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

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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

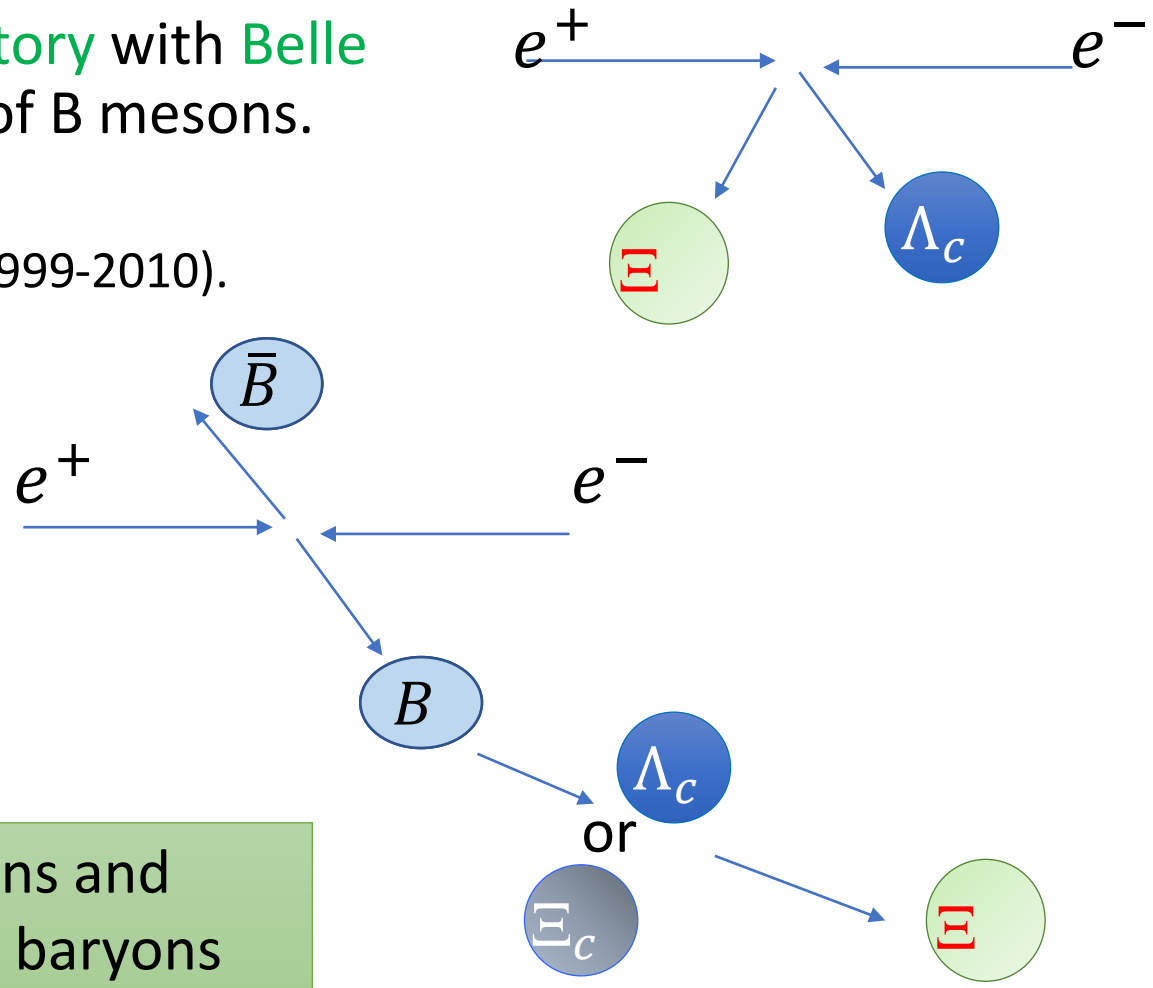
Belle experiment

- 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).

$\sqrt{s}$~10.6 GeV
1 ab^{-1} integrated luminosity

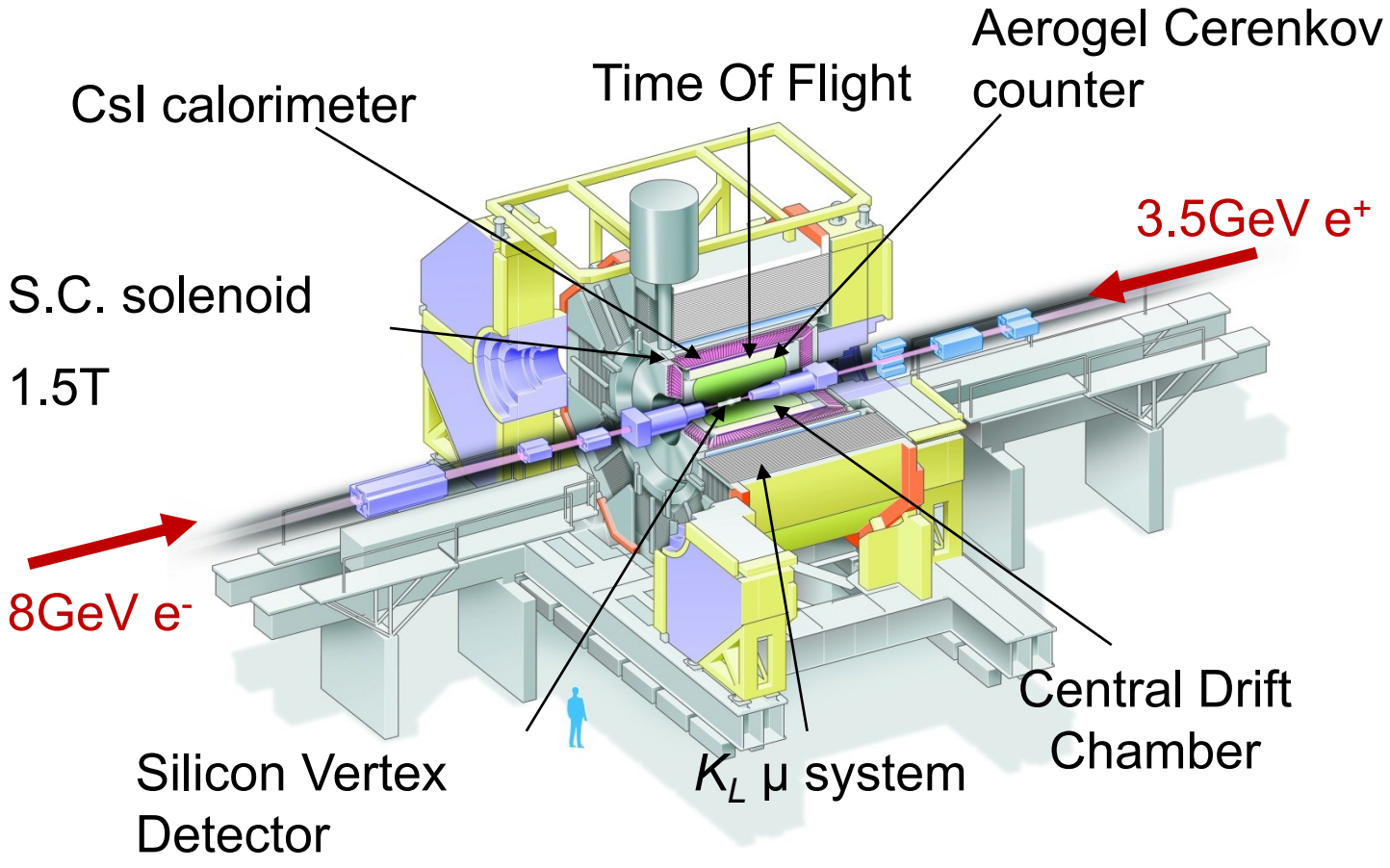
A lot of hadrons → hadron physics

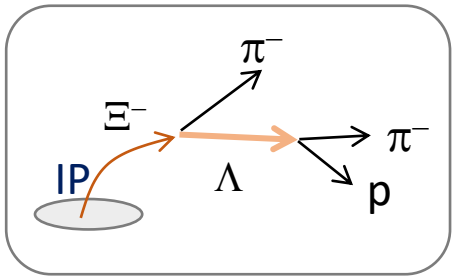


Huge data enable to study charmed baryons and resonant substructure in decays of charmed baryons

Access to various production/decay processes.

Belle detector





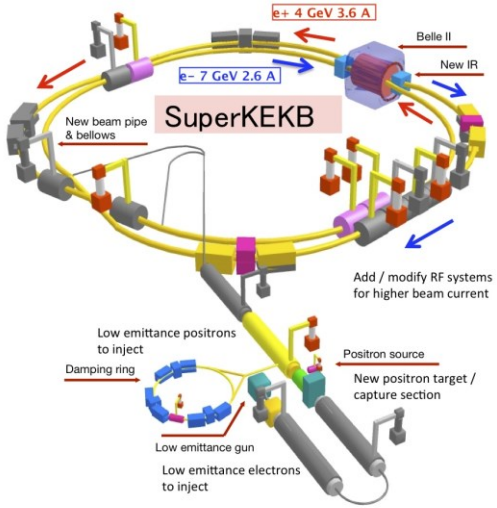
$c\tau_{\Lambda} = 7.98\ cm$
$c\tau_{\Xi^-} = 4.91\ cm$

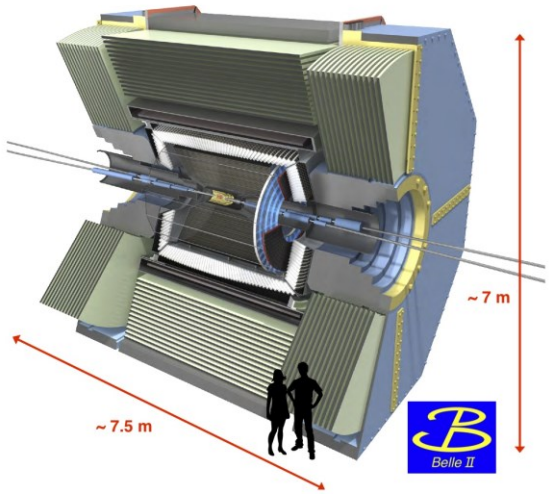
Detect charged particle($e^{\pm}$ $\mu^{\pm}$ $\pi^{\pm}$ $K^{\pm}$ p) and γ

