Charmed hadron lifetimes in the HQE approach

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PDG (2018)

	10^{-13}s
D^0_d	4.101±0.015
D^+	10.40±0.07
D^+_s	5.00±0.07

	10^{-12}s
B^0_d	1.520±0.004
B^0_s	1.510±0.005
B^+	1.638±0.004

	10^{-13}s
Ξ_c^+	4.42±0.26
Λ_c^+	2.00±0.06
Ξ_c^0	$1.12^{+0.13}_{-0.10}$
Ω_c^0	0.69±0.12

due mainly to FOCUS

	10^{-12}s
Λ_b^0	1.470±0.009
Ξ_b^0	1.479±0.030
Ξ_b^-	1.571±0.030
Ω_b^-	$1.64^{+0.18}_{-0.17}$

Lifetimes of Ω_c^0 & Ξ_{cc}^{++} measured by LHCb recently

Lifetimes of heavy baryons

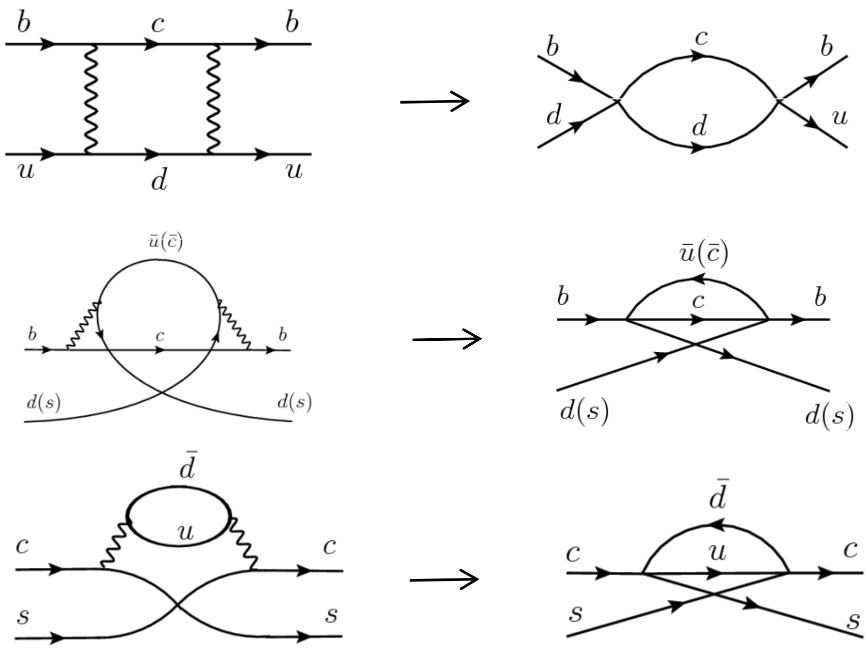
Heavy quark expansion:

$$\Gamma(H_Q \to f) = \frac{G_F^2 m_Q^5}{192\pi^3} V_{CKM} \left(A_0 + \frac{A_2}{m_Q^2} + \frac{A_3}{m_Q^3} + \ldots \right)$$

$$= \frac{G_F^2 m_Q^5}{192\pi^3} \left(c_{3,Q} \frac{\langle H_Q | \overline{Q} Q | H_Q \rangle}{2m_{H_Q}} + \frac{c_{5,Q}}{m_Q^2} \frac{\langle H_Q | \overline{Q} \sigma . G Q | H_Q \rangle}{2m_{H_Q}} + \frac{c_{6,Q}}{m_Q^3} \frac{\langle H_Q | T_6 | H_Q \rangle}{2m_{H_Q}} + \ldots \right)$$

- A_0 **term from the decay of heavy quark Q**
  $\Rightarrow$ **Lifetimes of all heavy hadrons** H_Q **are the same in** $m_Q \to \infty$ **limit**
- **No linear 1/m_Q corrections, known as Luke's theorem**
- A_2 **term arises from the interaction of heavy quark spin with gluon**
- A_3 **term consists of dim-6 four-quark operators which will induce the spectator effects responsible for lifetime differences**

Spectator effects described by dim-6 four-quark operators:



W-exchange

destructive P.I.
(Pauli interference)

constructive P.I.
(only for charmed baryons)

- **Although spectator effects are** $1/m_Q^3$ **suppressed, they are numerically important due to a p.s. enhancement factor of** $16\pi^2$ **relative to heavy quark decay**

Examples of dim-6 four-quark operators for spectator effects

$$\mathcal{T}_{6,ann}^{\mathcal{B}_Q,q_1} = \frac{G_F^2 m_Q^2}{2\pi}\,\xi\,(1-x)^2\Big\{(c_1^2+c_2^2)(\bar{Q}Q)(\bar{q}_1q_1)+2c_1c_2(\bar{Q}q_1)(\bar{q}_1Q)\Big\}$$

$$\mathcal{T}_{6,int+}^{\mathcal{B}_Q,q_3} = -\frac{G_F^2 m_Q^2}{6\pi}\,\xi\Big\{c_2^2\Big[(\bar{Q}Q)(\bar{q}_3q_3)-\bar{Q}^\alpha(1-\gamma_5)q_3^\beta\bar{q}_3^\beta(1+\gamma_5)Q^\alpha\Big]$$
$$+\ (2c_1c_2+N_cc_1^2)\Big[(\bar{Q}q_3)(\bar{q}_3Q)-\bar{Q}(1-\gamma_5)q_3\bar{q}_3(1+\gamma_5)Q\Big]\Big\},$$

$$(\bar{q}_1q_2)\equiv\bar{q}_1\gamma_\mu(1-\gamma_5)q_2$$

How to evaluate hadronic matrix elements?

