Phenomenological Study on Charmed Baryon Decays

Attempt to decipher non-perturbative contributions

Online Flavour Physics Lecture

Leaving for 李政道研究所 TSUNG-DAO LEE INSTITUTE

刘 佳 韦

UCAS

June 8, 2023

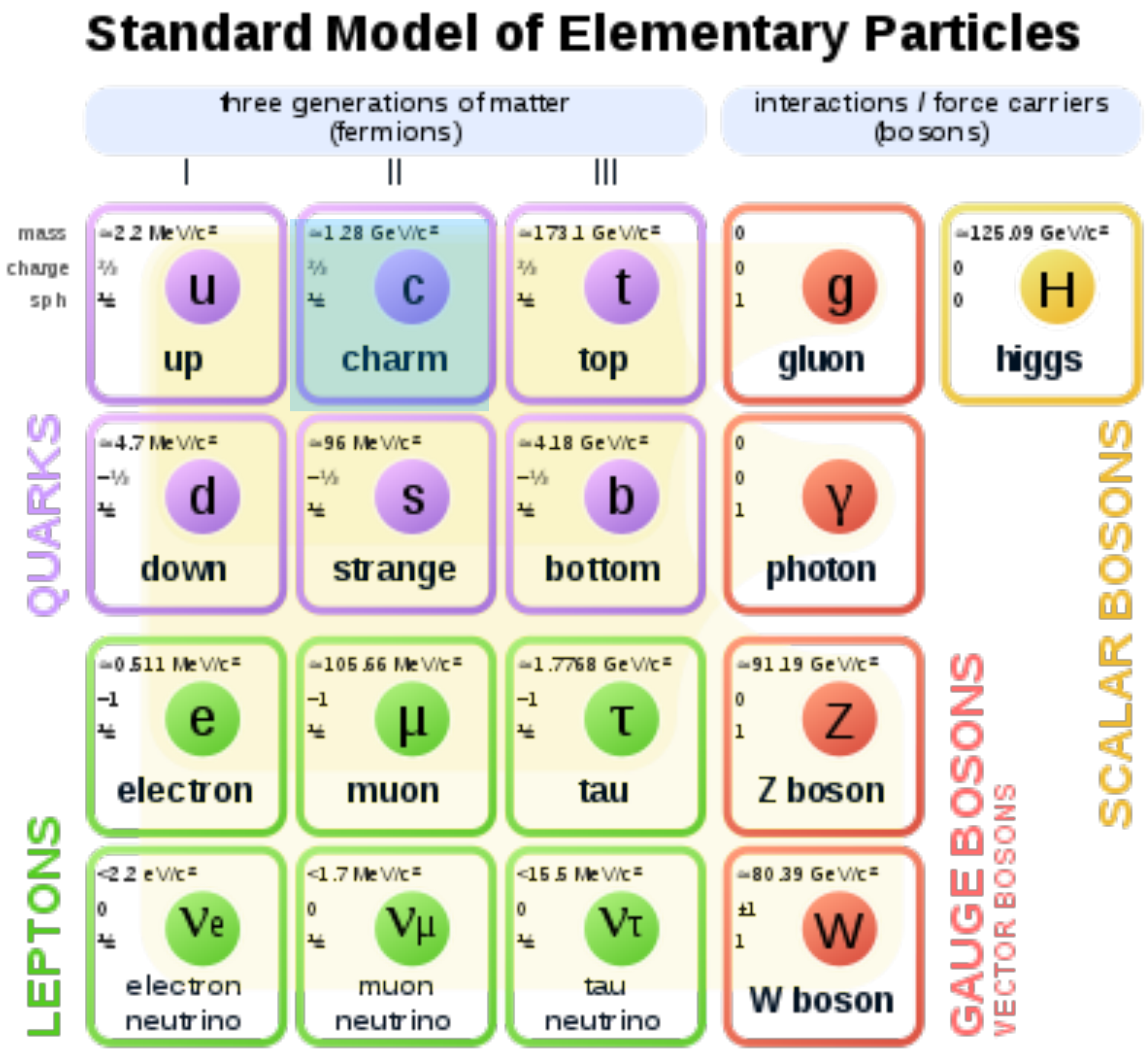
Histories of Charm Quark - November revolution

A discovery of extremely massive, narrow and high pyramid.

Charm

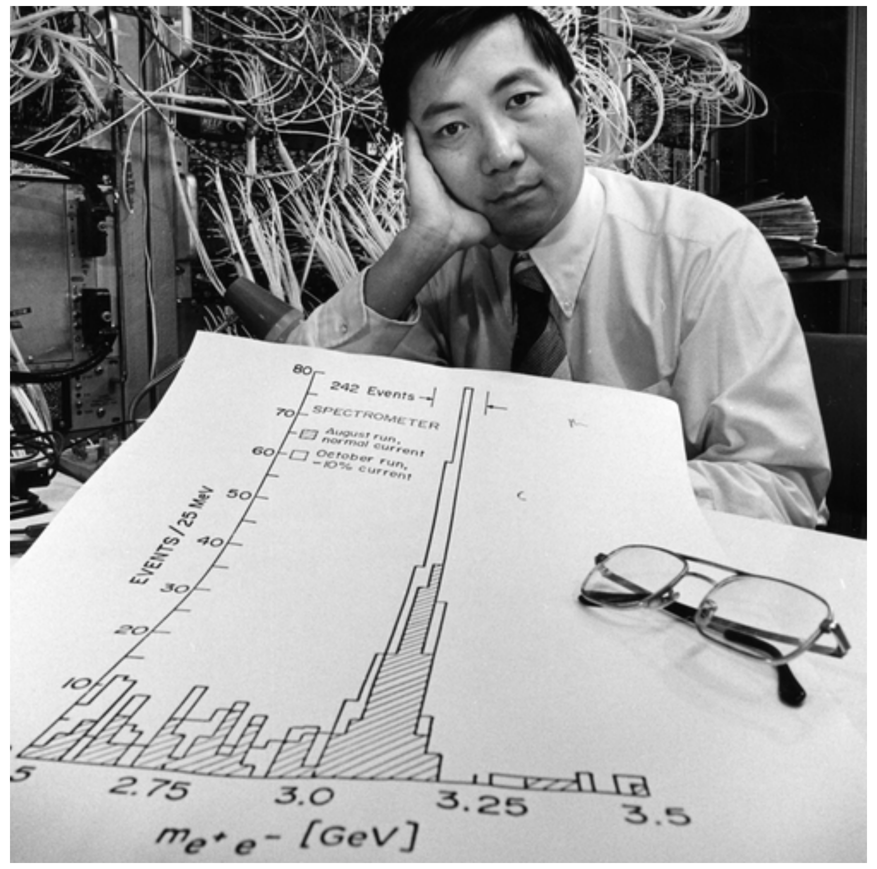
China element

中国元素



A. Khare, ``The November J/ψ revolution: Twenty five years later,''
Curr. Sci. 77, 1210 (1999)

At the East coast of US: Received by PRL on Nov. 12, 1974



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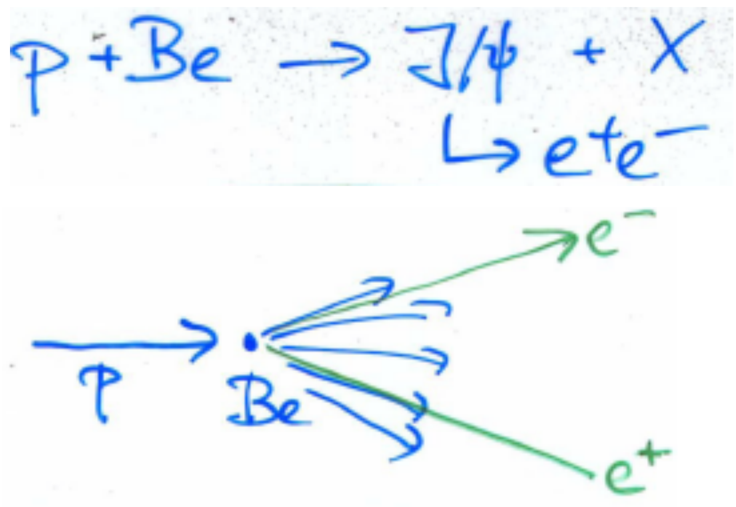
Brookhaven (Proton Synchrotron)



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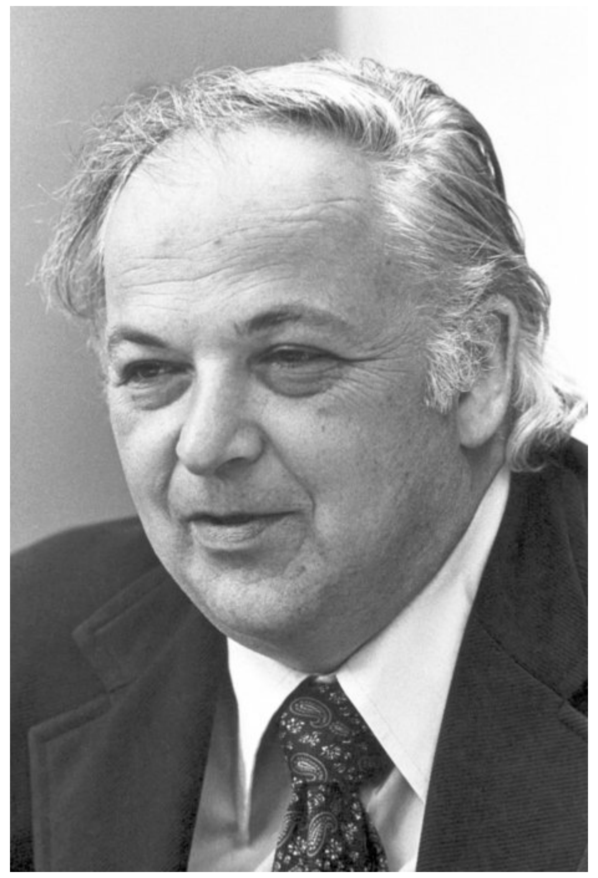
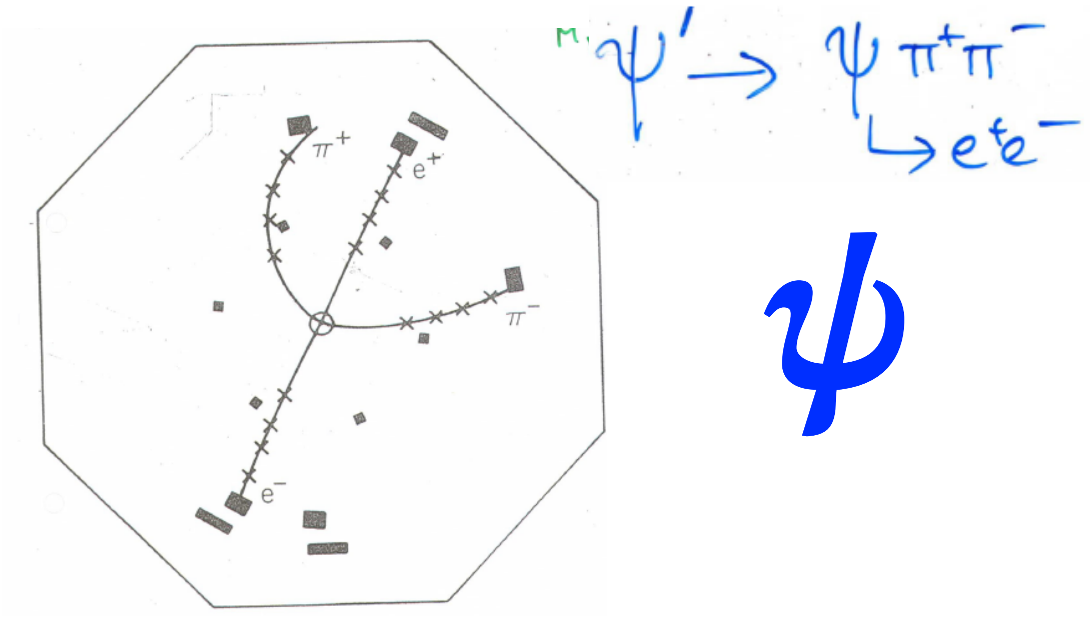


Burton Richter

SLAC (e^+e^- storage ring at 4.5-6 GeV)



Nov. 9 adjusted the machine to 3.1 GeV

Slide from Pro. Chaoqiang Geng

• Histories of Charm Quark - November revolution

A discovery of extremely massive, narrow and high pyramid.

Charm **China element** 中国元素

Contrary to popular belief, the e^+e^- storage ring is not the best place to look for vector mesons. In the e^+e^- storage ring the energy is well defined. A systematic search for heavier mesons requires a continuous variation and monitoring of the energy of the two colliding beams, a difficult task requiring almost infinite time. Storage ring is best suited to perform detailed studies of vector meson parameters once they have been found.

The $e^+e^- \to$ hadron cross section is presumed to go through the one-photon intermediate state with angular momentum, parity, and charge conjugation quantum numbers $J^{PC}=1^{--}$. It is difficult to understand how, without involving new quantum numbers or selection rules, a resonance in this state which decays to hadrons could be so narrow.

A. Khare, ``The November J/ψ revolution: Twenty five years later,''
Curr. Sci. 77, 1210 (1999)

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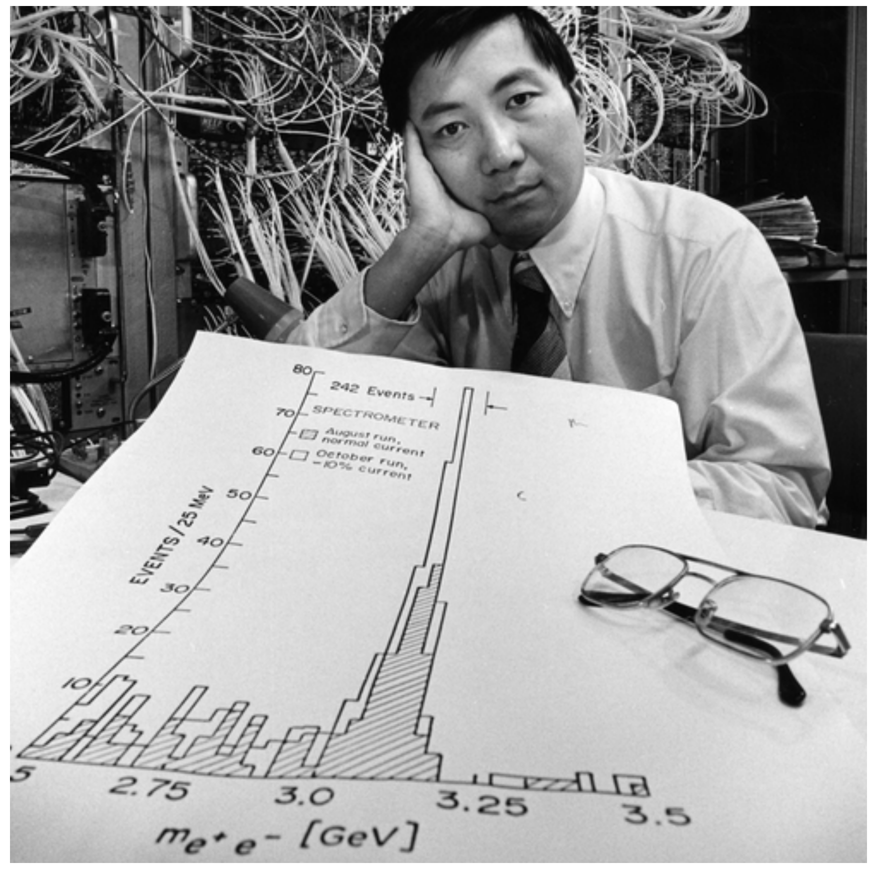

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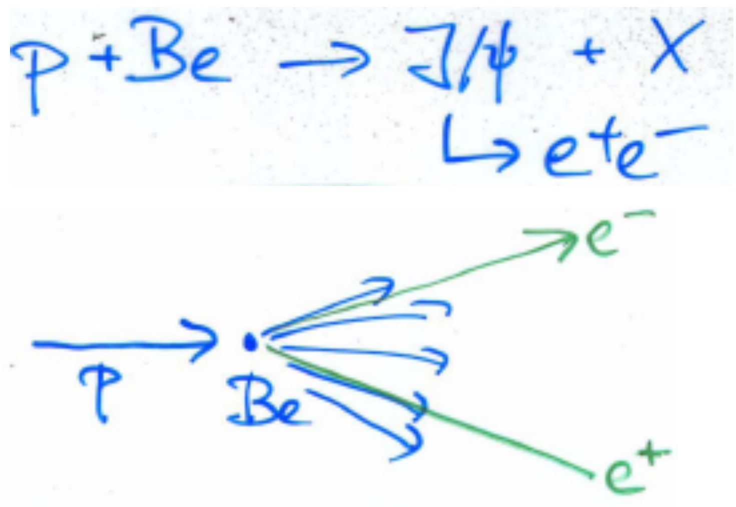

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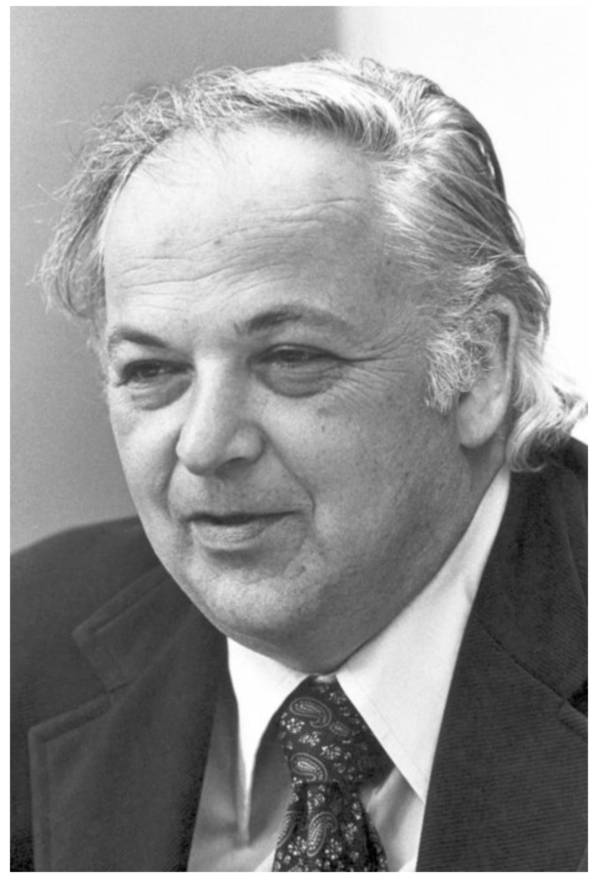

Burton Richter

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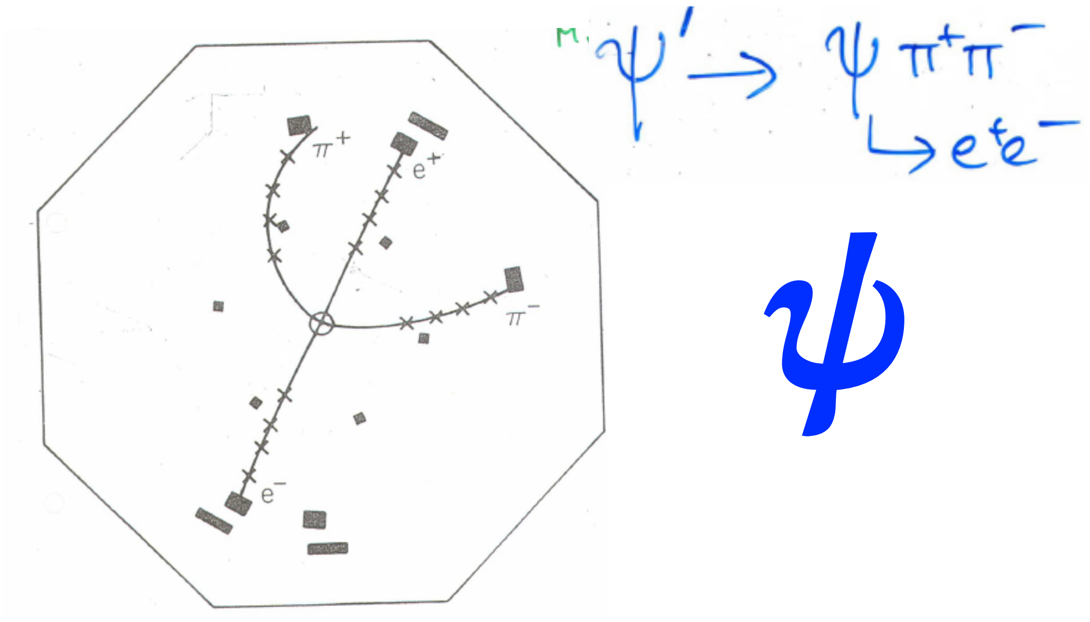


Nov. 9 adjusted the machine to 3.1 GeV

Slide from Pro. Chaoqiang Geng

Histories of Charm Quark - November revolution

A discovery of extremely massive, narrow and high pyramid.

