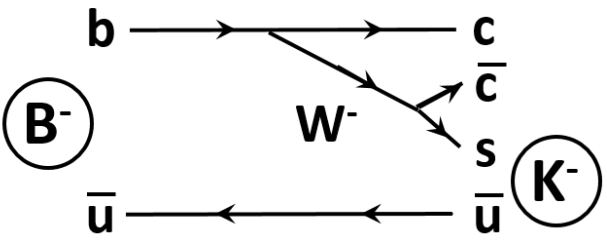
Prospect in hadron spectroscopy at Belle II

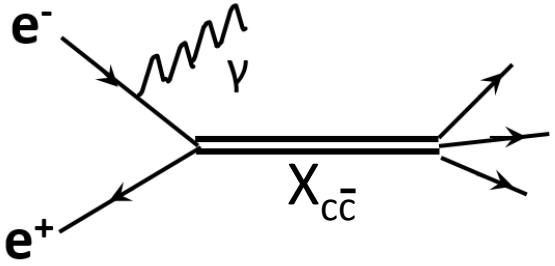
Y. Kato (KMI, Nagoya)

Kobayashi-Maskawa Institute for the Origin of Particles and the Universe

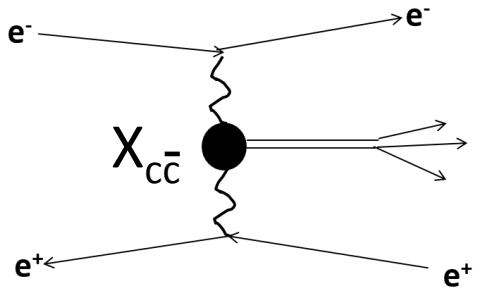
B-factory = hadron factory!



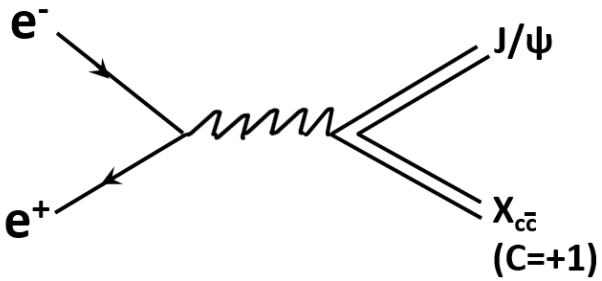
B meson decay
- 1^+, $0^{-/+}$ ….
- X(3872), Z(4430)….
- Open charm hadrons



Initial state radiation
- $J^{PC}=1^{--}$
- Y(4260)

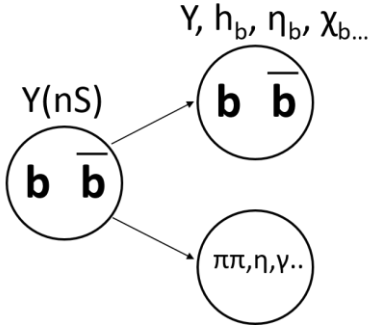


Two photon collision
- $J^{PC}=0^{++}$, 2^{++}….
- Extract two photon width



Double charmonium
- C-even charmonium

$e^+e^-\to c\bar{c}$
Charm mesons/baryons



Bottomonium transition
Z_b states

"New hadrons" from B-factories

Hadron Type

Reaction

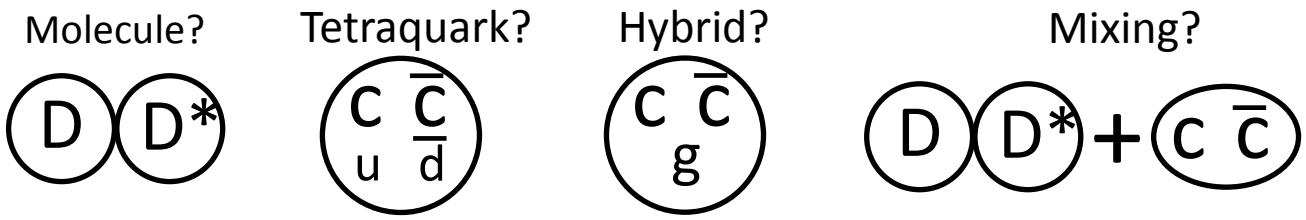
	Charmonium	Bottomonium	D, $D_{(s)}$	Charmed baryon	Hyperon
B-decay	$\eta_c(2S)$ $\psi_2(3823)$ $X(3872)$ $X(3915)$ $Z_c(4050)$ $Z_c(4250)$ $Z_c(4430)$ $Z_c(4200)$		$D^*_0(2400)$ $D_1(2430)$	$\Xi_c(2930)$	Belle BaBar
Initial State Radiation	$Y(4260)$ $Z(3900)$ $Y(4008)$ $Y(4360)$ $Y(4660)$				
Double charmonium	$X(3860) \doteqdot \chi_{c0}(2P)$ $X(3940)$ $X(4160)$				
Two photon	$\chi_{c2}(2P)$				
$e^+e^- \to c\bar{c}$			$D^*_{s0}(2317)$ $D_0(2550)$ $D_J^*(2600)$ $D_J(2740)$ $D_3^*(2750)$ $D^*_{s1}(2700)$ $D^*_{s1}(2860)$ $D_{sJ}(3040)$	$\Sigma_c(2800)$ $\Lambda_c(2940)$ $\Xi_c(2980)$ $\Xi_c(3080)$ $\Omega_c(2770)$ $\Xi_c(3055)$	
Y(nS) decay		$Z_b(10610)$ $Z_b(10650)$ $\eta_b(1S)$ $\eta_b(2S)$ $h_b(1P)$ $h_b(2P)$			$\Omega(2012)$

~ 40 new hadrons!

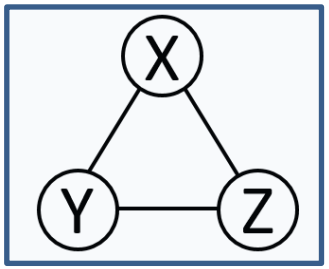
(Some states may be missed)

What we want to know further?

- Nature of **each XYZ?**
  - Steve's talk

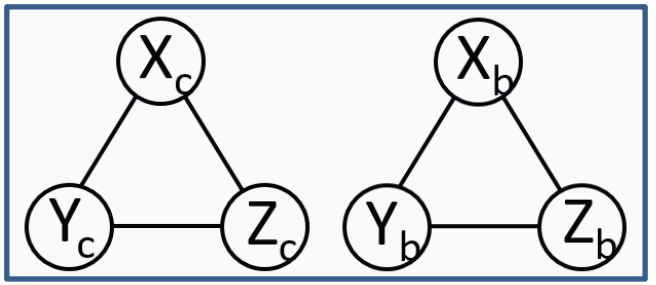


- Understand (part of) XYZ in a **unified way?**
  - Fengkun's talk



New multiplet?

