New tests of lepton universality using rare B decays with $K_S$ mesons in the final state at LHCb

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On behalf of the LHCb collaboration

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Sheldon was a true all round physicist, having made major contributions to data analysis, detector construction and phenomenology. He was co-spokesperson of both the CLEO and BTeV Collaborations. He was LHCb Upgrade Coordinator 2008-2011, and a driving force behind the Upstream Tracker.

He had a profound impact on the LHCb physics programme and was a lead proponent of a large number of LHCb Physics papers.

He was a constant innovator and inspiration to all those who knew him. We will greatly miss him.

Our deepest condolences to his wife Marina Artuso, & family.

The paper is dedicated to Sheldon.

Words prepared by Chris Parkes, LHCb Spokesperson.
Why $b \to s\ell^+\ell^-$ decays?

- $b \to s\ell^+\ell^-$ transitions are **flavour-changing neutral current** (FCNC) processes → forbidden at tree level in the Standard Model (SM).
- Supressed in SM (branching fractions $\mathcal{O}(10^{-7}) - \mathcal{O}(10^{-6})$) and hence sensitive to **New Physics** (NP).
- Particles associated with NP quantum fields can have masses above reach of direct searches at LHC.
$b \to s \ell^+ \ell^-$ transitions can be described using an **Effective Field Theory**

- zoom out to $b$ quark scale $\sim 4.8$ GeV
- integrate out short distance (high energy) interactions
- short distance interactions parametrised using **Wilson Coefficients**

**Effective Field Theory of $b \to s \ell^+ \ell^-$**

- $W^+$
- $\gamma/Z^0$
- $u,c,t$
- $\ell^+$
- $\ell^-$

**Longer distances**

- $C_9$ electroweak vector
- $C_{10}$ electroweak axial vector
- $C_7$ electromagnetic
**Effective Field Theory of** $b \rightarrow s \ell^+ \ell^-$

Hamiltonian defined in terms of **Wilson Coefficients** $[C_i^{(r)}]$ and **Operators** $[\mathcal{O}_i^{(r)}]$

\[
\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')
\]

- **Wilson Coefficients** encode short-distance physics (the bit we’re interested in)
- **Operators** describe low-energy QCD (described using **form factors**), which have large theory uncertainties
Several **anomalies** in $b \rightarrow s\ell^+\ell^-$ decays emerged over the past decade:

- **Branching fractions of $b \rightarrow s\mu^+\mu^-$ decays**

  - Multiple measurements are below SM predictions at low dilepton mass squared ($q^2$)
  - SM predictions suffer from large hadronic uncertainties
Several anomalies in $b \rightarrow s \ell^+ \ell^-$ decays emerged over the past decade:

- **Branching fraction of $B_{(s)}^0 \rightarrow \mu^+ \mu^-$ decays**

![Graph showing branching fraction of $B_{(s)}^0 \rightarrow \mu^+ \mu^-$ decays](image-url)

*ATLAS-CONF-2020-049*
Several **anomalies** in $b \rightarrow s \ell^+ \ell^-$ decays emerged over the past decade:

- **Angular analyses:** $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
  - Large number of observables offering complementary information on NP
  - SM uncertainties smaller than for BFs
  - Combined tension between latest LHCb analysis and SM at **3.3 sigma** when floating $Re(C_9)$
  - Extent of hadronic contributions still matter of debate
Several **anomalies** in $b \to s\ell^+\ell^-$ decays emerged over the past decade:

- **Angular analyses**: $B^+ \to K^{*+} \mu^+\mu^-$

  - Combined tension with SM at **3.1 sigma** when floating $Re(C_9)$

*Phys. Rev. Lett. 126 (2021) 161802*
Several **anomalies** in $b \to s \ell^+ \ell^-$ decays emerged over the past decade:

- **Tests of lepton universality**

  In the SM couplings of gauge fields to the three charged leptons ($e, \mu, \tau$) are identical → known as **Lepton Universality**

  Ratios of the form:

  $$ R_H = \frac{\int_{q^2_{\min}}^{q^2_{\max}} d\mathcal{B}(B \to H\mu^+\mu^-) dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} d\mathcal{B}(B \to He^+e^-) dq^2} \cong 1 $$

  in the SM, except for small corrections due to different lepton masses.

