

Lifetimes of singly & doubly charmed baryons

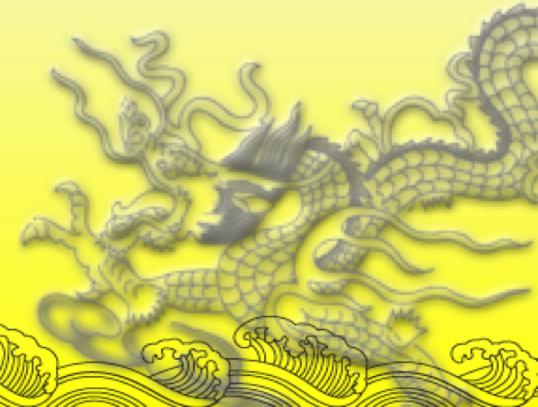
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PDG (2018)

	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

	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^-	$1.64^{+0.18}_{-0.17}$

due mainly to FOCUS

New measurement of Ω_c^0 lifetime by LHCb

1807.02024

New precision measurement of Λ_c^+ , Ξ_c^+ , Ξ_c^0 lifetimes by LHCb

1906.08350

	PDG(2018)	LHCb	Average	(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			

Recall that $\tau(\Lambda_b^0) \approx (1.14 \pm 0.08) \text{ ps}$ before 2000, and
 $\tau(\Lambda_b^0) \approx (1.470 \pm 0.010) \text{ ps}$ nowadays

$$\frac{\tau(\Lambda_b^0)}{\tau(B^0)} = 0.79 \pm 0.06 \text{ ('96)},$$

$$\frac{\tau(\Lambda_b^0)}{\tau(B^0)} = 0.964 \pm 0.007 \text{ ('19)}$$

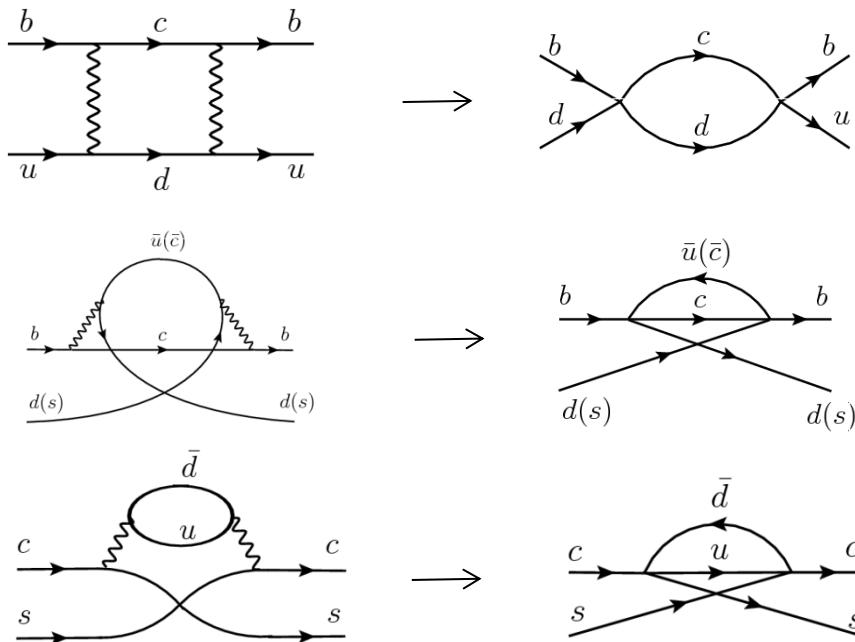
Lifetimes of heavy baryons

Heavy quark expansion:

$$\begin{aligned}\Gamma(H_Q \rightarrow f) &= \frac{G_F^2 m_Q^5}{192\pi^3} V_{CKM} \left(A_0 + \frac{A_2}{m_Q^2} + \frac{A_3}{m_Q^3} + \dots \right) \\ &= \frac{G_F^2 m_Q^5}{192\pi^3} \left(c_{3,Q} \frac{\langle H_Q | \bar{Q}Q | H_Q \rangle}{2m_{H_Q}} + \frac{c_{5,Q}}{m_Q^2} \frac{\langle H_Q | \bar{Q} \sigma.GQ | H_Q \rangle}{2m_{H_Q}} + \frac{c_{6,Q}}{m_Q^3} \frac{\langle H_Q | T_6 | H_Q \rangle}{2m_{H_Q}} + \dots \right)\end{aligned}$$

