Angular analyses at CMS

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FCNC process $b \rightarrow s \mu^+ \mu^-$

Rare B-decay anomalies and logical possible BSM models

CMS rare B-decay angular analyses

- Angular analysis of the decay: $B^0 \rightarrow K^*0 \mu^+ \mu^-$

- Angular analysis of the decay: $B^+ \rightarrow K^+ \mu^+ \mu^-$

Summary
**FCNC processes $b \to s \mu^+ \mu^-$**

- The rare decays $B^0(+) \to K^{*0(+)\mu^+\mu^-}$ are $b \to s \mu^+ \mu^-$ flavor-changing neutral current (FCNC) processes mediated by electroweak loop and box diagrams, and sensitive to physics BSM.

- Clean experimental signature; robust theory calculation; high sensitivity.

\[ H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^* \sum_i C_i O_i + C'_i O'_i + \sum_i \frac{c}{\Lambda_{\text{NP}}^2} O_{\text{NP}} \]

Left handed \quad Right handed, $\frac{m_s}{m_b}$ suppressed

- $i = 1, 2$ \quad Tree
- $i = 3 - 6, 8$ \quad Gluon penguin
- $i = 7$ \quad Photon penguin
- $i = 9, 10$ \quad EW penguin
- $i = S, P$ \quad (Pseudo)scalar penguin

- Effective theory: different processes are sensitive to different operators

<table>
<thead>
<tr>
<th>Operator $O_i$</th>
<th>$B_{s,d} \to X_{s,d} \mu^+ \mu^-$</th>
<th>$B_{s,d} \to \mu^+ \mu^-$</th>
<th>$B_{s,d} \to X_{s,d} \gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_7 \sim m_b (\bar{s}<em>L \sigma^{\mu\nu} b_R) F</em>{\mu\nu}$</td>
<td>√</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>$O_9 \sim (\bar{s}<em>L \gamma^\mu b_L) (\bar{\ell}</em>\gamma \mu \ell)$</td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>$O_{10} \sim (\bar{s}<em>L \gamma^\mu b_L) (\bar{\ell}</em>\gamma 5 \gamma_{\mu \ell})$</td>
<td></td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>$O_{S,P} \sim (\bar{s} b)<em>{S,P} (\bar{\ell} \ell)</em>{S,P}$</td>
<td>(√)</td>
<td></td>
<td>(√)</td>
</tr>
</tbody>
</table>
The rare B-decay anomalies in recent experimental results.

Possible BSM models

- Heavy \( Z' \) model
- \( SU(2)_L \) singlet or triplet
- \text{arXiv:1403.1269, 1501.00993, 1503.03477, 1611.02703, ...} 
- Leptoquark model
- Spin 0 or 1
- \text{arXiv:01511.01900, 1503.01084, 1704.05835, 1512.01560, 1511.06024, 1408.1627, ...} 
- Other new heavy scalars/vectors also leptoquark possible

LHCb: 2.6\( \sigma \) tension in \([1 - 6] \text{ GeV}^2 \) bin

With the vector coupling \( \Delta C_9 = -1.04 \pm 0.25 \)
Angular analysis: $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- The process can be fully described by the three angles ($\theta_\ell$, $\theta_K$, $\phi$) and the dimuon invariant mass squared $q^2$.
- Robust SM calculation of several angular parameters, $A_{FB}$, $F_L$, $P_1$ and $P_5'$, are available for much of the phase space.
- Discrepancy of the angular parameters vs $q^2$ with respect to SM might be hint of NP.

![Diagram](image)

Angular analysis: $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- Using 20.5 fb$^{-1}$ of 8 TeV pp data taken in 2012
  - Control channels: $B^0 \rightarrow K^{*0} J/\psi (\mu^+ \mu^-)$, $B^0 \rightarrow K^{*0} \psi' (\mu^+ \mu^-)$
- Two channels can contribute to the final state $K^+ \pi^- \mu^+ \mu^-$:
  - **P-wave** resonant channel, $K^+ \pi^-$ from the meson vector resonance $K^{*0}$ decay;
  - **S-wave** non-resonant channel, $K^+ \pi^-$ don’t come from any resonance.

