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Light Baryon Spectroscopy from e^+e^- Collision Experiments

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Outline

- **Introduction**
- **Selected light baryon results from BELLE**
  - observation of structures near KN threshold in $\Lambda\pi$ system
  - observation of a threshold cusp at the $\Lambda\eta$ threshold in the pK^- system
  - observation of $\Omega(2012)^- \to \Xi(1530)\, K^-$
- **Selected light baryon results from BESIII**
  - $\psi(3686) \to \Lambda\bar{\Lambda}\pi^0$, $\Lambda\bar{\Lambda}\eta$ and $\Lambda\bar{\Lambda}\omega$
  - $J/\psi \to \pi\Lambda\bar{\Sigma}$
  - Study of excited Ξ states in $\psi(3686) \to K^-\Lambda\bar{\Xi}^+ + c.c.$
- **Summary**

• N* and Δ* status (PDG 2024)

- Mostly from PWA of πN scattering data.
- The dedicated facilities at Bonn, Grenoble, and Mainz, and at the JLab and Spring-8
- High-precision cross sections and polarization observables provide more information

			Status as seen in									
Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***						
$N(1520)$	$3/2^-$	****	****	****	****	**	****					
$N(1535)$	$1/2^-$	****	****	****	***	*	****					
$N(1650)$	$1/2^-$	****	****	****	***	*	****	*				
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*			
$N(1680)$	$5/2^+$	****	****	****	****	***	*	*	*			
$N(1700)$	$3/2^-$	***	**	***	***	*	*			*		
$N(1710)$	$1/2^+$	****	****	****	*		***	**	*	*	*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	*	*	
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**		*	**
$N(1990)$	$7/2^+$	**	**	**			*	*	*			
$N(2000)$	$5/2^+$	**	**	*	**	*	*				*	
$N(2040)$	$3/2^+$	*		*								
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*	
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**
$N(2120)$	$3/2^-$	***	***	**	**	**		**	*		*	*
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*	
$N(2220)$	$9/2^+$	****	**	****			*	*	*			
$N(2250)$	$9/2^-$	****	**	****			*	*	*			
$N(2300)$	$1/2^+$	**		**								
$N(2570)$	$5/2^-$	**		**								
$N(2600)$	$11/2^-$	***		***								
$N(2700)$	$13/2^+$	**		**								

			Status as seen in					
Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	ΣK	$N\rho$	$\Delta\eta$
$\Delta(1232)$	$3/2^+$	****	****	****				
$\Delta(1600)$	$3/2^+$	****	****	***	****			
$\Delta(1620)$	$1/2^-$	****	****	****	****			
$\Delta(1700)$	$3/2^-$	****	****	****	****	*	*	
$\Delta(1750)$	$1/2^+$	*	*	*		*		
$\Delta(1900)$	$1/2^-$	***	***	***	*	**	*	
$\Delta(1905)$	$5/2^+$	****	****	****	**	*	*	**
$\Delta(1910)$	$1/2^+$	****	***	****	**	**		*
$\Delta(1920)$	$3/2^+$	***	***	***	***	**		**
$\Delta(1930)$	$5/2^-$	***	*	***	*	*		
$\Delta(1940)$	$3/2^-$	**	*	**	*			*
$\Delta(1950)$	$7/2^+$	****	****	****	**	***		
$\Delta(2000)$	$5/2^+$	**	*	**	*		*	
$\Delta(2150)$	$1/2^-$	*		*				
$\Delta(2200)$	$7/2^-$	***	***	**	***	**		
$\Delta(2300)$	$9/2^+$	**		**				
$\Delta(2350)$	$5/2^-$	*		*				
$\Delta(2390)$	$7/2^+$	*		*				
$\Delta(2400)$	$9/2^-$	**	**	**				
$\Delta(2420)$	$11/2^+$	****	*	****				
$\Delta(2750)$	$13/2^-$	**		**				
$\Delta(2950)$	$15/2^+$	**		**				

• Λ* and Σ* status (PDG 2024)

Starve for data. Mostly from γp and K-p experiments. New analyses performed by Kent group, JPAC group……

Particle	J^P	Overall status	Status as seen in — $N\overline{K}$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	$1/2^+$	****			$N\pi$ (weak decay)
$\Lambda(1380)$	$1/2^-$	**	**	**	
$\Lambda(1405)$	$1/2^-$	****	****	****	
$\Lambda(1520)$	$3/2^-$	****	****	****	$\Lambda\pi\pi, \Lambda\gamma, \Sigma\pi\pi$
$\Lambda(1600)$	$1/2^+$	****	***	****	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1670)$	$1/2^-$	****	****	****	$\Lambda\eta$
$\Lambda(1690)$	$3/2^-$	****	****	***	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1710)$	$1/2^+$	*	*	*	
$\Lambda(1800)$	$1/2^-$	***	***	**	$\Lambda\pi\pi, N\overline{K}^*$
$\Lambda(1810)$	$1/2^+$	***	**	**	$N\overline{K}^*$
$\Lambda(1820)$	$5/2^+$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1830)$	$5/2^-$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1890)$	$3/2^+$	****	****	**	$\Sigma(1385)\pi, N\overline{K}^*$
$\Lambda(2000)$	$1/2^-$	*	*	*	
$\Lambda(2050)$	$3/2^-$	*	*	*	
$\Lambda(2070)$	$3/2^+$	*	*	*	
$\Lambda(2080)$	$5/2^-$	*	*	*	
$\Lambda(2085)$	$7/2^+$	**	**	*	
$\Lambda(2100)$	$7/2^-$	****	****	**	$N\overline{K}^*$
$\Lambda(2110)$	$5/2^+$	***	**	**	$N\overline{K}^*$
$\Lambda(2325)$	$3/2^-$	*	*		
$\Lambda(2350)$	$9/2^+$	***	***	*	
$\Lambda(2585)$		*	*		

Particle	J^P	Overall status	Status as seen in — $N\overline{K}$	$\Lambda\pi$	$\Sigma\pi$	Other channels
$\Sigma(1193)$	$1/2^+$	****				$N\pi$ (weak decay)
$\Sigma(1385)$	$3/2^+$	****		****	****	$\Lambda\gamma$
$\Sigma(1580)$	$3/2^-$	*	*	*	*	
$\Sigma(1620)$	$1/2^-$	*	*	*	*	
$\Sigma(1660)$	$1/2^+$	***	***	***	***	
$\Sigma(1670)$	$3/2^-$	****	****	****	****	
$\Sigma(1750)$	$1/2^-$	***	***	**	***	$\Sigma\eta$
$\Sigma(1775)$	$5/2^-$	****	****	****	**	
$\Sigma(1780)$	$3/2^+$	*	*	*	*	
$\Sigma(1880)$	$1/2^+$	**	**	*		
$\Sigma(1900)$	$1/2^-$	**	**	*	**	
$\Sigma(1910)$	$3/2^-$	***	*	*	**	
$\Sigma(1915)$	$5/2^+$	****	***	***	***	
$\Sigma(1940)$	$3/2^+$	*	*		*	
$\Sigma(2010)$	$3/2^-$	*	*	*		
$\Sigma(2030)$	$7/2^+$	****	****	****	**	$\Delta(1232)\overline{K}, N\overline{K}^*, \Sigma(1385)\pi$
$\Sigma(2070)$	$5/2^+$	*	*		*	
$\Sigma(2080)$	$3/2^+$	*		*		
$\Sigma(2100)$	$7/2^-$	*	*	*	*	
$\Sigma(2110)$	$1/2^-$	*	*	*	*	
$\Sigma(2230)$	$3/2^+$	*	*	*	*	
$\Sigma(2250)$		**	**	*	*	
$\Sigma(2455)$		*	*			
$\Sigma(2620)$		*	*			
$\Sigma(3000)$		*	*	*		
$\Sigma(3170)$		*				

• Ξ* status (PDG 2024)

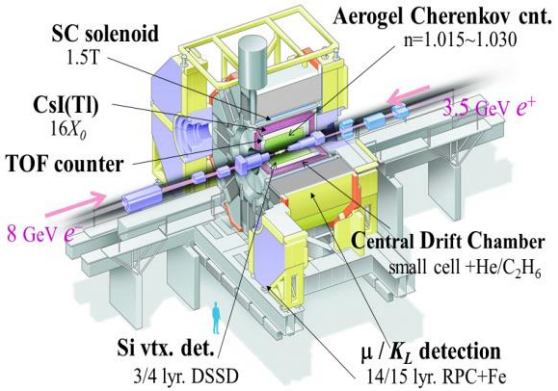
Most of our present knowledge of Ξ resonances comes from the low-statistics data samples recorded in the early days. In Recent years, significant contributions have come from collider experiments.

