Photon polarization in $b \rightarrow s \gamma$ transitions at LHCb

Albert Puig (EPFL) on behalf of the LHCb collaboration
Photon polarization in $b \to s \gamma$ transitions at LHCb

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$b \rightarrow s\gamma$
Rare $B$ decays

- FCNC with $\Delta F=1$ are forbidden at tree level in the SM, so they proceed through loop (box, penguin) diagrams
  - In extensions of the SM, these loop processes may receive contributions from new virtual particles

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C'_i O'_i) + h.c.$$  
NP may modify the Wilson Coefficients

- Rare decays can be used for indirect searches of New Physics
  - Highly suppressed in the SM
  - Highly sensitive to NP effects
Radiative $B$ decays

- Rare penguin FCNC transitions with a final-state (real) photon
- Discovered by CLEO in 1993 (PRL 71.674)
- Studied extensively by CLEO, BaBar, Belle and LHCb

HFAG BRs for $B^0$
Radiative $B$ decays

- Access to possible NP through the virtual loop (2HDM, SUSY...)
  - Transitions especially sensitive to NP in the $C_{7γ}$ coefficient

- Exclusive decays difficult from the theoretical point of view due to form factor
  - Find form-factor free observables, such as $CP$ and isospin asymmetries

- Photon polarization as test of the SM
Radiative $B$ decays

- Access to possible NP through the virtual loop (2HDM, SUSY...)
  - Transitions especially sensitive to NP in the $C_{7\gamma}$ coefficient

- Exclusive decays difficult from the theoretical point of view due to form factor
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- Photon polarization as test of the SM
Challenges for radiative decays

• Distinct experimental signature with a high $E_T$ photon
  - Large levels of background are expected in a $pp$ machine

• Mass resolution dominated by photon reconstruction

![Graphs](image)

$\sigma \approx 95\text{MeV}$

$\sigma \approx 25\text{MeV}$

[Nucl. Phys. B 867 (2012)]

[PRL 110 (2013) 221601]
Photon polarization in $b \rightarrow s \gamma$ transitions at LHCb

Albert Puig (EPFL) on behalf of the LHCb collaboration
The LHCb experiment
The LHCb experiment

- Precise tracking
- Good mass and IP resolution
- Good vertex resolution
The LHCb experiment

Calorimeter system
Trigger
Photon reconstruction

Excellent particle identification
$\pi/K$ separation over 2-100 GeV
Powerful muon id
LHCb Run-I summary

![Graph showing integrated luminosity by year for 2010, 2011, and 2012.]

- 2012: 4 + 4 TeV
  - Delivered Luminosity: 2.21 fb⁻¹
  - Recorded Luminosity: 2.08 fb⁻¹
- 2011: 3.5 + 3.5 TeV
  - Delivered Luminosity: 1.21 fb⁻¹
  - Recorded Luminosity: 1.10 fb⁻¹
- 2010: 3.5 + 3.5 TeV
  - Delivered Luminosity: 0.04 fb⁻¹
  - Recorded Luminosity: 0.04 fb⁻¹
Photon polarization in $b \rightarrow s \gamma$ transitions at LHCb

Albert Puig (EPFL) on behalf of the LHCb collaboration
Photon polarization in the SM

- The $b \rightarrow s \gamma$ process has a particular structure in the SM

$$\bar{s} \Gamma(b \rightarrow s \gamma) \mu b = \frac{e}{(4\pi)^2} \frac{g^2}{2M_W^2} V_{ts}^* V_{tb} F_2 \bar{s} i \sigma_{\mu\nu} q^\nu \left( m_b \frac{1 + \gamma_5}{2} + m_s \frac{1 - \gamma_5}{2} \right) b$$

- The $W$ boson couples only left-handedly
- The requirement of a chirality flip leads to left-handed photon dominance
Photon polarization in the SM

\[ m_s \bar{s}_R \sigma_{\mu \nu} q^\nu b_L \]

\[ m_b \bar{s}_L \sigma_{\mu \nu} q^\nu b_R \]

\[ \frac{m_s}{m_b} \approx 0.02 \ll 1 \]
Photon polarization in the SM

• The chiral structure of the $b \to s \gamma$ process and the fact that the $W$ couples only left-handedly causes the photons to be (almost completely) circularly polarized

$$O_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R$$

- Never confirmed to high precision!

