Theory overview on $B \to K^* \ell^+ \ell^-$ and other rare decays

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Outline

- Motivations
- Theoretical framework
- Definition of observables
- Few words on other rare decays
- Implications
  - Supersymmetry
  - Model independent analysis
- SuperIso
- Flavour Les Houches Accord
- Conclusion

Motivations

- Flavour violation occurs only via W
- FCNC can only happen in loops
  $\rightarrow$ FCNC's are excellent probes for new physics!
- Most popular FCNC: $b \rightarrow s\gamma$
  extremely useful and powerful
  but limited number of related observables
- $b \rightarrow s\ell^+\ell^-$ on the other hand gives rise to a variety of observables!
  main drawback: low statistics
  but promising experimental situation!

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Framework

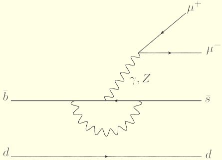
- Effective field theory approach
- Separation of short-distance from long-distance QCD in an effective Hamiltonian
  $\rightarrow$ Particles with mass larger than the factorization scale are integrated out
- Calculation of the short distance quantities (Wilson coefficients)
- Calculation of matrix elements of local quark operators (form factors)
- For large recoil energy (small q^2), QCD factorization (QCDF) and Soft Collinear Effective Theory (SCET)
- For small recoil energy (large q^2), Operator Product Expansion (OPE) and Heavy Quark Effective Theory (HQET)

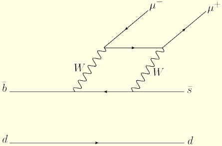
Effective Hamiltonian

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum_{i=1\cdots 10,S,P} \left(C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu) \right) \right)$$

New physics:

- Corrections to the Wilson coefficients: $C_i \to C_i + \Delta C_i^{NP}$
- Additional operators: $\sum_j C_j^{NP} \mathcal{O}_j^{NP}$





$\mathcal{O}$perators

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

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

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

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

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

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

Primed operators: opposite chirality to the unprimed ones: vanish or highly suppressed in the SM

Wilson coefficients

Wilson coeff.	description	SM	enhancement in models
$C_{1,2}$	charged current	YES	
$C_{3,\ldots,6}$	QCD penguins	YES	SUSY
$C_{7,8}$	γ, g-dipole	YES	SUSY, large $\tan\beta$
$C_{9,10}$	(axial-)vector	YES	SUSY
$C_{S,P}$	(pseudo-)scalar	$\sim m_l m_b/m_W^2$	SUSY, large $\tan\beta$, R-parity viol.
$C'_{S,P}$	(pseudo-)scalar flipped	$\sim m_l m_s/m_W^2$	SUSY, R-parity viol.
$C'_{3,\ldots,6}$	QCD peng. flipped	$\sim m_s/m_b$	SUSY
$C'_{7,8}$	γ, g-dipole flipped	$\sim m_s/m_b$	SUSY, esp. large $\tan\beta$
$C'_{9,10}$	(axial-)vector flipped	$\sim m_s/m_b$	SUSY
$C_{T,T5}$	tensor	negligible	leptoquarks

G. Hiller, arXiv:0911.4054

Wilson coefficients

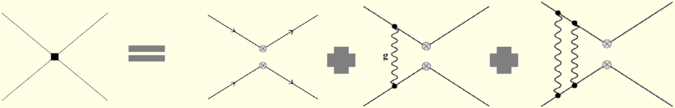
- Wilson coefficients encode short-distance physics and possible NP effects
- Calculated at the matching scale $\mu = m_W$
- Perturbative expansion in powers of $\alpha_s(m_W)$
- Evolved down to scales $\mu \sim m_b$ according to the solution of the renormalization group equations

The Wilson coefficients are expanded as:

$$C_i = C_i^{(0)} + \frac{\alpha_s}{4\pi} C_i^{(1)} + \left(\frac{\alpha_s}{4\pi}\right)^2 C_i^{(2)} + O(\alpha_s^3)\,,$$

$C_i^{(0)}$: tree-level contributions, vanish for all operators but $\mathcal{O}_2$
$C_i^{(n)}$: n-loop contributions

Matching



Matching each order of the Wilson coefficients C_i with the full theory

Calculating higher order corrections is crucial in B-physics.

For example, scale uncertainty of branching fraction of $B \to X_s \ell^+ \ell^-$:

$$\text{NLO: 15-20\%} \to \text{NNLO: 3-5\%}$$

Renormalization Group Evolution

Evolving the $C_i^{eff}(\mu)$ from the matching scale $\mu \sim M_W$ to scale $\mu \sim m_b$ using the RGE:

$$\mu \frac{d}{d\mu} C_i^{eff}(\mu) = C_j^{eff}(\mu) \gamma_{ji}^{eff}(\mu)$$

driven by the anomalous dimension matrix $\hat{\gamma}^{eff}(\mu)$:

$$\hat{\gamma}^{eff}(\mu) = \frac{\alpha_s(\mu)}{4\pi} \hat{\gamma}^{(0)eff} + \frac{\alpha_s^2(\mu)}{(4\pi)^2} \hat{\gamma}^{(1)eff} + \cdots$$

$\hat{\gamma}^{eff}$ can be decomposed in perturbative series
$\rightarrow$ RGE performed order by order

Form factors

The $B \to K^*$ matrix elements can be expressed in terms of seven form factors depending on q^2:

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

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

with $A_3(q^2) = \frac{m_B+m_{K^*}}{2m_{K^*}}\,A_1(q^2) - \frac{m_B-m_{K^*}}{2m_{K^*}}\,A_2(q^2)$ and $A_0(0)=A_3(0)$