- Understand **charm and bottom in a unified way?**
  - Umberto's talk



Further new multiplet?

- What we can learn from **open charm hadrons?**
  - Heavy quark symmetry
  - Exotic states
  - Di-quark degree of freedom

Outline

- Overview of hadron spectroscopy at B-factories

- Charmed mesons
  - Heavy quark spin symmetry
  - B-factory achievements
  - $D_s(2317)^+$, $D_s(2460)^+$

- Charmed baryons
  - Di-quark in charmed baryons
  - B-factory achievements
  - Spin determinations, new states, strange factory.

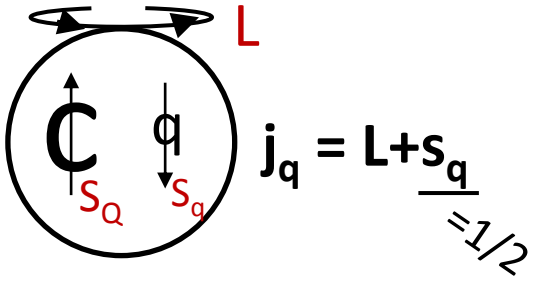
- "Rediscoveries" in Belle II phase 2

See review paper
"Open charm hadron spectroscopy at B-factories" (arXiv:1810.03748)
for more detail

Charmed mesons

Heavy quark spin symmetry (HQSS)

- The spin-spin interaction $\propto 1/m_q m_Q \fallingdotseq 0$ $m_Q \to \infty$
  $\to S_Q$ is conserved.

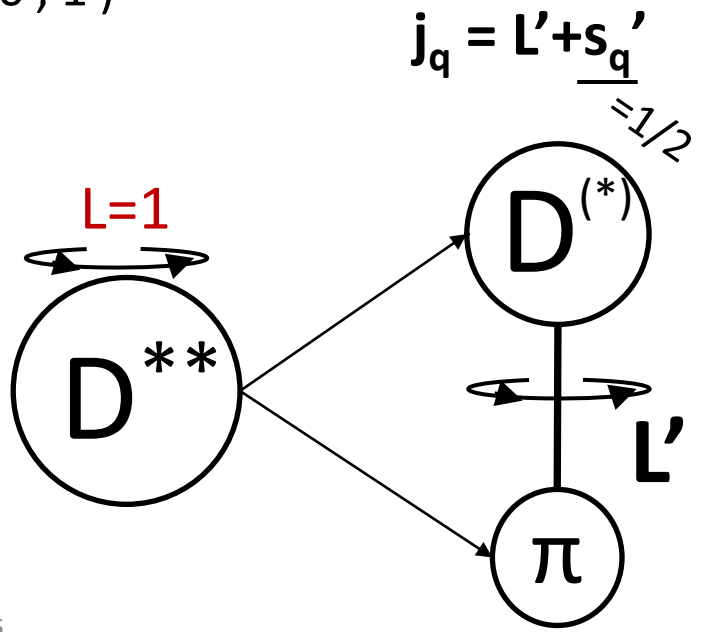


- Total spin $J = S_Q + j_q$
  $\to j_q$ is also a good quantum number.
  $J = j_q \pm 1/2 \to$ Heavy quark spin doublet (degenerate in heavy quark limit).

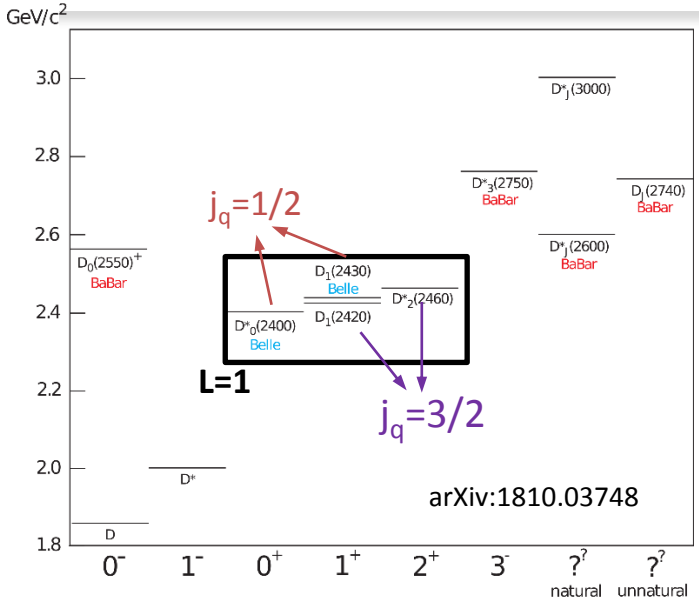
- ex: The ground states (L=0) have $j_q^p = 1/2 \to D$ and D^* $(0^-, 1^-)$

- In case of L=1,
  j_q = either 1/2 or 3/2 → two HQS doublets.

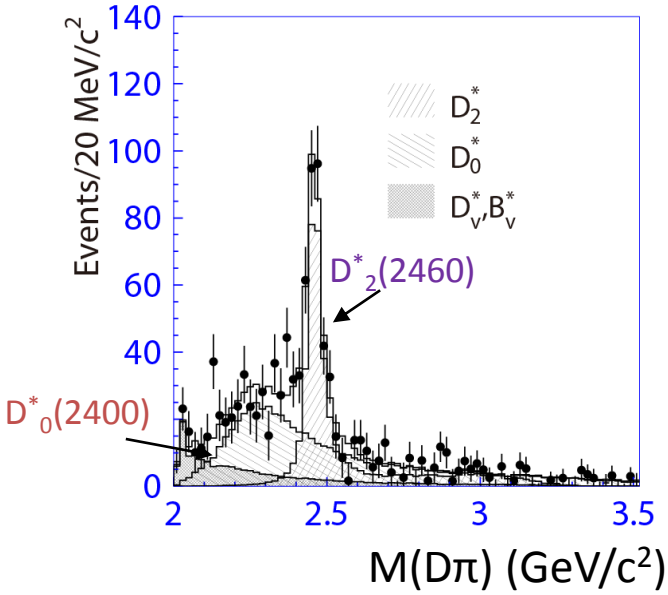
- In $D^{**} \to D^{(*)}\pi$ decay, L' between $D^{(*)}$ pi is S-wave for $j_q = 1/2$ and D-wave for $j_q = 3/2$.
  → Two broad and two narrow states.