• QCD corrections coming from $C_2$ are expected to be in the 1-10% range [Bečirević et al]
And beyond the SM?

- Several NP models introduce right-handed currents

- New particles can change the chirality inside the loop, producing chiral enhancement
  - $m_t/m_b$ from LRSM [Babu et al]
  - $m_{\text{SUSY}}/m_b$ in SUSY with $\delta_{\text{RL}}$ mass insertions [Gabbiani et al]

- Still “large” room for NP despite the constraints coming from $B_s$ oscillation parameters, $B_s \rightarrow \mu\mu$...
  - New penguins around the corner?
Measuring the polarization

- Time-dependent analyses of $B_{(s)} \to f^{CP} \gamma$, e.g., $B_s \to \phi \gamma$ and $B^0 \to K_s \pi^0 \gamma$

- Transverse asymmetry in $B^0 \to K^* l^+ l^-$ (pollution from $C_9$ and $C_{10}$)

- Angular distribution of radiative decays with 3 charged tracks in the final state, e.g., $B \to K \pi \pi \gamma$

- $b$-baryons: $\Lambda_b \to \Lambda^{(*)} \gamma$, $\Xi_b \to \Xi^{(*)} \gamma$
Complementary approaches

[Bečirević et al]
Measuring the polarization

• Time-dependent analyses of $B_{(s)} \to f^{CP} \gamma$, e.g., $B_s \to \phi \gamma$ and $B^0 \to K_S \pi^0 \gamma$

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• $b$-baryons: $\Lambda_b \to \Lambda^{(*)} \gamma$, $\Xi_b \to \Xi^{(*)} \gamma$
$B \to K\pi\pi\gamma$ in Belle and BaBar

- Belle observed $B \to K_1(1270)^+\gamma$ and BaBar $B \to K_2^*(1430)^+\gamma$
- Both BaBar and Belle have measured the inclusive BR

<table>
<thead>
<tr>
<th></th>
<th>BR</th>
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<tbody>
<tr>
<td>$K_1(1270)^+\gamma$</td>
<td>$(4.3 \pm 1.2) \times 10^{-5}$</td>
</tr>
<tr>
<td>$K_1(1400)^+\gamma$</td>
<td>$&lt; 1.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>$K_2^*(1430)^+\gamma$</td>
<td>$(1.45 \pm 0.43) \times 10^{-5}$</td>
</tr>
<tr>
<td>$K^+\pi^+\pi^-\gamma$</td>
<td>$(2.76 \pm 0.18) \times 10^{-5}$</td>
</tr>
<tr>
<td>$K^0\pi^+\pi^0\gamma$</td>
<td>$(4.5 \pm 0.52) \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Belle, [Yang et al] (2005)
BaBar, [Aubert et al] (2007)
Why 3 charged particles?

- Three tracks is the minimum needed to build a $P$-odd triple product proportional to the photon polarization using the final state momenta.

\[ \vec{p}_\gamma \cdot (\vec{p}_1 \times \vec{p}_2) \] changes sign with photon helicity.
Interference needed!

- The decay amplitude is required to have a non trivial phase due to final state interactions in order to preserve $T$
  - Knowledge of this phase is required to interpret measurements in terms of photon polarization

- In the case of $K\pi\pi$ final states, this means
  - Interference between two intermediate $K^*\pi$ states with different charges (isospin-related amplitudes) only for final states with neutrals
  - Interference between intermediate $K^*\pi$ and $\rho K$ amplitudes
  - Interference between different partial waves into $K^*\pi$ or $\rho K$
Photon polarization in $B \rightarrow K_{\text{res}} \gamma$

- If we consider $B \rightarrow K_{\text{res}}^{(i)} \gamma$ we can define the photon polarization as

$$\lambda^{(i)} = \frac{|c^{(i)}_R|^2 - |c^{(i)}_L|^2}{|c^{(i)}_R|^2 + |c^{(i)}_L|^2}$$

