第十九届重味物理与CP破坏研讨会

Recent results of charmed baryons (non-CPV)

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Outline

- **About decays**
  - SCS decay $\Lambda_c^+ \rightarrow pK_S^0K_S^0$ and CF decay $\Lambda_c^+ \rightarrow pK_S^0\eta$
  - SCS decay $\Omega_c^0 \rightarrow \Xi^-\pi^+, \Omega^-K^+$, and DCS decay $\Omega_c^0 \rightarrow \Omega^-\pi^+$
  - Radiative decay $\Lambda_c^+ \rightarrow \Sigma^+\gamma$ and $\Xi_c^0 \rightarrow \Xi^0\gamma$
  - Measurement of the $Br(\Xi_c^0 \rightarrow \Lambda_c^+\pi^-)$
  - Semileptonic decay: $\Omega_c^0 \rightarrow \Omega^-l^+\nu$
- **About resonances**
  - Cups at M_{pK} in $\Lambda_c^+ \rightarrow pK^-\pi^+$ decay
  - Evidence of $\Lambda_c(2910)^+$ in $\overline{\mathrm{B}}^0 \rightarrow \Lambda_c(2910)^+\bar{p}$

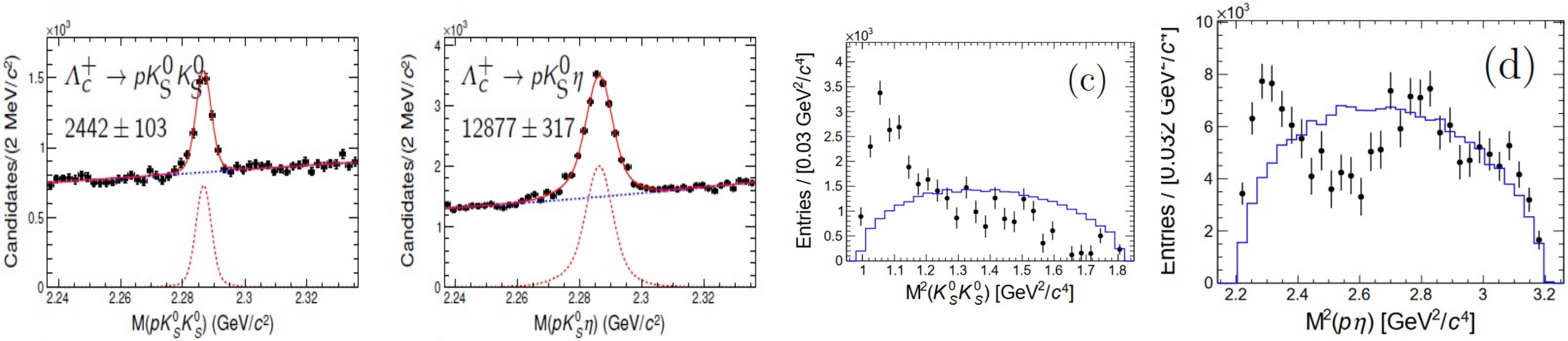
SCS decay $\Lambda_c^+ \to pK_S^0K_S^0$ and $\Lambda_c^+ \to pK_S^0\eta$

- The weak decays of charmed baryons provide an excellent platform for understanding QCD with transitions involving the charm quark.

arXiv: 2210.01995, Accepted by PRD

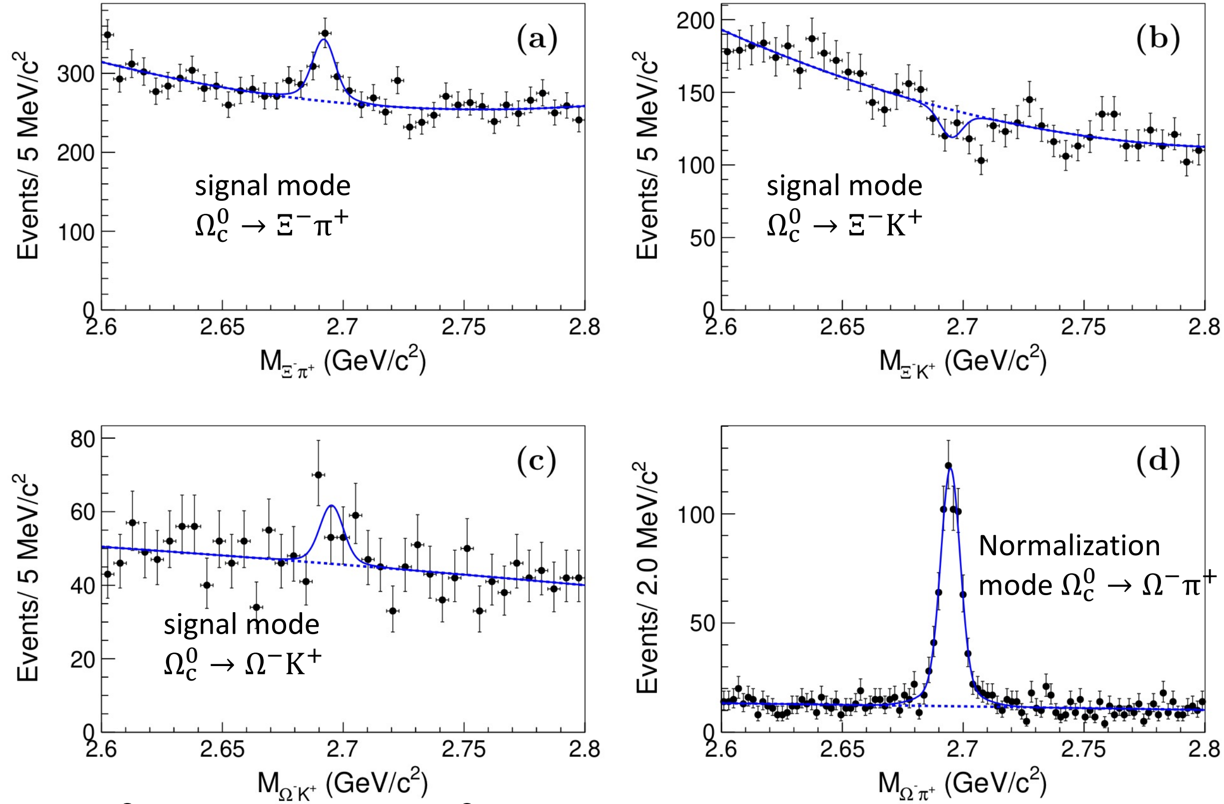
- Their decay amplitudes consist of factorizable and non-factorizable contributions, the latter approached by various models: covariant confined quark model, current algebra, $SU(3)_F$ symmetry, etc.

