On the resonant and non-resonant effects in the $B \to K^* \nu \bar{\nu}$

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Work in progress

- $B \to K^*(\to K\pi)\nu\bar{\nu}$ is governed by $b \to s\bar{\nu}\nu$ FCNC transition and therefore sensitive to new physics

- The form factors are the only source of hadronic uncertainty in $B \to K^*\nu\bar{\nu}$

- The standard model short distance physics of $b \to s\bar{\nu}\nu$ transition is very well known

- Experimentally challenging, expected to be seen in the near future (Belle II)

- For new physics searches, resonant $B \to (K_0^*, \kappa)(\to K\pi)\nu\bar{\nu}$ and non-resonant $B \to K\pi\nu\bar{\nu}$ backgrounds become important

The $b \to s\bar{\nu}\nu$ effective Hamiltonian is

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

Altmannshofer *et al.* JHEP **0904** (2009) 022, Buras *et al.* JHEP **1502**, 184 (2015)

$C_L = -X(m_t^2/m_W^2)/\sin^2\theta$, including NLO QCD corrections and two-loop electroweak corrections
Buchalla *et al.* Nucl. Phys. B **400** (1993) 225/Nucl. Phys. B **548** (1999) 309, Misiak Phys. Lett. B **451** (1999) 161, Brod *et al.* Phys. Rev. D **83**, 034030 (2011)

$X(t) = 1.469 \pm 0.017$ Girrbach Noe arXiv:1410.3367

$C_R = 0$ in the Standard Model

The hadronic matrix elements of the vector and axial vector currents between the B and the final K^* are

$$\langle K^*(k,n)|\bar{s}\gamma_\mu b|B(p_B)\rangle = \epsilon_{\mu\nu\alpha\beta}\epsilon_n^{*\,\nu} p_B^\alpha k^\beta \frac{2iV(q^2)}{m_B + m_{K^*}},$$

$$\langle K^*(k,n)|\bar{s}\gamma_\mu\gamma_5 b|B(p_B)\rangle = -\epsilon^*_{n\,\mu}(m_B + m_{K^*})A_1(q^2) + (p_{B\,\mu} + k_\mu)\frac{\epsilon_n^* \cdot q}{m_B + m_{K^*}}A_2(q^2) +$$
$$+ q_\mu(\epsilon_n^* \cdot q)\frac{2m_{K^*}}{q^2}(A_3(q^2) - A_0(q^2)),$$

we use the form factors from combined fit to results in Lattice QCD and light-cone sum rules Bharucha *et al.* JHEP **08** (2016) 098, Horgan *et al.* Phys. Rev. D **89**, 094501 (2014), Ball *et al.* Phys. Rev. D **71**, 014029 (2005)

the B to K_0^* hadronic matrix element is

$$\langle K_0^*(k)|\bar{s}\gamma_\mu\gamma_5 b|B(p_B)\rangle = (p_B + k)_\mu f_+(q^2) + q_\mu f_-(q^2)$$

f_+ is known from calculations in the QCD sum rules Aliev *et al.* Phys. Rev. D **76**, 074017 (2007)

$$f_+(\hat{q}^2) = \frac{f_+(0)}{1 - a_+\hat{q}^2 + b_+\hat{q}^4}, \quad \hat{q}^2 = q^2/m_B^2$$

the parameters are $f_+(0) = 0.31 \pm 0.08$, $a_+ = 0.81$, $b_+ = -0.21$

we limit the region of validity to 14 GeV^2

The $B \to K^* \nu\bar{\nu}$ transversity amplitudes

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

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

$$H_0(q^2) = -\frac{(C_L - C_R)}{2m_{K^*}\sqrt{q^2}}\left[(m_B + m_{K^*})(m_B^2 - m_{K^*}^2 - q^2)A_1(q^2) - \frac{\lambda(m_B^2, q^2, m_{K^*}^2)}{m_B + m_{K^*}} A_2(q^2)\right].$$

The $B \to K_0^* \nu\bar{\nu}$ transversity amplitude

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

finite width of the K^* and the K_0^*, κ are taken into account by Breit-Wigner functions

$$\widetilde{BW}_{K^*}(p^2) = \frac{1}{p^2 - m_{K^*}^2 + im_{K^*}\Gamma_{K^*}},$$

$$\widetilde{BW}_{\text{scalar}}(p^2) = -\frac{g_\kappa}{p^2 - (m_\kappa - i\Gamma_\kappa/2)^2} + \frac{1}{p^2 - (m_{K_0^*} - i\Gamma_{K_0^*}/2)^2}$$