- **A_0 term from the decay of heavy quark Q**
⇒ Lifetimes of all heavy hadrons H_Q are the same in $m_Q \rightarrow \infty$ 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

$$\begin{aligned}\mathcal{T}_{6,ann}^{\mathcal{B}_Q,q_1} &= \frac{G_F^2 m_Q^2}{2\pi} \xi (1-x)^2 \left\{ (c_1^2 + c_2^2)(\bar{Q}Q)(\bar{q}_1 q_1) + 2c_1 c_2 (\bar{Q}q_1)(\bar{q}_1 Q) \right\} \\ \mathcal{T}_{6,int+}^{\mathcal{B}_Q,q_3} &= -\frac{G_F^2 m_Q^2}{6\pi} \xi \left\{ c_2^2 \left[(\bar{Q}Q)(\bar{q}_3 q_3) - \bar{Q}^\alpha (1-\gamma_5) q_3^\beta \bar{q}_3^\beta (1+\gamma_5) Q^\alpha \right] \right. \\ &\quad \left. + (2c_1 c_2 + N_c c_1^2) \left[(\bar{Q}q_3)(\bar{q}_3 Q) - \bar{Q}(1-\gamma_5) q_3 \bar{q}_3 (1+\gamma_5) Q \right] \right\}, \\ (\bar{q}_1 q_2) &\equiv \bar{q}_1 \gamma_\mu (1-\gamma_5) q_2\end{aligned}$$

How to evaluate hadronic matrix elements?

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

$$\begin{aligned}\langle B_q | (\bar{b}q)(\bar{q}b) | B_q \rangle &= f_{B_q}^2 m_{B_q}^2 B_1, & \langle B_q | (\bar{b}q) | 0 \rangle &= i f_{B_q} m_{B_q} \\ \langle B_q | \bar{b}(1-\gamma_5)q\bar{q}(1+\gamma_5)b | B_q \rangle &= f_{B_q}^2 m_{B_q}^2 B_2, \\ \langle B_q | (\bar{b}t^a q)(\bar{q}t^a b) | B_q \rangle &= f_{B_q}^2 m_{B_q}^2 \varepsilon_1, \\ \langle B_q | b t^a (1-\gamma_5)q\bar{q} t^a (1+\gamma_5)b | B_q \rangle &= f_{B_q}^2 m_{B_q}^2 \varepsilon_2\end{aligned}$$

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

$$\langle \mathcal{B}_b | (\bar{b}q)(\bar{q}b) | \mathcal{B}_b \rangle = f_{B_q}^2 m_{B_q} m_{\mathcal{B}_b} L_1,$$

$$\langle \mathcal{B}_b | \bar{b}(1 - \gamma_5)q\bar{q}(1 + \gamma_5)b | \mathcal{B}_b \rangle = f_{B_q}^2 m_{B_q} m_{\mathcal{B}_b} L_2,$$

$$\langle \mathcal{B}_b | (\bar{b}b)(\bar{q}q) | \mathcal{B}_b \rangle = f_{B_q}^2 m_{B_q} m_{\mathcal{B}_b} L_3,$$

$$\langle \mathcal{B}_b | \bar{b}^\alpha(1 - \gamma_5)q^\beta\bar{q}^\beta(1 + \gamma_5)b^\alpha | \mathcal{B}_b \rangle = f_{B_q}^2 m_{B_q} m_{\mathcal{B}_b} L_4.$$

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

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

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

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

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

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

$\tilde{B}=1$ 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: $m_b^{1S} = 4.691 \pm 0.037 \text{ GeV}$, $m_b^{pole} \sim 4.65 \text{ GeV}$,
 $m_b^{kin} = 4.554 \pm 0.018 \text{ GeV}$, $\bar{m}_b(\bar{m}_b) = 4.19 \pm 0.04 \text{ GeV}$
- To NLO-QCD, the dependence on quark mass definition will be considerably weaker.
- We employ kinetic b-quark mass as the calculated $B \rightarrow X_c e^+ \nu_e$ 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	$\tau(10^{-12}s)$	Expt ($10^{-12}s$)
	Γ^{dec}	Γ^{ann}	Γ^{int}	Γ^{semi}	Γ^{tot}	$\tau(10^{-12}s)$
B^+	3.102	0	-0.267	1.000	3.834	1.717
B_d^0	3.102	0.040	0	1.000	4.142	1.589
B_s^0	3.102	0.055	0	1.000	4.157	1.583

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

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

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

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

KLR = Kirk, Lenz, Rauch

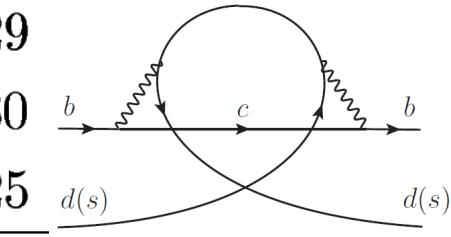
$$\left. \frac{\tau(B^+)}{\tau(B_d^0)} \right|_{\text{expt}} = 1.076 \pm 0.004,$$

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

in excellent agreement with experiment!