Form factors are hadronic quantities → non-perturbative calculation

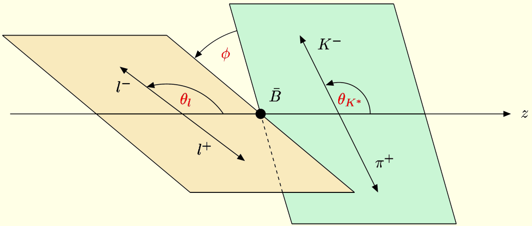
→ lattice calculation, but no full set of form factors available yet
→ QCD sum rules on the light-cone (LCSR)

Exclusive vs Inclusive

- The effective field theory approach serves as a theoretical framework for both inclusive and exclusive modes
- Wilson coefficients enter both inclusive and exclusive processes
- The calculational approaches to the matrix elements of the operators differ in both cases.
- Inclusive: dominated by the partonic contributions
- Non-perturbative effects are small
- Exclusive: simpler from the experimental point of view, but large non perturbative effects.

Observables

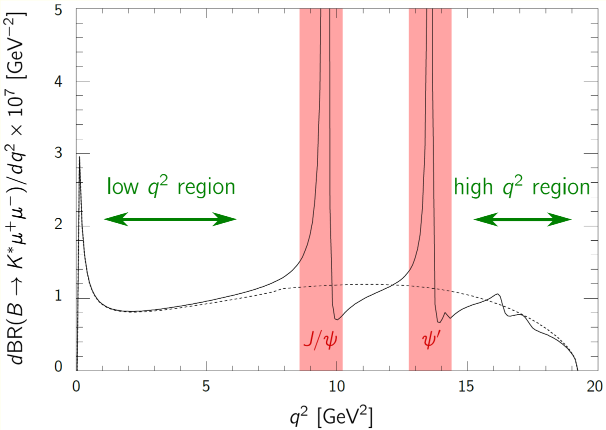
Angular distributions



The full angular distribution of the decay $\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-$ with $\bar{K}^{*0} \to K^-\pi^+$ on the mass shell is completely described by four independent kinematic variables:

- q^2: dilepton invariant mass squared
- θ_ℓ: angle between ℓ^- and the $\bar{B}$ in the dilepton frame
- θ_{K^*}: angle between K^- and $\bar{B}$ in the $K^-\pi^+$ frame
- ϕ: angle between the normals of the $K^-\pi^+$ and the dilepton planes

Low q^2 vs high q^2



Low q^2 vs high q^2

- Low q^2
  - reliable q^2 spectrum
  - small $1/m_b$ corrections
  - sensitivity to the interference of C_7 and C_9
  - high rate
  - difficult to perform a fully inclusive measurements
  - long-distance effects not fully under control
  - non-negligible scale and m_c dependence
- High q^2
  - negligible scale and m_c dependence due to the strong sensitivity to C_{10}
  - easier to perform a fully inclusive measurement (small hadronic invariant mass)
  - negligible long-distance effects of the type $B \to J/\Psi X_s \to X_s + X' \ell^+ \ell^-$
  - q^2 spectrum not reliable
  - sizable $1/m_b$ corrections
  - low rate.

Differential decay distribution

Differential decay distribution:

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

with

$$\begin{aligned} J(q^2, \theta_\ell, \theta_{K^*}, \phi) = {} & J_1^s \sin^2\theta_{K^*} + J_1^c \cos^2\theta_{K^*} + (J_2^s \sin^2\theta_{K^*} + J_2^c \cos^2\theta_{K^*}) \cos 2\theta_\ell \\ & + J_3 \sin^2\theta_{K^*} \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_{K^*} \sin 2\theta_\ell \cos\phi \\ & + J_5 \sin 2\theta_{K^*} \sin\theta_\ell \cos\phi + J_6 \sin^2\theta_{K^*} \cos\theta_\ell + J_7 \sin 2\theta_{K^*} \sin\theta_\ell \sin\phi \\ & + J_8 \sin 2\theta_{K^*} \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_{K^*} \sin^2\theta_\ell \sin 2\phi \end{aligned}$$

and

$$4m_\ell^2 \leqslant q^2 \leqslant (M_B - m_{K^*})^2, \quad -1 \leqslant \cos\theta_\ell \leqslant 1, \quad -1 \leqslant \cos\theta_{K^*} \leqslant 1, \quad 0 \leqslant \phi \leqslant 2\pi$$

Transversity amplitudes

The functions J_{1-9} can be written in terms of the transversity amplitudes, A_0, $A_\|$, $A_\perp$, A_t, and A_S:

$$
\begin{aligned}
J_1^s &= \frac{(2+\beta_\ell^2)}{4}\left[|A_\perp^L|^2 + |A_\|^L|^2 + (L\to R)\right] + \frac{4m_\ell^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R}{}^* + A_\|^L A_\|^{R}{}^*\right)\\
J_1^c &= |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\ell^2}{q^2}\left[|A_t|^2 + 2\mathrm{Re}(A_0^L A_0^{R}{}^*)\right] + \beta_\ell^2|A_S|^2\\
J_2^s &= \frac{\beta_\ell^2}{4}\left[|A_\perp^L|^2 + |A_\|^L|^2 + (L\to R)\right] \quad , \quad J_2^c = -\beta_\ell^2\left[|A_0^L|^2 + (L\to R)\right]\\
J_3 &= \frac{1}{2}\beta_\ell^2\left[|A_\perp^L|^2 - |A_\|^L|^2 + (L\to R)\right]\\
J_4 &= \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Re}(A_0^L A_\|^{L}{}^*) + (L\to R)\right]\\
J_5 &= \sqrt{2}\beta_\ell\left[\mathrm{Re}(A_0^L A_\perp^{L}{}^*) - (L\to R) - \frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_\|^L A_S{}^* + A_\|^R A_S{}^*)\right]\\
J_6^s &= 2\beta_\ell\left[\mathrm{Re}(A_\|^L A_\perp^{L}{}^*) - (L\to R)\right] \quad , \quad J_6^c = 4\beta_\ell\frac{m_\ell}{\sqrt{q^2}}\,\mathrm{Re}\left[A_0^L A_S{}^* + (L\to R)\right]\\
J_7 &= \sqrt{2}\beta_\ell\left[\mathrm{Im}(A_0^L A_\|^{L}{}^*) - (L\to R) + \frac{m_\ell}{\sqrt{q^2}}\mathrm{Im}(A_\perp^L A_S{}^* + A_\perp^R A_S{}^*)\right]\\
J_8 &= \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Im}(A_0^L A_\perp^{L}{}^*) + (L\to R)\right]\\
J_9 &= \beta_\ell^2\left[\mathrm{Im}(A_\|^{L}{}^* A_\perp^L) + (L\to R)\right]
\end{aligned}
$$

with $\beta_\ell = \sqrt{1 - \frac{4m_\ell^2}{q^2}}$

Transversity amplitudes

$$A_{\perp,\parallel} = (H_{+1} \mp H_{-1})/\sqrt{2}, \qquad A_0 \equiv H_0$$

Transversity amplitudes at low q^2, up to corrections of $O(\alpha_s)$:

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

$$A_{\parallel}^{L,R} = -N\sqrt{2}(M_B^2 - m_{K^*}^2)\left[\left[(C_9^{\rm eff} - C_9^{\rm eff\prime}) \mp (C_{10} - C_{10}')\right]\frac{A_1(q^2)}{M_B - m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\rm eff} - C_7^{\rm eff\prime})T_2(q^2)\right]$$

$$A_0^{L,R} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(C_9^{\rm eff} - C_9^{\rm eff\prime}) \mp (C_{10} - C_{10}')\right]\left[(M_B^2 - m_{K^*}^2 - q^2)(M_B + m_{K^*})A_1(q^2) - \lambda\frac{A_2(q^2)}{M_B + m_{K^*}}\right]\right.$$
$$\left. + 2m_b(C_7^{\rm eff} - C_7^{\rm eff\prime})\left[(M_B^2 + 3m_{K^*}^2 - q^2)T_2(q^2) - \frac{\lambda}{M_B^2 - m_{K^*}^2}T_3(q^2)\right]\right\}$$

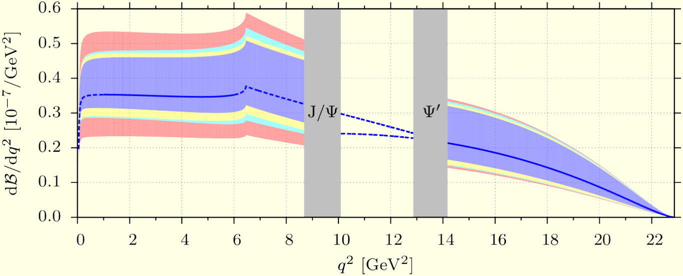
$$A_t = \frac{N}{\sqrt{q^2}}\lambda^{1/2}\left[2(C_{10} - C_{10}') + \frac{q^2}{m_\ell}(C_P - C_P')\right]A_0(q^2)$$

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

where $N = \left[\frac{G_F^2\alpha_{em}^2}{3\cdot 2^{10}\pi^5 M_B}|V_{tb}V_{ts}^*|^2\,\hat{s}\sqrt{\lambda}\,\beta_l\right]^{1/2}$ and $\lambda = M_B^4 + m_{K^*}^4 + q^4 - 2(M_B^2 m_{K^*}^2 + m_{K^*}^2 q^2 + M_B^2 q^2)$

Dilepton invariant mass spectrum

$$\frac{d\Gamma}{dq^2} = \frac{3}{4}\left(J_1 - \frac{J_2}{3}\right)$$

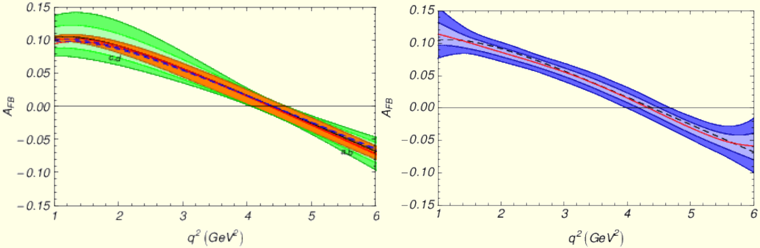


blue: uncertainties from form factors
yellow: uncertainties from CKM matrix elements
cyan: uncertainties from short-distance input
red: uncertainties from subleading $1/m_b$ corrections

Bobeth et al., arXiv:1111.2558

Forward backward asymmetry

$$A_{\rm FB}(q^2) \equiv \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_l \, \frac{d^2\Gamma}{dq^2\, d\cos\theta_l} \Bigg/ \frac{d\Gamma}{dq^2} = \frac{3}{8} J_6 \Bigg/ \frac{d\Gamma}{dq^2}$$

