Light scalars in NMSSM and $B \to K^* ll$ angular observables

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Outline

Interest in Rare B decays

- Rare B Decays ($b \to (s, d)\gamma, b \to (s, d)l^+l^-, ...$) are Flavour-Changing-Neutral-Current (FCNC) processes ($|\Delta B| = 1$, $|\Delta Q| = 0$); not allowed at the tree level in the SM
- In principle sensitive to physics beyond the SM (BSM), such as supersymmetry. Precise experiments and theory are needed to establish or definitively rule out BSM effects in Flavor physics
- Rare B-decays have enjoyed great attention in the current and past experimental programme in flavour physics, with the present frontier being LHC
- In the SM, they determine the weak mixing CKM matrix elements $|V_{td}|$ and $|V_{ts}|$
- Can provide a new information of the long-distance QCD effects in a matrix elements of the effective tensor and pseudotensor currents between the initial and final hadronic states
- Could provide essential background for other rare decays with smaller BR

Motivation (Searches for Higgs bosons below 125 GeV)

- LEP (2.3σ) indicating the existence of a scalar particle with a mass of $\sim 98 GeV$ in the $ee \to Z(H \to bb)$ process [Phys. Lett. B565, (2003)]
- CMS LHC (2.8σ) indication on a particle with a mass of $\sim 96 GeV$ in the $pp \to H \to \gamma\gamma$ process [CMS, 2018]
- Light Higgs with a significant singlet component can avoid standard constraints [C. Beskidt, W. de Boer, D.I. Kazakov, PLB782 (2018)]

Differential decay distribution ($B \to K^* ll$)

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_K d\phi} = \frac{9}{32\pi} J(q^2, \theta_l, \theta_K, \phi),$$

$$\begin{aligned} J(q^2, \theta_l, \theta_K, \phi) = \\ J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l + \\ J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + \\ J_5\sin 2\theta_K\sin\theta_l\cos\phi + (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + \\ J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi + \\ J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi. \end{aligned}$$

$$J_{6c} \to S_{6c}$$

more detail in backup

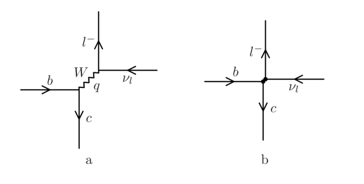
Problems

- Try to find scenarios within a non-minimal supersymmetric model (NMSSM) with an additional singlet supermultiplet that are compatible with known experiments.
- Analysis of rare (FCNC) B mesons decays in the found allowed regions of model parameters. Study of the possibility of enhance the signal due to the effects of New Physics.

SM contributions (+ NMSSM?) to Wilson coefficients

$$H_{eff}(b \to q) = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^* \sum_i C_i O_i + h.c.$$

A.Grozin



- C_{1-6} dominated by QCD contributions and hardly sensitive to NP!
- C_{7-10} are generated in the SM and sensitive to many NP models
- $C_{S,P}$ vanish in the SM but can be sizable in models with extended Higgs sector
- $C_S - C_S'$ and $C_P - C_P'$ scalar coefficients

	$b \to s$	
γ	$B \to X_s\gamma$ $B \to K^*\gamma$	$O_{7,8}$
$\ell^+\ell^-$	$B \to K\ell^+\ell^-$ $B \to K^*\ell^+\ell^-$ $B \to X_s\ell^+\ell^-$	$O_{7,8}, O_9, O_{10}$
	$B_s \to \mu^+\mu^-$	$O_{10}, O_{S,P}$
$\nu\bar{\nu}$	$B \to X_s\nu\bar{\nu}$ $B \to K\nu\bar{\nu}$ $B \to K^*\nu\bar{\nu}$	O_ν