- Experimentally, the investigation of charmed baryons is more challenging than that of charmed mesons. (mainly due to lower production rates)



$$\mathcal{B}(\Lambda_c^+ \to pK_S^0K_S^0) = (2.35 \pm 0.12 \pm 0.12) \times 10^{-4}\text{, (First observation)}$$
$$\mathcal{B}(\Lambda_c^+ \to pK_S^0\eta) = (4.35 \pm 0.10 \pm 0.22) \times 10^{-3}\text{, (Vs PDG } (4.15 \pm 0.90) \times 10^{-3}\text{)}$$

SCS decay $\Omega_c^0 \to \Xi^-\pi^+, \Omega^- K^+$, and DCS decay $\Omega_c^0 \to \Xi^- K^+$



arXiv: 2209.08583,
Accepted by JHEP

First evidence of $\Omega_c^0 \to \Xi^-\pi^+$ with a signal significance of **4.5σ** including systematic uncertainties.

No significant signals are found in $\Omega_c^0 \to \Omega^- K^+$ and $\Omega_c^0 \to \Xi^- K^+$.

$$\mathcal{B}(\Omega_c^0 \to \Xi^-\pi^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+) = 0.253 \pm 0.053 \pm 0.030$$

Larger than current algebra and pole [PRD 101, 094033] 0.104 and LFQM [CPC 42, 093101] 1.96×10^{-3}

The upper limits at 90% CL:

$$\mathcal{B}(\Omega_c^0 \to \Omega^- K^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+) < 0.29.$$

$$\mathcal{B}(\Omega_c^0 \to \Xi^- K^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+) < 0.070$$

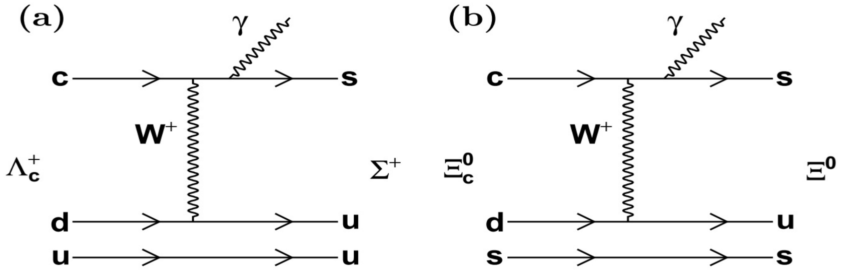
Consistent with current algebra and pole [PRD 101, 094033] 1.1×10^{-2} and LFQM [CPC 42, 093101] 1.7×10^{-4}

Weak radiative decays $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$

- Weak radiative decays of charmed hadrons are dominated by the long-range nonperturbative processes that can enhance the branching fractions up to 10^{-4}, whereas short-range interactions are predicted to yield rates at the level of 10^{-8}[1,2]

- At the Cabibbo-favored level, there are two decay modes for the weak radiative decays of anti-triplet charmed baryons induced from $cd \to us\gamma$, i.e., $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$ decays.

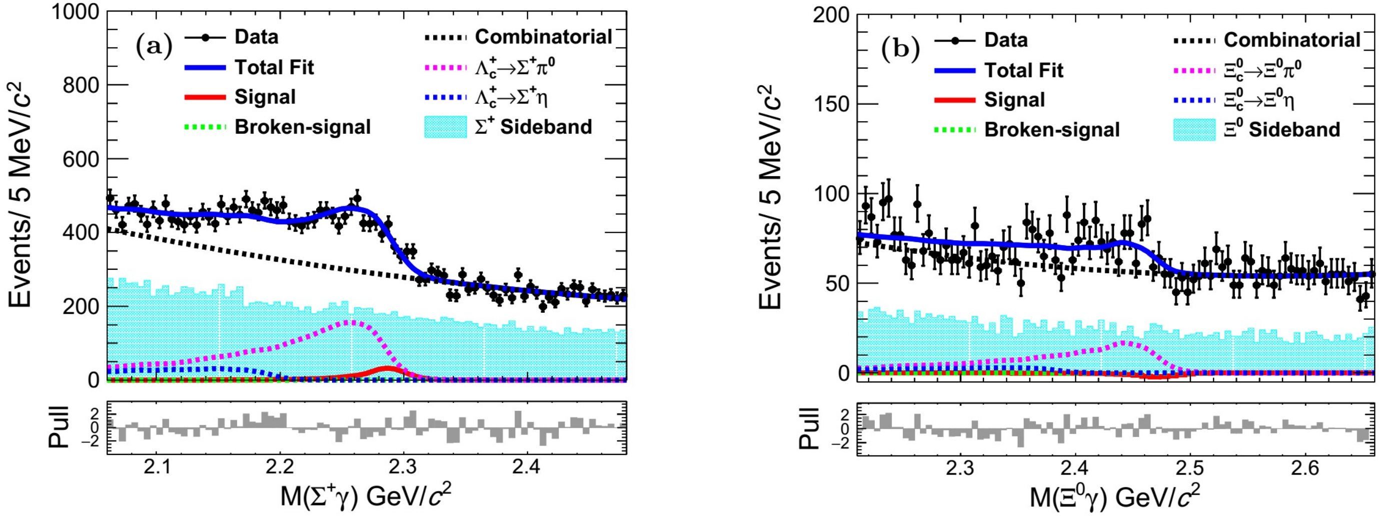
- The theoretical estimates of branching fractions cover ranges of $(4.5 - 29.1)\times 10^{-5}$ and $(3.0 - 19.5) \times 10^{-5}$ for $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$ decays, respectively [3-6].



