Photon polarization determination of $b \to s\gamma$

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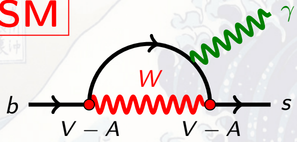
Outline

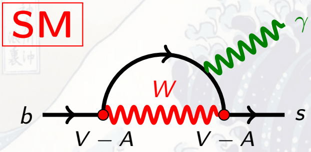
1. The $b \to s\gamma$ process and the photon polarization
2. Methods of the photon polarization determination
3. Future prospects of the photon polarization measurement
4. Conclusions and perspectives

SM



$$\mathcal{M}(b \to s\gamma)^{\mathrm{SM}} = \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} F_2 \frac{e}{16\pi^2} \bar{s}\sigma_{\mu\nu} q^\nu \left(\underbrace{m_b \frac{1+\gamma_5}{2}}_{b_R \to s_L \gamma_L} + \underbrace{m_s \frac{1-\gamma_5}{2}}_{b_L \to s_R \gamma_R} \right) b\, \varepsilon^{\mu *}$$

- In the SM, since $m_s/m_b \simeq 0.02 \ll 1$, photons are predominantly left(right)-handed in the $\overline{B}(B)$-decays.



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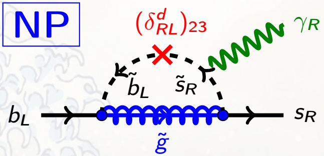

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- In the SM, since $m_s/m_b \simeq 0.02 \ll 1$, photons are predominantly left(right)-handed in the $\overline{B}$(B)-decays.
- NP can induce new Dirac structures and lead to an excess of right(left)-handed photons, without contradicting with the measured $\mathcal{B}(B \to X_s\gamma)$.

The photon polarization has not been measured precisely yet $\Rightarrow$ its measurement could provide a test of physics beyond the SM, namely right-handed currents.

Photon polarization determination: 3 methods

There are 3 methods proposed to measure the ratio $\mathcal{M}_R/\mathcal{M}_L$ ($\simeq 0$ in the SM):

1. Time-dependent CP-asymmetry in SuperB golden channel
   $B^0 \to K^{*0}(\to K_S\pi^0)\gamma$ [Atwood et al., Phys.Rev.Lett.79('97)]

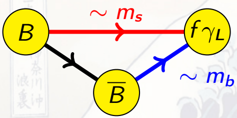
$$S_{f\gamma} = -\xi_f \frac{2|\mathcal{M}_L\mathcal{M}_R|}{|\mathcal{M}_L|^2+|\mathcal{M}_R|^2}\sin(\phi_M-\phi_L-\phi_R)$$

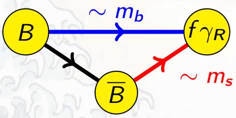
2. Transverse asymmetries in $B^0 \to K^{*0}(\to K^-\pi^+)\ell^+\ell^-$ [Kruger&Matias, Phys.Rev.D71('05);Becirevic&Schneider, Nucl.Phys.B854('11)]

$$\mathcal{A}_T^{(2)} = -\frac{Re[\mathcal{M}_R\mathcal{M}_L^*]}{|\mathcal{M}_R|^2+|\mathcal{M}_L|^2}, \quad \mathcal{A}_T^{(im)} = \frac{Im[\mathcal{M}_R\mathcal{M}_L^*]}{|\mathcal{M}_R|^2+|\mathcal{M}_L|^2}$$

3. K_1 three-body decay method in $B \to K_1(\to K\pi\pi)\gamma$ [Gronau et al., Phys.Rev.Lett.88, Phys.Rev.D66 ('02)]

$$\lambda_\gamma = \frac{|\mathcal{M}_R|^2-|\mathcal{M}_L|^2}{|\mathcal{M}_R|^2+|\mathcal{M}_L|^2}$$





- Time-dependent $\mathcal{A}_{CP}$ in neutral B-mesons results from the interference of mixing and decay `[Atwood et al., Phys.Rev.Lett.79('97)]`.

$$\mathcal{A}_{CP}(t) \equiv \frac{\Gamma(\overline{B}(t) \to f\gamma) - \Gamma(B(t) \to f\gamma)}{\Gamma(\overline{B}(t) \to f\gamma) + \Gamma(B(t) \to f\gamma)} \simeq S_{f\gamma} \sin(\Delta m t)$$

$$S_{f\gamma} = -\xi_f \frac{2|\mathcal{M}_L \mathcal{M}_R|}{|\mathcal{M}_L|^2 + |\mathcal{M}_R|^2} \sin(\phi_M - \phi_L - \phi_R)$$

where $\phi_{L,R} = \arg(\mathcal{M}_{L,R})$ and ϕ_M is the $B_d - \overline{B}_d$ mixing phase.

