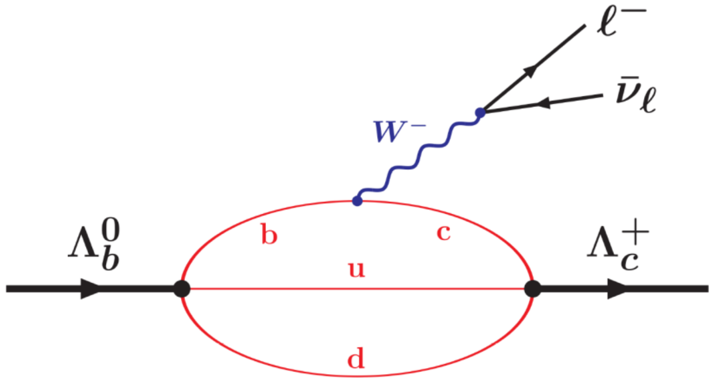
Branching ratio of $\Lambda_b \rightarrow \Lambda_c\, e^- \bar{\nu}_e$ decay



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Introduction

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01

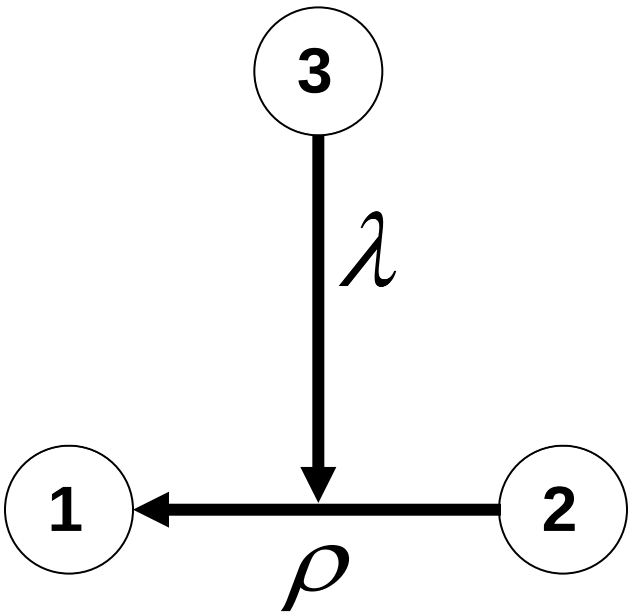
$\Lambda_c(2595)^+\pi^-$, $\Lambda_c(2595)^+ \to \Lambda_c^+\pi^+\pi^-$		$(3.4 \pm 1.5) \times 10^{-4}$
$\Lambda_c(2625)^+\pi^-$, $\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-$		$(3.3 \pm 1.3) \times 10^{-4}$
$\Sigma_c(2455)^0\pi^+\pi^-$, $\Sigma_c^0 \to \Lambda_c^+\pi^-$		$(5.7 \pm 2.2) \times 10^{-4}$
$\Sigma_c(2455)^{++}\pi^-\pi^-$, $\Sigma_c^{++} \to \Lambda_c^+\pi^+$		$(3.2 \pm 1.6) \times 10^{-4}$
$\Lambda_c^+ p\overline{p}\pi^-$		$(2.65 \pm 0.29) \times 10^{-4}$
$\Sigma_c(2455)^0 p\overline{p}$, $\Sigma_c^0 \to \Lambda_c^+\pi^-$		$(2.4 \pm 0.5) \times 10^{-5}$
$\Sigma_c(2520)^0 p\overline{p}$, $\Sigma_c(2520)^0 \to \Lambda_c^+\pi^-$		$(3.2 \pm 0.7) \times 10^{-5}$
$\Lambda_c^+\ell^-\overline{\nu}_\ell$ anything	[v]	(10.9 ± 2.2) %
$\Lambda_c^+\ell^-\overline{\nu}_\ell$		$(6.2 {}^{+1.4}_{-1.3})$ %
$\Lambda_c^+\pi^+\pi^-\ell^-\overline{\nu}_\ell$		(5.6 ± 3.1) %
$\Lambda_c(2595)^+\ell^-\overline{\nu}_\ell$		$(7.9 {}^{+4.0}_{-3.5}) \times 10^{-3}$
$\Lambda_c(2625)^+\ell^-\overline{\nu}_\ell$		$(1.3 {}^{+0.6}_{-0.5})$ %
$p h^-$	[x]	$< 2.3 \times 10^{-5}$
$p\pi^-$		$(4.5 \pm 0.8) \times 10^{-6}$
pK^-		$(5.4 \pm 1.0) \times 10^{-6}$

The semileptonic decay of heavy hadrons is a unique tool for determining the elements of the Cabibbo–Kobayashi–Maskawa (CKM) matrix.