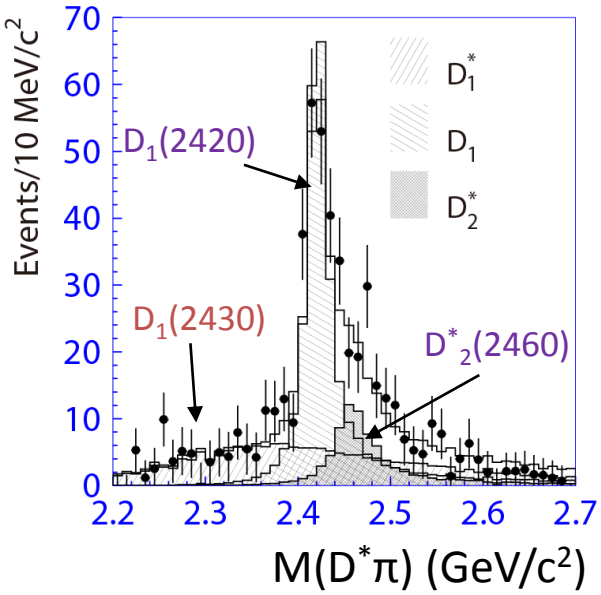


D meson family by B-factories



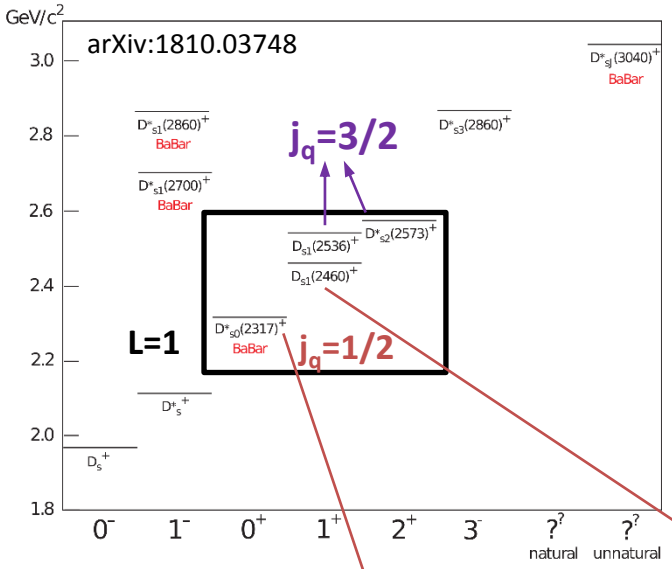
- Before the start of B-factory, L=1, j_q = 3/2 were discovered = $D_1(2420)$, $D^*_2(2460)$
- Belle observed j_q = 1/2 states, $D^*_0(2400)$ and $D_1(2430)$.
- Indeed two narrow states and two broad states!
- BaBar observed many higher states.



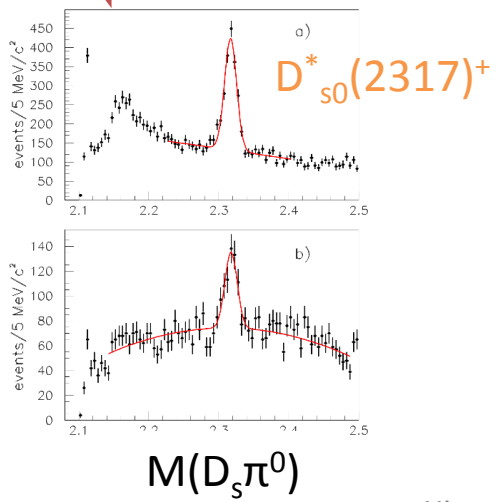


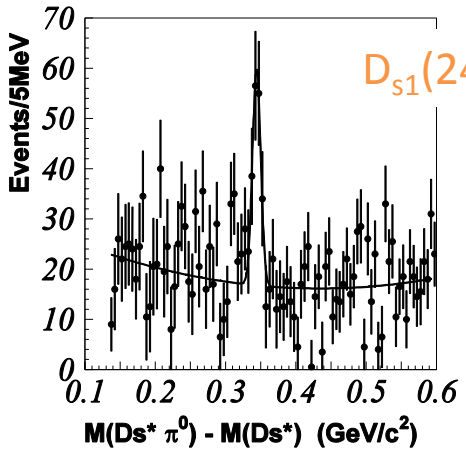
Phys. Rev. D 69, 112002

So how is D_s meson family?



- Before the start of B-factory, L=1, j_q = 3/2 are discovered = $D_{s1}(2536)$, $D^*_{s2}(2573)$
- BaBar observed $D^*_{s0}(2317)^+$ and CLEO observed $D_{s1}(2460)^+$.
- Widths are very narrow
  - $D^{(*)}_s{}^+\pi^0$ is isospin violating decay.
- The mass is too small ($D^{(*)}K$ channel not opened)
  - ~ 100 MeV smaller than quark model prediction.
  - Even smaller than non-strange charm partner.



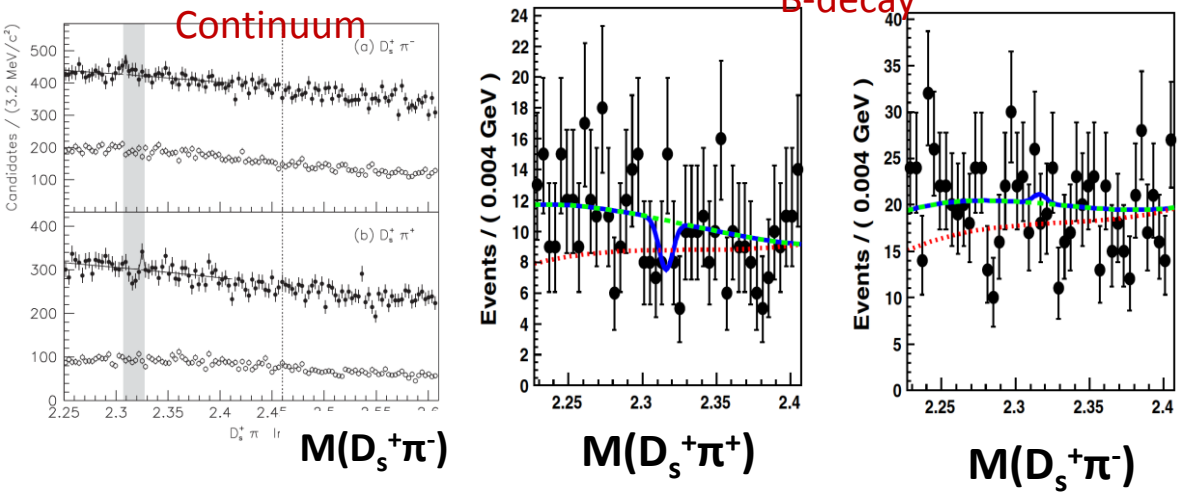


Nature of $D^*_{s0}(2317)$ and $D_{s1}(2460)$?

- Many models ... (cs, molecule, tetraquark..)

- **Simple cs state?**
  - Masses significantly below the predictions.

