Determining the photon polarization of the $b \to s\gamma$ using the $B \to K_1(1270)\gamma \to (K\pi\pi)\gamma$ decay

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The Role of Heavy Fermions in Fundamental Physics
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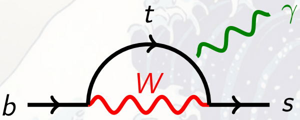
Outline

1. Introduction: the $\mathbf{b} \to \mathbf{s}\gamma$ process and the photon polarization
2. How to determine the polarization
   - $B \to K_1(\to K\pi\pi)\gamma$: new method
3. Right-handed currents constraints
4. Conclusions and perspectives

Why are we interested in measuring the photon polarization of $b \to s\gamma$?



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

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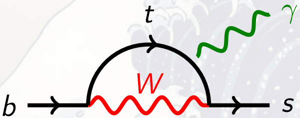

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- In the SM since $m_s / m_b \ll 1$, photons are predominantly left (right)-handed in the $\bar{B}(B)$-decays.
- NP can induce new Dirac structures and lead to an excess of right(left)-handed photons, without contradicting with the measured $\mathcal{B}(B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

The measurement of the photon polarization could provide a test of physics beyond the SM, namely right-handed currents.

Right-handed currents in NP beyond the SM

How much right-handed currents is allowed?

At present, Br measurements of the inclusive and exclusive $b \to s\gamma$ processes *do not put very strong constraints* on the right-handed currents yet since *it is not a direct* measurement ($Br \propto |\mathcal{M}_L^{SM} + \mathcal{M}_L^{NP}|^2 + |\mathcal{M}_R^{SM} + \mathcal{M}_R^{NP}|^2$).

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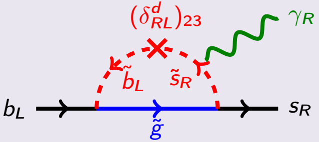
Some NP models predict significant contribution of the right-handed currents

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

$$\mathcal{L}_{soft}^{MSSM} = \tilde{Q}_L^\dagger m_{\tilde{Q}}^2 \tilde{Q}_L + \tilde{\bar{u}}_R^\dagger m_{\tilde{\bar{u}}}^2 \tilde{\bar{u}}_R + \tilde{\bar{d}}_R^\dagger m_{\tilde{\bar{d}}}^2 \tilde{\bar{d}}_R + v_u \tilde{\bar{u}}_R a_u \tilde{Q}_L + v_d \tilde{\bar{d}}_R a_d \tilde{Q}_L + \ldots$$

- The soft SUSY breaking terms induce the chirality flip on the internal lines $\Rightarrow$ this leads to the enhancement factor $m_{\tilde{g}}/m_b$ compared to the SM.



$$\mathcal{M}_{\tilde{g}}^{SUSY}(b_L \to s_R \gamma_R) \propto m_{\tilde{g}} \times (\delta_{RL}^d)_{23} \times \text{loop}$$

Photon polarization determination: 3 methods

1. Method 1: CP asymmetry in $B_q(t) \to f^{CP}\gamma$

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

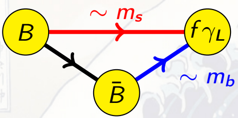
2. Method 2: transverse asymmetry in $B^0 \to K^{*0}(\to K^-\pi^+)\ell^+\ell^-$

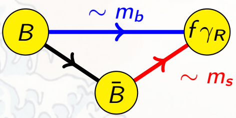
$$\mathcal{A}_T^{(2)} = -\frac{\mathcal{M}_R\mathcal{M}_L^* + \mathcal{M}_R^*\mathcal{M}_L}{|\mathcal{M}_R|^2 + |\mathcal{M}_L|^2}$$

3. Method 3: K_1 three-body decay method in $B \to K_1\gamma$

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

1. CP-asymmery in $B^0 \to K^{*0}(\to K_S\pi^0)\gamma$, $B_s \to \phi\gamma$





- Time-dependent CP-asymmetry in neutral B-mesons results from the interference of mixing and decay *[Atwood et al.,Phys.Rev.Lett.79 ('97)]*.

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

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

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

- In the SM

$$\begin{array}{ll} b \to s\gamma & |\mathcal{M}_R/\mathcal{M}_L| \simeq m_s/m_b, \\ & \phi_L = \phi_R \simeq 0 \\ B^0 - \bar{B}^0 & \phi_M = 2\beta \simeq 43^\circ \\ B_s - \bar{B}_s & \phi_M \simeq 0 \end{array} \Rightarrow \begin{cases} S_{K_S\pi^0\gamma} & \simeq -(2m_s/m_b)\sin(2\beta) \\ (S^{\exp}_{K_S\pi^0\gamma} & = -0.15 \pm 0.2) \\ S_{\phi\gamma} & \simeq 0 \end{cases}$$

