

E_c Spectroscopy at Belle

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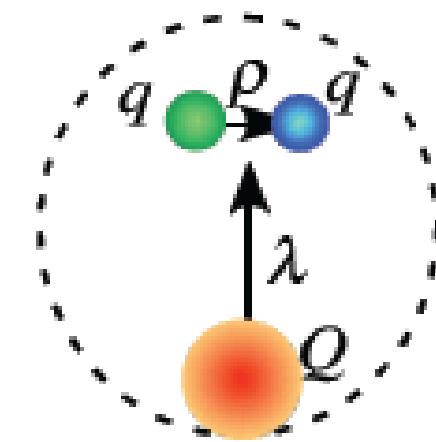
Reimei Workshop@Inha U.



Introduction – Heavy quark baryons

- **Heavy quark in Baryon**

- Bare quark \doteq constituent quark
- Makes a “static core”, light quarks play around
 \rightarrow Diquark correlation enhanced?
- New symmetry – heavy quark symmetry
 \rightarrow Hyperfine doublet for heavy quark spin.

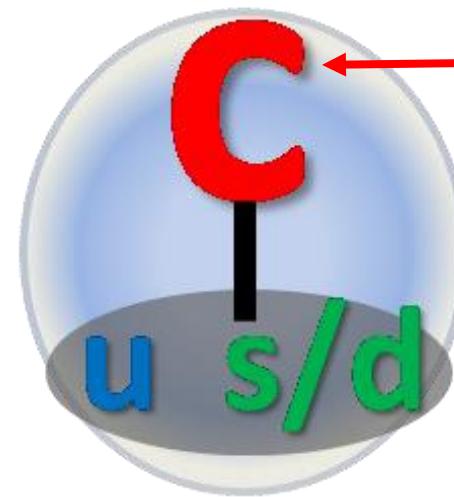


Nucleon



Indistinguishable pairs

Charmed baryon

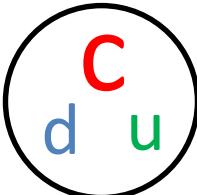
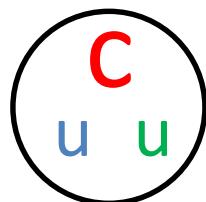


HQS: spin
Approximately
conserved

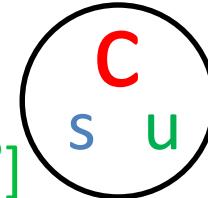
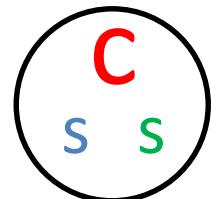
Light di-quark with inert charm?

Observed charmed baryons

Λ_c^+	$(1/2^+)$	$\Sigma_c(2455)$ ($1/2^+$)	Ξ_c	$(1/2^+)$	Ω_c	$(1/2^+)$
$\Lambda_c(2595)^+$	$1/2^-$	$\Sigma_c(2520)$ ($3/2^+$)	Ξ'_c	$(1/2^+)$	$\Omega_c(2770)$ ($3/2^+$)	
$\Lambda_c(2625)^+$	$(3/2^-)$	$\Sigma_c(2800)$??	$\Xi_c(2645)$	$(3/2^+)$		
$[\Lambda_c(2765)^+]$??]		$\Xi_c(2790)$	$(1/2^-)$		
$\Lambda_c(2880)^+$	$5/2^+$		$\Xi_c(2815)$	$(3/2^-)$		
$\Lambda_c(2940)^+$??		$[\Xi_c(2930)]$??]		
			$\Xi_c(2980)$??		
			$\Xi_c(3055)$??		
			$\Xi_c(3080)$??		
			$[\Xi_c(3123)]$??]		

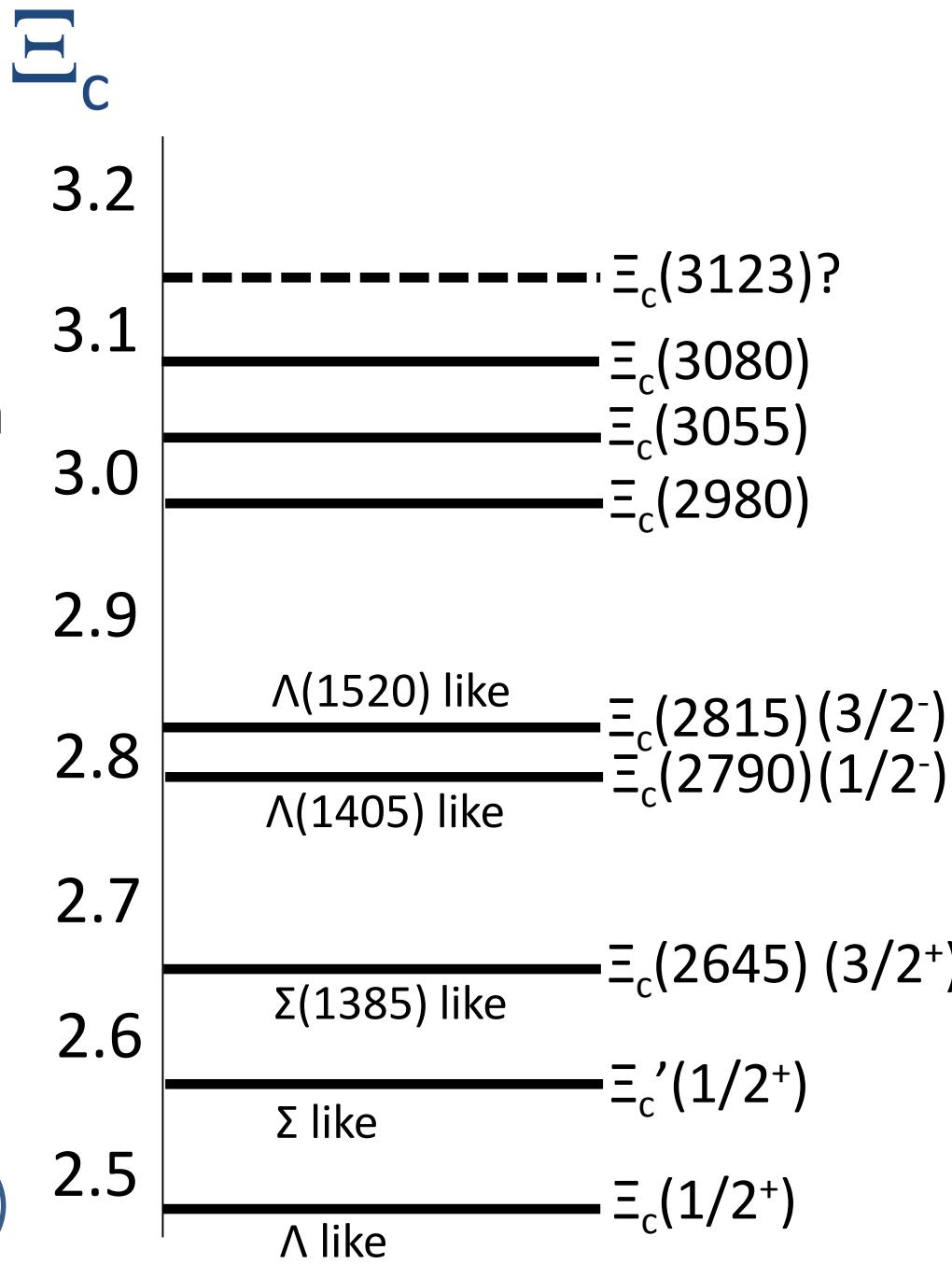
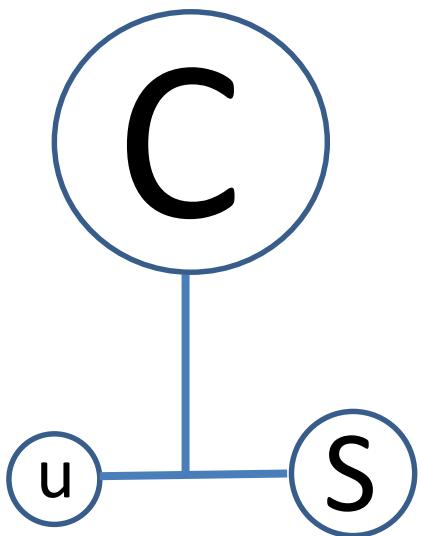


CLEO 8(7) (1995~2001)
 BELLE 3 (2006~)
 BABAR 5(2) (2007~)

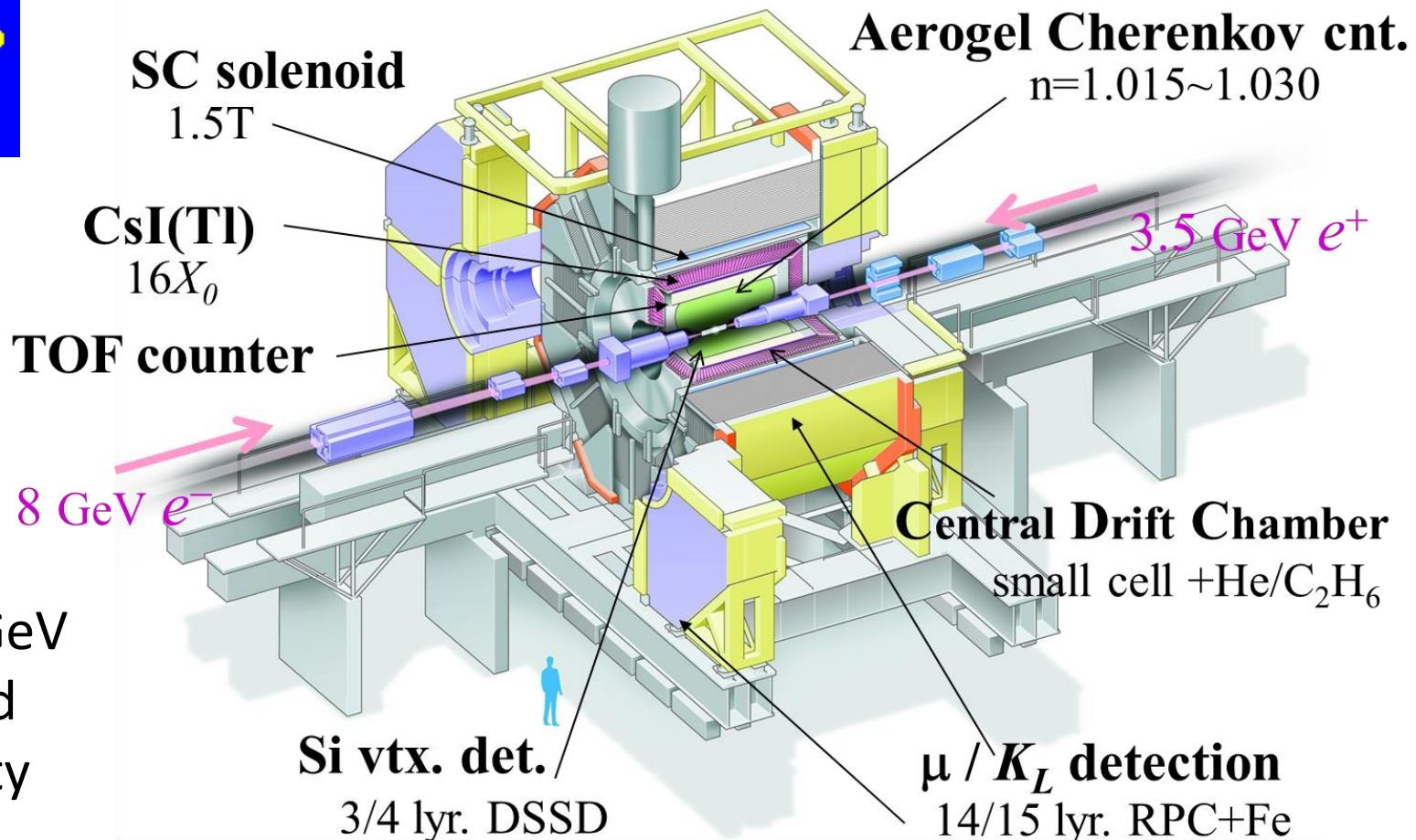


- Good description by quark model for low-lying states up to L=1.
- Higher excited states observed, but no established identification
 - Spin-parity? λ/ρ mode excitation? Exotics?
- Precisions are still poor.

