$b \to s\ell\ell$ results from CMS

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on behalf of CMS collaboration

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LHCP  
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Introduction

- Flavour-changing neutral current decays $b \to s \ell^+ \ell^-$ are doubly suppressed in the Standard Model.
- Good laboratory to probe new-physics effects, through angular analysis and branching fraction measurement.
- The $B^0 \to K^* \mu \mu$ decay:
  - Flavour eigenstate ($B^0 / \bar{B}^0$) can be identified through the $K^* \to K^- \pi^+$ decay.
  - Allows measuring a large set of angular parameters, sensitive to Wilson coefficients $C_7^{(i)}, C_9^{(i)}, C_{10}^{(i)}, C_{S,P}^{(i)}$.
- The $B^+ \to K^+ \mu \mu$ decay:
  - Allows measuring the muon forward-backward asymmetry.
- Both channels are experimentally accessible, thanks to the fully-charged final states and easy-to-identify muon pair.
$B^0 \rightarrow K^*(892)\mu^+\mu^- \rightarrow K^+\pi^-\mu^+\mu^-$ angular analysis

- Fully described by three angles: $\theta_\ell$, $\theta_K$, $\phi$ and $q^2 = M_{\mu\mu}^2$
- Robust SM calculations of several angular parameters in most of the phase space
  - forward-backward asymmetry of the muons, $A_{FB}$,
  - longitudinal polarization fraction of the $K^*$, $F_L$
  - set of clean parameters, $P_i$ and $P'_i$
- The $q^2$ range has been divided in 9 bins
  - 7 signal bins, in each of them the angular analysis is performed independently
  - 2 control-region bins, covering the two resonant decays
    - $B^0 \rightarrow J/\psi K^*$
    - $B^0 \rightarrow \psi' K^*$
Two analyses were performed and published by CMS with 2011 and 2012 data

The parameter space was reduced by integrating over the $\phi$ angular variable

$A_{FB}$ and $F_L$ parameters and differential branching fraction were measured

No deviations from SM prediction

The analysis presented here is performed on the same dataset and uses the same selection criteria as the previous 2012 analysis
Angular decay rate

- Final state $K^+\pi^-\mu^+\mu^-$ has contribution from P-wave ($K^*$), S-wave, and interference.
- In total, the decay rate has 14 parameters: fold around $\phi = 0$ and $\theta_\ell = \pi/2$ to reduce them.

$$\frac{1}{d\Gamma/dq^2 dq^2 d\cos\theta_\ell d\cos\theta_K} = \frac{9}{8\pi} \left\{ \frac{2}{3} \left[ (F_S + A_S \cos\theta_K) \left( 1 - \cos^2\theta_\ell \right) + A_S^5 \sqrt{1 - \cos^2\theta_K} \sqrt{1 - \cos^2\theta_\ell \cos\phi} \right] 
+ (1 - F_S) \left[ 2F_L \cos^2\theta_K \left( 1 - \cos^2\theta_\ell \right) \right. \left. + \frac{1}{2} (1 - F_L) \left( 1 - \cos^2\theta_K \right) \left( 1 + \cos^2\theta_\ell \right) \right. \right. 
+ \left. \frac{1}{2} P_1(1 - F_L)(1 - \cos^2\theta_K)(1 - \cos^2\theta_\ell) \cos 2\phi \right. 
+ \left. 2P'_5 \cos\theta_K \sqrt{F_L (1 - F_L)} \sqrt{1 - \cos^2\theta_K} \sqrt{1 - \cos^2\theta_\ell \cos\phi} \right\}$$

- 6 angular parameters left: fit with all of them free to float not possible (low statistics, proximity of physical boundaries)
Angular decay rate

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- In total, the decay rate has 14 parameters: fold around $\phi = 0$ and $\theta_\ell = \pi/2$ to reduce them

\[
\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_K d\phi} = \frac{9}{8\pi} \left\{ \frac{2}{3} \left[ (F_S + A_S \cos \theta_K) \left( 1 - \cos^2 \theta_\ell \right) + A_S^5 \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta_\ell} \cos \phi \right] + (1 - F_S) \left[ 2F_L \cos^2 \theta_K \left( 1 - \cos^2 \theta_\ell \right) + \frac{1}{2} (1 - F_L) \left( 1 - \cos^2 \theta_K \right) \left( 1 + \cos^2 \theta_\ell \right) \right] + \frac{1}{2} P_1(1 - F_L)(1 - \cos^2 \theta_K)(1 - \cos^2 \theta_\ell) \cos 2\phi + 2P'_5 \cos \theta_K \sqrt{F_L (1 - F_L)} \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta_\ell} \cos \phi \right\}
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+ (1 - F_S) \left[ 2F_L \cos^2 \theta_K \left(1 - \cos^2 \theta_{\ell}\right) + \frac{1}{2} (1 - F_L) \left(1 - \cos^2 \theta_K\right) \left(1 + \cos^2 \theta_{\ell}\right) \right] \\
+ \frac{1}{2} P_1 (1 - F_L) (1 - \cos^2 \theta_K) (1 - \cos^2 \theta_{\ell}) \cos 2\phi \\
+ 2P_1' \cos \theta_K \sqrt{F_L} \left[1 - F_L \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta_{\ell}} \cos \phi \right] \right\}
\]