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$$\mathcal{A}_T^{(2)} = -\frac{\mathcal{M}_R\mathcal{M}_L^* + \mathcal{M}_R^*\mathcal{M}_L}{|\mathcal{M}_R|^2 + |\mathcal{M}_L|^2}$$

3. Method 3: K_1 three-body decay method in $B \to K_1\gamma$

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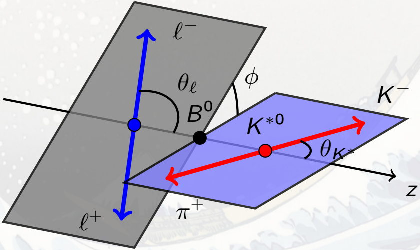
2. Transverse asymmetry in $B^0 \to K^{*0}(\to K^-\pi^+)\ell^+\ell^-$

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 asymmetry *[Kruger& Matias, Phys.Rev.D71('05)]*.

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

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

$$\mathcal{A}_T^{(2)} = -\frac{\mathcal{M}_R\mathcal{M}_L^* + \mathcal{M}_R^*\mathcal{M}_L}{|\mathcal{M}_R|^2 + |\mathcal{M}_L|^2}$$



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In *[Phys.Rev.Lett.88,Phys.Rev.D66('02)]* Gronau *et al.* proposed that the angular distribution of the **three-body** decay of K_{res} in $B \to K_{res}\gamma$ decay carries the photon polarization information.

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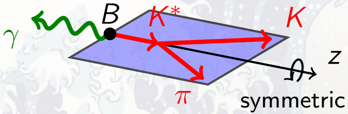

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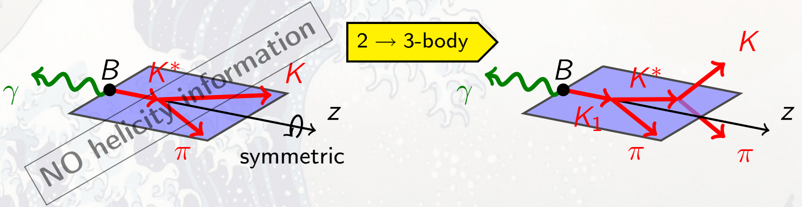

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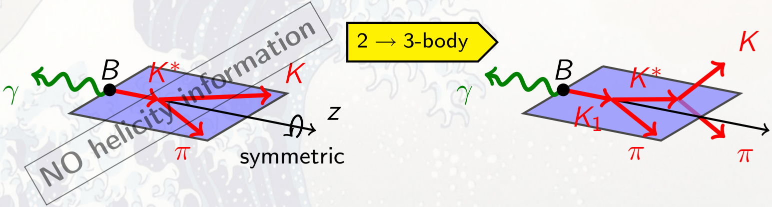


- There are two known $K_1(1^+)$ states, decaying into $K\pi\pi$ final state via $K^*\pi$ and ρK modes: $K_1(1270)$ and $K_1(1400)$.
- One of the decay channels $B \to K_1\gamma$, namely $B^+ \to K_1^+(1270)\gamma$, is finally measured ($\mathcal{B} = (4.3 \pm 1.2) \times 10^{-5}$), while $B^+ \to K_1^+(1400)\gamma$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

We investigate the feasibility of determining the photon polarization using the $B \to K_1(1270)\gamma$ channel.

The decay distribution of $\bar{B} \to \bar{K}_1\gamma \to (\bar{K}\pi\pi)\gamma$ is given by the master formula:

$$\frac{d^3\Gamma}{ds_{13}ds_{23}d\cos\theta} \propto \frac{1}{4}|\vec{\mathcal{J}}|^2(1+\cos^2\theta) + \boxed{\lambda_\gamma}\frac{1}{2}Im[\vec{n}\cdot(\vec{\mathcal{J}}\times\vec{\mathcal{J}}^*)]\cos\theta$$

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

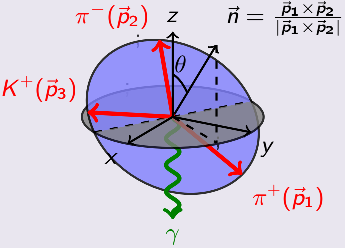
$\simeq -1(+1) + O(m_s^2/m_b^2)$ in the SM

for $\bar{B}(B)$ respectively.

K_1-reference frame

$\vec{\mathcal{J}} = \mathcal{C}_1(s_{13}, s_{23})\vec{p}_1 - \mathcal{C}_2(s_{13}, s_{23})\vec{p}_2$

$\Leftrightarrow$ K_1-decay helicity amplitude.



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Formalism

The decay distribution of $\bar{B} \to \bar{K}_1\gamma \to (\bar{K}\pi\pi)\gamma$ is given by the master formula:

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for $\bar{B}(B)$ respectively.

