Baryon spectroscopy at BESIII

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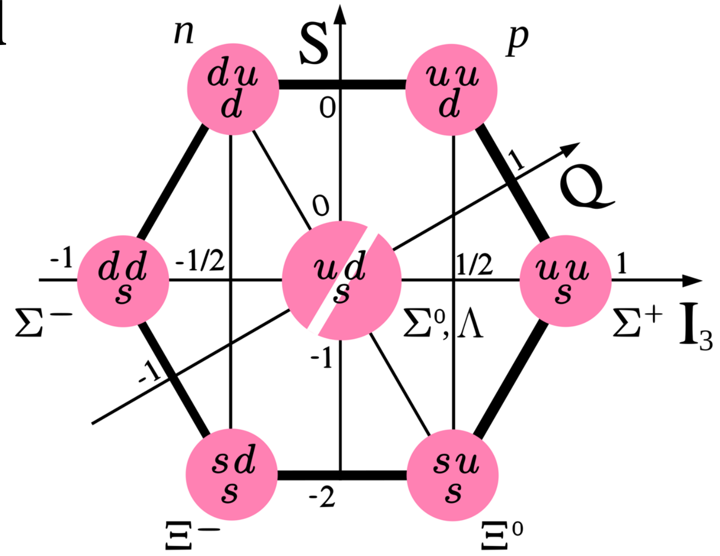
Outline

- Motivation
- BEPCII and BESIII detector
- Recent results
- Summary

Baryonic States

- All ground baryonic states are well established
  - Good agreement between experimental data and quark model
- The excited spectrum is much less clear
  - Many more states predicted than observed
- Insight to hadron structure



A simple 3-quark structure for the light baryons

Issues in baryon spectroscopy:

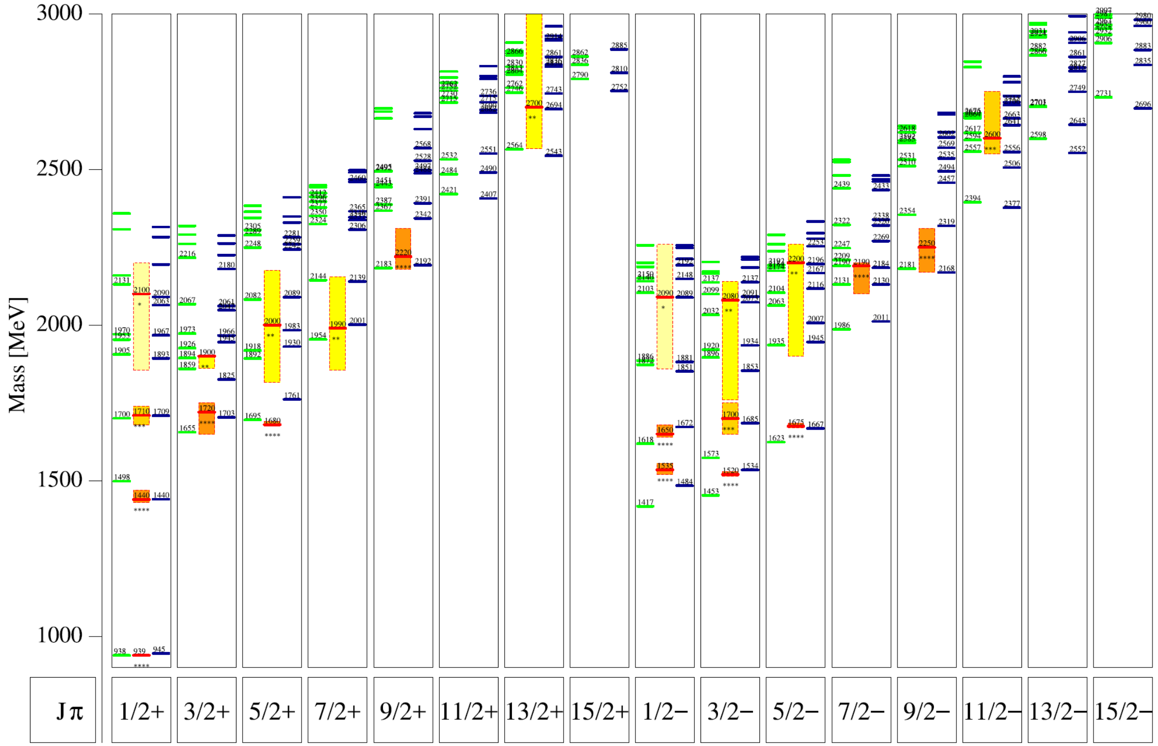
- Threshold enhancement
- Missing resonance of N^*, Λ^*, Σ^*, ...
- Multiquark baryon
- ……

Missing Resonances

- Many of the predicted resonances were not observed experimentally
- Experimental and theoretical efforts
- Experimentally:
  - baryon resonances may couple very weakly to single pions
- Theoretically:
  - the baryon spectrum can be modeled with fewer effective
  - degrees of freedom (quark-diquark or Y/Δ-type models)

Relativistic quark model
Nucleon-resonances spectrum
Potential model: A(green) and C(blue)

Prog.Part.Nucl.Phys. **125 (2022) 103949**



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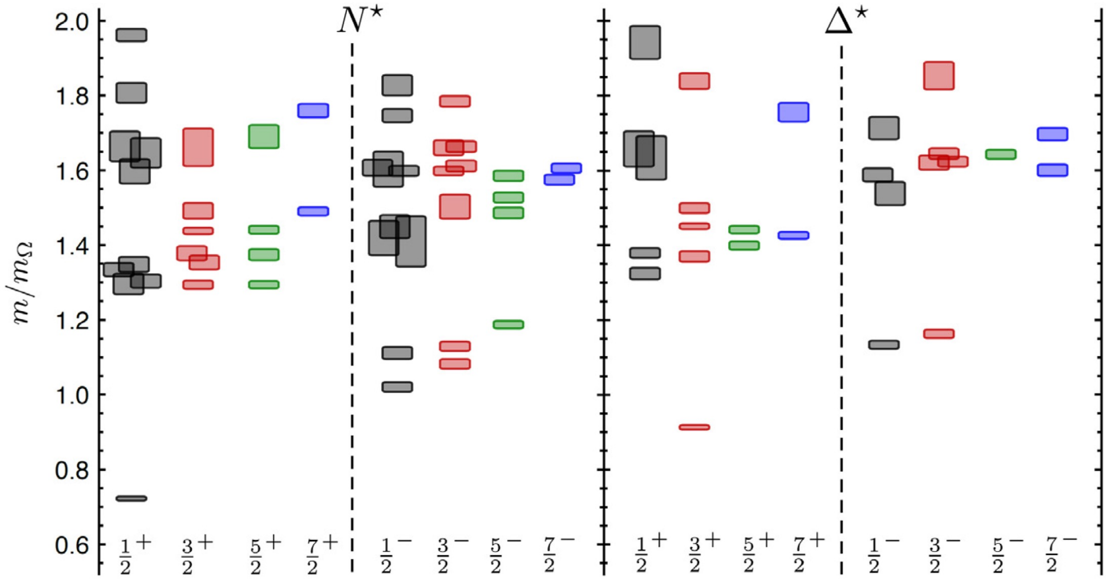
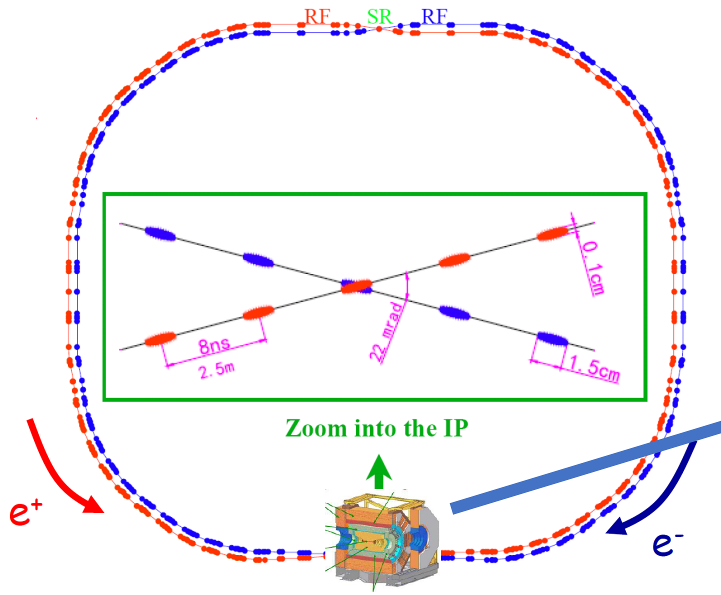
Lattice QCD
Nucleon- and Δ-resonances spectrum
$m_\pi = 396$ MeV
$m_\Omega \simeq 1672$ MeV

