Rare decays at LHCb

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On behalf of the LHCb experiment

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Rare decays as a probe for New Physics

SM: Flavour changing neutral currents only occur at loop-level

\[ b \rightarrow s l^+ l^- \] transitions give a unique glimpse to higher scale:

[\text{e.g.} enhancement/suppression of decay rate, angular distributions and new sources of CP violation]

New particles can contribute at loop and/or tree level.
Flavour change neutral current processes

Rare $b$ decays are a multi-scale problem: $\Lambda_{NP}^2 \gg m_W \gg m_b > \Lambda_{QCD}$

FCNC effective hamiltonian described as operator product expansion

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$$

**Wilson coefficients** ("effective coupling")

**Local operator**

$$\mathcal{H}_{NP} = \frac{\kappa}{\Lambda_{NP}^2} O_i$$

**NP scale**

**Flavour-violating coupling**

Sensitivity to Wilson coefficients

$$B^0_{(s)} \rightarrow l^+ l^-$$

$$b \rightarrow s l^+ l^-$$

$$[C_{10}, C_S, C_P]$$

$$[C_7, C_9, C_{10}]$$
This talk covers some recent results related to $b \rightarrow s l^+l^-$ transitions at LHCb

- Angular analyses of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ and $B^0_s \rightarrow \phi\mu^+\mu^-$ decays with 3 fb$^{-1}$ dataset
  

- Measurements of differential branching fractions of $B \rightarrow K^{(*)}\mu^+\mu^-$, $B^0_s \rightarrow \phi\mu^+\mu^-$ and $\Lambda^0_b \rightarrow \Lambda\mu^+\mu^-$
  
  [Previous results + LHCb-PAPER-016-012, to be submitted to JHEP]

- Remark: Lepton flavour universality tests are covered in a dedicated talk
  
  [see B. Hamilton’s talk]

[3 fb$^{-1}$ Run-I (2011/12) at 7/8 TeV]
[Expect around 5 fb$^{-1}$ Run-II at 13 TeV]
First observation of $B^0_s \rightarrow \mu^+\mu^-$

Clean theoretical prediction, GIM and helicity suppressed in SM

\[ \mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9} \]
\[ \mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10} \]

C. Bobeth et al., PRL 112, 101801 (2014)

Very sensitive to NP: possible (pseudo) scalar enhancement

ATLAS enters the game!

[see U. De Sanctis]

Precision for $B^0(s) \rightarrow \mu^+\mu^-$ can be improved with Run-II dataset

\[ \mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (2.8_{-0.6}^{+0.7}) \times 10^{-9} \]
Significance of 6.2\(\sigma\) and compatible with SM at 1.2\(\sigma\)

\[ \mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (3.9_{-1.4}^{+1.6}) \times 10^{-10} \]
Significance of 3.0\(\sigma\) and compatible with SM at 2.2\(\sigma\)
Angular analyses using $b \to sll$ transitions

[sensitivity to $C_7, C_9, C_{10}$]

LHCb results: $\mathcal{L} = 3 \text{ fb}^{-1} - 2011 + 2012$ dataset

Angular analysis of the $B^0 \to K^{*0}[K^+\pi^-]\mu^+\mu^-$

[JHEP 02 (2016) 104]

Angular analysis of the $B^0_s \to \phi[K^+K^-]\mu^+\mu^-$

[JHEP 09 (2015) 179]
The rare decay $B^0 \rightarrow K^{*0}[K^+\pi^-]\mu^+\mu^-$

Large number of observables: BF fractions, CP asymmetries and angular observables (5-dimension)

Sensitive to several $q^2$ regimes: e.g. new vector or axial-vector currents and virtual photon polarisation

Reconstructed as a four track final state, i.e. kaon, pion and di-muon

$J/\psi(1S)$

Tree level: $b \rightarrow c\bar{c}s$

$\psi(2S)$

$C_7^{(t)}C_9^{(t)}$ interference

$C_9^{(t)}$ and $C_{10}^{(t)}$

Long distance contributions from $c\bar{c}$ above open charm threshold

$4[m(\mu)]^2$

di-muon invariant mass squared, $q^2$
The rare decay $B^0 \rightarrow K^{*0}[K^+\pi^-]\mu^+\mu^-$

