The invariant and helicity amplitudes in the transitions

\[ \Lambda_b \rightarrow \Lambda^*(\frac{1}{2}^\pm, \frac{3}{2}^\pm) + J/\psi \]

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Summary
Introduction to $\Lambda^0_b$

- Search for New Physics (NP) beyond the Standard Model (SM).
  - Violation of lepton universality in decay $B^- \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau$ at the level of four standard deviations.
  - Presence of a sizable discrepancy between data and SM predictions in decay $B \rightarrow K^* \mu^+ \mu^-$. 
- The study of $\Lambda_b$ decays is complementary to measurement of observables from $B$ meson decays.
- The production of $\Lambda_b$ baryon is around $\sim 5\%$ of the total $b$-hadrons at the LHC.
- Branching fractions, masses and lifetimes measurements for $\Lambda_b$ baryon were performed with LHCb data, as well as distributions and asymmetries of the decays of $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$. 
- The LHCb collaboration has performed an angular analysis of the decay $\Lambda_b \rightarrow \Lambda J/\psi$
Introduction to $\Lambda_b^0$

- Large yields of decays $\Lambda_b^0 \rightarrow J/\psi K^- p$ are available at LHCb.

- This decay can proceed either via the chain

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

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

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

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

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 \( \Lambda_b \)-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 \( \Lambda \)-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

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

Quark currents

$$J_M(x) = \int dx_1 \int dx_2 \, F_M(x; x_1, x_2) \cdot \bar{q}_{f_1}^a(x_1) \Gamma_M q_{f_2}^a(x_2)$$  \text{Meson}$$

$$J_B(x) = \int dx_1 \int dx_2 \int dx_3 \, F_B(x; x_1, x_2, x_3)$$

$$\times \Gamma_1 q_{f_1}^{a_1}(x_1) \left[ \varepsilon^{a_1 a_2 a_3} q_{f_2}^{T a_2}(x_2) C \Gamma_2 q_{f_3}^{a_3}(x_3) \right]$$  \text{Baryon}$$

$$J_T(x) = \int dx_1 \ldots \int dx_4 \, F_T(x; x_1, \ldots, x_4)$$

$$\times \left[ \varepsilon^{a_1 a_2 c} q_{f_1}^{T a_1}(x_1) C \Gamma_1 q_{f_2}^{a_2}(x_2) \right] \cdot \left[ \varepsilon^{a_3 a_4 c} \bar{q}_{f_3}^{T a_3}(x_3) \Gamma_2 C \bar{q}_{f_4}^{a_4}(x_4) \right]$$  \text{Tetraquark}
Semileptonic decays of $B$ meson

$O^\mu = \gamma^\mu (1 - \gamma_5)$

$\Phi_B (- (k + w_{13} p_1)^2)$  $\Phi_{D(*)} (- (k + w_{23} p_2)^2)$
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.

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

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

Here $\ell = e$ or $\mu$.

The combined difference between the measured and expected values has a significance of about $4\sigma$. 
Analyzing New Physics in the decays $B \rightarrow D(\ast)\tau\nu_\tau$

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

$$\mathcal{H}_{\text{eff}} \propto G_F V_{cb} [(1 + V_L) O_{V_L} + V_R O_{V_R} + S_L O_{S_L} + S_R O_{S_R} + T_L O_{T_L}]$$

where the four-fermion operators are written as

$$O_{V_L} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) \quad O_{V_R} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma_\mu P_L \nu_\tau)$$

$$O_{S_L} = (\bar{c}P_L b)(\bar{\tau}P_L \nu_\tau) \quad O_{S_R} = (\bar{c}P_R b)(\bar{\tau}P_L \nu_\tau)$$

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

- $V_{L,R}, S_{L,R},$ 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

NP form factors in the full momentum transfer range

$$0 \leq q^2 \leq q^2_{\text{max}} = (m_{\bar{B}^0} - m_{D^*(\pm)})^2$$
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 $O_{SR}$ is excluded at $2\sigma$ and is not presented here.
- In each allowed region at $2\sigma$ we find the best-fit value for each NP coupling.