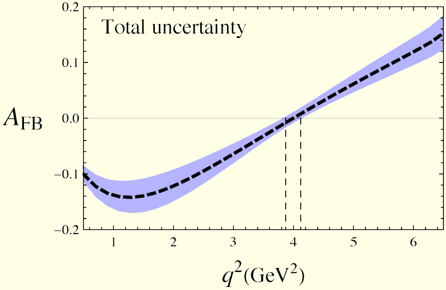


Theory prediction | LHC@10fb^{-1}

Egede et al., arXiv:0807.2589

Forward backward asymmetry zero-crossing

Reduced theoretical uncertainties



Lunghi and Soni, arXiv:1007.4015

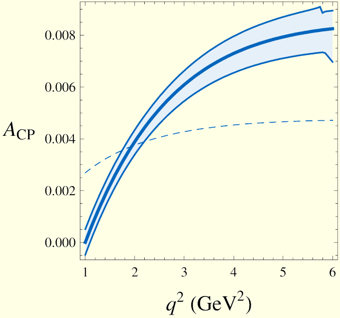
$$q_0^2 \simeq -2 m_b m_B \frac{C_9^{\rm eff}(q_0^2)}{C_7} + O(\alpha_s, \Lambda/m_b)$$

CP asymmetry

$$A_{CP}(q^2) \equiv \frac{\frac{d\Gamma}{dq^2}(\bar{B} \to \bar{K}^* \ell^+ \ell^-) - \frac{d\Gamma}{dq^2}(B \to K^* \ell^+ \ell^-)}{\frac{d\Gamma}{dq^2}(\bar{B} \to \bar{K}^* \ell^+ \ell^-) + \frac{d\Gamma}{dq^2}(B \to K^* \ell^+ \ell^-)}$$

$$A_{CP}(q^2) = \frac{3}{4}(2A_1^s + A_1^c) - \frac{1}{4}(2A_2^s + A_2^c)\,, \qquad A_i^{(a)}(q^2) \equiv (J_i^{(a)} - \bar{J}_i^{(a)}) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

CKM suppressed
$\to$ tiny in the SM



Altmannshofer et al., arXiv:0811.1214

Isospin asymmetry

Non-factorizable graphs: annihilation or spectator-scattering diagrams

Isospin asymmetry arises when a photon is radiated from the spectator quark

→ depends on the charge of the spectator quark

→ different for charged and neutral B meson decays

$$\frac{dA_I}{dq^2} \equiv \frac{\frac{d\Gamma}{dq^2}(B^0 \to K^{*0}\ell^+\ell^-) - \frac{d\Gamma}{dq^2}(B^- \to K^{*-}\ell^+\ell^-)}{\frac{d\Gamma}{dq^2}(B^0 \to K^{*0}\ell^+\ell^-) + \frac{d\Gamma}{dq^2}(B^- \to K^{*-}\ell^+\ell^-)}$$

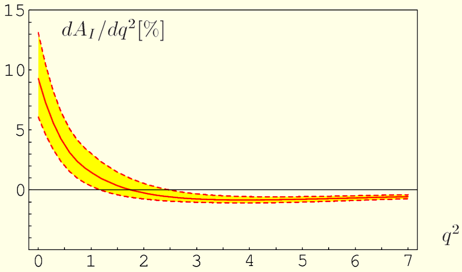
The SM is sensitive to C_5 and C_6 at small q^2, but to C_3 and C_4 at larger q^2

Need to calculate higher order effects!

Isospin asymmetry

Measurement of a significant deviation from zero in the range $2 < q^2 < 7$ GeV^2 may indicate New Physics

At $q^2 = 0$, the results of $B \to K^*\gamma$ is recovered.



Feldmann and Matias, JHEP 0301 (2003) 074

Transverse asymmetries

The transverse asymmetries are written as:

$$A_T^{(1)}(q^2) = \frac{-2\Re(A_\parallel A_\perp^*)}{|A_\perp|^2 + |A_\parallel|^2}$$

$$A_T^{(2)}(q^2) = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}$$

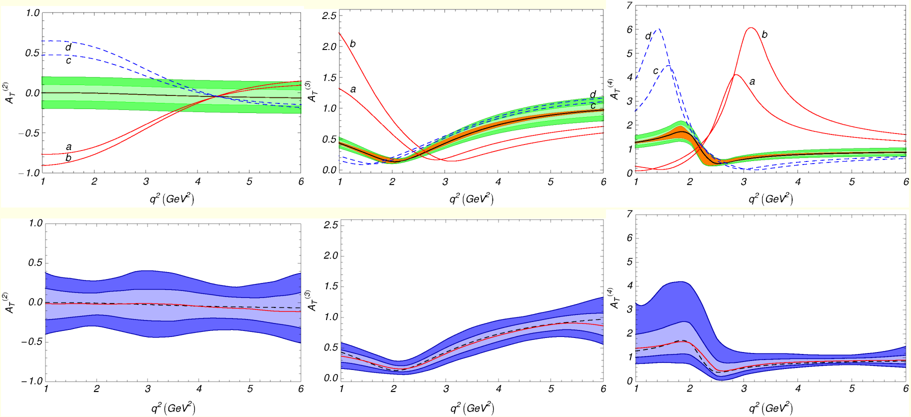
$$A_T^{(3)}(q^2) = \frac{|A_{0L}A_{\parallel L}^* + A_{0R}^* A_{\parallel R}|}{\sqrt{|A_0|^2|A_\perp|^2}}$$

$$A_T^{(4)}(q^2) = \frac{|A_{0L}A_{\perp L}^* - A_{0R}^* A_{\perp R}|}{|A_{0L}A_{\parallel L}^* + A_{0R}^* A_{\parallel R}|}$$

where

$$A_i A_j^* \equiv A_{iL}(q^2)A_{jL}^*(q^2) + A_{iR}(q^2)A_{jR}^*(q^2) \quad (i,j = 0, \parallel, \perp)$$

