Baryons at BESIII

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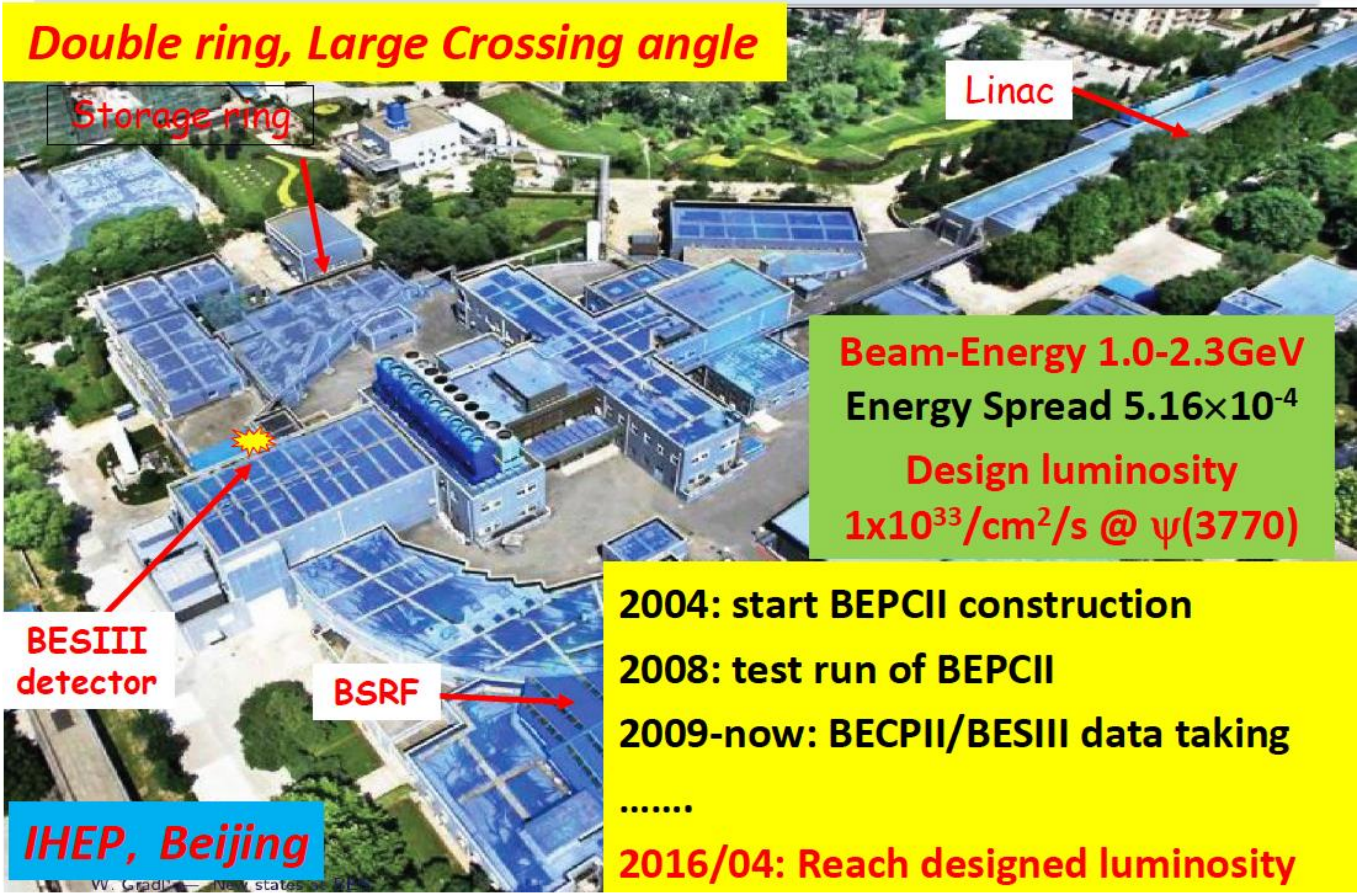
- Introduction
- Λ_c physics at BESIII
- Baryon spectroscopy at BESIII

Beijing Electron Positron Collider (BEPCII)

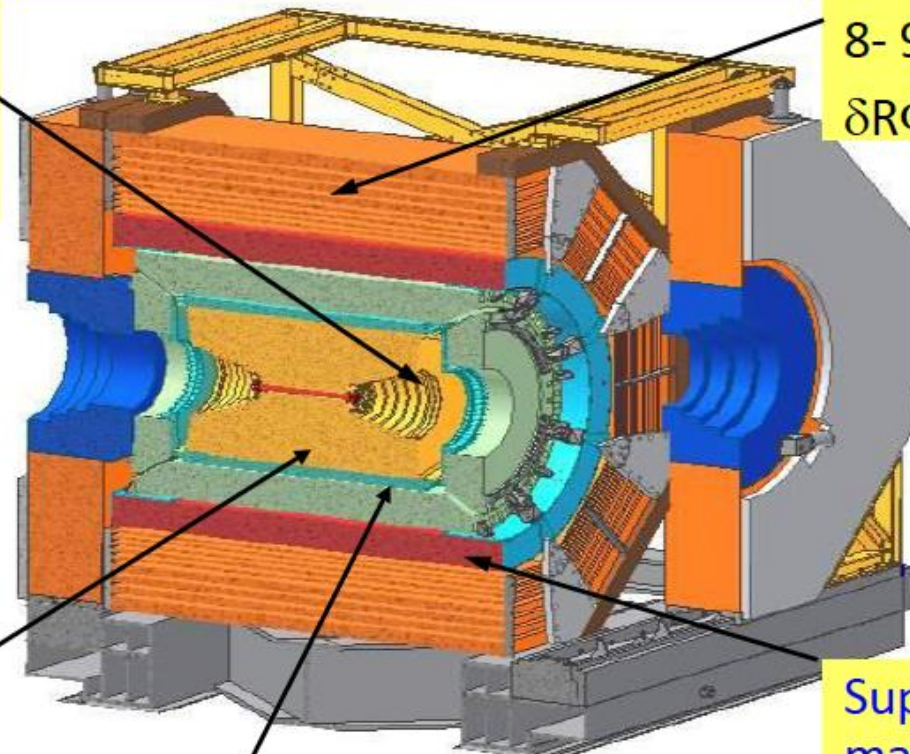


Beijing Spectroscopy (BESIII) Detector

NIM A614, 345 (2010)

Drift Chamber (MDC)
$\sigma P/P$ ($^0/_0$) = 0.5%(1GeV)
$\sigma_{dE/dx}$ ($^0/_0$) = 6%

μCounter
8- 9 layers RPC
$\delta R\Phi$=1.4 cm~1.7 cm



Time Of Flight (TOF)
σ_T : 90 ps Barrel
110 ps endcap

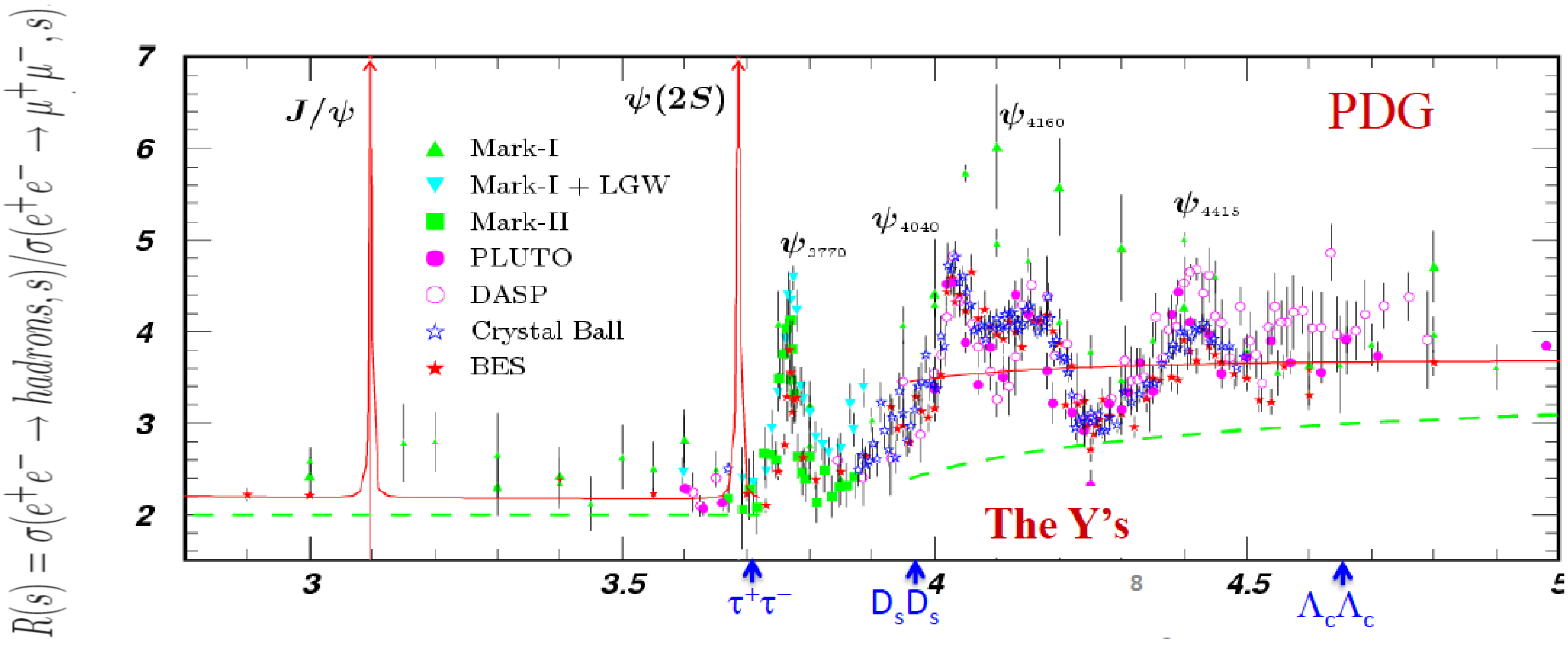
ETOF (MRPC) upgraded (σ_T=55ps)

Super-conducting magnet (1.0 Tesla)

EMC: $\sigma E/\sqrt{E}$($^0/_0$) = 2.5 % (1 GeV)
(CsI) $\sigma_{z,\phi}$(cm) = 0.5 - 0.7 cm/$\sqrt{E}$

Features of the BEPC Energy Region

- **Rich of resonances: charmonia and charmed mesons**
- **Threshold characteristics (pairs of τ, D, D_s, …)**
- **Transition between smooth and resonances, perturbative and non-perturbative QCD**
- **Energy location of the gluonic excitations and multi-quark states**



Physics at BESIII

Charmonium physics:

- spectroscopy
- transitions and decays

Light hadron physics:

- meson & baryon spectroscopy
- glueball, hybrid, multiquark
- two-photon physics
- e.m. form factors of nucleon

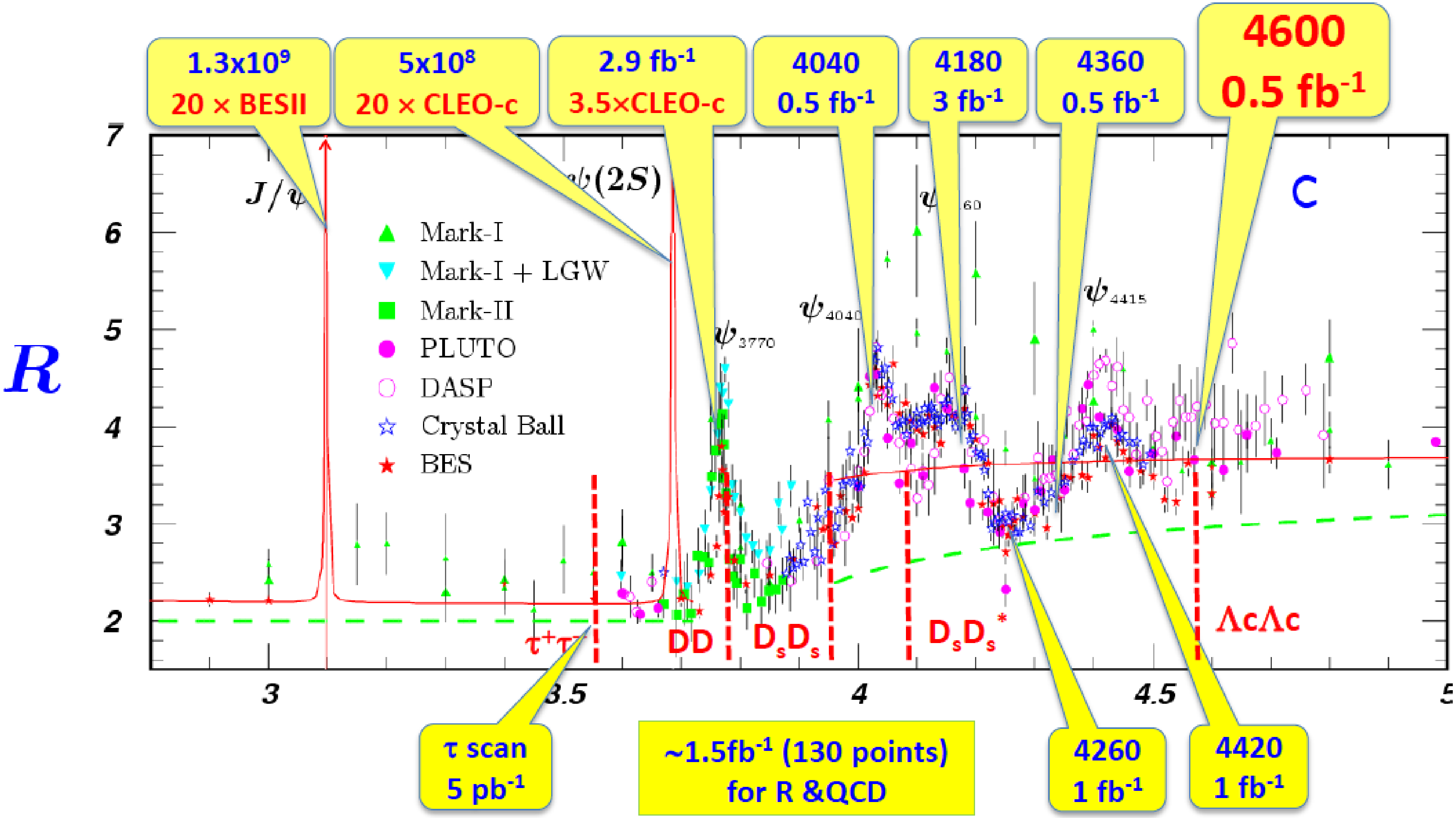
Open charm physics:

- **charmed mesons**
  - decay constant, form factors
  - CKM matrix: Vcd, Vcs
  - D^0-D^0bar mixing and CP violation
  - rare/forbidden decays
- $\boldsymbol{\Lambda_c}$

Tau and QCD physics

New physics

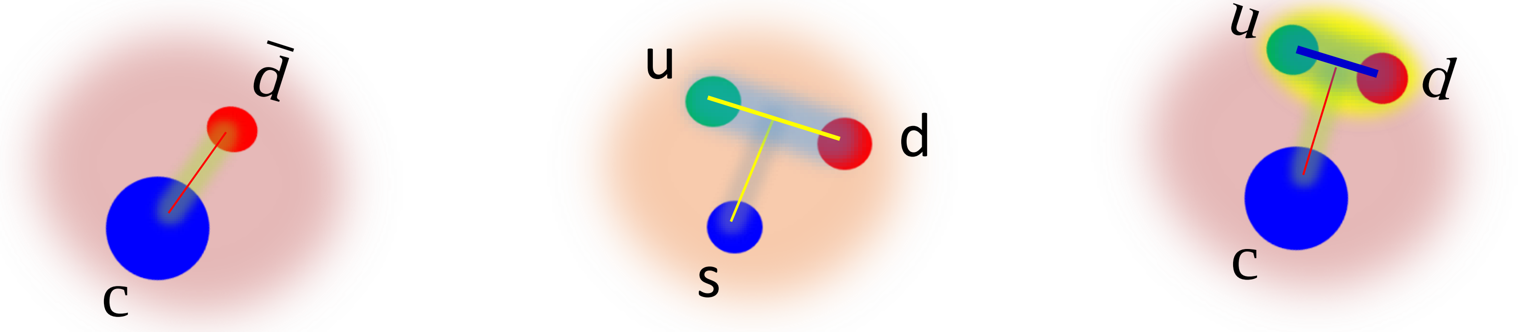
Data collected at BESIII



Λ_c^+ PHYSICS AT BESIII

Quark Model picture

Λ_c^+: a heavy quark (c) with a unexcited spin-zero diquark (u-d)



Charmed meson ($D^+[c\bar{d}]$)

$m_d << m_c$ → **quark + heavy quark**
(q) (Q)

Strange baryons ($\Lambda[uds]$)

$m_u, m_d \approx m_s$ → **(qqq)** uniform

Charmed baryon ($\Lambda_c[udc]$)

$m_u, m_d << m_c$ → **diquark + quark**
(qq) (Q)

