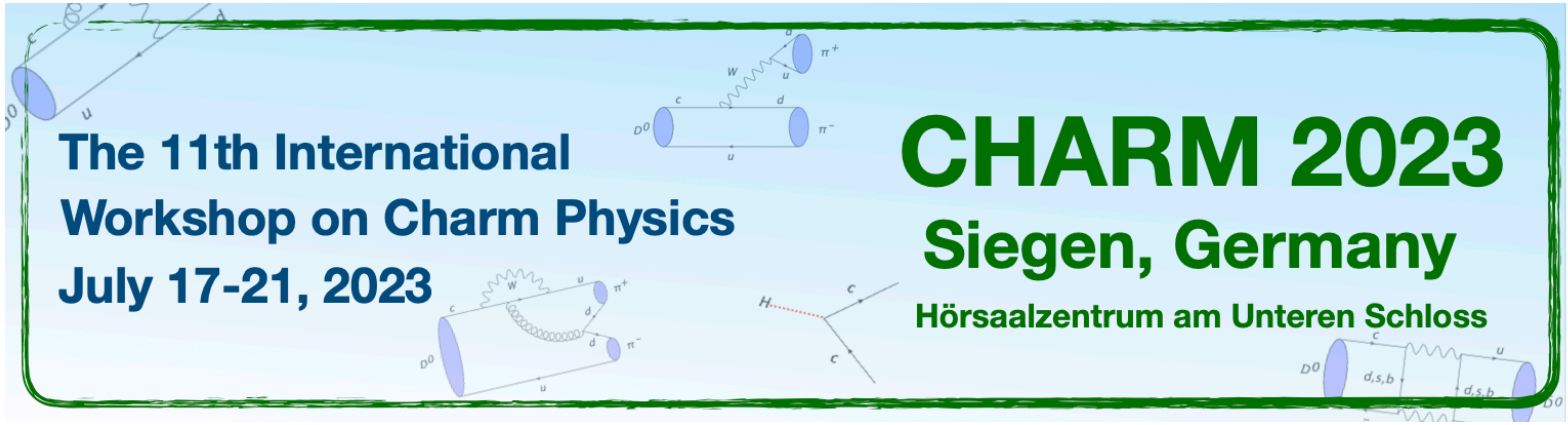
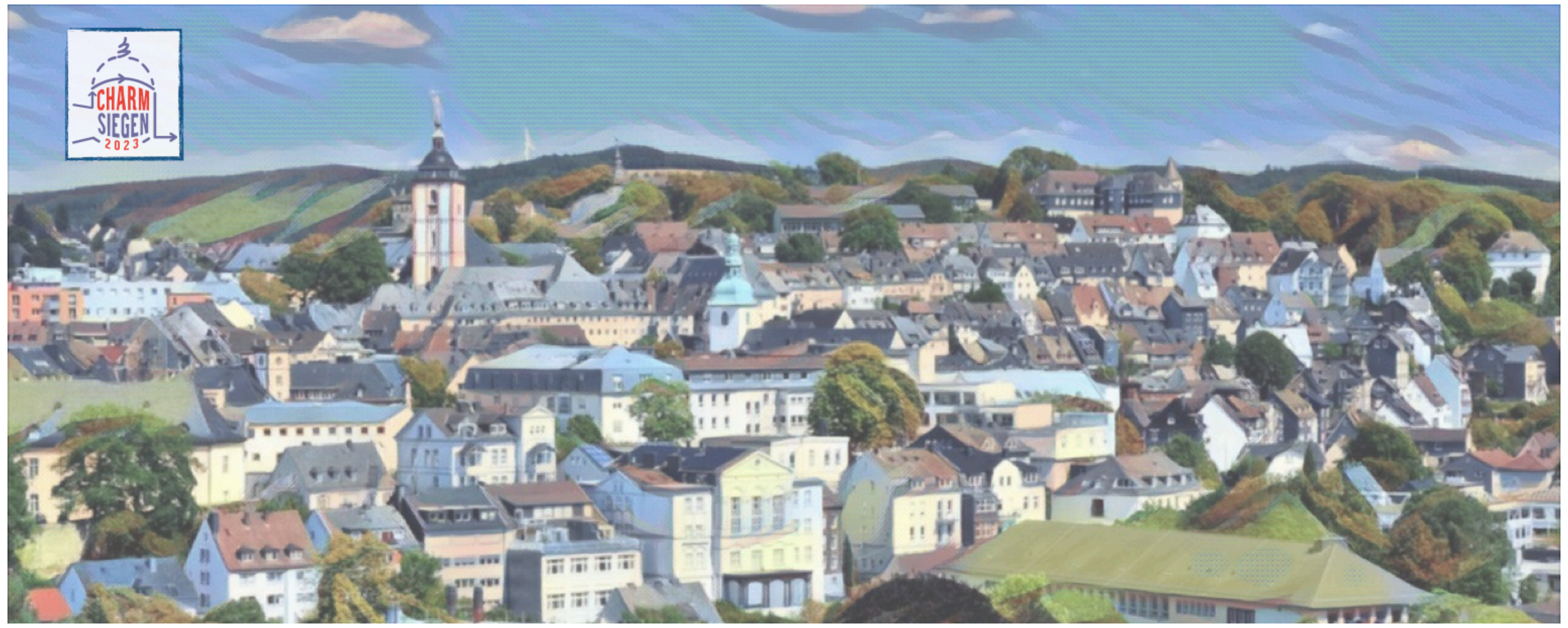




Doubly Charmed Baryon Decays in Quark Models

Fanrong Xu
Jinan University, China
July 20, 2023

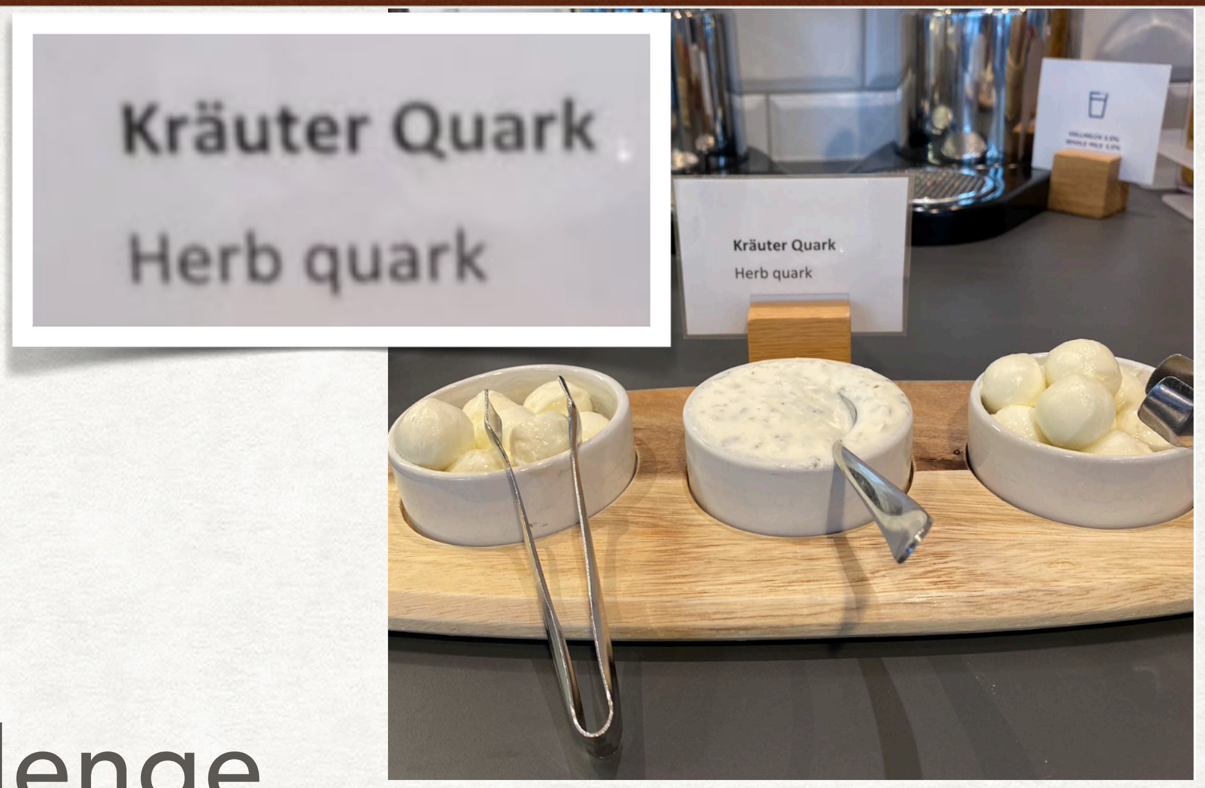
暨南大學
JINAN UNIVERSITY

In collab with Hai-Yang Cheng, Peng-Yu Niu, Shuge Zeng

OUTLINE

- Introduction
- Model setup
- Non-perturbative parameters in quark models
- Results and discussion

