Recent Progress in Baryon Spectroscopy at BESIII

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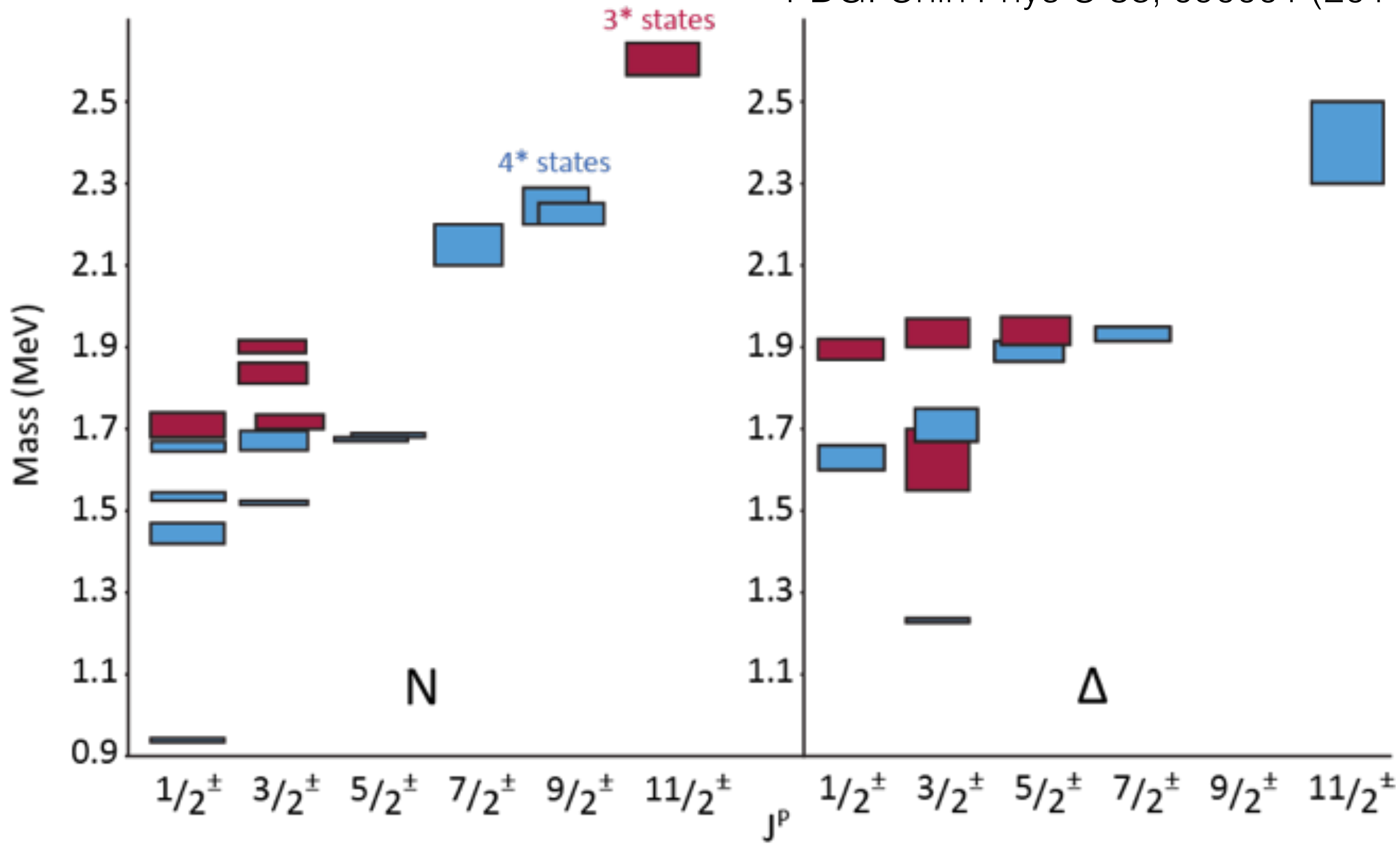
Nucleon resonance spectrum

- All ground state baryons are known
  - ➡ Good agreement with even basic versions of the quark model
- The excited spectrum is much less clear, with many more states predicted than observed

*Up to 2.4 GeV, about 45 N states are predicted, but only 15 are established (**four-** or **three-**star) and 10 are tentative (two- or one-star)*

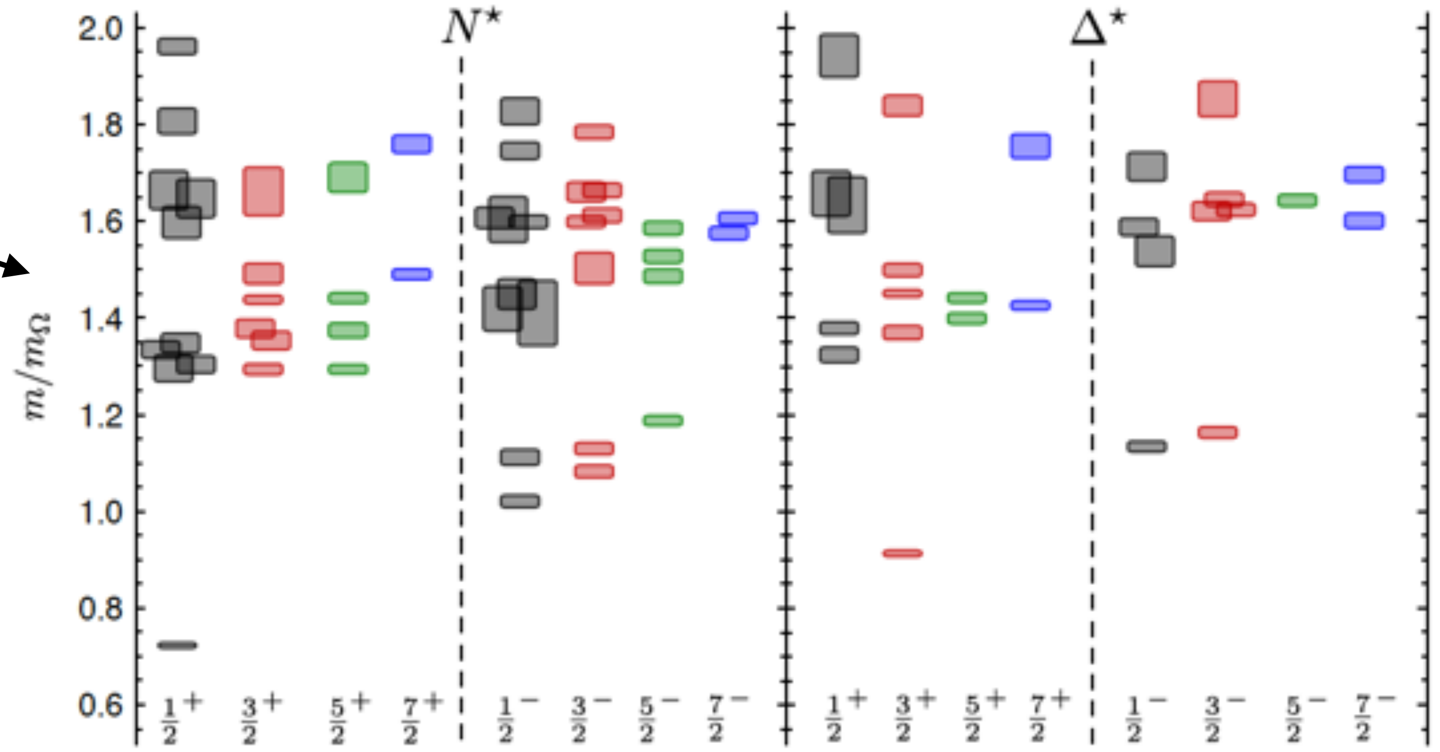
PDG: Chin Phys C 38, 090001 (2014)



The "missing resonance" problem

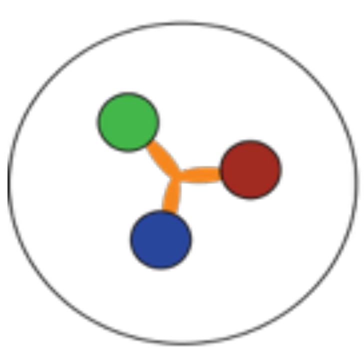
- There is strong experimental efforts with data from meson beam experiments with complementary efforts in theory (lattice QCD)
- Important goal: search for "missing resonances" not observed experimentally
  - **Experimentally**: baryon resonances may couple very weakly to single pions

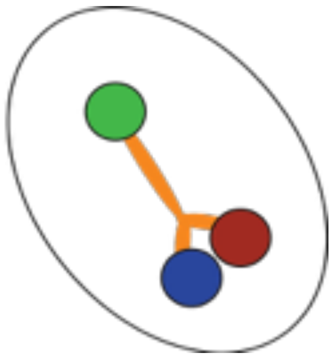
Edwards et al. PRD 84 074508 (2011)