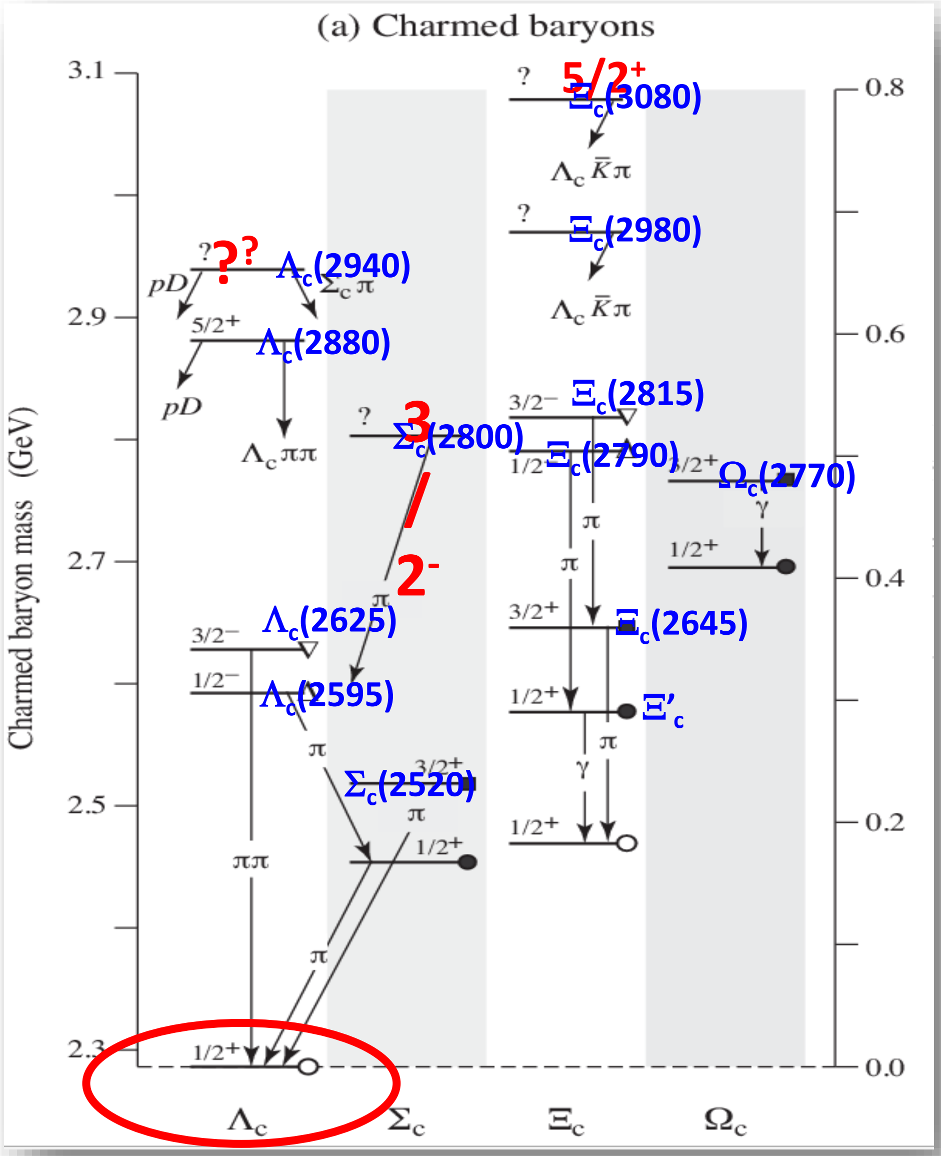
Heavy Quark Effective Theory :

- ☐ diquark correlation is enhanced by weak Color Magnetic Interaction with a heavy quark
- ☐ More reliable prediction of heavy-light quark transition without dealing with light degrees of freedom that have net spin or isospin.

Λ_c^+ may provide complementary powerful test on internal dynamics to charmed meson does

Cornerstone of charmed baryon Spectroscopy

- **The lightest charmed baryon**
- **Most of the charmed baryons will eventually decay to Λ_c^+**
- **The Λ_c^+ is one of important tagging hadrons in c-quark counting in the productions at high energies and bottom baryon decays**
- **$B(\Lambda_c^+ \to pK^-\pi^+)$: dominant error for V_{ub} via baryon decay**



The Λ_c^+ Decays

Λ_c Measurements [PDG2015]

Λ_c^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	$\Delta B/B$
Hadronic modes with a p: $S=-1$ final states				
$p\overline{K}^0$		(3.21 ± 0.30) %		9.3%
$pK^-\pi^+$		$(6.84^{+0.32}_{-0.40})$ %		5.8%
$p\overline{K}^*(892)^0$	[q]	(2.13 ± 0.30) %		14.1%
$\Delta(1232)^{++}K^-$		(1.18 ± 0.27) %		22.9%
$\Lambda(1520)\pi^+$	[q]	(2.4 ± 0.6) %		25.0%
$pK^-\pi^+$ nonresonant		(3.8 ± 0.4) %		10.5%
$p\overline{K}^0\pi^0$		(4.5 ± 0.6) %		13.3%
$p\overline{K}^0\eta$		(1.7 ± 0.4) %		23.5%
$p\overline{K}^0\pi^+\pi^-$		(3.5 ± 0.4) %		11.4%
$pK^-\pi^+\pi^0$		(4.6 ± 0.8) %		13.0%
$pK^*(892)^-\pi^+$	[q]	(1.5 ± 0.5) %		33.3%
$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(5.0 ± 0.9) %		18.0%
$\Delta(1232)\overline{K}^*(892)$		seen		
$pK^-\pi^+\pi^+\pi^-$		$(1.5\pm 1.0)\times 10^{-3}$		66.7%
$pK^-\pi^+\pi^0\pi^0$		(1.1 ± 0.5) %		45.4%
Hadronic modes with a p: $S=0$ final states				
$p\pi^+\pi^-$		$(4.7\pm 2.5)\times 10^{-3}$		45.4%
$pf_0(980)$	[q]	$(3.8\pm 2.5)\times 10^{-3}$		53.2%
$p\pi^+\pi^+\pi^-\pi^-$		$(2.5\pm 1.6)\times 10^{-3}$		64.0%
pK^+K^-		$(1.1\pm 0.4)\times 10^{-3}$		36.4%
$p\phi$	[q]	$(1.12\pm 0.23)\times 10^{-3}$		
pK^+K^- non-ϕ		$(4.8\pm 1.9)\times 10^{-4}$		
Hadronic modes with a hyperon: $S=-1$ final states				
$\Lambda\pi^+$		(1.46 ± 0.13) %		8.9%
$\Lambda\pi^+\pi^0$		(5.0 ± 1.3) %		26.0%
$\Lambda\rho^+$		< 6 %	CL=95%	
$\Lambda\pi^+\pi^+\pi^-$		(3.59 ± 0.28) %		7.8%
$\Sigma(1385)^+\pi^+\pi^-$, $\Sigma^{*+}\to\Lambda\pi^+$		(1.0 ± 0.5) %		20.0%
$\Sigma(1385)^-\pi^+\pi^+$, $\Sigma^{*-}\to\Lambda\pi^-$		$(7.5\pm 1.4)\times 10^{-3}$		18.7%
$\Lambda\pi^+\rho^0$		(1.4 ± 0.6) %		42.8%
$\Sigma(1385)^+\rho^0$, $\Sigma^{*+}\to\Lambda\pi^+$		$(5\pm 4)\times 10^{-3}$		80.0%
$\Lambda\pi^+\pi^+\pi^-$ nonresonant		< 1.1 %	CL=90%	
$\Lambda\pi^+\pi^+\pi^-\pi^0$ total		(2.5 ± 0.9) %		36.0%
$\Lambda\pi^+\eta$	[q]	(2.4 ± 0.5) %		20.8%
$\Sigma(1385)^+\eta$	[q]	(1.16 ± 0.35) %		30.2%
$\Lambda\pi^+\omega$	[q]	(1.6 ± 0.6) %		37.5%
$\Lambda\pi^+\pi^+\pi^-\pi^0$, no η or ω		$< 9\times 10^{-3}$	CL=90%	
$\Lambda K^+\overline{K}^0$		$(6.4\pm 1.3)\times 10^{-3}$	S=1.6	20.3%
$\Xi(1690)^0K^+$, $\Xi^{*0}\to\Lambda\overline{K}^0$		$(1.8\pm 0.6)\times 10^{-3}$		33.3%
$\Sigma^0\pi^+$		(1.43 ± 0.14) %		10.0%
$\Sigma^+\pi^0$		(1.37 ± 0.30) %		21.9%
$\Sigma^+\eta$		$(7.5\pm 2.5)\times 10^{-3}$		33.3%
$\Sigma^+\pi^+\pi^-$		(4.9 ± 0.5) %		10.2%
$\Sigma^+\rho^0$		< 1.8 %	CL=95%	
$\Sigma^-\pi^+\pi^+$		(2.3 ± 0.4) %		17.4%
$\Sigma^0\pi^+\pi^0$		(2.5 ± 0.9) %		36.0%
$\Sigma^0\pi^+\pi^+\pi^-$		(1.13 ± 0.31) %		27.4%
$\Sigma^+\pi^+\pi^-\pi^0$		—		
$\Sigma^+\omega$	[q]	(3.7 ± 1.0) %		27.1%
$\Sigma^+K^+K^-$		$(3.8\pm 0.6)\times 10^{-3}$		15.8%
$\Sigma^+\phi$	[q]	$(4.3\pm 0.7)\times 10^{-3}$		16.3%
$\Xi(1690)^0K^+$, $\Xi^{*0}\to\Sigma^+K^-$		$(1.11\pm 0.29)\times 10^{-3}$		26.2%
$\Sigma^+K^+K^-$ nonresonant		$< 9\times 10^{-4}$	CL=90%	
Ξ^0K^+		$(5.3\pm 1.3)\times 10^{-3}$		24.5%
$\Xi^-K^+\pi^+$		$(7.0\pm 0.8)\times 10^{-3}$	S=1.1	11.4%
$\Xi(1530)^0K^+$	[q]	$(3.5\pm 1.0)\times 10^{-3}$		28.6%
Hadronic modes with a hyperon: $S=0$ final states				
ΛK^+		$(6.9\pm 1.4)\times 10^{-4}$		20.3%
$\Lambda K^+\pi^+\pi^-$		$< 6\times 10^{-4}$	CL=90%	
Σ^0K^+		$(5.7\pm 1.0)\times 10^{-4}$		17.5%
$\Sigma^0K^+\pi^+\pi^-$		$< 2.9\times 10^{-4}$	CL=90%	
$\Sigma^+K^+\pi^-$		$(2.3\pm 0.7)\times 10^{-3}$		30.4%
$\Sigma^+K^*(892)^0$	[q]	$(3.8\pm 1.2)\times 10^{-3}$		31.6%
$\Sigma^-K^+\pi^+$		$< 1.3\times 10^{-3}$	CL=90%	
Doubly Cabibbo-suppressed modes				
$pK^+\pi^-$		$< 3.1\times 10^{-4}$	CL=90%	
Semileptonic modes				
$\Lambda\ell^+\nu_\ell$	[r]	(2.8 ± 0.4) %		
$\Lambda e^+\nu_e$		(2.9 ± 0.5) %		17.2%
$\Lambda\mu^+\nu_\mu$		(2.7 ± 0.6) %		22.2%

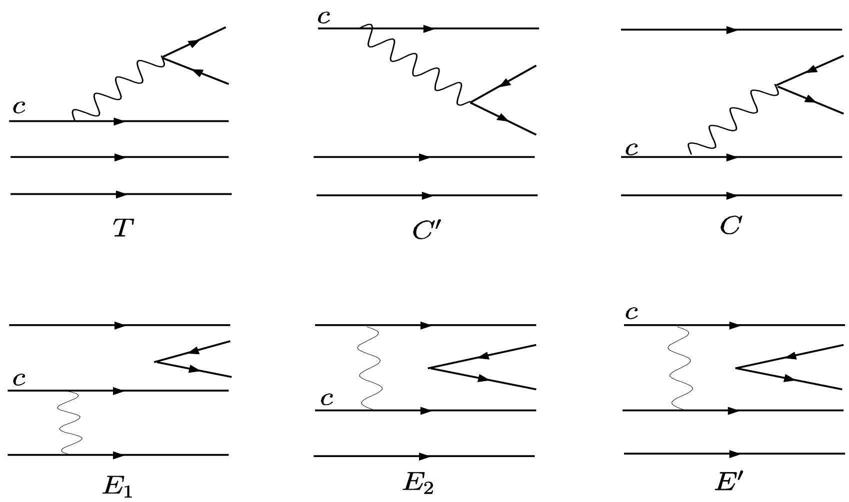
HTTP://PDG.LBL.GOV Page 32 Created: 10/6/2015 12

- Total branching fraction small than 65%.
- Lots of unknown decay channels
- Quite large uncertainties, most larger than 20%
- Most BFs are measured relative to $\Lambda_c^+\to pK^-\pi^+$

Λ_c^+ weak Decays

- Contrary to charm meson, receive **sizable non-factorization W-exchange** contribution

Chau, HYC, Tseng 96



- Two distinct **internal W emission** diagrams, three different **W exchange diagrams**

- Need information of **decay asymmetry** to extract s-wave and p-wave amplitudes separately

- Exotic search in $\Lambda_c^+ \to \phi \mathrm{p}\pi^0$: an analog to Pc in $\Lambda_b^0 \to J/\psi \mathrm{p} K^-$

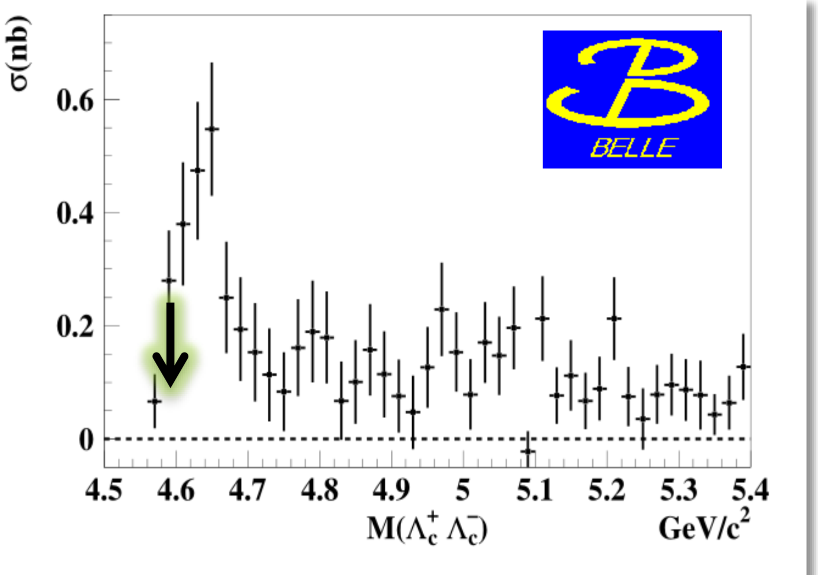
Λ_c^+ Data at BESIII

First time to run around 4.6 GeV in 2014, marvelous achievement of BEPCII

available data set at BESIII

Energy(GeV)	lum.(1/pb)
4.575	~48
4.580	~8.5
4.590	~8.1
4.600	~567

PRL 101 (2008) 172001

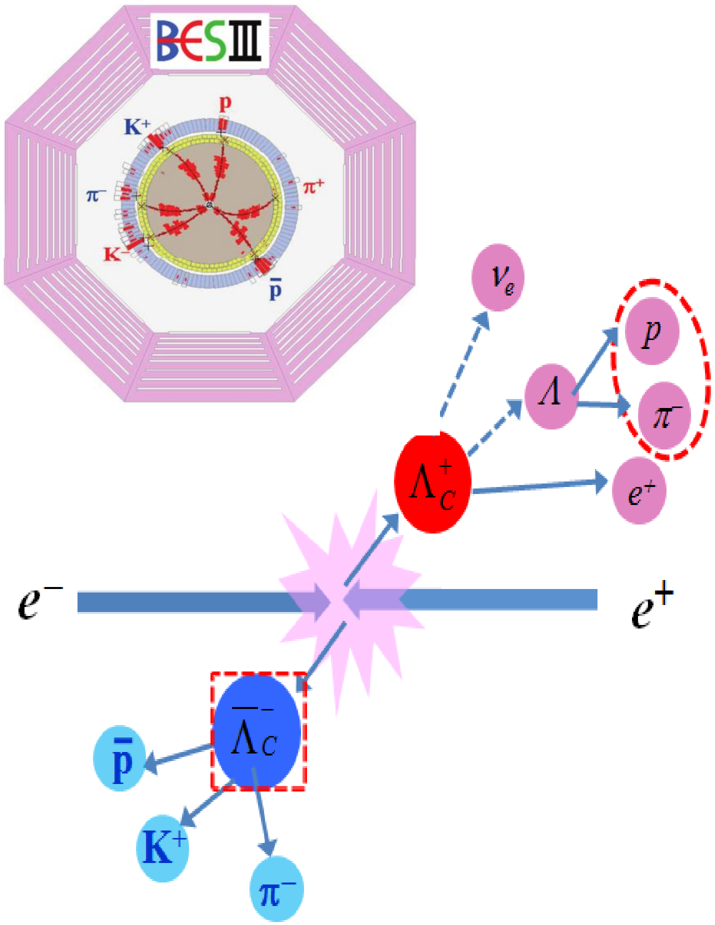


Λ_c^+ Measurement using the threshold pair-productions via e^+e^- annihilations is unique: ***the most simple and straightforward***

First time to systematically study charmed baryon at threshold!