Lifetimes of singly bottom baryons

	Γ^{dec}	Γ^{ann}	Γ^{int}	Γ^{semi}	Γ^{tot}	$\tau(10^{-12} s)$	$\tau_{\text{expt}}(10^{-12} s)$
Λ_b^0	3.108	0.219	-0.051	1.056	4.332	1.520	$1.470 + 0.009$ $\bar{u}(\bar{c})$
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 $\tau(\Omega_b^-) > \tau(\Xi_b^-) > \tau(\Xi_b^0) \sim \tau(\Lambda_b^0)$

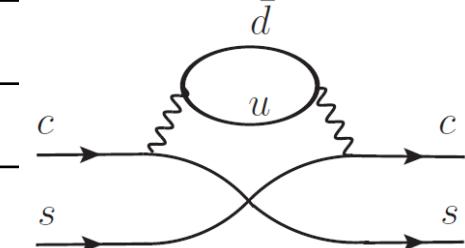
$$\frac{\tau(\Xi_b^-)}{\tau(\Lambda_b^0)} \Big|_{\text{theo}} = 1.073^{+0.009}_{-0.004}, \quad \frac{\tau(\Xi_b^-)}{\tau(\Lambda_b^0)} \Big|_{\text{expt}} = 1.089 \pm 0.028.$$

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

$$\frac{\tau(\Xi_b^-)}{\tau(\Xi_b^0)} \Big|_{\text{theo}} = 1.054^{+0.006}_{-0.002}, \quad \frac{\tau(\Xi_b^-)}{\tau(\Xi_b^0)} \Big|_{\text{expt}} = 1.11 \pm 0.16,$$

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

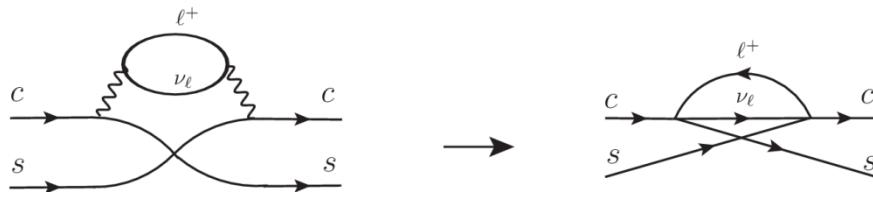
	Dec	Ann	Int (-)	Int (+)	Semi	τ ($10^{-13}s$)	Expt ($10^{-13}s$)
Ξ_c^+	1	s^2	1	c^2	small P.I.	3.06	4.42 ± 0.26
Λ_c^+	1	c^2	1	s^2	no P.I.	2.91	
Ξ_c^0	1	1		c^2	small P.I.	1.62	
Ω_c^0	1	$6s^2$		$10/3 c^2$	large P.I.	1.06	



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

**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 $\tau(\Xi_c^+)/\tau(\Lambda_c^+) = 2.21 \pm 0.15$,
- $\tau(\Xi_c^+)/\tau(\Xi_c^0) = 3.95 \pm 0.47$
- $1/m_c$ expansion not well convergent and sensible

$$\Gamma(B_c \rightarrow f) = \frac{G_F^2 m_c^5}{192\pi^3} V_{CKM} (A_0 + \frac{A_2}{m_c^2} + \frac{A_3}{m_c^3} + \frac{A_4}{m_c^4} \dots) \quad A_4: \text{dim-7 operators}$$

Consider subleading $1/m_c$ corrections to spectator effects:

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

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

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

$$P_4^q = \frac{1}{m_Q^2} \bar{Q} \stackrel{\leftarrow}{D}_\rho (1 - \gamma_5) D^\rho q \bar{q} (1 + \gamma_5) Q.$$

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

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

Beneke, Buchalla, Dunietz ('96): width difference in B_s - \bar{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