$0 \lesssim |g_\kappa| \lesssim 0.2$ and arg $\in [\pi, \pi/2]$

Becirevic *et al.* Nucl. Phys. B **868** (2013) 368

Denote $H_{0,\parallel,\perp} \to \widetilde{H}_{0,\parallel,\perp}$ and $H_0' \to \widetilde{H}_0'$

the $B \to K\pi$ matrix elements for vector and the axial vector currents are Lee *et al.* Phys. Rev. D **46** (1992) 5040

$$\langle K\pi|\bar{s}\gamma_\mu b|B\rangle = h\epsilon_{\mu\nu\alpha\beta}p_B^\nu(p_K^\alpha + p_\pi^\alpha)(p_K^\beta - p_\pi^\beta)$$
$$\langle K\pi|\bar{s}\gamma_\mu\gamma_5 b|B\rangle = -i\,w_+(p_{K\mu} + p_{\pi\mu}) - iw_-(p_{K\mu} - p_{\pi\mu}) - irq_\mu\ .$$

at leading order in heavy hadron chiral perturbation theory (HHχPT) Lee *et al.* Phys. Rev. D **46** (1992) 5040, Buchalla *et al.* Nucl. Phys. B **525** (1998) 333

$$w_\pm(q^2, p^2, \theta_K) = \pm\frac{gf_{B_d}}{2f^2}\frac{m_B}{v\cdot p_\pi + \Delta}\,, \quad v = p_B/m_B, \quad \Delta = m_{B^*} - m_B\,, f^2 = f_\pi f_K\,,$$

$$h(q^2, p^2, \theta_K) = \frac{g^2 f_{B_d}}{2f^2}\frac{1}{(v\cdot p_\pi + \Delta)(v\cdot p_{K\pi} + \Delta + \mu_s)}\,, \quad \mu_s = m_{B_s} - m_B\ .$$

HHχPT is valid when the 3-momentum of final state pseudoscalars are soft
(we take the region of validity from 14 GeV^2 to the kinematic endpoint)

HHχPT coupling $g = 0.569 \pm 0.076$ Flynn *et al.* 2013

we add 20% uncertainty on $w_\pm$ and h

the $B \to K\pi\nu\bar{\nu}$ transversity amplitudes are

$$H^{\rm nr}_{0,\|} = (C_L - C_R)F^{\rm nr}_{0,\|}\,, \quad H^{\rm nr}_{\perp} = (C_L + C_R)F^{\rm nr}_{\perp}\,.$$

the $B \to K\pi\nu\bar{\nu}$ transversity form factors read

$$F^{\rm nr}_{\perp} = \frac{\lambda^{1/2}(m^2_{K\pi}, m^2_K, m^2_\pi)\lambda^{1/2}(m^2_B, p^2, q^2)}{2\sqrt{p^2}}\, h \sin\theta_K,$$

$$F^{\rm nr}_{\|} = -\sin\theta_K \frac{\lambda^{1/2}(p^2, m^2_K, m^2_\pi)}{\sqrt{p^2}}\, w_-\,,$$

$$F^{\rm nr}_{0} = \frac{i}{2\sqrt{q^2}}\Bigg[w_+\lambda^{1/2}(m^2_B, q^2, p^2) + w_-\frac{1}{p^2}\bigg((m^2_K - m^2_\pi)\lambda^{1/2}(m^2_B, q^2, p^2) - (m^2_B - p^2 - q^2)\lambda^{1/2}(m^2_K, m^2_\pi, p^2)\cos\theta_K\bigg)\Bigg].$$

the transversity amplitudes can be expanded in terms of associated Legendre polynomials P^m_ℓ

$$F^{\rm nr}_0 = \sum_{\ell=0} a^\ell_0(q^2, p^2)\, P^{m=0}_\ell(\cos\theta_K)\,,$$

$$F^{\rm nr}_\| = \sum_{\ell=1} a^\ell_\|(q^2, p^2)\, \frac{P^{m=1}_\ell(\cos\theta_K)}{\sin\theta_K}\,,$$

$$F^{\rm nr}_\perp = \sum_{\ell=1} a^\ell_\perp(q^2, p^2)\, \frac{P^{m=1}_\ell(\cos\theta_K)}{\sin\theta_K}\,.$$

the three fold differential distribution is

$$\frac{d^3\Gamma}{dq^2 dp^2 d\cos\theta_K} = 3\mathcal{N}(q^2)\left[|\widetilde{H_\perp} + e^{i\,\delta_{K*}} H_\perp^{\rm nr}|^2 + |\widetilde{H_\parallel} + e^{i\,\delta_{K*}} H_\parallel^{\rm nr}|^2 + |\widetilde{H_0} + e^{i\,\delta_{K*}} H_0^{\rm nr} + \widetilde{H_0}'|^2\right].$$

