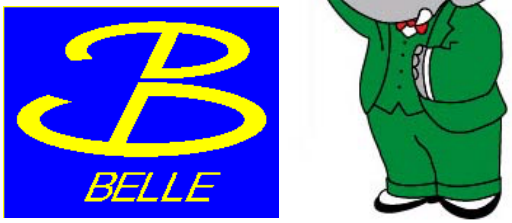
Hadron physics from electron colliders, Belle and BaBar

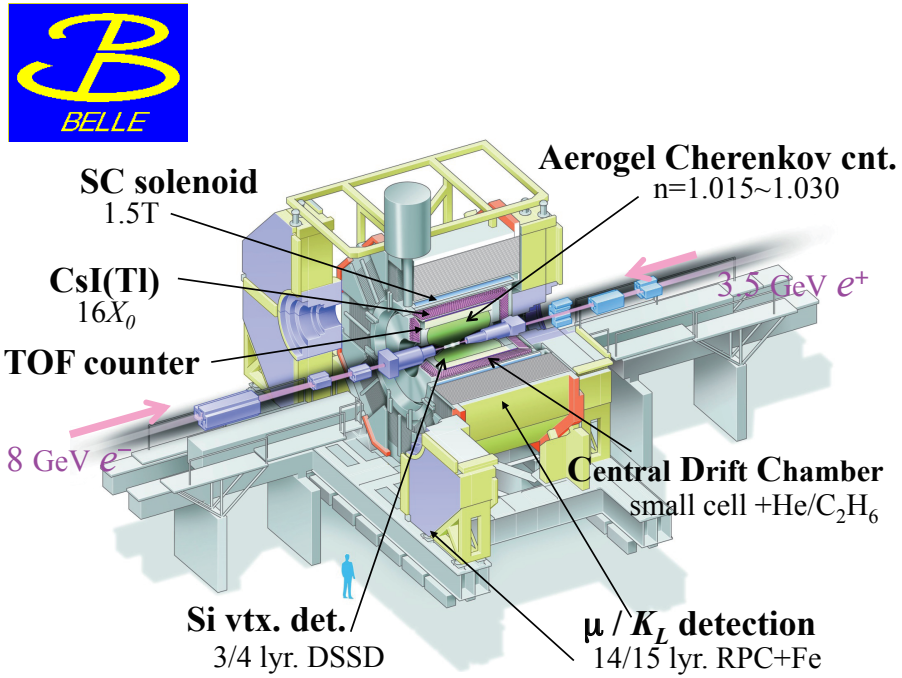
M. Niiyama (Kyoto U.)

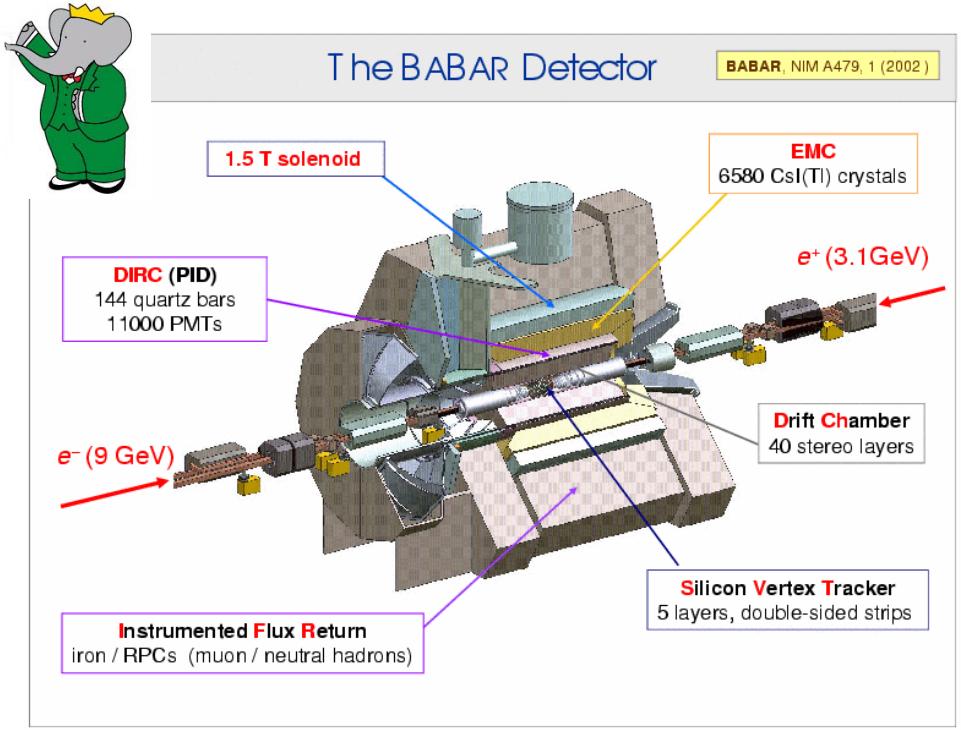
- Charged charmonium like states
- Baryon spectroscopy



Belle and BaBar experiments

- Asymmetric energy e^+e^- collider
- $\Upsilon(4S)$ and some other energies
- Integrated luminosity ~1000 fb^{-1} (Belle), 550 fb^{-1} (BaBar)
- General purpose detector
  - Detect charged particles and photons
  - Good momentum/vertex resolution → **Suitable for hadron physics!**
  - K/π separation up to 3.5 GeV/c





Discovery of new hadrons at Belle and BaBar

Belle
BaBar

Hadron type

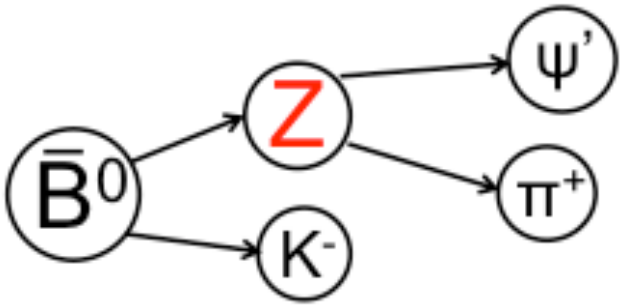
Reactoin

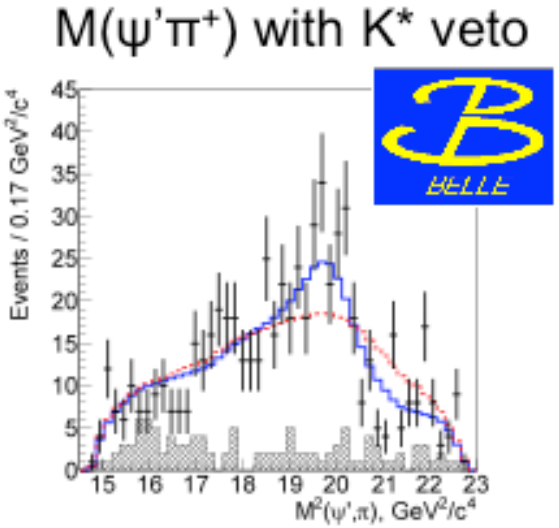
	Charmonium (like)	D(s)	Charmed baryon	Bottomonium
B-decay	$\eta_c(2S)$ X(3872) $Z_c(4050)$ $Z_c(4250)$ $Z_c(4430)$ $Z_c(4200)$	$D_1(2430)$ $D_s(2700)$		
ISR	Y(4260) Z(3900) Y(4008) Y(4660)			
Double charmonium	X(3940) X(4160)			
Two photon	$\chi_{c2}(2P)$			
Continuum			$\Sigma_c(2800)$ $\Lambda_c(2940)^+$ $\Xi_c(2980)$ $\Xi_c(3080)$ $\Omega_c(2770)$ $\Xi_c(3055)$ $Ds_0(2317)$	
Y(5S) decay				$Z_b(10610)$ $Z_b(10650)$ $h_b(1P)$ $h_b(2P)$ $\eta_b(2S)$

*some states may be missed.

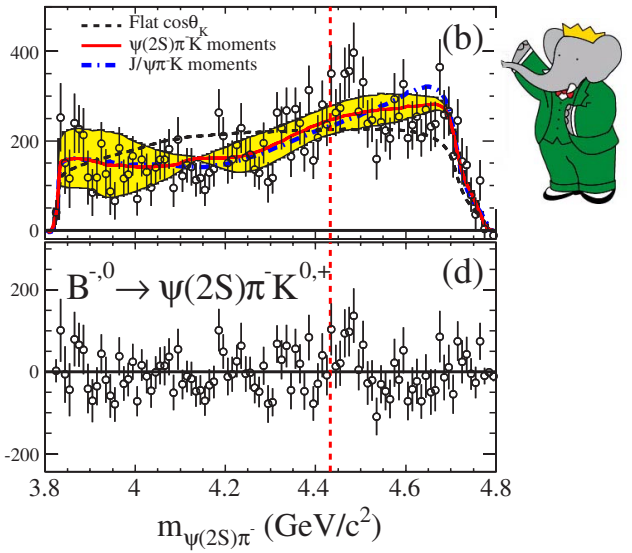
Y.Kato's talk at JPS meeting (2015)

$Z_c(4430)^+$ Belle and BaBar results





Phys. Rev. D **88**, 074026 (2013)



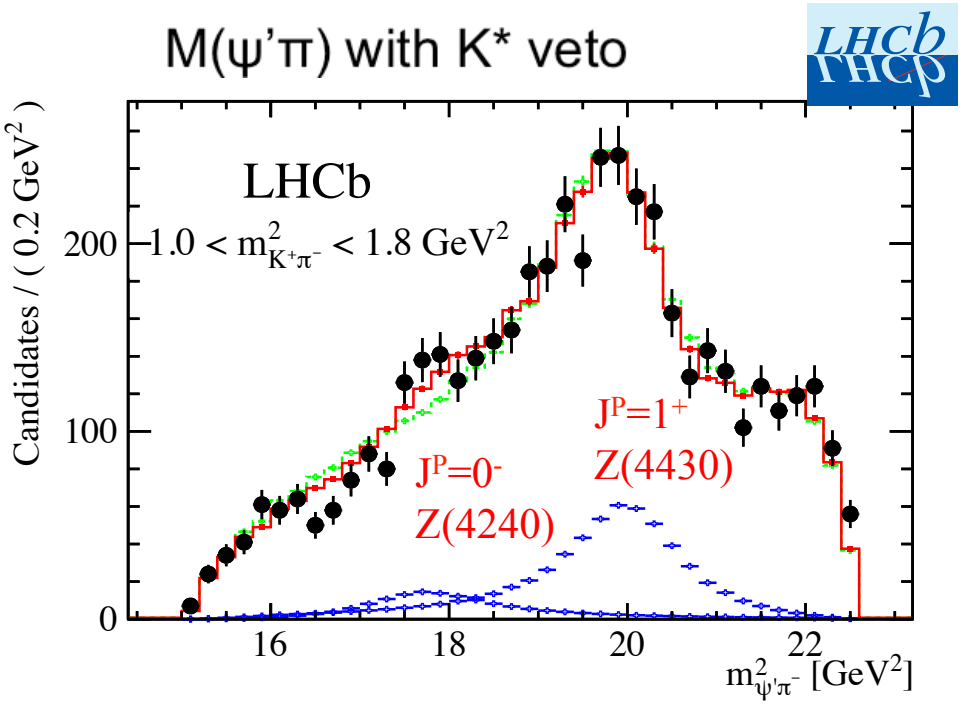
Phys. Rev. D79, 112001(2009)