  - Hadronic uncertainties (which affect BFs and angular observables) cancel in ratio down to $\mathcal{O}(10^{-4})$ [JHEP 07 (2007) 040]
  - QED corrections up to $\mathcal{O}(10^{-2})$ [EPJC76 (2016) 8, 440], [JHEP 12 (2020) 104]

**Significant deviation from unity unambiguous evidence of New Physics**
Several **anomalies** in $b \to s\ell^+\ell^-$ decays emerged over the past decade:

- **Tests of lepton universality**

  $B^0 \to K^{*0}\ell^+\ell^-$ (3 fb$^{-1}$)

  \[
  R_{K^{*0}} = 0.66^{+0.11}_{-0.07} \text{(stat)} \pm 0.03 \text{(syst)} \quad [0.045 < q^2/\text{GeV}^2 < 1.1]
  \]

  \[
  R_{K^{*0}} = 0.69^{+0.11}_{-0.07} \text{(stat)} \pm 0.05 \text{(syst)} \quad [1.1 < q^2/\text{GeV}^2 < 6.0]
  \]

  2.2–2.5σ deviation from SM in each bin. [IHEP 08 (2017) 55]

  \[
  \Lambda_b \to pK^-\ell^+\ell^- \quad (5 \text{ fb}^{-1})
  \]

  \[
  R_{pK^-} = 0.86^{+0.14}_{-0.11} \text{(stat)} \pm 0.05 \text{(syst)}
  \]

  Agrees with SM at 1σ. [IHEP 05 (2020) 40]

  $B^+ \to K^+\ell^+\ell^-$ (9 fb$^{-1}$)

  \[
  R_{K^+} = 0.846^{+0.042}_{-0.039} \text{(stat)} +^{0.013}_{-0.012} \text{(syst)}
  \]

  **3.1σ deviation** from SM.

  [arxiv: 2103.11769 (submitted to Nature Physics)]
Global Fits

- Combination of all $b \rightarrow s\ell^+\ell^-$ measurements (and $B_s^0 \rightarrow \mu^+\mu^-$) through fit for Wilson Coefficients

- Anomalies can be explained **coherently** by:
  - new vector coupling $C_{9}^{bs\mu\mu}$
  - new vector-axial vector coupling with $C_{9}^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$

![Global Fits Diagram](image)

*Note: other global fits are available*

- Altmannshofer & Stangl, arxiv:2103.13370
- Algueró et al., arXiv:2104.08921
- Cuichini et al., EPJ C79 (2019) 719
- Hurth et al., arXiv:2104.10058
Possible coherent explanation involving tree-level new physics competing with SM loop and box diagrams.

May be probing Z’ or leptoquarks at high mass scales, potentially within reach of direct production at LHC.

» Further measurements are required to clarify situation
New Tests of Lepton Universality

**Today:** tests of lepton universality using 2011-2012 and 2016-2018 dataset

\[ B^0 \rightarrow K_S^0 \ell^+ \ell^- \ (9 \text{ fb}^{-1}) \]

\[ R_{K^0_S} = \frac{\int_{1.1 \text{ GeV}^2}^{6.0 \text{ GeV}^2} \frac{d\mathcal{B}(B^0 \rightarrow K_S^0 \mu^+ \mu^-)}{dq^2} dq^2}{\int_{1.1 \text{ GeV}^2}^{6.0 \text{ GeV}^2} \frac{d\mathcal{B}(B^0 \rightarrow K_S^0 e^+ e^-)}{dq^2} dq^2} \]

\[ B^+ \rightarrow K^{*+} \ell^+ \ell^- \ (9 \text{ fb}^{-1}) \]

\[ R_{K^{*+}} = \frac{\int_{0.045 \text{ GeV}^2}^{6.0 \text{ GeV}^2} \frac{d\mathcal{B}(B^+ \rightarrow K^{*+} \mu^+ \mu^-)}{dq^2} dq^2}{\int_{0.045 \text{ GeV}^2}^{6.0 \text{ GeV}^2} \frac{d\mathcal{B}(B^0 \rightarrow K^{*+} e^+ e^-)}{dq^2} dq^2} \]