m_π = 400 MeV

three quarks



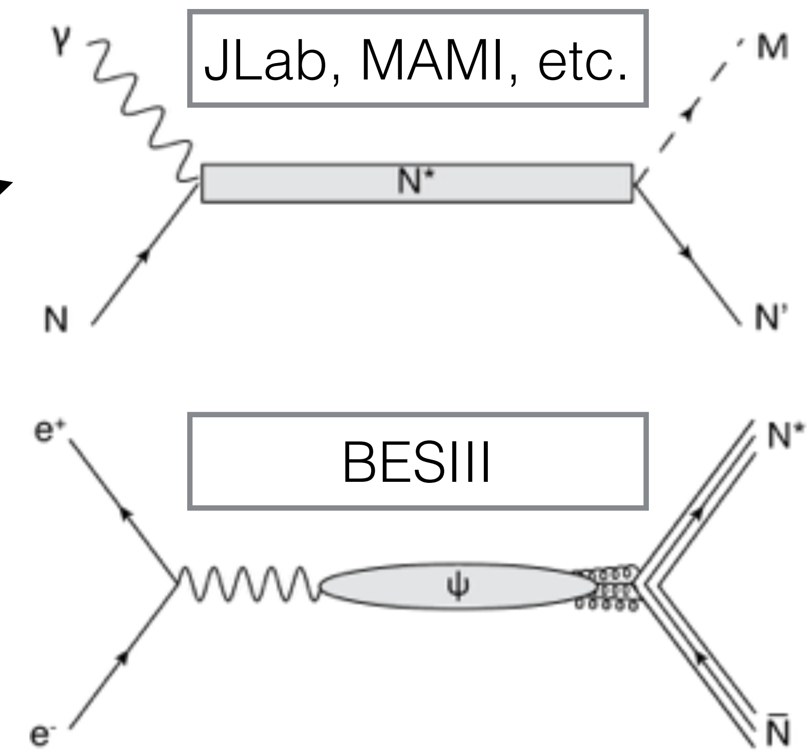


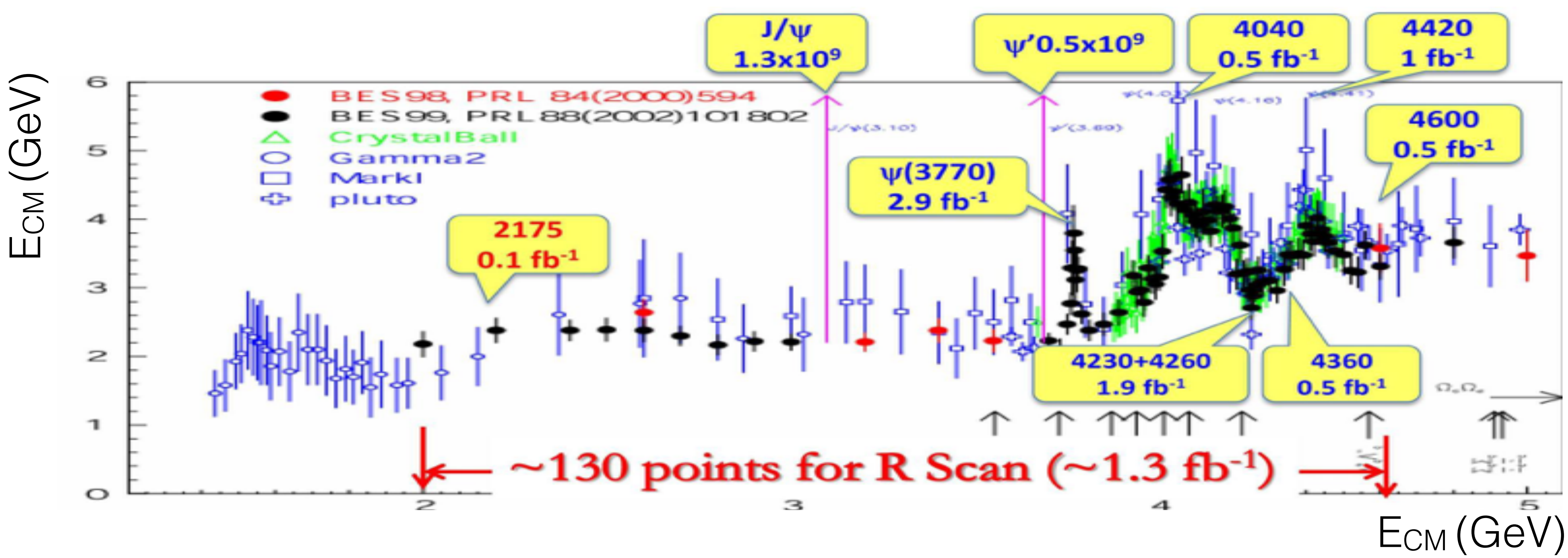
quark-diquark

- **Theoretically**: may indicate that the baryon spectrum can be modeled with *fewer effective degrees of freedom* (quark-diquark models)
  - Do not suffer from problem of extra resonances

Baryon spectroscopy at BESIII

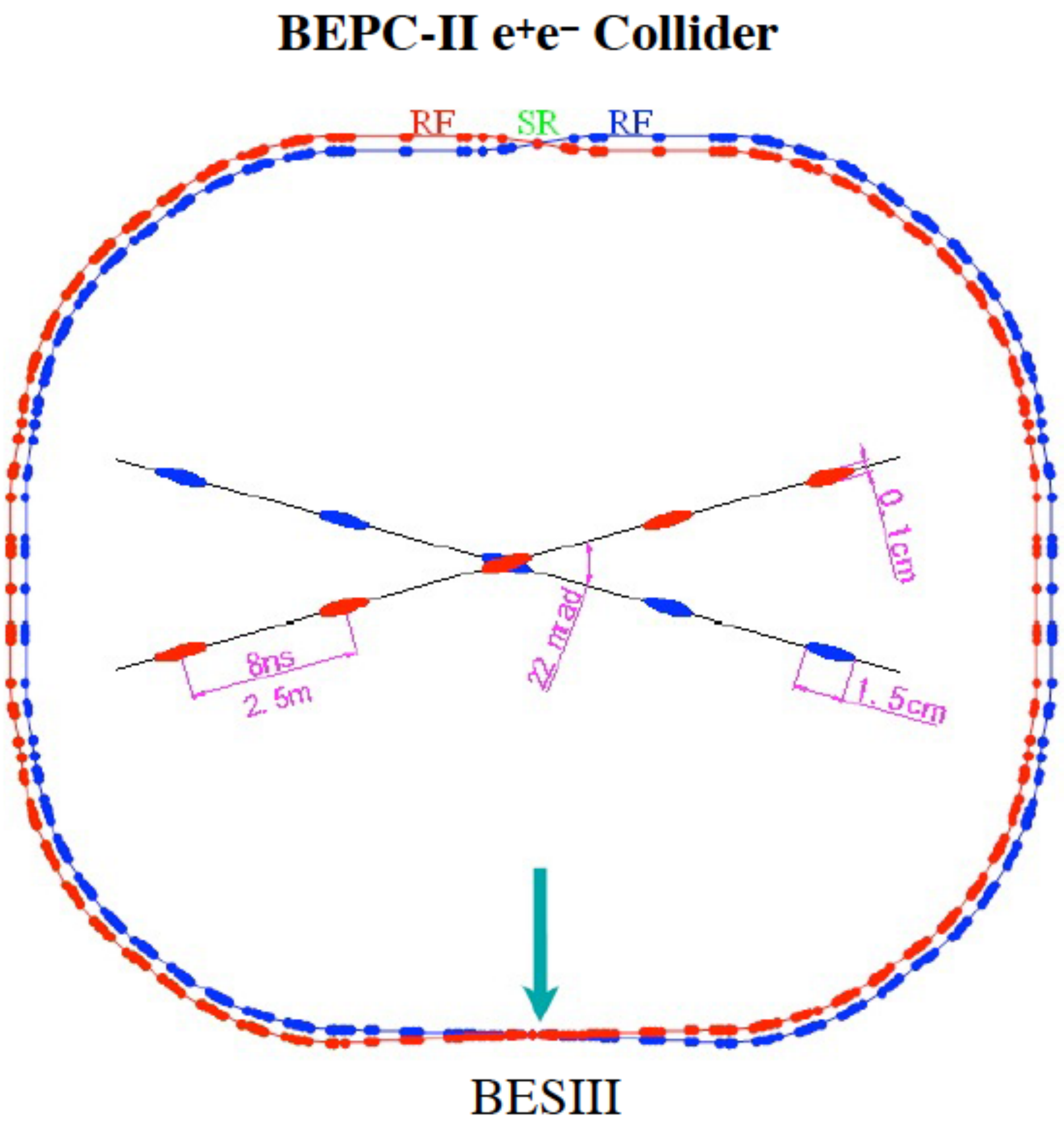
- Charmonium decays offer complementary information to existing data
  - Coupling of unobserved states through conventional production channels could be small, but coupling may be large to gggN: $\psi \longrightarrow N\bar{N}\,(\pi/\eta/\eta'/\omega/\phi)$, $\bar{p}\Sigma\pi$, $\bar{p}\Lambda K$
  - High statistics charmonium samples are available at BESIII





BESIII at BEPCII

- The physics goals of BESIII cover a diverse range:
  Light hadron spectroscopy, charm physics, τ physics, charmonium physics
- e^+e^- collisions in the charmonium region
  - Use the properties and decays of charmonium states to study QCD