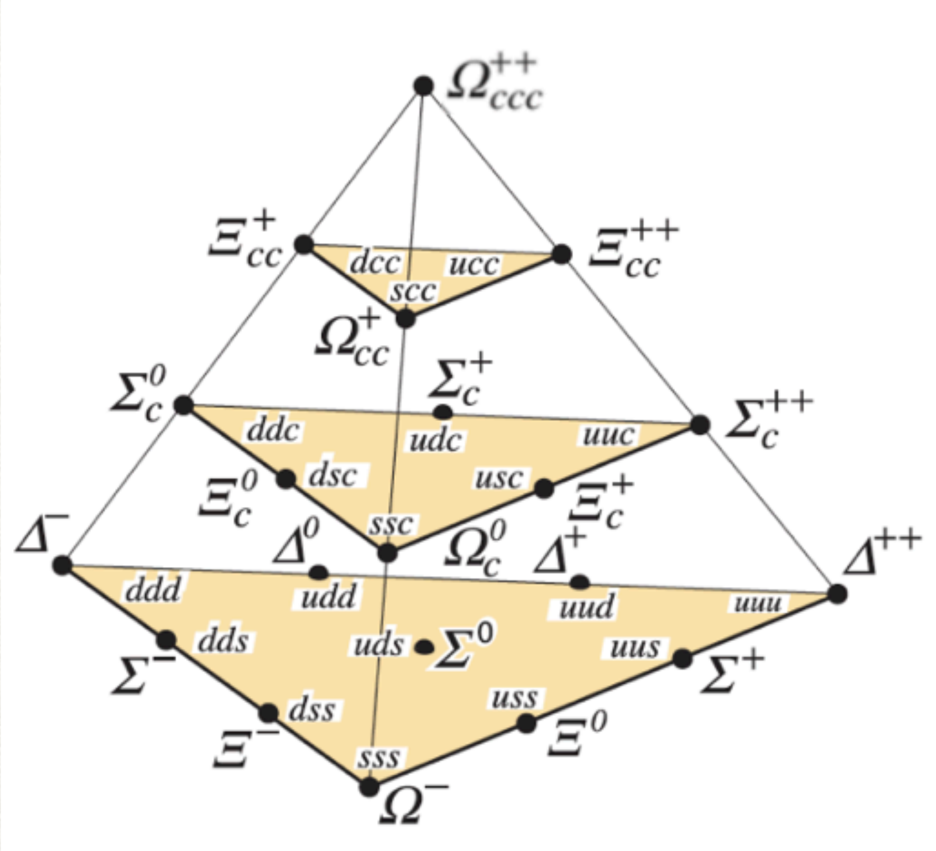
INTRODUCTION



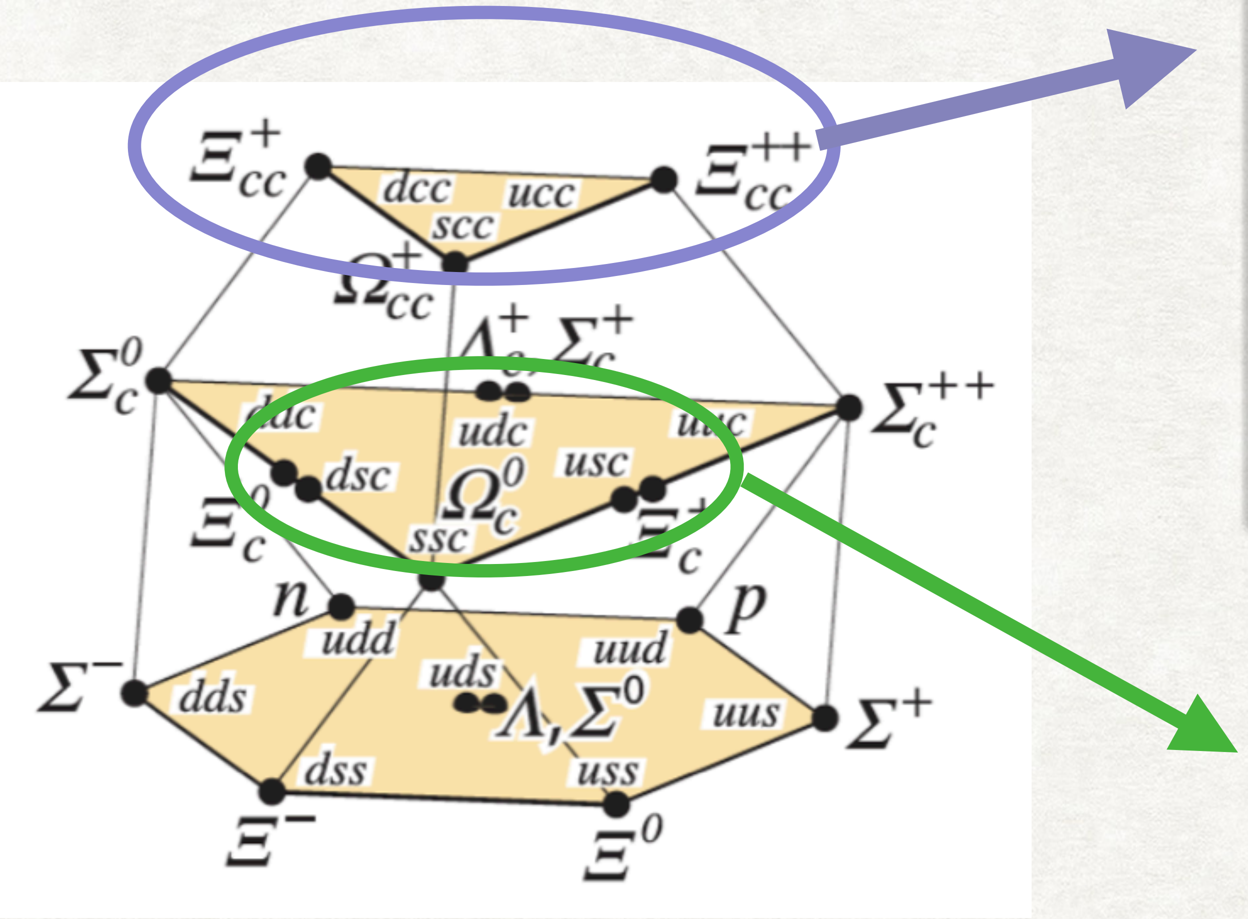
Siegen breakfast

Towards charmed baryons

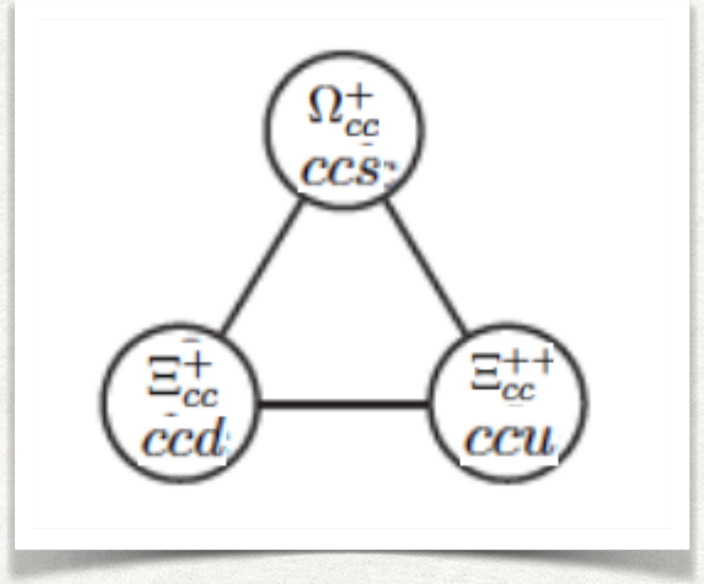
- Charm quark is special for its mass implying the theoretical challenge.
  talk given by K. Vos
- Baryons provide a good platform to study charm physics.

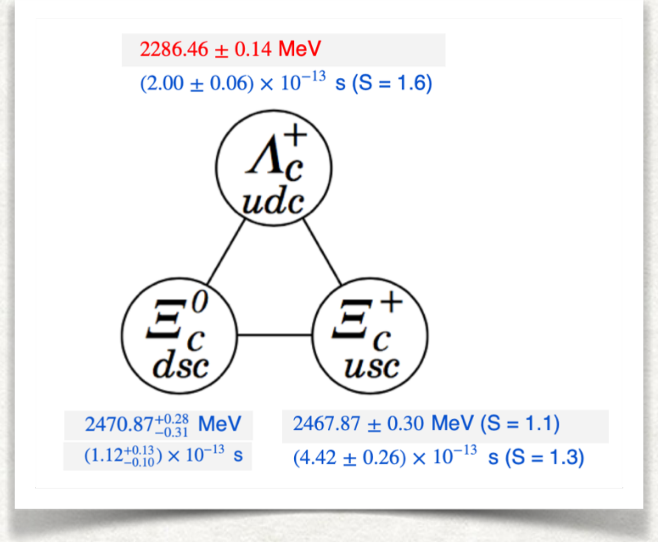


SU(4) 20-plet with an SU(3) decuplet



SU(4) 20-plet with an SU(3) octet





- Topics of charmed baryons: **lifetimes**, **masses**, **decays**, CPV…

Charm 2025 ?

H.-Y. Cheng, B. Melic, A. Schwartz …

S. Collins, P. Spradlin, …

H.-Y. Cheng, P. Sparadlin, Y. Xu…
& this talk

INTRODUCTION

Doubly charmed baryon family

- The first observed doubly charmed baryon Ξ_{cc}^{++} : mass and lifetime

Selected for a Viewpoint in *Physics*
PRL **119,** 112001 (2017) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017

Observation of the Doubly Charmed Baryon Ξ_{cc}^{++}

R. Aaij *et al.*[*]
(LHCb Collaboration)

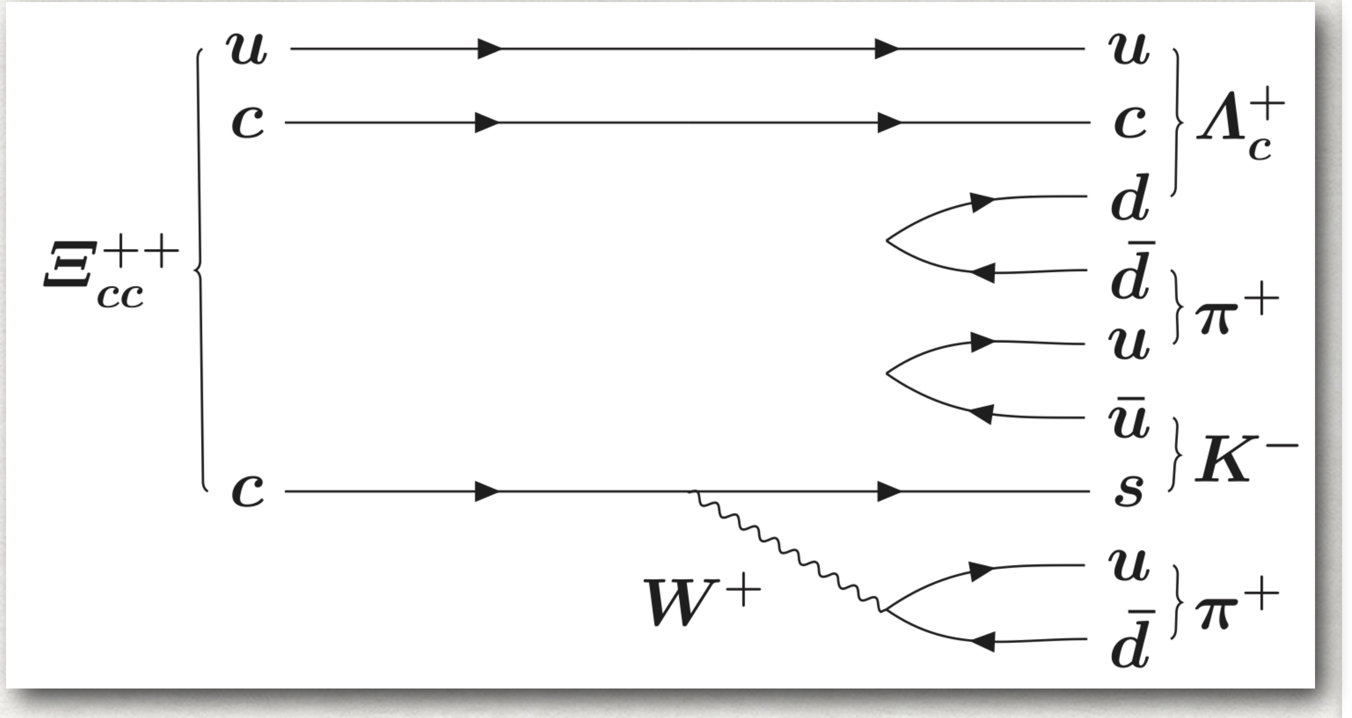
(Received 6 July 2017; revised manuscript received 2 August 2017; published 11 September 2017)

