Lifetimes of heavy baryons

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- Up-to-date predictions for the lifetimes of weakly decaying heavy baryons in Heavy Quark Expansion (HQE) framework

- Baryons names and their quark contents:

Single charm		Single bottom		Double charm	
Λ_c^+	(cud)	Λ_b^0	(bud)	Ξ_{cc}^{++}	(ccu)
Ξ_c^+	(cus)	Ξ_b^0	(bus)	Ξ_{cc}^+	(ccd)
Ξ_c^0	(cds)	Ξ_b^-	(bds)	Ω_{cc}^0	(ccs)
$\cdots\cdots$		$\cdots\cdots$			
Ω_c^0	(css)	Ω_b^-	(bss)		

Based on:

Charm mesons and single charm baryons:

[2204.11935] with J. Gratrex and B. Melić

Bottom baryons:

[2301.07698] with J. Gratrex, A. Lenz, B. Melić, M. L. Piscopo and A. V. Rusov

Double charm baryons:

[In preparation] with L. Dulibić, J. Gratrex and B. Melić

Related analyses for heavy mesons can be found in:

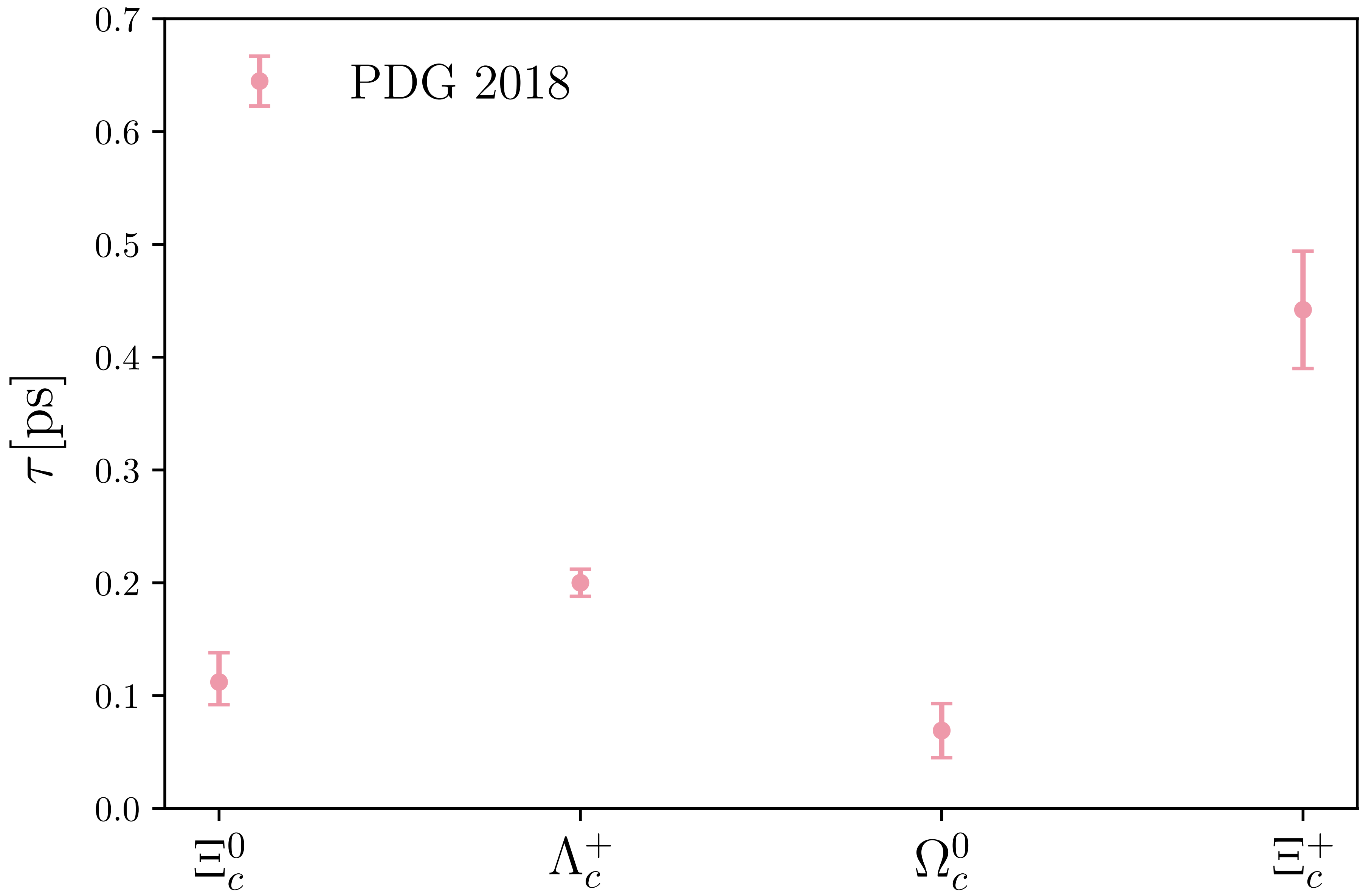
[2109.13219] by D. King, A. Lenz, M.L. Piscopo, Th. Rauh, A.V.Rusov, C. Vlahos
[2208.02643] by A. Lenz, M.L. Piscopo, A.V. Rusov

Our analyses involve:

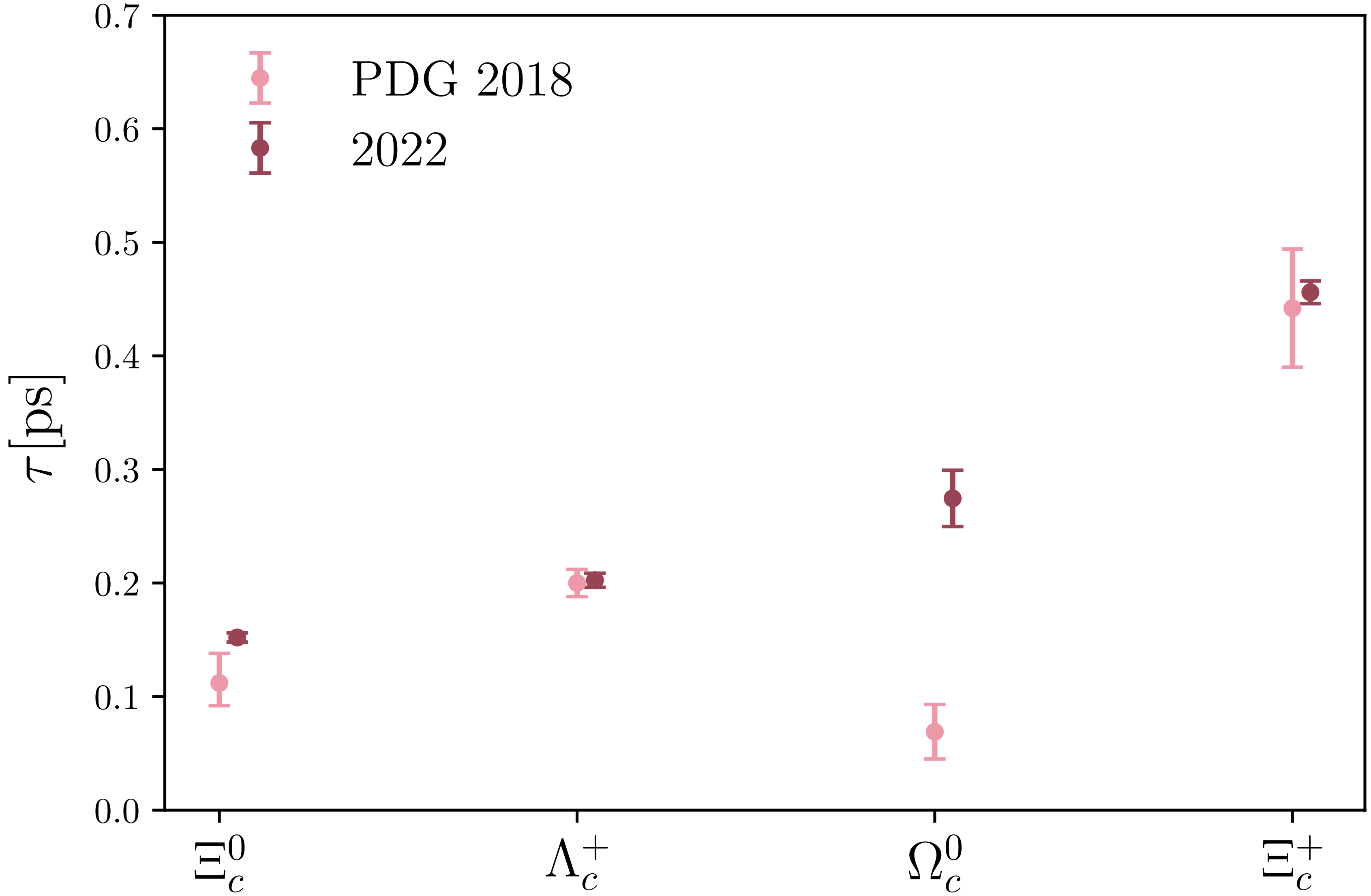
- Implementing new Wilson coefficient for the Darwin operator
- Including radiative QCD corrections to the Wilson coefficients, where available
- Updating numerical inputs, including new estimates of non-perturbative matrix elements

Experimental status

c-baryon lifetimes

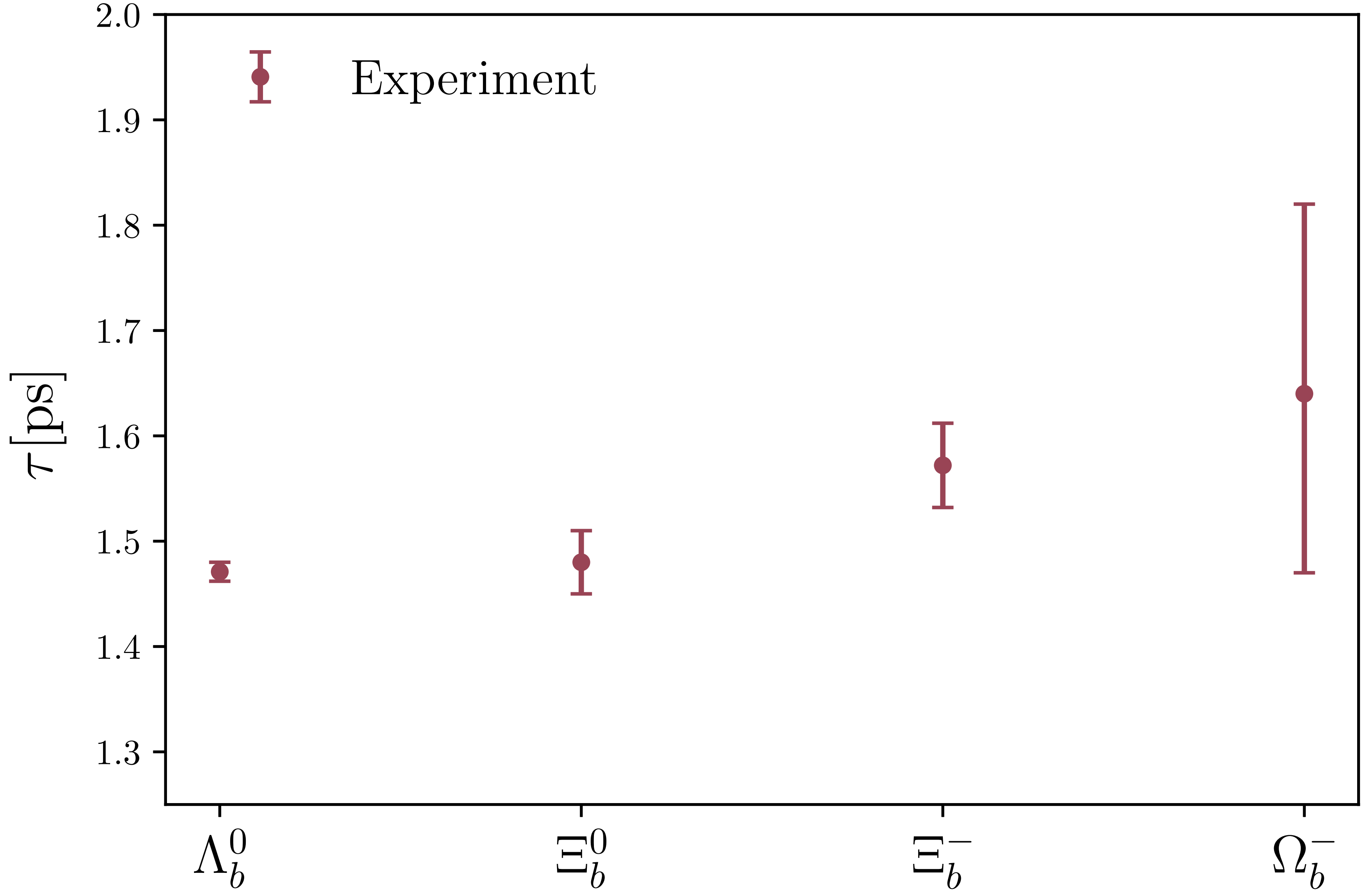


LHCb Update



- The latest LHCb measurements [LHCb, 1906.08350, 2109.01334] $\tau(\Omega_c)$ are four times larger than, and inconsistent with earlier findings

b-baryon lifetimes



Theoretical background

Theoretical Background (Heavy Quark Expansion)

- According to optical theorem the total decay width is given by the imaginary part of the forward matrix element (ME) of the transition operator

$$\Gamma_H = \frac{1}{2m_H}\Im\langle H|T|H\rangle\,, \qquad T = i\int d^4x\, T[\mathscr{H}_{eff}(x)\mathscr{H}_{eff}(0)]$$

$\mathscr{H}_{eff}$ denotes $\Delta C\,(\Delta B) = 1$ weak effective Hamiltonian.