[1]PRD 52, 6383 (1995); [2] PLB 382, 415 (1996); [3] PRD 28, 2176 (1983); [4] PRD 47, 2858 (1993); [5] PRD 51, 1199 (1995); [6] arXiv:2109.01216.

Weak radiative decays $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$

- There are no evident $\Lambda_c^+ \to \Sigma^+\gamma$ or $\Xi_c^0 \to \Xi^0\gamma$ signals.
- The signal significance of $\Lambda_c^+ \to \Sigma^+\gamma$ decay is only 2.2σ, after considering the systematic uncertainty.



arXiv:2206.12517
Accepted by PRD

- Taking $\Lambda_c^+ \to pK^-\pi^+$ and $\Xi_c^0 \to \Xi^-\pi^+$ as normalization channels, the upper limits at 90% confidence level (C.L.) on the ratios of branching fractions are

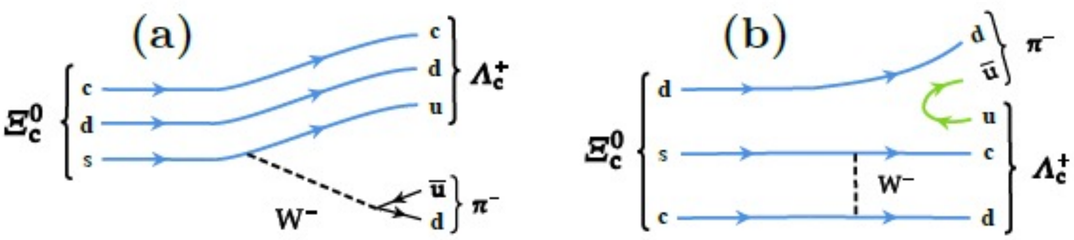
$$\frac{\mathrm{Br}(\Lambda_c^+ \to \Sigma^+\gamma)}{\mathrm{Br}(\Lambda_c^+ \to pK^-\pi^+)} < 3.99\times10^{-3} \qquad \frac{\mathrm{Br}(\Xi_c^0 \to \Xi^0\gamma)}{\mathrm{Br}(\Xi_c^0 \to \Xi^-\pi^+)} < 1.15\times10^{-2}$$

- The upper limits at 90% C.L. on the absolute branching fractions are determined to be

$$\mathrm{Br}(\Lambda_c^+ \to \Sigma^+\gamma) < 2.55\times10^{-4} \qquad \mathrm{Br}(\Xi_c^0 \to \Xi^0\gamma) < 1.73\times10^{-4}$$

Measurement of the $B(\Xi_c^0 \to \Lambda_c^+\pi^-)$

- There is a special class of weak decay, the heavy-flavor-conserving nonleptonic decays, that proceeds via the decay of the s quark, i.e. $\Xi_c^0 \to \Lambda_c^+\pi^-$.
- The decay width of $\Xi_c^0 \to \Lambda_c^+\pi^-$ is based on the size of the s quark decay amplitude of $s \to u(\bar{u}d)$ and the weak scattering amplitude $cs \to dc$.



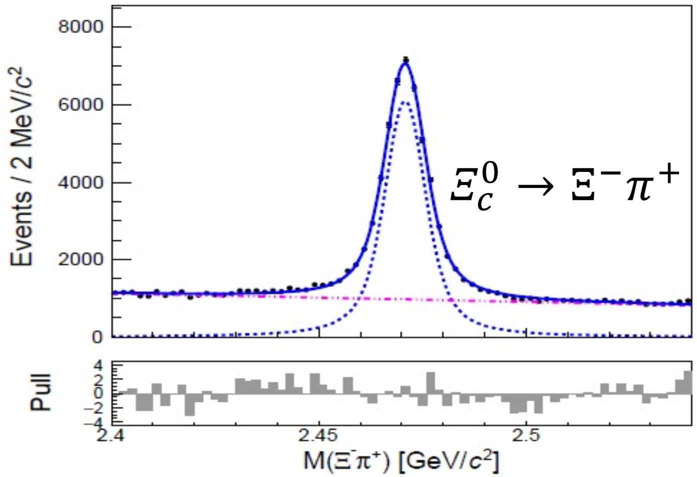
The Feynman diagrams of the (a) $s \to u(\bar{u}d)$ and (b) $cs \to dc$ modes of $\Xi_c^0 \to \Lambda_c^+\pi^-$.

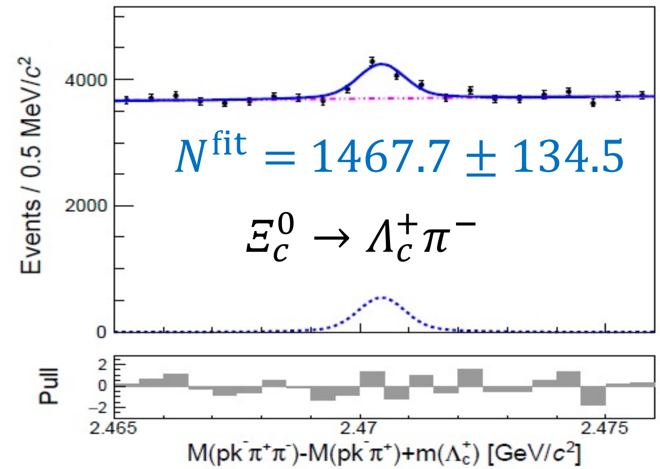
- The branching fraction of $\Xi_c^0 \to \Lambda_c^+\pi^-$ have been predicted based on the heavy quark expansion and the heavy quark symmetry (HQS).