BESIII at BEPCII

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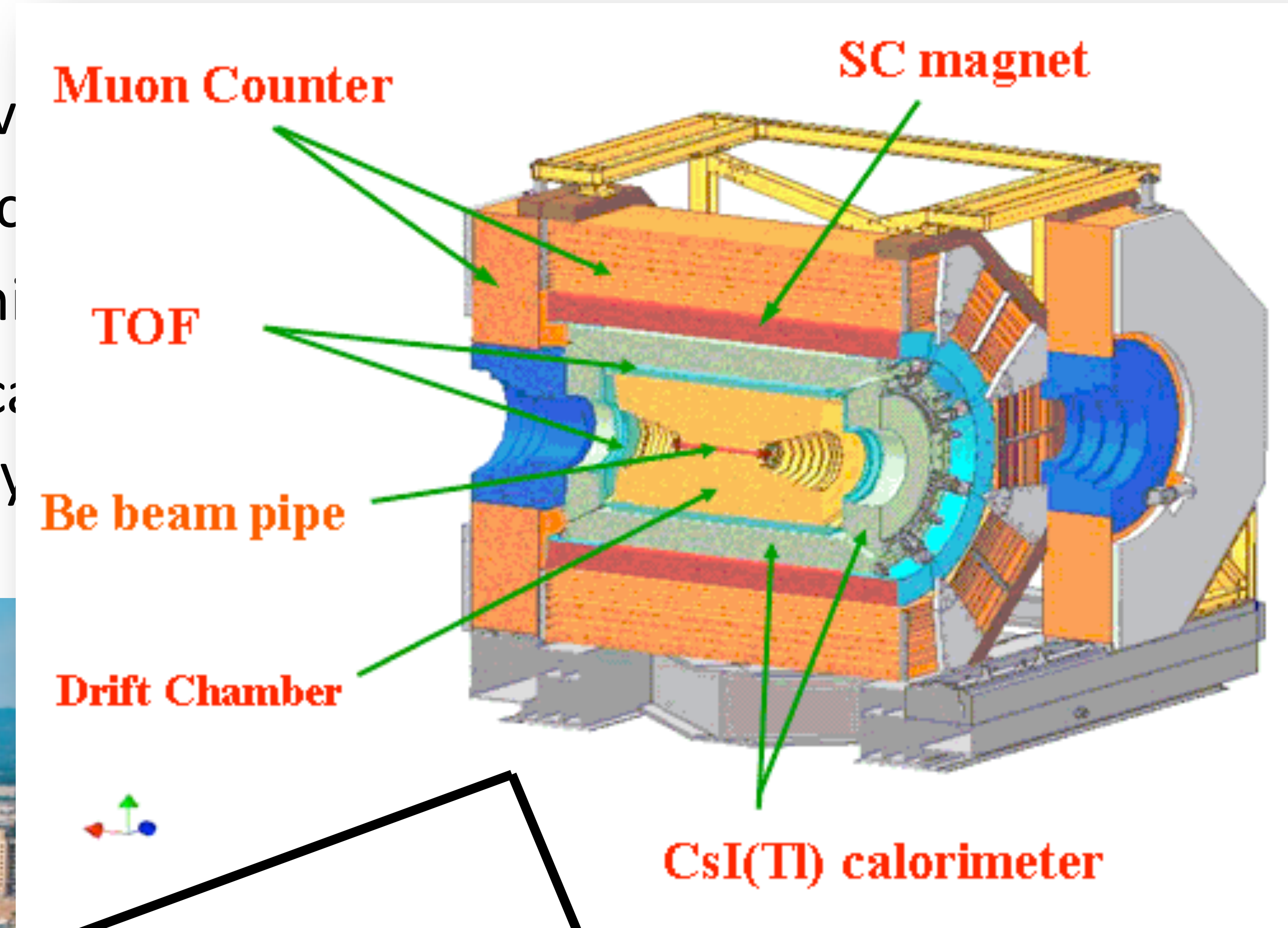
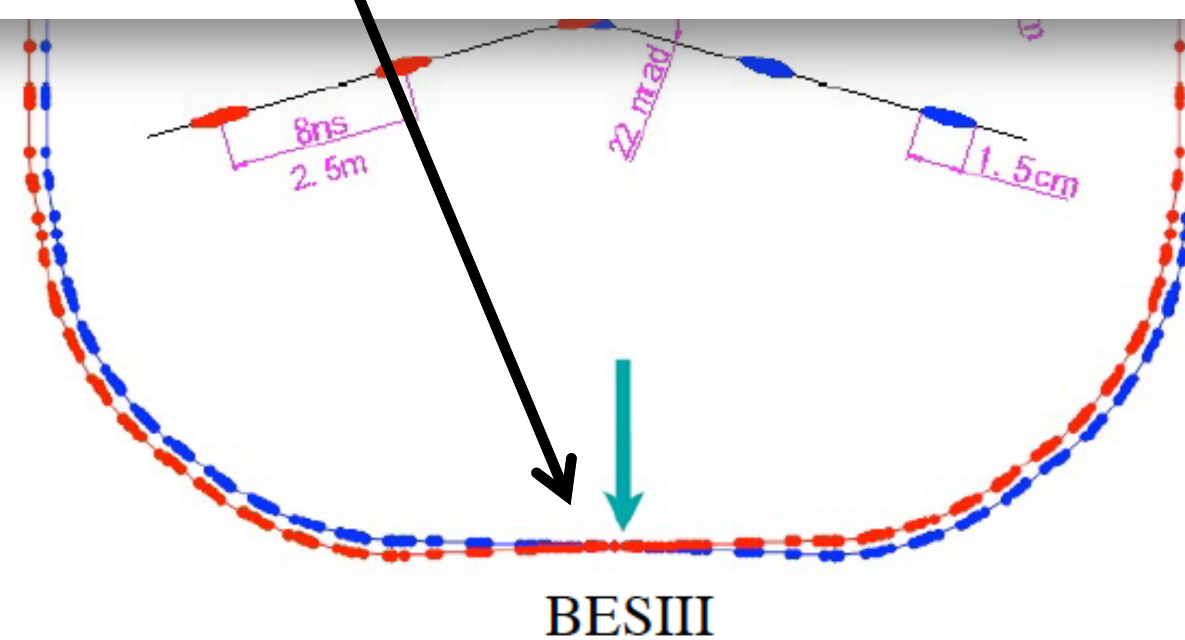




Recent BESIII results in baryon spectroscopy

- Measurements of $\psi(3686) \to \bar{p}K^+\Sigma^0$ and $\chi_{cJ} \to \bar{p}K^+\Lambda$
- Observation of the decay $\psi(3686) \to \Lambda\bar{\Sigma}^{\pm}\pi^{\mp}$
- Measurements of $\psi(3686) \to (\gamma)K^{\mp}\Lambda\bar{\Xi}^{\pm}$
- Partial wave analysis of $\psi(3686) \to p\bar{p}\eta$
- Observation of two new N* resonances in $\psi(3686) \to p\bar{p}\pi^0$
- Observation of $J/\psi \to p\bar{p}a_0(980)$
- Observation of enhanced $\Lambda\bar{\Lambda}$ production near threshold
- Absolute branching fraction measurements of Λ_c^+ near threshold
- Absolute branching fraction measurement of $\Lambda_c \to \Lambda e^+\nu$

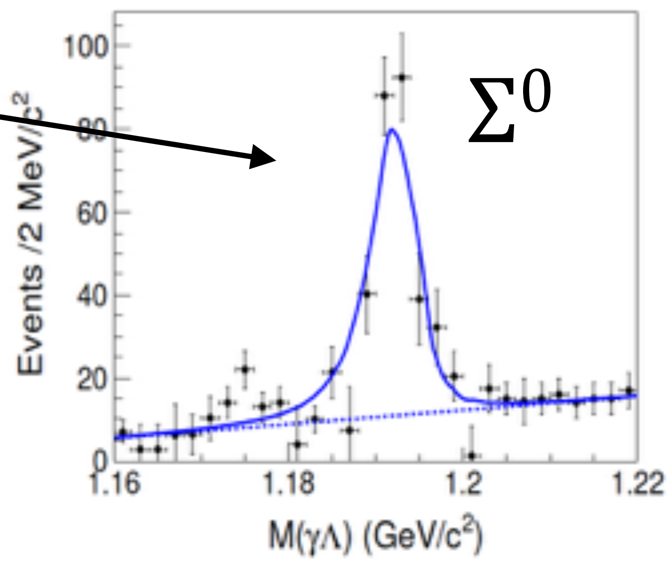
- Using data samples collected in 2009

- Preliminary results

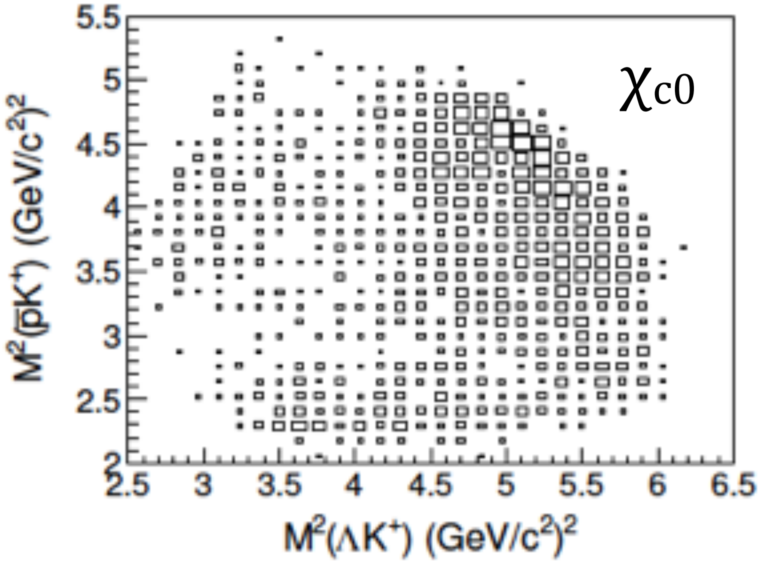
Measurements of $\psi(3686) \to \bar{p}K^+\Sigma^0$ and $\chi_{cJ} \to \bar{p}K^+\Lambda$

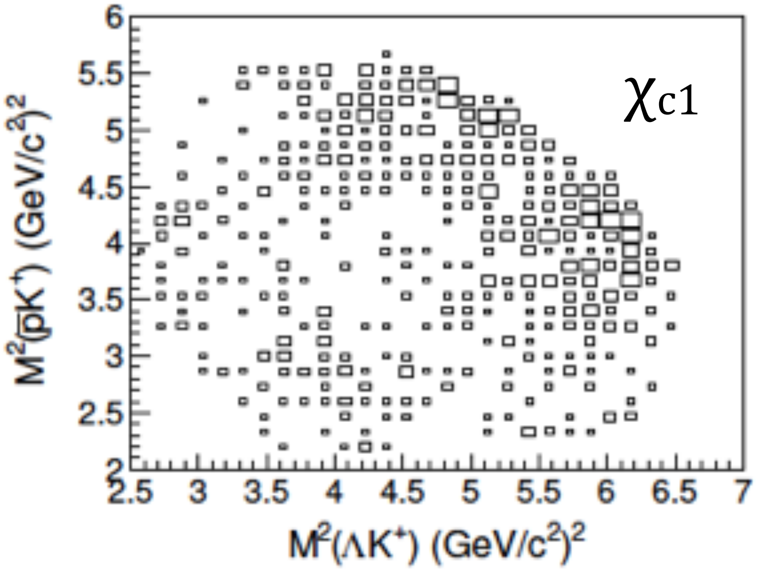
- First measurement of $\psi' \to \bar{p}K^+\Sigma^0$
- Improved measurements for $\chi_{cJ} \to \bar{p}K^+\Lambda$
- Anomalous enhancement near threshold in $\chi_{cJ} \to \bar{p}K^+\Lambda$

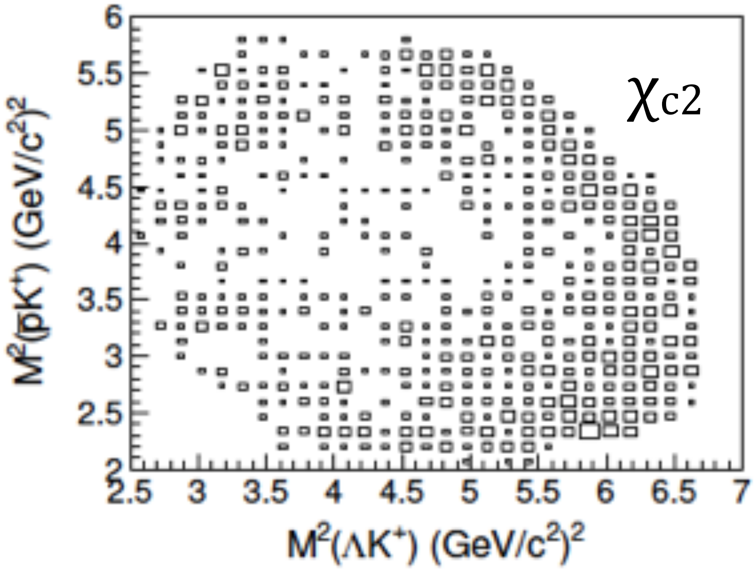
BESIII: PRD 87, 012007 (2013)



channel	$\psi' \to \bar{p}K^+\Sigma^0 + c.c.$	$\chi_{c0} \to \bar{p}K^+\Lambda + c.c.$	$\chi_{c1} \to \bar{p}K^+\Lambda + c.c.$	$\chi_{c2} \to \bar{p}K^+\Lambda + c.c.$
$\mathcal{B}$(BESIII)	$(1.67 \pm 0.13 \pm 0.12) \times 10^{-5}$	$(13.2 \pm 0.3 \pm 1.0) \times 10^{-4}$	$(4.5 \pm 0.2 \pm 0.4) \times 10^{-4}$	$(8.4 \pm 0.3 \pm 0.6) \times 10^{-4}$
PDG		$(10.2 \pm 1.9) \times 10^{-4}$	$(3.2 \pm 1.0) \times 10^{-4}$	$(9.1 \pm 1.8) \times 10^{-4}$



