

Baryon spectroscopy at BESIII

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OUTLINE

- ❖ **Status of BEPCII/BESIII**
- ❖ **Recent results of baryon spectroscopy from BESIII**
 - ✓ **Two hyperons in $\psi(3686) \rightarrow K^- \Lambda \Xi^+$**
 - ✓ **Excited strange baryons in $\psi(3686) \rightarrow \Lambda \bar{\Sigma}^+ \pi^-$**
 - ✓ **Two new excited baryon states in $\psi(3686) \rightarrow p \bar{p} \pi^0$**
 - ✓ **N(1535) in $\psi(3686) \rightarrow p \bar{p} \eta$**
- ❖ **Summary and perspective**



The BEPCII Collider

BEMS (beam energy measurement system):
based on Compton backscattering

Beam energy: 1.0 - 2.3 GeV

Peak Luminosity:

achieved: $0.85 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} @ 3770 \text{ MeV}$

Optimum energy: 1.89 GeV

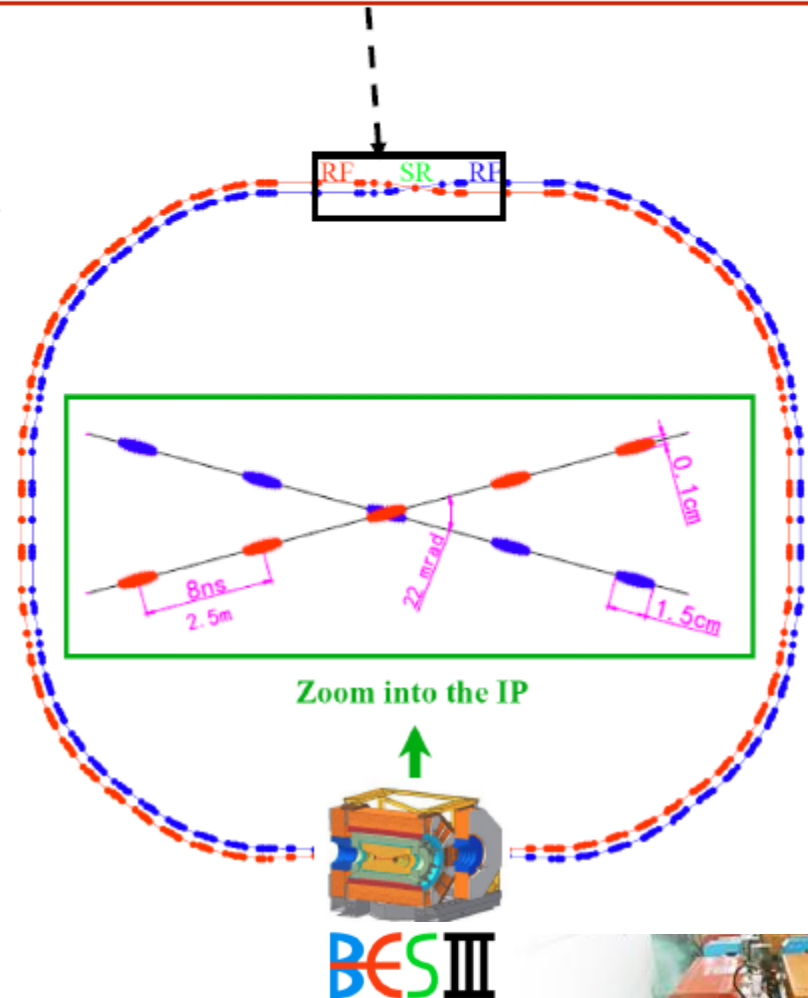
Energy spread: 5.16×10^{-4}

No. of bunches: 93

Bunch length: 1.5 cm

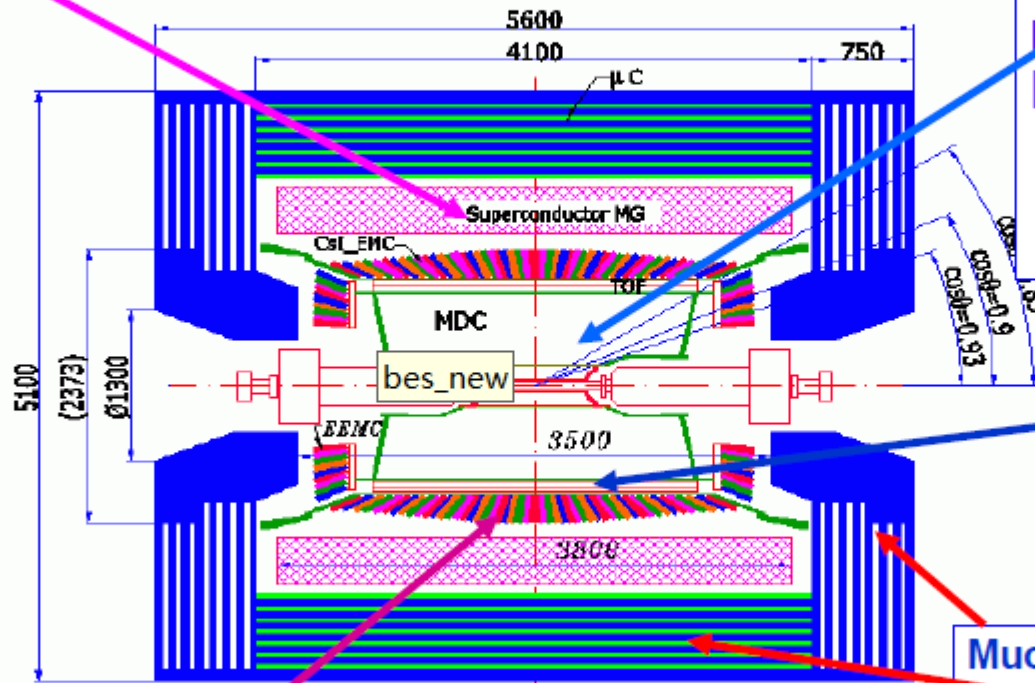
Total current: 0.91 A

Circumference: 237m



The BESIII detector

Solenoid Magnet: 1 T Super conducting



MDC: small cell & He gas

$\sigma_{xy} = 130 \mu\text{m}$
 $\delta p/p = 0.5\% @ 1\text{GeV}$
 $dE/dx = 6\%$

TOF:

$\sigma_T = 90 \text{ ps}$
 Barrel
 110 ps
 Endcap

Muon ID: 8~9 layer RPC
 $\sigma_{R\phi} = 1.4 \text{ cm} \sim 1.7 \text{ cm}$

EMCAL: CsI crystal
 $\Delta E/E = 2.5\% @ 1 \text{ GeV}$
 $\sigma_{\phi,z} = 0.5 \sim 0.7 \text{ cm}/\sqrt{E}$

Data Acquisition:
 Event rate = 3 kHz
 Throughput ~ 50 MB/s

Trigger: Tracks & Showers
 Pipelined; Latency = 6.4 μs

The new BESIII detector is hermetic for neutral and charged particle with excellent resolution, PID, and large coverage.



