Baryon spectroscopy at BESIII

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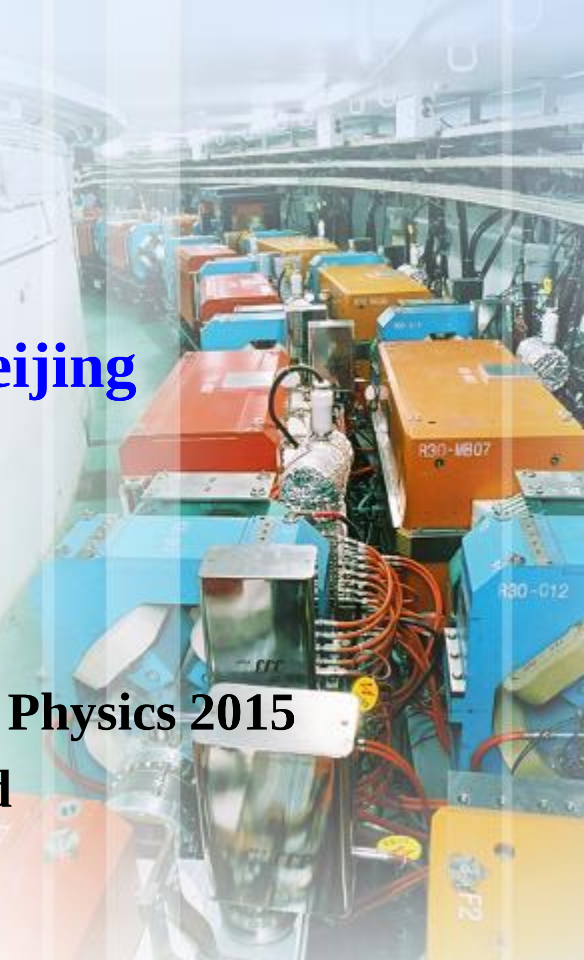


International Workshop on Hadron Nuclear Physics 2015

July 7-11, 2015, Krabi, Thailand

OUTLINE

- ❖ **Status of BEPCII/BESIII**
- ❖ **Recent results of baryon spectroscopy from BESIII**
  - ✓ **Two hyperons in $\psi(3686) \to K^- \Lambda \, \Xi^+$**
  - ✓ **Exited strange baryons in $\psi(3686) \to \Lambda \, \bar{\Sigma}^+ \pi^-$**
  - ✓ **Two new excited baryon states in $\psi(3686) \to p \, \bar{p} \, \pi^0$**
  - ✓ **N(1535) in $\psi(3686) \to p \, \bar{p} \, \eta$**
- ❖ **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: $0.85 \times 10^{33} cm^{-2}s^{-1}$@3770 MeV

