Theoretical Progresses on Double-Charm Baryons

Fu-Sheng Yu

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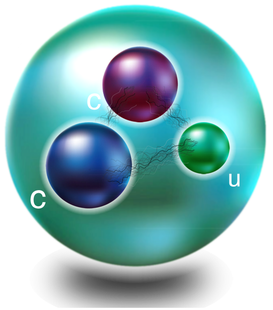


Hadron Physics Online Forum, 2020.05.29

Outline

1. Introduction: why double-charm baryon?

2. Role of decay in the observation

3. Recent theoretical progresses

1. Why double-charm baryons?

- Double-charm baryons are predicted in SU(4) quark model

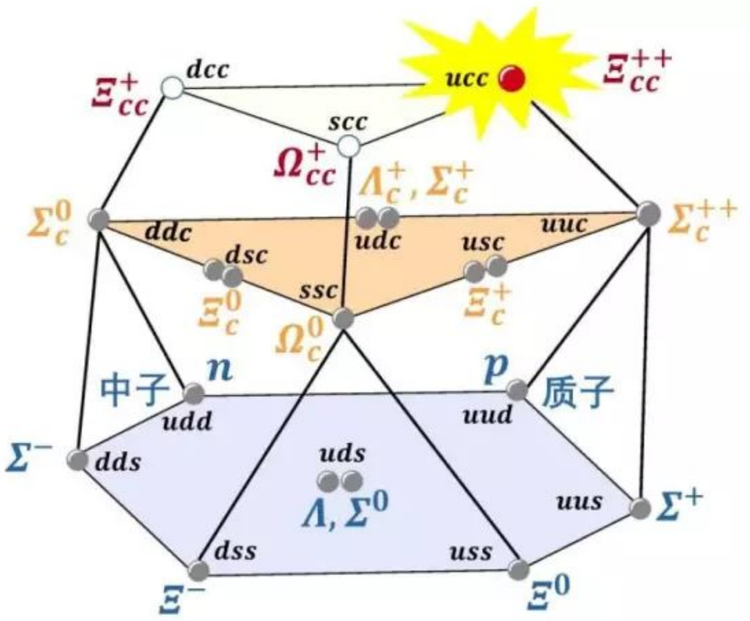
  De Rujula, Georgi and Glashow, 1975;
  Jaffe, J. E. Kiskis, 1976; Ponce, 1979

- Not established in exp until 2017 by LHCb

  $m(\Xi_{cc}^{++}) = (3621.40 \pm 0.78)\ \mathrm{MeV}$ See Ji-bo's talk

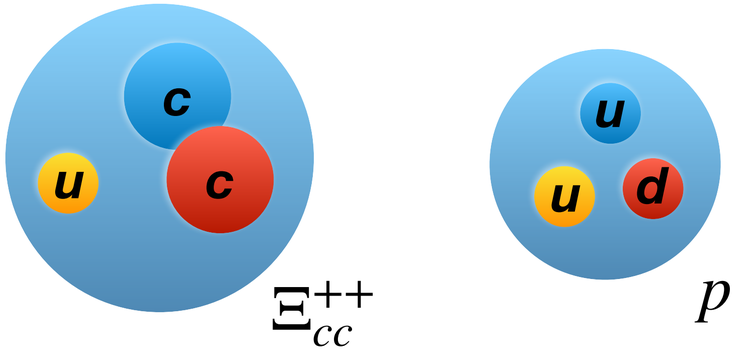
- To complete the hadron spectrum

  See review by Chen, Chen, Liu, Liu, Zhu, 2017



1. Why double-charm baryons?

- A heavy ‘double-star’ system with an attached light ‘planet’, much different from light baryons
- Open a new window for QCD properties



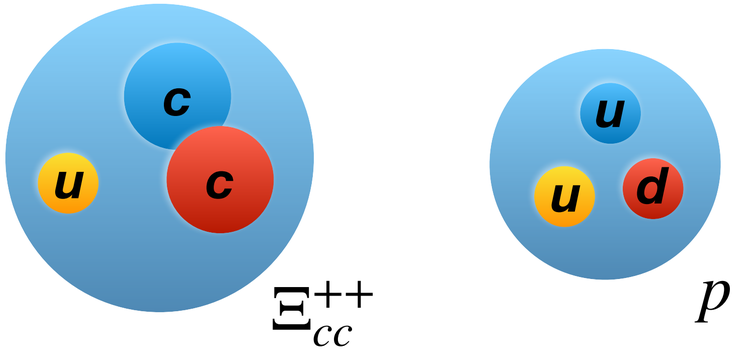
1. Why double-charm baryons?