- It can be shown that photon polarization is independent of the $K$ resonance and can be expressed as [Gronau et al]

$$\frac{|c^{(i)}_R|}{|c^{(i)}_L|} = \frac{|C_{7R}|}{|C_{7L}|} \Rightarrow \lambda^{(i)} = \frac{|C_{7R}|^2 - |C_{7L}|^2}{|C_{7R}|^2 + |C_{7L}|^2} \equiv \lambda_{\gamma}$$

+1 for $\bar{b}$ and -1 for $b$
Photon polarization in $B \to K_{\text{res}} \gamma$

- In the case of overlapping resonances

$$d\Gamma(B \to K\pi\pi\gamma) = \left| \sum_i \frac{c_R^{(i)} A_R^{(i)}}{s - M_i^2 - iM - i\Gamma_i} \right|^2 + \left| \sum_i \frac{c_L^{(i)} A_L^{(i)}}{s - M_i^2 - iM - i\Gamma_i} \right|^2$$

so (introducing the expression of the weak amplitudes)

$$d\Gamma(B \to K\pi\pi\gamma) \propto (|A_R|^2 + |A_L|^2) + \lambda_\gamma(|A_R|^2 - |A_L|^2)$$

- It’s interesting to note that

$$P_\gamma = \frac{d\Gamma(B \to K\pi\pi\gamma_R) - d\Gamma(B \to K\pi\pi\gamma_L)}{d\Gamma(B \to K\pi\pi\gamma_R) + d\Gamma(B \to K\pi\pi\gamma_L)}$$

is only equal to $\lambda_\gamma$ in the case of one resonance
Angular distribution in $B \rightarrow K\pi\pi\gamma$

- The photon polarization can be inferred from the polarization of the $K$
Angular distribution in $B \to K\pi\pi\gamma$

- The amplitude of one $K$ resonance decay can be described by the helicity amplitude $J_\mu$

$$A^{(i)}_{L(R)}(s, s_{13}, s_{23}, \cos \theta) = \epsilon^{\mu}_{K,L(R)} \mathcal{J}_\mu$$

- Considering only one $(1^+)$ intermediate resonance

$$\frac{d\Gamma(K_{L(R)} \to K\pi\pi)}{ds \, ds_{13} \, ds_{23} \, d\cos \theta} \propto \frac{1}{4} |\mathcal{J}|^2 (1 + \cos^2 \theta) \mp \frac{1}{2} \cos \theta \, \text{Im} \left[ \bar{n} \cdot (\mathcal{J} \times \mathcal{J}^*) \right]$$

and therefore [Kou et al] [Gronau et al]

$$\frac{d\Gamma(B \to K_{\text{res}}\gamma \to K\pi\pi\gamma)}{ds \, ds_{13} \, ds_{23} \, d\cos \theta} \propto \frac{1}{4} |\mathcal{J}|^2 (1 + \cos^2 \theta) + \lambda_{\gamma} \frac{1}{2} \cos \theta \, \text{Im} \left[ \bar{n} \cdot (\mathcal{J} \times \mathcal{J}^*) \right]$$
But life is not so beautiful

- Interference between $1^+$, $1^-$, $2^+$ resonances [Gronau et al]

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

$$+ |B|^2 \left\{ \frac{1}{4} |\mathcal{K}|^2 (\cos^2 \theta + \cos^2 2\theta) + \frac{1}{2} \lambda_\gamma \text{Im} \left[ \vec{n} \cdot (\mathcal{K} \times \mathcal{K}^*) \right] \cos \theta \cos 2\theta \right\} + |C|^2 \frac{1}{2} \sin^2 \theta +$$

$$+ \left\{ \frac{1}{2} (3 \cos^2 \theta - 1) \text{Im} \left[ AB^* \vec{n} \cdot (\mathcal{J} \times \mathcal{K}^*) \right] + \lambda_\gamma \text{Re} \left[ AB^* \vec{n} \cdot (\mathcal{J} \cdot \mathcal{K}^*) \right] \cos^3 \theta \right\}$$

need to know $J$ and $K$!

