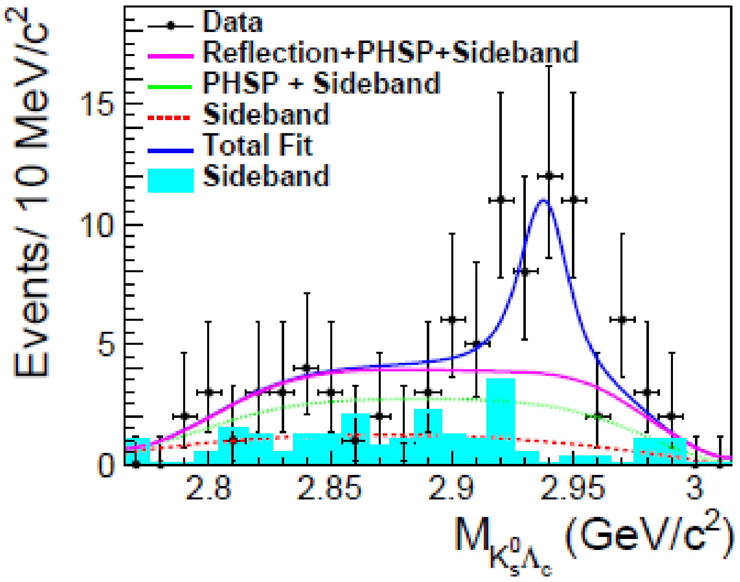
- Resonance structures are seen in Ξ_c^+ decay.
- Only $\Xi(1530)$ is seen in the sideband spectrum.
- Some resonances can be generated through the charmed baryons but may not be generated in a prompt production.



Observation of $\Xi_c(2923)$ / $\Xi_c(2939)$

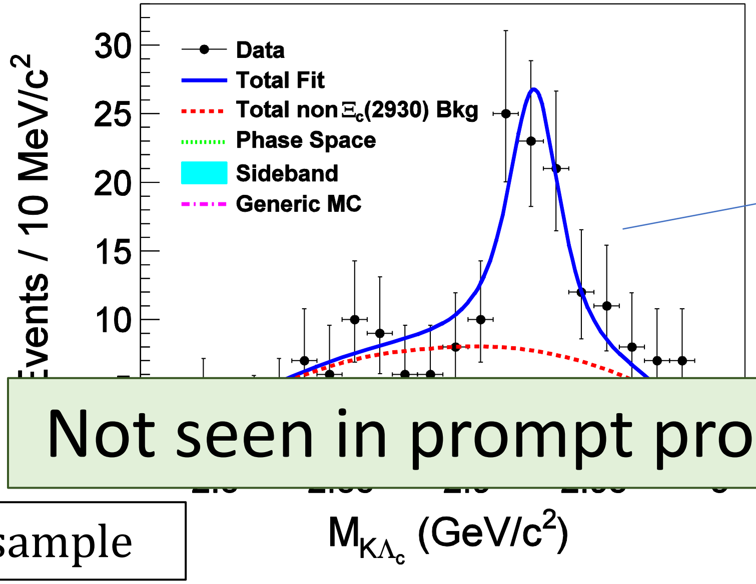
EPJC78, 928 (2018)

$B^0 \to K_s \Lambda_c^+ \overline{\Lambda}_c^-$,
$\Xi_c(2930)^- \to \overline{\Lambda}_c^- K_s$



EPJ C78, 252 (2018)

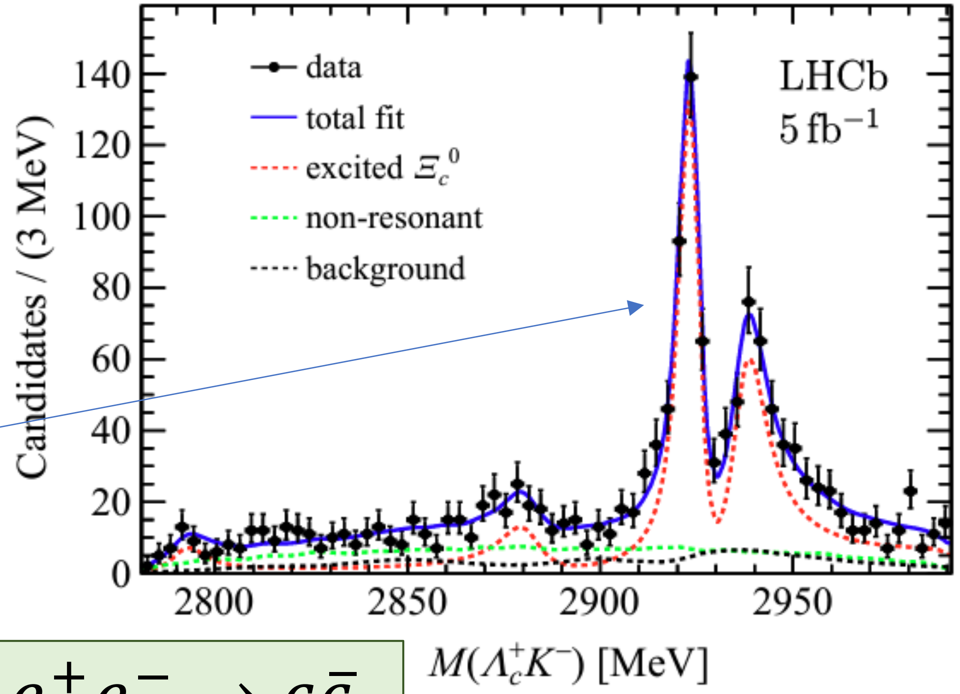
$B^- \to K^- \Lambda_c^+ \overline{\Lambda}_c^-$,
$\Xi_c(2930)^0 \to \Lambda_c^+ K^-$