- **Tetraquark?**
  - Isospin one preferred, but partner searches failed. (CS/BR one order smaller)



- **$D^{(*)}$ K molecule state ?**
  - They are just ~40 MeV below $D^{(*)}K$ threshold
  - $M_{DS1(2460)} - M_{D^*s0(2317)} \doteqdot M_{D^*} - M_D$ can be explained by HQSS (arxiv: 1712.07957).

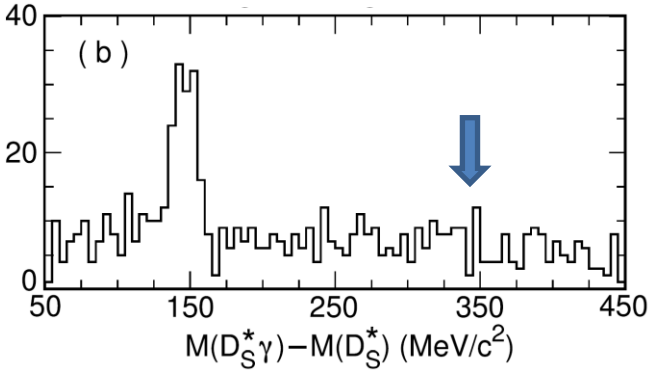
Phys. Rev. D 74, 032007

Phys. Rev. D 91, 092011

Future measurements

- **Radiative decay**
  - $\frac{\Gamma(D^*_{s0}(2317) \to D^*_s{}^+ \gamma)}{\Gamma(D^*_{s0}(2317) \to D_s{}^+ \pi^0)} < 5.9\%$
  - Theory predictions:
    - -- Molecule: 0.7 - 1.8% (Phys. Rev. D 76, 014005) and $10 \pm 4\%$ (Eur.Phys.J. A50 149)
    - -- $c\bar{s}$: 19% (Phys.Lett. B568 254-260)
  - Statistics limited. Belle II can reach < 1%

Phys. Rev. D 68, 032002



- **Total width**
  - Only upper limit: 3.8 MeV for $D^*_{s0}(2317)$ and 3.5 MeV for $D^*_{s1}(2460)$.
  - Prediction: O(10 keV) in $c\bar{s}$ picture, ~100 keV in molecule.
  - Measure width of ~100 keV with π^0 is a challenge.
    - -- The mass resolution is ~6 MeV/c^2 at Belle for $D_s(2317)^+$.
    - -- May possible at PANDA by $pp^{bar} \to D_S\, D_S(2317)^+$ cross section at threshold.
  - Need an idea to improve the mass resolution.
    - -- Use B-decay and apply additional constraint.

Charmed baryons

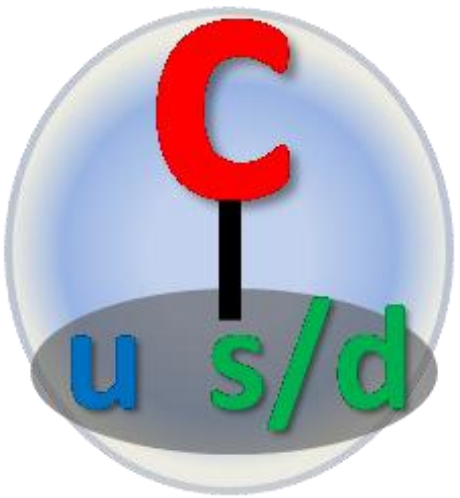
Physics of charmed baryons

- Charm quark is heavy: (1500 MeV/c^2) > u,d,s quarks (300-500 MeV/c^2)
- spin-spin interaction $\propto 1/m_1 m_2$
- Di-quark correlation in light quarks (more simple! New d.o.f!).

Nucleon

Every pair can not be distinguished.

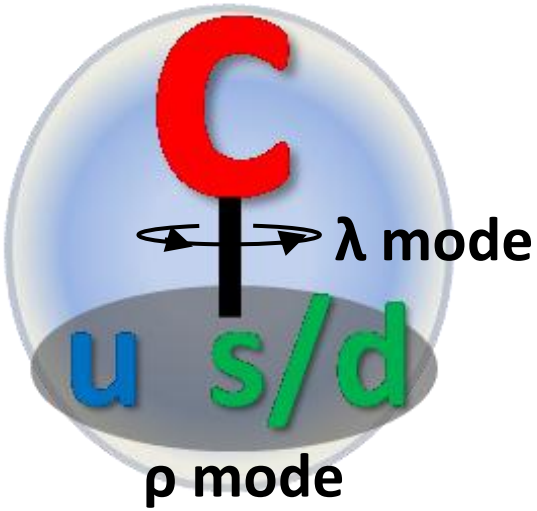
Charmed baryon



Light di-quark and charm quark.

Excitation modes

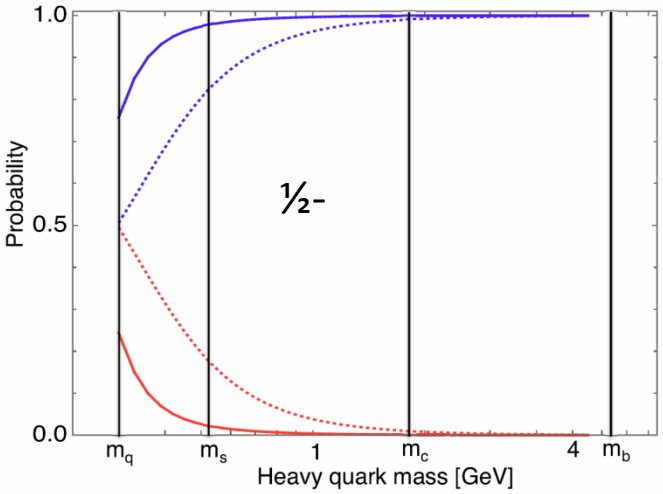
- There are two kind of excitation modes.
  - λ mode: excitation between c quark and u-d di-quark.
  - ρ mode: excitation in the di-quarks.



$$\frac{h\omega_\rho}{h\omega_\lambda} = \sqrt{\frac{3m_Q}{2m_q + m_Q}} \sim= \sqrt{3}$$