***Phys.Rev.D* 84 (2011) 074508**

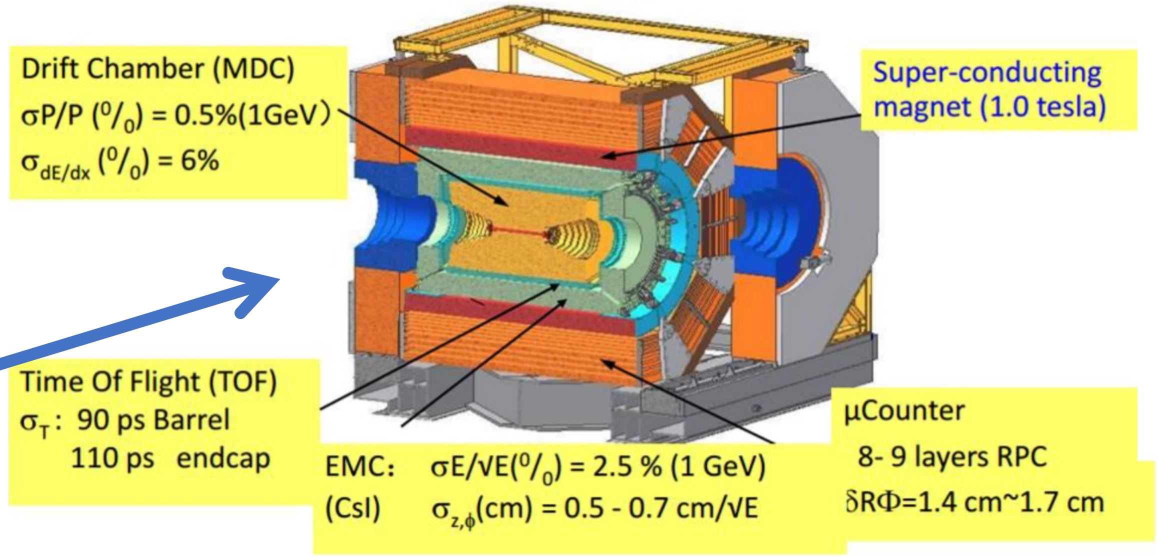


BESIII at BEPCII

Beijing Electron-Positron Collider II



The BESIII Detector

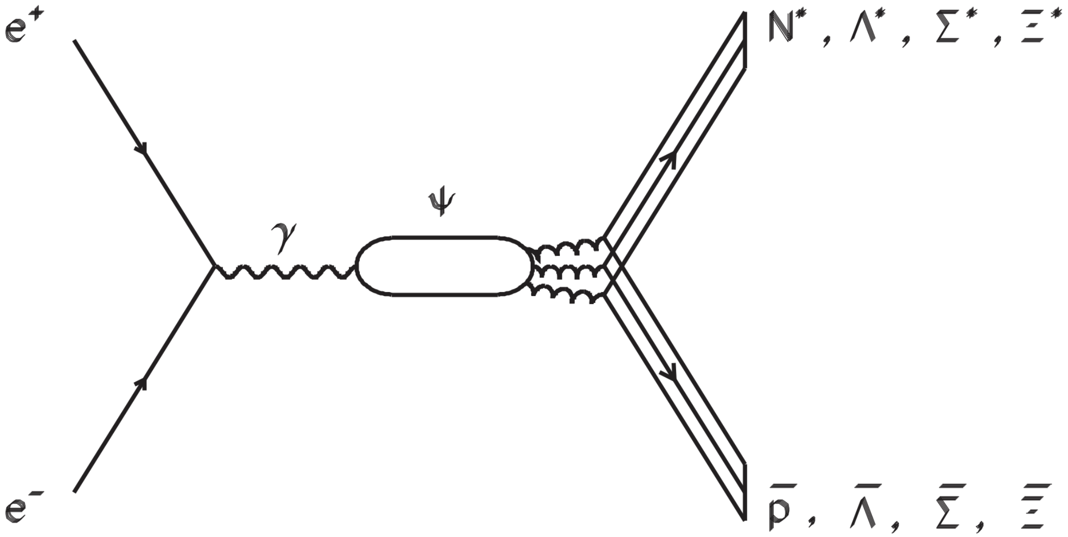


Symmetric electron-positron collider BEPCII:

- energy range: $\sqrt{s} = 2.0 - 4.6$ GeV (~5 GeV since summer 2019)
- design luminosity achieved: 1×10^{33} cm^{-2} s^{-1} $\left(at\ \psi(3770)\right)$
- operating since 2008

Why BESIII is complementary for baryon spectroscopy study?

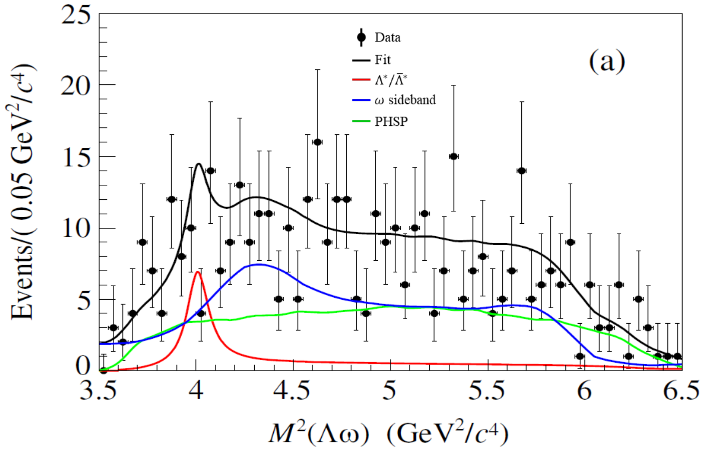
- When compared to hadron collider or fixed target experiments, electron positron collision has a different production method:
  - the direct production: vector state
  - Background is low, and the initial state (energy, J^{PC}) is known
  - Could run the collisions on the critical points, such as J/ψ peak, where the cross section is large.
  - Coupling of unobserved states through conventional production channels could be small, but coupling may be large to ggN:
    - $\psi \to N\bar{N}(\pi/\eta/\eta'/\omega/\phi), pK\bar{\Lambda}, pK\bar{\Sigma}$

