Probing New Physics with $b \to s\mu^+\mu^-$ and $b \to s\nu\bar{\nu}$ transitions

based on: JHEP **01** (2009) 019 (arXiv:0811.1214 [hep-ph]) and JHEP **04** (2009) 022 (arXiv:0902.0160 [hep-ph])

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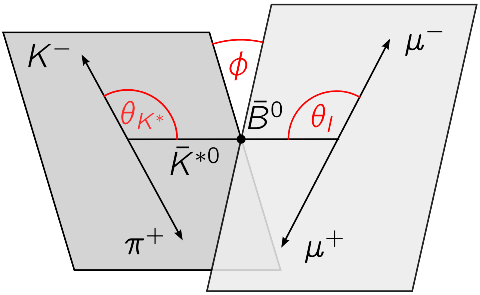
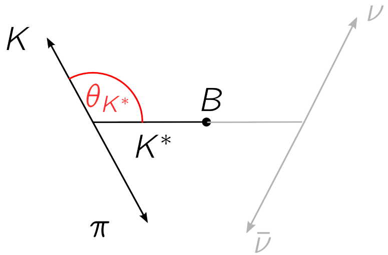
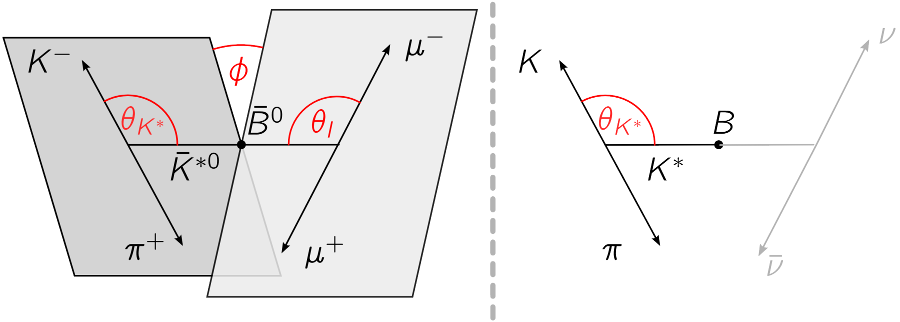
Technische Universität München

Introduction







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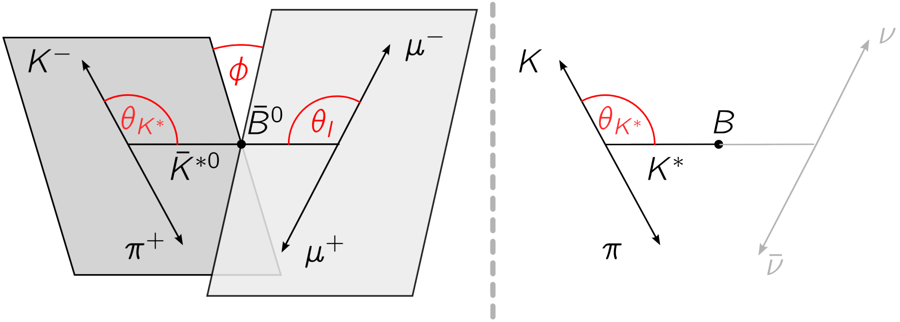

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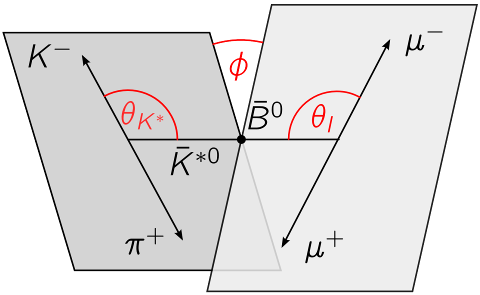

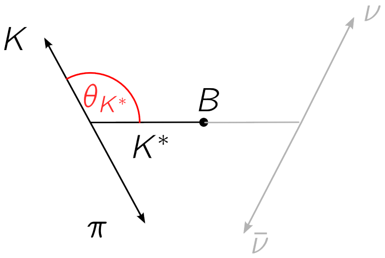

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- charge-conjugated mode $B^0 \longrightarrow K^{*0}(\longrightarrow K^+\pi^-)\mu^+\mu^-$ $\longrightarrow$ self-tagging & sensitive to CP violation!

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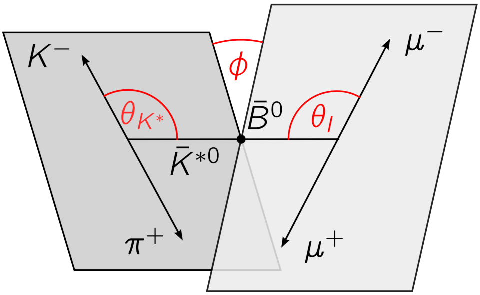

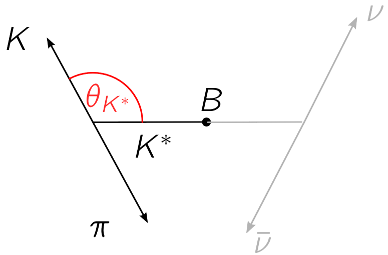

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- Massless, neutral particles in the final states $\longrightarrow$ transparent study of Z peguin effects.