- $S_{f\gamma}$ determines the ratio $\mathcal{M}_R/\mathcal{M}_L$ and the phase of B-mixing.
- In the SM

$$\begin{array}{ll} b \to s\gamma & |\mathcal{M}_R/\mathcal{M}_L| \simeq \frac{m_s}{m_b}, \\ & \phi_L = \phi_R \simeq 0 \\ B^0 - \overline{B}^0 & \phi_M = 2\beta \simeq 43^\circ \end{array} \Rightarrow \begin{cases} S^{SM}_{K_S\pi^0\gamma} & \simeq -\frac{2m_s}{m_b} \sin 2\beta \ll 1 \\ S^{exp}_{K_S\pi^0\gamma} & = -0.15 \pm 0.2 \ \texttt{[HFAG('10)]} \end{cases}$$

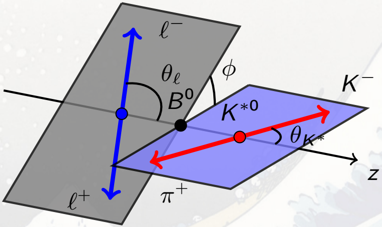
(2) Transverse asymmetries in $B^0 \to K^{*0}(\to K^- \pi^+)\ell^+\ell^-$

Analysis of the angular distributions in $B^0 \to K^{*0}(\to K^-\pi^+)\ell^+\ell^-$ in the low $\ell^+\ell^-$ inv.mass region and measurement of the transverse asymmetries [Kruger&Matias, Phys.Rev.D71('05); Becirevic&Schneider, Nucl.Phys.B854('11)].

$$\frac{d^2\Gamma}{dq^2 d\phi} = \frac{1}{2\pi}\frac{d\Gamma}{dq^2}\left[1 + \frac{1}{2}F_T(q^2)\left(A_T^{(2)}(q^2)\cos 2\phi + A_T^{(\mathrm{im})}(q^2)\sin 2\phi\right)\right]$$

$$A_T^{(2)}(q^2) = -\frac{2Re[\mathcal{M}_R\mathcal{M}_L^*]}{|\mathcal{M}_R|^2 + |\mathcal{M}_L|^2}$$

$$A_T^{(im)}(q^2) = \frac{2Im[\mathcal{M}_R\mathcal{M}_L^*]}{|\mathcal{M}_R|^2 + |\mathcal{M}_L|^2}$$



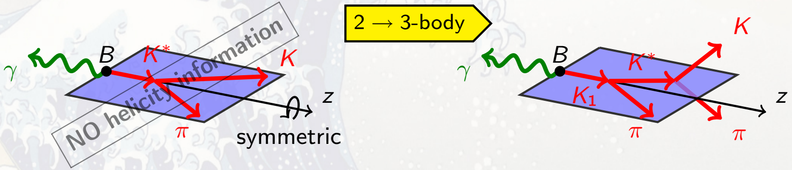
In the heavy quark and large E_{K^*} limit ($\Leftrightarrow q^2 \to 0$)

$$A_T^{(2)}(0) = \frac{2Re[C_{7\gamma}^{eff}C_{7\gamma}^{\prime\, eff\,*}]}{|C_{7\gamma}^{eff}|^2 + |C_{7\gamma}^{\prime\, eff}|^2}$$

$$A_T^{(im)}(0) = \frac{2Im[C_{7\gamma}^{eff}C_{7\gamma}^{\prime\, eff\,*}]}{|C_{7\gamma}^{eff}|^2 + |C_{7\gamma}^{\prime\, eff}|^2}$$

But for $q^2 \gtrsim 1$ GeV^2 the $\mathcal{O}_{9,10}$ contribution becomes important!