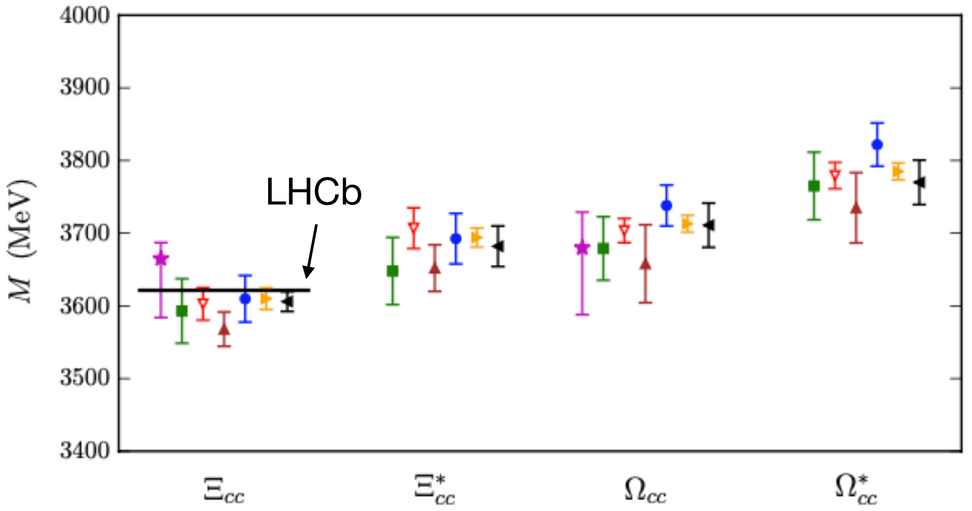
- A heavy ‘double-star’ system with an attached light ‘planet’, much different from light baryons

- Open a new window for QCD properties

- Lattice predictions are consistent with LHCb measurement

PDG review on Quark Model





Lattice predictions

2. Role of Decay in the observation

- Two problems in the exp searches: Production and Decay

$$N \propto \sigma \cdot BR$$

- Production problem was solved at the beginning of LHC running

$$\sigma(pp \to \Xi_{cc}) \sim \sigma(pp \to B_c)$$

C.H.Chang, C.F.Qiao, J.X.Wang, X.G.Wu, 2005, 2006

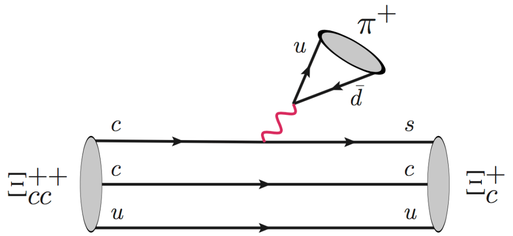
X.G.Wu, Sci.China.PMA, 2020

  - B_c meson has been well studied at LHCb
  - Large amount of Ξ_{cc} are expected in early days of LHCb

- So the last problem is the Decay of doubly charmed baryons

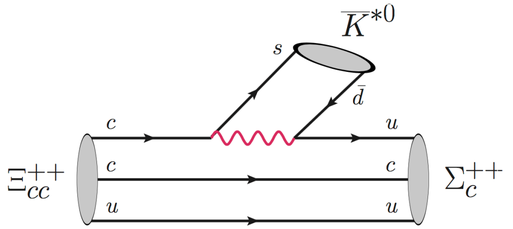
2. Role of Decay in the observation

- Decay properties are the key problem in the LHCb searches of doubly charmed baryons. FSY, Sci.China.PMA, 2020



- The 1/2+ ground states can only decay weakly, $\Delta C = 1$

- More than 100 processes of charmed hadrons decays, due to the high energy scale of charm. See D and Λ_c decays.



- Exp measurements have to choose one or some of them.

- Statistics requires: largest branching ratios and easily detected

2. Role of Decay in the observation

- Evidence

$\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+}$ SELEX, 2002

- But not confirmed

$\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+}$ FOCUS, 2002

$\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+}$ Babar, Belle, 2006,2013

$\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+}$ LHCb, 2013

Largest production

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Misleading process

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Misleading process

2016, LHCb Run II,
What discovery channel?

Ji-bo He

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Largest production

Misleading process

2016, LHCb Run II,
What discovery channel?

Ji-bo He

Require:
Theoretical predictions

2. Role of Decay in the observation

- Two difficulties in theoretical studies on double-charm baryon decays:

  dynamics is challenging

  1. charm —> non-perturbation

  2. baryon —> three body

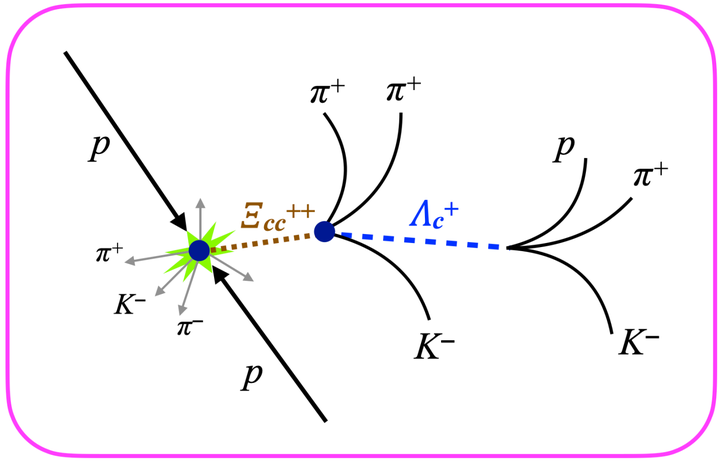
- Two essential aspects of weak decays: { lifetimes; branching ratios