- 6 angular parameters left:
  fit with all of them free to float not possible (low statistics, proximity of physical boundaries)
- $F_L$, $F_S$, and $A_s$ fixed from previous CMS measurement
Angular decay rate

- Final state $K^+ \pi^- \mu^+ \mu^-$ has contribution from P-wave ($K^*$), S-wave, and interference.
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+ (1 - F_S) \left[ 2F_L \cos^2 \theta_K \left(1 - \cos^2 \theta_\ell\right) + \frac{1}{2} (1 - F_L) \left(1 - \cos^2 \theta_K\right) \left(1 + \cos^2 \theta_\ell\right) \right] \\
+ \frac{1}{2} P_1 (1 - F_L) (1 - \cos^2 \theta_K) (1 - \cos^2 \theta_\ell) \cos 2\phi \\
+ 2P_5' \cos \theta_K \sqrt{F_L (1 - F_L)} \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta_\ell} \cos \phi \right\} \]

- 6 angular parameters left: fit with all of them free to float not possible (low statistics, proximity of physical boundaries).
- $F_L$, $F_S$, and $A_s$ fixed from previous CMS measurement.
- $P_1$ and $P_5'$ measured, $A_s^5$ nuisance parameter.
Fit pdf description

\[
p.d.f.(m, \cos \theta_K, \cos \theta_l, \phi) = Y_C^S \cdot \left( S_R^R(m) \cdot S^a(\cos \theta_K, \cos \theta_l, \phi) \cdot \epsilon^R(\cos \theta_K, \cos \theta_l, \phi) \right) \\
+ \frac{f^M}{1 - f^M} \cdot S_M^M(m) \cdot S^a(-\cos \theta_K, -\cos \theta_l, -\phi) \cdot \epsilon^M(\cos \theta_l, \cos \theta_K, \phi) \\
+ Y_B \cdot B^m(m) \cdot B^{\cos \theta_K}(\cos \theta_K) \cdot B^{\cos \theta_l}(\cos \theta_l) \cdot B^\phi(\phi).
\]
Fit pdf description

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\]

Signal components for correctly-tagged and mis-tagged events, each composed by:

- double-Gaussian mass shape
- angular decay rate
- 3D efficiency function
  (using non-parametric Kernel-Density-Estimator)

Flavour state assignment based on \( M(K\pi) \) value

- mis-tagged event fraction 14%, measured on MC
Fit pdf description

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+ \frac{f^M}{1 - f^M} \cdot S^M(m) \cdot S^a(-\cos \theta_K, -\cos \theta_l, -\phi) \cdot \epsilon^M(\cos \theta_l, \cos \theta_K, \phi) \\
+ Y_B \cdot B^m(m) \cdot B^{\cos \theta_K}(\cos \theta_K) \cdot B^{\cos \theta_l}(\cos \theta_l) \cdot B^\phi(\phi).
\]

Signal components for **correctly-tagged** and **mis-tagged** events, each composed by:

- double-Gaussian mass shape
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- 3D efficiency function
  
  (using non-parametric Kernel-Density-Estimator)

Flavour state assignment based on \(M(K\pi)\) value

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**Background component**

- exponential mass shape
- polynomial shape for each angular variable
- factorization of angular components tested
**Fit algorithm**

- Two-step fit performed for 7 (+2 control regions) $q^2$ bins:
  - fit $m$ side bands to determine the background shape
  - fit whole mass spectrum with 5 floating parameters (2 yields, $P_1$, $P'_5$, $A_5$)
- Unbinned extended maximum likelihood estimator used
  - find maximum of $L$ inside the physically allowed region
- **Blind procedure**: before fitting the signal mass region on data, the fit procedure has been fully tested and validated on simulation
- Statistical uncertainty using Feldman-Cousins method
**Systematic uncertainties**

<table>
<thead>
<tr>
<th>Source</th>
<th>$P_1(\times 10^{-3})$</th>
<th>$P_5(\times 10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation mismodeling</td>
<td>1–33</td>
<td>10–23</td>
</tr>
<tr>
<td>Fit bias</td>
<td>5–78</td>
<td>10–120</td>
</tr>
<tr>
<td>Finite size of simulated samples</td>
<td>29–73</td>
<td>31–110</td>
</tr>
<tr>
<td>Efficiency</td>
<td>17–100</td>
<td>5–65</td>
</tr>
<tr>
<td>Kπ mistagging</td>
<td>8–110</td>
<td>6–66</td>
</tr>
<tr>
<td>Background distribution</td>
<td>12–70</td>
<td>10–51</td>
</tr>
<tr>
<td>Mass distribution</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Feed-through background</td>
<td>4–12</td>
<td>3–24</td>
</tr>
<tr>
<td>$F_L, F_S, A_S$ uncertainty propagation</td>
<td>0–210</td>
<td>0–210</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>2–68</td>
<td>0.1–12</td>
</tr>
<tr>
<td>Total</td>
<td>100–230</td>
<td>70–250</td>
</tr>
</tbody>
</table>