- The angular distribution of the three-body decay of K_{res} in $B \to K_{res}\gamma$ decay provides a direct determination of the $K_{res}(\Leftrightarrow \gamma)$ polarization [Gronau et al., Phys.Rev.Lett.88, Phys.Rev.D66 ('02)].



(3) Polarization determination in $B \to K_1(\to K\pi\pi)\gamma$

How to measure the polarization: basic idea

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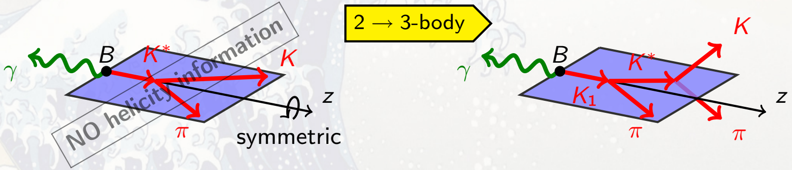


- There are two known $K_1(1^+)$ states, decaying into $K\pi\pi$ final state via $K^*\pi$ and $K\rho$ modes: $K_1(1270)$ and $K_1(1400)$.
- One of the decay channels $B \to K_1\gamma$, namely $B^+ \to K_1^+(1270)\gamma$, is finally measured ($\mathcal{B} = (4.3 \pm 1.2) \times 10^{-5}$), while $B^+ \to K_1^+(1400)\gamma$ is suppressed ($\mathcal{B} < 1.5 \times 10^{-5}$) [Belle, Phys.Rev.Lett.94('05)].

We investigated the feasibility of determining the photon polarization using the $B \to K_1(1270)\gamma$ channel [Kou,LeYaouanc&AT, Phys.Rev.D83('11)].

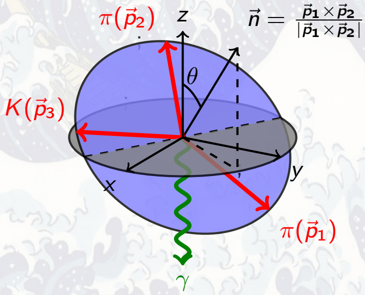
The decay distribution of $B \to K_1\gamma \to (K\pi\pi)\gamma$ is given by the master formula:

$$\frac{d\Gamma}{ds_{13}\,ds_{23}\,d\cos\theta} \propto \frac{1}{4}|\vec{\mathcal{J}}|^2(1+\cos^2\theta) + \boxed{\lambda_\gamma}\frac{1}{2}Im[\vec{n}\cdot(\vec{\mathcal{J}}\times\vec{\mathcal{J}}^*)]\cos\theta$$

$$\lambda_\gamma = \frac{|\mathcal{M}_R|^2 - |\mathcal{M}_L|^2}{|\mathcal{M}_R|^2 + |\mathcal{M}_L|^2} \simeq -1(+1)$$

in the SM for $\overline{B}(B)$ respectively

$\vec{\mathcal{J}} = \mathcal{C}_1(s_{13}, s_{23})\vec{p}_1 - \mathcal{C}_2(s_{13}, s_{23})\vec{p}_2 \Leftrightarrow$ K_1-decay helicity amplitude.



Previous method of Gronau *et al.*

In the original proposal, only the θ-dependence was considered (up-down asymmetry):

$$\mathcal{A}_{up-down} = \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}}$$

$$= \frac{3}{4}\boxed{\lambda_\gamma}\frac{\int ds_{13}ds_{23}\, Im[\vec{n}\cdot(\vec{\mathcal{J}}\times\vec{\mathcal{J}}^*)]}{\int ds_{13}ds_{23}|\vec{\mathcal{J}}|^2}$$

[Gronau et al., Phys.Rev.Lett.88]

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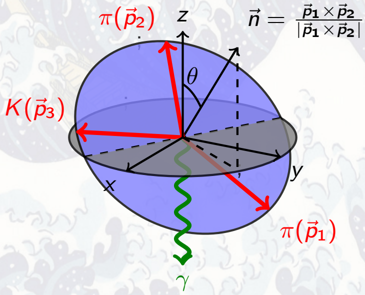


New method: DDLR
(Davier, Duflot, Le Diberder, Rougé)