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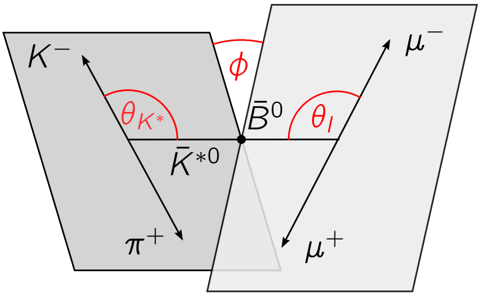

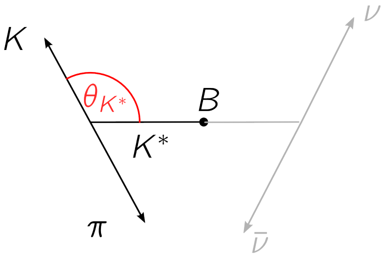

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- Massless, neutral particles in the final states $\longrightarrow$ transparent study of Z peguin effects.
- Super-B facilities make the measurement realistic

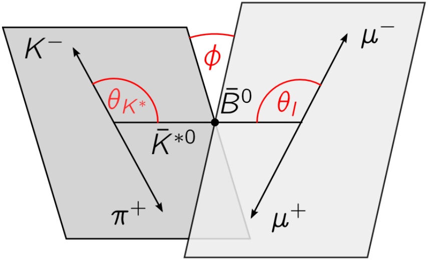
The Structure of this talk

- Motivation&Introduction
- $B \to K^*(\to K\pi)\mu^+\mu^-$
  - Theory (Observables etc.)
  - SM predictions
  - New Physics effects (MSSM scenarios)
- $B \to K^*(\to K\pi)\nu\bar{\nu}$ ($B \to K\nu\bar{\nu}$ and $B \to X_S\nu\bar{\nu}$)
  - Theory (Observables etc.)
  - SM predictions
  - New Physics effects (Model independent analysis, generic bsZ couplings, invisible scalars)
- Conclusions

Part I: $B \to K^* \mu^+ \mu^-$

$B \to K^*(\to K\pi)\mu^+\mu^-$ Angular Decay Distribution

The decay $\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\mu^+\mu^-$



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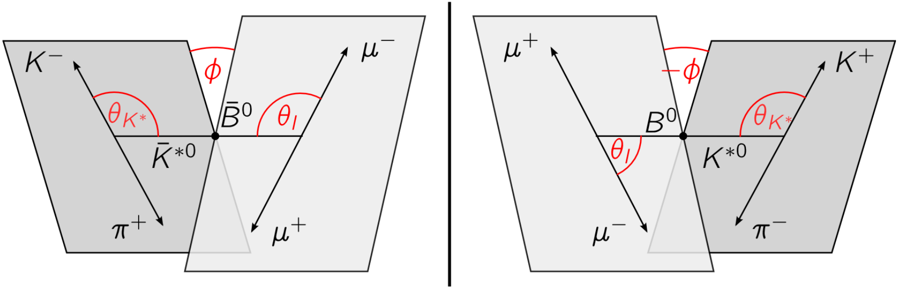
CP



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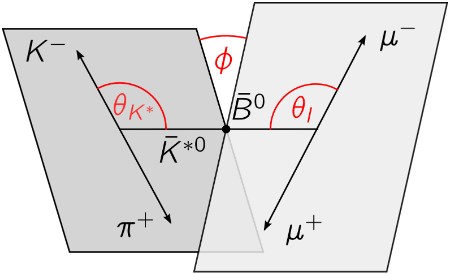

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} I(q^2, \theta_l, \theta_{K^*}, \phi)$$

$$q^2 = (p_{\mu^-} + p_{\mu^+})^2$$

[Krüger, Sehgal, Sinha, Sinha (1999)]

$$\begin{aligned} I(q^2, \theta_l, \theta_{K^*}, \phi) = {} & I_1^s \sin^2\theta_{K^*} + I_1^c \cos^2\theta_{K^*} + (I_2^s \sin^2\theta_{K^*} + I_2^c \cos^2\theta_{K^*}) \cos 2\theta_l \\ & + I_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi \\ & + I_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi \\ & + (I_6^s \sin^2\theta_{K^*} + I_6^c \cos^2\theta_{K^*}) \cos\theta_l + I_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi \\ & + I_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi \,. \end{aligned}$$

Angular coefficient functions $I_i^{(a)}(q^2)$ measurable by full angular fit to $d^4\Gamma$!