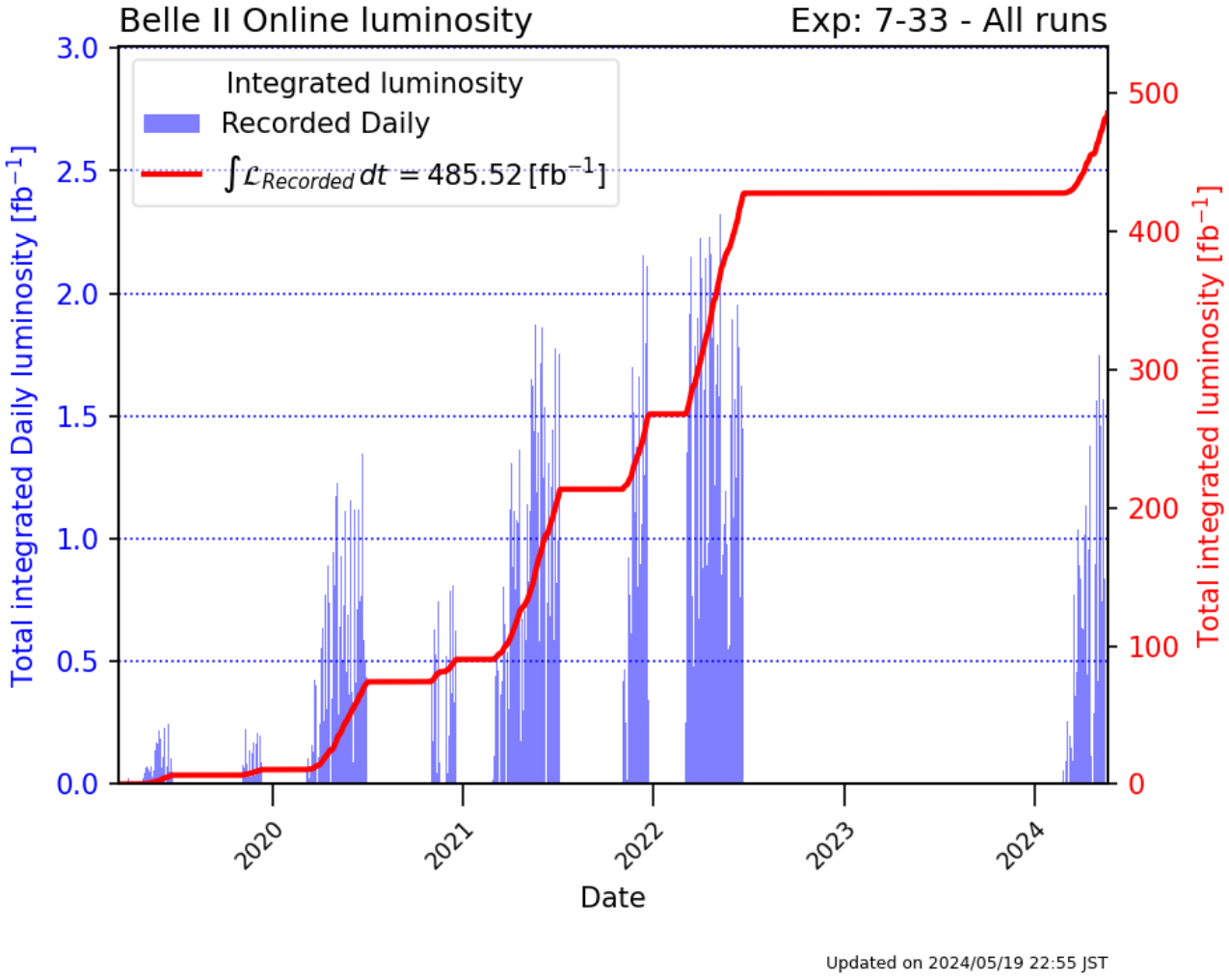
Belle → Belle II experiment

- Belle II experiment
  KEKB -> SuperKEKB
  Belle detector -> Belle II detector
  2 times higher beam current
- Belle II experiment is now running.

Upgrades in all parts of the detector







Ξ^* hyperon and cusp structures in Λ_c^+ decay

Physics motivation -Status of Ξ*

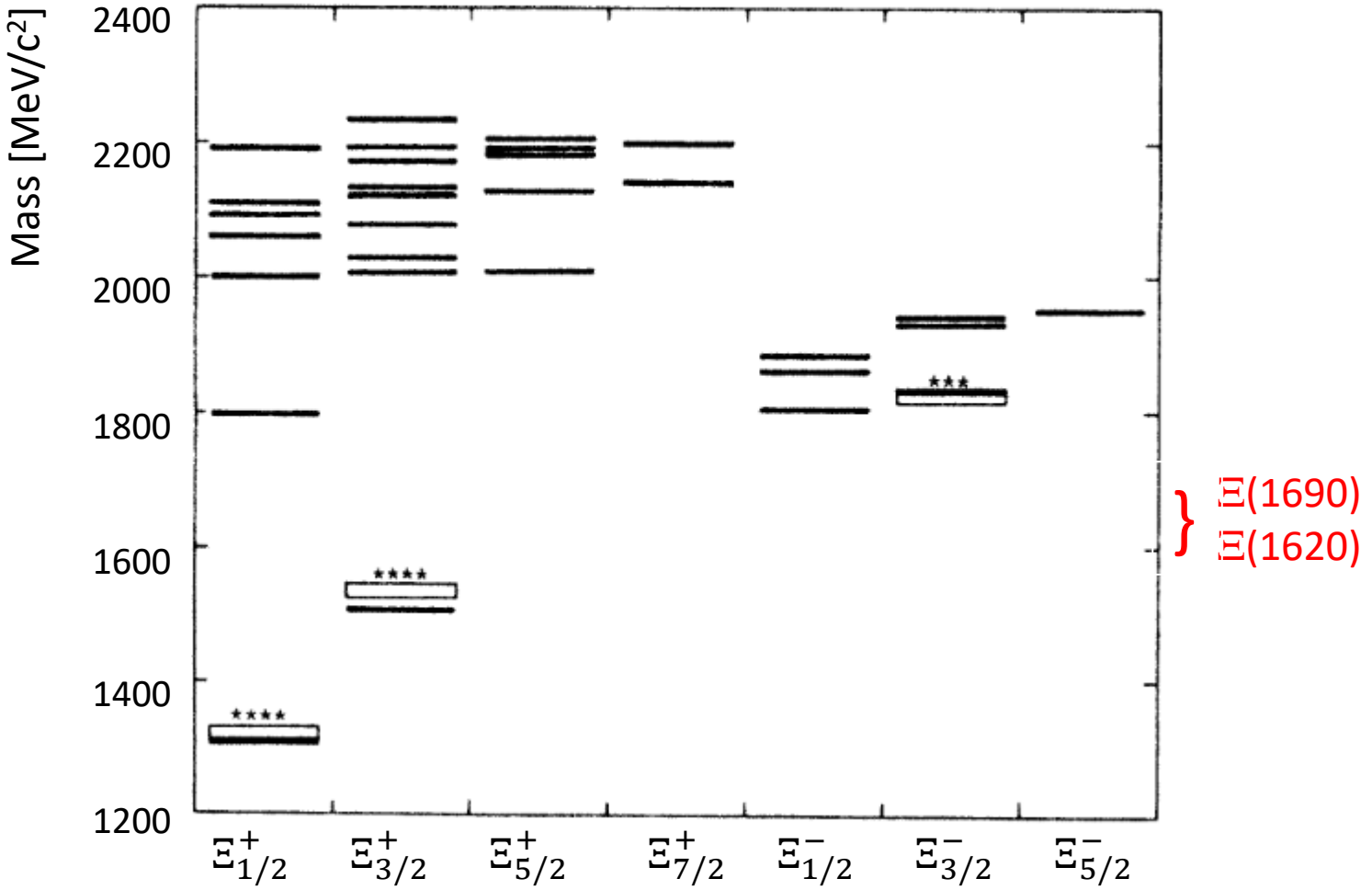
From PDG

MM	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

- Not much is known about Ξ*
- First excited state is not found
- Analog of Λ(1405) with ½-
- Ξ(1620)/Ξ(1690) are candidates for ½⁻, ½⁺
  → Inconsistent with constituent quark model

Prediction by constituent QM

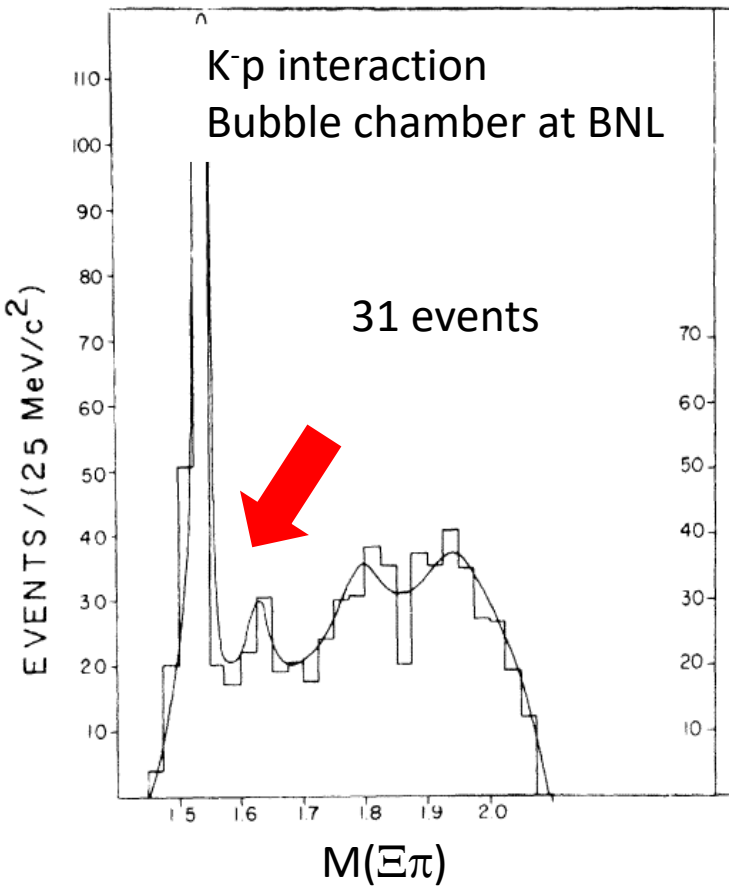
S.Capstick and N. Isgur, PRD34, 2809(1986)



- Predicted first excited state in constituent quark model is around 1800 MeV.