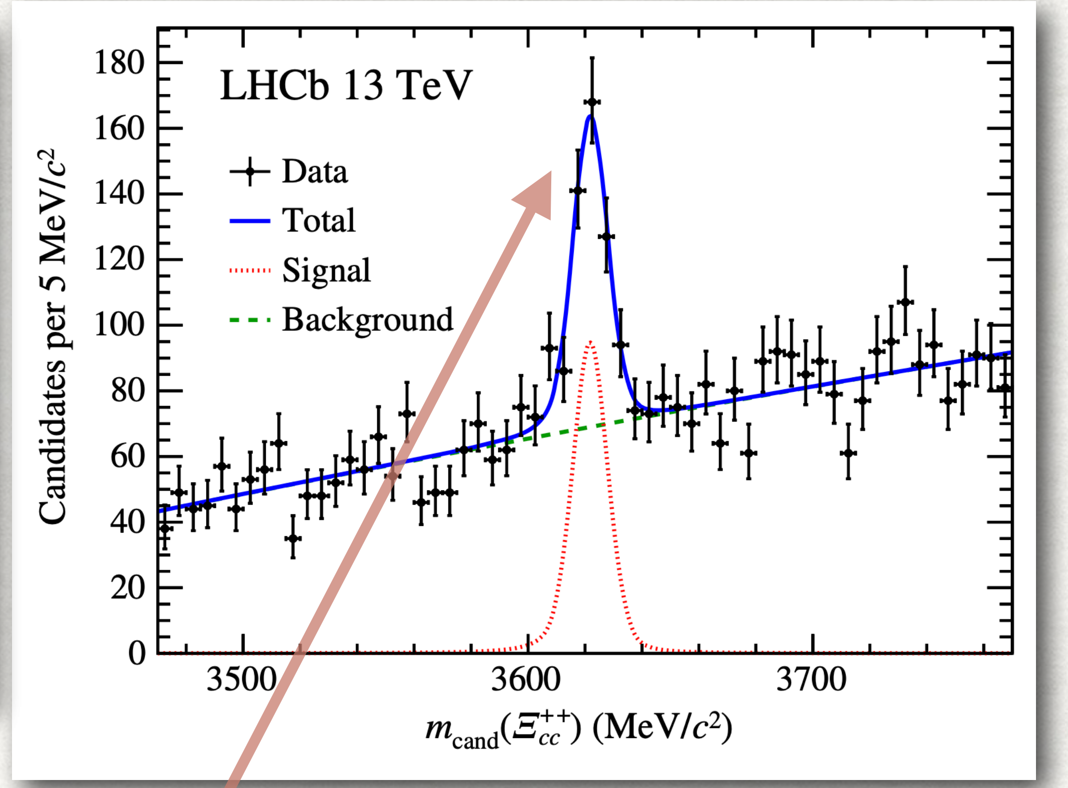
PHYSICAL REVIEW LETTERS **121,** 052002 (2018)
Editors' Suggestion

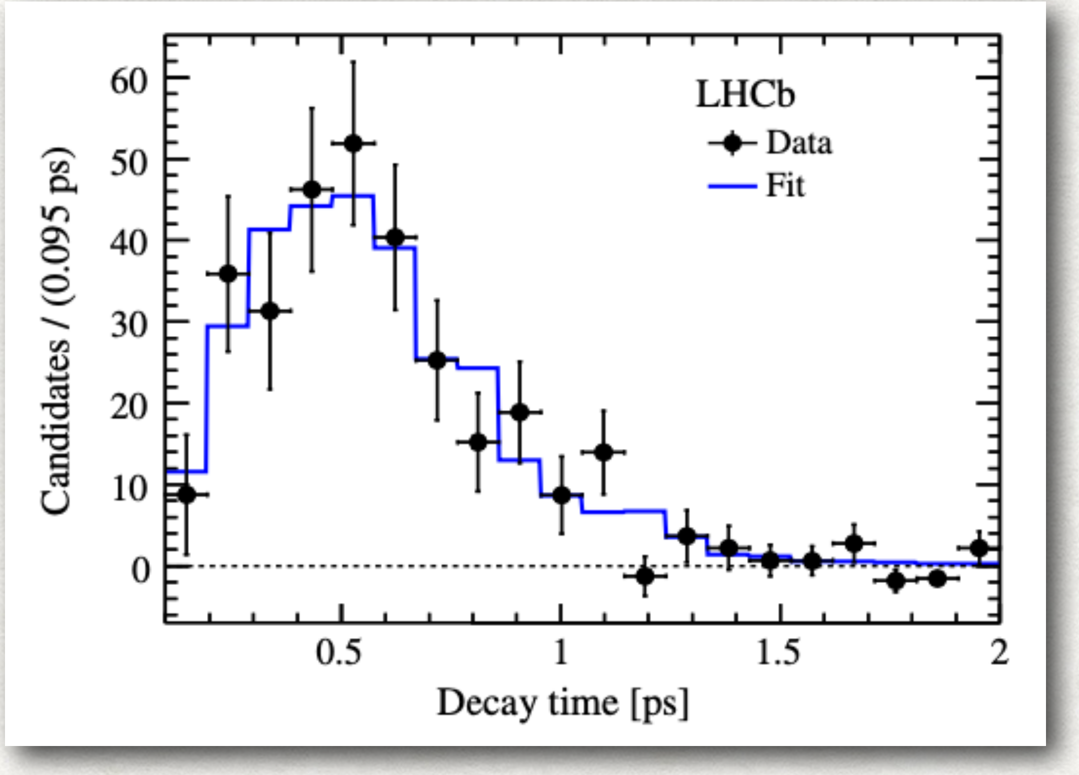
Measurement of the Lifetime of the Doubly Charmed Baryon Ξ_{cc}^{++}

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 7 June 2018; revised manuscript received 24 June 2018; published 31 July 2018)







$3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$

$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}(\text{stat}) \pm 0.014(\text{syst})\ \text{ps}$

INTRODUCTION

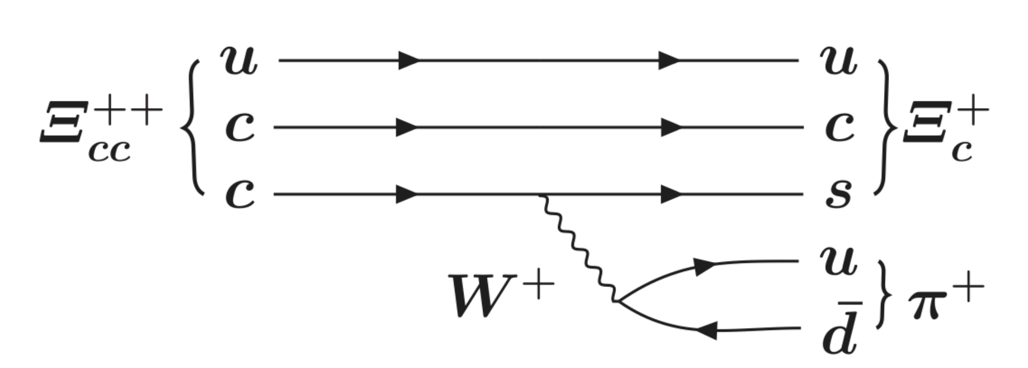
Decays of Ξ_{cc}^{++}

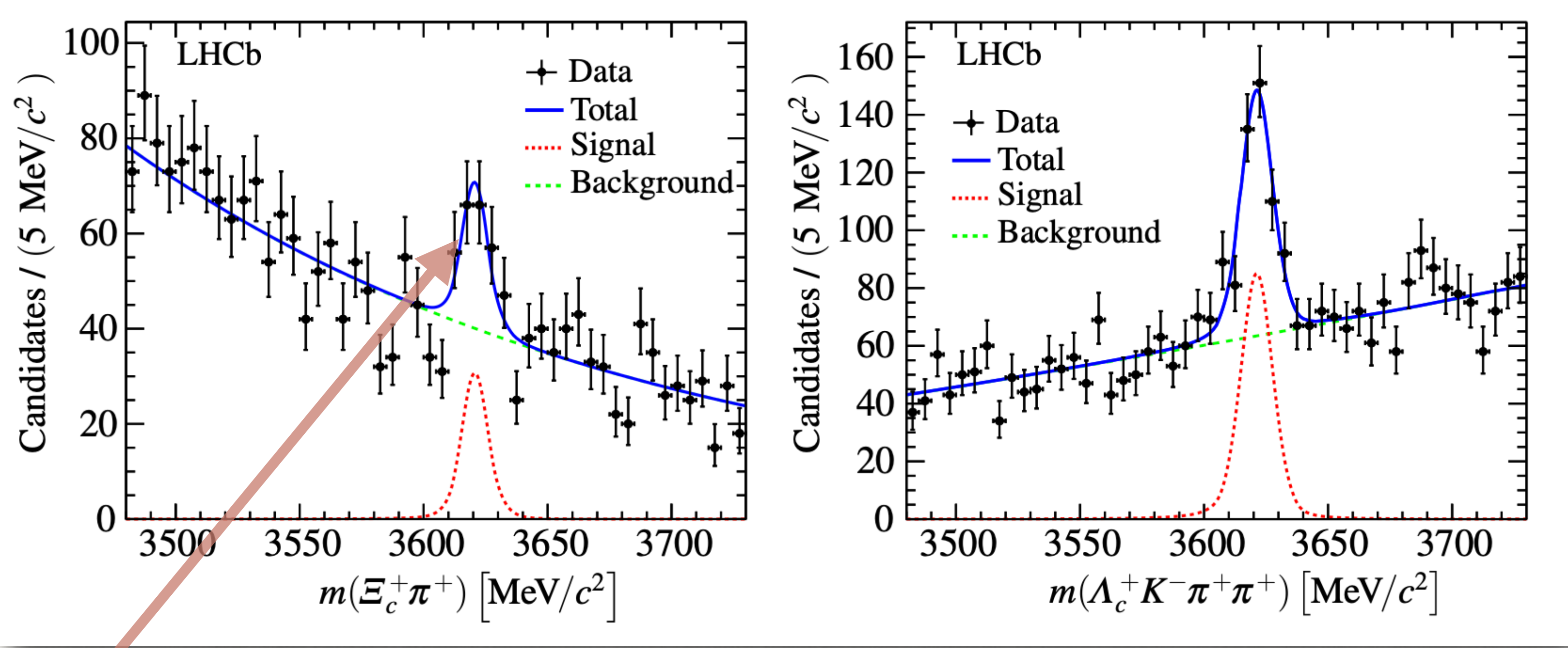
PHYSICAL REVIEW LETTERS **121,** 162002 (2018)