Optimum energy: 1.89 GeV

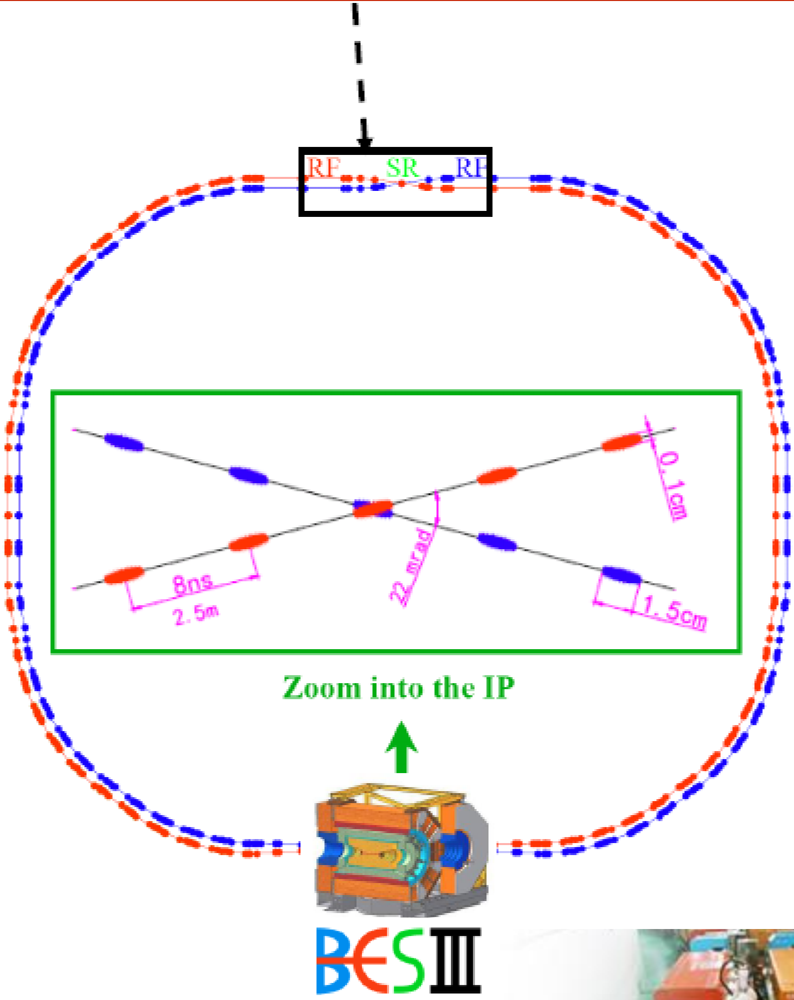
Energy spread: 5.16×10^{-4}

No. of bunches: 93

Bunch length: 1.5 cm

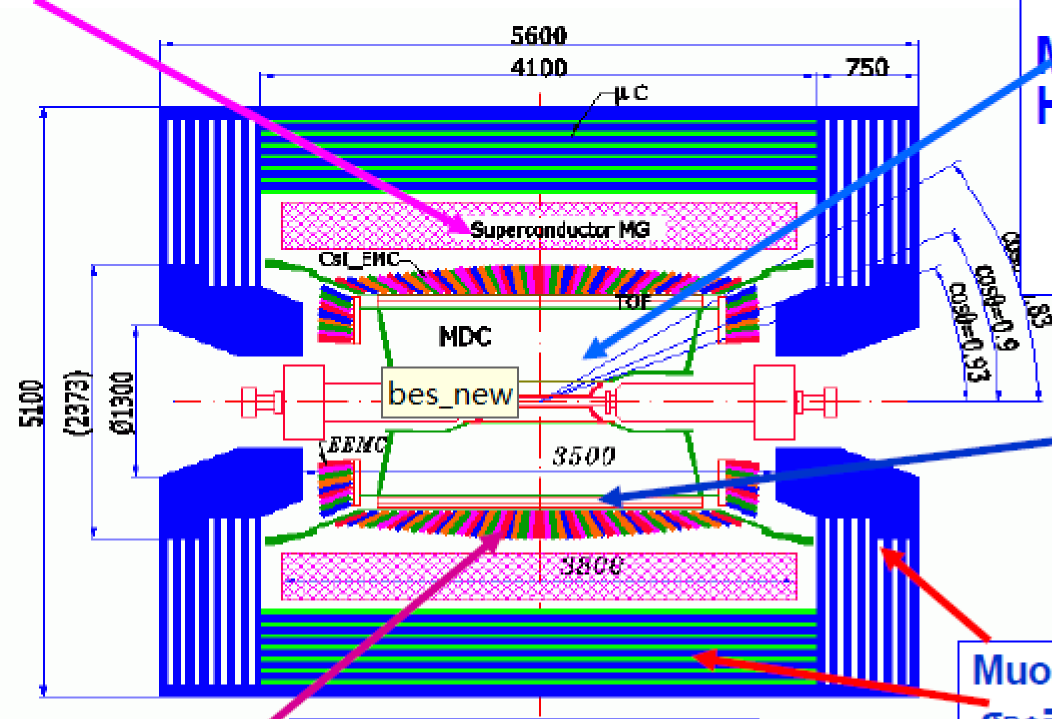
Total current: 0.91 A

Circumference: 237m



The BESIII detector

Solenoid Magnet: 1 T Super conducting



MDC: small cell & He gas

σ_{xy}=130 μm
$\delta p/p$ = 0.5% @1GeV
dE/dx=6%

TOF:

σ_T = 90 ps Barrel
110 ps Endcap

Muon ID: 8~9 layer RPC

$\sigma_{R\Phi}$=1.4 cm~1.7 cm

EMCAL: CsI crystal

$\Delta E/E$ = 2.5% @1 GeV
$\sigma_{\varphi,z}$ = 0.5~0.7 cm/$\sqrt{E}$

Data Acquisition:

Event rate = 3 kHz
Throughput ~ 50 MB/s

Trigger: Tracks & Showers

Pipelined; Latency = 6.4 μs

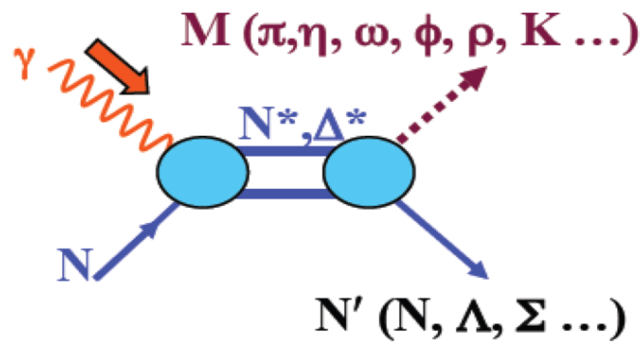
The new BESIII detector is hermetic for neutral and charged particle with excellent resolution, PID, and large coverage.

Baryon spectroscopy

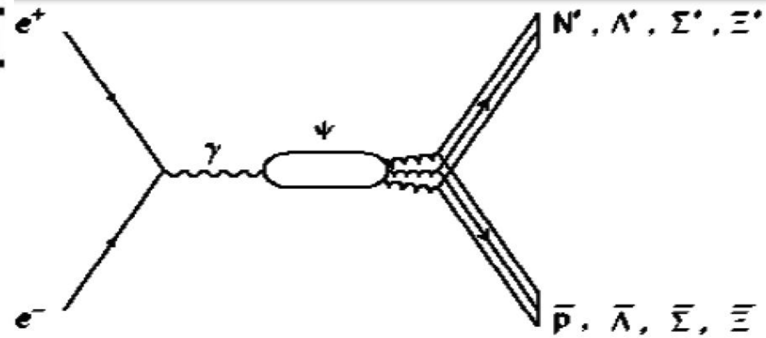
- **Baryon spectroscopy is an important field to understand the internal structure of hadrons.**
- **The established baryons are described by three-quark (qqq) configurations.**
- **Non-relativistic quark model:**
  - **It is quite successful in interpreting baryon resonances.**
  - **It also provides 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, ….

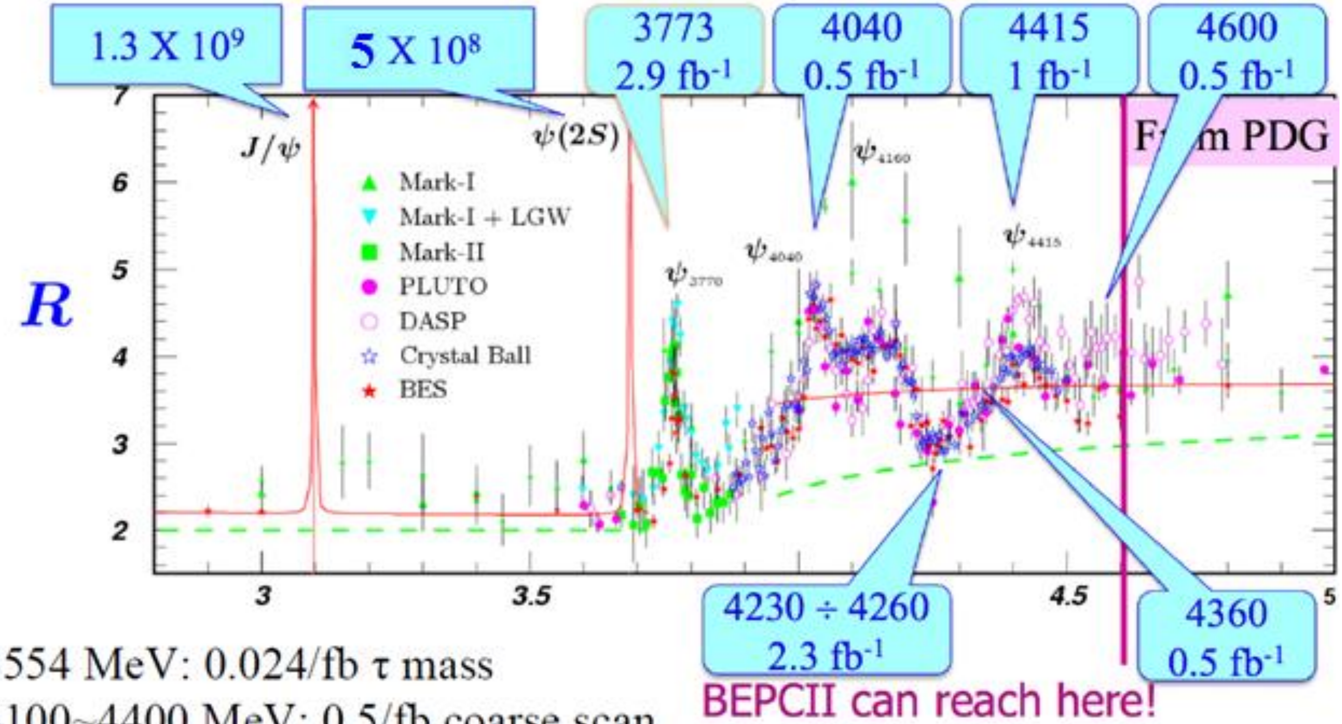


$$J/\psi(\psi') \to \bar{B}BM \;\Rightarrow\; N^*, \Lambda^*, \Sigma^*, \Xi^*$$



- ✓ **Isospin 1/2 filter:** $\psi \to N\bar{N}\pi$, $\psi \to N\bar{N}\pi\pi$
- ✓ **Missing N* with small couplings to** πN **&** γN **, but large coupling to gggN :** $\psi \to N\bar{N}\pi/\eta/\eta'/\omega/\phi, \bar{p}\Sigma\pi, \bar{p}\Lambda K$ …
- ✓ **Not only study excited nucleons, but also baryons** Λ^*, Σ^*, Ξ^*
- ✓ **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 $\psi(3686)\to K^-\Lambda\bar{\Xi}^+$+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