Charm | *China element* | 中国元素

Featured in Physics | Milestone

Experimental Observation of a Heavy Particle J

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, Sau Lan Wu, and Y. Y. Lee

Phys. Rev. Lett. **33**, 1404 (1974) – Published 2 December 1974

Physics Focus: *Landmarks*—The Charming Debut of a New Quark

Show Abstract

Featured in Physics | Milestone

Discovery of a Narrow Resonance in e^+e^- Annihilation

J. -E. Augustin *et al.*

Phys. Rev. Lett. **33**, 1406 (1974) – Published 2 December 1974

Physics Focus: *Landmarks*—The Charming Debut of a New Quark

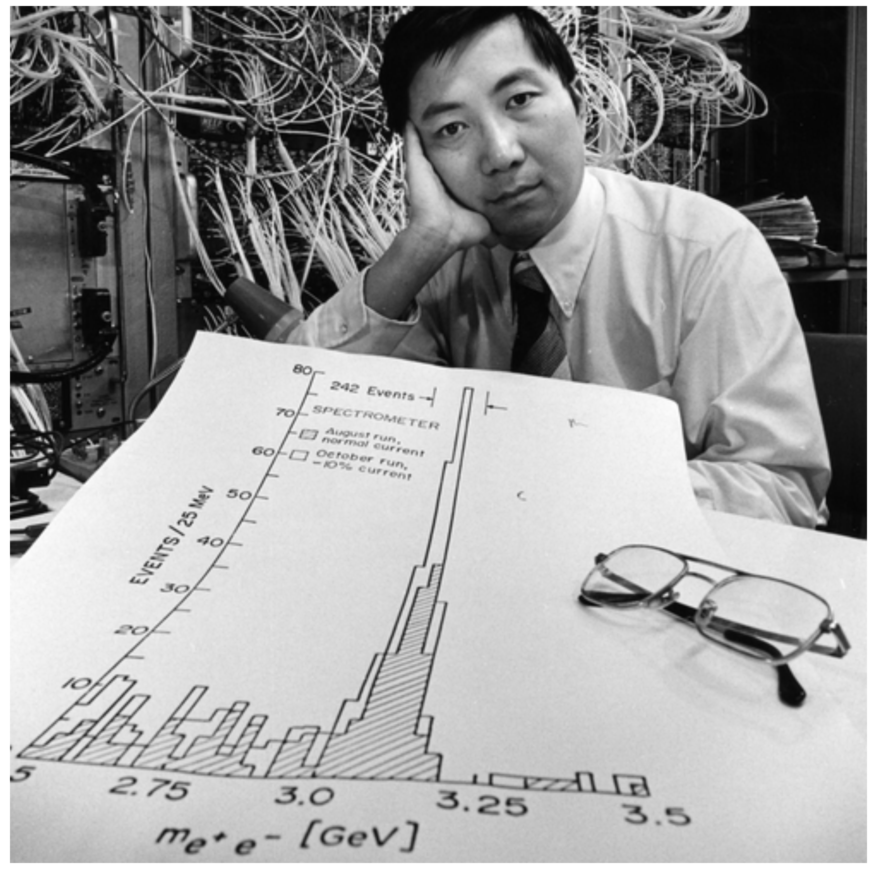
Show Abstract

Preliminary Result of Frascati (ADONE) on the Nature of a New 3.1-GeV Particle Produced in e^+e^- Annihilation

C. Bacci *et al.*

Phys. Rev. Lett. **33**, 1408 (1974) – Published 2 December 1974

At the East coast of US: Received by PRL on Nov. 12, 1974



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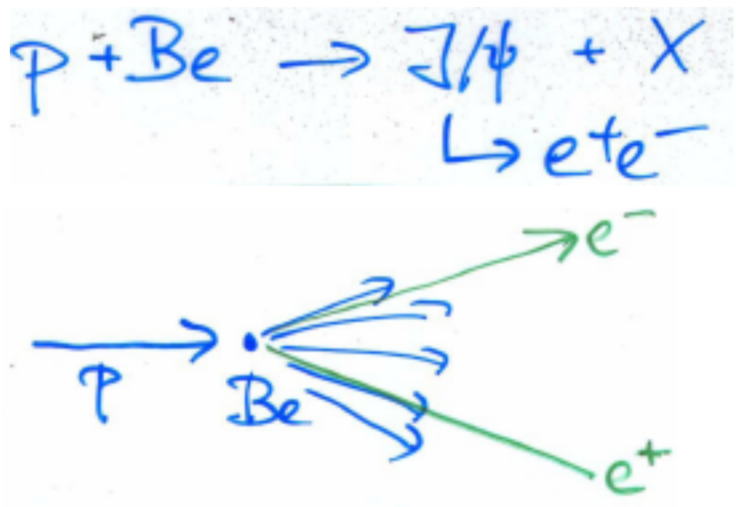

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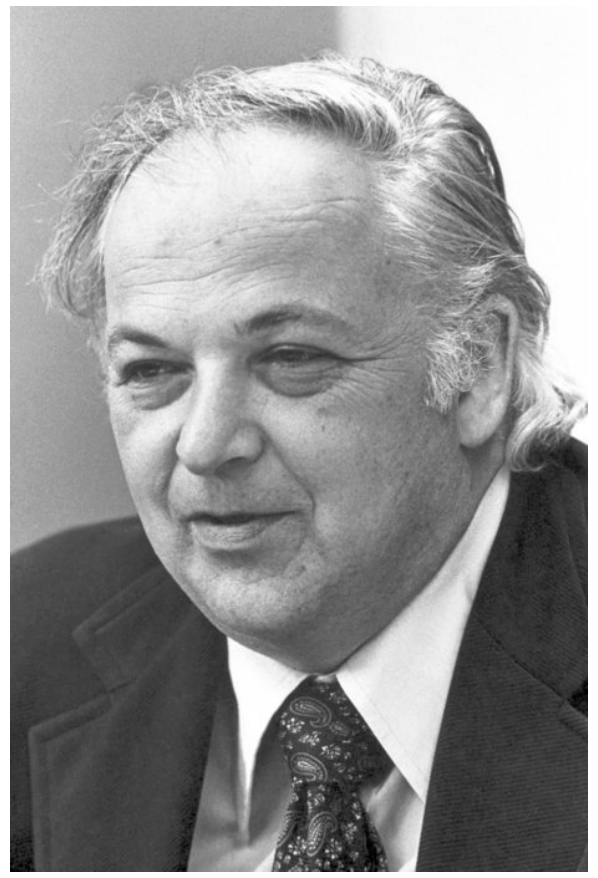

Burton Richter

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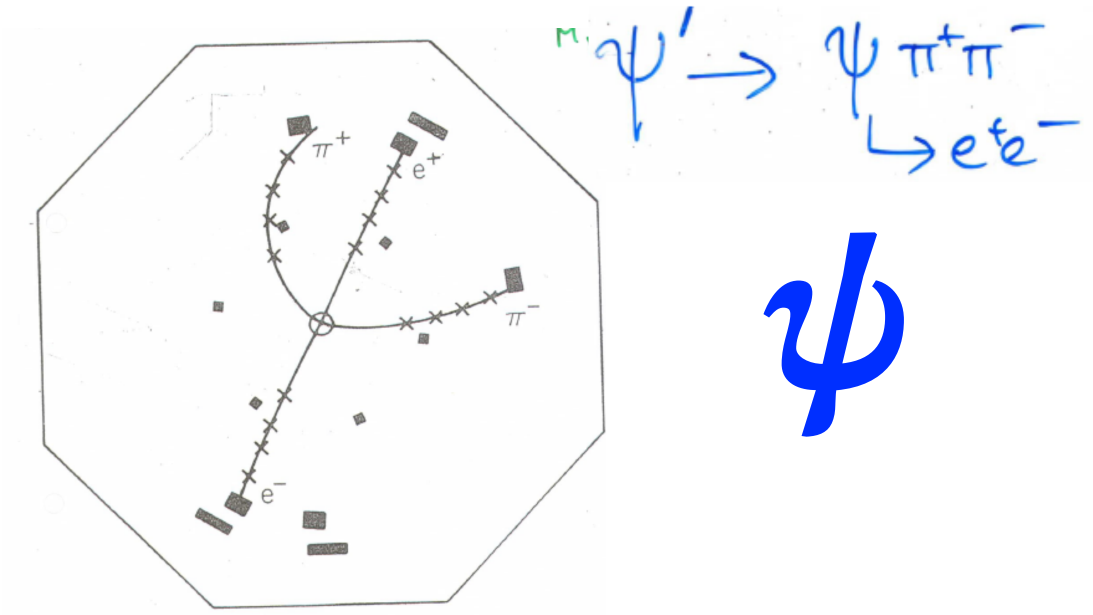


Nov. 9 adjusted the machine to 3.1 GeV

Slide from Pro. Chaoqiang Geng

• Charmed baryons spectra

State	J^P	Mass	Width	Decay modes
Λ_c^+	$\frac{1}{2}^+$	2286.46 ± 0.14		weak
$\Lambda_c(2595)^+$	$\frac{1}{2}^-$	2592.25 ± 0.28	2.6 ± 0.6	$\Lambda_c\pi\pi, \Sigma_c\pi$
$\Lambda_c(2625)^+$	$\frac{3}{2}^-$	2628.11 ± 0.19	< 0.97	$\Lambda_c\pi\pi, \Sigma_c\pi$
$\Lambda_c(2765)^+$	$?^?$	2766.6 ± 2.4	50	$\Sigma_c\pi, \Lambda_c\pi\pi$
$\Lambda_c(2860)^+$	$\frac{3}{2}^+$	$2856.1^{+2.3}_{-6.0}$	68^{+12}_{-22}	$\Sigma_c^{(*)}\pi, \Lambda_c\pi\pi, D^0p, D^+n$
$\Lambda_c(2880)^+$	$\frac{5}{2}^+$	2881.63 ± 0.24	$5.6^{+0.8}_{-0.6}$	$\Sigma_c^{(*)}\pi, \Lambda_c\pi\pi, D^0p, D^+n$
$\Lambda_c(2940)^+$	$\frac{3}{2}^-$	$2939.6^{+1.3}_{-1.5}$	20^{+6}_{-5}	$\Sigma_c^{(*)}\pi, \Lambda_c\pi\pi, D^0p, D^+n$
$\Sigma_c(2455)^{++}$	$\frac{1}{2}^+$	2453.97 ± 0.14	$1.89^{+0.09}_{-0.18}$	$\Lambda_c\pi$
$\Sigma_c(2455)^+$	$\frac{1}{2}^+$	2452.9 ± 0.4	< 4.6	$\Lambda_c\pi$
$\Sigma_c(2455)^0$	$\frac{1}{2}^+$	2453.75 ± 0.14	$1.83^{+0.11}_{-0.19}$	$\Lambda_c\pi$
$\Sigma_c(2520)^{++}$	$\frac{3}{2}^+$	$2518.41^{+0.21}_{-0.19}$	$14.78^{+0.30}_{-0.40}$	$\Lambda_c\pi$
$\Sigma_c(2520)^+$	$\frac{3}{2}^+$	2517.5 ± 2.3	< 17	$\Lambda_c\pi$
$\Sigma_c(2520)^0$	$\frac{3}{2}^+$	2518.48 ± 0.20	$15.3^{+0.4}_{-0.5}$	$\Lambda_c\pi$
$\Sigma_c(2800)^{++}$	$?^?$	2801^{+4}_{-6}	75^{+22}_{-17}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
$\Sigma_c(2800)^+$	$?^?$	2792^{+14}_{-5}	62^{+60}_{-40}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
$\Sigma_c(2800)^0$	$?^?$	2806^{+5}_{-7}	72^{+22}_{-15}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
Ξ_c^+	$\frac{1}{2}^+$	2467.71 ± 0.23		weak
Ξ_c^0	$\frac{1}{2}^+$	2470.44 ± 0.28		weak
$\Xi_c'^+$	$\frac{1}{2}^+$	2578.2 ± 0.5		$\Xi_c\gamma$
$\Xi_c'^0$	$\frac{1}{2}^+$	2578.7 ± 0.5		$\Xi_c\gamma$
$\Xi_c(2645)^+$	$\frac{3}{2}^+$	2645.10 ± 0.30	2.14 ± 0.19	$\Xi_c\pi$
$\Xi_c(2645)^0$	$\frac{3}{2}^+$	2646.16 ± 0.25	2.35 ± 0.22	$\Xi_c\pi$
$\Xi_c(2790)^+$	$\frac{1}{2}^-$	2791.9 ± 0.5	8.9 ± 1.0	$\Xi_c'\pi, \Xi_c\pi$
$\Xi_c(2790)^0$	$\frac{1}{2}^-$	2793.9 ± 0.5	10.0 ± 1.1	$\Xi_c'\pi, \Xi_c\pi$
$\Xi_c(2815)^+$	$\frac{3}{2}^-$	2816.51 ± 0.25	2.43 ± 0.26	$\Xi_c^*\pi, \Xi_c\pi\pi, \Xi_c'\pi$
$\Xi_c(2815)^0$	$\frac{3}{2}^-$	2819.79 ± 0.30	2.54 ± 0.25	$\Xi_c^*\pi, \Xi_c\pi\pi, \Xi_c'\pi$
$\Xi_c(2923)^0$	$?^?$	2923.04 ± 0.35	7.1 ± 2.0	$\Lambda_c\bar{K}$
$\Xi_c(2930)^+$	$?^?$	2942 ± 5	15 ± 9	$\Lambda_c\bar{K}$
$\Xi_c(2930)^0$	$?^?$	2938.55 ± 0.30	10.2 ± 1.4	$\Lambda_c\bar{K}$
$\Xi_c(2970)^+$	$?^?$	2964.3 ± 1.5	$20.9^{+2.4}_{-3.5}$	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, \Xi_c\pi\pi$
$\Xi_c(2970)^0$	$?^?$	2967.1 ± 1.7		$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, \Xi_c\pi\pi$
$\Xi_c(3055)^+$	$?^?$	3055.9 ± 0.4	7.8 ± 1.9	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
$\Xi_c(3080)^+$	$?^?$	3077.2 ± 0.4	3.6 ± 1.1	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
$\Xi_c(3080)^0$	$?^?$	3079.9 ± 1.4	5.6 ± 2.2	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
Ω_c^0	$\frac{1}{2}^+$	2695.2 ± 1.7		weak
$\Omega_c(2770)^0$	$\frac{3}{2}^+$	2765.9 ± 2.0		$\Omega_c\gamma$
$\Omega_c(3000)^0$	$?^?$	3000.41 ± 0.22	4.5 ± 0.7	$\Xi_c\bar{K}$
$\Omega_c(3050)^0$	$?^?$	3050.20 ± 0.13	< 1.2	$\Xi_c\bar{K}$
$\Omega_c(3065)^0$	$?^?$	3065.46 ± 0.28	3.5 ± 0.4	$\Xi_c\bar{K}$
$\Omega_c(3090)^0$	$?^?$	3090.0 ± 0.5	8.7 ± 1.3	$\Xi_c'\bar{K}, \Xi_c\bar{K}$
$\Omega_c(3120)^0$	$?^?$	3119.1 ± 1.0	< 2.6	$\Xi_c'\bar{K}, \Xi_c\bar{K}$

Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$

PRL **118** 8, 182001 (2017)

		$\Omega_c(3000)^0$	$\Omega_c(3050)^0$	$\Omega_c(3065)^0$	$\Omega_c(3090)^0$	$\Omega_c(3120)^0$
	Agaev *et al.* [58]	$1/2^-$	$3/2^-$	$1/2^+$	$1/2^+$	$3/2^+$
	Aliev *et al.* [59]	$1/2^-$		$3/2^-$		
陈兵&刘翔	B. Chen, X. Liu [60]	$1/2^-$	$3/2^-$	$5/2^-$	$1/2^-$	$3/2^-$
陈华星&毛強&刘翔& 朱世琳	H. Chen *et al.* [43]	$1/2^-$	$1/2^-$	$1/2^-$ or $1/2^+$		$3/2^+$
鄭海揚&蔣正偉	Cheng, Chiang [61]	$1/2^-$	$3/2^-$	$5/2^-$	$1/2^+$	$3/2^+$
	Faustov, Galkin [62]	$3/2^-$	$5/2^-$	$3/2^-$	$1/2^+$	$3/2^+$
黄虹霞&平加伦&王凡	Huang *et al.* [63]					$1/2^-$
贾多杰& Ji-Hai Pan &Cheng-qun Pang	Jia *et al.* [64]	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
	Karliner, Rosner [65]: (i)	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
	(ii)	$3/2^-$	$3/2^-$	$5/2^-$	$1/2^+$	$3/2^+$
	Padmanath *et al.* [66]	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
	Santopinto *et al.* [67]	$1/2^-$	$3/2^-$	$1/2^-$	$3/2^-$	$5/2^-$
王凯雷&肖立叶&钟显辉&赵强	K. Wang *et al.* [68]	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$	$1/2^+$ or $3/2^+$
王伟&朱瑞林	W. Wang, R.L. Zhu [69]	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
	Z. Wang [70]	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
王志刚&Xing-Ning Wei &Ze-Hui Yan	Z. Wang *et al.* [71]	$1/2^-$			$3/2^-$ or $1/2^+$	$3/2^+$
Hui-Min Yang&陈华星	Yang, H. Chen [72]	$1/2^-$ or $3/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
赵泽&Dan-Dan Ye&张爱林	Z. Zhao *et al.* [73]: (i)	$1/2^+$	$5/2^+$	$3/2^-$	$3/2^-$	$5/2^+$
	(ii)	$3/2^+$	$7/2^+$	$5/2^-$	$5/2^-$	$7/2^+$

*Names are cited according to Inspire.hep

Observation of excited Ω_c^0 baryons in $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays

LHCb collaboration[†]

PRD **104**, L091102 (2021)

State	$J = 1/2$	$J = 3/2$	$J = 5/2$
$\Omega_c(3000)^0$	$0.5\,\sigma$	$0.8\,\sigma$	$0.4\,\sigma$
$\Omega_c(3050)^0$	$2.2\,\sigma$	$0.1\,\sigma$	$1.2\,\sigma$
$\Omega_c(3065)^0$	$3.6\,\sigma$	$0.6\,\sigma$	$1.2\,\sigma$
$\Omega_c(3090)^0$	$0.3\,\sigma$	$0.8\,\sigma$	$0.5\,\sigma$

Tables from Pro. Hai-Yang Cheng, Chin. J. Phys. 78, 324

• Charmed baryons decays

BESIII : $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$ at 4.6 GeV, providing clean background

Observation of the Singly Cabibbo Suppressed Decay $\Lambda_c^+ \to n\pi^+$

M. Ablikim *et al.* (BESIII Collaboration)
Phys. Rev. Lett. **128**, 142001 – Published 4 April 2022

Belle : e^+e^- collisions at $\Upsilon(4S)$ or $\Upsilon(5S)$

Measurements of the Branching Fractions of the Semileptonic Decays $\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$ and the Asymmetry Parameter of $\Xi_c^0 \to \Xi^-\pi^+$

Y. B. Li *et al.* (Belle Collaboration)
Phys. Rev. Lett. **127**, 121803 – Published 17 September 2021

LHCb : pp collisions, largest charmed hadron samples

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

R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **119**, 112001 – Published 11 September 2017