	Γ^{dec}	Γ^{ann}	Γ_-^{int}	Γ_+^{int}	Γ^{semi}	Γ^{tot}	$\tau(10^{-13} s)$	$\tau_{\text{expt}}(10^{-13} s)$
Λ_c^+	0.886	1.479	-0.400	0.042	0.215	2.221	2.96	2.00 ± 0.06
Ξ_c^+	0.886	0.085	-0.431	0.882	0.726	2.148	3.06	4.42 ± 0.26
Ξ_c^0	0.886	1.591		0.882	0.726	4.084	1.61	$1.12^{+0.13}_{-0.10}$
Ω_c^0	1.019	0.515		2.974	1.901	6.409	1.03	0.69 ± 0.12

■ with $1/m_c$ corrections to spectator effects

	Γ^{dec}	Γ^{ann}	Γ_-^{int}	Γ_+^{int}	Γ^{semi}	Γ^{tot}	$\tau(10^{-13} s)$	$\tau_{\text{expt}}(10^{-13} s)$
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

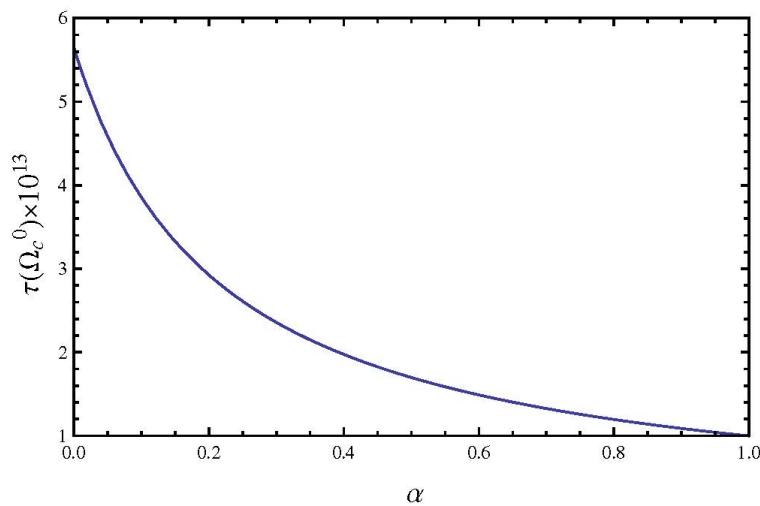
- Shortest-lived Ω_c^0 becomes longest-lived one after $1/m_c$ corrections !!!

Ω_c^0	Γ^{dec}	Γ^{ann}	Γ_{-}^{int}	Γ_{+}^{int}	Γ^{semi}	Γ^{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

$$\Gamma_{+}^{\text{int}} = \Gamma_6^{\text{int}} + \Gamma_7^{\text{int}},$$

$$\Gamma^{\text{semi}} = \Gamma_6^{\text{semi}} + \Gamma_7^{\text{semi}}$$

Destructive contributions from Γ_7^{int} & Γ_7^{semi} are too large to justify the validity of HQE



Introduce a parameter α
 $\Gamma_7^{\text{int}} \rightarrow \Gamma_7^{\text{int}}(1-\alpha)$, $\Gamma_7^{\text{semi}} \rightarrow \Gamma_7^{\text{semi}}(1-\alpha)$
to describe the degree of suppression for Γ_7^{int} & Γ_7^{semi}

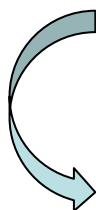
Guideline for α : positive Γ_{+}^{int} &
 Γ^{semi} with results close to that of Ξ_c

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

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



$$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0) \quad \text{PDG2018}$$

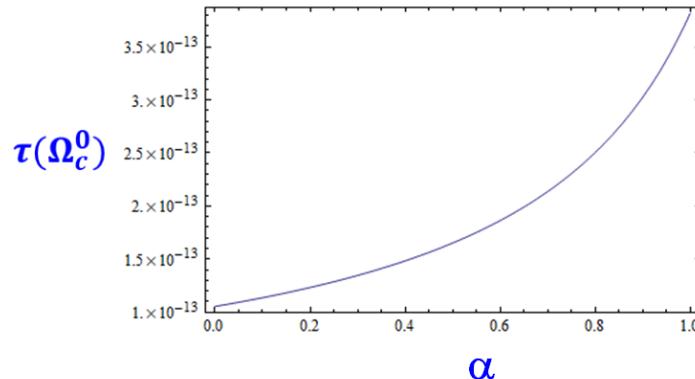
$$\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$$