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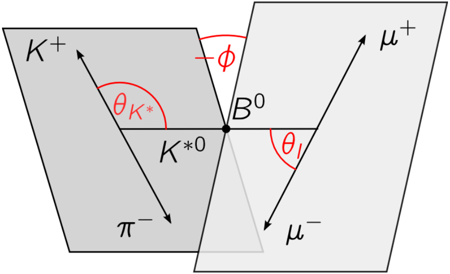

$$\frac{d^4\bar{\Gamma}}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi}\bar{I}(q^2, \theta_l, \theta_{K^*}, \phi)$$

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Angular Observables

- We have:
  - 12 angular coefficient functions $I_i^{(a)}(q^2)$ from $\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\mu^+\mu^-$
  - 12 angular coefficient functions $\bar{I}_i^{(a)}(q^2)$ from $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

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- We define:
  - CP-averaged angular coefficients

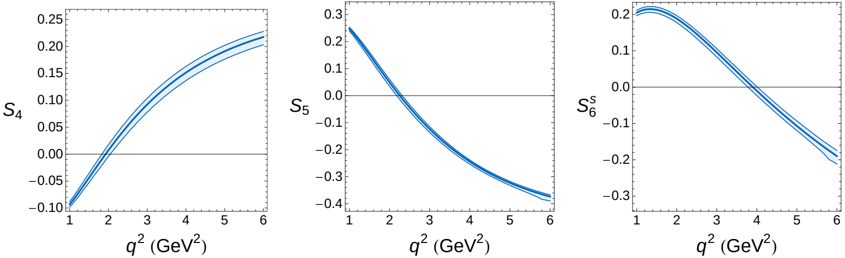
$$S_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) + \bar{I}_i^{(a)}(q^2)\right) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

  - CP asymmetries [Krüger, Sehgal, Sinha, Sinha (1999); Bobeth, Hiller, Piranishvili (2008)]

$$A_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) - \bar{I}_i^{(a)}(q^2)\right) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2} .$$

- $S_i^{(a)}$ and $A_i^{(a)}$ can be extracted from $d^4(\Gamma \pm \bar{\Gamma})$!

New Physics Impact on S_4, S_5 and S_6^s



- In the SM, S_4, S_5 and S_6^s each have a zero in q^2
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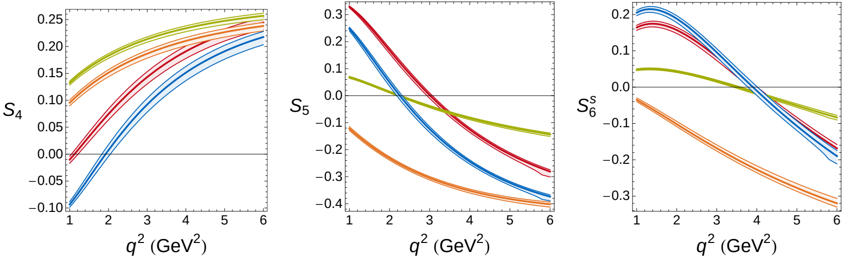

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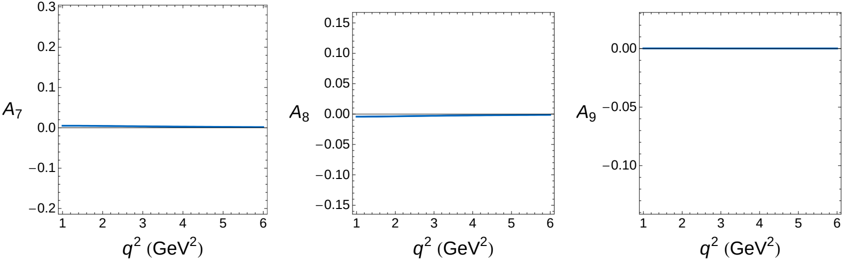
- Flavour-blind MSSM: $\tan\beta = 40$, $A_{\tilde{t}} = 900$ GeV, $\mathrm{Arg}(\mu A_{\tilde{t}}) = 50°$

[Altmannshofer, Buras, Paradisi (2008)]

- MSSM with complex $(\delta_d)_{32}^{LR}$ mass insertion $\rightarrow$ complex C_7'
- MSSM with complex $(\delta_{d,u})_{32}^{LR}$ mass insertions $\rightarrow$ complex $C_7^{(\prime)}$, C_{10}
- Pattern of effects highly model-dependent!

