Photon polarization in $b \rightarrow s \gamma$ decays

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In collaborations with A. Tayduganov and A. Le Yaouanc

Implications of LHCb measurements and future prospects
@ CERN (14-16 October)
Why Photon Polarization of $b \rightarrow s\gamma$?

- The $b \rightarrow s\gamma$ process is a good probe of fundamental properties of SM as well as BSM (top mass, new particle mass/coupling etc...).
- The left-handed nature of the $W$-boson coupling of SM predicts:

  - $W$-boson couples only left-handed
  - $\gamma$ of $b \rightarrow s\gamma$ should be circularly-polarized*

  $b \rightarrow s\gamma_L$ (left-handed polarization)
  $\bar{b} \rightarrow \bar{s}\gamma_R$ (right-handed polarization)

*There is small fraction $(m_s/m_b)$ of admixture
How do we measure it?

- **However**, the polarization of $b \rightarrow s \gamma$ has never been confirmed at a high precision yet $\Rightarrow$ challenges for LHCb/Belle II!

**proposed methods**

- **Method I**: Time dependent CP asymmetry in $B_d \rightarrow K_S \pi^0 \gamma$, $B_s \rightarrow K^+ K^- \gamma$
  (called $S_{K_S\pi^0\gamma}$, $S_{K^+K^-\gamma}$)
  
  Atwood *et al.* PRL79, Muheim PLB ‘08

- **Method II**: Transverse asymmetry in $B_d \rightarrow K^* l^+ l^-$ (called $A_T^{(2)}$, $A_T^{(im)}$)
  
  Kruger, Matias PRD71, Becirevic, Schneider, NPB854

- **Method III**: $B \rightarrow K_{\text{res}} (\rightarrow K \pi \pi \pi) \gamma$ (called $\lambda_\gamma$)
  
  Gronau *et al.* PRL88, E.K. Le Yaouanc, Tayduganov PRD83

- **Method IV**: $\Lambda_b \rightarrow \Lambda^{(*)} \gamma$, $\Xi_b \rightarrow \Xi^{*} \gamma$ ...
  
  Gremm *et al.* ‘95, Mannel *et al.* ’97, Hiller *et al.* ’01, ’07, Legger *et al.* ’07, Oliver *et al.* ‘10

- **Method V**: Angular distribution, CP observables in $B \rightarrow PV \gamma$ ($\Phi K \gamma$, $\rho K \gamma$...)
  
  Atwood *et al.* ‘07

*These are complementary, and none is more important than the others!*
How do we measure it?

• However, the polarization of $b \rightarrow s \gamma$ has never been confirmed at a high precision yet $\rightarrow$ challenges for LHCb/Belle II!

Method I: Time dependent CP asymmetry in $B_d \rightarrow K_S \pi^0 \gamma$ $B_s \rightarrow K^+ K^- \gamma$
(called $S_{KS\pi^0\gamma}$, $S_{K^+K^-\gamma}$)

Method II: Transverse asymmetry in $B_d \rightarrow K^- l^+ l^-$ (called $\alpha_T(2)$, $\alpha_T(3m)$)

Method III: $B \rightarrow K_{res} (\rightarrow K \pi \pi) \gamma$ (called $\lambda \gamma$)

Method IV: $\Lambda_b \rightarrow \Lambda(\star) \gamma$, $\Xi_b \rightarrow \Xi(\star) \gamma$ ...

Method V: Angular distribution, CP observables in $B \rightarrow PV \gamma$ (good $\Phi_K \gamma$, $\rho_K \gamma$ ...)

<table>
<thead>
<tr>
<th>Re $[C_{7\gamma}^{eff}/C_{7\gamma}^{NP}]$</th>
<th>Im $[C_{7\gamma}^{eff}/C_{7\gamma}^{NP}]$</th>
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Expected constraint from $S_{KS\pi\gamma}$ measurement with 2% precision

Current bound $S_{KS\pi^0\gamma} = -0.15 \pm 0.2$

Becirevic, EK, Le Yaouanc, Tayduganov JHEP08 ('12)
How do we measure it?

- However, the polarization of \( b \rightarrow s \gamma \) has never been confirmed at a high precision yet \( \Rightarrow \) challenges for LHCb/Belle II!