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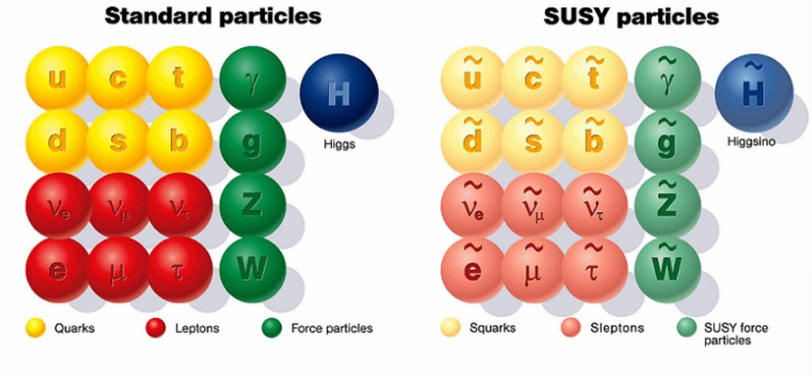
SUSY



Standard particles
SUSY particles
u c t γ H
d s b g
Higgs
Z
W
e μ τ
Higgsino
Quarks
Leptons
Force particles
Squarks
Sleptons
SUSY force particles

NMSSM particles

Superfield	*Bosons*	*Fermions*	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge					
G^a	gluon g^a	gluino $\tilde{g}^a$	8	0	0
V^k	Weak $W^k (W^\pm, Z)$	wino, zino $\tilde{w}^k (\tilde{w}^\pm, \tilde{z})$	1	3	0
V'	Hypercharge $B(\gamma)$	bino $\tilde{b}(\tilde{\gamma})$	1	1	0
Matter					
L_i	sleptons $\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons $L_i = (\nu, e)_L$	1	2	−1
E_i	sleptons $\tilde{E}_i = \tilde{e}_R$	leptons $E_i = e_R$	1	1	2
Q_i	squarks $\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks $Q_i = (u, d)_L$	3	2	1/3
U_i	squarks $\tilde{U}_i = \tilde{u}_R$	quarks $U_i = u_R^c$	3^*	1	−4/3
D_i	squarks $\tilde{D}_i = \tilde{d}_R$	quarks $D_i = d_R^c$	3^*	1	2/3
Higgs					
H_1	Higgses H_1	higgsinos $\tilde{H}_1$	1	2	−1
H_2	Higgses H_2	higgsinos $\tilde{H}_2$	1	2	1
		S			