Mode	[Phys. Rev. D 46, 5060 (1992)]	[Phys. Rev. D 100, 114030 (2019)]	[Phys. Lett. B 757, 330 (2016)]	[Phys. Lett. B 750, 653 (2015)]	JHEP 03, 028 (2016)
$\Xi_c^0 \to \Lambda_c^+\pi^-$	0.39×10^{-3}	$> (0.25 \pm 0.15)\times10^{-3}$	$(1.34 \pm 0.53)\times10^{-3}$	$< 3.9\times10^{-3}$	0.17

Measurement of the $B(\Xi_c^0 \to \Lambda_c^+\pi^-)$

arXiv:2206.08527
Accepted by PRD





$$\frac{Br(\Xi_c^0 \to \Lambda_c^+\pi^-)}{Br(\Xi_c^0 \to \Xi^-\pi^+)} = (3.8 \pm 0.4\ (\text{stat.}) \pm 0.04\ (\text{syst.})) \times 10^{-3}$$

$$Br(\Xi_c^0 \to \Lambda_c^+\pi^-) = (5.4 \pm 0.5 \pm 0.5 \pm 1.2) \times 10^{-3}$$

- The result is consistent with previous measurement by LHCb experiment [PRD 102, 071101 (2020)] and recent theoretical calculation, and larger than the previous theoretical predictions [PLB 826, 136916 (2022)].

Semileptonic decay: $\Omega_c^0 \to \Omega^- l^+ \nu$

Semileptonic decays of charmed baryons:

- be calculated with QCD factorization approach
- The cleanest processes among charm decays
- Decay rate depend on CKM matrix element $|V_{cq}|$ and strong interaction (form factor)
- Verify lepton universality.

$$\langle\Omega\,(p',s',s'_z)\,|V_\mu|\,\Omega_c(p,s,s'_z)\rangle = \bar{u}\,(p',s'_z)\,[\frac{p^\alpha}{m_{\Omega_c}}(F_1^V\gamma_\mu + F_2^V\frac{p_\mu}{m_{\Omega_c}} + F_3^V\frac{p'_\mu}{m_\Omega}) + g^{\alpha\mu}F_4^V]\gamma_5 u(p,s_z)$$

$$\langle\Omega\,(p',s',s'_z)\,|A_\mu|\,\Omega_c(p,s,s'_z)\rangle = \bar{u}\,(p',s'_z)\,[\frac{p^\alpha}{m_{\Omega_c}}(F_1^A\gamma_\mu + F_2^A\frac{p_\mu}{m_{\Omega_c}} + F_3^A\frac{p'_\mu}{m_\Omega}) + g^{\alpha\mu}F_4^A]u(p,s_z)$$

Comparing with $\frac{1}{2}^+ \to \frac{1}{2}^+$

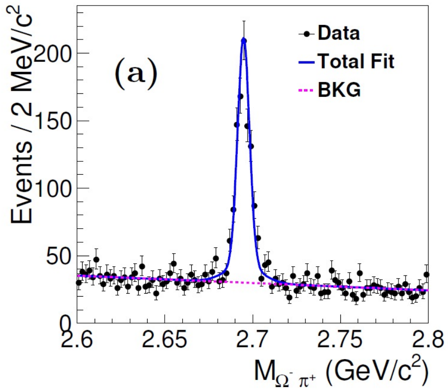
$$\langle B_q(p',s')|V_\mu|B_Q(p,s)\rangle = \overline{u}(p',s')\left(F_1(q^2)\gamma_\mu + F_2(q^2)\frac{p_\mu}{m_{B_Q}} + F_3(q^2)\frac{p'_\mu}{m_{B_q}}\right)u(p,s)$$

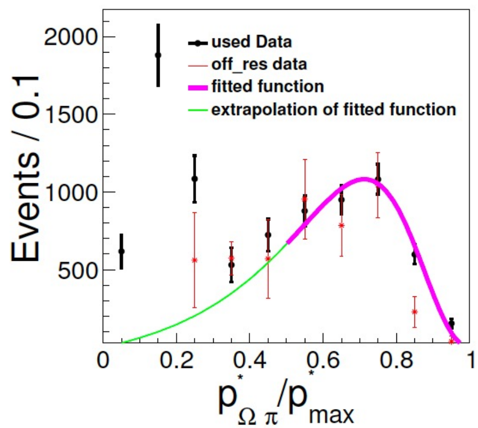
$$\langle B_q(p',s')|A_\mu|B_Q(p,s)\rangle = \overline{u}(p',s')\left(G_1(q^2)\gamma_\mu + G_2(q^2)\frac{p_\mu}{m_{B_Q}} + G_3(q^2)\frac{p'_\mu}{m_{B_q}}\right)\gamma_5 u(p,s)$$

Semileptonic decay: $\Omega_c^0 \rightarrow \Omega^- l^+ \nu$

$\Omega_c^0 \rightarrow \Omega^- \pi^+$: Fragmentation Function extraction

Phys. Rev. D 105, L091101 (2022)





Peterson's fragmentation function

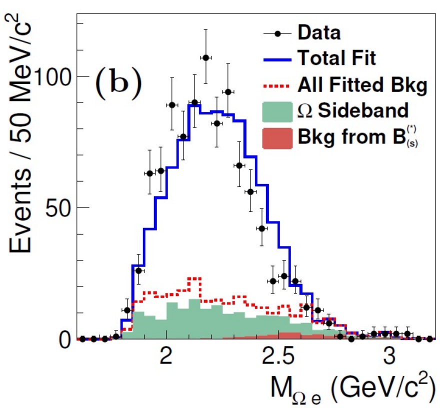
$$\frac{dN}{dx_p} \approx \frac{1}{x_p} \cdot \frac{1}{\left(1 - \frac{1}{x_p} - \frac{\epsilon_p}{1-x_p}\right)^2}$$

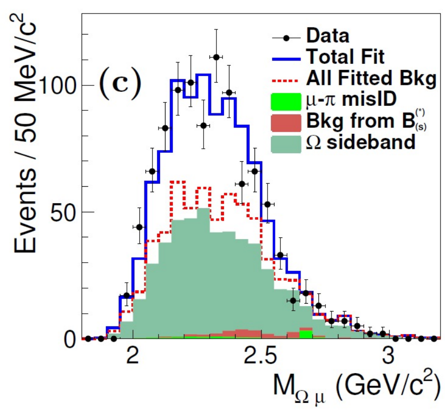
PRD 27, 105 (1983).