The chosen semileptonic $\Lambda_b \to \Lambda_c\ l\ \nu$ transition is one of the prominent decay channels out of the manifold available channels of the Λb baryon reported by PDG.

The experimental group like DELPHI collaboration and LHCb collaboration reported their measurement on the slope parameter ρ^2 of the Isgur-Wise function and the branching ratio of the semileptonic transition of Λ_b baryon.

Framework: Hypercentral constituent quark model (HCQM)



Jacobi Coordinates

$$\rho = \frac{r_1 - r_2}{\sqrt{2}}$$

$$\lambda = \frac{r_1 + r_2 - 2r_3}{\sqrt{6}}$$

Hyperspherical Coordinates

$$x = \sqrt{\rho^2 + \lambda^2}$$ ⇒ Hyperradius (Size)

$$\xi = \arctan\left(\frac{\rho}{\lambda}\right)$$ ⇒ Hyperangle (Form)

Framework: Hypercentral constituent quark model (HCQM)

Quark Wave Function Factorization

$$\psi(x, \xi, \Omega_\rho, \Omega_\lambda) = \psi_{\nu\gamma}(x) \quad Y_{\gamma, l_\rho, l_\lambda}$$

Dynamics

Geometry

Where,

ν Hyperradial excitation

γ Grandangular quantum number

The hyperspherical harmonics, satisfying the eigenvalue relation

$$L^2(\Omega)Y(\Omega) = \gamma(\gamma + 4)\, Y(\Omega)$$

Framework: Hypercentral constituent quark model (HCQM)

$$\frac{P_x^2}{2m} = -\frac{\hbar^2}{2m}(\Delta_\rho + \Delta_\lambda) = -\frac{\hbar^2}{2m}\left(\frac{\partial^2}{\partial x^2} + \frac{5}{x}\frac{\partial}{\partial x} + \frac{L^2(\Omega)}{x^2}\right) \qquad V(x) = \frac{\tau}{x} + \beta x + V_0$$

$$\left[\frac{d^2}{dx^2} + \frac{5}{x}\frac{d}{dx} - \frac{\gamma(\gamma+4)}{x^2}\right]\psi_{\nu\gamma}(x) = -2m\left[E - V(x)\right]\psi_{\nu\gamma}(x)$$

$$\psi_{\nu\gamma} = \left[\frac{(\nu-\gamma)!(2g)^6}{(2\nu+5)(\nu+\gamma+4)!}\right]^{\frac{1}{2}}(2gx)^{\gamma} \times e^{-gx} L_{\nu-\gamma}^{2\gamma+4}(2gx)$$

$$M_B = \sum m_i + \langle H \rangle$$

The wave function parameter g and hence the energy eigenvalue are obtained by applying virial theorem. The baryon masses are determined by the sum of the model quark masses, kinetic energy and potential energy.

m_u	m_d	m_c	m_b	n_f	$\alpha_s(\mu_0 = 1\text{ GeV})$
0.330	0.350	1.55	4.95	4	0.6

Isgur-Wise function for the Semileptonic transition of $\Lambda_b \rightarrow \Lambda_c e^- \bar{\nu}_e$

Approximation → $m_{b,c} \rightarrow \infty$

$$m_b, m_c \gg \Lambda_{QCD}$$

$$F_1(q^2) = G_1(q^2) = \xi(\omega), \;\; F_2 = F_3 = G_2 = G_3 = 0$$

$$\xi(\omega) = 1 - \rho^2(\omega - 1) + c(\omega - 1)^2 + \cdots \qquad \rho^2 = -\frac{d\xi(\omega)}{d\omega}|_{\omega=1}$$

$$\omega = \frac{m^2_{\Lambda_b} + m^2_{\Lambda_c} - q^2}{2m_{\Lambda_b} m_{\Lambda_c}}$$

Isgur-Wise function for the Semileptonic transition of $\Lambda_b \rightarrow \Lambda_c\, e^{-}\bar{\nu}_e$