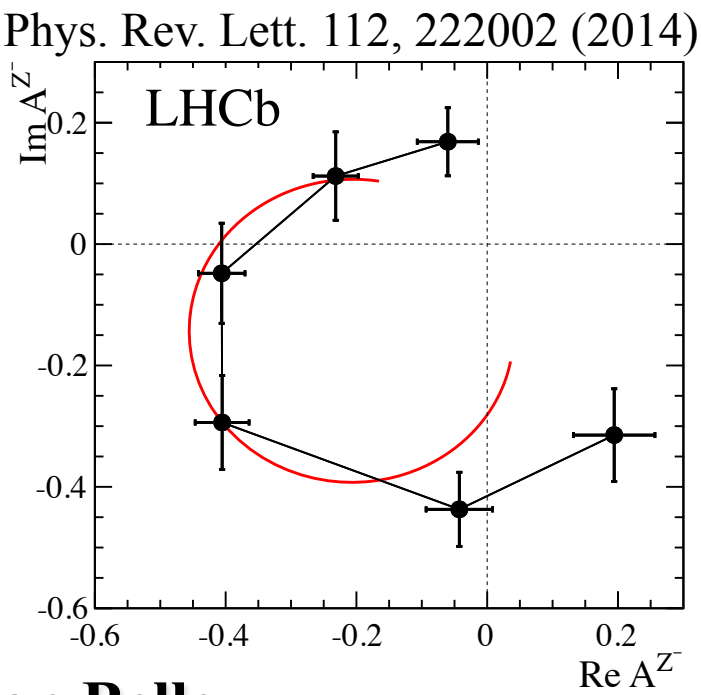
- $\Psi'\pi^+$ decay, charged state with $c\bar{c}$ → **Genuine 4 quark state!**
- Amplitude analysis in [$M(K^-\pi^+)$, $M(\psi'\pi^+)$, $\cos(\Theta)$, φ] w/ K^* resonances
- Belle : 6.4 σ significance, $M=4485\pm22^{+28}_{-11}$ MeV, $\Gamma=200^{+41}_{-46}{}^{+26}_{-35}$ MeV

  $Br(B^0\to Z^-K^+, Z^-\to\psi'\pi^-) = (3.2^{+1.8}_{-0.9}{}^{+5.3}_{-1.6}) \times 10^{-5}$

  $J^P=1^+$ is favored with 3.4 σ
- BaBar : 95% CL upper limit, $Br(B^0\to Z^-K^+, Z^-\to\psi'\pi^-)<3.1 \times 10^{-5}$

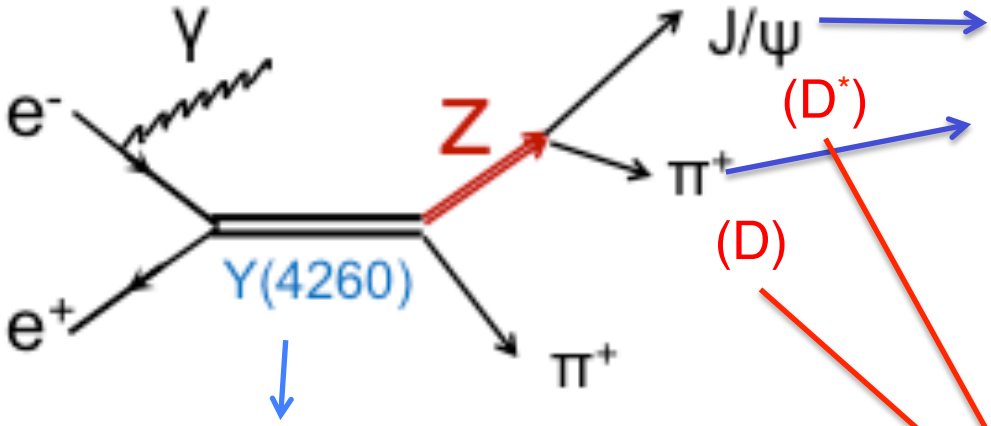
Confirmation by LHCb



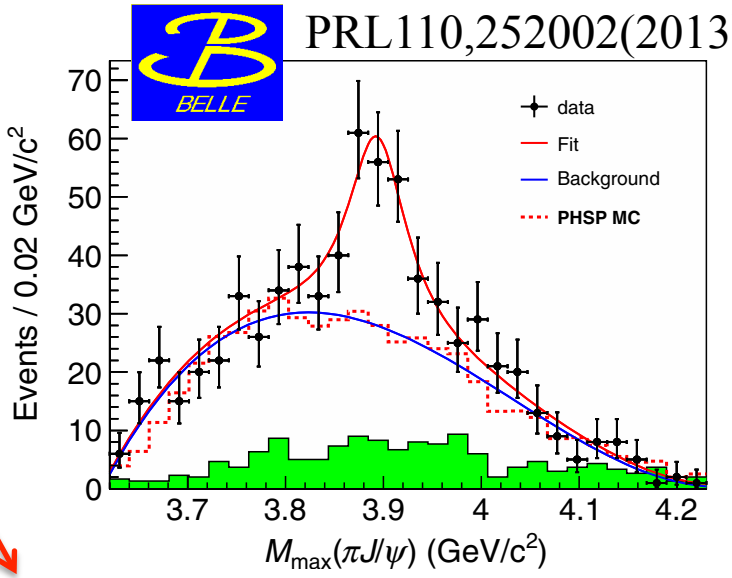


- **12 times more $B^0 \to \psi' \pi^- K^+$ events than Belle.**
- **Amplitude analysis as same as Belle and BaBar.**
- **13.9 σ significance, $M=4475\pm7^{+15}_{-25}$ MeV, $\Gamma=172\pm13^{+37}_{-34}$ MeV consistent with Belle.**
- **$J^P=1^+$ is determined with 8σ.**
- **$Z_c(4430)^+$ is established!**

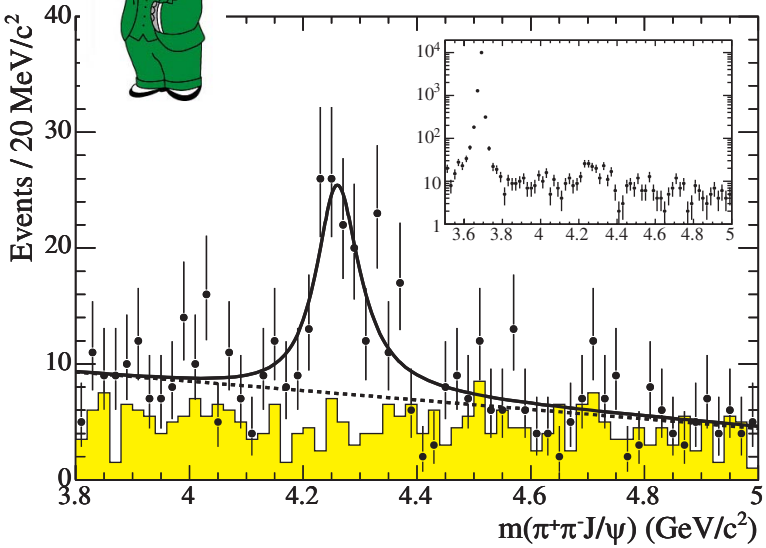
$Z_c(3900)^+$:another charged charmonium-like



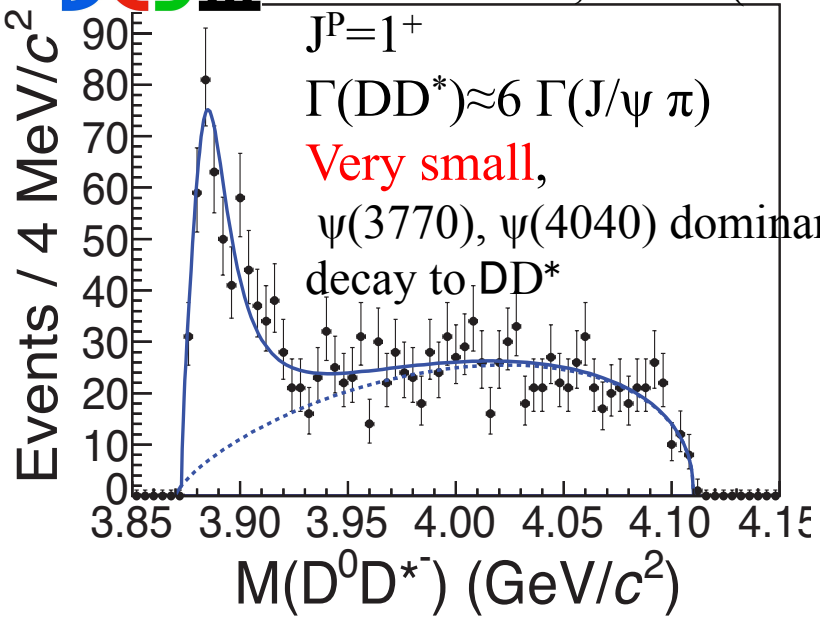
PRL110,252002(2013)



PRL95,142001(2005)



BESIII PRL112,022001(2014)