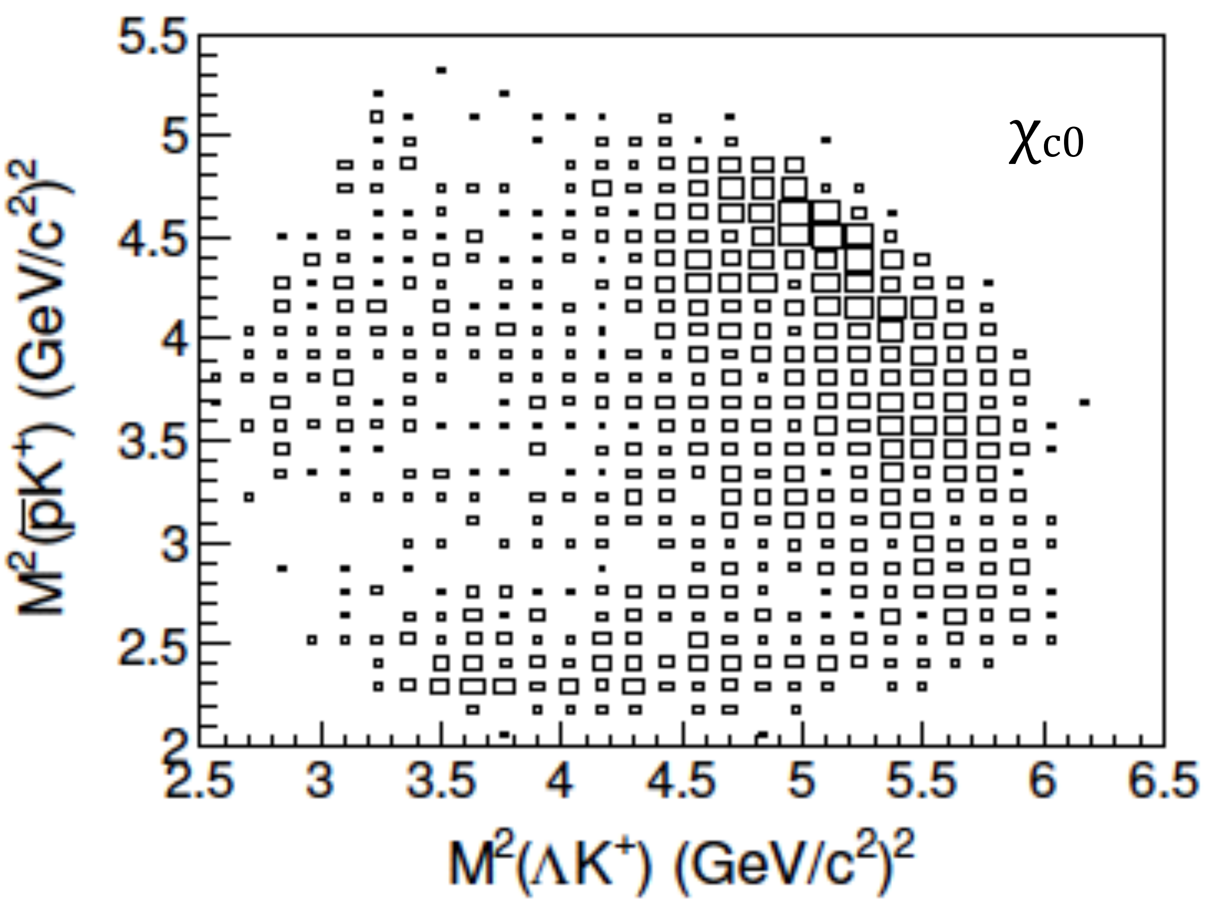


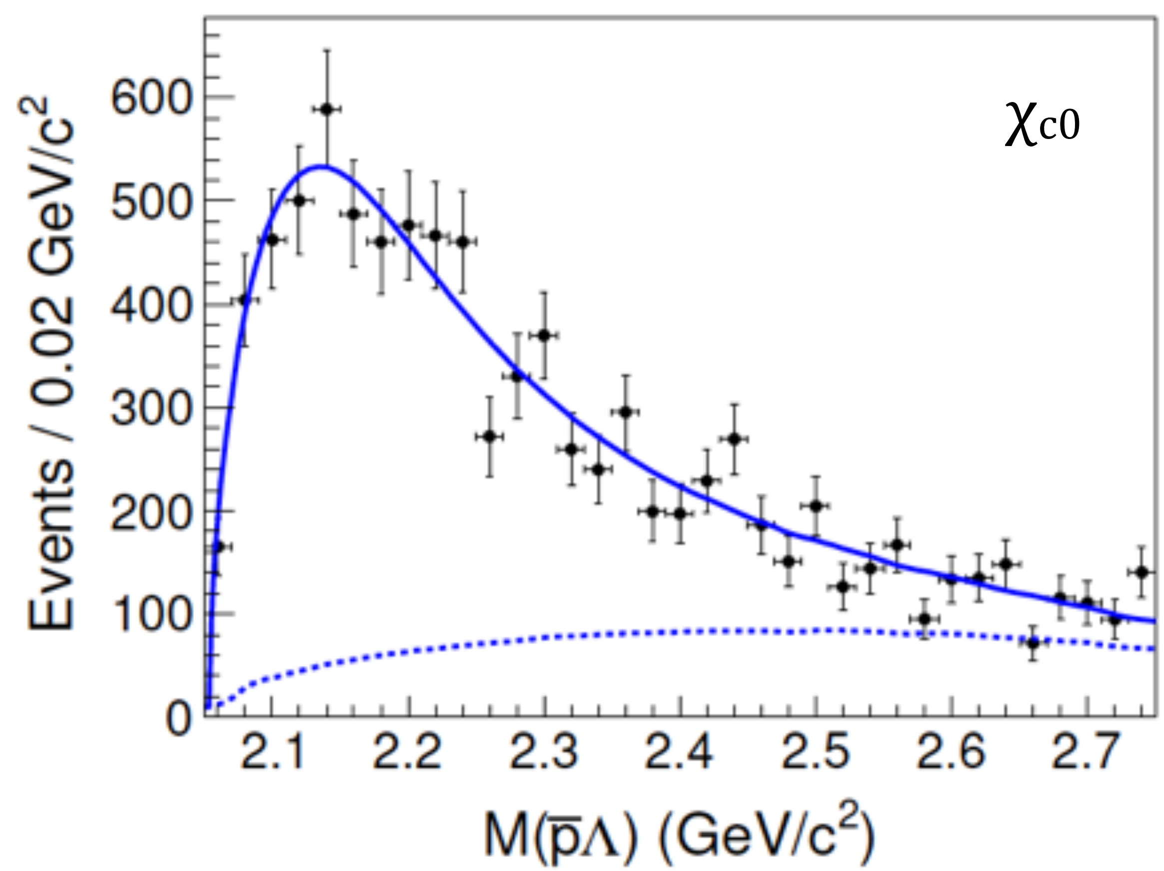


Measurements of $\psi(3686) \to \bar{p}K^{+}\Sigma^{0}$ and $\chi_{cJ} \to \bar{p}K^{+}\Lambda$

- Anomalous enhancement near threshold in $\chi_{cJ} \to \bar{p}K^{+}\Lambda$
  - May correspond to similar structure in J/ψ decays to the same final state (also $J/\psi \to \gamma p\bar{p}$)
  - May be a quasi bound dibaryon state, an enhancement due to final state interactions, or interference of high mass N* and Λ* states

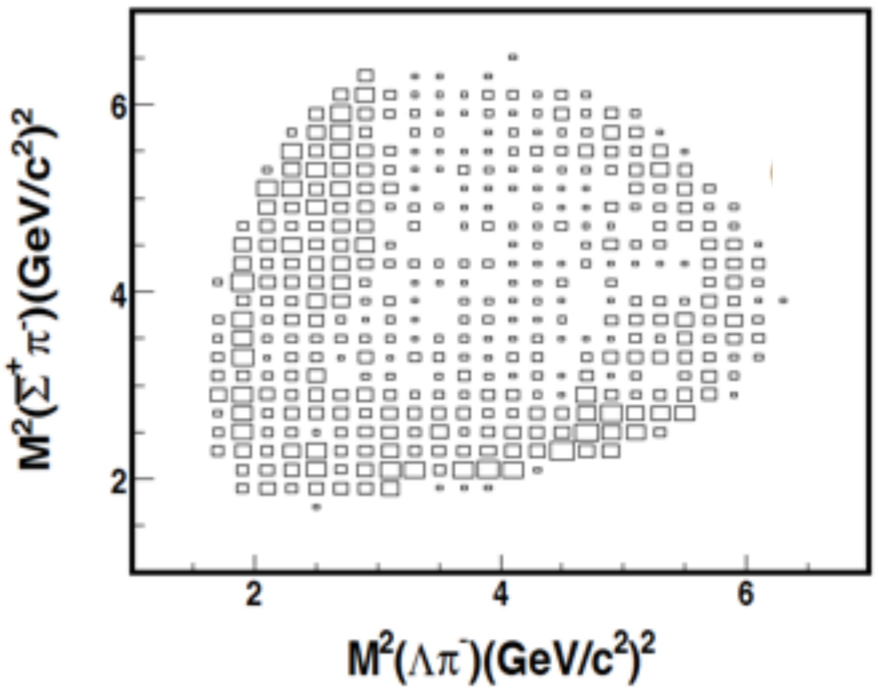
BESIII: PRD 87, 012007 (2013)





