Revisiting $B \to K^* \nu\bar{\nu}$ decays

based on PRD 95 (2017) with D. Das and G. Hiller,
Ivan Nišandžić

Technische Universität Dortmund

ivan.nisandzic@tu-dortmund.de

Portorož 2017: New physics at the junction of flavor and collider phenomenology

21. April 2017

- $B \to K^*(\to K\pi)\nu\bar{\nu}$ induced via $b \to s\nu\bar{\nu}$ FCNC rare transitions, therefore potentially sensitive to the BSM physics effects
- not subjected to long-distance effects from charm quarks
- related to $b \to s\ell\ell$ transitions via $SU(2)_L$ invariance
- experimentally challenging, not observed yet. Hope is that Belle-II would manage to measure observables in $B \to K^*\nu\nu$
- The current best limit from the Belle Collaboration

$$\mathcal{B}(B \to K^{*0}\bar{\nu}\nu) < 1.8 \times 10^{-5}, \text{ close to the SM prediction } \sim 10^{-5}$$

- For new physics searches, important to check the resonant $(B \to (\text{scalars})(\to K\pi)\nu\bar{\nu})$ and non resonant $B \to K\pi\nu\bar{\nu}$ backgrounds

Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\lambda_t \frac{\alpha}{8\pi}\Big[(C_L + C_R)(\bar{s}\gamma_\mu b) + (C_R - C_L)(\bar{s}\gamma_\mu\gamma_5 b)\Big]\sum_i \bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_i + \text{h.c.} \quad (1)$$

- short distance physics within SM known precisely:
- $C_L^{SM} = -X(m_t^2/m_W^2)/\sin^2\theta$, NLO QCD, two-loop EW corrections [Buchalla, Buras (1993); Misiak, Urban (1999), Brod, Gorbahn, Stamou (2011)],
- $X(m_t) = 1.469 \pm 0.017$ [Buras, Girrbach-Noe, Niehoff, Straub, (2014)]

Effects of scalar resonances

Total resonant amplitude for fixed polarization n of the final $K\pi$ pair can be written as

$$\mathcal{A}(B \to K_{res}(n)(\to K\pi)\bar{\nu}_i\nu_i) = -\frac{4G_F}{\sqrt{2}}\lambda_t\frac{\alpha}{8\pi}\sum_{res}\langle K\pi|K_{res}(n)\rangle\Big[(C_L+C_R)\langle K_{res}(n)|\bar{s}\gamma_\mu b|B\rangle + (C_R-C_L)\langle K_{res}(n)|\bar{s}\gamma_\mu\gamma_5 b|B\rangle\Big]\ell^\mu\widetilde{BW}_{res}(p^2). \quad (2)$$

Transversity amplitudes for $B \to K^*\nu\bar{\nu}$ [FFs from Bharucha, Straub, Zwicky (2016); Horgan et al. (2014)]

$$H_\perp(q^2) = \frac{\sqrt{2}(C_L+C_R)\lambda^{1/2}(m_B^2,q^2,m_{K^*}^2)}{m_B+m_{K^*}}V(q^2), \quad (3)$$

$$H_\parallel(q^2) = \sqrt{2}(C_L-C_R)(m_B+m_{K^*})A_1(q^2), \quad (4)$$

$$H_0(q^2) = -\frac{1}{2m_{K^*}\sqrt{q^2}}(C_L-C_R)\Big[(m_B+m_{K^*})(m_B^2-m_{K^*}^2-q^2)A_1(q^2) \quad (5)$$

$$-\frac{\lambda(m_B^2,q^2,m_{K^*}^2)}{m_B+m_{K^*}}A_2(q^2)\Big]. \quad (6)$$

Transversity amplitudes for $B \to K_0^* \nu \bar{\nu}$ [QCDSR FFs from Aliev, Azizi, Savci (2007)]

$$H_0'(q^2) = (C_R - C_L) \frac{\lambda^{1/2}(m_B^2, q^2, m_{K_0^*}^2)}{\sqrt{q^2}} f_+(q^2) \,. \tag{7}$$