- **Meson matrix elements: bag parameters guided by vacuum insertion approximation (VIA)**

$$\langle B_q|(\bar{b}q)(\bar{q}b)|B_q\rangle = f_{B_q}^2m_{B_q}^2B_1,$$
$$\langle B_q|\bar{b}(1-\gamma_5)q\bar{q}(1+\gamma_5)b|B_q\rangle = f_{B_q}^2m_{B_q}^2B_2,$$
$$\langle B_q|(\bar{b}\,t^aq)(\bar{q}\,t^ab)|B_q\rangle = f_{B_q}^2m_{B_q}^2\varepsilon_1,$$
$$\langle B_q|b\,t^a(1-\gamma_5)q\bar{q}\,t^a(1+\gamma_5)b|B_q\rangle = f_{B_q}^2m_{B_q}^2\varepsilon_2$$

$$\langle B_q|(\bar{b}q)|0\rangle = if_{B_q}m_{B_q}$$

VIA $\Rightarrow$ $B_i = 1$, $\varepsilon_i = 0$

estimated using QCD sum rules, LQCD,..., and updated recently by Kirk, Lenz, Rauch using HQET sum rules ('17)

$$B_1=1.028^{+0.064}_{-0.056},\quad B_2=0.988^{+0.087}_{-0.079},\quad \varepsilon_1=-0.107^{+0.028}_{-0.029},\quad \varepsilon_2=-0.033^{+0.021}_{-0.021}$$

Baryon matrix elements: quark model

$$\langle \mathcal{B}_b|(\bar{b}q)(\bar{q}b)|\mathcal{B}_b\rangle = f^2_{B_q} m_{B_q} m_{\mathcal{B}_b} L_1,$$
$$\langle \mathcal{B}_b|\bar{b}(1-\gamma_5)q\bar{q}(1+\gamma_5)b|\mathcal{B}_b\rangle = f^2_{B_q} m_{B_q} m_{\mathcal{B}_b} L_2,$$
$$\langle \mathcal{B}_b|(\bar{b}b)(\bar{q}q)|\mathcal{B}_b\rangle = f^2_{B_q} m_{B_q} m_{\mathcal{B}_b} L_3,$$
$$\langle \mathcal{B}_b|\bar{b}^\alpha(1-\gamma_5)q^\beta\bar{q}^\beta(1+\gamma_5)b^\alpha|\mathcal{B}_b\rangle = f^2_{B_q} m_{B_q} m_{\mathcal{B}_b} L_4,$$

$\mathcal{B}_b$: **antitriplet baryon T_b or sextet baryon Ω_b**

$$L_1^{T_b} = -\frac{1}{6} r_{T_b}, \quad L_2^{T_b} = \frac{1}{12} r_{T_b}, \quad L_3^{T_b} = \frac{1}{6}\tilde{B} r_{T_b}, \quad L_4^{T_b} = -\frac{1}{12}\tilde{B} r_{T_b}$$
$$L_1^{\Omega_b} = -r_{\Omega_b}, \quad L_2^{\Omega_b} = -\frac{1}{6} r_{\Omega_b}, \quad L_3^{\Omega_b} = \tilde{B} r_{\Omega_b}, \quad L_4^{\Omega_b} = \frac{1}{6}\tilde{B} r_{\Omega_b}.$$

r is a wave function ratio $\quad r_{\Lambda_b} = \left|\psi_{bq}^{\Lambda_b}(0)\right|^2 / \left|\psi_{b\bar{q}}^{B}(0)\right|^2$

$$|\psi_{b\bar{q}}^{B}(0)|^2 = \frac{1}{12} f_B^2 m_B$$

$\tilde{B}$ defined by $\quad \langle \mathcal{B}_b|(\bar{b}b)(\bar{q}q)|\mathcal{B}_b\rangle = -\tilde{B}\langle \mathcal{B}_b|(\bar{b}q)(\bar{q}b)|\mathcal{B}_b\rangle$

$$\langle \mathcal{B}_b|(\bar{b}q)(\bar{q}b) + (\bar{b}b)(\bar{q}q)|\mathcal{B}_b\rangle = 0$$

$\tilde{B}$=1 in valence-quark approx, valid at hadronic scale

Lifetimes of bottom mesons

- Wilson coefficients c_3, c_5, c_6 to NLO are available to B & D, but not to heavy baryons, while c_7 is known to LO only.
- For the reason of consistency, we focus on LO-QCD study.
- To LO-QCD, it is sensitive to the definition of quark mass: e.g. pole, $\overline{\text{MS}}$, kinetic, 1S scheme.
- PDG: $m_b^{1S} = 4.691 \pm 0.037$ GeV, $m_b^{pole} \sim 4.65$ GeV, $m_b^{kin} = 4.554 \pm 0.018$ GeV, $\overline{m}_b(\overline{m}_b) = 4.19 \pm 0.04$ GeV
- To NLO-QCD, the dependence on quark mass definition will be considerably weaker.
- We employ kinetic b-quark mass as the calculated $B \to X_c e^+ \nu_e$ rate to LO is very close to the measured one.