- data with $p^*_{\Omega\ell(\pi)}/p^*_{\max}$>0.5 used in fit
- $\epsilon_p = 0.1160 \pm 0.014$

$\Omega_c^0 \rightarrow \Omega^- \mu^+ \nu$: signal extraction

Data-driven method used for BKG shape





$$\frac{\mathcal{B}(\Omega_c^0 \rightarrow \Omega^- e^+ \nu)}{\mathcal{B}(\Omega_c^0 \rightarrow \Omega^- \pi^+)} = \mathbf{1.98 \pm 0.15}$$

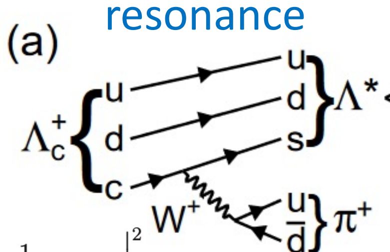
Previous: 2.4 ± 1.2 [PRL 89, 171803 (2002)]

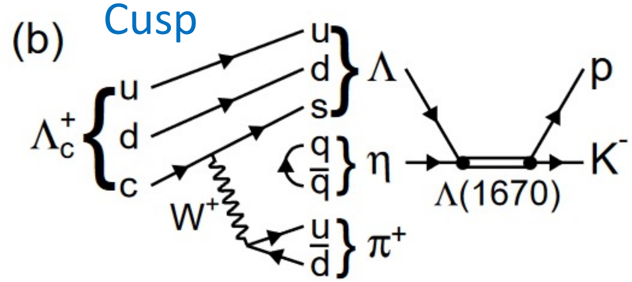
$$\frac{\mathcal{B}(\Omega_c^0 \rightarrow \Omega^- \mu^+ \nu)}{\mathcal{B}(\Omega_c^0 \rightarrow \Omega^- \pi^+)} = \mathbf{1.94 \pm 0.21}$$

Consistent with LFU

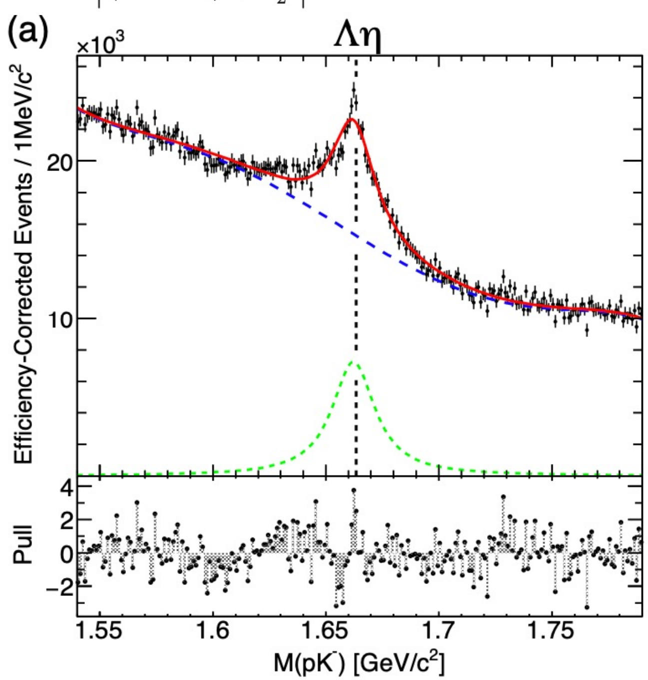
Cups at M_{pK} in $\Lambda_c^+ \to pK^-\pi^+$ decay ArXiv: 2209.00050

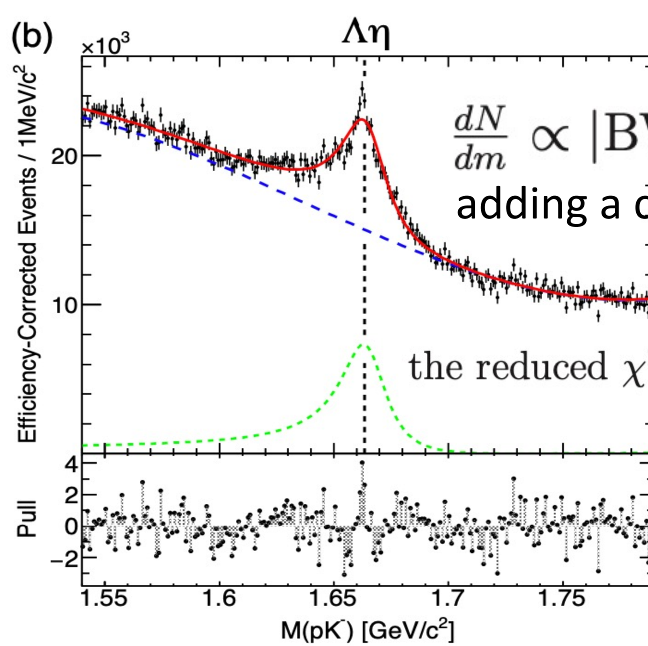
- **Cusp: a discontinuity in the derivative of spectrum function**
  - always appears exactly at the threshold,
  - its position does not reflect the pole position of a resonance





$$\frac{dN}{dm} \propto |\mathrm{BW}(m)|^2 = \left|\frac{1}{(m-m_0)+i\frac{\Gamma_0}{2}}\right|^2$$





