The invariant and helicity amplitudes in the transitions

$\Lambda_b \to \Lambda^*(\frac{1}{2}^{\pm}, \frac{3}{2}^{\pm}) + J/\psi$

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Contents

Introduction to Λ_b^0

- Search for New Physics (NP) beyond the Standard Model (SM).
  - Violation of lepton universality in decay $B^- \to D^{(*)}\tau^-\bar{\nu}_\tau$ at the level of four standard deviations.
  - Presence of a sizable discrepancy between data and SM predictions in decay $B \to K^*\mu^+\mu^-$.
- The study of Λ_b decays is complementary to measurement of observables from B meson decays.
- The production of Λ_b baryon is around $\sim$ 5% of the total b-hadrons at the LHC.
- Branching fractions, masses and lifetimes measurements for Λ_b baryon were performed with LHCb data, as well as distributions and asymmetries of the decays of $\Lambda_b \to \Lambda\,\mu^+\mu^-$.
- The LHCb collaboration has performed an angular analysis of the decay $\Lambda_b \to \Lambda J/\psi$

Introduction to Λ_b^0

- Large yields of decays $\Lambda_b^0 \to J/\psi\, K^-\, p$ are available at LHCb.
- This decay can proceed either via the chain

$$\Lambda_b^0 \to J/\psi\, \Lambda^{(*)}(\to K^-\, p)$$

or via the resonant structure in the $J/\psi\, p$

$$\Lambda_b^0 \to K^- P_c^+(\to J/\psi\, p)$$

- The LHCb reported observation of two $J/\psi\, p$ resonances consistent with pentaquark states.

  R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. 115, 072001 (2015)

Introduction to Λ_b^0

- In my talk I am going to discuss the last results in our study of the weak decays of **b-hadrons**
- The hadronic form factors of the transitions $B \to D^{(*)}$ and $\Lambda_b \to \Lambda^{(*)}$ are calculated in the framework of covariant confined quark model previously developed by us.
- First, I present the analysis of NP effects in the semileptonic B-decays and its extension to Λ_b -decays.
- Second, I report the results of calculation of the invariant and helicity amplitudes in the transitions $\Lambda_b \to \Lambda^{(*)}(J^P) + J/\psi$ where the $\Lambda^{(*)}(J^P)$ are Λ-type (sud) ground and excited states with quantum numbers $J^P = \frac{1}{2}^{\pm}, \frac{3}{2}^{\pm}$.

Covariant quark confined model

Main assumption: **hadrons interact via quark exchange only**

Interaction Lagrangian

$$\mathcal{L}_{int} = g_H \cdot H(x) \cdot J_H(x)$$

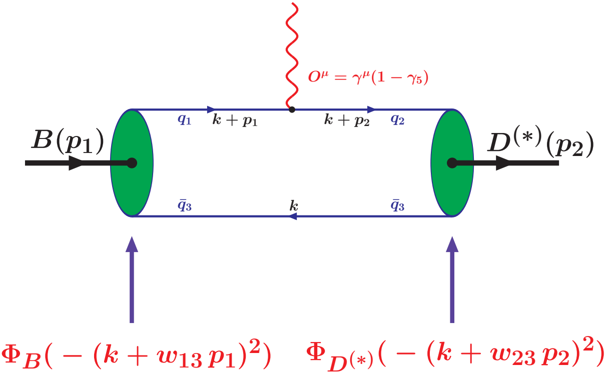
Quark currents

$$J_M(x) = \int dx_1 \int dx_2 \, F_M(x; x_1, x_2) \cdot \bar{q}^a_{f_1}(x_1) \, \Gamma_M \, q^a_{f_2}(x_2) \qquad \textbf{Meson}$$

$$J_B(x) = \int dx_1 \int dx_2 \int dx_3 \, F_B(x; x_1, x_2, x_3) \qquad \textbf{Baryon}$$
$$\times \, \Gamma_1 \, q^{a_1}_{f_1}(x_1) \left[\varepsilon^{a_1 a_2 a_3} q^{T\, a_2}_{f_2}(x_2) C \, \Gamma_2 \, q^{a_3}_{f_3}(x_3) \right]$$

$$J_T(x) = \int dx_1 \ldots \int dx_4 \, F_T(x; x_1, \ldots, x_4) \qquad \textbf{Tetraquark}$$
$$\times \left[\varepsilon^{a_1 a_2 c} q^{T\, a_1}_{f_1}(x_1) \, C\Gamma_1 \, q^{a_2}_{f_2}(x_2) \right] \cdot \left[\varepsilon^{a_3 a_4 c} \bar{q}^{T\, a_3}_{f_3}(x_3) \, \Gamma_2 C \, \bar{q}^{a_4}_{f_4}(x_4) \right]$$