- In order to determine λ_γ, compared to the experimental decay distribution, we need a precise expression for $\mathcal{J}$.
- In principle, $\mathcal{J}$ can be extracted from data (e.g. Dalitz analysis of $B \to J/\psi K_1$ *[Belle ('10)]*) or computed within a quark model *[Kou,Le Yaouanc&A.T., in preparation]*.

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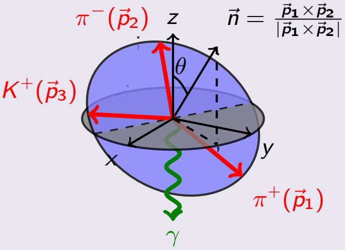

Up-down asymmetry

In the original proposal by Gronau et al., only the θ-dependence on the polarization was considered (up-down asymmetry)

$$\mathcal{A}_{up-down} = \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}} = \frac{3}{4} \boxed{\lambda_\gamma} \frac{\int ds_{13} ds_{23} Im[\vec{n} \cdot (\vec{\mathcal{J}} \times \vec{\mathcal{J}}^*)]}{\int ds_{13} ds_{23} |\vec{\mathcal{J}}|^2}$$

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New method

In our work, we take into account the Dalitz variable (s_{13},s_{23}) dependence, which carries the further information of the polarization (it was pointed out in the ALEPH analysis of $\tau \to a_1(\to \pi\pi\pi)\nu$ *[Davier et al., Phys.Lett.B306 ('93)]*). In this method, we use the quantity, called ω

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

[Kou,Le Yaouanc&A.T., hep-ph/1011.6593]

$\lambda_\gamma \equiv \frac{\Gamma(B\to K_{1R}\gamma_R)-\Gamma(B\to K_{1L}\gamma_L)}{\Gamma(B\to K_1\gamma)} \simeq 1 + O(m_s^2/m_b^2)$ in the SM

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.

3. K_1 three-body decay method

Results: Monte Carlo simulation

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Expected $\lambda_\gamma^{(SM)}$ from $B \to K_1(1270)\gamma$:

N_{events}	1k	10k
$B^+ \to K^+\pi^-\pi^+\gamma$	1.00±0.18	1.00±0.06
$B^+ \to K^0\pi^+\pi^0\gamma$	1.00±0.12	1.00±0.04
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- For 10k events the error on λ_γ is $< 10\%$.
- The use of the Dalitz plot information improves the sensitivity by a factor 2 compared to the pure angular $\cos\theta$-fit.

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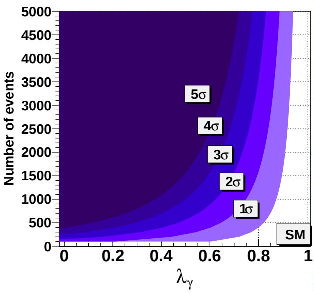
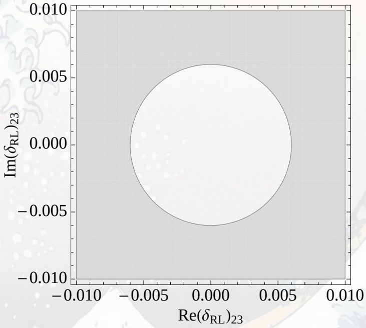
Exclusion plot for $\lambda_\gamma^{(SM)}$ for $B^+ \to (K^0\pi^+\pi^0)_{K_1(1270)^+}\gamma$



Future constraints on right-handed currents

- $\mathcal{B}(B \to X_s\gamma)^{\exp} = (3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$

$$((\delta^d_{LR})_{23} = (\delta^d_{LL})_{23} = (\delta^d_{RR})_{23} = 0)$$



[Becirevic, Kou, Lefrancois, Schune, A.T., work in progress]

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  $S^{\text{exp}}_{K_S\pi^0\gamma} = -0.15 \pm 0.2$
  $\sigma(S)_{\text{LHCb}} \approx 0.2$ at 2 fb^{-1},
  $\sigma(S)_{\text{SuperB}} \approx 0.02$ at 75 ab^{-1},
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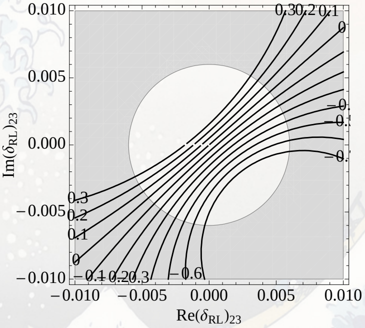

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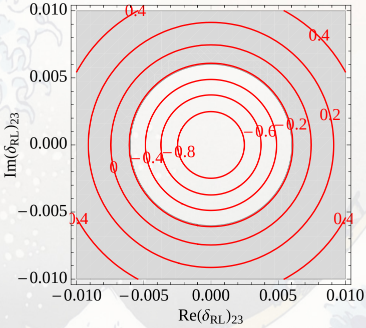

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  $\sigma(\lambda_\gamma)_{\rm th} \sim 0.2$
- $A_T^{(2)}$ potential measurement from angular analysis of $B^0 \to K^{*0}(\to K^-\pi^+)\ell^+\ell^-$.
  $\sigma(A_T^{(2)})_{\rm LHCb} \approx 0.2$ at 2 fb^{-1}.