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

$$\tau(\Omega_c^0) = 2.31 \times 10^{-13} \text{ s} \quad \text{for } \alpha=0.25$$

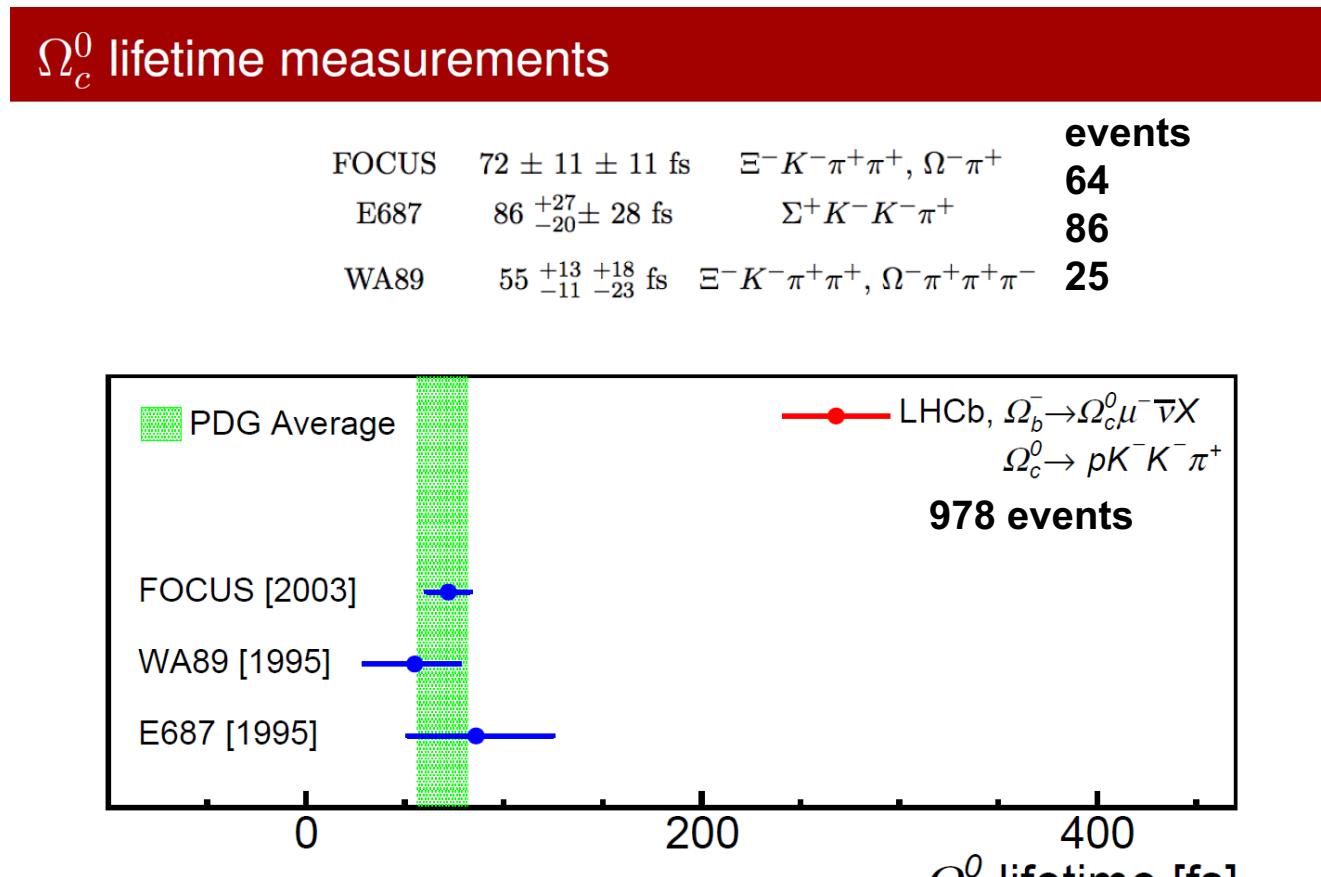
	Γ^{dec}	Γ^{ann}	Γ^{int}_{-}	Γ^{int}_{+}	Γ_{SL}	Γ^{tot}	$\tau(10^{-13} \text{ s})$	$\tau_{\text{expt}}(10^{-13} \text{ s})$
Λ_c^+	1.012	1.883	-0.209	0.021	0.308	3.015	2.18	2.00 ± 0.06
Ξ_c^+	1.012	0.115	-0.189	0.353	0.524	1.854	3.55	4.42 ± 0.26
Ξ_c^0	1.012	2.160		0.351	0.524	4.083	1.61	$1.12^{+0.13}_{-0.10}$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