Semileptonic decays of B meson



Violation of lepton universality in semileptonic B-decays

Measurements of the ratios of semileptonic branching fractions remove the dependence on $|V_{cb}|$, lead to a partial cancellation of theoretical uncertainties related to hadronic effects, and reduce of the impact of experimental uncertainties.

$$\mathcal{R}_D = \frac{\mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D\ell^-\bar{\nu}_\ell)} = \begin{cases} 0.300 \pm 0.008 & \text{SM} \\ 0.397 \pm 0.040_{\rm stat} \pm 0.028_{\rm syst} & \text{HFAG} \end{cases}$$

$$\mathcal{R}_{D^*} = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\nu_\tau)}{\mathcal{B}(\bar{B} \to D^*\ell^-\nu_\ell)} = \begin{cases} 0.252 \pm 0.003 & \text{SM} \\ 0.316 \pm 0.016_{\rm stat} \pm 0.010_{\rm syst} & \text{HFAG} \end{cases}$$

Here $\ell = e$ or μ.
The combined difference between the measured and expected values has a significance of about 4σ.

Effective Hamiltonian for the quark-level transition $b \to c\tau^-\bar{\nu}_\tau$:

$$\mathcal{H}_{\rm eff} \propto G_F V_{cb}\left[(1+V_L)\mathcal{O}_{V_L} + V_R\mathcal{O}_{V_R} + S_L\mathcal{O}_{S_L} + S_R\mathcal{O}_{S_R} + T_L\mathcal{O}_{T_L}\right]$$

where the four-fermion operators are written as

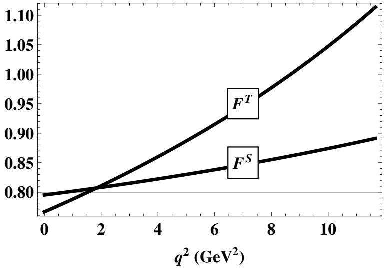
$$\mathcal{O}_{V_L} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) \qquad \mathcal{O}_{V_R} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma_\mu P_L \nu_\tau)$$

$$\mathcal{O}_{S_L} = (\bar{c}P_L b)(\bar{\tau}P_L \nu_\tau) \qquad \mathcal{O}_{S_R} = (\bar{c}P_R b)(\bar{\tau}P_L \nu_\tau)$$

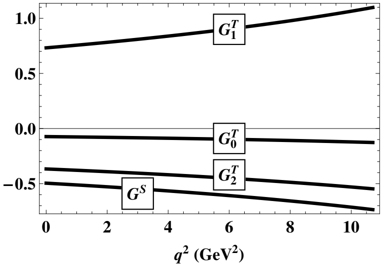
$$\mathcal{O}_{T_L} = (\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\tau}\sigma_{\mu\nu}P_L \nu_\tau)$$

- $V_{L,R}$, $S_{L,R}$, and T_L - complex Wilson coefficients governing NP.
- In the SM: $V_{L,R} = S_{L,R} = T_L = 0$.
- Assumption: neutrino is always left handed and NP only affects leptons of the third generation.

Form factors for NP operators



$\bar{B}^0 \to D$



$\bar{B}^0 \to D^*$

NP form factors in the full momentum transfer range

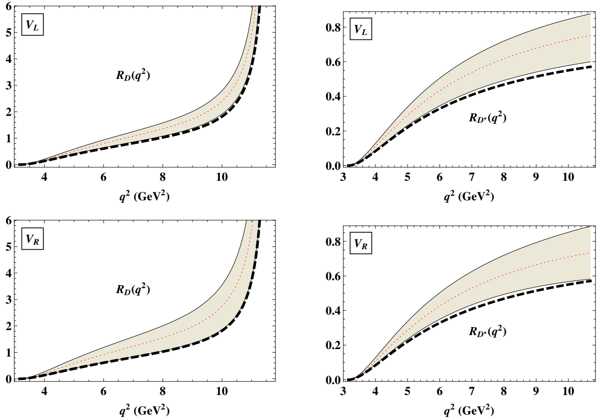
$$0 \le q^2 \le q^2_{max} = (m_{\bar{B}^0} - m_{D^{(*)}})^2$$