Lifetimes of bottom mesons

Using the bag parameters obtained by Kirk, Lenz, Rauh as input

Dec | Ann | Int(-) | Semi | τ (10^{-12}s) | Expt (10^{-12}s)

	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma^{\rm int}$	$\Gamma^{\rm semi}$	$\Gamma^{\rm tot}$	$\tau(10^{-12}s)$	$\tau_{\rm expt}(10^{-12}s)$
B^+	3.102	0	−0.267	1.000	3.834	1.717	1.638 ± 0.004
B_d^0	3.102	0.040	0	1.000	4.142	1.589	1.520 ± 0.004
B_s^0	3.102	0.055	0	1.000	4.157	1.583	1.510 ± 0.005

$$\left.\frac{\tau(B^+)}{\tau(B_d^0)}\right|_{\rm theo} = 1.074^{+0.017}_{-0.016},$$

$$\left.\frac{\tau(B_s^0)}{\tau(B_d^0)}\right|_{\rm theo} = 0.9964 \pm 0.0024,$$

$$\left.\frac{\tau(B^+)}{\tau(B_d^0)}\right|_{\rm KLR} = 1.082^{+0.022}_{-0.026},$$

$$\left.\frac{\tau(B_s^0)}{\tau(B_d^0)}\right|_{\rm KLR} = 0.9994 \pm 0.0025$$

KLR = Kirk, Lenz, Rauch

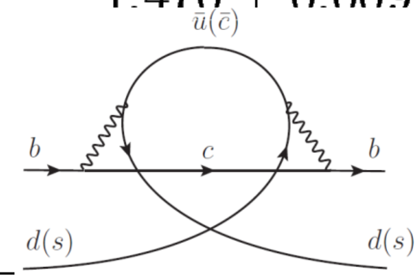
$$\left.\frac{\tau(B^+)}{\tau(B_d^0)}\right|_{\rm expt} = 1.076 \pm 0.004,$$

$$\left.\frac{\tau(B_s^0)}{\tau(B_d^0)}\right|_{\rm expt} = 0.994 \pm 0.004,$$

in excellent agreement with experiment!

Lifetimes of singly bottom baryons

	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma^{\rm int}$	$\Gamma^{\rm semi}$	$\Gamma^{\rm tot}$	$\tau(10^{-12}s)$	$\tau_{\rm expt}(10^{-12}s)$
Λ_b^0	3.108	0.219	−0.051	1.056	4.332	1.520	1.470 ± 0.009
Ξ_b^0	3.108	0.223	−0.082	1.056	4.305	1.529	
Ξ_b^-	3.108		−0.127	1.056	4.037	1.630	
Ω_b^-	3.105		−0.330	1.040	3.815	1.725	



HYC ('18)

Lifetime hierarchy $\tau(\Omega_b^-) > \tau(\Xi_b^-) > \tau(\Xi_b^0) \sim \tau(\Lambda_b^0)$

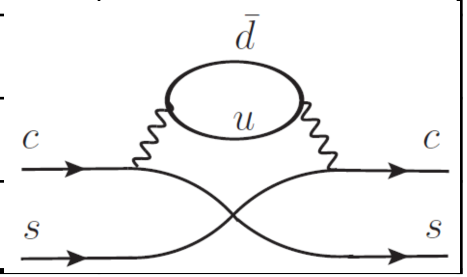
$$\frac{\tau(\Xi_b^-)}{\tau(\Lambda_b^0)}\bigg|_{\rm theo} = 1.073^{+0.009}_{-0.004}, \qquad \frac{\tau(\Xi_b^-)}{\tau(\Lambda_b^0)}\bigg|_{\rm expt} = 1.089 \pm 0.028$$

$$\frac{\tau(\Lambda_b^0)}{\tau(B_d^0)}\bigg|_{\rm theo} = 0.953^{+0.006}_{-0.008}, \qquad \frac{\tau(\Lambda_b^0)}{\tau(B_d^0)}\bigg|_{\rm expt} = 0.964 \pm 0.007$$

$$\frac{\tau(\Omega_b^-)}{\tau(\Xi_b^-)}\bigg|_{\rm theo} = 1.054^{+0.006}_{-0.002}, \qquad \frac{\tau(\Omega_b^-)}{\tau(\Xi_b^-)}\bigg|_{\rm expt} = 1.11 \pm 0.16,$$

Heavy quark expansion (HQE) in $1/m_b$ works very well for B mesons and bottom baryons!

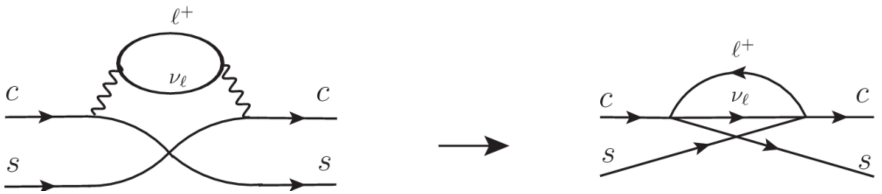
	Dec	Ann	Int (-)	Int (+)	Semi	τ (10^{-13}s)	Expt (10^{-13}s)
Ξ_c^+	1	s^2	1	c^2	small P.I.	3.06	4.42±0.26
Λ_c^+	1	c^2	1	s^2	no P.I.	2.91	
Ξ_c^0	1	1		c^2	small P.I.	1.62	
Ω_c^0	1	$6s^2$		10/3 c^2	large P.I.	1.06	



$s=\sin\theta_C$, $c=\cos\theta_C$

additional constructive P.I. contribution to Γ^{semi}

Voloshin ('96)



- **Lifetime hierarchy $\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$ according to PDG is understood qualitatively, but not quantitatively.**
- **It is difficult to explain $\tau(\Xi_c^+)/\tau(\Lambda_c^+) = 2.21\pm0.15$,**

  $\tau(\Xi_c^+)/\tau(\Xi_c^0) = 3.95\pm0.47$
- **$1/m_c$ expansion not well convergent and sensible**

$$\Gamma(B_c \to f) = \frac{G_F^2 m_c^5}{192\pi^3} V_{CKM} \left(A_0 + \frac{A_2}{m_c^2} + \frac{A_3}{m_c^3} + \frac{A_4}{m_c^4} \ldots\right)$$