Decay fully described by three helicity angles

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_k + F_L \cos^2 \theta_k \right.$$ 

$$+ \frac{1}{4} (1 - F_L) \sin^2 \theta_k \cos 2\theta_l$$ 

Fraction of longitudinal polarisation of the $K^*$

$$-F_L \cos^2 \theta_k \cos 2\theta_l + S_3 \sin^2 \theta_k \sin^2 \theta_l \cos 2\phi$$ 

Forward-backward asymmetry of the dilepton system

$$+ S_4 \sin 2\theta_k \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_k \sin \theta_l \cos \phi$$ 

$$+ \frac{4}{3} A_{FB} \sin^2 \theta_k \cos \theta_l + S_7 \sin 2\theta_k \sin \theta_l \sin \phi$$ 

$$+ S_8 \sin 2\theta_k \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_k \sin 2\theta_l \sin 2\phi$$

- $F_L$, $A_{FB}$ and $S_i$ are combinations of $K^{*0}$ spin amplitudes sensitive to $C_7^{(*)}$, $C_9^{(*)}$, $C_{10}^{(*)}$ and form factors

- S-wave pollution is also taken into account $\rightarrow$ additional observable
The $B^0 \rightarrow K^*[0][K^+\pi^-]\mu^+\mu^-$ signal

Vetoes in the $q^2$ range to reduce contamination from tree level decays 

$[8.0, 11.0] \cup [12.5, 15.0]$ GeV$^2$

Signal decay clearly visible as vertical band after the full selection

$LHCb, JHEP 02 (2016) 104$
First full angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

Simultaneously fit to $m_{K\pi\mu\mu}$ and $m_{K\pi}$ masses to constrain S-wave fraction

Observables determined in each bin using the LH fit of decay angles
$B^0 \rightarrow K^{*0}\mu^+\mu^-$ fit results $[F_L, A_{FB}, S_5]$

Full set of CP-averaged angular terms [+correlations] and CP-asymmetries

In general a good agreement with the SM predictions is observed

Mild tension with $A_{FB}$ and some tension in $S_5$
Consider ratios of observables where leading form-factor uncertainties cancel, e.g.:

\[ P_5' = \frac{S_5}{\sqrt{F_L(1 - F_L)}} \]

[S. Descotes-Genon et al. JHEP 1204 (2012) 104]

Preliminary results from Belle confirmed tension seen in LHCb

NB: CMS/ATLAS could also measure \( P_5' \) (e.g. CMS: \(~345\) signal events in [1.0, 6.0] GeV\(^2\) bin - 50\% of the LHCb yield, slightly lower S/B)

Local tension with SM predictions (2.8 and 3.0\( \sigma \))

Global analysis finds deviation corresponding to 3.4\( \sigma \)
Moments analysis and zero crossing points

Angular observables can also be obtained using principal moments

Robust estimator even for small datasets (allows us to bin more finely in $q^2$)

Statistically less precise than the result of the maximum likelihood fit

Zero crossing points determined by parametrising the angular distribution with $q^2$ dependent decay amplitudes

$q_0^2(S_5) \in [2.49, 3.95] \text{ GeV}^2/c^4$ at 68% CL

$q_0^2(A_{FB}) \in [3.40, 4.87] \text{ GeV}^2/c^4$ at 68% CL

SM: $q_0^2(A_{FB}) \sim [3.9, 4.4] \text{ GeV}^2/c^4$

The rare decay $B^0_s \rightarrow \phi[K^+K^-][\mu^+\mu^-]$

Analogous process for the $B^0_s$ system

- Narrow $\phi$ resonance, clean signal extraction (e.g. small number of partially reconstructed background)
- $K^+K^-\mu^+\mu^-$ final state not self-tagging: reduced number of observables
  - $[F_L, S_{3,4,7} \text{ and } A_{5,6,8,9} \text{ - compatible with SM}]$