- **Fit bias** with cocktail signal $MC + toy$ background from data side-bands
- **MC stat** due to limited statistics in efficiency shape evaluation
- **Efficiency**: comparing $F_L$ on CR wrt PDG
- **Kπ mistag** evaluated in $J/\psi$ control region and propagated to all bins

**Propagation of $F_L$, $F_S$, and $A_S$ uncertainties:**
- Generate pseudo experiments, with x100 events, for each $q^2$ bin
- Fit with $F_L, F_S, A_S$ free to float and with $F_L, F_S, A_S$ fixed
- Ratio of stat. uncert. on $P_1$ and $P_5'$ with free and fixed fit used to estimate syst uncertainties
Results: fit projection for second bin: $2.0 < q^2 < 4.3$ GeV$^2$
Results

- **SM-DHMV** prediction computed using
  - soft form factors + parametrised power corrections
  - hadronic charm-loop contribution derived from calculations

- Results compatible with SM predictions within uncertainties

- No significant deviations from other experimental results
**B⁺ → K⁺μ⁺μ⁻ angular analysis**

- Fully described by the angle $\theta_\ell$ and $q^2 = M_{\mu\mu}^2$;
- Angular decay rate:

\[
\frac{1}{d\Gamma/dq^2} \frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = \frac{3}{4} (1 - F_H) (1 - \cos^2\theta_\ell) + \frac{1}{2} F_H + A_{FB} \cos\theta_\ell
\]

- The forward-backward asymmetry of the muons, $A_{FB}$, and the angular parameter $F_H$ can be extracted through an angular analysis.
- Range of $q^2$ divided in 9 bins
  - Analysis performed in 7 signal bins
  - 2 bins containing the resonant decays $B^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow \psi' K^+$ used as control channels
  - 2 additional special bins: [1-6] GeV$^2$ (clean predictions) and [1-22] GeV$^2$ (full signal)
Fit algorithm

\[ p.d.f.(m, \cos \theta_l) = Y_S \cdot S_i(m) \cdot S_i^a(\cos \theta_l) \cdot \epsilon_i(\cos \theta_l) + Y_B \cdot B_i^m(m) \cdot B_i^{\cos \theta_l}(\cos \theta_l) \]

- Signal pdf component
  - double Gaussian mass shape
  - efficiency parameterised from MC with 6th-order polynomial
- Background pdf component
  - exponential mass shape
  - polynomial (3rd- or 4th-order) + Gaussian for the angular shape
- Two-step fit performed:
  - fit \( m \) side bands to determine the background shape (fixed in second step)
  - fit whole mass spectrum with 4 floating parameters (2 yields + 2 angular param)
- Unbinned extended maximum likelihood estimator used
- Statistical uncertainty using Feldman-Cousins method
Validation and systematic uncertainties

Several validation steps

- With signal MC sample (both high statistics and data-like)
- With resonant control regions

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>$A_{FB} \times 10^{-2}$</th>
<th>$F_H \times 10^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finite size of MC samples</td>
<td>0.4–1.8</td>
<td>0.9–5.0</td>
</tr>
<tr>
<td>Efficiency description</td>
<td>0.1–1.5</td>
<td>0.1–7.8</td>
</tr>
<tr>
<td>Simulation mismodeling</td>
<td>0.1–2.8</td>
<td>0.1–1.4</td>
</tr>
<tr>
<td>Background parametrization model</td>
<td>0.1–1.0</td>
<td>0.1–5.1</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>0.1–1.7</td>
<td>0.1–3.3</td>
</tr>
<tr>
<td>Dimuon mass resolution</td>
<td>0.1–1.0</td>
<td>0.1–1.5</td>
</tr>
<tr>
<td>Fitting procedure</td>
<td>0.1–3.2</td>
<td>0.4–25</td>
</tr>
<tr>
<td>Background distribution</td>
<td>0.1–7.2</td>
<td>0.1–29</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>1.6–7.5</td>
<td>4.4–39</td>
</tr>
</tbody>
</table>

Dominant systematic uncertainty from background description
Results: fit projections for special bin $1 < q^2 < 6 \text{ GeV}^2$
Results

- Inner error bar is statistical uncertainty
- Full bar is total uncertainty
- Results compatible with SM predictions within uncertainties
Summary

FCNC rare decays are being extensively studied in CMS

- $B^0 \rightarrow K^* \mu\mu$ angular analysis has been extended to measure $P_1$ and $P'_5$ parameters
- $B^+ \rightarrow K^+ \mu\mu$ angular analysis performed for the first time in CMS, to measure $A_{FB}$ and $F_H$ parameters
- no significant deviation from SM prediction seen within the uncertainties
- a dedicated trigger is collecting a larger statistics at 13 TeV
- Stay tuned
Backup slides
Motivation