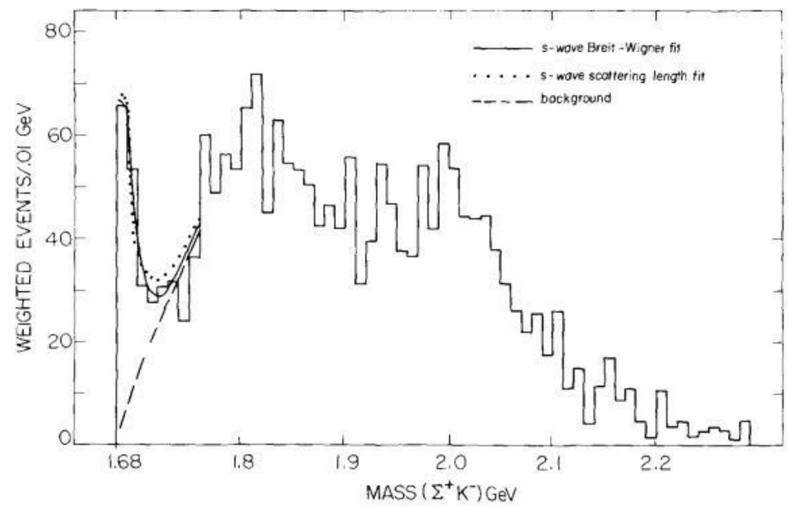
Particle	J^P	Overall status	Status as seen in $\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
$\Xi(1318)$	1/2+	****					Decays weakly
$\Xi(1530)$	3/2+	****	****				
$\Xi(1620)$		*	*				
$\Xi(1690)$		***		***	**		
$\Xi(1820)$	3/2−	***	**	***	**	**	
$\Xi(1950)$		***	**	**		*	
$\Xi(2030)$		***		**	***		
$\Xi(2120)$		*		*			
$\Xi(2250)$		**					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 $\psi(3686)\rightarrow K^-\Lambda\ \bar{\Xi}^+$+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

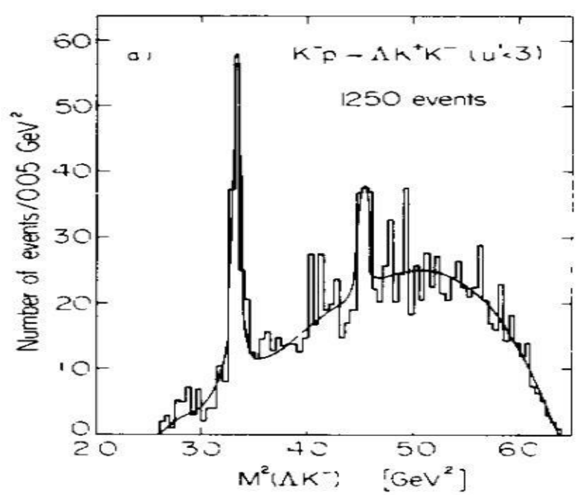
- Its existence has been confirmed by other experiments, WASA89, Belle, but its spin parity was not well determined.



- In 2008, BABAR determined spin-parity of $\Xi(1690)$ to be $J^P = ½^-$ 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 indicated that $\Xi(1820)$ favors negative parity of $J = 3/2$.



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

- **At present $\Xi(1690)$ and $\Xi(1820)$ are firmly established.**

- **Further investigation of their properties is important to the understanding of Ξ^* states.**

- **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 $\psi(3686)\to K^-\Lambda\ \bar{\Xi}^+$+c.c.

data sample: 106×10^6 ψ'

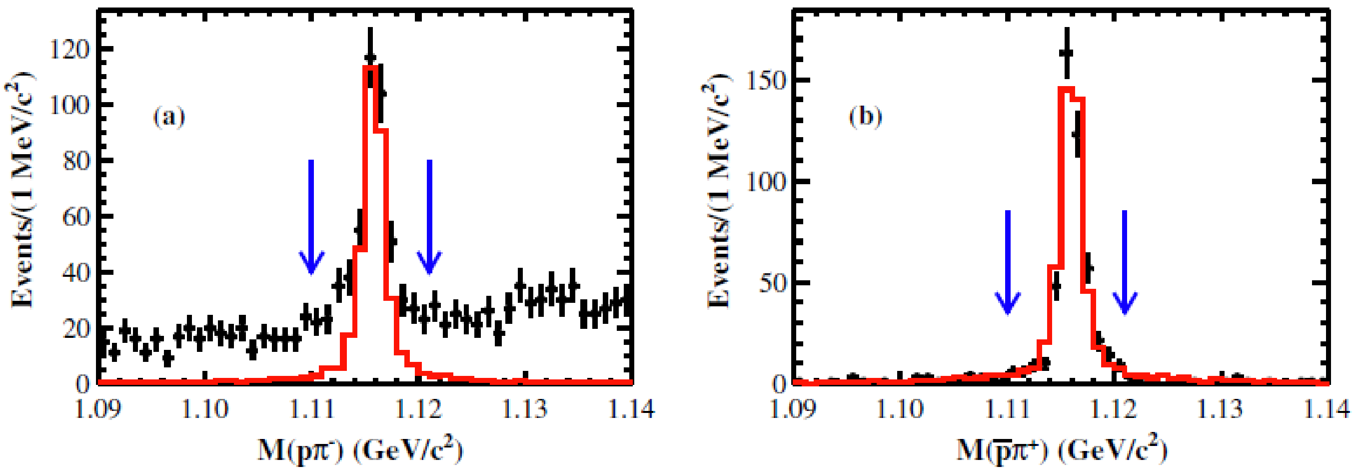
PRD 91, 092006 (2015)

The decays is reconstructed from cascade decay:

$\psi(3686)\text{->}K^-\Lambda\bar{\Xi}^+$

$\bar{\Xi}^+ \to \bar{\Lambda}\pi^+$, $\bar{\Lambda} \to \bar{p}\pi^+$

$\Lambda \to p\pi^-$



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

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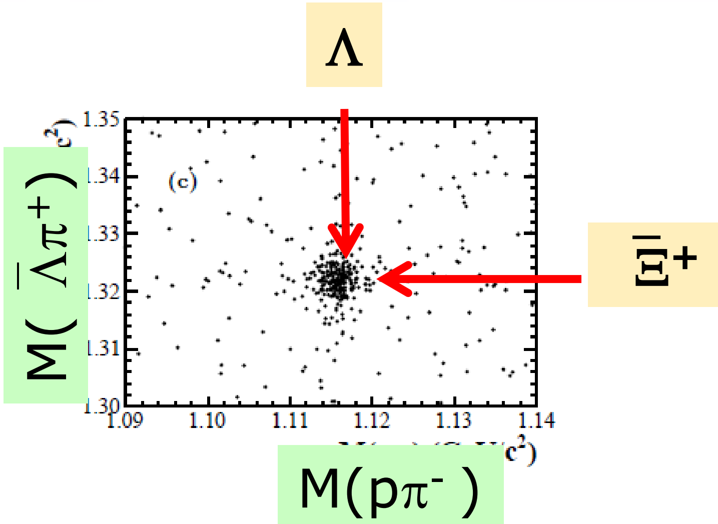
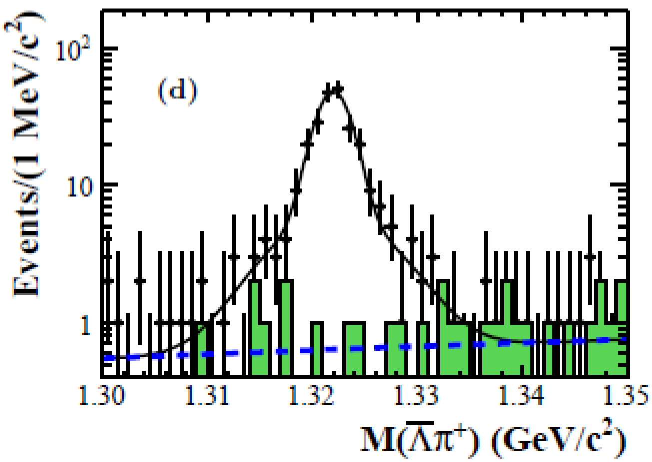


- Signal: double Gaussian function.
- bg: a first order Chebychev polynomial
- non - $\bar{\Xi}^+$ bg estimated with the $\psi(3686)$ inclusive MC sample

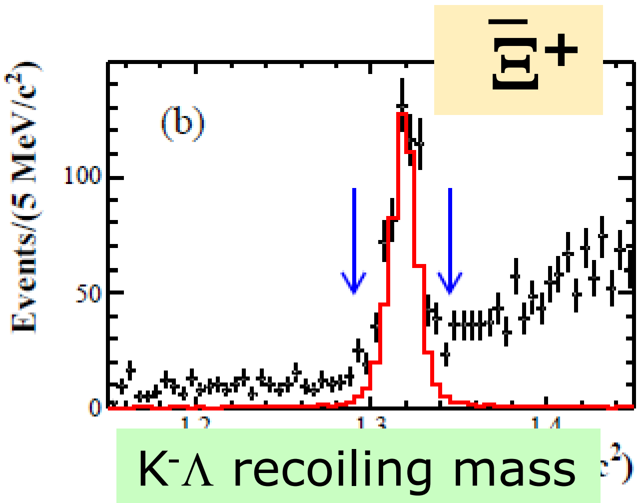
an extended unbinned maximum likelihood fit is performed.



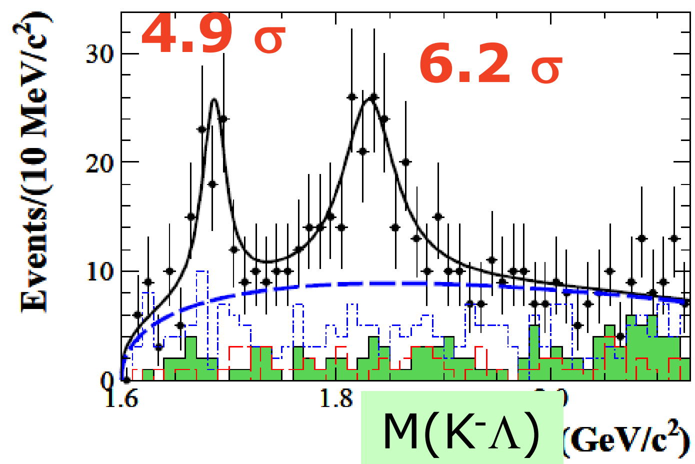
$$B(\psi(3686)\to K^-\Lambda\bar{\Xi}^+) = (3.86\pm0.27\pm0.32)\times10^{-5}$$

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

PRD 91, 092006 (2015)



an extended un-binned maximum likelihood fit is performed to determine the resonance parameters and event yields of the exited hyperons Ξ^*