First Observation of the Doubly Charmed Baryon Decay $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 9 July 2018; revised manuscript received 1 August 2018; published 17 October 2018)





$$3620.6 \pm 1.5(\text{stat}) \pm 0.4(\text{syst}) \pm 0.3(\Xi_c^+)\ \text{MeV}/c^2$$

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+\pi^+) \times \mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+) \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.035 \pm 0.009(\text{stat}) \pm 0.003(\text{syst}).$$

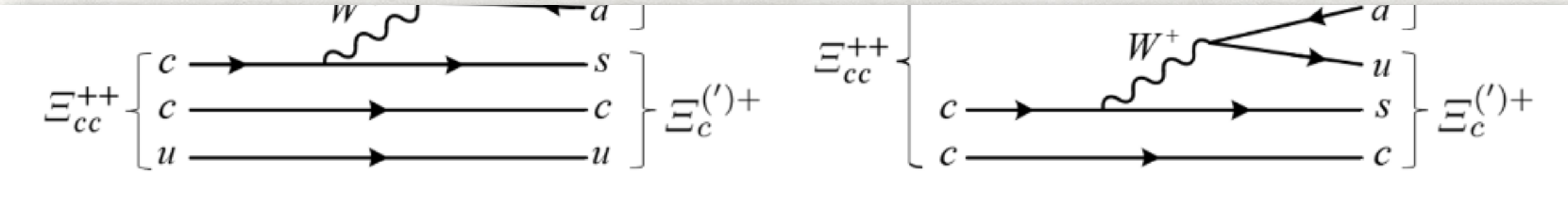
JHEP

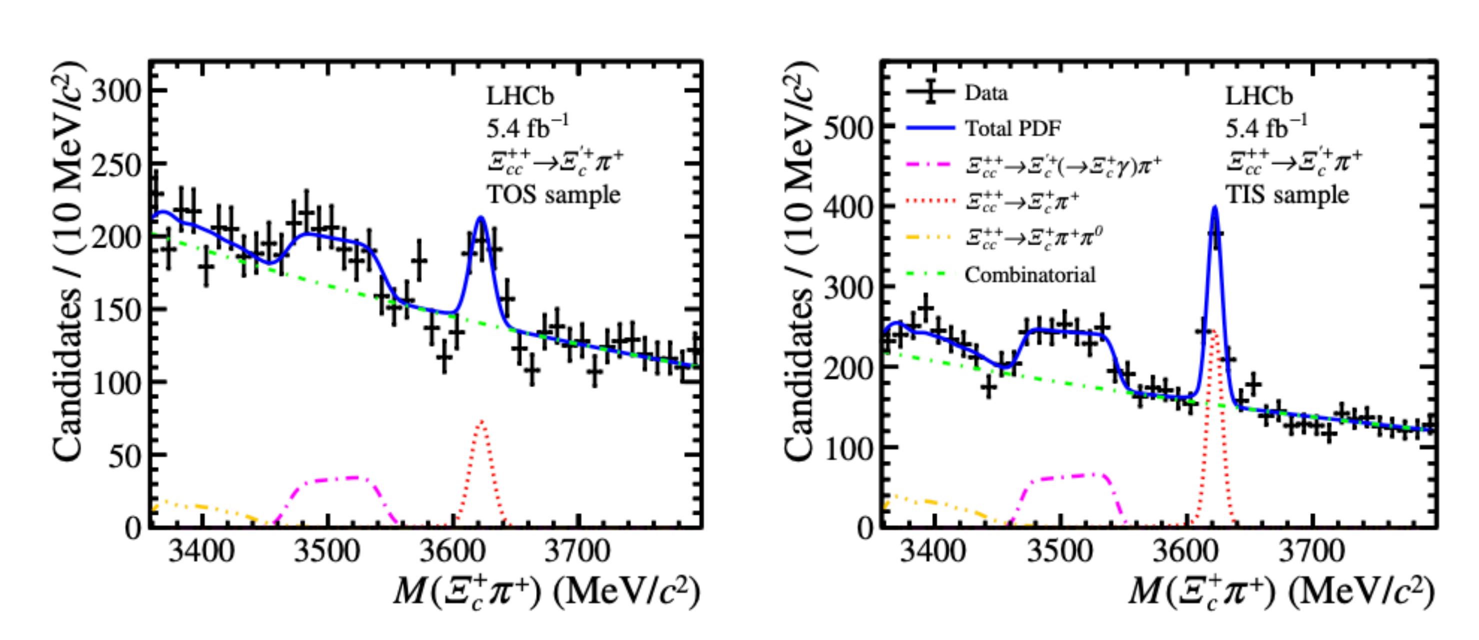
Published for SISSA by Springer

Received: *February 14, 2022*
Revised: *April 1, 2022*
Accepted: *April 8, 2022*
Published: *May 6, 2022*

Observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+$

The LHCb collaboration





$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+)} = 1.41 \pm 0.17 \pm 0.10$$

INTRODUCTION

Extracting information of Ξ_{cc}^{++} decays from experimental results

$$R \equiv \frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+)} = 1.41 \pm 0.17 \pm 0.10$$

LHCb JHEP 05 (2022), 038

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+) \times \mathcal{B}(\Xi_c^{+} \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^{+}K^-\pi^+\pi^+) \times \mathcal{B}(\Lambda_c^{+} \to pK^-\pi^+)} = 0.035 \pm 0.009(\text{stat.}) \pm 0.003(\text{syst.})$$

LHCb PRL 121,162002 (2018)

$$\mathcal{B}(\Lambda_c^{+} \to pK^-\pi^+) = (6.28 \pm 0.32)\%$$

$$\mathcal{B}(\Xi_c^{+} \to pK^-\pi^+) = (0.62 \pm 0.30)\%$$

PDG

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^{+}K^-\pi^+\pi^+)} = 0.35 \pm 0.20$$

$$\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^{+}K^-\pi^+\pi^+) \approx \tfrac{2}{3}\mathcal{B}(\Xi_{cc}^{++} \to \Sigma_c^{++}\overline{K}^{*0})$$

$$\mathcal{B}(\Xi_{cc}^{++} \to \Sigma_c^{++}\overline{K}^{*0}) = 5.61\%$$

T. Gutsche *et al., PRD 100, 114037 (2019)*

$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+)_{\text{expt}} \approx (1.33 \pm 0.74)\%$$

INTRODUCTION

- Incomplete list of recent papers on Ξ_{cc}^{++} decays

[1] W. Wang, Z. P. Xing and J. Xu, "Weak Decays of Doubly Heavy Baryons: SU(3) Analysis," Eur. Phys. J. C **77**, 800 (2017) [arXiv:1707.06570 [hep-ph]].

[2] A. S. Gerasimov and A. V. Luchinsky, "Weak decays of doubly heavy baryons: Decays to a system of π mesons," Phys. Rev. D **100**, 073015 (2019) [arXiv:1905.11740 [hep-ph]].

[3] H. W. Ke, F. Lu, X. H. Liu and X. Q. Li, "Study on $\Xi_{cc} \to \Xi_c$ and $\Xi_{cc} \to \Xi'_c$ weak decays in the light-front quark model," Eur. Phys. J. C **80**, no.2, 140 (2020) [arXiv:1912.01435 [hep-ph]].

[4] Y. J. Shi, W. Wang and Z. X. Zhao, "QCD Sum Rules Analysis of Weak Decays of Doubly-Heavy Baryons," Eur. Phys. J. C **80**, no.6, 568 (2020) [arXiv:1902.01092 [hep-ph]].

[5] T. Gutsche, M. A. Ivanov, J. G. Körner, V. E. Lyubovitskij and Z. Tyulemissov, "Ab initio three-loop calculation of the W-exchange contribution to nonleptonic decays of double charm baryons," Phys. Rev. D **99**, 056013 (2019) [arXiv:1812.09212 [hep-ph]].

[6] Y. J. Shi, Z. X. Zhao, Y. Xing and U. G. Meißner, "W-exchange contribution to the decays $\Xi_{cc}^{++} \to \Xi_c^{(\prime)+}\pi^+$ using light-cone sum rules," Phys. Rev. D **106** (2022) no.3, 034004 [arXiv:2206.13196 [hep-ph]].

[7] J. J. Han, H. Y. Jiang, W. Liu, Z. J. Xiao and F. S. Yu, "Rescattering mechanism of weak decays of double-charm baryons," Chin. Phys. C **45**, no.5, 053105 (2021) [arXiv:2101.12019 [hep-ph]].

[8] N. Sharma and R. Dhir, "Estimates of W-exchange contributions to Ξ_{cc} decays," Phys. Rev. D **96** (2017) no.11, 113006 [arXiv:1709.08217 [hep-ph]].

[9] H. W. Ke and X. Q. Li, "Revisiting the transition $\Xi_{cc}^{++} \to \Xi_c^{(\prime)+}$ to understand the data from LHCb," Phys. Rev. D **105** (2022) no.9, 096011 [arXiv:2203.10352 [hep-ph]].

[11] H. Y. Cheng, G. Meng, F. Xu and J. Zou, Phys. Rev. D **101**, no.3, 034034 (2020) doi:10.1103/PhysRevD.101.034034 [arXiv:2001.04553 [hep-ph]].

[12] S. Zeng, F. Xu, P. Y. Niu and H. Y. Cheng, Phys. Rev. D **107**, no.3, 034009 (2023) doi:10.1103/PhysRevD.107.034009 [arXiv:2212.12983 [hep-ph]].