- **Isospin partners** of \( B^+ \rightarrow K^+ \ell^+ \ell^- \) and \( B^0 \rightarrow K_S^0 \ell^+ \ell^- \): expect same NP contributions

- More difficult to reconstruct due to long-lived \( K_S^0 \) in final state

- **First measurements at LHC** – previously measured by Belle with statistical uncertainties ~50%
The LHCb Experiment

**Particle identification from two ring-imaging Cherenkov (RICH) detectors, calorimeter and muon system**

**Electromagnetic calorimeter triggers and identifies electrons and recovers bremsstrahlung photons**

**Muon system triggers and identifies muons**

**VELO identifies displaced beauty hadron decays**
Electrons and muons have very different signatures in the experiment.
Electrons radiate bremsstrahlung photons when interacting with detector. Photons radiated before the magnet lead to underestimation of momentum and energy.

**Bremsstrahlung recovery** searches for energy deposits in the calorimeter and adds back to electron energy.
Even after brem. recovery mass resolution for electron modes is poorer than for muon modes.

Efficiency to reconstruct and select electron modes is \(~20\%\) that of muon modes.

Controlling different efficiencies for electrons and muons is key challenge of analysis.
Measure $R_K(\ast)$ as double ratio compared to control decays:

$$B \to J/\psi(\ell^+ \ell^-)K(\ast)$$

where the $J/\psi$ decays to either $e^+e^-$ or $\mu^+\mu^-$ at an equal rate. Branching fraction $\sim 1/1000$.

Many systematic effects cancel precisely in double ratio – highly robust against biases.

Same strategy as previous $R$ measurements except we fit $R_{K(\ast)}^{-1}$ to keep low yield electron modes in the numerator $\rightarrow$ uncertainties more Gaussian.
Additionally:

- aim for **first observations** of $B^0 \to K^0_S e^+ e^-$ and $B^+ \to K^{*+} e^+ e^-$ decays
- measurements of their **differential branching fractions**

\[
\frac{d\mathcal{B}(B \to K^{(*)} e^+ e^-)}{dq^2} = \frac{N(B \to K^{(*)} e^+ e^-)}{\epsilon(B \to K^{(*)} e^+ e^-)} \cdot \frac{\epsilon(B \to J/\psi(e^+ e^-)K^{(*)})}{N(B \to J/\psi(e^+ e^-)K^{(*)})} \cdot \frac{\mathcal{B}(B \to J/\psi(e^+ e^-)K^{(*)})}{q_{max}^2 - q_{min}^2}
\]
Signal modes:

\[ B^+ \rightarrow K^{*+} \ell^+ \ell^- : \quad [0.045 < q^2/\text{GeV}^2 < 6.0] \]
\[ B^0 \rightarrow K^0_S \ell^+ \ell^- : \quad [1.1 < q^2/\text{GeV}^2 < 6.0] \]

Control modes:

\[ B^0 \rightarrow J/\psi(e^+e^-)K^0_S \text{ and } B^+ \rightarrow J/\psi(e^+e^-)K^{*+} : \quad [6.0 < q^2/\text{GeV}^2 < 11.0] \]
\[ B^0 \rightarrow J/\psi(\mu^+\mu^-)K^0_S \text{ and } B^+ \rightarrow J/\psi(\mu^+\mu^-)K^{*+} : \quad [8.98 < q^2/\text{GeV}^2 < 10.02] \]

\[ K^{*+} \text{ mass:} \]

\[ |m(K^0_S \pi^+) - m(K^{*+})_{\text{PDG}}| < 300 \text{ MeV} \]

Expect roughly 22% S-wave component based on LHCb \( B^0 \rightarrow K^+\pi^- \mu^+\mu^- \) analysis. \([\text{JHEP 11 (2016) 47}]\)
Level 0 Trigger

- **Muon** decays selected by L0 muon trigger
- **Electron** decays selected by L0 electron or hadron trigger or be triggered on ‘independent’ part of underlying event

High-Level Trigger (HLT)

- HLT1: candidates selected using **single track** trigger requiring high $p_T$ and impact parameter
- HLT2: candidates selected using **topological** triggers