Analysis Technique

$\Lambda_c^+ \bar{\Lambda}_c^-$ pair production at e^+e^- collision at mass threshold, no additional hadron in final states



- **Tagging method :**
  - Single tag (ST) : reconstruct one Λ_c^+
  - Double tag (DT) : fully reconstruct $\Lambda_c^+ \bar{\Lambda}_c^-$ pair
- **Two important variables:**

$$M_{BC} = \sqrt{E_{beam}^2 - |\overrightarrow{p}_{\bar{\Lambda}_c^-}|^2}$$

$$\Delta E = E - E_{beam}$$

- **Advantages:**
  - Clean environment
  - Straightforward and model independent absolute BRs measurement
  - Some systematic uncertainties canceled in DT method

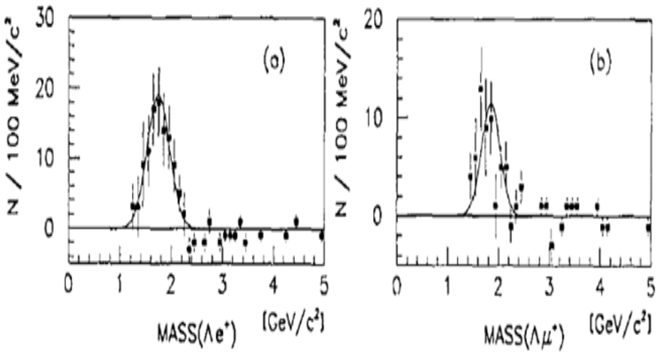
Semi-Leptonic decay $\Lambda_c^+ \to \Lambda l^+ \nu_l$

- **ARGUS first measurement :**

  Phys. Lett. B 269, 234 (1991).

$$\sigma(e^+e^- \to \Lambda_c^+ X)\cdot \mathrm{BR}(\Lambda_c^+ \to \Lambda e^+ X) = 4.20 \pm 1.28 \pm 0.71\ \mathrm{pb}$$

$$\sigma(e^+e^- \to \Lambda_c^+ X)\cdot \mathrm{BR}(\Lambda_c^+ \to \Lambda \mu^+ X) = 3.91 \pm 2.02 \pm 0.90\ \mathrm{pb}$$

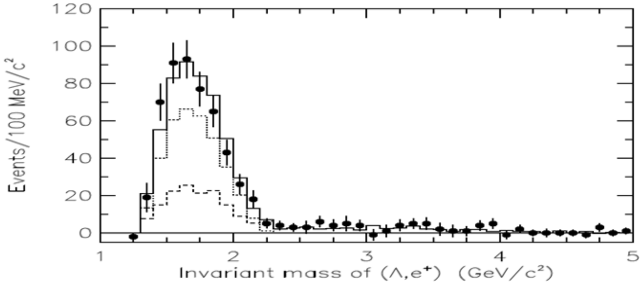


- **CLEO improved measurement :**

  Phys. Lett. B 323, 219 (1994).

$$\sigma(e^+e^- \to \Lambda_c^+ X)\cdot \mathrm{BR}(\Lambda_c^+ \to \Lambda e^+ X) = 4.87 \pm 0.28 \pm 0.69\ \mathrm{pb}$$

$$\sigma(e^+e^- \to \Lambda_c^+ X)\cdot \mathrm{BR}(\Lambda_c^+ \to \Lambda \mu^+ X) = 4.43 \pm 0.51 \pm 0.64\ \mathrm{pb}$$



- **Combined with the $\tau(\Lambda_c^+)$ and the assumption of form factors**

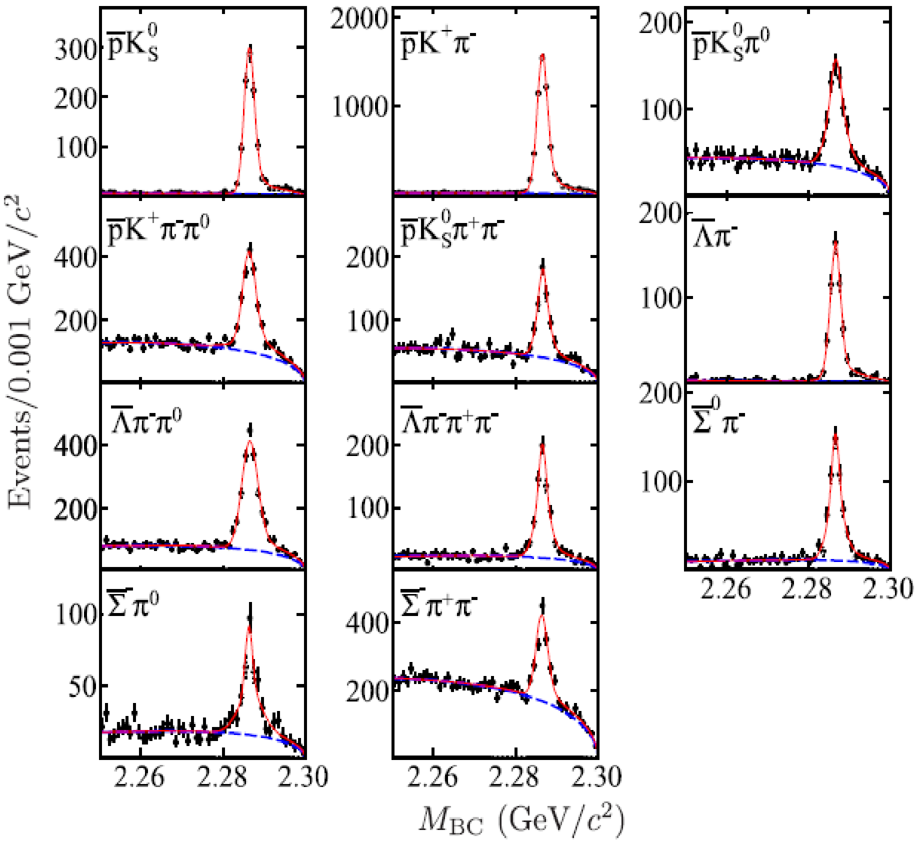
$\Lambda \ell^+ \nu_\ell$	***PDG 2015***	[r]	(2.8 ± 0.4) %
$\Lambda e^+ \nu_e$			(2.9 ± 0.5) %
$\Lambda \mu^+ \nu_\mu$			(2.7 ± 0.6) %

Not a direct measurement!

Theoretical calculations on the BF ranges from 1.4% to 9.2%

The measurement of $\Lambda_c^+ \to \Lambda l^+ \nu_l$

Double tag method **11 tag modes :** $M_{BC} = \sqrt{E_{beam}^2 - |\overrightarrow{p}_{\bar{\Lambda}_c^-}|^2}$



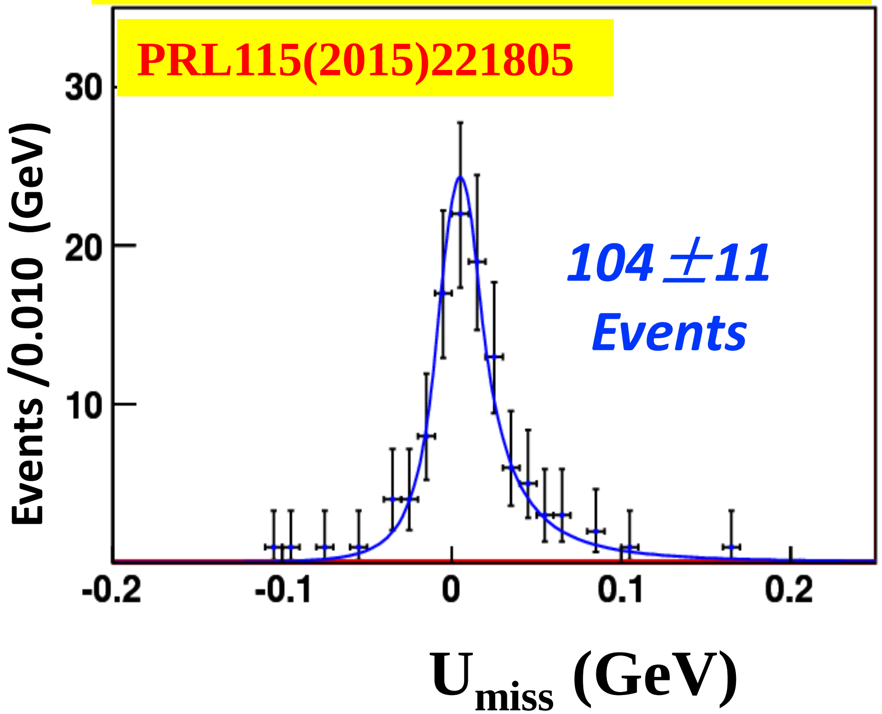
Mode	ΔE (GeV)	$N_{\bar{\Lambda}_c^-}$
$\bar{p}K_S^0$	[−0.025, 0.028]	1066 ± 33
$\bar{p}K^+\pi^-$	[−0.019, 0.023]	5692 ± 88
$\bar{p}K_S^0\pi^0$	[−0.035, 0.049]	593 ± 41
$\bar{p}K^+\pi^-\pi^0$	[−0.044, 0.052]	1547 ± 61
$\bar{p}K_S^0\pi^+\pi^-$	[−0.029, 0.032]	516 ± 34
$\bar{\Lambda}\pi^-$	[−0.033, 0.035]	593 ± 25
$\bar{\Lambda}\pi^-\pi^0$	[−0.037, 0.052]	1864 ± 56
$\bar{\Lambda}\pi^-\pi^+\pi^-$	[−0.028, 0.030]	674 ± 36
$\bar{\Sigma}^0\pi^-$	[−0.029, 0.032]	532 ± 30
$\bar{\Sigma}^-\pi^0$	[−0.038, 0.062]	329 ± 28
$\bar{\Sigma}^-\pi^+\pi^-$	[−0.049, 0.054]	1009 ± 57

ST yields: 14415±159 events with 11 ST modes

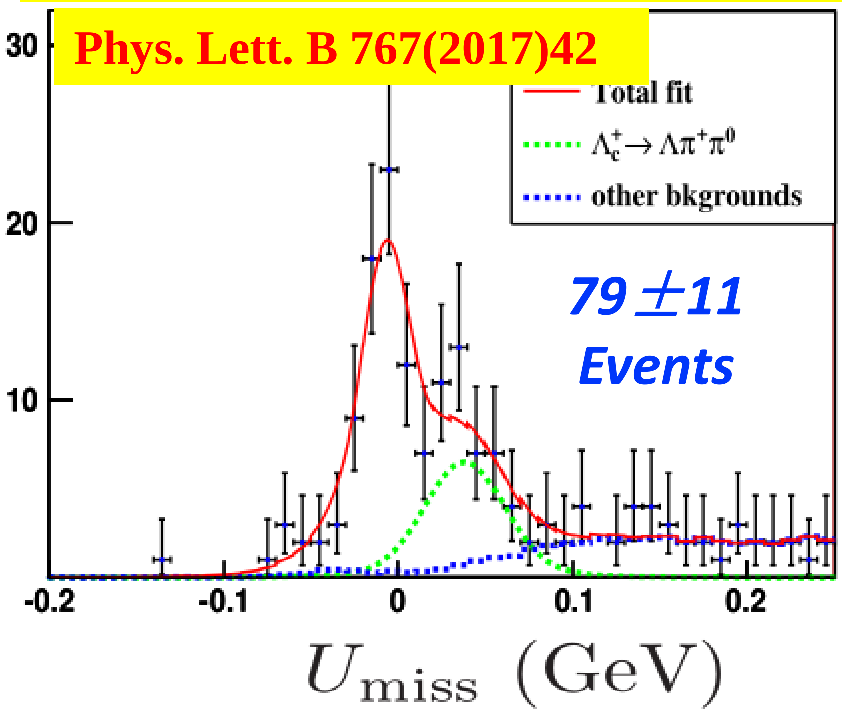
BFs of $\Lambda_c^+ \to \Lambda l^+ \nu_l$ decay

First direct measurement, optimized variables : $U_{\rm miss} = E_{\rm miss} - c|\vec{p}_{\rm miss}|$

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



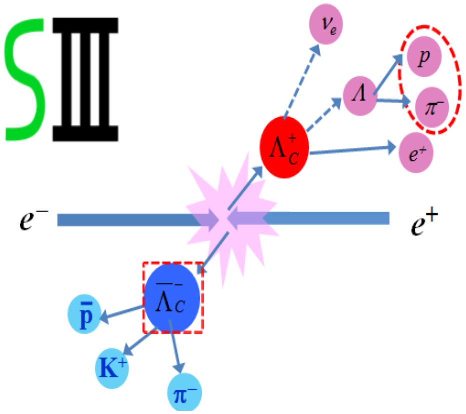
$B[\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu] = (3.49 \pm 0.46 \pm 0.26)\%$



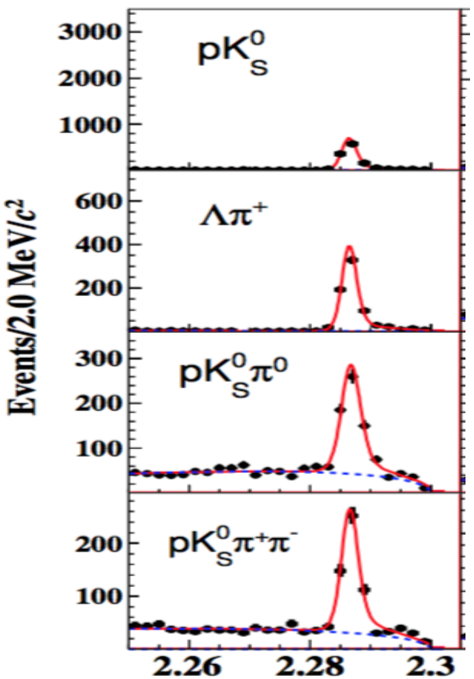
$\Gamma[\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu] / \Gamma[\Lambda_c^+ \to \Lambda e^+ \nu_e] = 0.96 \pm 0.16 \pm 0.04$

Important for test and calibrate the LQCD and lepton universality.

Absolute BFs of Λ_c^+ Cabibbo-Favored Hadronic decays

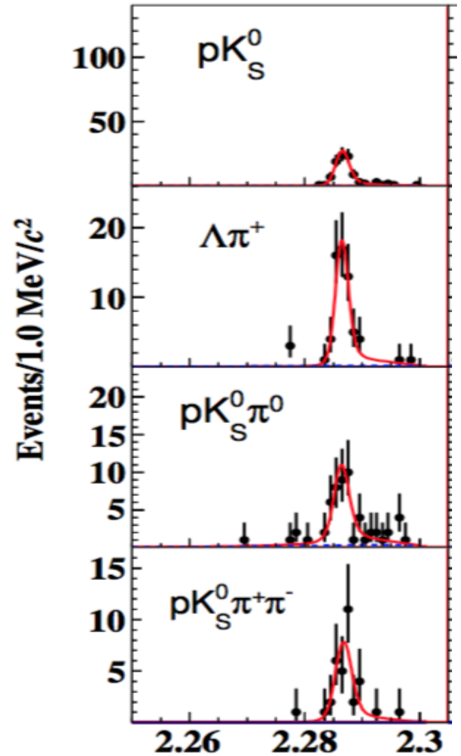


Signal Tag Variable : $M_{\rm BC} = \sqrt{E_{\rm beam}^2 - |\vec{p}_{\bar{\Lambda}_c^-}|^2}$



ST yields

modes	N_i^{ST}
pK_S	1243 ± 37
$pK^-\pi^+$	6308 ± 88
$pK_S\pi^0$	558 ± 33
$pK_S\pi^+\pi^-$	454 ± 28
$pK^-\pi^+\pi^0$	1849 ± 71
$\Lambda\pi^+$	706 ± 27
$\Lambda\pi^+\pi^0$	1497 ± 52
$\Lambda\pi^+\pi^-\pi^+$	609 ± 31
$\Sigma^0\pi^+$	586 ± 32
$\Sigma^+\pi^0$	271 ± 25
$\Sigma^+\pi^+\pi^-$	836 ± 43
$\Sigma^+\omega$	157 ± 22



DT yields

Decay modes	N_{-j}^{DT}
pK_S	89 ± 10
$pK^-\pi^+$	390 ± 21
$pK_S\pi^0$	40 ± 7
$pK_S\pi^+\pi^-$	29 ± 6
$pK^-\pi^+\pi^0$	148 ± 14
$\Lambda\pi^+$	59 ± 8
$\Lambda\pi^+\pi^0$	89 ± 11
$\Lambda\pi^+\pi^-\pi^+$	53 ± 7
$\Sigma^0\pi^+$	39 ± 6
$\Sigma^+\pi^0$	20 ± 5
$\Sigma^+\pi^+\pi^-$	56 ± 8
$\Sigma^+\omega$	13 ± 3

Very clean backgrounds!!!