* (All points compatible with $\mathrm{BR}(B \to X_s \gamma)$, $\mathrm{BR}(B \to X_s \ell^+ \ell^-)$, $\Delta M_{s,d}$, …)

New Physics Impact on A_7, A_8 and A_9



- All CP asymmetries $A_i^{(a)}$ tiny in the SM
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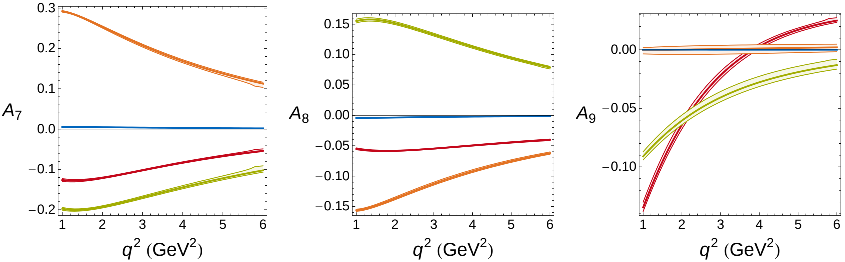

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Part II: $B \longrightarrow K^*\nu\bar{\nu}$

double differential decay distribution of $B \to K^* \nu \bar{\nu}$

$$B \to K^*(\to K\pi)\mu^+\mu^-$$

$$\frac{d^4\bar{\Gamma}}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi}$$
$$= I_1^s \sin^2\theta_{K^*} + I_1^c \cos^2\theta_{K^*}$$
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$$B \to K^* \nu\bar{\nu}$$

$$\frac{d^2\Gamma}{ds_B d\cos\theta_{K^*}}$$
$$= \frac{3}{4}\frac{d\Gamma_T}{dq^2}\sin^2\theta_{K^*} + \frac{3}{2}\frac{d\Gamma_L}{dq^2}\cos^2\theta_{K^*}$$

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$$= \frac{3}{4}\frac{d\Gamma_T}{dq^2} \sin^2\theta_{K^*} + \frac{3}{2}\frac{d\Gamma_L}{dq^2} \cos^2\theta_{K^*}$$

Differences

- neutrinos escape the detector unmeasured
- there are no strong phases $\to$ no CP asymmetries

double differential decay distribution of $B \to K^* \nu\bar{\nu}$

$B \to K^*(\to K\pi)\mu^+\mu^-$

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polarization fractions

$$F_{L,T} = \frac{d\Gamma_{L,T}/ds_B}{d\Gamma/ds_B}\,, \quad F_L = 1 - F_T\,.$$

- $s_B = q^2$
- $\frac{d\Gamma}{ds_B} = \frac{d\Gamma_L}{ds_B} + \frac{d\Gamma_T}{ds_B}$

Effective Hamiltonian for $b \to s\nu\nu$ transistions

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu\right) \;+\; \text{h.c.}\;,$$

$$\mathcal{O}_{R,L}^\nu = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_{R,L} b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)\;.$$

- **Standard Model**: $(C_L^\nu)^{\text{SM}} = -6.38 \pm 0.06$ and $(C_R^\nu)^{\text{SM}} = 0$
- **B decays**:
  - $B \to X_s \nu\bar{\nu}$
  - $B \to K \nu\bar{\nu}$
  - $B \to K^* \nu\bar{\nu}$

$B \to X_s \nu\bar{\nu}$ and $B \to K^* \nu\bar{\nu}$

$$\frac{d\Gamma(B \to K\nu\bar{\nu})}{ds_B} \propto \left[f_+^K(s_B)\right]^2 |C_L^\nu + C_R^\nu|^2 \ .$$

$$\frac{d\Gamma(B \to X_s\nu\bar{\nu})}{ds_b} \propto m_b^5 \kappa(0)(|C_L^\nu|^2 + |C_R^\nu|^2)$$

- $s_b = q^2/m_b^2$, where q^2 is the invariant mass of the neutrino-antineutrino pair
- **problem**: theoretical uncertainties, in particular from m_b^5
- **common approach**: normalization to the inclusive semileptonic decay rate $\Gamma(B \to X_c e \bar{\nu}_e)$
- **our approach**: use the m_b in the 1S scheme [Hoang,Ligeti, Manohar '98,Hoang '00], which is known to 1 % precision, $\to$ reduction of the error uncertainty in the branching ratio to less than 10 %

Our SM predictions & Experiment

Four observables in $B \to K^* \nu\bar{\nu}$, $B \to K^* \nu\bar{\nu}$ and $B \to X_s \nu\bar{\nu}$:

Observable	Our SM prediction	Experiment
$\mathrm{BR}(B \to K^* \nu\bar{\nu})$	$(6.8^{+1.0}_{-1.1}) \times 10^{-6}$	$< 80 \times 10^{-6}$
$\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu})$	$(4.5 \pm 0.7) \times 10^{-6}$	$< 14 \times 10^{-6}$
$\mathrm{BR}(B \to X_s \nu\bar{\nu})$	$(2.7 \pm 0.2) \times 10^{-5}$	$< 64 \times 10^{-5}$
$\langle F_L(B \to K^* \nu\bar{\nu}) \rangle$	0.54 ± 0.01	–