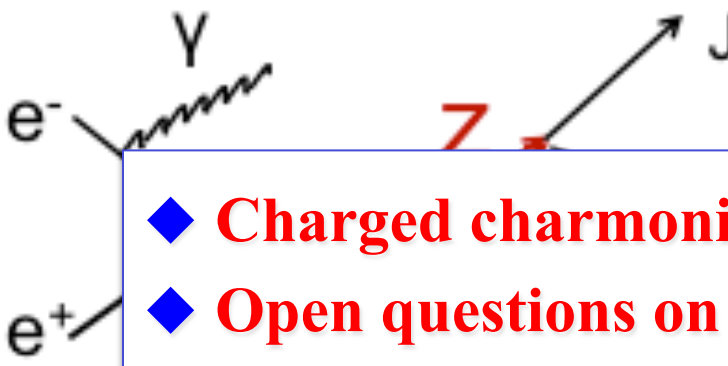
$J^P=1^+$

$\Gamma(DD^*)\approx 6\,\Gamma(J/\psi\,\pi)$

Very small,

$\psi(3770)$, $\psi(4040)$ dominantly decay to DD*

$Z_c(3900)^+$:another charged charmonium-like



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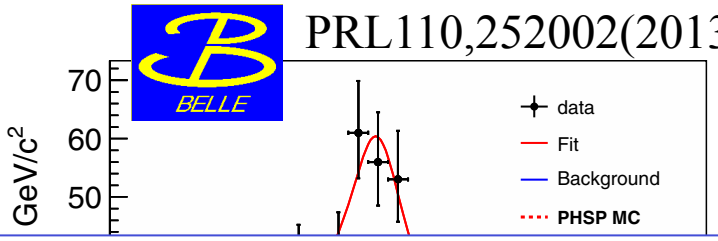
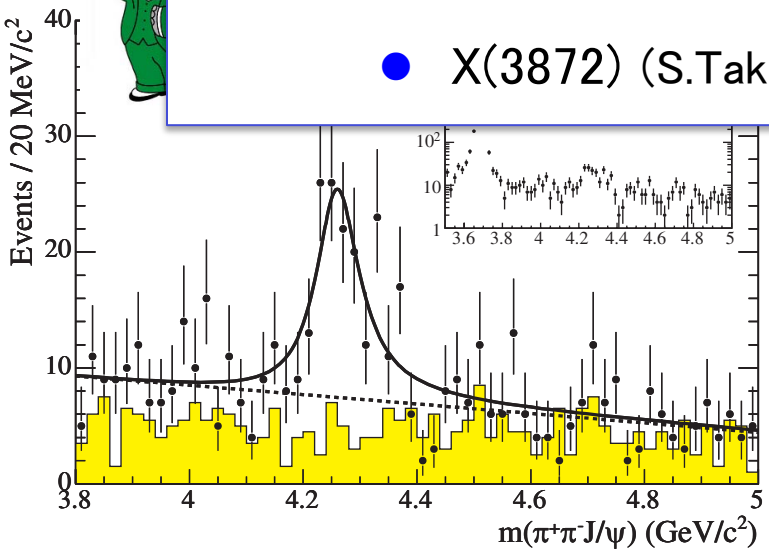
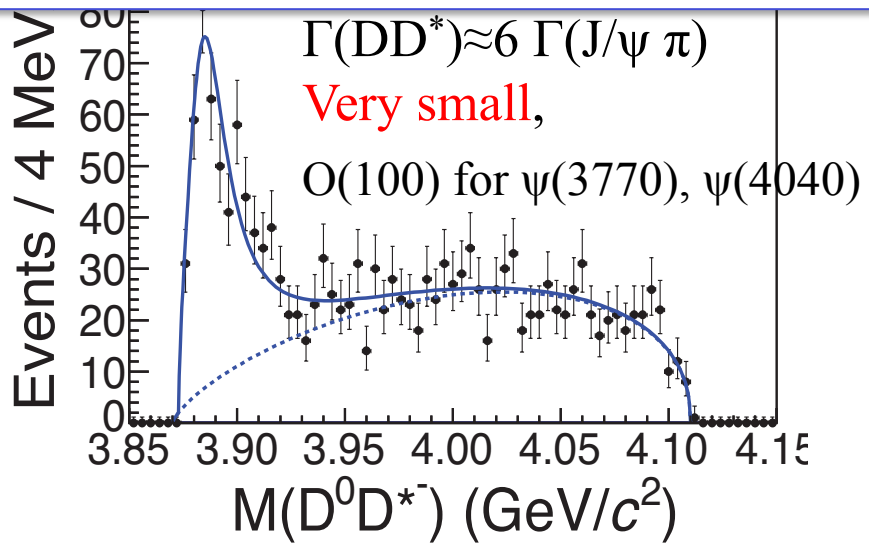


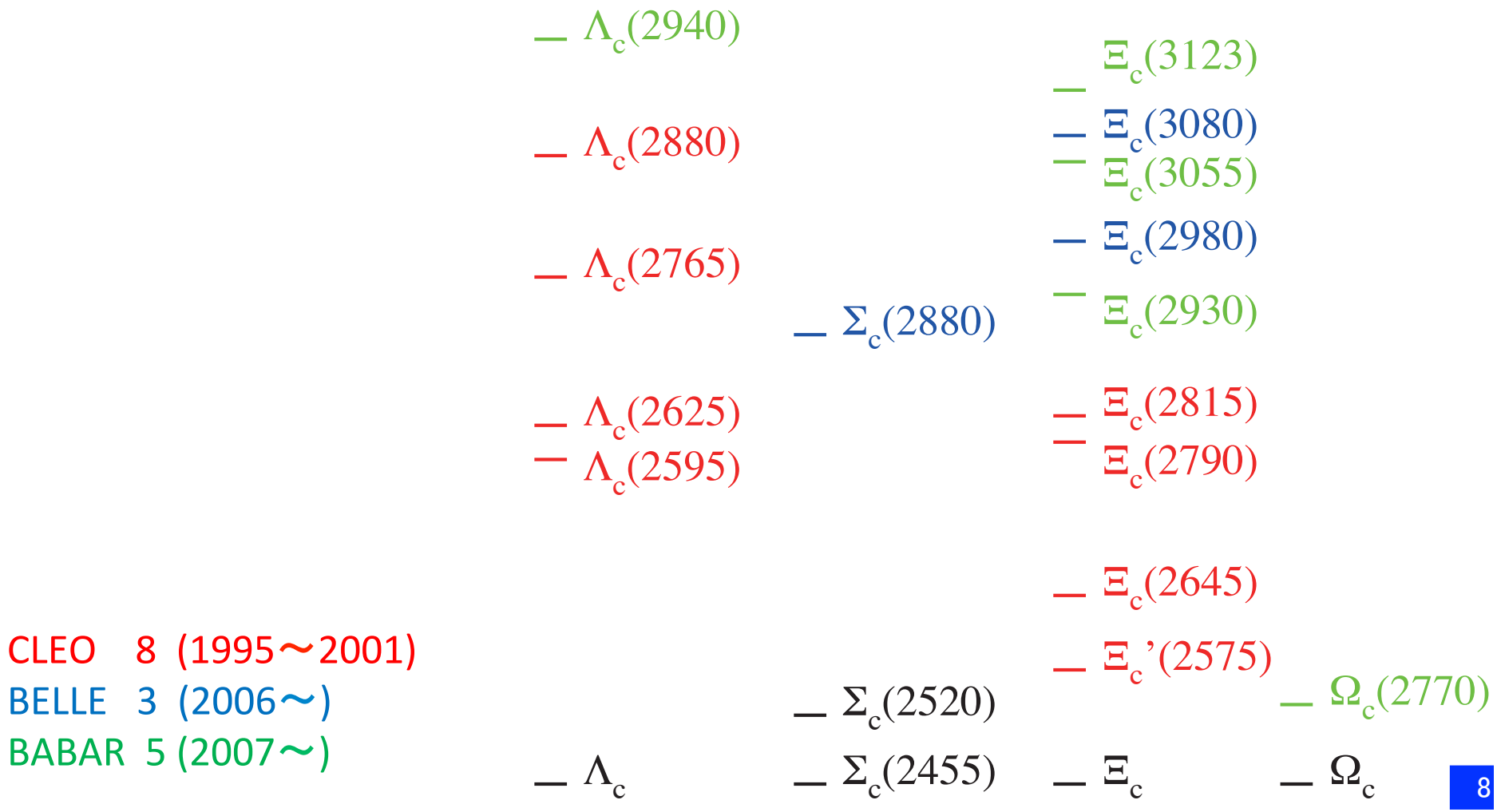
- **Charged charmonium-like states are established.**
- **Open questions on their internal structure.**
  - **S-wave J/ψ π, (ψ' π) or $D\bar{D}^*$ molecule?**
  - **$c\bar{c}$ core exists?**
    - X(3872) (S.Takeuchi, K. Shimizu, M. Takizawa PTEP 2014, 123D01)





Charmed baryon spectroscopy

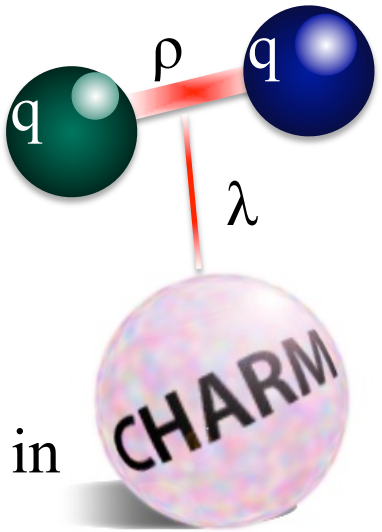
- **21 charmed baryons are listed in PDG 2014.**
  - **16 of them are firstly observed in e^+e^- collider experiment.**
  - **Recently Belle and BaBar identified many excited Ξ_c's.**



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

Diquark in charmed baryon

- Diquark correlation
  - Important for tetraquark, pentaquark system
  - Strong attraction for J=0, flavor singlet diquark
  - Color spin interaction : $1/m_{q1}m_{q2}$
    - suppress charm-light quark interaction
  - Diquark-charm (λ), q-q (ρ) excitation may decouple in charmed baryon spectroscopy.



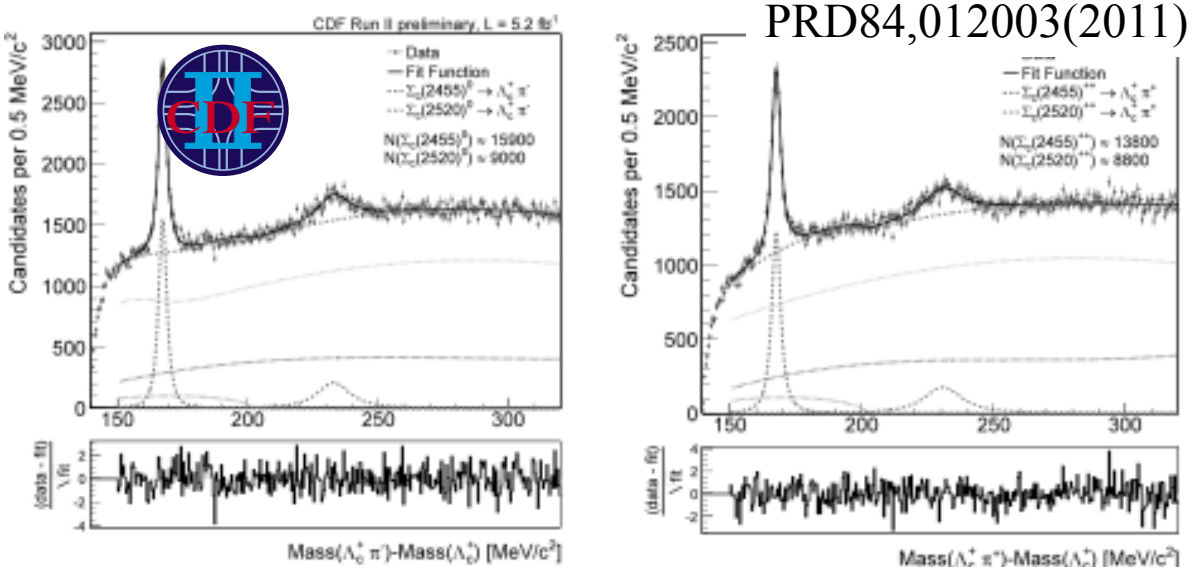
- Experimental issues
  - Precise mass, width, branching ratio for understanding wave function
  - Charged/neutral partner to identify isospin.
  - Spin-parity determination
    - For charm baryons, J^P are from quark model prediction except for $\Lambda_c(2880)^+$

Precise mass and width measurement of Σ_c baryons

Isospin mass splittings of Σ_c

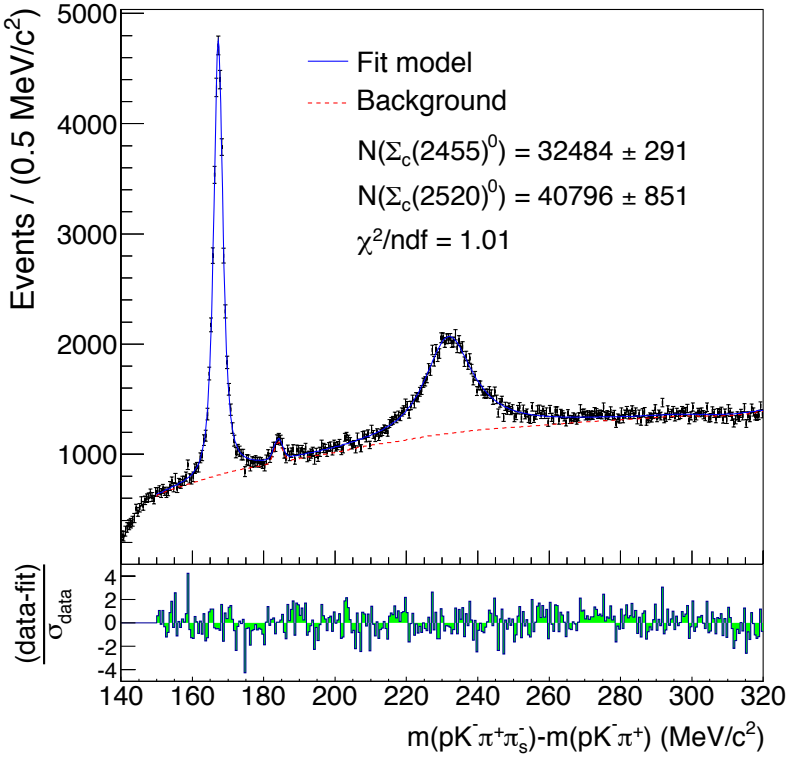
- Naïve expectation:
  - $m(u) < m(d) \rightarrow m(\Sigma_c^{++})(uuc) < m(\Sigma_c^{0})$ (ddc)
- Experimental measurement
  - $m(\Sigma_c(2455)^{++})$-$m(\Sigma_c(2455)^{0}) = 0.24 \pm 0.09$ MeV (PDG)
  - Σ hyperons : $m(\Sigma^{+})$ (uus) <$m(\Sigma^{-})$ (dds) as expected,
- Theoretical models
  - Electromagnetic potential, hyperfine interaction
- Experimental accuracy is still not enough to conclude the mass ordering (< 3σ). → **High precision measurement at Belle!**