- $\text{BF for } B^0_s \rightarrow \phi[\mu^+\mu^-] \text{ shows some tension}$

$F_{L}$

$B^0_s \rightarrow \phi\mu^+\mu^-$ shows some tension

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R. Coutinho (UZH) - Barcelona workshop
Measurements of differential branching fractions

LHCb results: $\mathcal{L} = 3\text{ fb}^{-1}$ – 2011 + 2012 dataset

An intriguing set of results: $B^0 \rightarrow K^{(*)}\mu^+\mu^-$, $B^0_s \rightarrow \phi\mu^+\mu^-$ and $\Lambda^0_b \rightarrow \Lambda\mu^+\mu^-$

Differential branching fractions

Large LHCb datasets allows for precise measurements of the differential BF

- Results hint towards lower rates than predicted by theory

[Theory uncertainty are correlated across the squared di-muon mass ($q^2$)]

**LHCb, JHEP 06 (2014) 133**

Bobeth et al [JHEP07(2011)067]
Bouchard et al [1310.3207] and Horgan et al [PRL112,212003(2014)]
Differential branching fractions

Similar experiment/theory disagreement seen in other channels

\[ [B_0^s \rightarrow \phi \mu^+\mu^-]: 1.1 < q^2 < 6.0 \text{ GeV}^2 \text{ is } 3.3\sigma \text{ from SM} \]

All branching fraction measurements potentially point to new physics in C_9

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R. Coutinho (UZH) - BEACH 2016
Differential BF of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

Analysis performed using 2011 $1 fb^{-1}$ LHCb dataset

$m^2_{K\pi} \in [796, 996] \text{ MeV}^2$: dominated by the $K^{*0}(892)$ resonance

- S-wave contribution expected to be bound down to 10%
  
  [e.g. (theory) Becirevic et al (NPB 868 (2013) 368), Dring et al [JHEP 10 (2013) 011]
  
  [e.g. (exp.) LHCb [JHEP08(2013)131]

- S-wave pollution addressed in the systematics uncertainties

$0.1 < q^2 < 19 \text{ GeV}^2 : F_S = 0.03 \pm 0.03$

$F_S$ could scale the BF up to 7%
Differential BF of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ (3 fb$^{-1}$)

Update of the differential BF (finer $q^2$ binning) with the full Run-I dataset

- Determination of the S-wave fraction of the $K^+\pi^-$ system in $B^0 \rightarrow K^+\pi^-\mu^+\mu^-$

Detection efficiency is modelled in terms of orthonormal Legendre polynomials as

$$
\epsilon(q^2, m_{K\pi}, \Omega) = \sum_{i,j,k} c_{i,j,k} P_i(m_{K\pi}) P_j(q^2) P_k(\Omega)
$$

where $\Omega$ is in related to $\cos \theta_K$, $\cos \theta_1$ and $\varphi$

Differential branching fraction measured relative to the decay $B^0 \rightarrow J/\psi K^{*0}$ (reduce possible systematic uncertainties)
Measurement of $F_S$ in $B^0 \rightarrow K^{*0} \mu^+\mu^-$

Determination of $F_S$ is performed through a fit to the kaon helicity angle $\theta_K$ and $m^2_{K\pi}$:

$$m^2_{K\pi} \in [644, 1200] \text{ and } [796, 996] \text{ MeV}^2$$

Explicitly modelling of the $m^2_{K\pi}$ spectrum:

- P-wave [$K^*(892)$]: Relativist BW
- S-wave [i.e. $K^*(1430)$ + NonRes]: LASS

Preliminary LHCb-PAPER-016-012, to be submitted to JHEP
Differential BF of $B^0 \to K^{*0}\mu^+\mu^-$