Transverse asymmetries



Egede et al., arXiv:0807.2589

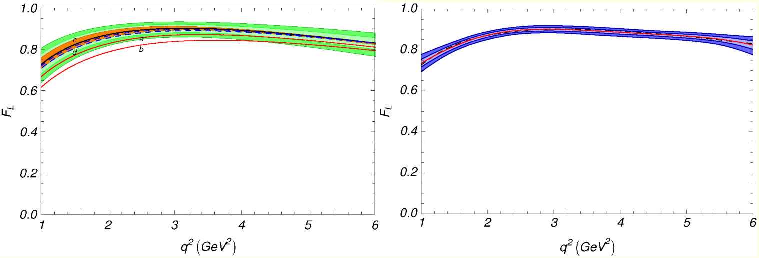
K^* polarization parameter and fractions

$$F_L(q^2) = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

$$F_T(q^2) = 1 - F_L(q^2) = \frac{|A_\perp|^2 + |A_\parallel|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

K^* polarization parameter:

$$\alpha_{K^*}(q^2) = \frac{2F_L}{F_T} - 1 = \frac{2|A_0|^2}{|A_\parallel|^2 + |A_\perp|^2} - 1$$

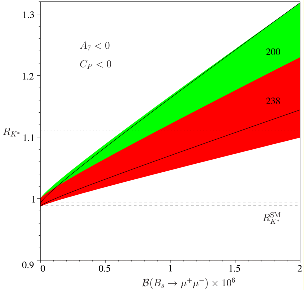


Egede et al., arXiv:0807.2589

$B \to K^* e^+ e^-$ vs. $B \to K^* \mu^+ \mu^-$

$$R_{K^*} \equiv \frac{\int_{4m_\mu^2}^{q^2_{\max}} dq^2 \, \frac{d\Gamma(B \to K^* \mu^+ \mu^-)}{dq^2}}{\int_{4m_\mu^2}^{q^2_{\max}} dq^2 \, \frac{d\Gamma(B \to K^* e^+ e^-)}{dq^2}}$$

Within the SM: $R_{K^*}^{\rm SM} = 1 + O(m_\mu^2/m_b^2) = 0.991 \pm 0.002$.



Interesting beyond the SM to constrain New Physics.

Hiller, Krüger, hep-ph/0310219

Other rare decays

More rare decays

- $\mathrm{BR}(B_s \to \mu^+\mu^-)$
- $\mathrm{BR}(B \to X_s\gamma)$
- $\Delta_{0-}(B \to K^*\gamma)$

Other interesting decays:

- $B \to \tau\nu$
- $B \to D\tau\nu$
- $D_s \to \tau\nu$
- $K \to \mu\nu$

$\mathrm{BR}(B_s \to \mu^+\mu^-)$

Effective Hamiltonian:

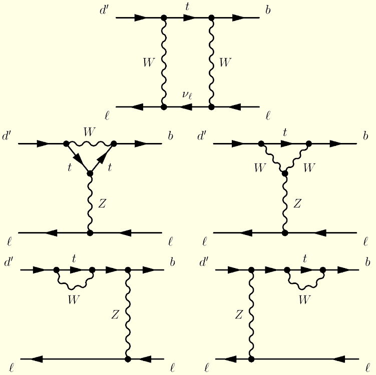
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{ts} \Big(\sum C_i(\mu)\mathcal{O}_i(\mu) + \sum C_{Q_i}(\mu) Q_i(\mu)\Big)$$

Important operators:

$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5\ell)$$

$$Q_1 = \frac{e^2}{16\pi^2}(\bar{s}^\alpha_L b^\alpha_R)(\bar{\ell}\,\ell)$$

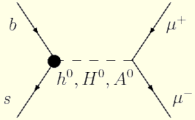
$$Q_2 = \frac{e^2}{16\pi^2}(\bar{s}^\alpha_L b^\alpha_R)(\bar{\ell}\gamma_5\ell)$$



$\mathrm{BR}(B_s \to \mu^+\mu^-)$

Very sensitive to new physics, especially for large $\tan\beta$:

SUSY contributions in $\mathrm{BR}(B_s \to \mu^+\mu^-)$ can lead to an O(100) enhancement over the SM!



$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{MSSM} \sim \frac{m_b^2 m_\mu^2 \tan^6\beta}{M_A^4}$$

Large uncertainty from the decay constant (f_{B_s})!

Experimental results:

LHCb: $\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.4 \times 10^{-8}$ at 95% C.L.
arXiv:1112.1600

CMS: $\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.9 \times 10^{-8}$ at 95% C.L.
arXiv:1107.5834

Combined LHCb + CMS: $\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.1 \times 10^{-8}$ at 95% C.L.
LHCb-CONF-2011-047, CMS PAS BPH-11-019