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

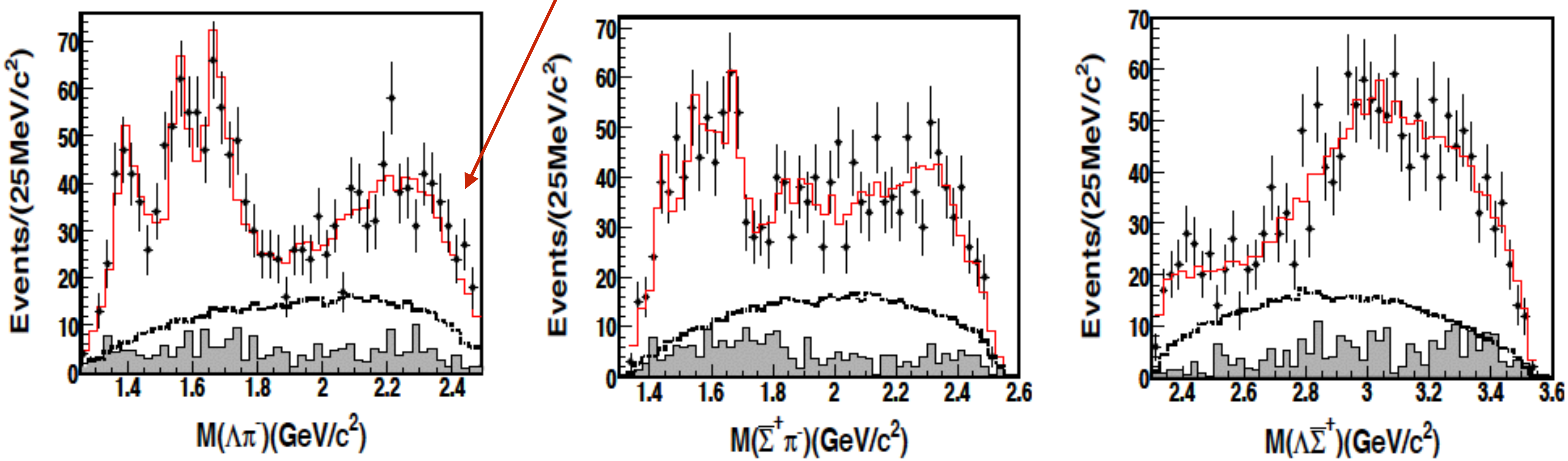
BESIII: PRD 88, 112007 (2013)



$$\mathcal{B}(\psi(3686) \to \Lambda\bar{\Sigma}^{+}\pi^{-}+c.c.) = (1.40\pm0.03\pm0.13)\times10^{-4}$$
$$\mathcal{B}(\psi(3686) \to \Lambda\bar{\Sigma}^{-}\pi^{+}+c.c.) = (1.54\pm0.04\pm0.13)\times10^{-4}$$

$$Q_{\Lambda\bar{\Sigma}^-\pi^+} = \frac{\mathcal{B}(\psi(3686) \to \Lambda\bar{\Sigma}^{-}\pi^{+})}{\mathcal{B}(J/\psi \to \Lambda\bar{\Sigma}^{-}\pi^{+})} = (9.3\pm1.2)\%$$

- Partial wave analysis used to determine detection efficiency
  - Includes sixteen possible intermediate excited states with at least two stars according to the PDG, with parameters fixed to world averages

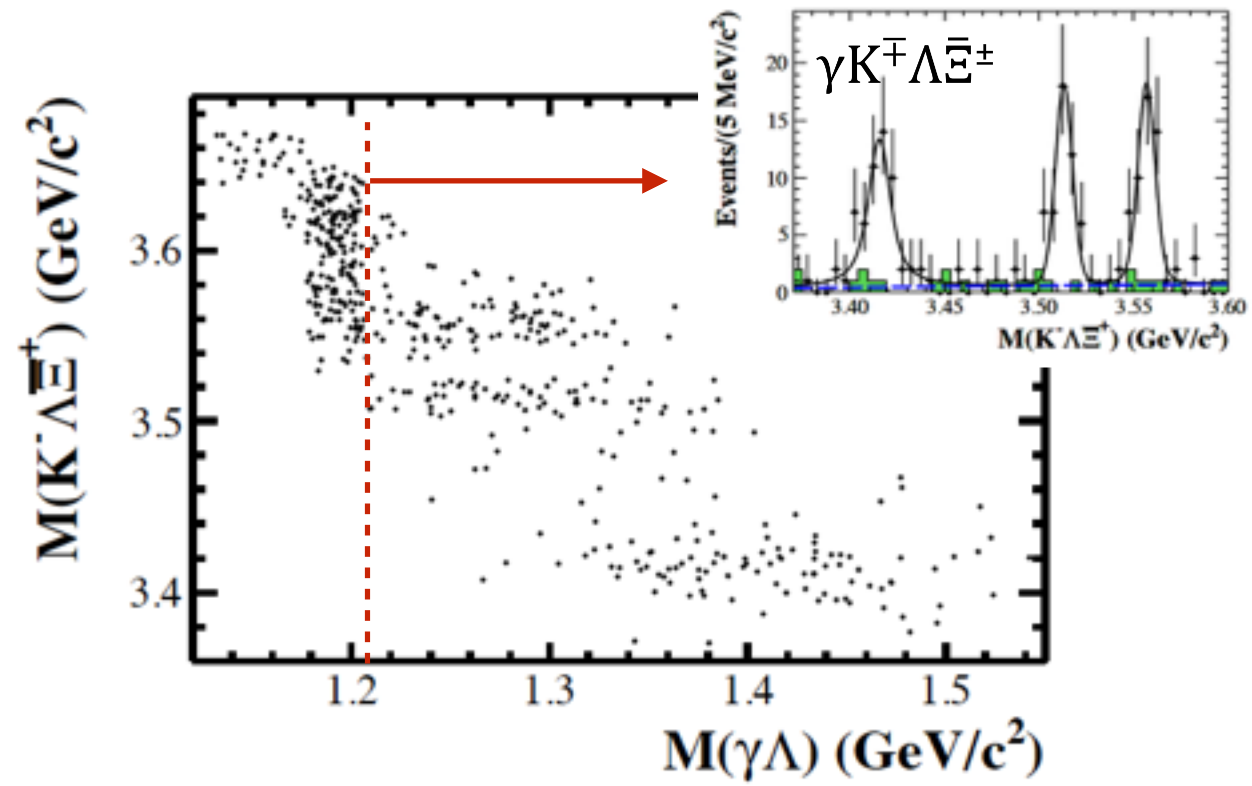


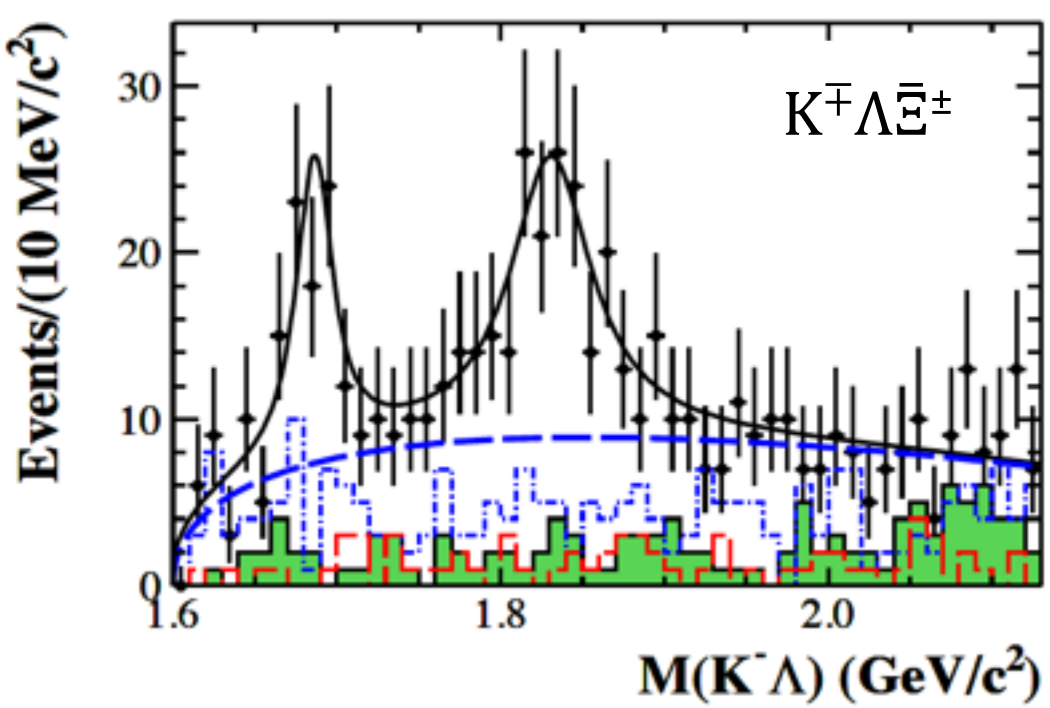
Measurements of $\psi(3686) \rightarrow (\gamma)K^{\mp}\Lambda\bar{\Xi}^{\pm}$

BESIII: PRD 91, 092006 (2015)

- $\psi(3686) \rightarrow (\gamma)K^{\mp}\Lambda\bar{\Xi}^{\pm}$; $\Lambda \rightarrow p\pi$, $\bar{\Xi} \rightarrow \Lambda\pi$; $\Lambda \rightarrow p\pi$