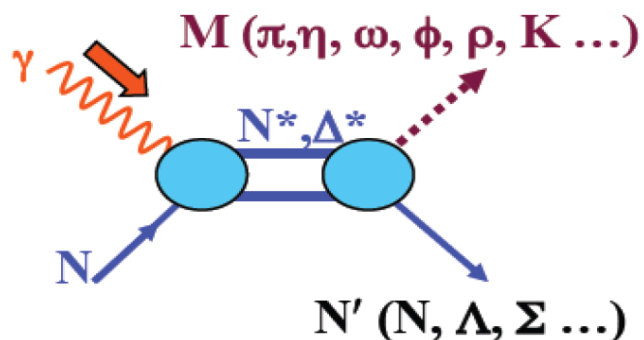
Baryon spectroscopy

- **Baryon spectroscopy is an important field to understand the internal structure of hadrons.**
- **The established baryons are described by three-quark (qqq) configurations.**
- **Non-relativistic quark model:**
 - **It is quite successful in interpreting baryon resonances.**
 - **It also provides an explicit classification for light baryons in terms of group symmetry.**
 - **It tends to predict far more excited states than are found experimentally (“miss resonance problem”).**
- **From theoretical point of view, this could be due to a wrong choice of the degrees of freedom.**
- **Experimentally, the situation is very complicated due to the large number of broad and overlapping states that are observed.**

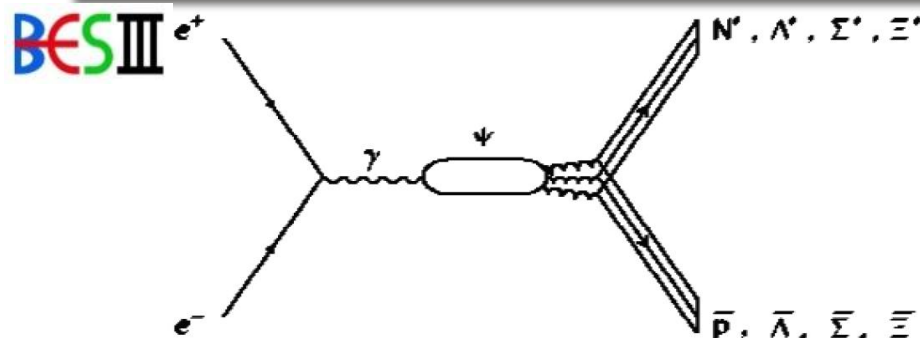


Charmonium decays can give novel insights into baryons and give complementary information to other experiments

JLab, ELSA, MAMI, ESRF,
Spring-8,



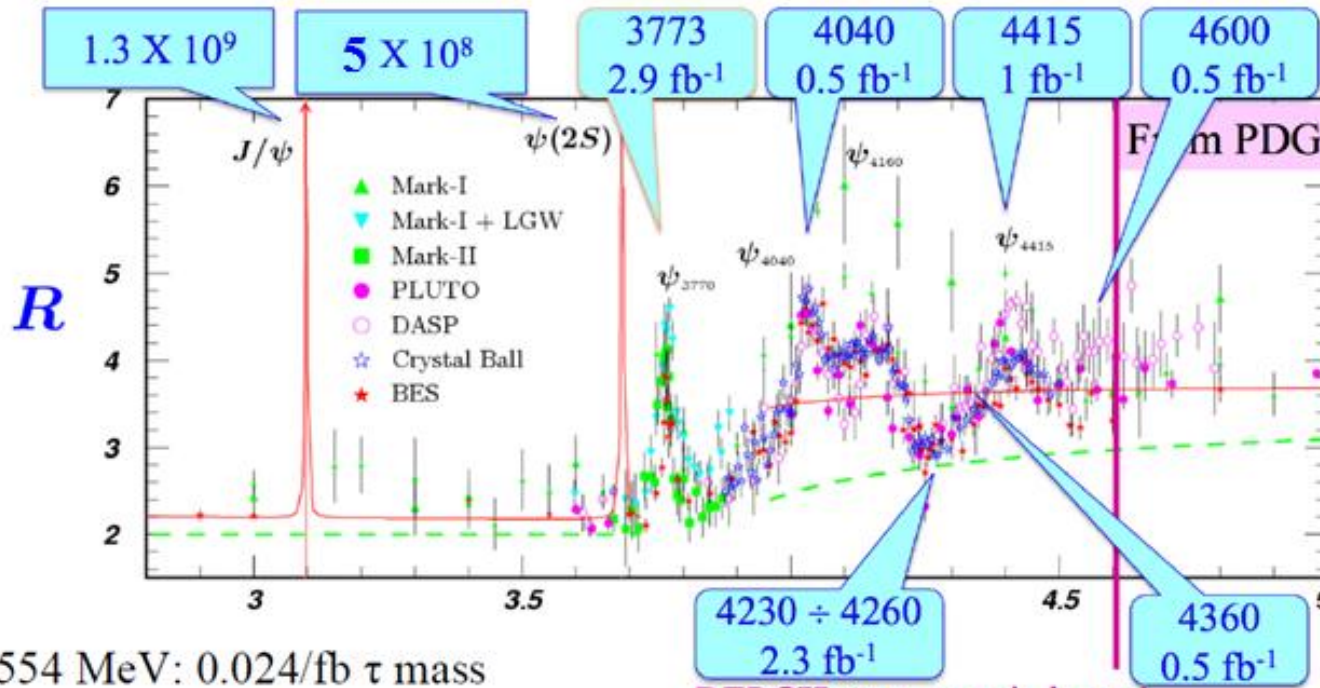
$$J/\psi(\psi') \rightarrow \bar{B}BM \Rightarrow N^*, \Lambda^*, \Sigma^*, \Xi^*$$



- ✓ **Isospin 1/2 filter:** $\psi \rightarrow N\bar{N}\pi, \psi \rightarrow N\bar{N}\pi\pi$
- ✓ **Missing N^* with small couplings to πN & γN , but large coupling to $gggN$:** $\psi \rightarrow N\bar{N}\pi/\eta/\eta'/\omega/\phi, \bar{p}\Sigma\pi, \bar{p}\Lambda K \dots$
- ✓ **Not only study excited nucleons, but also baryons $\Lambda^*, \Sigma^*, \Xi^*$**
- ✓ **Gluon-rich environment: a favorable place for producing hybrid ($qqqg$) baryons**
- ✓ **High statistics of charmonium @ BESIII**



Baryon spectroscopy



- 3554 MeV: 0.024/fb τ mass
- 4100~4400 MeV: 0.5/fb coarse scan
- 3850~4590 MeV: 0.5/fb fine scan
- In 2015, we have done energy scan at 2000—3000 MeV

High statistics of charmonium @ BESIII provide an opportunity to study baryon spectroscopy.



Observation of two hyperons $\Xi^-(1690)$ and $\Xi^-(1820)$ in $\psi(3686) \rightarrow K^- \Lambda \bar{\Xi}^+ + \text{c.c.}$

Theoretically : Quark model predicts over 30 Ξ^* states,

Experimentally: 11 Ξ^* states observed to date, few of them are well established with spin parity determined