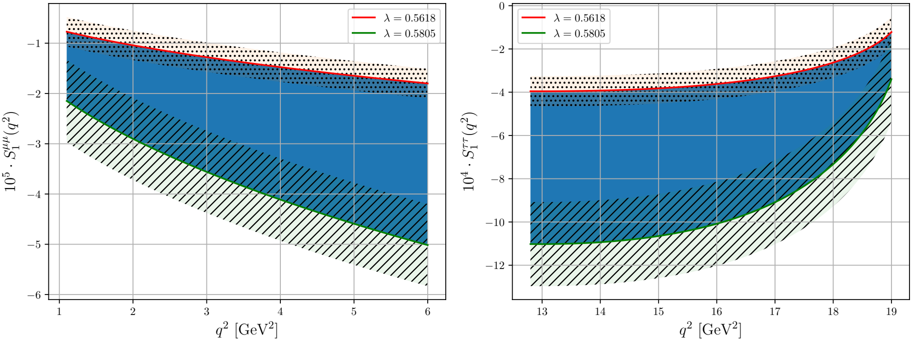
NMSSM parametres

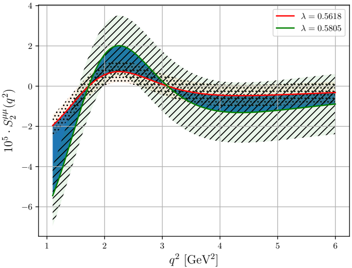
- $m_0, m_{1/2}$ are the common mass scales of the spin 0 (1/2) SUSY particles at the GUT scale
- A_0 is the trilinear coupling of the CMSSM Higgs sector at the GUT scale
- A_λ, A_κ are the corresponding trilinear soft breaking terms
- $\tanh\beta = \frac{v_u}{v_d}$ ratio of the vevs of the Higgs doublets
- λ represents the coupling between the Higgs singlet and doublets $\lambda S H_u \cdot H_d$
- κ the self-coupling of the singlet $\kappa S^3/3$
- μ_{eff} represents an effective Higgs mixing parameter and is related to the vev of the singlet s via the coupling λ, i.e. $\mu_{eff} \equiv \lambda s$

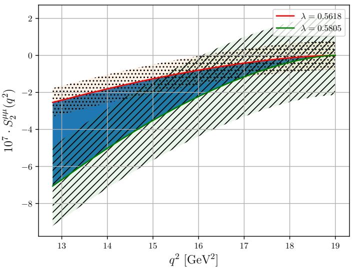
Observables in NMSSM

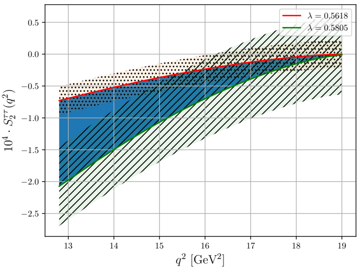
$$S_1 = -\frac{\beta_l\sqrt{q^2}}{4m_l}\frac{J_{6c}}{J_{2c}}$$

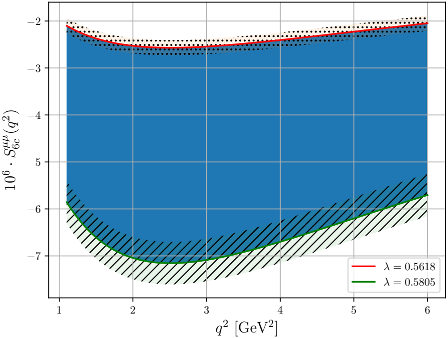
$$S_2 = \ldots$$



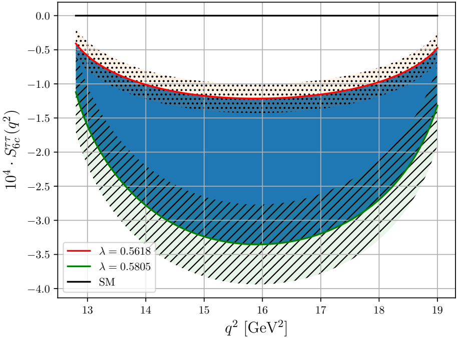

$\lambda = 0.5618$
$\lambda = 0.5805$
$10^5 \cdot S_2^{\mu\mu}(q^2)$
q^2 [GeV^2]


$\lambda = 0.5618$
$\lambda = 0.5805$
$10^7 \cdot S_2^{\mu\mu}(q^2)$
q^2 [GeV^2]

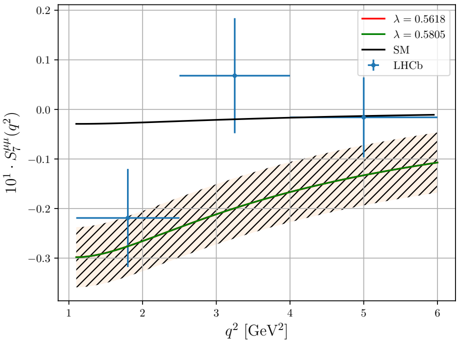

$\lambda = 0.5618$
$\lambda = 0.5805$
$10^4 \cdot S_2^{\tau\tau}(q^2)$
q^2 [GeV^2]