Decay	Branching fraction
$\psi(3686) \rightarrow K^-\Lambda\bar{\Xi}^+$	$(3.86 \pm 0.27 \pm 0.32) \times 10^{-5}$
$\psi(3686) \rightarrow \Xi(1690)^-\bar{\Xi}^+,\ \Xi(1690)^- \rightarrow K^-\Lambda$	$(5.21 \pm 1.48 \pm 0.57) \times 10^{-6}$
$\psi(3686) \rightarrow \Xi(1820)^-\bar{\Xi}^+,\ \Xi(1820)^- \rightarrow K^-\Lambda$	$(12.03 \pm 2.94 \pm 1.22) \times 10^{-6}$
$\psi(3686) \rightarrow K^-\Sigma^0\bar{\Xi}^+$	$(3.67 \pm 0.33 \pm 0.28) \times 10^{-5}$
$\psi(3686) \rightarrow \gamma\chi_{c0},\ \chi_{c0} \rightarrow K^-\Lambda\bar{\Xi}^+$	$(1.90 \pm 0.30 \pm 0.16) \times 10^{-5}$
$\psi(3686) \rightarrow \gamma\chi_{c1},\ \chi_{c1} \rightarrow K^-\Lambda\bar{\Xi}^+$	$(1.32 \pm 0.20 \pm 0.12) \times 10^{-5}$
$\psi(3686) \rightarrow \gamma\chi_{c2},\ \chi_{c2} \rightarrow K^-\Lambda\bar{\Xi}^+$	$(1.68 \pm 0.26 \pm 0.15) \times 10^{-5}$
$\chi_{c0} \rightarrow K^-\Lambda\bar{\Xi}^+$	$(1.96 \pm 0.31 \pm 0.16) \times 10^{-4}$
$\chi_{c1} \rightarrow K^-\Lambda\bar{\Xi}^+$	$(1.43 \pm 0.22 \pm 0.12) \times 10^{-4}$
$\chi_{c2} \rightarrow K^-\Lambda\bar{\Xi}^+$	$(1.93 \pm 0.30 \pm 0.15) \times 10^{-4}$





- Observe two hyperons, Ξ(1690) and Ξ(1820) in M(KΛ)
  - Both are well established states
  - Resonance parameters consistent with the PDG

	$\Xi(1690)^-$	$\Xi(1820)^-$
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_{PDG}(MeV/c^2)	1690±10	1823±5
Γ_{PDG}(MeV)	<30	24^{+15}_{-10}

Partial wave analysis of ψ(3686) → $p\bar{p}\eta$

- Intermediate state N(1535) → pη is dominant
- No evidence for a $p\bar{p}$ resonance, indicating that the threshold enhancement in previous results may be explained by interference between the N(1535) and phase space

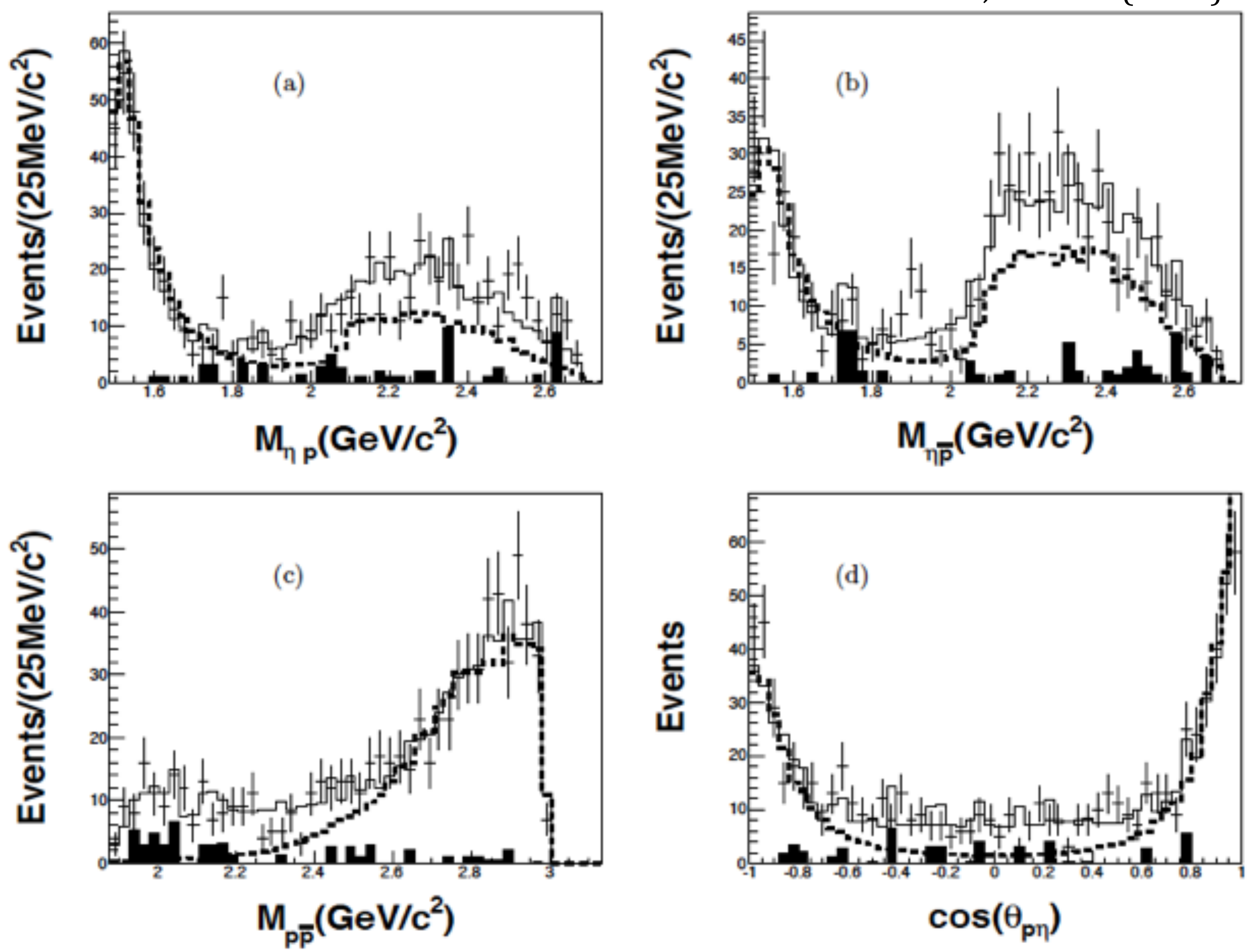
Mass and width of N(1535)

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

PDG value:

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

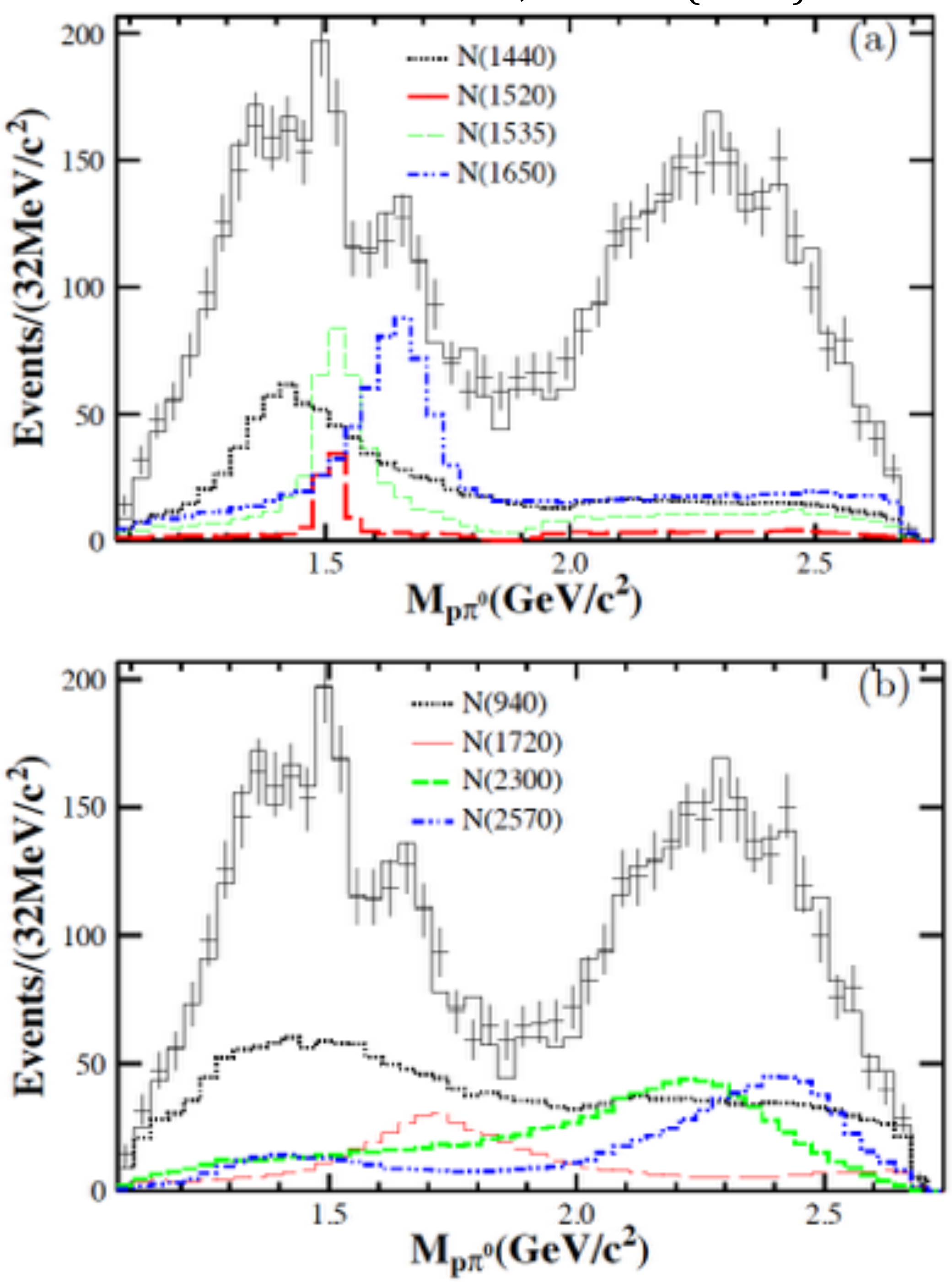
BESIII: PRD 88, 032010 (2013)



$$B(\psi' \to N(1535)\bar{p}) \times B(N(1535) \to p\eta) + c.c. = (5.2 \pm 0.3^{+3.2}_{-1.2} \times 10^{-5})$$

Observation of two new N* resonances in $\psi(3686) \rightarrow p\bar{p}\pi^0$

BESIII: PRL 110, 022001 (2013)