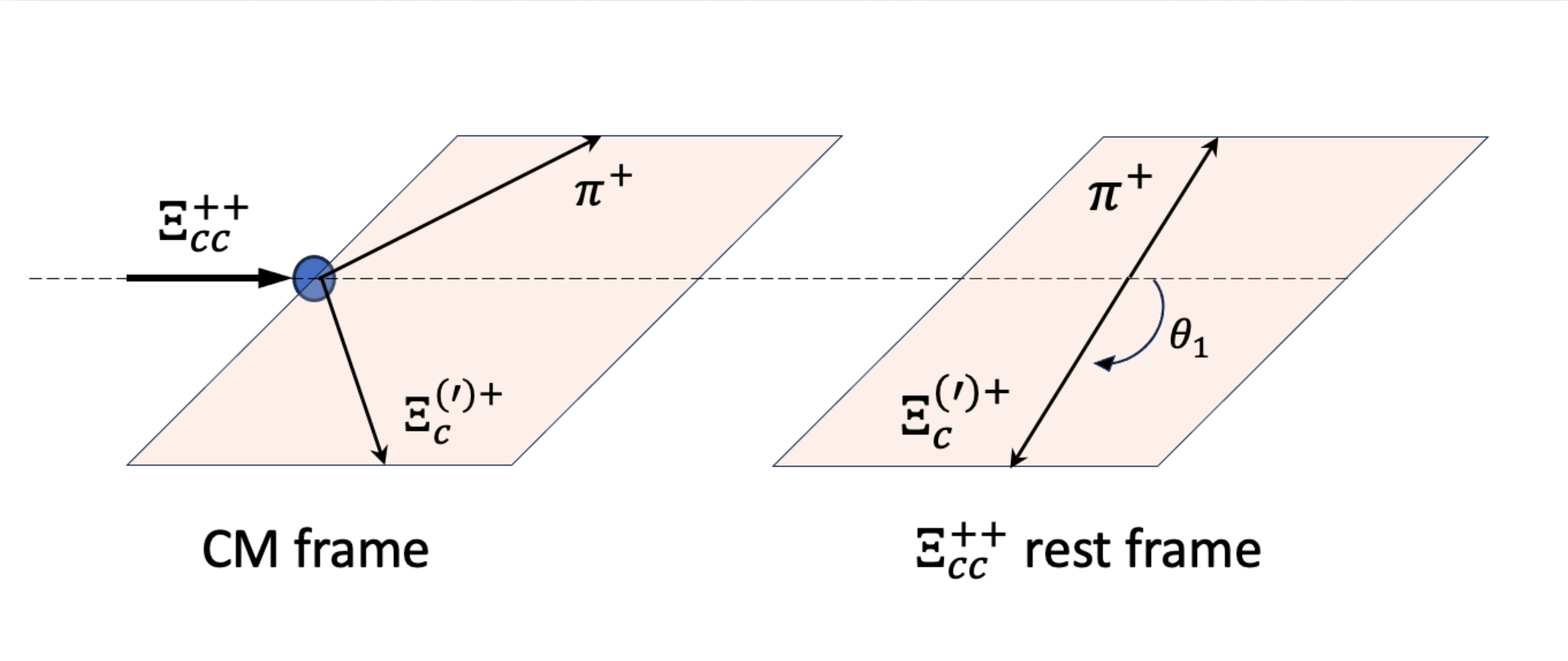
…

KINEMATICS

- Partial wave amplitudes

$$M(\mathcal{B}_i \to \mathcal{B}_f P) = i\bar{u}_f(A - B\gamma_5)u_i,$$

dynamics



- Physical observables

$$\Gamma = \frac{p_c}{8\pi}\left[\frac{(m_i+m_f)^2-m_P^2}{m_i^2}|A|^2+\frac{(m_i-m_f)^2-m_P^2}{m_i^2}|B|^2\right]$$

decay width or branching fraction

absolute size of amplitudes

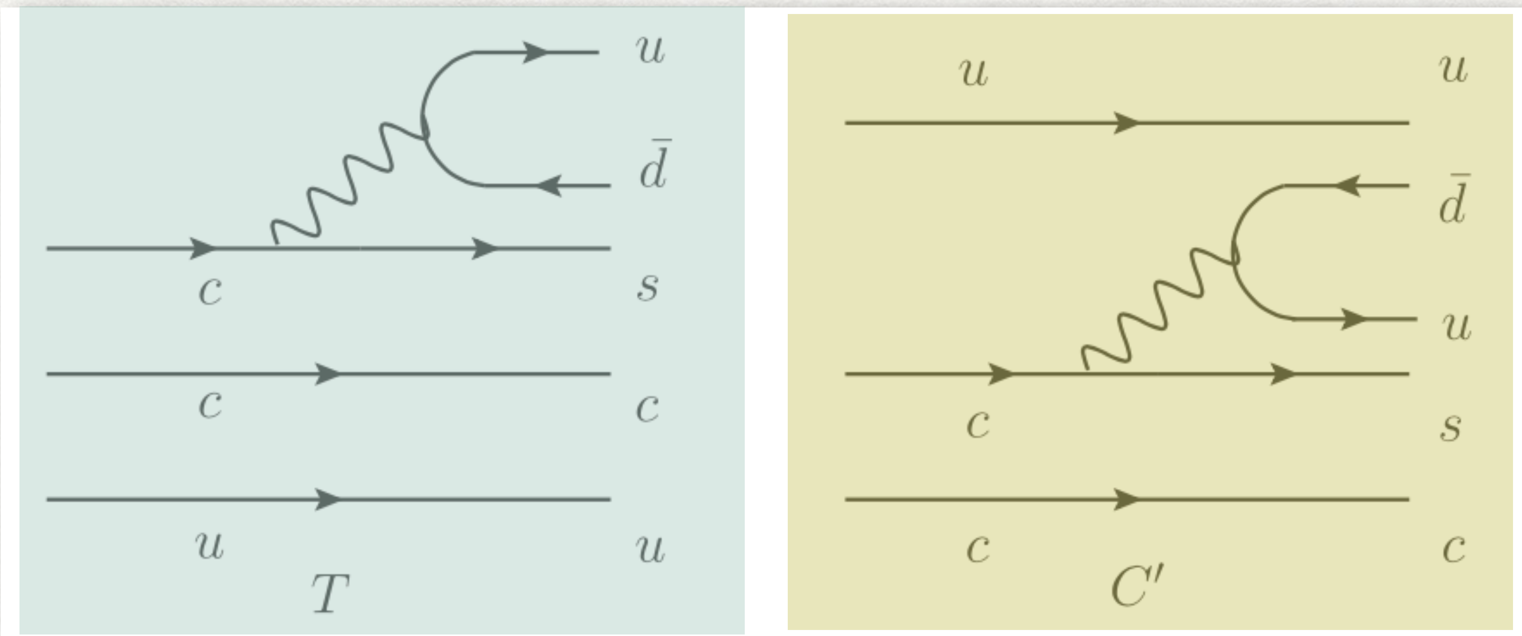
$$\alpha = \frac{2\kappa \mathrm{Re}(A^*B)}{|A|^2+\kappa^2|B|^2}$$

longitudinal polarization

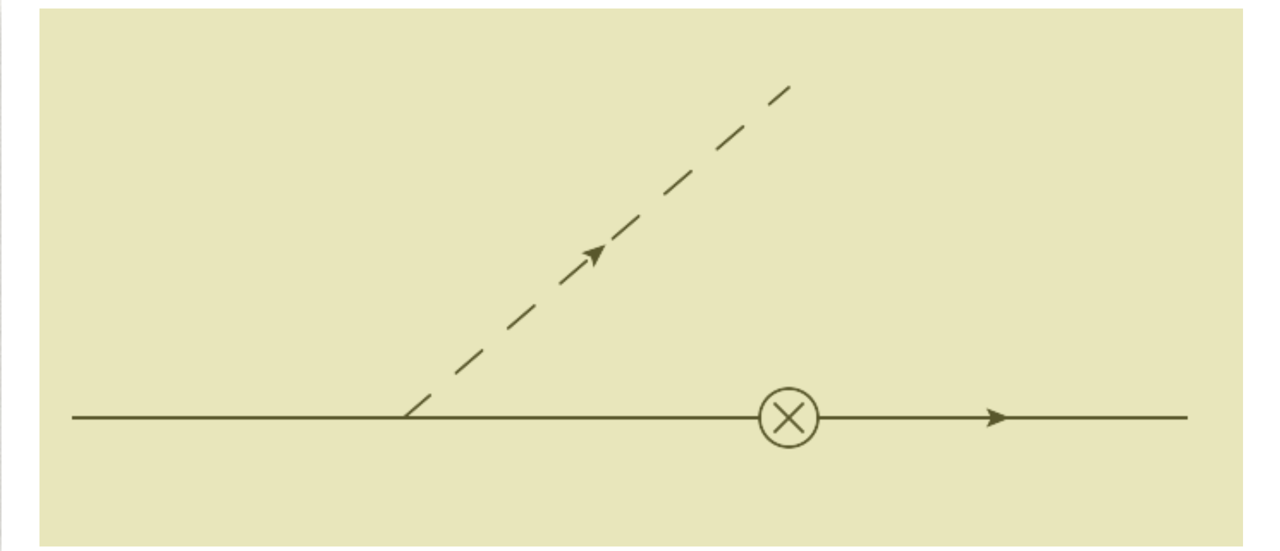
relative size and phase of amplitudes

DYNAMICS: TOPOLOGICAL DIAGRAMS & POLE MODEL

- topological diagram method
  - a tool to manipulate fit (meson case: Chau & Cheng PRL56(1986)1655)
  - **a tool to assist in analyzing dynamics**



factorizable non-factorizable



$$A^{\rm fac} = \frac{G_F}{\sqrt{2}} a_{1,2} V^*_{ud} V_{cs} f_P (m_{\mathcal{B}_{cc}} - m_{\mathcal{B}_c}) f_1(q^2),$$

$$B^{\rm fac} = -\frac{G_F}{\sqrt{2}} a_{1,2} V^*_{ud} V_{cs} f_P (m_{\mathcal{B}_{cc}} + m_{\mathcal{B}_c}) g_1(q^2)$$

$$A^{\rm pole} = -\sum_{B^*_n(1/2^-)} \left[\frac{g_{B_f B^*_n P} b_{n^* i}}{m_i - m_{n^*}} + \frac{b_{f n^*} g_{B^*_n B_i P}}{m_f - m_{n^*}} \right],$$

$$B^{\rm pole} = \sum_{B_n} \left[\frac{g_{B_f B_n P} a_{ni}}{m_i - m_n} + \frac{a_{fn} g_{B_n B_i P}}{m_f - m_n} \right],$$

DETAILED AMPLITUDES

A summary of all amplitudes

factorizable amplitudes

$$A^{\rm fac} = \frac{G_F}{\sqrt{2}} a_{1,2} V_{ud}^* V_{cs} f_P (m_{\mathcal{B}_{cc}} - m_{\mathcal{B}_c}) f_1(q^2),$$

$$B^{\rm fac} = -\frac{G_F}{\sqrt{2}} a_{1,2} V_{ud}^* V_{cs} f_P (m_{\mathcal{B}_{cc}} + m_{\mathcal{B}_c}) g_1(q^2)$$

non-perturbative parameters

non-factorizable amplitudes

$$A^{\rm nf}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) = \frac{1}{f_\pi}(-a_{\Xi_c^+ \Xi_{cc}^+}),$$