- New feature
 - All 3 quarks have different masses
 - flavor symmetry broken
- Many states with different configurations
- interesting playground



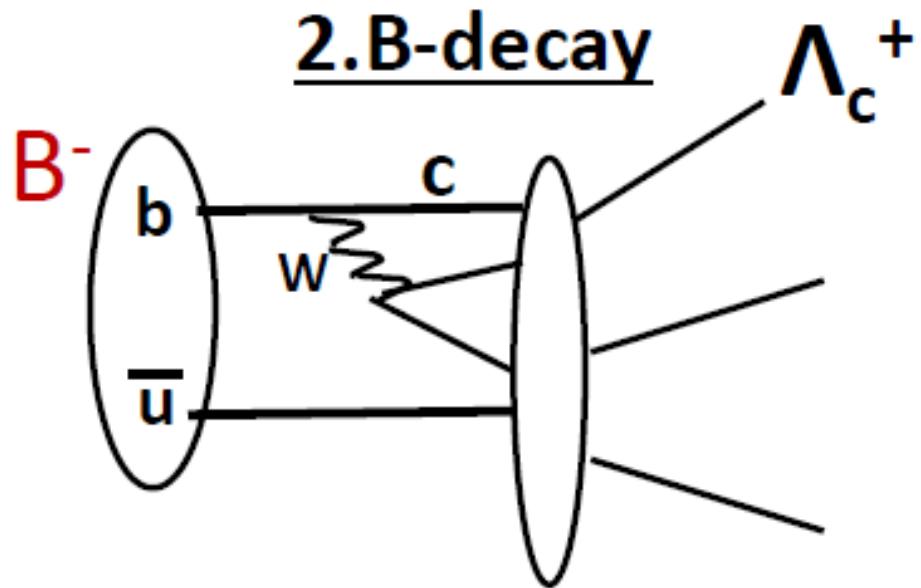
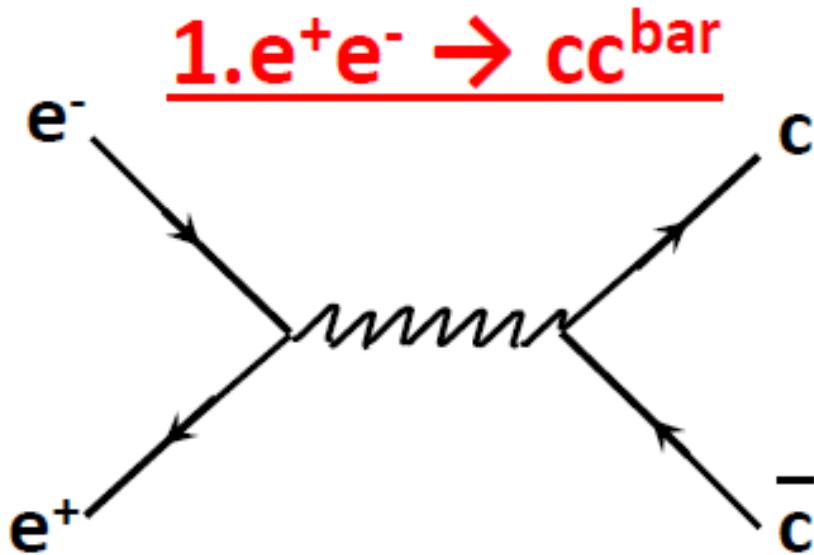
Belle experiment



- $\sqrt{s}\sim 10.6$ GeV
- Integrated Luminosity $> 1 \text{ ab}^{-1}$

Almost 4π , good momentum resolution ($\Delta p/p \sim 0.1\%$), EM calorimeter, PID & Si Vertex detector

Charm production in B factory



Production is flavor blind,
only q^2 matters

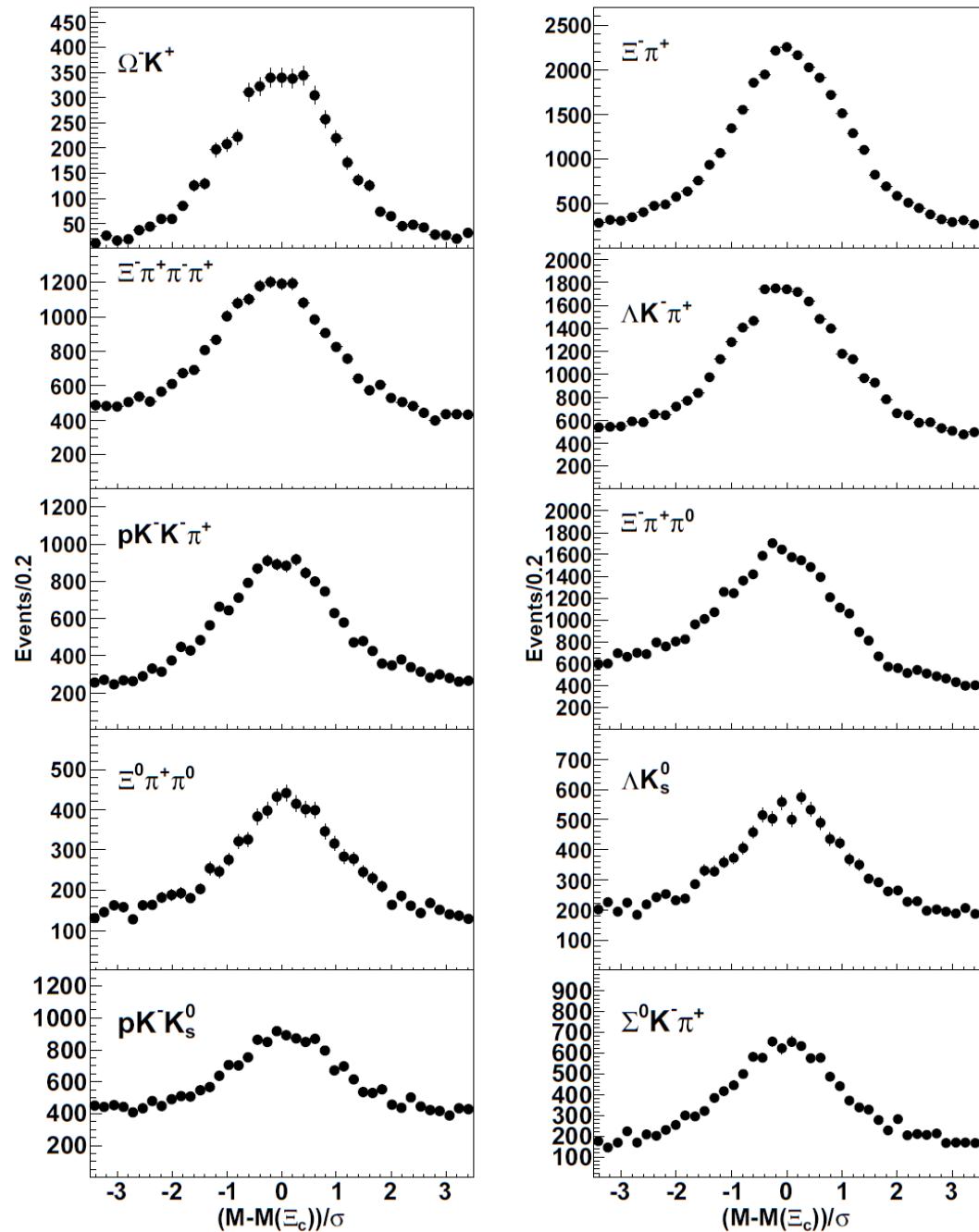
Baryons produced via
fragmentation

B is efficiently produced via
 $Y(4s)$

Once bottom is produced, it
favorably decays into charm.
 $BR(B \rightarrow \Lambda_c X) \sim 5\%$

Ξ_c signals

- 10 modes for Ξ_c^0
- 7 modes for Ξ_c^+
- Large statistics with good S/N ratio
 - $O(10^5)$ reconstructed

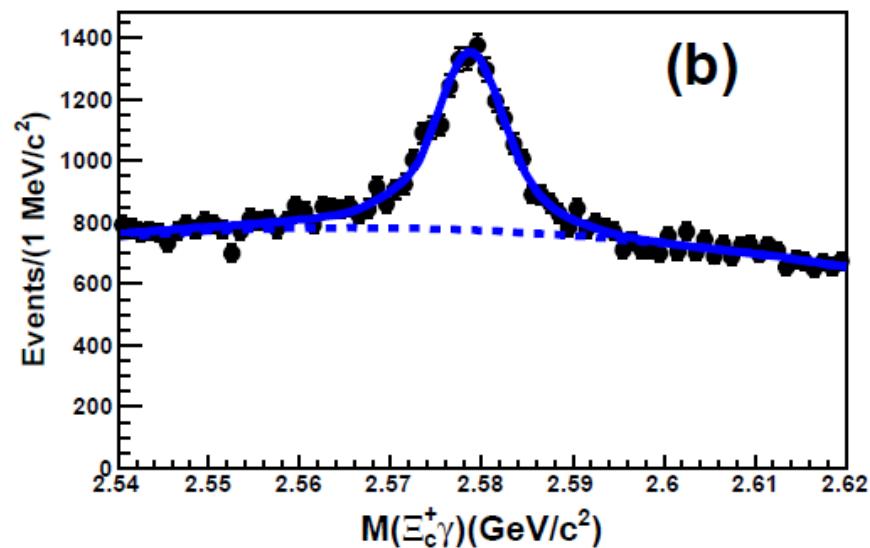
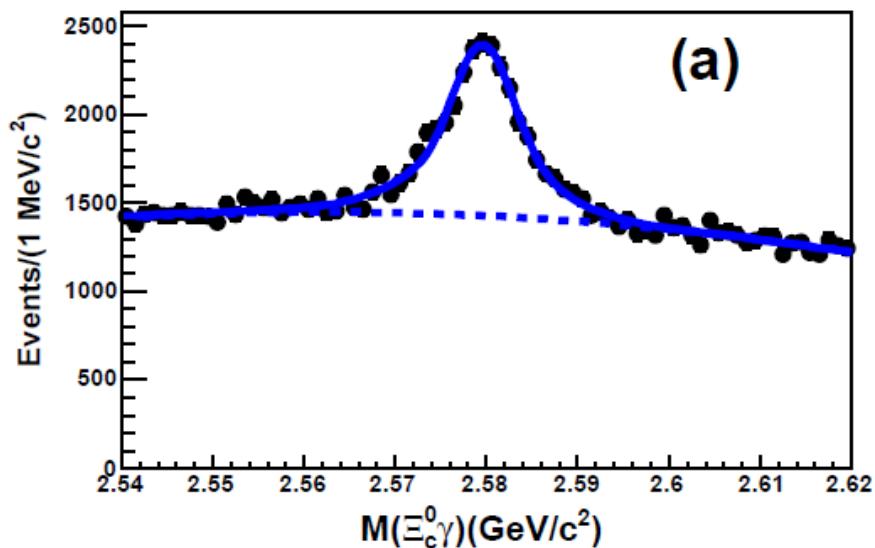


Measurements

- Various Ξ_c resonances are observed in $\Xi_c\pi$, $\Xi_c\pi\pi$, $\Lambda_c K\pi$, and ΛD .
- Masses & widths are precisely determined for 7 states:
 $\Xi'_c(2580)$, $\Xi_c(2645)$, $\Xi_c(2790)$, $\Xi_c(2815)$, $\Xi_c(2980)$,
 $\Xi_c(3055)$, and $\Xi_c(3080)$
 - Fundamental information to identify the nature of these states.
 - Significant mass difference in isodoublets observed.