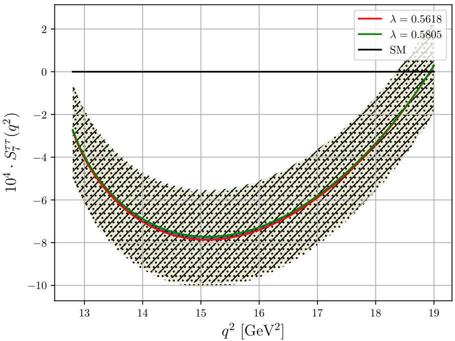
−2
−3
−4
−5
−6
−7
$10^6 \cdot S_{6c}^{\mu\mu}(q^2)$
1
2
3
4
5
6
q^2 [GeV^2]
$\lambda = 0.5618$
$\lambda = 0.5805$



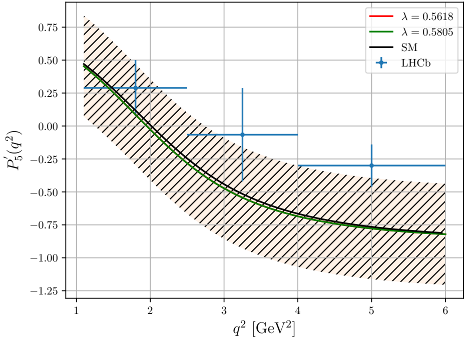
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
$10^4 \cdot S_{6c}^{\tau\tau}(q^2)$
13
14
15
16
17
18
19
q^2 [GeV^2]
$\lambda = 0.5618$
$\lambda = 0.5805$
SM

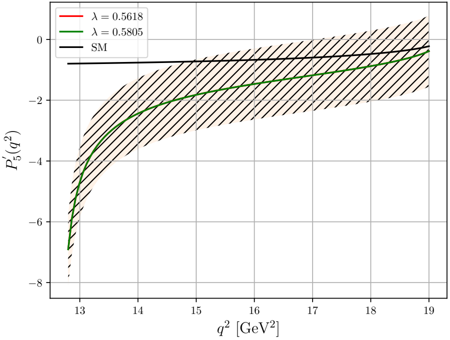


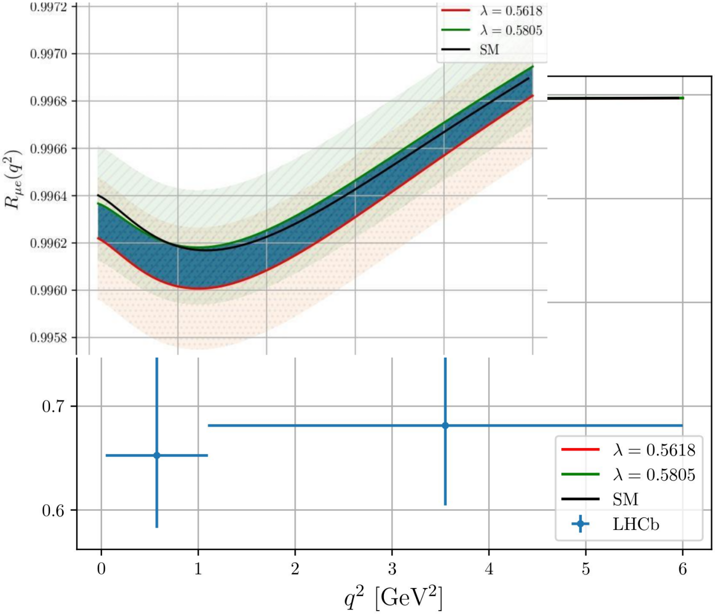
$\lambda = 0.5618$
$\lambda = 0.5805$
SM
LHCb
$10^1 \cdot S_7^{\mu\mu}(q^2)$
q^2 [GeV^2]