Particle	J^P	Overall status	Status as seen in $\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$
$\Xi(1318)$	1/2+	****				
$\Xi(1530)$	3/2+	****	****			
$\Xi(1620)$		**	**			
$\Xi(1690)$		***	**	***	**	
$\Xi(1820)$	3/2−	***	**	***	**	**
$\Xi(1950)$		***	**	**		*
$\Xi(2030)$		***		**	***	
$\Xi(2120)$		*		*		
$\Xi(2250)$		**				
$\Xi(2370)$		**				
$\Xi(2500)$		*		*	*	

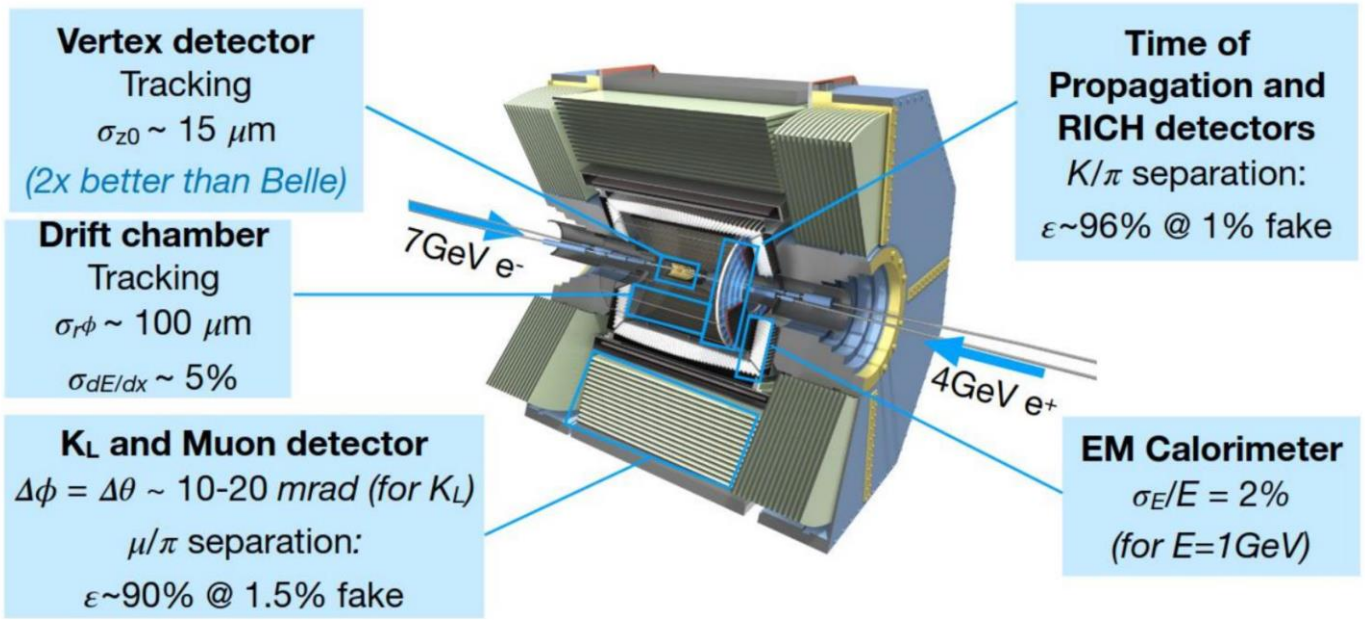
Study light baryons experimentally

- Fixed-target experiments
  - Photo-/electro-production exps., e.g. JLAB, ELSA@Bonn, MAMI, …
    $\gamma N\ (e^- N) \rightarrow (e^-)\ N^*/\Delta^*$
    $\gamma N\ (e^- N) \rightarrow (e^-)\ K\ \Lambda^*\ /\Sigma^*$
  - π/K-induced production exps., e.g. HADES@GSI, J-PARC in Japan, JLAB…
    $\pi N \rightarrow N^*/\Delta^*$, …
- Collider experiments
  - e^+e^- collision exps., e.g. BESIII, BELLE(2), BaBar, …
    - directly from $e^+e^- \rightarrow J/\psi$ or $\psi(2S) \rightarrow$ baryon + anti-baryon
    - from c-baryons or b-baryons decay
  - pp collision exps., e.g. LHC
    from b-baryons decay

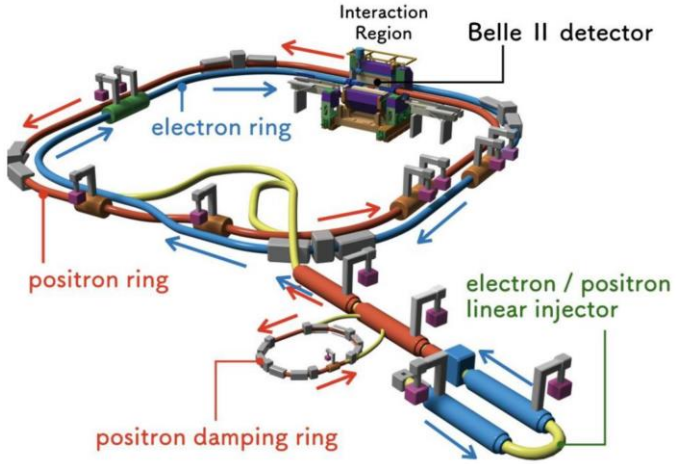
BELLE (BELLE II) @KEKB (SuperKeKB)



From BELLE to BELLE II



- Beams: 8 X 3.5 GeV, 22mrad crossing
- Data taking: 1999 – 2010
- On/off/Scan Υ(nS) peaks
- Total luminosity: 980 fb^{-1}
- 772M $B\bar{B}$ events @$\Upsilon(4S)$

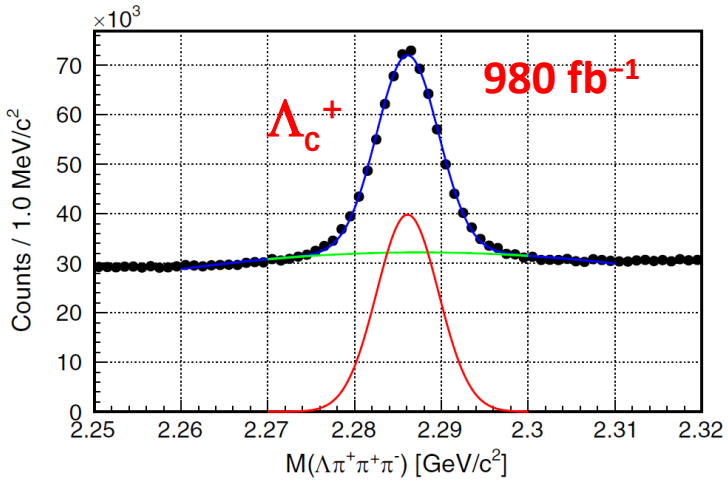


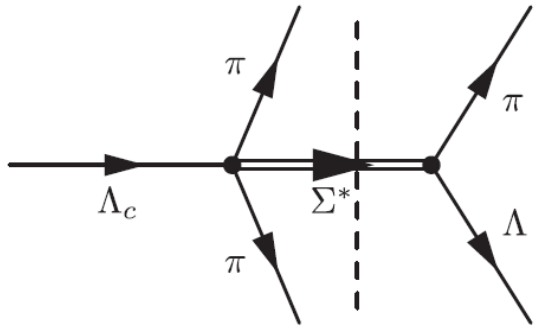
- SuperKEKB
  - higher beam current (× 2)
  - smaller beam focus (×1/20) @IR
- Belle II upgrades
  In all parts of the detector
(vertex, resolution, trigger, and DAQ, …)

Structures near $\overline{K}N$ threshold in $\Lambda\pi$ system

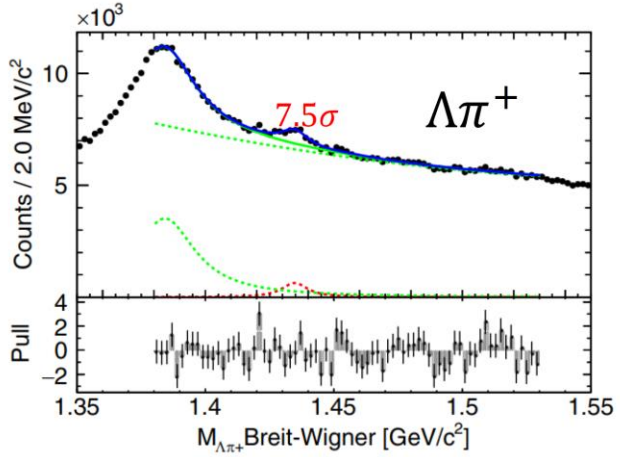
Belle, PRL 130, 151903 (2023)

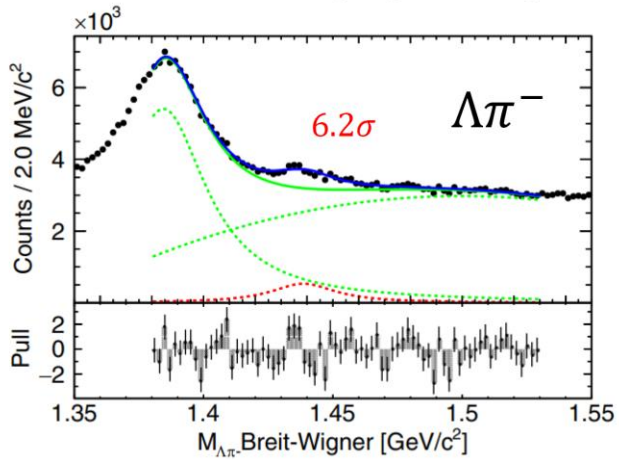
$\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$