Physics See Viewpoint: A Doubly Charming Particle

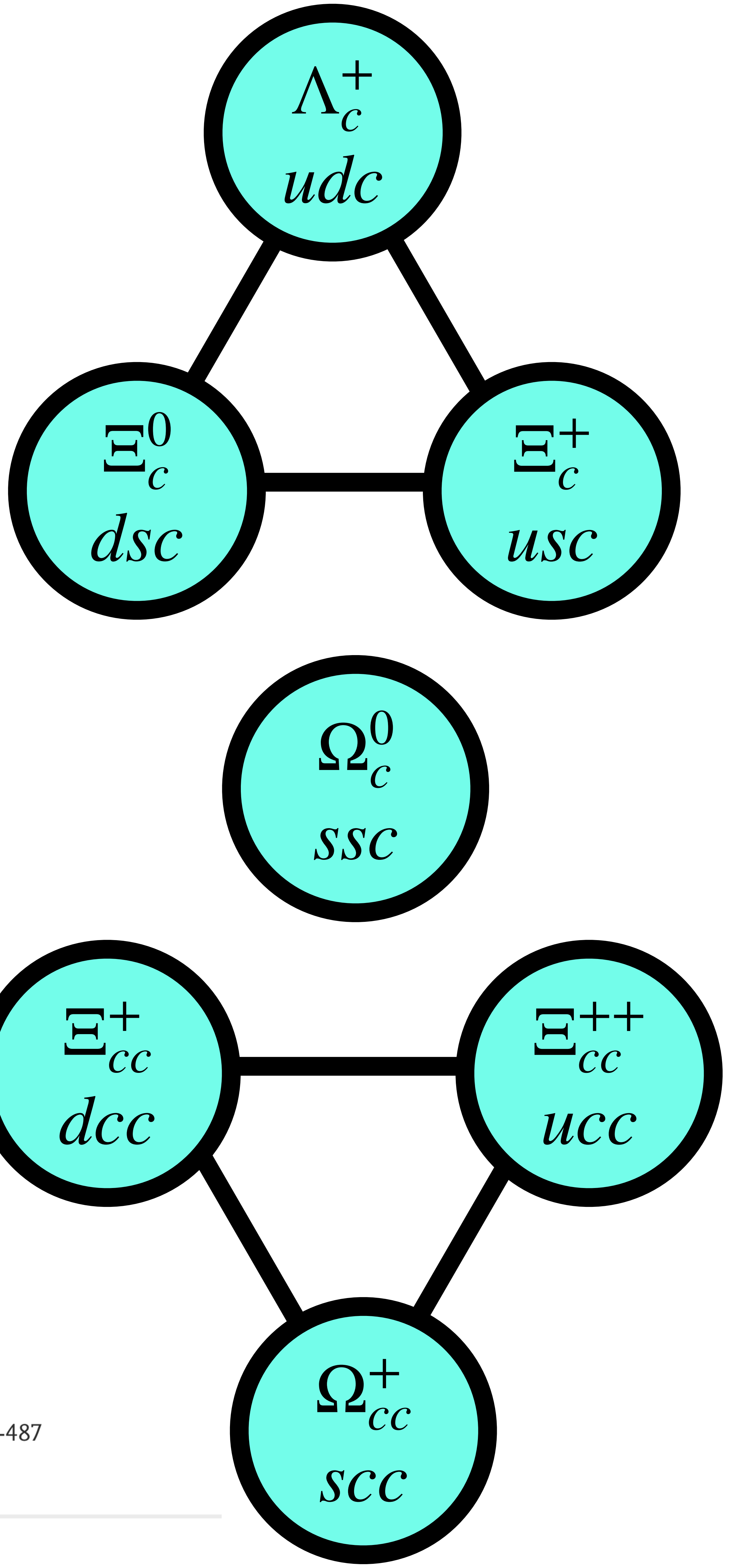
ELSEVIER

Science Bulletin
Volume 67, Issue 5, 15 March 2022, Pages 479-487

Article

Measurement of the lifetimes of promptly produced Ω_c^0 and Ξ_c^0 baryons

LHCb Collaboration [1]



Phenomenological Study of Charmed Baryon Decays

Inclusive decays

Operator product and heavy quark expansions

Exclusive decays

Current algebra, pole model and SU(3) flavor

Inclusive decays - theory

Optical theorem :

$$S = \underbrace{1}_{\text{w/o scattering}} + \underbrace{iT}_{\text{w/ scattering}} \qquad {}_{out}\langle b | a \rangle_{in} = \langle b | S | a \rangle \qquad \langle b | T | a \rangle = (2\pi)^4 \delta^4 (p_a - p_b) A_{a \to b}$$

w/o scattering w/ scattering

$$S^\dagger S = 1 \to T^\dagger T = iT^\dagger - iT \qquad \sum_b \int d\Omega_b \langle a | T^\dagger | b \rangle \langle b | T | a \rangle = 2\mathrm{Im}\big(\langle a | T | a \rangle\big)$$

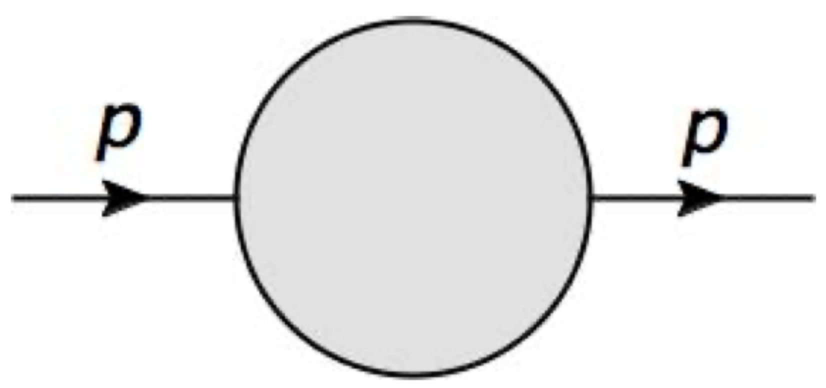
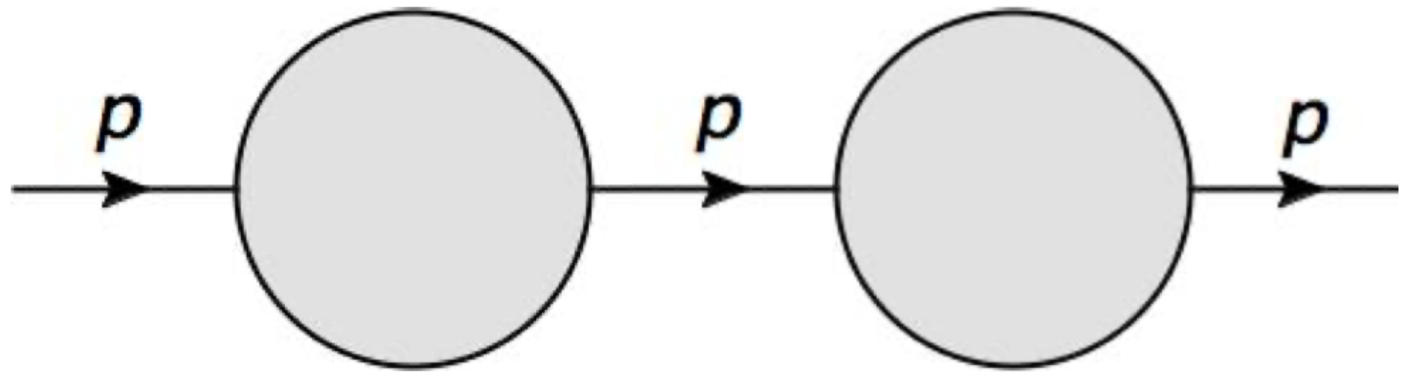
Valid only for on-shell

$$\frac{1}{m_a}\mathrm{Im}\left(A_{a\to a}\right) = \frac{1}{\underbrace{2m_a}} \sum_b \int d\Omega_b \left| A_{a \to b} \right|^2 \overset{\text{Valid only for on-shell}}{=} \Gamma_{\text{total}}$$

Kinetic factor depends on normalizations of states : $\langle a | a \rangle = 2E(2\pi)^3 \delta^3 \left(\vec{p} - \vec{p}\,' \right)$

$a^* \to e^+ e^-$

Valid only for on-shell

$\mathrm{Im}\Big($  $\Big) = m_a \Gamma_{\text{total}}$, $\sum\Big($  $\Big) \overset{\text{Valid only for on-shell}}{=} \dfrac{1}{p^2 - m^2 + im\Gamma}$

• Inclusive decays - theory

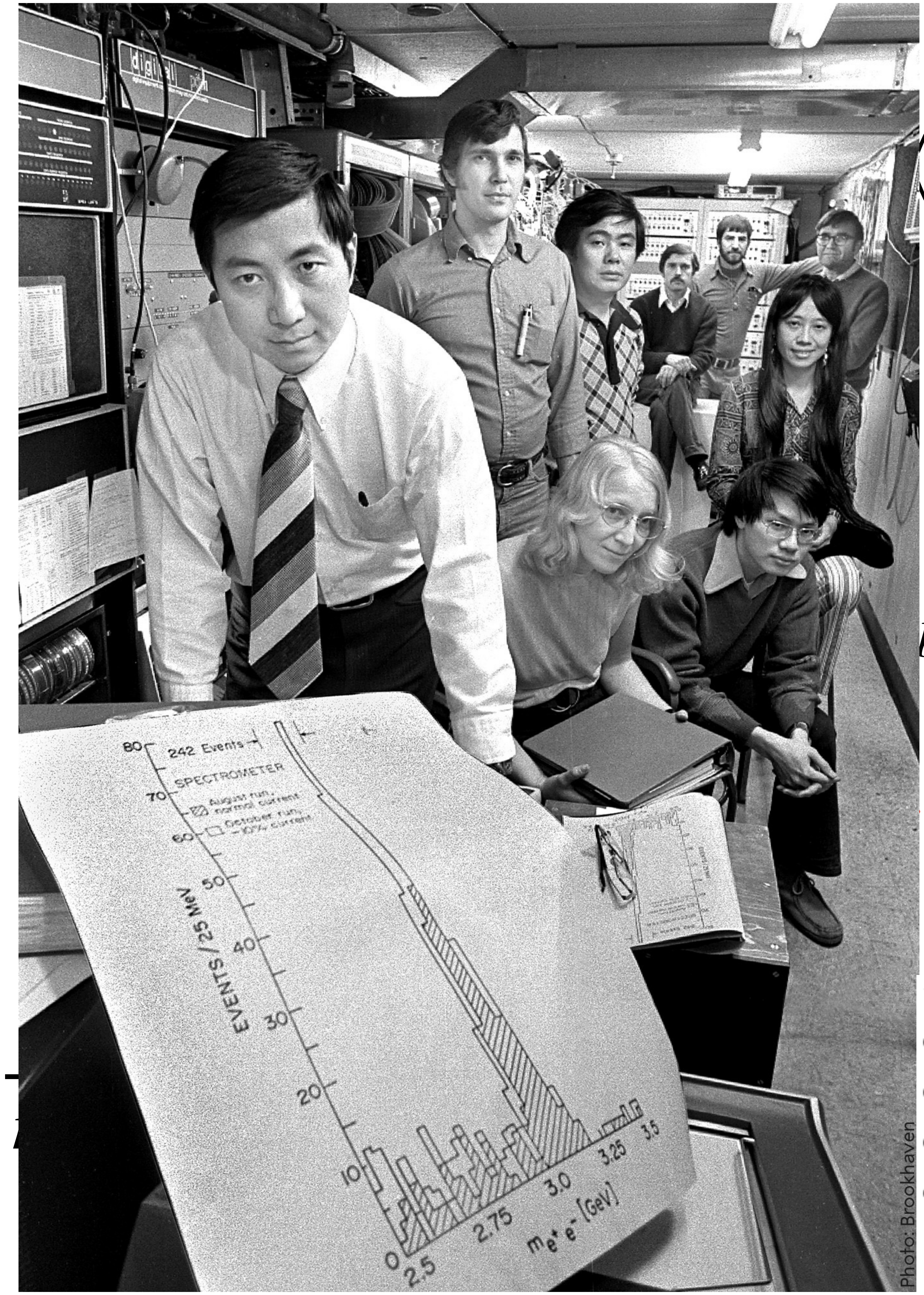


Photo: Brookhaven

$\langle b | S | a \rangle$

$$\langle b | T | a \rangle = (2\pi)^4 \delta^4(p_a - p_b) A_{a \to b}$$

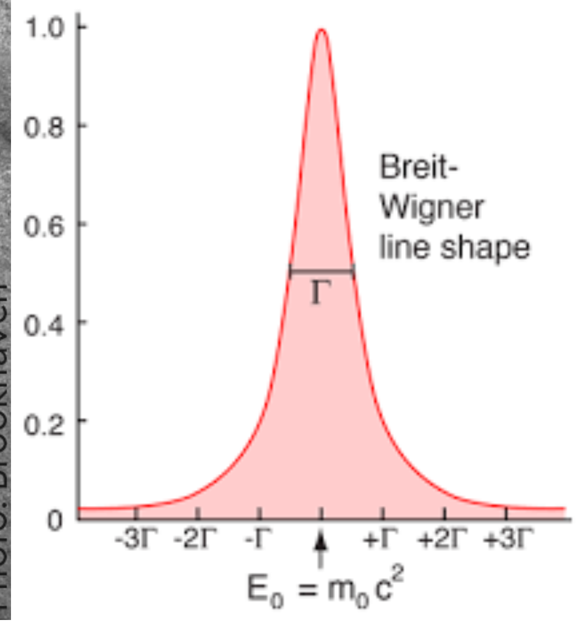
$$\sum_b \int d\Omega_b \langle a | T^\dagger | b \rangle \langle b | T | a \rangle = 2\mathrm{Im}\big(\langle a | T | a \rangle\big)$$

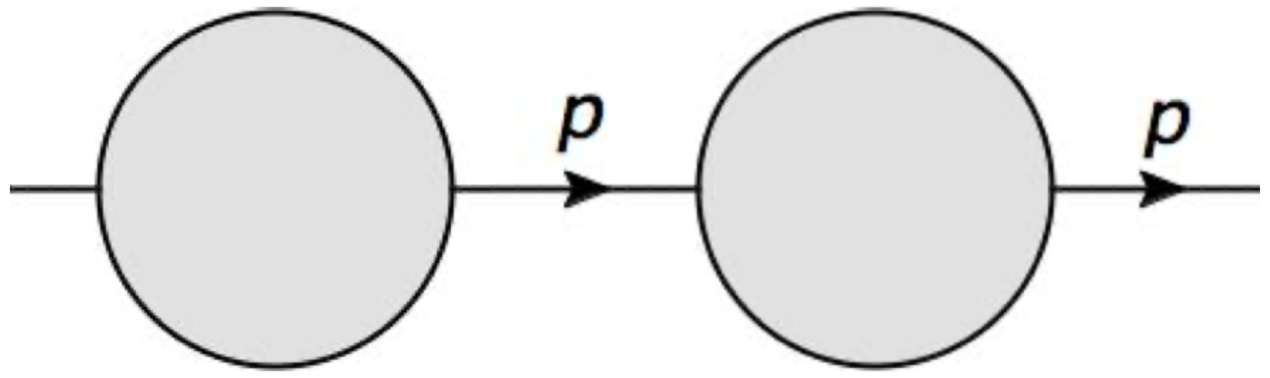
Valid only for on-shell

$$b \left| A_{a \to b} \right|^2 = \Gamma_{\text{total}}$$

$= 2E(2\pi)^3 \delta^3 (\vec{p} - \vec{p}\,')$

Valid only for on-shell





$$) = \frac{1}{p^2 - m^2 + im\Gamma}$$

Inclusive decays - theory

$c \xrightarrow{W} s \xrightarrow{W} c$ The amplitudes are in the second order of weak interaction.

$$\frac{1}{m_a}\mathrm{Im}\left(A_{a\to a}\right) = \frac{1}{2m_a}\sum_b \int d\Omega_b \left|A_{a\to b}\right|^2 = \Gamma_{\mathrm{total}}$$

Final state = Initial one

Sum over the final states

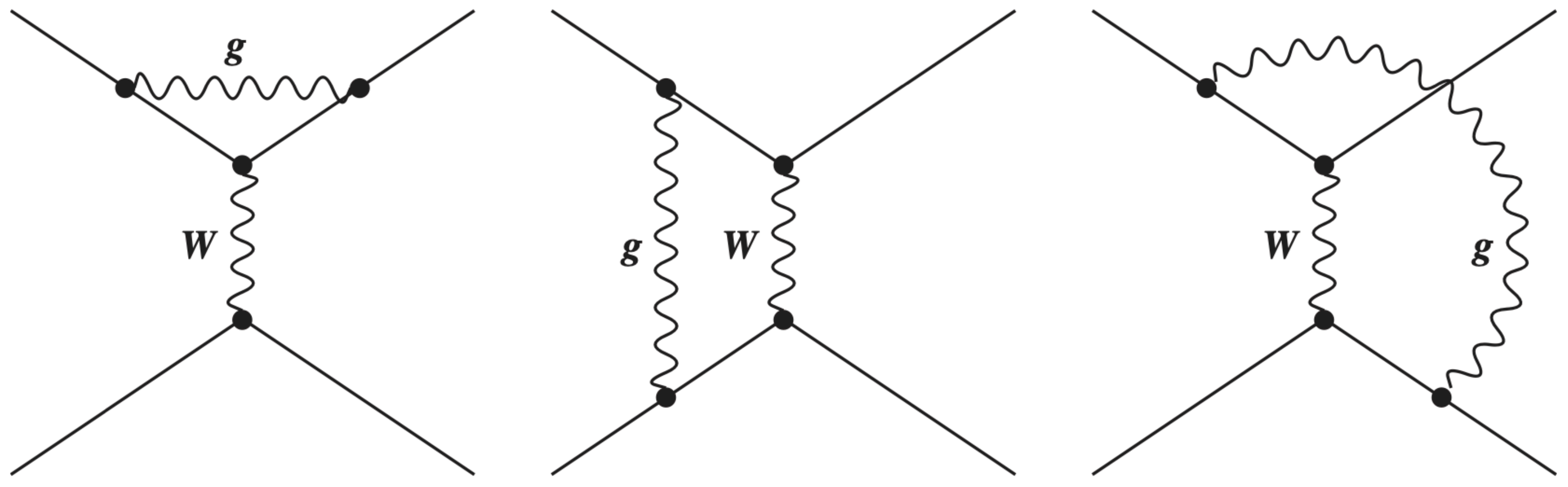
Time-ordering operator

$$\mathrm{Im}\left(A_{a\to a}\right) = \frac{i}{2}\int \left\langle T\left(\mathscr{H}_{eff}(x)\mathscr{H}_{eff}(0)\right)\right\rangle d^4x$$

Non-local

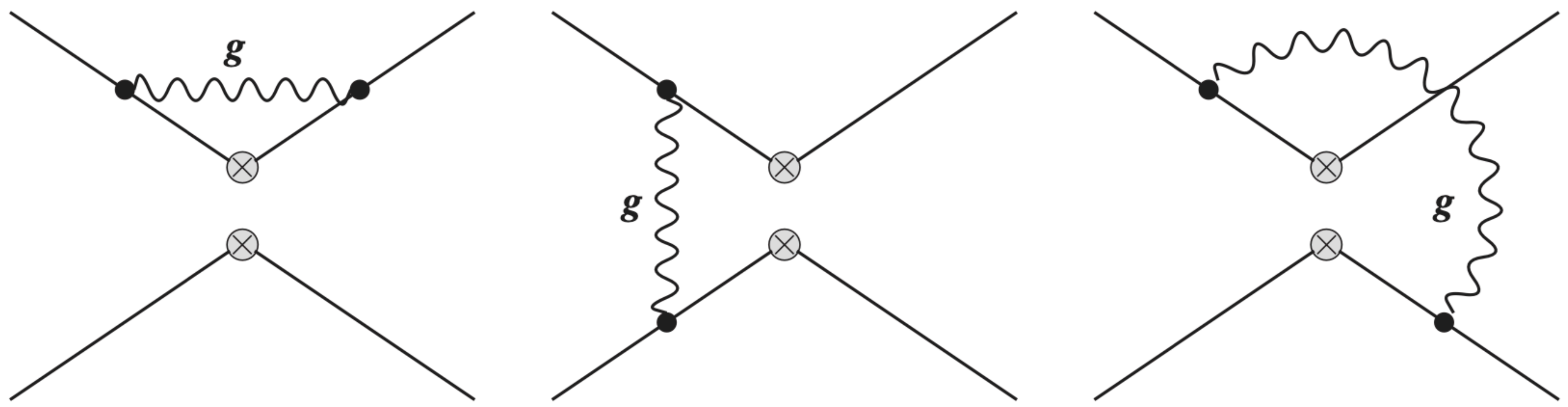
$$\mathrm{Im}\left(A_{a\to a}\right) = \sum_{n\in\mathcal{N}} \frac{m_Q^k}{m_Q^n}\left\langle C_n O_n\right\rangle$$