The search for new physics can be performed via different paths:

- **direct searches**
  - try to produce any new particle and detect it via its decay or interaction with the detector

- **indirect searches**
  - perform precise measurement of processes and compare with Standard Model prediction
  - New Physics present in the loops can be seen if a significant discrepancy wrt to SM prediction is present.
The validity range

To guarantee that the decay rate is always positively defined, the parameters have physical boundaries:

- interference terms $A_s^{(5)}$ have a definition range dependent on $F_L$, $F_S$, and $P_1$
- to have a positive P-wave component, $P_1$ and $P'_5$ must satisfy: $(P'_5)^2 - 1 < P_1 < 1$
  - purple line in the graph
- to have a positive decay rate, an additional boundary need to be considered
  - depends on all the parameters
  - no analytic description available
  - computed numerically for each $q^2$ bin, using the fixed values of $F_L$, $F_S$, and $A_s$
  - grey lines in the graphs represent the boundary for different $A_s^{5}$ values within its range

Main cause of fit convergence problems $\rightarrow$ floating parameter $A_s^{5}$ and its influence on the physical boundary
Dataset selection for $B^0 \rightarrow K^* \mu \mu$

**Trig**  Dedicated HLT trigger path:
- Low pt dimuon, displaced, low invariant mass

$\mu$  $p_T^{\mu} > 3.5$ GeV, $p_T^{\mu\mu} > 6.9$ GeV,
with high-quality displaced vertex

$h$  $p_T^h > 0.8$ GeV, $|M(K\pi) - M_{K^*}| < 90$ MeV,
$M_{KK} > 1.035$ ($\phi$ veto), displaced from the primary vertex

$B^0$  $p_t > 8$ GeV, $|\eta| < 2.2$, with four-body displaced vertex
requirement and global momentum alignment

- both $B^0$ and $\bar{B}^0$ considered
- anti radiation cut against feed-down of $J/\psi/\psi'$

**CR**  $J/\psi$ and $\psi'$ resonances used as control regions
and treated in the same way.

No PID to distinguish $K$ from $\pi$, flavour state assignment based on which hypothesis $M(K^+\pi^-/K^-\pi^+)$ is closer to $M_{K^*}(PDG)$
mistag rate 14% (MC)
Efficiency and closure test (right tag)

- Numerator and denominator of efficiency are separately described with nonparametric technique implemented with a kernel density estimator on unbinned distributions.
- Final efficiency distributions in the p.d.f. obtained from the ratio of 3D histograms derived from the sampling of the kernel density estimators.

Closure test:
- Compute efficiency with half of the MC simulation and use it to correct the other half.
- Same test performed both for correctly and mistagged events independently.
Efficiency and closure test (wrong tag)

- Numerator and denominator of efficiency are separately described with nonparametric technique implemented with a kernel density estimator on unbinned distributions
- Final efficiency distributions in the p.d.f. obtained from the ratio of 3D histograms derived from the sampling of the kernel density estimators

Closure test:
- compute efficiency with half of the MC simulation and use it to correct the other half
- same test performed both for correctly and mistagged events independently
Background considered included:

- Partially reconstructed $B^0$ decay might pollute left $M_{B^0}$ side bands
  - restrict left s.b. ($5.1 < M < 5.6$ GeV, default $5 < M < 5.6$ GeV)
  - redo fit: change in $P_1$ and $P_5'$ within the systematics uncertainties.
- $B^{\pm} \rightarrow K^{\pm} \mu \mu$ plus and additional random $\pi^{\mp}$:
  - distribution ends at $M > 5.4$ GeV, further reduced by $\cos \alpha$ cut, and BR similar to $B^0 \rightarrow K^* \mu \mu$
- $\Lambda_b \rightarrow pKJ/\psi(\mu^+ \mu^-)$
  - look at event in the $M_{K\pi\mu\mu} \approx M_{B^0}$ peak, reconstruct them using $p, K$ mass hypothesis: no peak seen.
- $B^0 \rightarrow DX$, with $D \rightarrow hh$ and $h$ mis-id as $\mu$
  - requires two mis-id: $P_{misld} \sim 1 \cdot 10^{-3}$: given $BR \sim 1 \cdot 10^{-3}$ negligible.
- $B^0 \rightarrow J/\psi(\mu\mu)K^*(K\pi)$, with one $h$ and one $\mu$ switched
  - $P_{misld\mu} \cdot (1 - \varepsilon_{\mu}) \sim 1 \cdot 10^{-4}$, $Y_{B^0 \rightarrow J/\psi \mu \mu} \sim 1.6 \cdot 10^5$: few events in bin close to $J/\psi$
  - $J/\psi$ feed contamination in close bin included in the fit model
Fit validation