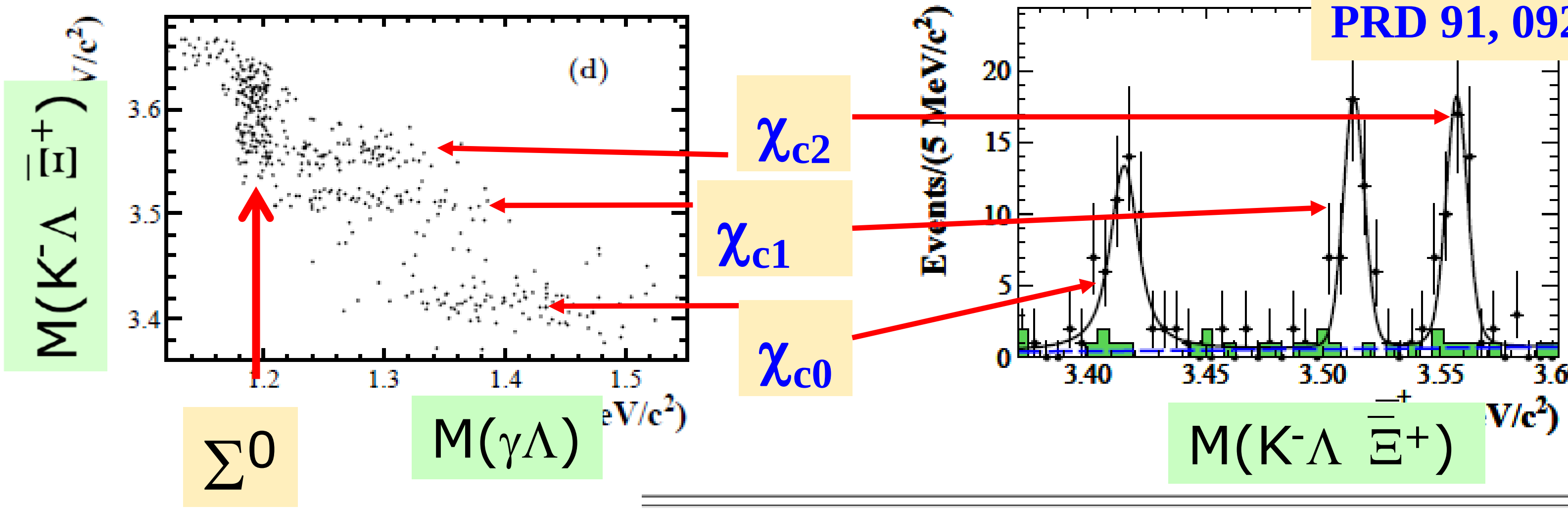


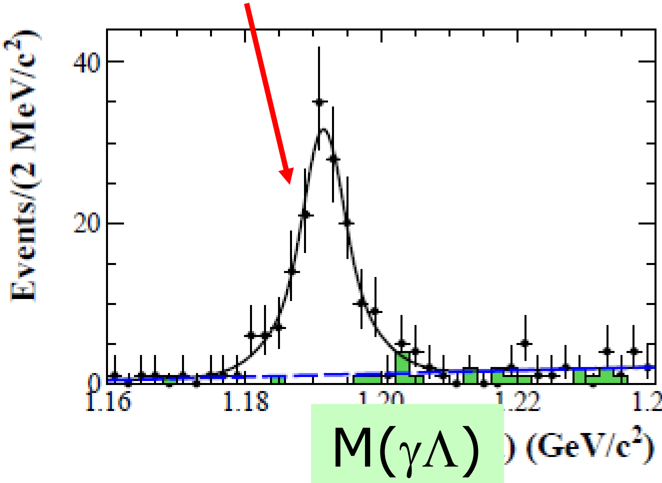
	$\Xi(1690)^-$	$\Xi(1820)^-$
M(MeV/c^2)	1687.7±3.8±1.0	1826.7±5.5±1.6
Γ(MeV)	27.1±10.0±2.7	54.4±15.7±4.2
Event yields	74.4±21.2	136.2±33.4
Significance(σ)	4.9	6.2
Efficiency(%)	32.8	26.1
$\mathcal{B}$ (10^{-6})	5.21±1.48±0.57	12.03±2.94±1.22
$M_{\rm PDG}$(MeV/c^2)	1690±10	1823±5
$\Gamma_{\rm PDG}$(MeV)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

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

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

PRD 91, 092006 (2015)





Decay	Branching fraction
$\psi(3686)\to K^-\Sigma^0\bar{\Xi}^+$	$(3.67\pm0.33\pm0.28)\times10^{-5}$
$\psi(3686)\to\gamma\chi_{c0},\ \chi_{c0}\to K^-\Lambda\bar{\Xi}^+$	$(1.90\pm0.30\pm0.16)\times10^{-5}$
$\psi(3686)\to\gamma\chi_{c1},\ \chi_{c1}\to K^-\Lambda\bar{\Xi}^+$	$(1.32\pm0.20\pm0.12)\times10^{-5}$
$\psi(3686)\to\gamma\chi_{c2},\ \chi_{c2}\to K^-\Lambda\bar{\Xi}^+$	$(1.68\pm0.26\pm0.15)\times10^{-5}$

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

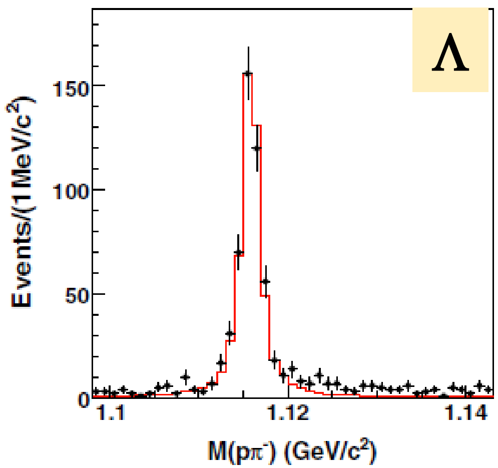
Observation of the decay $\psi(3686) \to \Lambda \bar{\Sigma}^{\pm}\pi^{\mp}$ + c.c.

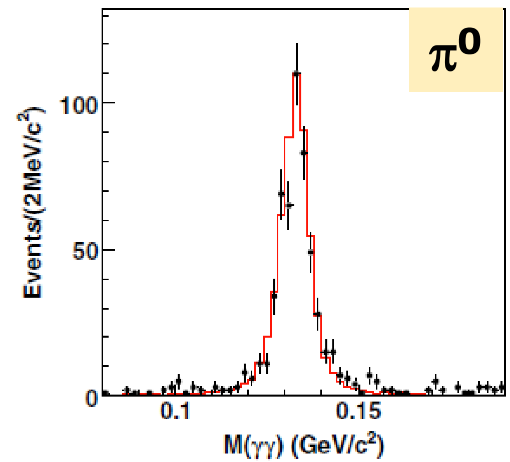
data sample: 106×10^{6} ψ'

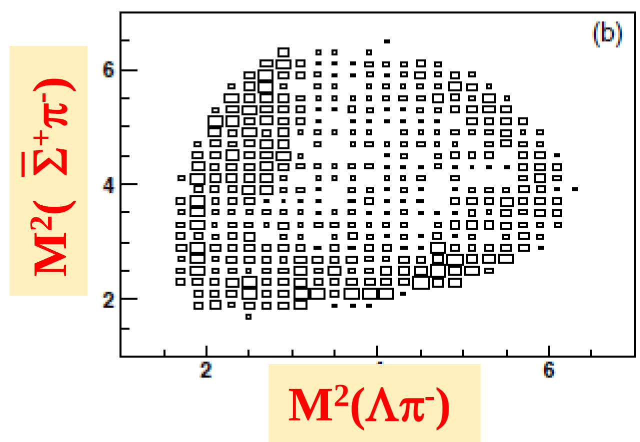
PRD 88, 112007 (2013)

The candidate events are reconstructed in six modes:

$\psi(3686) \to$
$\Lambda\bar{\Sigma}^{+}\pi^{-}(\bar{\Sigma}^{+} \to \bar{n}\pi^{+})$
$\bar{\Lambda}\Sigma^{-}\pi^{+}(\Sigma^{-} \to n\pi^{-})$
$\Lambda\bar{\Sigma}^{-}\pi^{+}(\bar{\Sigma}^{-} \to \bar{n}\pi^{-})$
$\bar{\Lambda}\Sigma^{+}\pi^{-}(\Sigma^{+} \to n\pi^{+})$
$\Lambda\bar{\Sigma}^{-}\pi^{+}(\bar{\Sigma}^{-} \to \bar{p}\pi^{0})$
$\bar{\Lambda}\Sigma^{+}\pi^{-}(\Sigma^{+} \to p\pi^{0})$