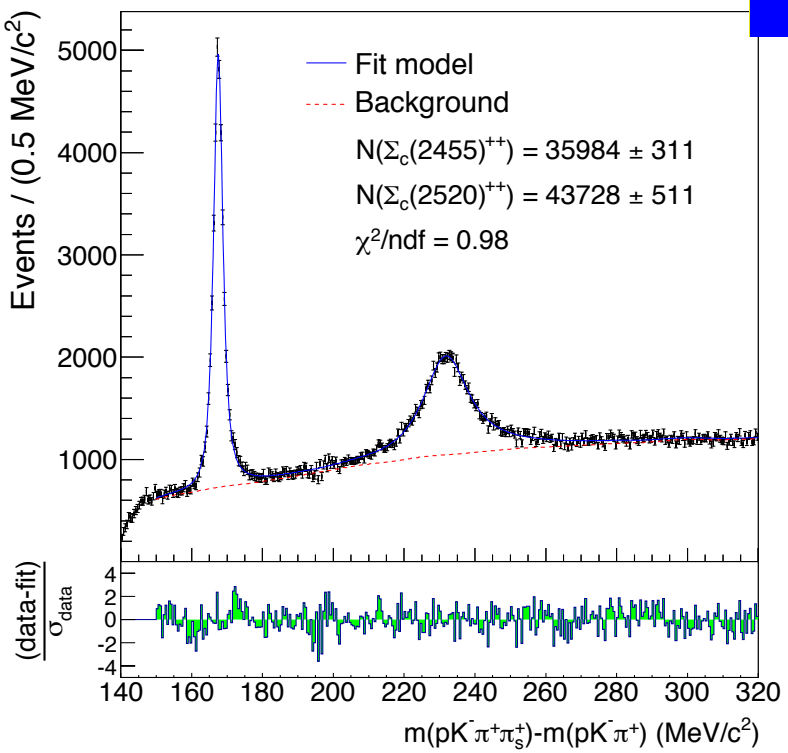
PRD84,012003(2011)



Results from Belle

PRD 89, 0911202 (2014)



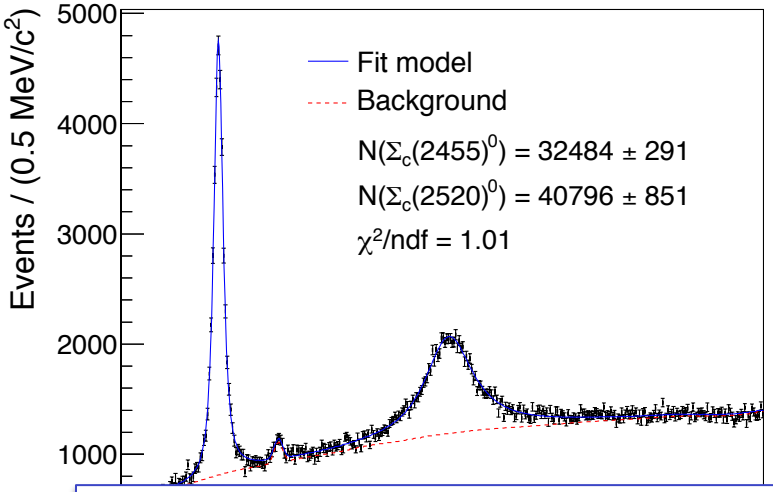


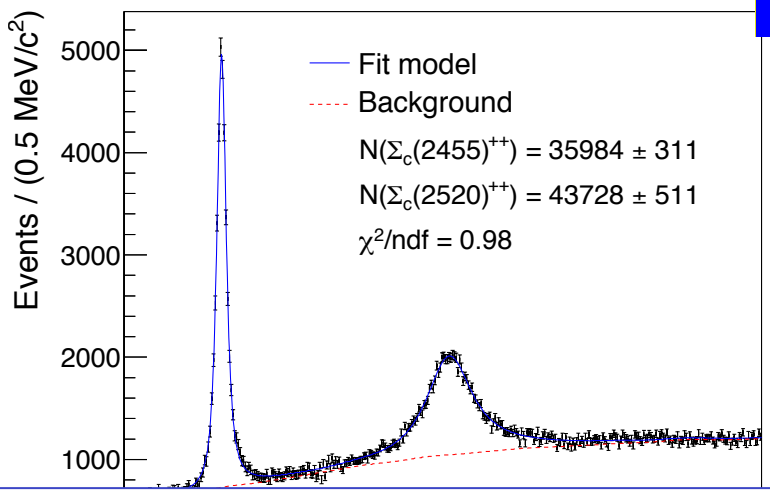
(MeV/c^2)	$m(\Sigma_c)-m(\Lambda_c^+)$	Decay widths (Γ)
$\Sigma_c(2455)^0$	167.29 ± 0.01 ± 0.02	1.76 ± 0.04 $^{+0.09}_{-0.21}$
$\Sigma_c(2455)^{++}$	167.51 ± 0.01 ± 0.02	1.84 ± 0.04 $^{+0.07}_{-0.20}$
$\Sigma_c(2520)^0$	231.98 ± 0.11 ± 0.04	15.41 ± 0.41 $^{+0.20}_{-0.32}$
$\Sigma_c(2520)^{++}$	231.99 ± 0.10 ± 0.02	14.77 ± 0.25 $^{+0.18}_{-0.30}$

Slide from S. Lee' talk at LLWI 2015

Results from Belle

PRD 89, 0911202 (2014)





- Factor 4 improvement of mass determination.
- Belle confirmed $m(\Sigma_c^{++}) > M(\Sigma_c^{0})$ with more than 10 σ.
- Precise input to understand wave functon.

(MeV/c²)	$m(\Sigma_c)-m(\Lambda_c^+)$	Decay widths (Γ)
$\Sigma_c(2455)^0$	167.29 ± 0.01 ± 0.02	$1.76 \pm 0.04\ ^{+0.09}_{-0.21}$
$\Sigma_c(2455)^{++}$	167.51 ± 0.01 ± 0.02	$1.84 \pm 0.04\ ^{+0.07}_{-0.20}$
$\Sigma_c(2520)^0$	231.98 ± 0.11 ± 0.04	$15.41 \pm 0.41\ ^{+0.20}_{-0.32}$
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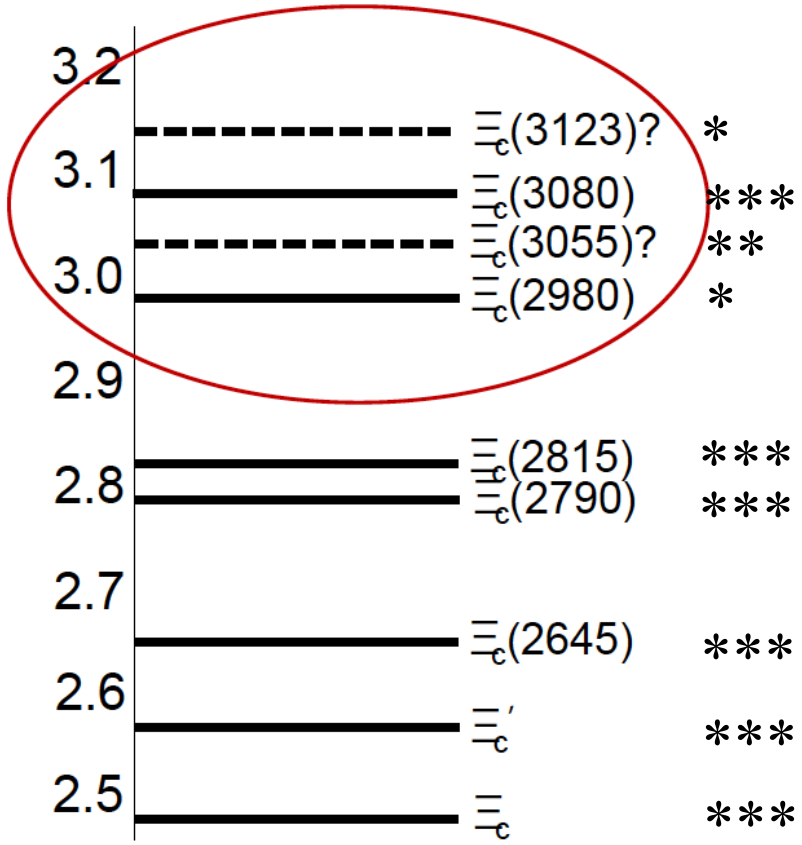
Slide from S. Lee' talk at LLWI 2015

Charm strange baryons, Ξ_c , Ω_c

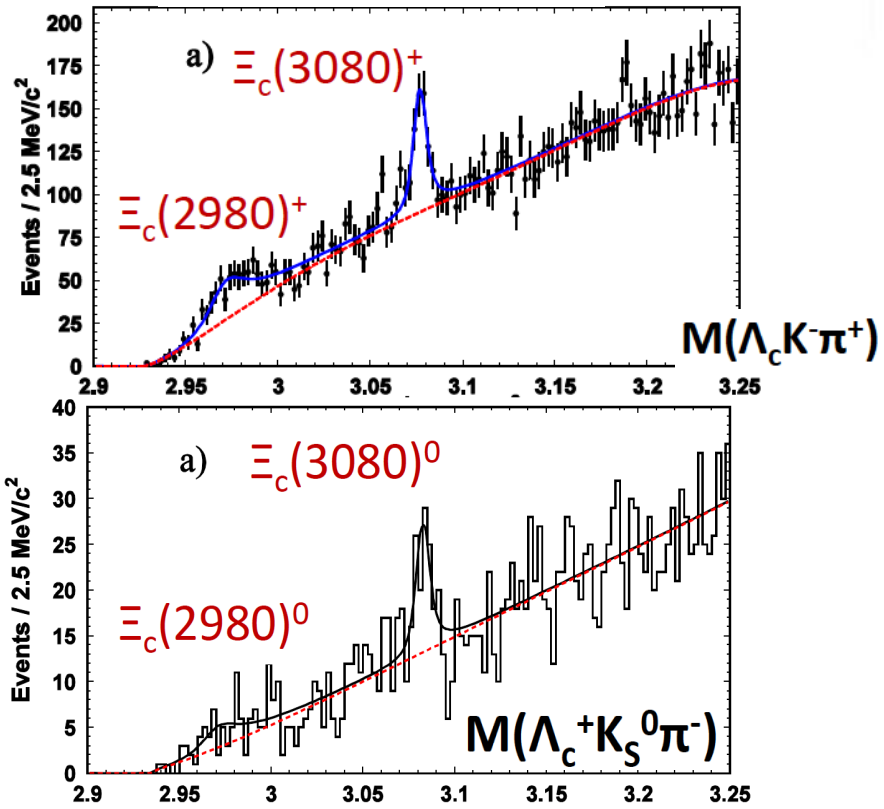


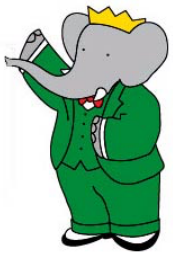
Charmed strange baryons Ξ_c , (usc, dsc)

- Belle observed $\Xi_c(2980)/(3080)^{+/0}$ in $\Lambda_c^+ K\pi$.
- BaBar confirmed them and reported $\Xi_c(3055)/(3123)^+$ in $\Sigma_c^{(*)++} K^-$.
- They are not confirmed yet and isospin partners are not observed.