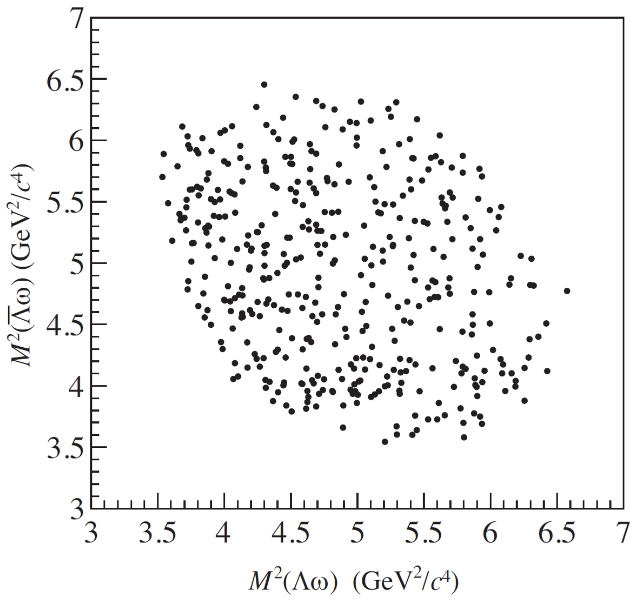


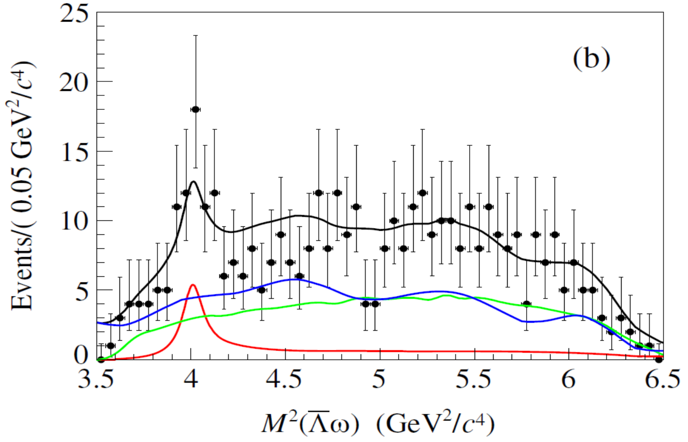
Evidence for $\Lambda^* \to \Lambda\omega$ in $\psi(3686) \to \Lambda\bar{\Lambda}\omega$

***Phys.Rev.D* 106 (2022) 11, 112011**

- ☐ Three body decay is a great opportunity to search for potential baryon excitation.
- ☐ Many excited hyperon states near the $\Lambda\omega$ threshold are performed in the past.
- ✓ Based on 448M $\psi(3686)$ events, the process $\psi(3686) \to \Lambda\bar{\Lambda}\omega$ is performed for the first time.
- ✓ An excited Λ state is investigated by an unbinned maximum likelihood fit to the Dalitz plot.







Evidence for $\Lambda^* \to \Lambda\omega$ in $\psi(3686) \to \Lambda\bar{\Lambda}\omega$

- $\mathcal{B}(\psi(3686) \to \Lambda\bar{\Lambda}\omega) = (3.30 \pm 0.34 \pm 0.29)\times 10^{-5}$
- For Λ^*:
  - Parameterization: An S-wave Breit-Wigner function convolved a Gaussian function
  - $M = 2001 \pm 7\ \mathrm{MeV}/c^2, \Gamma = 36 \pm 7\ \mathrm{MeV}$
  - Statistical significance: 3.0σ
  - $\mathcal{B}(\psi(3686) \to \Lambda^*\bar{\Lambda} + c.c. \to \Lambda\bar{\Lambda}\omega) < 1.40\times 10^{-5}$ @ 90% confidence level.

➢ The branching fraction of $\psi(3686) \to \Lambda\bar{\Lambda}\omega$ is measured for the first time.

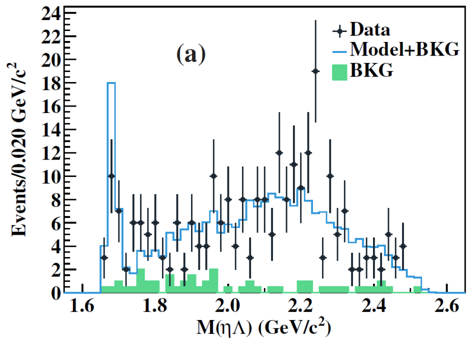
➢ An potential excited Λ state was seen with 3.0σ around $2.0\ \mathrm{GeV}/c^2$, the mass is near to $\Lambda(2000)$, $\Lambda(2050)$ or $\Lambda(2070)$, but the width is too narrow.

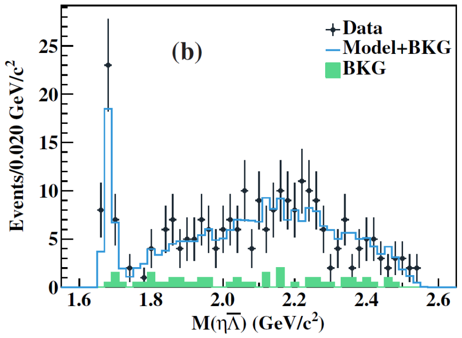
Source	Λ^* in This work	$\Lambda(2000)$	$\Lambda(2050)$	$\Lambda(2070)$
Mass (MeV/c^2)	2001 ± 7	≈ 2000	2056 ± 22	2070 ± 24
Γ (MeV)	36 ± 7	(125~255)	493 ± 61	370 ± 50
Significance/ Existence	3.0σ	*	*	*

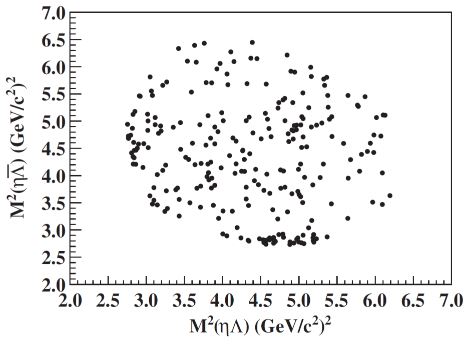
Λ^* near $\Lambda\eta$ threshold in $\psi(3686) \to \Lambda\bar{\Lambda}\eta$

Phys.Rev.D **106 (2022) 7, 072006**

- ☐ Search for isospin violation decay of $\psi(3686) \to \Lambda\bar{\Lambda}\pi^0$
- ☐ Search for Λ^* in $\Lambda\pi^0$ and $\Lambda\eta$ mass spectrum
- ✓ Based on 448M $\psi(3686)$ events
- ✓ The branching fraction of $\psi(3686) \to \Lambda\bar{\Lambda}\pi^0$ is measured with 3.7σ statistical significance for the first time
- ✓ Due to the low statistical, no clear struture is found in the $\Lambda\pi^0$ mass spectrum.
- ✓ A PWA is performed for $\psi(3686) \to \Lambda\bar{\Lambda}\eta$, and a Λ^* near the $\Lambda\eta$ threshold is performed.