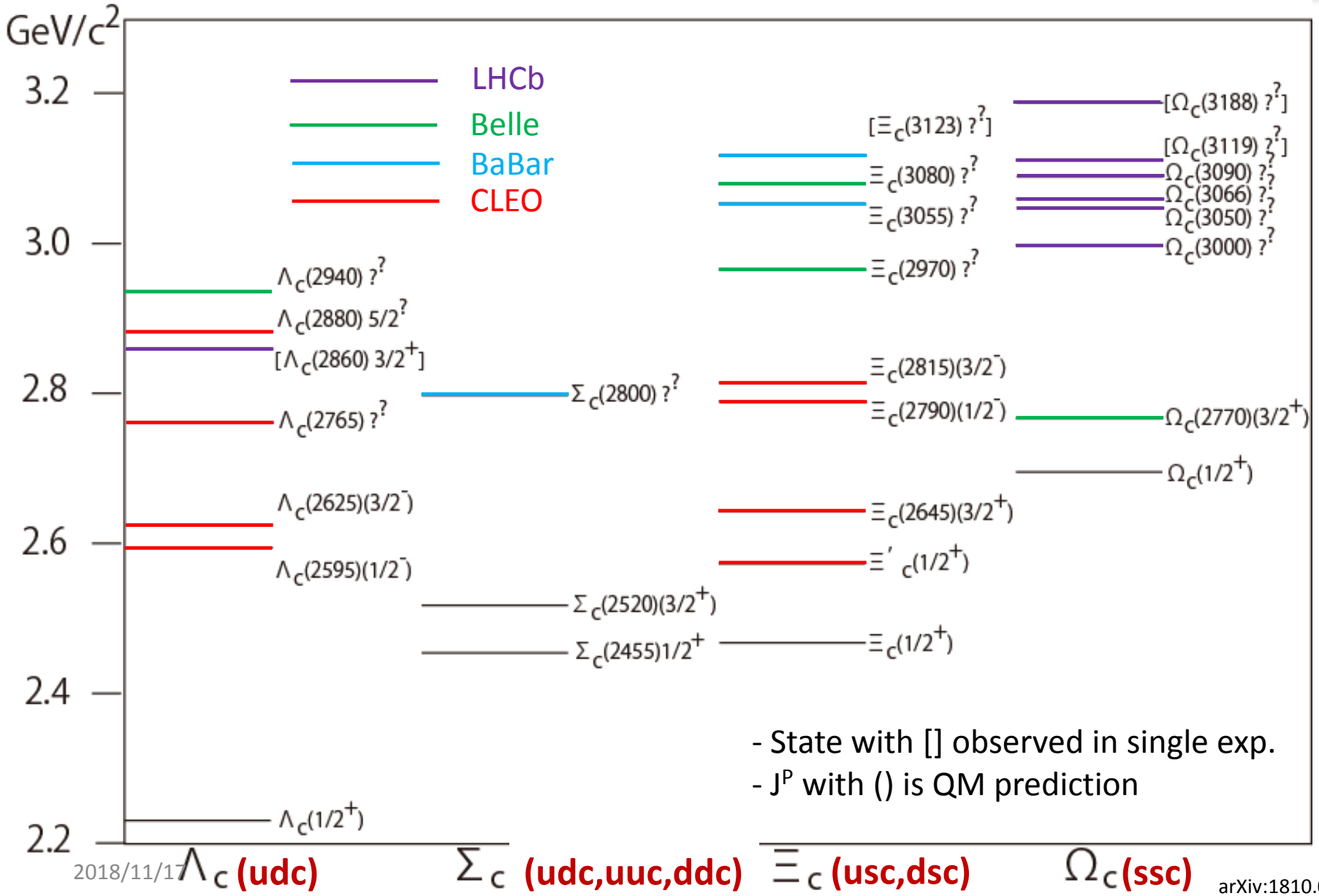
The fraction of λ mode for the 1st excited state.

T. Yoshida et al. PRD 92, 114029 (2015)



- No clear indication of ρ and λ mode yet.
- **There should be two $J^P=1/2^-$ states.**
- Experimentally, discover charmed baryons, study the property and check global consistency with di-quark picture.

Observed charmed baryons



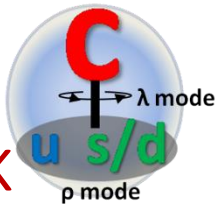
arXiv:1810.03748

Achievements and missing things

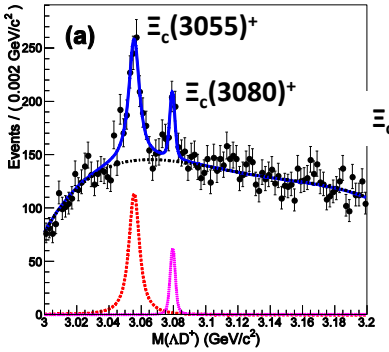
- All the ground states and many excited states observed.
- J^P for a few states determined.
- Many decay modes observed.
  - Separation of λ - ρ mode.
- Very precise mass determinations.
  - Isospin splitting depends on baryons.

However…

- Still two $1/2^-$ states not observed!
  - Even for λ mode, it is from QM.

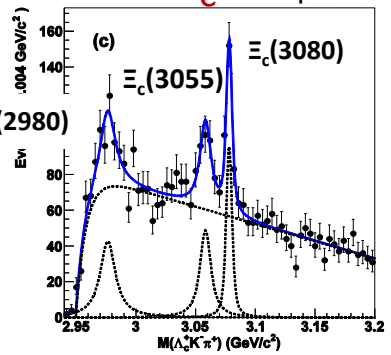


ΛD



Phys. Rev. D 94, 032002

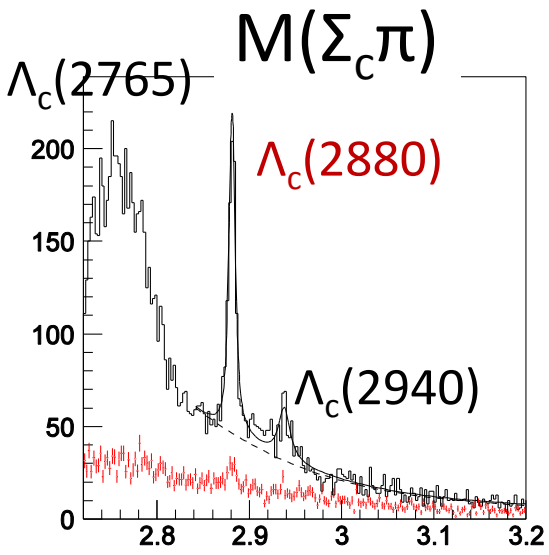
$\Sigma_c K$



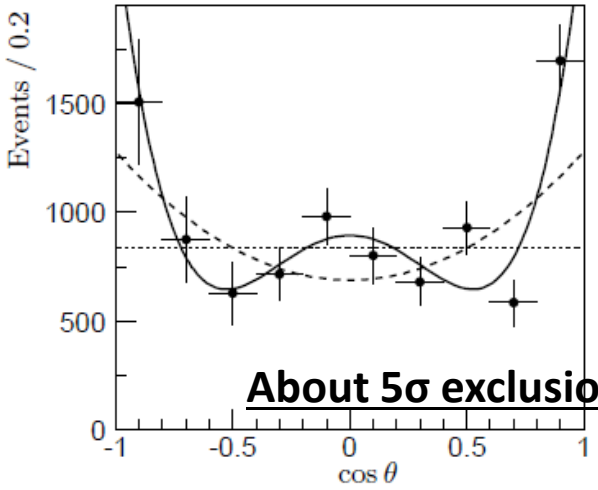
Phys. Rev. D 89, 052003

Particle	$M(\Xi_c^+) - M(\Xi_c^0)$ (MeV/c^2)
$\Xi_c(2645)$	$-0.85 \pm 0.09 \pm 0.08 \pm 0.48$
$\Xi_c(2815))$	$-3.47 \pm 0.12 \pm 0.05 \pm 0.48$
$\Xi_c(2980))$	$-4.8 \pm 0.1 \pm 0.2 \pm 0.5$
$\Xi_c'^+$	$-0.8 \pm 0.1 \pm 0.1 \pm 0.5$
$\Xi_c(2790))$	$-3.3 \pm 0.4 \pm 0.1 \pm 0.5$