Isgur-Wise function in HCQM

Phys. Rev. D **90**, 074024 (2014)
Eur. Phys. J. C 80:926 (2020)

$$\xi(\omega) = 16\pi^2 \int_0^\infty |\psi_{\nu\gamma}(x)|^2 \cos(px)\, x^5\, dx$$

$$\cos(px) = 1 - \frac{p^2x^2}{2!} + \frac{p^4x^4}{4!} + \cdots \qquad p^2 = 2m^2(\omega - 1)$$

Slope and Curvature of the Isgur-Wise function

- The slope and curvature of the Isgur-Wise function in HCQM can be derived as

$$\rho^2 = 16\pi^2 m^2 \int_0^\infty |\psi_{\nu\gamma}(x)|^2 x^7 \, dx$$

$$c = \frac{8}{3}\pi^2 m^4 \int_0^\infty |\psi_{\nu\gamma}(x)|^2 x^9 \, dx$$

Differential and Total Decay Width

$$\frac{d\Gamma}{d\omega} = \frac{2}{3} m_{\Lambda_c}^4 m_{\Lambda_b} A\xi^2(\omega)\sqrt{\omega^2 - 1}\left[3\omega(\eta + \eta^{-1}) - 2 - 4\omega^2\right]$$

To calculate the total decay width, we have integrated the above Equation over the solid angle as

$$\Gamma = \int_1^{\omega_{max}} \frac{d\Gamma}{d\omega}\, d\omega$$

where the upper bound of the integration ω_{max} is the maximal recoil ($q^2 = 0$) and it can be written as

$$\omega_{max} = \frac{m_{\Lambda_b}^2 + m_{\Lambda_c}^2}{2\, m_{\Lambda_b} m_{\Lambda_c}}$$

Result

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Slope (ρ^2)	Approach	
1.58	This work	
$1.63 \pm 0.07 \pm 0.08$	LHCb collaboration	PRD **96**, 112005 (2017)
1.51	Relativistic quark model	PRD **73**, 094002 (2006)
1.35 ± 0.13	QCD sum rule	Phys. Lett. B **629**, 27 (2005)
$1.2^{+0.8}_{-1.1}$	Lattice QCD	Phys. Rev. D **57**, 6948 (1998)
1.61	Hyperspherical	Phys. Rev. D **90** 074024 (2014)
1.3	Large-N_c limit	Nucl. Phys. B **396**, 38–52 (1993)
2.4	MIT bag model	Z. Phys. C **59**, 677 (1993)
1.4-1.6	Bethe–Salpeter equation	Phys. Rev. D **54**, 4629 (1996)
1.47	Light-front approach	Phys. Rev. D **77** 014020 (2008)
1.5	Spectator quark model	Z. Phys. C **51** 321 (1991)
$2.03 \pm 0.46^{+0.72}_{-1.00}$	DELPHI collaboration	Phys. Lett. B **585**, 63 (2004)

Result

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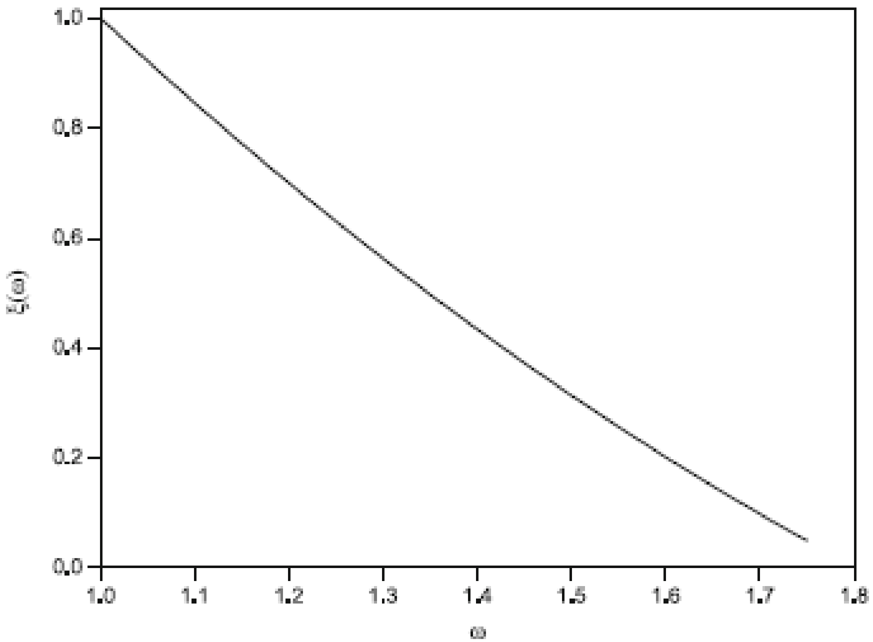