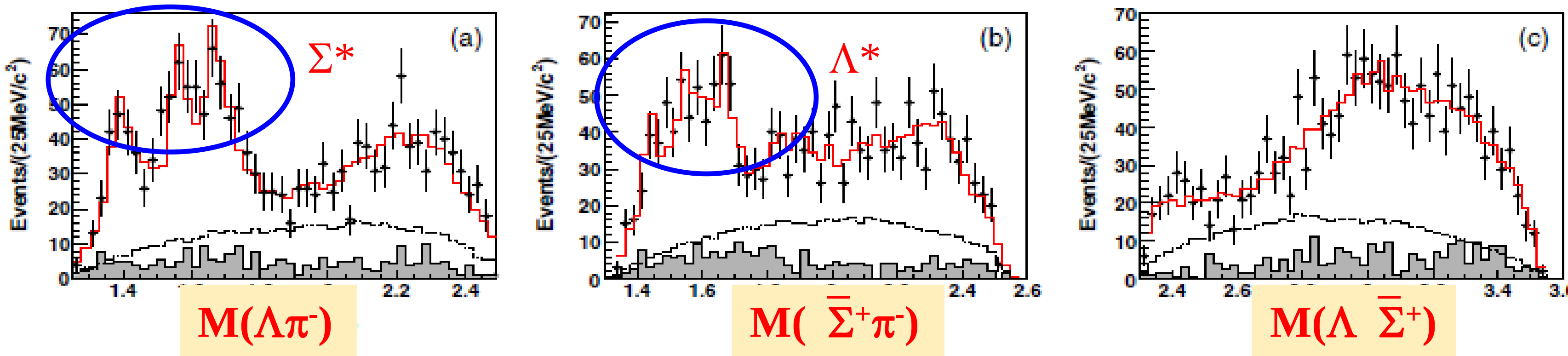




Observation of the decay $\psi(3686)\to\Lambda\bar{\Sigma}^{\pm}\pi^{\mp}$ + c.c.

data sample: 106×10^{6} ψ'

PRD 88, 112007 (2013)



- **Excited strange baryons around 1.4 to 1.7GeV/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**

$$\mathcal{B}(\psi(3686)\to\Lambda\bar{\Sigma}^{+}\pi^{-}+\text{c.c.}) = (1.40\pm0.03\pm0.13)\times10^{-4}$$

$$\mathcal{B}(\psi(3686)\to\Lambda\bar{\Sigma}^{-}\pi^{+}+\text{c.c.}) = (1.54\pm0.04\pm0.13)\times10^{-4}$$

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

- In 2001, BESII experiment started a baryon program with the study of N(1535) and N(1650) in the decay of $J/\psi \to p\bar{p}\eta$ using PWA.

- In 2006, BESII observed a new exited nucleon, N(2065), in the decay $J/\psi \to p\bar{n}\pi^-$ +c.c. , and subsequently confirmed in $J/\psi \to p\bar{p}\pi^0$.

- BESII also studied $\psi(3686) \to p\bar{p}\gamma\gamma$, where both $p\bar{p}\pi^0$ and $p\bar{p}\eta$ were observed, and $\psi(3686) \to p\bar{p}\eta$ for the first time. In both decays, there was weak evidence for a $p\bar{p}$ threshold mass enhancement, but no PWA was performed.

- Using 24.5×10^6 $\psi(3686)$ events. CLEO-c collaboration studied $\psi(3686) \to p\bar{p}\pi^0$, in which N(1535) and a $p\bar{p}$ enhancement were investigated.

These results show that J/ψ and $\psi(3686)$ decays offer a unique place to study baryon spectroscopy.

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

data sample: 106×10^6 ψ'

PRL 110, 022001 (2013)

- **Proton and anti-proton are identified using dE/dx and TOF information**
- **At least two photos are selected**

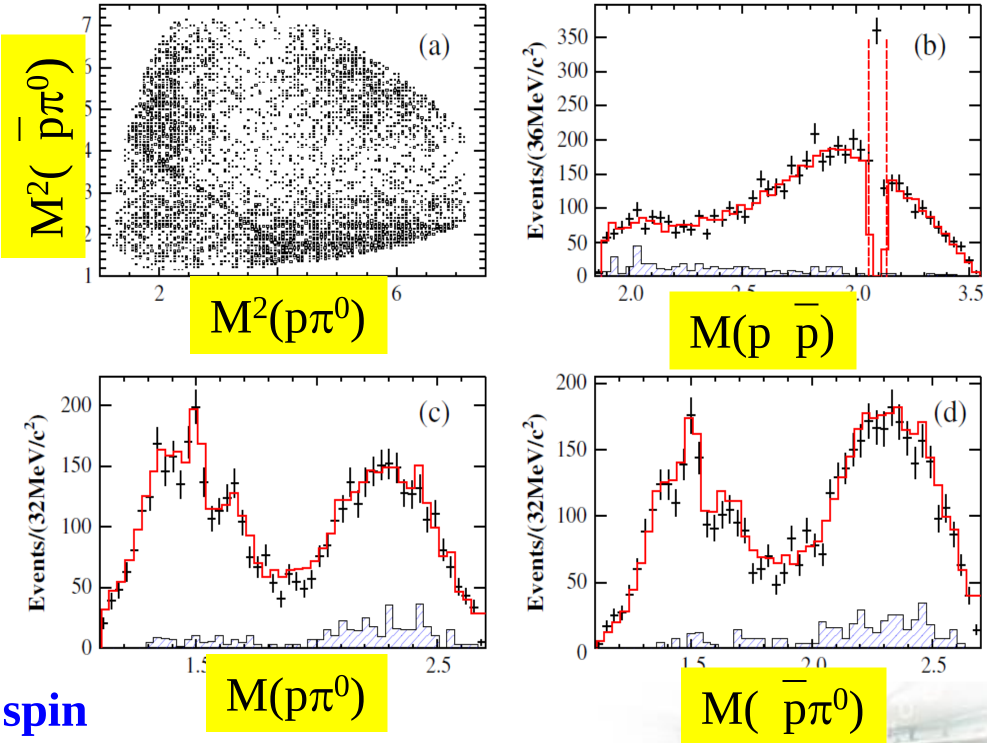
➢ **To better understand the components of this decays, PWA is pursued.**

➢ **Dominated by two-body decays:**

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

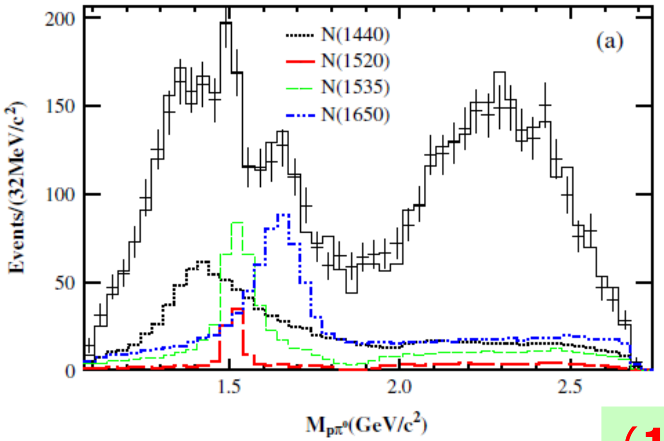
$\psi(3686)\to p\bar{N}^*$, $N^*\to \bar{p}\pi^0$ +c.c.