BR($B \to X_s\gamma$)

$$\text{BR}(\bar{B} \to X_s\gamma)_{E_\gamma > E_0} = \text{BR}(\bar{B} \to X_c e\bar{\nu})_{\rm exp} \left|\frac{V_{ts}^* V_{tb}}{V_{cb}}\right|^2 \frac{6\alpha_{\rm em}}{\pi C} [P(E_0) + N(E_0)]$$

$$C = \left|\frac{V_{ub}}{V_{cb}}\right|^2 \frac{\Gamma[\bar{B} \to X_c e\bar{\nu}]}{\Gamma[\bar{B} \to X_u e\bar{\nu}]}$$

$$\begin{aligned} P(E_0) &= P^{(0)}(\mu_b) + \alpha_s(\mu_b)\left[P_1^{(1)}(\mu_b) + P_2^{(1)}(E_0,\mu_b)\right] \\ &+ \alpha_s^2(\mu_b)\left[P_1^{(2)}(\mu_b) + P_2^{(2)}(E_0,\mu_b) + P_3^{(2)}(E_0,\mu_b)\right] + \mathcal{O}\left(\alpha_s^3(\mu_b)\right) \end{aligned}$$

$$\left\{\begin{aligned} P^{(0)}(\mu_b) &= \left(C_7^{(0)\rm eff}(\mu_b)\right)^2 \\ P_1^{(1)}(\mu_b) &= 2C_7^{(0)\rm eff}(\mu_b)C_7^{(1)\rm eff}(\mu_b) \\ P_1^{(2)}(\mu_b) &= \left(C_7^{(1)\rm eff}(\mu_b)\right)^2 + 2C_7^{(0)\rm eff}(\mu_b)C_7^{(2)\rm eff}(\mu_b) \end{aligned}\right.$$

M. Misiak et al., Phys. Rev. Lett. 98 (2007)

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M. Misiak et al., Phys. Rev. Lett. 98 (2007)

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M. Misiak et al., Phys. Rev. Lett. 98 (2007)

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M. Misiak et al., Phys. Rev. Lett. 98 (2007)

BR($B \to X_s\gamma$)

- Theoretical values for the SM:
  NNLO (Misiak & Steihauser '07): BR($\bar{B} \to X_s\gamma$) $= (3.15 \pm 0.23) \times 10^{-4}$
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Reduced scale dependence:

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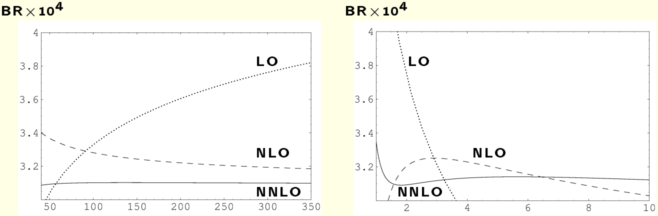
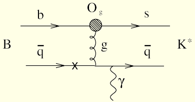


μ_W-dependence μ_b-dependence

M. Misiak et al., Phys. Rev. Lett. 98 (2007)

Isospin Asymmetry

$$\Delta_{0-} \equiv \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) - \Gamma(B^- \to K^{*-}\gamma)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) + \Gamma(B^- \to K^{*-}\gamma)}$$



$$\Delta_{0-} = \mathrm{Re}(b_d - b_u)$$

$$b_q = \frac{12\pi^2 f_B\, Q_q}{m_b\, T_1^{B\to K^*} a_7^c} \left(\frac{f_{K^*}^\perp}{m_b} K_1 + \frac{f_{K^*} m_{K^*}}{6\lambda_B m_B} K_2 \right)$$

$$a_7^c = C_7 + \frac{\alpha_s(\mu) C_F}{4\pi}\Big(C_1(\mu) G_1(s_p) + C_8(\mu) G_8\Big) + \frac{\alpha_s(\mu_h) C_F}{4\pi}\Big(C_1(\mu_h) H_1(s_p) + C_8(\mu_h) H_8\Big)$$

In the Standard Model: $\Delta_{0-} \simeq 8\%$

Kagan and Neubert, Phys. Lett. B539 (2002)
Bosch and Buchalla, Nucl. Phys. B621 (2002)

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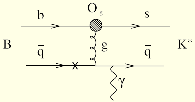

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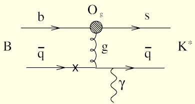

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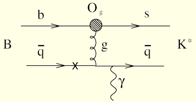

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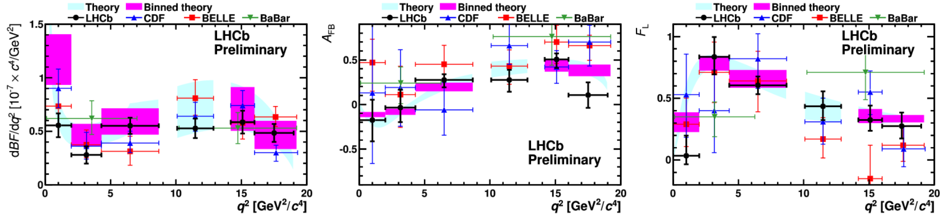
Implications

Experimental results



LHCb-CONF-2011-038

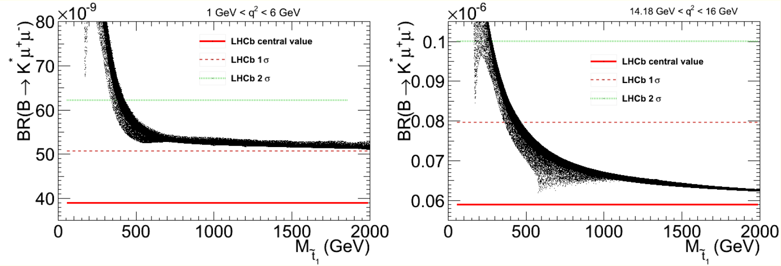
Observable	q^2 interval	LHCb results	SM prediction
$\langle dBR(B \to K^*\mu^+\mu^-)/dq^2 \rangle$	[1, 6]	$(0.39 \pm 0.06 \pm 0.02) \times 10^{-7}$	$(0.56 \pm 0.15) \times 10^{-7}$
$\langle dBR(B \to K^*\mu^+\mu^-)/dq^2 \rangle$	[14.18, 16]	$(0.59 \pm 0.10 \pm 0.03) \times 10^{-7}$	$(0.69 \pm 0.20) \times 10^{-7}$
$\langle A_{FB}(B \to K^*\mu^+\mu^-) \rangle$	[1, 6]	$-0.10 \pm 0.14 \pm 0.05$	-0.06 ± 0.03
$\langle A_{FB}(B \to K^*\mu^+\mu^-) \rangle$	[14.18, 16]	$0.50 \pm 0.09 \pm 0.03$	0.44 ± 0.11
$\langle F_L(B \to K^*\mu^+\mu^-) \rangle$	[1, 6]	$0.57 \pm 0.11 \pm 0.03$	0.77 ± 0.04
$\langle F_L(B \to K^*\mu^+\mu^-) \rangle$	[14.18, 16]	$0.33 \pm 0.11 \pm 0.04$	0.36 ± 0.17