Fig. 1 The Isgur-Wise function ($\xi(\omega)$) for the $\Lambda_b \to \Lambda_c\ \ell\ \bar{\nu}$ semileptonic decay

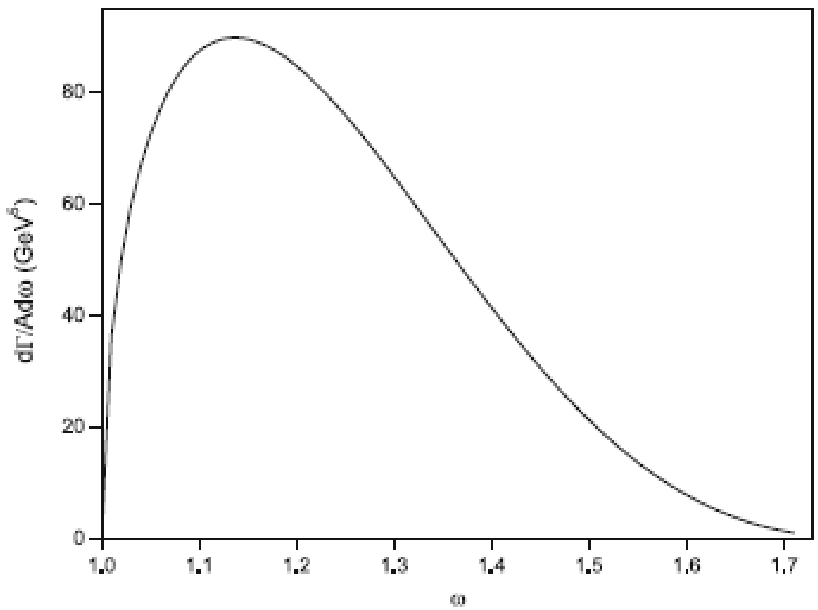

Fig. 2 The variation of differential decay rate for the $\Lambda_b \to \Lambda_c\ \ell\ \bar{\nu}$ semileptonic decay

RESULT

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Deacay Width Γ (10^{10} S^{-1})	References	Branching Ratio (%)	References
4.11	Present Work	6.04	Present Work
3.52	Phys. Rev. D **97**, 074007 (2018)	6.04±1.70	Phys. Rev. D **97**, 074007 (2018)
5.02	Phys. Rev. D **73**, 094002 (2006)	6. 9	Phys. Rev. D **73**, 094002 (2006)
4.42	Phys. Rev. D **94**, 073008 (2016)	6.48	Phys. Rev. D **94**, 073008 (2016)
4.86	Phys. Rev.D**91**, 074001 (2015)	6.9	Phys. Rev.D**91**, 074001 (2015)
5.39	Phys. Rev. D **56**, 348 (1997)	4.83	Phys. Rev. D **93**, 054003 (2016)
5.9	Phys. Rev. D **43**, 2939 (1991)	${6.2_{-1.3}}^{+1.4}$	Phys. Rev.D**98**, 030001 (2018) Particle Data Group
4.92	Phys. Rev. D **90**, 074024 (2014)	${6.2_{-0.8}}^{+1.1}$	(DELPHI Collaboration). Phys. Lett. B **585**, 63 (2004)

RESULT AND CONCLUSIONS

- The calculated value for the slope at zero recoil of the baryonic Isgur-Wise function is 1.58 which fairly agrees with other theoretical predictions.

- The predicted value for the slope of the Isgur-Wise function is in accordance with the experimental value 1.63±0.07±0.08, recently reported by LHCb collaboration.

- By comparing the slope of the Isgur-Wise function at the zero recoil point for the heavy baryon and the heavy meson, we predict that the Isgur-Wise function for the baryons should be a much steeper function of ω than the corresponding function for mesons.

- The HCQM gives plausible predictions for the Isgur-Wise function, decay width and the branching ratio corresponding to the $\Lambda_b \rightarrow \Lambda_c\ e^- \bar{\nu}_e$ semileptonic decay

Thank You