Allowed regions for NP couplings

- It is important to note that while determining these regions, we also take into account a theoretical error of 10% for the ratios $R(D^{(*)})$.
- The operator $\mathcal{O}_{S_R}$ is excluded at 2σ and is not presented here.
- In each allowed region at 2σ we find the best-fit value for each NP coupling.

$$\begin{aligned} V_L &= -1.33 + i\,1.11, \qquad V_R = 0.03 - i\,0.60, \\ S_L &= -1.79 - i\,0.22, \qquad T_L = 0.38 - i\,0.06. \end{aligned}$$

Ratios of branching fractions $R_D(q^2)$ (left) and $R_{D^*}(q^2)$ (right)



- **Thick black dashed lines are the SM prediction**
- **Gray bands include NP effects corresponding to the 2σ for $V_{L/R}$**
- **Red dotted lines represent the best fit values of the NP couplings**

Tau polarization in the decays $\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau$

R. Alonso, A. Kobach and J. Martin Camalich, "New physics in the kinematic distributions of $\bar{B} \to D^{(*)}\tau^-(\to \ell^-\bar{\nu}_\ell\nu_\tau)\bar{\nu}_\tau$," Phys. Rev. D 94, no. 9, 094021 (2016)

- **First measurement by Belle:** S. Hirose *et al.* [Belle Collaboration], "Measurement of the τ lepton polarization and R(D^*) in the decay $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$," Phys. Rev. Lett. 118, no. 21, 211801 (2017)

$$P_L^\tau = -0.38 \pm 0.51(\text{stat.})^{+0.21}_{-0.16}(\text{syst.}) \qquad (\text{in } \bar{B}^0 \to D^*\tau^-\bar{\nu}_\tau)$$

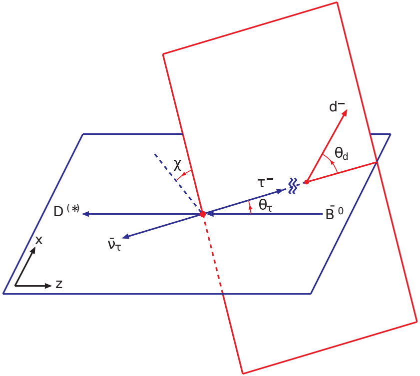
- **This pioneering measurement has opened a completely new window on the analysis of the dynamics of semileptonic $B \to D^{(*)}$ transitions.**
- **The hope is that, with the Belle II super-B factory nearing completion, more precise values of the polarization can be achieved in the future, which would shed more light on the search for possible NP in these decays.**

Analyzing the polarization of the tau through its decays

M. A. Ivanov, J. G. Körner and C. T. Tran, Phys. Rev. D 95, no. 3, 036021 (2017)

Analyzing modes for the τ^- polarization:

$$\tau^- \to \pi^-\nu_\tau \quad (10.83\%), \qquad \tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau \quad (17.41\%),$$
$$\tau^- \to \rho^-\nu_\tau \quad (25.52\%), \qquad \tau^- \to e^-\bar{\nu}_e\nu_\tau \quad (17.83\%).$$



In W rest frame, θ_τ - angle between $\vec{p}_\tau$ and the direction opposite to the direction of the $D^{(*)}$

In τ rest frame, θ_d - angle between d^- and the longitudinal polarization axis, which is chosen to coincide with the direction of the τ in the W rest frame.

χ - azimuthal angle.

q^2 averages of the polarization components and the total polarization.

