Experimental status of $b \rightarrow s(d) \mu^+ \mu^-$ transitions

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Conference on Flavour Physics and CP violation
2020.06.08
FCNC processes $b \rightarrow s(d)\mu^+\mu^-$: golden indirect probes of NP

Effective theory: Different processes are sensitive to different operators

"B anomalies" $\Rightarrow$ flood of NP models

- Sensitive to NP
- Additional suppression occurs through the factor $V_{td}$
- Could constrain $|V_{td}/V_{ts}|$

Clean exp signature; robust theory calc; high sensitivity
LHC experiments for heavy flavor decays

- Unprecedented large datasets
- Flexible triggers
- Large silicon tracking
- Strong magnetic field
- Broad acceptance
- Superb muon systems
- Great complementarity

For both ATLAS and CMS experiments, di muon decays provide a particularly clean signature to trigger on in order to reconstruct quarkonium states. [1] PRL 114, 191802

2020/6/8  FPCP2020  Dayong Wang
The analyzed pp collision datasets

Run 1
\[ \sqrt{s} = 7-8 \text{ TeV} \]
Long Shutdown 1
Run 2
\[ \sqrt{s} = 13 \text{ TeV} \]

LHC delivered pp lumi to ATLAS & CMS

LHCb collected lumi: \(~1\text{fb}^{-1}(7\text{TeV}), \sim2\text{fb}^{-1}(8\text{TeV}), \sim2+3.5\text{fb}^{-1}(13\text{TeV})\)
Flagship $b \rightarrow s \mu^+ \mu^-$ measurements

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ Decay Parameters

Complete description of the decay rate: 11 variables, with physics constraints
Simplified decay rate parameters

With limited statistics, symmetry is usually used to simplify the decay rate parameters.

\[
\frac{1}{\Gamma} \frac{d^3 \Gamma}{d \cos \theta_K d \cos \theta_l dq^2} = \frac{9}{16} \left\{ \frac{2}{3} \left[ F_S + A_S \cos \theta_K \right] (1 - \cos^2 \theta_l) \\
+ (1 - F_S) \left[ 2F_L \cos^2 \theta_K (1 - \cos^2 \theta_l) \\
+ \frac{1}{2} (1 - F_L) (1 - \cos^2 \theta_K) (1 + \cos^2 \theta_l) \\
+ \frac{4}{3} A_{FB} (1 - \cos^2 \theta_K) \cos \theta_l \right] \right\}
\]

- \( F_S \): fraction of S-wave (~few %)
- \( A_S \): interference amplitude
- \( A_{FB} \) and \( F_L \) do not depend on \( \phi \), efficiency nearly constant.

\( F_L \): Fraction of longitudinal polarization of the K*  
\( A_{FB} \): Forward-backward asymmetry of the dilepton system

Example: CMS 2013/2016 parameterization
Early results with reduced parameters

- BaBar: Phys. Rev. D 86 (2012) 032012,
- LHCb (3 fb⁻¹): JHEP 08 (2013) 131

results are in good agreement with the SM predictions
Fitting optimized variables: LHCb

\[ P_1 = \frac{2 S_3}{(1 - F_L)} = A_T^{(2)} \]
\[ P_2 = \frac{2 A_{FB}}{3 (1 - F_L)} \]
\[ P_3 = \frac{-S_9}{(1 - F_L)} \]
\[ P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L (1 - F_L)}} \]
\[ P'_6 = \frac{S_7}{\sqrt{F_L (1 - F_L)}} \]


JHEP 02 (2016) 104
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: CMS $P_1$ and $P_5'$ results

Fit in seven $q^2$ bins from 1 to 19 $GeV^2$, yielding 1397 signal and 1794 bkg evts.

Consistent with SM and previous measurements.

LHCb: JHEP 02 (2016) 104

S-wave and S-P wave interference

P-wave

Based on 8TeV data, 20.3 fb\(^{-1}\)
- Three exclusive bins of q\(^2\) in the range 0.04 to 6.0 GeV\(^2\)
- Yield: 348 signals, 439 bkgs
- Three parameters extracted in each fit
- Compatible with the results of LHCb, CMS, Belle

\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \text{ angular analysis: ATLAS} \]
LHCb 2020 updates

- Analyzed with both $S_i$ basis (8 obs.) and $P_i$ basis (7 obs.)
- Combining Run1 and 2016 datasets with a simultaneous fit
- Angular efficiencies measured in MC with the method of moments
- S-wave included in the fit function, with the S-P interference as well