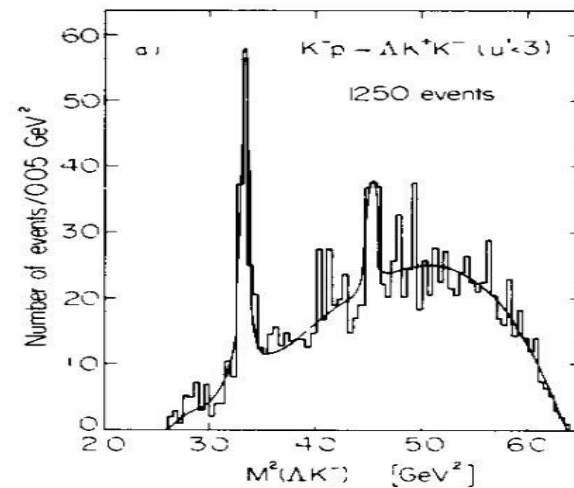
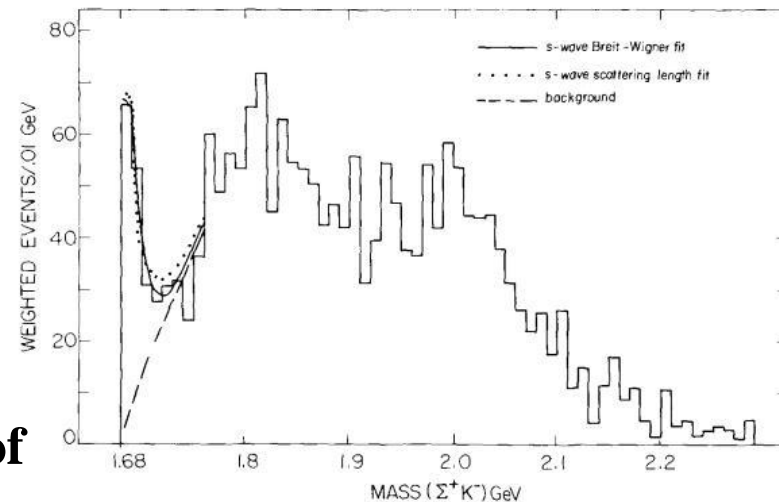
Particle	J^P	Overall status	Status as seen in			
			$\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$ Other channels
$\Xi(1318)$	$1/2^+$	****				Decays weakly
$\Xi(1530)$	$3/2^+$	****	****			
$\Xi(1620)$		*	*			
$\Xi(1690)$		***		***	**	
$\Xi(1820)$	$3/2^-$	***	**	***	**	**
$\Xi(1950)$		***	**	**		*
$\Xi(2030)$		***		**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

Most observations and measurements from bubble chamber experiment or diffractive Kp interaction.



Observation of two hyperons $\Xi(1690)$ and $\Xi(1820)$ in $\psi(3686) \rightarrow K^- \Lambda \bar{\Xi}^+ + \text{c.c.}$

- In 1978, the $\Xi(1690)$ was first observed in the $(\Sigma \bar{K})$ final state in the reaction $K^- p \rightarrow (\Sigma \bar{K}) K \pi$ at CERN
- In 2008, BABAR determined spin-parity of $\Xi(1690)$ to be $J^P = 1/2^-$ in $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$
- In 1976, $\Xi(1820)$ was first observed in $K^- \Lambda$ mass spectrum in Kp scattering at CERN.
- In 1987, CERN-SPS experiment determined spin-parity of $\Xi(1820)$ to be $J^P = 3/2^-$



Observation of two hyperons $\Xi(1690)$ and $\Xi(1820)$ in $\psi(3686) \rightarrow K^- \Lambda \bar{\Xi}^+ + \text{c.c.}$

- At present $\Xi(1690)$ and $\Xi(1820)$ are firmly established.
- Further investigation of their properties is important to the understanding of Ξ^* .
- Besides from scattering experiment, decays from charmonium states offer a good opportunity to search for additional Ξ^* states.
- Our knowledge of charmonium decays into hadrons, especially to hyperons, is limited. The precise measurements of the branching fractions may help provide a better understanding of the decay mechanism.

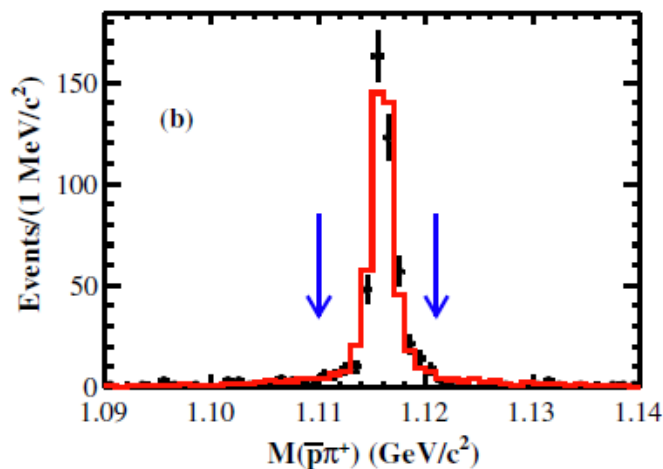
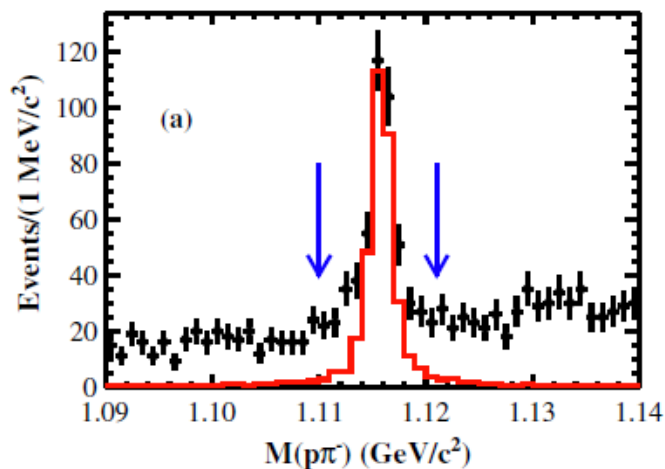
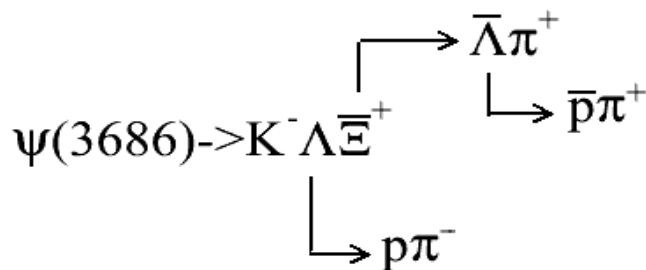


Observation of two hyperons $\Xi^-(1690)$ and $\Xi^-(1820)$ in $\psi(3686) \rightarrow K^- \Lambda \bar{\Xi}^+ + \text{c.c.}$

data sample: $106 \times 10^6 \psi'$

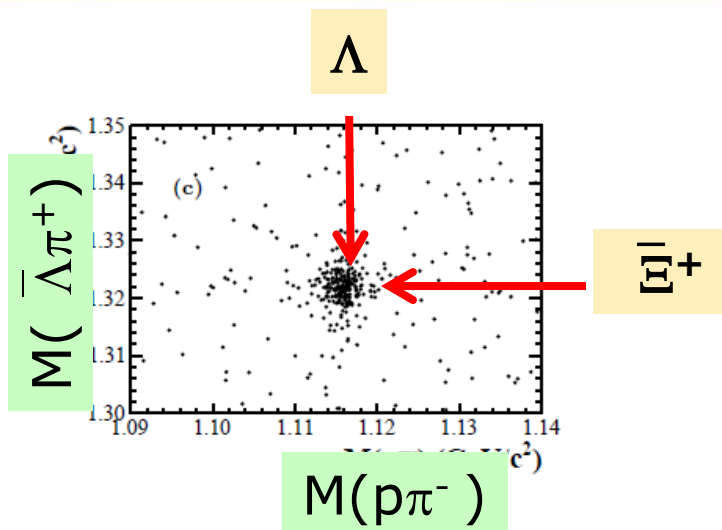
PRD 91, 092006 (2015)

The decays is reconstructed
from cascade decay:

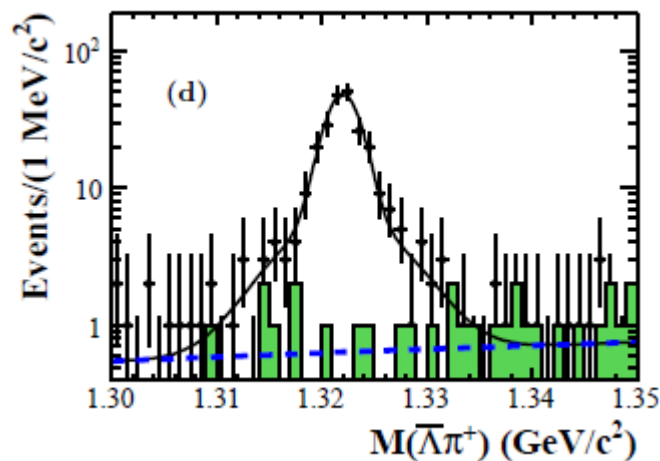


Observation of two hyperons $\Xi^-(1690)$ and $\Xi^-(1820)$ in $\psi(3686) \rightarrow K^- \Lambda \bar{\Xi}^+ + \text{c.c.}$

PRD 91, 092006 (2015)



an extended unbinned maximum likelihood fit is performed.