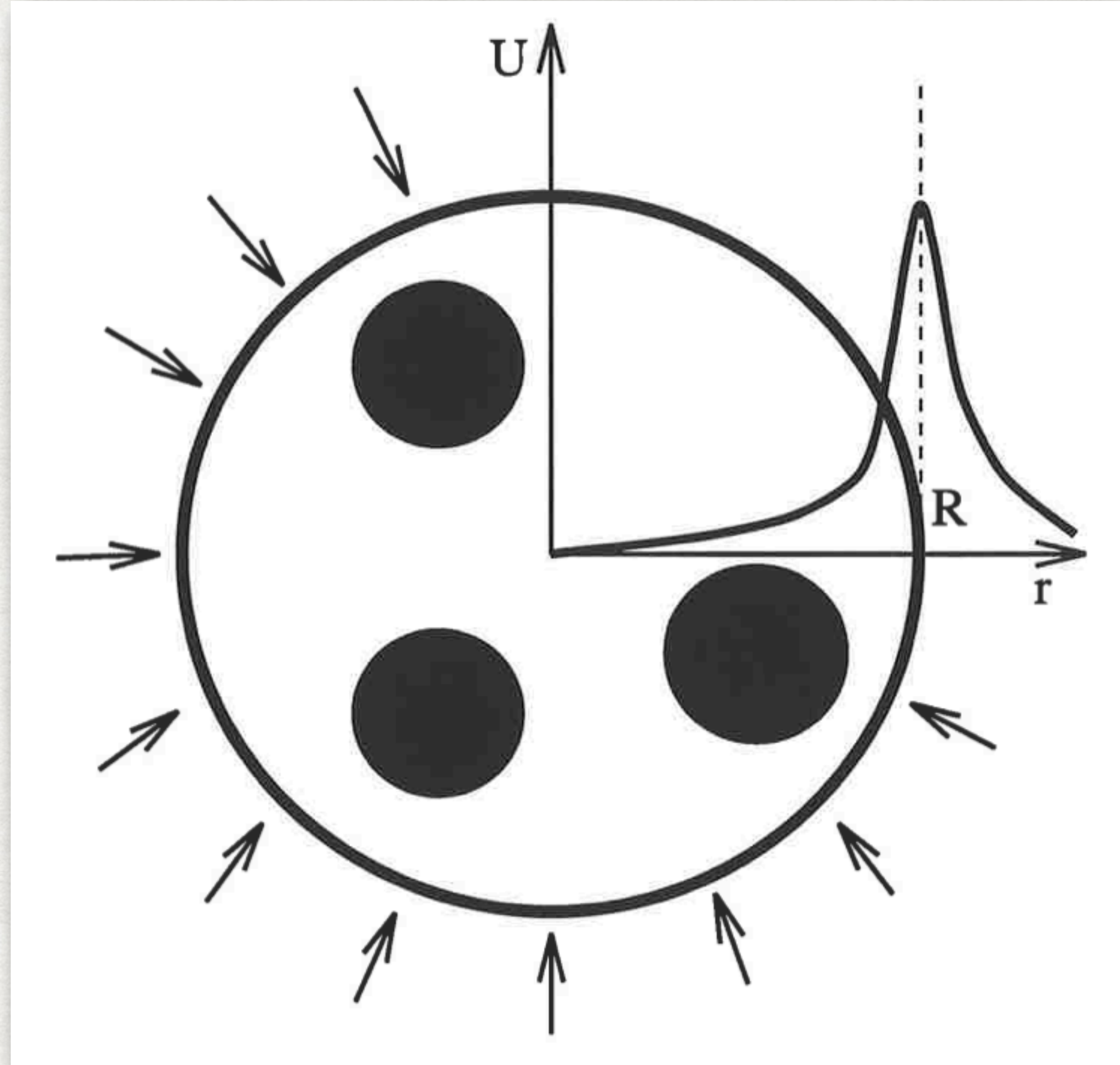
$$A^{\rm nf}(\Xi_{cc}^{++} \to \Xi_c'^+ \pi^+) = \frac{1}{f_\pi}(-a_{\Xi_c'^+ \Xi_{cc}^+}),$$

$$B^{\rm nf}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) = \frac{1}{f_\pi}\left(a_{\Xi_c^+ \Xi_{cc}^+} \frac{m_{\Xi_{cc}^{++}} + m_{\Xi_{cc}^+}}{m_{\Xi_c^+} - m_{\Xi_{cc}^+}} g_{\Xi_{cc}^+ \Xi_{cc}^{++}}^{A(\pi^+)}\right),$$

$$B^{\rm nf}(\Xi_{cc}^{++} \to \Xi_c'^+ \pi^+) = \frac{1}{f_\pi}\left(a_{\Xi_c'^+ \Xi_{cc}^+} \frac{m_{\Xi_{cc}^{++}} + m_{\Xi_{cc}^+}}{m_{\Xi_c'^+} - m_{\Xi_{cc}^+}} g_{\Xi_{cc}^+ \Xi_{cc}^{++}}^{A(\pi^+)}\right),$$

- Lattice QCD
- QCD sum rule
- Quark Models

MIT BAG MODEL (STATIC BAG MODEL)



MIT bag model

$$[i\gamma^\mu \partial_\mu - (m+U)]\,\psi = 0, \qquad U = \begin{cases} 0, & r < R \\ U_0, & r \geqslant R \end{cases}$$

$$\psi(\boldsymbol{r}) = N_{n\kappa} \begin{pmatrix} j_l(pr) \\ -i\mathrm{sgn}(\kappa)(\boldsymbol{\sigma}\cdot\boldsymbol{r})j_{l'}(pr) \end{pmatrix} \chi$$

$$N_{n\kappa} = \left(\int_0^R dr\, r^2 (j_l^2(pr) + j_{l'}^2(pr)) \right)^{-\frac{1}{2}}$$

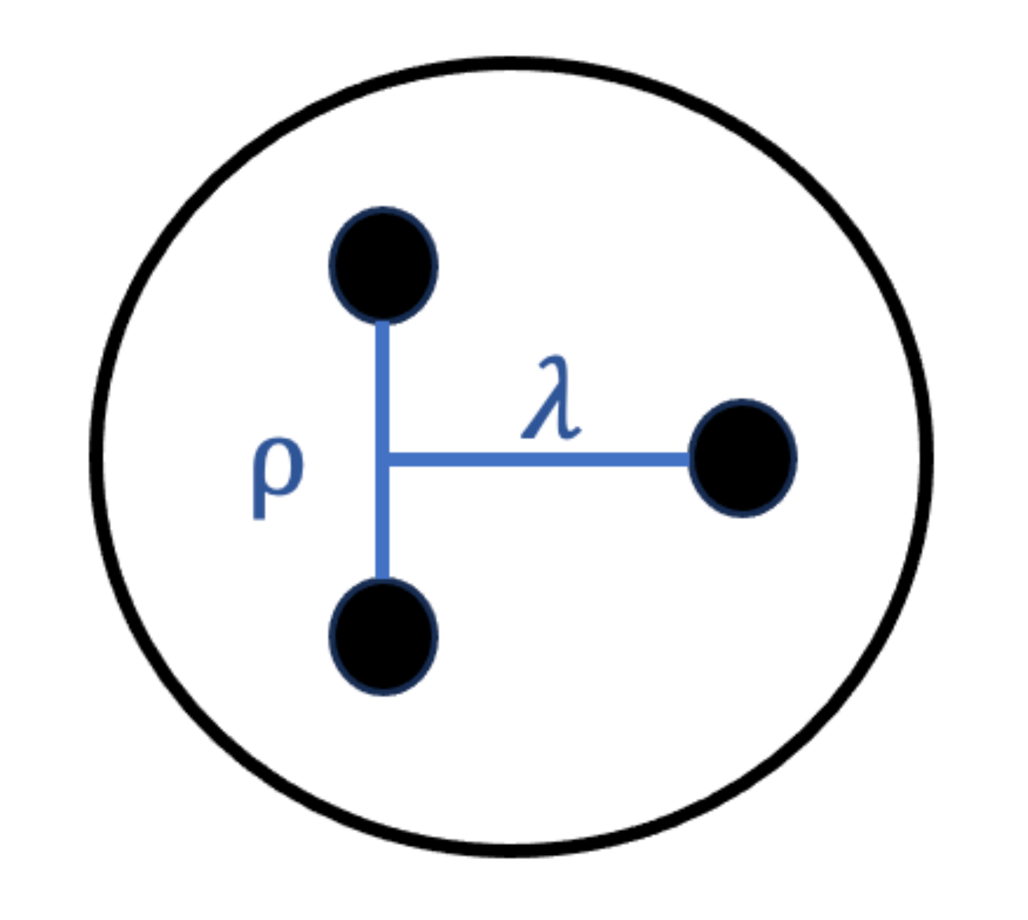
$$\psi = \begin{pmatrix} iu(r)\chi \\ v(r)\boldsymbol{\sigma}\cdot\hat{\mathbf{r}}\chi \end{pmatrix}$$

Baryon wave function:

$$|\mathcal{B}^\uparrow\rangle = \frac{1}{\sqrt{6}} \epsilon^{\alpha\beta\gamma} \int \chi_s^\uparrow \phi_{\alpha\beta\gamma}^{abc}(x_1, x_2, x_3) \Psi_{\mathcal{B}(q_1 q_2 q_3)}(x_1, x_2, x_3)[d^3x]|0\rangle$$

$$\Psi_{\mathcal{B}(q_1 q_2 q_3)}(x_1, x_2, x_3) = \psi_{q_1}(x_1)\psi_{q_2}(x_2)\psi_{q_3}(x_3)$$

NON-RELATIVISTIC QUARK MODEL



NR quark model

$$H = \sum_{i=1}^{3} \frac{\mathbf{p}_i^2}{2m_i} + \frac{1}{2} K \sum_{i<j} (\mathbf{r}_i - \mathbf{r}_j)^2$$

$$H = \frac{\mathbf{p}^2}{2M} + \frac{\mathbf{p}_\rho^2}{2m_\rho} + \frac{\mathbf{p}_\lambda^2}{2m_\lambda} + \frac{1}{2} m_\rho \omega_\rho^2 \boldsymbol{\rho}^2 + \frac{1}{2} m_\lambda \omega_\lambda^2 \boldsymbol{\lambda}^2$$

$$\boldsymbol{R}_c = \frac{m_1 \boldsymbol{r}_1 + m_2 \boldsymbol{r}_2 + m_3 \boldsymbol{r}_3}{m_1 + m_2 + m_3}, \quad \boldsymbol{\rho} = \boldsymbol{r}_1 - \boldsymbol{r}_2, \quad \boldsymbol{\lambda} = \frac{m_1 \boldsymbol{r}_1 + m_2 \boldsymbol{r}_2}{m_1 + m_2} - \boldsymbol{r}_3.$$

$$\boldsymbol{p} = M\dot{\boldsymbol{R}}_c = \boldsymbol{p}_1 + \boldsymbol{p}_2 + \boldsymbol{p}_3, \quad \boldsymbol{p}_\rho = m_\rho \dot{\boldsymbol{\rho}} = \frac{m_2}{m_1 + m_2} \boldsymbol{p}_1 - \frac{m_1}{m_1 + m_2} \boldsymbol{p}_2, \quad \boldsymbol{p}_\lambda = m_\lambda \dot{\boldsymbol{\lambda}} = \frac{m_3(\boldsymbol{p}_1 + \boldsymbol{p}_2) - (m_1 + m_2)\boldsymbol{p}_3}{(m_1 + m_2 + m_3)}.$$