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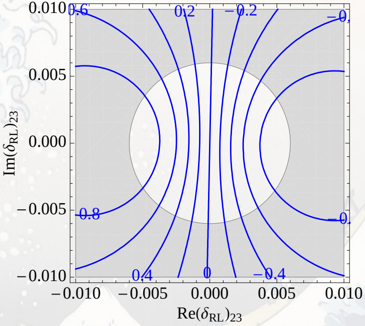

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  $S^{\exp}_{K_S\pi^0\gamma} = -0.15 \pm 0.2$
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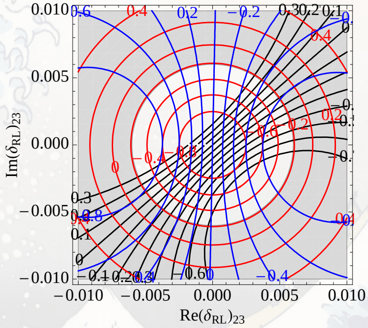
  $\sigma(S)_{\text{SuperB}} \approx 0.02$ at 75 ab^{-1},
  $\sigma(S)_{\text{BelleII}} \approx 0.03$ at 50 ab^{-1}.
- λ_γ potential measurement from ω-distribution in
  $B \to (K\pi\pi)_{K_1(1270)}\gamma$.
  $\sigma(\lambda_\gamma)_{\text{th}} \sim 0.2$
- $A_T^{(2)}$ potential measurement from angular analysis of
  $B^0 \to K^{*0}(\to K^-\pi^+)\ell^+\ell^-$.
  $\sigma(A_T^{(2)})_{\text{LHCb}} \approx 0.2$ at 2 fb^{-1}.

$((\delta^d_{LR})_{23} = (\delta^d_{LL})_{23} = (\delta^d_{RR})_{23} = 0)$



[Becirevic,Kou,Lefrancois,Schune,A.T., work in progress]

Conclusions and perspectives

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4. Perspective: the right-handed currents will be very strictly constrained by the future experiments, LHCb and SuperB. I showed an example of SUSY with large RL mass insertion. It was demonstrated that combining the three methods, we will be able to constrain $(\delta^d_{RL})_{23}$ at the level of 10^{-3}.

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

BACKUP SLIDES

$B \to K_1(1^+)$ form factors

The matrix element of the leading operator $\mathcal{O}_7$ can be parametrized in terms of hadronic form factors using the following conventions:

$$\langle K_1|\bar{s}\sigma_{\mu\nu}\gamma_5 q^\nu b|\bar{B}\rangle = i\epsilon_{\mu\nu\rho\sigma}\varepsilon^{\nu*}_{K_1} p^\rho_B p^\sigma_{K_1} 2F_1^{K_1}(q^2)$$

$$\langle K_1|\bar{s}\sigma_{\mu\nu} q^\nu b|\bar{B}\rangle = F_2^{K_1}(q^2)\left[\varepsilon^*_{K_1\mu}(m_B^2 - m_{K_1}^2) - (\varepsilon^*_{K_1}\cdot p_B)(p_B + p_{K_1})_\mu\right] + F_3^{K_1}(q^2)(\varepsilon^*_{K_1}\cdot p_B)\left[q_\mu - \frac{q^2}{m_B^2 - m_{K_1}^2}(p_B + p_{K_1})_\mu\right]$$

- $F_1^{K_1}(0) = F_2^{K_1}(0)$ in order to avoid a kinematic singularity at $q^2 = 0$.
- Since the outgoing photon is on-shell, $q^2 = 0$ and $q_\mu \varepsilon^{*\mu} = 0 \Rightarrow$ the last term, proportional to $F_3^{K_1}$, vanishes and hence the matrix element is parametrized with only one form factor $F_1^{K_1}(0)$:

$$\langle K_{1L}\gamma_L|\mathcal{O}_{7L}|\bar{B}\rangle = \langle K_{1R}\gamma_R|\mathcal{O}_{7R}|\bar{B}\rangle = i\frac{e}{8\pi^2} m_b (m_B^2 - m_{K_1}^2) F_1^{K_1}(0)$$

- The form factors of the mass eigenstates are related to $F_1^{K_{1A,B}}$, which can be calculated with LCSR, as following:

$$F_1^{K_1(1270)}(0) = F_1^{K_{1A}}(0)\sin\theta_{K_1} + F_1^{K_{1B}}(0)\cos\theta_{K_1}$$
$$F_1^{K_1(1400)}(0) = F_1^{K_{1A}}(0)\cos\theta_{K_1} - F_1^{K_{1B}}(0)\sin\theta_{K_1}$$