Local



Matching at μ

$$\frac{1}{q^2 - M_W^2} \to -\frac{1}{M_W^2}$$



$$\mathscr{H}_{eff} = \frac{G_F}{\sqrt{2}}\lambda\left[c_1(\bar{q}_1 q_2)_{V-A}(\bar{q}_3 q_4)_{V-A} + c_2(\bar{q}_3 q_2)_{V-A}(\bar{q}_1 q_4)_{V-A}\right]$$

$$\mathcal{S}_{nl} = \int d^4x \mathscr{L}_{\mathrm{kin}} - \frac{g_2^2}{8}\int d^4x d^4y J_\mu^-(x)\Delta^{\mu\nu}(x,y)J_\nu^+(y)$$

$$\Delta^{\mu\nu}(x,y) = \frac{g^{\mu\nu}}{M_W^2}\delta^{(4)}(x-y) + \mathcal{O}\left(\frac{1}{M_W^4}\right)$$

Figures from Rev. Mod. Phys. 68, 1125(1996)

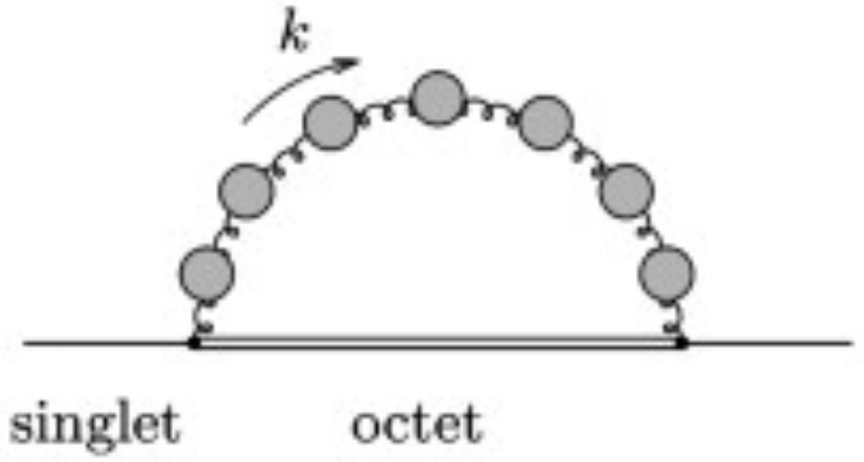
• Inclusive decays - theory

Problem unsolved : renormalon ambiguity

M. Beneke, ``Pole mass renormalon and its ramifications,''
Eur. Phys. J. ST **230**, no.12-13, 2565-2579

A. Boushmelev, T. Mannel and K. K. Vos,
``Alternative Treatment of the Quark Mass in the Heavy Quark Expansion,''
[arXiv:2301.05607 [hep-ph]]

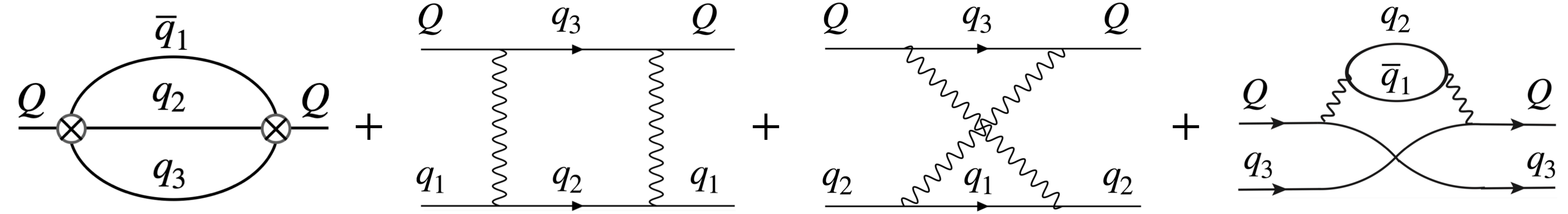
Pole mass is essentially a non-perturbative quantity



$$\frac{1}{m_a}\mathrm{Im}\left(A_{a\to a}\right) = \frac{1}{m_a}\sum_{n\in\mathcal{N}}\frac{m_Q^k}{m_Q^n}\left\langle C_n O_n\right\rangle \propto \frac{m_Q^5}{M_W^4}\Big(1+O(1/m_Q)\Big)$$

Separating energy scales $\underbrace{M_W}_{\frac{G_F}{\sqrt{2}}c_{1,2}} \gg \underbrace{m_Q}_{C_n} \gg \underbrace{\Lambda_{QCD}}_{\langle O_n\rangle}$

$$\frac{1}{m_a}\mathrm{Im}\Big(\ \ldots\ \Big) = \Gamma_{\text{total}}$$



$$\propto m_Q^5\left\langle \overline{Q}Q\right\rangle \qquad \propto (4\pi)^2 m_Q^2\left\langle \overline{Q}\Gamma_\mu Q\bar{q}\gamma^\mu(1-\gamma_5)q\right\rangle$$

Parity conservation : $\langle \bar{c}\gamma_5 c\rangle = 0$

To the leading order of m_Q, the light quark fields must be left-handed.

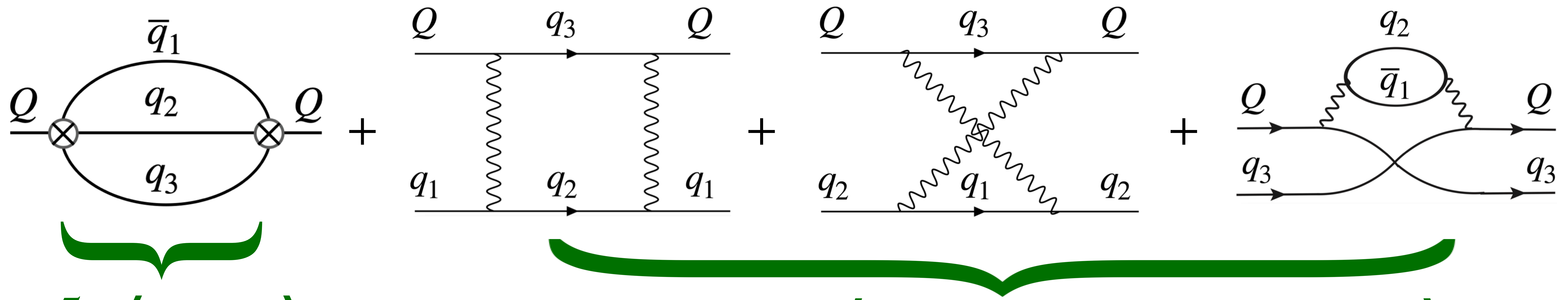
To leading order α_s , counter terms are not needed for imaginary parts of the amplitudes

- ## Inclusive decays - theory

$(m_b, m_c, \Lambda_{QCD}) = (4.8, 1.5, 0.3)$ GeV

$$\left[\left(\frac{\Lambda_{QCD}}{m_b}\right)^3, \left(\frac{\Lambda_{QCD}}{m_c}\right)^3, 16\pi^2\right] \approx \left(\frac{1}{4000}, \frac{1}{125}, 160\right)$$

$\frac{1}{m_a}\mathrm{Im}\Big($



$\Big) = \Gamma_{\text{total}}$

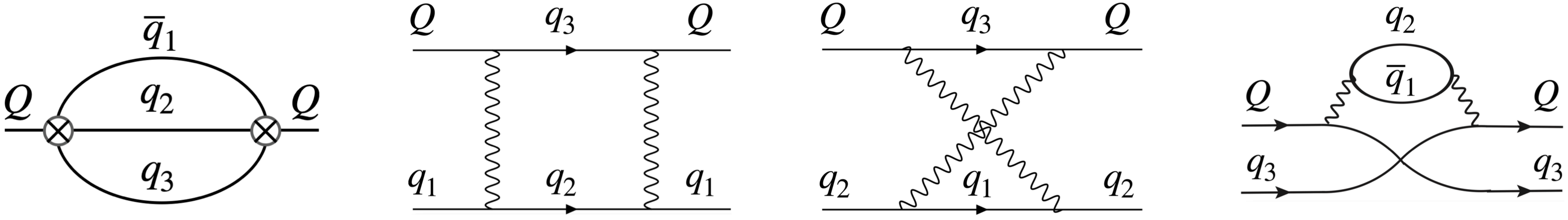
$$m_Q^5 \langle \overline{Q}Q \rangle \qquad 16\pi^2 m_Q^2 \left\langle \overline{Q}\Gamma_\mu Q \bar{q}\gamma^\mu(1-\gamma_5)q \right\rangle$$

Parity conservation : $\langle \bar{c}\gamma_5 c \rangle = 0$

To the leading order of m_Q, the light quark fields must be left-handed.

To leading order α_s , counter terms are not needed for imaginary parts of the amplitudes

Inclusive decays - theory



q_1 & q_2 can be leptons

$$\frac{G_F^2 m_Q^5}{192\pi^3}\,\xi\left(c_{3,Q}\bar{Q}Q+\frac{c_{5,Q}}{m_Q^2}\bar{Q}\sigma\cdot GQ+\frac{c_{6,Q}}{m_Q^3}T_6+\frac{c_{7,Q}}{m_Q^4}T_7+\cdots\right)$$

Dim-4 operator is missing due to the Luke's theorem.

Two-quark operator coefficients to leading order

$$\begin{aligned} c_{3,c}^{\rm NL} &= \left(N_c c_1^2+N_c c_2^2+2c_1c_2\right)\left(I_0(x,0,0)|V_{ud}|^2+I_0(x,x,0)|V_{us}|^2\right),\\ c_{5,c}^{\rm NL} &= -\left(N_c c_1^2+N_c c_2^2+2c_1c_2\right)\left(I_1(x,0,0)|V_{ud}|^2+I_1(x,x,0)|V_{us}|^2\right)\\ &\quad -8c_1c_2\left(I_2(x,0,0)|V_{ud}|^2+I_2(x,x,0)|V_{us}|^2\right),\end{aligned}$$

$$\begin{aligned} I_0(x,0,0) &= (1-x^2)(1-8x+x^2)-12x^2\ln x,\\ I_1(x,0,0) &= \frac{1}{2}(2-x\frac{d}{dx})I_0(x,0,0)=(1-x)^4,\end{aligned}$$

Four-quark operator coefficients to leading order

$$\begin{aligned} \Gamma_{6,we}^{\mathcal{B}_Q,q_1} &= \frac{G_F^2 m_Q^2}{2\pi}\,\xi_Q\,(1-x_Q)^2\left\{(c_1^2+c_2^2)\tilde{L}_{\mathcal{B}_Q}^{q_1}+2c_1c_2L_{\mathcal{B}_Q}^{q_1}\right\},\\ \Gamma_{6,int-}^{\mathcal{B}_Q,q_2} &= -\frac{G_F^2 m_Q^2}{6\pi}\,\xi_Q(1-x_Q)^2\left\{c_1^2\left[\left(1+\frac{x_Q}{2}\right)\tilde{L}_{\mathcal{B}_Q}^{q_2}-(1+2x_Q)(\tilde{S}_{\mathcal{B}_Q}^{q_2}-\tilde{P}_{\mathcal{B}_Q}^{q_2})\right]\right.\\ &\quad\left.+\ (2c_1c_2+N_cc_2^2)\left[\left(1+\frac{x_Q}{2}\right)L_{\mathcal{B}_Q}^{q_2}-(1+2x_Q)(S_{\mathcal{B}_Q}^{q_2}-P_{\mathcal{B}_Q}^{q_2})\right]\right\},\\ \Gamma_{6,int+}^{\mathcal{B}_Q,q_3} &= -\frac{G_F^2 m_Q^2}{6\pi}\,\xi_Q\left[c_2^2\left(\tilde{L}_{\mathcal{B}_Q}^{q_3}-\tilde{S}_{\mathcal{B}_Q}^{q_3}+\tilde{P}_{\mathcal{B}_Q}^{q_3}\right)+(2c_1c_2+N_cc_1^2)\left(L_{\mathcal{B}_Q}^{q_3}-S_{\mathcal{B}_Q}^{q_3}+P_{\mathcal{B}_Q}^{q_3}\right)\right],\end{aligned}$$

$$\begin{aligned} L_{\mathcal{B}_Q}^q &\equiv \left\langle\left(Q_\alpha^\dagger L^\mu q_\alpha\right)\left(q_\beta^\dagger L_\mu Q_\beta\right)\right\rangle_{\mathcal{B}_Q}, & \tilde{L}_{\mathcal{B}_Q}^q &\equiv \left\langle\left(Q_\alpha^\dagger L^\mu q_\beta\right)\left(q_\beta^\dagger L_\mu Q_\alpha\right)\right\rangle_{\mathcal{B}_Q}\\ S_{\mathcal{B}_Q}^q &\equiv \langle(\overline{Q}_\alpha q_\alpha)\,(\overline{q}_\beta Q_\beta)\rangle_{\mathcal{B}_Q}, & \tilde{S}_{\mathcal{B}_Q}^q &\equiv \langle(\overline{Q}_\alpha q_\beta)\,(\overline{q}_\beta Q_\alpha)\rangle_{\mathcal{B}_Q},\\ P_{\mathcal{B}_Q}^q &\equiv \langle(\overline{Q}_\alpha\gamma_5 q_\alpha)\,(\overline{q}_\beta\gamma_5 Q_\beta)\rangle_{\mathcal{B}_Q}, & \tilde{P}_{\mathcal{B}_Q}^q &\equiv \langle(\overline{Q}_\alpha\gamma_5 q_\beta)\,(\overline{q}_\beta\gamma_5 Q_\alpha)\rangle_{\mathcal{B}_Q},\end{aligned}$$

Inclusive decays - numerical results

Hai-Yang Cheng, March 19, 2018

	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma^{\rm int}_{-}$	$\Gamma^{\rm int}_{+}$	$\Gamma_{\rm SL}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}s)$	$\tau_{\rm expt}(10^{-13}s)$
Λ_c^+	1.012	1.883	−0.209	0.021	0.308	3.015	2.18	2.00 ± 0.06
Ξ_c^+	1.012	0.115	−0.189	0.353	0.524	1.854	3.55	4.42 ± 0.26
Ξ_c^0	1.012	2.160		0.351	0.524	4.083	1.61	$1.12^{+0.13}_{-0.10}$
Ω_c^0	1.155	0.126		0.346	0.520	2.855	2.31	0.69 ± 0.12

By the end of the work, I was very disappointed because although the lifetime of Ξ_c^+ as well as its ratio to Λ_c^+ lifetime were largely improved by including dim-7 effects, the predicted Ω_c lifetime becomes the longest one, opposite to the experiment.

LHCb, June 8, 2018

	$\tau(\Xi_c^+)$	$\tau(\Lambda_c^+)$	$\tau(\Xi_c^0)$	$\tau(\Omega_c^0)$
PDG (2004-2018) [10]	442 ± 26	200 ± 6	112^{+13}_{-10}	69 ± 12
LHCb (2018) [12]				268 ± 26
LHCb (2019) [14]	457 ± 6	203.5 ± 2.2	154.5 ± 2.6	
PDG (2020) [11]	456 ± 5	202.4 ± 3.1	153 ± 6	268 ± 26
LHCb (2021) [15]			148.0 ± 3.2	276.5 ± 14.1
World average (2021)	456 ± 5	202.4 ± 3.1	152.0 ± 2.0	274.5 ± 12.4

(The Belle II Collaboration)

We report on a measurement of the Ω_c^0 lifetime using $\Omega_c^0 \to \Omega^-\pi^+$ decays reconstructed in $e^+e^- \to c\bar{c}$ data collected by the Belle II experiment and corresponding to 207 $\rm fb^{-1}$ of integrated luminosity. The result, $\tau(\Omega_c^0) = 243 \pm 48\,(\rm stat) \pm 11\,(\rm syst)$ fs, agrees with recent measurements indicating that the Ω_c^0 is not the shortest-lived weakly decaying charmed baryon.

• Inclusive decays - numerical results

Hai-Yang Cheng, March 19, 2018

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In addition, the author of [40] enhanced wavefunctions of charmed baryons by an arbitrary coefficient $y = 1.75$, presumably with the intention of bringing lifetimes of antitriplet baryons into agreement with experiment. After then obtaining a large lifetime for Ω_c^0, and a negative semileptonic decay rate $\Gamma^{\rm SL}(\Omega_c^0)$, a second arbitrary factor, designed to suppress large and negative $\Gamma_{7,{\rm int}^+}$ contributions, was introduced. Our results show, however, that

J. Gratrex, B. Melić and I. Nišandžić, ``Lifetimes of singly charmed hadrons,''
JHEP 07, 058 (2022)

• Inclusive decays - numerical results

$$L^q_{\mathcal{B}_Q} \equiv \left\langle \left(Q^\dagger_\alpha L^\mu q_\alpha\right)\left(q^\dagger_\beta L_\mu Q_\beta\right)\right\rangle_{\mathcal{B}_Q}, \qquad \tilde{L}^q_{\mathcal{B}_Q} \equiv \left\langle \left(Q^\dagger_\alpha L^\mu q_\beta\right)\left(q^\dagger_\beta L_\mu Q_\alpha\right)\right\rangle_{\mathcal{B}_Q}$$

$$S^q_{\mathcal{B}_Q} \equiv \langle (\overline{Q}_\alpha q_\alpha)(\overline{q}_\beta Q_\beta)\rangle_{\mathcal{B}_Q}, \qquad \tilde{S}^q_{\mathcal{B}_Q} \equiv \langle (\overline{Q}_\alpha q_\beta)(\overline{q}_\beta Q_\alpha)\rangle_{\mathcal{B}_Q},$$

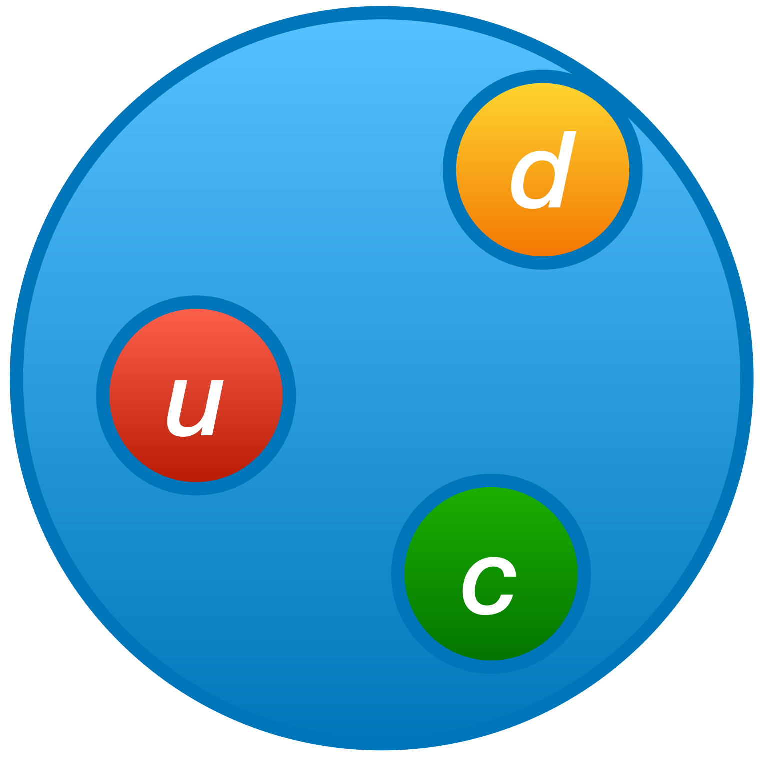
$$P^q_{\mathcal{B}_Q} \equiv \langle (\overline{Q}_\alpha \gamma_5 q_\alpha)(\overline{q}_\beta \gamma_5 Q_\beta)\rangle_{\mathcal{B}_Q}, \qquad \tilde{P}^q_{\mathcal{B}_Q} \equiv \langle (\overline{Q}_\alpha \gamma_5 q_\beta)(\overline{q}_\beta \gamma_5 Q_\alpha)\rangle_{\mathcal{B}_Q},$$

Z. X. Zhao, 2101.11874 P. Colangelo and F. De Fazio, PLB **387**, 371(1996)

$$L^{q_I}_{\Lambda_b} = -3.2 \pm 1.6 \& -2.38 \pm 0.11 \pm 0.34 \pm 0.22$$

From QCD and HQET sum rules

Model	$(\mathcal{B}_Q, q)$	(Λ_b, q_I)	(Ξ_b, q_I)	(Ξ_b, s)	(Ω_b, s)	(Λ_c, q_I)	(Ξ_c, q_I)	(Ξ_c, s)	(Ω_c, s)
	$L^q_{\mathcal{B}_Q}$	-5.44	-5.15	-5.88	-34.12	-4.83	-4.87	-5.34	-31.63
BM [a]	$S^q_{\mathcal{B}_Q}$	2.44	2.32	2.74	-5.41	1.96	1.98	2.32	-4.65
	$P^q_{\mathcal{B}_Q}$	-0.27	-0.25	-0.20	-0.62	-0.44	-0.44	-0.34	-1.12
	$L^q_{\mathcal{B}_Q}$	$-13(5)$	$-14(5)$	$-18(6)$	$-126(60)$	$-5.1(15)$	$-5.4(16)$	$-7.4(22)$	$-46(14)$
NRQM	$S^q_{\mathcal{B}_Q}$	7(2)	7(2)	9(3)	$-21(10)$	2.5(8)	2.7(8)	3.7(11)	$-7.7(23)$
	$P^q_{\mathcal{B}_Q}$	0	0	0	0	0	0	0	0