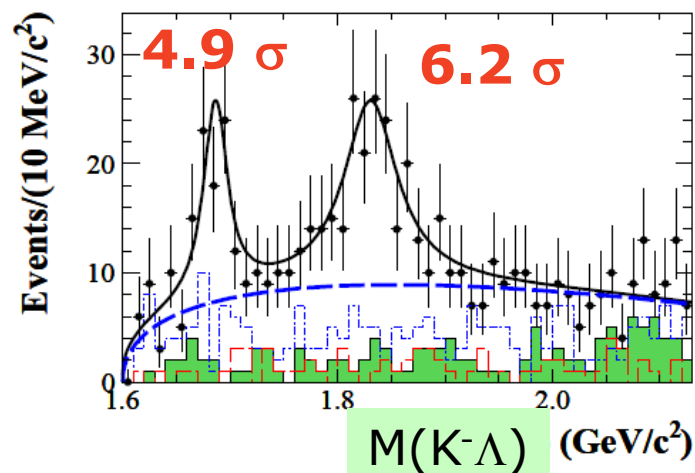
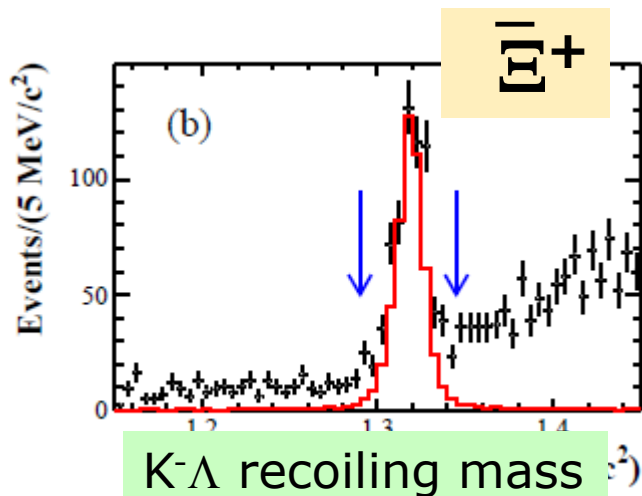
- Signal: double Gaussian function.
- bg: a first order Chebychev polynomial
- non - $\bar{\Xi}^+$ bg estimated with the $\psi(3686)$ inclusive MC sample & side band events from data

$$B(\psi(3686) \rightarrow K^- \Lambda \bar{\Xi}^+) = (3.86 \pm 0.27 \pm 0.32) \times 10^{-5}$$



Observation of two hyperons $\Xi^-(1690)$ and $\Xi^-(1820)$ in $\psi(3686) \rightarrow K^- \Lambda \bar{\Xi}^+ + \text{c.c.}$

PRD 91, 092006 (2015)

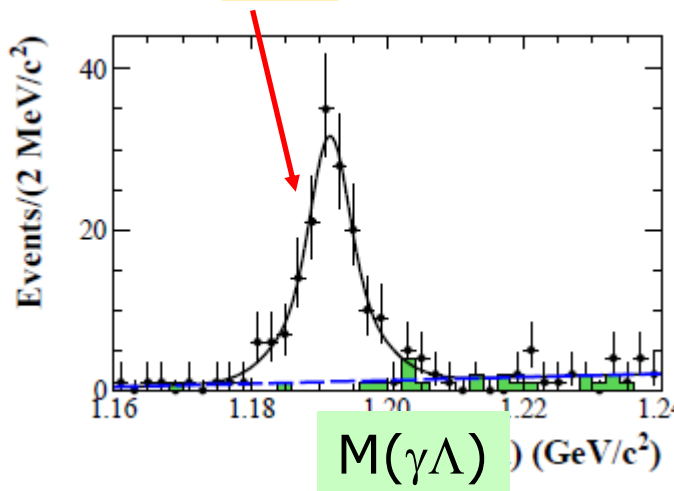
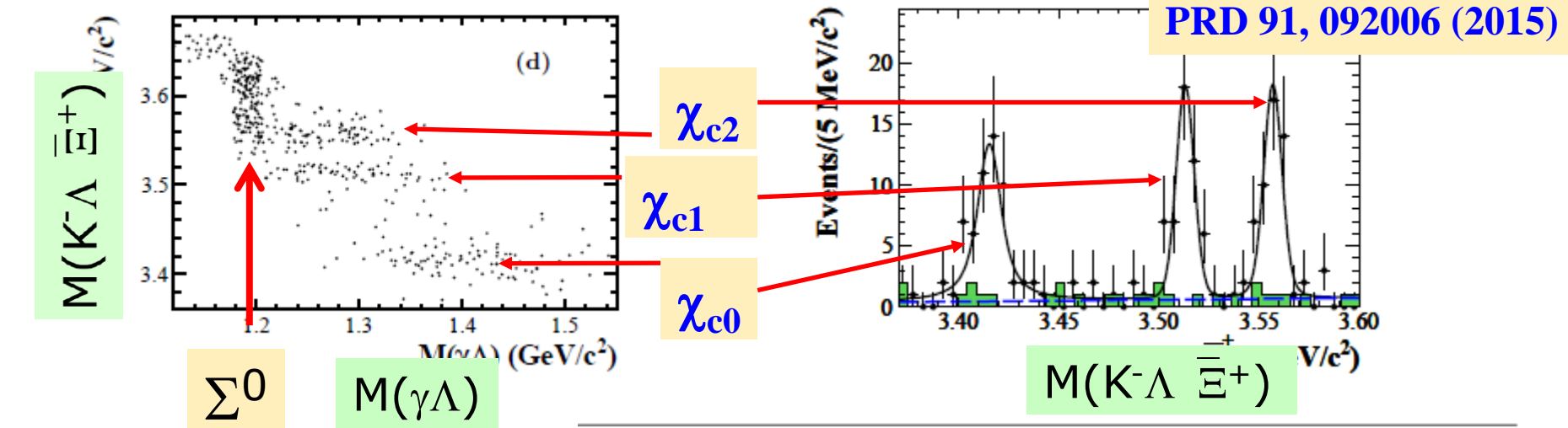


	$\Xi(1690)^-$	$\Xi(1820)^-$
$M(\text{MeV}/c^2)$	$1687.7 \pm 3.8 \pm 1.0$	$1826.7 \pm 5.5 \pm 1.6$
$\Gamma(\text{MeV})$	$27.1 \pm 10.0 \pm 2.7$	$54.4 \pm 15.7 \pm 4.2$
Event yields	74.4 ± 21.2	136.2 ± 33.4
Significance(σ)	4.9	6.2
Efficiency(%)	32.8	26.1
$\mathcal{B} (10^{-6})$	$5.21 \pm 1.48 \pm 0.57$	$12.03 \pm 2.94 \pm 1.22$
$M_{\text{PDG}}(\text{MeV}/c^2)$	1690 ± 10	1823 ± 5
$\Gamma_{\text{PDG}}(\text{MeV})$	< 30	24^{+15}_{-10}