**First** exclusive measurement of the differential BF of $B^0 \to K^{*}(892)^0\mu^+\mu^-$

\[
\frac{dB[B^0 \to K^{*}(892)^0\mu^+\mu^-]}{dq^2} = \frac{R_\epsilon}{q^2_{max} - q^2_{min}} \left(1 - F_S|_{1200}^{1200}\right) \frac{N_{K^{*0}\mu\mu}}{N_{J/\psi K^{*0}}} B(B^0 \to J/\psi K^{*0}) B(J/\psi \to \mu^+\mu^-)
\]

Results compatible both with SM predictions and new physics scenarios hinted by $R_K$ and other $b \to sll$ branching fractions

Measurements of the S-wave fraction are compatible with theory predictions and previous estimations

Bharucha et al [1503.05534]
Global fits to $b \to s$ data

Several attempts to interpret LHCb data by performing global fits

Consistent picture, data favours modified vector coupling ($C_{NP9} \neq 0$) at $[3,4]\sigma$

Possible interpretations:

- NP physics scenario, *e.g.* vector-like contribution could come from new tree level $Z'$ with a mass of a few TeV
- Problem with our understanding of QCD, *e.g.* not properly estimating contribution for charm loops

Understanding requires more data and theoretical work!

Branching fractions, angular observables and combination
General conclusions

- Flavour observables in rare decays allow for NP searches and can place many strong constraints on NP models

- Some interesting tensions seen in data on $b \rightarrow s l^+l^-$ processes, e.g. $B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular observables, $B^0_s \rightarrow \phi\mu^+\mu^- \text{BF, R}_K$

- Still many interesting results are foreseen with LHCb Run-I dataset
  - Significant effort ongoing to extend these measurements (i.e. angular and BF) to $b \rightarrow s e^+e^-$ transitions, e.g. final states with $\phi$, $K^{*0}$ and $\Lambda^{(*)}$
  - Understand the effect of $c\bar{c}$ resonances by measuring the interference of resonant and penguin contributions in $B^+ \rightarrow K^+\mu^+\mu^-$
  - Angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu$ with higher $K^{*0}$ states (SPD)

- Run-II data will boost precision even further!
\[ B^0 \rightarrow K^{*0}\mu^+\mu^- \text{ likelihood fit} \]

First determination of all eight CP-averaged observables in a single fit: allow to quote correlation matrix to include in global fits

Perform likelihood fit to the decay angles and \( m_{K\pi\mu\mu} \) in \( q^2 \) bins, simultaneously fitting \( m_{K\pi} \) to constraint \( F_S \)

\[
\log L = \sum_i \log [\epsilon (\Omega, q^2) \mathcal{P}(\Omega) \mathcal{P}_{\text{sig}}(m_{K\pi\mu\mu})] \\
+ (1 - f_{\text{sig}}) \mathcal{P}_{\text{bkg}}(\Omega) \mathcal{P}_{\text{bkg}}(m_{K\pi\mu\mu})] \\
+ \sum_i \log [f_{\text{sig}} \mathcal{P}_{\text{sig}}(m_{K\pi}) + (1 - f_{\text{sig}}) \mathcal{P}_{\text{bkg}}(m_{K\pi})]
\]

\( \mathcal{P}_{\text{sig}} \) is given by \( \frac{1}{d(\Gamma + \tilde{\Gamma})} \frac{d^3(\Gamma + \tilde{\Gamma})}{d\tilde{\Omega}} \)  

Background term is modelled by a 2\textsuperscript{nd} order Chebychev polynomials
\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \text{ angular distribution} \]

The differential branching fraction is given by

\[
\frac{d^4 \Gamma[\bar{B}^0 \rightarrow K^{*0} \mu^+ \mu^-]}{dq^2 \, d\Omega} = \frac{9}{32\pi} \sum_i I_i(q^2) f_i(\Omega)
\]

\[
\frac{d^4 \bar{\Gamma}[B^0 \rightarrow K^{*0} \mu^+ \mu^-]}{dq^2 \, d\Omega} = \frac{9}{32\pi} \sum_i \bar{I}_i(q^2) f_i(\Omega)
\]