Λ^* near $\Lambda\eta$ threshold in $\psi(3686) \to \Lambda\bar{\Lambda}\eta$

- $\mathcal{B}(\psi(3686) \to \Lambda\bar{\Lambda}\pi^0) = (1.42 \pm 0.39 \pm 0.59)\times 10^{-6}$
- $\mathcal{B}(\psi(3686) \to \Lambda\bar{\Lambda}\eta) = (2.34 \pm 0.18 \pm 0.52)\times 10^{-5}$
- For the Λ^*:
  - Parameterization: $BW(s) = \frac{1}{m_0^2 - m^2 - i m_0 \Gamma_0}$
  - $M = (1672 \pm 5 \pm 6)\ \mathrm{MeV}/c^2, \Gamma = (38 \pm 10 \pm 19)\ \mathrm{MeV}$
  - $\mathcal{B}(\psi(3686) \to \Lambda(1670)\bar{\Lambda} + c.c. \to \Lambda\bar{\Lambda}\eta) = (1.29 \pm 0.31 \pm 0.62)\times 10^{-5}$

➢ The isospin violation decay, $\psi(3686) \to \Lambda\bar{\Lambda}\pi^0$, is observed with over 3σ

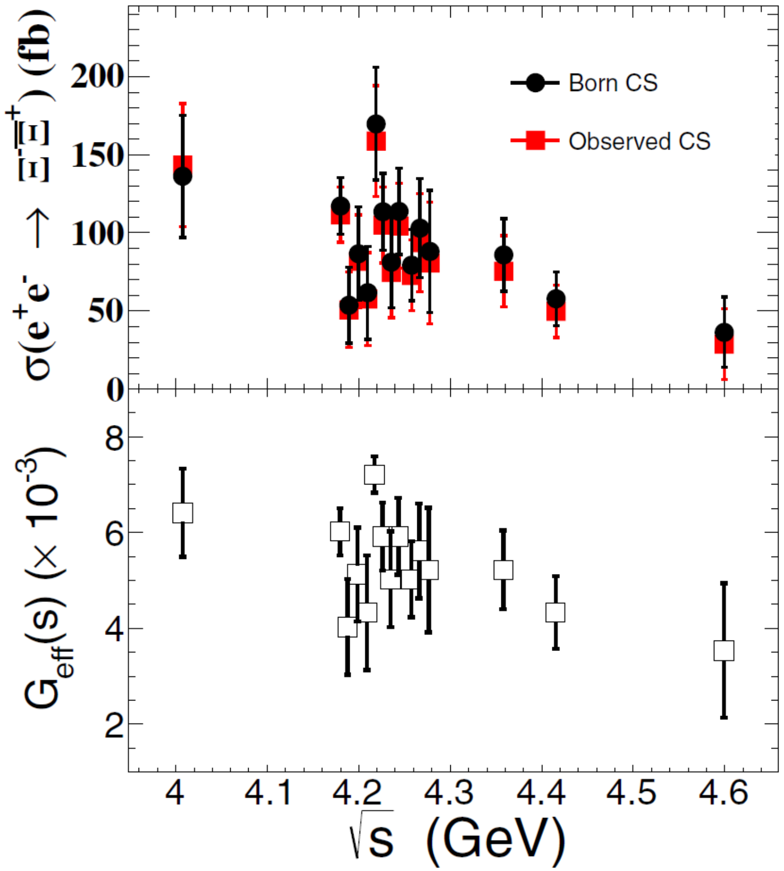
➢ The structure near $\Lambda\eta$ threshold can be described with $\Lambda(1670)$

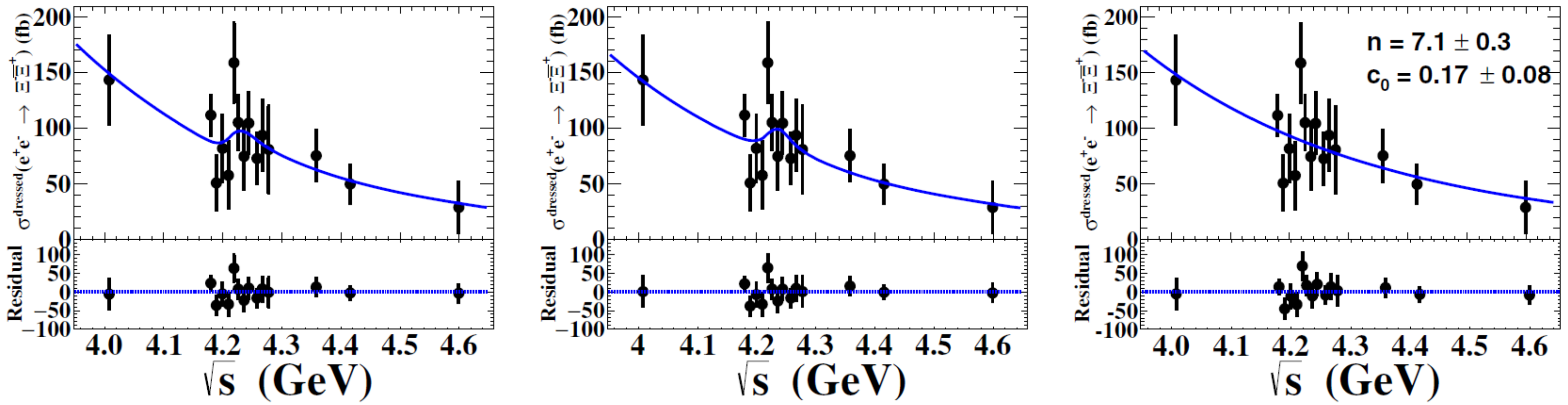
Source	Λ^* in This work	$\Lambda(1670)$	$\Lambda(1690)$
J^P	$1/2^-$	$1/2^-$	$3/2^-$
Mass (MeV/c^2)	$1672 \pm 5 \pm 6$	1670~1678	1685~1695
Γ (MeV)	$38 \pm 10 \pm 19$	25~35	60~80

Observation of Ξ^* in $e^+e^- \rightarrow \Xi^- + anything$

Phys.Rev.Lett. 124 (2020) 3, 032002

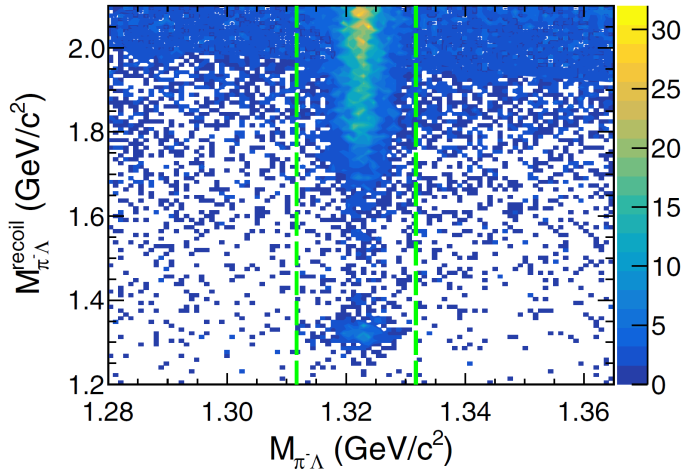
- ☐ Search for charmonium states above open-charm
- ☐ Measure the effective form factors
- ☐ Search for the excited Ξ states
- ✓ Analysis based on 11.0 fb^{-1} events, from 4.1 to 4.6 GeV, 15 energy points.
- ✓ Using the single tag method to improve efficiency