Lifetime is important

1. Longer lifetime ⇒ Larger branching ratios

$$BR_i = \Gamma_i \cdot \tau$$

2. Longer lifetime ⇒ Higher efficiency to reject backgrounds in hadron colliders



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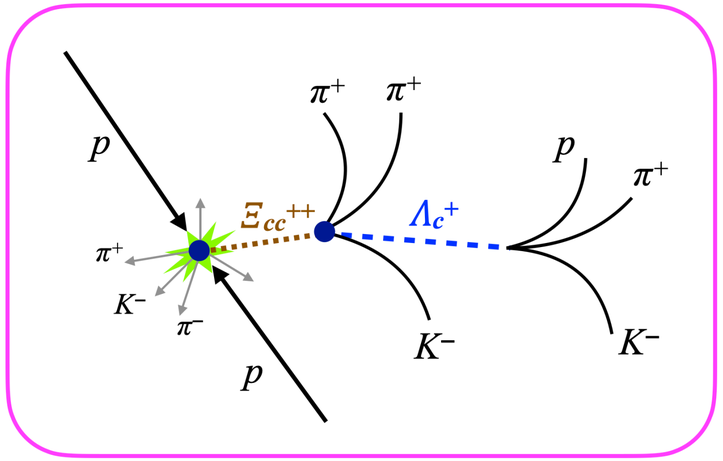

- Large ambiguity in predictions

Literatures	Ξ_{cc}^{++} (fs)	Ξ_{cc}^{+} (fs)
Karliner, Rosner, 2014	185	53
Kiselev, Likhoded, 2002	460±50	160±50
Chang, Li, Li, Wang, 2007	670	250

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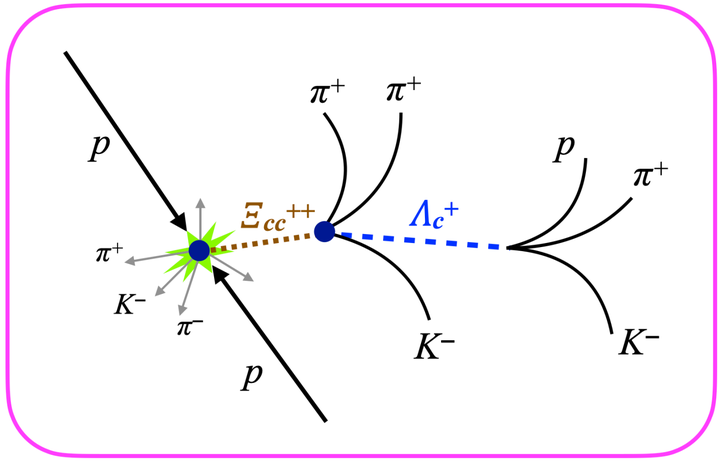


- Large ambiguity in predictions
- But less ambiguity in the ratio

$$\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+})$$

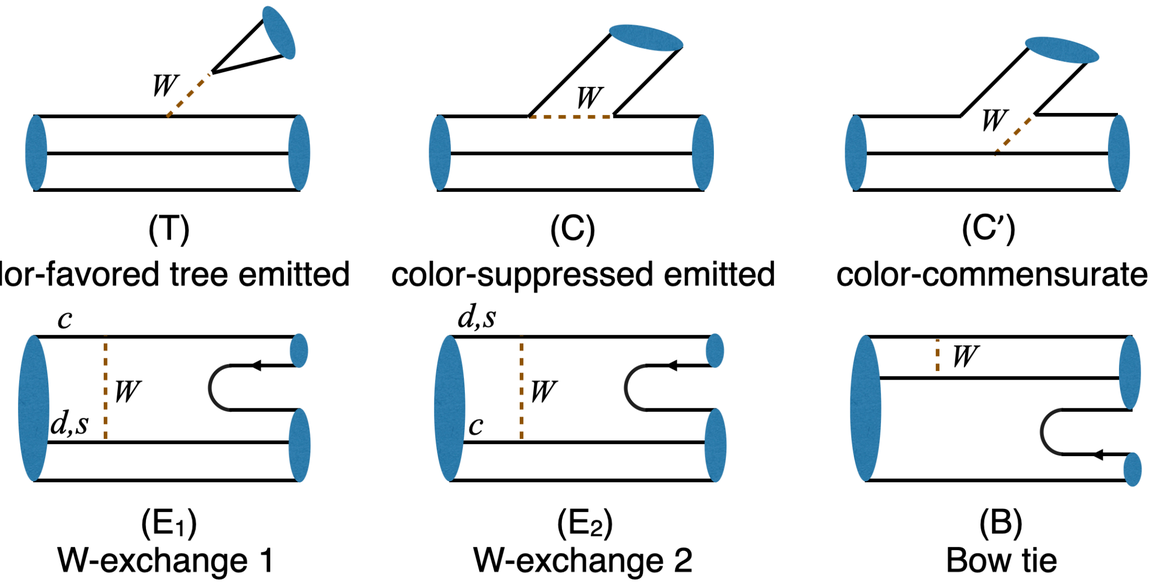
- Recommend Ξ_{cc}^{++} rather than Ξ_{cc}^{+}

Literatures	Ξ_{cc}^{++} (fs)	Ξ_{cc}^{+} (fs)
Karliner, Rosner, 2014	185	53
Kiselev, Likhoded, 2002	460±50	160±50
Chang, Li, Li, Wang, 2007	670	250

$$\tau(\Xi_{cc}^{++}) \sim 3\ \tau(\Xi_{cc}^{+})$$

Branching Fractions

- Topological diagrammatic approach is suitable for hadronic charm decays
- Include non-perturbative contributions
- It works well in D decays
- It needs experimental data



