Recent Results on Rare B Decays with BaBar

Martino Margoni
Universita` di Padova and INFN
on behalf of the BaBar Collaboration

Motivation

\[ B \rightarrow K^* \, l^+l^- \]
\[ B^+ \rightarrow K^+ \, \tau^+\tau^- \]
\[ B \rightarrow K \pi\pi\gamma \]

\{ Radiative Penguins \}
Motivation
Rare B decays: New Physics probes

Search for deviations from Standard Model (SM) predictions due to virtual contributions of new heavy particles in loop processes

- Compare experimental results with very precise SM expectations

The most interesting processes are those that are strongly suppressed in the SM: FCNC (X_{s} l^{+} l^{-}) [but also X_{s} \gamma, leptonic decays, LFV, CPV in B^0 mixing, c & \tau]

- New Physics (NP) could increase expectations by orders of magnitude [e.g. A. Buras, arXiv:0910.1032]

Rare B decays can probe high scales potentially sensitive to NP beyond the direct reach of LHC:

\[ \Lambda_{NP} \sim \frac{M_{W}}{g^2} \sqrt{\frac{16\pi^2}{|V_{ts}^* V_{tb}|}} \sim 10 \text{ TeV} \]
Rare B decays: New Physics probes

Weak decay of hadron $M$ into final state $F$ described via an Effective Hamiltonian expressed by means of Operator Product Expansion:

$$A(M \rightarrow F) = \langle F | H_{\text{eff}} | M \rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{\text{CKM}} C_i(\mu) \langle F | Q_i(\mu) | M \rangle$$

$C_i(\mu)$: Wilson Coefficients (perturbative short distance couplings)

$Q_i(\mu)$: Hadronic Matrix Elements (non-perturbative long distance effects)

- NP could modify Wilson Coefficients $C_i(\mu)$ and/or add new $Q_i(\mu)$ operators

Complementary information from different rare decays:

$B \rightarrow \mu\mu$: Scalar/Pseudoscalar interactions

$B \rightarrow K^{(*)}\mu\mu$: Vector/axial interactions
Measurement of Angular Asymmetries in the Decay
$B \rightarrow K^* \pi^+ \pi^-$

[471 $\Upsilon(4S)$ events]

Phys. Rev. D93, 052015 (2016)
$B \rightarrow \kappa^*/\pm/\mp$

**FCNC process forbidden at tree level, BR~$10^{-6}$: Probe the SM!**

- **Sensitive to the effects of NP in photon, vector and axial-vector couplings which can enter at the same order as SM contributions**
- **Complementary information to $B \rightarrow \mu^+\mu^-$**

- **Amplitudes expressed using OPE in terms of:**
  - **Hadronic Form Factors**
    - (accuracy ~20%)
    - [A. Barucha et al. arXiv 1004.3249]
  - **Wilson coefficients** $C_{eff}^7$, $C_{eff}^9$, $C_{eff}^{10}$
  - **Clean theoretical predictions especially at low $q^2=m^2(\mu^+\mu^-)$**
  - **Experimentally clean signature**

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The decay $B \rightarrow K^* l^+ l^-$ involves observables such as:

- Forward-backward muon asymmetry ($A_{FB}$)
- Fraction of longitudinally polarized $K^*$ ($F_L$)

Differential Amplitudes:

\[
\frac{1}{\Gamma(q^2)} \frac{d\Gamma}{d(\cos \theta_K)} = \frac{3}{2} F_L(q^2) \cos^2 \theta_K + \frac{3}{4} (1 - F_L(q^2))(1 - \cos^2 \theta_K)
\]

\[
\frac{1}{\Gamma(q^2)} \frac{d\Gamma}{d(\cos \theta_\ell)} = \frac{3}{4} F_L(q^2)(1 - \cos^2 \theta_\ell) + \frac{3}{8} (1 - F_L(q^2))(1 + \cos^2 \theta_\ell) + A_{FE}(q^2) \cos \theta_\ell.
\]

Kinematics of the decay $B \rightarrow V l^+ l^-$ ($V = K^*$, $\phi$, $\rho$) determined by three angles:

- $\theta_l$, $\theta_K$, $\phi$

Event Yields reconstructed in bins of $q^2 = m^2(l^+ l^-)$

Observables Include:

- $A_{FB}$ (forward-backward muon asymmetry)
- $F_L$ (fraction of longitudinally polarized $K^*$)
- $P_2 = -\frac{2}{3} \frac{A_{FB}}{1 - F_L}$ (with lower uncertainty from hadronic Form Factors)
B → K* /+-

**Kinematics of the decay B → V /+-**

(V=K*, φ, ρ) determined by three angles:

- θl, θK, φ

Event Yields reconstructed in bins of

q²=m²( /+-)

**Differential Amplitudes:**

\[
\frac{1}{\Gamma(q^2)} \frac{d\Gamma}{d(\cos \theta_K)} = \frac{3}{2} F_L(q^2) \cos^2 \theta_K + \frac{3}{4} (1 - F_L(q^2))(1 - \cos^2 \theta_K)
\]

\[
\frac{1}{\Gamma(q^2)} \frac{d\Gamma}{d(\cos \theta_l)} = \frac{3}{4} F_L(q^2)(1 - \cos^2 \theta_l) + \frac{3}{8} (1 - F_L(q^2))(1 + \cos^2 \theta_l) + A_{FE}(q^2) \cos \theta_l.
\]

**Non-resonant S-wave B → Kπ /+- contribution neglected**

- Reflects in absolute bias ~ 0.01 on F_L & A_{FB} (smaller than statistical & systematic uncertainties)
**Measurement performed using 5 modes:**

- $B^+ \rightarrow K^{*+} (\rightarrow K_s^+ \pi^+) \mu^+ \mu^-$, $B^+ \rightarrow K^{*+} (\rightarrow K_s^+ \pi^+) e^+ e^-$, $B^+ \rightarrow K^{*+} (\rightarrow K^0 \pi^0) e^+ e^-$
- $B^0 \rightarrow K^{*0} (\rightarrow K^+ \pi^-) \mu^+ \mu^-$, $B^+ \rightarrow K^{*0} (\rightarrow K^+ \pi^-) e^+ e^-$

- $K^* \ J/\psi$ and $K^* \psi(2S)$ regions used as control samples to validate fitting procedure.

<table>
<thead>
<tr>
<th>$q^2$ bin</th>
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<td>$q_6^2$</td>
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**Events reconstructed by means of:**

- $m_{ES} = \sqrt{E_{Beam}^*} - P_B^* \cdot 2$
- $\Delta E = E_B^* - E_{Beam}^*$

**Candidate multiplicity $\sim 1.4$ (1.1) in dielectron (dimuon) modes.**

**Best candidate selected based on $\Delta E$**
Measurement performed using 5 modes:

\[ B^+ \rightarrow K^{*+} (\rightarrow K^+_s \pi^+) \mu^+\mu^- , B^+ \rightarrow K^{*+} (\rightarrow K^+_s \pi^+) e^+\mu^- , B^+ \rightarrow K^{*+} (\rightarrow K^+\pi^0) e^+e^- \]

\[ B^0 \rightarrow K^{*0} (\rightarrow K^+\pi^-) \mu^+\mu^- , B^+ \rightarrow K^{*0} (\rightarrow K^+\pi^-) e^+e^- \]

\[ K^* J/\psi \text{ and } K^* \psi(2S) \text{ regions used as control samples to validate fitting procedure} \]

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BKG from Continuum and \( B\bar{B} \) reduced using a Likelihood Ratio (\( L_R \)) defined from outputs of eight BDTs exploiting kinematical and topological quantities.
Yields, PDFs shapes & normalizations in the different $q^2$ bins extracted by a 3D ($m_{ES}$, $m(K\pi)$, $L_R$) fit

Example: $q^2 > 14.21$ GeV$^2$

$B^0 \rightarrow K^+\pi^- e^+e^-$

$B^0 \rightarrow K^+\pi^- \mu^+\mu^-$

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$B \rightarrow K^* l^+ l^-$

$F_L$ in the different $q^2$ bins extracted as only free parameter by a 4D($m_{ES}$, $m(K\pi)$, $L_R$, $\cos(\theta_K)$) fit using PDFs defined in the previous step

Fit model for $F_L$ and $A_{FB}$ validated on $K^* J/\psi$ and $K^* \psi(2S)$

BKG shapes from $m_{ES}$ side bands (checked on LFV $B \rightarrow K^* e\mu$)

First $B^+ \rightarrow K^{*+} l^+ l^-$ angular analysis

Example: $1 < q^2 < 6$ GeV$^2$

\[ \frac{1}{\Gamma(q^2)} \frac{d\Gamma}{d(\cos\theta_K)} = \frac{3}{2} F_L(q^2) \cos^2\theta_K + \frac{3}{4} (1 - F_L(q^2))(1 - \cos^2\theta_K) \]
$B \rightarrow K^*/l^+l^-$

$A_{FB}$ in the different $q^2$ bins extracted as only free parameter by a
4D($m_{ES}$, $m(K\pi)$, $L_R$, $\cos(\theta_l)$) fit using PDFs defined in the previous step
$F_L$ fixed to previous result