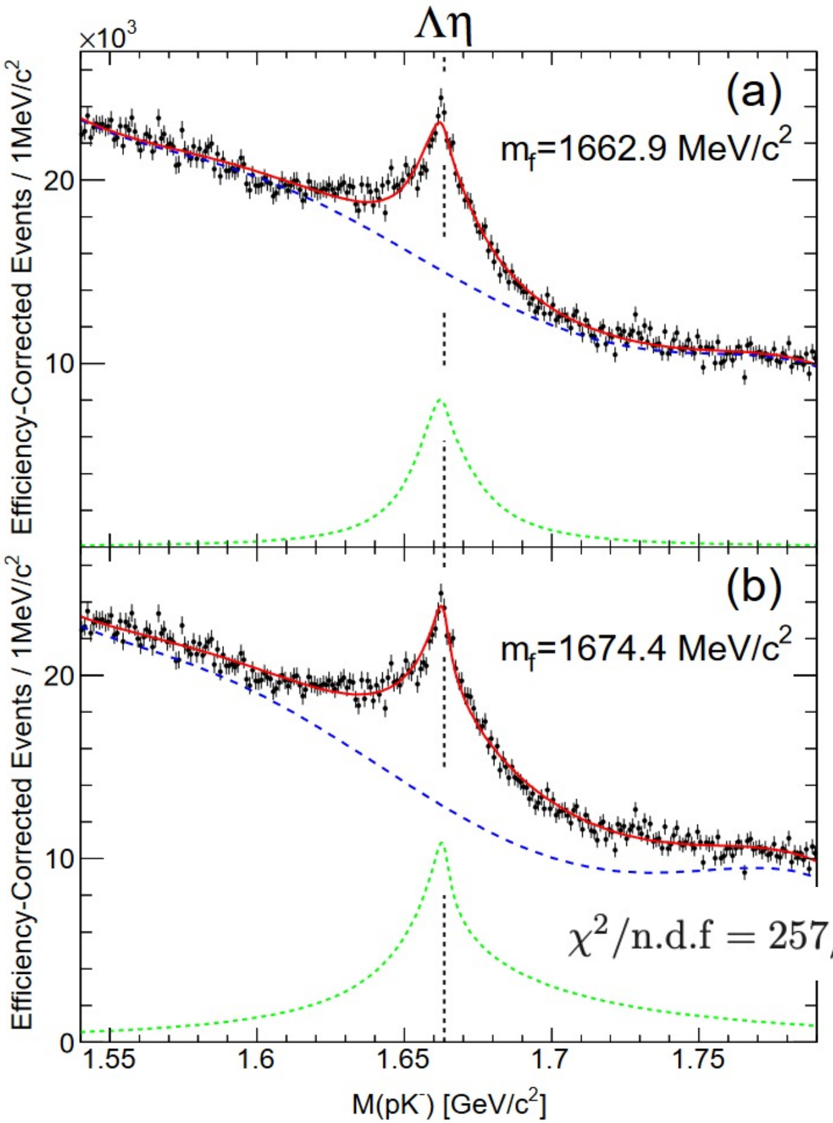
$$\frac{dN}{dm} \propto |\mathrm{BW}(m) + re^{i\theta}|^2$$

adding a complex constant

the reduced χ^2 of 1.27 (308/243)

Cups at M_{pK} in $\Lambda_c^+ \to pK^-\pi^+$ decay

arXiv: 2209.00050
Submitted to PRL



$\chi^2/\mathrm{n.d.f} = 257/243\ (p = 0.25)$

non-relativistic Flatte function

$$\frac{dN}{dm} \propto |f(m)|^2 = \left|\frac{1}{m - m_f + \frac{i}{2}\left(\Gamma' + \bar{g}_{\Lambda\eta}k\right)}\right|^2$$

In particular, the Flatte function reproduces the shape near the peak point better than the BW function.

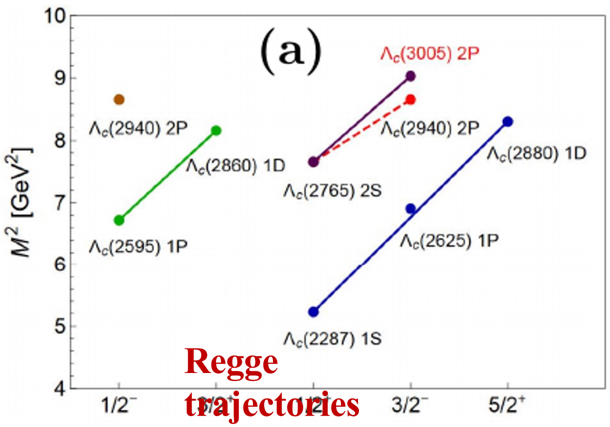
These results show that the present peaking structure is explained better by a threshold cusp than to a new hadron resonance by more than 7σ.

Γ' and $\bar{g}_{\Lambda\eta}$ = (27.2±1.9) MeV and 0.258±0.023.