- **Method I:** Time dependent CP asymmetry in \( B_d \rightarrow K_S \pi^0 \gamma \) \( B_s \rightarrow K^+K^-\gamma \)
  - (called \( S_{K_S\pi^0\gamma}, S_{K^+K^-\gamma} \))
  - Atwood et al. PRL79

- **Method II:** Transverse asymmetry in \( B_d \rightarrow K^* l^+ l^- \)
  - (called \( A_{T(2)}, A_{T(\text{im})} \))
  - Gronau et al PRL88, E.K. Le Yaouanc, Tayduganov PRD83

- **Method III:** \( B \rightarrow K_{\text{res}}(\rightarrow K\pi\pi) \)
  - Gremm et al.'95, Mannel et al '97, Legger et al '07, Oliver et al '10

- **Method IV:** \( \Lambda_b \rightarrow \Lambda^(*)\gamma \), \( \Xi_b \rightarrow \Xi^*(\rightarrow \Xi\pi\pi) \)

- **Method V:** Angular distribution, CP observables in \( B \rightarrow PV\gamma \)
  - (\( \Phi_{K\gamma}, \rho_{K\gamma} \))
  - Atwood et al. '07

**Comparison of the three methods**

- **Expected constraint from** \( A_T(2), A_T^{(\text{im})} \) \( \text{measurement with 10}\% \text{ precision} \)

**Assumption for \( \gamma^*/Z \) penguin \( (C_9, C_{10} \text{ contributions}) \) necessary!**

*Becirevic, EK, Le Yaouanc, Tayduganov JHEP08 (‘12)*
How do we measure it?

• **However**, the polarization of $b \rightarrow s \gamma$ has never been confirmed at a high precision yet $\Rightarrow$ challenges for LHCb/Belle II!

**proposed methods**

- Method I: Time dependent CP asymmetry in $B_d \rightarrow K_{S} \pi^{0} \gamma$ $B_s \rightarrow K^{+} K^{-} \gamma$
  (called $S_{K_{S} \pi^{0} \gamma}$, $S_{K^{+} K^{-} \gamma}$)
  
  \[ \text{Atwood et al. PRL79} \]

- Method II: Transverse asymmetry in $B_d \rightarrow K^{*} l^{+} l^{-}$ (called $A_T^{(2)}$, $A_T^{(im)}$)
  
  \[ \text{Gronau et al} \]

- Method III: $B \rightarrow K_{\text{res}}(\rightarrow K \pi \pi \pi) \gamma$ (called $\lambda_{\gamma}$)
  
  \[ \text{Gronau et al} \]

- Method IV: $\Lambda_{b} \rightarrow \Lambda^{(*)} \gamma$, $\Xi_{b} \rightarrow \Xi^{*} \gamma$ ...
  
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- Method V: Angular distribution, CP observables in $B \rightarrow PV \gamma$
  (called $\Phi_{K \gamma}$, $\rho_{K \gamma}$...)
  
  \[ \text{Atwood et al. '07} \]

\[ \text{Becirevic, EK, Le Yaouanc, Tayduganov JHEP08 ('12)} \]

\[ \text{Comparison of the three methods} \text{ proposed methods} \text{ measurement with 10% precision} \]

\[ \text{Expected constraint from $\lambda$ measurement with 10% precision} \]

\[ \text{Becirevic, EK, Le Yaouanc, Tayduganov in preparation} \]
Up-Down Asymmetry of \( B \rightarrow K_{\text{res}} \gamma \rightarrow (K \pi \pi) \gamma \)

Gronau, Grossman, Pirjol, Ryd PRL88(’01)
Gronau, Pirjol PRD66(’02)

**Up-Down Asymmetry**: Count the number of events with photon above/below the \( K_{\text{res}} \) decay plane and subtract them.

\[
A = \frac{\int_{0}^{1} \cos \theta \frac{d\Gamma}{d\cos \theta} - \int_{-1}^{0} \cos \theta \frac{d\Gamma}{d\cos \theta}}{\int_{-1}^{1} \cos \theta \frac{d\Gamma}{d\cos \theta}}
\]
First measurement of Up-Down Asymmetry at LHCb!

A = -0.085±0.019(stat)±0.003(syst)

[100-1300] & [1400-1600] added (?!)

No resonance study done by LHCb so far. But results look similar to the Belle result.