First $B^+ \rightarrow K^{*+} l^+l^-$ angular analysis

Example: $1 < q^2 < 6 \text{ GeV}^2$

\[
\frac{1}{\Gamma(q^2)} \frac{d\Gamma}{d(\cos\theta_l)} = \frac{3}{4} F_L(q^2)(1 - \cos^2\theta_l) + \frac{3}{8} (1 - F_L(q^2))(1 + \cos^2\theta_l) + A_{FB}(q^2) \cos\theta_l.
\]

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Angular Variables Results versus $q^2$: Tension with SM in $B^+ F_L$ at low $q^2$
Angular Variable Results for $1 < q^2 < 6 \text{ GeV}^2$

$1 < q^2 < 6 \text{ GeV}^2$: Perturbative window with theory error under good control, away from $q^2 \rightarrow 0$ photon pole and $c\bar{c}$ resonances at higher $q^2$

Small $F_L$ value for $B^+ \rightarrow K^* l^+ l^-$ (First Angular Analysis)
\[ P_2 = \frac{-2}{3} \frac{A_{FB}}{1 - F_L} \]: Reduced theoretical uncertainty & greater sensitivity to non-SM contributions


Theoretical predictions available only at low \( q^2 \) \[ \text{JHEP 1412, 125 (2014)} \]

Slight tension observed with SM
$B \rightarrow K^*/\pm/\mp$

$P_2 = -\frac{2}{3} \frac{A_{FB}}{1 - F_L}$: Reduced theoretical uncertainty & greater sensitivity to non-SM contributions


Result dominated by statistical error
Systematics from BKG modeling, signal angular efficiency, PDFs parameterization & cross feed from different signal decays
$B^+ \rightarrow K^+ \tau^+ \tau^-$

“Search for $B^+ \rightarrow K^+ \tau^+ \tau^-$ at the BaBar Experiment”

[471 $\Upsilon(4S)$ events]

arXiv:1605.09637

$B^+ \rightarrow K^+ \tau^+ \tau^-$

Highly suppressed in the SM: $\text{BR} \sim (1-2) \times 10^{-7}$

Provides additional sensitivity to New Physics due to third-generation couplings & large $\tau$ mass

$\psi(2S)$

$\tan \beta = 30$

Different Higgs mass scenarios

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<td>$m_{h^0}$ (GeV)</td>
<td>$m_{H^\pm}$ (GeV)</td>
</tr>
<tr>
<td>Mass set-1</td>
<td>80</td>
</tr>
<tr>
<td>Mass set-2</td>
<td>250</td>
</tr>
<tr>
<td>Mass set-3</td>
<td>100</td>
</tr>
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Measurement performed using only leptonic $\tau$ decays:

- $B^+ \rightarrow K^+ \tau^+ \tau^-$, $\tau \rightarrow \mu \nu_{\tau} \nu_{\mu}$, $\tau \rightarrow e \nu_{\tau} \nu_e$

- Three signal modes: ee, $\mu\mu$, $e\mu$

Many neutrinos in the final states: lack of kinematic constraints

- Signal events selected on the recoil of fully reconstructed hadronic $B \rightarrow DX$ decays ($B_{\text{tag}}$) ($D = D^{(*)0}, D^{(*)\pm}, D^{(*)}, J/\psi$; $X < 6 h$ ($h=K, \pi$))

\[ B^+ \rightarrow K^+ \tau^+ \tau^- \]

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$B^+ \rightarrow K^+ \tau^+ \tau^-$

**B\(_{\text{tag}}\) Reconstruction**

B hadronic decays selected by means of \(m_{ES} \& \Delta E\)

Best candidate per event retained from the highest purity mode (computed from MC) \& \(\Delta E\)

Only B\(_{\text{tag}}\) candidates with Purity > 40% used \(\rightarrow \varepsilon(B_{\text{tag}}) = (0.2 - 0.4)\%\)

Continuum events suppressed by exploiting a Likelihood Selector consisting of six event-shape variables (e.g. Thrust, missing momentum vector, \(P(B_{\text{tag}})\), angles between them,...)