- It can be shown that $\lambda_\gamma$ goes with odd powers of $\cos \theta$

$$\frac{d\Gamma(\sum B \rightarrow K_{\text{res}} \gamma \rightarrow P_1 P_2 P_3 \gamma)}{ds \, ds_{13} \, ds_{23} \, d\cos \theta} \propto \sum_{j=\text{even}} a_j(s_{13}, s_{23}) \cos^j \theta + \lambda_\gamma \sum_{j=\text{odd}} a_j(s_{13}, s_{23}) \cos^j \theta$$
Up-down asymmetry

• We can exploit the structure of the decay rate and define the up-down asymmetry

\[ A_{UD} \equiv \frac{\int_0^1 d\cos \theta \frac{d\Gamma}{d\cos \theta} - \int_{-1}^0 d\cos \theta \frac{d\Gamma}{d\cos \theta}}{\int_{-1}^1 d\cos \theta \frac{d\Gamma}{d\cos \theta}} = C \lambda_\gamma \]

where \( C \) takes into account the integral over the Dalitz plot and the angular distribution

• This asymmetry is expected to be \(~0.3\lambda_\gamma\) in isolated neutral \( K_1 \) decays and \(~0.1\lambda_\gamma\) in charged ones (less interference)
$B^\pm \rightarrow K^\pm \pi^\mp \pi^\pm \gamma$ at LHCb

- In LHCb we have studied the charged mode $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$ (and charge conjugate)
  - Inclusive study with $K\pi\pi$ system mass in the $[1.1, 1.9]$ GeV/$c^2$ range

- Analysis performed in the full data set recorded by LHCb in 2011 and 2012, corresponding to 3/fb

- Preliminary conference note including only 2012 data and with simple counting approach was shown at EPS 2013 [LHCb-CONF-2013-009]
Analysis strategy

• $B$ candidates mass fit

• Assessment of the $K\pi\pi$ mass spectrum

• Angular study
  - Provide angular distribution to help theory calculations

• Determination of up-down asymmetry
  - Obtain significance with respect to the no-polarization scenario
• Exploit the special features of $B$ decays

• Selection criteria:
  - High $E_T$ photon (>3.0 GeV)
  - Multivariate tool with kinematical variables
  - Charged particle identification
  - Photon identification (separation from charged e-m particles and other neutral e-m particles)
Backgrounds

• Combinatorial (exponential)

• Partially reconstructed background (Argus $\otimes$ Gaussian)
  - Missing $\pi$, $B \rightarrow K\pi\pi\eta(\rightarrow \gamma\gamma)$ (negligible) and general partial.

• Peaking backgrounds (suppressed with specific cuts)
  - $B^+ \rightarrow \overline{D}^0(\rightarrow K^+\pi\pi^0)\pi^+$, $B^+ \rightarrow \overline{D}^{*0}(\overline{D}^0(\rightarrow K^+\pi)\gamma)\pi^+$ and $B^+ \rightarrow K^{*+}(\rightarrow K^+\pi^0)\pi^+\pi$.

• Contamination from neutral $B^0 \rightarrow K_1(1270)^0\gamma$ (negligible)

• Crossfeed from $B^+ \rightarrow \pi\pi\pi\gamma$ (suppressed with PID)
Backgrounds

- Combinatorial (exponential)

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  - $B^+ \rightarrow \bar{D}^0(\rightarrow K^+\pi^0)\pi^+$, $B^+ \rightarrow \bar{D}^{*0}(\rightarrow \bar{D}^0(\rightarrow K^+\pi))\pi^+$ and $B^+ \rightarrow K^{*+}(\rightarrow K^+\pi^0)\pi^+\pi^-$

- Contamination from neutral $B^0 \rightarrow K_1(1270)^0\gamma$ (negligible)

- Crossfeed from $B^+ \rightarrow \pi\pi\pi\gamma$ (suppressed with PID)
Mass fit

- Unbinned maximum likelihood fit to the invariant mass of the $B$ candidates
- Simultaneously fit 2011 and 2012 to account for slightly different calorimeter performance
  - Share shape parameters except for the $B$ mass resolution
  - Different background contamination
- Signal shape fixed from MC
- Background shapes partially fixed from MC
  - Free combinatorial and partially reconstructed background tail
Mass distribution