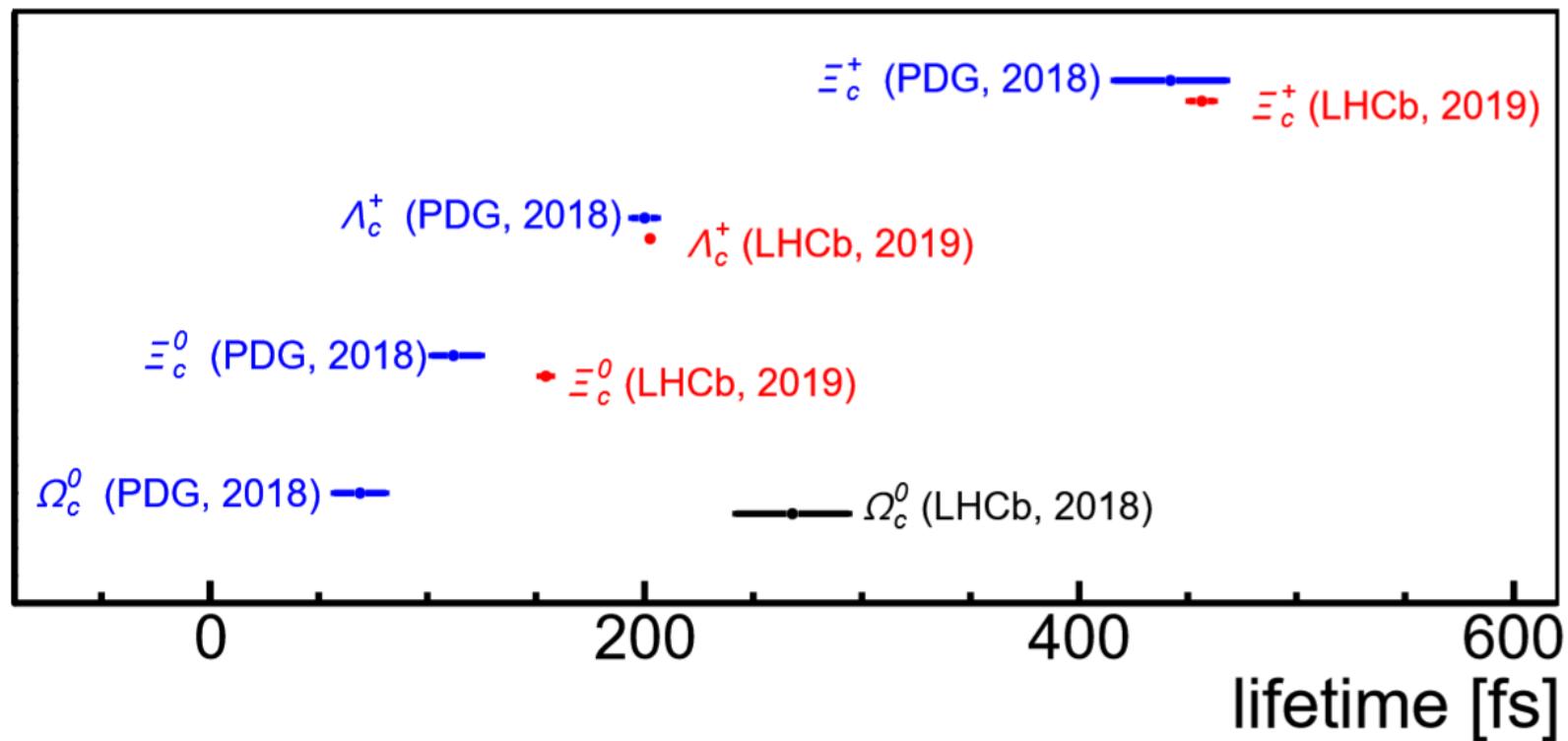
$\Gamma(\Xi_c^+)$ is suppressed, while $\Gamma(\Lambda_c^+)$ is enhanced, so that $\tau(\Xi_c^+)/\tau(\Lambda_c^+)$ becomes 1.63. However, $\Gamma_+^{\text{int}}(\Omega_c^0)$ becomes negative and $\Gamma_{\text{SL}}^{\text{SL}}(\Omega_c^0)$ too small. Introduce a parameter α to $\Gamma_{\text{dim}-7}^{\text{int}}(\Omega_c^0)$ & $\Gamma_{\text{dim}-7}^{\text{SL}}(\Omega_c^0)$. In general, Ω_c^0 is no longer shortest-lived. For example, $\alpha = 0.75$ leads to $\tau(\Omega_c^0) = 2.3 \times 10^{-13} \text{ s}$ and hence $\tau(\Omega_c^0) > \tau(\Lambda_c^+)$.