\[ V_L = -1.33 + i 1.11, \quad V_R = 0.03 - i 0.60, \]
\[ S_L = -1.79 - i 0.22, \quad T_L = 0.38 - i 0.06. \]
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 $2\sigma$ for $V_{L/R}$
- Red dotted lines represent the best fit values of the NP couplings
Tau polarization in the decays $\bar{B}^0 \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$


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

\[ P_{\tau}^\tau = -0.38 \pm 0.51\text{(stat.)}^{+0.21}_{-0.16}\text{(syst.)} \quad \text{(in $\bar{B}^0 \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$)} \]

This pioneering measurement has opened a completely new window on the analysis of the dynamics of semileptonic $B \rightarrow D^{(*)}$ 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


Analyzing modes for the $\tau^-$ polarization:

$$
\begin{align*}
\tau^- &\rightarrow \pi^- \nu_\tau \ (10.83\%), \\
\tau^- &\rightarrow \rho^- \nu_\tau \ (25.52\%), \\
\tau^- &\rightarrow \mu^- \bar{\nu}_\mu \nu_\tau \ (17.41\%), \\
\tau^- &\rightarrow e^- \bar{\nu}_e \nu_\tau \ (17.83\%).
\end{align*}
$$

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

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

$\chi$ - azimuthal angle.
The $q^2$ averages of the polarization components and the total polarization.

\[ \bar{B}^0 \rightarrow D \]

|             | $\langle P^D_L \rangle$ | $\langle P^D_T \rangle$ | $\langle P^D_N \rangle$ | $\langle |\vec{P}^D| \rangle$ |
|-------------|-------------------------|-------------------------|-------------------------|-------------------------|
| 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]            |

\[ \bar{B}^0 \rightarrow D^* \]

|             | $\langle P^D_{L*} \rangle$ | $\langle P^D_{T*} \rangle$ | $\langle P^D_{N*} \rangle$ | $\langle |\vec{P}^D_{*}| \rangle$ |
|-------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 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 2$\sigma$ 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:

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


to be compared with the recent LHCb data:

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

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

$$B(\Lambda_b \to \Lambda \gamma) = 0.4 \times 10^{-5} \quad \text{(experimental upper bound < 130 \times 10^{-5})}$$
The angular decay distribution for the cascade decay $\Lambda_b \rightarrow \Lambda(\rightarrow p\pi^-)\ell^+\ell^-$
Asymmetries $A_{FB}^{\ell}$ and $A_{FB}^{h}$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$A_{FB}^{\ell}$</th>
<th>$A_{FB}^{h}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b \rightarrow \Lambda e^+e^-$</td>
<td>$3.2 \times 10^{-10}$</td>
<td>$-0.321$</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow \Lambda \mu^+\mu^-$</td>
<td>$1.7 \times 10^{-4}$</td>
<td>$-0.300$</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow \Lambda \tau^+\tau^-$</td>
<td>$5.9 \times 10^{-4}$</td>
<td>$-0.265$</td>
</tr>
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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

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

$$\mathcal{H}_N = \sum_{\lambda_2, \lambda_V} |H_{\lambda_2, \lambda_V}|^2$$
The helicity amplitudes $H_{\lambda_2,\lambda_V}$ 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 $1/2^+ \rightarrow 1/2^\pm$ this implies that the two $\Lambda^{(*)}(1/2)$ states are almost purely left-handed.
The weak decays of $\Lambda_b$ 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 $\bar{B}^0 \rightarrow D(\ast)\tau^-\bar{\nu}_\tau$ based on an effective Hamiltonian including NP operators and calculated form factors.
We calculated the invariant and helicity amplitudes in the transitions $\Lambda_b \to \Lambda^{(*)}(J^P) + J/\psi$ where the $\Lambda^{(*)}(J^P)$ are $\Lambda$-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 $\Lambda^*(1405, \frac{1}{2}^-)$. 