- Observe ~14000 signal events in the $[1.1,1.9]$ GeV/$c^2$ $K\pi\pi$ mass region
Background-subtracted $K\pi\pi$ mass spectrum

- Many (unclear) contributions in the $K\pi\pi$ mass spectrum
  - Impossible to separate the resonances without full Dalitz analysis
Background-subtracted $K\pi\pi$ mass spectrum

- Many (unclear) contributions in the $K\pi\pi$ mass spectrum
  - Impossible to separate the resonances without full Dalitz analysis
Angle definition

- In order to avoid cancellations due to symmetries, neutral $K\pi\pi$ combinations require a change of the sign of $\cos \theta$ according to $s_{12}$ and $s_{13}$

$$\vec{n} = \vec{p}_{\pi,\text{slow}} \times \vec{p}_{\pi,\text{fast}}$$

- The same convention is used for consistency
Angle definition

- The sign of the $\lambda_y$ parameter changes with the charge of the $B$ meson (positive for $B^-$ and negative for $B^+$)

- When putting together the data, take the change of sign by taking into account the sign of the charge of the $B$ candidate

$$\cos \hat{\theta} = \text{sign}(\text{charge } B^\pm) \cos \theta$$
Angular distribution

- Angular distributions for each region of $K\pi\pi$ mass are obtained as a simultaneous fit of the mass of the B candidates in bins of $\cos\theta$
  - Used 20 bins in the angular variable
  - All fit parameters shared

- Yields for each bin are corrected with the selection acceptance and then normalized to the total yield
Systematic uncertainties

- Effect of bin migration, evaluated with pseudo experiments
  - Use angle-dependent resolution
  - Determined as a covariance matrix between bins
- Fit model, evaluated by testing alternative modelizations
- Parameters fixed from simulation, including acceptance, evaluated using simulated pseudo experiments
Systematic uncertainties

- Effect of bin migration, evaluated with pseudo experiments
  - Use angle-dependent resolution
  - Determined as a covariance matrix between bins
- Fit model, evaluated by testing alternative modelizations
- Parameters fixed from simulation, including acceptance, evaluated using simulated pseudo experiments

Largest systematic

Strong correlations between bins

40
Angular fit

- Angular distributions for each region are fitted with a combination of Legendre polynomials up to order 4

\[
f(\cos \hat{\theta}; c_0 = 0.5, c_1, c_2, c_3, c_4) = \sum_{i=0}^{4} c_i L_i(\cos \hat{\theta})
\]

- A $\chi^2$ fit is performed taking into account the full statistical and systematic covariance matrices

- The up-down asymmetry is determined with the relation

\[
A_{ud} = \frac{c_1 - c_3/4}{2c_0}
\]
Angular fit results

Nominal fit
No odd components
Angular fit coefficients

• The coefficients of the angular fit are obtained for each of the four $K\pi\pi$ mass regions

<table>
<thead>
<tr>
<th></th>
<th>[1.1, 1.3]</th>
<th>[1.3, 1.4]</th>
<th>[1.4, 1.6]</th>
<th>[1.6, 1.9]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_1$</td>
<td>6.3±1.7</td>
<td>5.4±2.0</td>
<td>4.3±1.9</td>
<td>−4.6±1.8</td>
</tr>
<tr>
<td>$c_2$</td>
<td>31.6±2.2</td>
<td>27.0±2.6</td>
<td>43.1±2.3</td>
<td>28.0±2.3</td>
</tr>
<tr>
<td>$c_3$</td>
<td>−2.1±2.6</td>
<td>2.0±3.1</td>
<td>−5.2±2.8</td>
<td>−0.6±2.7</td>
</tr>
<tr>
<td>$c_4$</td>
<td>3.0±3.0</td>
<td>6.8±3.6</td>
<td>8.1±3.1</td>
<td>−6.2±3.2</td>
</tr>
<tr>
<td>$A_{UD}$</td>
<td>6.9±1.7</td>
<td>4.9±2.0</td>
<td>5.6±1.8</td>
<td>−4.5±1.9</td>
</tr>
</tbody>
</table>

• We expect that these results prove to be a useful input for theorists
Up-down asymmetry results

- Four independent up-down asymmetries are obtained
Photon polarization from $A_{UD}$?