- Given $m_Q \gg \Lambda_{QCD}$, applying the Heavy Quark Expansion (HQE) in powers of $\sim \Lambda_{QCD}/m_Q$, expanding the T in a series of local operators

- The LO term arises from the decay of a free heavy quark, leading to the expectation of equal lifetimes, e.g. $\tau(\Lambda_b)/\tau(B_d) \simeq 1$.

- Decay width in a schematic form:

$$\Gamma(H) = \frac{G_F^2 m_Q^5}{192\,\pi^3}\Bigg[c_3 + \frac{c_\pi \mu_\pi^2 + c_G \mu_G^2}{m_Q^2} + \frac{c_\rho \rho_D^3}{m_Q^3} + \dots$$
$$+ \frac{16\pi^2}{2m_H}\Bigg(\sum_{i,q} \frac{c_{6,i}^q \langle H|O_i^q|H\rangle}{m_Q^3} + \frac{c_{7,i}^q \langle H|P_i^q|H\rangle}{m_Q^4} + \dots\Bigg)\Bigg]$$

- Wilson coefficients c_i have individual perturbative α_s-expansions

- The hadronic MEs: $\mu_\pi^2\,, \mu_G^2\,, \rho_D^3\,, \langle H|O_i^q|H\rangle$ are nonperturbative and depend on the hadron H

- First row in the expansion: non-spectator two-quark contributions. Universal up to small differences in values of $\mu_\pi^2, \mu_G^2, \rho_D^3$:

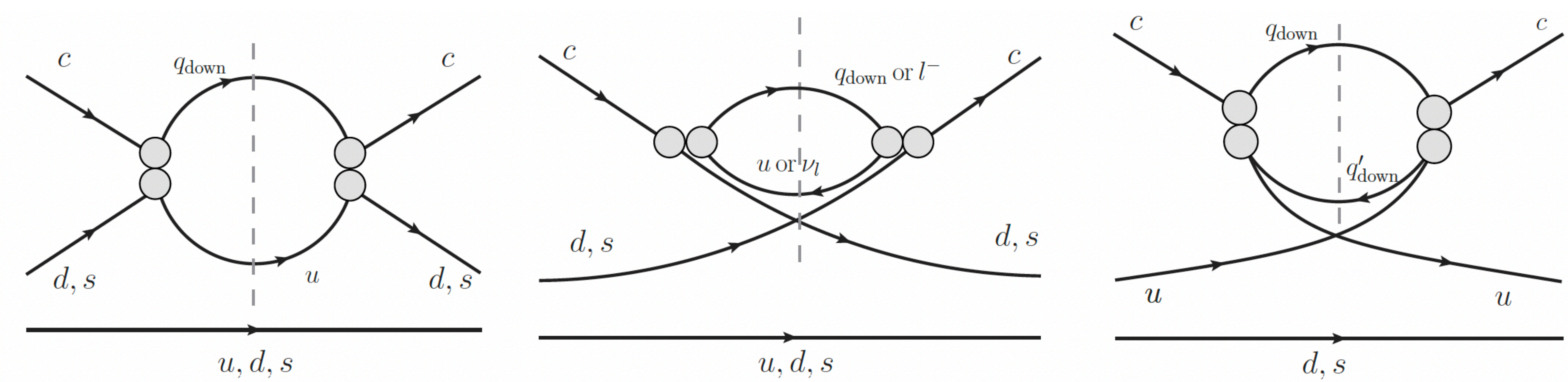
$$2M_{\mathscr{B}}\mu_\pi^2(\mathscr{B}) \equiv -\langle \mathscr{B}|\bar{Q}_v(iD_\mu)(iD^\mu)Q_v|\mathscr{B}\rangle\,,$$
$$2M_{\mathscr{B}}\mu_G^2(\mathscr{B}) \equiv \langle \mathscr{B}|\bar{Q}_v(iD_\mu)(iD_\nu)(-i\sigma^{\mu\nu})Q_v|\mathscr{B}\rangle\,,$$
$$2M_{\mathscr{B}}\rho_D^3(\mathscr{B}) \equiv \langle \mathscr{B}|\bar{Q}_v(iD_\mu)(iv\cdot D)(iD^\mu)Q_v|\mathscr{B}\rangle\,.$$

- Second row: MEs of four-quark operators. Dimension-6 basis:

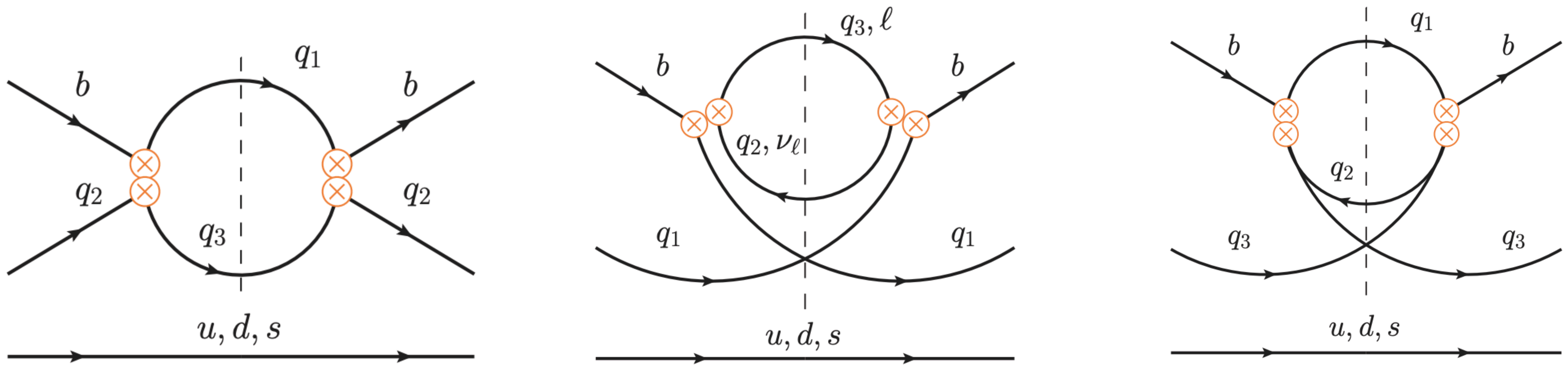
$$O_1^q = (\bar{c}_i q_i)_{V-A}(\bar{q}_j c_j)_{V-A}\,, \qquad O_2^q = (\bar{c}_i q_i)_{S-P}(\bar{q}_j c_j)_{S+P}\,,$$
$$\tilde{O}_1^q = (\bar{c}_i q_j)_{V-A}(\bar{q}_j c_i)_{V-A}\,, \qquad \tilde{O}_2^q = (\bar{c}_i q_j)_{S-P}(\bar{q}_j c_j)_{S+P}\,.$$

- Sensitive to light quark flavours. The primary drivers of lifetime splittings.