Folding the p.d.f. around $\phi = 0$ and $\theta_\ell = \pi/2$.

\[
\frac{1}{d\Gamma /dq^2 dq^2 d\cos \theta_\ell d\cos \theta_K d\phi} = \frac{9}{8\pi} \left\{ \frac{2}{3} \left[ (F_S + A_S \cos \theta_K) (1 - \cos^2 \theta_\ell) + A_S^5 \sqrt{1 - \cos^2 \theta_K} \right] \right. \\
\left. \sqrt{1 - \cos^2 \theta_\ell \cos \phi} + (1 - F_S) \left[ 2F_L \cos^2 \theta_K (1 - \cos^2 \theta_\ell) \right. \\
\left. + \frac{1}{2} (1 - F_L) (1 - \cos^2 \theta_K) (1 + \cos^2 \theta_\ell) + \frac{1}{2} P_1 (1 - F_L) \right] \left. \right. \\
\left. (1 - \cos^2 \theta_K)(1 - \cos^2 \theta_\ell) \cos 2 \phi + 2P_5' \cos \theta_K \sqrt{F_L (1 - F_L)} \right. \\
\left. \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta_\ell \cos \phi} \right] \}
\]

- $F_L, F_S, A_S$: fixed from previous CMS measurement \cite{Phys.Lett.B 753 (2016) 424}
- $P_1, P_5'$: recently measured parameters
- $A_S^5$: nuisance parameter
The pdf and efficiency

- The probability density function and efficiency

\[
p.d.f.(m, \theta_K, \theta_l, \phi) = \left[ Y_S^C \right] S^C(m) S^a(\theta_K, \theta_l, \phi) \epsilon^C(\theta_K, \theta_l, \phi) \]

\[
+ \left[ \frac{f_M}{1-f_M} \right] S^M(m) S^a(-\theta_K, -\theta_l, \phi) \epsilon^M(\theta_K, \theta_l, \phi) \]

\[
+ Y_B B^m(m) B^{\theta_K}(\theta_K) B^{\theta_l}(\theta_l) B^\phi(\phi).
\]

- **Signal** contribution: mass shape (double Gaussian), decay rate, and 3D efficiency function.

- **Background** contribution: mass shape (exponential) and different degrees polynomial functions for each angular variable.

\[ q^2 \text{ bin: } 2 < q^2 < 4.3 \text{ GeV}^2 \]

Correctly tagged events
Fitting and validation

**Fitting strategy:**
- Parameters are extracted from un-binned extended maximum likelihood fit in each bin:
  \[ m(K^+\pi^-\mu^+\mu^-), \cos\theta_\ell, \cos\theta_K, \phi. \]
- Fit performed in two steps:
  1. Fit sidebands to determine angular background shape, fixed in the next step;
  2. Fit whole mass spectrum, 5 free parameters, \( A_5, P_1, P'_1 \), yields.
- Feldman-Cousins method with nuisance parameters.

**Validation with data control channels:**
- Fit performed with \( F_L \) free to float;
- \( F_L \) measured agrees with PDG value.

\[ B^0 \rightarrow K^{*0}J/\psi(\mu^+\mu^-) \]
Fitting result projections

$q^2$ bin: $2 < q^2 < 4.3$ GeV$^2$

![Graphs showing invariant mass and angular distributions for $K^0 \rightarrow K^* \mu^+ \mu^-$]
### Systematic uncertainty

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>$P_1(10^{-3})$</th>
<th>$P'_5(10^{-3})$</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 – 119</td>
</tr>
<tr>
<td>MC statistical uncertainty</td>
<td>29 – 73</td>
<td>31 – 112</td>
</tr>
<tr>
<td>Efficiency</td>
<td>17 – 100</td>
<td>5 – 65</td>
</tr>
<tr>
<td>$K\pi$ 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 – 126</td>
<td>0 – 200</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>2 – 68</td>
<td>0.1 – 12</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>60 – 220</td>
<td>70 – 230</td>
</tr>
</tbody>
</table>

**$F_L, F_S, A_S$ uncertainty propagation:**
- Generate a large data, $\mathcal{O}(100 \times \text{data})$, pseudo experiments (one per $q^2$);
- Fit with all 6 angular parameters free to float;
- Fit with $F_L, F_S, A_S$ fixed;
- Ratio of uncertainties between free and partially-fixed fit is used to compute the systematic uncertainty.
The events are fit in seven $q^2$ bins from 1 to 19 GeV$^2$, yielding 1397 signal events in total.

The measured $P_1$ and $P'_5$ are consistent with the SM predictions and previous measurements within the uncertainties.
Angular analysis: $B^+ \to K^+ \mu^+ \mu^-$

- Using 20.5 fb$^{-1}$ of 8 TeV pp data taken in 2012
  Control channels: $B^+ \to K^+ \eta \psi(\mu^+ \mu^-), B^+ \to K^+ \psi'(\mu^+ \mu^-)$

- The decay for the process $B^+ \to K^+ \mu^+ \mu^-$ can be described by $\cos \theta_\ell$ and $q^2 = m_{\mu^+ \mu^-}^2$

- The differential decay:

$$\frac{1}{\Gamma} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{d \cos \theta_\ell} = \frac{3}{4} (1 - F_H) (1 - \cos^2 \theta_\ell) + \frac{1}{2} F_H + A_{FB} \cos \theta_\ell$$

  \[0 \leq F_H \leq 3, \ |A_{FB}| \leq \min(1, F_H/2)\]

$\theta_\ell$: $\ell = \mu$, the angle between the $\mu^+(\mu^-)$ and the $K^-(K^+)$ in the rest frame of the dimuon system.