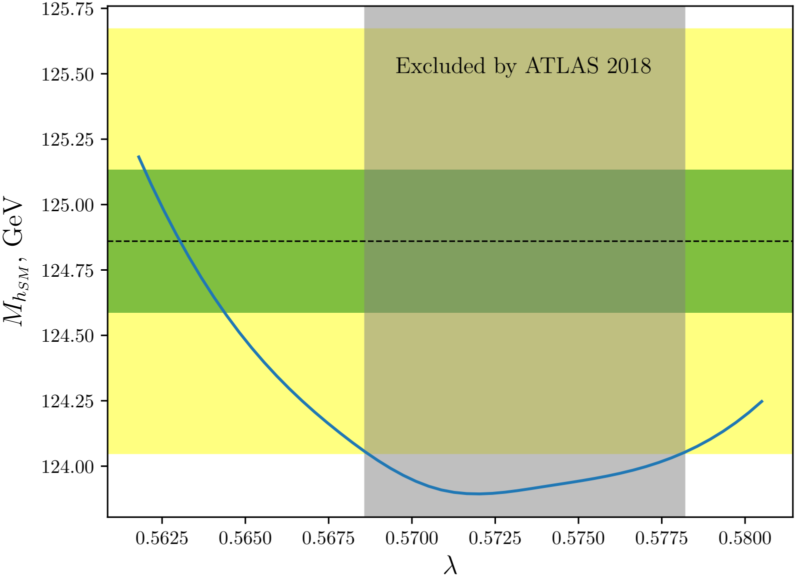
$\lambda = 0.5618$
$\lambda = 0.5805$
SM
$10^4 \cdot S_7^{\tau\tau}(q^2)$
q^2 [GeV^2]


λ = 0.5618
λ = 0.5805
SM
LHCb
$P_5'(q^2)$
q^2 [GeV^2]

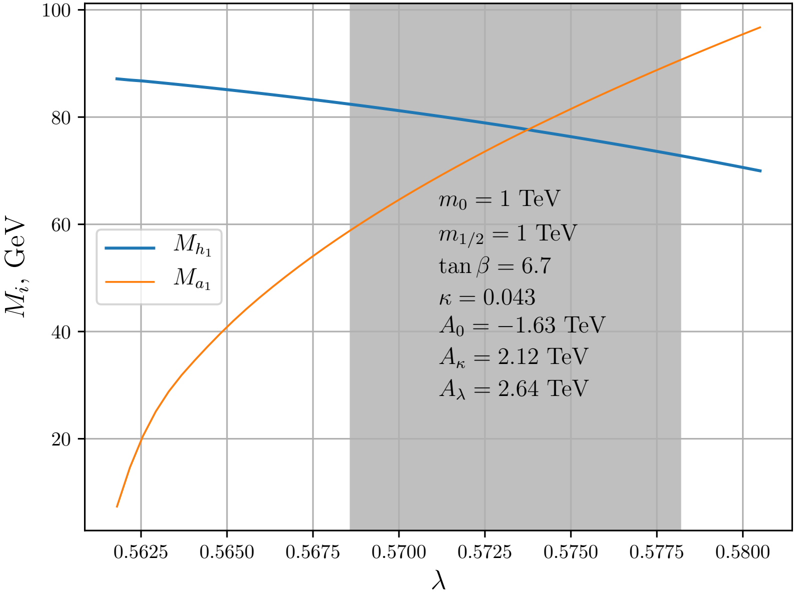

λ = 0.5618
λ = 0.5805
SM
$P_5'(q^2)$
q^2 [GeV^2]



0.9972
0.9970
0.9968
0.9966
0.9964
0.9962
0.9960
0.9958
$R_{\mu e}(q^2)$
$\lambda = 0.5618$
$\lambda = 0.5805$
SM
0.7
0.6
$\lambda = 0.5618$
$\lambda = 0.5805$
SM
LHCb
0
1
2
3
4
5
6
q^2 [GeV^2]



125.75
125.50
125.25
125.00
124.75
124.50
124.25
124.00
$M_{h_{SM}}$, GeV
Excluded by ATLAS 2018
0.5625
0.5650
0.5675
0.5700
0.5725
0.5750
0.5775
0.5800
λ