A= -0.085±0.019(stat)±0.003(syst)

Comparison to Belle ‘05

B⁺→K⁺π⁺π⁻γ
M(K⁺π⁺π⁻)
Interpreting Up-Down Asymmetry

\[ A = \frac{\int_0^1 \cos \theta \frac{d\Gamma}{d\cos \theta} - \int_{-1}^0 \cos \theta \frac{d\Gamma}{d\cos \theta}}{\int_{-1}^1 \cos \theta \frac{d\Gamma}{d\cos \theta}} = \frac{3}{4} \frac{\langle Im(\hat{n} \cdot (\vec{J} \times \vec{J}^*)) \rangle}{\langle |\vec{J}|^2 \rangle} \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2} \]

\[ A = -0.085 \pm 0.019 \text{(stat)} \pm 0.003 \text{(syst)} \]

LHCb-CONF-2013-009

Source of imaginary part: overlap of two Breite-Wigner

*Most likely, \( K_1 \) can decays through \((K\pi)s\pi\), too.
Computing $J$ function

Tayduganov, E.K. Le Yaouanc PRD85 (’12)

- Modeling $J$ function (two resonance example):
  
  Assume $K_1 \rightarrow K \pi \pi \pi$ comes from quasi-two-body decay, e.g. $K_1 \rightarrow K^* \pi$, $K_1 \rightarrow \rho K$, then, $J$ function can be written in terms of:
  
  - 4 form factors (S,D partial wave amplitudes)
  - 2 couplings ($g_{K^*K\pi}, g_{\rho\pi\pi}$)
  - 1 relative phase between two channels

- Model parameters are extracted by fitting to data:

  - $\sqrt{Br(K_1(1270) \rightarrow K^*\pi)/Br(K_1(1270) \rightarrow \rho K)} = 0.24 \pm 0.09$
  - $\sqrt{Br(K_1(1400) \rightarrow \rho K)/Br(K_1(1400) \rightarrow K^*\pi)} = 0.01 \pm 0.01$
  - $\sqrt{Br(K_1(1400) \rightarrow K^*\pi)_{D-wave}/Br(K_1(1400) \rightarrow K^*\pi)_{S-wave}} = 0.04 \pm 0.01$
  - $\sqrt{Br(K_1(1270) \rightarrow K^*\pi)_{D-wave}/Br(K_1(1270) \rightarrow K^*\pi)_{S-wave}} = 2.67 \pm 0.95$

Brandenburg et al, Phys Rev Lett, 36 (’76)
Otter et al, Nucl Phys, B106 (’77)
Daum et al, Nucl Phys, B187 (’81)

Re-analysis is on-going at COMPASS (x10 more statistic)!!

Missing information (phase, amplitudes etc.) are complemented by the $^3P_0$ pair creation model
\[ \mathcal{B}^0 \to K_{10}^0(1400) \gamma \to (K^+\pi^-\pi^0)\gamma \]

\[
\frac{d\Gamma}{ds_{13}ds_{23}d\cos \theta} \propto \frac{1}{4}|\vec{J}|^2(1 + \cos^2 \theta) + \frac{1}{2} \lambda \Im \left[ \vec{n} \cdot (\vec{J} \times \vec{J}^*) \right] \cos \theta
\]

\[ K_1^0(p) \to \pi^-(p_1)\pi^0(p_2)K^+(p_3) \]

- **K* dominance**
- **K*+ - K*0 interference**

Gronau, Grossman, Pirjol, Ryd PRL88(01)

\[ A \sim = (0.21 \sim 0.26) \lambda \gamma \]

However, the Belle has shown that the decay rate for this channel is quite suppressed (c.f. mixing angle).

A sign function \( \text{sign}(s_{13} - s_{23}) \) has to be introduced to avoid the cancelation of the asymmetry.

After taking into account the sign function, we find:

\[ A \sim = (0.21 \sim 0.26) \lambda \gamma \]

However, the Belle has shown that the decay rate for this channel is quite suppressed (c.f. mixing angle).
\[ B^0 \rightarrow K_1^0(1400) \gamma \rightarrow (K^+\pi^-\pi^0)\gamma \]

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\frac{d\Gamma}{ds_{13} ds_{23} d\cos \theta} \propto \frac{1}{4} |\vec{J}|^2 (1 + \cos^2 \theta) + \frac{1}{2} \lambda \text{Im} \left[ \vec{n} \cdot (\vec{J} \times \vec{J}^*) \right] \cos \theta
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K* dominance
K*-K*0 interference

Gronau, Grossman, Pirjol, Ryd PRL88('01)

A sign function \( \text{sign}(s_{13}-s_{23}) \) has to be introduced to avoid the cancelation of the asymmetry.