Propagations of K^*, K_0^*, κ parametrized in terms of Breit-Wigner(like) parametrizations

$$\begin{aligned} \widetilde{BW}_{K^*}(p^2) &= \frac{1}{p^2 - m_{K^*}^2 + i m_{K^*}\Gamma_{K^*}}, \\ \widetilde{BW}_{\rm scalar}(p^2) &= -\frac{g_\kappa}{p^2 - (m_\kappa - i\Gamma_\kappa/2)^2} + \frac{1}{p^2 - (m_{K_0^*} - i\Gamma_{K_0^*}/2)^2}. \end{aligned} \tag{8}$$

first term in $\widetilde{BW}_{\rm scalar}$ for κ state $0 \le |g_\kappa| \le 0.2,\ arg(g_\kappa) = (\pi/2, \pi)$ [Becirevic, Tayduganov (2013)], consistent with measurements in $B \to K^*\ell\ell$ LHCb[1606.04731], LHCb[arXiv:1609.04736] The transversity amplitudes:

$$\begin{aligned} \widetilde{H}_{\parallel,\perp}(q^2, p^2, \cos\theta) &= -i\frac{1}{\sqrt{2}} g_{K^*K\pi} |\vec{p'}_K| \sin\theta_K\, \widetilde{BW}_{K^*}(p^2)\, H_{\parallel,\perp}(q^2), \\ \widetilde{H}_0(q^2, p^2, \cos\theta) &= -g_{K^*K\pi} |\vec{p'}_K| \cos\theta_K\, \widetilde{BW}_{K^*}(p^2)\, H_0(q^2), \\ \widetilde{H}'_0(q^2, p^2) &= g_{K_0^*K\pi} \widetilde{BW}_{\rm scalar}(p^2)\, H'_0(q^2), \end{aligned} \tag{9}$$

$K^*_{(0)}, \kappa \to K\pi$ couplings can be extracted from the data:

$$\langle K^i(p_K)\pi^j(p_\pi)|K^*(k,n)\rangle = c_{ij}(\epsilon_n \cdot p_K) g_{K^*K\pi}, \quad \langle K^i(p_K)\pi^j(p_\pi)|K^*_0(k)\rangle = c_{ij} g_{K^*_0 K\pi} \,. \tag{10}$$

Three-fold differential decay rate:

$$\frac{d^2\Gamma}{dq^2 dp^2 d\cos\theta_K} = a(q^2,p^2) + b(q^2,p^2)\cos\theta_K + c(q^2,p^2)\cos^2\theta_K. \tag{11}$$

with linear term probing interferences

$$b(q^2,p^2)\cos\theta_K \sim -2|\vec{p}_K|\Re(H_0 {H'}^*_0).$$

Observables:

$$\frac{d\Gamma}{dq^2} = 2\left(a(q^2) + \frac{c(q^2)}{3}\right), \tag{12}$$

$$F_L = \frac{d\Gamma_L/dq^2}{d\Gamma/dq^2}, \quad \frac{d\Gamma_L}{dq^2} = \frac{2}{3}\left(a(q^2) + c(q^2)\right), \tag{13}$$

SM predictions:

$$Br = (9.49 \pm 1.01) \times 10^{-6}, \quad \langle F_L \rangle = 0.49 \pm 0.04. \tag{14}$$

consistent with [Buras, Girrbach-Noe, Niehoff, Straub, (2014)]. We go beyond NWA. In addition, $A^K_{\rm FB}$, or $A^K_{\rm FB\,L}$:

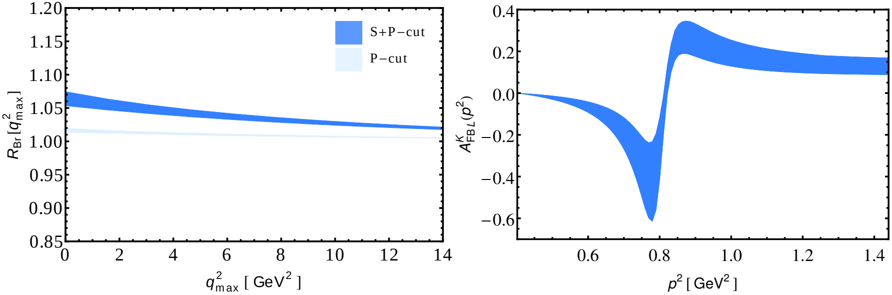
$$A^K_{\rm FB\,(L)} \equiv \frac{\int_0^1 d\cos\theta_K \frac{d^2\Gamma}{dq^2 d\cos\theta_K} - \int_{-1}^0 d\cos\theta_K \frac{d^2\Gamma}{dq^2 d\cos\theta_K}}{\Gamma_{(L)}} = \frac{b(q^2,p^2)}{\Gamma_{(L)}}, \tag{15}$$

induced by interference of the K^* with intermediate scalar states.

In $A^K_{\rm FB}$ C_L cancels when $C_R = 0$, in $A_{\rm FB\,(L)}$ both $C_{L,R}$ cancel, assuming Hamiltonian (1)

Two different integration regions for p^2

$[(m_{K^*} - 0.1\,\text{GeV})^2, (m_{K^*} + 0.1\,\text{GeV})^2]$	P-cut (signal region for K^*)
$[(m_K + m_\pi)^2, 1.44\,\text{GeV}^2]$	(S+P)-cut



$R_{Br} = \frac{\Gamma_V + \Gamma_S}{\Gamma_V}$ as a function of bin size.
Effect of scalars at level of percent in signal region.
A^K_{FB} probes the hadronic model independently of Wilson coefficients, would be challenging assess experimentally.

Non-resonant effects

The non-resonant matrix elements of the (axial-) vector currents between the B and the $K\pi$ parametrized in terms of form factors $w_\pm, h$, functions of p^2, q^2, θ_K. (r drops in limit $m_\nu \to 0$)

$$\begin{aligned}\langle K^i \pi^j | \bar{s}\gamma_\mu b | B\rangle &= c_{ij} h\, \epsilon_{\mu\nu\alpha\beta} p_B^\nu (p_K^\alpha + p_\pi^\alpha)(p_K^\beta - p_\pi^\beta), \\ \langle K\pi | \bar{s}\gamma_\mu \gamma_5 b | B\rangle &= c_{ij} \big[-i\, w_+ (p_{K\mu} + p_{\pi\mu}) - i w_- (p_{K\mu} - p_{\pi\mu}) - i r q_\mu \big].\end{aligned} \tag{16}$$

Leading order Heavy-Hadron-Chiral-Perturbation-Theory (HHχPT) results [Lee, Lu, Wise (1992)]

$$\begin{aligned} w_\pm(q^2, p^2, \theta_K) &= \pm \frac{g f_{B_d}}{2 f^2} \frac{m_B}{v\cdot p_\pi + \Delta}, \\ h(q^2, p^2, \theta_K) &= \frac{g^2 f_{B_d}}{2f^2} \frac{1}{(v\cdot p_\pi + \Delta)(v\cdot p_{K\pi} + \Delta + \mu_s)}, \end{aligned} \tag{17}$$

HHχPT coupling g related to $B^* \to B\pi$ coupling, evaluated on Lattice, $g = 0.569 \pm 0.076$ [Flynn et al. (2015)], previous evaluations [Abada et al (2002), Becirevic et al (2009)]

- Region of validity of HHχPT: soft π, K - large q^2. We take $q^2 > 14\,\mathrm{GeV}^2$

The non-resonant $B \to K\pi\nu_i\bar{\nu}_i$ decay amplitude

$$\mathcal{A}(B \to K\pi\nu_i\bar{\nu}_i) = -\frac{4G_F}{\sqrt{2}}\lambda_t \frac{\alpha}{8\pi}\left[(C_L + C_R)\langle K\pi|\bar{s}\gamma_\mu b|B\rangle + (C_R - C_L)\langle K\pi|\bar{s}\gamma_\mu\gamma_5 b|B\rangle\right]\ell^\mu. \tag{18}$$