- Two hyperons $\Xi^-(1690)$ and $\Xi^-(1820)$ are observed in $\psi(3686) \rightarrow K^- \Lambda \bar{\Xi}^+ + \text{c.c.}$
- Resonance parameters consist with PDG



Measurement of $\psi(3686) \rightarrow \gamma K^- \Lambda \bar{\Xi}^+ + \text{c.c.}$



Decay	Branching fraction
$\psi(3686) \rightarrow K^- \Sigma^0 \bar{\Xi}^+$	$(3.67 \pm 0.33 \pm 0.28) \times 10^{-5}$
$\psi(3686) \rightarrow \gamma \chi_{c0}, \chi_{c0} \rightarrow K^- \Lambda \bar{\Xi}^+$	$(1.90 \pm 0.30 \pm 0.16) \times 10^{-5}$
$\psi(3686) \rightarrow \gamma \chi_{c1}, \chi_{c1} \rightarrow K^- \Lambda \bar{\Xi}^+$	$(1.32 \pm 0.20 \pm 0.12) \times 10^{-5}$
$\psi(3686) \rightarrow \gamma \chi_{c2}, \chi_{c2} \rightarrow K^- \Lambda \bar{\Xi}^+$	$(1.68 \pm 0.26 \pm 0.15) \times 10^{-5}$

Measurement of the branching fractions of $\psi(3686) \rightarrow K^- \Sigma^0 \bar{\Xi}^+ + \text{c.c.}$ and $\psi(3686) \rightarrow \gamma \chi_{cJ} \rightarrow \gamma K^- \Lambda \bar{\Xi}^+ + \text{c.c.}$ (J=0,1,2) for the first time

Observation of the decay $\psi(3686) \rightarrow \Lambda \bar{\Sigma}^{\pm} \pi^{\mp} + \text{c.c.}$

data sample: $106 \times 10^6 \psi'$

PRD 88, 112007 (2013)

The candidate events are reconstructed in six modes:

$\psi(3686) \rightarrow$

$\Lambda \bar{\Sigma}^+ \pi^- (\bar{\Sigma}^+ \rightarrow \bar{n} \pi^+)$

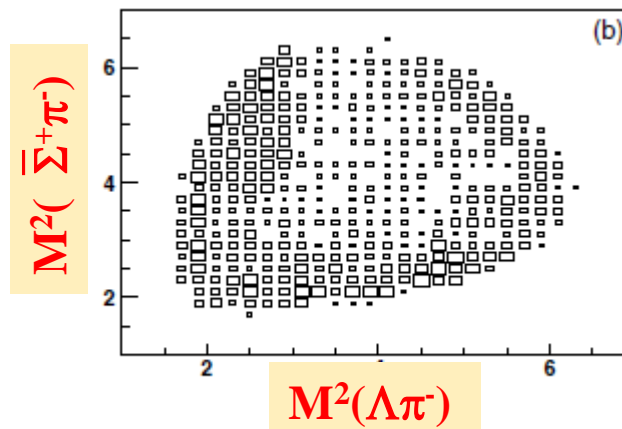
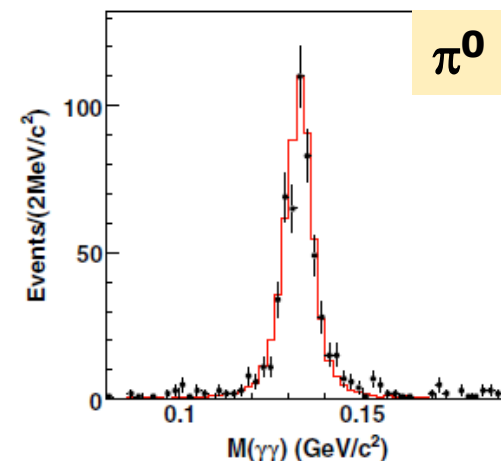
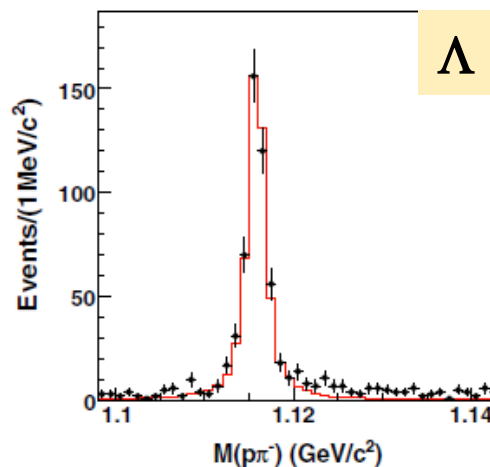
$\bar{\Lambda} \Sigma^- \pi^+ (\Sigma^- \rightarrow n \pi^-)$

$\Lambda \bar{\Sigma}^- \pi^+ (\bar{\Sigma}^- \rightarrow \bar{n} \pi^-)$

$\bar{\Lambda} \Sigma^+ \pi^- (\Sigma^+ \rightarrow n \pi^+)$

$\Lambda \bar{\Sigma}^- \pi^+ (\bar{\Sigma}^- \rightarrow \bar{p} \pi^0)$

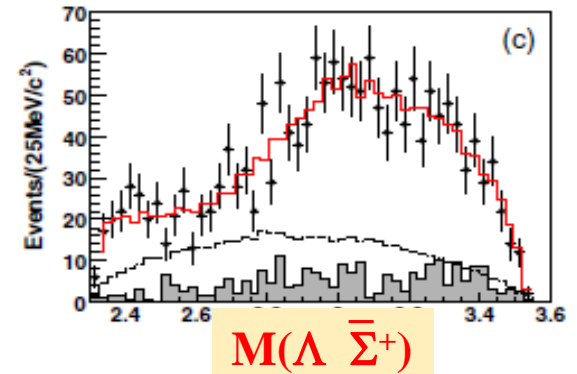
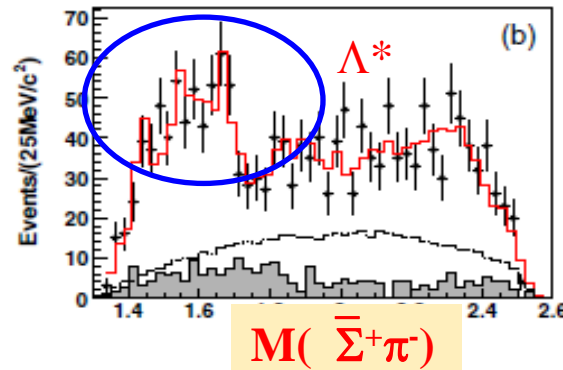
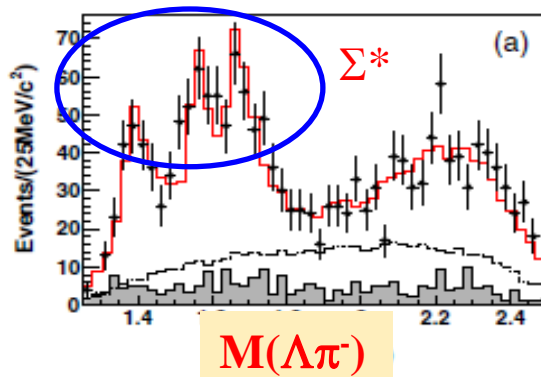
$\bar{\Lambda} \Sigma^+ \pi^- (\Sigma^+ \rightarrow p \pi^0)$



Observation of the decay $\psi(3686) \rightarrow \Lambda \bar{\Sigma}^{\pm} \pi^{\mp} + \text{c.c.}$

data sample: $106 \times 10^6 \psi'$

PRD 88, 112007 (2013)