- Three topologies relevant for baryons: Weak Exchange, Constructive/ Destructive Pauli interference



Second row: spectator contributions



- $16\pi^2$ factor (loop enhancement) compared the two-quark contributions.
- For the charm, the spectator dimension-6 can even dominate over the 'leading' dimension-3. Compare $16\pi^2(\Lambda_{QCD}/m_c)^3 \sim 6$ to $16\pi^2(\Lambda_{QCD}/m_b)^3 \sim 0.3$
- Unlike in the case of mesons, no expectation of helicity suppression (all topologies relevant)

Matrix elements

Nonspectator MEs

- For μ_π^2, μ_G^2 follow the standard approach by exploiting the HQE for a heavy hadron mass

- Chromomagnetic term for $\Omega_{c(b)}$

$$\mu_G^2(\Omega_Q) = \frac{2}{3}(m^2_{\Omega^*_Q} - m^2_{\Omega_Q}) + \mathcal{O}(1/m_Q), \quad Q = c \text{ or } b$$

- The spin structure of the light constituents in single-heavy baryon triplet: $\mu_G^2(\mathcal{T}_Q) = 0$

- Extracting μ_π^2 involves combining b- and c baryons and mesons and employing more assumptions, e.g. for Λ_b

$$(\overline{M_D} - M_{\Lambda_c}) - (\overline{M_B} - M_{\Lambda_b}) = \left(\frac{1}{2m_c} - \frac{1}{2m_b}\right)(\mu_\pi^2(B) - \mu_\pi^2(\Lambda_b)) + \mathcal{O}\left(\frac{1}{m_c}, \frac{1}{m_b}\right)$$

$\overline{M}_D$ - spin averaged mass. $\mu_\pi^2(B)$ from the fit [Bordone, Capdevila, Gambino, 2107.00604]

Nonspectator MEs: Darwin

- Recently, the Darwin contribution has been evaluated for nonleptonic decays [Mannel, Moreno, Pivovarov, 2004.09485], [Lenz, Piscopo, Rusov, 2004.09527]

- Sizeable contribution for charm, $\sim 20\,\%$ of the dimension-three and five

- Relate the Darwin ME to those of dimension-6 via gluon field equation of motion

$$2M_{\mathscr{B}}\rho_D^3(\mathscr{B}) = g_s^2 \sum_{q=u,d,s} \langle \mathscr{B} | -\frac{1}{8}O_1^q + \frac{1}{24}\tilde{O}_1^q + \frac{1}{4}O_2^q - \frac{1}{12}\tilde{O}_2^q | \mathscr{B} \rangle + \mathcal{O}(1/m_Q)$$

Four-quark MEs: dimension-6

- The vacuum insertion approximation (VIA) is not available for baryons
- Treat baryon four-quark matrix elements in non-relativistic constituent quark model (NRCQM) - somewhat similar in spirit to the VIA
- The constituent model provides good fit of heavy hadron masses [Karliner, Rosner, 1408.5877]
- Applying such an approach to B mesons, e.g. for the estimate of the decay constant, would lead to the values not inconsistent with measurements/lattice
- The model relates the MEs to baryon wave functions at origin, e.g.

$$\frac{\langle \mathcal{T}_b | \mathcal{O}_1^q | \mathcal{T}_b \rangle}{2M_{\mathcal{T}_b}} = -\,|\psi^{\mathcal{T}_b}(0)|^2, \qquad \frac{\langle \Omega_b | \mathcal{O}_1^q | \Omega_b \rangle}{2M_{\Omega_b}} = -\,6\,|\psi^{\Omega_b}(0)|^2$$

- Use constituent model to express baryon masses in terms of wave functions [Rujula, Georgi, Glashow PRD12 147 (1975)]

$$M_{\mathscr{B}} = \sum_i m_i^{\mathscr{B}} + \ldots + \sum_{i>j} \frac{16\pi\alpha_s}{9} \frac{\langle \vec{s}_i \vec{s}_j \rangle}{m_i^{\mathscr{B}} m_j^{\mathscr{B}}} |\psi^{\mathscr{B}}(0)|^2$$

Similar equations for mesons, with different spin-term prefactor, $m_i^{\mathscr{B}}$ is constituent quark masses in a baryon - values from mass spectra fits [Karliner, Rosner, 1408.5877]

- Combining these relations for the hyperfine partners (e.g. $1/2^+$ and $3/2^+$) results in the wave functions in terms of the mass splittings, e.g.

$$\frac{\langle \Xi_b^0 | \mathcal{O}_1^u | \Xi_b^0 \rangle}{2M_{\Xi_b}} = \frac{\langle \Xi_b^- | \mathcal{O}_1^d | \Xi_b^- \rangle}{2M_{\Xi_b}} = -y_{\tilde{q}} \frac{4}{3} \frac{M_{\Xi_b^*} - M_{\Xi_b'}}{M_{B^*} - M_B} |\psi^B(0)|^2$$

with $|\psi^{B_q}(0)|^2 = 1/12\, F_{B_q}^2(\mu_0)$.

Four-quark, dimension-7

- Going one step further in $1/m_Q$ $\rightarrow$ dimension-7 four-quark operators

$$P_1^q = m_q(\bar{Q}_i(1-\gamma_5)q_i)(\bar{q}_j(1-\gamma_5)Q_j)\,, \quad P_2^q = \frac{1}{m_Q}(\bar{Q}_i\overleftarrow{D}_\rho\gamma_\mu(1-\gamma_5)D^\rho q_i)(\bar{q}_j\gamma^\mu(1-\gamma_5)Q_j)\,,$$

e.t.c

- Initially given in terms of QCD field Q
- Expressing them in terms of HQET field h_v introduces a proliferation of local and nonlocal terms → unclear on how to estimate the MEs
- For b-baryons, the $1/m_b$ under control, dimension-7 as an addition to uncertainty
- For charm baryons, dimension seven is up to $50\,\%$ of the dimension-6
- Constituent model relations/scaling arguments within the QCD basis, e.g.

$$\langle \mathcal{T}_c | P_1^q | \mathcal{T}_c \rangle \simeq \frac{1}{2} m_q |\psi_{cq}^{\mathcal{T}_c}(0)|^2\,, \qquad \langle \mathcal{T}_c | P_2^q | \mathcal{T}_c \rangle \simeq -\Lambda_{QCD} |\psi_{cq}^{\mathcal{T}_c}(0)|^2$$