A_4: dim-7 operators

Consider subleading 1/m_c corrections to spectator effects:

$$P_1^q = \frac{m_q}{m_Q} \bar{Q}(1-\gamma_5) q \bar{q}(1-\gamma_5) Q, \qquad P_2^q = \frac{m_q}{m_Q} \bar{Q}(1+\gamma_5) q \bar{q}(1+\gamma_5) Q,$$

$$P_3^q = \frac{1}{m_Q^2} \bar{Q} \overleftarrow{D}_\rho \gamma_\mu (1-\gamma_5) D^\rho q \bar{q} \gamma^\mu (1-\gamma_5) Q, \qquad P_4^q = \frac{1}{m_Q^2} \bar{Q} \overleftarrow{D}_\rho (1-\gamma_5) D^\rho q \bar{q} (1+\gamma_5) Q,$$

$$P_5^q = \frac{1}{m_Q} \bar{Q} \gamma_\mu (1-\gamma_5) q \bar{q} \gamma^\mu (1-\gamma_5) (i\not{D}) Q, \qquad P_6^q = \frac{1}{m_Q} \bar{Q} (1-\gamma_5) q \bar{q} (1+\gamma_5) (i\not{D}) Q,$$

Beneke, Buchalla, Dunietz ('96): width difference in B_s-$\underline{B}_s$ system
Gabbiani, Onishchenko, Petrov ('03,'04): lifetime difference of heavy hadrons
Lenz, Rauh ('13): D meson lifetimes

obtained by expanding forward scattering amplitude in light quark momentum and matching the result onto operators containing derivative insertions

Gabbiani, Onishchenko, Petrov ('03,'04)

Dim-7 4-quark operator is either 4-quark operator times m_q or 4-quark operator with an additional or two derivatives

■ to $1/m_c^3$

Charmed baryon lifetimes

	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma^{\rm int}_-$	$\Gamma^{\rm int}_+$	$\Gamma^{\rm semi}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}s)$	$\tau_{\rm expt}(10^{-13}s)$
Λ_c^+	0.886	1.449	−0.397	0.039	0.283	2.26	2.91	2.00 ± 0.06
Ξ_c^+	0.886	0.083	−0.427	0.839	0.771	2.153	3.06	4.42 ± 0.26
Ξ_c^0	0.886	1.559		0.839	0.771	4.055	1.62	$1.12^{+0.13}_{-0.10}$
Ω_c^0	1.019	0.505		2.830	1.881	6.235	1.06	0.69 ± 0.12

■ with $1/m_c$ corrections to spectator effects

	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma^{\rm int}_-$	$\Gamma^{\rm int}_+$	$\Gamma^{\rm semi}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}s)$	$\tau_{\rm expt}(10^{-13}s)$
Λ_c^+	0.886	2.179	−0.211	0.022	0.215	3.091	2.12	2.00 ± 0.06
Ξ_c^+	0.886	0.133	−0.186	0.407	0.437	1.677	3.92	4.42 ± 0.26
Ξ_c^0	0.886	2.501		0.405	0.435	4.228	1.56	$1.12^{+0.13}_{-0.10}$
Ω_c^0	1.019	0.876		−0.559	−0.256	1.079	6.10	0.69 ± 0.12

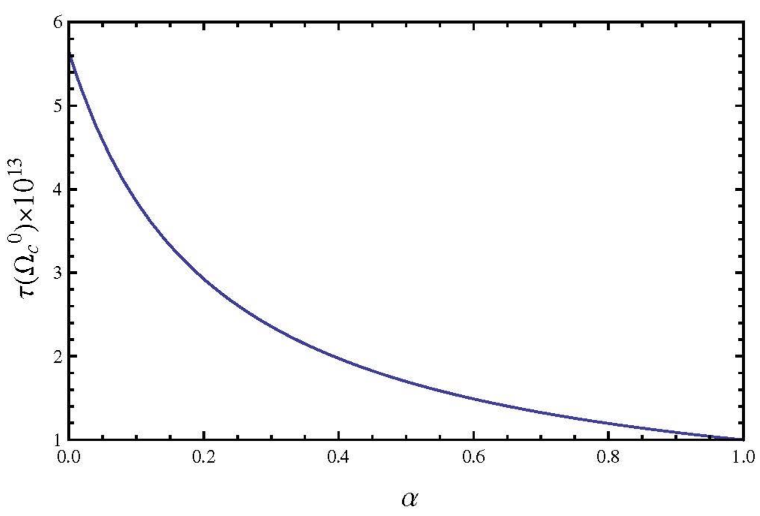
- $\Gamma(\Lambda_c^+)$ enhanced, $\Gamma(\Xi_c^+)$ suppressed
  $\Rightarrow \tau(\Xi_c^+)/\tau(\Lambda_c^+)$ is increased from 1.03 to 1.84

- Shortest-lived Ω_c becomes longest-lived one after $1/m_c$ corrections !!!