- **Fit with BW, describes Σ*:**





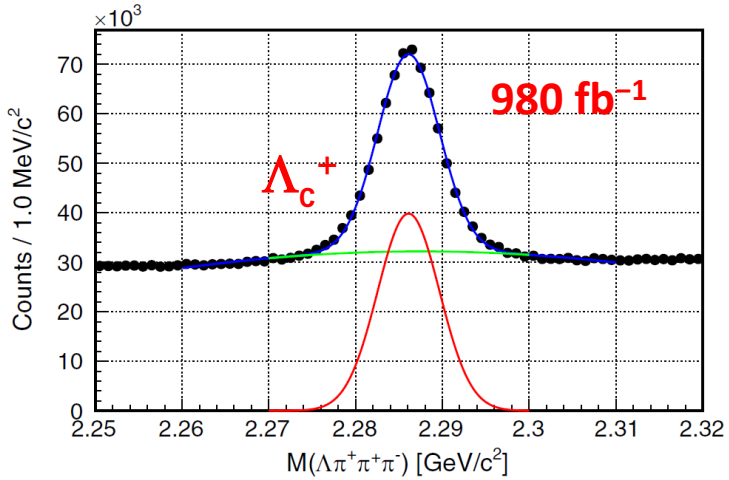
Mode	$E_{\rm BW}$ (MeV/c^2)	Γ (MeV/c^2)	χ^2/NDF
$\Lambda\pi^+$	1434.3 ± 0.6	11.5 ± 2.8	74.4/68
$\Lambda\pi^-$	1438.5 ± 0.9	33.0 ± 7.5	92.3/68

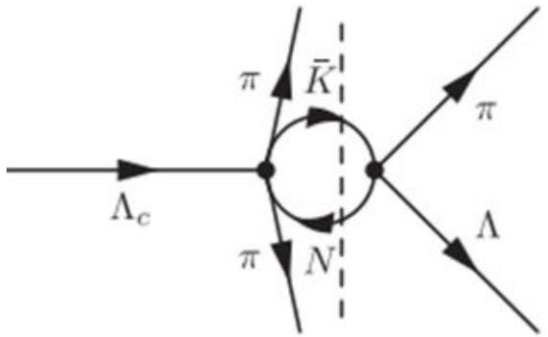
- **The only known I=1 state in this mass region is Σ(1385).**
- **QM doesn't predict any more states**
- **Σ*: exotic state?**

Structures near $\bar{K}N$ threshold in $\Lambda\pi$ system

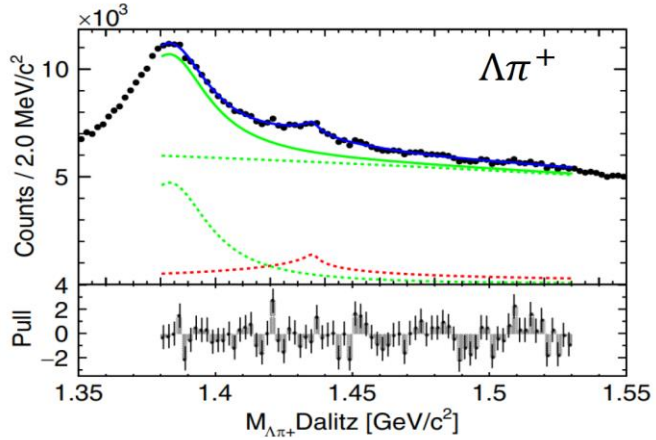
Belle, PRL 130, 151903 (2023)

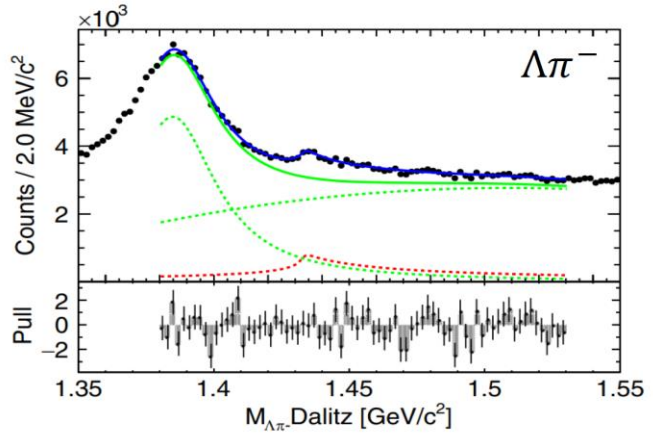
$\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$





- $\bar{K}N$ cusp : fit with Dalitz Model, neglect Λ_c^+ form factor
  K-N complex scattering length A=a+ib





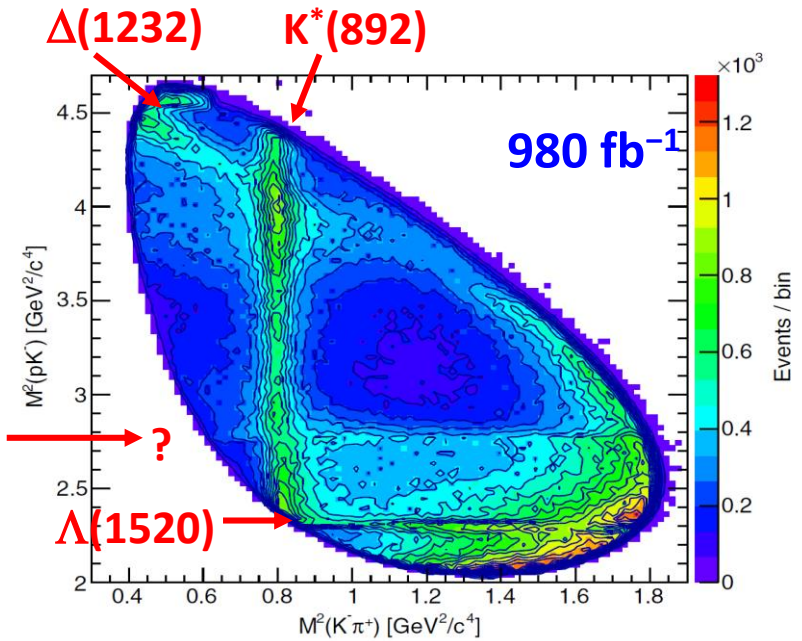
Mode	a (fm)	b (fm)	χ^2/NDF
$\Lambda\pi^+$	0.48 ± 0.32	1.22 ± 0.83	68.9/68
$\Lambda\pi^-$	1.24 ± 0.57	0.18 ± 0.13	78.1/68

- Scattering length is larger than previous K-p exps.

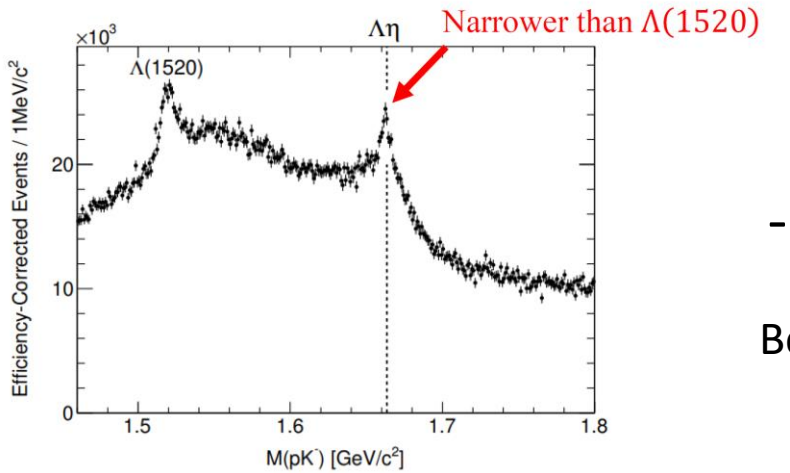
Limited by the statistics and the shape of the background, cannot distinguish between Σ resonances and $\bar{K}N$ threshold cusps.

A threshold cusp at the Λη threshold in the pK⁻ system

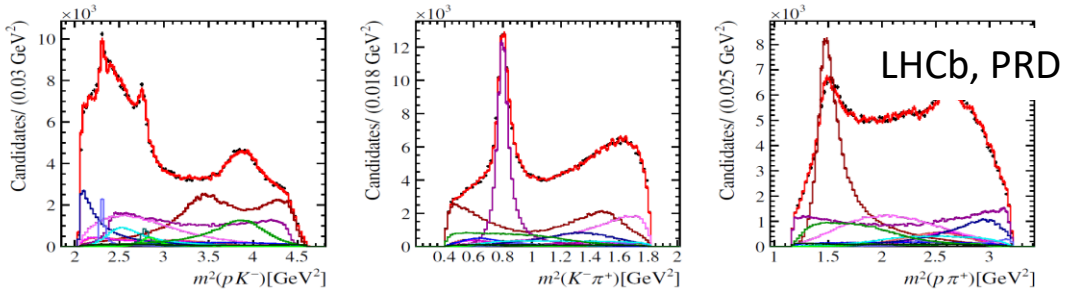
Belle, PRD 108, L031104 (2023)



Belle. PRL 117, 011801 (2016)



- Observation of Doubly Cabibbo-Suppressed (DCS) decay $\Lambda_c^+ \to pK^+\pi^-$ at Belle in 2016.
- Hint of a peaking structure in the pK^- mass spectrum near the $\Lambda\eta$ threshold (from Dalitz plot)
- A similar structure seen by LHCb in $\Lambda_c^+ \to pK^-\pi^+$