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

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





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

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)

$O(1/m_c^4)$

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

HQE is not applicable to Ω_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)

	PDG(2018)	LHCb	Theory($1/m_c^3$)	Theory($1/m_c^4$)
Ξ_c^+	4.42±0.26	4.568±0.055	2.91	3.92
Λ_c^+	2.00±0.06	2.035±0.022	3.06	2.12
Ξ_c^0	1.12^{+0.13}_{-0.10}	1.545±0.025	1.62	1.56
Ω_c^0	0.69±0.12	2.68±0.26	1.06	2.3 ~ 3.3

$1/m_c^3$

	Γ^{dec}	Γ^{ann}	Γ_-^{int}	Γ_+^{int}	Γ^{semi}	Γ^{tot}	$\tau(10^{-13} s)$	$\tau_{\text{expt}}(10^{-13} s)$
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

$1/m_c^4$ with α

	Γ^{dec}	Γ^{ann}	Γ_-^{int}	Γ_+^{int}	Γ^{semi}	Γ^{tot}	$\tau(10^{-13} s)$	$\tau_{\text{expt}}(10^{-13} s)$
Λ_c^+	0.886	2.179	-0.211	0.022	0.215	3.091	2.12	2.03 ± 0.02
Ξ_c^+	0.886	0.133	-0.186	0.407	0.437	1.677	3.92	4.56 ± 0.05
Ξ_c^0	0.886	2.501		0.405	0.435	4.228	1.56	1.53 ± 0.02
Ω_c^0	1.019	0.876		0.394	0.326	2.616	2.52	2.68 ± 0.26

Lifetimes of doubly charmed baryons

with Yan-Liang Shi

Lifetimes of doubly charmed baryons

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

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

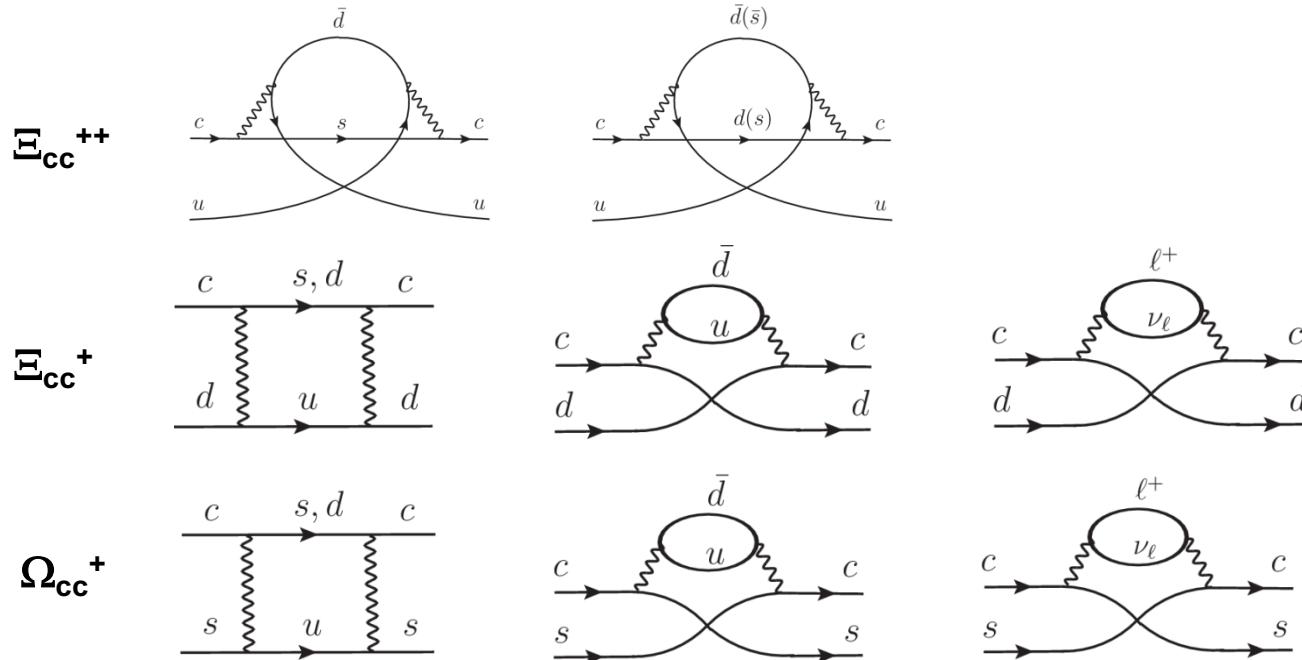
	Kiselev et al ('98)	Kiselev et al ('99)	Guberina et al ('99)	Chang et al ('08)	Karliner, Rosner ('14)
Ξ_{cc}^{++}	4.3 ± 1.1	4.6 ± 0.5	15.5	6.7	1.85
Ξ_{cc}^+	1.1 ± 0.3	1.6 ± 0.5	2.2	2.5	0.53
Ω_{cc}^+		2.7 ± 0.6	2.5	2.1	