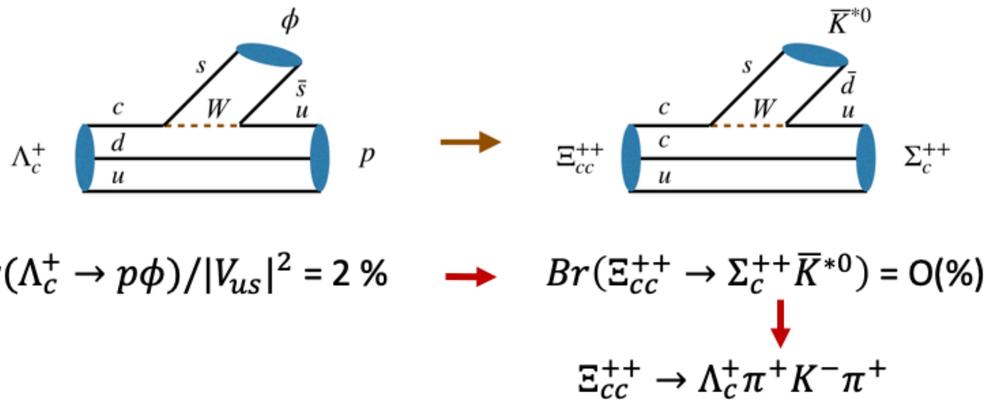
Branching Fractions

- Hierarchy of topological diagrams in heavy quark expansion

SCET: |C/T|~|C'/T|~|E/T|~O($\Lambda_{\rm QCD}/m_Q$) Leibovich, Ligeti, Stewart, Wise, 2004

charm decay: |C/T|~|C'/T|~|E/T|~O($\Lambda_{\rm QCD}/m_c$)~1

- BESIII measurements on Λ_c^+ decays are important



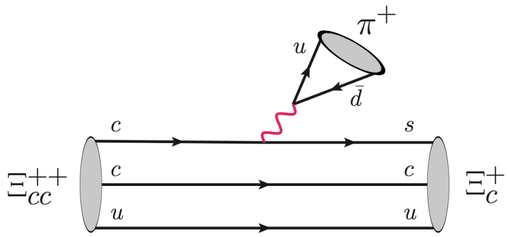
$\Lambda_c^+ \to$

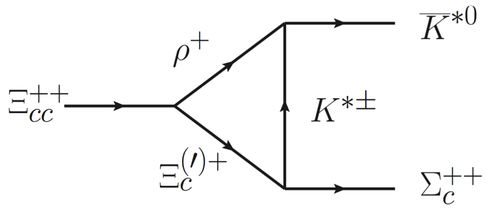
Modes	Representation	$\mathcal{B}_{\rm exp}$
$p\overline{K}^0$	$\lambda_{sd}(C+E)$	$(3.04 \pm 0.17)\%$
$\Lambda^0\pi^+$	$\lambda_{sd}(T-C'+B-E)/\sqrt{2}$	$(1.24 \pm 0.08)\%$
$\Delta^{++}K^-$	$\lambda_{sd}E$	$(1.18 \pm 0.27)\%$

So far dynamics is almost ready

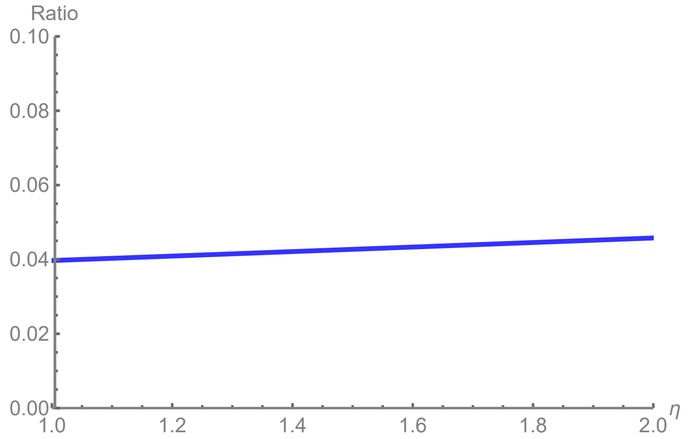
Branching Fractions

- Theoretical framework:
  - Short-distance contributions: factorization
  - Long-distance contributions: rescattering effects of final-state interaction





- Theoretical uncertainty is under control in the **ratio** of branching fractions of different processes



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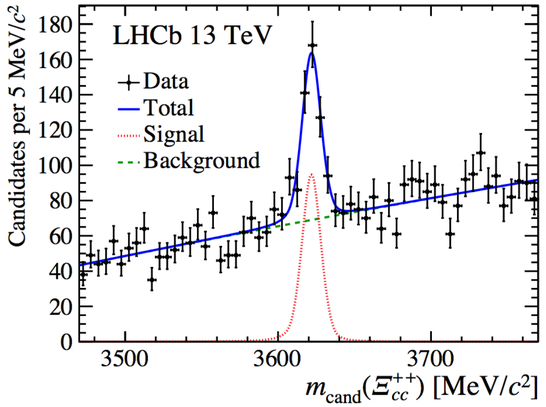
Discovery potentials of doubly charmed baryons*