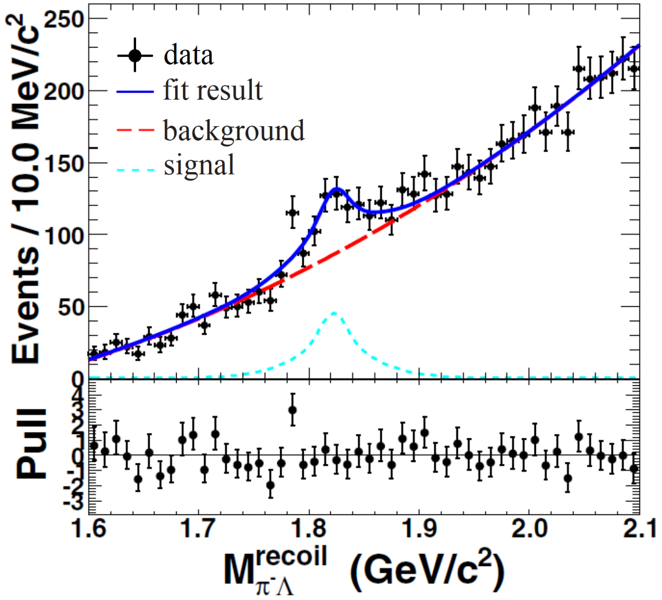




Observation of Ξ^* in $e^+e^- \to \Xi^- + anything$

- $\Gamma_{ee}\mathcal{B}(\psi(4260) \to \Xi^-\bar{\Xi}^+) < 0.27\times10^{-3}$ eV @ 90% C.L.
- A structure is observed in the recoil mass spectrum of $\pi^-\Lambda$
  - Parameterization:
    A BW function convolved a double Gaussian function
  - Statistical significance: $6.2\sigma - 6.5\sigma$
  - $M = (1825.5 \pm 4.7 \pm 4.7)\ \mathrm{MeV}/c^2$
  - $\Gamma = (17.0 \pm 15.0 \pm 7.9)$ MeV





➢ The upper limits on the products of the electronic partial width and the branching fractions of $\psi(4260) \to \Xi^-\bar{\Xi}^+$ is measured for the first time.

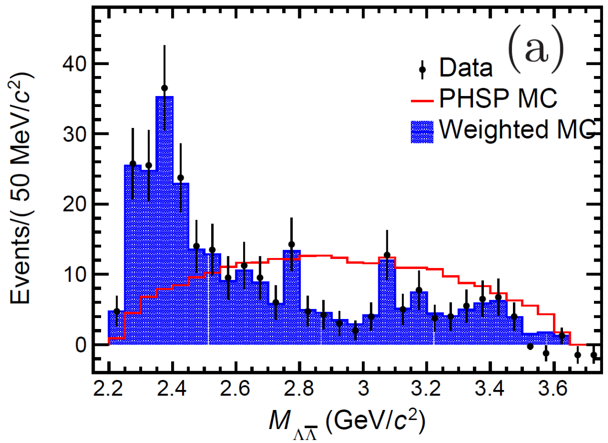
➢ The EFFs are measured at the 15 energy points.

➢ An excited Ξ baryon is observed around 1820 MeV with 6.2—6.5σ statistical significance. The mass and width of Ξ^* are consistent with $\Xi(1820)$ and the first updated in 33 years.

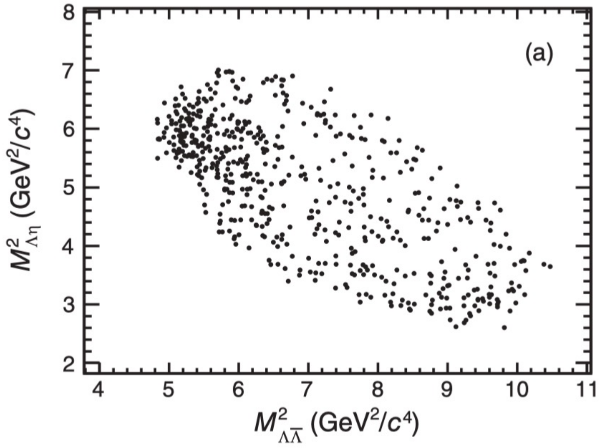
$\Lambda\bar{\Lambda}$ threshold enhancement in $e^+e^- \to \Lambda\bar{\Lambda}\eta$

***Phys.Rev.D* 107 (2023) 11, 112001**

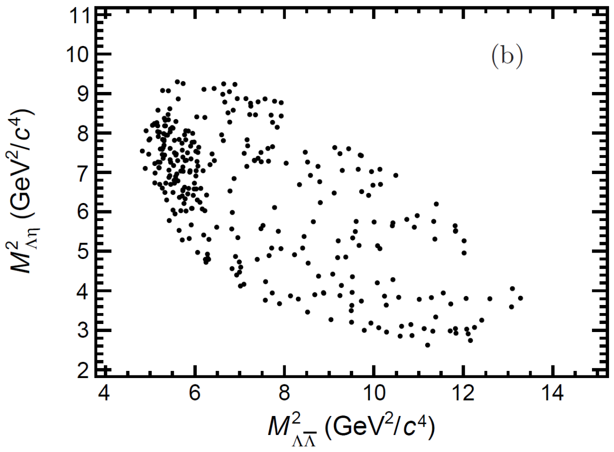
- ☐ Search for charmonium states
- ☐ Search for the enhancement near $\Lambda\bar{\Lambda}$ threshold
- ☐ Search for Λ^* in the $\Lambda\eta$ mass spectrum
- ✓ Based on the data events at 31 energy points (3.5~4.7 GeV)
- ✓ Partial reconstruction technique to achieve higher efficiency.



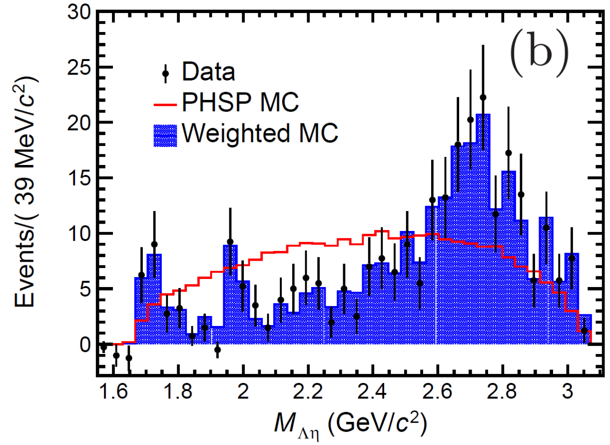
$\sqrt{s} = 4.178$ GeV



$\sqrt{s} = 3.773$ GeV



$\sqrt{s} = 4.178$ GeV



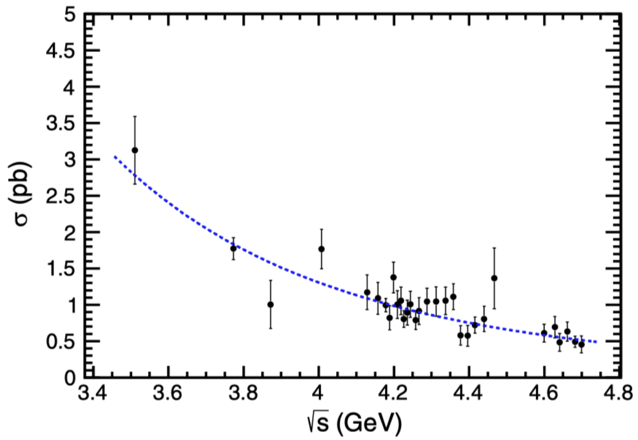
$\Lambda\bar{\Lambda}$ threshold enhancement in $e^+e^- \to \Lambda\bar{\Lambda}\eta$