extensive fit validation with MC: used as **systematics**
  - compare fit results with MC input values (**sim mismodeling**)
  - compare with data-like MC (**fit bias**)
    - signal only correct tag
    - signal correct+wrong tag
    - signal + background
  - Data control channel (**J/ψ** and **ψ′**), comparing fit results with PDG (**F_L**) (**efficiency**)
  - compare **P_1** and **P_5′** on **J/ψ** and **ψ′** w/ and w/o **F_L** fixed: no bias

\[
\frac{\mathcal{B}(B^0 \rightarrow K^*\psi')}{\mathcal{B}(B^0 \rightarrow K^*J/\psi)} = \frac{Y_{\psi'}\epsilon_{J/\psi}}{\epsilon_{\psi'} Y_{J/\psi}} \frac{\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)}{\mathcal{B}(\psi' \rightarrow \mu^+\mu^-)} = 0.480 \pm 0.008{\text{(stat)}} \pm 0.055{\text{(R_{\mu\mu})}}
\]

vs PDG 0.484 ± 0.018{\text{(stat)}} ± 0.011{\text{(syst)}} ± 0.012{\text{(R_{\psi e})}}
Fit Validation (2)

Several validation steps are performed with simulation:

- with statistically precise MC signal sample: compare fit results with input values to the simulation (simulation mismodeling)
- with 200 data-like MC signal+background samples: compare average fit results with fit to the statistically precise MC signal sample (fit bias)
- with pseudo-experiments

Validation with data control channels:

- Fit performed with $F_L$ free to vary
- The difference of $F_L$ with respect to PDG value is propagated to the signal $q^2$ bins as systematic uncertainty (efficiency)
Fit procedure

- The decay rate can become negative for certain values of the angular parameters ($P_1$, $P_5'$, $A^5_s$).
- The presence of such a physically allowed region greatly complicates the numerical maximisation process of the likelihood by MINUIT and especially the error determination by MINOS, in particular next to the boundary between physical and unphysical regions.
- The best estimate of $P_1$ and $P_5'$ is computed by:
  - discretise the bi-dimensional space $P_1$-$P_5'$
  - maximise the likelihood as a function of $Y_s$, $Y_B$, and $A^5_s$ at fixed values of $P_1$, $P_5'$
  - fit the likelihood distribution with a 2D-gaussian function
  - the maximum of this function inside the physically allowed region is the best estimate.

- To ensure correct coverage for the uncertainties of $P_1$ and $P_5'$, the Feldman-Cousins method is used in a simplified form: the confidence interval’s construction is performed only along two 1D paths determined by profiling the 2D-gaussian description of the likelihood inside the physically allowed region.

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FC stat uncertainties determination

- To ensure correct coverage for the uncertainties of $P_1$ and $P_2'$, the Feldman-Cousins method is used in a simplified form: the confidence interval's construction is performed only along the two 1D paths determined by profiling the 2D-gaussian description of likelihood inside the physically allowed region:
  - generate 100 pseudo-experiments for each point of the path
  - fit and rank according to the likelihood-ratio
  - confidence interval bound is found when data likelihood-ratio exceeds the 68.3% of the pseudo-experiments

- Due to the limited number of pseudo-experiments, statistical fluctuations are present
- To produce a robust result, the ranking of the data likelihood-ratio is plotted for several scan points
- The intersection is then computed using a linear fit
# CMS results (table)

<table>
<thead>
<tr>
<th>$q^2$ (GeV$^2$)</th>
<th>Signal yield</th>
<th>$P_1$</th>
<th>$P'_5$</th>
<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00–2.00</td>
<td>80 ± 12</td>
<td>+0.12$^{+0.46}_{-0.47}$ ± 0.10</td>
<td>+0.10$^{+0.32}_{-0.31}$ ± 0.07</td>
<td>−0.0526</td>
</tr>
<tr>
<td>2.00–4.30</td>
<td>145 ± 16</td>
<td>−0.69$^{+0.58}_{-0.27}$ ± 0.23</td>
<td>−0.57$^{+0.34}_{-0.31}$ ± 0.18</td>
<td>−0.0452</td>
</tr>
<tr>
<td>4.30–6.00</td>
<td>119 ± 14</td>
<td>+0.53$^{+0.24}_{-0.33}$ ± 0.19</td>
<td>−0.96$^{+0.22}_{-0.21}$ ± 0.25</td>
<td>+0.4715</td>
</tr>
<tr>
<td>6.00–8.68</td>
<td>247 ± 21</td>
<td>−0.47$^{+0.27}_{-0.23}$ ± 0.15</td>
<td>−0.64$^{+0.15}_{-0.19}$ ± 0.13</td>
<td>+0.0761</td>
</tr>
<tr>
<td>10.09–12.86</td>
<td>354 ± 23</td>
<td>−0.53$^{+0.20}_{-0.14}$ ± 0.15</td>
<td>−0.69$^{+0.11}_{-0.14}$ ± 0.13</td>
<td>+0.6077</td>
</tr>
<tr>
<td>14.18–16.00</td>
<td>213 ± 17</td>
<td>−0.33$^{+0.24}_{-0.23}$ ± 0.20</td>
<td>−0.66$^{+0.13}_{-0.20}$ ± 0.18</td>
<td>+0.4188</td>
</tr>
<tr>
<td>16.00–19.00</td>
<td>239 ± 19</td>
<td>−0.53 ± 0.19 ± 0.16</td>
<td>−0.56 ± 0.12 ± 0.07</td>
<td>+0.4621</td>
</tr>
</tbody>
</table>
Fit Bin 1