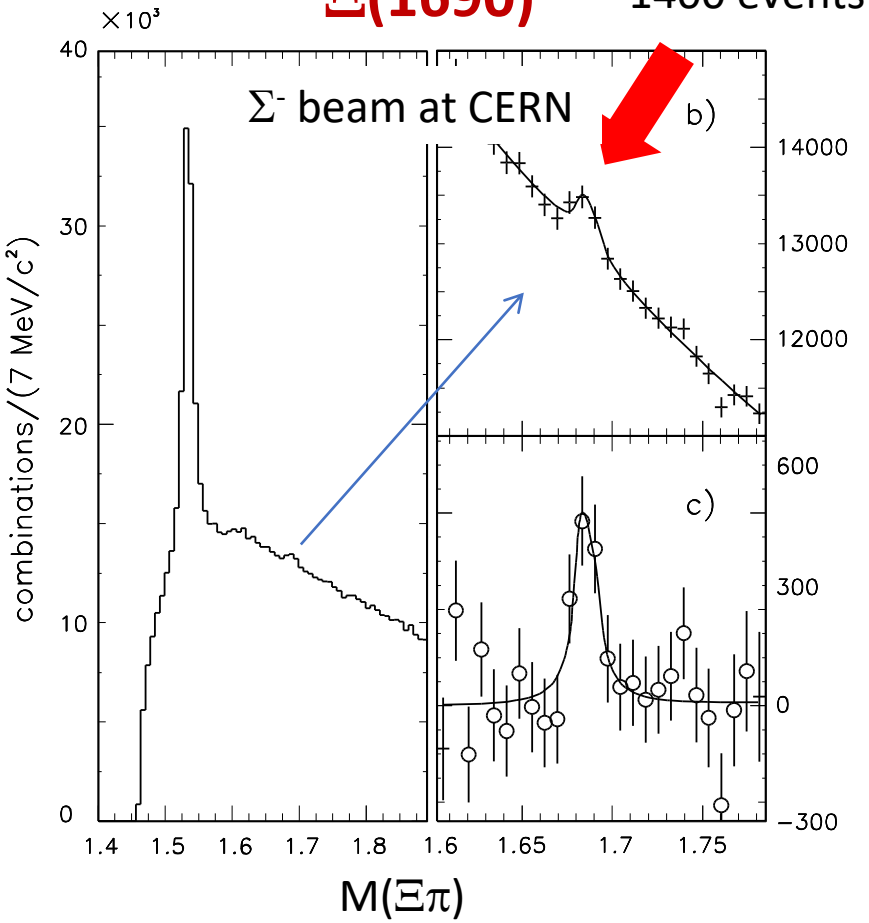
Previous experiments of $\Xi(1620)^0/\Xi(1690)^0$

$\Xi(1620)^0$



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

$\Xi(1690)^0$ 1400 events



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

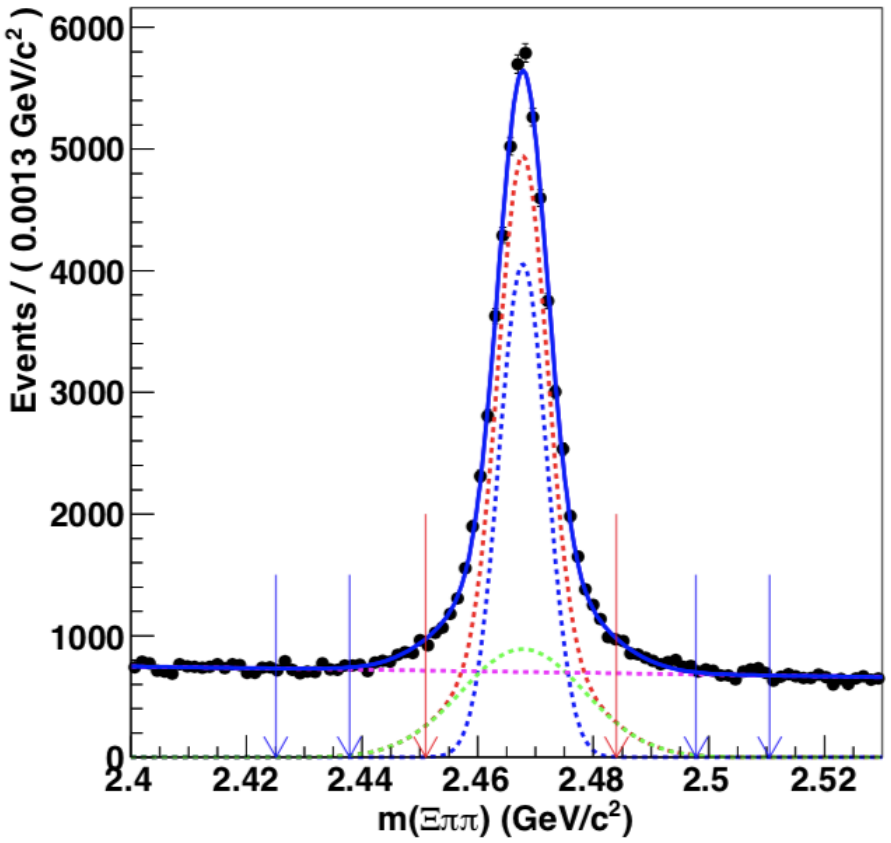
https://doi.org/10.1103/PhysRevLett.122.072501

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

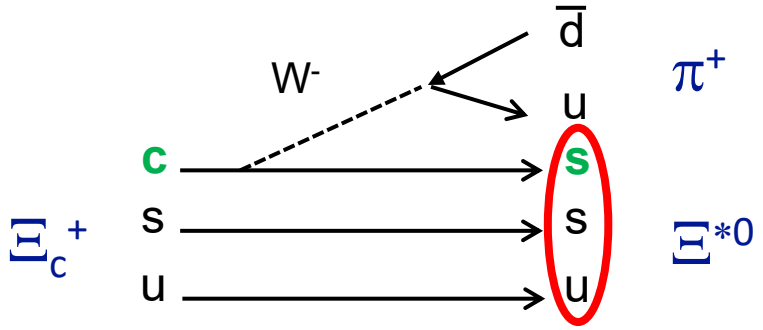
Ξ^{*0} in $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ at Belle

Ξ_c^+

~50,000 events

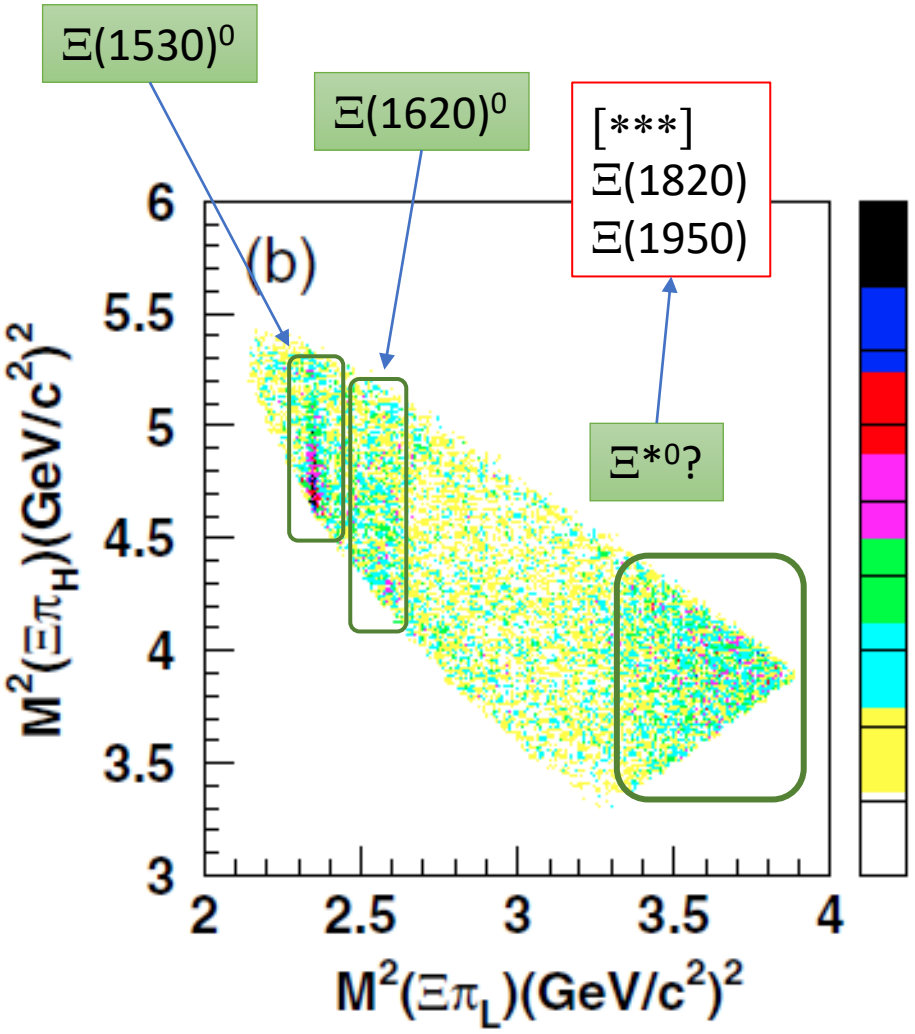


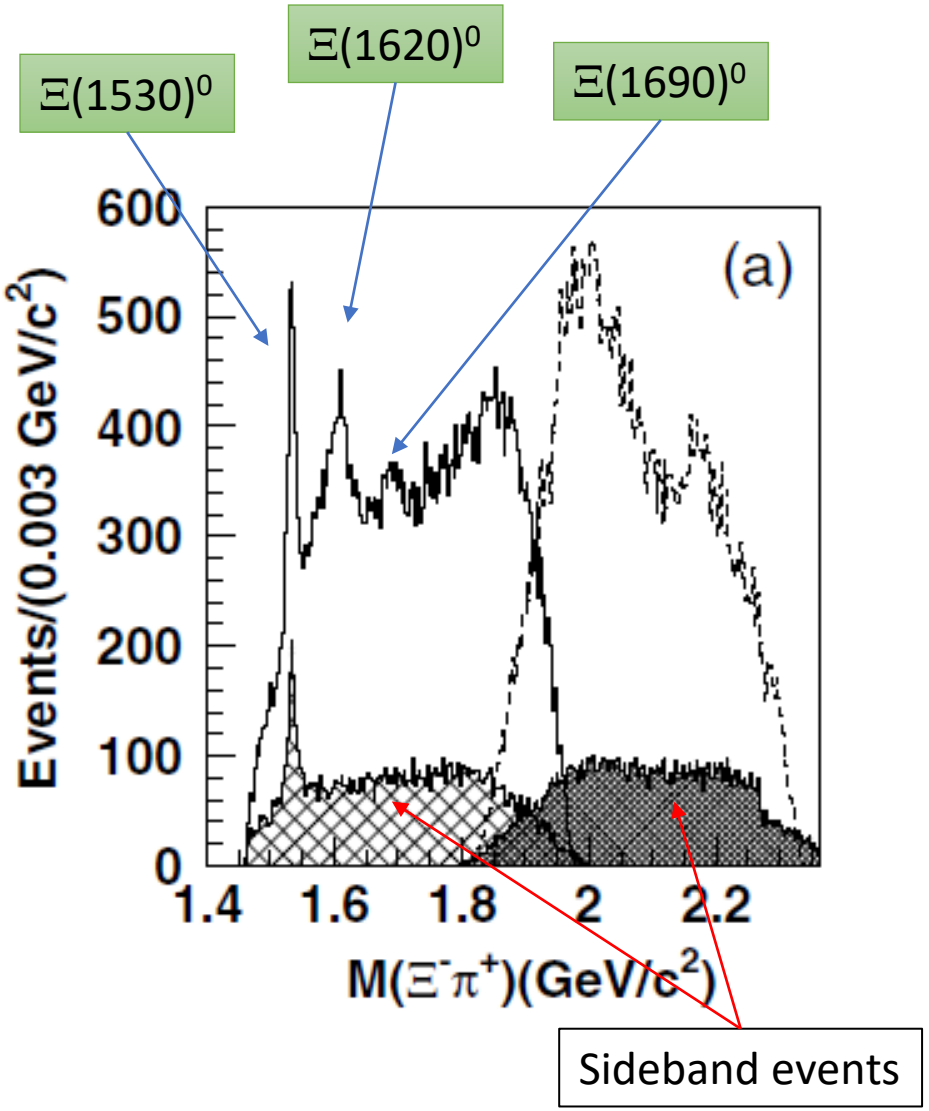
As a substructure in weak decay of charmed baryons
Many charmed baryons in Belle data
Charmed baryon has advantage.