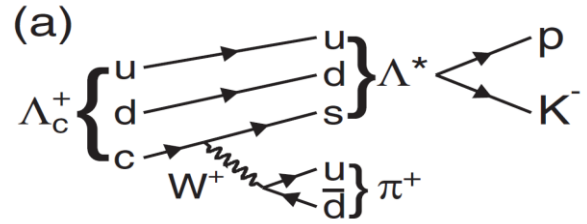
LHCb, PRD 108, 012023 (2023)

- Narrow peak observed in $\Lambda_c^+ \to pK^-\pi^+$ at Belle

Belle, PRD 108, L031104 (2023)

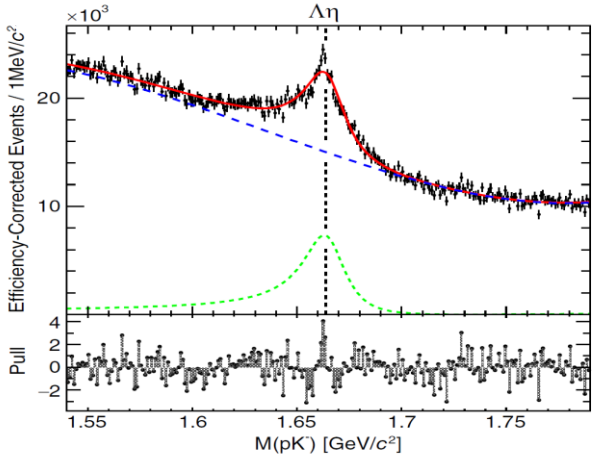
Two approaches to describe the narrow peak:

- **Breit-Wigner for a new resonance**



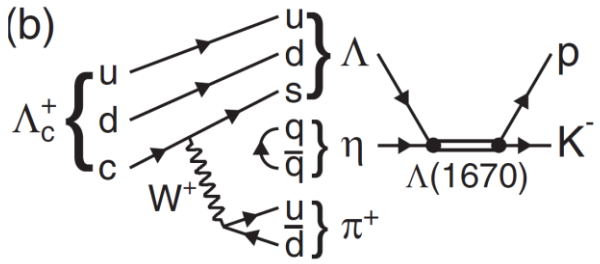
Adding a complex constant to the non-relativistic BW coherently to have a better fit.

$dN/dm \propto | BW(m) + r\, e^{i\theta} |^2$



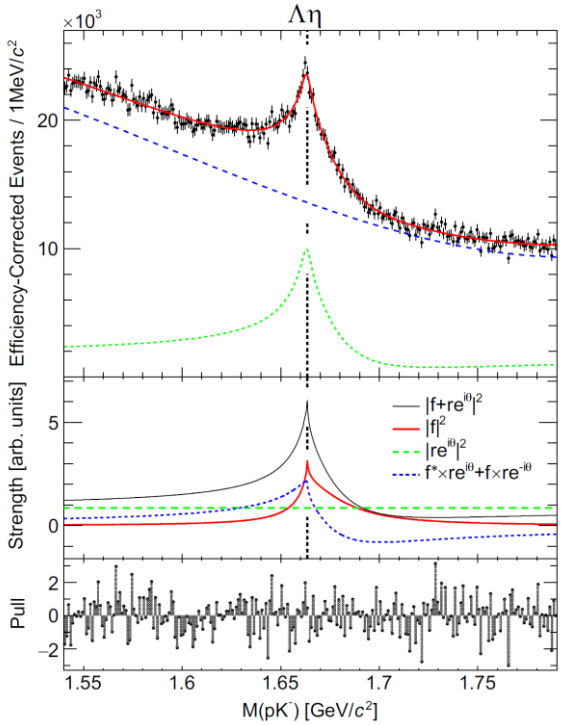
Mass (MeV/c^2)	Width (MeV)	χ^2/ndof
1665.4±0.5	23.8±1.2	1.27(308/243)

- **A cusp enhanced by nearby Λ(1670) pole, described by a non-relativistic Flatte function**



Adding a complex constant to the non-relativistic Flatte function.

Mass (MeV/c^2)	Width (MeV)	$g_{\Lambda\eta}$	χ^2/ndof
1674.4(fix)	27.2±1.9	0.258±0.023	1.06(257/243)

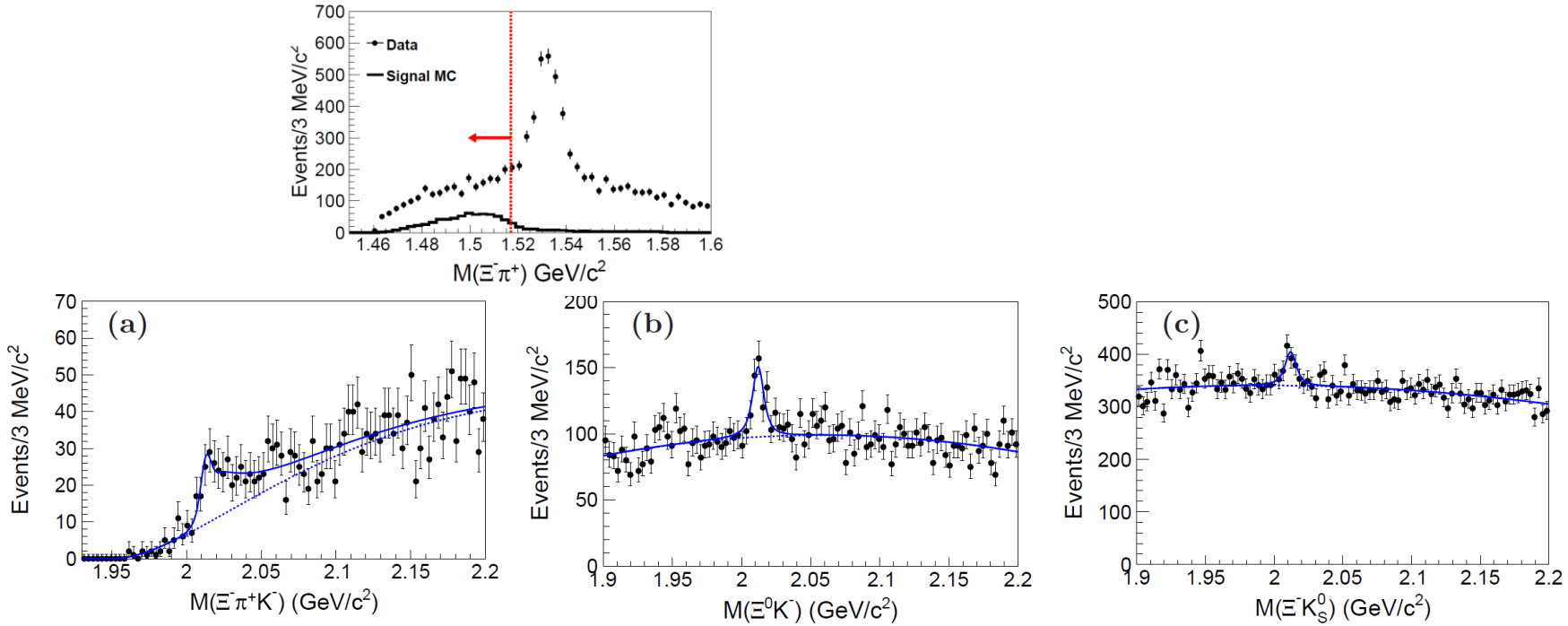


Flatte function is slightly favored than BW function.

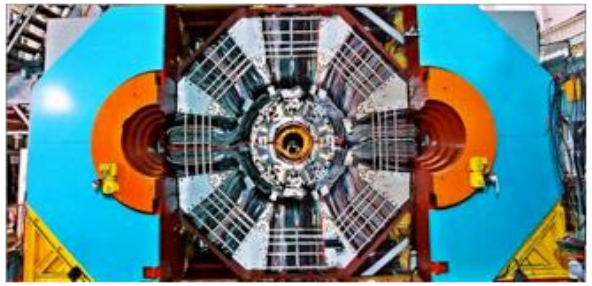
Observation of $\Omega(2012)^- \to \Xi(1530)\,\bar{K}$

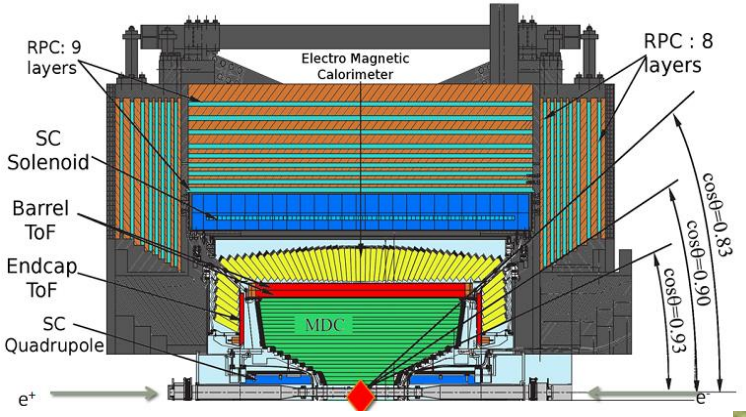
Belle, arXiv:2207.03090

- Only 4 excited Ω^- baryons listed on PDG -- $\Omega(2012)^-$, $\Omega(2250)^-$, $\Omega(2380)^-$, $\Omega(2470)^-$
- $\Omega(2250)^-$, $\Omega(2380)^-$, $\Omega(2470)^-$ observed four decades ago
- $\Omega(2012)^-$ first observed by Belle in 2018, from its decays to Ξ^0K^- and $\Xi^-K_s^0$