$\Xi_c'(2580)$

$\Sigma_c(2455)$ analog, $J^P=1/2^+$

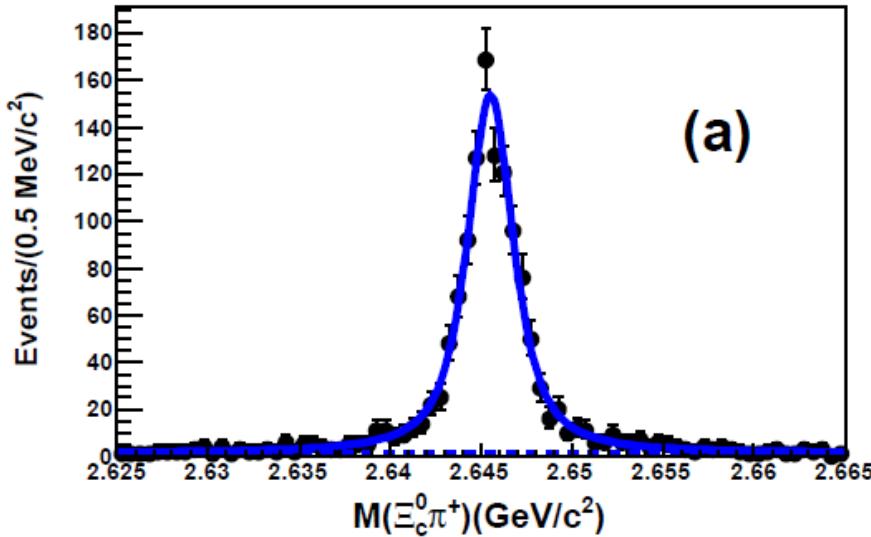


- Mass: $\Xi_c'^+$: $2578.4 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$
 $[\text{MeV}]$ $\Xi_c'^0$: $2579.2 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$

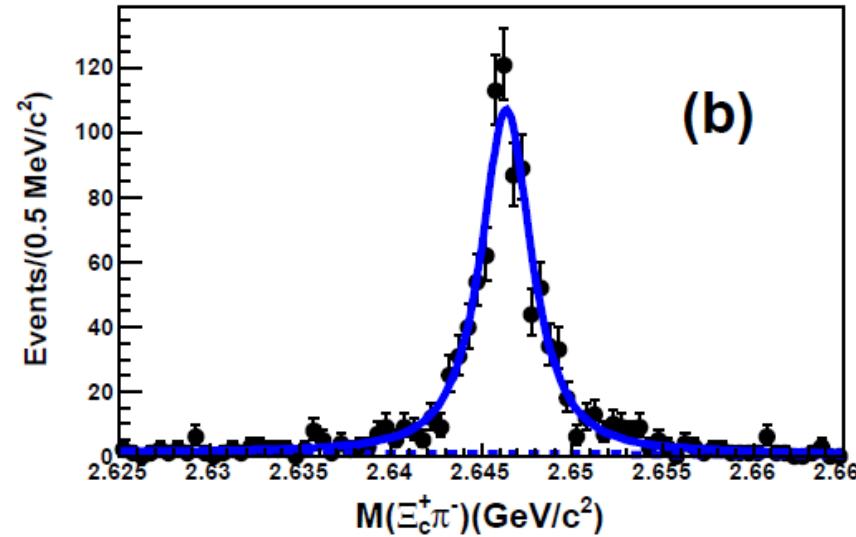
$$\Delta M = 0.8 \text{ MeV}$$

$\Xi_c(2645)$

$\Sigma_c^*(2520)$ analog, $J^P=3/2^+$



(a)



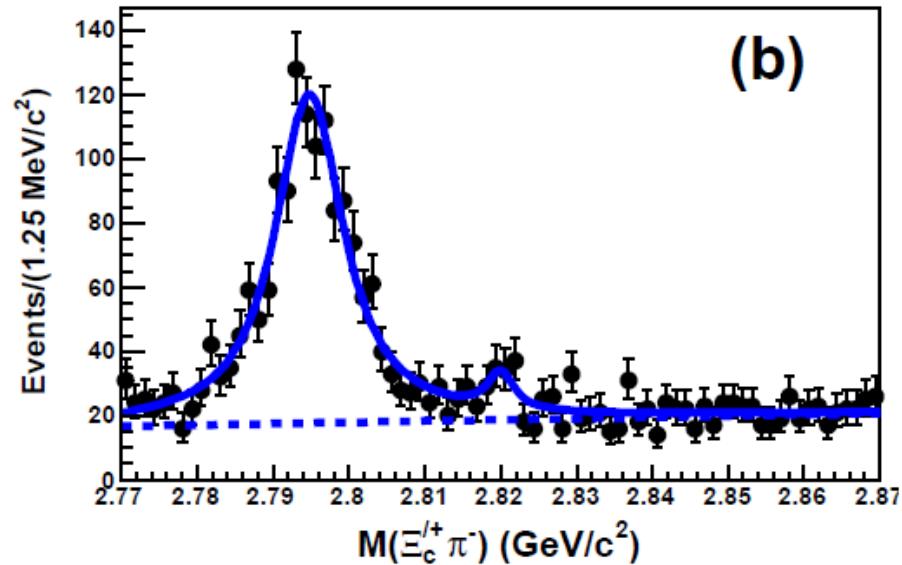
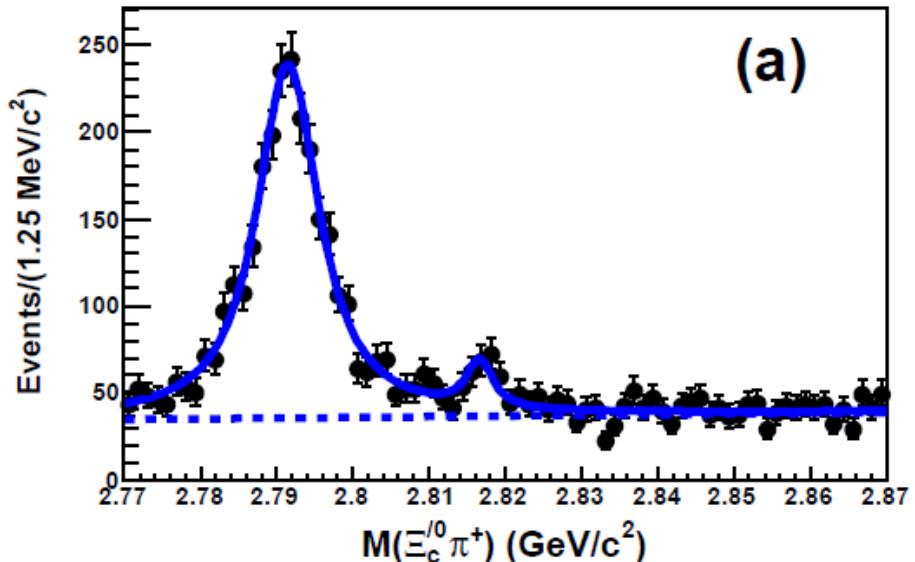
(b)

$$\Delta M = 0.8 \text{ MeV}$$

- Mass: $\Xi_c(2645)^+ : 2645.58 \pm 0.06 \pm 0.07^{+0.28}_{-0.40}$
 $\Xi_c(2645)^0 : 2646.43 \pm 0.07 \pm 0.07^{+0.28}_{-0.40}$
- Width: $\Xi_c(2645)^+ : 2.06 \pm 0.13 \pm 0.13$
 $\Xi_c(2645)^0 : 2.35 \pm 0.18 \pm 0.13$

$\Xi_c(2790)$

$\Lambda_c(2593)$ analog, $J^P=1/2^-$

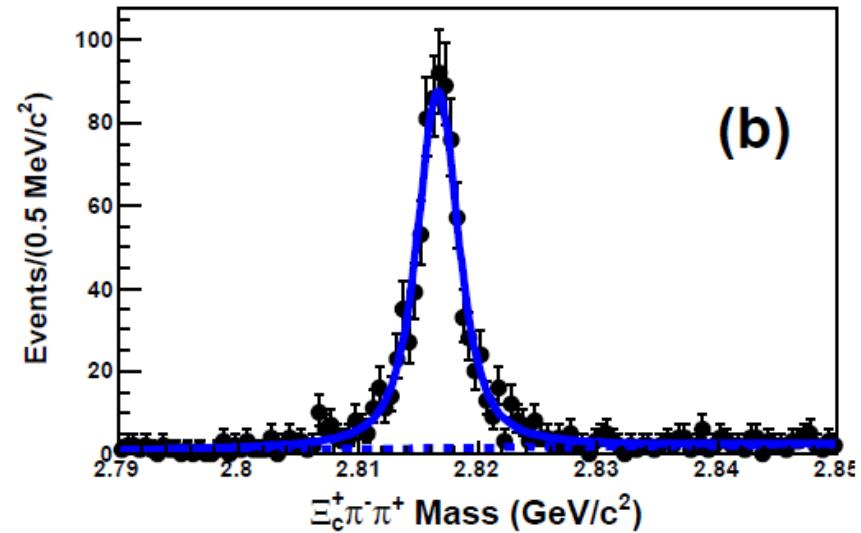
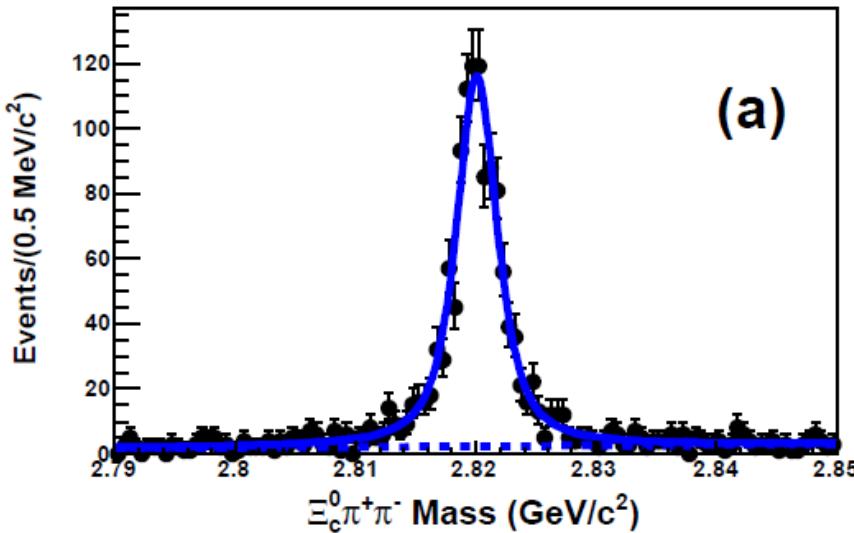


$$\Delta M = 3.3 \text{ MeV}$$

- Mass: $\Xi_c(2790)^+ : 2791.6 \pm 0.2 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$
 $\Xi_c(2790)^0 : 2794.9 \pm 0.3 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$
- Width: $\Xi_c(2790)^+ : 8.9 \pm 0.6 \pm 0.8$
 $\Xi_c(2790)^0 : 10.0 \pm 0.7 \pm 0.8$