Some specifics for double-charm baryons

- A system with two c-quarks - cc-pair viewed as diquark ($\mathscr{D}$)
- Two contributions to a given ME, in the example of the mass expansion

$$M_{\mathscr{B}_{cc}} = 2m_c + \bar{\Lambda} + \frac{\mu_\pi^2(\mathscr{B}_{cc})}{2m_c} - \frac{\mu_{G\,\mathscr{D}-q}^2(\mathscr{B}_{cc})}{2m_c} - \frac{\mu_{G\,c-c}^2(\mathscr{B}_{cc})}{2m_c} + \ldots$$

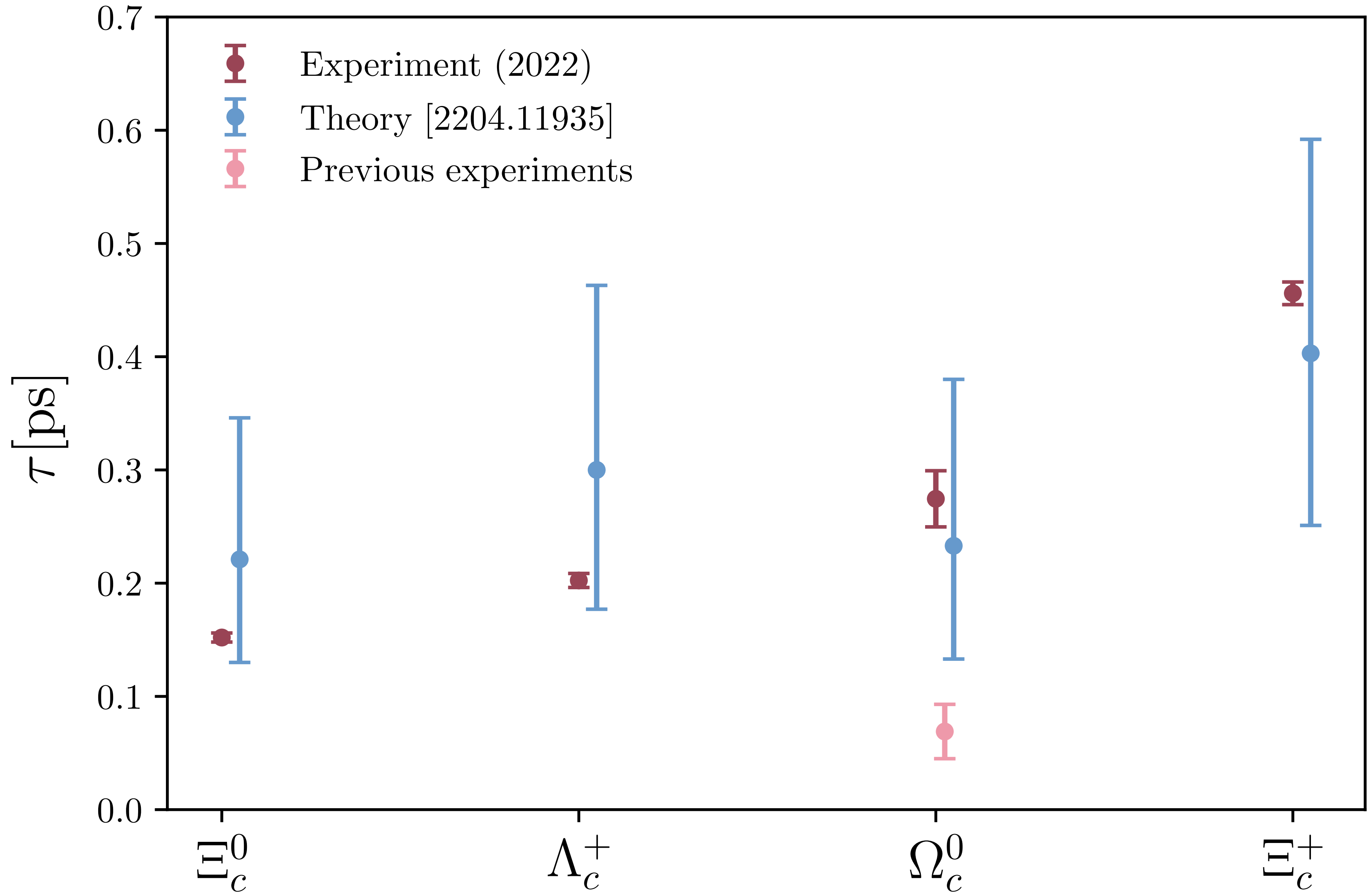
- The 'additional' c-c term accessed by NRQCD expansions, e.g. up to $\mathscr{O}(v^7)$

$$\bar{Q}Q = \psi_Q^\dagger \psi_Q - \frac{1}{2m_c^2}\psi_Q^\dagger (i\overrightarrow{D})^2 \psi_Q - \frac{1}{2m_c^2}\psi_Q^\dagger (g_s \sigma \cdot B)\psi_Q$$
$$-\frac{1}{4m_c^3}\psi_Q^\dagger (g_s \overrightarrow{\mathscr{D}} \cdot \overrightarrow{E})\psi_Q + \frac{3}{8}\psi_Q^\dagger (i\,\overrightarrow{D})^4 \psi_Q + \ldots$$

in terms of non relativistic 2-component Pauli spinor field ψ_Q.