Fitting and uncertainties

Still statistical error dominating

<table>
<thead>
<tr>
<th>Source</th>
<th>$F_L$</th>
<th>$S_3-S_9$</th>
<th>$P_{1-P_8}$</th>
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<tbody>
<tr>
<td>Acceptance stat. uncertainty</td>
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<td>&lt; 0.01</td>
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<td>Acceptance polynomial order</td>
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<td>Data-simulation differences</td>
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<td>&lt; 0.01</td>
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<tr>
<td>Acceptance variation with $q^2$</td>
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<td>&lt; 0.01</td>
<td>&lt; 0.09</td>
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<tr>
<td>$m(K^+\pi^-)$ model</td>
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<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
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<tr>
<td>Background model</td>
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<td>&lt; 0.01</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td>Peaking backgrounds</td>
<td>&lt; 0.01</td>
<td>&lt; 0.02</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td>$m(K^+\pi^-\mu^+\mu^-)$ model</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
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<tr>
<td>$K^+\mu^+\mu^-$ veto</td>
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<tr>
<td>Trigger</td>
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<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Bias correction</td>
<td>&lt; 0.02</td>
<td>&lt; 0.01</td>
<td>&lt; 0.03</td>
</tr>
</tbody>
</table>

- Acceptance: change of efficiency functions
- Peaking BG: reflections
- bias correction: due to boundaries
LHCb 2020: fitting results

LHCb Run 1 + 2016

\( F_1 \)

\( q^2 [\text{GeV}^2/c^4] \)

\( A_{FB} \)

\( q^2 [\text{GeV}^2/c^4] \)

\( S_4 \)

\( q^2 [\text{GeV}^2/c^4] \)

\( S_5 \)

\( q^2 [\text{GeV}^2/c^4] \)

SM from ASZB
LHCb 2020: updated tensions

- Tension is confirmed with 2016 data
- Local tension in $P_5'$: $2.5\sigma / 2.9\sigma$
- Global tension slightly increases
- The exact significance depends on the nuisance parameters and $q^2$ bins
Prospects for HL-LHC

- Yields of fully reconstructed $B^0 \to K^{*0} \mu^+ \mu^-$ decays: LHCb: 440k, CMS: 700k
- Precise determination of the angular observables in narrow bins of $q^2$ or using a $q^2$-unbinned approach

CMS-PAS-FTR-18-033

LHCB-PUB-2018-009

ATL-PHYS-PUB-2019-003
Other $b \to s \mu^+ \mu^-$ measurements

\[ B_s^0 \to \Phi \mu^+ \mu^- \]
\[ \Lambda_b \to \Lambda \mu^+ \mu^- \]
\[ B^+ \to K^+ \mu^+ \mu^- \]
\[ B^0 \to K_s^0 \mu^+ \mu^- \]
$B_s^0 \to \Phi \mu^+ \mu^-$

$\Lambda_b \to \Lambda \mu^+ \mu^-$

JHEP 06 (2015) 115

JHEP 09 (2015) 179

JHEP 09 (2018) 146

3fb$^{-1}$

5fb$^{-1}$

LHCb

angular observables
The differential decay rate of the $B^+ (B^-)$ decay, as a function of $\cos \theta_l$, can be written as:

$$
\frac{1}{\Gamma} \frac{d\Gamma[B^+ \rightarrow K^+ \mu^+ \mu^-]}{d \cos \theta_l} = \frac{3}{4} (1 - F_H)(1 - \cos^2 \theta_l) + \frac{1}{2} F_H + \mathcal{A}_{FB} \cos \theta_l
$$

$$
0 \leq F_H \leq 3, \quad |\mathcal{A}_{FB}| \leq \min(1, \ F_H/2)
$$

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

$\mathcal{A}_{FB}$ : $\mu^+ \mu^-$ forward-backward asymmetry.

$F_H$ : the contribution from (pseudo)scalar and tensor amplitudes to the decay width.
**$K\mu^+\mu^-$: LHCb angular analyses**

- Results agree with SM
- $1\text{fb}^{-1}$ Differential BF result is below prediction
  - JHEP 02 (2013) 105
- Deviation from LFU
  - r.f. Mick’s talk

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**JHEP 05 (2014) 082**

- **$B^+ \rightarrow K^+ \mu^+\mu^-$**
- **$B^0 \rightarrow K_s^0 \mu^+\mu^-$**

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<table>
<thead>
<tr>
<th>$F_H$</th>
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<tbody>
<tr>
<td>1.5</td>
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<table>
<thead>
<tr>
<th>$A_{FB}$</th>
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<tbody>
<tr>
<td>0.2</td>
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<table>
<thead>
<tr>
<th>$q^2$ [GeV$^2$/c$^4$]</th>
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<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>20</td>
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</tbody>
</table>

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Dayong Wang
\[ \text{PDF}(m, \theta_l) = Y_S \cdot S(m) \cdot S(\theta_l) \cdot \varepsilon(\theta_l) + Y_B \cdot B(m) \cdot B(\theta_l) \]

The measured \( A_{FB} \) and \( F_H \) show good agreement with the SM predictions within the uncertainty.