$A \to V_{ij}(\to P_i P_j) P_k$ decay

- The decay amplitude of the axial-vector meson A to some vector (V_{ij}) and pseudoscalar (P_k) mesons can be expressed in the following Lorentz invariant form:

$$\mathcal{M}(A \to V_{ij} P_k) = \varepsilon_\mu^{(A)} T^{\mu\nu} \varepsilon_\nu^{(V_k)*} \ , \quad T^{\mu\nu} = f g^{\mu\nu} + h p_{V_{ij}}^\mu p_A^\nu$$

  The unknown effective couplings f and h can be related to the partial wave amplitudes a_S and a_D as

$$f = -\left(a_S + \frac{a_D}{\sqrt{2}}\right), \quad h = \left[\left(1 - \frac{m_{V_{ij}}}{E_{V_{ij}}}\right) a_S + \left(1 + 2\frac{m_{V_{ij}}}{E_{V_{ij}}}\right) \frac{a_D}{\sqrt{2}}\right] \frac{E_{V_{ij}}}{m_A \vec{p}_k^2}$$

  where $E_{V_{ij}}$ and $\vec{p}_k (= -\vec{p}_{V_{ij}})$ are the energy of the vector meson and the momentum of pseudoscalar meson in the A-reference frame.

- The amplitude of the subsequent decay $V_{ij} \to P_i P_j$ can be parametrized in terms of the effective coupling $g_{V_{ij} P_i P_j}$ (which can be determined from the measured partial decay width of V_{ij}):

$$\mathcal{M}(V_{ij} \to P_i P_j) = g_{V_{ij} P_i P_j} \cdot \varepsilon_\mu^{(V_{ij})} (p_i - p_j)^\mu$$

$A \to V_{ij}(\to P_i P_j) P_k$ decay

Parametrizing the propagation of V_{ij} with the relativistic Breit-Wigner form $BW_{V_{ij}}(s_{ij}) = 1/(s_{ij} - m^2_{V_{ij}} - i m_{V_{ij}} \Gamma_{V_{ij}})$, one can write the total amplitude of the A-decay chain as

$$\mathcal{M}(A \to (P_i P_j)_{V_{ij}} P_k) = \varepsilon^{(A)}_\mu (f g^{\mu\nu} + h p^\mu_{V_{ij}} p^\nu_A) \varepsilon^{(V_{ij})*}_\nu BW_{V_{ij}}(s_{ij}) g_{V_{ij} P_i P_j} \varepsilon^{(V_{ij})}_\sigma (p_i - p_j)^\sigma$$

Summing over the V_{ij}-polarizations, one obtains the total Lorentz invariant amplitude:

$$\mathcal{M}(A \to (P_i P_j)_{V_{ij}} P_k) = \varepsilon^{(A)}_\mu J^\mu_{ijk}, \quad J^\mu_{ijk} = c_k(s_{ij}) p^\mu_k - c_i(s_{ij}) p^\mu_i$$

$$c_k(s_{ij}) = g_{V_{ij} P_i P_j} \left[-(f + h(m_A^2 - p_A \cdot p_k)) \left(1 + \frac{m_i^2 - m_j^2}{m^2_{V_{ij}}}\right) + 2h(p_A \cdot p_i) \right] BW_{V_{ij}}(s_{ij})$$

$$c_i(s_{ij}) = 2 g_{V_{ij} P_i P_j} f BW_{V_{ij}}(s_{ij})$$

If there are several possible channels of the A-decay to the same charged final state $P_1 P_2 P_3$, one has to sum over the all possible diagrams with different intermediate vector resonance states:

$$\mathcal{M}(A \to P_1 P_2 P_3) = \sum_{V_{ij}} (I_i, I_i^z; I_j, I_j^z | I_{V_{ij}}, I^z_{V_{ij}})(I_{V_{ij}}, I^z_{V_{ij}}; I_k, I_k^z | I_A, I_A^z)$$

$$\times \mathcal{M}(A \to (P_i P_j)_{V_{ij}} P_k) = \varepsilon^{(A)}_\mu \mathcal{J}^\mu = \varepsilon^{(A)}_\mu (\mathcal{C}_1(s_{13}, s_{23}) p^\mu_1 - \mathcal{C}_2(s_{13}, s_{23}) p^\mu_2)$$

Estimating the $\mathcal{J}$-function

$\mathcal{J}$-function represents the $K_1 \to K\pi\pi$ decay amplitude.

Assuming that this process comes from the vector-pseudoscalar meson intermediate state, $K_1 \to VP_1 \to P_1P_2P_3$, $\mathcal{J}$ contains

- two form factors for $K_1 \to VP_1$ (one can express them in terms of S and D partial wave amplitudes)
- one coupling for $V \to P_2P_3$

which, in principle, can be determined from the experiment. But due the non sufficient amount of data we have to use some model to predict $\mathcal{J}$.