After taking into account the sign function, we find: \( A \approx (0.21 \sim 0.26) \lambda \gamma \)

However, the Belle has shown that the decay rate for this channel is quite suppressed (c.f. mixing angle).
\[ \mathbf{B}^+ \rightarrow \mathbf{K}_1^+(1270) \gamma \rightarrow (\mathbf{K}^+\pi^-\pi^+)\gamma \]

\[ \frac{d\Gamma}{ds_{13} ds_{23} d\cos \theta} \propto \frac{1}{4} |\vec{J}|^2 (1 + \cos^2 \theta) + \frac{1}{2} \text{Im} \left[ \vec{n} \cdot (\vec{J} \times \vec{J}^*) \right] \cos \theta \]

- \( \rho^0 \) dominance
- \( \rho^0K-K^*\pi \) interference

Tayduganov, E.K. Le Yaouanc PRD85 ('12)

\[ \mathbf{K}^*(\pi/\rho K) \text{ with plus relative sign} \]

\[ \mathbf{K}^*(\pi/\rho K) \text{ with minus relative sign} \]

\[ \mathbf{K}^*(\pi/\rho K)(K\pi)_{S\pi} \text{ with sign predicted by our model} \]
\[ B^+ \rightarrow K_1^+(1270) \gamma \rightarrow (K^+ \pi^- \pi^+) \gamma \]

\[
\frac{d\Gamma}{ds_{13}ds_{23}d\cos \theta} \propto \frac{1}{4} |\vec{J}|^2 (1 + \cos^2 \theta) + \frac{1}{2} Im \left[ \vec{n} \cdot (\vec{J} \times \vec{J}^*) \right] \cos \theta
\]

\[ K_1^+(p) \rightarrow \pi^+(p_1)\pi^-(p_2)K^+(p_3) \]

\[ \rho^0 \] dominance
\[ \rho^0-K^*0 \] interference

After taking into account the sign function (although it is, a priori, not necessary), we find: \[ A\sim=(0.07\sim0.12) \lambda_\gamma \]

Further verification of the phases between different channels and size of \((K\pi)_S\pi\) is important.

Sensitivity can be improved up to a factor of two by knowing the Dalitz information.

Tayduganov, E.K. Le Yaouanc PRD83 (’11)

Tayduganov, E.K. Le Yaouanc PRD85 (’12)
Conclusions

- The polarization of $b \rightarrow s \gamma$ has never been confirmed at a high precision yet → challenges for LHCb/Belle II!

- LHCb has shown the first result on the Up-Down Asymmetry in charged $B^{\pm} \rightarrow K\pi\pi\pi\gamma$ channel.

- Interpretation of this result requires further resonance study as well as detailed information on the $K$-resonance decay.

- We have obtained the $J$ function (for the case of $[1^+]K_1$) using ACMMOR data complemented by $^3P_0$ model. Our result can be improved further once the new COMPASS data is interpreted. A full angular analysis of $B^{\pm} \rightarrow K_1J/\psi$ is very useful to obtain a more model independent result.

- Hope we can discuss further during the workshop!
Backup slides
New COMPASS data!

COMPASS '12

ACMMOR '81

[Graphs showing mass distributions for different decay modes: $1^0K^+(892)[01]\pi^-$ and $1^0p(770)[01]K^-$.]
Difference between $K_{1(1270)}$ & $K_{1(1400)}$

In PDG:

$K_{1(1270)}$: $J^P = 1^+$, $M = 1.27$ MeV, $\Gamma = (90 \pm 20)$ MeV

$K_{1(1400)}$: $J^P = 1^+$, $M = 1.40$ MeV, $\Gamma = (174 \pm 13)$ MeV

$Br(\rho K) : Br(K^{*0}\pi) : Br(K^{*0}(1430)\pi) = (42 \pm 6) : (16 \pm 5) : (28 \pm 4)$

$Br(K^{*0}\pi) : Br(\rho K) = (94 \pm 6) : (3 \pm 3)$