Non-resonant transversity amplitudes:

$$H_\perp^{\mathrm{nr}} = (C_L + C_R)F_\perp^{\mathrm{nr}}\,,\, H_{0,\|}^{\mathrm{nr}} = (C_L - C_R)F_\perp^{nr} \tag{19}$$

with corresponding transversity FFs

$$
\begin{aligned}
F_{\perp}^{\mathrm{nr}} &= \sin\theta_K \frac{\lambda^{1/2}(m_{K\pi}^2, m_K^2, m_\pi^2)\lambda^{1/2}(m_B^2, p^2, q^2)}{2\sqrt{p^2}} h, \\
F_{\parallel}^{\mathrm{nr}} &= -\sin\theta_K \frac{\lambda^{1/2}(p^2, m_K^2, m_\pi^2)}{\sqrt{p^2}} w_-, \\
F_0^{\mathrm{nr}} &= \frac{i}{2\sqrt{q^2}}\left[w_- \frac{1}{p^2}\left((m_K^2 - m_\pi^2)\lambda^{1/2}(m_B^2, q^2, p^2) - (m_B^2 - p^2 - q^2)\lambda^{1/2}(m_K^2, m_\pi^2, p^2)\cos\theta_K\right)\right. \\
&\quad \left. + w_+ \lambda^{1/2}(m_B^2, q^2, p^2)\right].
\end{aligned}
\tag{20}
$$

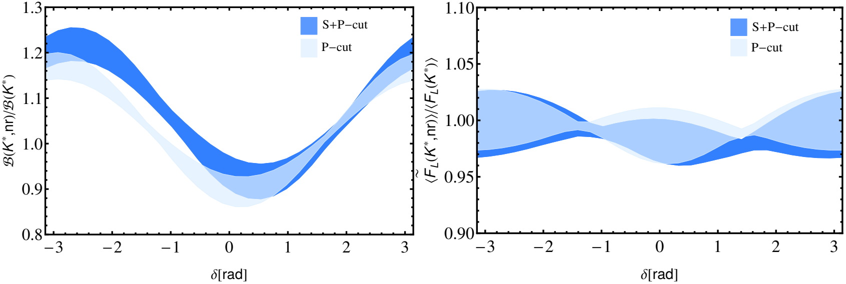
The diff. decay rate includes resonant and non-resonant amplitudes. Interference important, include unknown relative strong phase δ

$$
\frac{d^3\Gamma}{dq^2 dp^2 d\cos\theta_K} \propto \left[|e^{-i\,\delta}\widetilde{H}_\perp + H_\perp^{\mathrm{nr}}|^2 + |e^{-i\,\delta}\widetilde{H}_\parallel + H_\parallel^{\mathrm{nr}}|^2 + |e^{-i\,\delta}\widetilde{H}_0 + H_0^{\mathrm{nr}} + e^{-i\,\delta}\widetilde{H}_0'|^2\right]. \tag{21}
$$

- NR amplitudes expanded in terms of $P^m l_\ell(\theta_K)$, distribution contains terms higher than quadratic in $\cos\theta$.
- Definition of F_L and $A^K_{\mathrm{FB\,(L)}}$ more subtle. Use the projections with $P^0_0 = 1, P^0_1 = \cos\theta_K, P^0_2 = 1/2(3\cos^2\theta_K - 1)$

$$\frac{d\Gamma_L}{dq^2} = \int_{-1}^{1} \frac{d^2\Gamma}{dq^2 d\cos\theta_K}\left(\frac{1}{3}P^0_0 + \frac{5}{3}P^0_2\right) d\cos\theta_K, \tag{22}$$

$$b(q^2, p^2) = \int_{-1}^{1} \frac{d^2\Gamma}{dq^2 dp^2 d\cos\theta_K}\frac{3}{2}P^0_1\, d\cos\theta_K\,, \tag{23}$$