- Therefore in the following, we estimate the $K_1 \to VP_1$ (namely $K_1 \to K^*\pi$, $K_1 \to \rho K$) form factors in the framework of the ${}^3P_0$ quark-pair-creation model *[Kou,Le Yaouanc&A.T., in preparation]*.

[Daum et al., Nucl.Phys.B187 ('81)]:

$$\mathcal{B}(K_1(1400) \to \rho K)/\mathcal{B}(K_1(1400) \to K^*\pi) = 0.01 \pm 0.01$$
$$\mathcal{B}(K_1(1400) \to (K^*\pi)_D)/\mathcal{B}(K_1(1400) \to (K^*\pi)_S) = 0.04 \pm 0.01$$
$$\mathcal{B}(K_1(1270) \to \rho K)/\mathcal{B}(K_1(1270) \to K^*\pi) = 4.16 \pm 1.56$$
$$\mathcal{B}(K_1(1270) \to (K^*\pi)_D)/\mathcal{B}(K_1(1270) \to (K^*\pi)_S) = 0.54 \pm 0.15$$

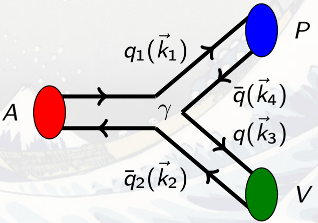
$^3P_0$ Qark-Pair-Creation Model (QPCM)

In order to compute $\mathcal{J}$, we use QPCM *[Le Yaouanc et al., Phys.Rev.D8 ('73), Phys.Rev.D9 ('74)]* to describe the intermediate $K_1 \to K^*\pi, \rho K$ decays.

1. QPCM is one of the simplest and most successful quark models which has a good predictive power.
2. The model has just one(!) universal phenomenological parameter- the quark pair-creation constant γ.
3. It is very good especially to compute the P-wave particles (and in this sense, better than the flux-tube-breaking model, for some case).

Basic idea

Instead of being created from quark lines, $q\bar{q}$ is created from anywhere within the hadronic matter and has the quantum numbers of the vacuum $\Rightarrow$ $q\bar{q}$-pair must be in a $^3P_0$ state, $SU(3)$ singlet and of null momentum.



K_1-mixing angle issue

- To understand the $K_1 \to K^*\pi, \rho K$ decays, first one has to explain the observed hierarchy *[Daum et al., Nucl.Phys.B187 ('81)]*:

$$\mathcal{B}(K_1(1400) \to \rho K)/\mathcal{B}(K_1(1400) \to K^*\pi) = 0.01 \pm 0.01$$
$$\mathcal{B}(K_1(1400) \to (K^*\pi)_D)/\mathcal{B}(K_1(1400) \to (K^*\pi)_S) = 0.04 \pm 0.01$$
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$$\mathcal{B}(K_1(1270) \to (K^*\pi)_D)/\mathcal{B}(K_1(1270) \to (K^*\pi)_S) = 0.54 \pm 0.15$$

- It can be explained with the help of the K_1 mixing angle: mass eigenstates $K_1(1270)$ and $K_1(1400)$ are considered as mixtures of $1^3P_1(K_{1A})$ and $1^1P_1(K_{1B})$ states *[Suzuki, Phys.Rev.D47 ('93)]*:

$$|K_1(1270)\rangle = |K_{1A}\rangle \sin\theta_{K_1} + |K_{1B}\rangle \cos\theta_{K_1}$$
$$|K_1(1400)\rangle = |K_{1A}\rangle \cos\theta_{K_1} - |K_{1B}\rangle \sin\theta_{K_1}$$

- Most interestingly, this mixing angle can give a good explanation of the observed suppression of the $B \to K_1(1400)\gamma$ channel *[Yang et al., Phys.Rev.Lett.94 ('05); Hatanaka& Yang, Phys.Rev.D77 ('08)]*:

$$\mathcal{B}(B \to K_1(1400)\gamma)/\mathcal{B}(B \to K_1(1270)\gamma) < 0.35$$

QPCM predictions for the K_1-decays

Partial wave amplitudes

$$a_S(K_1(1270) \to K^*\pi/\rho K) = \mathcal{S}_{K^*/\rho}(\sqrt{2}\sin\theta_{K_1} \mp \cos\theta_{K_1})$$
$$a_D(K_1(1270) \to K^*\pi/\rho K) = \mathcal{D}_{K^*/\rho}(-\sin\theta_{K_1} \mp \sqrt{2}\cos\theta_{K_1})$$
$$a_S(K_1(1400) \to K^*\pi/\rho K) = \mathcal{S}_{K^*/\rho}(\sqrt{2}\cos\theta_{K_1} \pm \sin\theta_{K_1})$$
$$a_D(K_1(1400) \to K^*\pi/\rho K) = \mathcal{D}_{K^*/\rho}(-\cos\theta_{K_1} \pm \sqrt{2}\sin\theta_{K_1})$$
$$\mathcal{S}_V = \gamma\sqrt{\frac{3}{2}}\frac{2\mathcal{I}_1^V - \mathcal{I}_0^V}{18}, \quad \mathcal{D}_V = \gamma\sqrt{\frac{3}{2}}\frac{\mathcal{I}_1^V + \mathcal{I}_0^V}{18}$$
$$\mathcal{I}^V_{m=0,\pm1} = \frac{1}{8}\int d^3\vec{k}\,\mathcal{Y}_1^m(\vec{k}_P - \vec{k})\psi_0^{(P)}(\vec{k})\psi_0^{(V)}(-\vec{k})\psi_1^{-m(K_1)}(\vec{k}_P + \vec{k})$$