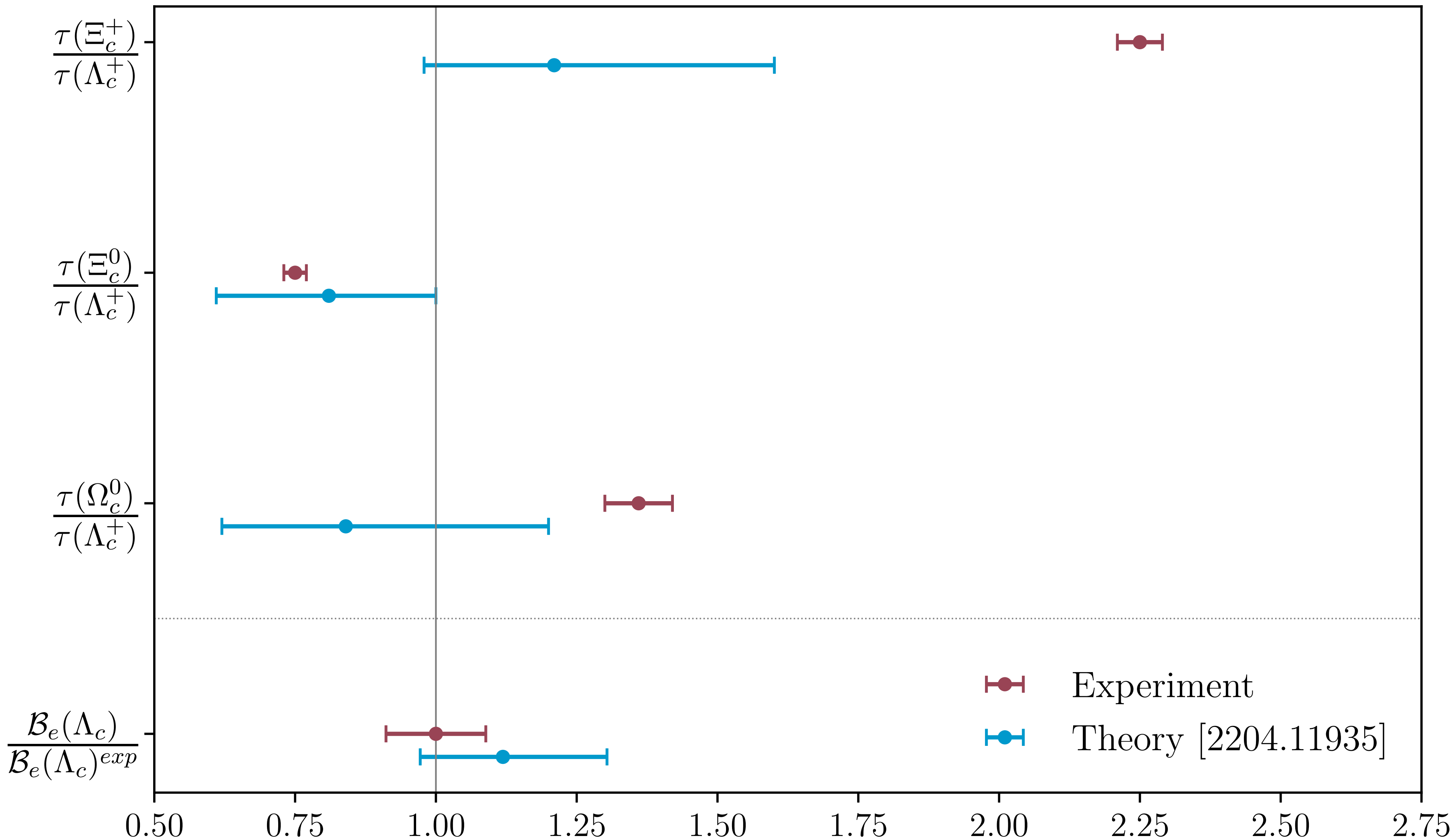
Results

c-baryon lifetimes



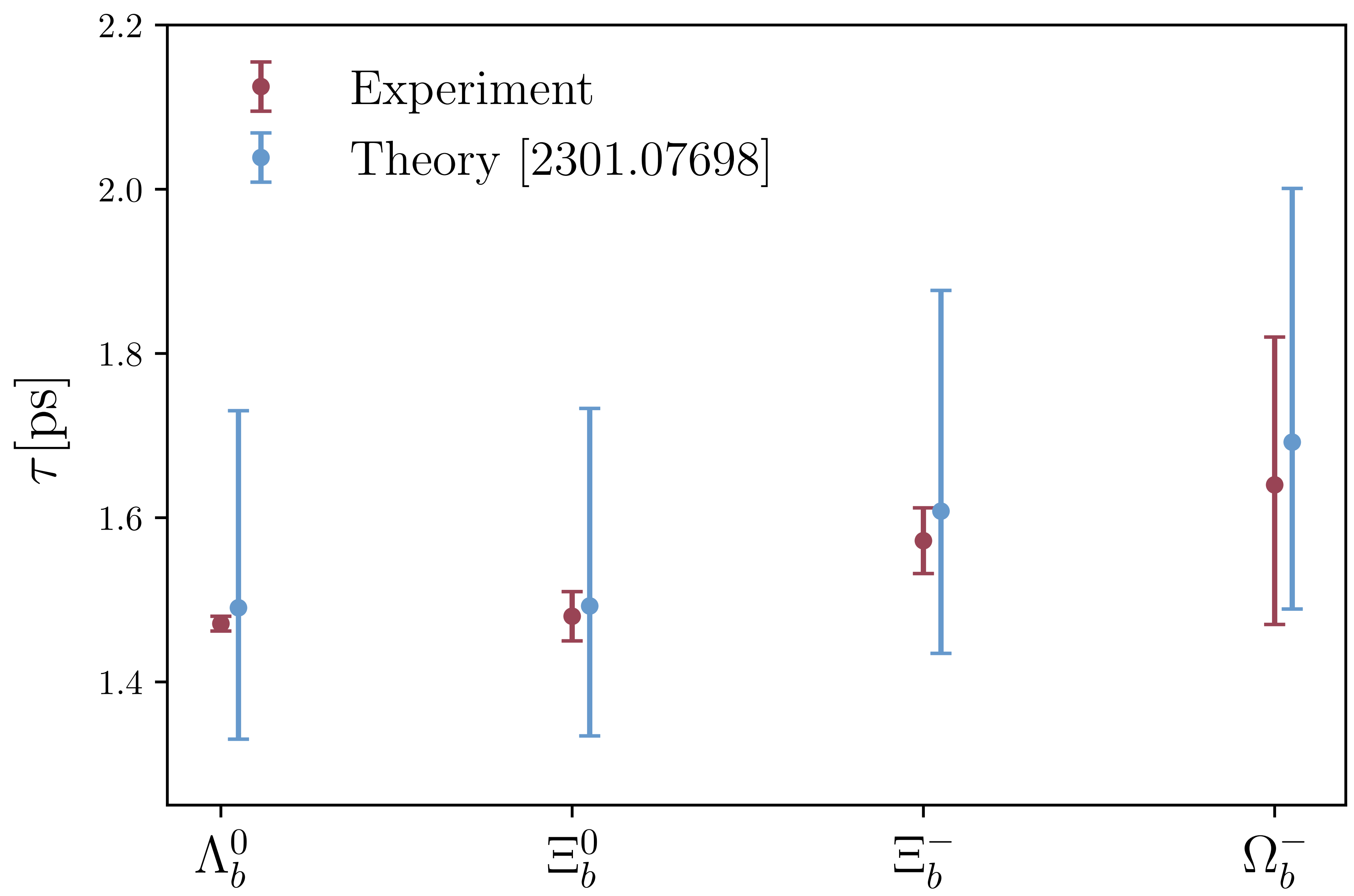
- New Ω_c-lifetime result accommodated well. Sizeable theoretical uncertainties