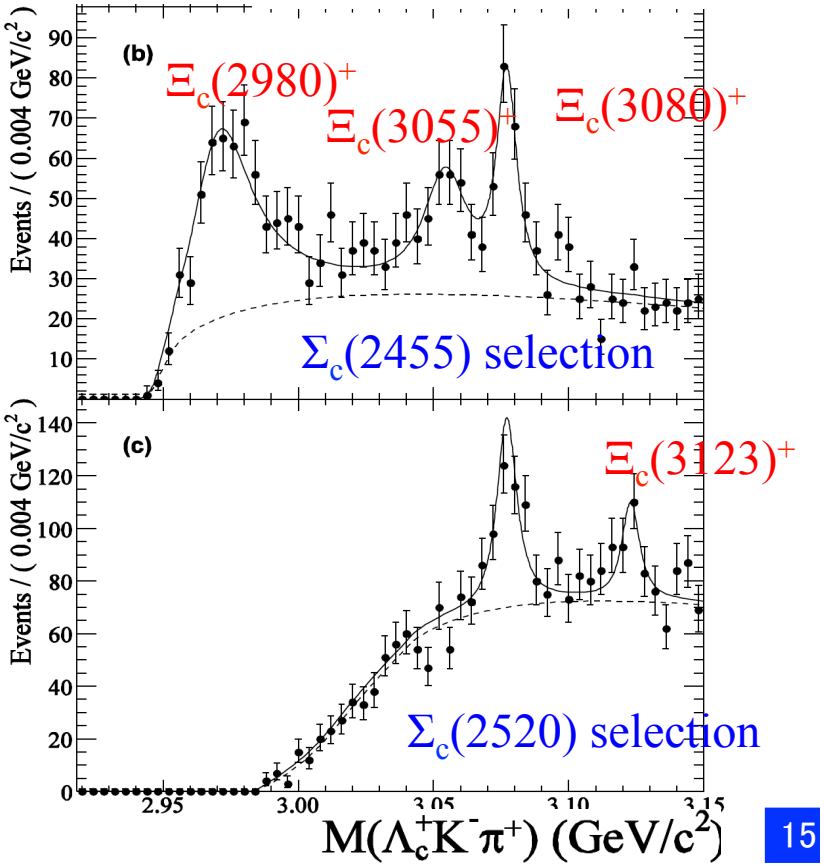
→ Study in Belle data!

Belle: PRL97,162001





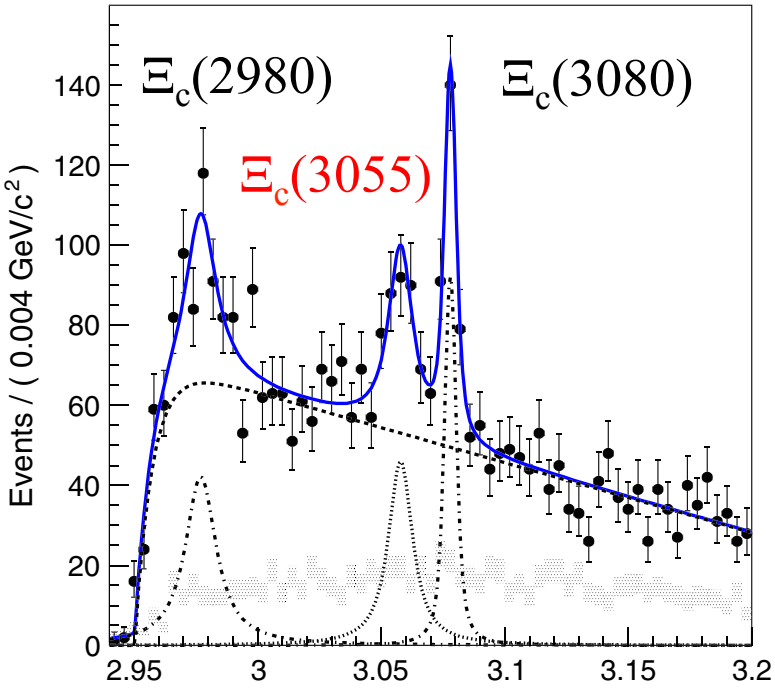
BaBar: PRD77,012002



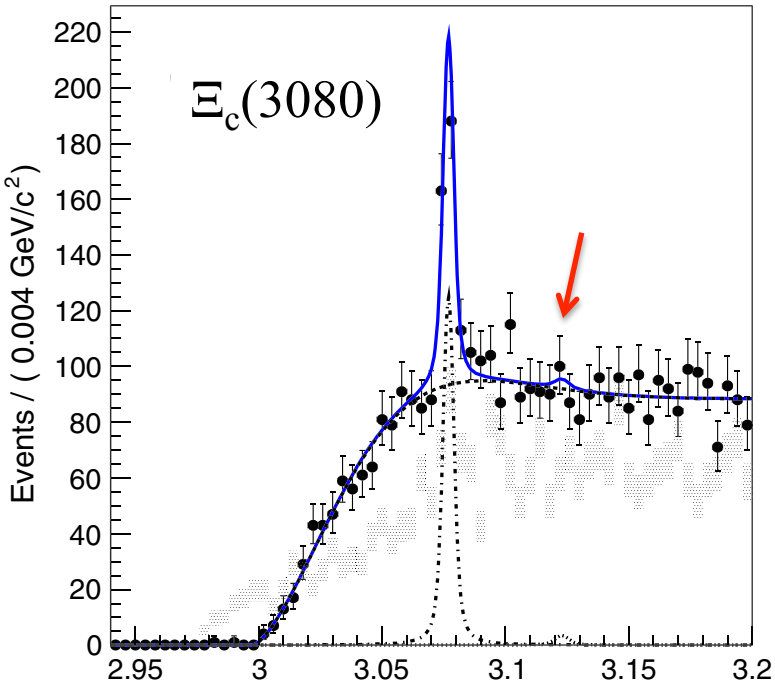
New results by Belle

(Phys. Rev. D **89**, 052003)

$M(\Sigma_c(2455)^{++}K^-)$



$M(\Sigma_c(2520)^{++}K^-)$



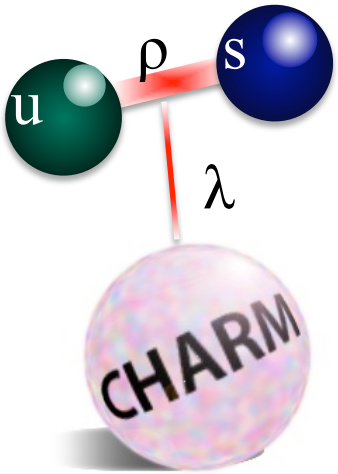
- Peaks of $\Xi_c(2980)^+$, $\Xi_c(3055)^+$, $\Xi_c(3080)^+$
- $\Xi_c(3055)^+$ is confirmed with 6.6σ.
- Peaks of $\Xi_c(3080)^+$, but no $\Xi_c(3123)^+$
- Upper Limit

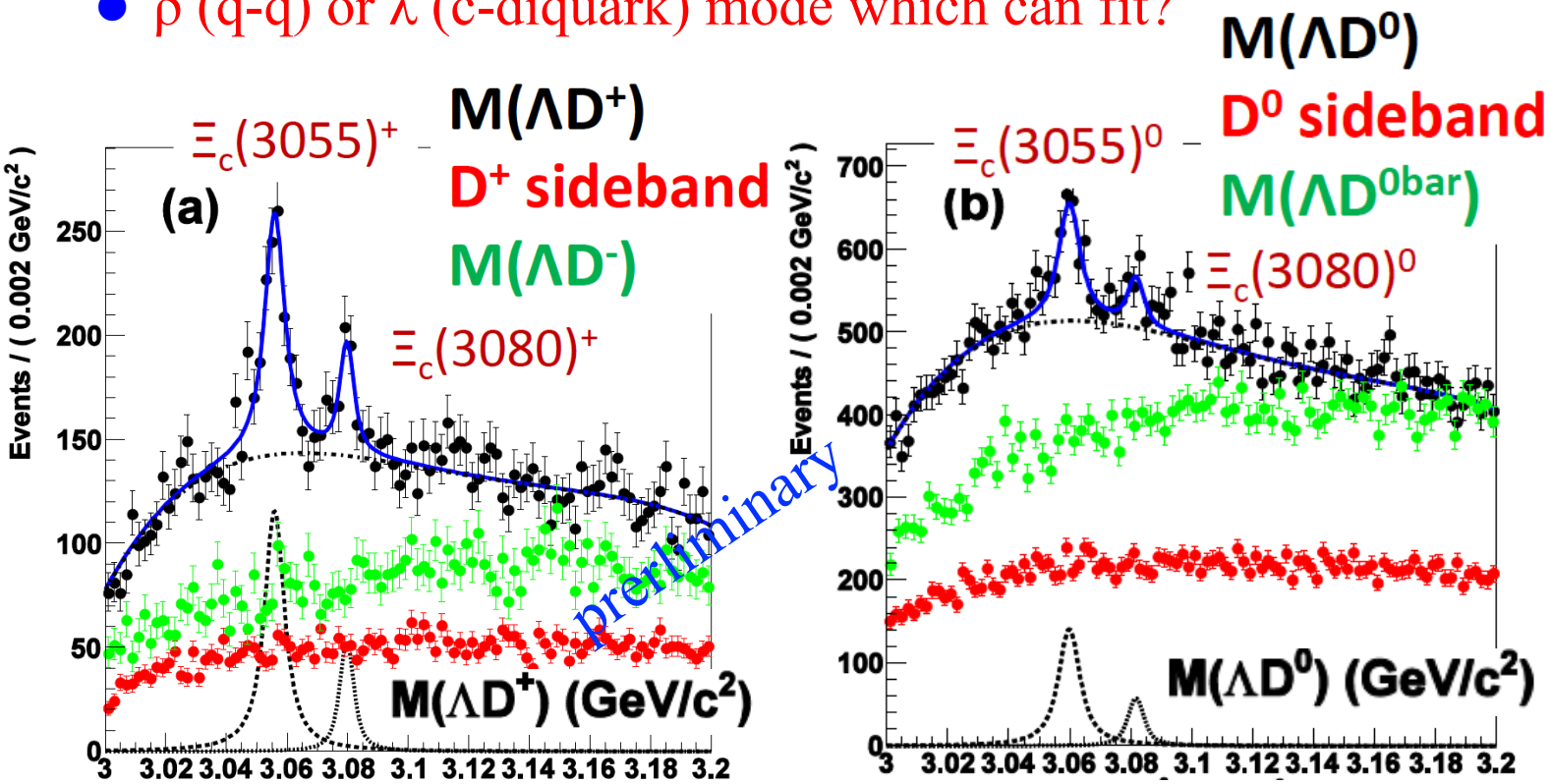
$\sigma(e^+e^- \to \Xi_c(3123)^+X) \bullet Br(\Xi_c(3123)^+ \bullet \Lambda_c^+)$