The CP-averaged and CP-asymmetry obs.:

\[
S_i = (I_i + \bar{I}_i) \bigg/ \left( \frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2} \right)
\]

\[
A_i = (I_i - \bar{I}_i) \bigg/ \left( \frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2} \right)
\]

\[
F_L = S_{1c} = \frac{|A_0^L|^2 + |A_0^R|^2}{|A_0^L|^2 + |A_0^R|^2 + |A|^2 + |A|^2 + |A|^2 + |A|^2}
\]
\[ I_1^\parallel = \frac{(2 + \beta_\mu^2)}{4} \left[ |A_\perp|^2 + |A_\parallel|^2 + (L \to R) \right] + \frac{4m_\mu^2}{q^2} \Re(A_\perp A_\perp^* + A_\parallel A_\parallel^*) \]

\[ I_1^\perp = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\mu^2}{q^2} \left[ |A_t|^2 + 2\Re(A_0^L A_0^R^*) \right] \]

\[ I_2^\perp = \frac{\beta_\mu^2}{4} \left\{ |A_\perp|^2 + |A_\parallel|^2 + (L \to R) \right\} \]

\[ I_2^\parallel = -\beta_\mu^2 \left\{ |A_0^L|^2 + (L \to R) \right\} \]

\[ I_3^\perp = \frac{\beta_\mu^2}{2} \left\{ |A_\perp|^2 - |A_\parallel|^2 + (L \to R) \right\} \]

\[ I_3^\parallel = \frac{\beta_\mu^2}{\sqrt{2}} \left\{ \Re(A_0^L A_\parallel^*) + (L \to R) \right\} \]

\[ I_5^\parallel = \sqrt{2}\beta_\mu \left\{ \Re(A_0^L A_\perp^*) - (L \to R) \right\} \]

\[ I_6 = 2\beta_\mu \left\{ \Re(A_\parallel A_\perp^*) - (L \to R) \right\} \]

\[ I_7 = \sqrt{2}\beta_\mu \left\{ \Re(A_0^L A_\parallel^*) - (L \to R) \right\} \]

\[ I_8 = \frac{\beta_\mu^2}{\sqrt{2}} \left\{ \Re(A_0^L A_\perp^*) + (L \to R) \right\} \]

\[ I_9 = \beta_\mu^2 \left\{ \Re(A_\parallel A_\perp^*) + (L \to R) \right\} \]

\[ A_\perp^{L(R)} = N\sqrt{2}\lambda \left\{ \left[ (C_9^{\text{eff}} + C_9^{\text{eff}}) \mp (C_{10}^{\text{eff}} + C_{10}^{\text{eff}}) \right] \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} \left( C_7^{\text{eff}} + C_7^{\text{eff}} \right) T_1(q^2) \right\} \]

\[ A_\parallel^{L(R)} = -N\sqrt{2}(m_B^2 - m_{K^*}^2) \left\{ \left[ (C_9^{\text{eff}} - C_9^{\text{eff}}) \mp (C_{10}^{\text{eff}} - C_{10}^{\text{eff}}) \right] \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} \left( C_7^{\text{eff}} - C_7^{\text{eff}} \right) T_2(q^2) \right\} \]

\[ A_0^{L(R)} = -\frac{N}{2m_{K^*}\sqrt{q^2}} \left\{ \left[ (C_9^{\text{eff}} - C_9^{\text{eff}}) \mp (C_{10}^{\text{eff}} - C_{10}^{\text{eff}}) \right] \left[ (m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*}) A_1(q^2) - \lambda \frac{A_2(q^2)}{m_B + m_{K^*}} \right] \right\} + 2m_b \left( C_7^{\text{eff}} - C_7^{\text{eff}} \right) \left[ (m_B^2 + 3m_{K^*}^2 - q^2) T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2} T_3(q^2) \right] \]
\( B^0 \rightarrow K^{*0} \mu^+ \mu^- \) S-wave pollution