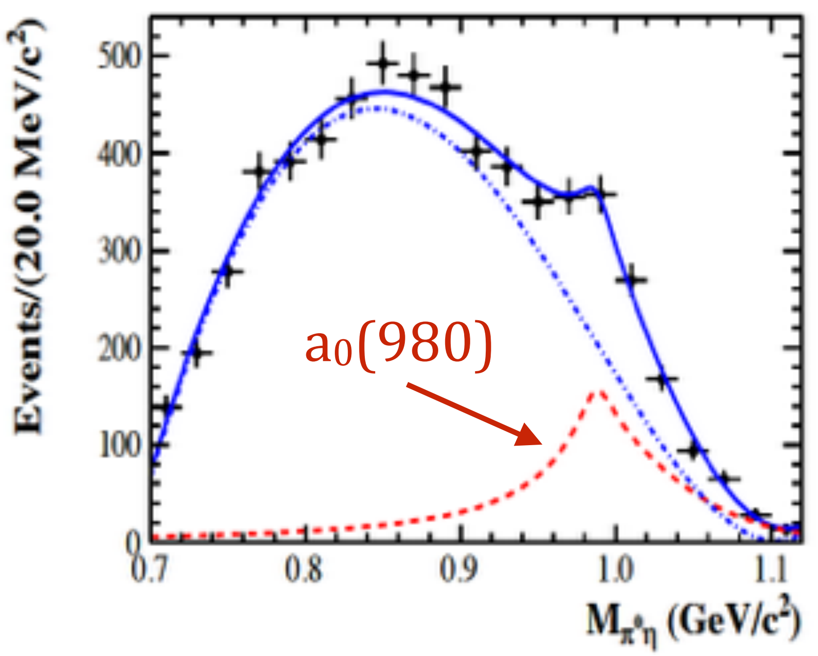
- In photon or meson beam studies, isospin 1/2 and 3/2 resonances are excited, complicating the analysis
- Δ resonances suppressed in charmonium decays to $p\bar{p}\pi^0$, giving a cleaner spectrum
  - Thought to be dominated by two body decays involving N* intermediate states
  - Also consider $p\bar{p}$ resonances ($\psi(3686) \rightarrow R\pi^0$)
- Seven N* states observed in partial wave analysis
  - Two new resonances, N(2300) with $J^P = 1/2^+$ and N(2570) with $J^P = 5/2^-$
  - Other five consistent with previous results

Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	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**	$\mathbf{11.7\sigma}$

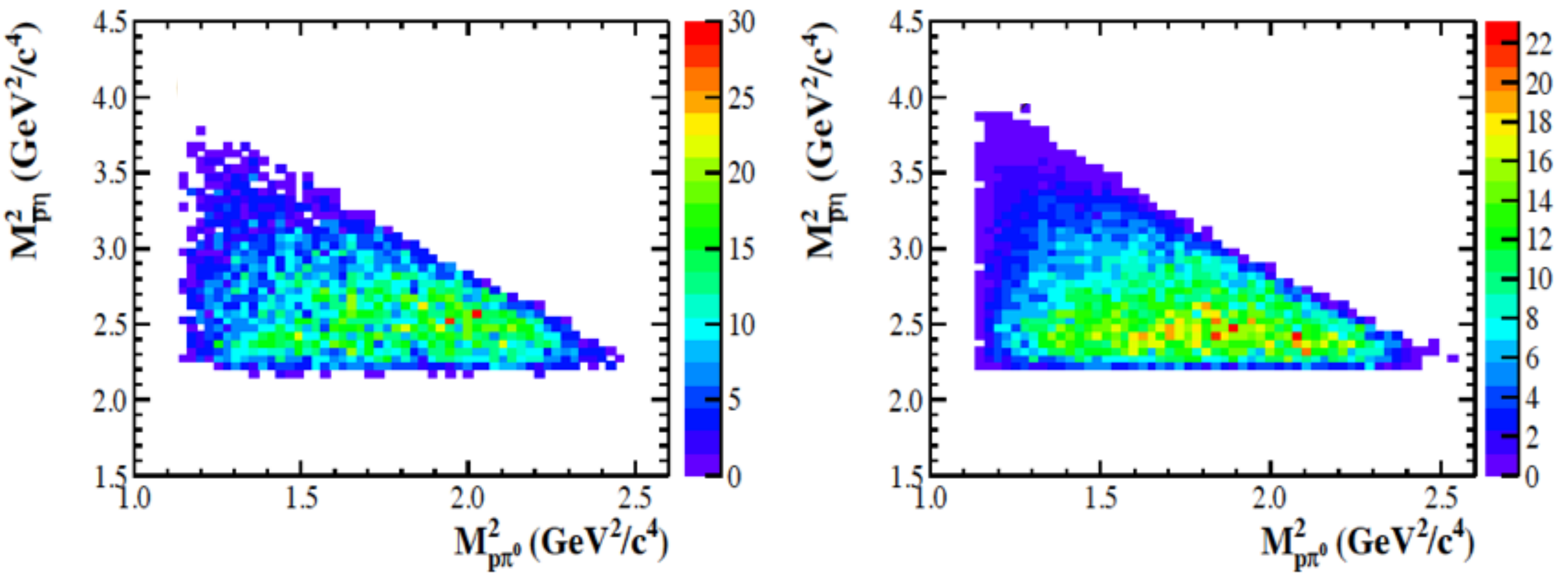
Observation of $J/\psi \to p\bar{p}a_0(980)$

- First observation of $J/\psi \to p\bar{p}a_0(980)$; $a_0(980) \to \pi^0\eta$
  - Significance = 3.2σ
- Applies a chiral unitary coupled channel approach
  - Four-body decays $J/\psi \to N\bar{N}MM$
  - $a_0(980)$ generated through Final State Interactions
  - Provides useful information on dynamics of four-body FSI processes

BESIII: PRD 90, 052009 (2014)



$$Br(J/\psi \to p\bar{p}a_0(980) \to p\bar{p}\pi^0\eta) = (6.8 \pm 1.2 \pm 1.3) \times 10^{-5}$$



Observation of enhanced $\Lambda\bar{\Lambda}$ production near threshold

- The Born cross section for $e^+e^- \to \gamma^* \to B\bar{B}$ can be expressed in terms of electromagnetic form factor G_E and G_M:

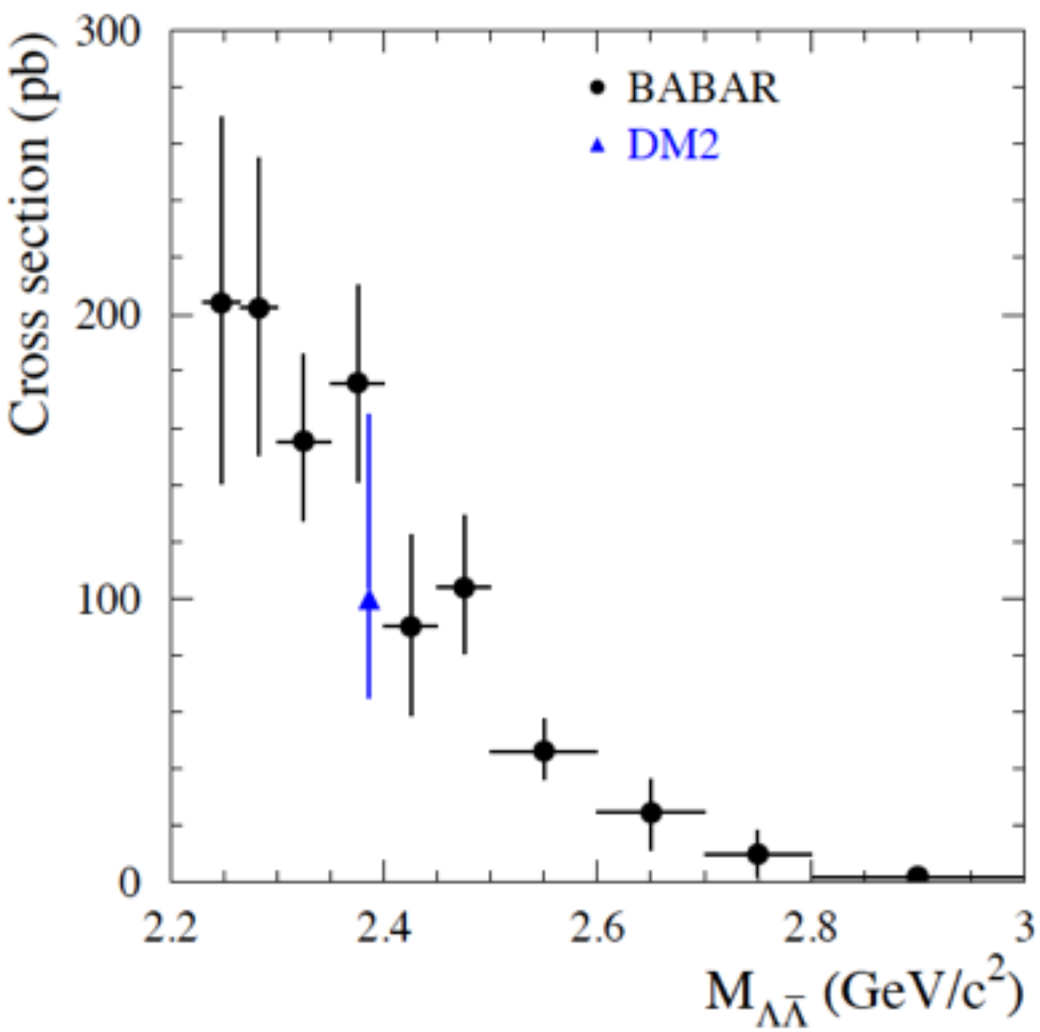
$$\sigma_{B\bar{B}}(m) = \frac{4\pi\alpha^2 C\beta}{3m^2}\left[|G_M(m)|^2 + \frac{1}{2\tau}|G_E(m)|^2\right]$$

$$C = \frac{\pi\alpha}{\beta}\frac{1}{1-exp(-\pi\alpha/\beta)} \text{ (charged) or 1 (neutral)}$$