$\Xi_c(2815)$

$\Lambda_c(2620)$ analog, $J^P=3/2^-$



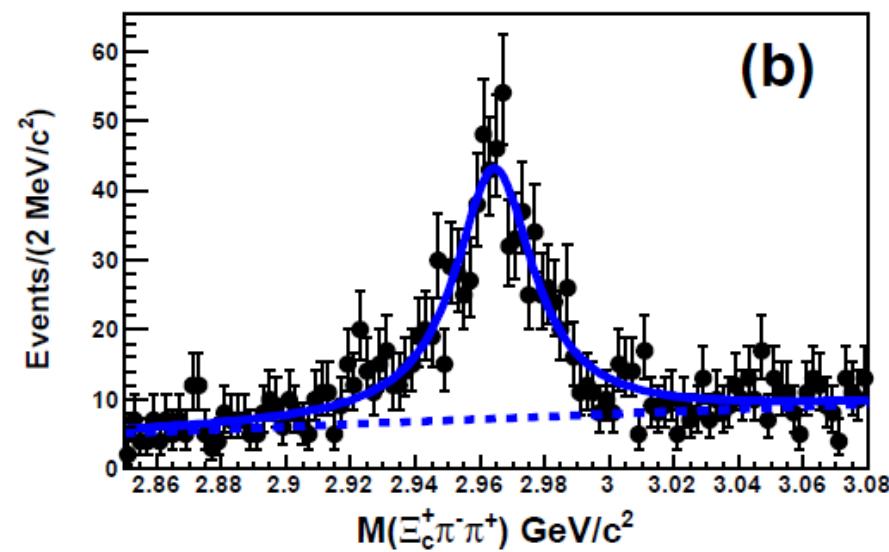
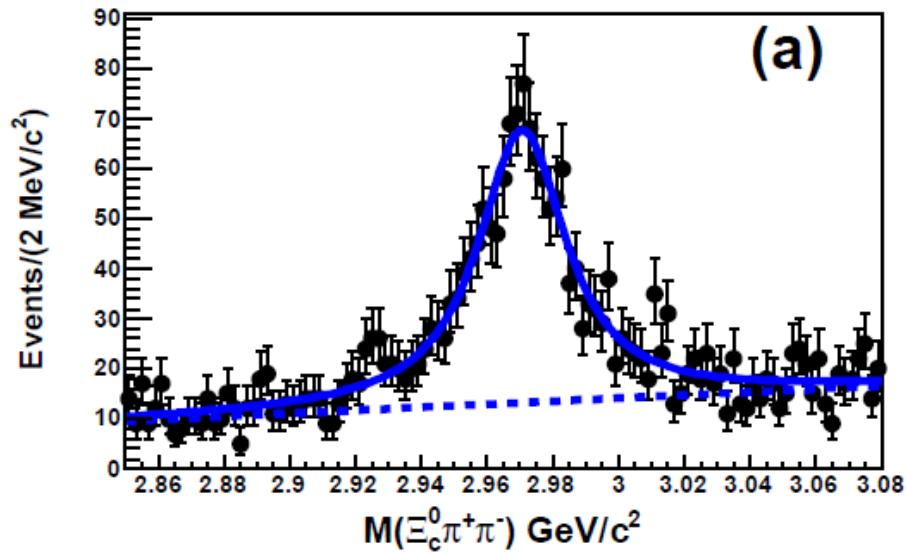
$$\Delta M = 3.5 \text{ MeV}$$

- Mass: $\Xi_c(2815)^+ : 2816.73 \pm 0.08 \pm 0.06^{+0.28}_{-0.40}$
 $\Xi_c(2815)^0 : 2820.20 \pm 0.08 \pm 0.07^{+0.28}_{-0.40}$
- Width: $\Xi_c(2815)^+ : 2.43 \pm 0.20 \pm 0.17$
 $\Xi_c(2815)^0 : 2.54 \pm 0.18 \pm 0.17$

– First observation of finite width

$\Xi_c(2980)$

$\Lambda_c(2765)$ analog??



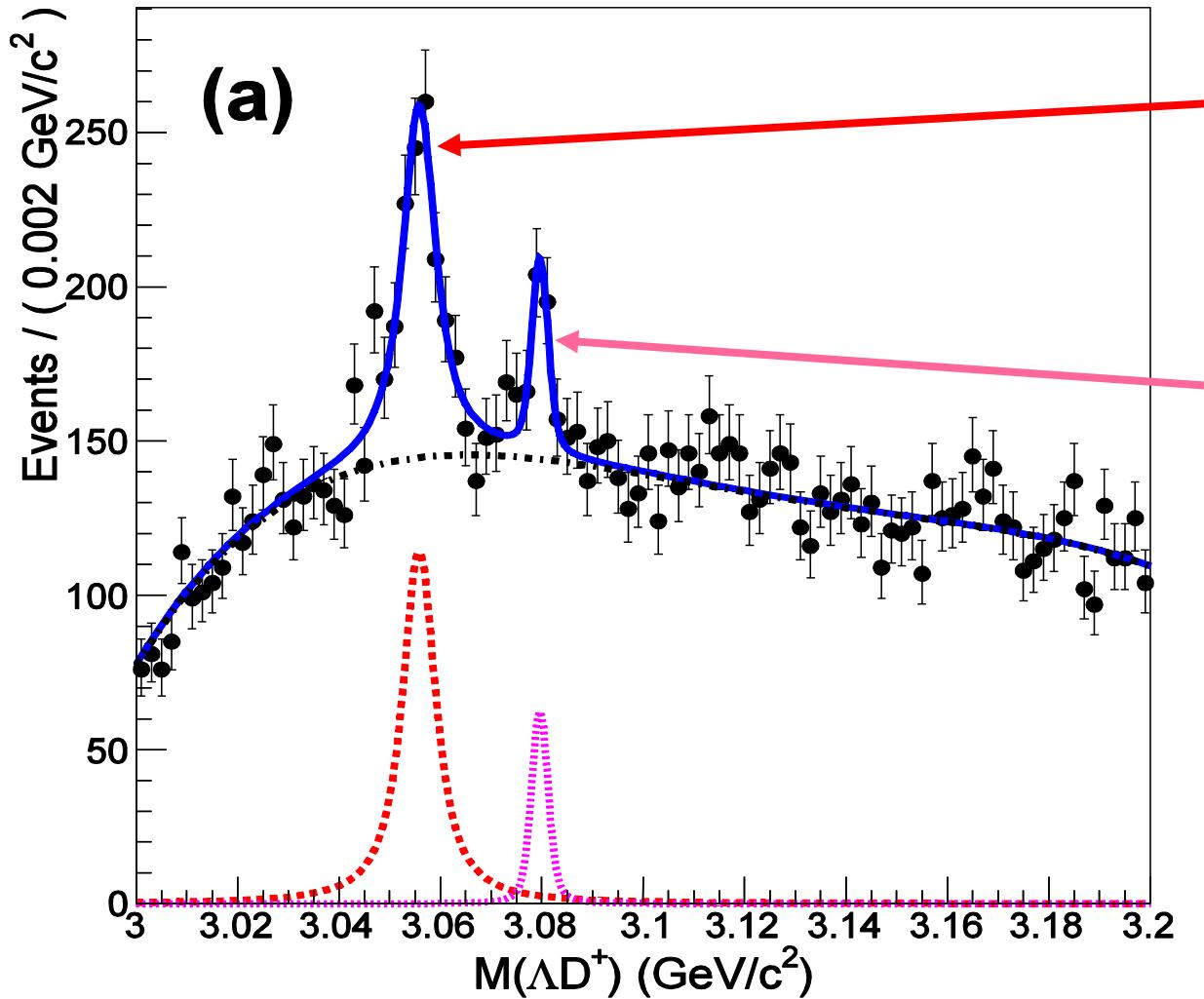
- Mass: $\Xi_c(2980)^+ : 2966.0 \pm 0.8 \pm 0.2^{+0.3}_{-0.4}$
 $\Xi_c(2980)^0 : 2670.8 \pm 0.7 \pm 0.2^{+0.3}_{-0.4}$
- Width: $\Xi_c(2980)^+ : 28.1 \pm 2.4^{+1.0}_{-5.0}$
 $\Xi_c(2980)^0 : 30.3 \pm 2.3^{+1.0}_{-1.8}$

$$\Delta M = 4.8 \text{ MeV}$$

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 $\Xi_c(3055)$, and $\Xi_c(3080)$
- New observations in ΛD mode:
 - $\Xi_c(3055)^0$ is newly discovered
 ΛD modes are firstly observed for $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$

Ξ_c^+ in ΛD^+ mode

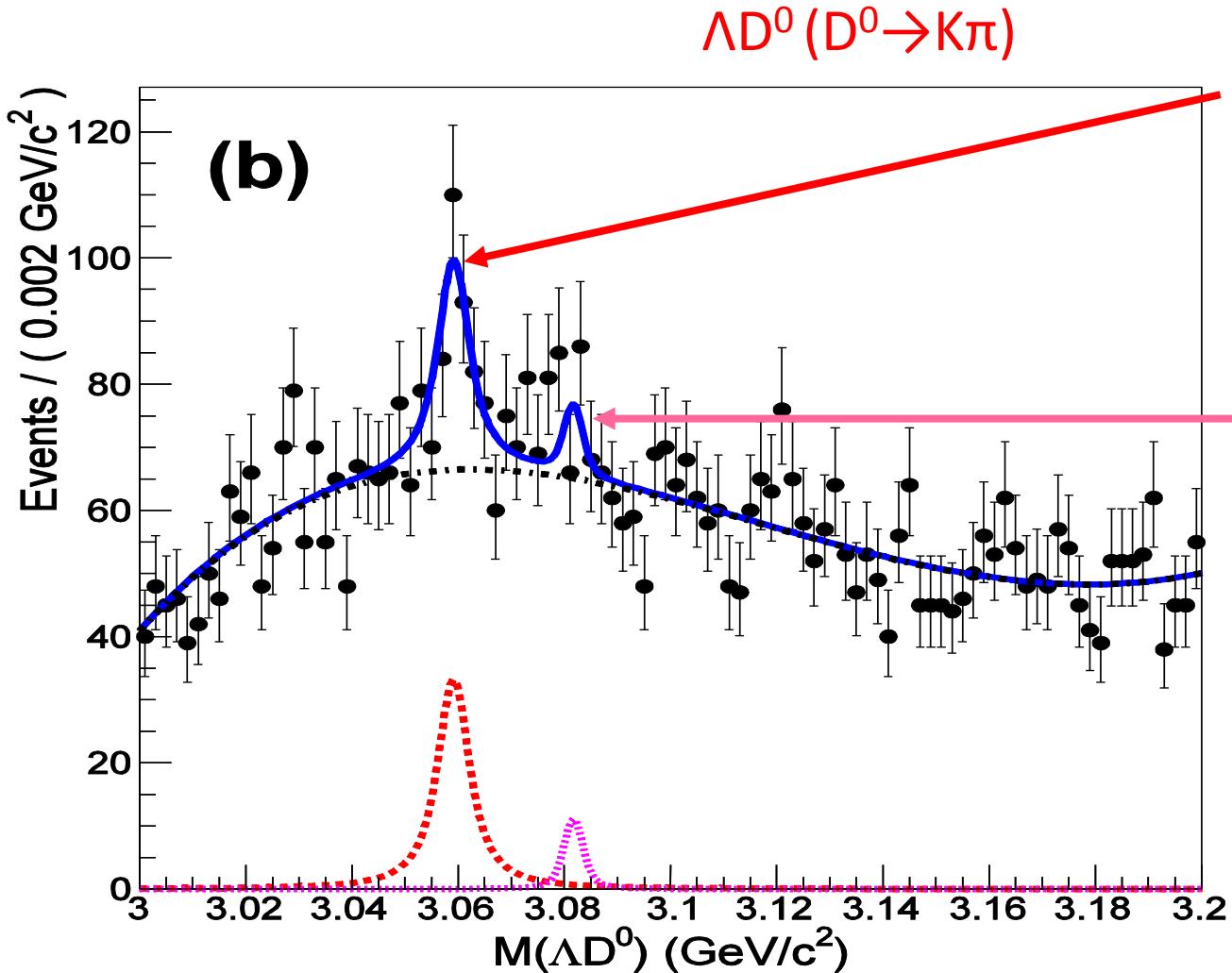


Large $\Xi_c(3055)^+$
significance 11.7σ

Small $\Xi_c(3080)^+$
significance 4.8σ

First observation of
these decay modes

Ξ_c^0 in ΛD^0 mode



$\Xi_c(3055)^0$
significance 8.6σ
(combined with other
decay modes of D^0)