$= 0.34$ fb $\Leftrightarrow$ $1.6 \pm 0.6 \pm 0.2$ fb by BaBar

Results of ΛD decay

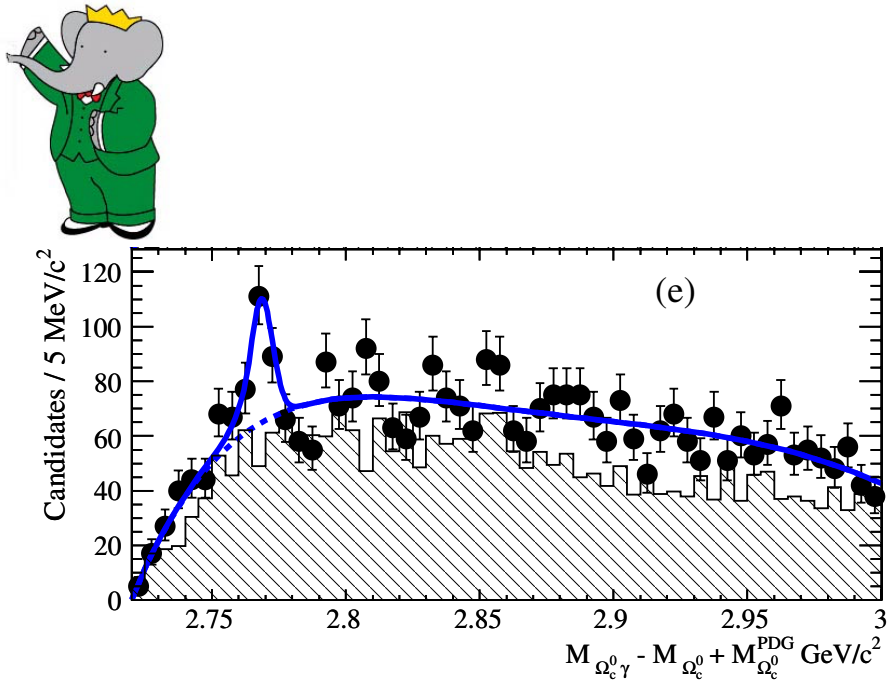
- $\Xi_c(3055)^+$ (11.7σ), $\Xi_c(3080)^+$(4.7σ) in ΛD^+
  - Further confirmation of $\Xi_c(3055)^+$
- $\Xi_c(3055)^0$ (7.6σ) , $\Xi_c(3080)^0$ (2.6σ) in ΛD^0
  - First observation of $\Xi_c(3055)^0$
- Decay modes should be related to wave function.
  - ρ (q-q) or λ (c-diquark) mode which can fit?



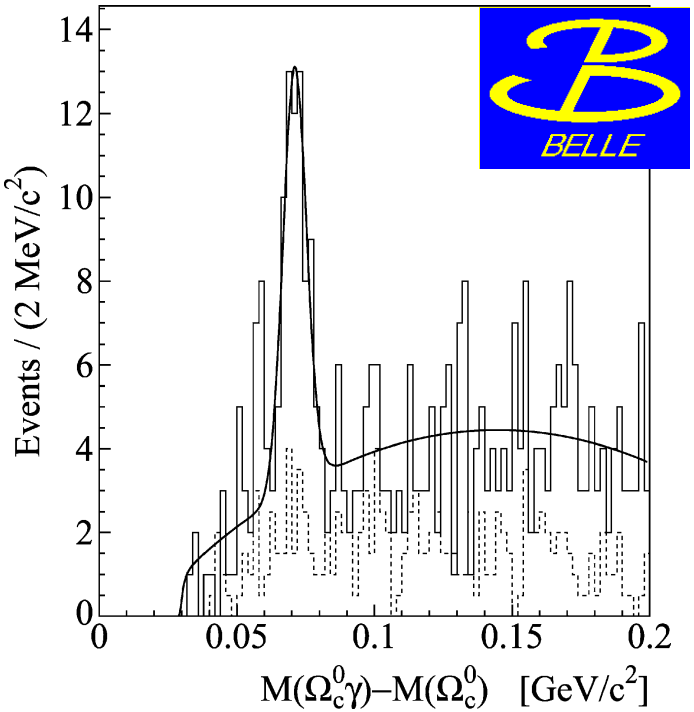


Radiative decay of excited Ω_c (ssc)

- General purpose detector : sensitive to charged paritcles and γ
- Excited Ω_c below pionic decay threshold is found.
  - What about Ω hyperons? → Further study in Belle and BaBar data is awaited.



PRL **97,** 232001 (2006)

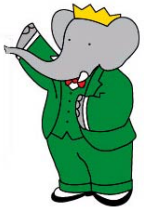


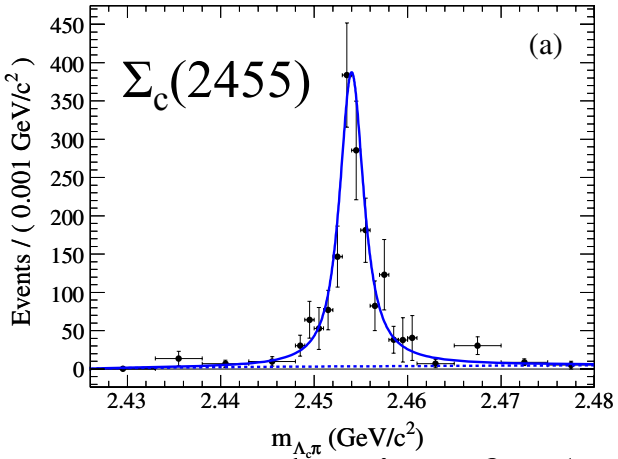
PLB672(2009) 1-5

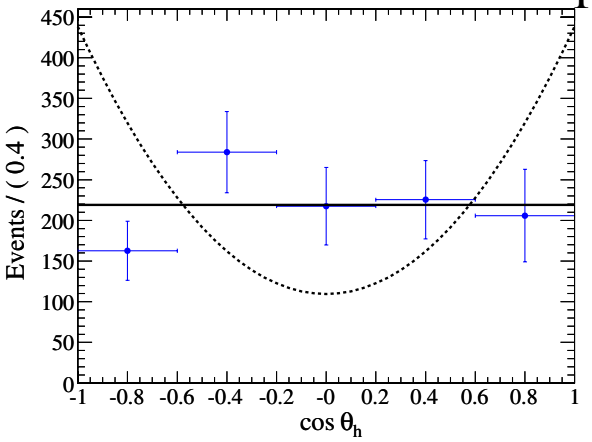
Quantum number determination

- J^P assignment of charmed baryons are mostly from quark model.
  - BaBar determined spin of $\Sigma_c(2455)$ in $B^- \to \Sigma_c(2455)^0 p^{bar}$ as ½.

PRD 78, 112003 (2008)



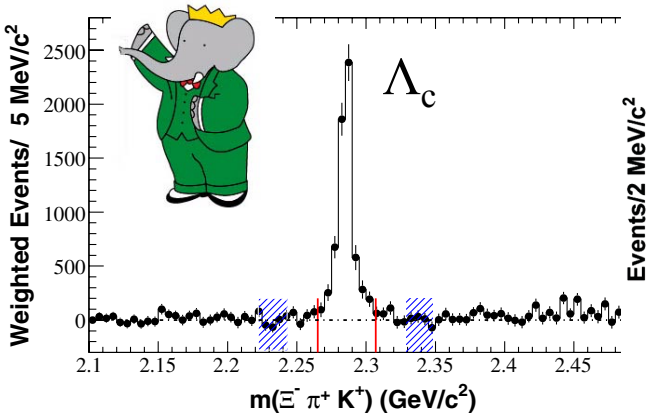


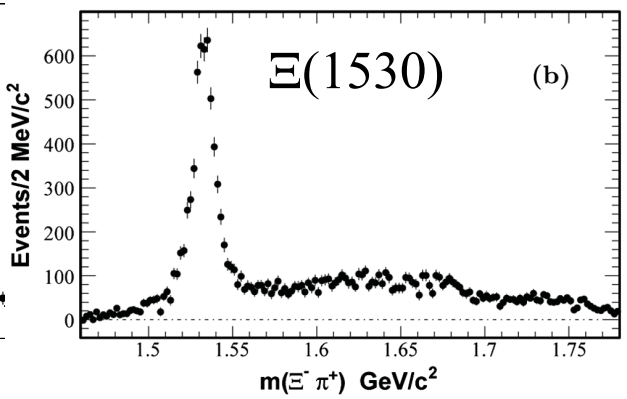


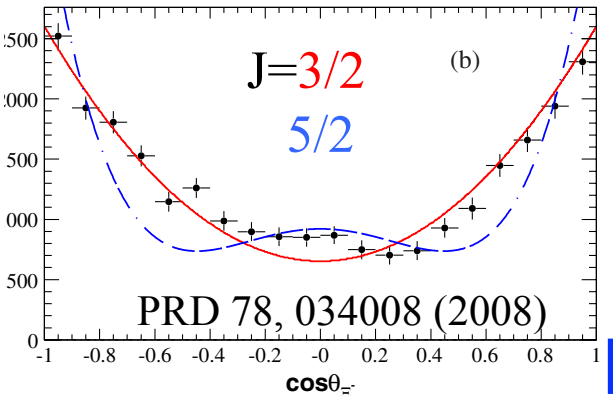
J=3/2

J=1/2

- BaBar measured spin of $\Xi(1530)$ hyperon as 3/2 from $\Lambda_c^+ \to \Xi^-\pi^+K^+$.
  - BaBar determined spin of Ω^- as ½ from $\Xi_c \to \Omega K$ decay, PRL97, 112001(2006).
  - Application for other resonances are interesting tasks for Belle, Belle II.