Fu-Sheng Yu(于福升)[1,2;1)] Hua-Yu Jiang(蒋华玉)[1,2] Run-Hui Li(李润辉)[3] Cai-Dian Lü(吕才典)[4,5;2)]
Wei Wang(王伟)[6;3)] Zhen-Xing Zhao(赵振兴)[6]

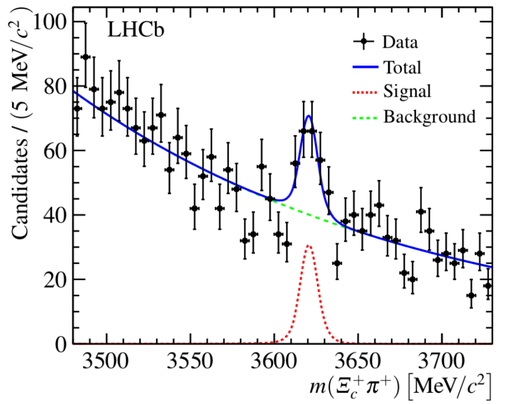
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ are the most favorable decay modes

July 2017



$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

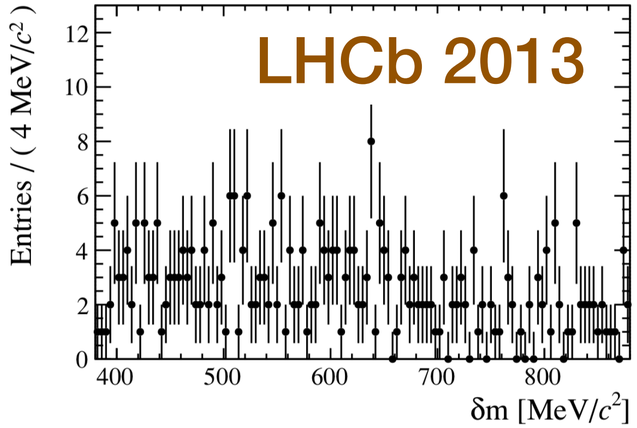
July 2018

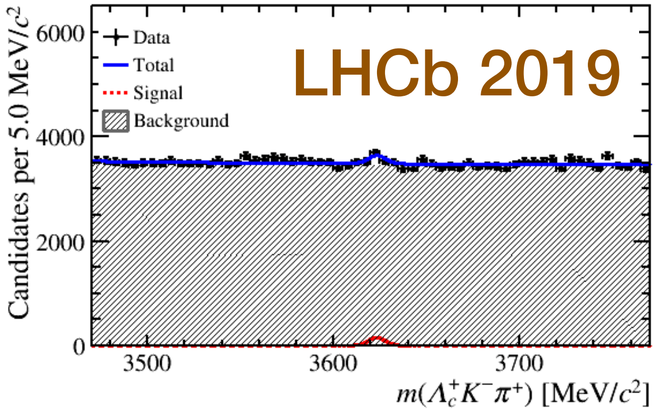


$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

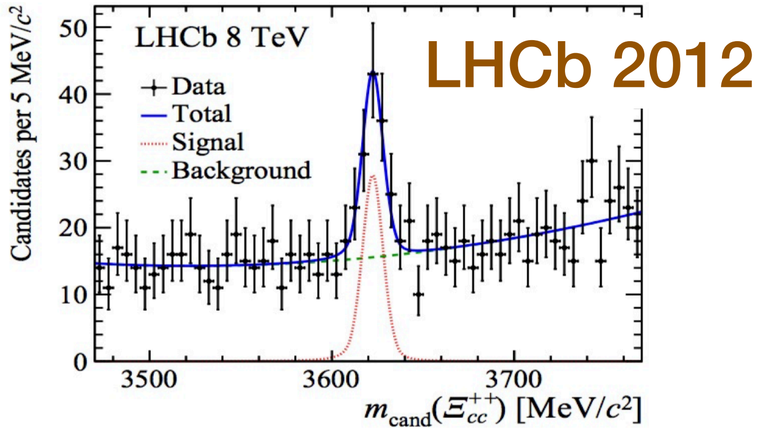
2. Role of Decay in the observation

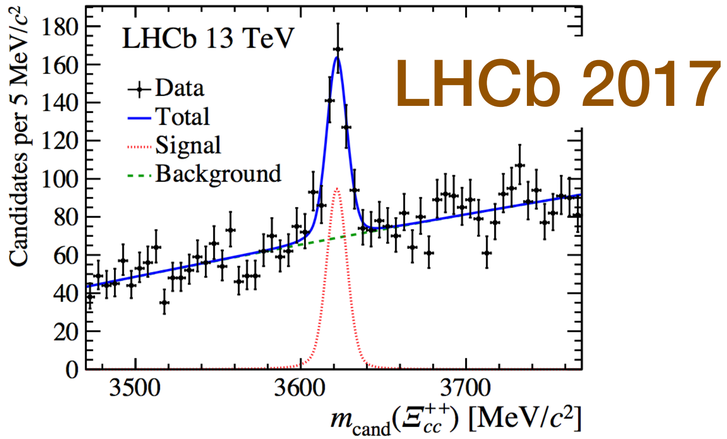
$$\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$$





$$\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{+}$$





3. Theoretical Progresses (I) : processes

- Decaying processes for Ξ_{cc}^{+} and Ω_{cc}^{+} $\quad \mathrm{B}_{cc} \to \mathrm{B}_c P,\ \mathrm{B}_c V,\ \mathrm{B}_{\mathbf{8}} D^{(*)}$