We take into account the Dalitz variable (s_{13},s_{23}) dependence, which carries the further information of the polarization:

$$\omega(s_{13}, s_{23}, \cos\theta) \equiv \frac{2Im[\vec{n}\cdot(\vec{\mathcal{J}}\times\vec{\mathcal{J}}^*)]\cos\theta}{|\vec{\mathcal{J}}|^2(1+\cos^2\theta)}$$

[Kou,LeYaouanc&AT, Phys.Rev.D83('11)]

Assuming that this process comes from the vector-pseudoscalar meson intermediate state ($K_1 \to K^*\pi,\ K\rho$), $\mathcal{J}$ contains 4 $K_1 \to VP$ partial wave amplitudes (S, D) and 2 $V \to PP$ couplings.

- There have been very important experimental studies of the K_1-decays ACCMOR, SLAC, B-factories, etc. Although some of the parameters are determined experimentally, there still remain some difficulties in their interpretation and application. In particular,
  - K_1-width issue and threshold effects
  - $K\rho/K^*\pi$ relative phase
  - treatment of the $K_1 \to$ scalar $+\,\pi$ channel
- Therefore, we estimate the $A_{S,D}(K_1 \to K^*\pi,\ K\rho)$ in the framework of the $^3P_0$ quark-pair-creation model [Kou,LeYaouanc&AT, hep-ph/1111.6307].
- In principle, the parameters of $\mathcal{J}$ can be extracted in a model-independent way from angular analysis of the $K\pi\pi$-system in $B \to J/\psi K_1$ [Belle, Phys.Rev.D83('10)] and/or in τ-decays measured at B-factories $\Rightarrow$ improvement expected by SuperB!

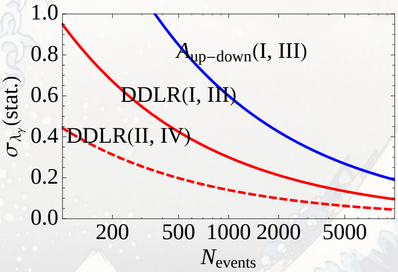
(3) Polarization determination in $B \to K_1(\to K\pi\pi)\gamma$

Sensitivity studies of λ_γ measurement in the DDLR method

We estimate the sensitivity of future experiments to λ_γ using "ideal" (i.e. detector effects and background are not taken into account) MC simulation.

Stat. errors to $\lambda_\gamma^{(SM)}$ from $B \to K_1(1270)\gamma$

N_{events}	10^3	10^4
(I) $B^+ \to K^+\pi^-\pi^+\gamma$	± 0.18	± 0.06
(II) $B^+ \to K^0\pi^+\pi^0\gamma$	± 0.12	± 0.04
(III) $B^0 \to K^0\pi^+\pi^-\gamma$	± 0.18	± 0.06
(IV) $B^0 \to K^+\pi^-\pi^0\gamma$	± 0.12	± 0.04

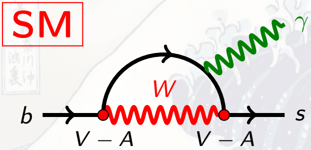


- For 10k events the error on λ_γ is $\lesssim 10\%$.

[Kou,LeYaouanc&AT, Phys.Rev.D83('11)]

- The use of the Dalitz plot information improves the sensitivity by a factor 2 compared to the pure angular $\cos\theta$-fit (or $\mathcal{A}_{up-down}$).

Future constraints on right-handed currents



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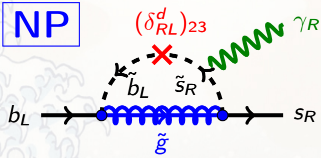


$$\mathcal{M}(b \to s\gamma) = \frac{4G_F}{\sqrt{2}} V^*_{ts} V_{tb} \frac{e}{16\pi^2} m_b \bar{s} \sigma_{\mu\nu} q^\nu \Big(\underbrace{C^{eff}_{7\gamma} \frac{1+\gamma_5}{2}}_{b_R \to s_L \gamma_L} + \underbrace{C'^{\,eff}_{7\gamma} \frac{1-\gamma_5}{2}}_{b_L \to s_R \gamma_R} \Big) b\, \varepsilon^{\mu *}$$