Ω_c^0	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma_-^{\rm int}$	$\Gamma_+^{\rm int}$	$\Gamma^{\rm semi}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}s)$
$1/m_c^3$	1.019	0.515		2.974	1.901	6.409	1.03
$1/m_c^4$	1.019	0.876		-0.559	-0.256	1.079	6.10

$\Gamma_+^{\rm int} = \Gamma_6^{\rm int} + \Gamma_7^{\rm int}$, $\Gamma^{\rm semi} = \Gamma_6^{\rm semi} + \Gamma_7^{\rm semi}$

Destructive contributions from $\Gamma_7^{\rm int}$ & $\Gamma_7^{\rm semi}$ are too large to justify the validity of HQE



Introduce a parameter α
$\Gamma_7^{\rm int} \to \Gamma_7^{\rm int}(1-\alpha)$, $\Gamma_7^{\rm semi} \to \Gamma_7^{\rm semi}(1-\alpha)$
to describe the degree of suppression for $\Gamma_7^{\rm int}$ & $\Gamma_7^{\rm semi}$

Guideline for α: positive $\Gamma_+^{\rm int}$ & $\Gamma^{\rm semi}$ with results close to that of Ξ_c

α	Γ^{dec}	Γ^{ann}	Γ^{int}_{+}	Γ^{semi}	Γ^{tot}	$\tau(10^{-13}s)$
0	1.019	0.876	−0.559	−0.256	1.079	6.10
0.12	1.019	0.876	−0.135	0.003	1.762	3.73
0.16	1.019	0.876	0.006	0.089	1.990	3.31
0.22	1.019	0.876	0.218	0.219	2.331	2.82
0.32	1.019	0.876	0.571	0.435	2.900	2.27
1	1.019	0.876	2.974	1.901	6.770	0.97

$$0.16 < \alpha < 0.32$$

We conjecture that

$$2.3\times 10^{-13}s < \tau(\Omega_c^0) < 3.3\times 10^{-13}s$$

$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$ **PDG2018**

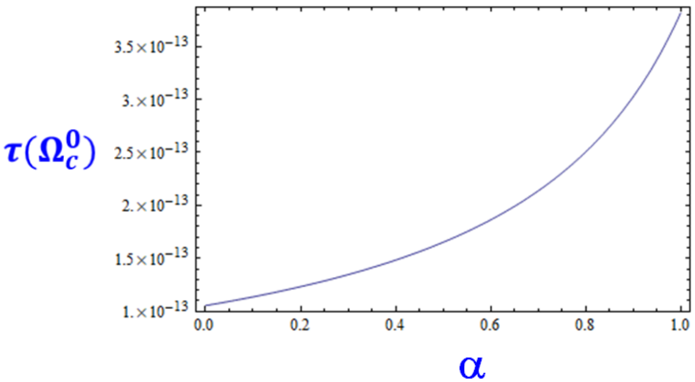
$\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$

Talk presented at HIEPA 2018 Workshop (March 19-21, 2018, Beijing)

$\tau(\Omega_c^0) = 2.31\times10^{-13}$s for $\alpha=0.25$

	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma_-^{\rm int}$	$\Gamma_+^{\rm int}$	$\Gamma_{\rm SL}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}s)$	$\tau_{\rm expt}(10^{-13}s)$
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

$\Gamma(\Xi_c^+)$ is suppressed, while $\Gamma(\Lambda_c^+)$ is enhanced, so that $\tau(\Xi_c^+)/\tau(\Lambda_c^+)$ becomes 1.63 . However, $\Gamma_+^{int}(\Omega_c^0)$ becomes negative and $\Gamma^{SL}(\Omega_c^0)$ too small. Introduce a parameter α to $\Gamma_{dim-7}^{int}(\Omega_c^0)$ & $\Gamma_{dim-7}^{SL}(\Omega_c^0)$.
In general, Ω_c^0 is no longer shortest-lived. For example, α = 0.75 leads to $\tau(\Omega_c^0) = 2.3\times10^{-13}$s and hence $\tau(\Omega_c^0) > \tau(\Lambda_c^+)$.



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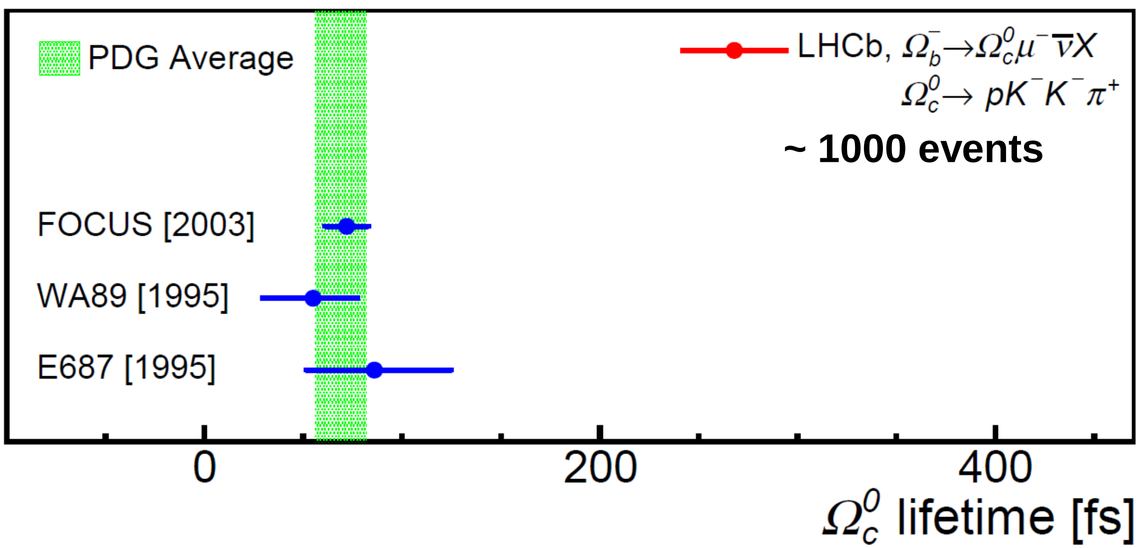
$\tau(\Omega_c^0) = (2.68 \pm 0.24 \pm 0.10 \pm 0.02) \times 10^{-13}$s, $\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+)$