Selection

- Candidates made by combining displaced dilepton pair with $K_S^0$ candidate (and $\pi^+$ for $B^+$ modes)
- Requirements on vertex quality, momentum and separation from primary interaction
- **Boosted decision trees** trained on data and simulation used to reject combinatorial background
Backgrounds

Backgrounds from mis-reconstructed b-hadron decays

**Reduced to negligible levels** by kinematic, mass and PID requirements:

<table>
<thead>
<tr>
<th><strong>$B^0$ backgrounds</strong></th>
<th><strong>$B^+$ backgrounds</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_b \rightarrow hh'\ell^+\ell^-$</td>
<td>$H_b \rightarrow hh'\pi^+\ell^+\ell^-$</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow \Lambda\ell^+\ell^-$</td>
<td>$\Lambda_b \rightarrow \Lambda hh\ell^+\ell^-$</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^- (K_S^0 X)Y$</td>
<td>$B^+ \rightarrow \overline{D}^0 (K_S^0 \pi^+ X)Y$</td>
</tr>
</tbody>
</table>

$X,Y=\pi^\pm$ or $\ell^\pm \nu_l$

**Modelled in the fits**

- **$B^0$**: part. reco. $B^+ \rightarrow K^{*+}(K_S^0\pi^+)\ell^+\ell^-$ and mis-ID $B^0 \rightarrow K_S^0\pi^+\pi^-$
- **$B^+$**: part. reco. $B \rightarrow K^{*+}(K_S^0\pi^+\pi^-)\ell^+\ell^-$ and mis-ID $B^+ \rightarrow K^{*+}\pi^+\pi^-$
Accurate calculation of efficiencies is essential to making an unbiased measurement.

Simulation is corrected using data-driven weights to improve agreement with data:

1. PID efficiencies
2. Electron tracking efficiency
3. Generated B kinematics
4. Event multiplicity
5. Fraction of $K_S^0$ mesons from long and downstream tracks
6. Trigger response
7. BDT response
8. $q^2$ resolution
**Yields** of control modes extracted using maximum likelihood fits:

- Resolution improved by constraining $J/\psi$ and $K_S^0$ mass
- Parameters of control mode PDFs from simulation except mean and width

**B^0**

<table>
<thead>
<tr>
<th>Mass (MeV/c^2)</th>
<th>Candidates / (10.5 MeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5200</td>
<td>-118,750 ± 360</td>
</tr>
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<td>5400</td>
<td>-</td>
</tr>
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**B^+**

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</tbody>
</table>

**Electrons**

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<thead>
<tr>
<th>Mass (MeV/c^2)</th>
<th>Candidates / (16.5 MeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5200</td>
<td>-21,080 ± 170</td>
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<td>5400</td>
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**Muons**

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</table>
**Maximum likelihood fits**

**Yields** of signal muon modes and $R_{K^(*)}$ extracted using simultaneous maximum likelihood fits to signal mass spectra:

- Resolution improved by constraining $K_s^0$ mass
- Parameters of signal PDFs from simulation
- Shifts in mean and width from control mode data fits

---

![Graphs showing maximum likelihood fits for $B^0$ and $B^+$ modes.](image)

**LHCb**

- **$B^0$**
  - Data 9 fb$^{-1}$
  - $B^0 \rightarrow K_s^0 \mu^+ \mu^-$
  - Comb. Back.
  - $N=115 \pm 15$

- **$B^+$**
  - Data 9 fb$^{-1}$
  - $B^+ \rightarrow K^*^+ \mu^+ \mu^-$
  - Comb. Back.
  - $N=221 \pm 17$
Yields of signal muon modes and $R_{K(*)}$ extracted using simultaneous maximum likelihood fits to signal mass spectra:

- Resolution improved by constraining $K^0_S$ mass
- Parameters of signal PDFs from simulation
- Shifts in mean and width from control mode data fits

$B^0 \rightarrow K^0_S \ell^+ \ell^-$ significance: 5.3σ

$B^+ \rightarrow K^{*+} \ell^+ \ell^-$ significance: 6.0σ
Yields of signal muon modes and $R_K^{(*)}$ extracted using simultaneous maximum likelihood fits to signal mass spectra:

- Resolution improved by constraining $K_S^0$ mass
- Parameters of signal PDFs from simulation
- Shifts in mean and width from control mode data fits