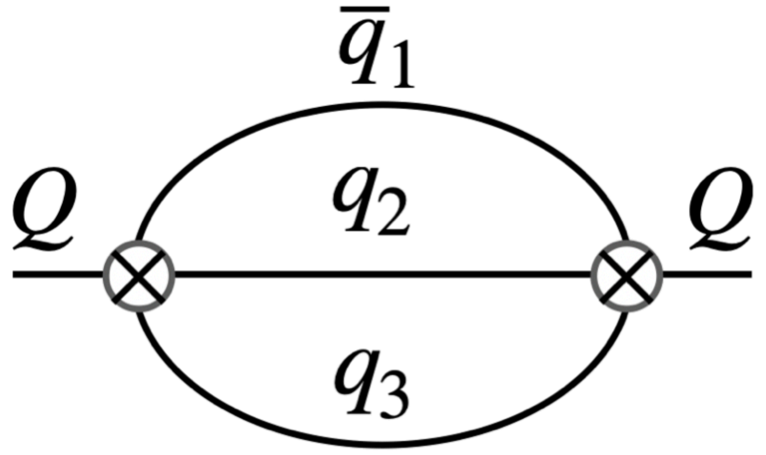
Bag is localized and it cannot be 3-momentum eigenstate. Underestimate the 4-quark operator by an order of 2. arXiv:2205.08158

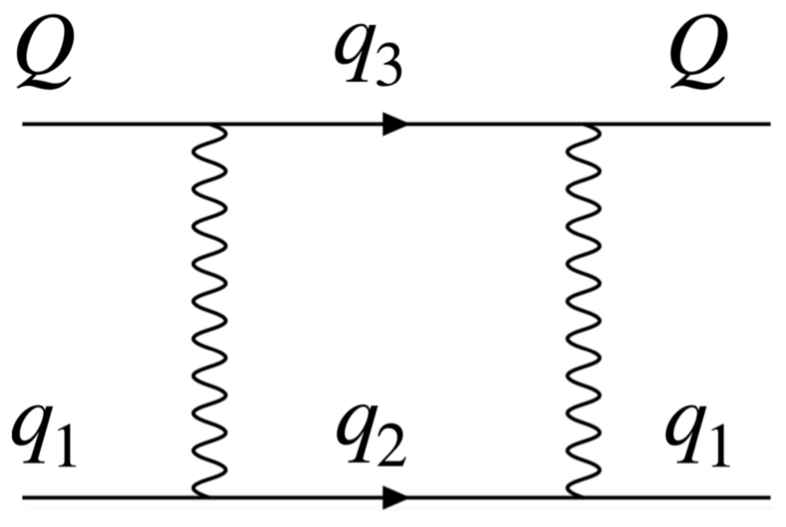
To reconcile the failure of HQE, a parameter of y = 7/4 has been introduced. Afterward an additional parameter α is introduced once again to diminish the effect of y.

H. Y. Cheng, ``Phenomenological Study of Heavy Hadron Lifetimes,'' JHEP **11**, 014 (2018)

A good physicist always makes two mistakes but not one.

Inclusive decays - numerical results

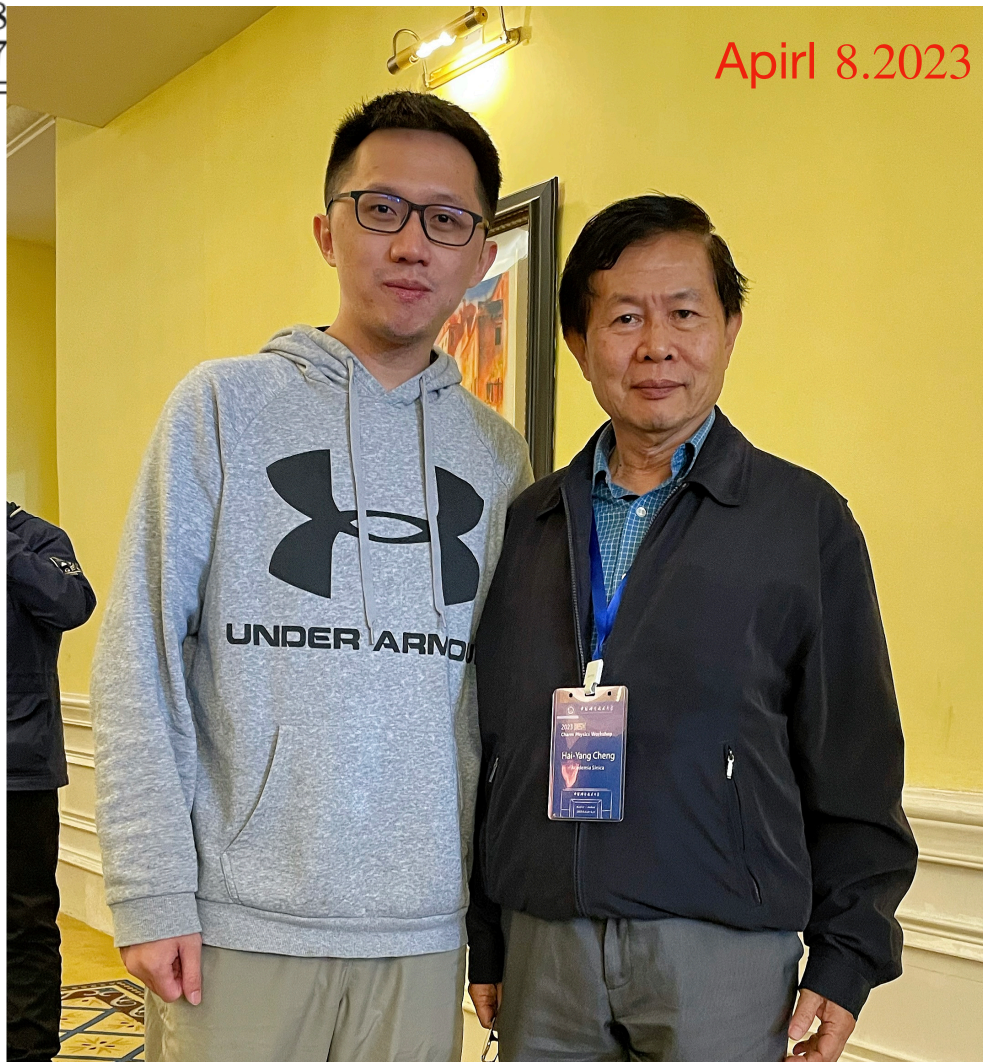
$\Gamma_3 =$ 

$\Gamma_{6,7} = \frac{1}{m_Q^3}$  $\cdots$

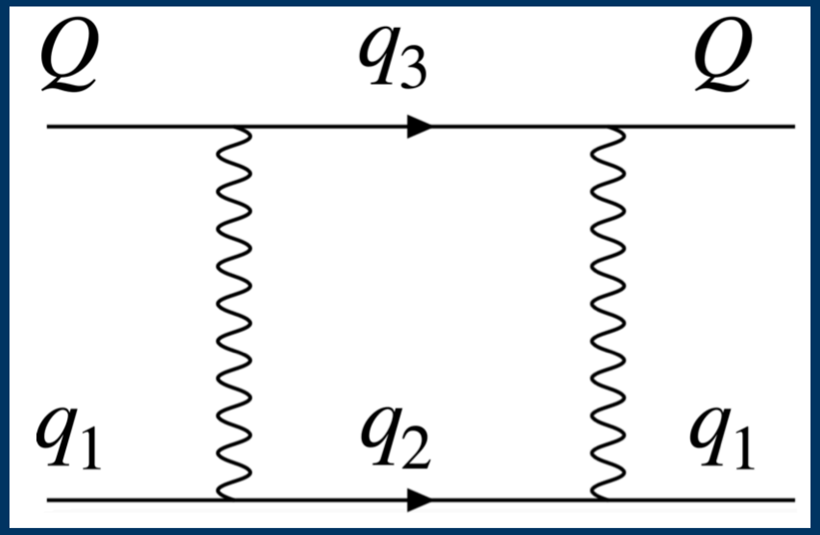
$\mathcal{B}_Q$		$\Gamma_3^{\rm NL}$	$\Gamma_3^{\rm SL}$	Γ_ρ	$\Gamma_6^{\rm NL}$	$\Gamma_6^{\rm SL}$	$\Gamma_7^{\rm NL}$	$\Gamma_7^{\rm SL}$	$\mathcal{BF}_e^{\rm SL}(\%)$
Λ_c^+	LO	$0.85(29)_m$	$0.40(13)_m$	0	0.75	0.01	0.49	0	$8.25(78)_m(44)_\mu(37)_4(37)_s$
	NLO	$1.27(42)_m$	$0.35(11)_m$	0.07	1.26	0.01	0.49	0	$4.57(42)_m(24)_\mu(21)_4(13)_s$
Ξ_c^0	LO	$0.86(28)_m$	$0.40(14)_m$	0	1.74	0.36	0.22	−0.15	$8.99(58)_m(29)_\mu(25)_4(43)_s$
	NLO	$1.27(42)_m$	$0.35(12)_m$	0.07	2.01	0.18	0.22	−0.15	$4.40(45)_m(22)_\mu(19)_4(30)_s$
Ξ_c^+	LO	$0.86(28)_m$	$0.40(14)_m$	0	0.26	0.35	−0.09	−0.15	$18.59(26)_m(22)_\mu(19)_4(39)_s$
	NLO	$1.27(42)_m$	$0.35(12)_m$	0.07	0.38	0.18	−0.09	−0.15	$8.57(20)_m(5)_\mu(5)_4(44)_s$
Ω_c^0	LO	$0.91(30)_m$	$0.42(14)_m$	0	2.34	1.22	−1.09	−0.83	$13.51(42)_m(10)_\mu(8)_4(23)_s$
	NLO	$1.34(44)_m$	$0.37(12)_m$	0.11	2.37	0.61	−1.09	−0.83	$1.88(1.33)_m(47)_\mu(40)_4(85)_s$
Λ_b	LO	$2.28(33)_m$	$1.67(18)_m$	0	0.07	0	0.02	0	$12.34(3)_m(1)_\mu(1)_4(6)_s$
	NLO	$2.78(42)_m$	$1.56(17)_m$	−0.02	0.11	0	0.02	0	$9.90(3)_m(3)_\mu(3)_4(3)_s$
Ξ_b^0	LO	$2.28(33)_m$	$1.67(18)_m$	0	0.07	0	0.01	0	$12.37(3)_m(0)_\mu(0)_4(6)_s$
	NLO	$2.78(41)_m$	$1.56(17)_m$	−0.02	0.11	0	0.01	0	$9.94(3)_m(2)_\mu(2)_4(4)_s$
Ξ_b^-	LO	$2.28(33)_m$	$1.67(18)_m$	0	−0.09	0	0	0	$12.91(9)_m(6)_\mu(6)_4(6)_s$
	NLO	$2.78(41)_m$	$1.56(17)_m$	−0.02	−0.07	0	0	0	$10.38(8)_m(2)_\mu(2)_4(3)_s$
Ω_b^-	LO	$2.28(33)_m$	$1.67(18)_m$	0	−0.17	0	−0.04	0	$13.38(15)_m(11)_\mu(10)_4(9)_s$
	NLO	$2.77(41)_m$	$1.55(16)_m$	−0.03	−0.15	0	−0.04	0	$10.76(11)_m(6)_\mu(5)_4(4)_s$

	BM [a]		NRQM		Experiment	
$\mathcal{B}_Q$	$\mathcal{BF}_e^{\rm SL}(\%)$	τ	$\mathcal{BF}_e^{\rm SL}(\%)$	τ	$\mathcal{BF}_e^{\rm SL}(\%)$	τ
Λ_c^+	4.57(54)	1.92(37)	$3.80^{+0.58}_{-0.57}$	$3.04^{+1.06}_{-0.80}$	3.95 ± 0.35	2.029(11)
Ξ_c^0	4.40(61)	1.66(32)	$4.31^{+0.87}_{-0.84}$	$2.31^{+0.84}_{-0.59}$	-	1.505(19)
Ξ_c^+	8.57(49)	3.27(76)	$12.74^{+2.54}_{-2.45}$	$4.25^{+1.22}_{-1.00}$	-	4.53(5)
Ω_c^0	1.88(1.69)	2.30(58)	$7.59^{+2.49}_{-2.24}$	$2.59^{+1.03}_{-0.70}$	-	2.43(12)
Λ_b	9.90(3)	1.48(22)	$11.0^{+0.6}_{-0.5}$	$1.490^{+0.176}_{-0.207}$	-	1.471(9)
Ξ_b^0	9.94(6)	1.49(22)	$11.1^{+0.6}_{-0.6}$	$1.493^{+0.177}_{-0.207}$	-	1.480(30)
Ξ_b^-	10.38(9)	1.55(23)	$11.7^{+0.7}_{-0.6}$	$1.608^{+0.194}_{-0.230}$	-	1.572(40)
Ω_b^-	10.76(14)	1.60(25)	$12.0^{+1.4}_{-1.4}$	$1.692^{+0.231}_{-0.261}$	-	$1.64^{+0.18}_{-0.17}$

- $\Gamma_3 > \Gamma_6$ for b-baryons but $\Gamma_6 > \Gamma_3$ in c-baryons.
- $\Gamma_6 > \Gamma_7$ indicating heavy quark expansion converges. However, it is not true for Ω_c.
- We are working on doubly charmed baryons currently.



What have we learned from charmed baryon lifetimes?



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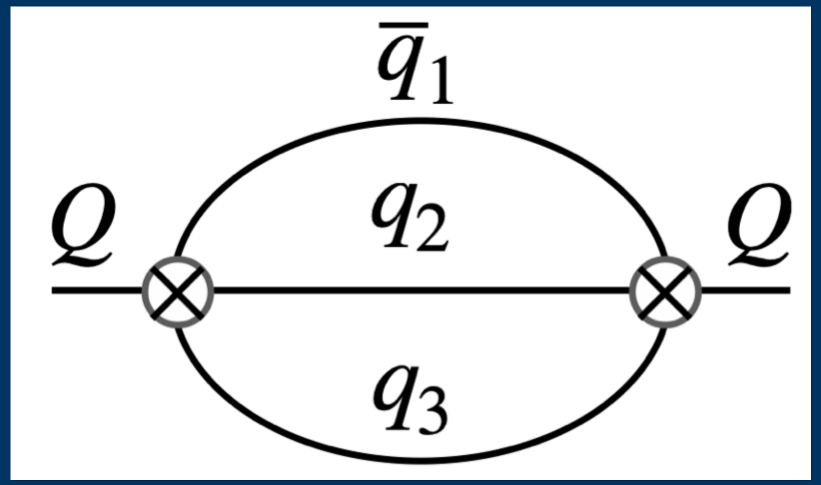


for $Q = c$

Depend on spectator quark

Independent of spectator quark

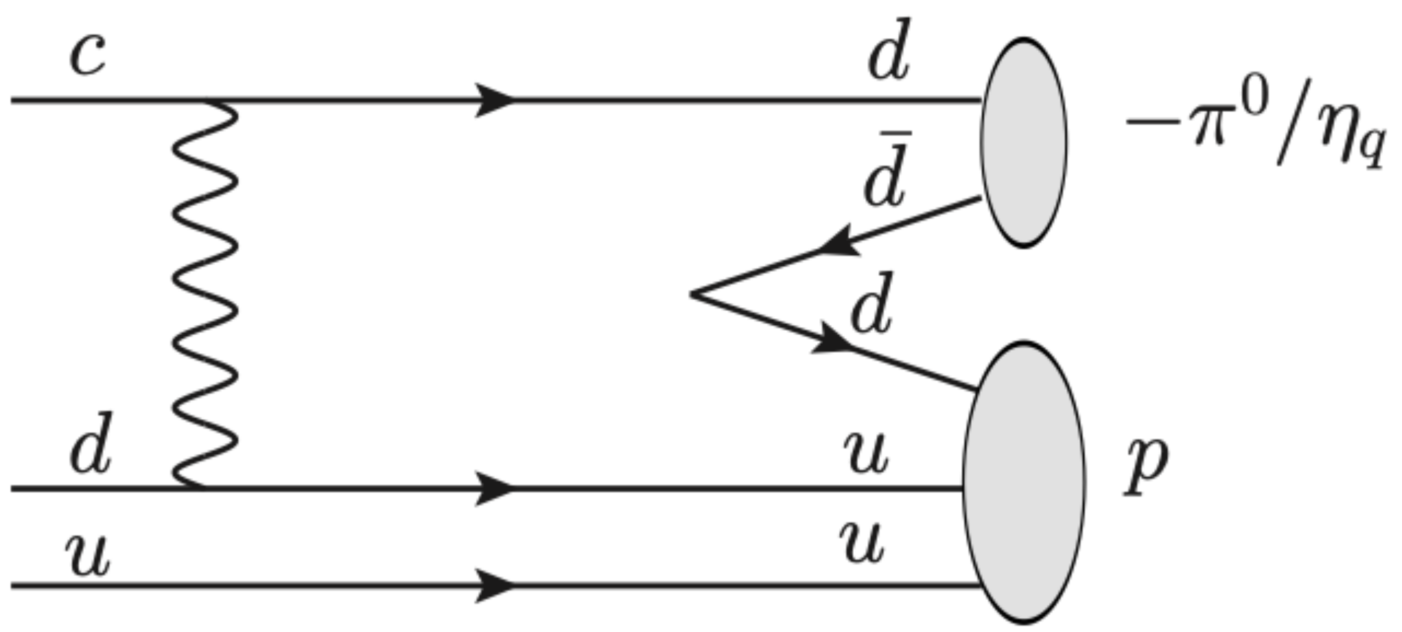
1. Non-factorizable effects shall be taken seriously in exclusive decays!
2. The $1/m_c$ expansion has to be carried out to fourth order at least.