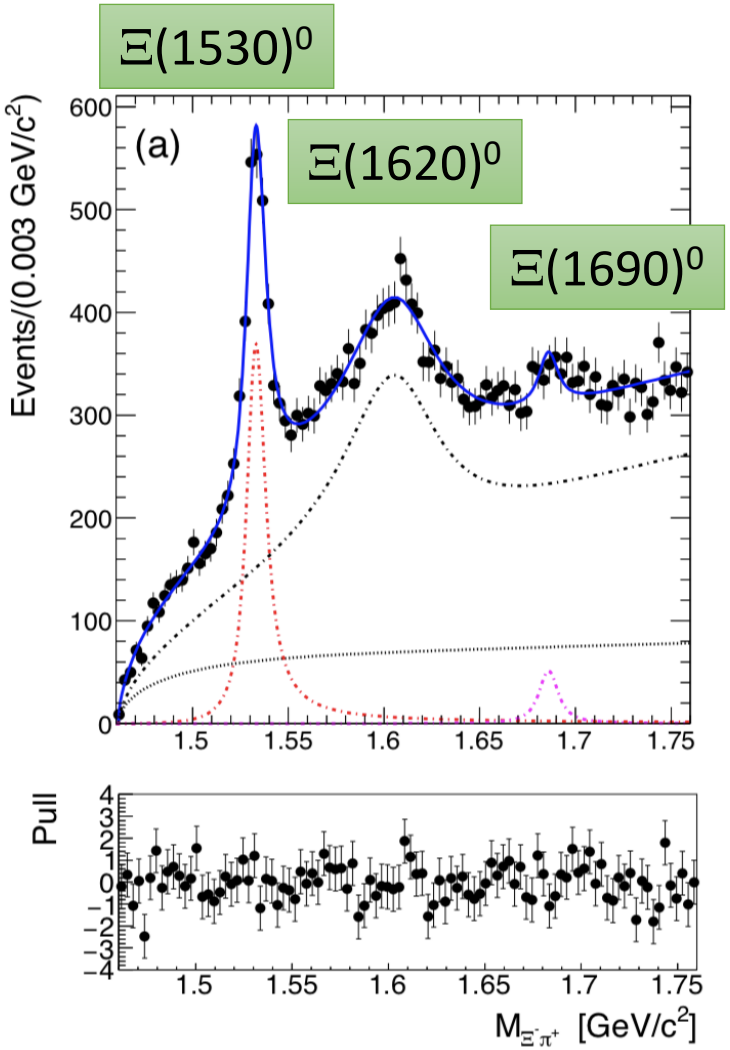
$$\Xi_c^+ \rightarrow \Xi^{*0}\pi^+ \rightarrow \Xi^-\pi^+\pi^+ \rightarrow \Lambda\pi^-\pi^+\pi^+ \rightarrow p\pi^-\pi^-\pi^+\pi^+$$

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





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



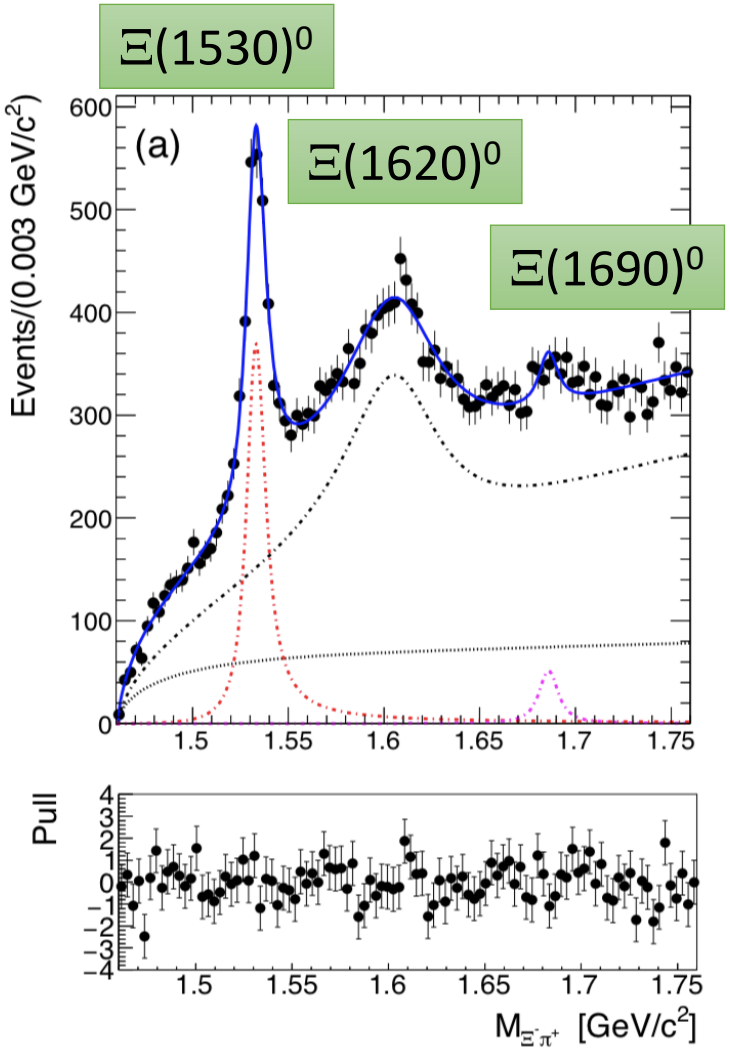
Determination of mass and width of Ξ(1620)⁰

✓ Fitting function:

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

Interference between Ξ(1620) and S-wave

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



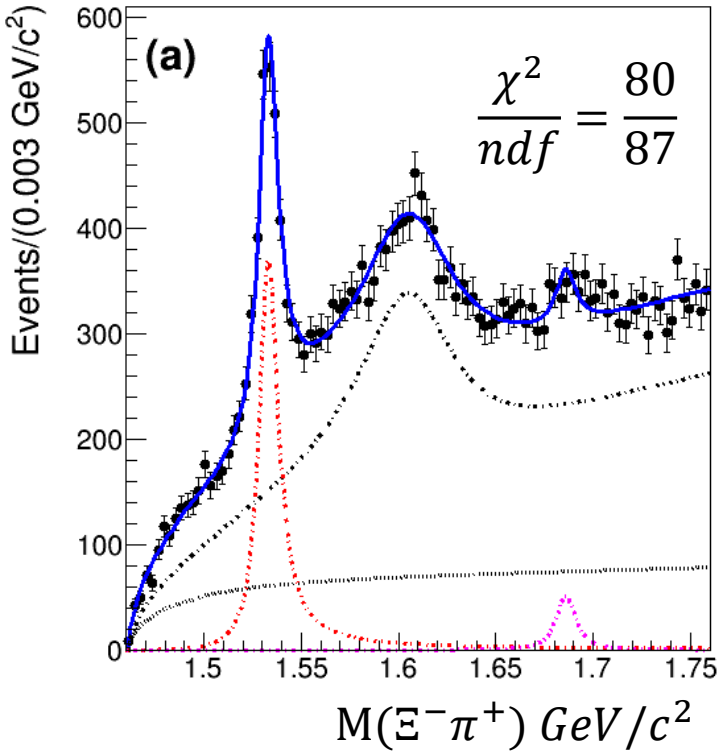
Determination of mass and width of $\Xi(1620)^0$

- 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

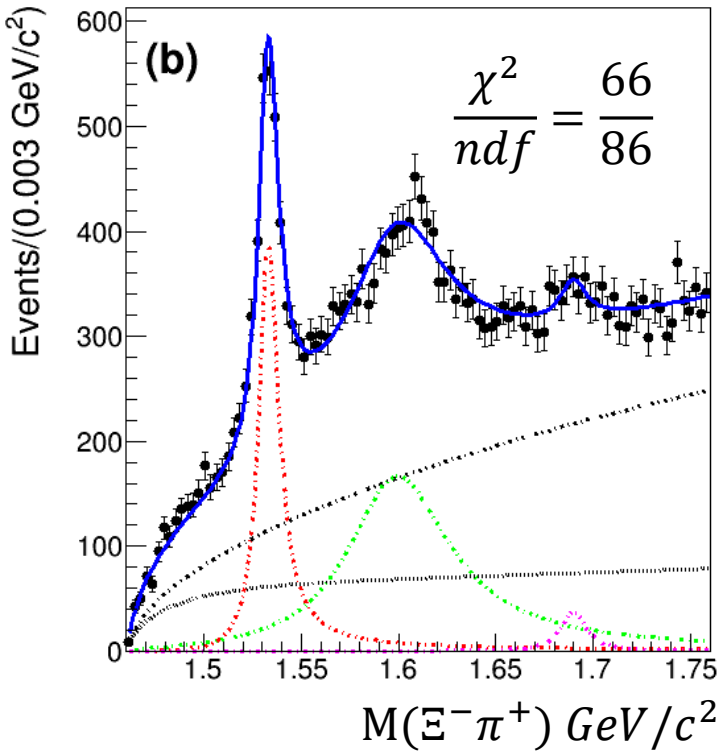
  25σ for $\Xi(1620)^0$, 4.0σ for $\Xi(1690)^0$

Fitting to invariant mass spectrum

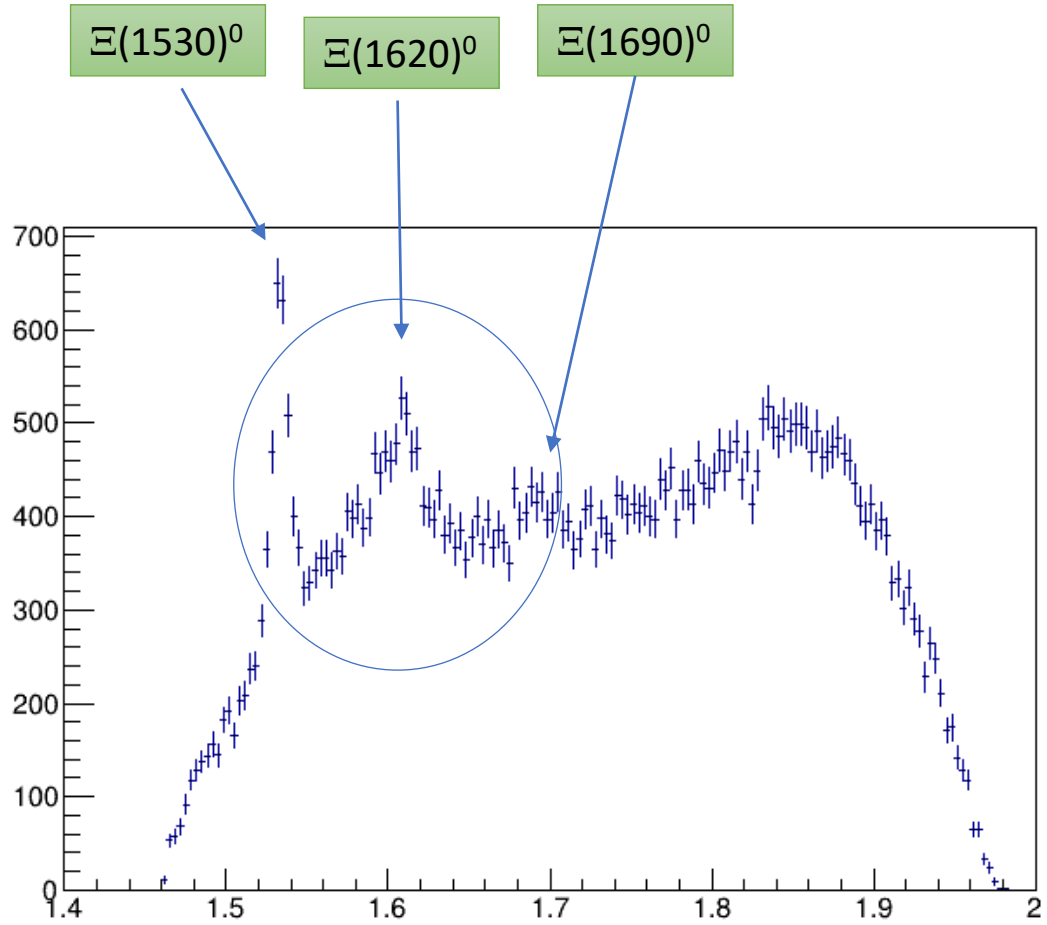
w/
Interference btw $\Xi(1620)$ and s-wave nonresonance



w/o interference



Mass spectrum



Asymmetric shape
is near $K\Lambda$ threshold.