A. Boletti (Universita & INFN Padova)
Fit Bin 2

A. Boletti (Universita & INFN Padova)

$b \rightarrow s \ell\ell$ at CMS

LHCP 7/6/2018 14 / 30
Fit Bin 3

---

**CMS**

**20.5 fb⁻¹ (8 TeV)**

<table>
<thead>
<tr>
<th>Graph</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Graph" /></td>
<td>Data Total fit Correctly tagged signal Mistagged signal Background</td>
</tr>
<tr>
<td><img src="image2" alt="Graph" /></td>
<td>Data Total fit Correctly tagged signal Mistagged signal Background</td>
</tr>
<tr>
<td><img src="image3" alt="Graph" /></td>
<td>Data Total fit Correctly tagged signal Mistagged signal Background</td>
</tr>
<tr>
<td><img src="image4" alt="Graph" /></td>
<td>Data Total fit Correctly tagged signal Mistagged signal Background</td>
</tr>
</tbody>
</table>

---

**A. Boletti (Universita & INFN Padova)**
Fit Bin 6

A. Boletti (Universita & INFN Padova)
Fit Bin 7 ($\psi'$)

\[ \text{Events / (0.028 GeV)} \]

\[ \text{Events / (0.05)} \]

\[ \text{Events / (0.1)} \]

\[ \text{Events / (0.15708)} \]
Fit Bin 8

---

**Backup (B^0 \rightarrow K^* \mu \mu)**

---

A.Boletti (Universita & INFN Padova)

---

b \rightarrow s\ell \ell at CMS

---

LHCP 7/6/2018 20 / 30
Fit Bin 9

\[ B^0 \rightarrow K^* \mu \mu \]

- **Backup \((B^0 \rightarrow K^* \mu \mu)\)**

- **A. Boletti (Universita & INFN Padova)**

- **b \rightarrow s\ell\ell at CMS**

- **LHCP 7/6/2018 21 / 30**
Anti-radiation cut

The signal sample is required to pass the selection:

- $m(\mu\mu) < m_{\psi}^{\text{PDG}} - 3\sigma_{m(\mu\mu)}$ or
- $m_{\psi}^{\text{PDG}} + 3\sigma_{m(\mu\mu)} < m(\mu\mu) < m_{\psi}^{\text{PDG}} - 3\sigma_{m(\mu\mu)}$ or
- $m(\mu\mu) > m_{\psi}^{\text{PDG}} + 3\sigma_{m(\mu\mu)}$;

for the control channel $B^0 \rightarrow K^{*0}(K^+\pi^-)/\psi'(\mu^+\mu^-)$ the requirement is:

- $|m(\mu\mu) - m_{\psi}^{\text{PDG}}| < 3\sigma_{m(\mu\mu)}$.

while for the $B^0 \rightarrow K^{*0}(K^+\pi^-)/\psi'(\mu^+\mu^-)$ channel is:

- $|m(\mu\mu) - m_{\psi}^{\text{PDG}}| < 3\sigma_{m(\mu\mu)}$.

To further reject feed-through from control channels →

**Events are rejected** if $m(\mu\mu) < m_{\psi}^{\text{PDG}}$, then:

- $|(m(K\pi\mu\mu) - m_{B^0}^{\text{PDG}}) - (m(\mu\mu) - m_{\psi}^{\text{PDG}})| < 160$ MeV/c$^2$;
- $|(m(K\pi\mu\mu) - m_{B^0}^{\text{PDG}}) - (m(\mu\mu) - m_{\psi}^{\text{PDG}})| < 60$ MeV/c$^2$;

while if $m_{\psi}^{\text{PDG}} < m(\mu\mu) < m_{\psi'}^{\text{PDG}}$, then:

- $|(m(K\pi\mu\mu) - m_{B^0}^{\text{PDG}}) - (m(\mu\mu) - m_{\psi}^{\text{PDG}})| < 60$ MeV/c$^2$;
- $|(m(K\pi\mu\mu) - m_{B^0}^{\text{PDG}}) - (m(\mu\mu) - m_{\psi'}^{\text{PDG}})| < 60$ MeV/c$^2$;

and if $m(\mu\mu) > m_{\psi'}^{\text{PDG}}$, then:

- $|(m(K\pi\mu\mu) - m_{B^0}^{\text{PDG}}) - (m(\mu\mu) - m_{\psi}^{\text{PDG}})| < 60$ MeV/c$^2$;
- $|(m(K\pi\mu\mu) - m_{B^0}^{\text{PDG}}) - (m(\mu\mu) - m_{\psi'}^{\text{PDG}})| < 30$ MeV/c$^2$. 
Anti-radiation cut 2

\[ m(K\pi\mu^+\mu^-) \text{ (GeV)} \]

- \( q^2 \text{ bin} \)
- \( 3\sigma \text{ cut} \)
- \( m(K\pi\mu\mu) \& m(\mu\mu) \text{ cut} \)
Backup ($B^0 \rightarrow K^{*0} \mu^+ \mu^-$)

Decay rate

\[ \frac{d^4 \Gamma}{dq^2 d\Omega} = \frac{9}{32\pi} \sum_i I_i \left( q^2 \right) f_i(\Omega) \]

- $\Gamma$ and $\Gamma_{\text{bar}}$: expression of the decay
- $f(\Omega)$: combinations of spherical harmonics
- $I$ and $I_{\text{bar}}$: $q^2$-dependent angular parameters (combinations of six complex decay amplitudes)

Assumptions / simplifications:
- CP-averaged measurement
- Massless limit, i.e. $q^2 \gg 4m^2_\mu$

8 independent angular parameters
Decay rate

Decay rate parameterisation

\[
\frac{d^4\Gamma}{dq^2 d\cos\theta_K d\cos\theta_J d\phi} = \frac{9}{32\pi} \left[ \frac{3}{4} F_L \sin^2\theta_K + F_L \cos^2\theta_K \\
+ \left( \frac{1}{4} F_L \sin^2\theta_K - F_L \cos^2\theta_K \right) \cos 2\theta_J + \frac{1}{2} P_1 F_L \sin^2\theta_K \sin^2\theta_J \cos 2\phi \\
+ \sqrt{F_L F_L'} \left( \frac{1}{2} P_4' \sin 2\theta_K \sin 2\theta_J \sin \phi + P_5' \sin 2\theta_K \sin \theta_J \cos \phi \right) \\
- \sqrt{F_L F_L'} \left( P_6' \sin 2\theta_K \sin \theta_J \sin \phi - \frac{1}{2} P_6' \sin 2\theta_K \sin 2\theta_J \sin \phi \right) \\
+ 2P_2 F_L \sin^2\theta_K \cos\theta_J - P_3 F_L \sin^2\theta_K \sin^2\theta_J \sin 2\phi \right] = \frac{d\Gamma^{4\text{-P-wave}}}{dq^2 d\Omega}
\]

For example \( P_5' = \frac{S_5}{\sqrt{F_L (1 - F_L)}} \)

Two channels can contribute to the final state \( K^+ \pi^- \mu^+ \mu^- \):

- **P-wave** channel, \( K^+ \pi^- \) from the meson vector resonance \( K^{*0} \) decay
- **S-wave** channel, \( K^+ \pi^- \) not coming from any resonance

We have to parametrise both decay rates!

\[
\frac{d\Gamma^{4\text{Total}}}{dq^2 d\Omega} = (1 - F_5) \frac{d\Gamma^{4\text{-P-wave}}}{dq^2 d\Omega} + \frac{d\Gamma^{4\text{S/SP-wave}}}{dq^2 d\Omega}
\]

\[
\frac{d\Gamma^{4\text{S/SP-wave}}}{dq^2 d\Omega} = \frac{3}{16\pi} \left[ F_S \sin^2\theta_J + A_5 \sin^2\theta_K \cos\theta_K + A_5^5 \sin\theta_K \cos 2\theta_K \cos\phi \\
+ A_5^6 \sin\theta_K \sin\theta_J \cos\phi + A_5^7 \sin\theta_K \sin\theta_J \sin\phi + A_5^8 \sin\theta_K \sin 2\theta_J \sin\phi \right]
\]

Both S-wave and S&P wave interference

6 independent parameters

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Efficiency parameterisation - $B^+ \to K^+ \mu \mu$

$\theta$ cos $1 - 0.5 - 0.5 1$

Efficiency (%)

CMS Simulation

$1 < q^2 < 2 \text{ GeV}^2$

$2 < q^2 < 4.3 \text{ GeV}^2$

$4.3 < q^2 < 8.88 \text{ GeV}^2$

$10.3 < q^2 < 12.86 \text{ GeV}^2$

$14.18 < q^2 < 16 \text{ GeV}^2$

$16 < q^2 < 18 \text{ GeV}^2$

$18 < q^2 < 22 \text{ GeV}^2$

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

$1 < q^2 < 22 \text{ GeV}^2$
Fit projections - $B^+ -$candidate mass

- $1 < q^2 < 2 \text{ GeV}^2$
- $2 < q^2 < 4.3 \text{ GeV}^2$
- $4.3 < q^2 < 8.68 \text{ GeV}^2$
- $10.3 < q^2 < 12.86 \text{ GeV}^2$
- $14.18 < q^2 < 16 \text{ GeV}^2$
- $16 < q^2 < 18 \text{ GeV}^2$
- $18 < q^2 < 22 \text{ GeV}^2$
- $1 < q^2 < 6 \text{ GeV}^2$
- $1 < q^2 < 22 \text{ GeV}^2$