$\Xi_c(3080)^0$
not significant

First observation of
 $\Xi_c(3055)^0$

Mass difference in isodoublets

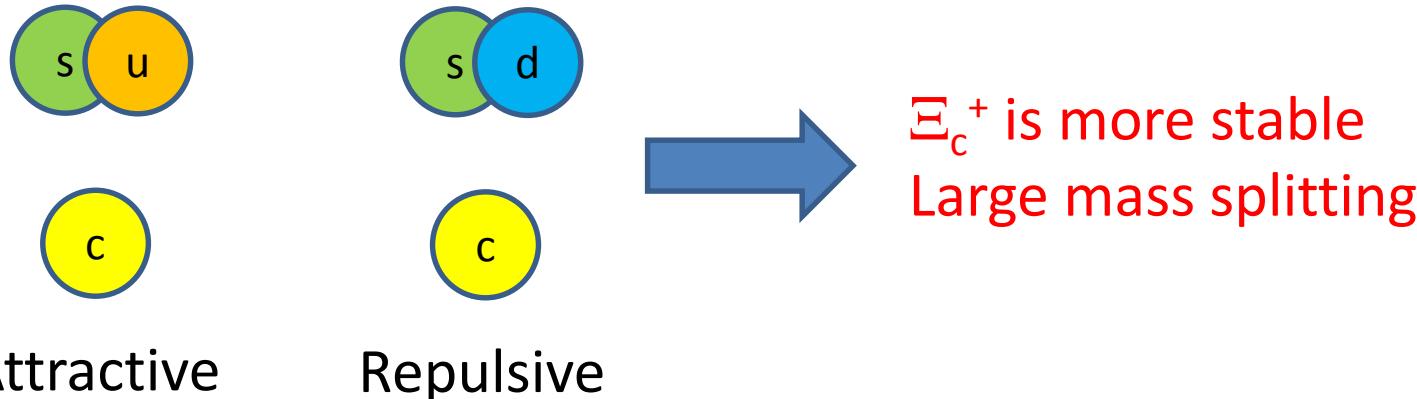
	Analog state/ J^P	$M(\Xi_c^0) - M(\Xi_c^+)$ (MeV)
Ξ_c (g.s.)	Λ_c $1/2^+$	2.93 ± 0.24
$\Xi'_c(2580)$	$\Sigma_c(2455)$, $1/2^+$	0.8 ± 0.5
$\Xi_c^*(2645)$	$\Sigma_c(2520)$, $3/2^+$	0.9 ± 0.5
$\Xi_c(2790)$	$\Lambda_c(2593)$, $1/2^-$	3.3 ± 0.7
$\Xi_c(2815)$	$\Lambda_c(2625)$, $3/2^-$	3.5 ± 0.5
$\Xi_c(2980)$?	4.8 ± 0.6
$\Xi_c(3055)$?	3.2 ± 0.9

Small mass difference ($\lesssim 1$ MeV) for Σ_c analog states
Larger mass difference (~ 3 MeV) for the others

Carries information on wavefunction

Interpretation in diquark picture

- When us/ds is a “good diquark” → Coulomb effect is large



- “Bad diquark” → Small mass splitting
 - Case for Ξ'_c & Ξ^*_c → Supportive for diquark picture
- Should be different for λ/ρ excitation, too.
 - ρ -mode → diquark is broken → small splitting
 - λ -mode → small interaction between c and u/d/s → large splitting
- $\Xi_c(2980)$, $\Xi_c(3050)$ – Λ_c analog with good diquark & λ mode excitation?

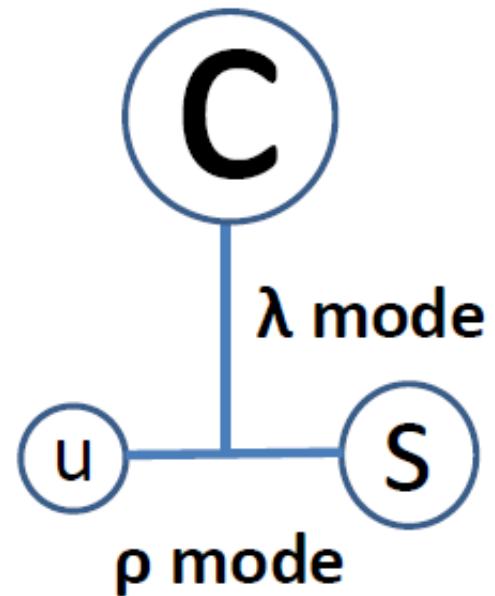
Measurements

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 $\Xi'_c(2580)$, $\Xi_c(2645)$, $\Xi_c(2790)$, $\Xi_c(2815)$, $\Xi_c(2980)$,
 $\Xi_c(3055)$, and $\Xi_c(3080)$
- New observations in ΛD mode:
 - $\Xi_c(3055)^0$ is newly discovered
 ΛD modes are firstly observed for $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$
 - Branching ratios of $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$ to $\Lambda D^+/\Sigma_c K$ mode are measured
→ Sensitive to structure of these states under heavy quark symmetry.

Branching ratios

PRD94, 032002 (2016)

- $B(\Xi_c(3055)^+ \rightarrow \Lambda D^+)/B(\Sigma_c^{++} K^-) = 5.09 \pm 1.01 \pm 0.76$
 $B(\Xi_c(3080)^+ \rightarrow \Lambda D^+)/B(\Sigma_c^{++} K^-) = 1.29 \pm 0.30 \pm 0.15$
 $B(\Xi_c(3080)^+ \rightarrow \Sigma_c^{*++} K^-)/B(\Sigma_c^{++} K^-) = 1.27 \pm 0.27 \pm 0.01$
- BR Reflects the structure of each resonance.
 - Naively, Large ΛD branching ratio suggests the excitation is in between c and us (λ mode), not in between s and u (ρ mode).
 - BR for heavy-quark spin doublet partner (e.g., from/to Σ_c^* and Σ_c) are related by heavy quark symmetry.
 - A challenge to theorists, together with mass & width



Analog state of $\Lambda_c(2880)$?

- Mass difference of low-lying Ξ_c and $\Lambda_c \sim 200$ MeV
 $\rightarrow \Xi_c(3080)$ is the analog of $\Lambda_c(2880)??$
- Branching ratio for $\Lambda_c(2880)$

$$B(\Lambda_c^* \rightarrow \Sigma_c^* \pi) / B(\Lambda_c^* \rightarrow \Sigma_c \pi) = 0.225 \pm 0.062 \pm 0.025$$
- The ratio is much larger for $\Xi_c(3080)$ Belle, PRL98 (2007) 262001
 - Must be similar (or even smaller for phase space) for analog states if HQS holds.
 - They are not analog?

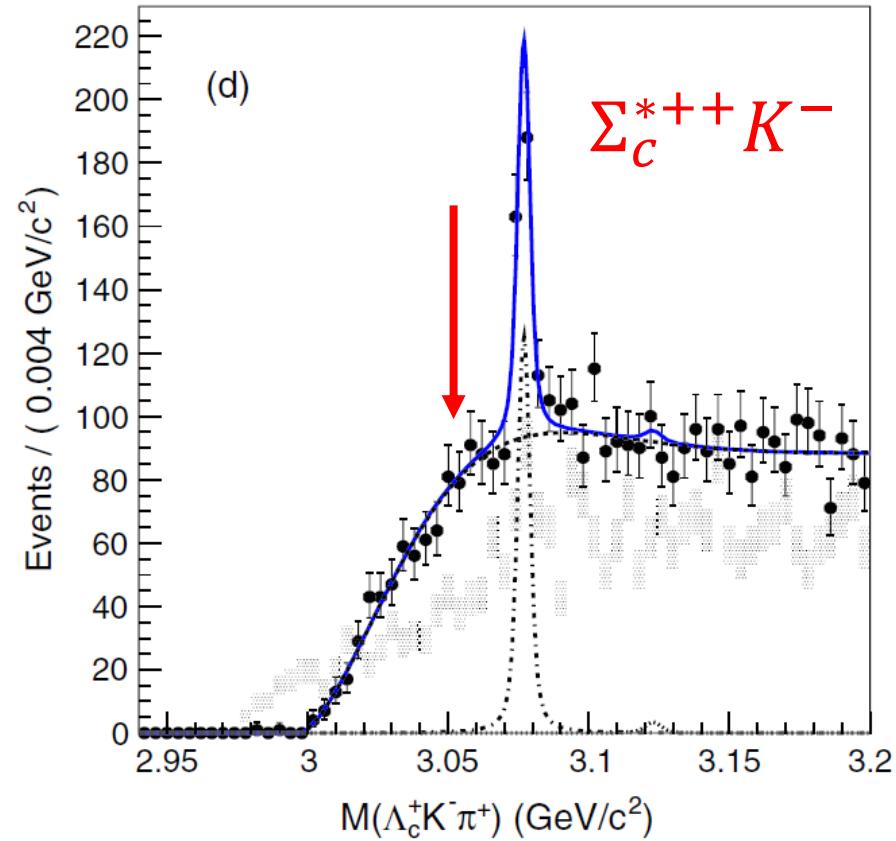
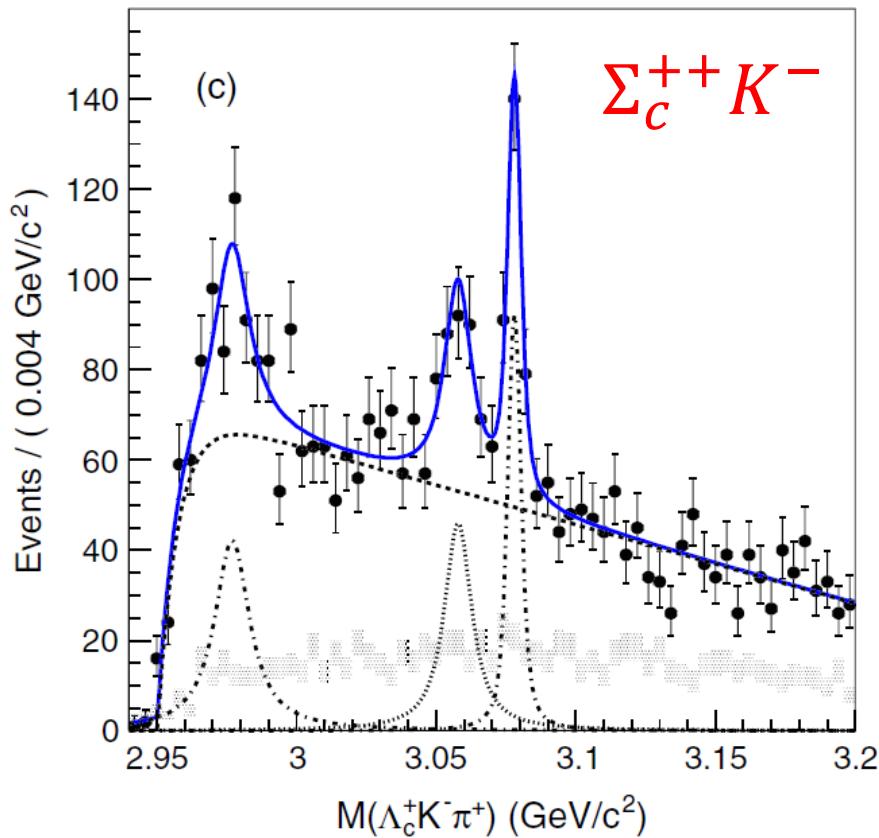
J^p	Λ_c^+	Ξ_c	$\Delta M(\text{Mev}/c^2)$	Note
$1/2^+$	$\Lambda_c(2286)^+$	$\Xi_c(2470)$	181	
$1/2^-$	$\Lambda_c(2595)^+$	$\Xi_c(2790)$	194	$\Lambda(1405)$ like
$3/2^-$	$\Lambda_c(2625)^+$	$\Xi_c(2815)$	188	$\Lambda(1520)$ like
??	$\Lambda_c(2765)^+??$	$\Xi_c(2980)??$	205	
$5/2^+$	$\Lambda_c(2880)^+$	$\Xi_c(3080)??$	200	

Analog state of $\Lambda_c(2880)$? (cont.)