$$|\mathcal{B}(\boldsymbol{P}_c)_{J,M}\rangle = \sum_{S_z, M_L; c_i} \langle L, M_L; S, S_z | J, M \rangle \int d\boldsymbol{p}_1 d\boldsymbol{p}_2 d\boldsymbol{p}_3 \delta^3(\boldsymbol{p}_1 + \boldsymbol{p}_2 + \boldsymbol{p}_3 - \boldsymbol{P}_c) \Psi_{N,L,M_L}(\boldsymbol{p}_1, \boldsymbol{p}_2, \boldsymbol{p}_3) \times \chi^{S,S_z}_{s_1,s_2,s_3} \frac{\epsilon_{c_1 c_2 c_3}}{\sqrt{6}} \phi_{i_1,i_2,i_3} b^\dagger_{c_1,i_1,s_1,\boldsymbol{p}_1} b^\dagger_{c_2,i_2,s_2,\boldsymbol{p}_2} b^\dagger_{c_3,i_3,s_3,\boldsymbol{p}_3} |0\rangle,$$

$$\langle \mathcal{B}(\boldsymbol{P'}_c)_{J,M} | \mathcal{B}(\boldsymbol{P}_c)_{J,M} \rangle = \delta^3(\boldsymbol{P'}_c - \boldsymbol{P}_c)$$

$$\Psi_{LM_L n_\rho l_\rho n_\lambda l_\lambda}(\boldsymbol{P}, \boldsymbol{p}_\rho, \boldsymbol{p}_\lambda) = \delta^3(\boldsymbol{P} - \boldsymbol{P}_c) \sum_m \langle LM_L | l_\rho m, l_\lambda M_L - m \rangle \psi_{n_\rho l_\rho m}(\boldsymbol{p}_\rho) \psi_{n_\lambda l_\lambda (M_L - m)}(\boldsymbol{p}_\lambda)$$

$$\psi_{nLm}(\boldsymbol{p}) = (i)^l (-1)^n \left[\frac{2n!}{(n + L + \frac{1}{2})!} \right]^{\frac{1}{2}} \frac{1}{\alpha^{L+\frac{3}{2}}} e^{-\frac{p^2}{2\alpha^2}} L_n^{L+\frac{1}{2}}\left(\frac{\boldsymbol{p}^2}{\alpha^2} \right) \mathcal{Y}_{Lm}(\boldsymbol{p})$$

MODEL ESTIMATIONS

$$\langle \mathcal{B}_c(p_2)|\bar{c}\gamma_\mu(1-\gamma_5)u|\mathcal{B}_{cc}(p_1)\rangle = \bar{u}_2\left[f_1(q^2)\gamma_\mu - f_2(q^2)i\sigma_{\mu\nu}\frac{q^\nu}{M} + f_3(q^2)\frac{q_\mu}{M} - \left(g_1(q^2)\gamma_\mu - g_2(q^2)i\sigma_{\mu\nu}\frac{q^\nu}{M} + g_3(q^2)\frac{q_\mu}{M}\right)\gamma_5\right]u_1$$

$$a_{\mathcal{B}'\mathcal{B}} \equiv \langle \mathcal{B}'|\mathcal{H}_{\rm eff}^{\rm PC}|\mathcal{B}\rangle = \frac{G_F}{2\sqrt{2}}V_{cs}V_{ud}^* c_- \langle \mathcal{B}'|O_-|\mathcal{B}\rangle$$

$\mathcal{B}_{cc} \to \mathcal{B}_c$	f_1		g_1		g^A		$\langle \mathcal{B}_f|O_-|\mathcal{B}_i\rangle$	
	MBM	NRQM	MBM	NRQM	MBM	NRQM	MBM	NRQM
$\Xi_{cc}^{++} \to \Xi_c^+\pi^+$	$\frac{\sqrt{6}}{2}X_1$	$\frac{\sqrt{6}}{2}X_2$	$\frac{\sqrt{6}}{6}X_1'$	$\frac{\sqrt{6}}{6}X_2$	$-\frac{1}{3}Y_1$	$-\frac{1}{3}Y_2$	$4\sqrt{6}Z_1$	$4\sqrt{6}Z_2$
$\Xi_{cc}^{++} \to \Xi_c'^+\pi^+$	$\frac{\sqrt{2}}{2}X_1$	$\frac{\sqrt{2}}{2}X_2$	$\frac{5\sqrt{2}}{6}X_1'$	$\frac{5\sqrt{2}}{6}X_2$	$-\frac{1}{3}Y_1$	$-\frac{1}{3}Y_2$	$-\frac{4\sqrt{2}}{3}Z_1'$	0

Bag model

$$X_1 = 4\pi\int_0^R r^2 dr(u_s u_c + v_s v_c)$$ 0.95

$$X_1' = 4\pi\int_0^R r^2 dr(u_s u_c - \frac{1}{3}v_s v_c)$$ 0.86

$$Y_1 = 4\pi\int_0^R r^2 dr(u_u^2 - \frac{1}{3}v_u^2)$$ 0.65

$$Z_1 = 4\pi\int_0^R r^2 dr(u_s u_u + v_s v_u)(u_c u_d + v_c v_d)$$ 2.19×10^{-3}

$$Z_1' = 4\pi\int_0^R r^2 dr(u_s v_u - v_s u_u)(u_c v_d - v_c u_d)$$ 4.47×10^{-5}

NRQM

$$X_2 = \left(\frac{16(m_s+m_u)^2\alpha_{\lambda1}\alpha_{\lambda2}\alpha_{\rho1}\alpha_{\rho2}}{D_1+D_2}\right)^{3/2}$$ 0.58

$$Y_2 = 8\left(\frac{\alpha_{\lambda1}\alpha_{\lambda3}\alpha_{\rho1}\alpha_{\rho3}}{(\alpha_{\lambda1}^2+\alpha_{\lambda3}^2)(\alpha_{\rho1}^2+\alpha_{\rho3}^2)}\right)^{3/2}$$ 1.00

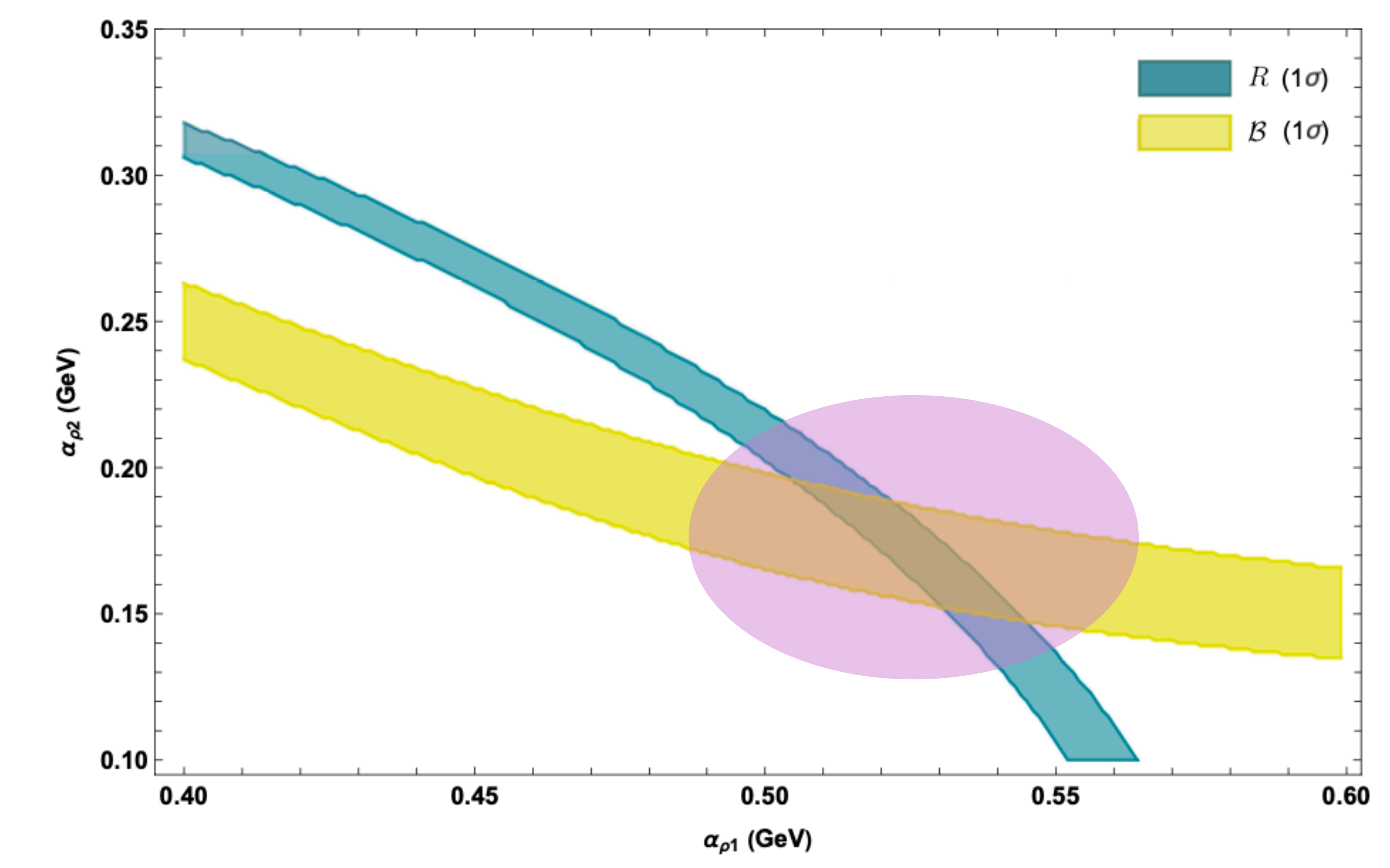
$$Z_2 = 128\sqrt{2}\pi^{3/2}\left(\frac{\alpha_{\lambda2}\alpha_{\lambda3}\alpha_{\rho2}\alpha_{\rho3}}{4\alpha_{\lambda2}^2+\alpha_{\lambda3}^2+4\alpha_{\rho3}^2}\right)^{3/2}$$ $Z_2 = 0.79$