- Excited strange baryons around 1.4 to $1.7 \text{ GeV}/c^2$ are observed
- Partial wave analysis (PWA) is performed in order to determine the correct detection efficiency
- The weighted averages of the branching fractions are determined to be

$$\begin{aligned} \mathcal{B}(\psi(3686) \rightarrow \Lambda \bar{\Sigma}^+ \pi^- + \text{c.c.}) \\ = (1.40 \pm 0.03 \pm 0.13) \times 10^{-4} \end{aligned}$$

$$\begin{aligned} \mathcal{B}(\psi(3686) \rightarrow \Lambda \bar{\Sigma}^- \pi^+ + \text{c.c.}) \\ = (1.54 \pm 0.04 \pm 0.13) \times 10^{-4} \end{aligned}$$



Observation of two new excited baryon states in $\psi(3686) \rightarrow p \bar{p} \pi^0$

- In 2001, BESII experiment studied N^* production in the decay of $J/\psi \rightarrow p \bar{p} \eta$ using PWA.
- BESII experiment observed a new resonance, $N(2065)$, in the decay $J/\psi \rightarrow p \bar{n} \pi^- + \text{c.c.}$
- In 2009, $N(2065)$ confirmed by BESII in the decay of $J/\psi \rightarrow p \bar{p} \pi^0$
- $\psi(3686) \rightarrow p \bar{p} \pi^0$ was studied by CLEO collaboration using 24.5×10^6 $\psi(3686)$ events.



Observation of two new excited baryon states in $\psi(3686) \rightarrow p \bar{p} \pi^0$

data sample: $106 \times 10^6 \psi'$

PRL 110, 022001 (2013)

- Proton and anti-proton are identified using dE/dx and TOF information

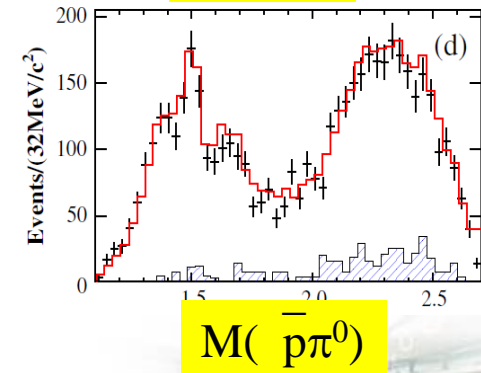
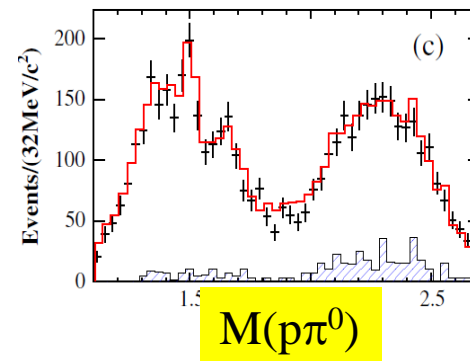
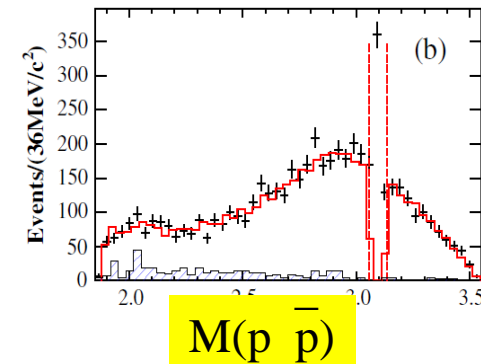
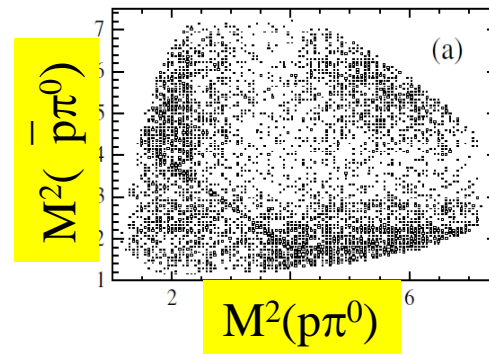
- At least two photos are selected

➤ Dominated by two-body decays

$$\psi(3686) \rightarrow X \pi^0, X \rightarrow p \bar{p}$$

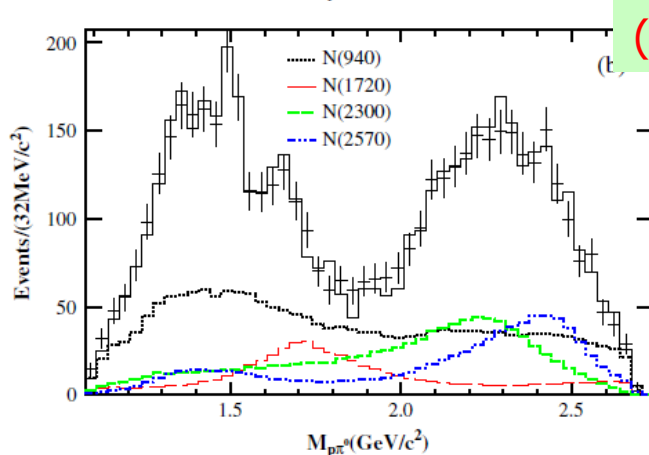
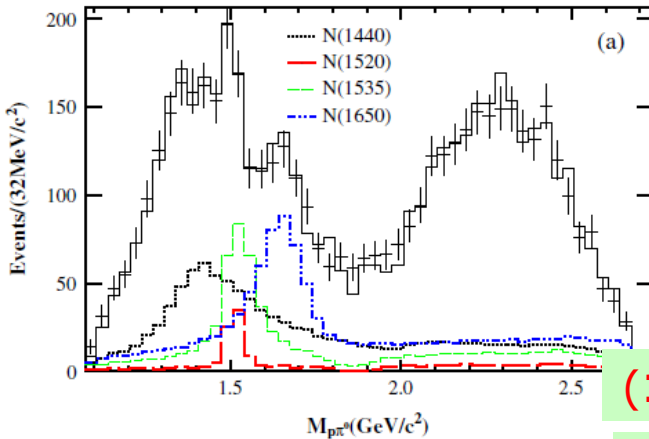
$$\psi(3686) \rightarrow p \bar{N}^*, N^* \rightarrow \bar{p} \pi^0 + \text{c.c.}$$

➤ In PWA, all N^* resonances up to 2.2 GeV with spin up to 5/2 listed in PDG are considered



Observation of two new excited baryon states in $\psi(3686) \rightarrow p \bar{p} \pi^0$

PRL 110, 022001 (2013)



Resonance	$M(\text{MeV}/c^2)$	$\Gamma(\text{MeV}/c^2)$	ΔS	ΔN_{dof}	Sig.
$N(1440)$	1390^{+11+21}_{-21-30}	$340^{+46+70}_{-40-156}$	72.5	4	11.5σ
$N(1520)$	1510^{+3+11}_{-7-9}	115^{+20+0}_{-15-40}	19.8	6	5.0σ
$N(1535)$	1535^{+9+15}_{-8-22}	120^{+20+0}_{-20-42}	49.4	4	9.3σ
$N(1650)$	1650^{+5+11}_{-5-30}	150^{+21+14}_{-22-50}	82.1	4	12.2σ
$N(1720)$	1700^{+30+32}_{-28-35}	$450^{+109+149}_{-94-44}$	55.6	6	9.6σ
$N(2300)$	$2300^{+40+109}_{-30-0}$	$340^{+30+110}_{-30-58}$	120.7	4	15.0σ
$N(2570)$	2570^{+19+34}_{-10-10}	250^{+14+69}_{-24-21}	78.9	6	11.7σ