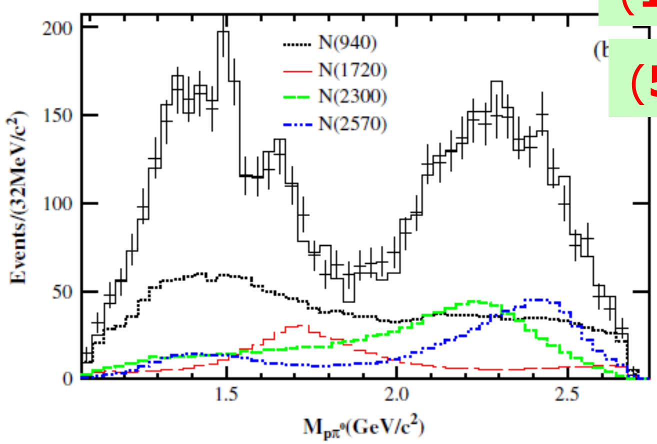
➢ **All N* resonances up to 2.2 GeV with spin up to 5/2 listed in PDG are considered.**



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

PRL 110, 022001 (2013)





(1/2+)

(5/2-)

Resonance	M(MeV/c^2)	Γ(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)	$\mathbf{2300^{+40+109}_{-30-0}}$	$\mathbf{340^{+30+110}_{-30-58}}$	**120.7**	**4**	$\mathbf{15.0\sigma}$
N(2570)	$\mathbf{2570^{+19+34}_{-10-10}}$	$\mathbf{250^{+14+69}_{-24-21}}$	**78.9**	**6**	$\mathbf{11.7\sigma}$

- **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 ppbar mass spectrum can be reproduced by the interference of N* resonances**

$B(\psi(3686)\to p\bar{p}\pi^0) = (1.65\pm0.03\pm0.15)\times10^{-4}$

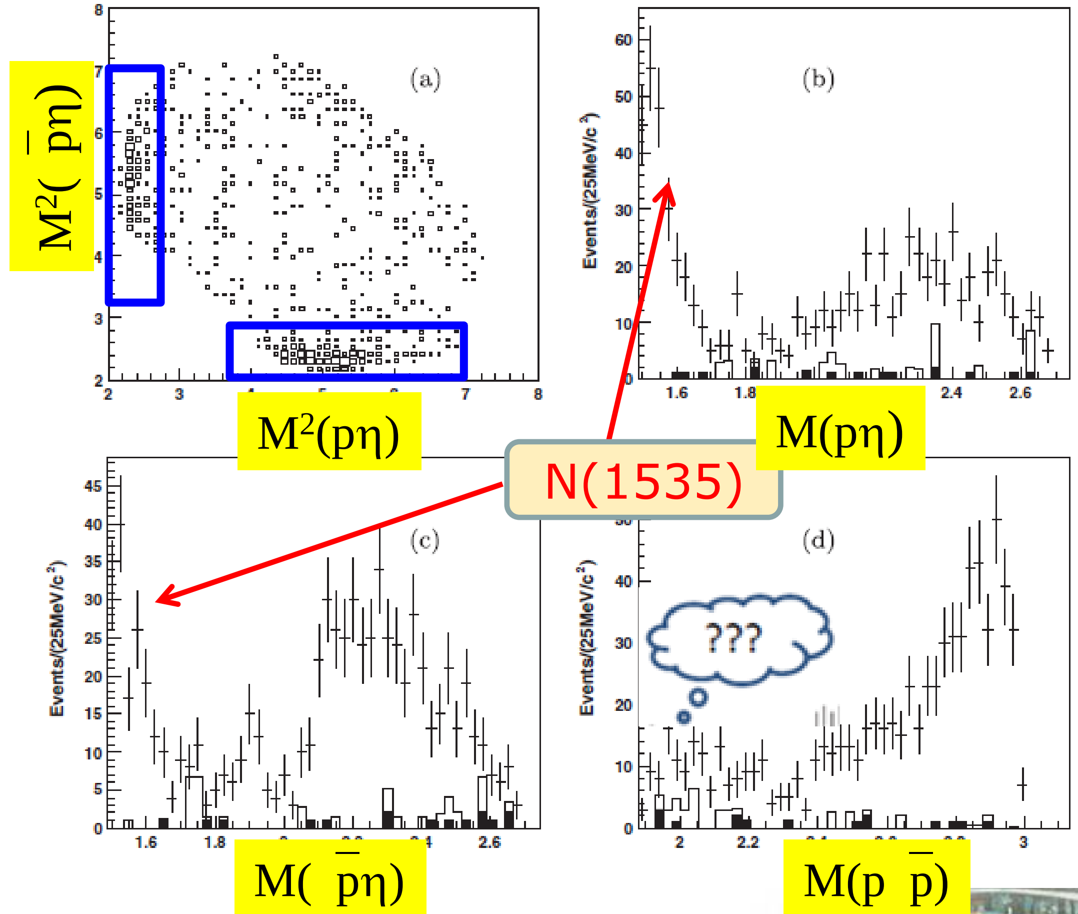
Study N(1535) in $\psi(3686)\to p\bar{p}\eta$ decay

data sample: 106×10^6 ψ'

PRD 88, 032010 (2013)

- ✓ **The decay topology is quite simple, $p\bar{p}\gamma\gamma$.**

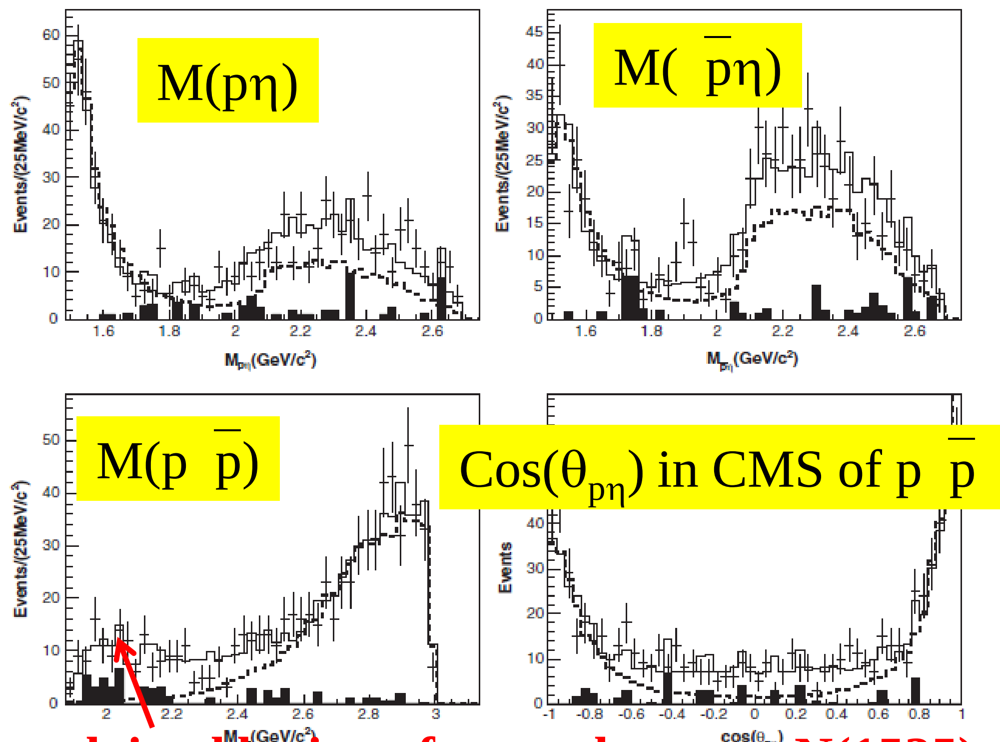
- ✓ **Two clusters corresponding to the $p\eta$ mass threshold enhancement are visible.**