No clear indication of new physics beyond the SM could be drawn from present results.
Global fits: try to be model-indep

\[ C_{9\mu}^{\text{NP}} = -C_{9'\mu}, \quad C_{10\mu}^{\text{NP}} = C_{10'\mu}. \]

"For the first time, the NP hypothesis is preferred over the SM by 5 \sigma in a general case when NP can enter SM-like operators and their chirally-flipped partners" [1]

"we confirm the presence of a sizeable discrepancy between data and SM predictions...The data can be consistently described by new physics in the form of a four-fermion contact interaction...[2]

The $b \rightarrow d \mu^+ \mu^-$ measurements

$B_s^0 \rightarrow \bar{K}^*0 \mu^+ \mu^-$

$\Lambda_b \rightarrow p \pi^- \mu^+ \mu^-$

$B^+ \rightarrow \pi^+ \mu^+ \mu^-$
Evidence for $B_s^0 \to \bar{K}^0 \mu^+ \mu^-$

\[ \text{BF} = [2.9\pm1.0\text{(stat)}\pm0.2\text{(syst)}\pm0.3\text{(norm)}] \times 10^{-8} \]

JHEP 07 (2018) 020
$\Lambda_b \to p \pi^- \mu^+ \mu^-$

\[
\frac{B(\Lambda_b^0 \to p\pi^-\mu^+\mu^-)}{B(\Lambda_b^0 \to J/\psi(\to \mu^+\mu^-)p\pi^-)} = 0.044 \pm 0.012 \pm 0.007
\]

JHEP04 (2017) 029

3fb$^{-1}$
$B^+ \rightarrow \pi^+ \mu^+ \mu^-$

$B(B^\pm \rightarrow \pi^\pm \mu^+ \mu^-) = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$

LHCb

Candidates / (10 MeV/c$^2$)

Candidates / (30 MeV/c$^2$)

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

$B^+ \rightarrow K^+ \mu^+ \mu^- X$

Combinatorial

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

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

$B^+ \rightarrow \bar{D}^0 \mu^+ \nu$

$B^0 \rightarrow \rho^0 \mu^+ \mu^-$

$B^0_s \rightarrow f_0 \mu^+ \mu^-$

Combinatorial

$B(B^\pm \rightarrow \pi^\pm \mu^+ \mu^-) = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$

JHEP 10 (2015) 034

LHCb

$dB/dq^2 (10^9 \text{ GeV}^2 c^4)$

LHCb

$0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad 10 \quad 11 \quad 12 \quad 13 \quad 14 \quad 15 \quad 16 \quad 17 \quad 18 \quad 19 \quad 20$

$q^2 (\text{GeV}^2 c^4)$
$B^+ \rightarrow \pi^+ \mu^+ \mu^-$

\[ \mathcal{A}_{CP} = \frac{\Gamma(B^- \rightarrow \pi^- \mu^+ \mu^-) - \Gamma(B^+ \rightarrow \pi^+ \mu^+ \mu^-)}{\Gamma(B^- \rightarrow \pi^- \mu^+ \mu^-) + \Gamma(B^+ \rightarrow \pi^+ \mu^+ \mu^-)} \]

\[ \mathcal{A}_{CP}(B^{\pm} \rightarrow \pi^{\pm} \mu^+ \mu^-) = -0.11 \pm 0.12 \pm 0.01 \]

JHEP 10 (2015) 034
Summary and outlook

- FCNC transitions $b \rightarrow s(d)\mu^+\mu^-$ are good probes of physics beyond standard model

- ATLAS, CMS & LHCb has performed extensive studies of these processes. Results with partial Run-II data emerging
  - Differential and total BFs
  - Angular analysis or angular moments
  - CP and other asymmetries

- More and updated analyses based on full Run-II data and beyond
  - To bring more and updated info ... Stay tuned!

Thanks for Your Attention