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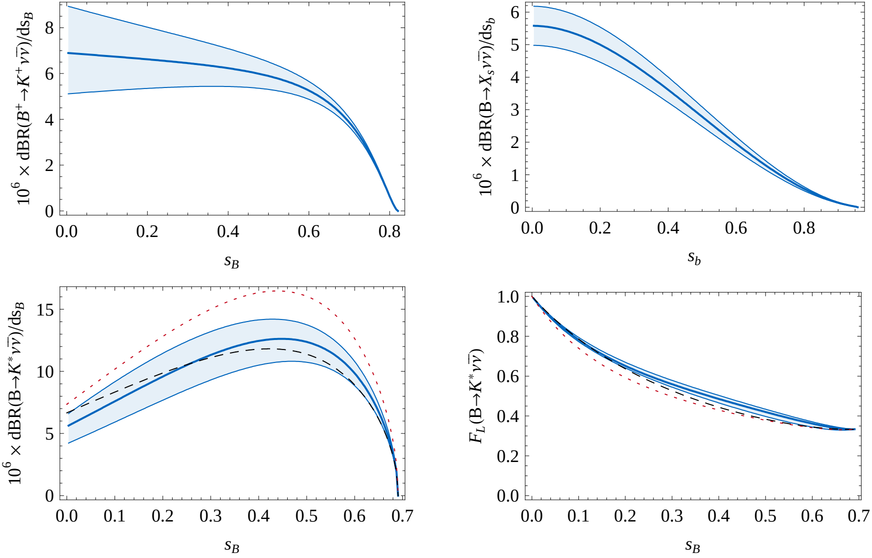

Model-independent constraints on Wilson coefficients

Only 2 combinations of the complex C_L^ν and C_R^ν enter the 4 observables:

$$\epsilon = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|(C_L^\nu)^{\text{SM}}|}\,, \qquad \eta = \frac{-\text{Re}\,(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}\,. \qquad (\epsilon, \eta)^{\text{SM}} = (1, 0)$$

$$\text{BR}(B \to K^* \nu\bar{\nu}) = 6.8 \times 10^{-6}\,(1 + 1.31\,\eta)\epsilon^2$$
$$\text{BR}(B \to K \nu\bar{\nu}) = 4.5 \times 10^{-6}\,(1 - 2\,\eta)\epsilon^2$$
$$\text{BR}(B \to X_s \nu\bar{\nu}) = 2.7 \times 10^{-5}\,(1 + 0.09\,\eta)\epsilon^2$$
$$\langle F_L \rangle = 0.54\,\frac{(1 + 2\,\eta)}{(1 + 1.31\,\eta)}$$

where $\langle F_L \rangle = \Gamma_L(B \to K^* \nu\bar{\nu})/\Gamma(B \to K^* \nu\bar{\nu})$

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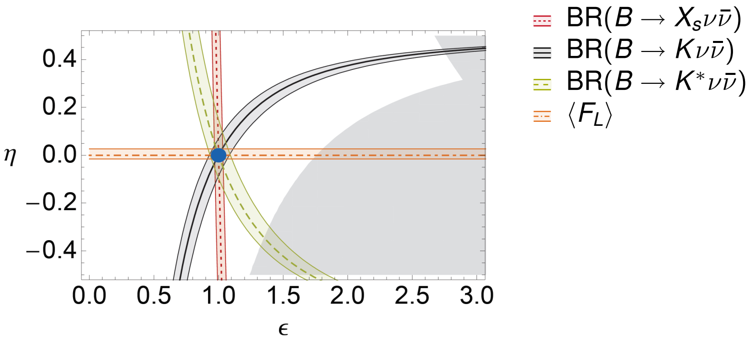
$$\epsilon = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|(C_L^\nu)^{\text{SM}}|}, \qquad \eta = \frac{-\text{Re}\,(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}. \qquad (\epsilon, \eta)^{\text{SM}} = (1, 0)$$



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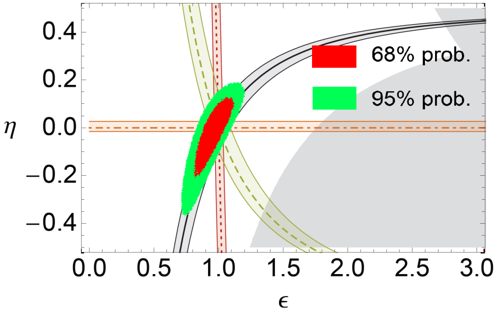

- BR($B \to X_s \nu\bar{\nu}$)
- BR($B \to K \nu\bar{\nu}$)
- BR($B \to K^* \nu\bar{\nu}$)
- $\langle F_L \rangle$
- projected sensitivity at Super*B*with 75ab^{-1} . [Talk of F. Renga@Super*B*Physics Workshop in Warwick]