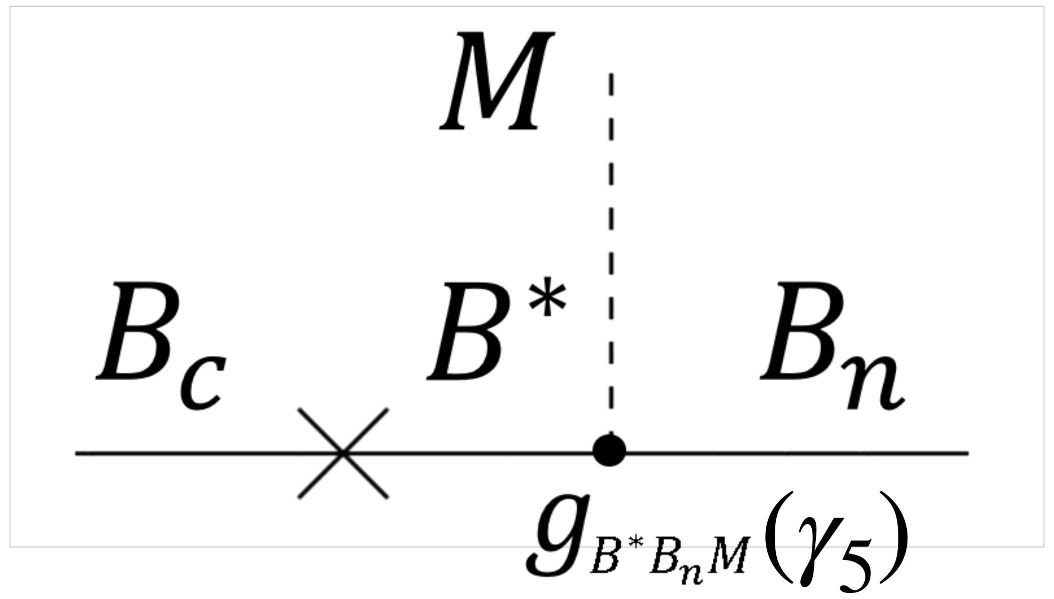
Tools for exclusive decays:

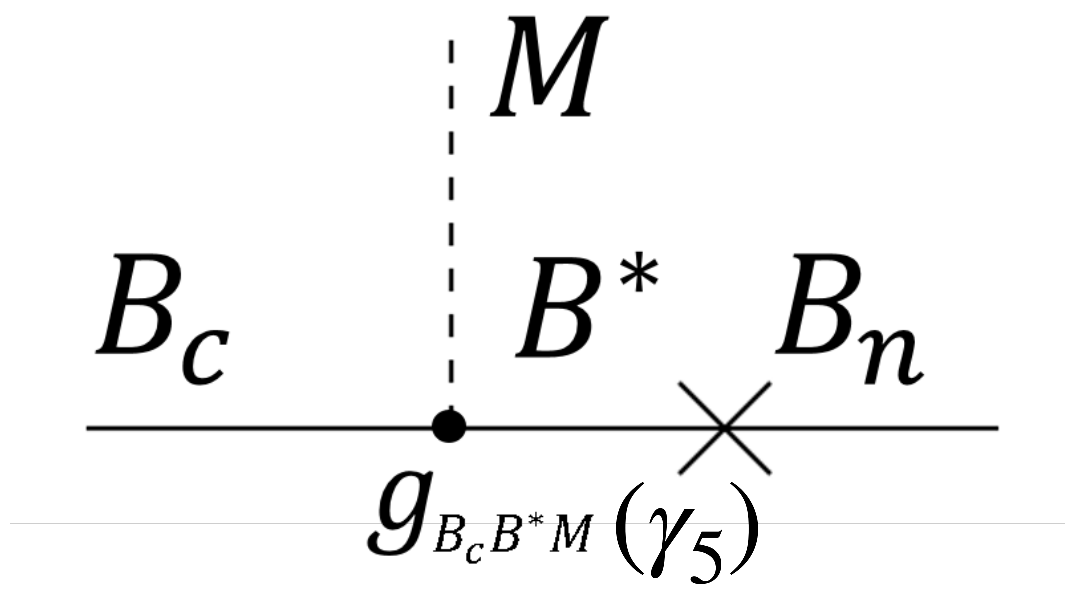
Pole model and SU(3) flavor symmetry

- **Exclusive decays - theory** $\frac{1}{2}^+ \to \frac{1}{2}^+ 0^-$

Pole model :







$\langle B^*_- | \mathcal{H}_{eff} | B_c \rangle = i b_c \bar{u}^* u_c$

$$J^P(B^*_-) = \frac{1}{2}^- \to \text{parity violated}$$

$$b_c \frac{g_{B^*_-B_nM}}{m_c - m^*} + b_n^* \frac{g_{B_cB^*_-M}}{m_n - m^*}$$

$p^\mu \gamma_\mu u_c = m_c u_c$ is used

$\langle B^*_+ | \mathcal{H}^{PC}_{eff} | B_c \rangle = a_c \bar{u}^* u_c$

$$J^P(B^*_+) = \frac{1}{2}^+ \to \text{parity conserved}$$

$$\left(a_c \frac{g_{B^*_+B_nM}}{m_c - m^*} + a_n^* \frac{g_{B_cB^*_+M}}{m_n - m^*} \right) \gamma_5$$

Goldberger Treiman relation : Partially conserved axial current

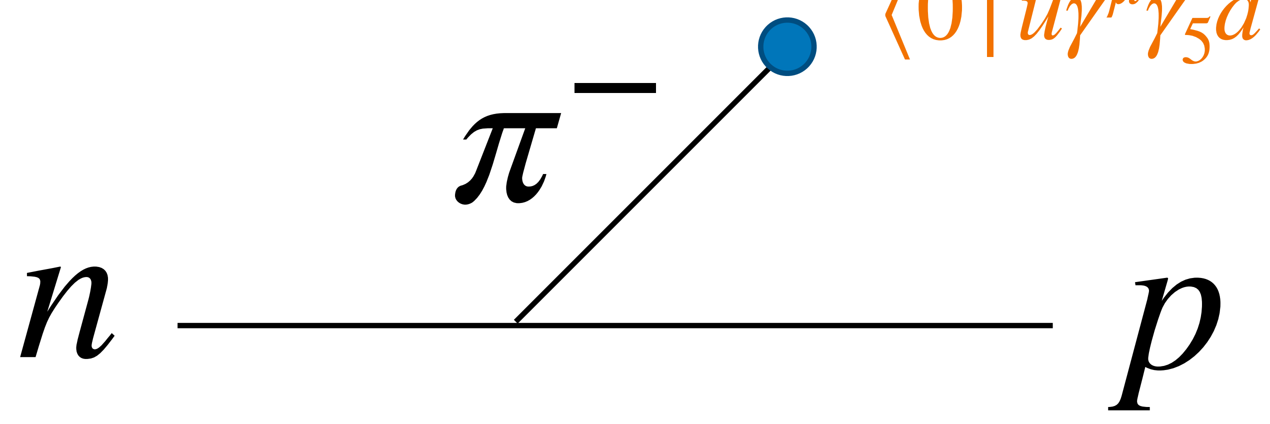
$$q_\mu \langle p | \bar{u}\gamma^\mu\gamma_5 d | n \rangle = q_\mu \bar{u}_p (g_1\gamma^\mu - g_2 i\sigma^{\mu\nu} q_\nu + g_3 q^\mu)\gamma_5 u_n = 0$$

$$q_\mu \langle B^*_- | \bar{u}\gamma^\mu\gamma_5 d | n \rangle = q_\mu \bar{u}^* (g_1\gamma^\mu - g_2 i\sigma^{\mu\nu} q_\nu + g_3 q^\mu) u_n = 0$$

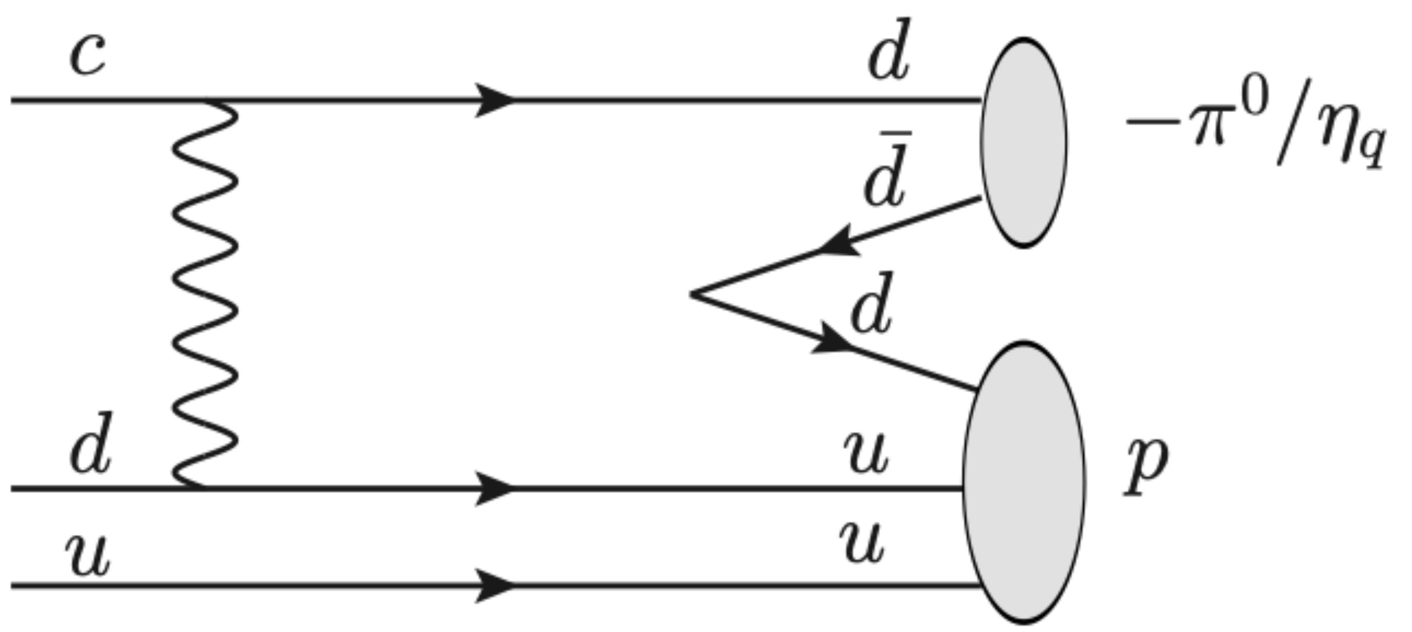
$$(m_n + m_p) g_1 = q^2 g_3 = g_{np\pi} f_\pi$$

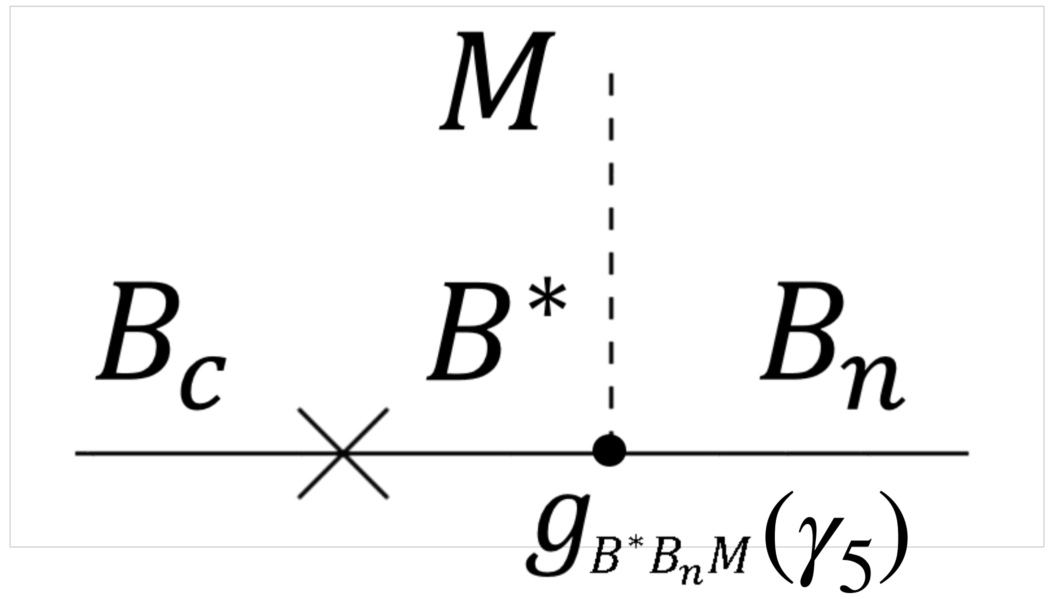
$$(m^*_- - m_n) g_1 = q^2 g_3 = g_{nB^*_-\pi} f_\pi$$

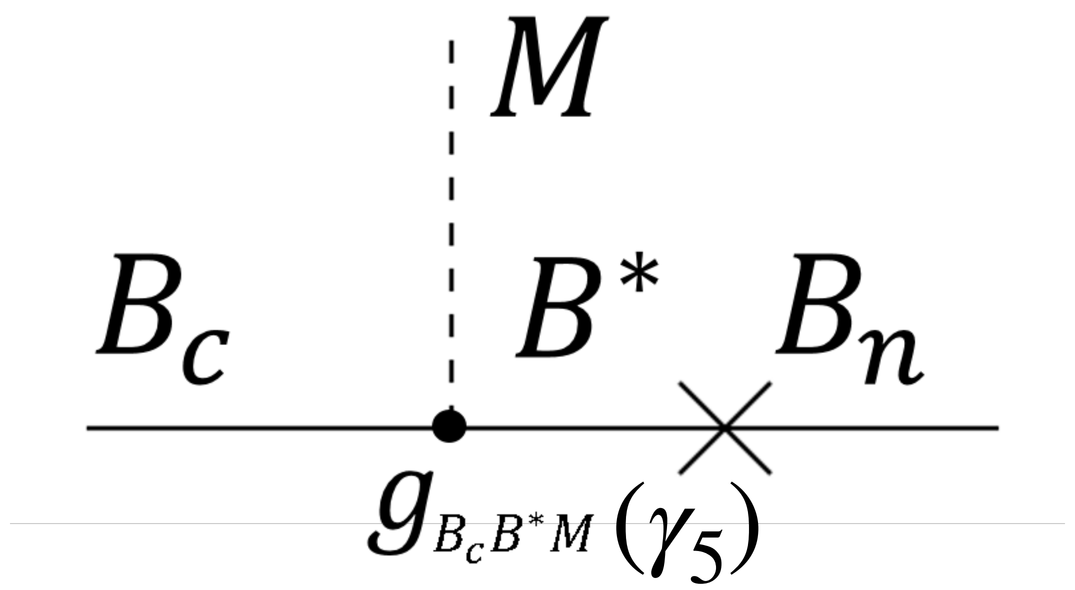
$\langle 0 | \bar{u}\gamma^\mu\gamma_5 d | \pi^- \rangle = i f_\pi q^\mu$



- **Exclusive decays - theory** $\frac{1}{2}^+ \to \frac{1}{2}^+ 0^-$ Pole model :







For direct calculations see : P. Y. Niu, Q. Wang and Q. Zhao, Phys. Lett. B **826**, 136916 (2022);
P. Y. Niu, J. M. Richard, Q. Wang and Q. Zhao, Phys. Rev. D **102**, no.7, 073005 (2020)

Uses of current algebra :

Using $m_n \approx m_c$. Crucial approximations and may not be valid.

$$\bar{u}_n \left(b_c \frac{g_{B^*_- B_n M}}{m_c - m^*} + b_n^* \frac{g_{B_c B^*_- M}}{m_n - m^*} \right) u_c \overbrace{=} - \frac{1}{f_\pi} \bar{u}_n \left(b_c g_{B^* B_n} - b_n^* g_{B_c B^*} \right) u_c$$

Assuming B^* dominates

$$= - \frac{1}{f_\pi} \left(\langle B_n | Q_5 | B^* \rangle \langle B^* | \mathscr{H}_{eff}^{PV} | B_c \rangle - \langle B_n | \mathscr{H}_{eff}^{PV} | B^* \rangle \langle B^* | Q_5 | B_c \rangle \right) \overbrace{=} - \frac{1}{f_\pi} \langle B_n | [Q_5, \mathscr{H}_{eff}^{PV}] | B_c \rangle$$

Extracting the parity conserving part

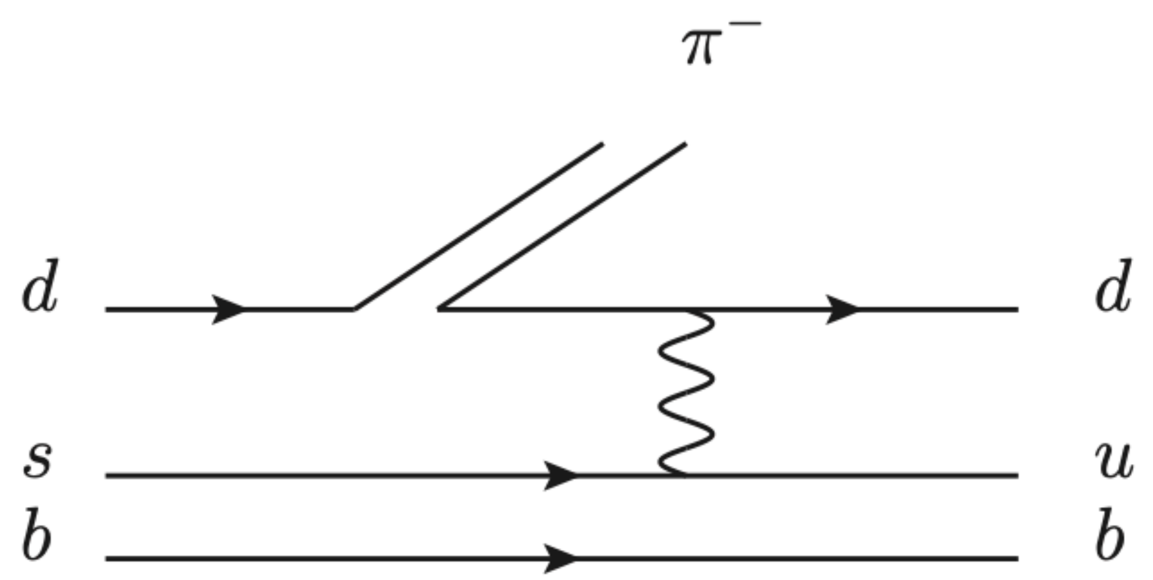
Using $[Q + Q_5, \mathscr{H}_{eff}] = 0$, we find $[Q_5, \mathscr{H}_{eff}^{PV}] = - [Q, \mathscr{H}_{eff}^{PC}]$.

$$Q_+ | n \rangle = \int d^3 \vec{x} \, \bar{u} \gamma^0 d \, | n \rangle = | p \rangle$$

Right-handed current commutes with the left-handed one

- **Exclusive decays - theory** $\frac{1}{2}^+ \to \frac{1}{2}^+ 0^-$

Pole model :



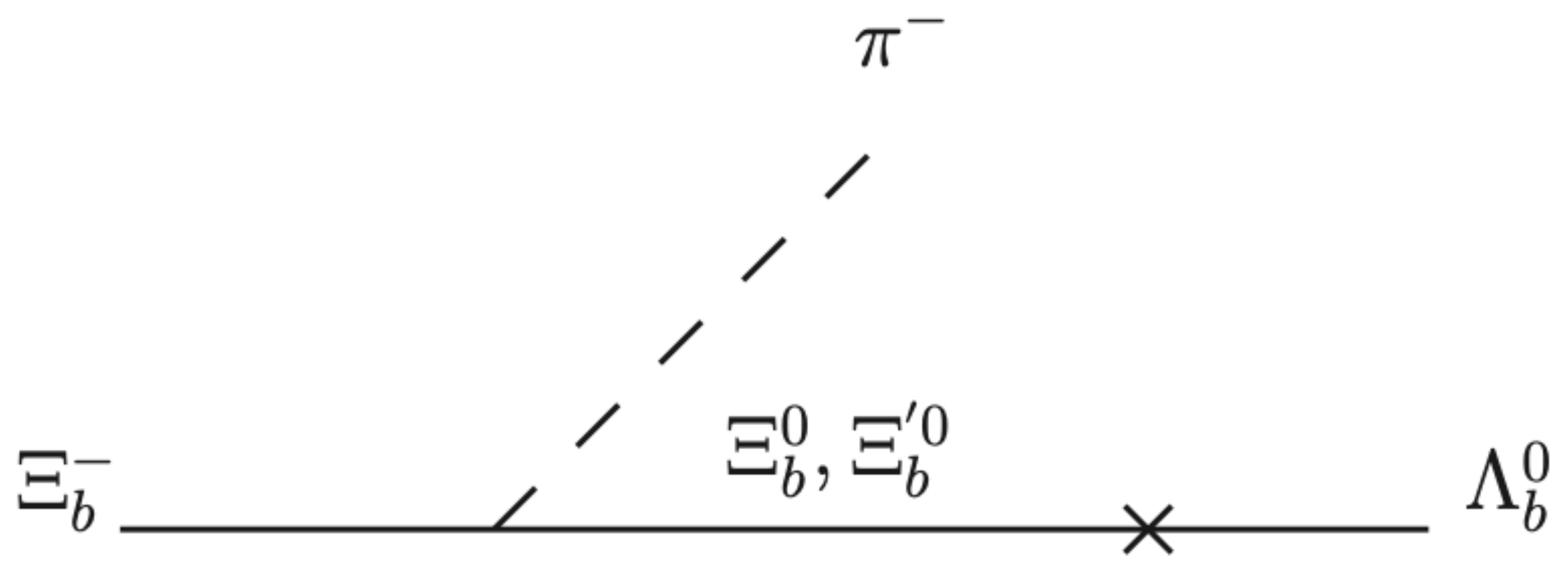


Figure from arXiv : 2209.00257v1

Heavy flavor conserving decays

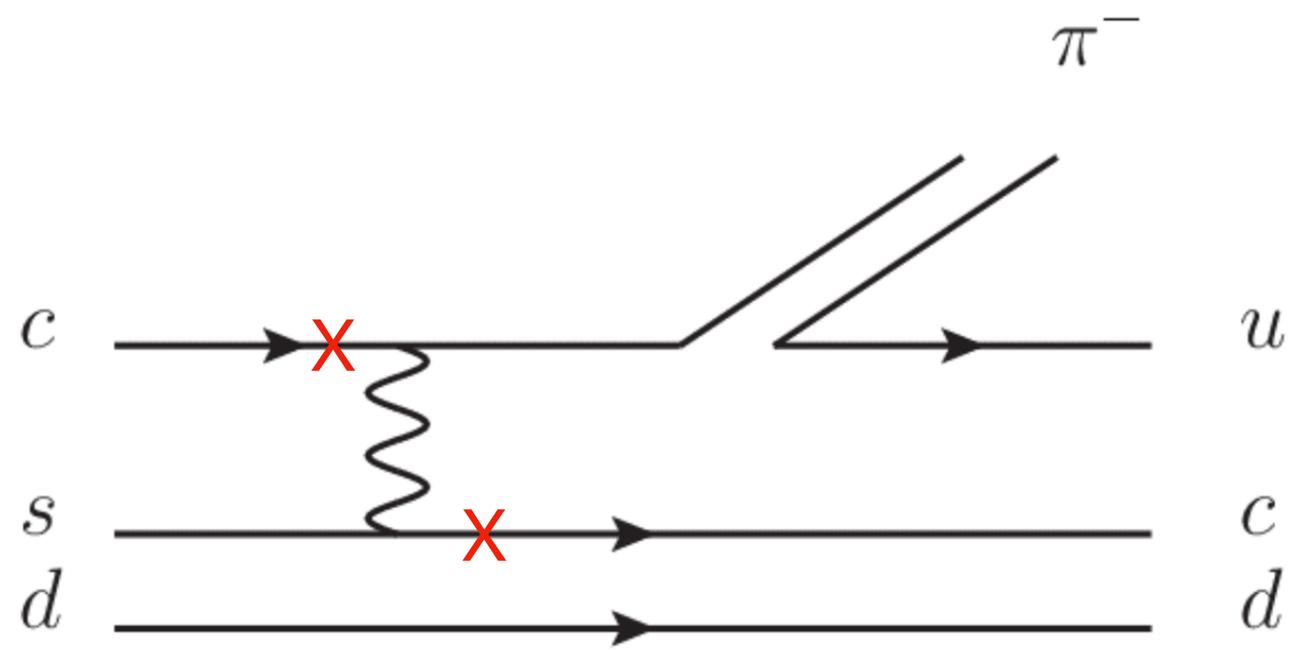
$m_n \approx m_c$ is an excellent approximation!