BESIII @ Beijing Electron Positron Collider (BEPC) – charm facility





MDC: spatial reso. 115μm
dE/dx reso: 5%
EMC: energy reso.: 2.4%
BTOF: time reso.: 70 ps
ETOF: time reso.: 120 → 60 ps

beam energy: 1.0 – 2.3 GeV (2.45)(2.8)

LINAC

e^+

e^-

BESIII detector

τ-charm Physics

2004: started BEPCII upgrade, BESIII construction
2009 - now: BESIII physics run

- **1989-2004 (BEPC):**
  L_{peak}=1.0x10^{31} /cm^{2}s
- **2009-now (BEPCII):**
  L_{peak}= 1.0 x10^{33}/cm^2(2016, designed L)
  L_{peak}= 1.1x10^{33}/cm^2(2023)

BESIII Data Samples

Totally about 50 fb^{-1} integrated luminosity from 2.0-4.95 GeV

Data sets collected so far include

- 10×10^9 J/ψ events
- 2.7×10^9 $\psi(2S)$ events
- 20 fb^{-1} $\psi(3770)$
- Scan data between

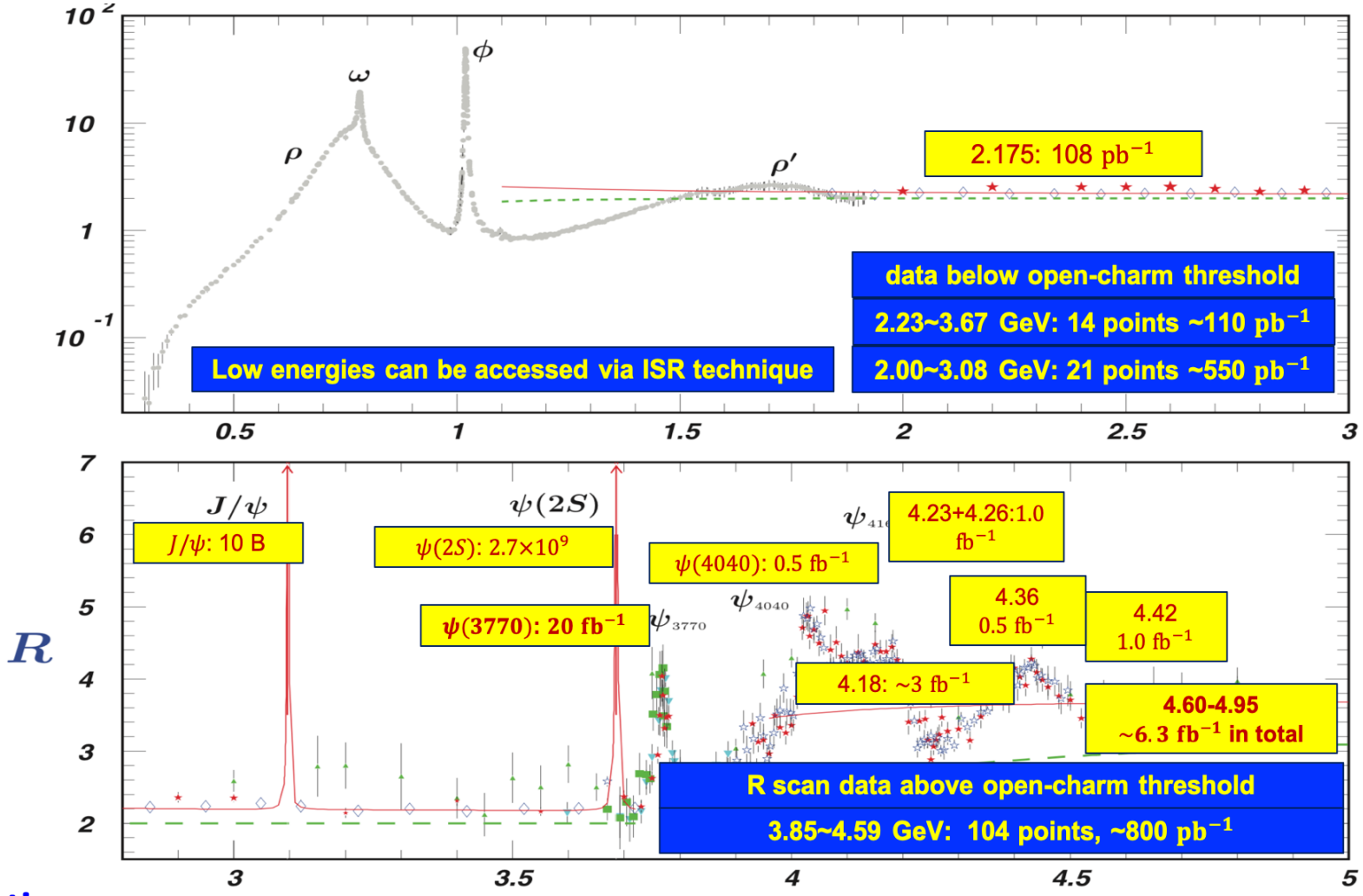
  1.84-1.97 GeV (13 points, 25 pb^{-1})

  2.0 and 3.08 GeV,

  and above 3.74 GeV
- Large datasets for XYZ studies:

  scan with >500 pb^{-1} per energy point

  space 10 – 20 MeV apart
- Entangled hadron pair-productions near thresholds: form-factors, relative phase, polarization and CP violation.



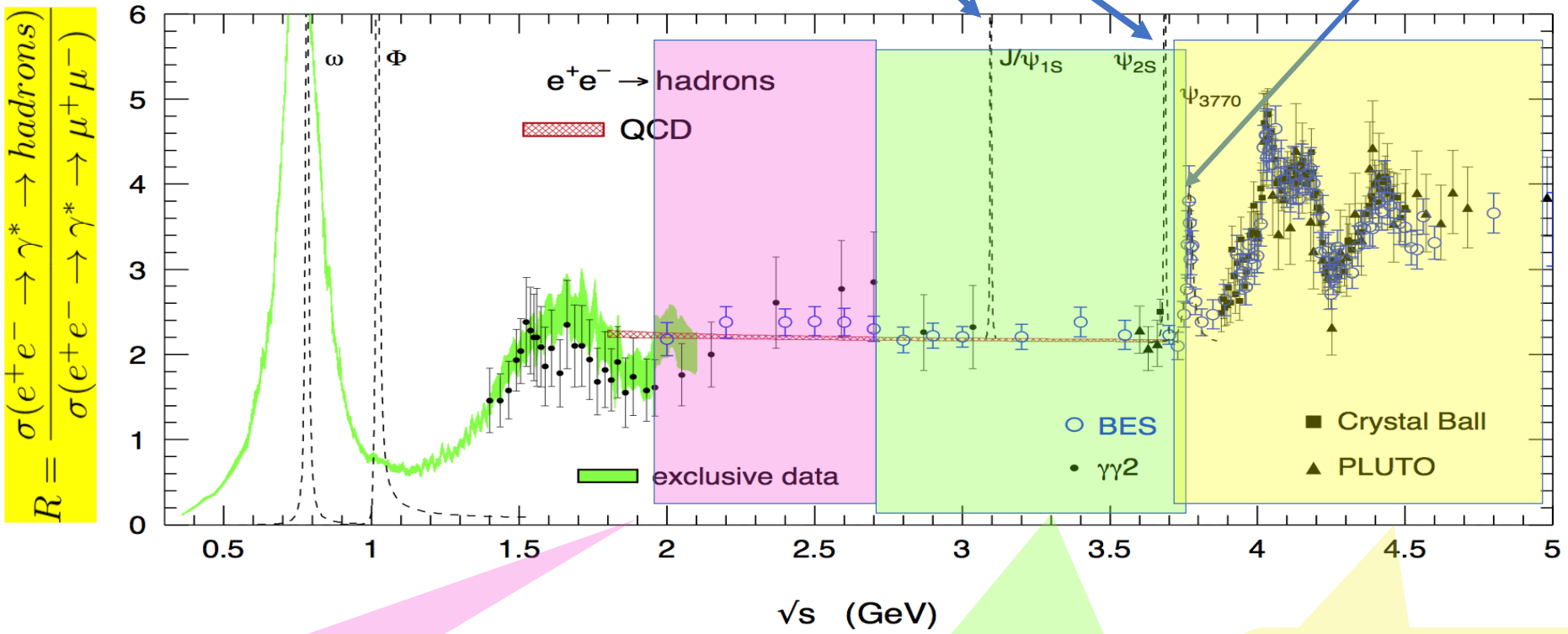
Hadron structure & dynamics in the non-perturbative QCD regime