M_i, GeV
100
80
60
40
20
0.5625
0.5650
0.5675
0.5700
0.5725
0.5750
0.5775
0.5800
λ
M_{h_1}
M_{a_1}
$m_0 = 1$ TeV
$m_{1/2} = 1$ TeV
$\tan\beta = 6.7$
$\kappa = 0.043$
$A_0 = -1.63$ TeV
$A_\kappa = 2.12$ TeV
$A_\lambda = 2.64$ TeV

Results

We considered a bounded NMSSM and found resolved parameter regions where the light singlet-like Higgs boson is predicted with a mass in the region of 80-100 GeV

We analyzed the characteristic manifestations of the light Higgs boson in the angular observables S_1, S_2, S_{6c}, S_7 of the $B \to K^{(*)} ll$ decay, which are due to contributions to the Wilson coefficients of scalar operators

We have shown that is not possible to compensate for the known deviations in the R_K, R_K^* and $P_5^{'}$ observables despite the existence of joint scenarios with experiments

Plans

In the NMSSM framework

- Calculation of contributions to the polarization asymmetries of leptons in $B \to K^* ll$
- Calculation of contributions to the $b \to dll$ processes ($B \to \pi ll$, $B \to \rho ll$)
- Implementation of calculations in the form of computer codes, convenient for numerical analysis
- Consideration of these observables in the analysis of the parameter space in the NMSSM

Consideration of rare transitions in supersymmetric extensions with an additional $U(1)'$ gauge superfield (USSM)

Thank you for your Attention!

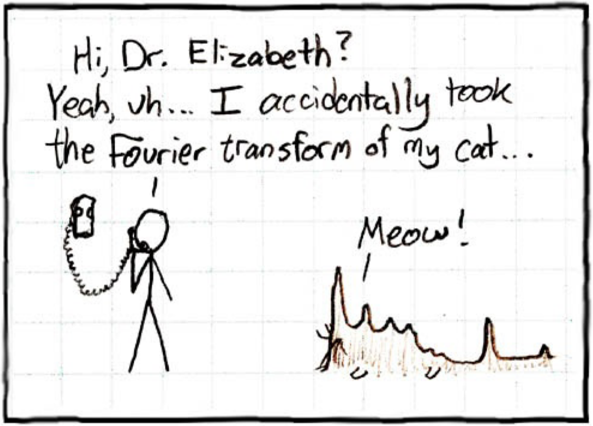


Figure: xkcd comics

Operators

Current-current operators

$$O_1 = (\bar{s}\gamma^{\mu} T^a P_L c) \otimes (\bar{c}\gamma_{\mu} T^a P_L b)$$
$$O_2 = (\bar{s}\gamma^{\mu} P_L c) \otimes (\bar{c}\gamma_{\mu} P_L b)$$

QCD penguin operators

$$O_3 = (\bar{s}\gamma^{\mu} P_L b) \otimes \Sigma_q (\bar{q}\gamma_{\mu} q)$$
$$O_4 = (\bar{s}\gamma^{\mu} P_L b) \otimes \Sigma_q (\bar{q}\gamma_{\mu} T^a q)$$
$$O_5 = (\bar{s}\gamma^{\mu}\gamma^{\nu}\gamma^{\rho} P_L b) \otimes \Sigma_q (\bar{q}\gamma_{\mu}\gamma_{\nu}\gamma_{\rho} q)$$
$$O_6 = (\bar{s}\gamma^{\mu}\gamma^{\nu}\gamma^{\rho} T^a P_L b) \otimes \Sigma_q (\bar{q}\gamma_{\mu}\gamma_{\nu}\gamma_{\rho} T^a q)$$

Dipole operators

$$O_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}$$

$$O_8 = \frac{g_S m_b}{e^2}(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu}$$