- The up-down asymmetry is proportional to $\lambda_\gamma$

\[ A_{UD} \equiv \frac{\int_0^1 \text{d} \cos \theta \frac{\text{d} \Gamma}{\text{d} \cos \theta} - \int_{-1}^0 \text{d} \cos \theta \frac{\text{d} \Gamma}{\text{d} \cos \theta}}{\int_{-1}^1 \text{d} \cos \theta \frac{\text{d} \Gamma}{\text{d} \cos \theta}} = C \lambda_\gamma \]

- But what is the proportionality constant?

- Combined work between theory and experiment is needed, but right now it’s not possible to translate a measurement of $A_{UD}$ into a measurement of $\lambda_\gamma$
  - Obtain the significance of the up-down asymmetry with respect of the $\lambda_\gamma = 0$ scenario
$A_{UD}$ significance

- Use the four independent up-down asymmetries to extract a combined significance with respect to the no-polarization scenario

- Up-down asymmetry is different from zero at $5.2\sigma$
$A_{UD}$ significance

- Use the four independent up-down asymmetries to extract a combined significance with respect to the no-polarization scenario

- Up-down asymmetry is different from zero at $5.2\sigma$

First observation of photon polarization in $b\to s\gamma$ transitions!
Cross checks

• Adding further orders in Legendre polynomials does not add information (extra parameters \( \sim 0 \))
  - Significance unchanged

• Further cross checks performed with counting experiment
  - Up-down asymmetries compatible
  - Lower significance (5.0\(\sigma\))
  - Difference in significances with respect to the angular fit match expectations from pseudo experiments
Conclusions

• LHCb has studied the $B^+ \rightarrow K^+ \pi \pi^+ \gamma$ decay with its full available statistics of 3/fb

• The angular distribution of the photon with respect to the plane defined by the final state hadrons has been characterized for different regions of their invariant mass
  - Impossible to extract photon polarization without further input
  - Aim to provide a valuable input for theorists

• Photon polarization has been observed for the first time in $b \rightarrow s \gamma$ transitions
What about the future?

• Further exploitation of the $B^+ \rightarrow K^+ \pi \pi \gamma$ decay requires either
  - Ability to control the $K\pi\pi$ mass spectrum in order to isolate certain resonances (to match theory papers)
  - Precise knowledge of the $K\pi\pi J$ function, which could be obtained from a Dalitz analysis of $B^+ \rightarrow K^+ \pi \pi J/\psi$

• Study of the neutral decay is more difficult in LHCb due to
  - Need for tagging in $B^0 \rightarrow K_S \pi \pi \gamma$ (loss of efficiency)
  - Two neutral particles in the final state in $B^0 \rightarrow K^+ \pi \pi^0 \gamma$
What about the future?

- LHCb can (and will) continue the study of the photon polarization through other paths
  - Proper time distribution of $B_s \to \phi \gamma$
  - Angular distribution in $B^0 \to K^* e^+ e^-$, already observed by LHCb [JHEP05(2013)159]
  - Angular distribution in $B^+ \to \phi K^+ \gamma$
  - Radiative $b$-baryon decays: $\Lambda_b \to \Lambda(*) \gamma$, $\Xi_b \to \Xi(*) \gamma$

- Stay tuned!

Seen by LHCb! [Nucl. Phys. B 867 (2012)]
And remember, watch out for the penguins!
Backup
News on $B \to K\pi\pi\gamma$ from BaBar

Eli Ben-Haim
Moriond EW (March 16th 2014)
Angle convention

- In neutral decays, it is necessary to redefine the angle $\theta$ in order to avoid cancellations due to the symmetries of $J$ with respect to the exchange of the two $\pi$.
- Not necessary in charged decays, but kept for consistency.

From E. Kou (LHCb Implications Workshop)