- *BR* measurement of the inclusive and exclusive $b \to s\gamma$ processes ($\mathcal{B}(B \to X_s\gamma)^{\text{exp}} = (3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$ [HFAG('10)]) is not a direct polarization determination:

$$\mathcal{B} \propto |C^{eff\ SM}_{7\gamma} + C^{eff\ NP}_{7\gamma}|^2 + |C'^{\,eff\ NP}_{7\gamma}|^2$$

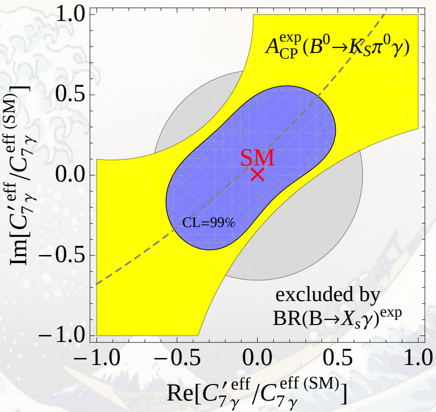
- In the SM, $C^{(\prime)\,eff}_{7\gamma}$ are real. Some NP models have extra sources of *CP*-violation $\Rightarrow$ $C^{(\prime)\,eff}_{7\gamma}$ can be complex.

Current constraints on $C'^{\,eff}_{7\gamma} / C^{eff}_{7\gamma}$

Here and in the following, we assume for illustration $C^{eff}_{7\gamma}$ to be purely SM-like (i.e. $C^{eff\,(NP)}_{7\gamma} = 0$).

- $\mathcal{B}(B \to X_s\gamma)^{\text{exp}} = (3.55 \pm 0.24) \times 10^{-4}$ [HFAG('10)]
- $S^{\text{exp}}_{K_S\pi^0\gamma} = -0.15 \pm 0.2$ [HFAG('10)]

There is still large area left for NP!



Future constraints on $C'^{\,eff}_{7\gamma} / C^{eff}_{7\gamma}$ combining various methods

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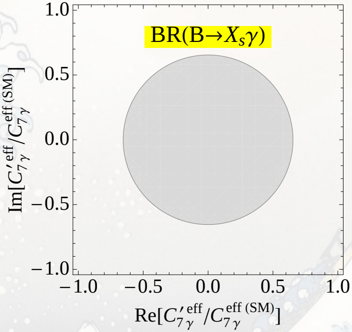
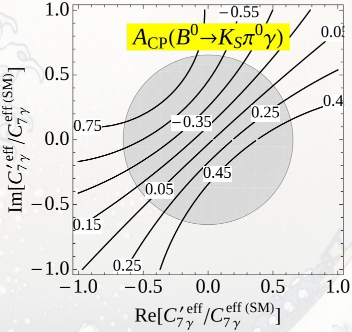


[Becirevic,Kou,LeYaouanc&AT, in preparation]

- $\mathcal{B}(B \to X_s\gamma)^{\text{exp}} = (3.55 \pm 0.24) \times 10^{-4}$ [HFAG('10)]

3 different methods give different constraints:

1. $\mathcal{A}_{CP}(B \to K_S\pi^0\gamma)$:
   $S^{\text{exp}}_{K_S\pi^0\gamma} = -0.15 \pm 0.2$ [HFAG('10)]
   $\sigma(S_{K_S\pi^0\gamma})^{\text{SuperB}} \approx 0.02$ at 75 ab^{-1}



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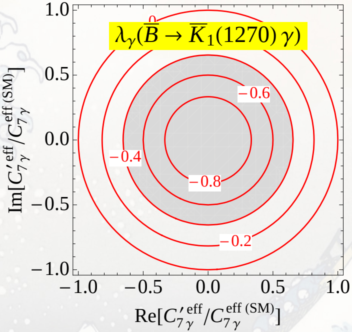

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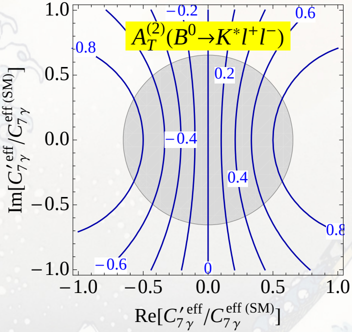