PRL 116, 052001 (2016)

Results of 12 CF hadronic BFs

- Straightforward and model independent — **PRL 116, 052001 (2016)**
- A least square global simultaneous fit : *[CPC 37, 106201 (2013)]*

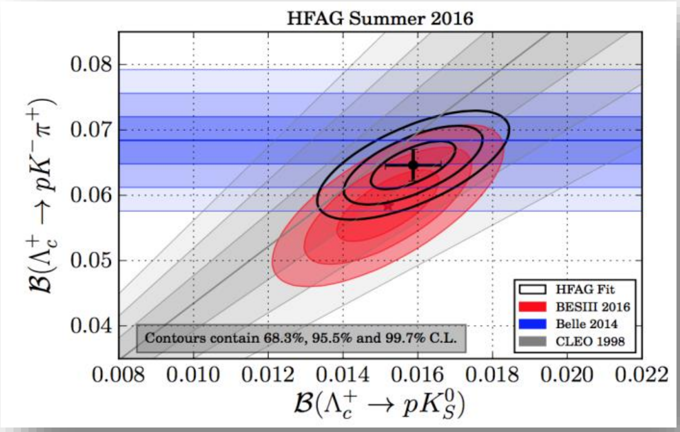
Mode	This work (%)	PDG (%)	BELLE $\mathcal{B}$
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30	
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50	
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35	
$pK^-\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0	
$\Lambda\pi^+$	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28	
$\Lambda\pi^+\pi^0$	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3	
$\Lambda\pi^+\pi^-\pi^+$	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7	
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28	
$\Sigma^+\pi^0$	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34	
$\Sigma^+\pi^+\pi^-$	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0	
$\Sigma^+\omega$	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0	

- $B(\Lambda_c^+ \to pK^-\pi^+)$: BESIII precision comparable with Belle's
- BESIII $B(\Lambda_c^+ \to pK^-\pi^+)$ is compatible with BELLE's with 2σ
- Improved precisions of the other 11 modes significantly

HFAG Fit to world BF data

- A fitter to constrain the 12 hadronic BFs and 1 SL BF, based on all the existing experimental data, overall χ^2/ndf=30.0/23=1.3
- Correlated systematics are fully taken into account

Mode	HFAG 2016 (%)	BESIII (%)	PDG 2014 (%)	BELLE (%)
pK_S^0	1.59 ± 0.07	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30	
$pK^-\pi^+$	6.46 ± 0.24	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK_S^0\pi^0$	2.03 ± 0.12	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50	
$pK_S^0\pi^+\pi^-$	1.69 ± 0.11	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35	
$pK^-\pi^+\pi^0$	5.05 ± 0.29	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0	
$\Lambda\pi^+$	1.28 ± 0.06	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28	
$\Lambda\pi^+\pi^0$	7.09 ± 0.36	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3	
$\Lambda\pi^+\pi^-\pi^+$	3.73 ± 0.21	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7	
$\Sigma^0\pi^+$	1.31 ± 0.07	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28	
$\Sigma^+\pi^0$	1.25 ± 0.09	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34	
$\Sigma^+\pi^+\pi^-$	4.64 ± 0.24	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0	
$\Sigma^+\omega$	1.77 ± 0.21	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0	
$\Lambda e^+\nu_e$	3.18 ± 0.32	$3.63 \pm 0.38 \pm 0.20$	2.1 ± 0.6	

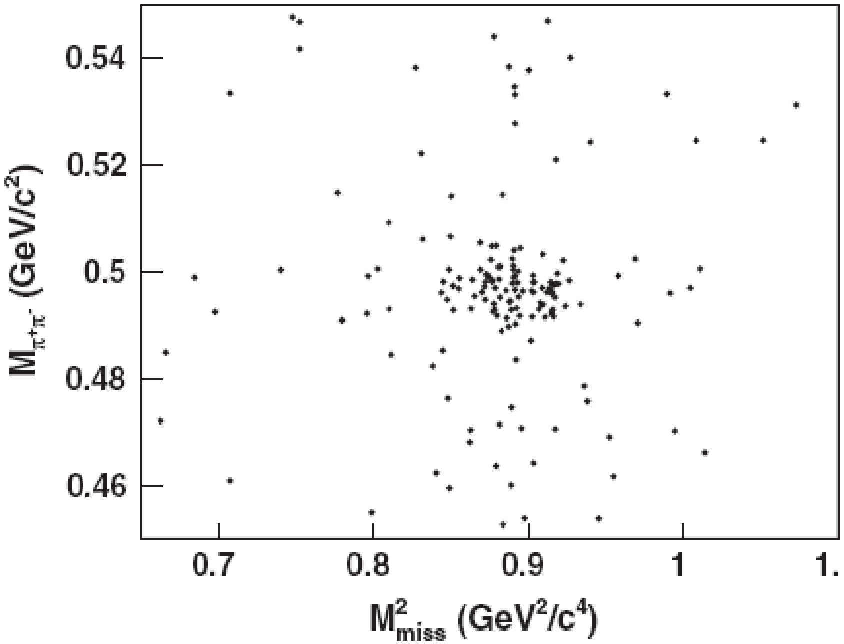


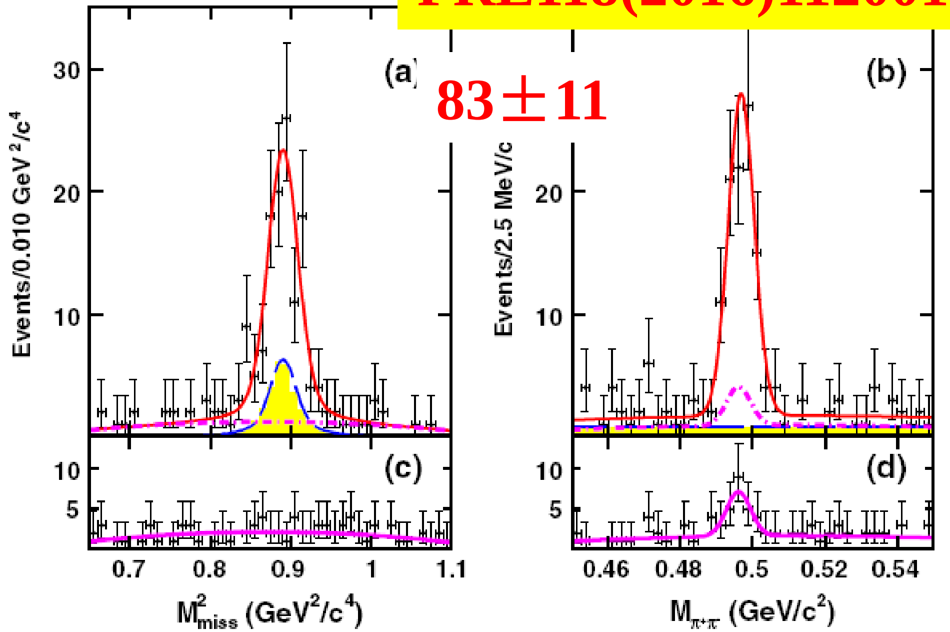
Precise $B(pK^-\pi^+)$ is useful for V_{ub} measurement via baryonic mode

Observation of $\Lambda_c^+ \to nK_S^0\pi^+$

First observation of Λ_c^+ decays involving the neutron in final states.

PRL118(2016)112001





$B[\Lambda_c^+ \to nK_S^0\pi^+] = (1.82 \pm 0.23 \pm 0.11)\%$
$B[\Lambda_c^+ \to nK^0\pi^+]/B[\Lambda_c^+ \to pK^-\pi^+] = 0.62 \pm 0.09$
$B[\Lambda_c^+ \to nK^0\pi^+]/B[\Lambda_c^+ \to pK^0\pi^0] = 0.97 \pm 0.16$

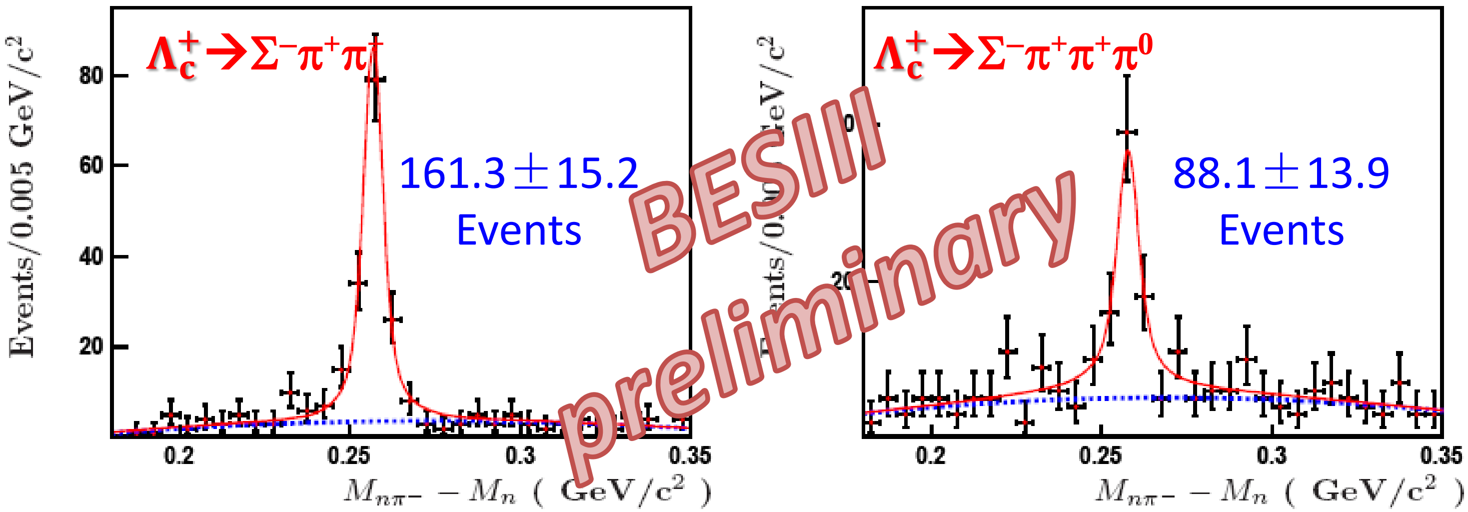
The phase difference between $I^{(0)}$ and $I^{(1)}$:
$\cos\delta = -0.24 \pm 0.08$
and relative strength: $|I^{(1)}|/|I^{(0)}| = 1.14 \pm 0.11$

The relative BF of neutron-involved mode to proton-involved mode is essential to test the isospin symmetry and extract the strong phases of different final states.

Measurement of $\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+ (\pi^0)$

- The total measured Λ_c^+ decay BFs is **~65%,** searching for more decay modes are important
- Only one Λ_c^+ decay involved Σ^- is observed, $B(\Lambda_c^+ \to \Sigma^- \pi^+ \pi^-) = (2.3 \pm 0.4)\%$, where Σ^- dominantly decay to $n\pi^-$

11 ST modes, 11415 ± 159 Λ_c^+ tagged candidates



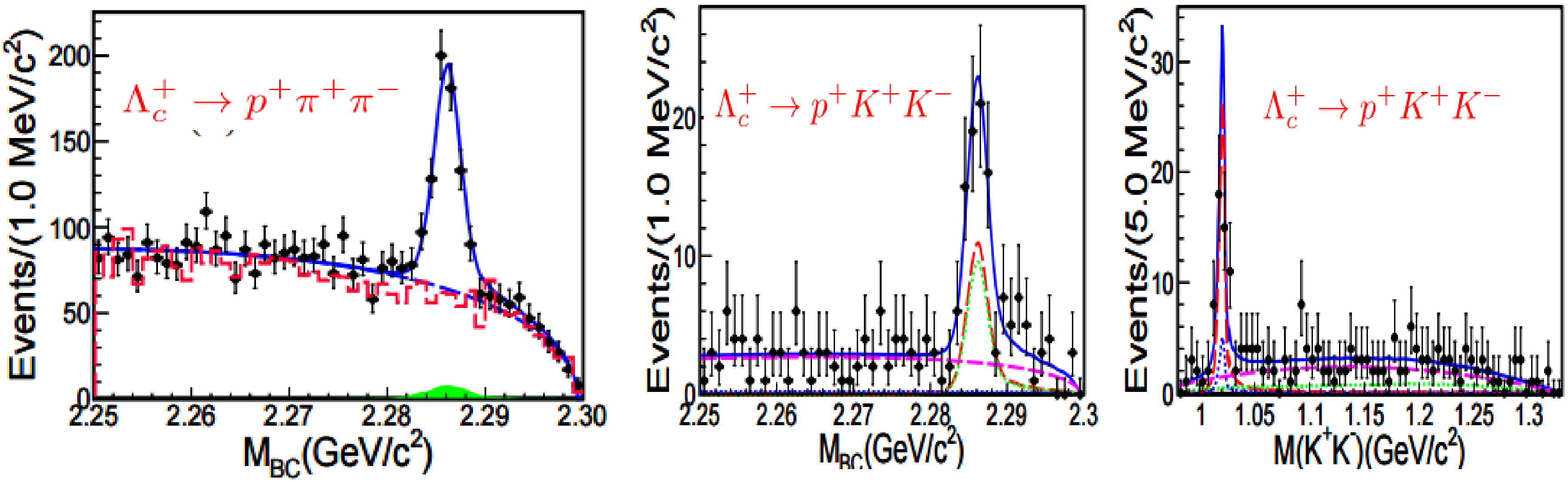
$B[\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+] = (1.81 \pm 0.17)\%$ [Improved precision]

$B[\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+ \pi^0] = (2.11 \pm 0.33)\%$ [first observation]

Statistical only,
totally uncertainty <5%

Single-Cabibbo-Suppressed decay of $\Lambda_c^+ \to p\pi^+\pi^-/K^+K^-$

Sensitive to non-factorizable contributions from W-exchanged process



Decay modes	$\mathcal{B}_{\text{mode}}/\mathcal{B}_{\text{ref.}}$ (this work)	$\mathcal{B}_{\text{mode}}/\mathcal{B}_{\text{ref.}}$ ([28])
$\Lambda_c^+ \to p\pi^+\pi^-$	$(6.70 \pm 0.48 \pm 0.25) \times 10^{-2}$	–
$\Lambda_c^+ \to p\phi$	$(1.81 \pm 0.33 \pm 0.13) \times 10^{-2}$	$0.015 \pm 0.002 \pm 0.002$
$\Lambda_c^+ \to pK^+K^-$ (non-ϕ)	$(9.36 \pm 2.22 \pm 0.71) \times 10^{-3}$	$0.007 \pm 0.002 \pm 0.002$
–	$\mathcal{B}_{\text{mode}}$	$\mathcal{B}$(PDG)
$\Lambda_c^+ \to p\pi^+\pi^-$	$(3.91 \pm 0.28 \pm 0.15 \pm 0.24) \times 10^{-3}$	$(3.5 \pm 2.0) \times 10^{-3}$ → **first observation**
$\Lambda_c^+ \to p\phi$	$(1.06 \pm 0.19 \pm 0.08 \pm 0.06) \times 10^{-3}$	$(8.2 \pm 2.7) \times 10^{-4}$
$\Lambda_c^+ \to pK^+K^-$ (non-ϕ)	$(5.47 \pm 1.30 \pm 0.41 \pm 0.33) \times 10^{-4}$	$(3.5 \pm 1.7) \times 10^{-4}$