\(LS > 0.5\) removes > 75% of BKG retaining 80% of the signal
$B^+ \rightarrow K^{+}\tau^{+}\tau^{-}$

$B \rightarrow K^{+}\tau^{+}\tau^{-}$ Reconstruction

- Signal candidates reconstructed from events with three charged particles, identified as $K^{+}$ two leptons, not belonging to $B_{\text{tag}}$
- Vetos applied against $J/\psi$, $D^{0} \rightarrow K\pi (\rightarrow \mu)$, $\gamma \rightarrow e^{+}e^{-}$, $\pi^{0} \rightarrow \gamma\gamma$

Dominant BKG from $B \rightarrow D^{(*)} l^{\pm} \nu$, $D^{(*)} \rightarrow K l^{\pm} \nu$ (same final-state) suppressed by a Neural Network using angles between momenta, $m(K^{+}l^{-})$ and missing energy
$\mathcal{B}^+ \to K^+ \tau^+ \tau^-$

BR for each of the signal modes:

$$\mathcal{B}_i = \frac{N_{\text{obs}}^i - N_{\text{bkg}}^i}{\epsilon_{\text{sig}}^i N_{BB}}$$

$N_{BB} = 471 \times 10^6$

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<td>$\epsilon_{\text{sig}}^i \times 10^{-5}$</td>
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<td>$N_{\text{obs}}$</td>
<td>45</td>
<td>39</td>
<td>92</td>
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- Signal efficiencies and expected Peaking BKG events (92%) obtained from simulation corrected to reproduce $B_{\text{tag}}$ data yield
- Expected combinatorial BKG events (8%) from data $m_{ES}$ Side Band
$B^+ \rightarrow K^+ \tau^+ \tau^-$

BR for each of the signal modes:

$$\mathcal{B}_i = \frac{N_{\text{obs}}^i - N_{\text{bkg}}^i}{\varepsilon_{\text{sig}}^i N_{B\bar{B}}}$$

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$N_{B\bar{B}} = 471 \times 10^6$

e$^+e^-$, $\mu^+\mu^-$ yields show consistency with expected BKG events.

$e\mu$ channel has excess of 3.7 $\sigma$:

- No evident signal-like behaviour or systematic problems from kinematic distributions.
$B^+ \rightarrow K^+ \tau^+ \tau^-$

BR for each of the signal modes:

$$\mathcal{B}_i = \frac{N_{\text{obs}}^i - N_{\text{bkg}}^i}{\epsilon_{\text{sig}}^i N_{BB}}$$

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Overall significance < 2$\sigma$:

$$\text{BR}(B^+ \rightarrow K^+ \tau^+ \tau^-) < 2.25 \times 10^{-3} \ (90\% \text{ CL})$$ First Measurement

Systematics from $B_{\text{tag}}$ yield correction, theoretical models for efficiency determination, PID, and Data/MC agreement
"Time-dependent analysis of $B^0 \rightarrow K_S \pi \pi^+ \gamma$ and studies of the $K^+ \pi^- \pi^+$ system in $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$ decays"

[471 $M\Upsilon(4S)$ events]

Radiative decays and the \( \gamma \) polarization

\( b \to s \gamma \): described in the SM as an interaction between left-handed quarks and right-handed antiquarks:

\[
\lambda = \frac{\vec{S} \cdot \vec{p}}{|\vec{p}|}
\]

\( b \to s \gamma_L \) & \( \bar{b} \to \bar{s} \gamma_R \)

\( B^0 \to f_{CP} \) & \( \bar{B}^0 \to X \)

\( B^0 \to f_{CP} \)

\( b \to s \gamma_{L/R} \) & \( \bar{b} \to \bar{s} \gamma_{R/L} \)

New heavy particles in the loop could enhance opposite helicity \( \gamma \) contribution

\( \Rightarrow \) Mixing induced CP Asymmetry \( = 0 \)

\( \Rightarrow \) Mixing induced CP Asymmetry \( \neq 0 \)
Measurement of \( A_{CP} \) in \( B^0 \rightarrow K_S \rho \gamma \)

\[
A_{CP}(\Delta t) = \frac{\Gamma(B^0(\Delta t) \rightarrow f_{CP}\gamma) - \Gamma(B^0(\Delta t) \rightarrow f_{CP}\gamma)}{\Gamma(B^0(\Delta t) \rightarrow f_{CP}\gamma) + \Gamma(B^0(\Delta t) \rightarrow f_{CP}\gamma)} = S_{f_{CP}} \sin(\Delta m_d\Delta t) - C_{f_{CP}} \cos(\Delta m_d\Delta t)
\]

- SM predicts \( S_{f_{CP}} = m_s/m_b = 0.02 \)
- Look for enhancement due to new-particle exchange

[\( \Delta t = t_{Rec} - t_{Tag} \) from distance between the two \( B^0 \) decay vertices in the event]

Experimentally: perform a time-dependent analysis of \( B^0 \rightarrow K_S \rho \gamma \)

Main Issue: dilution from irreducible BKG from non CP eigenstates:

- CP eigenstate \( B^0 \rightarrow K_S \rho \gamma \)
- Non CP eigenstate \( B^0 \rightarrow K^*(K_S \pi)\pi \gamma \)
Measurement of $A_{CP}$ in $B^0 \rightarrow K_S \rho \gamma$

$$A_{CP} (\Delta t) = \frac{\Gamma ( B^0 (\Delta t) \rightarrow f_{CP} \gamma) - \Gamma ( B^0 (\Delta t) \rightarrow f_{CP} \gamma)}{\Gamma ( B^0 (\Delta t) \rightarrow f_{CP} \gamma) + \Gamma ( B^0 (\Delta t) \rightarrow f_{CP} \gamma)} = S_{f_{CP}} \sin (\Delta m_d \Delta t) - C_{f_{CP}} \cos (\Delta m_d \Delta t)$$

SM predicts $S_{f_{CP}} = m_s / m_b = 0.02$

Look for enhancement due to new-particle exchange

Experimentally: perform a time-dependent analysis of $B^0 \rightarrow K_S \rho \gamma$

Main Issue: dilution from irreducible BKG from non CP eigenstates:

$\Delta t = t_{Rec} - t_{Tag}$ from distance between the two $B^0$ decay vertices in the event

CP eigenstate $B^0 \rightarrow K_S \rho \gamma$    
Non CP eigenstate $B^0 \rightarrow K^* (K_S \pi) \pi \gamma$

Dilution: $D_{K_S^0 \rho \gamma} = S_{K_S^0 \pi^+ \pi^- \gamma}$

Effective value on inclusive $K_S \pi \pi \gamma$ sample

Signal value

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Measurement of $A_{CP}$ in $B^0 \rightarrow K^0 \rho \gamma$

Dilution expressed in terms of few resonant decay modes:

$\rho^0 K_S, K^*\pi^-, K^*-\pi^+, (K\pi)^*\pi^-, (K\pi)^*\pi^+\pi^- S$-wave $(K^*_0(1430) + NR \text{ component})$ and their interference:

\[
D_{K^0\rho\gamma} = \frac{S_{K^0\pi\pi\gamma}}{S_{K^0\rho\gamma}} = \frac{\int \left| A_{\rho K^0_S}\right|^2 - \left| A_{K^*\pi^-}\right|^2 - \left| A_{(K\pi)^*\pi^-}\right|^2 + 2\Re(A_{\rho K^0_S}^*A_{K^*\pi^-}) + 2\Im(A_{\rho K^0_S}^*A_{(K\pi)^*\pi^-}) dm^2}{\int \left| A_{\rho K^0_S}\right|^2 + \left| A_{K^*\pi^-}\right|^2 + \left| A_{(K\pi)^*\pi^-}\right|^2 + 2\Re(A_{\rho K^0_S}^*A_{K^*\pi^-}) + 2\Im(A_{\rho K^0_S}^*A_{(K\pi)^*\pi^-}) dm^2}
\]

[LAL-15-75 (2015)]

Ideal World: Perform a time-dependent Amplitude Analysis

Real World: Not enough statistics, dilution computed from the amplitudes of the intermediate resonances from $B^+ \rightarrow K^+\pi^+\pi^-\gamma$

assuming Isospin Symmetry
$B^+ \rightarrow K^+\pi^+\pi^-\gamma$ Selection

$B^+ \rightarrow K^+\pi^+\pi^-\gamma$ events selected by means of:

- $1.5 < E^*_\gamma < 3.5 \text{ GeV}$
- $m_{ES}^*$
- $\Delta E$

Continuum BKG suppressed using a Fisher exploiting topological quantities

$e^+e^- \rightarrow \tau(4S) \rightarrow B\bar{B}$
$e^+e^- \rightarrow q\bar{q}$

$p_B^* \sim 340 \text{ MeV/c}$

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\[ B^+ \rightarrow K^+\pi^+\pi^-\gamma \]  

Selection

- \( B^+ \rightarrow K^+\pi^+\pi^-\gamma \) signal yield extracted from an unbinned fit to \( m_{ES}, \Delta E \) and Fisher discriminant:
  - \( N_{\text{sig}} = 2441 \pm 91 \pm 5 \)
  - \( \text{BF}(B^+ \rightarrow K^+\pi^+\pi^-\gamma) = (24.5 \pm 0.9 \pm 1.2) \times 10^{-6} \)

- \( m(K\pi\pi), m(K\pi) \) and \( m(\pi\pi) \) spectra obtained using \( S \) Plot technique

\[ [\text{NIM A 555, 356-369 (2005)}] \]
\[ B^+ \to K^+\pi^+\pi^- \gamma \] Analysis