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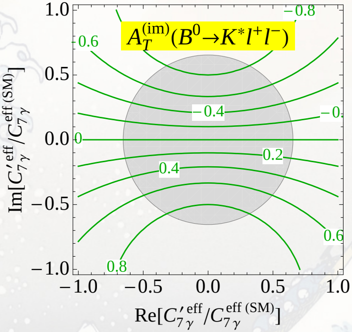

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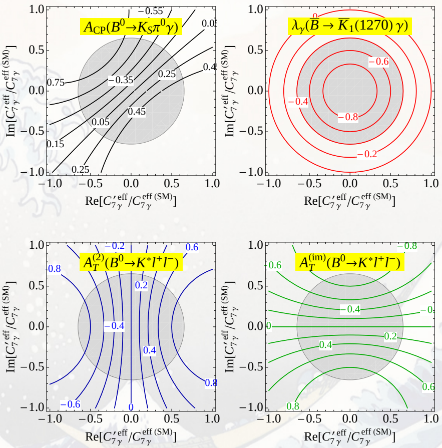

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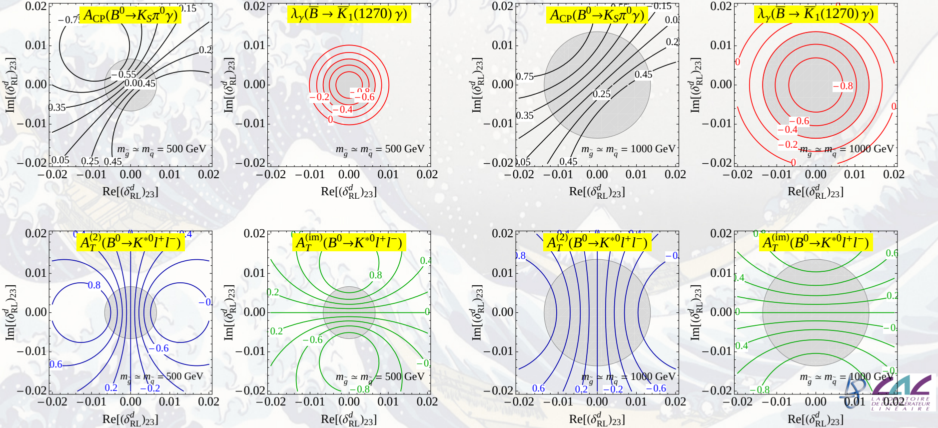
Future constraints on $(\delta^d_{RL})_{23}$ combining various methods

Here we present the potential constraints on $(\delta^d_{RL})_{23}$ which has already been studied using the CP-asymmetry in $B \to \phi K_S$, $B \to \eta' K_S$ and $\mathcal{B}(b \to s\gamma)$ [Khalil&Kou, Phys.Rev.D67('03), Phys.Rev.Lett.91('03); see also "Physics at Super B Factory", hep-ex/1002.5012].

$m_{\tilde g} \simeq m_{\tilde q} = 500$ GeV $\qquad\qquad$ $m_{\tilde g} \simeq m_{\tilde q} = 1000$ GeV



Conclusions and perspectives

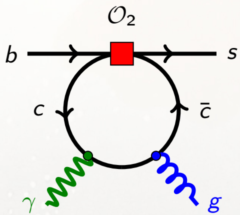
1. There is still a lot of space left for NP beyond the SM.
2. The $b \to s\gamma$ process can provide stringent constraints on some of the NP parameters.
3. Perspective: the right-handed currents will be very strictly constrained by SuperB and LHCb. It was demonstrated that combining the three methods,
   - time-dependent CP-asymmetry in $B^0 \to K^{*0}(\to K_S\pi^0)\gamma$
   - transverse asymmetries $A_T^{(2)}$, $A_T^{(im)}$ in $B^0 \to K^{*0}(\to K^-\pi^+)\ell^+\ell^-$
   - K_1 three-body decay method in $B \to K_1(\to K\pi\pi)\gamma$

   we will be able to constrain $C_{7\gamma}^{\prime\,eff}/C_{7\gamma}^{eff}$ and in particular $(\delta_{RL}^d)_{23}$ quite precisely.