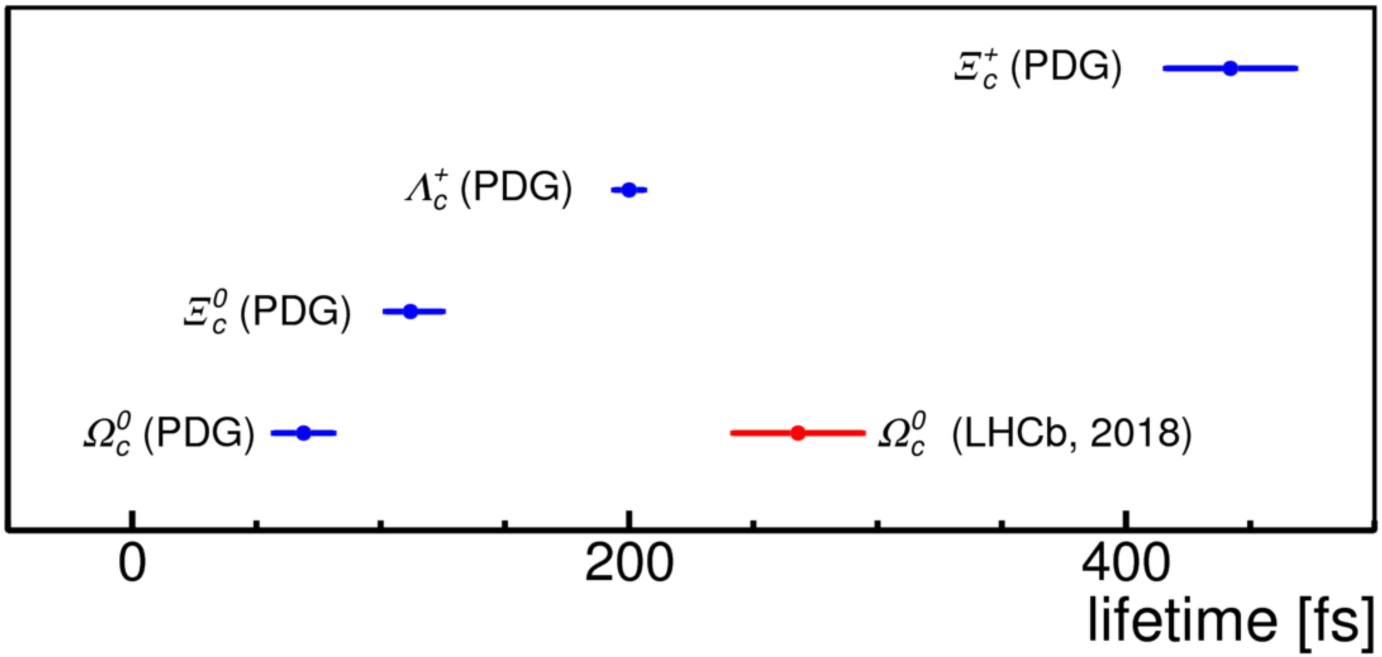
Four-times larger than the world average of $(0.69 \pm 0.12) \times 10^{-13}$s from fixed target experiments!

Ω_c^0 lifetime measurements

			events
FOCUS	$72 \pm 11 \pm 11$ fs	$\Xi^- K^- \pi^+ \pi^+$, $\Omega^- \pi^+$	64
E687	$86\,^{+27}_{-20} \pm 28$ fs	$\Sigma^+ K^- K^- \pi^+$	86
WA89	$55\,^{+13}_{-11}\,^{+18}_{-23}$ fs	$\Xi^- K^- \pi^+ \pi^+$, $\Omega^- \pi^+ \pi^+ \pi^-$	25



M. Fontana (INFN Cagliari and CERN) LHCP - Bologna 08-06-2018 15 / 13



$\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$

Charmed baryon lifetimes in HQE

$O(1/m_c^3)$ $\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$ PDG('18)

$O(1/m_c^4)$ $\tau(\Omega_c^0) > \tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$

$O(1/m_c^4)$ with α $\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$ LHCb('18)

Lifetimes of doubly charmed baryons

with Yan-Liang Shi

Lifetimes of doubly charmed baryons

$$\Xi_{cc}^{++} = (ccu),\ \Xi_{cc}^{+} = (ccd),\ \Omega_{cc}^{+} = (ccs)$$

in units of $\tau(10^{-13}\ s)$

	Kiselev et al ('98)	Kiselev et al ('99)	Guberina et al ('99)	Chang et al ('08)	Karliner, Rosner ('14)
Ξ_{cc}^{++}	4.3±1.1	4.6±0.5	15.5	6.7	1.85
Ξ_{cc}^{+}	1.1±0.3	1.6±0.5	2.2	2.5	0.53
Ω_{cc}^{+}		2.7±0.6	2.5	2.1	