$\bar{B}^0 \to D$

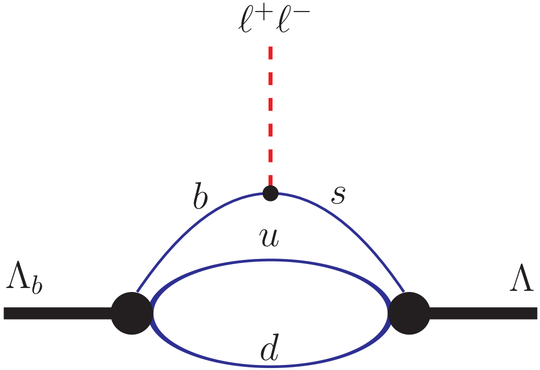
	$< P_L^D >$	$< P_T^D >$	$< P_N^D >$	$< \lvert\vec{P}^D\rvert >$
SM & CCQM	0.33	0.84	0	0.91
S_L	$[0.36, 0.67]$	$[-0.68, 0.33]$	$[-0.76, 0.76]$	$[0.89, 0.96]$
T_L	$[0.13, 0.31]$	$[0.78, 0.83]$	$[-0.17, 0.17]$	$[0.79, 0.90]$

$\bar{B}^0 \to D^*$

	$< P_L^{D^*} >$	$< P_T^{D^*} >$	$< P_N^{D^*} >$	$< \lvert\vec{P}^{D^*}\rvert >$
SM & CCQM	-0.50	0.46	0	0.71
S_L	$[-0.40, -0.14]$	$[0.47, 0.62]$	$[-0.20, 0.20]$	$[0.69, 0.70]$
T_L	$[-0.36, 0.24]$	$[-0.61, 0.26]$	$[-0.17, 0.17]$	$[0.23, 0.69]$
V_R	-0.50	$[0.32, 0.43]$	0	$[0.48, 0.67]$

The predicted intervals for the polarizations in the presence of NP are given in correspondence with the 2σ allowed regions of the NP couplings.

$\Lambda_b - \Lambda$ transition



Branching fractions of decays $\Lambda_b \to \Lambda + \ell^+\ell^-$ and $\Lambda_b \to \Lambda + \gamma$

Our results:

$$\mathcal{B}(\Lambda_b \to \Lambda\mu^+\mu^-) = 1.0 \cdot 10^{-6}$$

T. Gutsche, M. A. Ivanov, J. G. Körner, V. E. Lyubovitskij and P. Santorelli, Phys. Rev. D 87 074031 (2013)

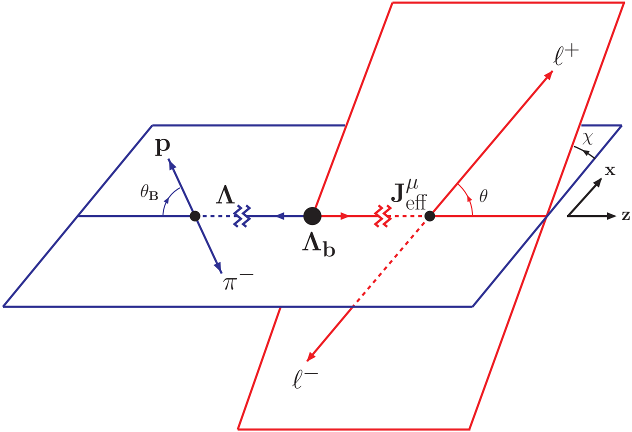
to be compared with the recent LHCb data:

$$\mathcal{B}(\Lambda_b \to \Lambda\mu^+\mu^-) = (0.96 \pm 0.16(\mathrm{stat}) \pm 0.13(\mathrm{syst}) \pm 0.21(\mathrm{norm})) \cdot 10^{-6}$$

RAaij *et al.* [LHCb Collaboration], arXiv:1306.2577 [hep-ex].

$\mathcal{B}(\Lambda_b \to \Lambda\gamma) = 0.4 \cdot 10^{-5}$ (experimental upper bound $< 130 \cdot 10^{-5}$)

The angular decay distribution for the cascade decay $\Lambda_b \to \Lambda(\to p\pi^-)\ell^+\ell^-$



Asymmetries A_{FB}^{ℓ} and A_{FB}^{h}

Mode	A_{FB}^{ℓ}	A_{FB}^{h}
$\Lambda_b \to \Lambda e^+ e^-$	3.2×10^{-10}	-0.321
$\Lambda_b \to \Lambda \mu^+ \mu^-$	1.7×10^{-4}	-0.300
$\Lambda_b \to \Lambda \tau^+ \tau^-$	5.9×10^{-4}	-0.265

Theoretical description of the decays $\Lambda_b \to \Lambda^{(*)}(\frac{1}{2}^{\pm}, \frac{3}{2}^{\pm}) + J/\psi$