$$\beta = \sqrt{1 - 4m_B^2/m^2} \qquad \tau = m^2/4m_B^2$$

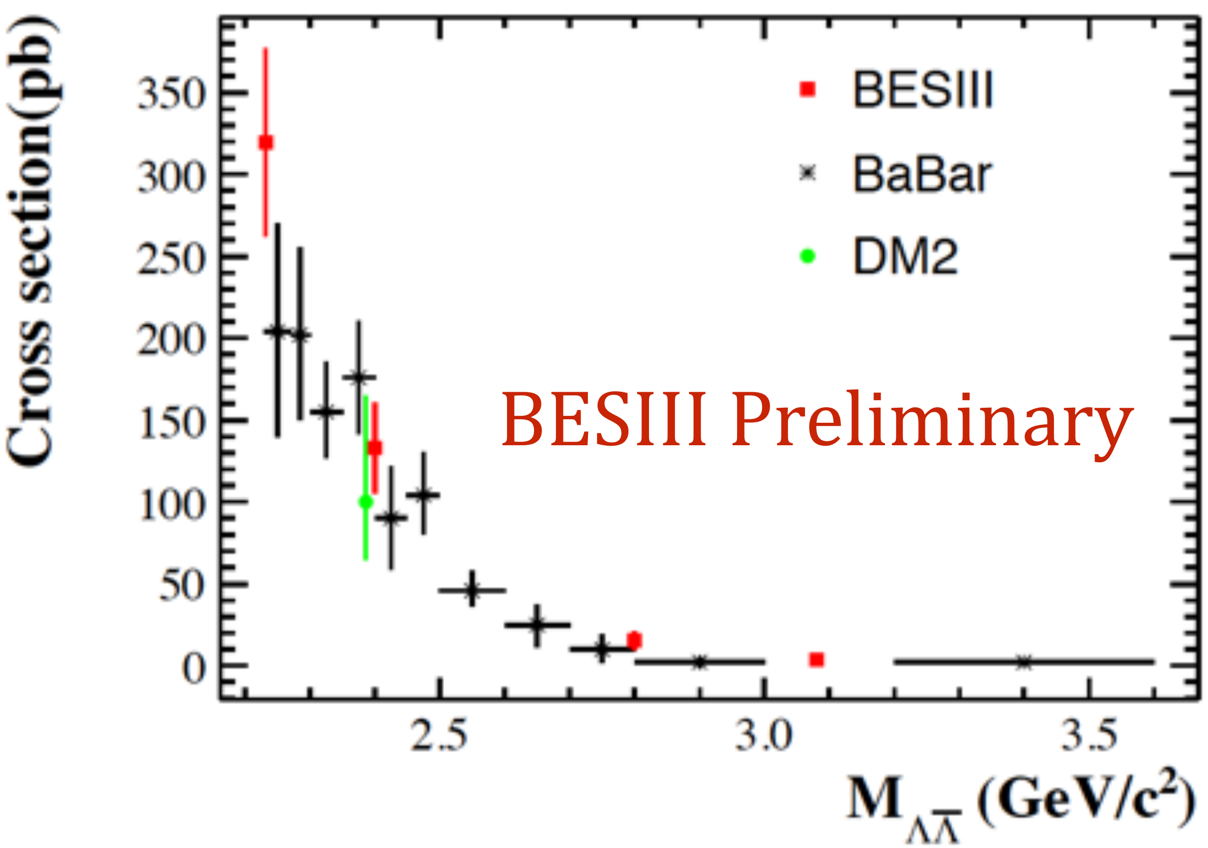
- For neutral pair production, the cross section is expected to increase with velocity near threshold.
- The process $e^+e^- \to \Lambda\bar{\Lambda}$ from BaBar, from threshold to 2.27 GeV, gives a non-zero cross section, 204 ± 60 ± 20 pb.

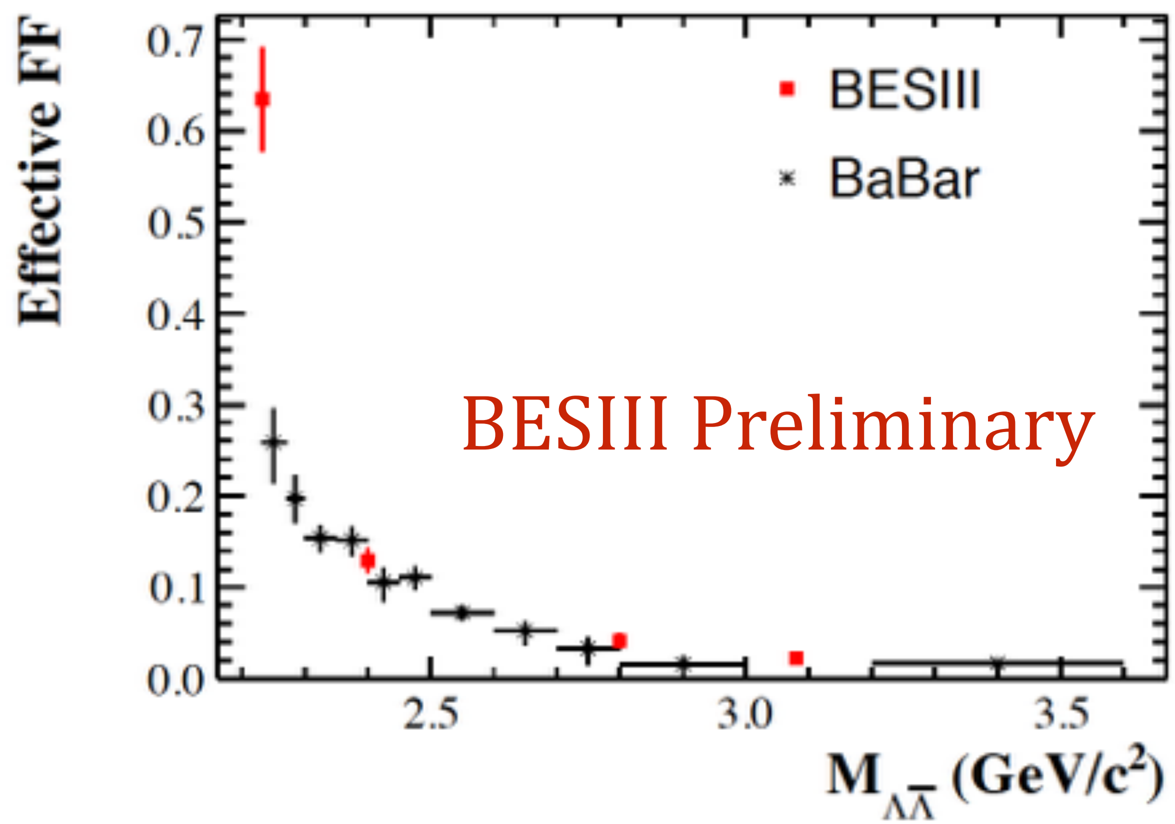
BaBar: PRD 76, 092006 (2007)



Observation of enhanced $\Lambda\bar{\Lambda}$ production near threshold

- Data sets collected at 2.2324 GeV, 2.40 GeV, 2.80 GeV, and 3.08 GeV
- The same scan method used to study $e^+e^- \rightarrow p\bar{p}$





- Surprisingly large cross section near threshold!
  - Data sample is too small to extract angular distributions
  - New scan data will provide precise measurements on effective FFs

Studies of Λ_c^+ near threshold

567 pb^{-1} at $\sqrt{s}$ = 4.6 GeV

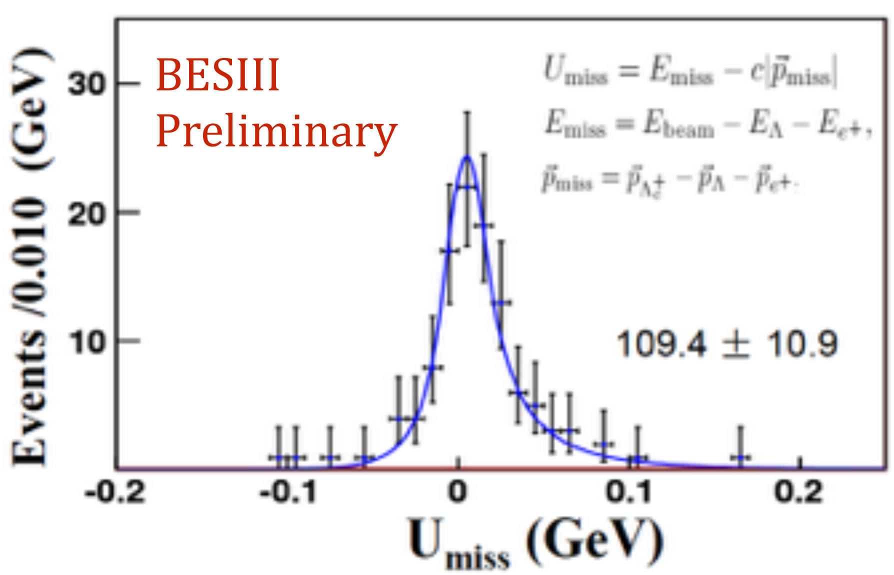
Absolute branching fraction measurements of Λ_c^+ near threshold

- B($pK^+\pi$) precision consistent with Belle, but BESIII result is smaller
- Precision improved on other 11 modes

Mode	This work(%)	PDG(%)	Belle(%)
pK_S^0	$1.47 \pm 0.08 \pm 0.03$	1.15 ± 0.30	
$pK^-\pi^+$	$5.64 \pm 0.27 \pm 0.22$	5.0 ± 1.3	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK_S^0\pi^0$	$1.75 \pm 0.12 \pm 0.05$	1.65 ± 0.50	
$pK_S^0\pi^+\pi^-$	$1.46 \pm 0.10 \pm 0.09$	1.30 ± 0.35	
$pK^-\pi^+\pi^0$	$4.22 \pm 0.23 \pm 0.28$	3.4 ± 1.0	
$\Lambda\pi^+$	$1.19 \pm 0.07 \pm 0.03$	1.07 ± 0.28	
$\Lambda\pi^+\pi^0$	$6.67 \pm 0.35 \pm$ [illegible]	3.6 ± 1.3	
$\Lambda\pi^+\pi^-\pi^+$	$3.66 \pm 0.23 \pm 0.17$	2.6 ± 0.7	
$\Sigma^0\pi^+$	[illegible] $\pm 0.08 \pm 0.03$	1.05 ± 0.28	
$\Sigma^+\pi^0$	[illegible] $\pm 0.09 \pm 0.03$	1.00 ± 0.34	
$\Sigma^+\pi^+\pi^-$	$4.05 \pm 0.23 \pm 0.20$	3.6 ± 1.0	
$\Sigma^+\omega$	$1.50 \pm 0.20 \pm 0.09$	2.7 ± 1.0	

BESIII Preliminary

Absolute branching fraction measurement of $\Lambda_c \to \Lambda e^+\nu$



$$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38 \pm 0.20)\%$$

PDG: 2.1 ± 0.6 %

For more details, see the talk by Xiaokang Zhou on Friday

Summary

- Charmonium decays have proven to be a useful laboratory to study excited nucleon and even hyperon states
  - Discover new states, provide complementary information to existing data on known states
- BESIII data allows for precise measurements of the charged Λ_c at threshold
- BESIII has collected 0.6 x 10^9 $\psi(3686)$ and 1.3 x 10^9 J/ψ decays
  - New results will be coming soon!