c-baryons ratios



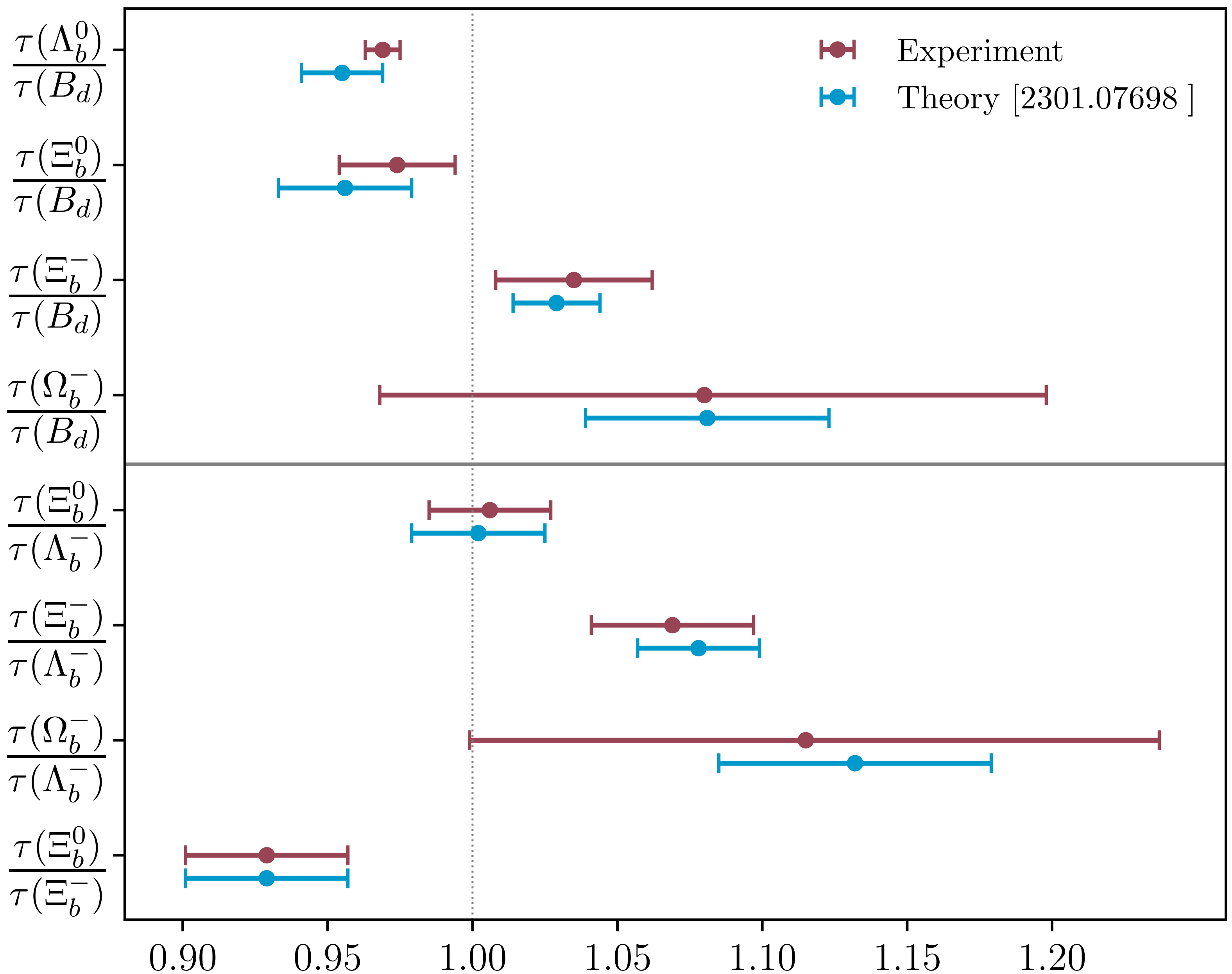
- Improved predictability of lifetime ratios due to cancellation of leading non-spectator terms
- Some tensions remain, particularly $\tau(\Xi_c^+)/\tau(\Lambda_c^+)$.

b-baryons lifetimes



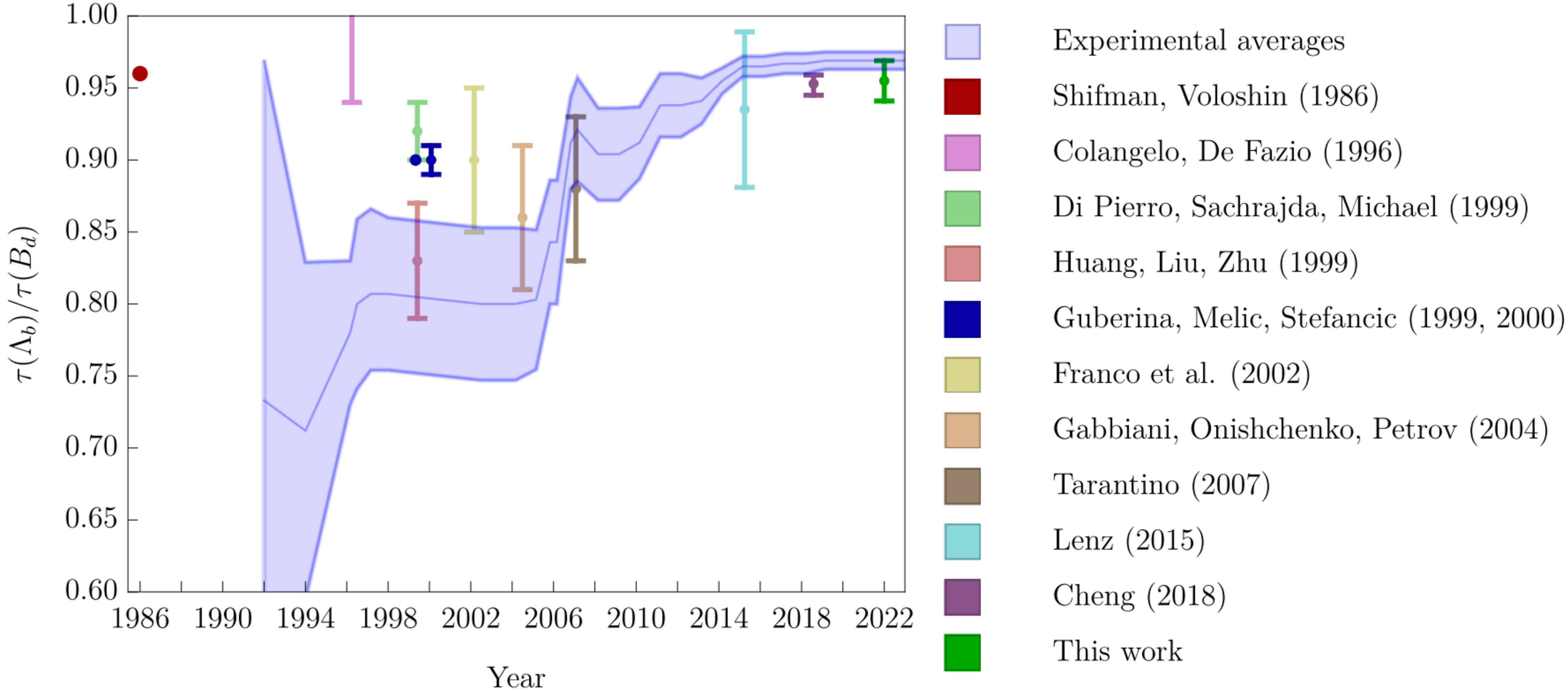
- Agreement with experiments for individual lifetimes