δ_{K*} is the relative strong phase between the resonant and the non-resonant modes

the two-fold differential distribution in the presence of K^* and scalars (κ, K_0^*)

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

for a pure K^* contribution only $a(q^2), c(q^2)$ are nonzero and the longitudinal polarization fraction is

$$F_L = \frac{d\Gamma_L/dq^2}{d\Gamma/dq^2}, \quad \frac{d\Gamma_L}{dq^2} = \frac{2}{3}(a(q^2) + c(q^2))\,, \quad \langle F_L\rangle = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\Gamma_L/dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\Gamma/dq^2}$$

in presence of non-resonant $B \to K\pi\nu\bar{\nu}$ the two-fold distribution is more complicated

$$\tilde{F}_L = \frac{d\tilde{\Gamma}_L/dq^2}{d\Gamma/dq^2}, \quad \frac{d\tilde{\Gamma}_L}{dq^2} = \int_{-1}^{1} \frac{d^2\Gamma}{dq^2 d\cos\theta_K}\left(\frac{1}{3}P_0^0 + \frac{2\cdot 2+1}{3}P_2^0\right) d\cos\theta_K.$$

– our analysis is done in the following two p^2 windows

P-window or signal window: $[(m_{K^*} - 0.1\text{GeV})^2, (m_{K^*} + 0.1\text{GeV})^2]$ Aaij *et al.* JHEP **1308** (2013) 131

S+P-window: $[(m_K + m_\pi)^2, 1.44\,\text{GeV}^2]$

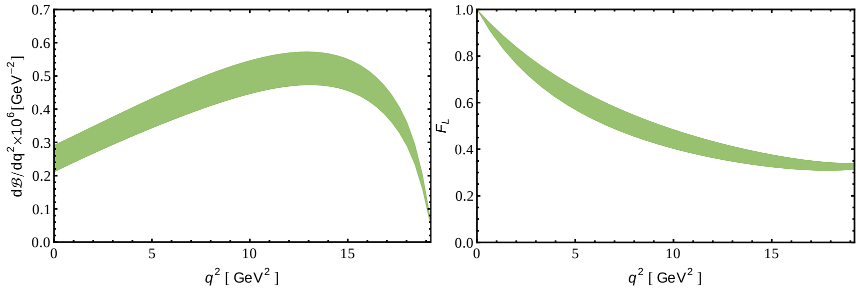

Figure: Differential branching ratio in q^2 (left) and longitudinal polarization fraction F_L (right) for a pure $B \to K^*(\to K\pi)\nu\bar{\nu}$ in the P-wave signal window with the K^* taken at finite width.

Linshapes

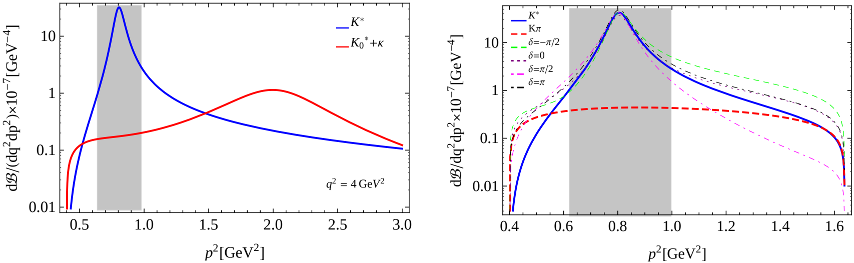

Figure: Left: Comparison of the p^2-lineshapes of the resonant K^*-contribution (solid blue line) and scalar meson contributions (K_0^*, κ) (red line) at $q^2 = 4\mathrm{GeV}^2$. The input parameters are set to the central values, and $g_\kappa = 0.2$, $\arg(g_\kappa) = \pi/2$. Right plot: Comparison of the p^2-lineshapes of the resonant K^*-contribution (solid blue), purely non-resonant contribution (dashed red) and the resulting lineshapes that also include the interferences, for several chosen values of the strong phase δ, at $q^2 = 16\mathrm{GeV}^2$. The vertical shaded region corresponds to the P-window region in p^2.

Impact of scalar background on branching ratio

– ratio of the integrated branching fractions as a function of the bin size in q^2:

$$R_{Br} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \int_{p^2_{\rm cut}} d^2\mathcal{B}(B \to K\pi\nu\bar{\nu})/(dq^2 dp^2)}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \int_{p^2_{\rm cut}} d^2\mathcal{B}(B \to (K^* \to K\pi)\nu\bar{\nu})/(dq^2 dp^2)}$$

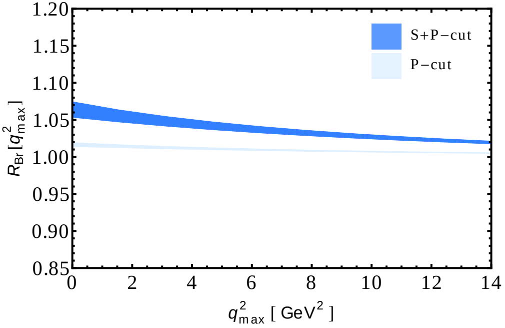

Figure: The $R_{Br}(q^2_{\rm max})$ is shown in the P- and S+P-wave signal window at large recoil. The bands correspond to the uncertainties due to form factors and input parameters.