S-wave contribution comes from other \( K^{*0} \) resonances with spin-0 configuration, e.g. \( K^{*0}(1430) \)

Introduce two additional decay amplitudes that result in six additional observables

\[
\frac{1}{d(\Gamma + \Gamma)/dq^2} \frac{d^3(\Gamma + \Gamma)}{d\Omega} \bigg|_{S+P} = (1 - F_S) \frac{1}{d(\Gamma + \Gamma)/dq^2} \frac{d^3(\Gamma + \Gamma)}{d\Omega} \bigg|_P \\
+ \frac{3}{16\pi} F_S \sin^2 \theta_I + S-P \text{ interference}
\]

Determination of \( F_S \) is performed by considering explicitly \( m_{K\pi} \)

- P-wave \([K^*(892)]\): Relativist BW
- S-wave \([i.e. \ K^*(1430) + \text{NonRes}]\): LASS
B^0 \rightarrow K^{*0}\mu^+\mu^- \text{ angular acceptance}

![Graphs showing relative efficiency with different ranges of 
\[ 0.1, 1.0 \text{ GEV}^2/c^4 \text{ and } 18.0, 19.0 \text{ GEV}^2/c^4 \text{ for } \cos \theta_K, \cos \theta_l, \text{ and } \phi \text{ with } \cos \theta_K \text{ and } \cos \theta_l \text{ distributions.}]

Trigger, reconstruction and selection distorts decay angles and q^2 distributions

Parametrise 4D distribution using Legendre polynomials

\[ \epsilon(\cos \theta_K, \cos \theta_l, \phi, q^2) = \sum_{i,j,m,n} P_i(\cos \theta_K)P_j(\cos \theta_l)P_m(\phi)P_n(q^2) \]

Coefficients determined from moments analysis of phase-space simulation of K^{*0}\mu^+\mu^-, cross-check with J/\psi K^{*0} data
# $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$F_L$</th>
<th>$S_{3-9}$</th>
<th>$A_{3-9}$</th>
<th>$P_{1-P'}$</th>
<th>$q_0^2$ GeV$^2$/c$^4$</th>
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<td>–</td>
<td>&lt; 0.01</td>
<td>&lt; 0.02</td>
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</tr>
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</table>

- Systematic uncertainties determined using high statistics toy simulations
- Measurement is statistically dominated (and will still be in Run-II)
$B^0 \rightarrow K^{*0}\mu^+\mu^-$ fit results [$F_L$, $S_3$, $S_4$, $S_5$]

LHCb, JHEP 02 (2016) 104
$B^0 \rightarrow K^{*0}\mu^+\mu^-$ fit results [$A_{FB}$, $S_7$, $S_8$, $S_9$]

$LHCb, JHEP 02 (2016) 104$
B^0 \rightarrow K^{*0}\mu^+\mu^- fit results [A_3, A_4, A_5, A_{6s}]

LHCb, JHEP 02 (2016) 104
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ fit results [$A_7$, $A_8$, $A_9$]
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ fit results $[P_1, P_2, P_3, P_4]$
$B^0 \rightarrow K^*_0 \mu^+ \mu^-$ fit results $[P'_5, P'_6, P'_8]$
B^0 \rightarrow K^{*0}\mu^+\mu^- moments analysis

Angular terms $f_i(\Omega)$ are orthogonal
\rightarrow can determine obs. via their moments $\hat{M}_i = \frac{1}{\sum_e w_e} \sum_e w_e f_i(\Omega_e)$

10-30\% less sensitive than Maximum Likelihood fit [F. Beaujean et al., PRD 91 (2015) 114012]
but allows narrow 1 GeV^2/c^4 wide $q^2$ bins

Consistency of the results checked using toys
\( B^0 \rightarrow K^{*0} \mu^+ \mu^- \) compatibility with the SM

\[ \chi^2 \] fit performed of measured \( S_i \) observables sing [EOS] package

Best fit found to be \( \Delta \text{Re}(C_9) = 1.04 \pm 0.25 \). MoM fit obtains \( \Delta \text{Re}(C_9) = 0.68 \pm 0.35 \) which is statistically compatible with the nominal model.
B^0 \rightarrow K^*0 \mu^+ \mu^- differential branching fraction