- Fitting the combination of the ratios of measured branching fractions, we found $\theta_{K_1} \simeq 50^\circ$.
- Using this model and the fitted value of θ_{K_1}, we obtained the $K_1 \to K^*\pi, \rho K$ form factors and thus the $\mathcal{J}$-function.

Spacial integrals in QPCM

For the axial meson decay ($A = K_{1A,B}$) into the ground states of vector ($V = K^*/\rho$) and pseudoscalar ($P = \pi/K$) mesons, the spacial integrals are given by

$$\mathcal{I}^{V}_{m=0,\pm1} = \int d^3\vec{k}_1 d^3\vec{k}_2 d^3\vec{k}_3 d^3\vec{k}_4 \delta(\vec{k}_1+\vec{k}_2-\vec{k}_A)\delta(\vec{k}_2+\vec{k}_3-\vec{k}_V)\delta(\vec{k}_4+\vec{k}_1-\vec{k}_P)\delta(\vec{k}_3+\vec{k}_4)$$
$$\times\mathcal{Y}^m_1(\vec{k}_3-\vec{k}_4)\psi^{(A)}(\vec{k}_1-\vec{k}_2)\psi^{(V)}(\vec{k}_2-\vec{k}_3)\psi^{(P)}(\vec{k}_4-\vec{k}_1)$$
$$= \frac{1}{8}\int d^3\vec{k}\mathcal{Y}^m_1(\vec{k}_P-\vec{k})\psi^{(P)}_0(\vec{k})\psi^{(V)}_0(-\vec{k})\psi_1^{-m(A)}(\vec{k}_P+\vec{k})$$

where $\psi^{L_z}_L$ are the normalized Fourier transforms of harmonic oscillator meson wave functions:

$$\psi^{(i)}_0(\vec{k}) = \frac{R_i^{3/2}}{\pi^{3/4}}\exp\left(-\frac{\vec{k}^2R_i^2}{8}\right), \quad \psi^{m(i)}_1(\vec{k}) = \sqrt{\frac{2}{3}}\frac{R_i^{5/2}}{\pi^{1/4}}\mathcal{Y}^m_1(\vec{k})\exp\left(-\frac{\vec{k}^2R_i^2}{8}\right)$$

Here $\mathcal{Y}^m_1(\vec{k}) = |\vec{k}|Y^m_1(\hat{\vec{k}}) = (\vec{\varepsilon}_m\vec{k})\sqrt{3/4\pi}$, R_i is the meson wave function radius and $\vec{\varepsilon}_m$ are the polarization vectors, defined as $\vec{\varepsilon}_0 = (0,0,1)$, $\vec{\varepsilon}_{\pm1} = \mp\frac{1}{\sqrt{2}}(1,\pm i,0)$.

$$\mathcal{I}^V_0 = -\frac{4\sqrt{3}}{\pi^{5/4}}\frac{R_A^{5/2}(R_VR_P)^{3/2}}{(R_A^2+R_V^2+R_P^2)^{5/2}}\left(1-\vec{k}_P^2\frac{(2R_A^2+R_V^2+R_P^2)(R_V^2+R_P^2)}{4(R_A^2+R_V^2+R_P^2)}\right)\exp\left[-\vec{k}_P^2\frac{R_A^2(R_V^2+R_P^2)}{8(R_A^2+R_V^2+R_P^2)}\right]$$
$$\mathcal{I}^V_1 = \frac{4\sqrt{3}}{\pi^{5/4}}\frac{R_A^{5/2}(R_VR_P)^{3/2}}{(R_A^2+R_V^2+R_P^2)^{5/2}}\exp\left[-\vec{k}_P^2\frac{R_A^2(R_V^2+R_P^2)}{8(R_A^2+R_V^2+R_P^2)}\right]$$

Maximum likelihood method

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

$$W(s_{13}, s_{23}, \cos\theta) = f(s_{13}, s_{23}, \cos\theta) + \lambda_\gamma g(s_{13}, s_{23}, \cos\theta) = f(1 + \lambda_\gamma \omega)$$