$B^+$s of the various resonances decaying to $K\pi\pi$ extracted from the $m(K\pi\pi)$ spectrum

<table>
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<tr>
<th>Mode</th>
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<tr>
<td>$B^+ \to K^+\pi^+\pi^- \gamma$</td>
<td>$\ldots$</td>
<td>$27.6 \pm 2.2$</td>
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<tr>
<td>$K_1(1270)^+\gamma$</td>
<td>$14.5^{+2.1+1.2}_{-1.4-1.2}$</td>
<td>$43 \pm 13$</td>
</tr>
<tr>
<td>$K_1(1400)^+\gamma$</td>
<td>$4.1^{+1.9+1.2}_{-1.2-1.0}$</td>
<td>$&lt;15$ at 90% C.L.</td>
</tr>
<tr>
<td>$K^*(1410)^+\gamma$</td>
<td>$11.0^{+2.2+2.1}_{-2.0-1.1}$</td>
<td>n/a</td>
</tr>
<tr>
<td>$K_2^*(1430)^+\gamma$</td>
<td>$1.2^{+1.0+1.2}_{-0.7-1.5}$</td>
<td>$14 \pm 4$</td>
</tr>
<tr>
<td>$K^*(1680)^+\gamma$</td>
<td>$15.9^{+2.2+3.2}_{-1.9-2.4}$</td>
<td>$&lt;1900$ at 90% C.L.</td>
</tr>
</tbody>
</table>

$B^+ \to K^+\pi^+\pi^- \gamma$
$B^+ \rightarrow K^{+}\pi^{+}\pi^{-}\gamma$ Analysis

- Extraction of the dilution from amplitudes of intermediate states decaying to $K\pi$ and $\pi\pi$
- Full amplitude analysis in the $m(K\pi)-m(\pi\pi)$ not possible due to small statistics
- Perform a 1D fit to $m(K\pi)$ using as inputs the BRs obtained from the $m(K\pi\pi)$ fit

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\mathcal{B}(B^+ \rightarrow \text{Mode}) \times 10^{-6}$</th>
<th>Previous world average $[18]$ ($\times 10^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^0\pi^+\gamma$</td>
<td>15.6 ± 0.6 ± 0.5</td>
<td>23.4 ± 0.9$^{+0.8}_{-0.7}$</td>
</tr>
<tr>
<td>$K^+\rho(770)^0\gamma$</td>
<td>8.1 ± 0.4$^{+0.8}_{-0.7}$</td>
<td>8.2 ± 0.4 ± 0.8 ± 0.02</td>
</tr>
<tr>
<td>$(K\pi)_0^0\pi^+\gamma$</td>
<td>10.3$^{+0.7}<em>{-0.8}$$^{+1.5}</em>{-2.0}$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>$(K\pi)^0_0\pi^+\gamma$ (NR)</td>
<td>$\cdots$</td>
<td>&lt; 20 at 90% CL</td>
</tr>
<tr>
<td>$K^*_0(1430)^0\pi^+\gamma$</td>
<td>0.82 ± 0.06$^{+0.12}_{-0.16}$</td>
<td>9.9 ± 0.7$^{+1.5}_{-1.9}$</td>
</tr>
<tr>
<td>$K^*_0(1430)^0\pi^+\gamma$ (NR)</td>
<td>$\cdots$</td>
<td>&lt; 9.2 at 90% CL</td>
</tr>
</tbody>
</table>
Extraction of the dilution from amplitudes of intermediate states decaying to $K\pi$ and $\pi\pi$.

Full amplitude analysis in the $m(K\pi)-m(\pi\pi)$ not possible due to small statistics.

Perform a 1D fit to $m(K\pi)$ using as inputs the BRs obtained from the $m(K\pi\pi)$ fit.

\[ D_{K^0_S\rho\gamma} = \Gamma(A_\rho, A_{K^*}, A_{(K\pi)S\text{-wave}}) = -0.78^{+0.19}_{-0.17} \]
Measurement of $A_{CP}$ in $B^0 \rightarrow K_S \gamma$

Time-dependent analysis of $B^0 \rightarrow K_S \gamma$ decays

Event yield and CP parameters $C$ and $S$ extracted from a fit to $m_{ES}$, $\Delta E$, Fisher and $\Delta t$

Sample divided in 6 mutually exclusive tagging categories $c$

\[ P^i_j (m_{ES}, \Delta E, \mathcal{F}, \Delta t, \sigma_{\Delta t}; q_{\text{tag}}, c) = P^i_j (m_{ES}) P^i_j (\Delta E) P^i_j (\mathcal{F}) P^i_j (\Delta t, \sigma_{\Delta t}; q_{\text{tag}}, c) \]