LHCb

PRD, 108, 012020 (2023)

$B^- \to K^- \Lambda_c^+ \overline{\Lambda}_c^-$,
$\Xi_c(2923)^0 / \Xi_c(2939)^0 \to \Lambda_c^+ K^-$



Not seen in prompt process in $e^+e^- \to c\bar{c}$

711 fb^{-1} at $\Upsilon(4S)$ data sample

Summary of Ξ^* study

- Decay processes
  - Invariant mass : select specific decay modes
  - Missing mass : include all decay modes

  ⇨ investigate the nature of resonances

- Production processes
  - K^- beam
  - Photon beam
  - e^+e^- collider

  → Direct (prompt) production / Substructure of charmed baryons

  investigate the nature of resonances

Some resonances select specific production processes, production processes can also be a valuable tool to investigate the nature of resonances.

$$\Lambda_c\ (2625)^+ \rightarrow \Lambda_c^+\pi^+\pi^- \text{ and } \Sigma_c\pi$$

PRD 107, 032008 (2023)

$\Lambda_c(2625)^+$ in PDG

$I(J^P) = 0(\frac{3}{2}^-)$ Status: ∗∗∗

- Mass difference

$$\Lambda_c(2625)^+ - \Lambda_c^+ = 341.65 \pm 0.13\ MeV$$

- Width

$$\Gamma < 0.97\ MeV$$

- Decay mode

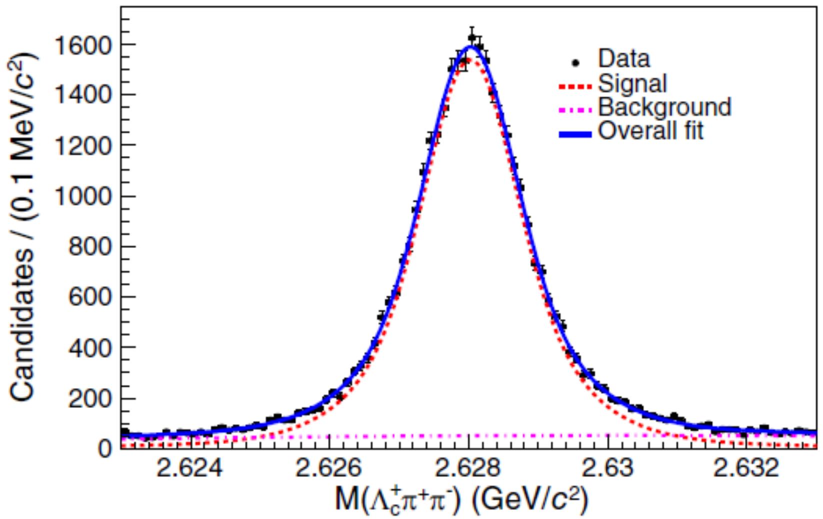
$$\Lambda_c^+\pi^+\pi^- \quad \sim 67\%\ (\mathrm{P-wave\ decay})$$
$$\Sigma_c^{++,0}\pi^{\pm} \quad < 5\%\ (\mathrm{D-wave\ decay})$$

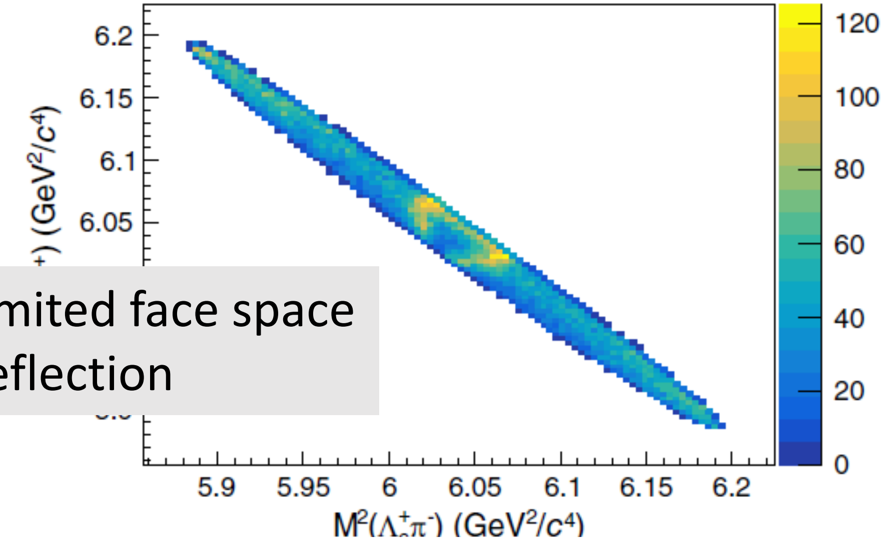
$J^p = 3/2-$ -> both P and D-wave decay

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$	$3/2^-$	***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***