$B(\Xi_c \rightarrow \Sigma_c^{*++} K^-)/B(\Sigma_c^{++} K^-)$ is small for $\Xi_c(3055)$

→ This may be the analog state of $\Lambda_c(2880)$

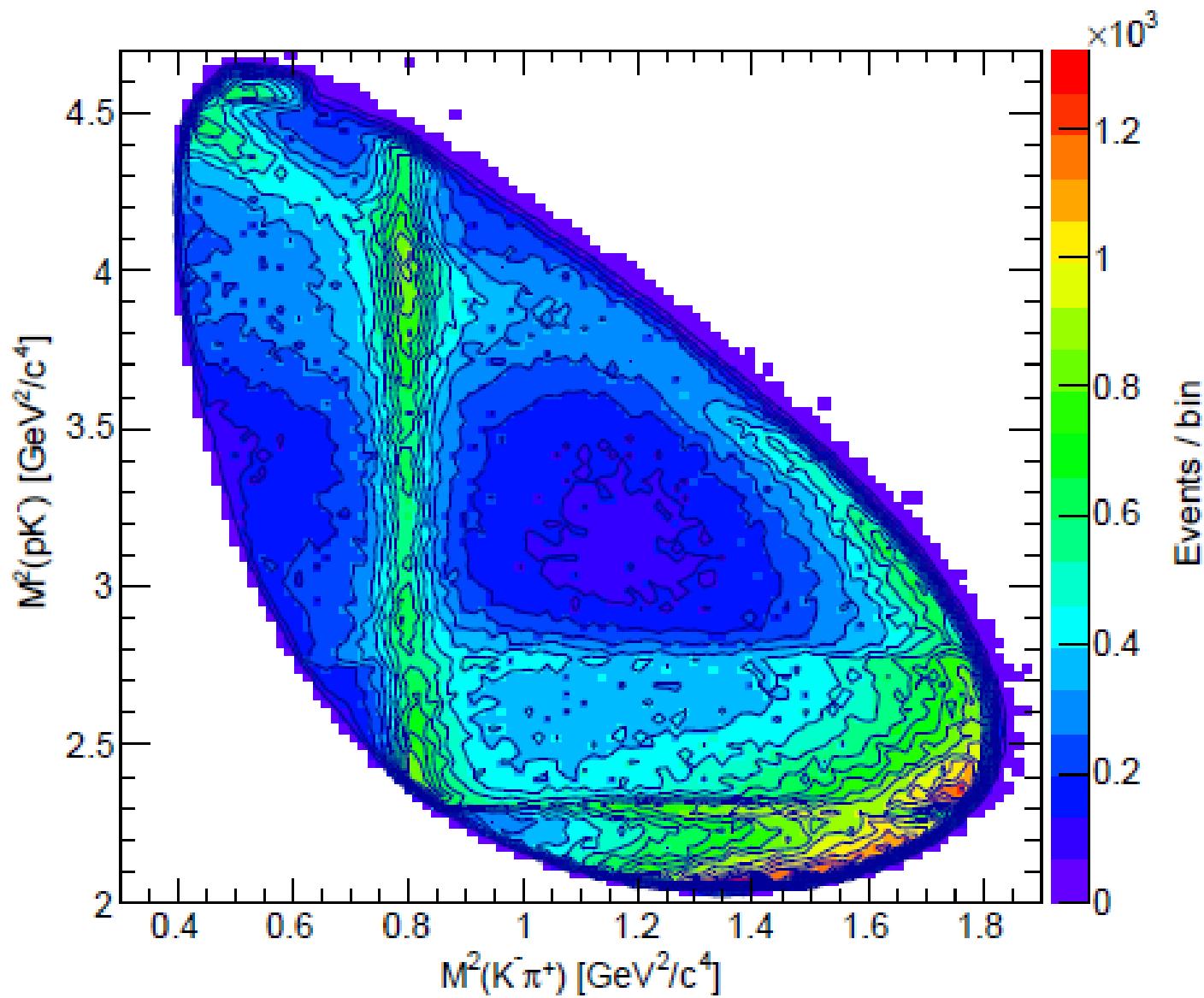
Belle, PRD 89, 052003



Summary & prospects

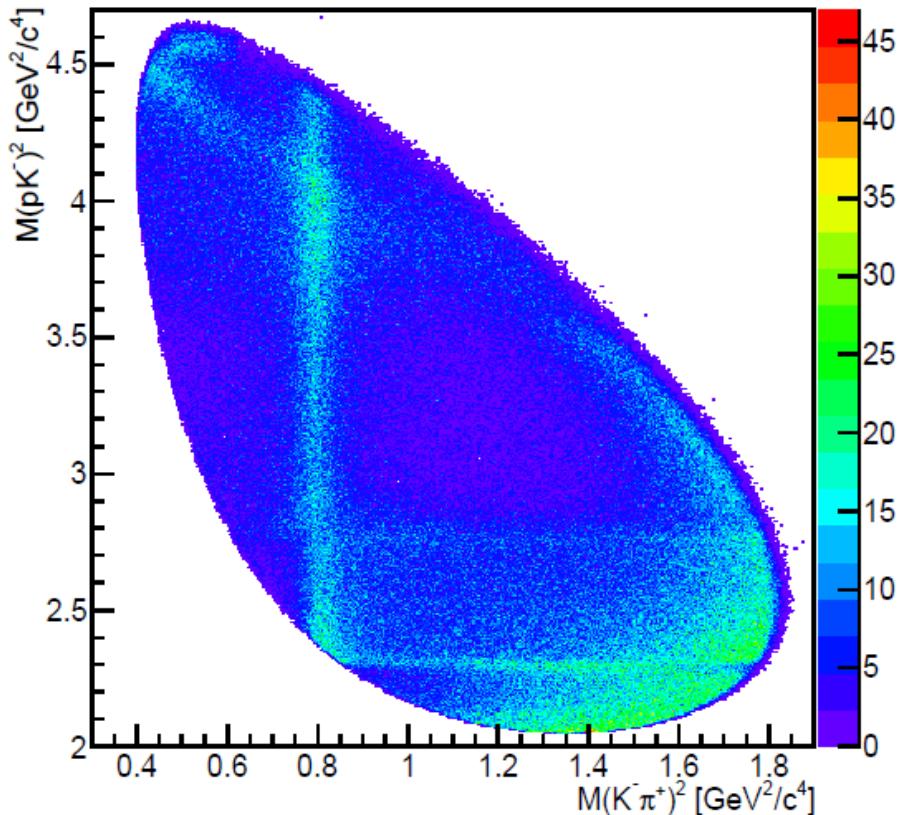
- Precise determination of mass & width for 7 states
- Mass differences in isodoublets
 - favorable for diquark picture.
 - ρ vs λ excitation
- Branching ratios for $\Lambda D/\Sigma_c K$ decay modes
 - λ mode $\rightarrow \Lambda D$, ρ mode $\rightarrow \Sigma_c K$?
 - $\Xi_c(3055)$ is more likely to be the analog of $\Lambda_c(2880)$ than $\Xi_c(3080)$
- Challenge for theories.
 - Now we have a lot of data, more than Λ_c & Σ_c combined
 - Please calculate!
- Yet more ongoing analyses - Interesting results coming soon.
- **Belle II is coming, too!**

Dalitz plot again: $\Lambda_c^+ \rightarrow p K^- \pi^+$

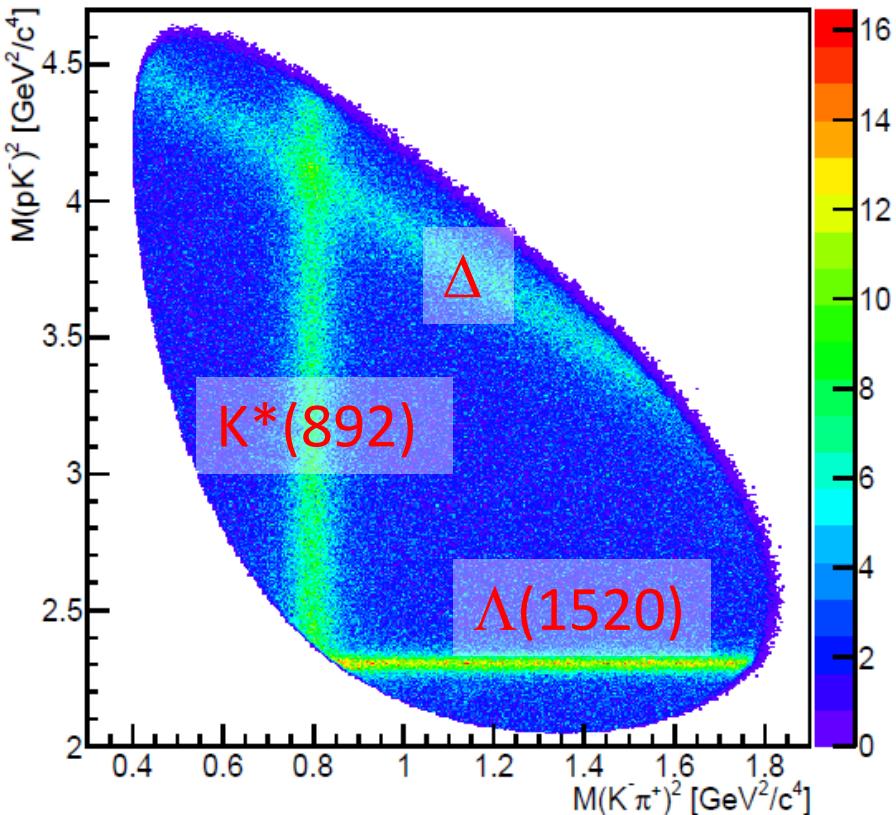


Comparison with MC

Real data



MC



- Quite a lot of difference – PDG sub-branches seem wrong
- Interesting structure in non-resonant region
- Hint for another Λ^*/Σ^* resonance seen. $\Lambda(1670)$?

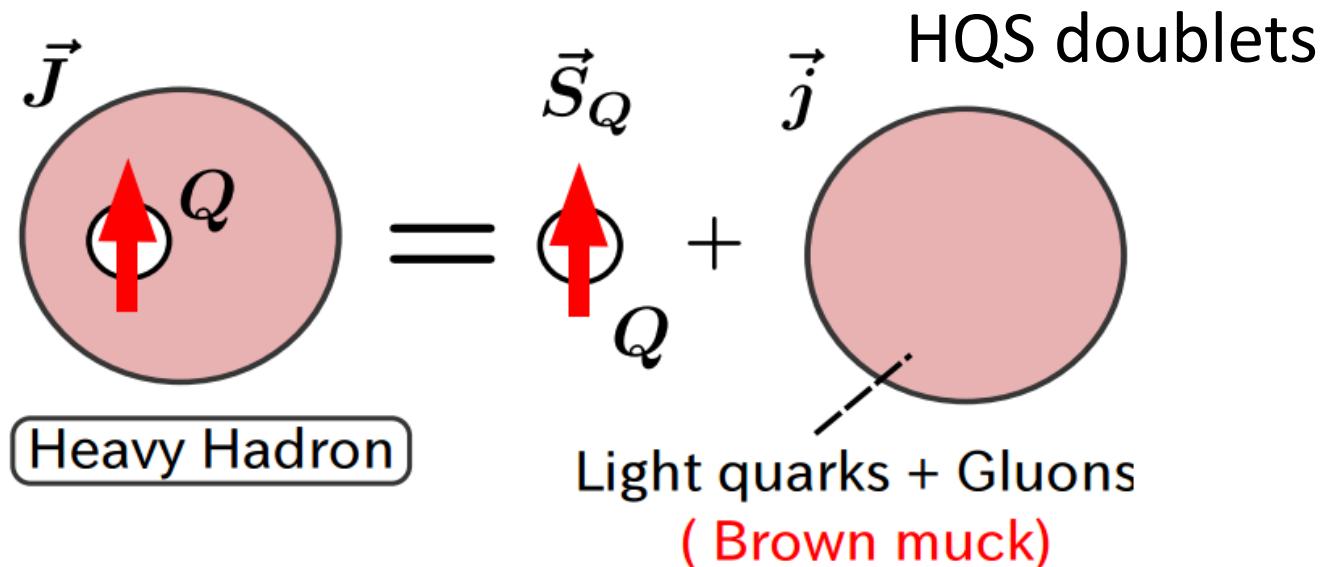
Heavy Quark Spin Symmetry and Mass degeneracy