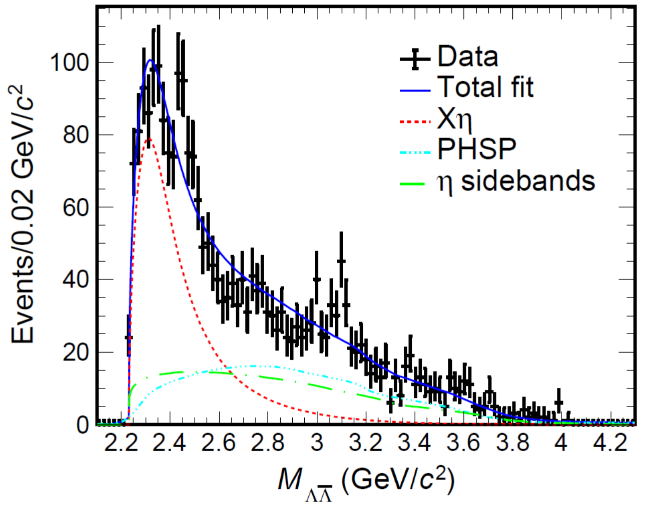
- The enhancement near $\Lambda\bar{\Lambda}$ threshold:
  - Parameterization: A BW function with mass-dependent width
  - $J^{PC} = 1^{--}, M = (2356 \pm 7 \pm 17)\ \mathrm{MeV}/c^2, \Gamma = (304 \pm 28 \pm 54)\ \mathrm{MeV}$

➢ No significant structure of charmonium state is observed in the line shape of the Born cross section

➢ A clear enhancement above pure phase space is observed near the $\Lambda\bar{\Lambda}$ mass threshold.

➢ Not any excited Λ state is observed due to the limit data.





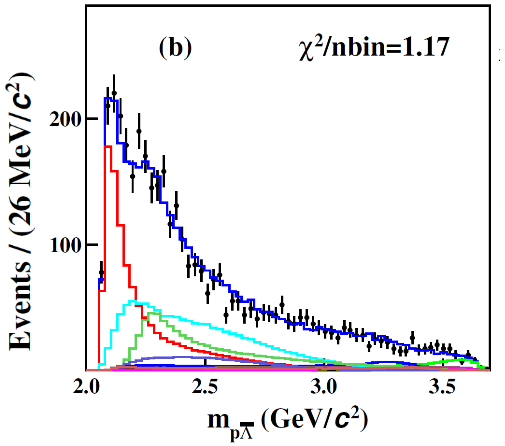
N^* and Λ^* in $e^+e^- \to pK^-\bar{\Lambda} + c.c.$ at 4.178 GeV

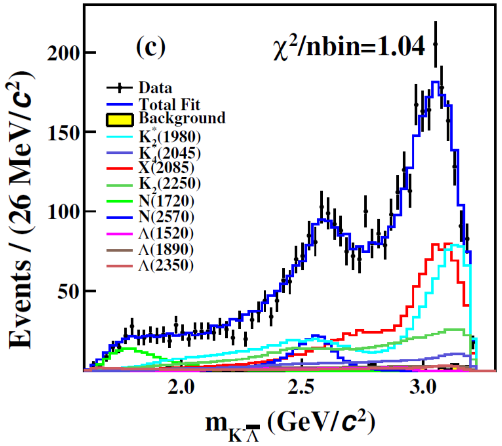
arXiv:2303.01989 [hep-ex]

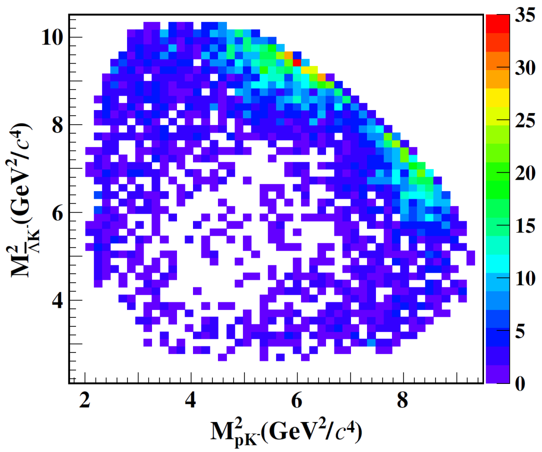
- Based on 3189 pb^{-1} events at 4.178 GeV, a partial wave analysis is performed.
- The intermediate states of baseline solution include:
  - K^*: $K_2^*(1980), K_4^*(2075), K_2(2250)$
  - Λ^*: $\Lambda(1520), \Lambda(1890), \Lambda(2350)$
  - N^*: $N(1720), N(2570)$
  - $p\Lambda$ enhancement: $X(2085)$
- The parameterization of K^*, Λ^* and N^*:

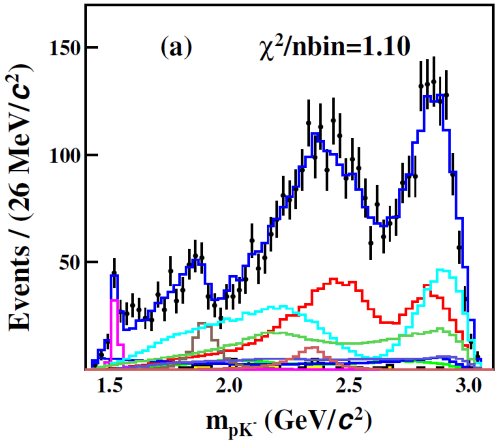
$$\mathrm{BW}(s) = \frac{1}{m_0^2 - m^2 - i m_0 \Gamma_0}$$

- The resonance parameters of K^*, Λ^* and N^* are fixed to the individual world average values.