- 5 well known N^* are measured
- Two new baryonic excited states $N(2300)(1/2^+)$ and $N(2570)(5/2^-)$ are observed!
- The structures in $p\bar{p}$ mass spectrum can be reproduced by the interference of N^* resonances

$$B(\psi(3686) \rightarrow p \bar{p} \pi^0) = (1.65 \pm 0.03 \pm 0.15) \times 10^{-4}$$

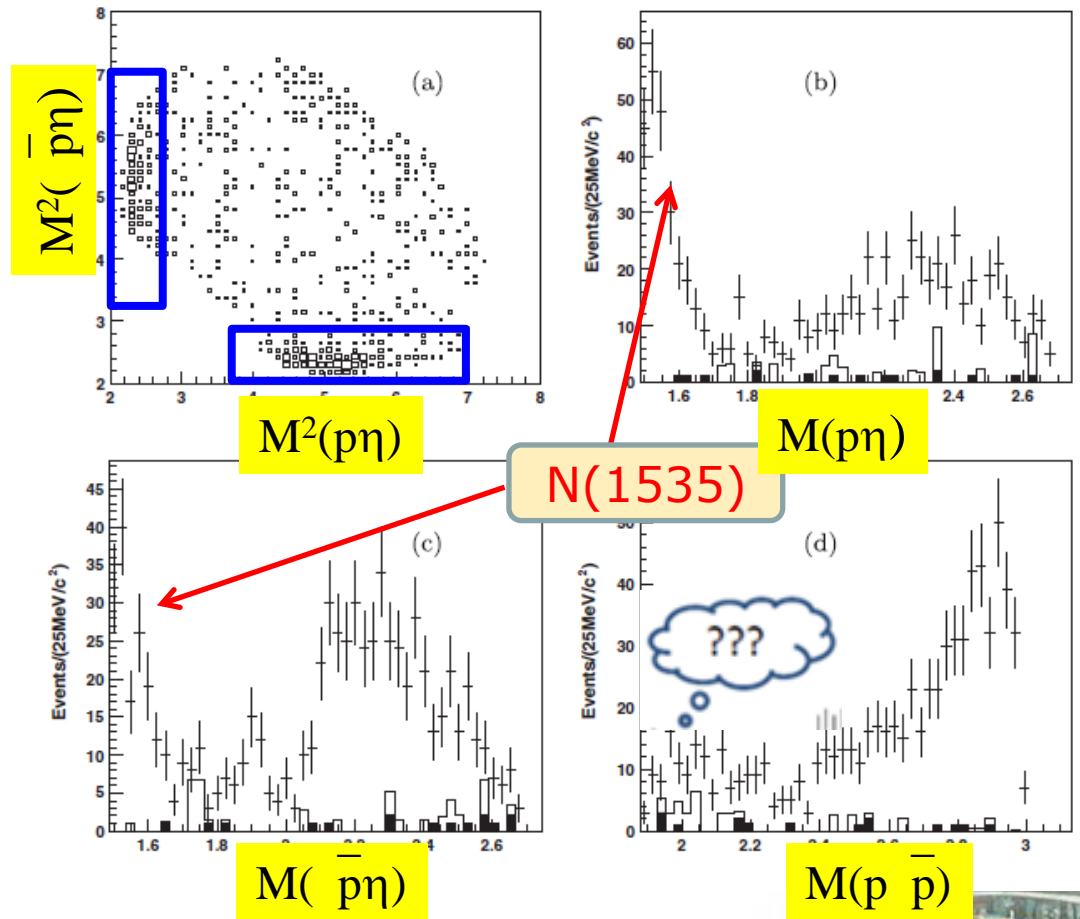
Study $N(1535)$ in $\psi(3686) \rightarrow p \bar{p} \eta$ decay

data sample: $106 \times 10^6 \psi'$

PRD 88, 032010 (2013)

✓ The decay topology is quite simple, $p \bar{p} \eta$.

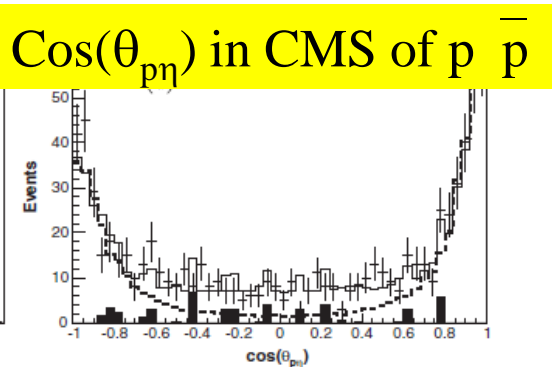
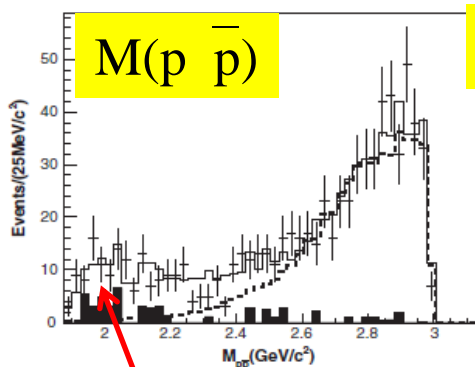
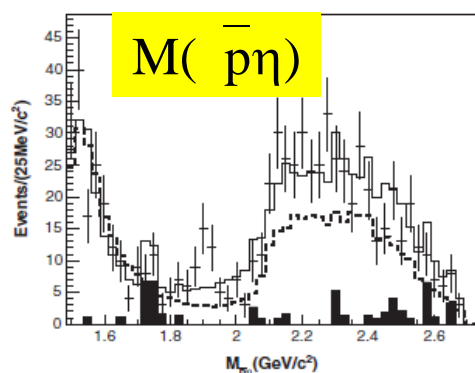
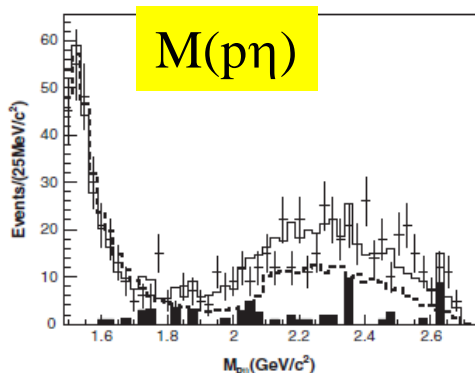
✓ Two clusters corresponding to the $p\eta$ mass threshold enhancement are visible.



Study N(1535) in $\psi(3686) \rightarrow p \bar{p} \eta$ decay

PRD 88, 032010 (2013)

- N(1535) and PHSP(1/2-) are dominant
- No evidence for a ppbar resonance



Mass and width of N(1535)

- ▶ $M = 1524 \pm 5_{-4}^{+10} \text{ MeV}/c^2$
- ▶ $\Gamma = 130_{-24}^{+27+57} \text{ MeV}/c^2$

PDG value:

- ▶ $M = 1525 \text{ to } 1545 \text{ MeV}/c^2$
- ▶ $\Gamma = 125 \text{ to } 175 \text{ MeV}/c^2$

Branching fraction:

$$\begin{aligned} & \text{▶ } B(\psi' \rightarrow N(1535)\bar{p}) \times B(N(1535) \rightarrow p\eta) + c.c. \\ & = (5.2 \pm 0.3_{-1.2}^{+3.2} \times 10^{-5}) \end{aligned}$$

explained by interference between N(1535) and phase space



Summary and perspective

- BESIII collected 0.5×10^9 $\psi(2S)$ and 1.3×10^9 J/ψ events.
- Many baryon states are presented:
 - $\Xi^-(1690)$ and $\Xi^-(1820)$ in $\psi(3686) \rightarrow K^- \Lambda \bar{\Xi}^+ + \text{c.c.}$
 - excited strange baryons Λ^* and Σ^* in $\psi(3686) \rightarrow \Lambda \bar{\Sigma}^\pm \pi^\mp$
 - excited baryon states $N(2300)$ and $N(2570)$ in $\psi(3686) \rightarrow p \bar{p} \pi^0$
 - $N(1535)$ in $\psi(3686) \rightarrow p \bar{p} \eta$
- Charmonium decays have proven to be a good lab for studying not only excited nucleon states, but also excited hyperons.
- Provide complementary information to other experiment.
- Expect more results from BESIII using full data sample.