Data
Total fit
Signal
Background
Fit projections - $\cos \theta_\ell$

<table>
<thead>
<tr>
<th>CMS</th>
<th>20.5 fb$^{-1}$ (8 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 &lt; q^2 &lt; 2$ GeV$^2$</td>
<td>Data, Total fit, Signal, Background</td>
</tr>
<tr>
<td>$2 &lt; q^2 &lt; 4.3$ GeV$^2$</td>
<td></td>
</tr>
<tr>
<td>$10.3 &lt; q^2 &lt; 12.86$ GeV$^2$</td>
<td></td>
</tr>
<tr>
<td>$14.18 &lt; q^2 &lt; 16$ GeV$^2$</td>
<td></td>
</tr>
<tr>
<td>$18 &lt; q^2 &lt; 22$ GeV$^2$</td>
<td></td>
</tr>
<tr>
<td>$1 &lt; q^2 &lt; 6$ GeV$^2$</td>
<td></td>
</tr>
<tr>
<td>$1 &lt; q^2 &lt; 22$ GeV$^2$</td>
<td></td>
</tr>
</tbody>
</table>

A. Boletti (Università & INFN Padova)

b $\rightarrow$ s$\ell\ell$ at CMS
## Fit results - $B^+ \rightarrow K^+ \mu \mu$

<table>
<thead>
<tr>
<th>$q^2$ (GeV$^2$)</th>
<th>$Y_S$</th>
<th>$A_{FB}$</th>
<th>$F_H$</th>
<th>$F_H$(EOS)</th>
<th>$F_H$(DHMV)</th>
<th>$F_H$(FLAVIO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00–2.00</td>
<td>169 ± 22</td>
<td>0.08 $^{+0.22}_{-0.19}$ ± 0.05</td>
<td>0.21 $^{+0.29}_{-0.21}$ ± 0.39</td>
<td>0.047</td>
<td>0.046</td>
<td>0.045</td>
</tr>
<tr>
<td>2.00–4.30</td>
<td>331 ± 32</td>
<td>$-0.04$ $^{+0.12}_{-0.12}$ ± 0.07</td>
<td>0.85 $^{+0.34}_{-0.31}$ ± 0.14</td>
<td>0.024</td>
<td>0.023</td>
<td>0.022</td>
</tr>
<tr>
<td>4.30–8.68</td>
<td>785 ± 42</td>
<td>0.00 $^{+0.04}_{-0.04}$ ± 0.02</td>
<td>0.01 $^{+0.02}_{-0.01}$ ± 0.04</td>
<td>—</td>
<td>0.012</td>
<td>0.011</td>
</tr>
<tr>
<td>10.09–12.86</td>
<td>365 ± 29</td>
<td>0.00 $^{+0.05}_{-0.05}$ ± 0.05</td>
<td>0.01 $^{+0.02}_{-0.01}$ ± 0.06</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>14.18–16.00</td>
<td>215 ± 19</td>
<td>0.01 $^{+0.06}_{-0.05}$ ± 0.02</td>
<td>0.03 $^{+0.03}_{-0.03}$ ± 0.07</td>
<td>0.007</td>
<td>0.007</td>
<td>0.006</td>
</tr>
<tr>
<td>16.00–18.00</td>
<td>262 ± 21</td>
<td>0.04 $^{+0.05}_{-0.04}$ ± 0.03</td>
<td>0.07 $^{+0.06}_{-0.07}$ ± 0.07</td>
<td>0.007</td>
<td>0.007</td>
<td>0.006</td>
</tr>
<tr>
<td>18.00–22.00</td>
<td>226 ± 20</td>
<td>0.05 $^{+0.05}_{-0.04}$ ± 0.02</td>
<td>0.10 $^{+0.06}_{-0.10}$ ± 0.09</td>
<td>0.008</td>
<td>0.009</td>
<td>0.008</td>
</tr>
<tr>
<td>1.00–6.00</td>
<td>778 ± 47</td>
<td>$-0.14$ $^{+0.07}_{-0.06}$ ± 0.03</td>
<td>0.38 $^{+0.17}_{-0.21}$ ± 0.09</td>
<td>0.025</td>
<td>0.025</td>
<td>0.020</td>
</tr>
<tr>
<td>1.00–22.00</td>
<td>2286 ± 73</td>
<td>0.00 $^{+0.02}_{-0.02}$ ± 0.03</td>
<td>0.01 $^{+0.01}_{-0.01}$ ± 0.06</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
Experiment comparison

![Graphs showing experiment comparison]

- $A_{FB}$ vs $q^2 (GeV^2)$
- $F_H$ vs $q^2 (GeV^2)$

Each graph compares data from CMS and LHCb, with CMS data marked as CMS 20.5/fb and LHCb data marked as LHCb 1/fb and LHCb 3/fb.