-> Interference?
Resonance or cusp?

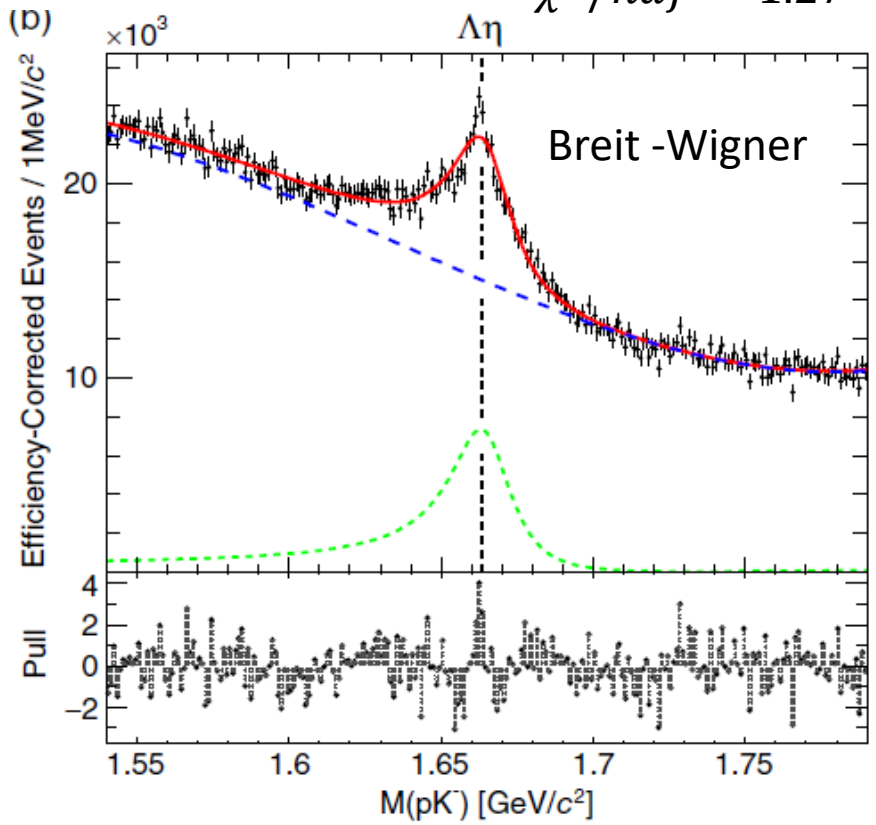
$1620 \sim M(\mathrm{K}\Lambda)$

PHYS. REV. D 108, L031104 (2023)

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

Resonance

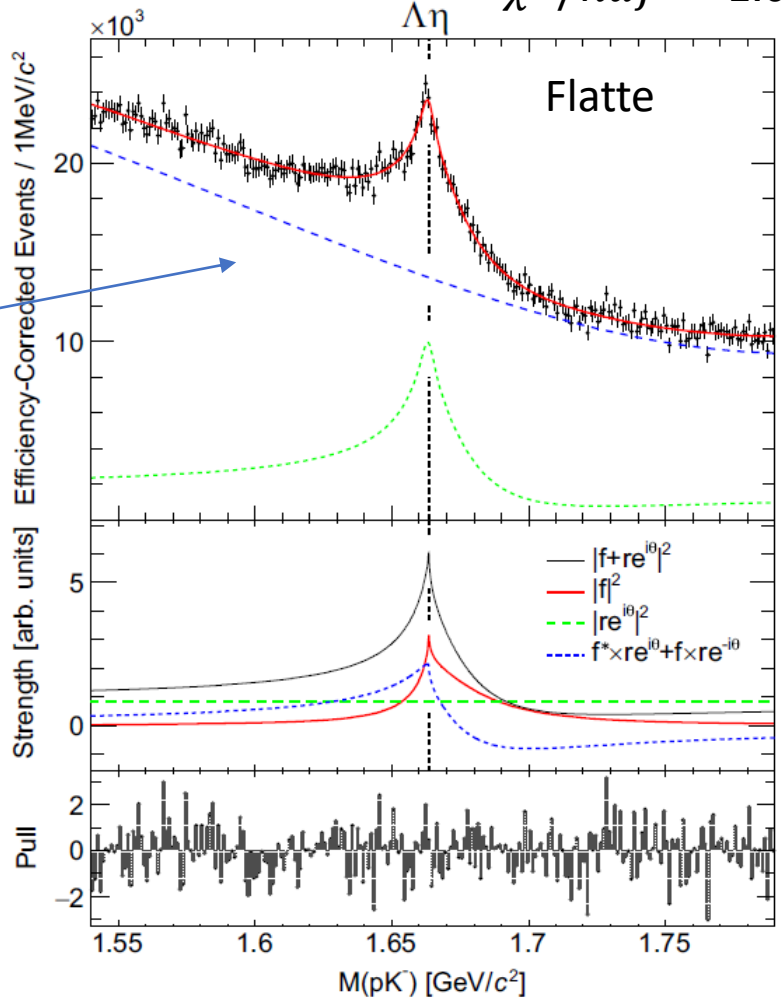
$\chi^2/ndf = 1.27$



Best fit

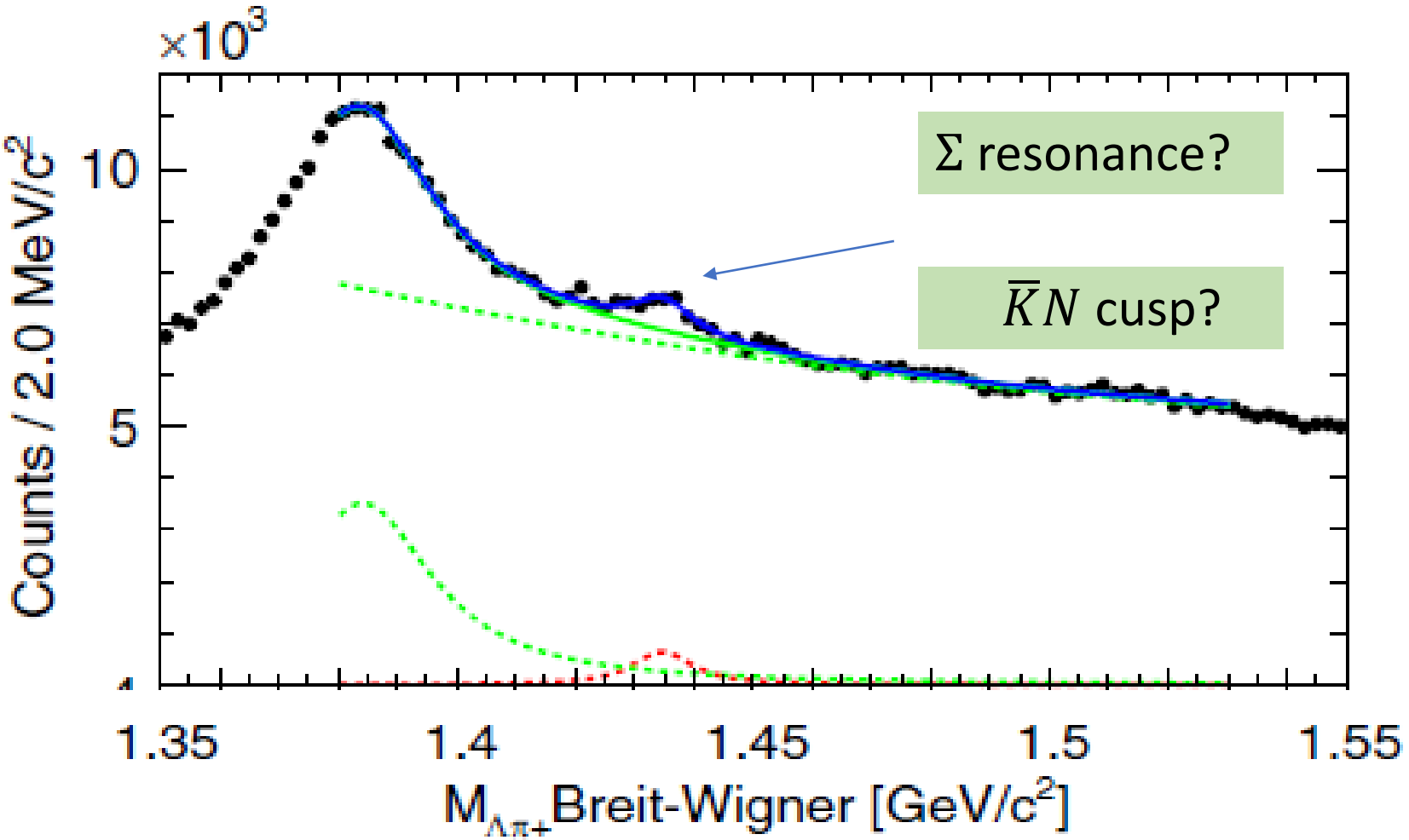
Cusp

$\chi^2/ndf = 1.06$



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

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



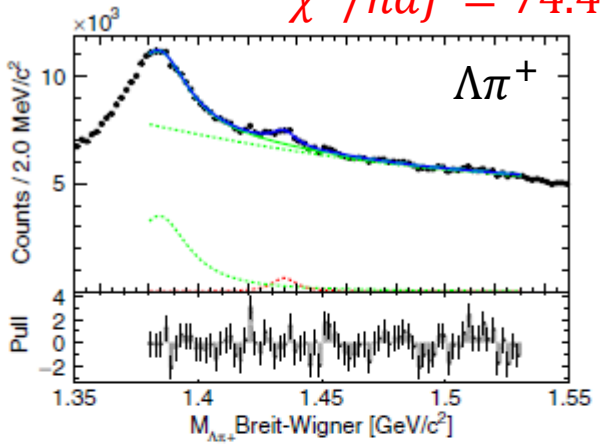
Signal in $M(\Lambda\pi^{\pm})$ in $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$

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

Σ resonance?