H.Y.Cheng, F.R.Xu, 2019

- Suggestion for measurements

$$\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+},\ \Xi_c^{+} \pi^{+} \pi^{-}$$

$$\Omega_{cc}^{+} \to \Xi_c^{+} K^{-} \pi^{+}$$

$$\mathcal{BR}(\Xi_{cc}^{+} \to \Xi_c^{+} \rho^{0}) \in [0.4\%, 2.5\%]$$

$$\mathcal{BR}(\Omega_{cc}^{+} \to \Xi_c^{+} \overline{K}^{*0}) \in [0.5\%, 3.3\%]$$

Run-Hui Li, 2017, 2018

3. Theoretical Progresses (II) : topological diagrams

Theoretical expectation: $\frac{|C|}{|T|} \sim \frac{|E_1|}{|C|} \sim \frac{|E_2|}{|C|} \sim O(\Lambda_{QCD}/m_c) \sim O(1)$

$$\frac{|\mathcal{A}(\Xi_{cc}^{++} \to \Sigma_c^{++} \bar{K}^0)|}{|\mathcal{A}(\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^+)|} \approx \frac{C_{LD}}{T_{SD}} \approx 0.45 \sim 1.03$$

$$\frac{|\mathcal{A}(\Xi_{cc}^{+} \to \Sigma_c^{++} K^-)|}{|\mathcal{A}(\Xi_{cc}^{++} \to \Sigma_c^{++} \bar{K}^0)|} = \frac{|E_1|}{|C|} = 0.38 \sim 0.39,$$

$$\frac{|\mathcal{A}(\Xi_{cc}^{++} \to \Xi_c^{+} \pi^+)_{LD}|}{|\mathcal{A}(\Xi_{cc}^{++} \to \Sigma_c^{++} \bar{K}^0)|} = \frac{|C'|}{|C|} = 1.22 \sim 1.27,$$

$$\frac{|\mathcal{A}(\Omega_{cc}^{+} \to \Sigma_c^{0} \pi^+)|}{|\mathcal{A}(\Xi_{cc}^{++} \to \Sigma_c^{++} K^0)|} = \frac{|E_2|}{|C|} = 0.39 \sim 0.40$$

J.J.Han, H.Y.Jiang, FSY, in preparation

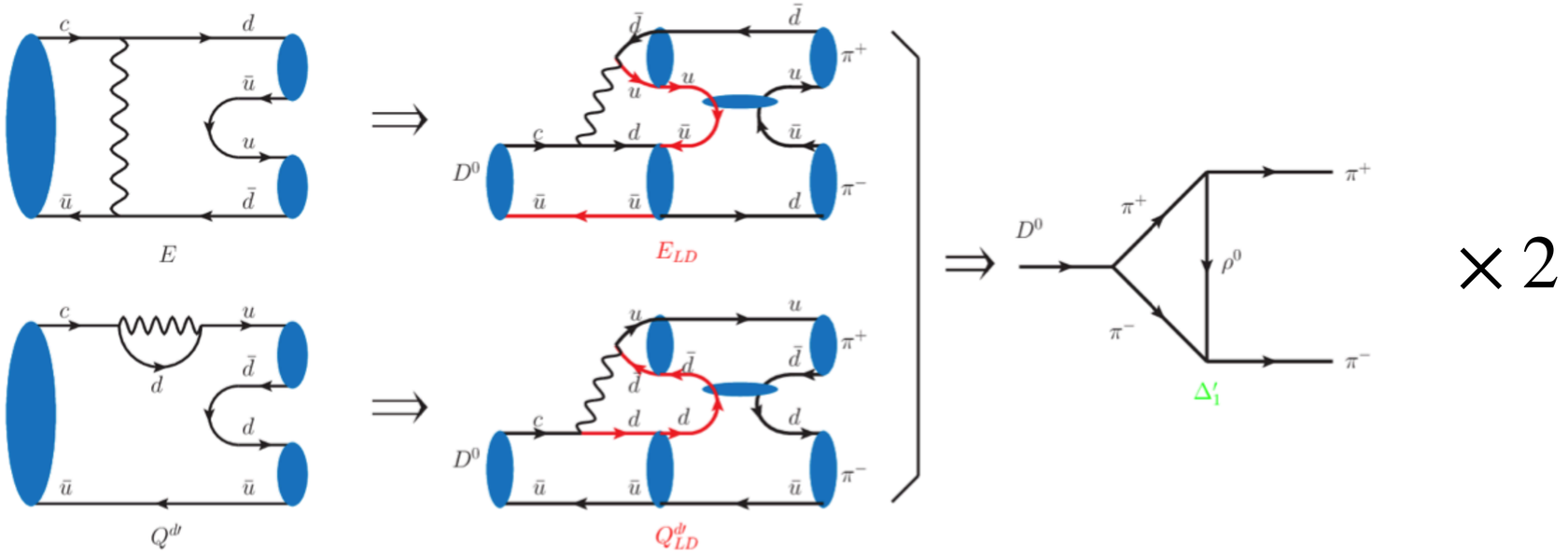
3. Theoretical Progresses (III) : topological-FSI