SUSY Implications

CMSSM, with $A_0 = 0$, $\tan\beta = 50$ and $\mu > 0$

Random scan over m_0, $m_{1/2}$

Comparison with the LHCb results, including theoretical uncertainties



preliminary results, SuperIso v3.2+

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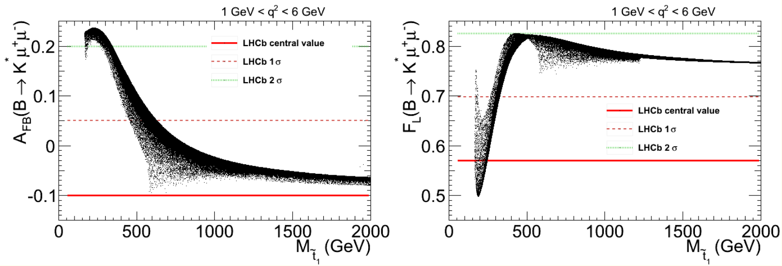
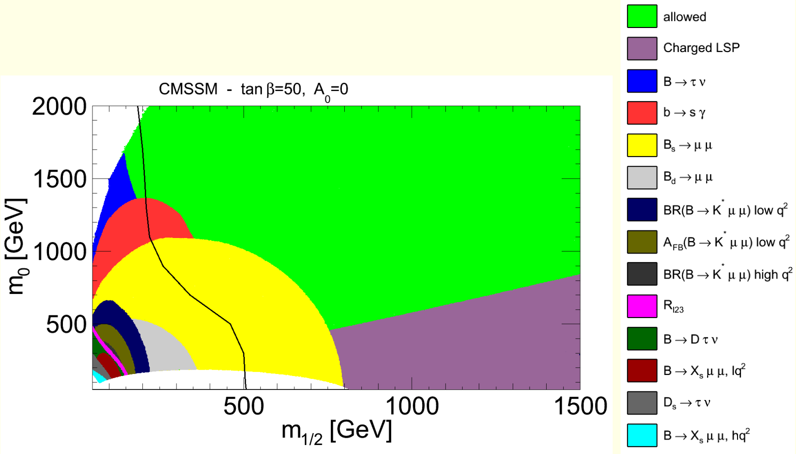


preliminary results, SuperIso v3.2+

Combined results

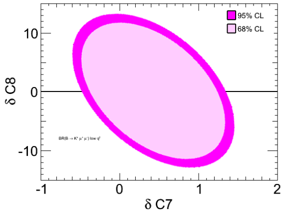
CMSSM, with $A_0 = 0$, $\tan\beta = 50$ and $\mu > 0$

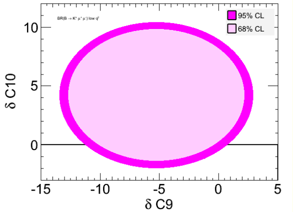


SuperIso v3.2+

Model independent analysis

δC_7, δC_8, δC_9, δC_{10}, δC_S, δC_P considered as real independent parameters





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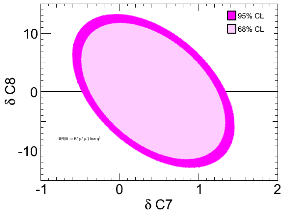