J^P determination at Belle



$\Lambda_c^+(2880)$ $\Sigma_c\pi$ decay angular distribution



J=5/2

J=3/2

J=1/2

Phys. Rev. Lett. 98, 262001

About 5σ exclusion for spin 1/2, 3/2

The decay angular distribution for spin 5/2.

$$W_{5/2} = \frac{3}{8}[\rho_{55}2(5\cos^4\theta - 2\cos^2\theta + 1) + \rho_{33}(-15\cos^4\theta + 14\cos^2\theta + 1) + \rho_{11}5(1-\cos^2\theta)^2]$$

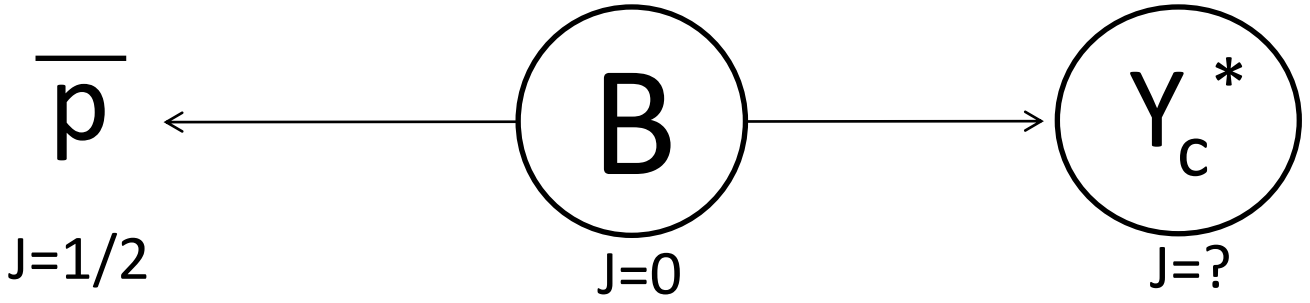
- Decay angular distribution depends on helicity fraction (ρ_{ii}).
  Difficult to predict ρ_{ii} in continuum production.

- If a charm baryon is not polarized (ρ_{ii} have same value), angular distribution becomes flat.
  → It is difficult to distinguish spin 1/2 and no polarization.

Spin prospect at Belle II

- B-meson two body decay constrains the helicity to be ½
  as B meson has spin zero and proton has spin ½. This largely reduce uncertainty

- Statistics at current B-factory is not good enough for higher excited states.

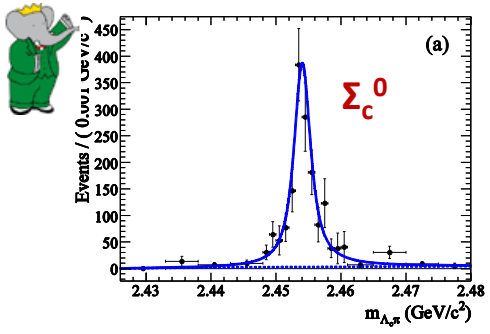


Higher excited states observed!

$B \to \Xi_c(2930)\Lambda_c$, $\Xi_c(2930) \to K\Lambda_c$

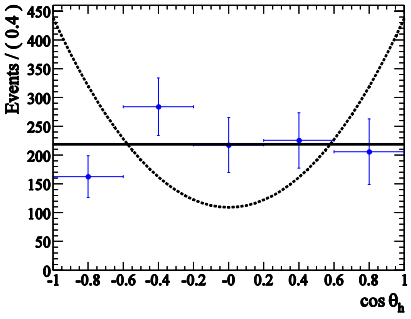
Example

$B \to \Sigma_c^0 p^{bar}$, $\Sigma_c \to \Lambda_c^+ \pi^-$

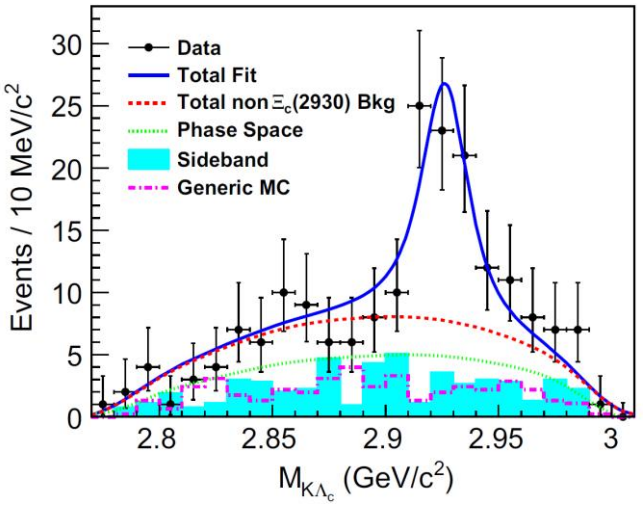


10.1103/PhysRevD.78.112003

$\Lambda_c^+ \pi^-$ angular distribution



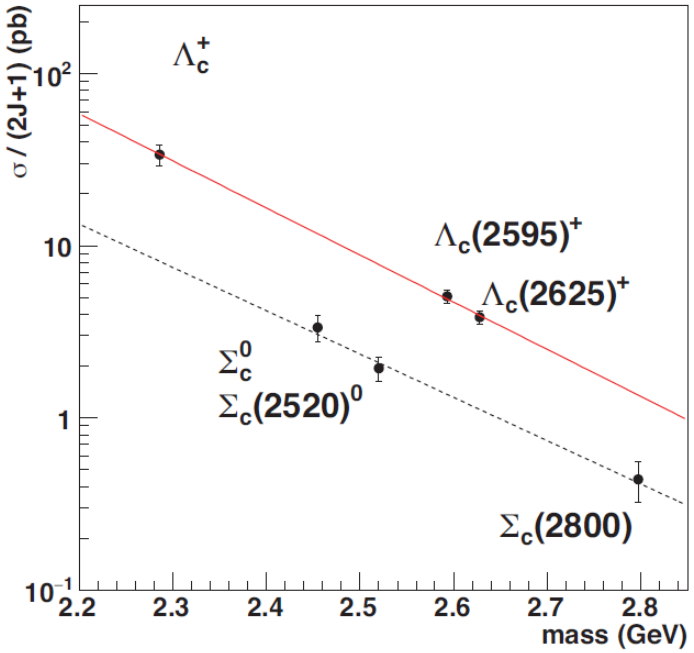
S=1/2, exclude 3/2 by ~4σ



Eur. Phys. J. C (2018) 78: 252.