The differential decay rate is given by

\[
\frac{d^5(\Gamma + \Gamma)}{dm_{K^\pi} dq^2 d\Omega^f} = \frac{1}{4\pi} G_S |f_{\text{LASS}}(m_{K^\pi})|^2 (1 - \cos 2\theta_f) + \\
\frac{3}{4\pi} G_P^0 |f_{\text{BW}}(m_{K^\pi})|^2 \cos^2 \theta_K (1 - \cos 2\theta_f) + \\
\frac{\sqrt{3}}{2\pi} \text{Re} \left[ (G_{\text{SP}}^R + iG_{\text{SP}}^I) f_{\text{LASS}}(m_{K^\pi}) f_{\text{BW}}^*(m_{K^\pi}) \right] \cos \theta_K (1 - \cos 2\theta_f) + \\
\frac{9}{16\pi} G_P^\perp |f_{\text{BW}}(m_{K^\pi})|^2 \sin^2 \theta_K \left(1 + \frac{1}{3} \cos 2\theta_f\right) + \\
\frac{3}{8\pi} S_3 (G_P^0 + G_P^\perp) |f_{\text{BW}}(m_{K^\pi})|^2 \sin^2 \theta_K \sin^2 \theta_f \cos 2\phi + \\
\frac{3}{2\pi} A_{FB} (G_P^0 + G_P^\perp) |f_{\text{BW}}(m_{K^\pi})|^2 \sin^2 \theta_K \cos \theta_f + \\
\frac{3}{4\pi} S_9 (G_P^0 + G_P^\perp) |f_{\text{BW}}(m_{K^\pi})|^2 \sin^2 \theta_K \sin^2 \theta_f \sin 2\phi',
\]

\[
G_S = |A_S^L(q^2)|^2 + |A_S^R(q^2)|^2 + |\bar{A}_S^L(q^2)|^2 + |\bar{A}_S^R(q^2)|^2,
\]

\[
G_{\text{SP}}^R + iG_{\text{SP}}^I = A_S^L A_0^L* + A_S^R A_0^R* + \bar{A}_S^L \bar{A}_0^L* + \bar{A}_S^R \bar{A}_0^R*,
\]

\[
G_P^0 = |A_0^L(q^2)|^2 + |A_0^R(q^2)|^2 + |\bar{A}_0^L(q^2)|^2 + |\bar{A}_0^R(q^2)|^2,
\]

\[
G_P^\perp = \sum_{i=1,\perp} |A_i^L(q^2)|^2 + |A_i^R(q^2)|^2 + |\bar{A}_i^L(q^2)|^2 + |\bar{A}_i^R(q^2)|^2
\]

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Fraction of S-wave

\[
F_{\text{S},a}^b = \frac{G_S \int_a^b dm_{K^\pi} |f_{\text{LASS}}(m_{K^\pi})|^2}{G_S \int_a^b dm_{K^\pi} |f_{\text{LASS}}(m_{K^\pi})|^2 + \left(G_P^0 + G_P^\perp\right) \int_a^b dm_{K^\pi} |f_{\text{BW}}(m_{K^\pi})|^2}
\]

The mass shapes are modelled as

\[
f_{\text{BW}}(m_{K^\pi}) = \sqrt{k} p \left(1 - \frac{k}{k_{892}}\right) \frac{B_1(k, k_{892}, d) B_1'(p, k_{892}, d)}{m_{K^\pi}^2 - m_{892}^2 - i m_{892} \Gamma_{892}(m_{K^\pi})}
\]

\[
f_{\text{LASS}}(m_{K^\pi}) = \sqrt{k} p B_1'(k, k_{1430}, d) \left(1 - \frac{1}{\cot \delta_B - i} + e^{2i\delta_B} \frac{1}{\cot \delta_R - i}\right)
\]