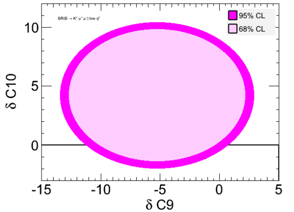

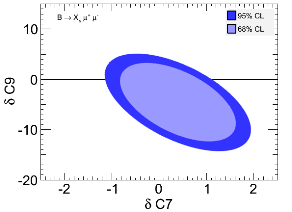

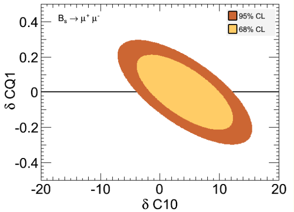

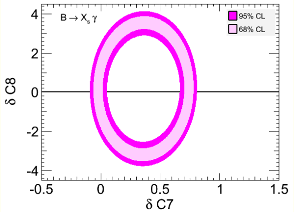

preliminary results, SuperIso v3.2+

Model independent analysis

Observables:
$BR(B \to X_s \gamma)$
$\Delta_0(B \to K^* \gamma)$
$BR(B_s \to \mu^+ \mu^-)$
$BR^{low}(B \to X_s \mu^+ \mu^-)$
$BR^{high}(B \to X_s \mu^+ \mu^-)$
$BR^{low}(B \to K^* \mu^+ \mu^-)$
$BR^{high}(B \to K^* \mu^+ \mu^-)$
$A_{FB}^{low}(B \to K^* \mu^+ \mu^-)$
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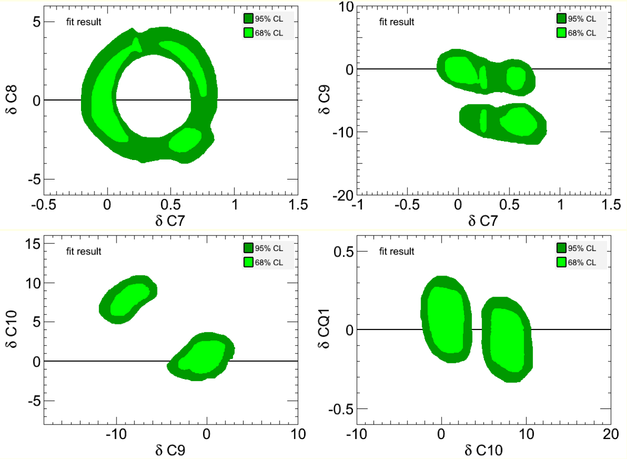
$F_L^{low}(B \to K^* \mu^+ \mu^-)$
$F_L^{high}(B \to K^* \mu^+ \mu^-)$



preliminary results, SuperIso v3.2+

see also: Hurth, Isidori, Kamenik, Mescia, Nucl.Phys. B808 (2009) 326
Descotes-Genon, Gosh, Matias, Ramon, JHEP 1106 (2011) 099
Altmannshofer, Paradisi, Straub, arXiv:1111.1257

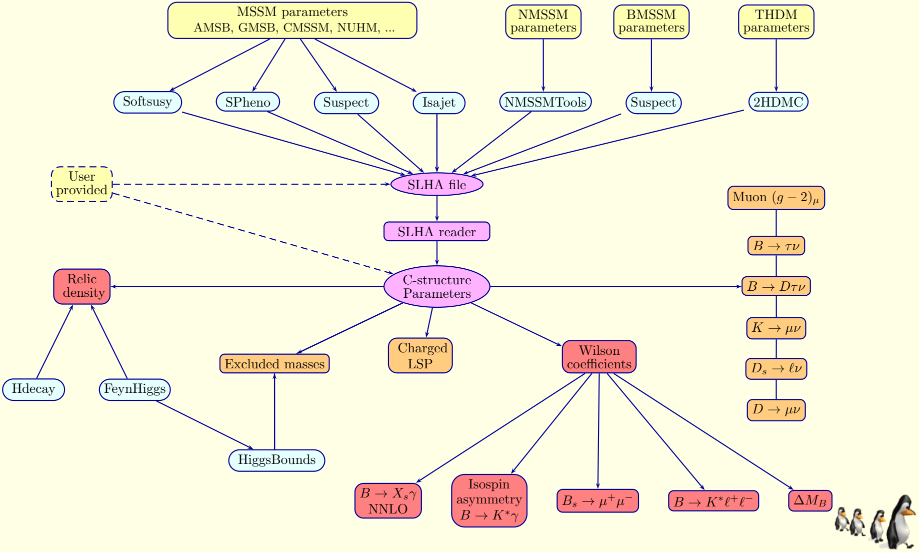
SuperIso

- public C program
- dedicated to the flavour physics observable calculations
- various models implemented
- interfaced to several spectrum calculators
- modular program with a well-defined structure
- complete reference manuals available

http://superiso.in2p3.fr

FM, Comput. Phys. Commun. 178 (2008) 745
FM, Comput. Phys. Commun. 180 (2009) 1579
FM, Comput. Phys. Commun. 180 (2009) 1718

SuperIso


MSSM parameters
AMSB, GMSB, CMSSM, NUHM, ...
NMSSM parameters
BMSSM parameters
THDM parameters
Softsusy
SPheno
Suspect
Isajet
NMSSMTools
Suspect
2HDMC
User provided
SLHA file
SLHA reader
C-structure Parameters
Relic density
Muon $(g-2)_\mu$
$B \to \tau\nu$
$B \to D\tau\nu$
$K \to \mu\nu$
$D_s \to \ell\nu$
$D \to \mu\nu$
Excluded masses
Charged LSP
Wilson coefficients
Hdecay
FeynHiggs
HiggsBounds
$B \to X_s\gamma$ NNLO
Isospin asymmetry $B \to K^*\gamma$
$B_s \to \mu^+\mu^-$
$B \to K^*\ell^+\ell^-$
ΔM_B

Flavour Les Houches Accord

Standard format for flavour related quantities, providing:

- A model independent parametrization
- A standalone flavour output in the FLHA format
- Based on the existing SLHA structure
- A clear and well-defined structure for interfacing computational tools of "New Physics" models with low energy flavour calculations
- That will allow different programs to talk and to be interfaced, and users to have a clear and well defined result that can eventually be used for different purposes

Involved people

F. Mahmoudi, S. Heinemeyer, A. Arbey, A. Bharucha, T. Goto, T. Hahn, U. Haisch, S. Kraml, M. Muhlleitner, J. Reuter, P. Skands, P. Slavich

For more information

- Official write-up: Comput. Phys. Commun. 183 (2012) 285-298 [arXiv:1008.0762]

Conclusion

- $B \to K^* \ell^+ \ell^-$ offers multiple sensitive observables
  $\to$ complementary information!
- Theory uncertainties under control
- With more data constraints will tighten!

- Great opportunities for LHCb
- further studies at future Super B
  $\to$ also the inclusive mode
- Important to combine different observables and constraints
  $\to$ find evidence for New Physics