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

PRD 88, 032010 (2013)

- ✓ The best solution indicates that N(1535) combined with an interfering PHSP is sufficient to describe the data



explained by interference between N(1535) and phase space, no evidence for $p\bar{p}$ resonace

Mass and width of N(1535)

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

PDG value:

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

Branching fraction:

- $B(\psi' \to N(1535)\bar{p}) \times B(N(1535) \to p\eta) + c.c.$

$$= (5.2 \pm 0.3^{+3.2}_{-1.2} \times 10^{-5})$$

Summary and perspective

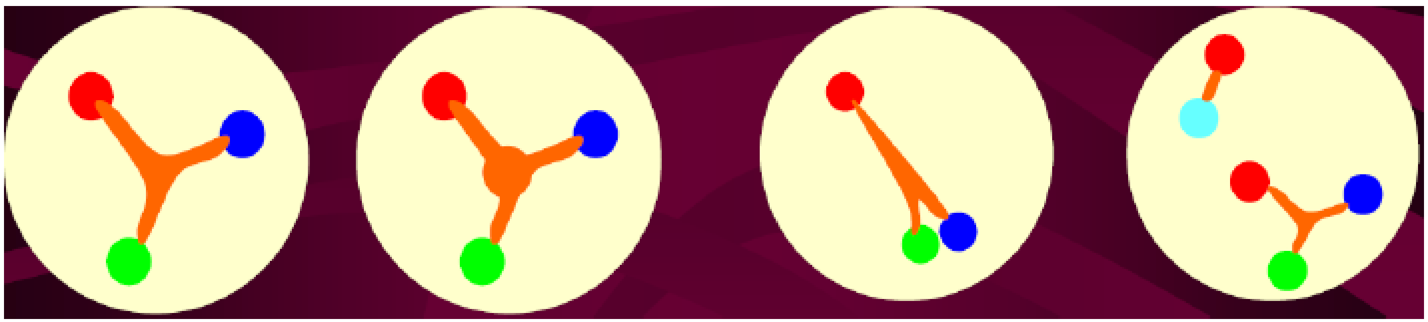
- **BESIII collected 0.5×10^9 $\psi(2S)$ and 1.3×10^9 J/ψ events.**
- **Many baryon states are presented:**
  - $\Xi^-(1690)$ and $\Xi^-(1820)$ in $\psi(3686)\to K^-\Lambda\bar{\Xi}^+$+c.c.
  - excited strange baryons Λ^* and Σ^* in $\psi(3686)\to\Lambda\bar{\Sigma}^\pm\pi^\mp$
  - excited baryon states N(2300) and N(2570) in $\psi(3686)\to p\bar{p}\pi^0$
  - N(1535) in $\psi(3686)\to p\bar{p}\eta$
- **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 experiments.**
- **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

...

$N_{predictied}$: $N_4>N_2>N_1>N_3$, $N_{observed} << N_1$

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

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

Phys.Rev.Lett. 110 (2013) 022001

data sample: 1.06×10^8 ψ'

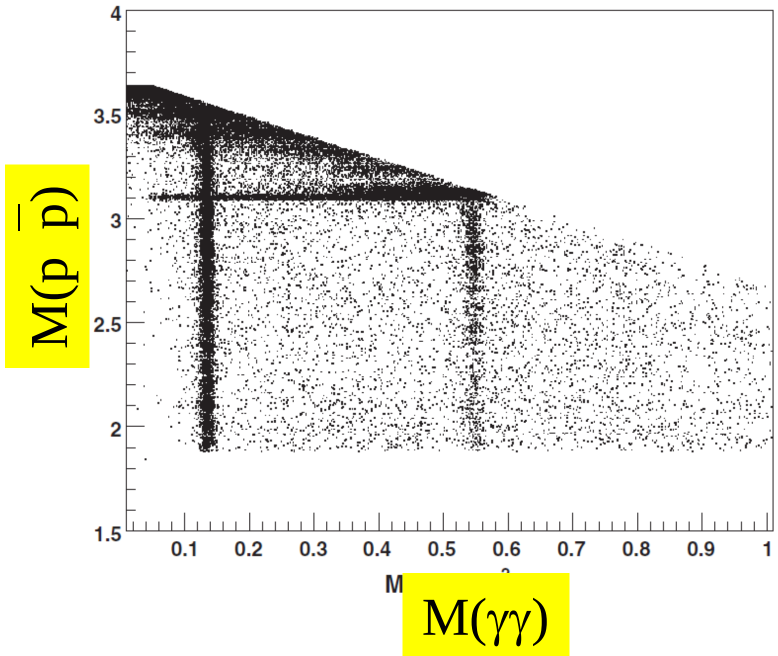
- **Proton and anti-proton are identified**
- **using dE/dx and TOF information**

$$\begin{array}{l} Pt > 300MeV/c^2 \\ |cos(\theta)| < 0.8 \end{array} \quad (\text{for } p, \bar{p})$$

- **4C-kinematic fit:**

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

- $$\begin{array}{l} |M_{\gamma\gamma} - M_{\pi^0}| < 15MeV/c^2 \\ |M_{p\bar{p}} - M_{J/\Psi}| > 0.04GeV/c^2 \end{array}$$



Two vertical bands: $\psi' \to \pi^0 p\bar{p}\,,\eta p\bar{p}$

Horizontal band: : $\psi' \to X + J/\psi\,, J/\psi \to p\bar{p}$

Study N(1535) in ψ(3686)→p $\bar{p}$η 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

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

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,

$$\rho_{NX}(s) = \frac{2q_{NX}(s)}{\sqrt{s}}$$

$$= \frac{\sqrt{(s-(M_N+M_X)^2)(s-(M_N-M_X)^2)}}{s}$$

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

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