Modified Z penguins

Effective flavour violating $\bar{b}sZ$ coupling

$$\mathcal{L}_{\text{eff}}^{\bar{b}sZ} = \frac{G_F}{\sqrt{2}} \frac{e}{\pi^2} m_Z^2 c_w s_w V_{tb}^* V_{ts} \, Z^\mu \left(Z_L \, \bar{b}\gamma_\mu P_L s + Z_R \, \bar{b}\gamma_\mu P_R s \right) \, ,$$

[Buchalla, Hiller, Isidori (2001)]

Motivation: In many models beyond the SM, NP effects in the Wilson coefficients $C_{L,R}^{\nu}$ are dominated by Z penguins. This couplings enter in:

- $C_{L,R}^{\nu}$
- B_s mixing
- $\text{BR}(B \to X_s \ell^+ \ell^-)$
- $\text{BR}(B_s \to \mu^+ \mu^-)$

$\Rightarrow$ interesting correlations

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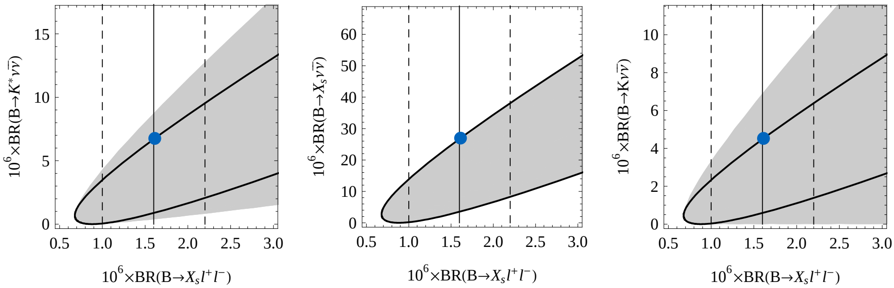

- black curves: $Z_R = 0$ and Z_L real
- shaded areas: arbitrary and complex $Z_{L,R}$

Decay to Invisible Scalars

effective Hamiltonian for flavour-changing quark-scalar

$$\mathcal{H}_{\text{eff}} = C_L^S \frac{m_b}{2} (\bar{s} P_L b) S^2 + C_R^S \frac{m_b}{2} (\bar{s} P_R b) S^2 \ .$$

$$\frac{d\Gamma(B \to X_s \not{E})}{ds_b} = \frac{d\Gamma(B \to X_s \nu \bar{\nu})}{ds_b} + \frac{d\Gamma(B \to X_s SS)}{ds_b} \ ,$$

Decay to Invisible Scalars

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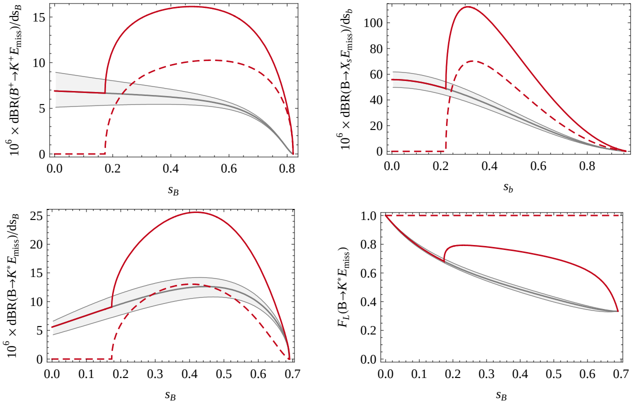

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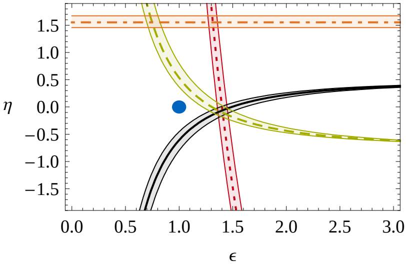

- characteristic kinematical edges in the spectra
  - model-dependence of cuts!
- observables no longer described in terms of (ϵ, η)!
- $\langle F_L \rangle$ displays the invalidity of extracting ϵ and η

Conclusions

- Part I:
  - The decay $B \to K^*(\to K\pi)\mu^+\mu^-$ gives access to **24 observables** sensitive to New Physics!
    - Theoretical and experimental uncertainties are minimized by choosing 12 CP averaged observables $S_i^{(a)}$ and 12 CP asymmetries $A_i^{(a)}$
  - Excellent channel for LHCb!
    - roughly 4000 signal events expected with $\int \mathcal{L} = 2\ \text{fb}^{-1}$ [Egede (2007)]
  - Correlations between the observables are highly model-dependent and thus allow to **distinguish** between different models of New Physics!
- Part II:
  - Theoretical uncertainties in the branching ratios of $B \to K^*\nu\bar{\nu}$, $B \to K\nu\bar{\nu}$ and $B \to X_s\nu\bar{\nu}$ are **comparable to or smaller than** projected experimental uncertainties at Super$B$
  - The **angular observable** F_L in $B \to K^*\nu\bar{\nu}$ probes right-handed currents
  - Introduction of an elegant way of visualization of constraints of the Wilson coefficients in the (ϵ, η) plane.