Topological quark diagram

FSI rescattering

Basic

Tool



One quark diagram —> one hadronic diagram

Ablikim, D.S.Du, M.Z.Yang, 2002

H.Y.Cheng, C.K.Chua, Soni, 2005

3. Theoretical Progresses (III) : topological-FSI

Topological quark diagram — Basic

FSI rescattering — Tool

One quark diagram —> one hadronic diagram

Ablikim, D.S.Du, M.Z.Yang, 2002

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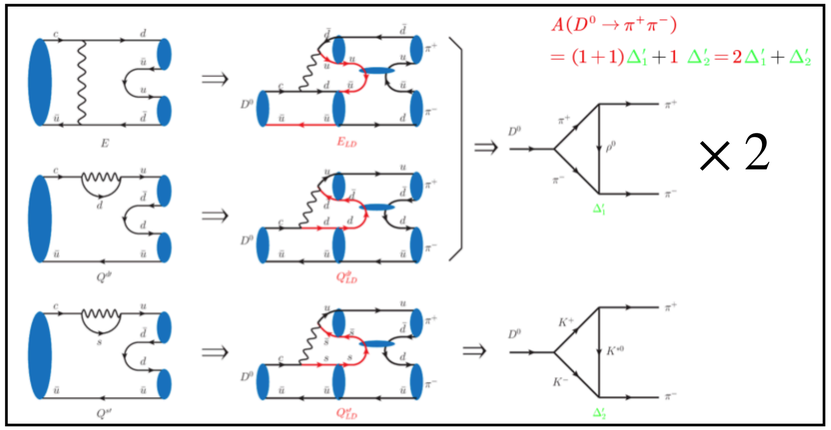
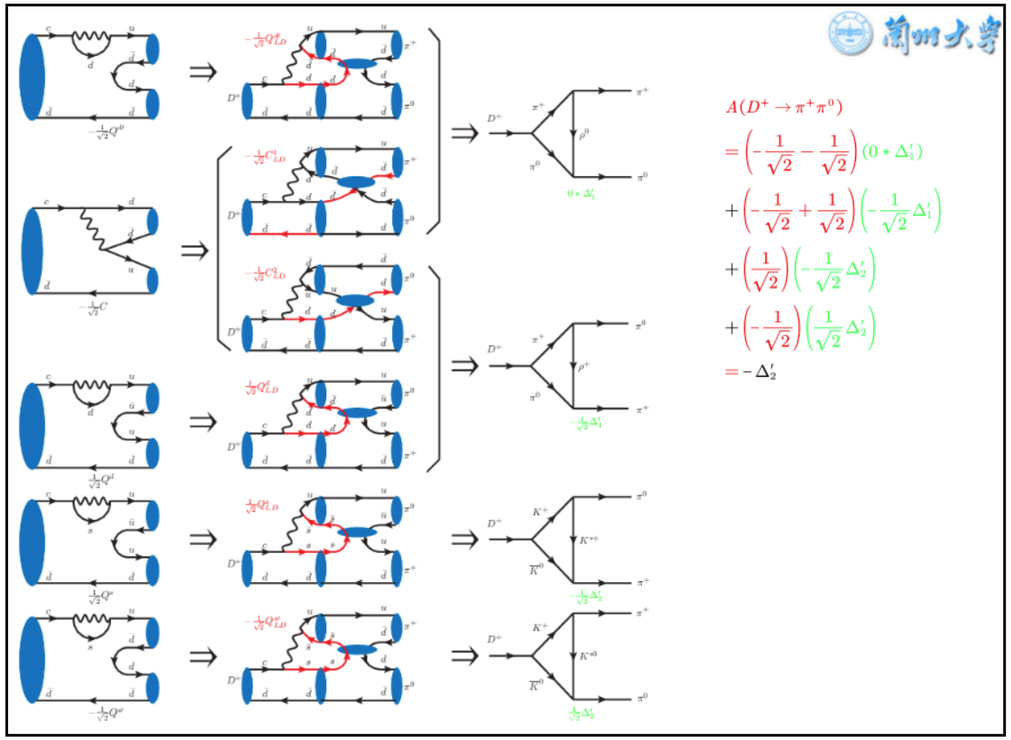
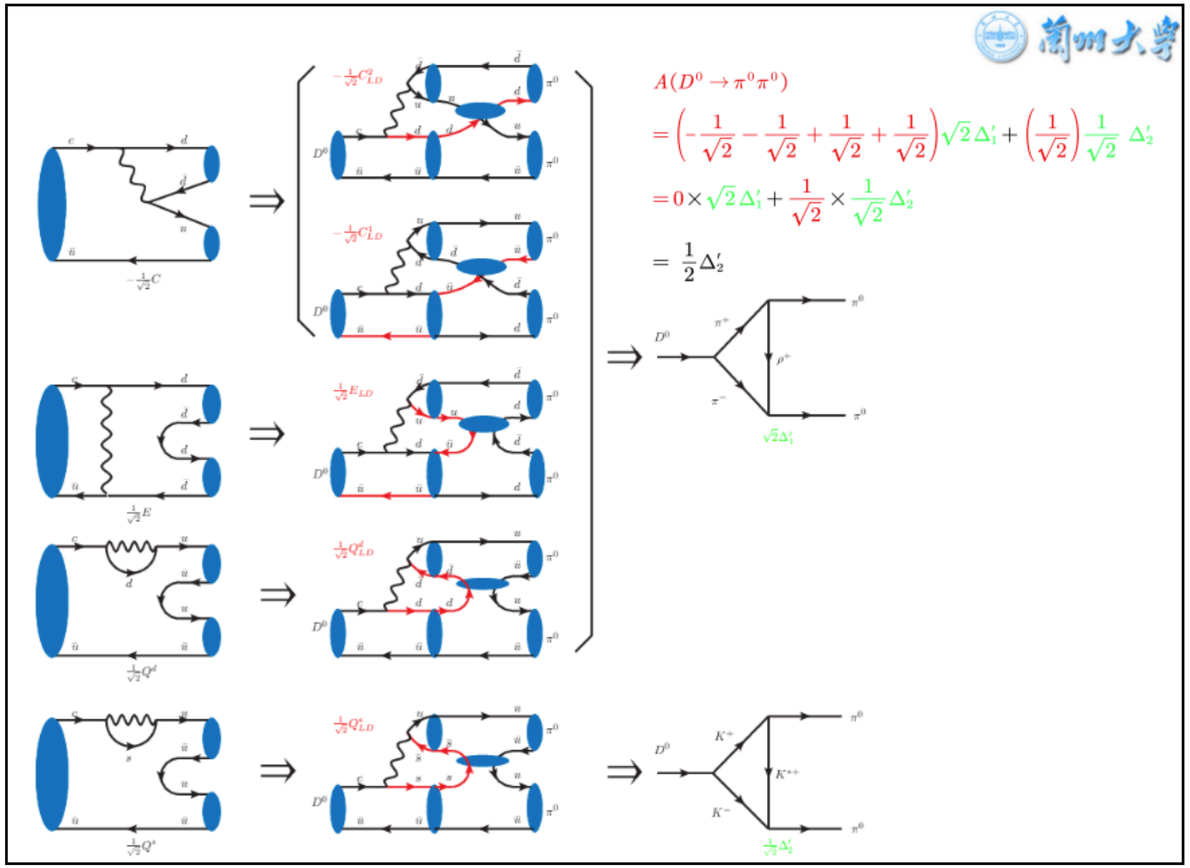
- To test the isospin triangle relation