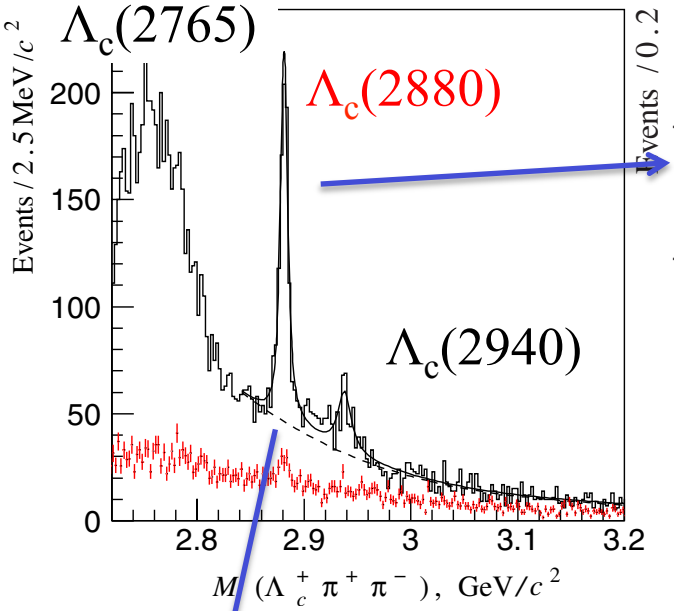


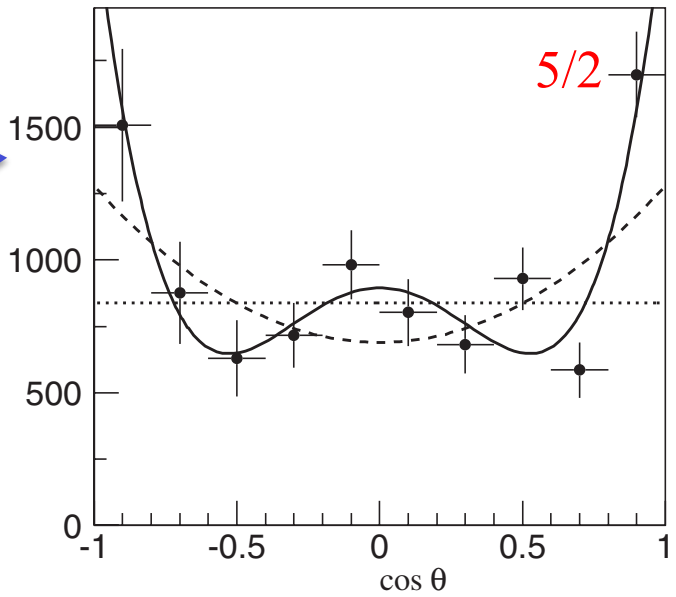




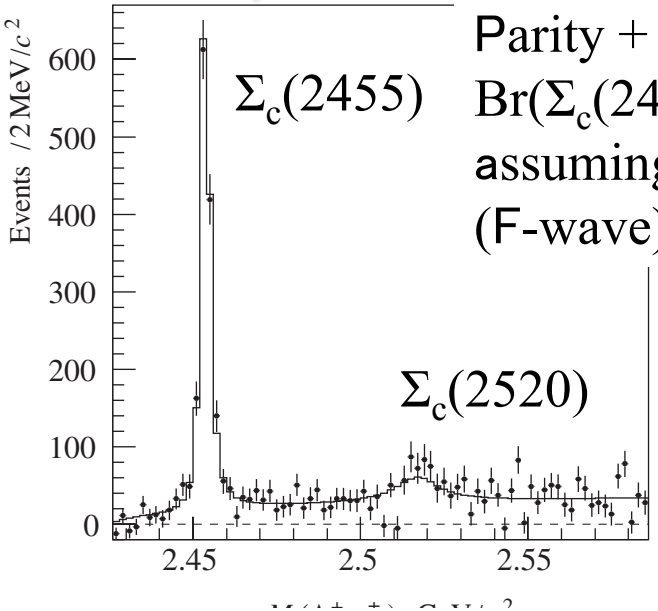
J^P of $\Lambda_c(2880)^+$ at Belle

PRL98,262001(2007)





Spin 5/2 : from decay angular distribution



Parity + : from
$Br(\Sigma_c(2455)\pi)/Br(\Sigma_c(2520)\pi)$
assuming heavy quark symmetry.
(F-wave)

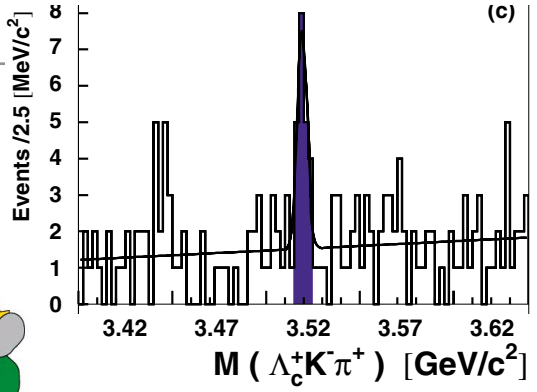
Application for other states is possible at Belle and Belle II.

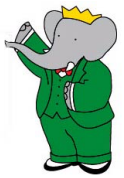
Search for Ξ_{cc}

SELEX, BaBar and Belle results

- Evidence in $M(\Lambda_c^+ K^- \pi^+)$ from SELEX at 3.52 GeV
- Not seen in BaBar ($232 fb^{-1}$) and Belle ($462 fb^{-1}$) data.

SELEX PRL89,112001(2002)



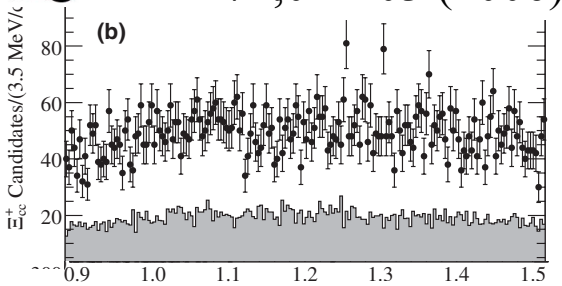


- Search using Belle full statistics has been performed.

No evidence.

95% UL of $\sigma(e^+e^- \to \Xi_{cc} X) \times Br(\Xi_{cc}^+ \to \Xi_c^0 \pi^+) \times Br(\Xi_c^+ \to \Xi^- \pi^+)$
0.076-0.35 fb ⇔ Theory 0.18-0.5 fb (Br=5%)

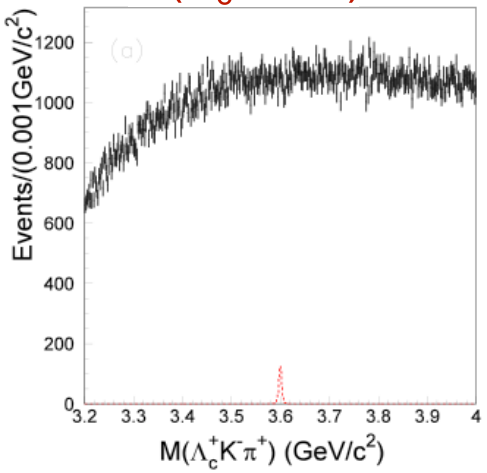
PRD 74,011103 (2006)



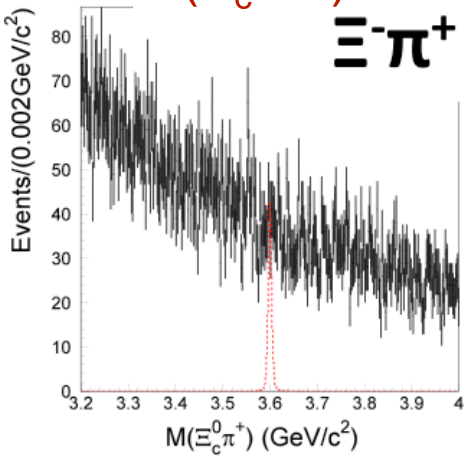
- LHCb also has negative result.

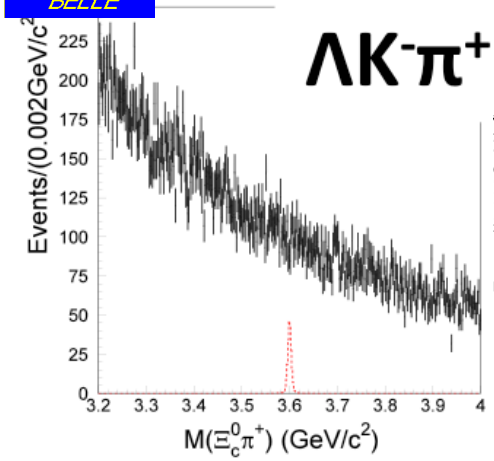
PRD 89.052003 (2014)

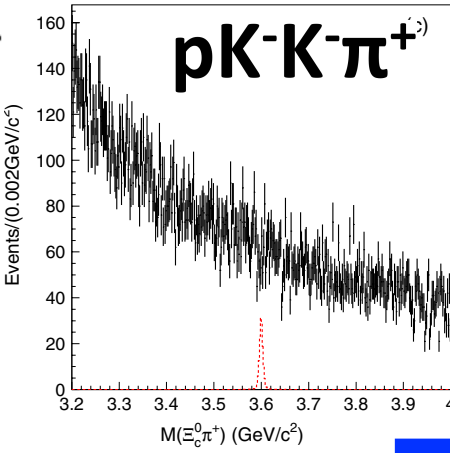
$M(\Lambda_c^+ K^- \pi^+)$



$M(\Xi_c^0 \pi^+)$





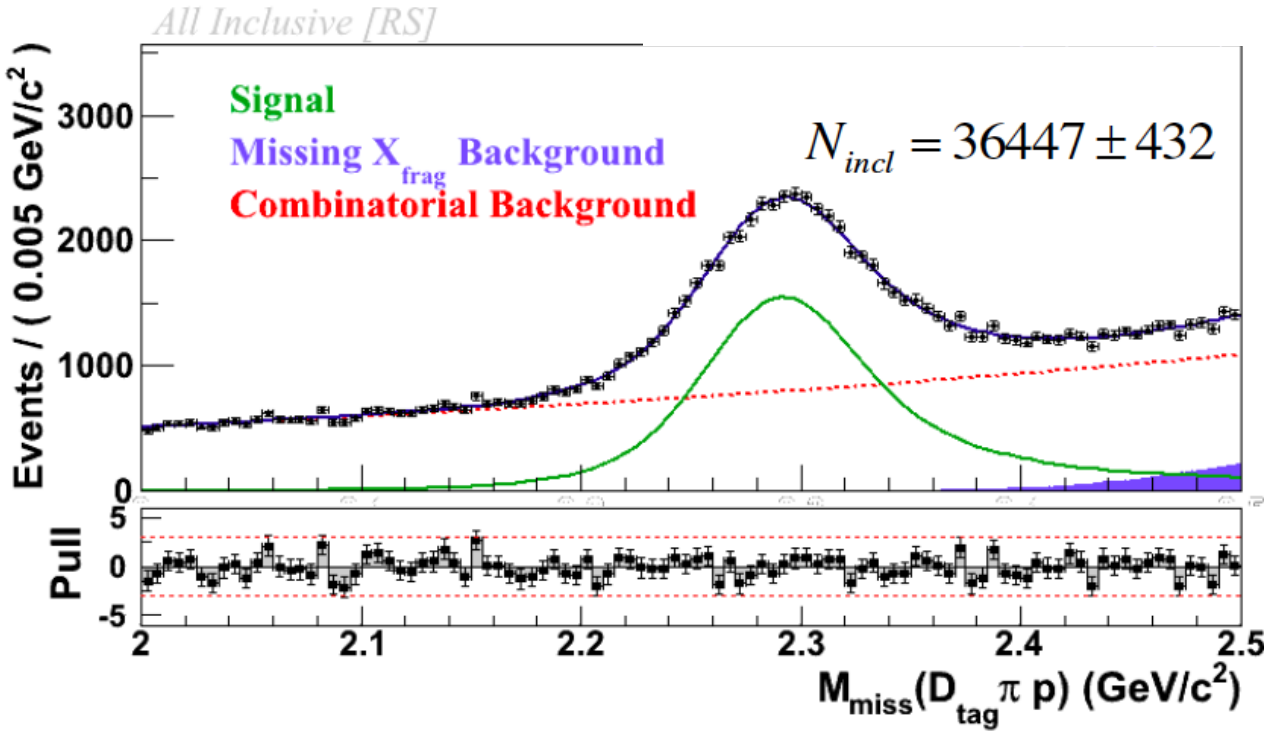


Absolute BR of Λ_c^+

Absolute BR of Λ_c^+

- PDG: BR($\Lambda_c^+ \to p K^- \pi^+$) = 5.0±1.3%
  - Combinaition of model-dependent measurements
- Normalization BR for charmed baryons
- $e^+e^- \to c\bar{c} \to D_{tag}\bar{p}\pi^+\Lambda_c^+$, $D_{tag} = D^{(*)-}$