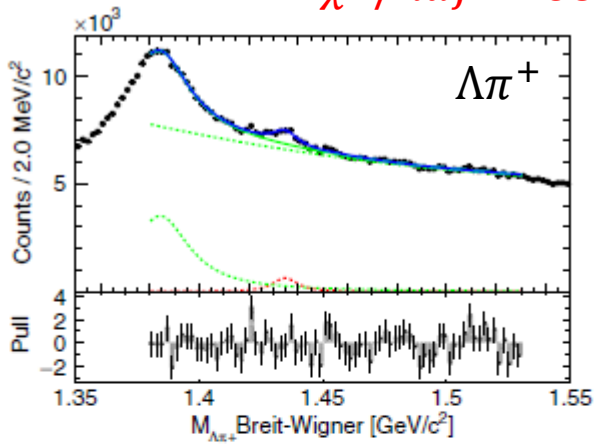
$\bar{K}N$ cusp

$\chi^2/ndf = 74.4/68$



(a)

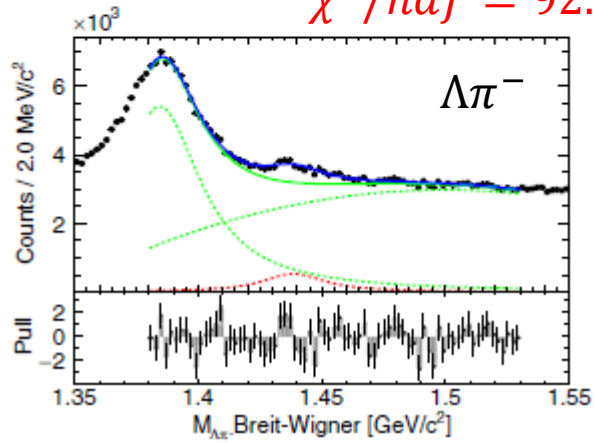
$\chi^2/ndf = 68.9/68$



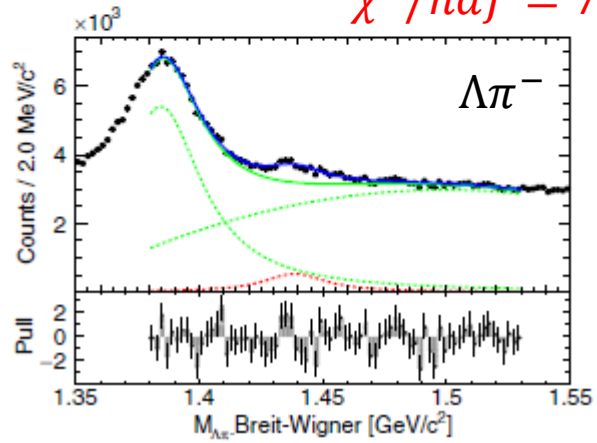
(a)

Not discriminate

$\chi^2/ndf = 92.3/68$



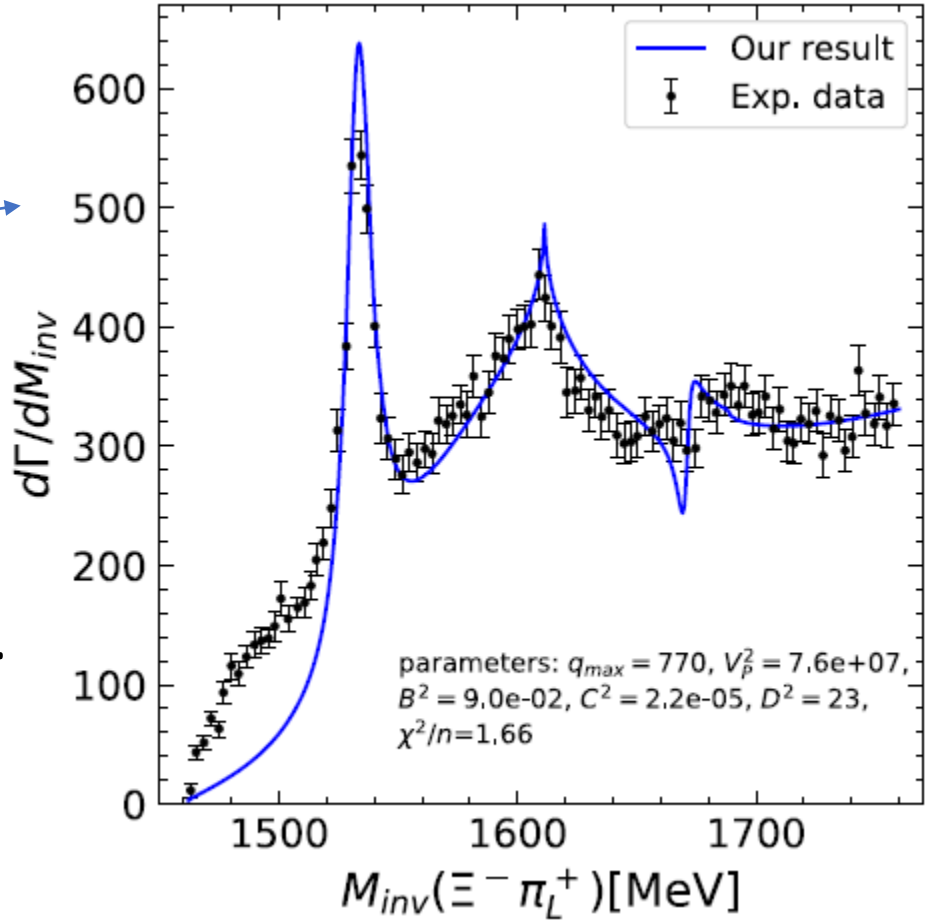
$\chi^2/ndf = 78.1/68$



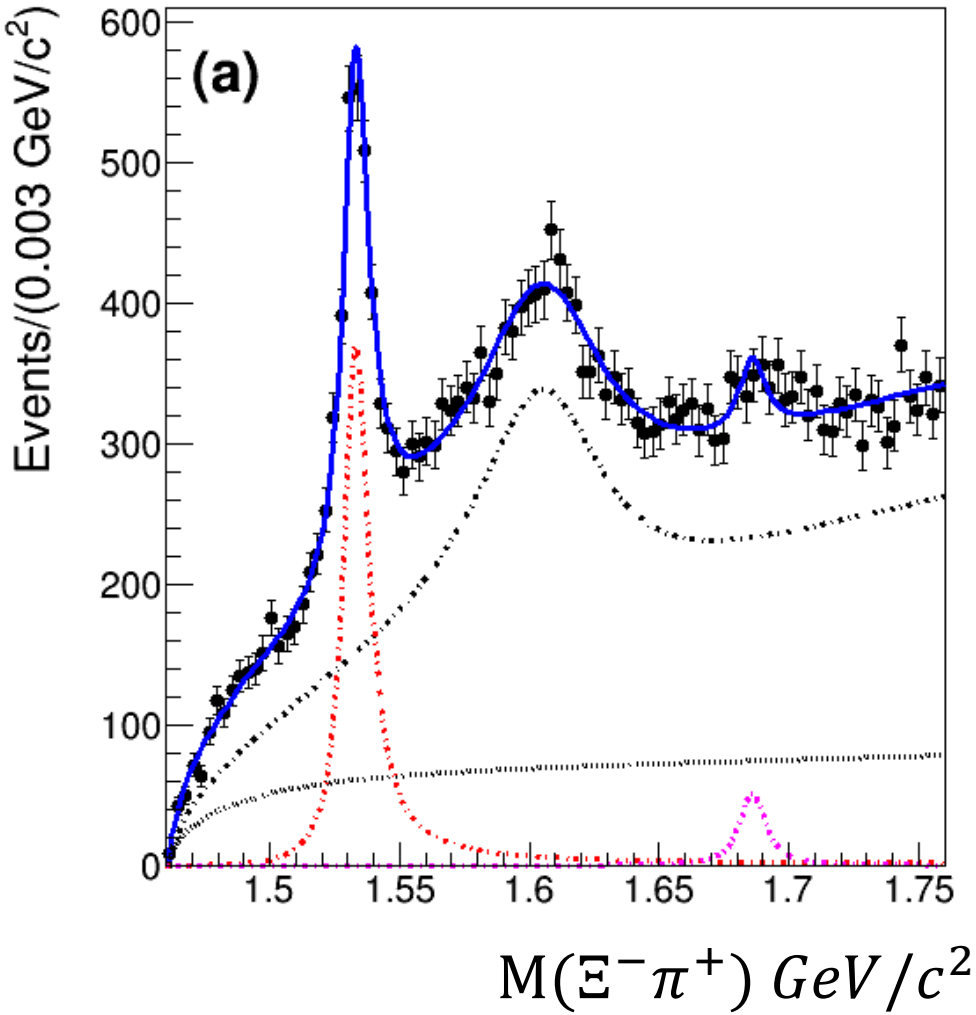
Theoretical calculations

Eur. Phys. J. C (2023) 83:954
These two resonances are generated dynamically from the interaction in coupled channels of $\pi\Xi, \bar{K}\Lambda, \bar{K}\Sigma, \eta\Xi$ within the chiral unitary approach.

Some studies can generate both Ξ(1620) and Ξ(1690).
Some studies mention the $\bar{K}N$ threshold effect.



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



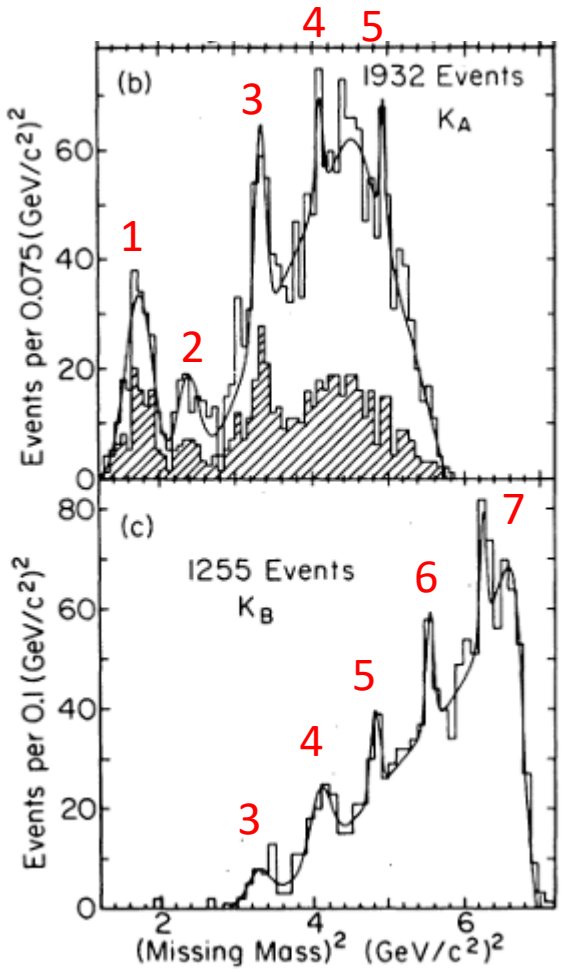
Asymmetric shape
is near $K\Lambda$ threshold.