BACKUP SLIDES

An additional helicity enhancement can be obtained by considering (at parton level) a three-particle final state: $b \to s\gamma g$. The dominant contribution comes from the four-quark operator

$$\mathcal{O}_2 = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)$$



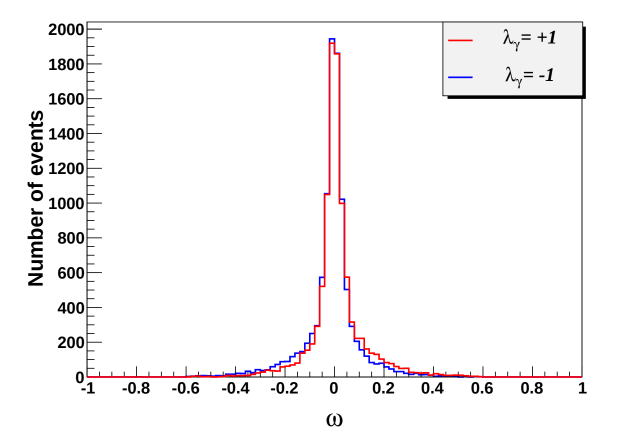
The soft ($|\vec{k}_g|^2 \ll 4m_c^2$) gluon contribution is estimated to be [Ball&Zwicky, Phys.Lett.B642('06)]:

$$\frac{\mathcal{M}(\overline{B} \to \overline{K}^* \gamma_R)}{\mathcal{M}(\overline{B} \to \overline{K}^* \gamma_L)} \simeq \frac{m_s}{m_b} - \frac{C_2}{C_7} \frac{L - \tilde{L}}{36 m_c^2 m_b T_1^{B \to K^*}(0)} \simeq \frac{m_s}{m_b} \times (0.8 \pm 0.2)$$

- Soft gluon correction enhances the leading term up to 20%.
- Additional hadronic corrections are expected to be smaller.

Determination of λ_γ in the DDLR method

ω-distribution



Example of MC ω-distribution for 10k of $B^+ \to (K^+\pi^-\pi^+)_{K_1(1270)}\gamma$ events with purely right-handed (red) and left-handed (blue) photons.

- Our PDF (i.e. the normalized decay width distribution) can be written as

$$W(s_{13}, s_{23}, \cos\theta) = f(s_{13}, s_{23}, \cos\theta) + \lambda_\gamma g(s_{13}, s_{23}, \cos\theta)$$

- Using the maximum likelihood method, we obtain λ_γ as a solution of the equation:

$$\boxed{\frac{\partial \ln \mathcal{L}}{\partial \lambda_\gamma} = \sum_{i=1}^{N_{\text{events}}} \frac{\omega_i}{1+\lambda_\gamma \omega_i} = 0}$$

$$\mathcal{L} = \prod_{i=1}^{N_{\text{events}}} W(s_{13}^i, s_{23}^i, \cos\theta^i)$$

$$\omega_i \equiv g(s_{13}^i, s_{23}^i, \cos\theta^i)/f(s_{13}^i, s_{23}^i, \cos\theta^i)$$

Notice: resulting solution does not depend on f and g separately but only on their ratio ω.

$$\omega(s_{13}, s_{23}, \cos\theta) \equiv \frac{2 Im[\vec{n}\cdot(\vec{\mathcal{J}}\times\vec{\mathcal{J}}^*)]\cos\theta}{|\vec{\mathcal{J}}|^2(1+\cos^2\theta)}$$

λ_γ extraction from ω-distribution

$$\boxed{\lambda_\gamma = \frac{\langle\omega\rangle}{\langle\omega^2\rangle}}$$

$$\sigma_{\lambda_\gamma}^{-2} = -\frac{\partial^2 \ln\mathcal{L}}{\partial {\lambda_\gamma}^2} = N\left\langle\left(\frac{\omega}{1+\lambda_\gamma\omega}\right)^2\right\rangle$$

One only has to sum ω and ω^2 over all the events $\Rightarrow$ no fit is needed !

$$\langle\omega^n\rangle \equiv \frac{1}{N_{\text{events}}}\sum_{i=1}^{N_{\text{events}}} \omega_i^n$$