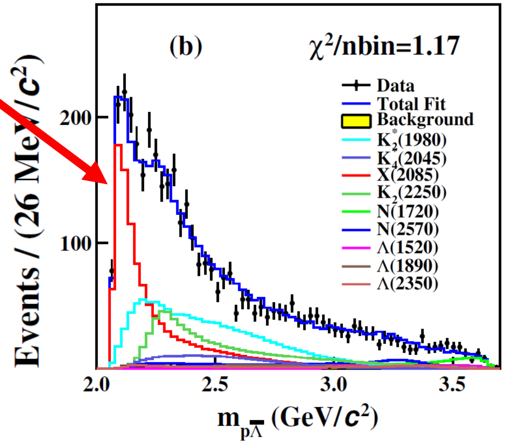




$p\bar{\Lambda}$ threshold enhancement in $e^+e^- \to pK^-\bar{\Lambda} + c.c.$

$\sqrt{s}$ = 4.178 GeV

$p\bar{\Lambda}$ threshold enhancement



J^P	M_{pole} (MeV)	Γ_{pole} (MeV)	$\sqrt{\Delta(-2\ln\mathcal{L})}$
1^+	2085 ± 6	62 ± 10	—
0^-	2095 ± 9	140 ± 6	9.3
1^-	2063 ± 12	130 ± 9	8.1
2^+	2077 ± 2	122 ± 8	9.8
2^-	2082 ± 16	46 ± 36	5.7

$\sqrt{s}$	$\mathcal{L}_{\text{int}}$	Year	M_{pole}	Γ_{pole}
4.008	482.0 ± 4.7	2011	2085 ± 14	50 ± 16
4.178	3189.0 ± 31.9	2016	2085 ± 6	62 ± 10
4.226	1100.9 ± 7.0	2013	2088 ± 10	68 ± 12
4.258	828.4 ± 5.5	2013	2083 ± 11	48 ± 10
4.416	1090.7 ± 7.2	2014	2088 ± 13	56 ± 12
4.682	1669.3 ± 9.0	2020	2092 ± 10	54 ± 10
Average	—	—	2086 ± 4	56 ± 5

The parameterization of $X(2085)$:

$$\mathrm{BW}(s) = \frac{1}{m_0^2 - m^2 - i m_0 \Gamma(m)}$$

$$\Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2l+1} \frac{m_0}{m} B_l^2(q, q_0, d)$$

$B_l^2(q, q_0, d)$: Blatt – Weisskopf barrier factor

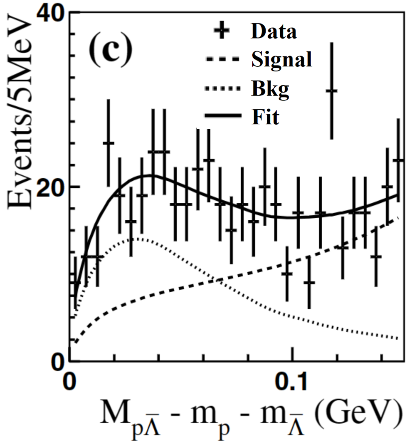
Significance $> 20\sigma$

- A threshold enhancement near $p\bar{\Lambda}$ threshold, $X(2085)$, is observed with:

$$J^P = 1^+, M_{\text{pole}} = (2086 \pm 4 \pm 6)\,\mathrm{MeV}/c^2, \Gamma_{\text{pole}} = (56 \pm 6 \pm 16)\ \mathrm{MeV}$$

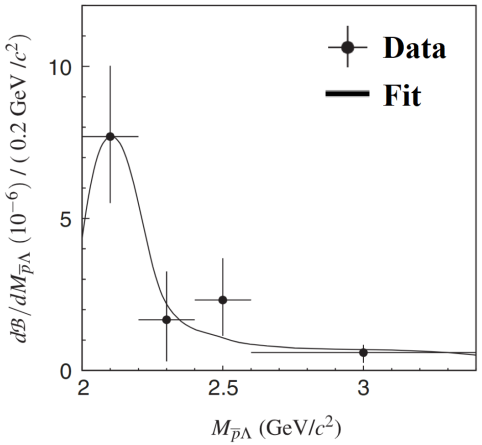
Result of $p\bar{\Lambda}$ threshold enhancement

$J/\psi \to pK^-\bar{\Lambda}$
BES Collaboration
Phys.Rev.Lett. 93 (2004) 112002



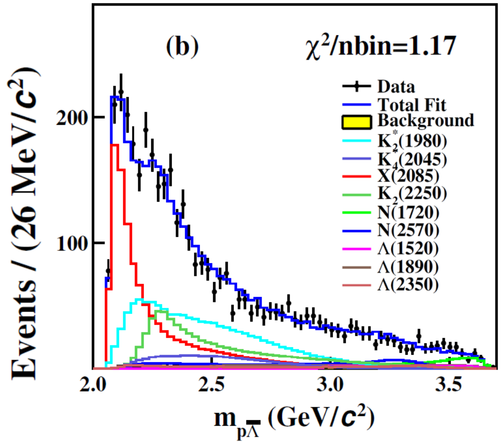
$X(2075)$
Significance $\approx 7\sigma$
$M = (2075 \pm 12 \pm 5)$ MeV
$\Gamma = (90 \pm 35 \pm 9)$ MeV

$B^+ \to p\bar{\Lambda}\bar{D}^0$
Belle Collaboration
Phys.Rev.D 84 (2011) 071501



Included in $X(2075)$ of PDG

$e^+e^- \to pK^-\bar{\Lambda}$
BESIII Collaboration
arXiv:2303.01989 [hep-ex]



$X(2085)$
Significance $> 20\sigma$
$J^P = 1^+$
$M = (2086 \pm 4 \pm 6)$ MeV
$\Gamma = (56 \pm 5 \pm 16)$ MeV

$\boxed{\text{No conclusion can be drawn that } X(2085) \text{ is the same structure as } X(2075) \text{ observed } J/\psi \to pK^-\bar{\Lambda} \text{ since limited information was given.}}$

Measurement of $\Sigma^+ \to p\gamma$ in $J/\psi \to \Sigma^+\bar{\Sigma}^-$

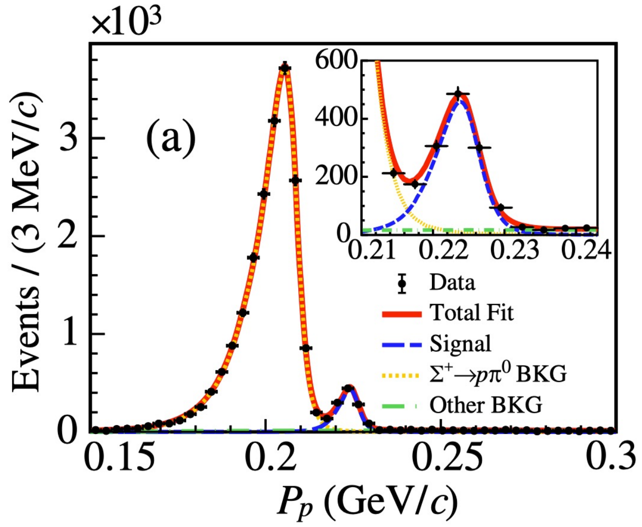
Phys.Rev.Lett. **130 (2023) 21, 211901**

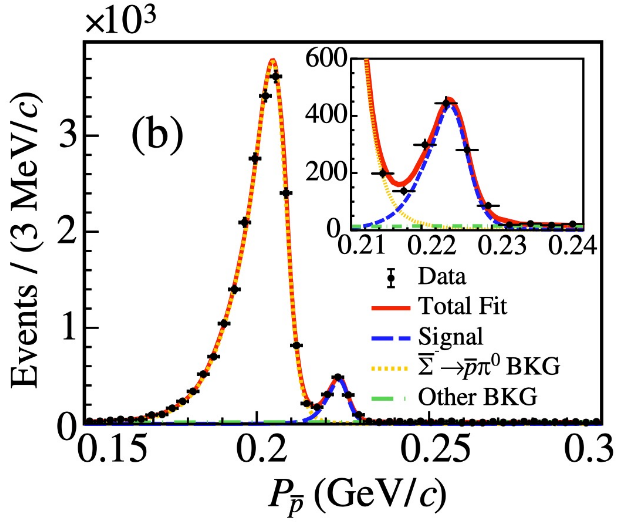
- Measure the absolute branching fraction and decay asymmetry parameter α_γ of $\Sigma^+ \to p\gamma$
- Through the decay asymmetry parameter, perform a test for CP violation in hyperon decay