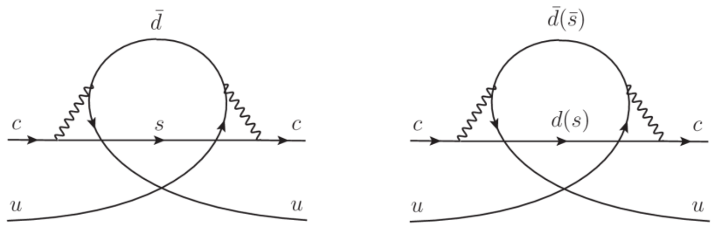
Large theoretical uncertainties

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

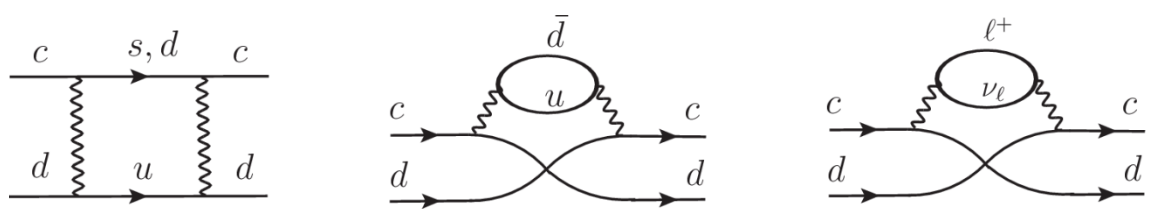
Lifetimes of doubly charmed baryons

	Dec	Ann	Int(-)	Int(+)	Semi	$\tau(10^{-13}\,s)$
Ξ_{cc}^{++}	1		1		1	1.9~15.5
Ξ_{cc}^{+}	1	1		s^2	$1 + s^2$ P.I.	0.5~ 2.5
Ω_{cc}^{+}	1	s^2		1	$1 + c^2$ P.I.	2.1~ 2.8

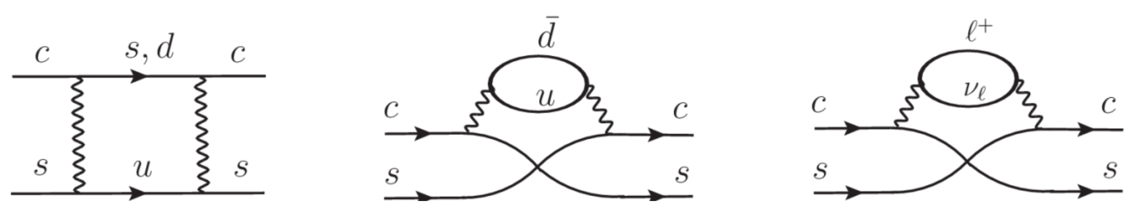
Ξ_{cc}^{++}



Ξ_{cc}^{+}



Ω_{cc}^{+}



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

- to $1/m_c^3$

	Γ^{dec}	Γ^{ann}	Γ^{int}_{-}	Γ^{int}_{+}	Γ^{semi}	Γ^{tot}	$\tau(10^{-13}s)$	$\tau_{expt}(10^{-13}s)$
Ξ_{cc}^{++}	2.198		−1.383		0.450	1.265	5.20	$2.56^{+0.28}_{-0.26}$
Ξ_{cc}^{+}	2.198	8.628		0.123	0.525	11.475	0.57	
Ω_{cc}^{+}	2.148	0.611		3.217	2.445	8.421	0.78	

$$\Gamma^{ann} \gg \Gamma^{int}_{+} \quad \Rightarrow \tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) > \tau(\Xi_{cc}^{+})$$

$$\Gamma^{semi}(\Omega_{cc}^{+}) \gg \Gamma^{semi}(\Xi_{cc}^{+}) > \Gamma^{semi}(\Xi_{cc}^{++})$$

- **After including $1/m_c$ corrections to spectator effects**

	Γ^{dec}	Γ^{ann}	Γ^{int}_{-}	Γ^{int}_{+}	Γ^{semi}	Γ^{tot}	$\tau(10^{-13}s)$	$\tau_{expt}(10^{-13}s)$
Ξ_{cc}^{++}	2.198		−0.437		0.451	2.212	2.98	$2.56^{+0.28}_{-0.26}$
Ξ_{cc}^{+}	2.198	12.260		0.030	0.469	14.958	0.44	
Ω_{cc}^{+}	2.148	0.979		−0.246	0.318	3.200	2.06	

- **$\tau(\Xi_{cc}^{++})$ becomes shorter, while $\tau(\Omega_{cc}^{+})$ becomes longer**
- **The use of HQE for Γ^{int}_{+} & Γ^{semi} for Ω_{cc} is not valid**

Needs to suppress Γ_7^{int} & Γ_7^{semi} to make the use of HQE sensible!

α	Γ^{dec}	Γ^{ann}	Γ_+^{int}	Γ^{semi}	Γ^{tot}	$\tau(10^{-13}s)$
0	2.148	0.979	−0.246	0.318	3.200	2.06
0.08	2.148	0.979	0.031	0.489	3.647	1.80
0.30	2.148	0.979	0.792	0.956	4.876	1.35
1	2.148	0.979	3.217	2.445	8.789	0.75

$$\Rightarrow \quad 0.75\times10^{-13}s < \tau(\Omega_{cc}^+) < 1.80\times10^{-13}s$$

$\tau(\Xi_{cc}^{++}) \sim 3.0\times10^{-13}$s, $\tau(\Xi_{cc}^{+}) \sim 0.45\times10^{-13}$s

$\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) > \tau(\Xi_{cc}^{+})$

LHCb: $\tau(\Xi_{cc}^{++}) = (2.56^{+0.24}_{-0.22}\pm0.14)\times10^{-13}$ s 1806.02744

$$\frac{\tau(\Xi_{cc}^{++})}{\tau(\Xi_{cc}^{+})} \sim 6.7$$

$\tau(10^{-13}s)$

	Ξ_{cc}^{++}	Ξ_{cc}^{+}	Ω_{cc}^{+}
Kiselev et al ('98)	4.3 ± 1.1	1.1 ± 0.3	
Kiselev et al ('99)	4.6 ± 0.5	1.6 ± 0.5	2.7 ± 0.6
Guberina et al ('99)	15.5	2.2	2.5
Chang et al ('08)	6.7	2.5	2.1
Karliner, Rosner ('14)	1.85	0.53	
Cheng, Shi ('18)	2.98	0.44	0.75 ~1.80
Berezhnoy et al ('18)*	2.6 ± 0.3	1.4 ± 0.1	1.8 ± 0.2
Expt	$2.56^{+0.28}_{-0.26}$		