Discovery of new excited states

Phys. Rev. D **97**, 072005



- Cross section decrease with mass by exponential curve (~1/2 with 100 MeV increase)
- CLEO reached discovery of $\Lambda_c^+(2880)$.
  B-factories reached $\Lambda_c(2940)^+$, $\Xi_c(3080)$, $\Omega_c(3119)^+$
  - ~200 MeV higher sensitivity.
- We may have another 2-300 MeV sensitivity at Belle II, right?
- ρ mode, Roper, and higher excited states.

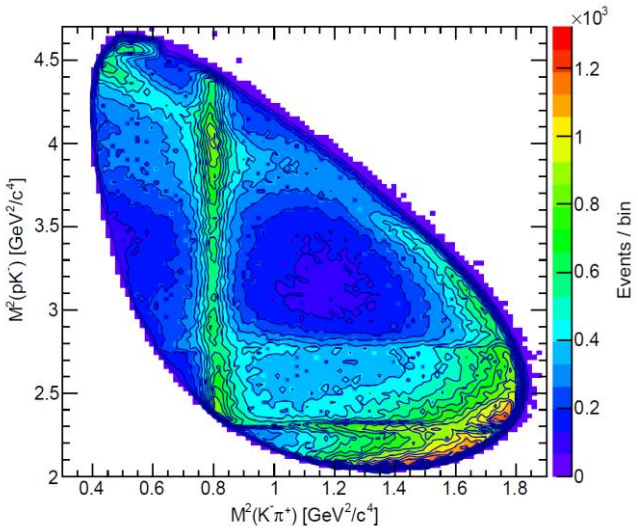
Charm baryon as strange factory

- Ground state charm baryons proceed via c→s transition.
  → Good laboratory to study baryons including strange quarks.

- There are couple of examples on these analysis recently from Belle.

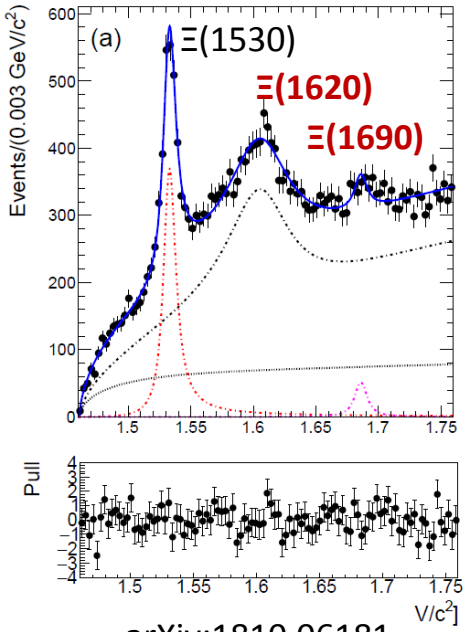
- Rare process, Ω_c decays, etc should be available at Belle II.

$\Lambda_c^+ \rightarrow pK^-\pi^+$



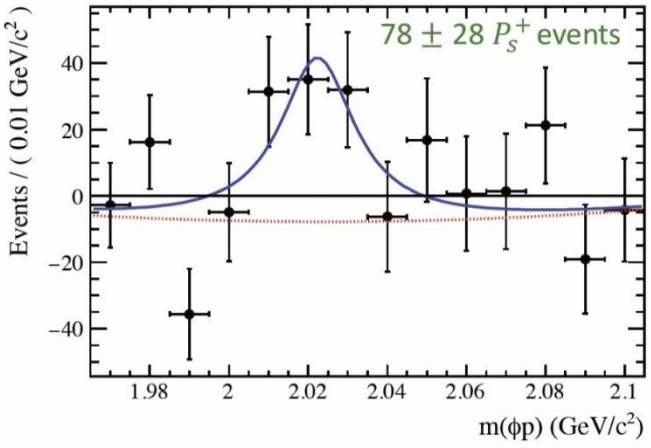
Phys. Rev. Lett. 117, 011801

$\Xi_c^+ \rightarrow \Xi^*\pi$, $\Xi^* \rightarrow \Xi^-\pi$



arXiv:1810.06181

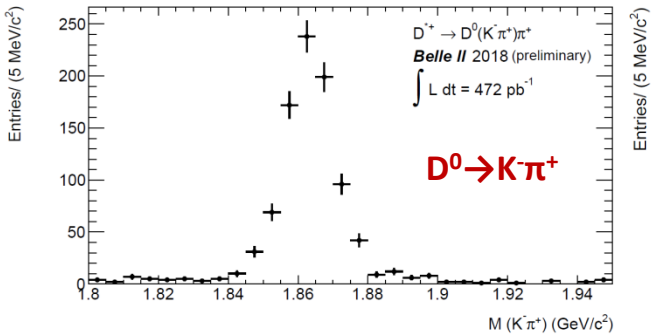
$\Lambda_c^+ \rightarrow P_s\pi^0$, $P_s \rightarrow \phi p$ (only 2σ)

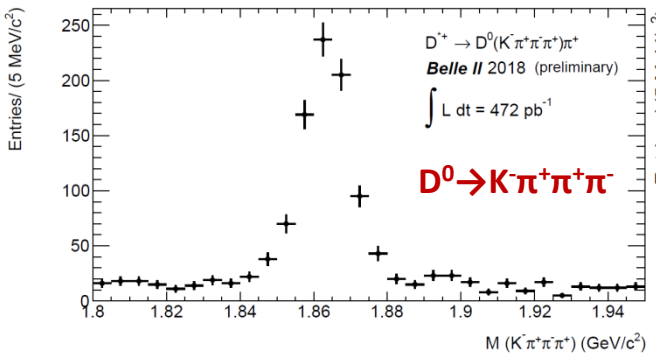


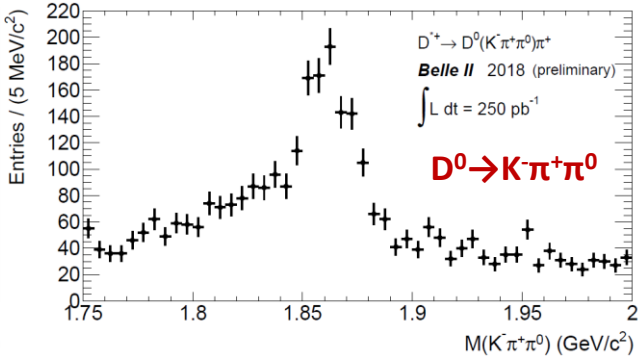
Phys. Rev. D 96, 051102(R)

Charm mesons already observed at Phase 2!