- Then, the log-likelihood function for a sample of N measurements is:

$$\ln \mathcal{L} = \ln \prod_{i=1}^{N} W(s_{13}^i, s_{23}^i, \cos\theta_i) = \sum_{i=1}^{N} \ln(1 + \lambda_\gamma \omega_i)$$

$$+\text{other terms independent of } \lambda_\gamma$$

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

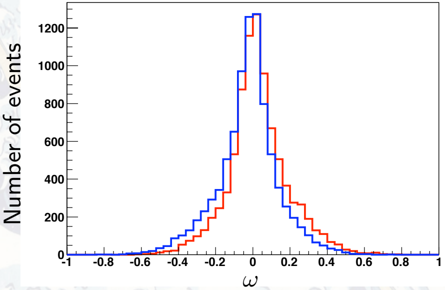
$$\frac{\partial \ln \mathcal{L}}{\partial \lambda_\gamma} = \sum_{i=1}^{N} \frac{\omega_i}{1 + \lambda_\gamma \omega_i} = N \langle \frac{\omega}{1 + \lambda_\gamma \omega} \rangle = 0$$

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

Since W depends on λ_γ **linearly**, one can reduce a multi-dimensional fit to a one-dimensional, using variable $\omega \equiv g/f$! *[Davier et al., Phys.Lett.B306 ('93)]*

Approximate solution for λ_γ

Example of 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.



NO fit is needed to extract λ_γ

When $\lambda_\gamma \omega \ll 1$:

$$\frac{\partial \ln \mathcal{L}}{\partial \lambda_\gamma} \simeq N(\langle\omega\rangle - \lambda_\gamma\langle\omega^2\rangle) = 0$$

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

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

$$\Rightarrow \boxed{\sigma_\lambda^2 \simeq \frac{1}{N\left(\langle\omega^2\rangle - 2\frac{\langle\omega\rangle\langle\omega^3\rangle}{\langle\omega^2\rangle}\right)}}$$

We only has to sum ω and ω^2 over all the events (no fit is needed).

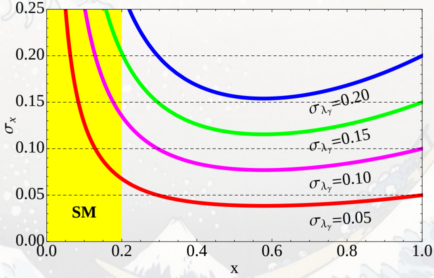
Comparison with the other methods: $\mathcal{A}_{CP}(B \to f^{CP}\gamma)$

Here we compare the precision of $x \equiv |\mathcal{M}_L/\mathcal{M}_R|$ measurement, using the methods of the $\mathcal{A}_{CP}(t)$ measurement in $B^0 \to (K_S\pi^0)_{K^*}\gamma$, $B_s \to \phi\gamma$ and $\lambda_\gamma = \frac{1-x^2}{1+x^2}$ determination in $B \to (K\pi\pi)_{K_1}\gamma$.

The error of x determination will be dependent on the measured value of $\lambda_\gamma(\Leftrightarrow x)$:

$$\sigma_x = \frac{(1+x^2)^2}{4x}\sigma_{\lambda_\gamma}$$

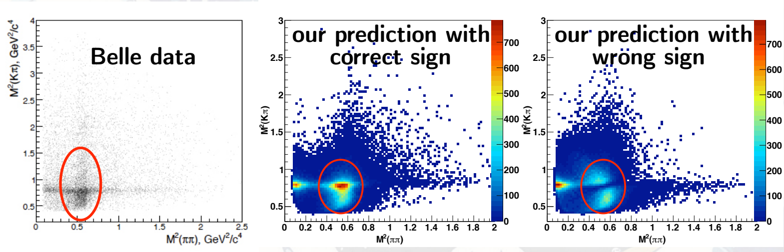
For some values of x, considerably different from the SM (i.e. 0), one can obtain a better sensitivity, compared to the $\mathcal{A}_{CP}$-method.



For instance, one can see from the Fig. that if we measure $\lambda_\gamma < 0.9(\Leftrightarrow x > 0.3)$ with the error $\sigma_{\lambda_\gamma} \approx 0.1$, we can have a smaller error on x, compared to the estimated $\sigma_x \simeq 0.1$ from potential measurement of $\mathcal{A}_{CP}$ at LHCb *[LHCB-ROADMAP4-001]*.

$Im[\vec{n} \cdot (\vec{\mathcal{J}} \times \vec{\mathcal{J}}^*)]$ is sensitive to the relative phase between $K^*\pi$ and ρK.

- The relative sign of two amplitudes, predicted by QPCM, can be verified using the recent exp. data on the $B \to K\pi\pi\psi$ decay [Belle ('10)].



- The interference between the ρK and $K^*\pi$ amplitudes is responsible for the abrupt fading of the $K^*(892)$ signal at $M_{K\pi} > M_{K^*(892)}$.
- We confirm the sign, predicted by QPCM.