***Based on the calculation of using $m_c=1.73\pm0.07$ GeV, $m_s=0.35\pm0.20$ GeV from a fit to the data of $\tau(\Xi_{cc}^{++})$.**

Lifetimes of doubly heavy baryons

$\tau(10^{-13}s)$ **1903.08148**

	Ξ_{bb}^0	Ξ_{bb}^-	Ω_{bb}^-
Likhoded et al ('99)	7.9	8.0	8.0
Kiselev et al ('02)	7.9	8.0	8.0
Karliner, Rosner ('14)	3.7	3.7	
Berezhnoy et al ('18)	5.2±0.095	5.3±0.096	5.3±0.093
Cheng, Xu ('19)	6.87	8.65	8.68

	Ξ_{bc}^+	Ξ_{bc}^0	Ω_{bc}^0
Kiselev et al ('00)	3.3±0.8	2.8±0.7	
Likhoded et al ('99)	2.8	2.6	2.7±0.6
Kiselev et al ('02)	3.0±0.4	2.7±0.3	2.2±0.4
Karliner, Rosner ('14)	2.44	0.93	
Berezhnoy et al ('18)*	2.4±0.2	2.2±0.18	1.8±0.088
Cheng, Xu ('19)	4.09 ~ 6.07	0.93 ~ 1.18	1.68 ~ 3.70

Conclusions

- **HQE in $1/m_b$ works well for the lifetimes of B mesons and bottom baryons.**

- **HQE in $1/m_c$ fails to provide a satisfactory description of the lifetimes of D mesons & charmed baryons to $O(1/m_c^3)$. Need to consider subleading $1/m_c$ corrections to spectator effects.**

- **Dim-7 operators are in the right direction to enhance $\Gamma(\Lambda_c^+)$ & suppress $\Gamma(\Xi_c^+)$, but they will render the lifetime of Ω_c^0 longer than Λ_c^0**

- **For doubly charmed baryons, we found $\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) > \tau(\Xi_{cc}^{+})$ with $\tau(\Xi_{cc}^{++}) \sim 0.30$ ps, $\tau(\Xi_{cc}^{+}) \sim 0.05$ ps,**

Dim-3 and -5 operators

$$\frac{\langle \Xi_{cc}|\bar{c}c|\Xi_{cc}\rangle}{2m_{\Xi_{cc}}} = 1 - \frac{\mu_\pi^2}{2m_c^2} + \frac{\mu_G^2}{2m_c^2}$$

$$\mu_\pi^2 \equiv \frac{1}{2m_{\Xi_{cc}}}\langle \Xi_{cc}|\bar{c}(i\vec{D})^2 c|\Xi_{cc}\rangle = -\frac{1}{2m_{\Xi_{cc}}}\langle \Xi_{cc}|\bar{c}(iD_\perp)^2 c|\Xi_{cc}\rangle$$

$$\mu_G^2 \equiv \frac{1}{2m_{\Xi_{cc}}}\langle \Xi_{cc}|\bar{c}\frac{1}{2}\sigma\cdot G c|\Xi_{cc}\rangle$$

$\boldsymbol{\sigma\cdot G \propto \vec{S}_c\cdot\vec{S}_q}$ **for singly heavy baryon**

$\boldsymbol{\propto \vec{S}_d\cdot\vec{S}_q,\ \vec{S}_1\cdot\vec{S}_2}$ **for doubly heavy baryon**

$\boldsymbol{\vec{S}_d = \vec{S}_1 + \vec{S}_2}$: **spin of the diquark**

$$\mu_G^2(\Xi_{cc}) = \frac{2}{3}(m_{\Xi_{cc}^*} - m_{\Xi_{cc}})m_c - \frac{4}{9}\pi\alpha_s\frac{|\psi^{cc}(0)|^2}{m_c}$$

HQET is not the appropriate EFT for hadrons with more than one heavy quark as T_Q is important and cannot be treated as a small perturbation $\Rightarrow$ HQET replaced by NRQCD (or pNRQCD)

$$\bar{Q} g_s \sigma \cdot G Q = -2\psi_Q^\dagger g_s \vec{\sigma} \cdot \vec{B} \psi_Q - \frac{1}{m_Q} \psi_Q^\dagger g_s \vec{D} \cdot \vec{E} \psi_Q + \cdots$$

Darwin term is of same order as chromomagetic field

$$\mu_G^2 = \frac{2}{3}(m_{\Xi_{cc}^*} - m_{\Xi_{cc}}) m_c - \frac{1}{9} g_s^2 \frac{|\psi^{cc}(0)|^2}{m_c} - \frac{1}{6} g_s^2 \frac{|\psi^{cc}(0)|^2}{m_c}$$

while Kiselev, Likhoded, Onischenko ('98) obtained

$$\mu_G^2 = -\frac{2}{3}(m_{\Xi_{cc}^*} - m_{\Xi_{cc}}) m_c - \frac{2}{9} g_s^2 \frac{|\psi^{cc}(0)|^2}{m_c} - \frac{1}{3} g_s^2 \frac{|\psi^{cc}(0)|^2}{m_c}$$