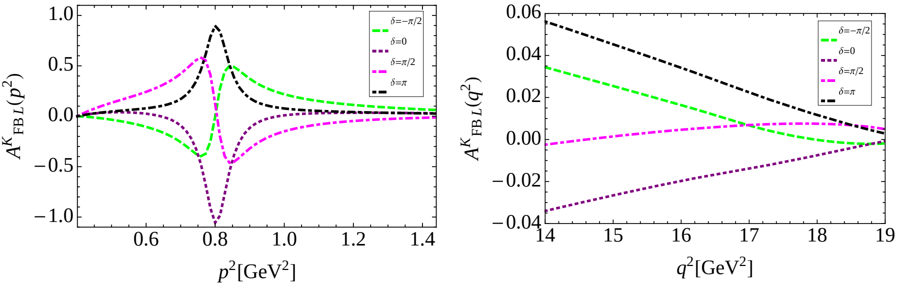
The effect up to $\mathcal{O}(0.1)$ in integrated Br (high q^2), depending on the strong phase. The effect of F_L at a percent level.

	low $q^2 \in [0-14]\,\mathrm{GeV}^2$	high $q^2 \in [14-19]\,\mathrm{GeV}^2$
$\mathcal{B}(B \to K^* \nu\bar{\nu})\|_{\mathrm{NWA}}$	6.96 ± 0.76	2.50 ± 0.22
$\mathcal{B}(B \to K^*(\to K\pi)\nu\bar{\nu})\|_{\text{P-cut}}$	6.01 ± 0.65	2.09 ± 0.22
$\mathcal{B}(B \to K^*(\to K\pi)\nu\bar{\nu})\|_{\text{S+P-cut}}$	6.80 ± 0.73	2.29 ± 0.23
$\mathcal{B}(B \to (\kappa, K_0^*)(\to K\pi)\nu\bar{\nu})\big\|_{\text{P-cut}}$	$[0.01 \ldots 0.07]$	–
$\mathcal{B}(B \to (\kappa, K_0^*)(\to K\pi)\nu\bar{\nu})\big\|_{\text{S+P-cut}}$	$[0.04 \ldots 0.30]$	–
$\mathcal{B}(B \to (K^* + \text{nonres})(\to K\pi)\nu\bar{\nu})\|_{\text{P-cut}}$	–	$2.09 \pm 0.22^{+0.42}_{-0.29}$
$\mathcal{B}(B \to (K^* + \text{nonres})(\to K\pi)\nu\bar{\nu})\|_{\text{S+P-cut}}$	–	$2.29 \pm 0.23^{+0.62}_{-0.27}$

Table: SM branching fractions in units of 10^{-6}

How to constraint the phase δ?

- Ratios of angular coefficients in $B \to K^* \ell\ell$, e.g. $I_7/I_5, I_7/I_6$ - sensitive to a phase above signal region (in p^2) [Das, Hiller, Jung (2015)]
- In $B \to K^* \nu\bar{\nu}$:



Summary

- Process $B \to K^* \nu\bar{\nu}$ free of charm effects, can be used for checking the FFs in entire q^2-region
- However, besides K^*, other resonant and non-resonant amplitudes enter $B \to K\pi\nu\bar{\nu}$ as well
- We check that scalar resonances result in small impact (percent-level in Br, negligible in F_L)
- NR effects seem more troubling, theoretically accessible in high q^2-region ($HH\chi PT$), depend on relative phase δ. Small effect on F_L. Important to constraint this phase.
- Crosschecks with $B \to K^* \ell\ell$ important.
- In the future: NR effects at low q^2?
- We use a plausible model to estimate the NR effects. Better theoretical understanding would be welcome.
- $B \to K^* \nu\bar{\nu}$ has access to a third generation lepton sector (ν_τ) as well, might shed some light on Lepton Universality Violation.