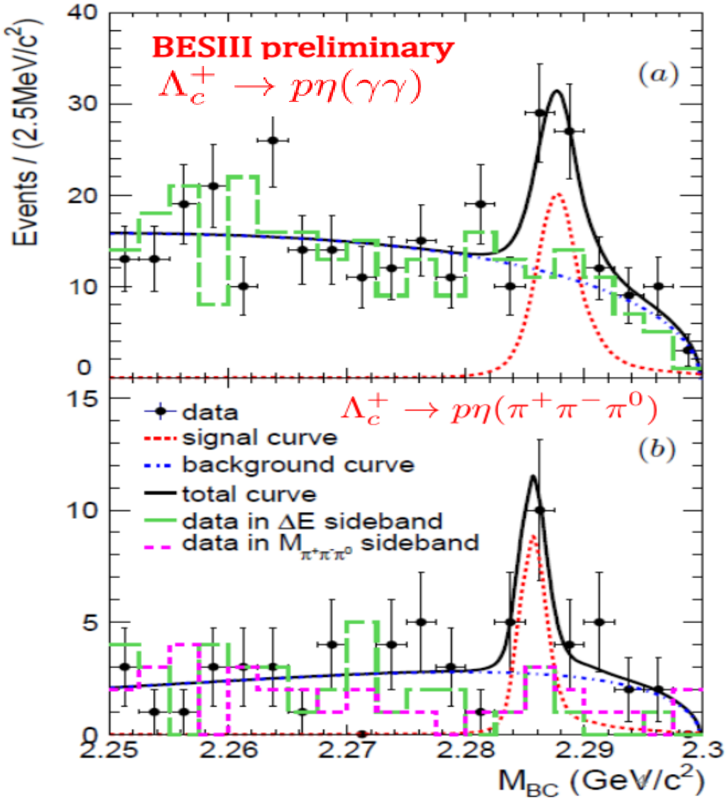
PRL117(2016)232002

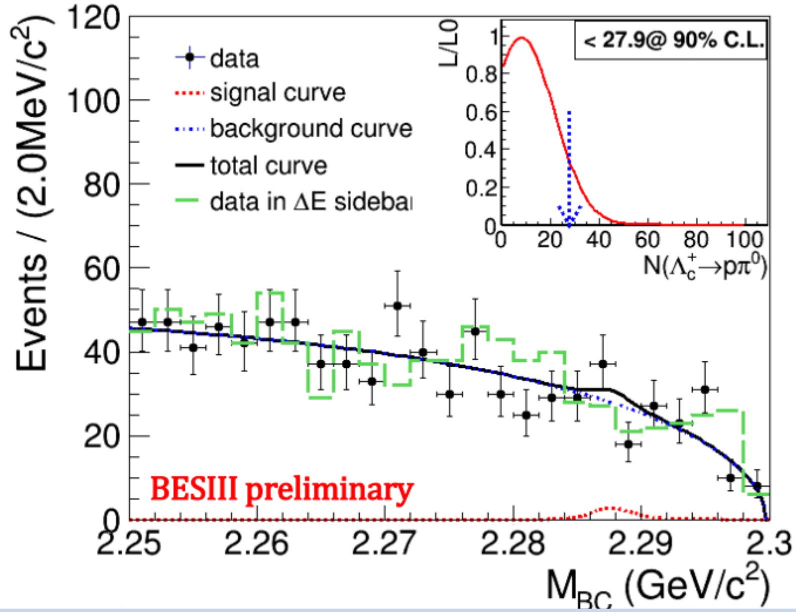
improved precision

SCS Decays $\Lambda_c^+ \rightarrow p\pi^0$ and $\Lambda_c^+ \rightarrow p\eta$

- Their relative size essential to understand the interference of different non-factorizable diagrams
- It is expected that $\Gamma(\Lambda_c^+ \rightarrow p\eta) >> \Gamma(\Lambda_c^+ \rightarrow p\pi^0)$

arXiv:1702.05279



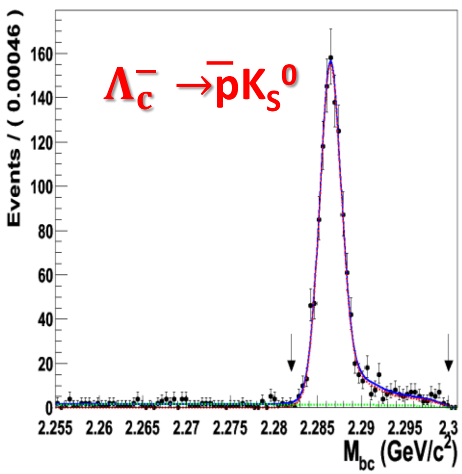


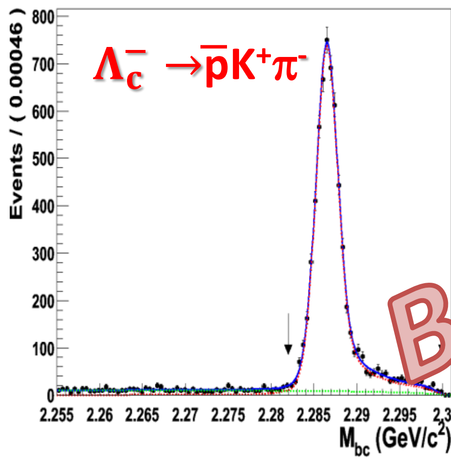
$$B = \frac{N^{obs}}{2 \cdot N_{\Lambda_c^+ \overline{\Lambda}_c^-} \cdot \varepsilon \cdot B_{int}}$$

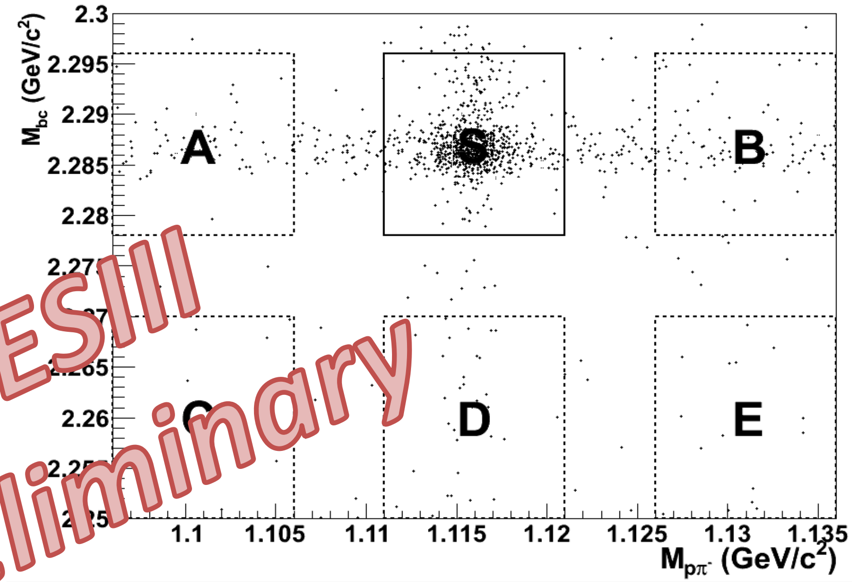
- BESIII preliminary results:
  $B(\Lambda_c^+ \rightarrow p\eta) = (1.24 \pm 0.28 \pm 0.10) \times 10^{-3}$;
  $B(\Lambda_c^+ \rightarrow p\pi^0) < 2.7 \times 10^{-4}$;
  $B(\Lambda_c^+ \rightarrow p\pi^0)/B(\Lambda_c^+ \rightarrow p\eta) < 0.24$
- First evidence for $\Lambda_c^+ \rightarrow p\eta$ with 4.2σ

The measurement of $\Lambda_c^+ \to \Lambda + X$

- The measurement is useful to test of HQET
- PDG2016 $B(\Lambda_c^+ \to \Lambda + X)$ = 35±11%







Tag modes	ΔE(GeV)	Yields
$\bar{\Lambda}_c^- \to \bar{p}K_S^0$	[-0.021, 0.019]	1220 ± 37
$\bar{\Lambda}_c^- \to \bar{p}K^+\pi^-$	[-0.020, 0.015]	6088 ± 85

$$\mathcal{A}_{CP} = \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) - \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) + \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}.$$

Decay mode	Branching fraction(%)	$\mathcal{A}_{CP}$
$\Lambda_c^+ \to \Lambda + X$	$38.02 \pm 3.24 \pm 0.61$	$0.02 \pm 0.06 \pm 0.01$
$\bar{\Lambda}_c^- \to \bar{\Lambda} + X$	$36.70 \pm 3.04 \pm 0.59$	

$\mathcal{B}(\Lambda_c^+ \to \Lambda + X) = (36.98 \pm 2.18)\%$

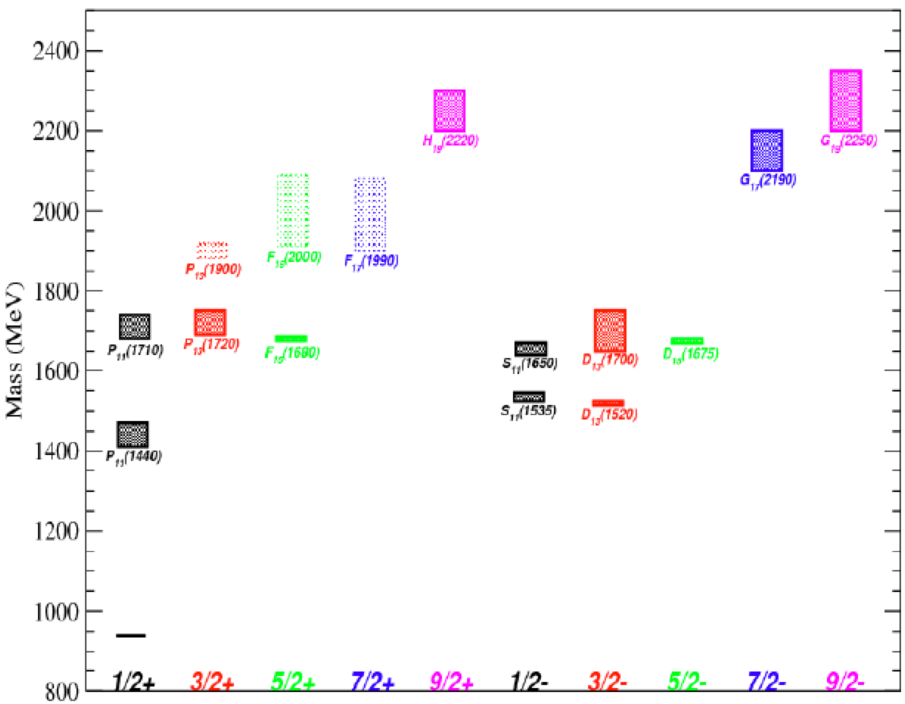
BARYON SPECTROSCOPY AT BESIII

Spectrum of Nucleon Resonances

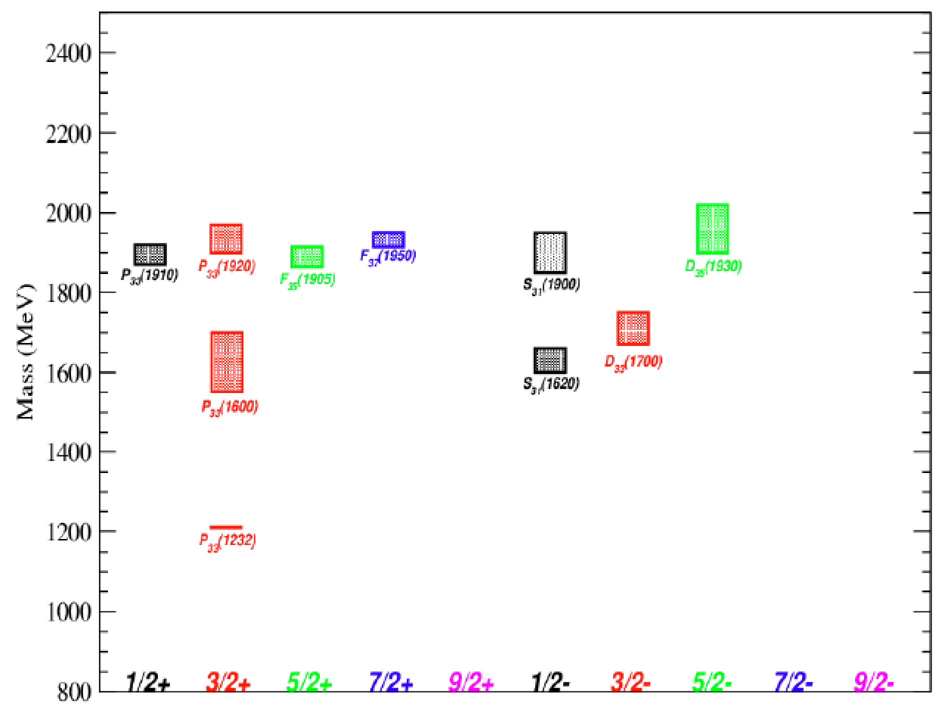
	****	***	**	*
N Spectrum	10	5	7	3
Δ Spectrum	7	3	7	5

→ Particle Data Group (Phys. Rev. D**86**, 010001 (2012))
→ Many open questions left

Nucleon Mass Spectrum (Exp): 4*, 3*, 2*

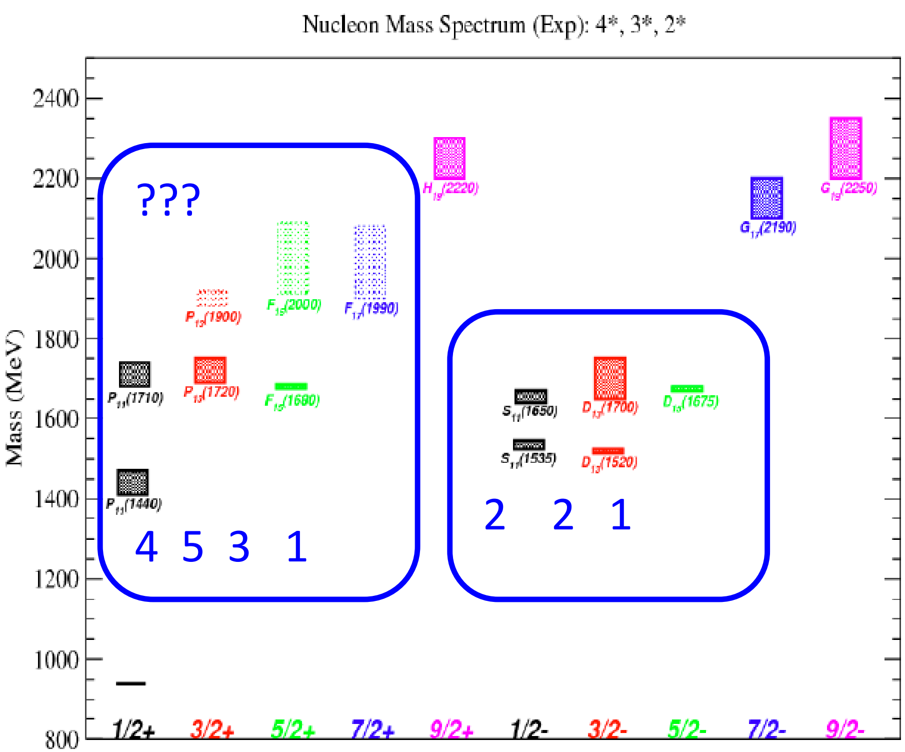


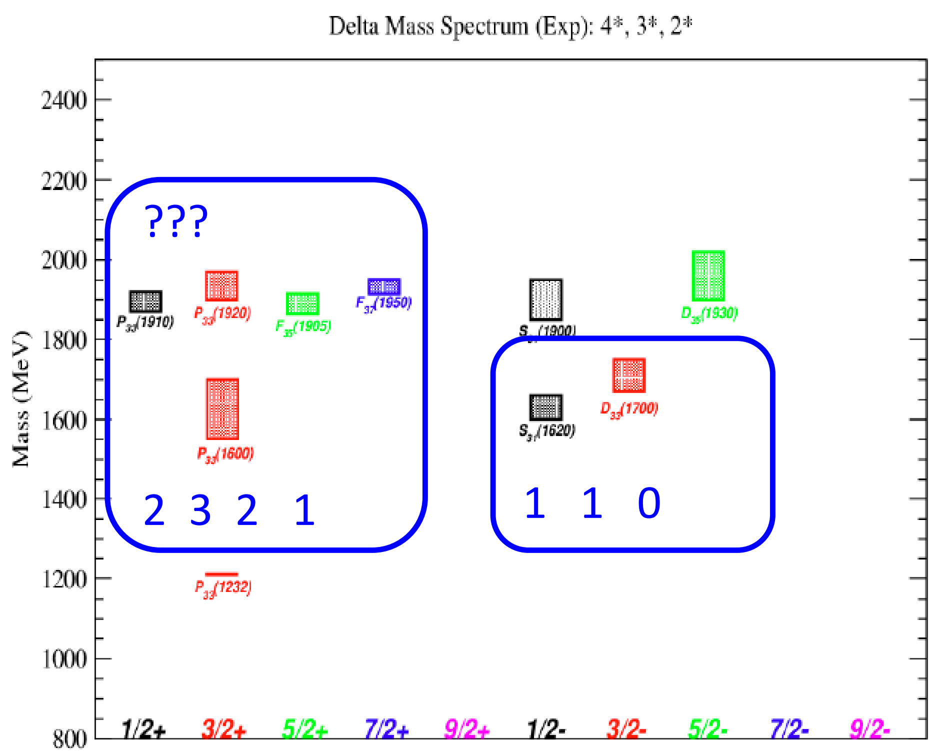
Delta Mass Spectrum (Exp): 4*, 3*, 2*



Where are the “missing” baryons?

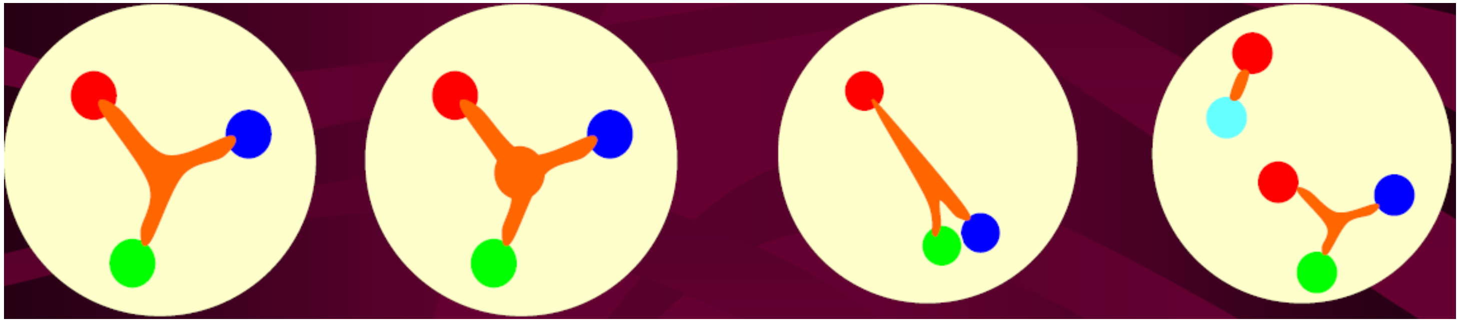
Quark models predict many more baryons than have been observed





Where are the "missing" baryons?