✓ Analysis based on 10 billion J/ψ events

✓ The absolute branching fraction is calculated by

$$\mathcal{B}(\Sigma^+ \to p\gamma) = \frac{N_{DT}^{obs}\varepsilon_{ST}}{N_{ST}^{obs}\varepsilon_{DT}}$$





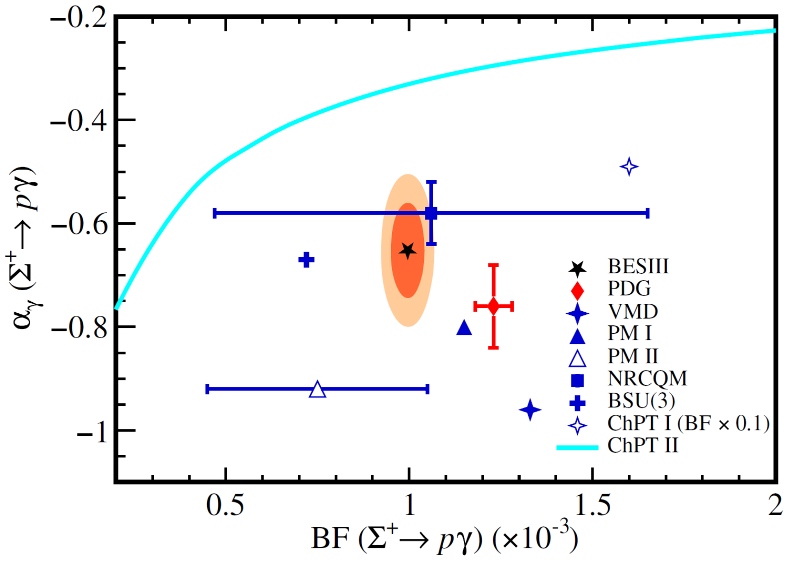
Measurement of $\Sigma^+ \to p\gamma$ in $J/\psi \to \Sigma^+\bar{\Sigma}^-$

Source	PDG 2022	Our result
$\mathcal{B}(\Sigma^+ \to p\gamma)\ \times 10^{-3}$	1.23 ± 0.05	$0.996 \pm 0.021 \pm 0.018$
α_γ	-0.76 ± 0.08	$-0.652 \pm 0.056 \pm 0.020$

- The CP violation is test through Δ_{CP} and A_{CP}:

$$\Delta_{CP} = \frac{\mathcal{B}_+ - \mathcal{B}_-}{\mathcal{B}_+ + \mathcal{B}_-} = 0.006 \pm 0.011_{\text{stat}} \pm 0.004_{\text{syst}},$$

$$A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+} = 0.095 \pm 0.087_{\text{stat}} \pm 0.018_{\text{syst}}.$$



➢ The accuracies improvement:

  ➢ Branching fraction: 78%, decay asymmetry parameter α_γ: 34%

➢ $\mathcal{B}(\Sigma^+ \to p\gamma)$ is lower than the PDG value by 4.2σ.

➢ No obvious CP violation is observed.

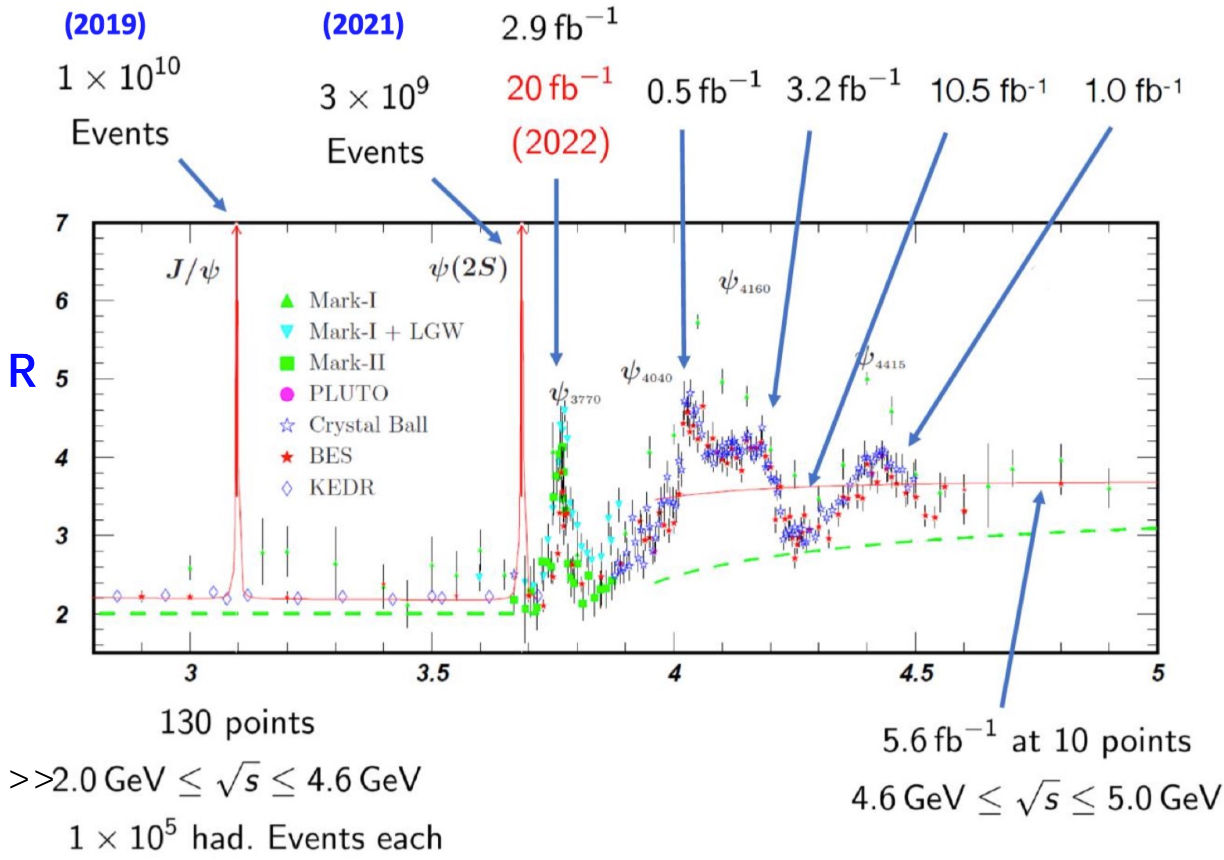
Summary

✓Overview of our recent result of baryon spectroscopy

✓Charmonium decays are the powerful tool to investigate excited nucleons and hyperons

➢BESIII has collected 10 billion J/ψ and about 3 billion $\psi(3686)$ events.

➢Many interesting analyses are now on performing and will come soon.



Thanks for your attention!