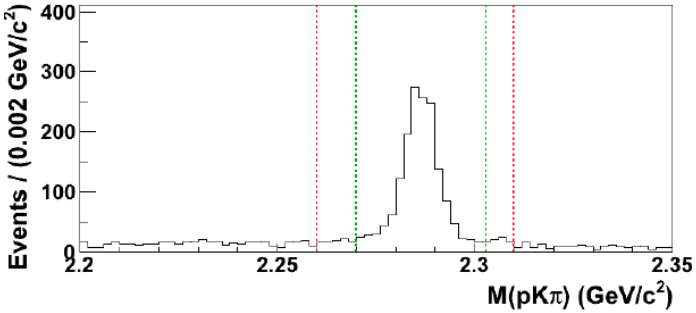
$$M_{miss}(D_{tag}X_{frag}p) = \sqrt{(p_{e^+} + p_{e^-} - p_{D_{tag}} - p_{X_{frag}} - p_p)^2}$$



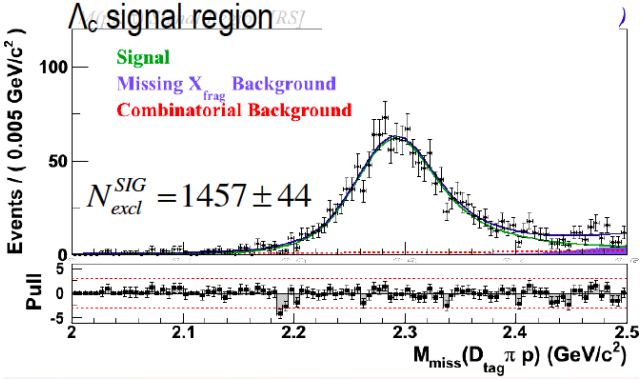
Absolute BR of Λ_c^+

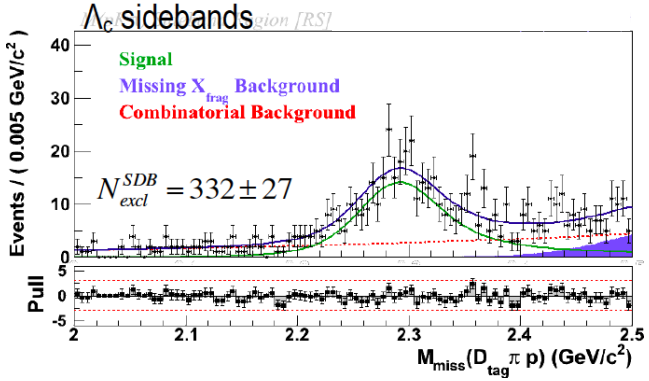
PRL113, 042002(2014)

- Exclusive Λ_c^+ sample within inclusive sample: all tracks from $\Lambda_c^+ \to p K^- \pi^+$ required



- Exclusive signal from M_{miss} for $M(pK^-\pi^+)$ in $\Lambda_c$signal region minus yield in sidebands





- $Br(\Lambda_c^+ \to pK^-\pi^+) = (6.84 \pm 0.24^{+0.21}_{-0.27})\%$
  - Slightly higher value than PDG with high precision.
- Significant improvement of current PDG value

  PDG(5.0±1.3%)

Source	Uncertainty [%]
Tracking	1.1
Proton ID	0.4
Efficiency	1.1
Dalitz model	1.1
f_{bias}	1.5
Bkg. subtraction	$^{+0.5}_{-0.9}$
Fit Model	$^{+1.7}_{-2.9}$
Total	$^{+3.0}_{-3.9}$

Baryon production rates

Baryon production rate in e^+e^- collision

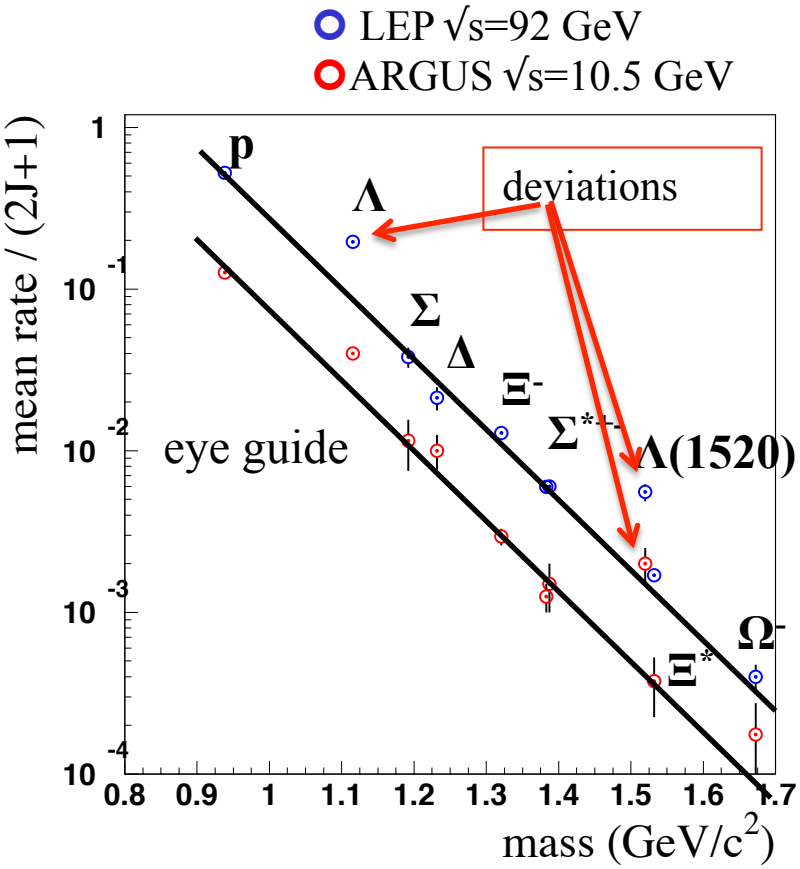
- Inclusive $e^+e^- \rightarrow h + X$ cross section

$$\frac{\sigma}{\sigma_{had}(2J+1)} \propto \exp(-\alpha m_{had})$$

  - Relativistic-string model
    S.B. Chun & C.D. Buchanan, PLB 308(1993)153
  - Thermodynamical model,
    F. Becattini Z.Phys. C69 (1996) 485

- Higher rate for Λ and Λ(1520) in LEP.
  - J=0, light (ud) di-quark in Λ?
    R.L.Jaffe, Phys.Rept.409,1 (2005)
- Higher rate for Λ(1520) in ARGUS.
- Feed down subtraction to Λ?
- How about charmed baryons?

  → Check with high precision Belle data!

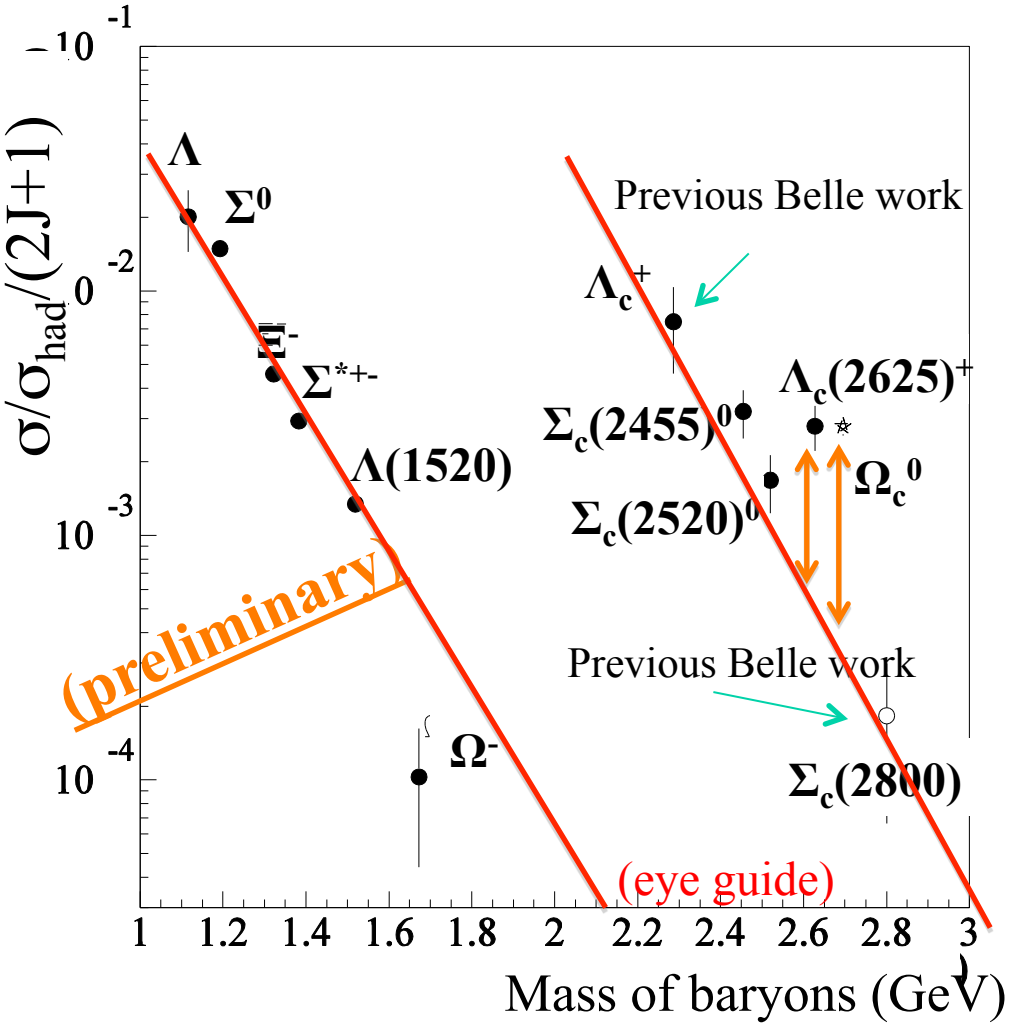


Preliminary results from Belle

- Enhancement of Λ, Λ(1520) is not clear.
  - ARGUS observation on Λ(1520) is not confirmed.
- Suppression of Ω^-
  - g → ss suppress? Check Ξ*
  - no J=0 diquark?
- High rate for $\Lambda_c(2625)^+$
  - Due to good diquark in Λ_c's?
  - Continue study

    ½⁻ $\Lambda_c(2595)^+$, 5/2⁺$\Lambda_c(2880)^+$
- Ω_c :no measurement of BR
  - phenomenological calculation.
    - BR(0.24±0.12%)
  - Theoretical input is needed!

- **Feed down to Λ,Σ,Σ*,Λ_c were subtracted**
- **σ_{had} = 2.794 nb**
- **w/o radiative correction**



Summary

- Charged charmonium-like states are established.
  - $J^P = 1^+$ for $Z_c(4430)$, $Z_c(3900)$ and $\Gamma(D\bar{D}^*)/\Gamma(J/\psi)$ of $Z_c(3900)$ are obtained.
    - $J/\psi\pi$ ($\psi'\pi$) or $D\bar{D}^*$ molecule, $c\bar{c}$ core is there?
  - More states have been discovered.
- Charmed baryon spectroscopy
  - Precise measurement of Σ_c isospin mass spliting. $\Delta m(\Sigma_c^{++} - \Sigma_c^0) = 0.22 \pm 0.014$ MeV
    - Comparison with quark model to obtain wave function.
  - Spectroscopy of excited Ξ_c's and Ω_c.
    - Mass, width, decay mode measurements.
    - Can we distinguish diquark (ρ, λ) excitation?
  - J^P assignments. $5/2^+$:$\Lambda_c(2880)^+$, ½:$\Sigma_c(2455)$, 3/2:$\Xi(1530)$, 1/2:Ω
  - Search for double charmed baryon.
  - Model independent absolute B.R. of Λ_c^+. $(6.84 \pm 0.24^{+0.21}_{-0.27})\%$
    - What about Ξ_c, Ω_c ? Even model dependent estimation is helpful.
  - Baryon production rates.
- Actively studied! More results will come from BaBar, Belle and Belle II