Evidence of $\Lambda_c(2910)^+$ in $\bar{B}^0 \to \Lambda_c(2910)^+ \bar{p}$

- $\boldsymbol{\Lambda_c(2940) \to \Sigma_c(2455)\pi}$: **the highest excited Λ_c state**
- **LHCb favor the $J^P = \frac{3}{2}^-$, but other values can not be excluded** JHEP 05, 030 (2017).
- **The mass of $\Lambda_c(2940)$ lower than the traditional expectation of quark model**

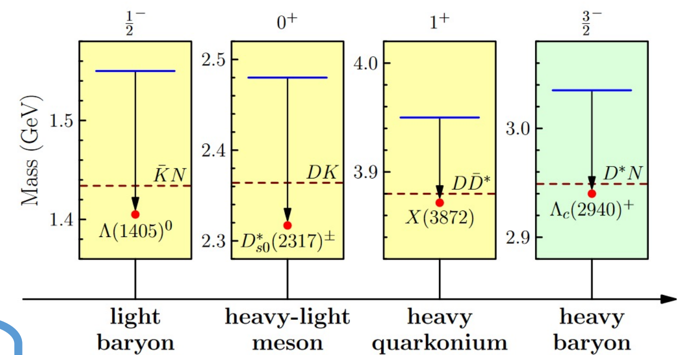
Int J Theor Phys 59, 1129 (2020)



Regge trajectories

State	J^P	Present	[9]	[10]	[11]	[16]	[20]	[21]	PDG [1]
$2P$	$\frac{1}{2}^-$	2.978	3.017	2.983	2.989	2.890		2.980	
$2P$	$\frac{3}{2}^-$	2.970	3.034	3.005	3.000	2.917		3.004	$2.9396^{+0.0014}_{-0.0015}$

[9]. Phys. Lett. B 659, 612 (2008).
[10]. Phys. Rev. D 84, 014025 (2011).
[11]. Phys. Rev. D 91, 054034 (2015).
[16]. Phys. Rev. D 92, 114029 (2015).
[21]. Eur. Phys. J. C 77, 154 (2017).



Theoretical interpretation:

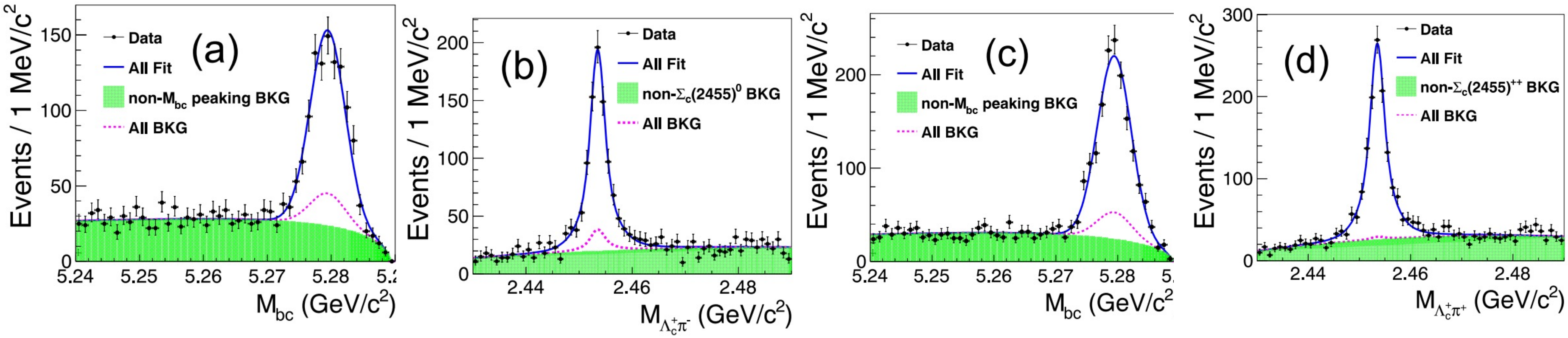
- $\boldsymbol{\Lambda_c(2940)}$: $J^P = \frac{1}{2}^-$ **state, lies in other Regge trajectories**
  - ➢ search for $\Lambda_c(3005)$
- **Similar to $\Lambda(1405), D_s(2317), X(3872)$,** D^*N **contribute in $\Lambda_c(2940)$**
  - ➢**Mass of $\Lambda_c\left(\frac{1}{2}^-, 2P\right)$ inverse, and larger than $\Lambda_c\left(\frac{3}{2}^-, 2P\right)$**

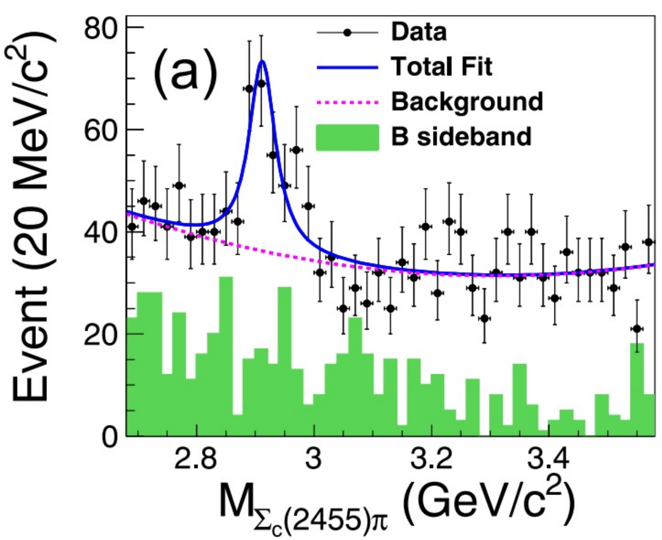
$\bar{B}^0 \to \Lambda_c^* \bar{p}$, $\Lambda_c^* \to \Sigma_c \pi$:
Search for Λ_c excited stats,
Also has constraint on J^P

Evidence of $\Lambda_c(2910)^+$ in $\overline{B}^0 \to \Lambda_c(2910)^+\bar{p}$

Evidence of a new excited $\Lambda_c(2910)^+$

arXiv: 2206.08822
accepted by PRL





- A new structure in $M_{\Sigma_c\pi}$ spectrum is seen

  $m = (2913.8 \pm 5.6 + 3.7)$ MeV/c²

  $\Gamma = (51.8 \pm 20.0 \pm 18.8)$ MeV
- Statistic significance: 6.1σ
- most conservative significance including syst. err: 4.2σ
- Possible $J^p = \frac{1}{2}^-$, agrees with $\Lambda_c\left(\frac{1}{2}^-, 2P\right)$, named: $\Lambda_c(2910)$
- Need more study to confirm its nature