Semileptonic operators

$$O_9 = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)$$

$$O_{10} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)$$

Scalar operators

$$O_S = \frac{m_b}{m_{B_s}}(\bar{s}P_R b)(\bar{l}l)$$

$$O_P = \frac{m_b}{m_{B_s}}(\bar{s}P_R b)(\bar{l}\gamma_5 l).$$

$$J_1^s = \frac{3}{4}\left\{\frac{(2+\beta_l^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)\right] + \frac{4m_l^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*}\right)\right\},$$

$$J_1^c = \frac{3}{4}\left\{|A_0^L|^2 + |A_0^R|^2 + \frac{4m_l^2}{q^2}\left[|A_t|^2 + 2\mathrm{Re}(A_0^L A_0^{R*})\right]\right\},$$

$$J_2^s = \frac{3\beta_l^2}{16}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)\right],$$

$$J_2^c = -\frac{3\beta_l^2}{4}\left[|A_0^L|^2 + (L \to R)\right],$$

$$J_3 = \frac{3}{8}\beta_l^2\left[|A_\perp^L|^2 - |A_\parallel^L|^2 + (L \to R)\right],$$

$$J_4 = \frac{3}{4\sqrt{2}}\beta_l^2\left[\mathrm{Re}(A_0^L A_\parallel^{L*}) + (L \to R)\right],$$

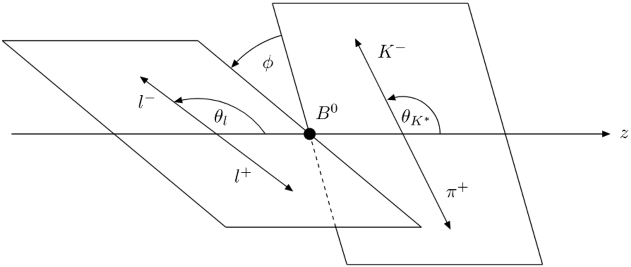
$$J_5 = \frac{3\sqrt{2}}{4}\beta_l\left[\mathrm{Re}(A_0^L A_\perp^{L*}) - (L \to R)\right],$$

$$J_6 = \frac{3}{2}\beta_l\left[\mathrm{Re}(A_\parallel^L A_\perp^{L*}) - (L \to R)\right],$$

$$J_7 = \frac{3\sqrt{2}}{4}\beta_l\left[\mathrm{Im}(A_0^L A_\parallel^{L*}) - (L \to R)\right],$$

$$J_8 = \frac{3}{4\sqrt{2}}\beta_l^2\left[\mathrm{Im}(A_0^L A_\perp^{L*}) + (L \to R)\right],$$

$$J_9 = \frac{3}{4}\beta_l^2\left[\mathrm{Im}(A_\parallel^{L*} A_\perp^L) + (L \to R)\right],$$


K^-
ϕ
l^-
θ_l
B^0
θ_{K^*}
z
l^+
π^+

Matrix element between B-meson and $K\pi$

$$M = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^{\star} \Big(\Big[\langle K\pi | (\bar{s}\gamma_\mu (C_9^{eff} P_L + C_9^{\prime eff} P_R) b) | B \rangle$$

$$- \frac{2m_B}{q^2} \langle K\pi | \bar{s} i \sigma_{\mu\nu} q_\nu (C_7^{eff} P_R + C_7^{\prime eff} P_L) b | B \rangle \Big] (\bar{l}\gamma_\mu l)$$

$$+ \langle K\pi | (\bar{s}\gamma_\mu (C_{10}^{eff} P_L + C_{10}^{\prime eff} P_R) b) | B \rangle (\bar{l}\gamma^\mu \gamma_5 l)$$

$$+ \langle K\pi | \bar{s}(C_S P_R + C_S^{\prime} P_L) b | \bar{B} \rangle (\bar{l} l) + \langle K\pi | \bar{s}(C_P P_R + C_P^{\prime} P_L) b | \bar{B} \rangle (\bar{l}\gamma_5 l) \Big) .$$