-> Interference?
Resonance or cusp?

Ξ^* in missing mass – production process

PRL 51.951 (1983)

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

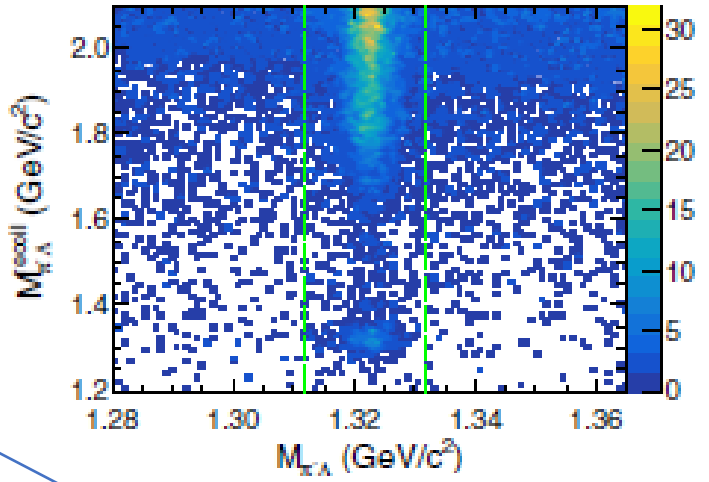


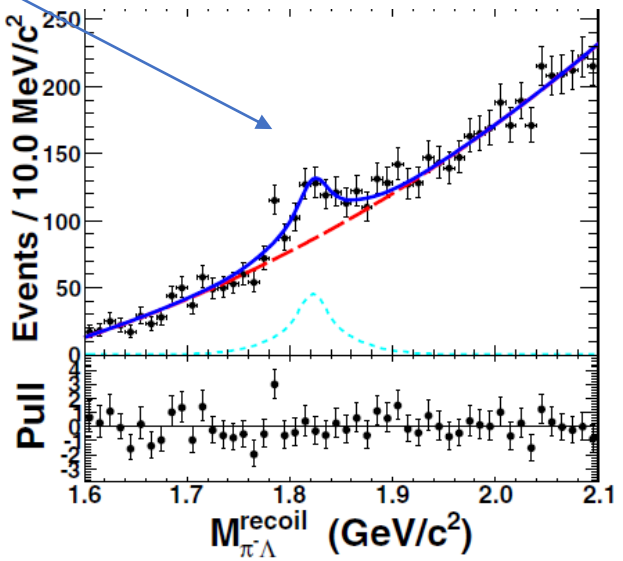
	Particle	J^P	Overall status
1	$\Xi(1318)$	$1/2+$	****
2	$\Xi(1530)$	$3/2+$	****
	$\Xi(1620)$		**
	$\Xi(1690)$		***
3	$\Xi(1820)$	$3/2-$	***
	$\Xi(1950)$		***
4	$\Xi(2030)$		***
	$\Xi(2120)$		*
5	$\Xi(2250)$		**
6	$\Xi(2370)$		**
7	$\Xi(2500)$		*

Missing??
Broad width / low statistics

PRL 124,032002(2020)

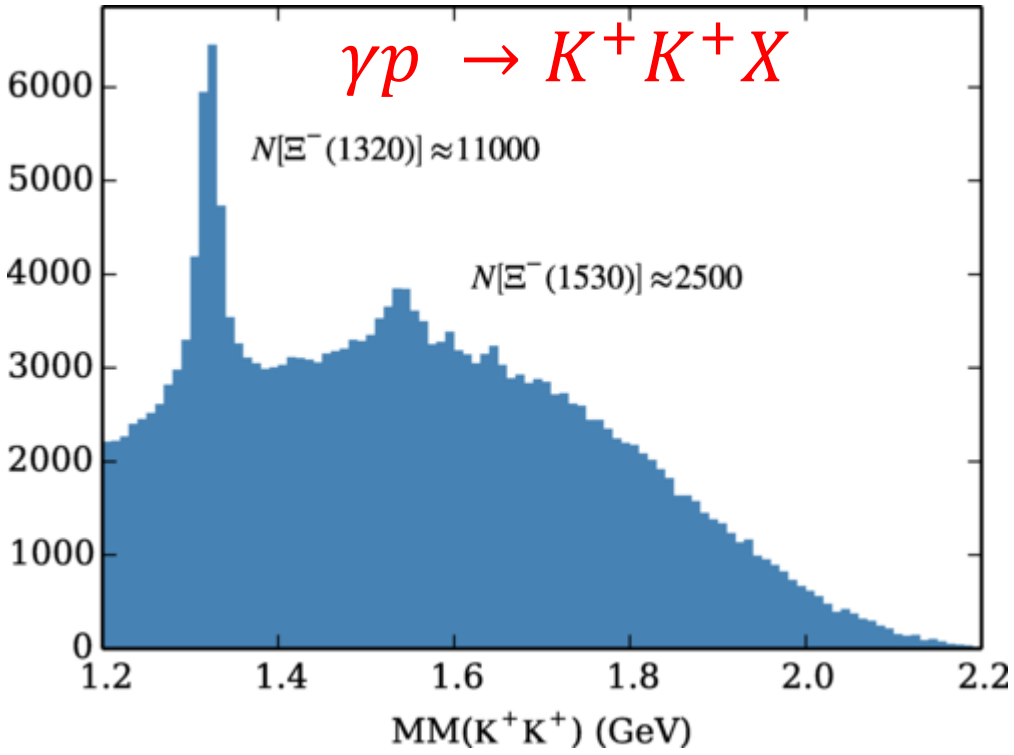
$e^+e^- \to \Xi^- \bar{\Xi}^+$

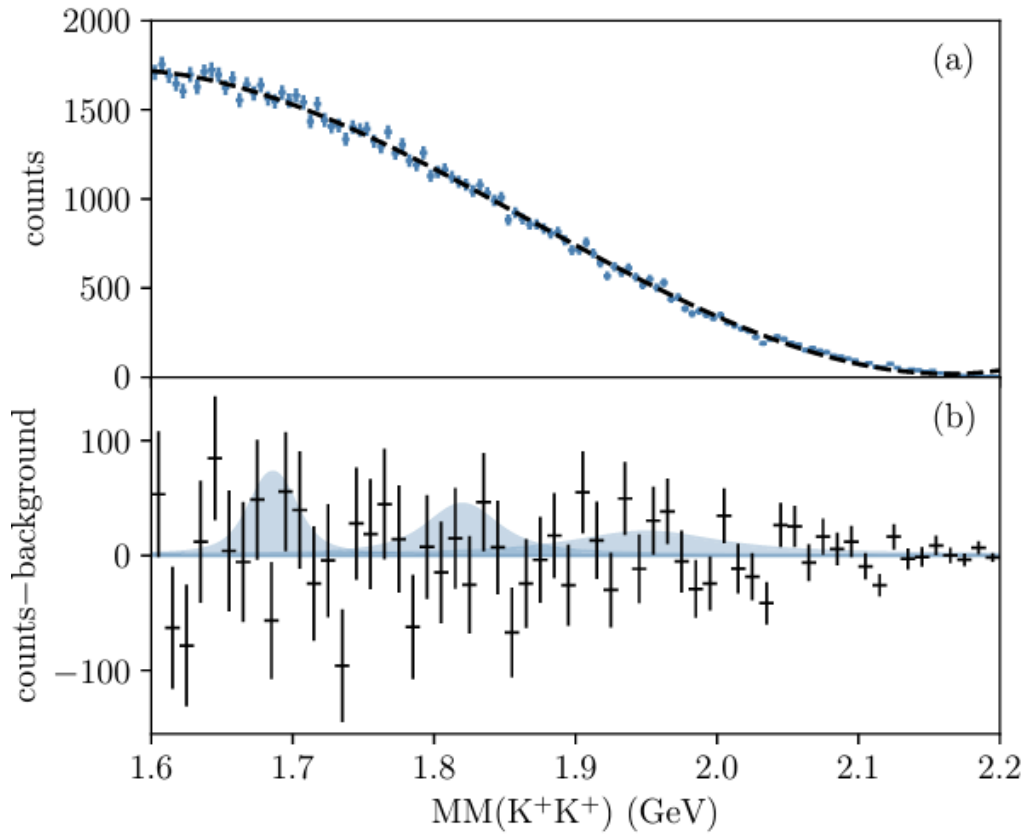




Missing mass of photoproduction from CLAS

PRC 98 062201(R)(2018)

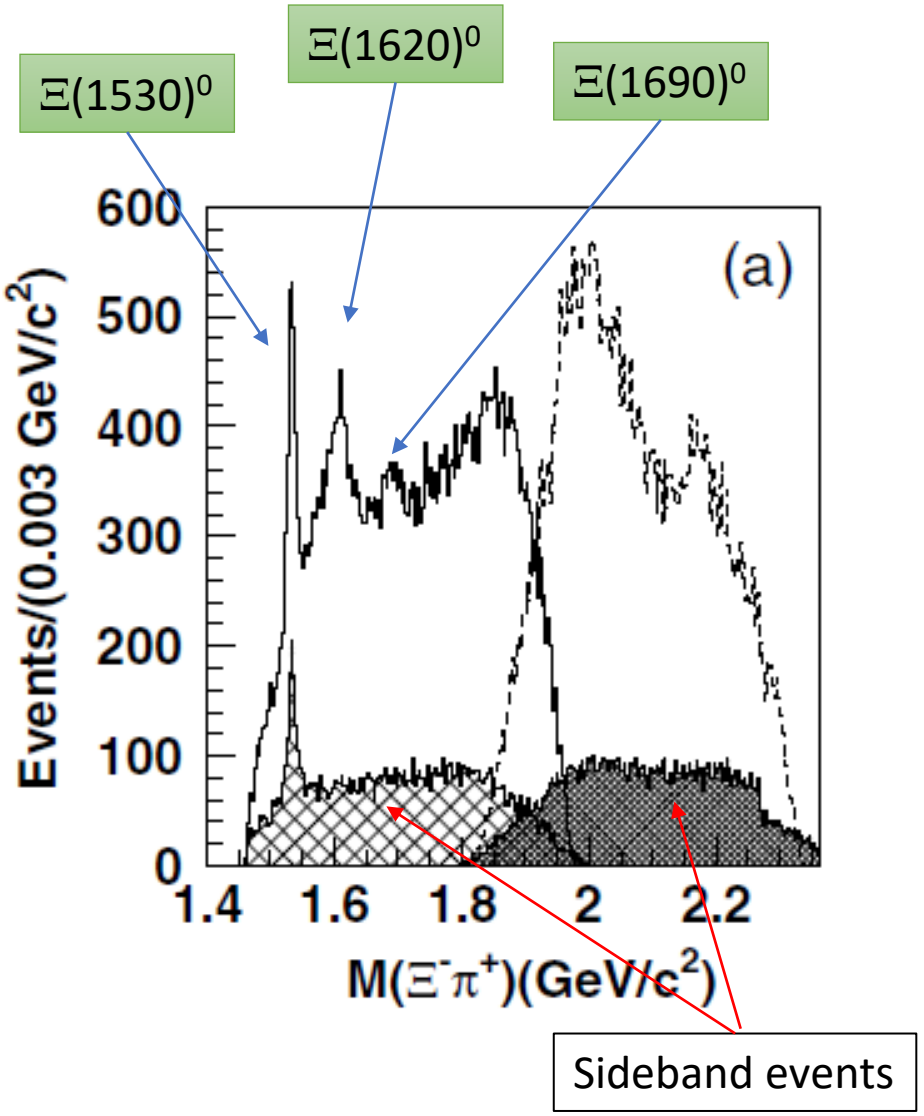




No evidence for higher mass Ξ^*

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

- Only $\Xi(1530)$ is seen in the sideband spectrum.
- Absent of resonances in the sideband spectrum