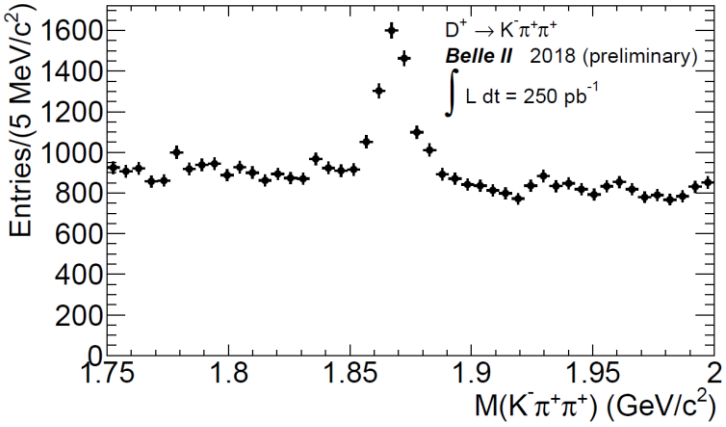
$D^{*+} \rightarrow D^0\pi^+$



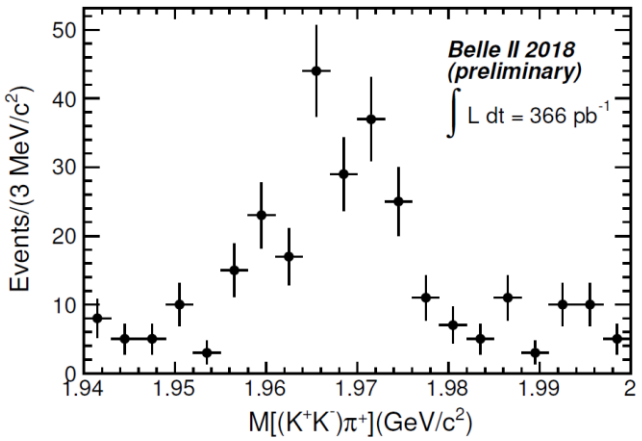




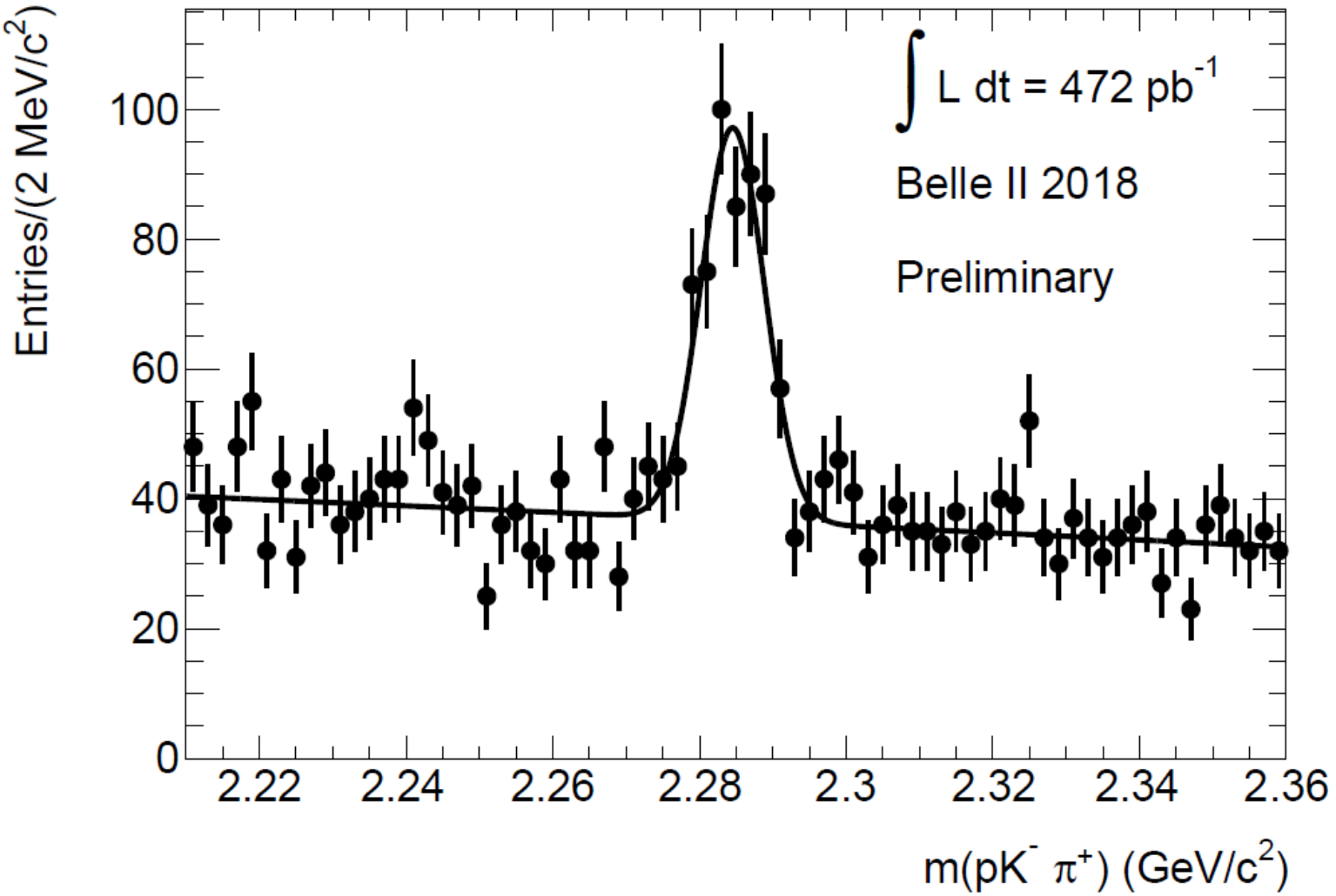
$D^+ \rightarrow K^-\pi^+\pi^+$



$D_s^+ \rightarrow \phi\pi^+$



… and Λ_c^+!



***To be approved?

Summary

- Charm hadrons is unique laboratory to explore low energy QCD.
- Homeworks from B-factory: $D_s(2317)^+$, $D_s(2460)^+$
  -- Radiative decay, decay width at Belle II.
- Understand Di-quark degree of freedom in charm baryons
  - Spin, observe new states..
- Charm baryon weak decay is another field for strange baryons.

Stay tuned for Belle II phase3!