Introduction

Heavy Quark Spin Symmetry (HQS)

N.Isgur,M.B.Wise,PLB232(1989)113

- **Suppression of Spin-spin force** in $m_Q \rightarrow \infty$.
- ⇒ Decomposition of **Heavy quark spin** and **Light components**
 $\vec{J} = \vec{L} + \vec{S} = \vec{S}_Q + \vec{j} \rightarrow J = j \pm 1/2$

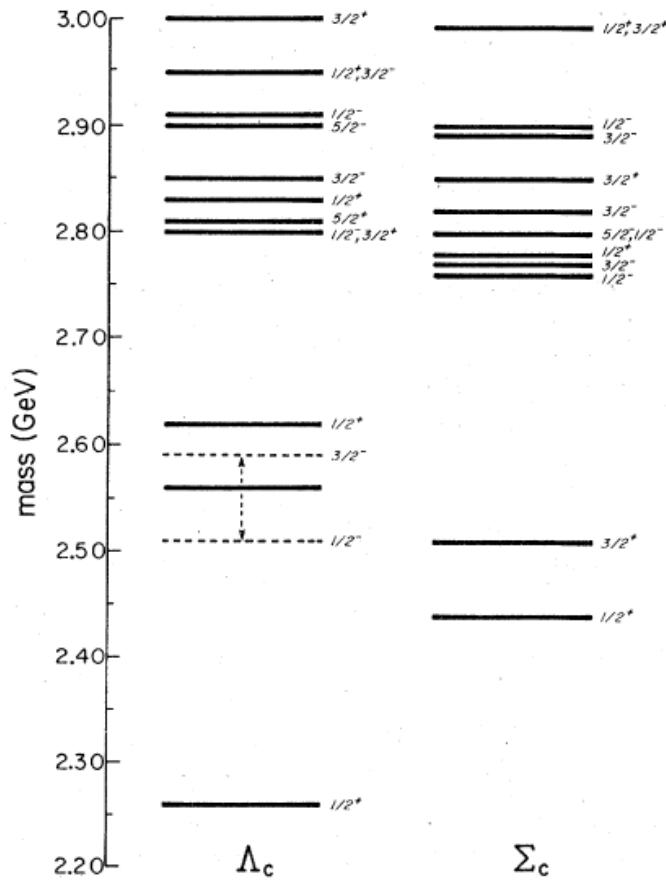


⇒ **Mass degeneracy** of hadrons with the different spins.

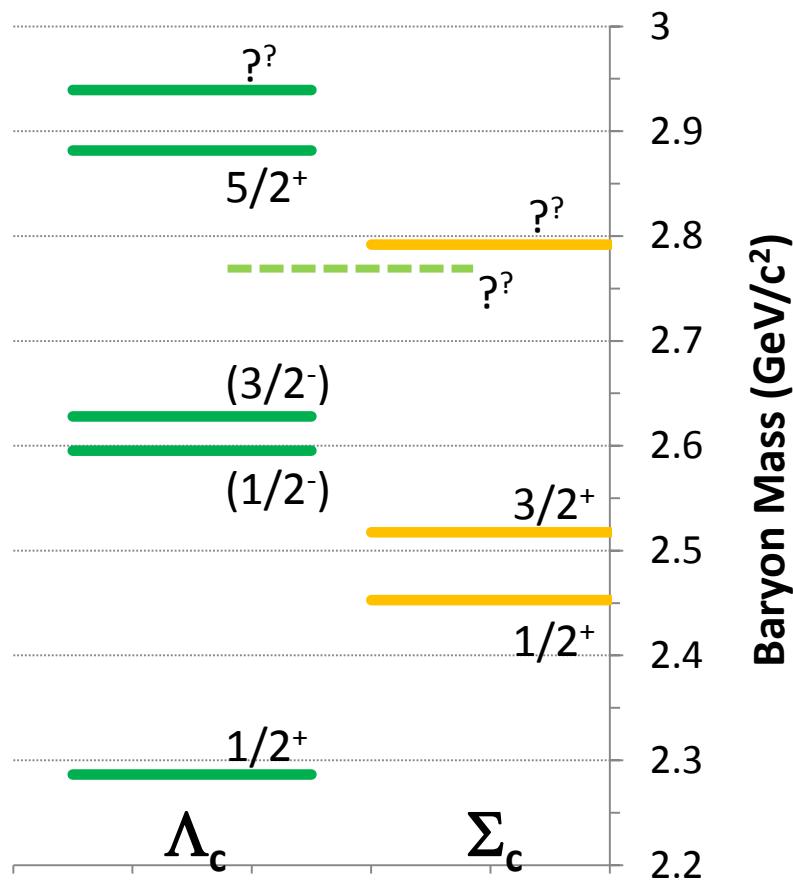
- Mass degeneracy of $\{D, D^*\}(Q\bar{q})$, $\{\eta_c, J/\psi\}(Q\bar{Q})$, $\{\Sigma_c, \Sigma_c^*\}(Qqq)$ (baryons)...

C=1 Baryon Spectrum

Quark model prediction
(L.A. Copley et. al, PRD20 (1979) 768)

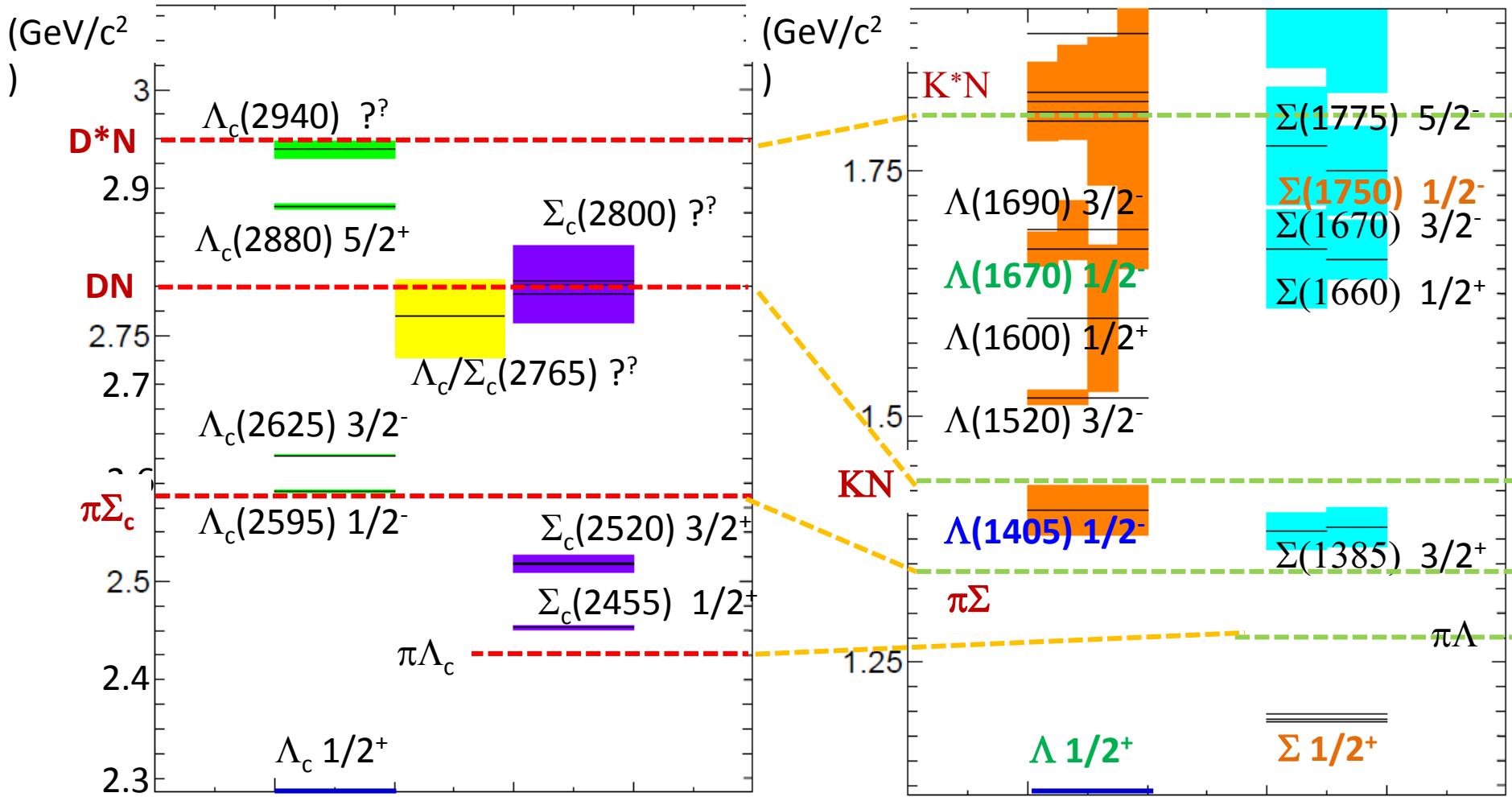


Observed
(PDG, 2012 online)