$A_{FB}$: $\mu^+\mu^-$ forward-backward asymmetry.

$F_H$: is a measure of the contribution from pseudoscalar, scalar and tensor amplitudes to the decay width $\Gamma$. 

\[
\begin{align*}
\theta_\ell : \ell &= \mu, \text{ the angle between the } \mu^+(\mu^-) \text{ and the } K^-(K^+) \text{ in the rest frame of the dimuon system.} \\
A_{FB} : &\mu^+\mu^- \text{ forward-backward asymmetry.} \\
F_H : &\text{ is a measure of the contribution from pseudoscalar, scalar and tensor amplitudes to the decay width } \Gamma.
\end{align*}
\]
The pdf and efficiency

The probability density function:

\[ \text{pdf}(m, \cos \theta_\ell) = Y_S \cdot S(m) \cdot S(\cos \theta_\ell) \cdot \varepsilon(\cos \theta_\ell) + Y_B \cdot B(m) \cdot B(\cos \theta_\ell) \]

- **Signal** contribution: mass shape (double Gaussian), decay rate, and efficiency function.

- **Background** contribution: mass shape (exponential) and angular variable (3rd or 4th degrees polynomial + a Gaussian function).

**Efficiency:**

- Factorized into an acceptance and a reco-efficiency, for each \(q^2\) bin.

- The signal efficiency \(\varepsilon(\cos \theta_\ell)\) is parametrized with a sixth-order polynomial.

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**Efficiency (%)**

CMS Simulation

| 1 < \(q^2\) < 22 GeV\(^2\) |

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Efficiency (%)

- 0.3
- 0.2
- 0.1

\(\cos \theta_\ell\)

-1
-0.5
0
0.5
1
Fitting and validation

**Fitting strategy:**

- Parameters are extracted from un-binned extended maximum likelihood fit in each bin:
  \[ m(K^+\mu^+\mu^-), \cos\theta_\ell \]
- Fit performed in two steps:
  1) Fit sidebands to determine background angular shape, fixed in the next step;
  2) Fit whole mass spectrum, 5 free parameters, \( A_{FB}, F_H \), yields and background mass shape parameters.
- Feldman-Cousins method with nuisance parameters

**Validations:**

- with resonant control regions
- with data-like signal MC sample
- with large size of signal MC sample
Projections of $B^+ \rightarrow K^+ \mu^+ \mu^-$
Projections of $\cos\theta_\ell$

- $1 < q^2 < 2$ GeV$^2$
- $2 < q^2 < 4.3$ GeV$^2$
- $4.3 < q^2 < 8.68$ GeV$^2$
- $10.3 < q^2 < 12.86$ GeV$^2$
- $14.18 < q^2 < 16$ GeV$^2$
- $16 < q^2 < 18$ GeV$^2$
- $18 < q^2 < 22$ GeV$^2$
- $1 < q^2 < 6$ GeV$^2$
- $1 < q^2 < 22$ GeV$^2$
The background used to fit the backgrounds can cause the results to change. To evaluate the effect of fitting a sample is assigned as the systematic uncertainty. The specific parametrization of the function without the detector simulation and reconstruction steps, and the standard signal simulation.

For each item, the range indicates the variation of the uncertainty in the signal.

### Table 1: Absolute values of the uncertainty contributions in the measurements of $A_{FB}$ and $F_H$

<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>
The events are fit in seven $q^2$ bins from 1 to 22 GeV$^2$, yielding 2286 signal events in total.

The measured $A_{FB}$ and $F_H$ show good agreement with the SM predictions within the uncertainties. No clear indication of new physics beyond the SM could be drawn from present results.
Summary

 keer FCNC transitions $b \rightarrow s \mu^+\mu^-$ are good probes of physics beyond standard model.

CMS has carried out the angular analyses of the decays $B^0 \rightarrow K^{*0} \mu^+\mu^-$ and $B^+ \rightarrow K^+ \mu^+\mu^-$. The measurements of $P_1, P'_5, A_{FB}$, and $F_H$ show no significant deviations from SM.

CMS is an ideal environment to study rare $B$-decays, more measurements are being prepared.

More data and future theoretical developments will clarify these anomalies.
Thank you!

Additional materials
A comparison with LHCb measurements

The CMS measurements have a better uncertainty estimation for the range of $q^2 > 14$ GeV$^2$.

Over all, the CMS measurements of $A_{FB}$ and $F_H$ from this angular analysis show good agreement with LHCb measurements within the uncertainty.