$c = \text{tagging category}$

$q_{\text{tag}} = 1 (B_{\text{tag}} = B^0)$

$q_{\text{tag}} = -1 (B_{\text{tag}} = \overline{B}^0)$
Measurement of $A_{CP}$ in $B^0 \to K_s \rho \gamma$

Time-dependent analysis of $B^0 \to K_s \rho \gamma$ decays

Event yield and CP parameters $C$ and $S$ extracted from a fit to $m_{ES}$, $\Delta E$, Fisher and $\Delta t$

Sample divided in 6 mutually exclusive tagging categories $c$

Tagging imperfection $D$, $\Delta D$ & $\Delta t$ Resolution $R_{\text{sig}}$ from quarkonium $\sin(2\beta)$ analysis [PRL 99, 171803 (2007)]
Measurement of $A_{CP}$ in $B^0 \rightarrow K_S \rho \gamma$

Results:

$\mathcal{B}(B^0 \rightarrow K_S \pi \pi \gamma) = (20.5 \pm 2.0^{+2.6}_{-2.2}) \times 10^{-6}$

$S_{K_S \pi \pi \gamma} = 0.14 \pm 0.25 \pm 0.03$

$C_{K_S \pi \pi \gamma} = -0.39 \pm 0.20^{+0.03}_{-0.02}$

After correcting for $D_{K^0_S \rho \gamma}$:

$S_{K_S \rho \gamma} = -0.18 \pm 0.32^{+0.06}_{-0.05}$

Systematics from resonance modelling and $\Delta E$, $m_{ES}$ and Fisher distributions shape

Results consistent with Belle [PRL 101, 251601 (2008)]
Conclusions
Conclusions

Rare B decays are an excellent laboratory for the search for physics beyond the SM.

In the last few years several new measurements from LHC & B-Factories experiments released with impressive experimental precision.

Almost all the results are in agreement with expectations but some tension is present in some sectors: BaBar F_{LL} for \( B^+ \to K^{(*)}l^+l^- \) (shown today), \( B \to K^{(*)}\mu\mu \) (P5', \( BR(B \to K\mu\mu) / BR(B \to \text{Kee}) \)),

(but also \( B \to D^{(*)}\tau\nu/B \to D^{(*)}\mu\nu \))

Strong constraints on NP models from flavor measurements.

Rich program of measurements is expected from LHC/Belle II experiments in the coming years.

Could we have chances to discover/understand NP in the flavor sector in the near future?
Backup
Event Yields:

<table>
<thead>
<tr>
<th>Mode</th>
<th>$q_0^2$</th>
<th>$q_1^2$</th>
<th>$q_2^2$</th>
<th>$q_3^2$</th>
<th>$q_4^2$</th>
<th>$q_5^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to K^* \ell^+ \ell^-$</td>
<td>40.8 ± 8.4</td>
<td>31.7 ± 7.1</td>
<td>11.9 ± 5.5</td>
<td>21.3 ± 8.5</td>
<td>31.9 ± 9.2</td>
<td>33.2 ± 7.8</td>
</tr>
<tr>
<td>$B^+ \to K^{**} \ell^+ \ell^-$</td>
<td>17.7 ± 5.2</td>
<td>8.7 ± 4.1</td>
<td>3.8 ± 4.0</td>
<td>7.7 ± 5.6</td>
<td>9.0 ± 4.8</td>
<td>9.4 ± 4.2</td>
</tr>
<tr>
<td>$B^0 \to K^{*0} \ell^+ \ell^-$</td>
<td>23.1 ± 6.6</td>
<td>22.9 ± 5.8</td>
<td>8.1 ± 3.8</td>
<td>13.7 ± 6.4</td>
<td>22.8 ± 7.8</td>
<td>23.8 ± 6.6</td>
</tr>
</tbody>
</table>

Systematics:
- PDF shapes and parameter statistical error
- $F_L$ statistical error propagated in $A_{FB}$ fit
- Modeling of BKG PDF shape and Signal efficiency
- Signal crossfeed
- Fit bias
- Stability vs cuts
**$B \to K^{*} \ell \ell$ Angular Analysis: $P_5'$ parameter**

- **LHCb full statistics result on $P_5'$: discrepancy at 3.4 $\sigma$ level**
  - [JHEP 02, 104 (2016)]

- **Belle confirms the tension at 2.1 $\sigma$ level** [arXiv:1604.04042]

- **Need to control the charm penguin to disentangle SM from NP in $C_7^{\text{eff}}$ and $C_9^{\text{eff}}$**