Backup

Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\left(\lambda_t \mathcal{H}_{\text{eff}}^{(t)} + \lambda_u \mathcal{H}_{\text{eff}}^{(u)}\right)$$

with the CKM combination $\lambda_i = V_{ib} V_{is}^*$ and

$$\begin{aligned}
\mathcal{H}_{\text{eff}}^{(t)} &= C_1 \mathcal{O}_1^c + C_2 \mathcal{O}_2^c + \sum_{i=3}^{6} C_i \mathcal{O}_i + \sum_{i=7,8,9,10,P,S} \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i'\right), \\
\mathcal{H}_{\text{eff}}^{(u)} &= C_1 (\mathcal{O}_1^c - \mathcal{O}_1^u) + C_2 (\mathcal{O}_2^c - \mathcal{O}_2^u)\,.
\end{aligned}$$

Effective Hamiltonian – operator basis

$$\mathcal{O}_7 = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}, \qquad \mathcal{O}'_7 = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu},$$

$$\mathcal{O}_8 = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} T^a P_R b) G^{\mu\nu\, a}, \qquad \mathcal{O}'_8 = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} T^a P_L b) G^{\mu\nu\, a},$$

$$\mathcal{O}_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu), \qquad \mathcal{O}'_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \mu),$$

$$\mathcal{O}_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu), \qquad \mathcal{O}'_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \gamma_5 \mu),$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2} m_b (\bar{s} P_R b)(\bar{\mu}\mu), \qquad \mathcal{O}'_S = \frac{e^2}{16\pi^2} m_b (\bar{s} P_L b)(\bar{\mu}\mu),$$

$$\mathcal{O}_P = \frac{e^2}{16\pi^2} m_b (\bar{s} P_R b)(\bar{\mu}\gamma_5 \mu), \qquad \mathcal{O}'_P = \frac{e^2}{16\pi^2} m_b (\bar{s} P_L b)(\bar{\mu}\gamma_5 \mu),$$

$B \to K^*$ form factors

$$\langle \bar{K}^*(k)|\bar{s}\gamma_\mu(1-\gamma_5)b|\bar{B}(p)\rangle =$$
$$- i\epsilon^*_\mu(m_B + m_{K^*})A_1(q^2) + i(2p-q)_\mu(\epsilon^*\cdot q)\,\frac{A_2(q^2)}{m_B+m_{K^*}}$$
$$+ iq_\mu(\epsilon^*\cdot q)\,\frac{2m_{K^*}}{q^2}\,\left[A_3(q^2) - A_0(q^2)\right] + \epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p^\rho k^\sigma\,\frac{2V(q^2)}{m_B+m_{K^*}},$$

$$\langle \bar{K}^*(k)|\bar{s}\sigma_{\mu\nu}q^\nu(1+\gamma_5)b|\bar{B}(p)\rangle = i\epsilon_{\mu\nu\rho\sigma}\epsilon^{*\nu}p^\rho k^\sigma\,2T_1(q^2)$$
$$+ T_2(q^2)\left[\epsilon^*_\mu(m_B^2 - m_{K^*}^2) - (\epsilon^*\cdot q)\,(2p-q)_\mu\right]$$
$$+ T_3(q^2)(\epsilon^*\cdot q)\left[q_\mu - \frac{q^2}{m_B^2 - m_{K^*}^2}\,(2p-q)_\mu\right],$$

$$\langle \bar{K}^*|\partial_\mu A^\mu|\bar{B}\rangle = (m_b + m_s)\langle \bar{K}^*|\bar{s}i\gamma_5 b|\bar{B}\rangle = 2m_{K^*}(\epsilon^*\cdot q)A_0(q^2). \qquad (1)$$

$B \to K^*(\to K\pi)\mu^+\mu^-$ amplitude

$$
\begin{aligned}
\mathcal{M} =& \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \Big\{ \Big[\langle K\pi | \bar{s}\gamma^\mu (C_9^{\text{eff}} P_L + C_9^{\prime\text{eff}} P_R) b | \bar{B} \rangle \\
& - \frac{2m_b}{q^2} \langle K\pi | \bar{s} i\sigma^{\mu\nu} q_\nu (C_7^{\text{eff}} P_R + C_7^{\prime\text{eff}} P_L) b | \bar{B} \rangle \Big] (\bar{\mu}\gamma_\mu \mu) \\
& + \langle K\pi | \bar{s}\gamma^\mu (C_{10}^{\text{eff}} P_L + C_{10}^{\prime\text{eff}} P_R) b | \bar{B} \rangle (\bar{\mu}\gamma_\mu \gamma_5 \mu) \\
& + \langle K\pi | \bar{s} (C_S P_R + C_S' P_L) b | \bar{B} \rangle (\bar{\mu}\mu) + \langle K\pi | \bar{s} (C_P P_R + C_P' P_L) b | \bar{B} \rangle (\bar{\mu}\gamma_5 \mu) \Big\}.
\end{aligned}
$$