13

Physics program

$\sigma(e^+e- \to J/\psi(\psi(2S)) = 3000\,nb(700\,nb)$

$\sigma(e^+e- \to \psi(3770)) = 6.5nb$



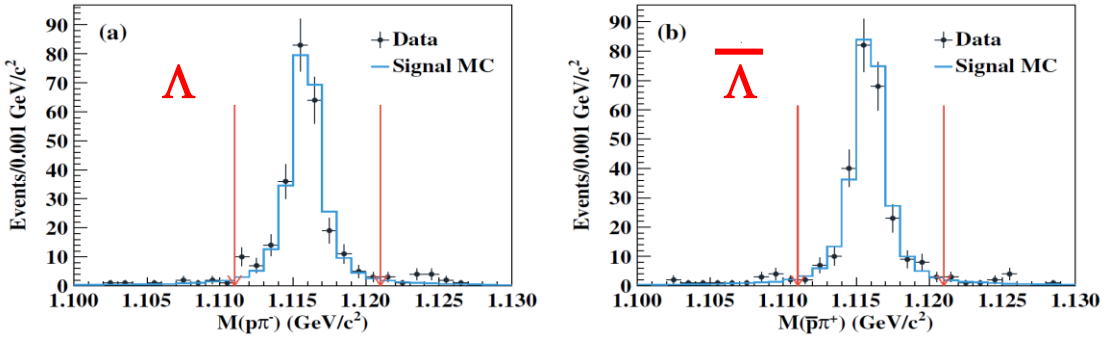
- Hadron form factors
- R values and QCD

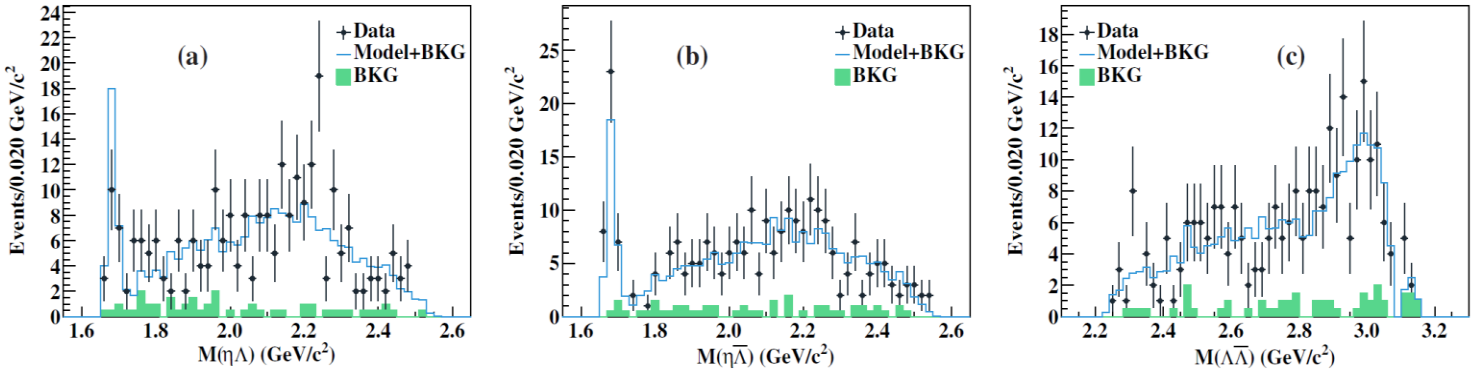
- Light hadron spectroscopy
- Gluonic and exotic states
- Physics with t lepton

- XYZ particles
- Charm mesons
- Charm baryons

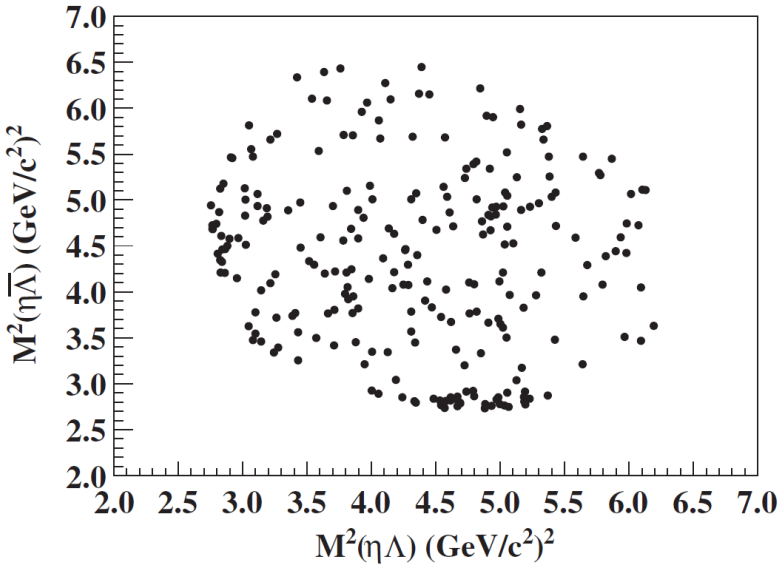
$\psi(3686) \to \Lambda\bar{\Lambda}\eta$

BESIII, PRD 106, 072006 (2022)





446M ψ(3686) data



- Totally about 218±17 events
- BG from η sideband
- Partial wave analysis is performed
- The peak favors Λ(1670)

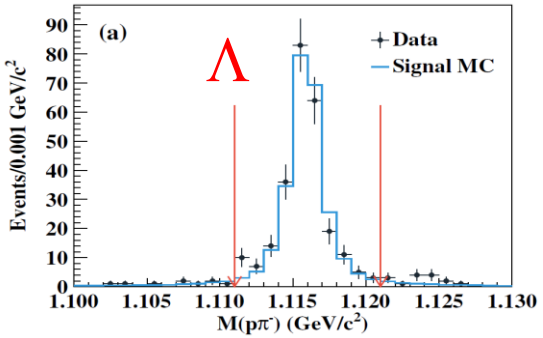
$$\mathrm{BW}(s) = \frac{1}{M_{\Lambda^*}^2 - s - iM_{\Lambda^*}\Gamma_{\Lambda^*}}$$

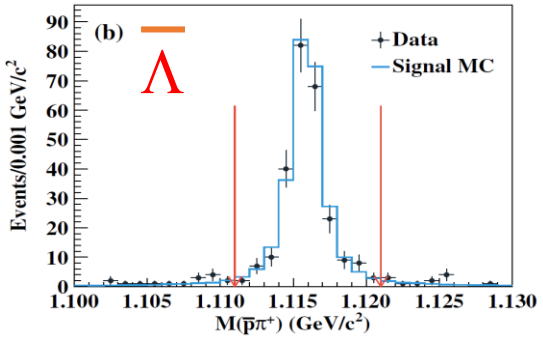
M=(1672 ±5 ±6) MeV/c², Γ=(38 ±10 ±19) MeV

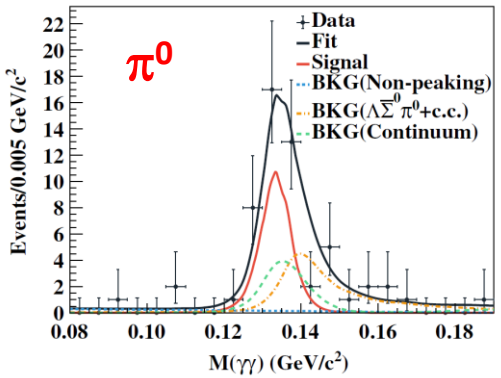
$\psi(3686) \to \Lambda\bar{\Lambda}\pi^0$ and $\Lambda\bar{\Lambda}\omega$

$\psi(3686) \to \Lambda\bar{\Lambda}\pi^0$

446M $\psi(3686)$ data



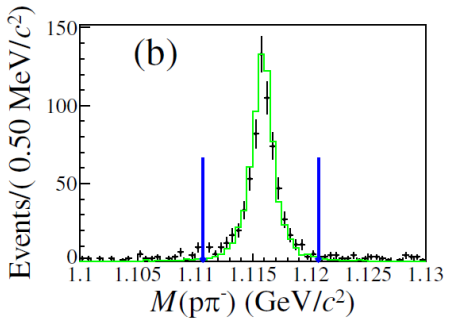


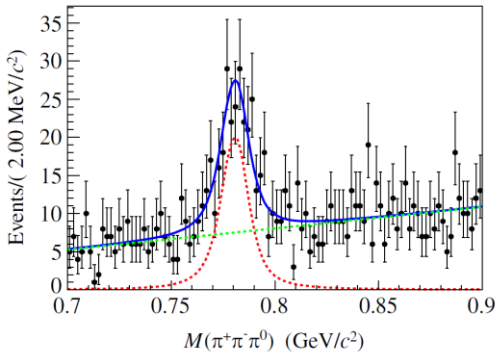


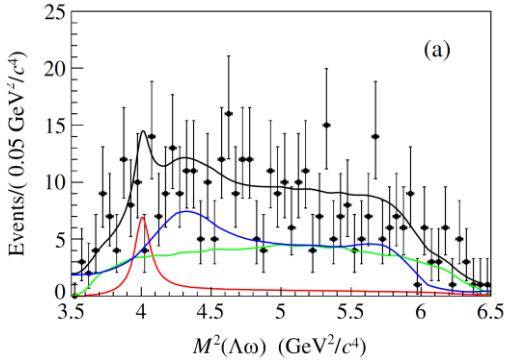
- Peaking BG from $\Lambda\Sigma^0\pi^0$ and continuum
- Evidence of isospin violating decay $\psi(3686) \to \Lambda\Lambda\pi^0$, ~3 σ

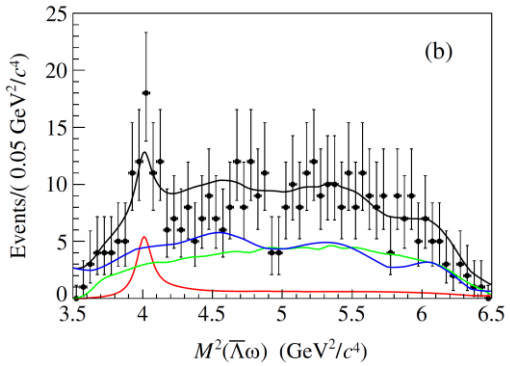
BESIII, PRD 106, 072006 (2022)