- 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 | ...

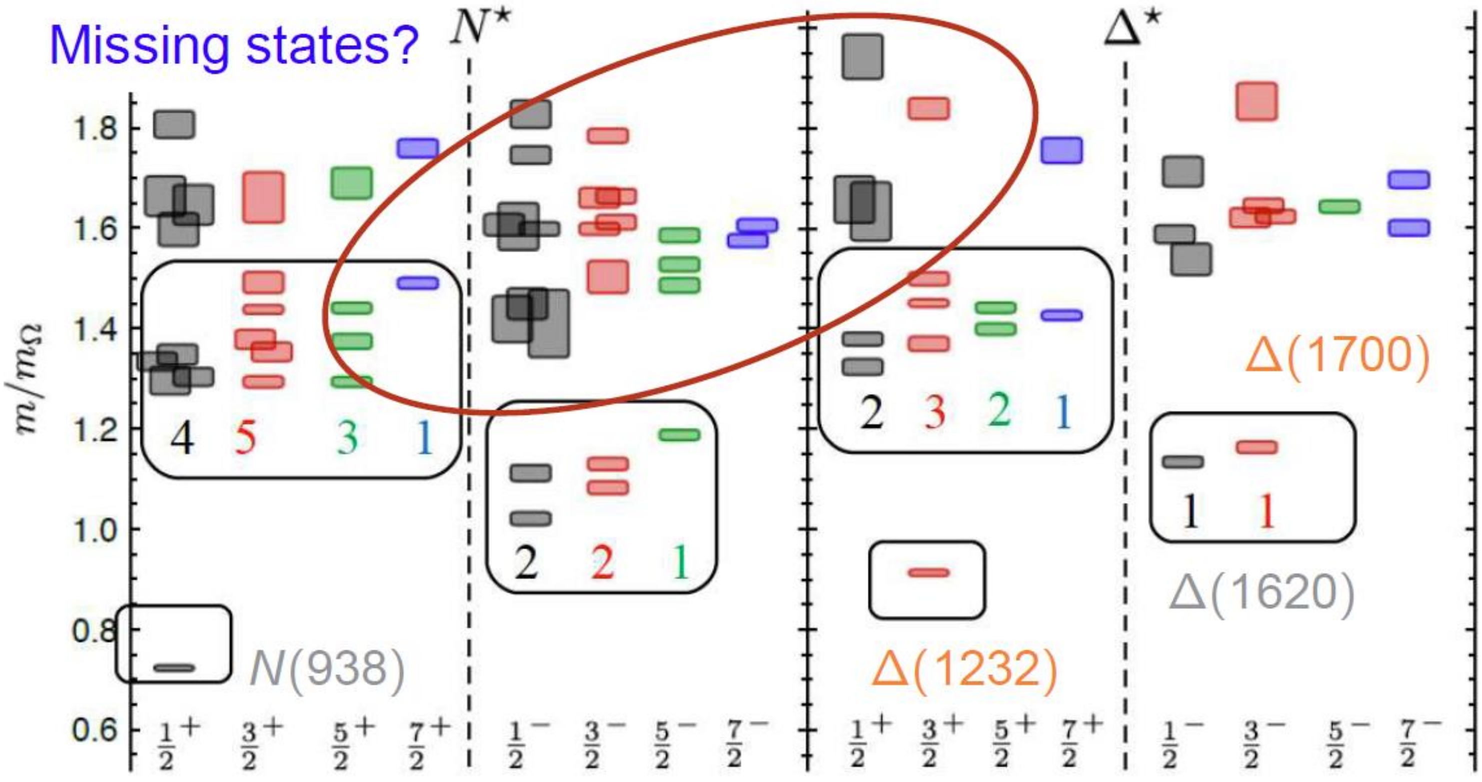
$N_{predictied}$: $N_4 > N_2 > N_1 > N_3$, $N_{observed} << N_1$

- Or have the resonances simply escaped detection?

Nearly all existing data result from πN experiments

Excited state baryon spectroscopy from lattice QCD

R. Edwards *et al.*, PR D84 074508 (2011)

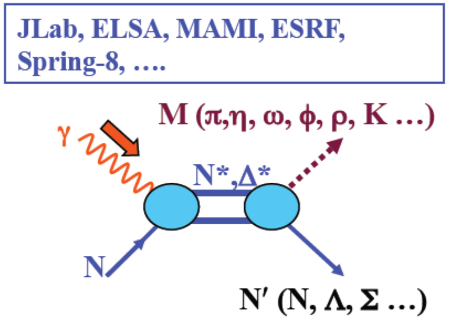


$m_\pi = 400$ MeV

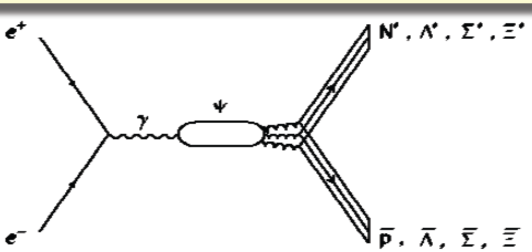
Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

➜ Counting of levels consistent with non-rel. quark model, no parity doubling

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



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



- ✓ Pure 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 N*, but also Λ^*, Σ^*, Ξ^*
- ✓ Gluon-rich eviroment: a favorable place for producing hybrid (qqqg) baryons
- ✓ Interference between N* and $\bar{N}$ * bands in $\psi \to N\bar{N}\pi$ Dalitz plots may help to distinguish some ambiguities in PWA of πN
- ✓ High statistics of charmonium @ BES III

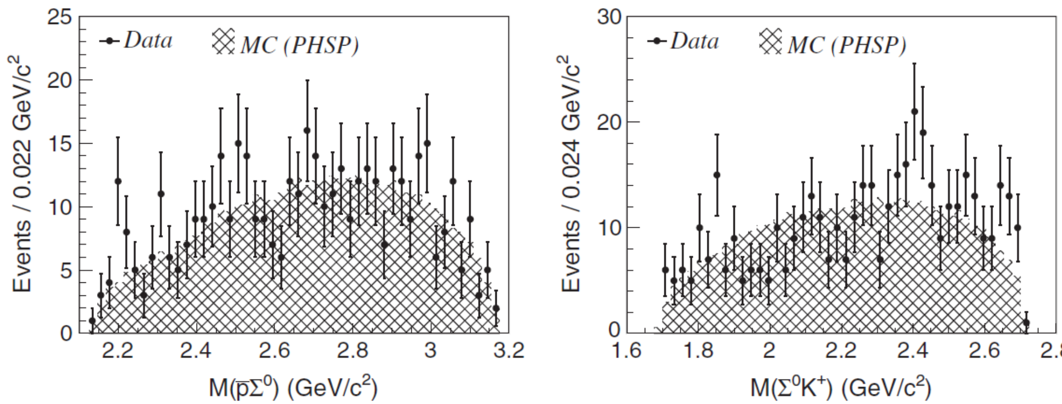
Recent results @ BESIII

- Measurements of $\psi' \to \bar{p}K^{+}\Sigma^{0}$ and $\chi_{cJ} \to \bar{p}K^{+}\Lambda$
- Measurements of $\psi' \to (\gamma)K^{-}\Lambda\bar{\Xi}^{+} + c.c.$
- Observation of $\psi' \to \Lambda\bar{\Sigma}^{\pm}\pi^{\mp} + c.c.$
- Observation of $\mathrm{J}/\psi \to a_0(980)p\bar{p}$
- Measurements of $\mathrm{J}/\psi \to \phi p\bar{p}$
- PWA of $\psi' \to \pi^{0}p\bar{p}$
- PWA of $\psi' \to \eta p\bar{p}$

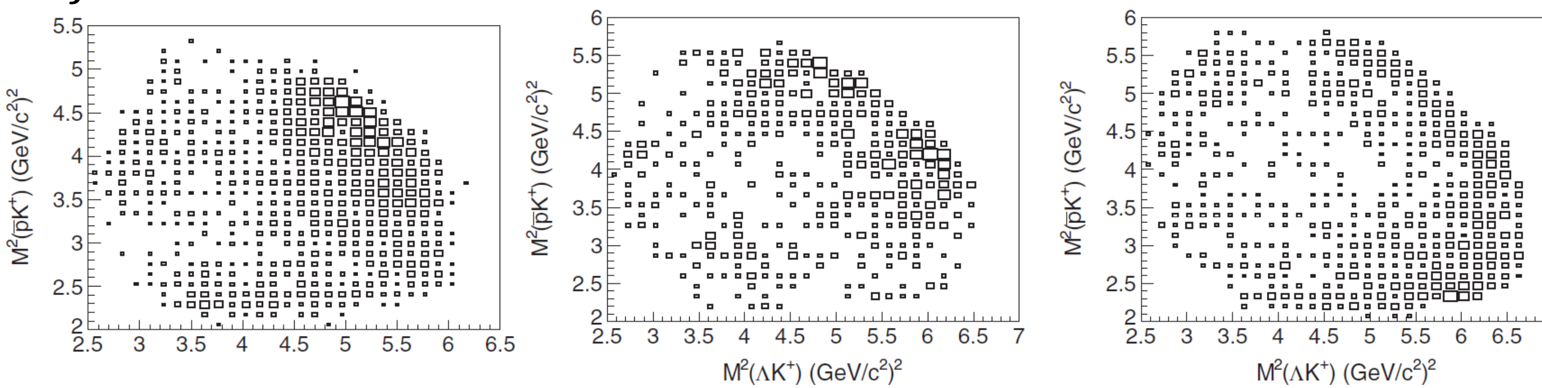
*These analyses based on 108*10^6 ψ' decays and 225*10^6 J/ψ decays.*

$\psi' \to \bar{p}K^+\Sigma^0, \Sigma^0 \to \gamma\Lambda$

BESIII Phys.Rev. D87, 012007 (2013)



$\psi' \to \gamma\chi_{cJ}, \chi_{cJ} \to \bar{p}K^+\Lambda$



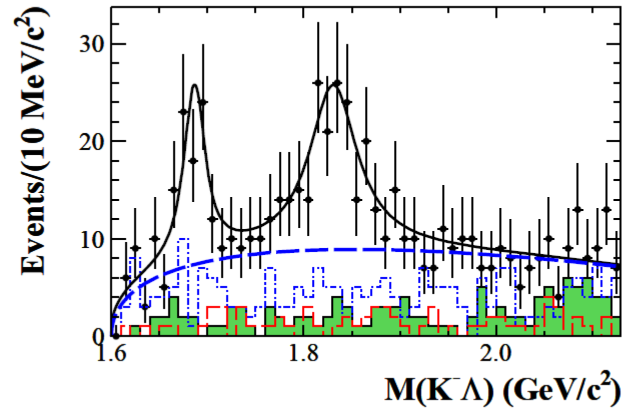
χ_{c0} χ_{c1} χ_{c2}

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		$(10.2 \pm 1.9) \times 10^{-4}$	$(3.2 \pm 1.0) \times 10^{-4}$	$(9.1 \pm 1.8) \times 10^{-4}$

BESIII Phys.Rev. D91, 092006 (2015)

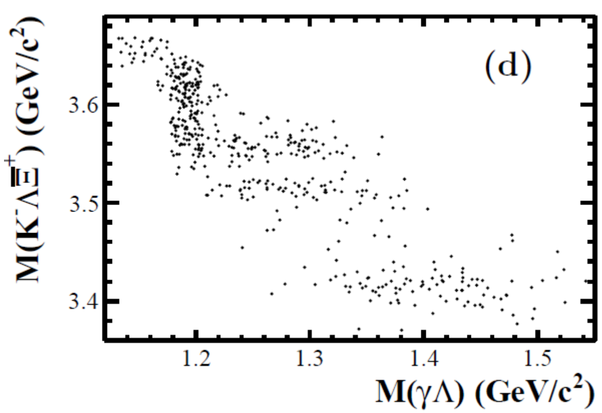
$\Xi^-(1690)$ *and* $\Xi^-(1820)$ *are* observed in $\psi' \to K^-\Lambda\bar{\Xi}^+ + c.c.$

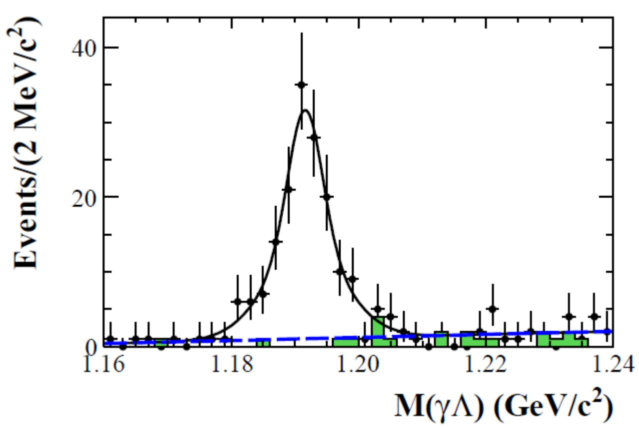
Resonance parameters consist with PDG

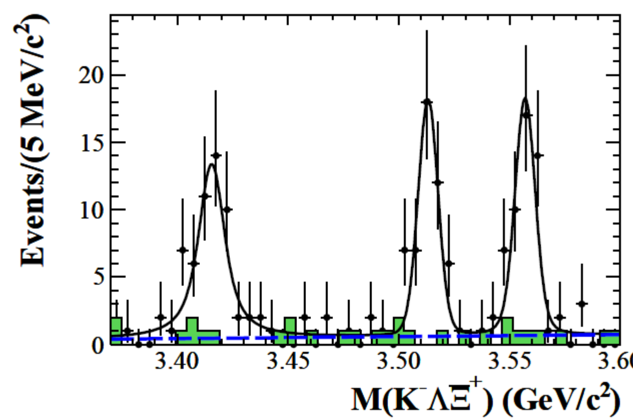


Decay	Branching fraction
$\psi(3686) \to K^-\Lambda\bar{\Xi}^+$	$(3.86 \pm 0.27 \pm 0.32) \times 10^{-5}$
$\psi(3686) \to \Xi(1690)^-\bar{\Xi}^+,\ \Xi(1690)^- \to K^-\Lambda$	$(5.21 \pm 1.48 \pm 0.57) \times 10^{-6}$
$\psi(3686) \to \Xi(1820)^-\bar{\Xi}^+,\ \Xi(1820)^- \to K^-\Lambda$	$(12.03 \pm 2.94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

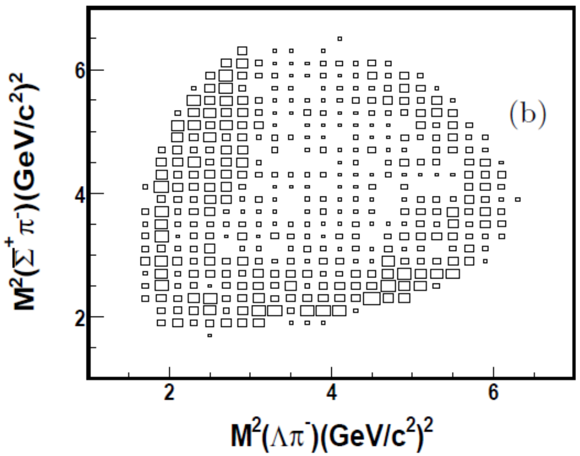
In the study of $\psi' \to \gamma K^-\Lambda\bar{\Xi}^+ + c.c.$*, the branching fraction of* $\psi' \to K^-\Sigma^0\bar{\Xi}^+ + c.c.$ and $\chi_{cJ} \to K^-\Lambda\bar{\Xi}^+ + c.c.$ *are measured*