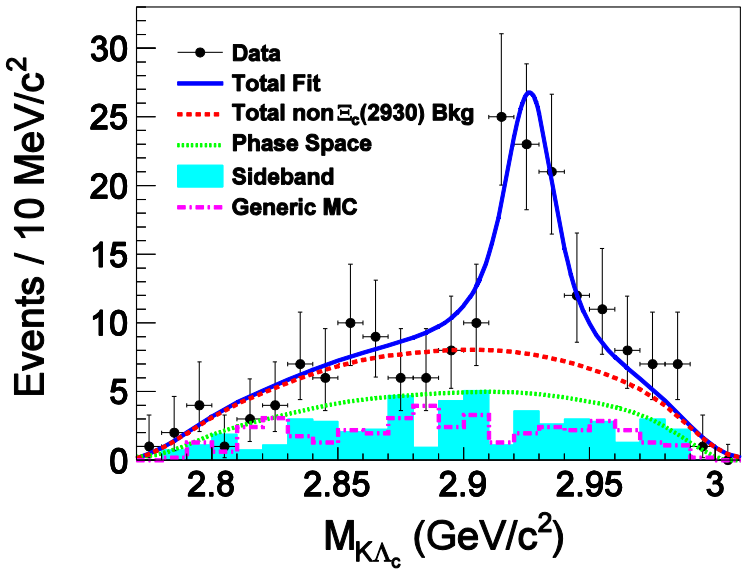
EPJ C78, 252 (2018) / EPJC78, 928 (2018)

Observation of $\Xi_c(2930)^{-,0}$

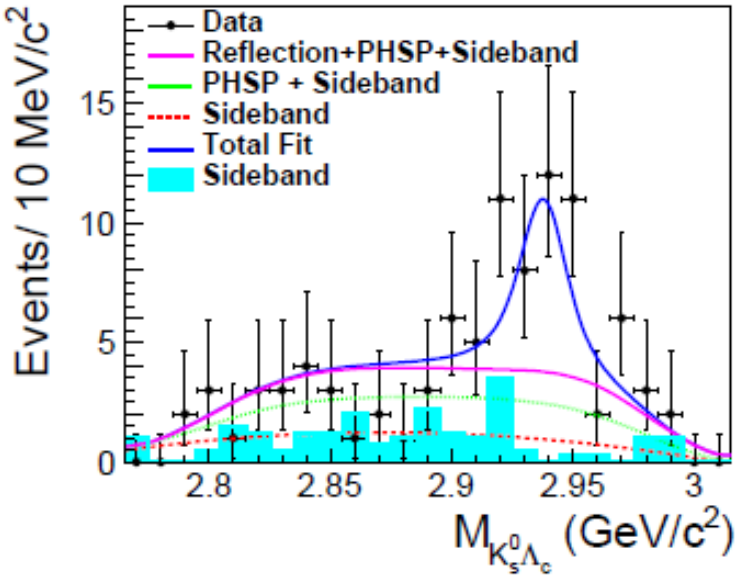
$B^- \to K^- \Lambda_c^+ \bar{\Lambda}_c^-$,
$\Xi_c(2930)^0 \to \Lambda_c^+ K^-$

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

$\Xi_c(2930)^0$



$\Xi_c(2930)^-$



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

Summary of Ξ^* study

- Production processes
  - K^- beam
  - Photon beam
  - e^+e^- collider
    → Direct (prompt) production / Substructure of charmed baryons
- Decay processes

  Invariant mass
  missing mass

$\Lambda_c\,(2625)^+ \to \Lambda_c^+\pi^+\pi^-$ 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

$$\Gamma < 0.97\ MeV$$

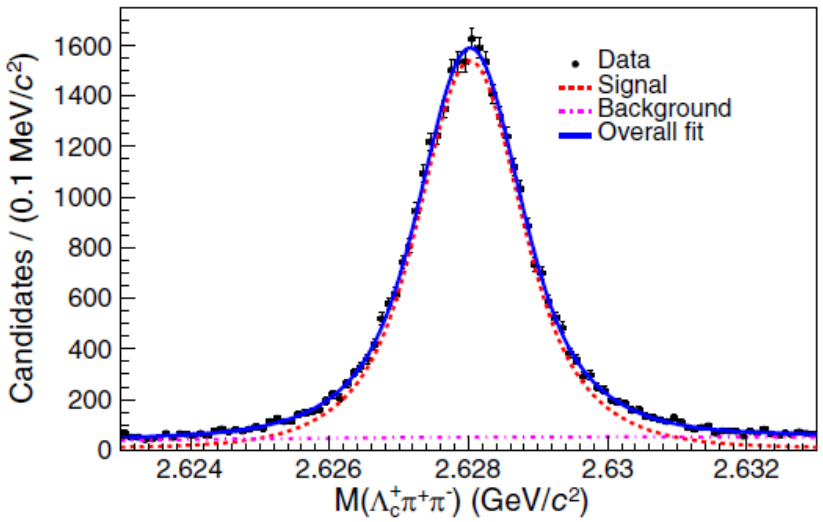
- Decay mode

$\Lambda_c^+\pi^+\pi^-$ ~67% (P − wave decay)

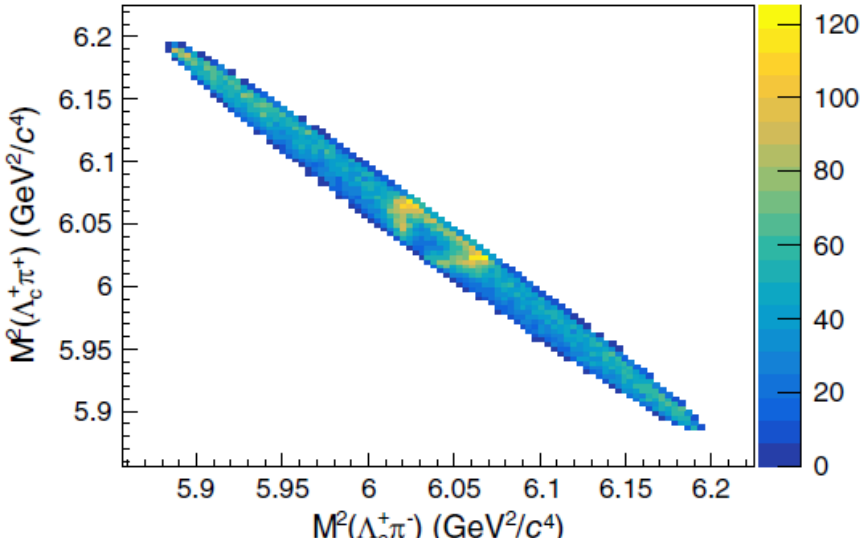
$\Sigma_c^{++,0}\pi^\pm$ < 5% (D − wave decay)

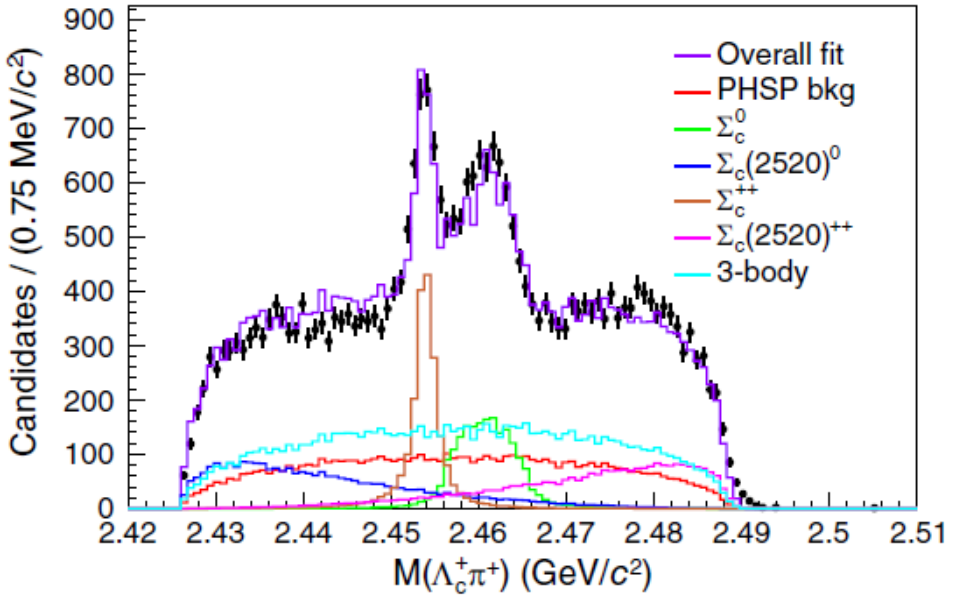
Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$	$3/2^-$	***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***

Measurement of $\Lambda_c\,(2625)^+ \to \Lambda_c^+\pi^+\pi^-$



Measurement of mass and width





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

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

- Mass difference

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

$(341.65 \pm 0.13\ MeV/c^2$ in PDG)

- Width

$$\Gamma < 0.52\ MeV$$

$(0.97\ MeV$ in PDG)

Much precise

- Branching fractions

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

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

$< 5\%$ in PDG

Summary

- Belle is actively working on hadron physics.
- Ξ^* resonances

  Observe $\Xi(1620)^0$ and $\Xi(1690)^0$ resonances in $\Xi_c^+ \to \Xi^-\pi^+\pi^+$

  $\Xi(1620)^0$ and $\Xi(1690)^0$ are candidates for $1/2^+$, $1/2^-$

  Finding structure at 1620 is asymmetric shape.

  There is another possibility for this structure, threshold cusp.
- Studies of thershold cusp

  Peak in pK^- of $\Lambda_c^+ \to pK^-\pi^+$ $\quad\to\quad$ the $\eta\Lambda$ threshold cusp

  Signal in $M(\Lambda\pi^\pm)$ in $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$ $\quad\to\quad$ the $\overline{K}N$ threshold cusp or Σ resonance?
- $\Lambda_c\,(2625)^+$

  Precise rearmament of mass and width, and first measurement of branching fraction ratio

  These measurements can be used as inputs to theoretical models to understand the $\Lambda_c(2625)^+$ resonance.
- Belle & Belle II will discover more hadrons, and measure observables of hadrons.