$\psi(3686) \to \Lambda\bar{\Lambda}\omega$





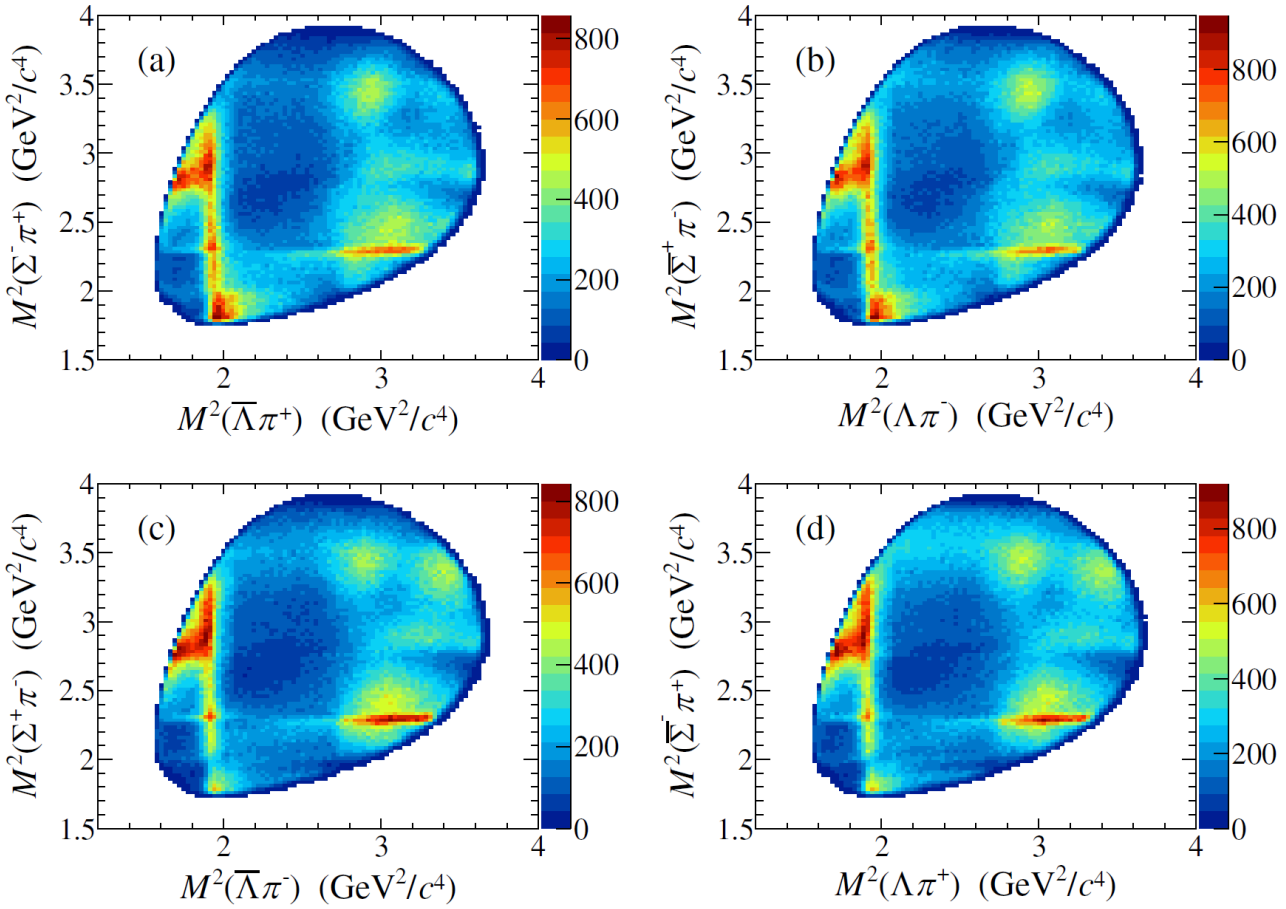




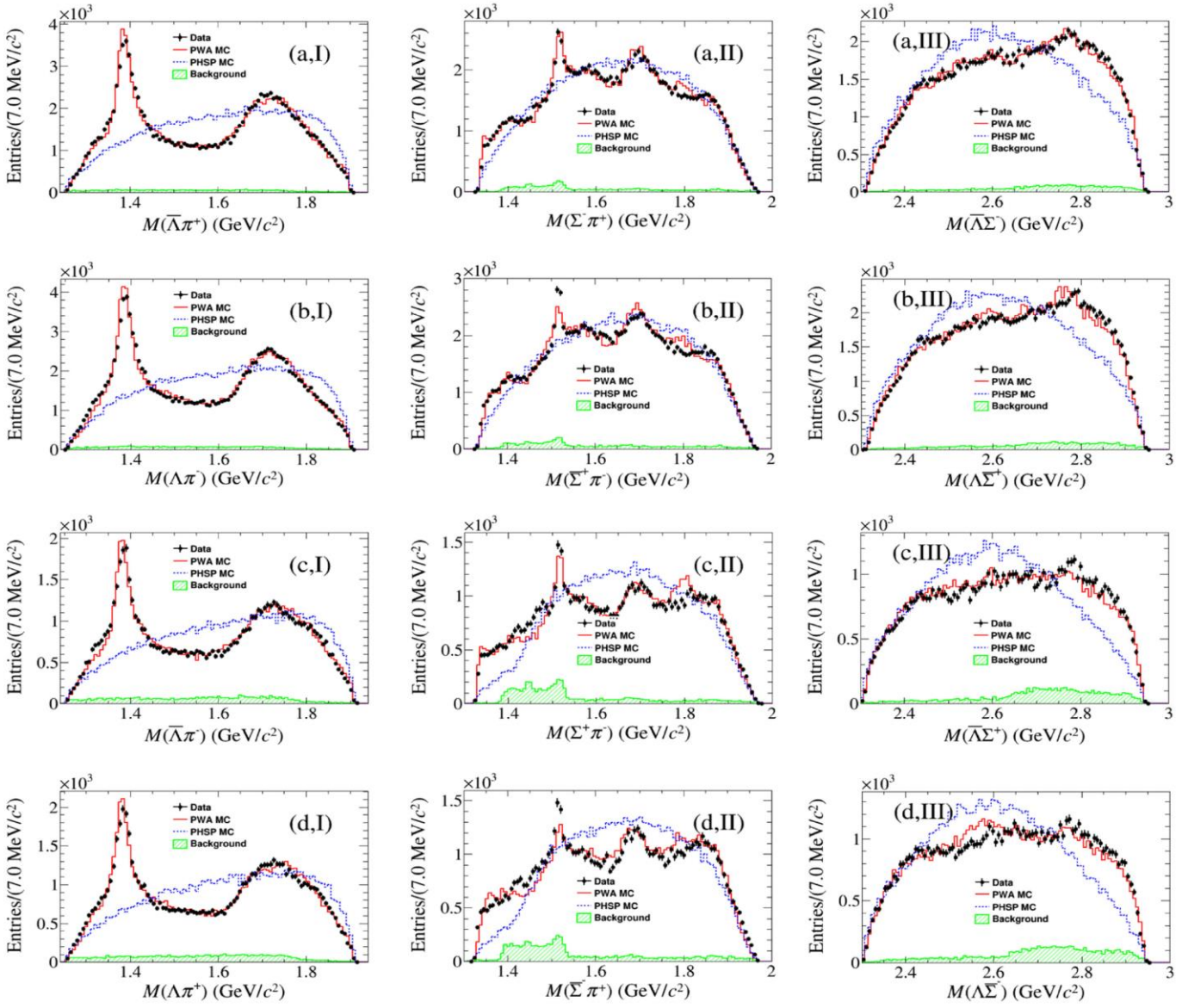
- Hint of the excited Λ state in $\Lambda\omega(\bar{\Lambda}\omega)$ mass spectrum
- 2.7 billion $\psi(3686)$ data will be analyzed

BESIII, PRD 106, 112011(2022)

$J/\psi \to \bar{\Lambda}\pi^+\Sigma^- + \text{c.c.}$ and $J/\psi \to \bar{\Lambda}\pi^-\Sigma^+ + \text{c.c.}$



BESIII, PRD 108, 112012(2023)



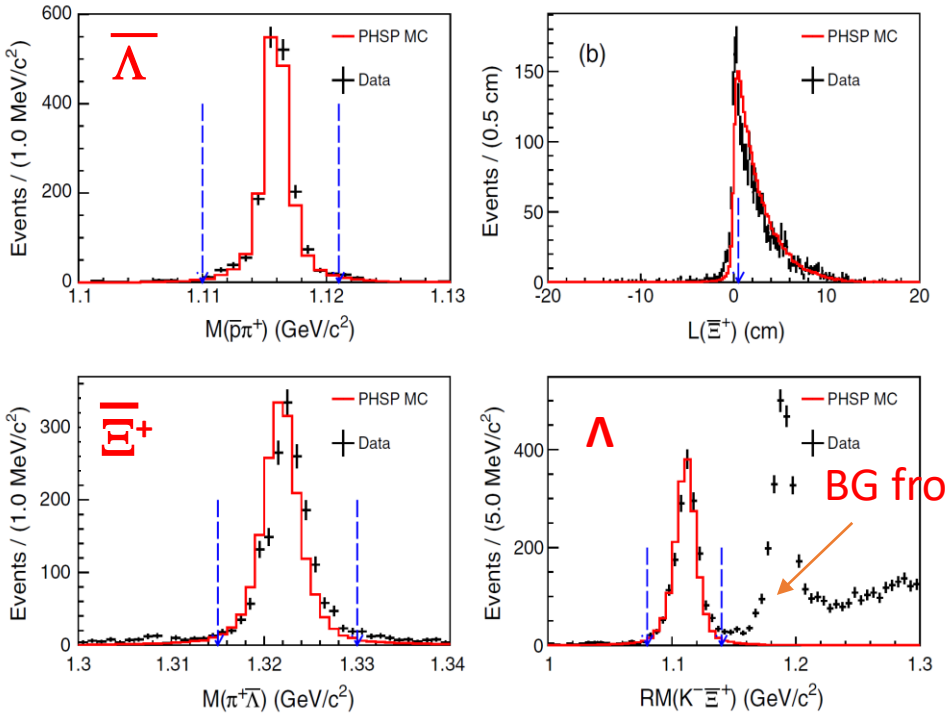
A full partial wave analysis is on the way.