Summary

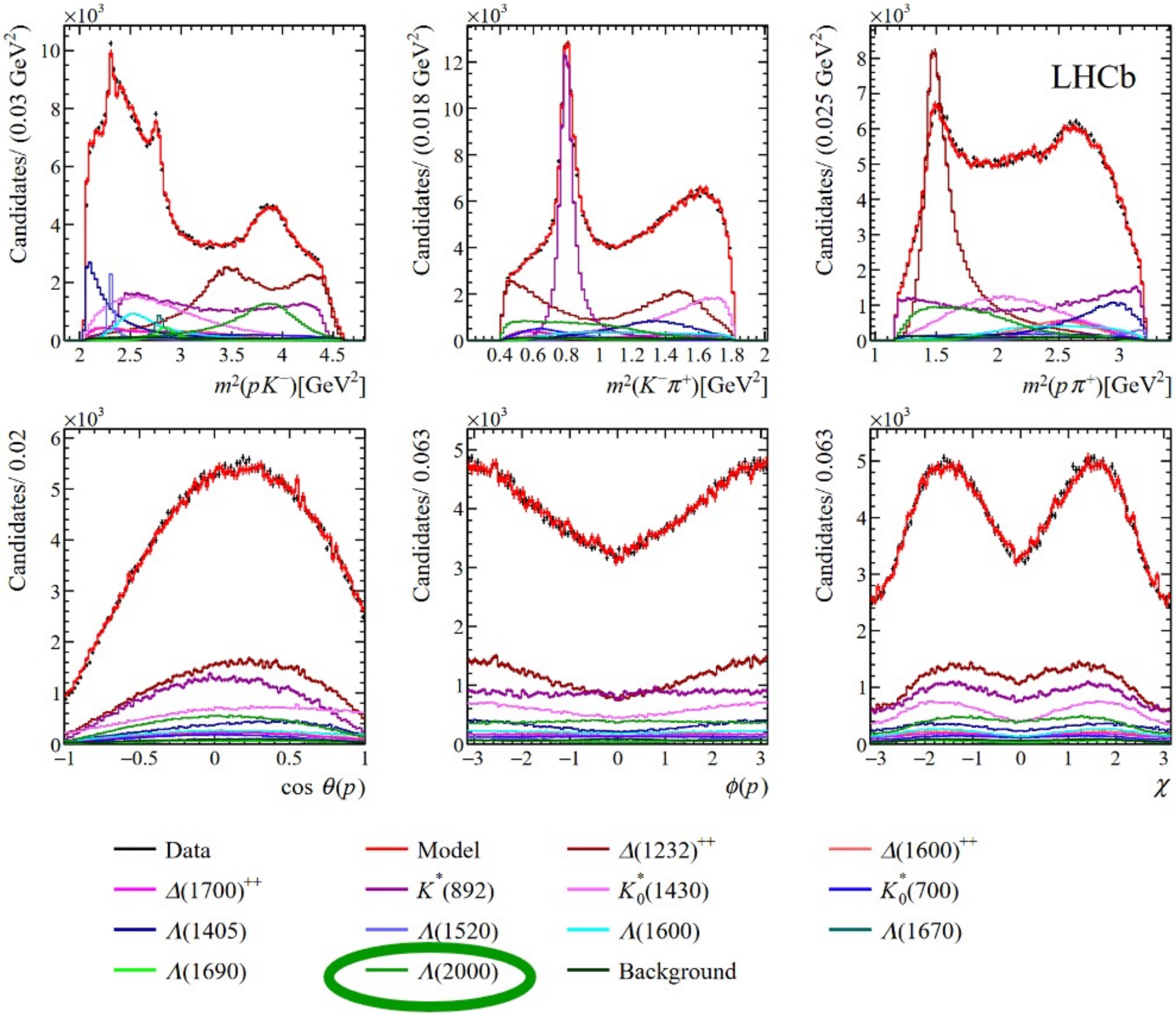
The study of charmed baryons at Belle:

Channel	Comments
$\Lambda_c^+ \to pK_S^0K_S^0$ $\Omega_c^0 \to \Xi^-\pi^+$	First observation
$\Lambda_c^+ \to pK_S^0\eta$ $\Xi_c^0 \to \Lambda_c^+\pi^-$ $\Omega_c^0 \to \Omega^- l^+\nu$	Improved precision
$\Lambda_c^+ \to \Sigma^+\gamma, \Xi_c^0 \to \Xi^0\gamma$ $\Omega_c^0 \to \Xi^-K^+, \Omega_c^0 \to \Omega^-K^+$	Most stringent constraints
M_{pK} in $\Lambda_c^+ \to pK^-\pi^+$ decay	A threshold cusp effect is preferred
$\overline{B}^0 \to \Lambda_c(2910)^+\overline{p}$	A new $\Lambda_c(2910) \to \Sigma_c(2455)\pi$ state is evident

Thank you!

Backup slides

The known particle with the closest mass and width to the structure is $\Lambda_c(2940)^+$. However, the mass of the structure differs from that of $\Lambda_c(2940)^+$[4] by 3.8σ with systematic uncertainty described below considered. Since the mass difference between the structure and $\Lambda_c(2940)^+$ agrees with the expected mass gap between $\Lambda_c(\frac{1}{2}^-, 2P)$ and $\Lambda_c(\frac{3}{2}^-, 2P)$ state in quark models [13, 18, 19, 23], the structure is a good candidate for the $\Lambda_c(\frac{1}{2}^-, 2P)$ state and is tentatively named as $\Lambda_c(2910)^+$. The $\bar{B}^0 \to \Lambda_c(2910)^+\bar{p}$ and $\Lambda_c(2910)^+ \to \Sigma_c(2455)^{0,++}\pi^\pm$ are S-wave decays under this assumption. However, further study is needed to confirm whether this state is an excited Λ_c or Σ_c.



ArXiv: 2208.03262

Based on the PWA from LHCb, seems the spectrum can been described by resonance