The matrix element of the exclusive decay

$$\Lambda_1(p_1, \lambda_1) \to \Lambda_2(p_2, \lambda_2) + V(q, \lambda_V)$$

is defined by

$$M(\Lambda_1 \to \Lambda_2 + V) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* C_W f_V M_V \langle \Lambda_2 | \bar{s} O_\mu b | \Lambda_1 \rangle \epsilon^{\dagger\,\mu}(\lambda_V),$$

The helicity amplitudes are given by

$$H_{\lambda_2 \lambda_V} = \langle \Lambda_2(p_2, \lambda_2) | \bar{s} O_\mu b | \Lambda_1(p_1, \lambda_1) \rangle \epsilon^{\dagger\,\mu}(\lambda_V) = H^V_{\lambda_2 \lambda_V} - H^A_{\lambda_2 \lambda_V}$$

For the decay width one finds

$$\Gamma(\Lambda_b \to \Lambda^* + V) = \frac{G_F^2}{32\pi} \frac{|p_2|}{M_1^2} |V_{cb} V_{cs}^*|^2 C_W^2 f_V^2 M_V^2 \mathcal{H}_N$$

$$\mathcal{H}_N = \sum_{\lambda_2, \lambda_V} |H_{\lambda_2, \lambda_V}|^2$$

Moduli squared of normalized helicity amplitudes

Λ^*	1116	1405	1890	1520
J^P	$\frac{1}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^+$	$\frac{3}{2}^-$
$\lvert\hat{H}_{+\frac{3}{2}+1}\rvert^2$	0	0	$3.50 \cdot 10^{-4}$	$0.84 \cdot 10^{-4}$
$\lvert\hat{H}_{+\frac{1}{2}+1}\rvert^2$	$2.34 \cdot 10^{-3}$	$1.27 \cdot 10^{-2}$	$3.19 \cdot 10^{-2}$	$2.26 \cdot 10^{-2}$
$\lvert\hat{H}_{+\frac{1}{2}0}\rvert^2$	$3.24 \cdot 10^{-4}$	$5.19 \cdot 10^{-3}$	$1.61 \cdot 10^{-3}$	$1.82 \cdot 10^{-3}$
$\lvert\hat{H}_{-\frac{1}{2}0}\rvert^2$	0.53	0.51	0.51	0.54
$\lvert\hat{H}_{-\frac{1}{2}-1}\rvert^2$	0.47	0.47	0.45	0.44
$\lvert\hat{H}_{-\frac{3}{2}-1}\rvert^2$	0	0	$3.34 \cdot 10^{-3}$	$1.06 \cdot 10^{-3}$

The helicity amplitudes H_{λ_2,λ_V} of the produced $\Lambda^{(*)}$ states are clearly dominated by the helicity configuration $\lambda_2 = -1/2$. For the spin 1/2 states in the transition $1/2^+ \to 1/2^\pm$ this implies that the two $\Lambda^{(*)}(1/2)$ states are almost purely left-handed.

Summary

- The weak decays of Λ_b baryon are complements to the well-analyzed B-meson decays. They provide independent tests of the Standard Model.
- The theoretical uncertainties mainly come from the hadronic parts, parametrized by the form factors.
- We used our covariant quark model to evaluate both meson-meson and baryon-baryon form factors in the full kinematical region of the momentum transfer squared.
- We performed an analysis of possible NP in the semileptonic decays $\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau$ based on an effective Hamiltonian including NP operators and calculated form factors.

Summary

- **We calculated the invariant and helicity amplitudes in the transitions $\Lambda_b \to \Lambda^{(*)}(J^P) + J/\psi$ where the $\Lambda^{(*)}(J^P)$ are Λ-type (sud) ground and excited states with quantum numbers $J^P = \frac{1}{2}^{\pm}, \frac{3}{2}^{\pm}$.**

- **We found that the values of the helicity amplitudes for the $\Lambda_b \to \Lambda^*(1520, \frac{3}{2}^{-}), \Lambda^*(1890, \frac{3}{2}^{+})$ transitions are suppressed compared with those for the transitions to the ground state $\Lambda(1116, \frac{1}{2}^{+})$ and the excited state $\Lambda^*(1405, \frac{1}{2}^{-})$.**