Transversity amplitudes

$$A_{\perp L,R} = N\sqrt{2}\lambda^{1/2}\Bigg[\Big[(C_9^{\text{eff}} + C_9^{\text{eff}\prime}) \mp (C_{10}^{\text{eff}} + C_{10}^{\text{eff}\prime})\Big]\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\text{eff}} + C_7^{\text{eff}\prime})T_1(q^2)\Bigg],$$

$$A_{\parallel L,R} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\Bigg[\Big[(C_9^{\text{eff}} - C_9^{\text{eff}\prime}) \mp (C_{10}^{\text{eff}} - C_{10}^{\text{eff}\prime})\Big]\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\text{eff}} - C_7^{\text{eff}\prime})T_2(q^2)\Bigg],$$

$$A_{0L,R} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\Bigg\{\Big[(C_9^{\text{eff}} - C_9^{\text{eff}\prime}) \mp (C_{10}^{\text{eff}} - C_{10}^{\text{eff}\prime})\Big] \times \Bigg[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})A_1(q^2) - \lambda\frac{A_2(q^2)}{m_B + m_{K^*}}\Bigg] + 2m_b(C_7^{\text{eff}} - C_7^{\text{eff}\prime})\Bigg[(m_B^2 + 3m_{K^*}^2 - q^2)T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2}T_3(q^2)\Bigg]\Bigg\},$$

Transversity amplitudes

$$A_t = \frac{N}{\sqrt{q^2}}\lambda^{1/2}\left[2(C_{10}^{\text{eff}} - C_{10}^{\text{eff}\prime}) + \frac{q^2}{2m_\mu}(C_P - C_P')\right] A_0(q^2),$$

$$A_S = -N\lambda^{1/2}(C_S - C_S')A_0(q^2),$$

$$N = V_{tb}V_{ts}^* \left[\frac{G_F^2\alpha^2}{3\cdot 2^{10}\pi^5 m_B^3} q^2 \lambda^{1/2}\beta_\mu\right]^{1/2},$$

$$\lambda = m_B^4 + m_{K^*}^4 + q^4 - 2(m_B^2 m_{K^*}^2 + m_{K^*}^2 q^2 + m_B^2 q^2)$$

$$\beta_\mu = \sqrt{1 - 4m_\mu^2/q^2}$$

Angular coefficients

$$I_1^s = \frac{(2+\beta_\mu^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R)\right] + \frac{4m_\mu^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R^*} + A_\parallel^L A_\parallel^{R^*}\right),$$

$$I_1^c = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\mu^2}{q^2}\left[|A_t|^2 + 2\mathrm{Re}(A_0^L A_0^{R^*})\right] + \beta_\mu^2|A_S|^2,$$

$$I_2^s = \frac{\beta_\mu^2}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R)\right],$$

$$I_2^c = -\beta_\mu^2\left[|A_0^L|^2 + (L\to R)\right],$$

$$I_3 = \frac{1}{2}\beta_\mu^2\left[|A_\perp^L|^2 - |A_\parallel^L|^2 + (L\to R)\right],$$

$$I_4 = \frac{1}{\sqrt{2}}\beta_\mu^2\left[\mathrm{Re}(A_0^L A_\parallel^{L^*}) + (L\to R)\right],$$

$$I_5 = \sqrt{2}\beta_\mu\left[\mathrm{Re}(A_0^L A_\perp^{L^*}) - (L\to R) - \frac{m_\mu}{\sqrt{q^2}}\mathrm{Re}(A_\parallel^L A_S^* + A_\parallel^R A_S^*)\right],$$

Angular coefficients

$$I_6^s = 2\beta_\mu \left[\mathrm{Re}(A_\parallel^L A_\perp^{L\,*}) - (L \to R) \right],$$

$$I_6^c = 4\beta_\mu \frac{m_\mu}{\sqrt{q^2}} \, \mathrm{Re}\left[A_0^L A_S^* + (L \to R) \right],$$

$$I_7 = \sqrt{2}\beta_\mu \left[\mathrm{Im}(A_0^L A_\parallel^{L\,*}) - (L \to R) + \frac{m_\mu}{\sqrt{q^2}} \, \mathrm{Im}(A_\perp^L A_S^* + A_\perp^R A_S^*) \right],$$

$$I_8 = \frac{1}{\sqrt{2}} \beta_\mu^2 \left[\mathrm{Im}(A_0^L A_\perp^{L\,*}) + (L \to R) \right],$$

$$I_9 = \beta_\mu^2 \left[\mathrm{Im}(A_\parallel^{L\,*} A_\perp^L) + (L \to R) \right].$$

$S_i^{(a)}$ and $A_i^{(a)}$ in the Standard Model