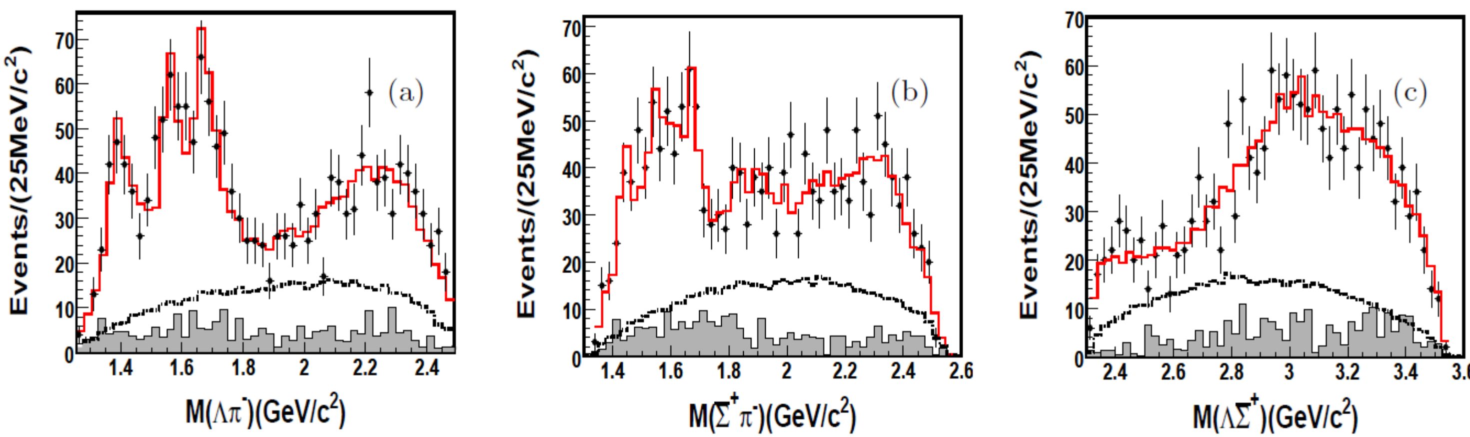


Observation of $\psi' \to \Lambda\bar{\Sigma}^{\pm}\pi^{\mp} + c.c.$



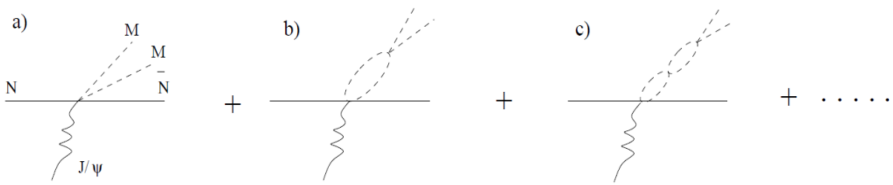
BESIII Phys.Rev. D88, 112007 (2013)

$$\mathcal{B}(\psi(3686) \to \Lambda\bar{\Sigma}^{+}\pi^{-} + c.c.) = (1.40 \pm 0.03 \pm 0.13) \times 10^{-4},$$
$$\mathcal{B}(\psi(3686) \to \Lambda\bar{\Sigma}^{-}\pi^{+} + c.c.) = (1.54 \pm 0.04 \pm 0.13) \times 10^{-4},$$

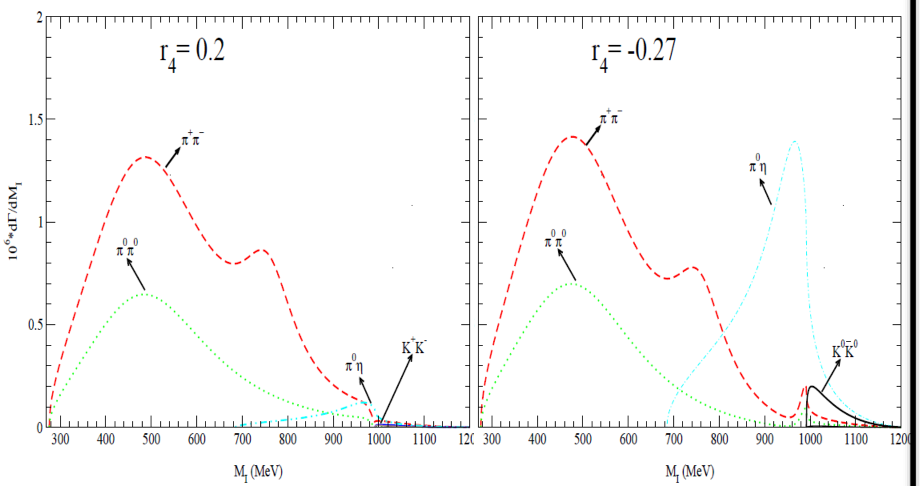


Observation of $\mathrm{J}/\psi \rightarrow a_0(980)p\bar{p}$

A chiral unitary approach including FSI [Phys.Rev. C68 015201]

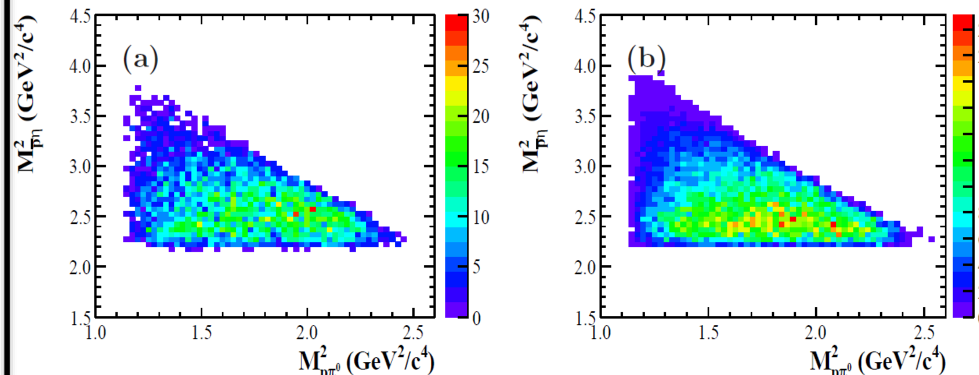


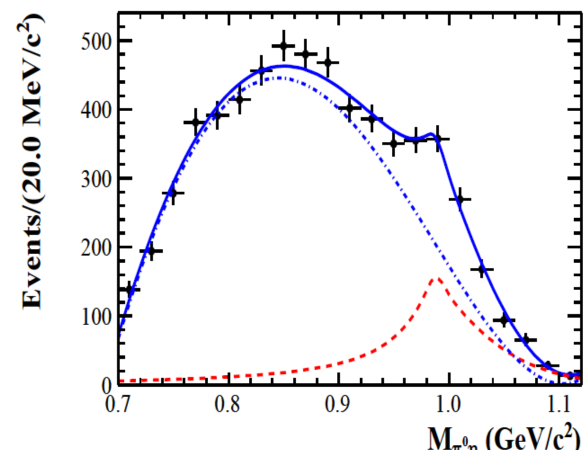
Ambiguities from fitting to $\mathrm{J}/\psi \rightarrow p\bar{p}\pi^+\pi^-$



* r_4 *is one of the coefficients in the parameterization of meson-meson amplitudes in [Phys.Rev. C68 015201].*

BESIII Phys.Rev. D90, 052009 (2014)





$$Br(J/\psi \rightarrow p\bar{p}a_0(980) \rightarrow p\bar{p}\pi^0\eta) = (6.8\pm1.2\pm1.3)\times10^{-5}$$

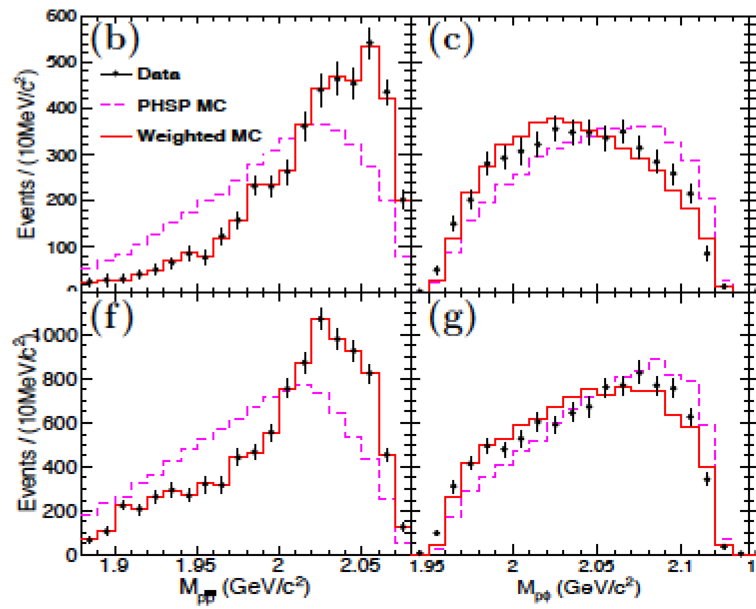
Comparing to Br($\mathrm{J}/\psi \rightarrow p\bar{p}\pi^+\pi^-$) in PDG, r_4=0.2 is preferable

Measurements of $J/\psi \rightarrow \phi p \bar{p}$

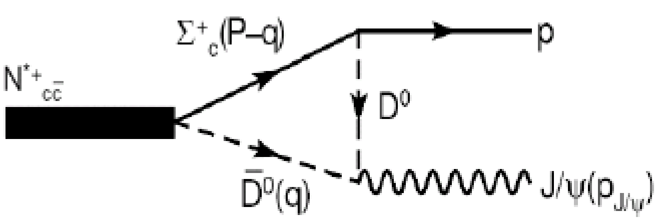
BESIII Phys.Rev. D93, 052010 (2016)

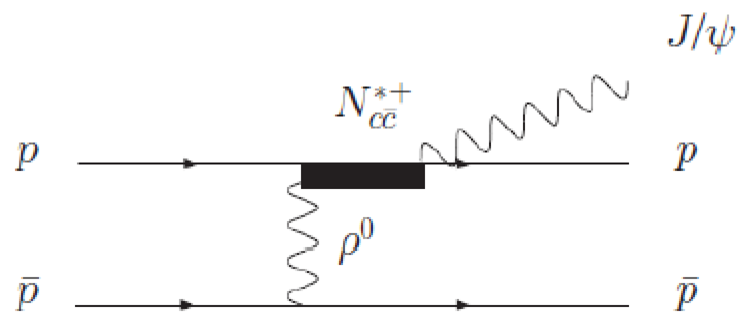
$\mathcal{B}(J/\psi \to p\bar{p}\phi) = [5.23 \pm 0.06\,(\mathrm{stat}) \pm 0.33\,(\mathrm{syst})] \times 10^{-5}$

No obvious threshold structure of $\bar{p}p$ or ϕp



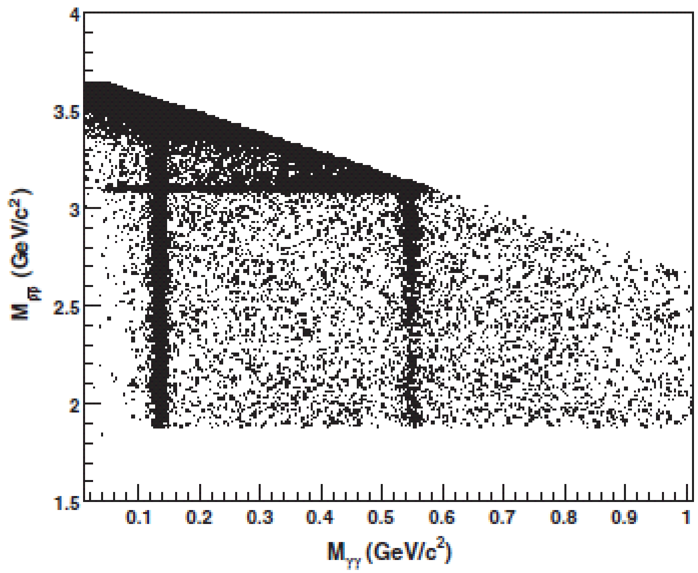
Baryons with hidden charm PRL105 (2010) 232001， PRC84 (2011) 015202





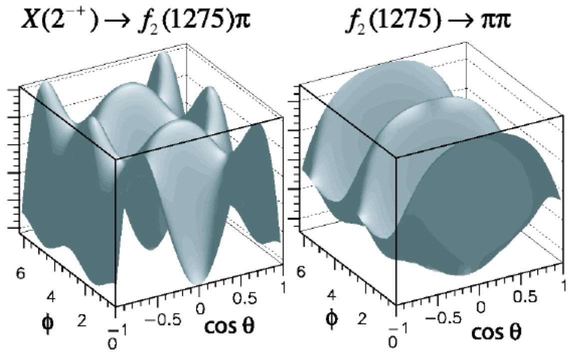
$\psi' \to \pi^0 p\bar{p}, \eta p\bar{p}$

Scatter plots of $p\bar{p}$ invariant mass versus $\gamma\gamma$ invariant mass



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

Partial wave analysis at BESIII



Tasks:

- ☐ **Map out the resonances**
- ☐ **Systematic determination of resonance properties:**
  - **spin-parity,**
  - **resonance parameters,**
  - **production properties,**
  - **decay properties, …**
    - ◆ resonances tend to be broad and plentiful, leading to intricate interference patterns, or buried under a background in the same and in other waves.

Event-based ML fit to all observables simultaneously

dynamic ↓ angular ↓

$$\omega(\xi) \equiv \frac{d\sigma}{d\Phi} = \left|\sum_i c_i R_i B(p,q) Z(L)\right|^2$$

Event-wise efficiency correction

$$P(\xi) = \frac{\omega(\xi)\epsilon(\xi)}{\int \omega(\xi)\epsilon(\xi)}$$

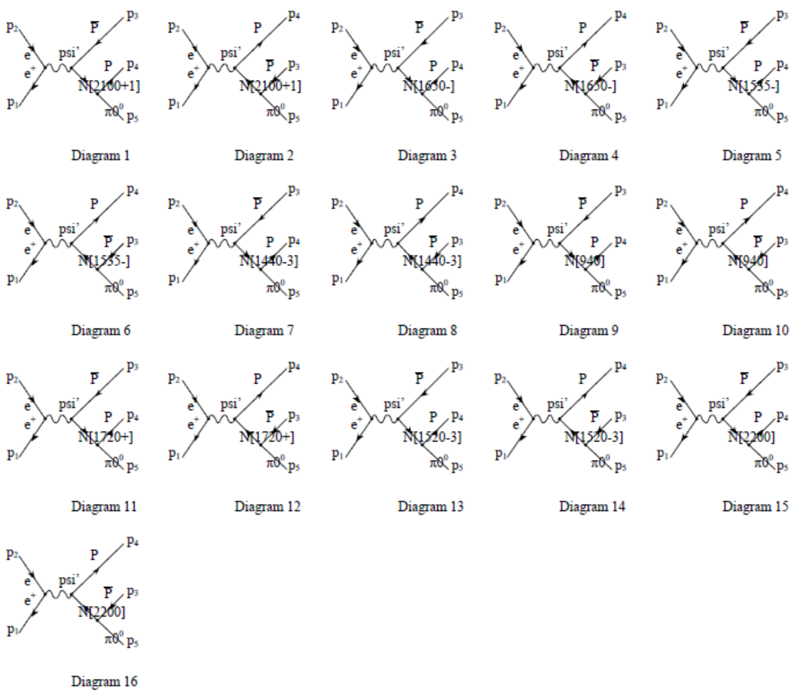
Tools: PWA

- ✓ **Decompose to partial wave amplitudes**
- ✓ **Make full use of data**
- ✓ **Handle the interference**
- ✓ **Extract resonance properties with high sensitivity and accuracy**

FDC-PWA: automatic generation of the complicated partial wave amplitudes for baryon spectroscopy

Feynman Diagram Calculation (FDC) Project by J.X Wang, Nucl.Instrum.Meth. A534 (2004) 241

Automatically generated Feynman diagrams in $\psi' \to \pi^0 p\bar{p}$



Using an effective Lagrangian approach and covariant tensors, FDC-PWA construct amplitudes with spin wave functions, propagators and effective couplings.