Thank You!

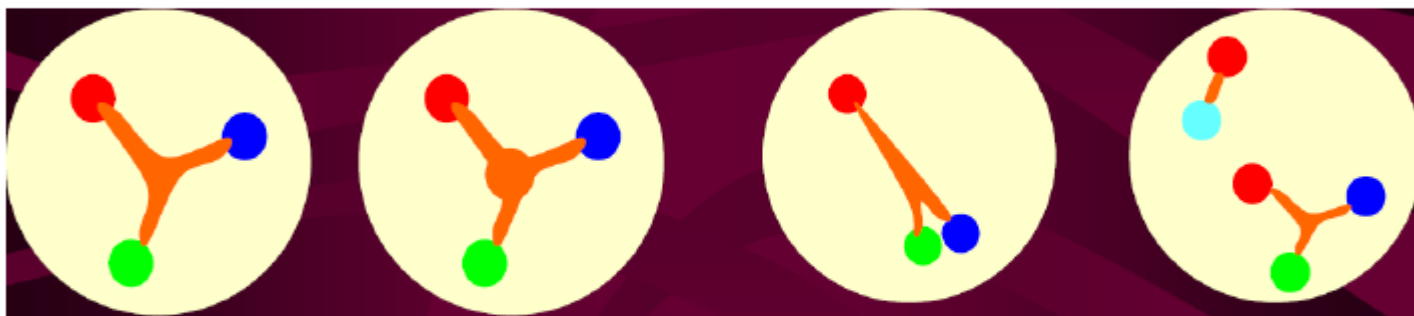


Back up



Baryon spectroscopy

- Are the states missing in the predicted spectrum because our models do not capture the correct degrees of freedom?



1, 3 quarks

2, quarks and
flux tubes

3, quark-diquark

4, multi quarks

- $N_{\text{predicted}}: N_4 > N_2 > N_1 > N_3, N_{\text{observed}} \ll N_1$
Or have the resonances simply escaped detection?

Nearly all existing data result from πN experiments



Observation of two new baryon excited states $N(2300)$ and $N(2570)$ in $\psi(3686) \rightarrow p \bar{p} \pi^0$

Selection of $p \bar{p} \pi^0$

- Proton and anti-proton are identified
- using dE/dx and TOF information

$$Pt > 300 \text{ MeV}/c^2 \quad (\text{for } p, \bar{p})$$

$$|\cos(\theta)| < 0.8$$

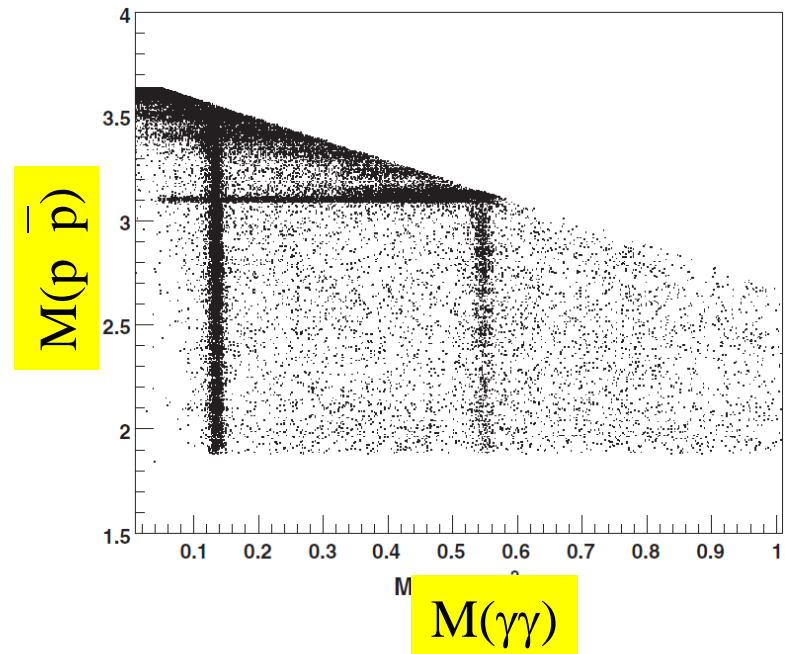
- 4C-kinematic fit:

$$\chi_{4C}^2(\gamma\gamma p\bar{p}) < 20$$

- $|M_{\gamma\gamma} - M_{\pi^0}| < 15 \text{ MeV}/c^2$
- $|M_{p\bar{p}} - M_{J/\psi}| > 0.04 \text{ GeV}/c^2$

Phys.Rev.Lett. 110 (2013) 022001

data sample: $1.06 \times 10^8 \psi'$



Two vertical bands: $\psi' \rightarrow \pi^0 p\bar{p}, \eta p\bar{p}$
 Horizontal band: $\psi' \rightarrow X + J/\psi, J/\psi \rightarrow p\bar{p}$



Study $N(1535)$ in $\psi(3686) \rightarrow p \bar{p} \eta$ decay

$N(1535)$

For $N(1535)$ with its mass close to the threshold of its dominant decay channel $N\eta$, the approximation of a constant width is not very good. Thus, a phase-space-dependent width for $N(1535)$ is also used

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

The phase-space-dependent widths can be written as

$$\Gamma_{N^*}(s) = \Gamma_{N^*}^0 \left(0.5 \frac{\rho_{N\pi}(s)}{\rho_{N\pi}(M_{N^*}^2)} + 0.5 \frac{\rho_{N\eta}(s)}{\rho_{N\eta}(M_{N^*}^2)} \right),$$

where $\rho_{N\pi}$ and $\rho_{N\eta}$ are the phase space factors for the $N\pi$ and $N\eta$ final states, respectively,

$$\begin{aligned} \rho_{NX}(s) &= \frac{2q_{NX}(s)}{\sqrt{s}} \\ &= \frac{\sqrt{(s - (M_N + M_X)^2)(s - (M_N - M_X)^2)}}{s} \end{aligned}$$



$$\text{PWA of } \psi' \rightarrow \pi^0 p \bar{p}$$

N(940) into virtual proton + pi0

are also considered. According to the framework of soft π meson theory [22], the off-shell decay process is needed in this channel. Thus, $N(940)$ with a mass of $940 \text{ MeV}/c^2$ and zero width is included. The $N(940)$ represents a virtual proton, which could emit a π^0 . The Feynman diagram of this process can be found in Ref. [15].

[15] M. Ablikim *et al.* (BES Collaboration), *Phys. Rev. D* **80**, 052004 (2009).

In summary, we studied the intermediate resonances, including their masses, widths, and spin parities, in the decay $\psi(3686) \rightarrow p \bar{p} \pi^0$. Two new N^* resonances are observed, in addition to five well-known N^* resonances. The masses and widths as well as the spin parities of the two new N^* states have been measured. The branching fractions of $\psi(3686) \rightarrow p \bar{p} \pi^0$ and the product branching fractions through each intermediate N^* state are measured. No clear evidence for $N(1885)$ or $N(2065)$ has been found. The hypothetical $p \bar{p}$ resonance has a significance of less than 4σ , indicating that the threshold enhancement most likely is due to interference of N^* intermediate resonances.