Extra sources of flavour violation in SUSY

- In the SM, the quark masses come from Yukawa couplings:

$$\mathcal{L}^{SM}_{Yukawa} = v \bar{u}_R y_u u_L + v \bar{d}_R y_d d_L + h.c.$$

- In SUSY, the squark mass can come from any combination of left and right couplings:

$$\mathcal{L}^{MSSM}_{soft} = \tilde{q}_L^\dagger m_Q^2 \tilde{q}_L + \tilde{u}_R^\dagger m_U^2 \tilde{u}_R + \tilde{d}_R^\dagger m_D^2 \tilde{d}_R + v_2 \tilde{u}_R^\dagger A_U \tilde{q}_L + v_1 \tilde{d}_R^\dagger A_D \tilde{q}_L + \dots$$

- $m^2_{Q,U,D}$ and $A_{U,D}$ are not diagonal in the quark eigenmass basis $\Rightarrow$ the squark propagators can change flavour and chirality:

Mass Insertion Approximation

- In the super-CKM basis, the source of flavour violation is left in the off-diagonal terms of the sfermion mass matrix: $(\Delta^q_{AB})_{ij}$ ($A, B = R, L$ and $\tilde{m}$ is the average squark mass).
- The sfermion propagator can then be expanded as

$$\langle \tilde{q}_{Ai} \tilde{q}^*_{Bj} \rangle = i(k^2 - m^2_{\tilde{q}} - \Delta^q_{AB})^{-1}_{ij} \simeq \frac{i\delta_{ij}}{k^2 - m^2_{\tilde{q}}} + \frac{i(\Delta^q_{AB})_{ij}}{(k^2 - m^2_{\tilde{q}})^2} + \dots$$

- The flavour violation in SUSY can be parametrized in a model independent way by the dimensionless parameters

$$(\delta^q_{AB})_{ij} \equiv \frac{(\Delta^q_{AB})_{ij}}{m^2_{\tilde{q}}}$$

Annual yield estimation

The annual yield of the $B \to (K\pi\pi)_{K_1}\gamma$ decay can be estimated as following:

$$\boxed{N_{annual} = N_B \times \mathcal{B}(B \to K_1\gamma) \times \mathcal{B}(K_1 \to K\pi\pi) \times \epsilon_{tot}}$$

$\mathcal{B}(B^+ \to (K^+\pi^-\pi^+)_{K_1(1270)}\gamma) = 4.3 \times 10^{-5} \times (0.16 * 4/9 + 0.42 * 1/6) \simeq 0.6 \times 10^{-5}$,
$\mathcal{B}(B^+ \to (K^0\pi^+\pi^0)_{K_1(1270)}\gamma) = 4.3 \times 10^{-5} \times (2 * 0.16 * 2/9 + 0.42 * 1/3) \times 1/3 \simeq 0.3 \times 10^{-5}$

- For $\int \mathcal{L}^{\text{LHCb}} = 2\ fb^{-1}$, $N_B \simeq 8 \times 10^{11}$, $\epsilon_{tot} \sim 0.1\%$ (as in $B \to K^*\gamma$ and $B_s \to \phi\gamma$ [LHCB-ROADMAP4-001]) $\Rightarrow$

$$N^{\text{LHCb}}_{annual}(B^+ \to (K^+\pi^-\pi^+)_{K_1(1270)}\gamma) \approx 5 \times 10^3$$
$$N^{\text{LHCb}}_{annual}(B^+ \to (K^0\pi^+\pi^0)_{K_1(1270)}\gamma) \approx 2.5 \times 10^3$$

- For $\int \mathcal{L}^{\text{SuperB}} = 75\ ab^{-1}$, $N_B \simeq 1.6 \times 10^{10}$, $\epsilon_{tot} \sim 1\%$ (as in $B \to K_1^+(1270)\gamma$ [Belle, Phys.Rev.Lett.94('05)]) $\Rightarrow$

$$N^{\text{SuperB}}_{annual}(B^+ \to (K^+\pi^-\pi^+)_{K_1(1270)}\gamma) \approx 1 \times 10^3$$
$$N^{\text{SuperB}}_{annual}(B^+ \to (K^0\pi^+\pi^0)_{K_1(1270)}\gamma) \approx 0.5 \times 10^3$$

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