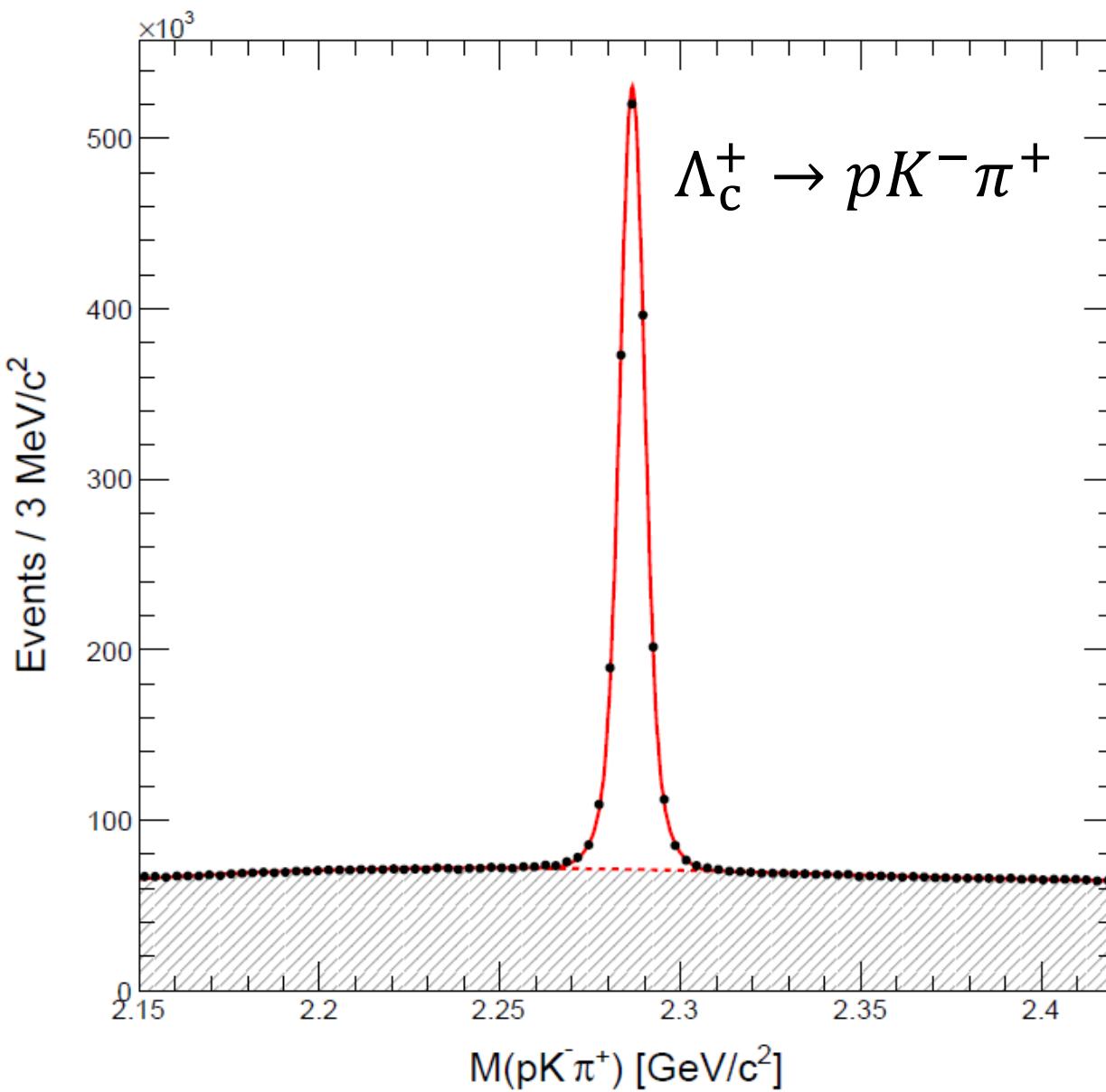
Both missing states & unknown states

Comparison with S=−1 baryons



Difference and Similarity are interesting

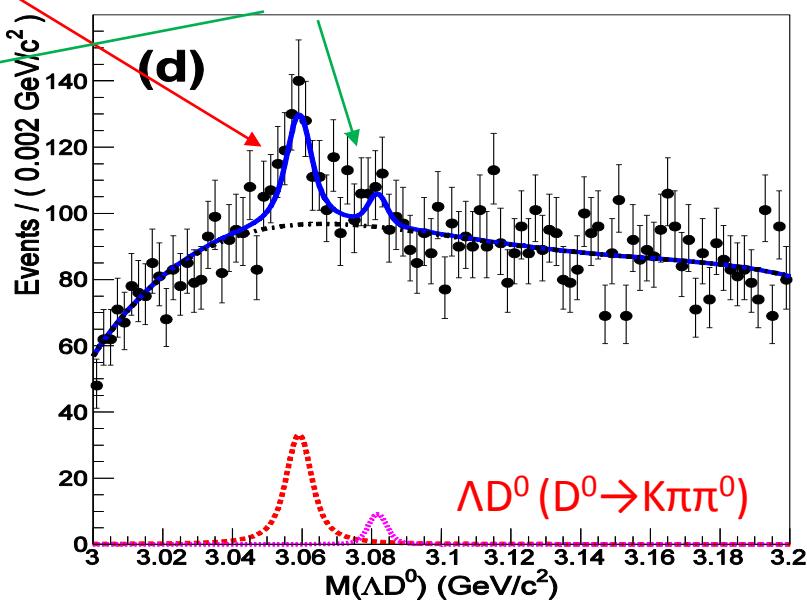
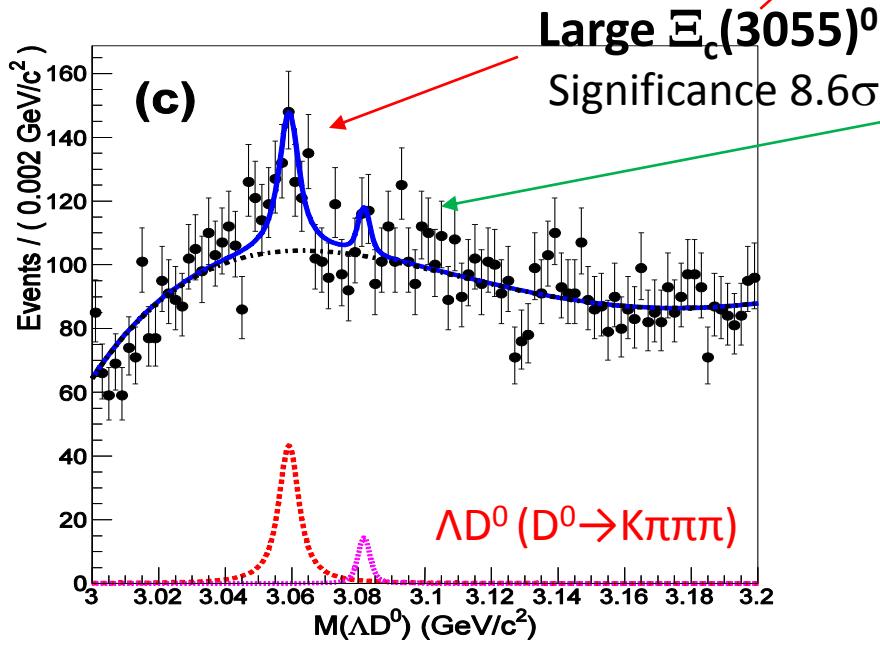
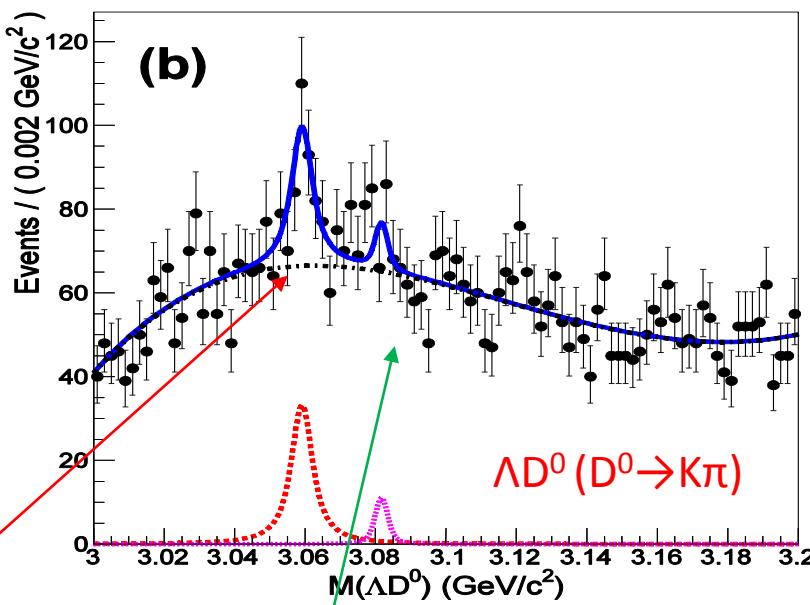
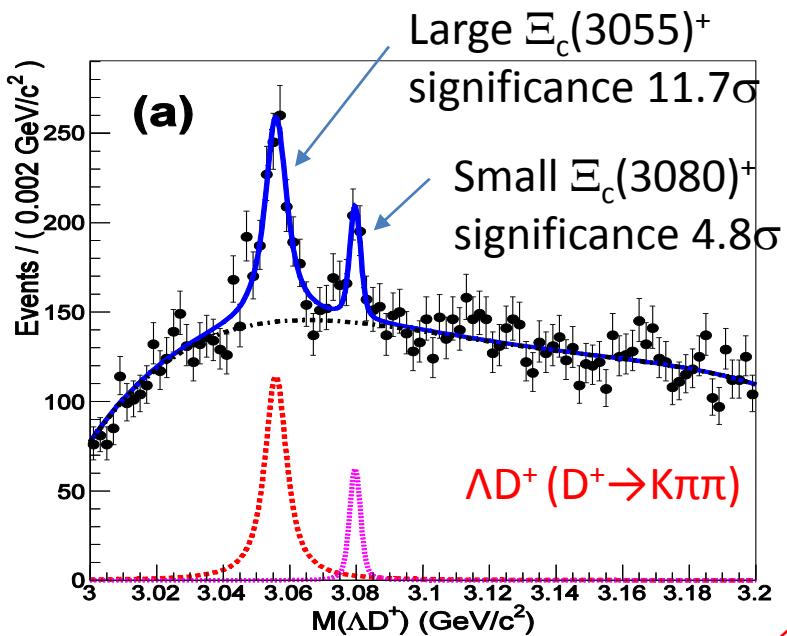
Huge statistics, good quality



> 1 M events
reconstructed

Resolution:
< 10 MeV FWHM

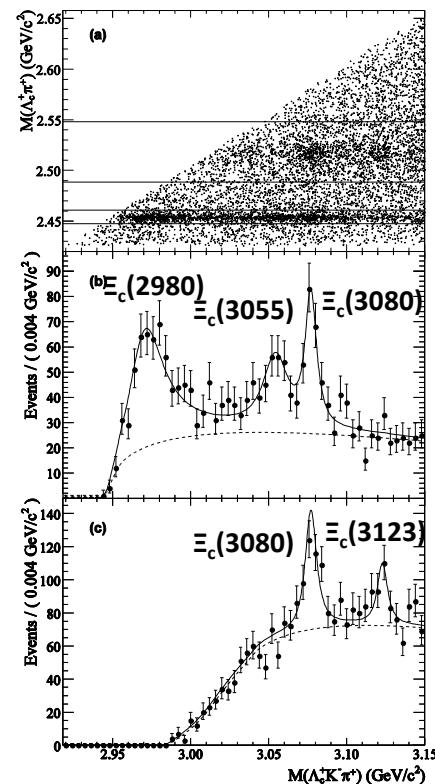
S/N ~ 10



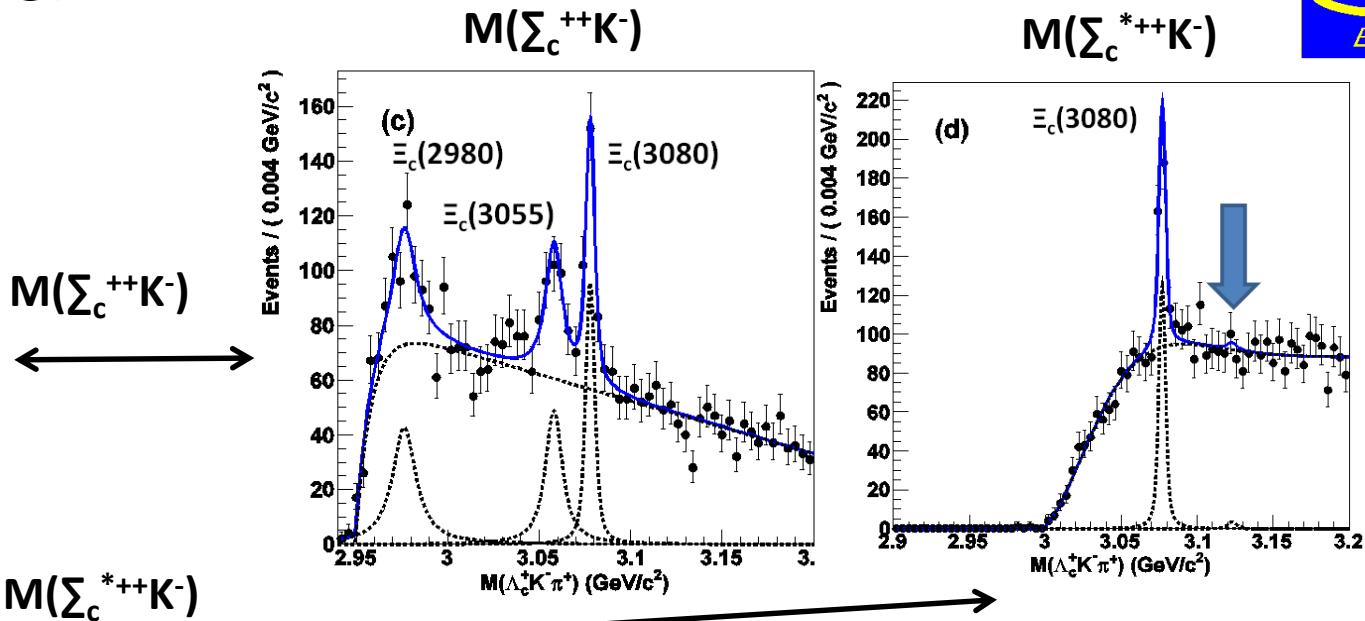
Higher excited states in $\Sigma_c^{++}K^-$ (past studies)

31

Phys. Rev. D 77, 012002



Phys. Rev. D 89, 052003



- Both Belle and BaBar observed
 $\Xi_c(2980)^+$, $\Xi_c(3055)^+$, and $\Xi_c(3080)^+$ in $\Sigma_c^{++}K^-$ final state.
 $\Xi_c(3080)^+$ in $\Sigma_c^{*++}K^-$ final state (only BaBar observed $\Xi_c(3123)^+$)