Capri 2016, 11-13 June 2016

M. Margonni - Università di Padova & INFN
$B \rightarrow K^* \mu^+ \mu^-$: CMS Results

Results consistent with SM

- Systematics from BKG PDF shapes, efficiency, simulation mismodeling and fit bias.
- Theoretical predictions:
  - Light-cone sum rules at low $q^2$ and extrapolation at high $q^2$ [JHEP 09 089 (2010), JHEP 02 010 (2013)]
  - Lattice [Phys. Rev. D89 094501 (2014)]
$B \to K^{*} \mu^{+}\mu^{-}$ Related quantities

$K^{*} \mu^{+}\mu^{-}$ tension motivates studies of differential BRs

All the results are "consistent" with SM at $<2.2 \sigma$

But all of them are lower than the predictions...

Capri 2016, 11-13 June 2016

M.Margoni Universita` di Padova & INFN
Measurements of related $b \rightarrow d\mu\mu$ channels very useful to reveal information on Minimal Flavor Violation nature of New Physics.

**LHCb** [JHEP 10, 034 (2015)]:

$\text{BR}(B^+ \rightarrow \pi^+\mu^+\mu^-) = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$ in agreement with MFV

$\frac{\text{BR}(B^+ \rightarrow \pi^+\mu^+\mu^-)}{\text{BR}(B^+ \rightarrow K^+\mu^+\mu^-)} = 0.037 \pm 0.008 \pm 0.001$

$|V_{td}|/|V_{ts}| = 0.24^{+0.05}_{-0.04}$ in agreement with box processes $(\Delta m_s/\Delta m_d)$ results.
$\mathcal{B}^+ \rightarrow K^+ \tau^+ \tau^-$

Signal efficiencies and expected Peaking BKG events (92%) from simulation corrected according to Data/MC ratio before NN cut:

\[
\left( \frac{N_{\text{Data}}}{N_{\text{MC}}} \right)_{\text{BKG}} = 0.913 \pm 0.020
\]

Expected combinatorial BKG events (8%) from data mEs Side Band

Data/MC $B_{\text{tag}}$ yields cross-checked using $B^+ \rightarrow D^0 \ell \nu, D^0 \rightarrow K\pi$ (before NN cut)
\[ \mathcal{B}^+ \rightarrow K^+ \tau^+ \tau^- \]

Cross checks to understand the excess:

- Excess present also in the \( \mathcal{B}_{\text{tag}} \) side band

Discriminating variable in the NN:

- \( s_B = \frac{q^2}{m_B^2} = \left( \frac{p_{B_{\text{sig}}} - p_K}{m_B^2} \right)^2 \), \( m(K^+\tau^-) \), \( K-\ell \) angle in the di-tau frame, lepton momentum, missing energy, e.m. energy not associated to \( \mathcal{B}_{\text{tag}} \)
- All of them compatible with BKG statistical fluctuation
\[ B^+ \rightarrow K^+ \tau^+ \tau^- \]

**Systematics:**
- **Theory (signal efficiency):** 3\% from shape of the \( q^2 \) distribution (Lattice QCD vs light cone sum rules)
- **Btag Yield:** 1.5\% from MC correction using \( m_{ES} \) sideband
- **PID:** 5\% from Data/MC comparison
- **\( \pi^0 \) Veto:** 3\%
- **NN cut:** 2.6\% from Data/MC checked on \( B^+ \rightarrow D^0 l \nu \) (\( D^0 \rightarrow K\pi \))
Measurement of $A_{CP}$ in $B^0 \rightarrow K_s \rho \gamma$

**Belle** [PRL 101, 251601 (2008)],

$S_{K_s \rho \gamma} = 0.11 \pm 0.33^{+0.05}_{-0.09}$

$A_{CP}$ (direct) = $0.05 \pm 0.18 \pm 0.06$

**LHCb** [PRL 112, 161901 (2014)],

$$A_{ud} \equiv \frac{\int_{-1}^{1} d \cos \theta \frac{d\Gamma}{d \cos \theta} - \int_{-1}^{0} d \cos \theta \frac{d\Gamma}{d \cos \theta}}{\int_{-1}^{1} d \cos \theta \frac{d\Gamma}{d \cos \theta}}$$

$\theta$ = angle between photon and $K\pi\pi$ plane normal

$m_{K\pi\pi}$ | 1.1, 1.3 | 1.3, 1.4 | 1.4, 1.6 | 1.6, 1.9
---|---|---|---|---
$A_{ud}$ | 6.9 ± 1.7 | 4.9 ± 2.0 | 5.6 ± 1.8 | -4.5 ± 1.9

5.2 $\sigma$ significance for nonzero up-down asymmetry

First measurement