MODEL INPUTS

$$\langle \mathcal{B}_c(p_2)|\bar{c}\gamma_\mu(1-\gamma_5)u|\mathcal{B}_{cc}(p_1)\rangle = \bar{u}_2\left[f_1(q^2)\gamma_\mu - f_2(q^2)i\sigma_{\mu\nu}\frac{q^\nu}{M} + f_3(q^2)\frac{q_\mu}{M} - \left(g_1(q^2)\gamma_\mu - g_2(q^2)i\sigma_{\mu\nu}\frac{q^\nu}{M} + g_3(q^2)\frac{q_\mu}{M}\right)\gamma_5\right]u_1$$

$$a_{\mathcal{B}'\mathcal{B}} \equiv \langle \mathcal{B}'|\mathcal{H}_{\rm eff}^{\rm PC}|\mathcal{B}\rangle = \frac{G_F}{2\sqrt{2}}V_{cs}V_{ud}^* c_- \langle \mathcal{B}'|O_-|\mathcal{B}\rangle$$

	$(\alpha_{\rho 1}, \alpha_{\rho 2})$	$f_1(m_P^2)$	$g_1(m_P^2)$	$g^{A(\pi)}_{\mathcal{B}'\mathcal{B}}$	$\langle \mathcal{B}_f|O_-|\mathcal{B}_i\rangle$
$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$					
MBM		0.577	0.222	−0.217	0.0214
NRQM					
Case 1	(0.50, 0.21)	0.709	0.236	−0.333	0.0310
Case 2	(0.51, 0.19)	0.574	0.191	−0.333	0.0247
Case 3	(0.53, 0.17)	0.425	0.141	−0.333	0.0191
$\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^+$					
MBM		0.386	0.703	−0.217	8.4×10^{-5}
NRQM					
Case 1	(0.50, 0.21)	0.397	0.662	−0.333	0
Case 2	(0.51, 0.19)	0.323	0.538	−0.333	0
Case 3	(0.53, 0.17)	0.240	0.400	−0.333	0



Ξ_{cc}^{++} : $\alpha_{\lambda 1} = \left[\frac{16 m_u}{3(2m_c + m_u)}\right]^{\frac{1}{4}} \alpha_{\rho 1}$

Ξ_c^{+} : $\alpha_{\lambda 2} = \left[\frac{4 m_c (m_s + m_u)^2}{3 m_s m_u (m_s + m_u + m_c)}\right]^{\frac{1}{4}} \alpha_{\rho 2}$

$\Xi_c'^{+}$: $\alpha_{\lambda 3} = \left[\frac{16 m_d}{3(2m_c + m_d)}\right]^{\frac{1}{4}} \alpha_{\rho 3}$

RESULTS

	$A^{\rm fac}$	$A^{\rm nf}$	$A^{\rm tot}$	$B^{\rm fac}$	$B^{\rm nf}$	$B^{\rm tot}$	$10^2\mathcal{B}$	α	R
$\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+$									
MBM	7.40	−10.79	−3.38	−15.06	18.91	3.85	0.69	−0.41	
NRQM Case 1	9.1	−15.6	−6.5	−16.0	27.4	11.4	3.01	−0.78	
Case 2	7.4	−12.4	−5.0	−13.0	21.8	8.8	1.83	−0.78	
Case 3	7.4	−10.8	−3.4	−15.1	18.9	3.8	0.69	−0.41	
$\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$									
MBM	4.49	−0.04	4.45	−48.50	0.06	−48.44	4.65	−0.84	6.74
NRQM Case 1	4.6	0	4.6	−45.6	0	−45.6	4.32	−0.89	1.44
Case 2	3.7	0	3.7	−37.1	0	−31.0	2.86	−0.89	1.56
Case 3	2.8	0	2.8	−27.6	0	−27.6	2.16	−0.89	1.32
LHCb									1.41 ± 0.20

$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^+)_{\rm expt} \approx (1.33 \pm 0.74)\%$

- NF amplitudes are suppressed for $\Xi_c^{\prime +}\pi^+$ mode, due to Korner-Pati-Woo theorem.
- Both S- and P-wave NF amplitudes in $\Xi_c^{+}\pi^+$ dominate and have destructive interference with factorizale ones
- MIT bag model estimation gives small $\Xi_c^{+}\pi^+$ and large ratio R.
- NR quark model estimation can reach experimental requirement, taking Case 2 as an example.
- The sizes of non-factorizable amplitudes: bag model < NRQM.

[15] J.G. Körner, *Octet behaviour of single-particle matrix elements* $\langle B'|Hw|B\rangle$ *and* $\langle M'|Hw|M\rangle$ *using a weak current-current quark Hamiltonian*, Nucl. Phys. B **25** (1971) 282 [INSPIRE].

[16] J.C. Pati and C.H. Woo, $\Delta I = \frac{1}{2}$ *rule with fermion quarks*, Phys. Rev. D **3** (1971) 2920 [INSPIRE].

COMPARISON

	A^{fac}	A^{nf}	A^{tot}	B^{fac}	B^{nf}	B^{tot}	$\mathcal{B}$	α	R
$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$									
MBM [11]	7.4	−10.8	−3.4	−15.1	18.9	3.8	0.69	−0.41	
NRQM									
Case 1	9.1	−15.6	−6.5	−16.0	27.4	11.4	3.01	−0.78	
Case 2	7.4	−12.4	−5.0	−13.0	21.8	8.8	1.83	−0.78	
Case 3	5.5	−9.6	−4.1	−9.6	16.8	7.2	1.20	−0.78	
Gutsche *et al.* [5]	−8.1	11.5	3.4	13.0	−18.5	−5.6	0.71	−0.57	
Sharma & Dhir [8]									
NRQM	7.38	0	7.38	−16.77	−24.95	−41.72	6.64	−0.99	
HQET	9.52	0	9.52	−19.45	−24.95	−44.40	9.19	−0.99	
Shi *et al.* [6]									
LCSR+HQET	9.52	−16.67	−7.18	−19.45	−20.47	−39.92	6.22	+0.99	
Ke & Li [9]									
$\theta = 16.27°$							2.14	−0.09	
$\theta = 85.54°$							2.14	−0.95	
Liu & Geng [31][4]									
SB ($\theta = -24.7°$)	4.83	−9.99	−5.16	5.16	13.6	18.8	2.24	−0.93	
HB ($\theta = 24.7°$)	7.08	−20.3	−13.2	−22.1	33.0	10.9	10.3	−0.30	

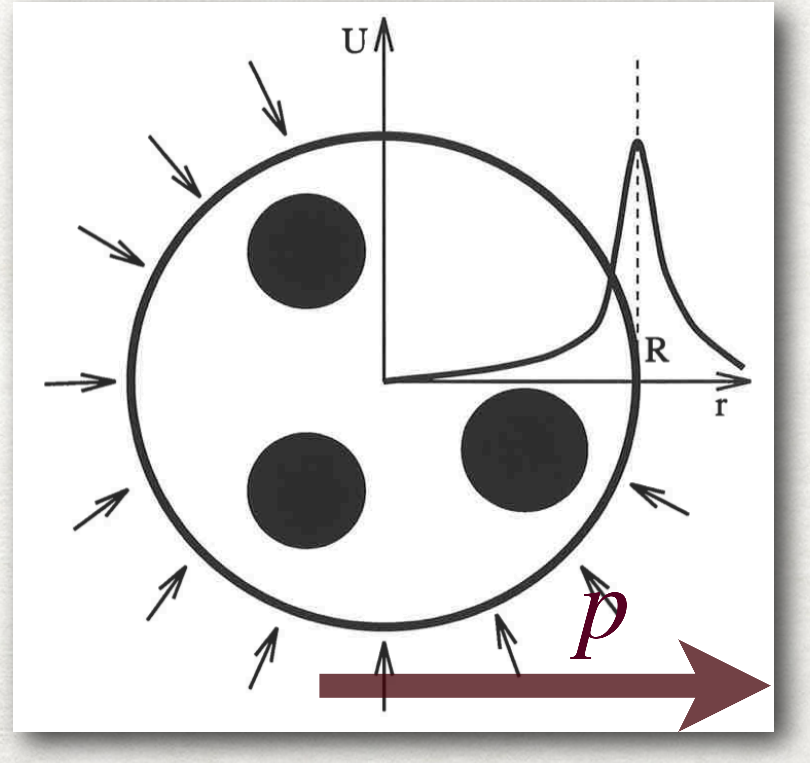
Ξ_c mixing

destructive

constructive

- current data on Br and R
- future measurement of α

help to discriminate theoretical studies



SUMMARY

- It is the time to study charmed baryon decays.

- The decays $\Xi_{cc}^{++} \to \Xi_c^{(\prime)+}\pi^+$ have been studied theoretically in the pole model with the assistance of topological diagrams.

- Non-factorizable contributions play an essential role in charmed baryon decays.

- Two quark model have been investigated in the calculation of non-perturbative parameters contributing to non-factorizable amplitudes.

- Current data (R and one branching fraction) can be explained in proper parameter space of NR quark model or bag model with sizable Ξ_c mixing.

- More experimental and theoretical progresses are anticipated.

Thank you for your attention!

BACKUP SLIDES

$\Xi_c - \Xi_c'$ mixing

$$R = 2\Gamma(\Xi_c^0 \to \Xi^- e^+ \nu_e)/3\Gamma(\Lambda_c^+ \to \Lambda e^+ \nu_e)$$

$$\mathcal{B}_{\rm Belle}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = (1.31 \pm 0.04 \pm 0.07 \pm 0.38)\% \,,$$

$$\mathcal{B}_{\rm ALICE}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = (2.43 \pm 0.25 \pm 0.35 \pm 0.72)\% \,,$$

$$\mathcal{B}_{\rm LQCD}(\Xi_c^0 \to \Xi^- e^+ \nu_e) = (2.38 \pm 0.44)\%$$

$$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11 \pm 0.07)\%$$

BESIII

$$R(\text{Belle}) = 0.33 \pm 0.10 \,, \quad R(\text{ALICE}) = 0.60 \pm 0.21 \,, \quad R(\text{LQCD}) = 0.59 \pm 0.11$$

$$R'_{av} = 0.46 \pm 0.07 \,, \quad R_{av} = 0.59 \pm 0.10$$

$$R(SU(3)_F) = 1$$

$$|\Xi_c\rangle = \cos\theta_c |\Xi_c^{\bar{\mathbf{3}}}\rangle + \sin\theta_c |\Xi_c^{\mathbf{6}}\rangle$$

$$|\Xi_c'\rangle = \cos\theta_c |\Xi_c^{\mathbf{6}}\rangle - \sin\theta_c |\Xi_c^{\bar{\mathbf{3}}}\rangle$$

$$\theta = (1.200 \pm 0.090 \pm 0.020)^\circ$$

$$\theta = (1.220 \pm 0.130 \pm 0.010)^\circ$$

$$|\theta_c| = 0.137(5)\pi$$

0.430398

C.Q. Geng, X.-N. Jin, C.-W. Liu, PLB 833 (2023) 137736

H. Liu, L. Liu, P. Sun, J. Tan, W. Wang, Y. Yang, Q. Zhang, 2303.17863[hep-lat]