Large theoretical uncertainties

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

Lifetimes of doubly charmed baryons

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



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

Dim-3 and -5 operators

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

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

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

$\sigma \cdot G \propto \vec{S}_c \cdot \vec{S}_q$ **for singly heavy baryon**
 $\propto \vec{S}_d \cdot \vec{S}_q, \vec{S}_1 \cdot \vec{S}_2$ **for doubly heavy baryon**

$\vec{S}_d = \vec{S}_1 + \vec{S}_2$: **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)

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

Darwin term is of same order as chromomagnetic 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

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

■ to $1/m_c^3$

	Γ^{dec}	Γ^{ann}	Γ^{int}_-	Γ^{int}_+	Γ^{semi}	Γ^{tot}	$\tau(10^{-13}s)$	$\tau_{\text{expt}}(10^{-13}s)$
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	

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

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

■ After including $1/m_c$ corrections to spectator effects

	Γ^{dec}	Γ^{ann}	Γ^{int}_-	Γ^{int}_+	Γ^{semi}	Γ^{tot}	$\tau(10^{-13}s)$	$\tau_{\text{expt}}(10^{-13}s)$
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

$$\Rightarrow \quad 0.75 \times 10^{-13} s < \tau(\Omega_{cc}^+) < 1.80 \times 10^{-13} s$$

$$\tau(\Xi_{cc}^{++}) \sim 3.0 \times 10^{-13} s, \quad \tau(\Xi_{cc}^+) \sim 0.45 \times 10^{-13} s$$

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

$$\text{LHCb: } \tau(\Xi_{cc}^{++}) = (2.56^{+0.24}_{-0.22} \pm 0.14) \times 10^{-13} s$$

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

	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	$0.75 \sim 1.80$
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 $m_c=1.73 \pm 0.07$ GeV,
 $m_s=0.35 \pm 0.20$ GeV from a fit to the data of $\tau(\Xi_{cc}^{++})$.

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

Lifetimes of doubly heavy baryons

with Fanrong Xu

Lifetimes of doubly heavy baryons $\tau(10^{-13}s)$

	Ξ_{bb}^0	Ξ_{bb}^-	Ω_{bb}^-
Likhoded et al ('99)			8.0
Kiselev et al ('02)			8.0
Karliner, Rosner ('14)			
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

$$\tau(\Omega_{bb}^-) \sim \tau(\Xi_{bb}^-) > \tau(\Xi_{bb}^0)$$

	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)	$4.09 \sim 6.07$	$0.93 \sim 1.18$	$1.68 \sim 3.70$

$$\tau(\Xi_{bc}^+) > \tau(\Omega_{bc}^0) > \tau(\Xi_{bc}^0)$$

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 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,

Outlook

1. What is the origin of the parameter α ? Any control on α ?
2. NLO corrections Alex Lenz, D. Wang,...
 B. Melic, O. Antipin, ...
3. Improve $\tau(\Xi_c^+)$
4. $1/m_c$ expansion to next order?
5. Confirmation of $\tau(\Xi_c^+)$ from other experiments

Steven Blusk: This should really get people thinking about how to make the theory more precise.

Alex Lenz: The lifetime of Ω_c^0 falls squarely inside the Standard Model. And it will probably take a few years of work to more precisely calculate higher order terms. But it is doable.