b-baryons ratios



- Excellent agreement in all lifetime ratios

History

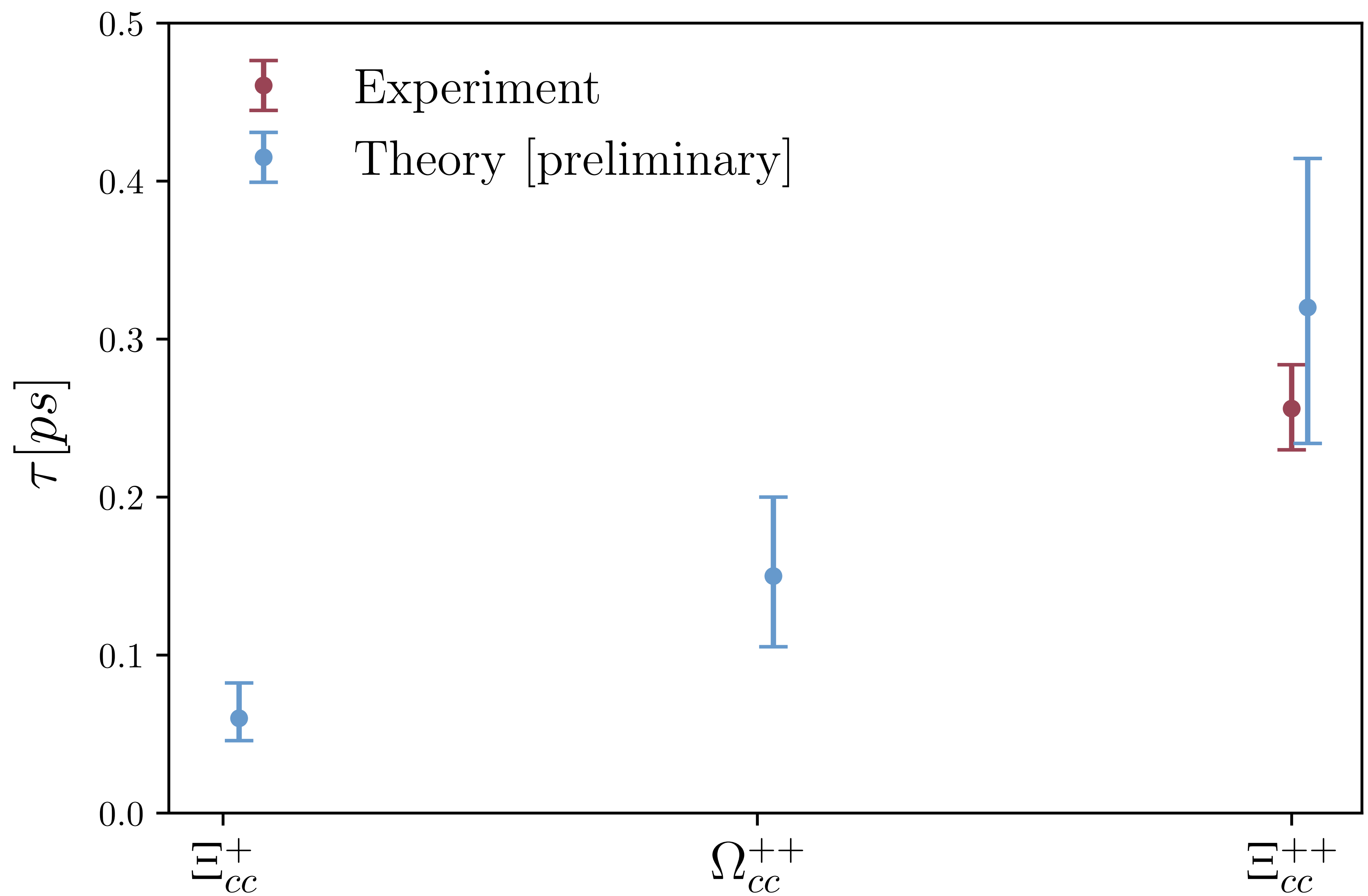


- Gradual historical convergence of both experimental and theoretical values
- Present day measurements compared our prediction:

$$\frac{\tau(\Lambda_b^0)}{\tau(B_d^0)}^{HQE} = 1 - (0.045 \pm 0.014)\,, \qquad \frac{\tau(\Lambda_b^0)}{\tau(B_d^0)}^{Exp} = 1 - (0.031 \pm 0.006)$$

Results

cc-baryons



- The measurement available for $\tau(\Xi_{cc}^{++})$ [LHCb, 1806.02744]
- Measuring Ξ_{cc}^{+} and Ω_{cc}^{+} with the expected LHCb Run-3 data was suggested as feasible

Remarks and conclusions: charm baryons

- Results for charm baryons broadly compatible with experiment, favouring recent LHCb result for the Ω_c-lifetime

- The question of the applicability of $1/m_c$ expansion due to slow $1/m_c$ -convergence remains open

- Question of optimal mass scheme for charm quark. E.g., the pole mass is problematic

$$m_c^{pole} = \overline{m}_c(\overline{m}_c)(1 + 0.16 + 0.15 + 0.21 + \ldots)$$

- For charm, we tested four mass-schemes: pole, $\overline{MS}$, kinetic, MSR. Effect: rearranging the α_s-expansions.

- At the *present* scale of numerical accuracy, the four schemes are not distinguishable – still important technically.

Remarks and conclusions: bottom baryons

- Theoretical values for lifetime ratios of b-baryons show an excellent consistency of HQE with the experimental data.

- Apart from evaluating further in $(\alpha_s, 1/m_b)$-expansions, which would be welcome,

- it is perhaps timely to revisit lattice QCD or the sum rules evaluations of four-quark MEs.

- Apart from the exploratory study in [UKQCD (Di Pierro, Sachrajda, Michael), 9906031], no lattice determinations for the four-quark baryonic matrix elements are available. Perhaps feasible.

- An alternative approach using HQET sum rules for the four-quark baryonic matrix elements, exploratory study in [Colangelo, De Fazio, 9604425], could be revisited in the future.

Thank you!