**First Observation!**

\[B^0 \rightarrow K_S^0 \ell^+ \ell^- \text{ significance: 5.3}\sigma\]

\[B^+ \rightarrow K^{*+} \ell^+ \ell^- \text{ significance: 6.0}\sigma\]
**Systematic Uncertainties**

**Dominant systematics (~2-3%):**
- statistical uncertainty on efficiencies

**Next-to-dominant (1-2%):**
- size of sample of simulated candidates used to determine PDF shapes
- models used for partially reconstructed and $J/\psi$ leakage backgrounds

**Sub-dominant (≤1%):**
- size of simulated samples used to determine correction weights
- PID efficiency correction: choice of binning and correlation in efficiency between the two electrons
- Choice of method used to calculate trigger correction
- imperfect modelling of muon track reconstruction efficiency
- residual mismodelling of the BDT classifier response in simulation
- residual contamination from cascade D decays
- residual bias in the fitting procedure evaluated using pseudoexperiments
Method validated by measuring double ratio:

\[
R^{-1}_{\psi(2S)K^{(*)}} = \frac{N(B\to\psi_{2S}(e^+e^-)K^{(*)})}{N(B\to\psi_{2S}(\mu^+\mu^-)K^{(*)})} \times \frac{N(B\to J/\psi(\mu^+\mu^-)K^{(*)})}{N(B\to J/\psi(e^+e^-)K^{(*)})} \times \frac{\epsilon(B\to\psi_{2S}(\mu^+\mu^-)K^{(*)})}{\epsilon(B\to\psi_{2S}(e^+e^-)K^{(*)})} \times \frac{\epsilon(B\to J/\psi(\mu^+\mu^-)K^{(*)})}{\epsilon(B\to J/\psi(e^+e^-)K^{(*)})}
\]

Finding:

\[
R^{-1}_{\psi(2S)K^0} = 1.014 \pm 0.030 \text{ (stat.)} \pm 0.020 \text{ (syst.)}
\]

Consistent with unity.
Method validated by measuring double ratio:

\[ R_{\psi(2S)K^{(*)}}^{-1} = \frac{N(B \to \psi_{2S}(e^+e^-)K^{(*)}) \cdot \epsilon(B \to \psi_{2S}(\mu^+\mu^-)K^{(*)})}{N(B \to J/\psi(\mu^+\mu^-)K^{(*)})} \cdot \frac{\epsilon(B \to J/\psi(e^+e^-)K^{(*)})}{N(B \to J/\psi(e^+e^-)K^{(*)})} \]

Finding:

\[ R_{\psi(2S)K^{*+}}^{-1} = 1.017 \pm 0.045 \text{ (stat.)} \pm 0.023 \text{ (syst.)} \]

Consistent with unity.
Validation of the method by measuring single ratio:

$$r_{J/\psi K(*)}^{-1} = \frac{N(B \to J/\psi(e^+e^-)K(*)\Delta t)}{N(B \to J/\psi(\mu^+\mu^-)K(*)\Delta t)} \cdot \frac{\epsilon(B \to J/\psi(\mu^+\mu^-)K(*)\Delta t)}{\epsilon(B \to J/\psi(e^+e^-)K(*)\Delta t)}$$

**Stringent test** of analysis due to lack of cancellation of electron vs muon systematics.

Finding:

$$r_{J/\psi K_S}^{-1} = 0.977 \pm 0.008 \text{ (stat.)} \pm 0.027 \text{ (syst.)}$$

and

$$r_{J/\psi K^{*+}}^{-1} = 0.965 \pm 0.011 \text{ (stat.)} \pm 0.045 \text{ (syst.)}$$