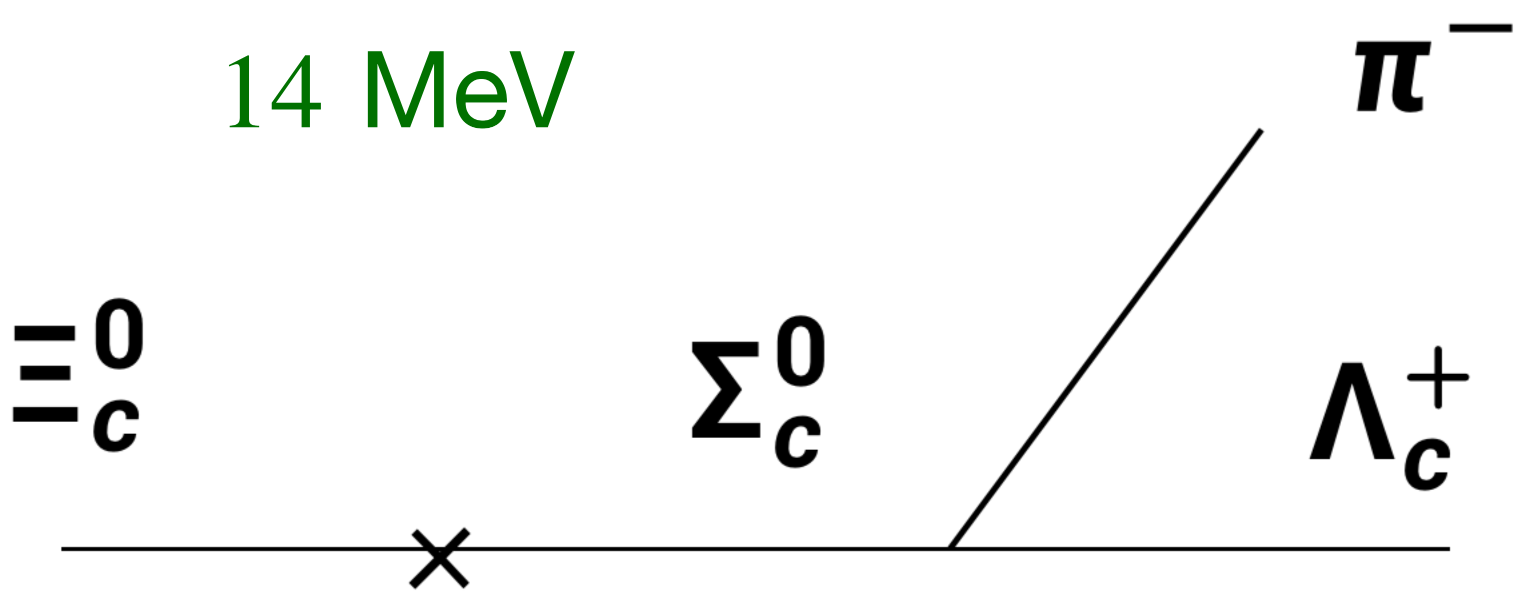
$$\bar{u}_n \left(b_c \frac{g_{B_n^* B_n M}}{m_c - m^*} + b_n^* \frac{g_{B_c B_c^* M}}{m_n - m^*} \right) u_c \overset{\frown}{=} - \frac{1}{f_\pi} \bar{u}_n \left(b_c g_{B^* B_n} - b_n^* g_{B_c B^*} \right) u_c$$

- Pole contributions are expected to be dominated. ✔
- Soft pion limit is reliable. ✔

$$\frac{1}{M_{\Xi_c} - M_{\Sigma_c^+} + i\frac{\Gamma_{\Sigma_c^+}}{2}}$$

$\underbrace{M_{\Xi_c} - M_{\Sigma_c^+}}$: 14 MeV

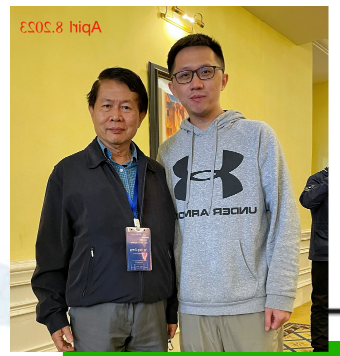




P. Y. Niu, Q. Wang and Q. Zhao, PLB **826**, 136916 (2022);
S. Groote and J. G. Körner, EPJC **82** 297 (2022).

Mode	$(CLY)^2$	Faller	Gronau	Voloshin	Niu	HYC	This work	Exp
$\Xi_c^0 \to \Lambda_c^+ \pi^-$	0.17	< 3.9	$0.18^{+0.23}_{-0.13}$ 1.34 ± 0.53 [a]	$>0.25 \pm 0.15$	5.8 ± 2.1	$1.76^{+0.18}_{-0.12}$	7.2 ± 0.7	5.4 ± 1.1
$\Xi_c^+ \to \Lambda_c^+ \pi^0$	0.11	< 6.1	<0.2 2.01 ± 0.80 [a]	–	11.1 ± 4.0	$3.03^{+0.29}_{-0.22}$	13.8 ± 1.4	–
$\Xi_b^- \to \Lambda_b^0 \pi^-$	7.0	$1.9 - 7.6$	6.4 ± 4.3	8 ± 3	1.4 ± 0.7	$4.67^{+2.29}_{-1.83}$	4.2 ± 0.5	6.0 ± 1.8
$\Xi_b^0 \to \Lambda_b^0 \pi^0$	2.5	$0.9 - 3.7$	3.2 ± 2.1	–	0.17 ± 0.15	$2.87^{+1.20}_{-0.99}$	2.6 ± 0.3	–

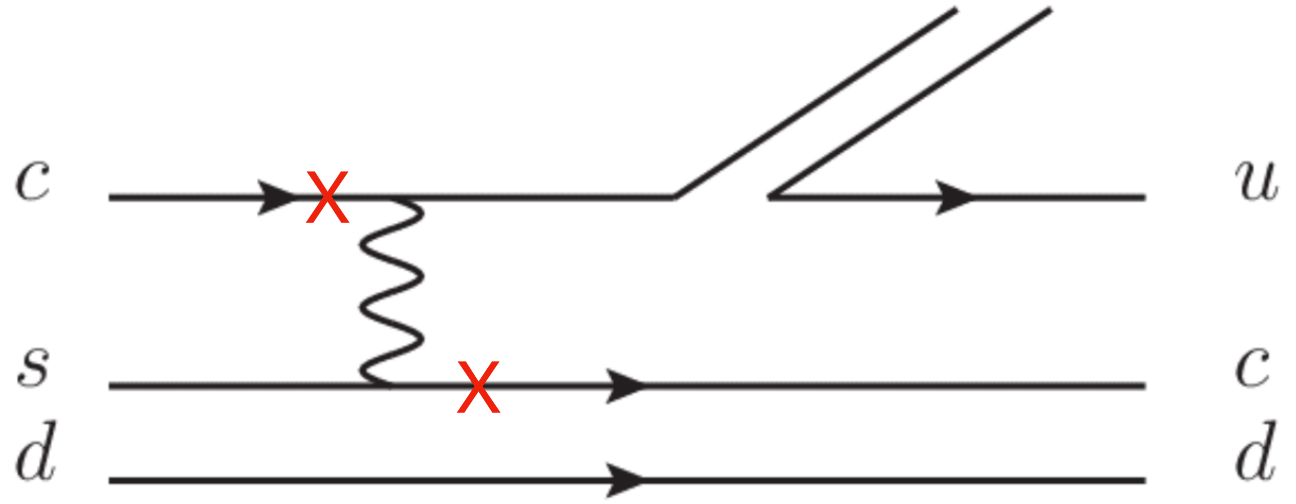
Tung-Mow Yan (顏東茂), Hai-Yang Cheng (鄭海揚), Chi-Yee Cheung (張志義), Guey-Lin Lin (林貴林), Yeu-Chung Lin (林育中), Hoi-Lai Yu (余海禮)

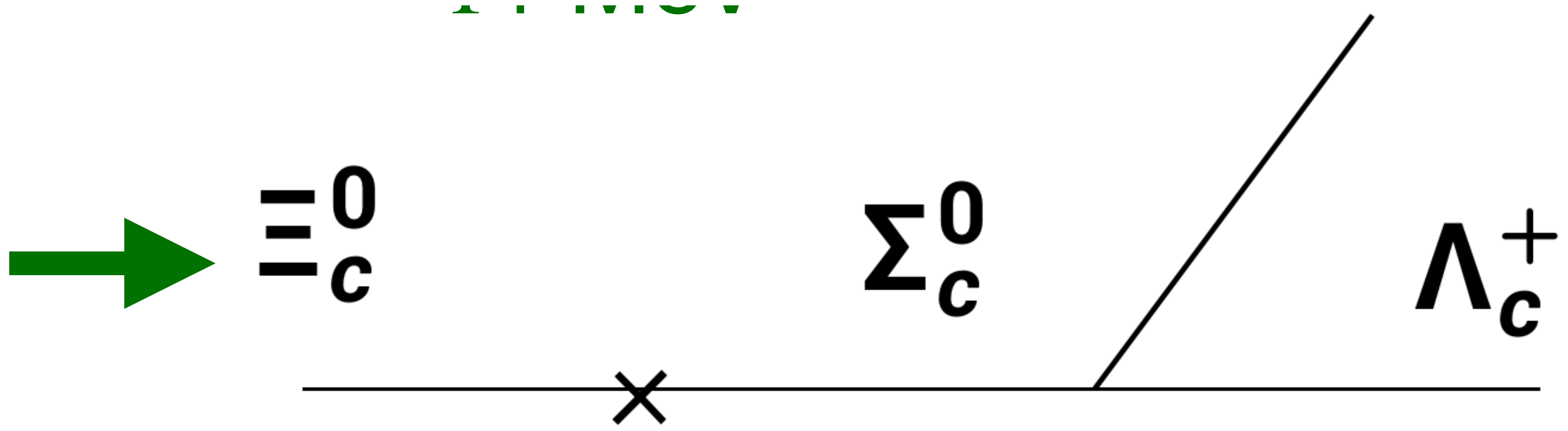


Did not consider charm-exchange

[LHCb], PRD **102**, 071101 (2020)

P. Y. Niu, Q. Wang and Q. Zhao, PLB **826**, 136916 (2022);
S. Groote and J. G. Körner, EPJC **82** 297 (2022).





• Exclusive decays - theory $\frac{1}{2}^+ \to \frac{1}{2}^+ 0^-$

$SU(3)$ group : $\mathbf{3} = (u, d, s)$

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{6} \oplus \underline{\bar{\mathbf{3}}}$$

$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = (\mathbf{1} \oplus \underline{\mathbf{8}} \oplus \mathbf{27})_S \oplus (\underline{\mathbf{8}} \oplus \mathbf{10} \oplus \overline{\mathbf{10}})_A$$

Combined to fulfilled the Fermi statistic

$$\mathbf{3} \otimes \bar{\mathbf{3}} = \underline{\mathbf{8} \oplus \mathbf{1}}$$

$$\mathbf{B}_c = (\Xi_c^0, -\Xi_c^+, \Lambda_c^+) ,$$

$$\mathbf{B}_n = \begin{pmatrix} \frac{1}{\sqrt{6}}\Lambda + \frac{1}{\sqrt{2}}\Sigma^0 & \Sigma^+ & p \\ \Sigma^- & \frac{1}{\sqrt{6}}\Lambda - \frac{1}{\sqrt{2}}\Sigma^0 & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix} ,$$

$$M = \begin{pmatrix} \frac{1}{\sqrt{2}}(\pi^0 + c_\phi \eta + s_\phi \eta') & \pi^+ & K^+ \\ \pi^- & \frac{1}{\sqrt{2}}(-\pi^0 + c_\phi \eta + s_\phi \eta') & K^0 \\ K^- & \bar{K}^0 & -s_\phi \eta + c_\phi \eta' \end{pmatrix} ,$$

$$H(\overline{15})_k^{ij} = \left(\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & s_c & 1 \\ s_c & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & -s_c^2 & -s_c \\ -s_c^2 & 0 & 0 \\ -s_c & 0 & 0 \end{pmatrix} \right) ,$$

$$H(6)_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 2 & -2s_c \\ 0 & -2s_c & 2s_c^2 \end{pmatrix} ,$$

$A_{(\mathbf{B}_c \to \mathbf{B}_n M)} =$ Generalized Wigner Eckart theorem

$$a_0 H(6)_{ij} (\mathbf{B}_c')^{ik} (\mathbf{B}_n)_k^j (M)_l^l + a_1 H(6)_{ij} (\mathbf{B}_c')^{ik} (\mathbf{B}_n)_k^l (M)_l^j + a_2 H(6)_{ij} (\mathbf{B}_c')^{ik} (M)_k^l (\mathbf{B}_n)_l^j +$$
$$a_3 H(6)_{ij} (\mathbf{B}_n)_k^i (M)_l^j (\mathbf{B}_c')^{kl} + a_0' (\mathbf{B}_n)_j^i (M)_l^l H(\overline{15})_i^{jk} (\mathbf{B}_c)_k + a_4 H(\overline{15})_k^{li} (\mathbf{B}_c)_j (M)_i^j (\mathbf{B}_n)_l^k +$$
$$a_5 (\mathbf{B}_n)_j^i (M)_i^l H(\overline{15})_l^{jk} (\mathbf{B}_c)_k + a_6 (\mathbf{B}_n)_i^j (M)_l^m H(\overline{15})_m^{li} (\mathbf{B}_c)_j + a_7 (\mathbf{B}_n)_i^l (M)_j^i H(\overline{15})_l^{jk} (\mathbf{B}_c)_k ,$$

Pedagogical reasoning

$SU(2)$ group

$$\frac{1}{2} \otimes \frac{1}{2} = 0 \oplus 1 \to \mathbf{2} \otimes \mathbf{2} = \mathbf{1} \oplus \mathbf{3}$$

Spin-half + spin-half = spin-0 + spin-1

• Exclusive decays - theory $\frac{1}{2}^+ \to \frac{1}{2}^+ 0^-$ SU(3) flavor symmetry :

channel	data	$SU(3)_F$	Current Algebra
$10^4\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)^a$	$4.7 \pm 0.9 \pm 0.1 \pm 0.3$	5.4 ± 0.7	7.2
$10^4\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)^a$	$4.8 \pm 1.4 \pm 0.2 \pm 0.3$	5.4 ± 0.7	7.2
$10^4\mathcal{B}(\Lambda_c^+ \to n\pi^+)^b$	$6.6 \pm 1.2 \pm 0.4$	8.5 ± 2.0	2.7
$\alpha(\Lambda_c^+ \to pK_S^0)^c$	$0.18 \pm 0.43 \pm 0.14$	$-0.89^{+0.26}_{-0.11}$	-0.90
$\alpha(\Lambda_c^+ \to \Lambda K^+)^d$	$-0.585 \pm 0.049 \pm 0.018$	0.32 ± 0.32	-0.96
$\alpha(\Lambda_c^+ \to \Sigma^0 K^+)^d$	$-0.55 \pm 0.18 \pm 0.09,$	~ -1	-0.73
$100\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)^e$	1.43 ± 0.32	2.21 ± 0.11	6.47
$100\mathcal{R}(\Xi_c^0 \to \Xi^- K^+)$	$2.75 \pm 0.51 \pm 0.25$	4.4	6.0
$100\mathcal{R}(\Xi_c^0 \to \Sigma^0 K_s^0)^f$	$3.8 \pm 0.6 \pm 0.4$	2.3 ± 1.8	< 0.4
$10\mathcal{R}(\Xi_c^0 \to \Sigma^+ K^-)^f$	$1.23 \pm 0.07 \pm 0.10$	2.7 ± 0.5	0.71
$100\mathcal{B}(\Xi_c^+ \to \Xi^0\pi^+)$	1.6 ± 0.8	0.38 ± 0.20	1.72
$\mathcal{R}(\Xi_c^+ \to \Xi^0\pi^+)$	1.1 ± 0.6	0.17 ± 0.09	0.27

[a] Phys. Rev. D **106**, 052003 (2022).
[b] Phys. Rev. Lett. **128**, 142001 (2022).
[c] Phys. Rev. D **100**, 072004 (2019).
[d] arXiv:2208.08695 [hep-ex].
[e] Phys. Rev. Lett. **122**, 082001 (2019).
[f] Phys. Rev. D **105**, L011102 (2022).

$$\mathscr{R}(X) := \frac{\mathscr{B}(X)}{\mathscr{B}(\Xi_c^0 \to \Xi^-\pi^+)}$$

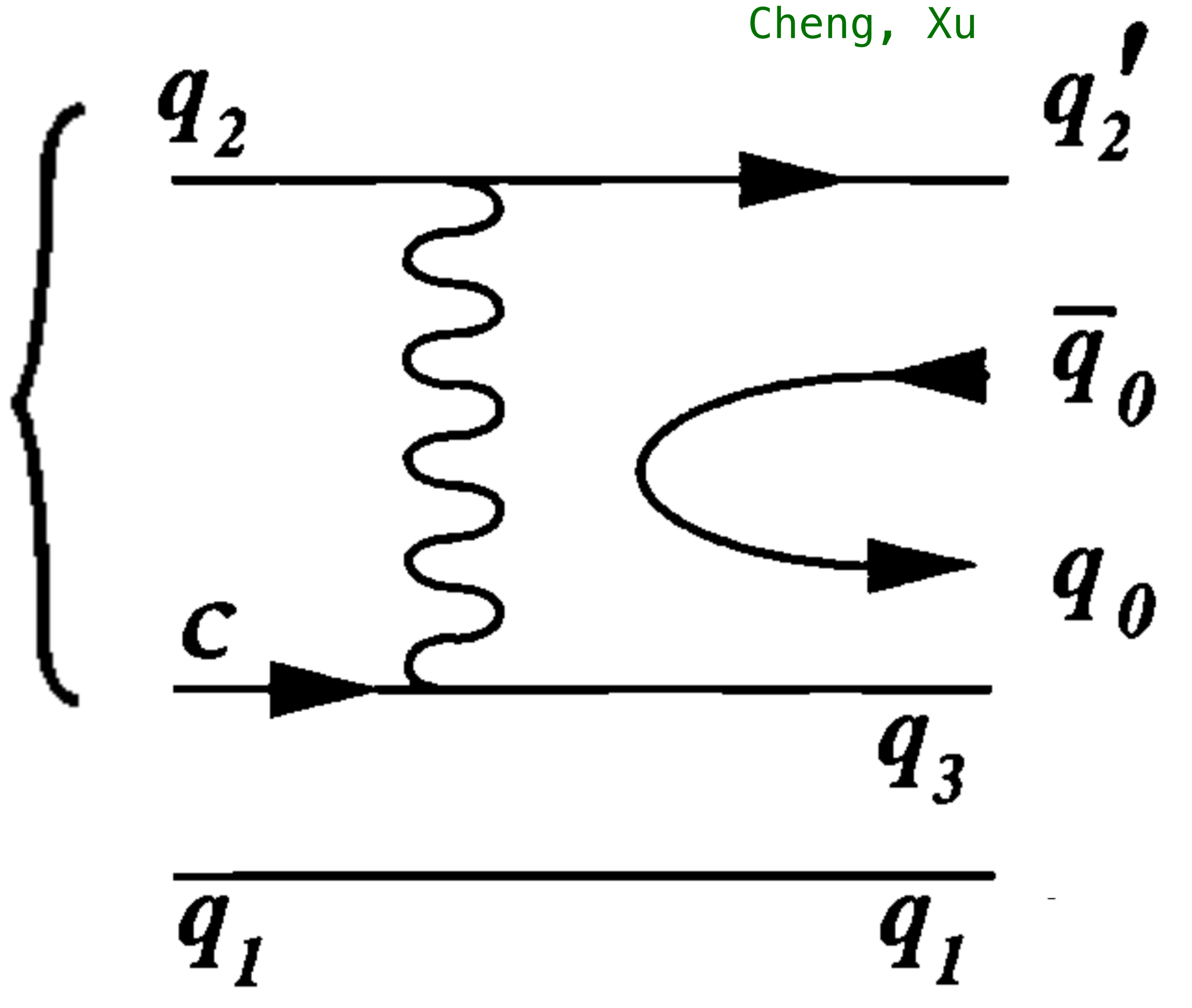
Input:

$10^4\mathscr{B}(\Lambda_c^+ \to \Sigma^0 K^+) = 5.2 \pm 0.8$

$100\mathscr{B}(\Xi_c^0 \to \Xi^-\pi^+) = 1.80 \pm 0.52$

PRD **101** 014011 (2020); PRD **97** 074028 (2018)

Cheng, Xu



$= 0$

Chau, Cheng, Tseng

PRD **54**, 2132 (1996)

$$O_+ = \frac{1}{2}\sum_{q,q'=d,s} V_{uq}V^*_{cq'}\left((\bar{u}q)(\bar{q}'c)+(\bar{q}'q)(\bar{u}c)\right)$$

Körner-Pati-Woo theorem

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Asymmetries of anti-triplet charmed baryon decays

C.Q. Geng [a,b,c,*], Chia-Wei Liu [b], Tien-Hsueh Tsai [b]
[a] Chongqing University of Posts & Telecommunications, Chongqing 400065
[b] Department of Physics, National Tsing Hua University, Hsinchu 300
[c] Physics Division, National Center for Theoretical Sciences, Hsinchu 300

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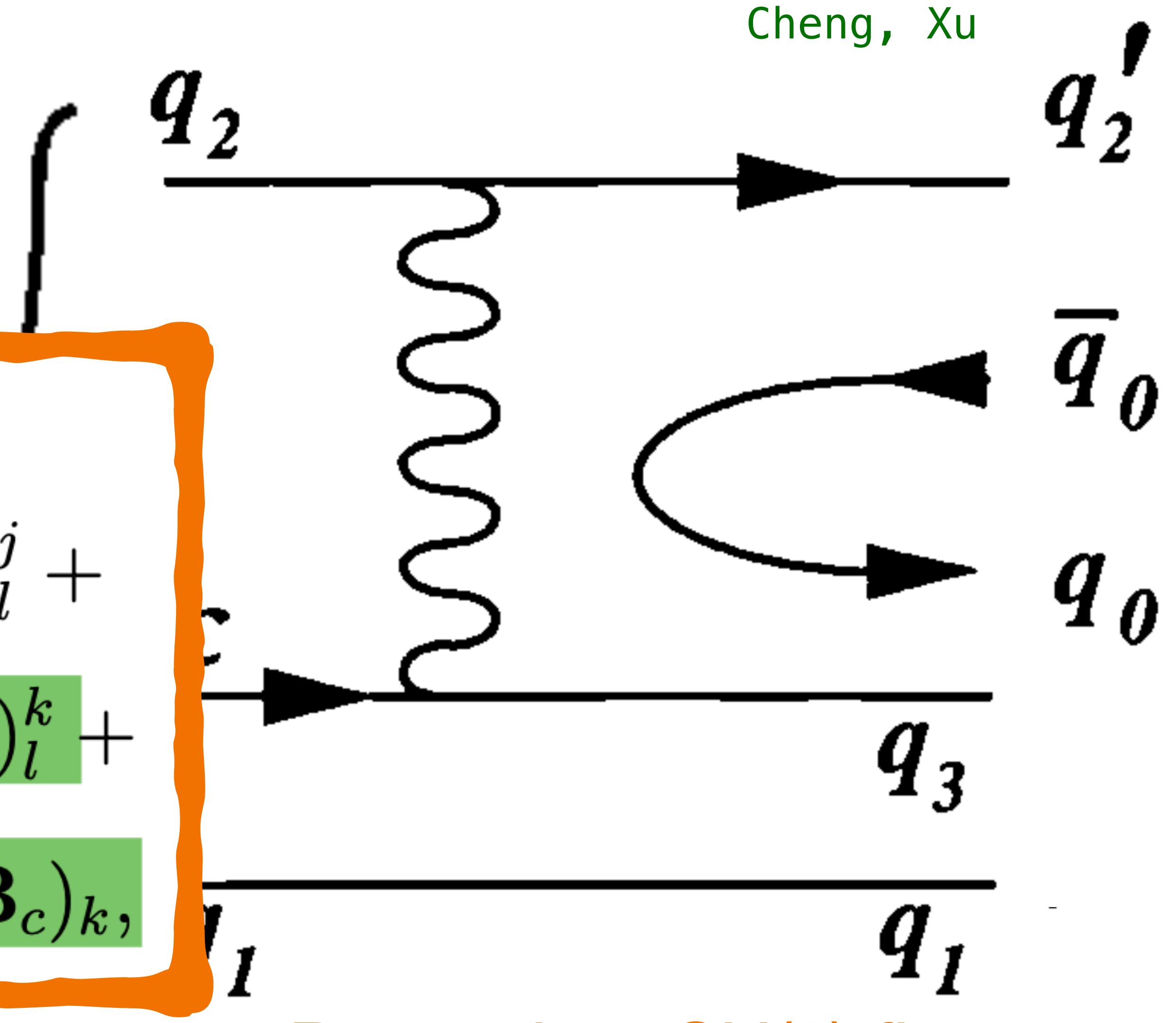
Cheng, Xu

$$A_{(\mathbf{B}_c \to \mathbf{B}_n M)} = a_0 H(6)_{ij}(\mathbf{B}_c')^{ik}(\mathbf{B}_n)_k^j (M)_l^l + a_1 H(6)_{ij}(\mathbf{B}_c')^{ik}(\mathbf{B}_n)_k^l (M)_l^j + a_2 H(6)_{ij}(\mathbf{B}_c')^{ik}(M)_k^l (\mathbf{B}_n)_l^j + a_3 H(6)_{ij}(\mathbf{B}_n)_k^i (M)_l^j (\mathbf{B}_c')^{kl} + a_0'(\mathbf{B}_n)_j^i (M)_l^l H(\overline{15})_i^{jk} (\mathbf{B}_c)_k + a_4 H(\overline{15})_k^{li} (\mathbf{B}_c)_j (M)_i^j (\mathbf{B}_n)_l^k + a_5 (\mathbf{B}_n)_j^i (M)_i^l H(\overline{15})_l^{jk} (\mathbf{B}_c)_k + a_6 (\mathbf{B}_n)_i^j (M)_l^m H(\overline{15})_m^{li} (\mathbf{B}_c)_j + a_7 (\mathbf{B}_n)_i^l (M)_j^i H(\overline{15})_l^{jk} (\mathbf{B}_c)_k,$$



$= 0$

Chau, Cheng, Tseng

PRD 54, 2132 (1996)

Better than SU(3) flavor symmetry.

$$= \frac{1}{2} \sum_{q,q'=d,s} V_{uq} V_{cq'}^* \left((\bar{u}q)(\bar{q}'c) + (\bar{q}'q)(\bar{u}c) \right)$$

Körner-Pati-Woo theorem

- Test the KPW theorem directly
- Protected by the isospin symmetry
- The only two channels in $\mathscr{B}_c \to \mathscr{B}P$.

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PRD **101** 014011 (2020); PRD **97** 074028 (2018)

Cheng, Xu

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[d] arXiv:2208.08695 [hep-ex].
[e] Phys. Rev. Lett. **122**, 082001 (2019).
[f] Phys. Rev. D **105**, L011102 (2022).

$\mathcal{B}(\Xi_c^0 \to \Sigma^0 K_s^0)$ is found to be 20 times smaller than $\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$

Cabibbo-favored

Cabibbo-suppressed, $V_{cd}^2 \approx 0.05$

Cabibbo-favored; large destructive interference

works empirically excellent.

$$\mathcal{R}(X) := \frac{\mathcal{B}(X)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)}$$

Input:

$10^4\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+) = 5.2 \pm 0.8$

$100\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = 1.80 \pm 0.52$

For the results w/o using KPW theorem :

C. P. Jia, D. Wang and F. S. Yu, NPB **956**, 115048 (2020);
Y. K. Hsiao, Y. L. Wang and H. J. Zhao, JHEP **09**, 035 (2022);
H. Zhong, F. Xu, Q. Wen and Y. Gu, JHEP **02**, 235 (2023);
Z. P. Xing, X. G. He, F. Huang and C. Yang, arXiv:2305.14854.

Exclusive decays - semileptonic

$\Xi_c^0 \to \Xi^- e^+ \nu_e$

$\mathscr{B}_{\text{Belle}} = (1.31 \pm 0.04 \pm 0.07 \pm 0.38)\,\%$

PRL **127** 121803 (2021)

$\mathscr{B}_{\text{ALICE}} = (2.43 \pm 0.25 \pm 0.35 \pm 0.72)\,\%$

PRL **127** 272001 (2021)

$\mathscr{B}_{\text{LQCD}} = (2.38 \pm 0.30 \pm 0.32 \pm 0.07)\,\%$

CPC **46** 011002 (2022)

$^*\mathscr{B}_{SU(3)} = (4.05 \pm 0.15)\,\%$

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

[BESIII], PRL **129**, 231803 (2022)

$\mathscr{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.80 \pm 0.19 \pm 0.11)\,\%$

Stefan Meinel, PRL **118**, 082001 (2017)

channel	branching ratio(%)	
	experimental data	fit data
$\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$	3.60 ± 0.40	1.94 ± 0.18
$\Lambda_c^+ \to \Lambda^0 \mu^+ \nu_\mu$	3.5 ± 0.5	1.87 ± 0.176
$\Xi_c^+ \to \Xi^0 e^+ \nu_e$	2.3 ± 1.5	6.53 ± 0.60
$\Xi_c^0 \to \Xi^- e^+ \nu_e$	1.54 ± 0.35	2.17 ± 0.20
$\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu$	1.27 ± 0.44	2.09 ± 0.19

X. G. He, F. Huang, W. Wang and Z. P. Xing, PLB **823**, 136765 (2021)

$$\frac{\Gamma(D_s^+ \to \phi e^+ \nu_e)}{\Gamma(D^+ \to \overline{K}^{*0} e^+ \nu_e)} = 0.91 \pm 0.06\,, \quad \frac{1}{2}\frac{\Gamma(D_s^+ \to K^0 e^+ \nu_e)}{\Gamma(D^+ \to \pi^0 e^+ \nu_e)} = 0.94 \pm 0.10\,,$$

Puzzle to be solved !

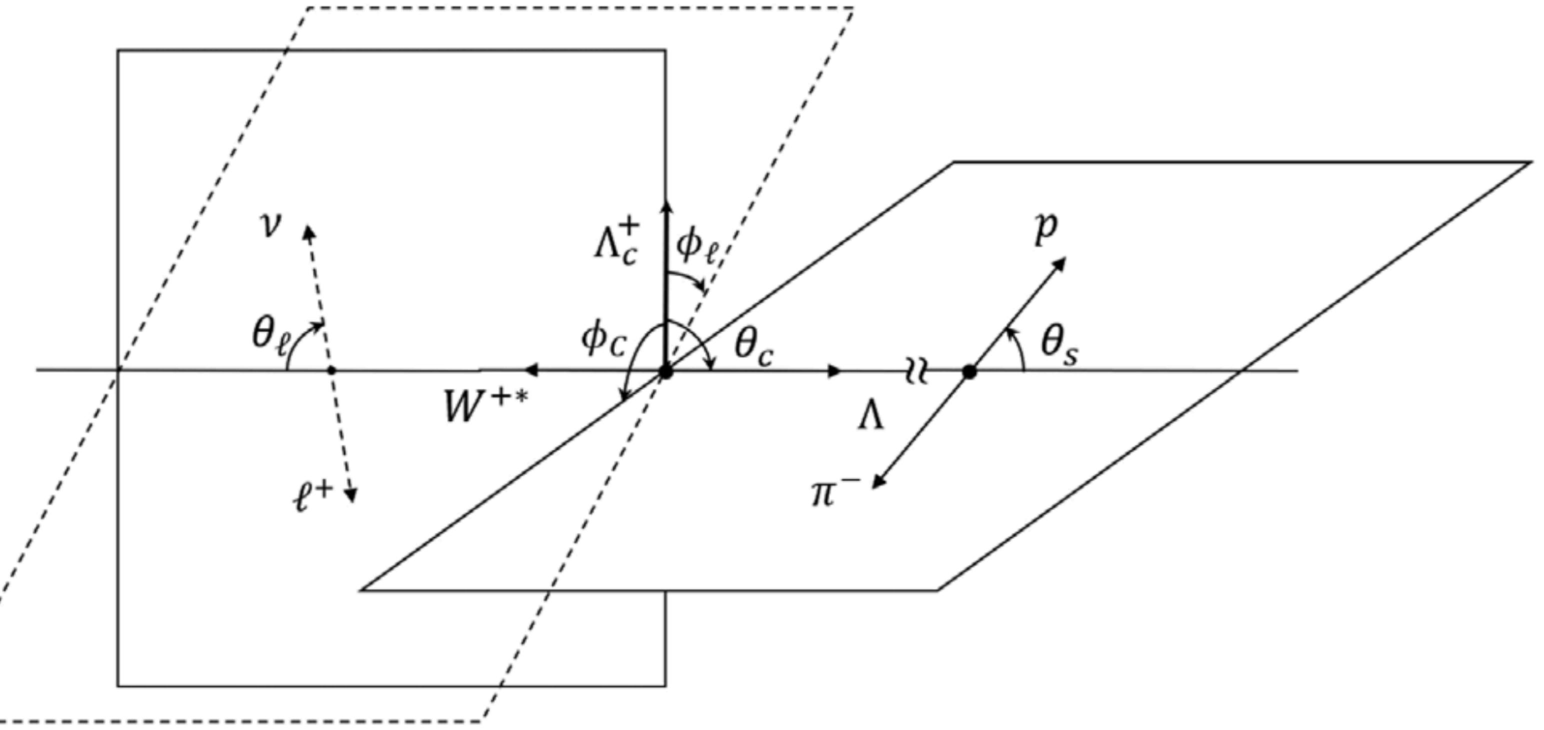
Several NP effects can still be examined due to the symmetry:

Lepton universality : $\Lambda_c^+ \to \Lambda e^+ \nu_e, \Lambda \mu^+ \nu_\mu$

[BESIII], arXiv:2306.02624

Time-reversal asymmetry: absent of strong phases

C. Q. Geng, X. N. Jin, C. W. Liu PRD **107**, 033008 (2023); J. P. Wang and F. S. Yu, arXiv:2208.01589



Conclusions and outlooks

- Heavy quark expansion to $1/m_c^4$ order is able to explain the observed lifetimes.

  → Experiment : $\Omega_c^0 \to X\ell^+\nu_\ell$, $\Xi_c \to X\ell^+\nu_\ell$ and lifetimes of doubly heavy baryons.

  → Theory : NLO coefficients of the dim-7 operators.

- The heavy flavor conserving decays can be well described by the current algebra.

  → Experiment : $\Xi_c^+ \to \Lambda_c^+\pi^0$, $\Xi_b^0 \to \Lambda_b\pi^0$ of which π^0 may impose difficulties.

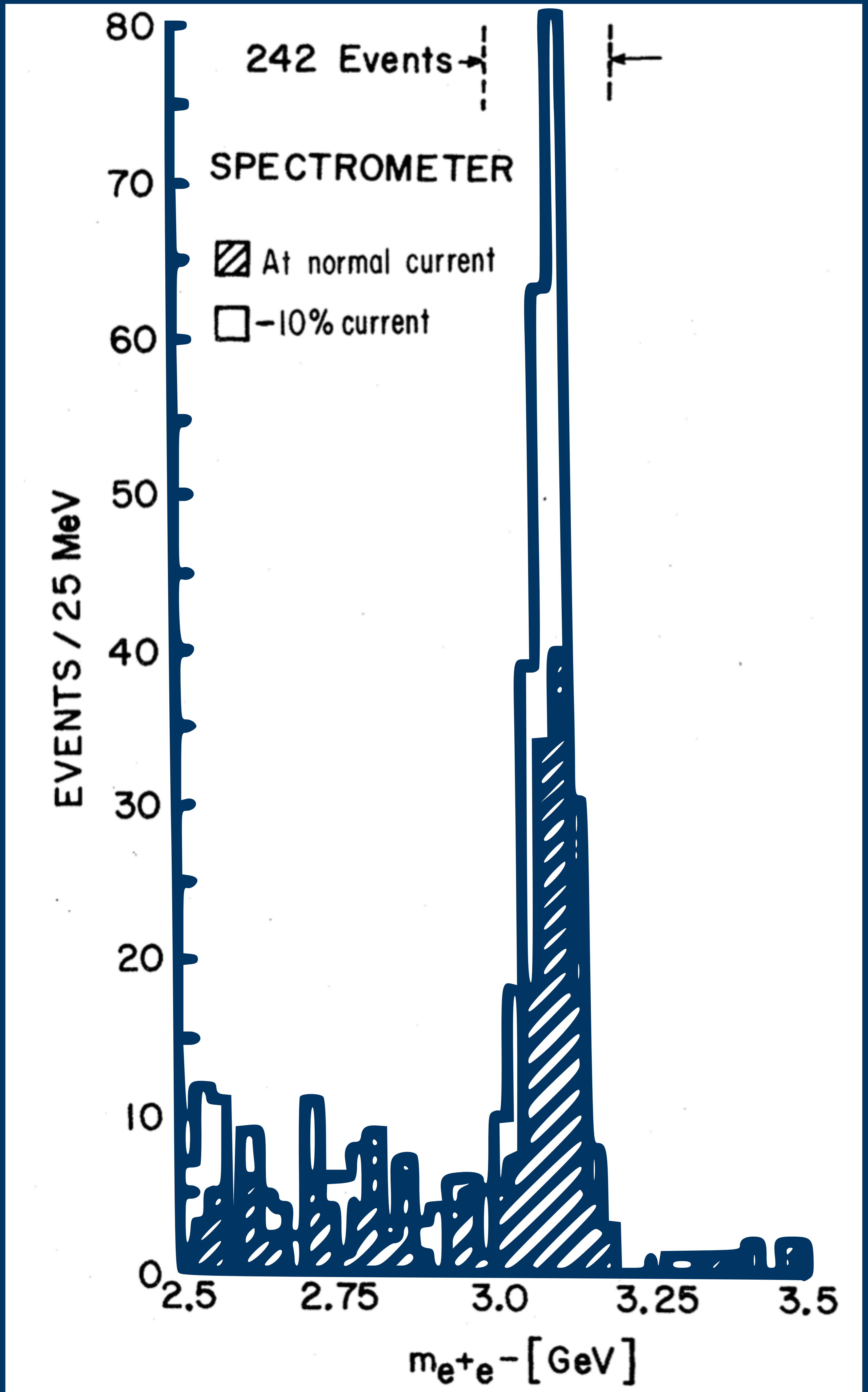
  Up-down asymmetries of $\Xi_Q \to \Lambda_Q\pi^-$.

  → Theory : Bridging the difference between the current algebra and direct pole evaluations.

- The SU(3) flavor symmetry seems to work well in the nonleptonic decays but broken badly in the semileptonic decays.

  → Experiment : Revisiting $\Xi_c^0 \to \Xi^- e^+\nu_e$, $\Xi_c^+ \to \Xi^0 e^+\nu_e$. Completing the data of nonleptonic two-body decays. As a bonus : $\Omega_c \to \Omega^- e^+\nu_e$.

  → Theory : The $SU(3)_F$ breaking mechanism in Ξ_c.



There is a light somewhere.
It may not be much light
but it beats the darkness.
-Charles Bukowski