Impact of non-resonant background on branching ratio

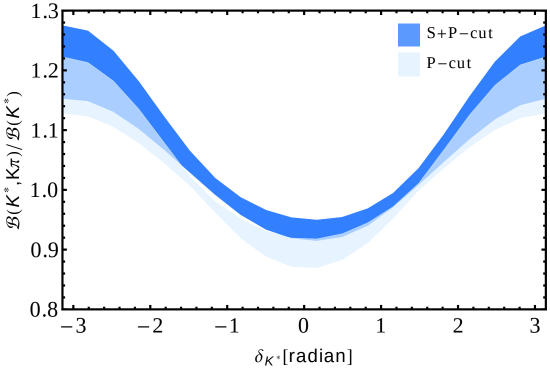

Figure: The ratio of total integrated branching ratio $\mathcal{B}(B \to (K^*, K\pi)(\to K\pi)\nu\bar{\nu})$ to $\mathcal{B}(B \to (K^*)(\to K\pi)\nu\bar{\nu})$ with respect to the relative strong phase δ_{K*}. The bands indicate uncertainties coming from form factors and input parameters. The light and dark bands correspond to P- and S+P-window cuts.

$\Longrightarrow$ the strong can be fixed from $B \to K^*\ell\ell$ and $B \to K\pi\ell\ell$ interference effects Das *et al.* 1506.06699

Preliminary Results

Total integrated branching ratio

	$\mathcal{B} \times 10^{-6}$ in [0-14] GeV^2	$\mathcal{B} \times 10^{-6}$ in [14-19] GeV^2
$\mathcal{B}(B \to K^*(\to K\pi)\nu\bar{\nu})\|_{\text{narrow}}$	6.97 ± 0.77	2.48 ± 0.26
$\mathcal{B}(B \to K^*(\to K\pi)\nu\bar{\nu})\|_{\text{P-cut}}$	5.91 ± 0.66	2.08 ± 0.21
$\mathcal{B}(B \to K^*(\to K\pi)\nu\bar{\nu})\|_{\text{P+S-cut}}$	6.51 ± 0.72	2.26 ± 0.23
$\mathcal{B}(B \to (K^*, K_0^*)(\to K\pi)\nu\bar{\nu})\|_{\text{P-cut}}$	5.95 ± 0.66	–
$\mathcal{B}(B \to (K^*, K_0^*)(\to K\pi)\nu\bar{\nu})\|_{\text{S+P-cut}}$	6.64 ± 0.72	–
$\mathcal{B}(B \to (K^*, \text{nonres})(\to K\pi)\nu\bar{\nu})\|_{\text{P-cut}}$	–	$2.12 \pm 0.22^{+0.44}_{-0.33}$
$\mathcal{B}(B \to (K^*, \text{nonres})(\to K\pi)\nu\bar{\nu})\|_{\text{S+P-cut}}$	–	$2.39 \pm 0.24^{+0.59}_{-0.27}$

$\Longrightarrow$ less sensitive to resonant scalars

Impact of non-resonant background on longitudinal polarization fraction

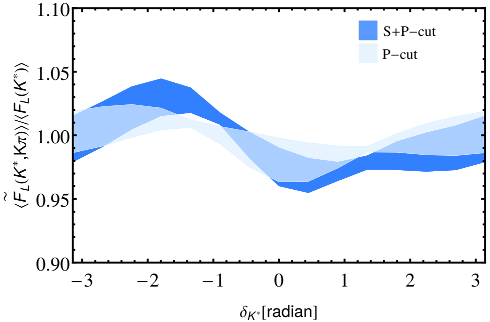

Figure: The total integrated longitudinal polarization fraction $\langle \tilde{F}_L(K^*, K\pi)\rangle$ to $\langle F_L(K^*)\rangle$ with respect to the relative strong phase δ_{K^*}. The bands indicate uncertainties coming from form factors and input parameters. The light and dark bands correspond to P- and S+P-window cuts.

Summary

we have studied the impacts of resonant and non-resonant backgrounds on $B \to K^* \nu\bar{\nu}$

depending on the relative strong phase there could be up to 30% effect on $\mathcal{B}$

F_L is less sensitive to the backgrounds, can be used to test form factors

Thank You