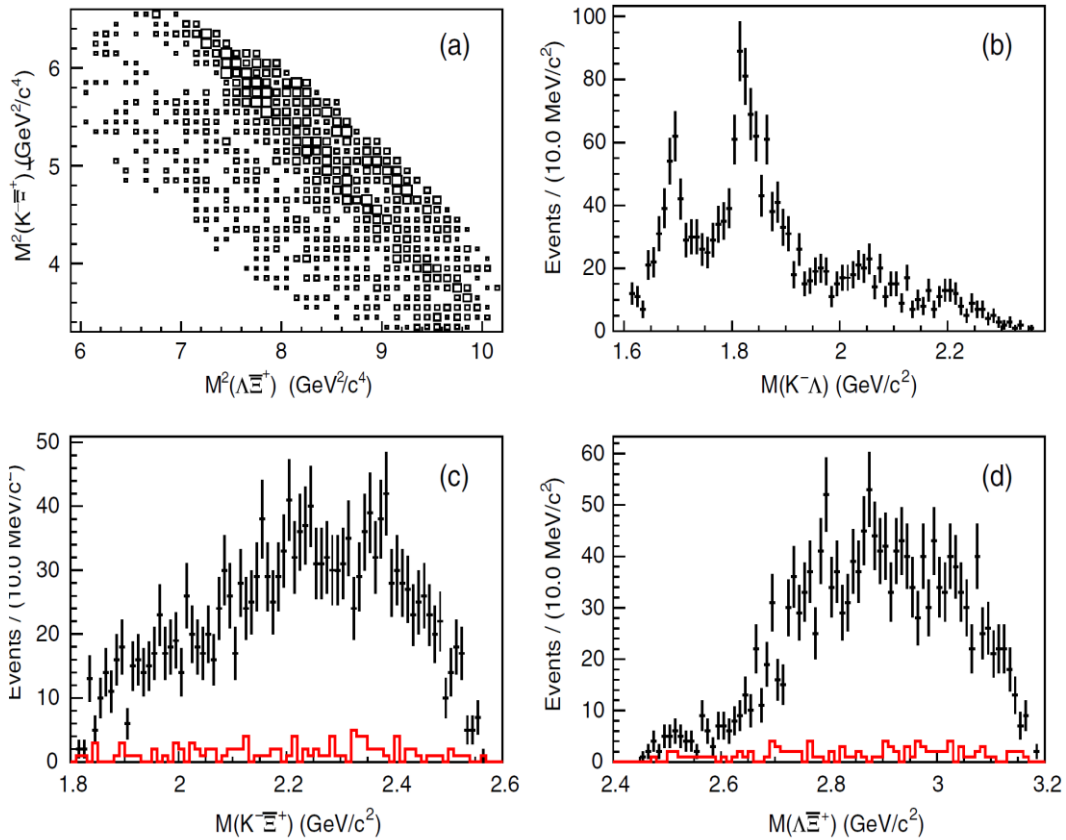
Study of excited Ξ states in ψ(3686) → $K^-\Lambda\bar{\Xi}^+$ + c.c.

446M ψ(3686) data

- Partial reconstruction is used to improve the statistics
  The four-momentum of prompt Λ is calculated from the recoil of $K^-\,\bar{\Xi}^+$ system

BESIII, PRD 109, 072008(2024)



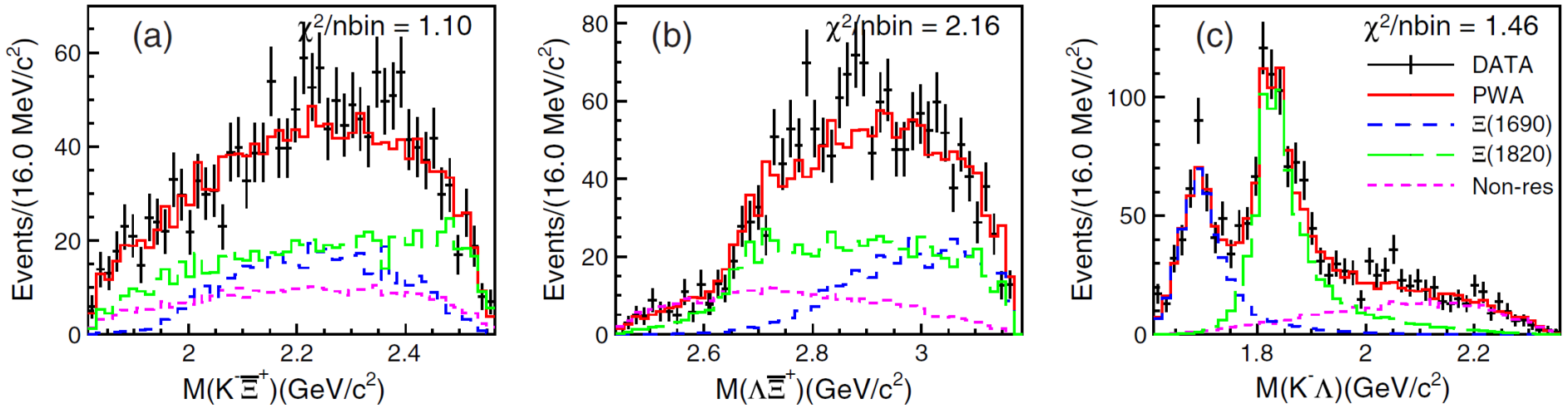


- Partial wave analysis is performed

$$\mathrm{BW}(s) = \frac{1}{M^2_{\Xi^*} - s_{K\Lambda} - iM_{\Xi^*}\Gamma_{\Xi^*}},$$

G. Penner and U. Mosel, Phys. Rev. C **66**, 055211 (2002).
W. H. Liang, P. N. Shen, B. S. Zou, and A. Faessler, Eur. Phys. J. A **21**, 487 (2004).

$$J = \frac{1}{2}: \; F_N(s_{K\Lambda}) = \frac{\lambda_1^4}{\lambda_1^4 + (s_{K\Lambda} - M^2_{\Xi^*})^2} \qquad J = \frac{3}{2}, \frac{5}{2}: \; F_N(s_{K\Lambda}) = e^{\frac{-|s_{K\Lambda} - M^2_{\Xi^*}|}{\lambda_2^2}}$$



Resonance	$I(J^P)$	M (MeV/c^2)	Γ (MeV)
$\Xi(1690)^-$	$1/2(1/2^-)$	$1685^{+3}_{-2} \pm 12$	$81^{+10}_{-9} \pm 20$
$\Xi(1820)^-$	$1/2(3/2^-)$	$1821^{+2}_{-3} \pm 3$	$73^{+6}_{-5} \pm 9$

A partial wave analysis for the full data set (2.7 billion ψ(3686)) is on the way.

Summary

- **from BELLE**
  - the structure near $\bar{K}N$ threshold in $\Lambda\pi$ mass spectrum, cannot distinguish whether it is a new resonance or a cusp
  - a threshold cusp at the $\Lambda\eta$ threshold in the pK^- system is observed
  - new decay mode of $\Omega(2012)^- \rightarrow \Xi(1530)\, K^-$ observed
- **from BESIII**
  - $\psi(3686) \rightarrow \Lambda\bar{\Lambda}\pi^0$, $\Lambda\bar{\Lambda}\eta$ and $\Lambda\bar{\Lambda}\omega$ (448 M data)
  - $J/\psi \rightarrow \pi\Lambda\bar{\Sigma}$, lots of intermediate states, full PWA is on the way
  - $\Xi(1690)$ (1/2-) and $\Xi(1820)$(3/2-) established in $\psi(3686) \rightarrow K^-\Lambda\bar{\Xi}^+ + c.c.$, PWA to a full data set (2.7 Billion $\psi(3686)$) on the way

✓ Large charmonium data samples from BESIII provide good chances.

Phase space not big enough for high mass excited baryon states.

✓ Decays of c-baryons and b-baryons: for light baryon study.

✓ Wait for BELLE II and BESIII/BEPCII upgrade.

Thanks for your attention