Precision predictions for $B \to \rho \tau \nu$ and $B \to \omega \tau \nu$
in the SM and beyond

EPS 2019 - Flavour Physics and CP Violation
Florian Bernlochner, Markus Prim, Dean Robinson | 12th July 2019
**Form Factors**

- **Form factors** encode the structure of matrix elements in terms of representations.

\[
\propto \left\langle M(p_M) \middle| u \gamma^{\mu} P_L b \middle| B(p_B) \right\rangle
\]

\[
\propto \sum T_i^\mu F_i(q^2)
\]
Form Factors - BCL Parametrization

The Bourrely-Caprini-Lellouch (BCL) parametrization is a model-independent ansatz for the form factors based on a fast converging series expansion of:

\[ z(q^2, t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}} \]

with

\[ t_+ = (m_B + m_M)^2 \]
\[ t_0 = (m_B + m_M)(\sqrt{m_B} - \sqrt{m_M})^2 \]

The form factors are expanded as:

\[ F_i(q^2) = P_i(q^2) \sum_k \alpha_k^i \left( z(q^2) - z(0) \right)^k \]

with

\[ P_i(q^2) = \left( 1 - \frac{q^2}{m_R^2} \right)^{-1} \quad m_R : \text{Mass of first resonance in spectrum} \]
Form Factors - $B \rightarrow V \ell \nu$ with $V = \rho, \omega$

- In total exist 8 independent form factors: $A_P, V, A_0, A_1, A_{12}, T_1, T_2, T_{23}$.
- The pseudoscalar form factor can be removed under the equations of motion:

$$A_P = -2 \frac{m_M}{m_b + m_u} A_0.$$

- 4 form factors contribute to the SM process: $V, A_0, A_1, A_{12}$.
- 3 form factors can contribute to BSM processes: $T_1, T_2, T_{23}$.
Form Factors - $B \to V \ell \nu$ with $V = \rho, \omega$ from Theory

- Theory predictions available from LCSR calculations:
  - JHEP 1608 (2016) 098
- Only valid up to $q^2 \approx 14 \text{ GeV}^2$.
- For $q^2 > 14 \text{ GeV}^2$ solely extrapolation available (no LQCD).
Differential Rate - Help from Experiment

- Fit form factor coefficients with theory and experimental input:
  - Phys.Rev. D83 (2011) 032007
  - Phys.Rev. D87 (2013) no.3, 032004

- Use normalized spectra to take $V_{ub}$ out of the equation.
Differential Rate - Fit Result

\[ \chi^2(\bar{a}) = \chi^2_{\text{LCSR}}(\bar{a}) + \sum_{\text{Exp}} \chi^2_{\text{Exp}}(\bar{a}) \]

Differential rate corrections are extracted from experimental data.

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Form factor corrections are extracted from experimental data.
Form factor corrections are extracted from experimental data.
Form Factor - Fit Result

- Only small improvement in the individual uncertainties of the form factors.
- But the fit allows to **constrain combinations of form factors**.
- This improves the precision on certain observables, e.g. $R(\rho)$ and $R(\omega)$. 
Predicting $R(\rho)$ and $R(\omega)$ in the SM

- Use fitted coefficients to predict $R(V)$.

\[
R(V) = \frac{\int q_{\text{max}}^2 \frac{d\Gamma(B \rightarrow V\tau\nu)}{dq^2}}{\int q_{\text{max}}^2 \frac{d\Gamma(B \rightarrow V\ell\nu)}{dq^2}} dq^2
\]

\[
\hat{R}(V) = \frac{\int q_{\text{max}}^2 \frac{d\Gamma(B \rightarrow V\tau\nu)}{dq^2}}{\int q_{\text{max}}^2 \frac{d\Gamma(B \rightarrow V\ell\nu)}{dq^2}} dq^2
\]

<table>
<thead>
<tr>
<th>$R(V)$</th>
<th>LCSR</th>
<th>Fit</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(\rho)$</td>
<td>0.532 ± 0.011</td>
<td>0.535 ± 0.008</td>
<td>25 %</td>
</tr>
<tr>
<td>$R(\omega)$</td>
<td>0.534 ± 0.018</td>
<td>0.546 ± 0.015</td>
<td>16 %</td>
</tr>
<tr>
<td>$\hat{R}(\rho)$</td>
<td>0.605 ± 0.007</td>
<td>0.606 ± 0.006</td>
<td>6 %</td>
</tr>
<tr>
<td>$\hat{R}(\omega)$</td>
<td>0.606 ± 0.012</td>
<td>0.612 ± 0.011</td>
<td>7 %</td>
</tr>
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</table>
Predicting $R(\rho)$ and $R(\omega)$ beyond the SM

The complete basis of the four-Fermi operators mediating the $b \rightarrow q\ell\nu$ decay:

$$i2\sqrt{2} V_{ub} G_F [\bar{q} \chi^i_j \gamma^\mu P_j b][\bar{\ell} \lambda^k_i \gamma^\mu P_l \nu]$$

- $\chi^i_j$: NP coupling to quark current.
- $\lambda^k_i$: NP coupling to lepton current.
- $j, l = L, R$: Helicity of $b$ quark or $\nu$ respectively.
- $i, k = S, V, T$: Type of current.
- NP couplings normalized to SM.
- Influence of new physics on $R(\rho)$ and $R(\omega)$ the same (both vector-like particles).
Predicting $R(\rho)$ and $R(\omega)$ beyond the SM

Scalar Currents

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Vector Currents

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**Tensor Currents**

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Summary & Outlook

- Form factors constrained from theory and experiment over whole $q^2$ range.
- Improved predictions of $\mathcal{O}(20\%)$ for $R(\rho)$ and $R(\omega)$
- Analysis of BSM physics influence on $R(\rho)$ and $R(\omega)$.
- No measurements of $R(\rho)$ and $R(\omega)$ yet.

- Results also available via HAMMER:
  - HAMMER: a tool for new physics searches in semileptonic decays at Belle II and LHCb by Stephan Duell (12 Jul 2019, 11:45)

- Measurement of the full differential decay rate allows data driven extraction of form factors in the future.
Backup
Predicting \( R(\rho) \) and \( R(\omega) \) beyond the SM

Scalar Currents

\[
R(\omega) = 0
\]

\[
\delta = 0
\]

\[
\chi_L^S \lambda_L^S, \chi_L^S \lambda_R^S, \chi_R^S \lambda_L^S, \chi_R^S \lambda_R^S
\]

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Correlations of $B \to \rho \ell \nu$

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$\chi^2$-Profiles of $B \rightarrow \omega \lnu$ Fit

- Precision predictions for $B \rightarrow \rho \lnu$ and $B \rightarrow \omega \lnu$ in the SM and beyond - Florian Bernlochner, Markus Prim, Dean Robinson

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Correlations of $B \rightarrow \omega \nu$

**$B \rightarrow \omega(\rightarrow 3\pi)\nu$ Prefit**

<table>
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**$B \rightarrow \omega(\rightarrow 3\pi)\nu$ Postfit**

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<tbody>
<tr>
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