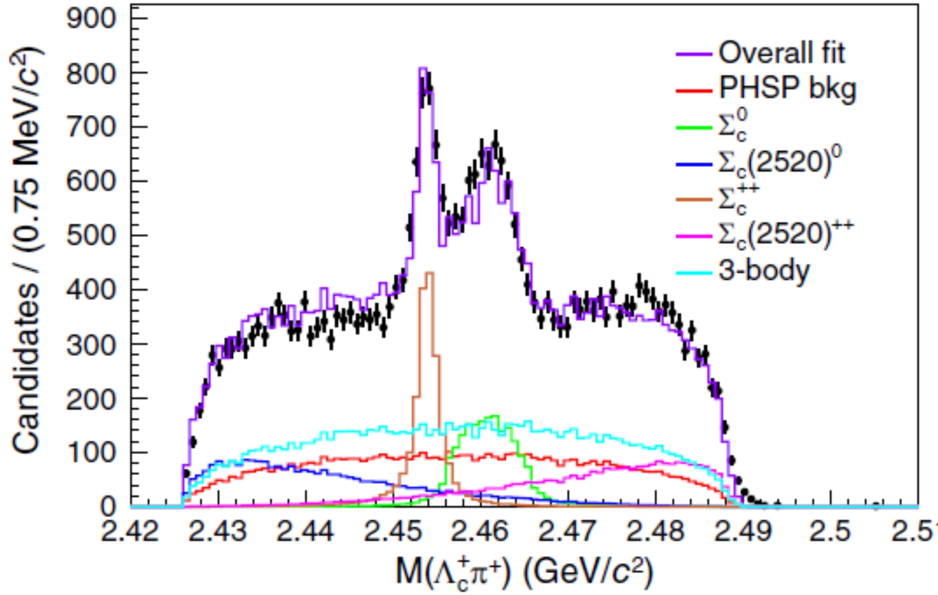
Measurement of $\Lambda_c\,(2625)^+ \rightarrow \Lambda_c^+\pi^+\pi^- / \Sigma_c\pi$

All data sample, 980 fb^{-1}





Limited face space
Reflection



Measurement of mass and width

Measurement of branching fractions,
$\Lambda_c(2625)^+ \rightarrow \Sigma_c^{++,0}\pi^{\pm}$ / $\Lambda_c^+\pi^+\pi^-$
by full Dalitz plot fit (AmpTool)

Measurement results of $\Lambda_c\,(2625)^+$

- Mass difference

$$\Lambda_c\,(2625)^+ - \Lambda_c^+ = 341.518 \pm 0.006 \pm 0.049\ MeV/c^2$$

$$(\text{World average}: 341.65 \pm 0.13\ MeV/c^2)$$

- Width

$$\Gamma < 0.52\ MeV$$

$$(\text{World average}: 0.97\ MeV)$$

Much precise

- Branching fraction ratios

$$\frac{B(\Lambda_c\,(2625)^+ \to \Sigma_c^0 \pi^-)}{B(\Lambda_c\,(2625)^+ \to \Lambda_c^+ \pi^+ \pi^-)} = (5.19 \pm 0.23 \pm 0.40)\%$$

$$\frac{B(\Lambda_c\,(2625)^+ \to \Sigma_c^{++} \pi^-)}{B(\Lambda_c\,(2625)^+ \to \Lambda_c^+ \pi^+ \pi^-)} = (5.13 \pm 0.26 \pm 0.32)\%$$

$$\text{World average}: < 5\%$$

Summary

- Belle & Belle II are actively working on hadron physics.
- Ξ^* resonances
  Observe $\Xi(1620)^0$ and $\Xi(1690)^0$ resonances in $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$
  Finding structure at 1620 is asymmetric shape.
  There is another possibility for this structure, threshold cusp.
- Studies of threshold cusp
  Peak in pK^- of $\Lambda_c^+ \rightarrow pK^-\pi^+$ $\rightarrow$ the $\eta\Lambda$ threshold cusp
  Signal in $M(\Lambda\pi^\pm)$ in $\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^+\pi^-$ $\rightarrow$ the $\bar{K}N$ threshold cusp or Σ resonance?
- $\Lambda_c\,(2625)^+$
  Precise measurement of mass and width, and first measurement of branching ratios
  These measurements can be used as inputs to theoretical models to understand $\Lambda_c(2625)^+$
- Belle & Belle II will discover more hadrons, and measure observables of hadrons.