For example, for $J/\psi \to \bar{N}N^*(\frac{3}{2}^+) \to \bar{N}(\kappa_1, s_1) \times N(\kappa_2, s_2)\pi(\kappa_3)$, the amplitude can be constructed as

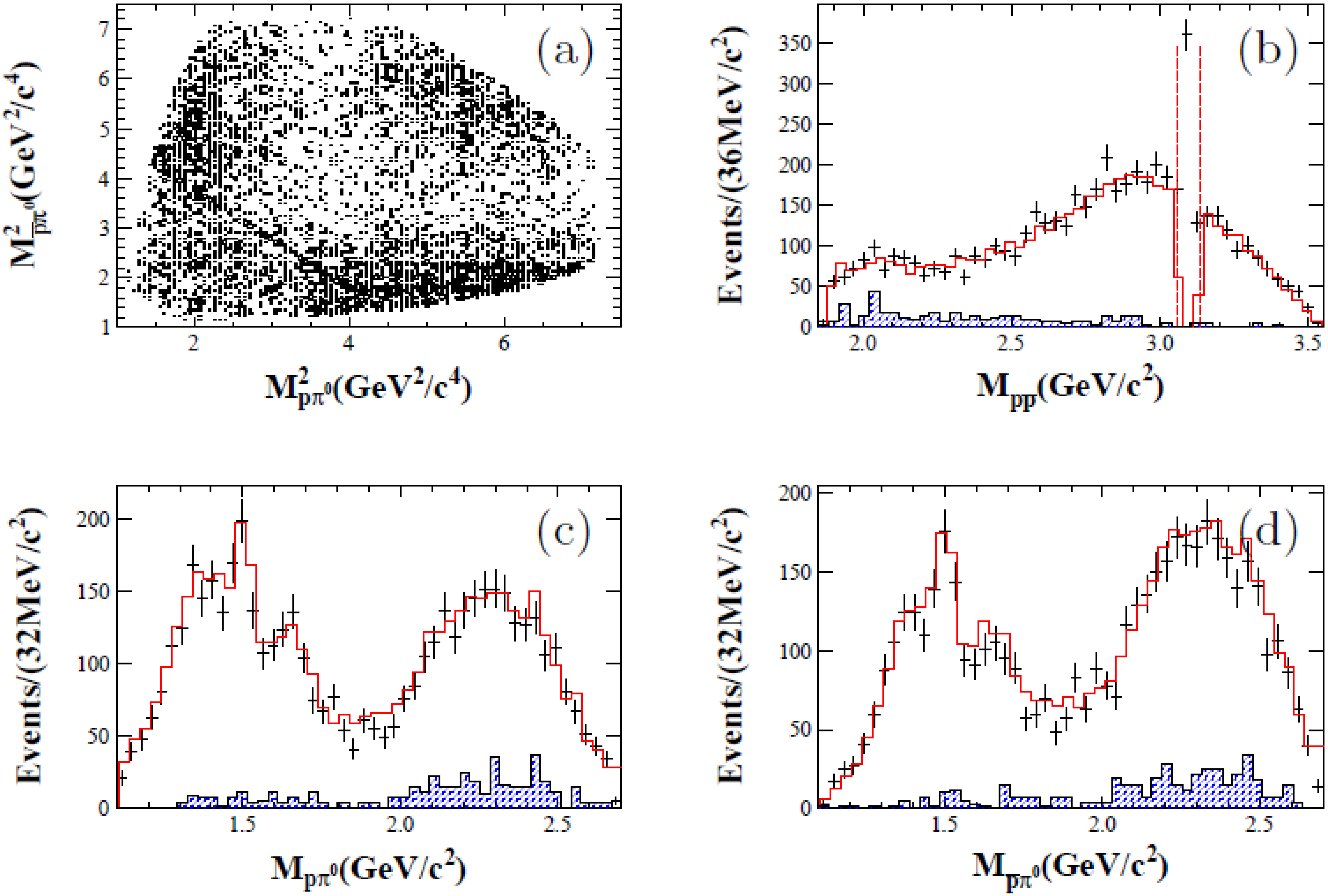
$$A_{(3/2)^+} = \bar{u}(\kappa_2, s_2)\kappa_{2\mu}P^{\mu\nu}_{3/2}(c_1 g_{\nu\lambda} + c_2\kappa_{1\nu}\gamma_\lambda + c_3\kappa_{1\nu}\kappa_{1\lambda})\gamma_5 v(\kappa_1, s_1)\psi^\lambda, \quad (4)$$

where $u(\kappa_2, s_2)$ and $v(\kappa_1, s_1)$ are $\frac{1}{2}$-spinor wave functions for N and $\bar{N}$, respectively; ψ^λ is the spin-1 wave function, i.e., the polarization vector for J/ψ. The c_1, c_2, and c_3 terms correspond to three possible couplings for the $J/\psi \to \bar{N}N^*(\frac{3}{2}^+)$ vertex. They can be taken as constant parameters or as smoothly varying vertex form factors. The spin $\frac{3}{2}^+$ propagator $P^{\mu\nu}_{3/2+}$ for $N^*(\frac{3}{2}^+)$ is

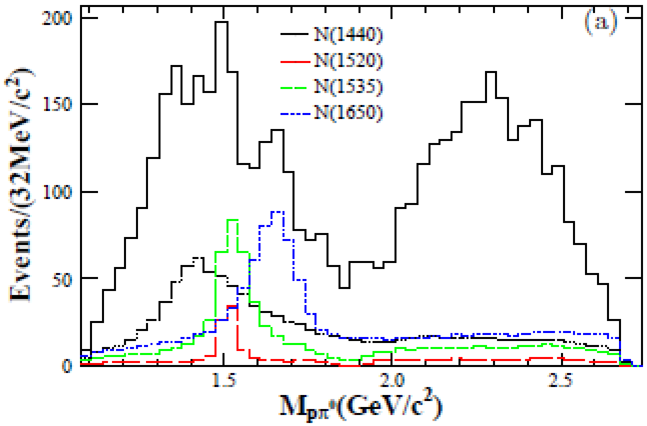
$$P^{\mu\nu}_{3/2+} = \frac{\gamma \cdot p + M_{N^*}}{M^2_{N^*} - p^2 + iM_{N^*}\Gamma_{N^*}}\left[g^{\mu\nu} - \frac{1}{3}\gamma^\mu\gamma^\nu - \frac{2p^\mu p^\nu}{3M^2_{N^*}} + \frac{p^\mu\gamma^\nu - p^\nu\gamma^\mu}{3M_{N^*}}\right], \quad (5)$$

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

BESIII Phys.Rev.Lett. 110 (2013) 022001



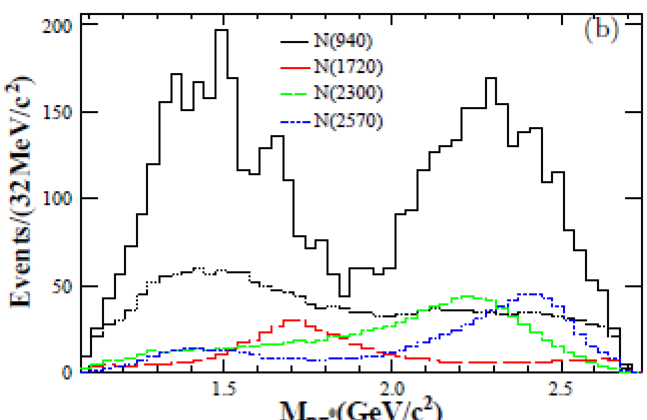
PWA of $\psi' \rightarrow \pi^0 p\bar{p}$



BESIII, Phys.Rev.Lett. 110 (2013) 022001

2 New N* are found (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
$N(2300)$	$2300^{+40+109}_{-30-0}$	$340^{+30+110}_{-30-58}$	120.7	4	15.0σ
$N(2570)$	2570^{+19+34}_{-10-10}	250^{+14+69}_{-24-21}	78.9	6	11.7σ



The energy dependent width BW for

$$\Gamma_{N(1440)} \rightarrow \Gamma_{N(1440)}\left(0.7\frac{B_1(q_{\pi N})\rho_{\pi N}(s)}{B_1(q_{\pi N}^{N*})\rho_{\pi N}(M_{N*}^2)} + 0.3\frac{B_1(q_{\pi\Delta})\rho_{\pi\Delta}(s)}{B_1(q_{\pi\Delta}^{N*})\rho_{\pi\Delta}(M_{N*}^2)}\right)$$

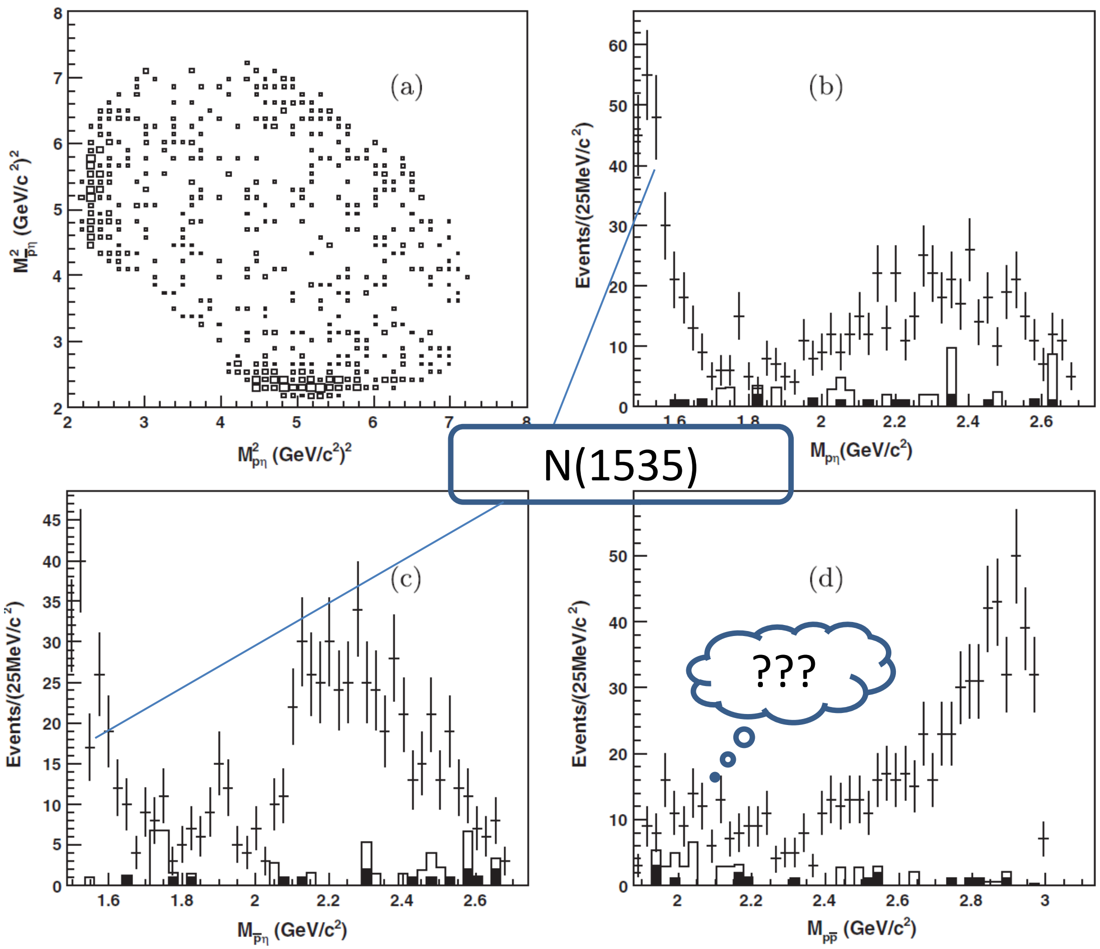
$$\Gamma_{N(1520)} \rightarrow \Gamma_{N(1520)}\frac{B_2(q_{\pi N})\rho_{\pi N}(s)}{B_2(q_{\pi N}^{N*})\rho_{\pi N}(M_{N*}^2)}$$

$$\Gamma_{N(1535)} \rightarrow \Gamma_{N(1535)}\left(0.5\frac{\rho_{\pi N}(s)}{\rho_{\pi N}(M_{N*}^2)} + 0.5\frac{\rho_{\eta N}(s)}{\rho_{\eta N}(M_{N*}^2)}\right)$$

The other N* use constant width BW

PWA of $\psi' \to \eta p\bar{p}$

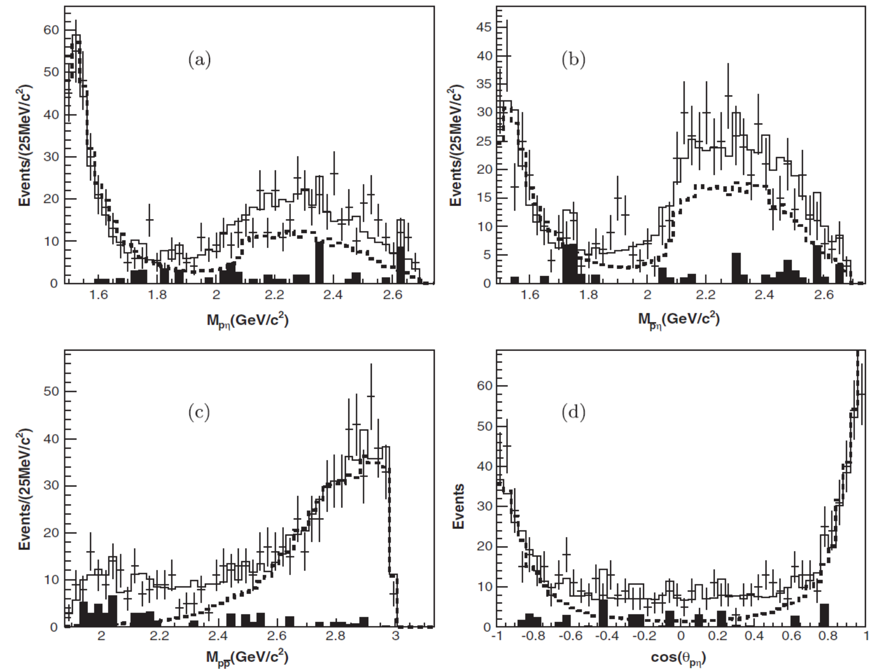
BESIII Phys.Rev. D88, 032010 (2013)



PWA of $\psi' \to \eta p\bar{p}$

BESIII PRD 88, 032010 (2013)

- N(1535) and PHSP(1/2-) are dominant
- No evidence for a $p\bar{p}$ resonance



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$/c^2$

Branching fraction:

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

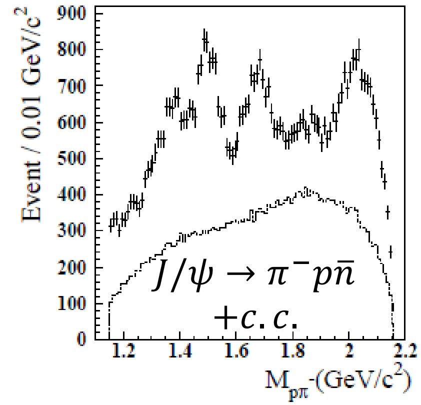
* For N(1535)

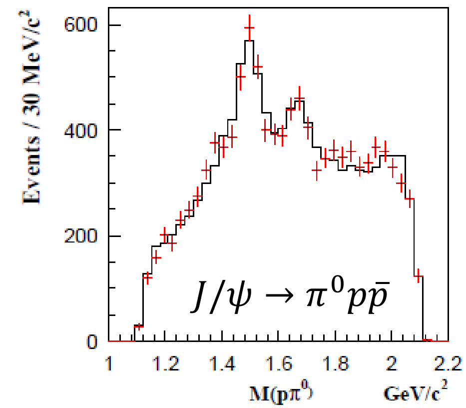
$$\mathrm{BW}(s) = \frac{1}{M^2_{N^*} - s - iM_{N^*}\Gamma_{N^*}(s)}$$

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

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

Summary of N*'s @ BES



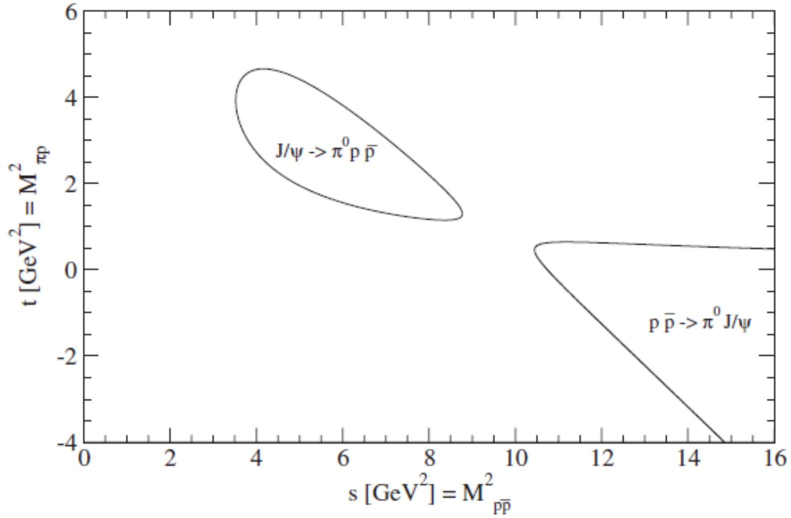


Modified from
Rept.Prog.Phys. 76 (2013) 076301
by V. Crede and W. Roberts

N*	PDG Rating (2014)	J/ψ			ψ'	
		$\pi^0 p\bar{p}$	$\pi^- p\bar{n} + c.c.$	$\eta p\bar{p}$	$\pi^0 p\bar{p}$	$\eta p\bar{p}$
N(1440)1/2+	****	**BES2**	**BES2**	**BES1**	**BES3**	
N(1520)3/2-	****	**BES2**			**BES3**	**BES3**
N(1535)1/2-	****	**BES2**		**BES1**	**BES3**	
N(1650)1/2-	****	**BES2**		**BES1**	**BES3**	
N(1710)1/2+	***	**BES2**				
N(1720)3/2+	****				**BES3**	
N(2040)3/2+	*	**BES2**	**BES2**			
N(2300)1/2+	**				**BES3**	
N(2570)5/2-	**				**BES3**	

Estimating cross sections of $\bar{p}p \to m\,\Psi$ from decay widths

PRD 73 096003 A. Lundborg, T. Barnes, U. Wiedner



- Cross Section Measurement of $e^+e^- \to \bar{p}p\pi^0$ at center-of-mass energies between 4.009 and 4.60 GeV, PLB 771 45 (2017)
  - [The upper limit on the Born cross section of $e^+e^- \to Y(4260) \to \bar{p}p\pi^0$ are given]

- Study of $e^+e^- \to \bar{p}p\pi^0$ in the Vicinity of the ψ(3770), PRD 90 032007 (2014)

Summary and outlook

- **The decays of charmonium provide a good laboratory for studying excited nucleons and hyperons**
  - **BESIII collected 0.6×10^9 ψ' and 1.3×10^9 J/ψ (and a lot of χ_c, η_c). The goal is to have 10^{10} J/ψ**
- **BEPCII/BESIII reach a new territory to charmed baryons**
  - **BESIII is unique to study charmed baryons, and is complementary to others experiments**
  - **The funding of BEPCII upgrade for increasing beam energy has been granted**

More results are expected…

Thank you for your attention