$$A(D^0 \to \pi^+\pi^-) - \sqrt{2}A(D^0 \to \pi^0\pi^0) = -\sqrt{2}A(D^+ \to \pi^+\pi^0)$$??







$$A(D^0 \to \pi^+\pi^-) - \sqrt{2}A(D^0 \to \pi^0\pi^0) = -\sqrt{2}A(D^+ \to \pi^+\pi^0)$$

$$2\Delta_1' + \Delta_2'\big|_{D^0 \to \pi^+\pi^-} - \sqrt{2}\left(\frac{1}{2}\Delta_2'\right)\Big|_{D^0 \to \pi^0\pi^0} \neq -\sqrt{2}(-\Delta_2')\big|_{D^+ \to \pi^+\pi^0}$$

3. Theoretical Progresses (III) : topological-FSI

Topological quark diagram

Basic

FSI rescattering

Tool —> Basic

Both approaches are independent

The SU(3)-symmetry relation should be satisfied

$$2\Delta_1' + \Delta_2'\Big|_{D^0\to\pi^+\pi^-} - \sqrt{2}\left(\frac{1}{2}\Delta_2'\right)\Big|_{D^0\to\pi^0\pi^0} \neq -\sqrt{2}\,(-\Delta_2')\Big|_{D^+\to\pi^+\pi^0}$$

$$\downarrow$$

$$(\Delta_1' + \Delta_2')\big|_{D^0\to\pi^+\pi^-} - \sqrt{2}\left(\sqrt{2}\Delta_1' + \frac{1}{\sqrt{2}}\Delta_2'\right)\Big|_{D^0\to\pi^0\pi^0} = -\sqrt{2}\left(\frac{1}{\sqrt{2}}\Delta_1'\right)\Big|_{D^+\to\pi^+\pi^0}$$

3. Recent theoretical progresses

- Lifetimes H.Y.Cheng, Shi, 2019
- Form factors Z.X.Zhao, Y.J.Shi, X.H.Hu, W.Wang, 2018, 2019
- Heavy diquark effective theory Y.J.Shi, Z.X.Zhao, W.Wang, 2020

Summary and Outlook

- Doubly charmed baryon is observed by LHCb
- Decay properties play an important role in the observation
- Theory-Experiment collaboration is essential

- Further studies:

1. Discovery potentials of Xi_cc^+, Omega_cc^+
2. Discovery potentials of Xi_bc, Omega_bc
3. Semileptonic decays
4. Effective theory of doubly heavy baryons
5. Lifetimes?
6. New physics and CPV?
7. Omega_ccc?

Thank you very much!