Both consistent with unity.
We also study $r^{-1}_{J/\psi K^*}$ differentially as a function of several variables that are differently distributed between signal and control modes.
Electron modes are observed for the first time

\[ B^0 \rightarrow K^0_S \ell^+ \ell^- \text{ significance: } 5.3\sigma \]

\[ \frac{dB(B^0 \rightarrow K^0_S e^+ e^-)}{dq^2} = 2.6 \pm 0.6 \pm 0.1 \times 10^{-8} \text{GeV}^{-2}c^4 \]

\[ [1.1 < q^2/\text{GeV}^2 < 6.0] \]

\[ B^+ \rightarrow K^{*+} \ell^+ \ell^- \text{ significance: } 6.0\sigma \]

\[ \frac{dB(B^+ \rightarrow K^{*+} e^+ e^-)}{dq^2} = 9.2^{+1.9+0.8}_{-1.8-0.6} \times 10^{-8} \text{GeV}^{-2}c^4 \]

\[ [0.045 < q^2/\text{GeV}^2 < 6.0] \]
Results: LFU Ratios

\[ R_{K^0}^{-1} = 1.51^{+0.40}_{-0.35} \text{(stat)}^{+0.09}_{-0.04} \text{(syst)} \]

\[ R_{K^*}^{-1} = 1.44^{+0.32}_{-0.29} \text{(stat)}^{+0.09}_{-0.06} \text{(syst)} \]

\[ R_{K^0} = 0.66^{+0.20}_{-0.15} \text{(stat)}^{+0.02}_{-0.04} \text{(syst)} \]

\[ R_{K^*} = 0.70^{+0.18}_{-0.13} \text{(stat)}^{+0.03}_{-0.04} \text{(syst)} \]

Inverting values and 1σ intervals

[1.1 < q^2/GeV^2 < 6.0]

Significance w.r.t SM: 1.5σ

[0.045 < q^2/GeV^2 < 6.0]

Significance w.r.t SM: 1.4σ
Results: Combination

Two results combined to evaluate total significance with respect to the SM:

- Fit for Wilson Coefficients using Flavio [arxiv:1810.08132]
- Float $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ (LFU ratios cannot disentangle $C_9$ and $C_{10}$)

Combined significance = 2σ

Best fit value:

$$C_9^{bs\mu\mu} = -0.8^{+0.4}_{-0.3}$$
Today:

- **First observation** of $B^0 \to K_S^0 e^+ e^-$ and $B^+ \to K^{*+} e^+ e^-$ decays at $5.3\sigma$ and $6.0\sigma$
- World’s most precise measurements of $B^0 \to K_S^0 e^+ e^-$ and $B^+ \to K^{*+} e^+ e^-$ differential branching fractions at low $q^2$
- World’s most precise **tests of lepton universality** in $B^0 \to K_S^0 \ell^+ \ell^-$ and $B^+ \to K^{*+} \ell^+ \ell^-$ decays

\[
R_{K_S^0} = 0.66^{+0.20}_{-0.15} \text{(stat)}^{+0.02}_{-0.04} \text{(syst)}
\]
\[
R_{K^{*+}} = 0.70^{+0.18}_{-0.13} \text{(stat)}^{+0.03}_{-0.04} \text{(syst)}
\]

- Values consistent with SM at $1.5\sigma$ and $1.4\sigma$
- Combined significance of WC fit compared to SM at $2\sigma$
- Same pattern as deviations seen in other LFU tests

Many other LFU tests in progress at LHCb with full Run 1 and Run 2 data...
The **LHCb Upgrade** is coming soon!

- (Almost) all-new detector to allow readout at 30 MHz
- Full software trigger
- Data taking with five times previous rate
Backup
Yields of control modes extracted using maximum likelihood fits:

- Resolution improved by constraining $J/\psi$ and $K_S^0$ mass
- Parameters of control mode PDFs determined from simulation with mean mass and mass resolution allowed to float in fit to data

<table>
<thead>
<tr>
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<th>Yield</th>
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Efficiencies

LHCb Simulation

Total $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ selection efficiency

$q^2 [GeV^2/c^4]$

LHCb Simulation

Total $B^0 \rightarrow K^+ e^- e^-$ selection efficiency

$q^2 [GeV^2/c^4]$

LHCb Simulation

Total $B^0 \rightarrow K^+ \mu^+ \mu^-$ selection efficiency

$q^2 [GeV^2/c^4]$

LHCb Simulation

Total $B^0 \rightarrow K^+ e^- e^-$ selection efficiency

$q^2 [GeV^2/c^4]
Angular Distributions

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\Omega} \bigg|_p = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_l \right.
\]

\[
\left. - F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi \right]
\]

\[
+ \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 \right]}

\]