LHCb RESULTS AND PERSPECTIVES

Opportunities at Future High Energy Colliders
IFT Madrid, June 2019

Bernardo Adeva, on behalf of the LHCb collaboration
LHCb RESULTS AND PERSPECTIVES: TALK OUTLINE

1. LHCb apparatus and Upgrade
2. CP-violation in b-sector
3. CP-violation in c-sector
4. Lepton universality (LU) anomalies in charged currents
5. LU and other anomalies in flavor-changing neutral currents
6. Opportunities in K-physics and other new physics searches
LHCb and UPGRADE
The LHCb detector at the LHC, JINST 3 (2008) S08005
**DETECTOR OPERATION RUN 1 AND RUN 2**

- LHCb designed to run at lower instantaneous luminosity $\mathcal{L}$ than ATLAS and CMS
- mean number of interactions per bunch crossing $\sim 1$
- pp beams displaced to reduce $\mathcal{L}$

- $\sim 3$ fb$^{-1}$ of pp collisions at 7-8 TeV in Run 1
- $\sim 6$ fb$^{-1}$ of pp collisions at 13 TeV in Run 2
- $\sim 9$ fb$^{-1}$ reached at the end of Run 2

*arXiv: 1412.6352*
THE LHCb UPGRADE I

All sub-detectors read out at 40 MHz for a FULLY SOFTWARE trigger
THE LHCb UPGRADE II

- Aims to **fully exploit the HL–LHC** for flavor physics in forward direction
- Expected to collect **$> 300 \text{ fb}^{-1}$** at $\mathcal{L}=2 \times 10^{34}$, 10 times higher than Upgrade I
- Green light from LHCC to proceed to detector TDR’s (expected ~ late 2020)
PROGRESS IN DETECTOR CONSTRUCTION

RICH MaPMT test stand

UT ASIC wire-bonded to a sensor

full size VELO RF boxes in “closed” position

prototype stave of UT

VELO module test setup

RICH photodetectors and readout

event builder prototype

prototype C-frame in construction at LHCb site
CP violation in $b$
THE KOBAYASHI-MASKAWA THEORY

- The CKM matrix must be UNITARY for a fixed number of quark generations (e.g. 3):
  \[ V_{CKM}^+ = V_{CKM} \iff \text{SINGLE-PHASE hypothesis} \]

- Which provides many relationships, such as **TRIANGLES**:

  \[
  \begin{align*}
  V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* &= 0 \\
  V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* &= 0 \\
  V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* &= 0
  \end{align*}
  \]

- Two independent phases characterize the first triangle:
  \[ \lambda \equiv \sin \theta_c \]

  \[ \beta \equiv \arg \left( -V_{cd}V_{cb}^*/(V_{td}V_{tb}) \right) \]
  \[ \gamma \equiv \arg \left( -V_{ud}V_{ub}^*/(V_{cd}V_{cb}) \right) \]

  **First evidence of CPV in B-mesons, BaBar 2001**

- The **flat triangles** with a very small side mean very significant predictions:
  - the phase \[ \beta_s \equiv \arg \left( -V_{ts}V_{tb}^*/(V_{cs}V_{cb}) \right) \] must be very small (\( \approx \lambda^4 \))
NEW LHCb MEASUREMENT OF $\gamma$

- $\gamma$ is measured through interference in $B^- \to DK^-$. No assumptions on D decay amplitude are made.

\[
\frac{A(B^- \to \bar{D}^0 K^-)}{A(B^+ \to D^0 K^+)} = r_B e^{i(\delta_B - \gamma)}
\]

- Many K/$\pi$ decay modes for $D^0$ meson are included.

- Neutral B-mesons ($B_s$, $B^0$) are also used, time dependent analysis with $B_s \to D_s^{\mp} K^{\pm}$

LHCb, JHEP 03 (2018) 059
CURRENT STATUS ON $\gamma$

- LHCb combination of tree-level measurements: $\gamma = (74.0^{+5.0}_{-5.8})^\circ$
  It is the most precise measurement from a single experiment \textit{LHCb-CONF-2018-002}

- World average of \textit{direct} measurements: $\gamma = (73.5^{+4.2}_{-5.1})^\circ$ \textit{HFLAV Winter 2018}

- \textit{Indirect} $V_{\text{CKM}}$ measurements throw the result: $\gamma_{\text{indirect}} = (65.8 \pm 2.2)^\circ$
  \textit{UTFIT Summer 2018}

- Both consistent within $\sim 2\sigma$. This is a most significant, and highly non trivial test, on:
  - the Kobayashi-Maskawa theory of CP-violation (\textit{single-phase} hypothesis)
  - the contribution of \textit{new physics} in tree-level diagrams

Small internal tensions between $B_s$ and $B^+$ will be followed as more data are collected.
MEASUREMENT OF $\phi_s^{cc}$ WITH $B_s^0 \rightarrow J/\psi K^+K^-$

- LHCb updated measurement of time dependent CP-violating observables in $B_s^0 \rightarrow J/\psi K^+K^-$ decays, adding a new sample of 117000 signal events (2015-16)

- Interference between the decay and $B_s^0 - \bar{B}_s^0$ mixing amplitudes is governed in the SM by the very small CKM phase $\beta_s$ (flat triangle) $\phi_s \approx -2\beta_s$ (ignoring sub-leading diagrams)

- Rather than predicted by the SM, the $\beta_s$ phase is strongly constrained by the CKM unitarity to:

  $-2\beta_s^{SM} = -0.0368^{+0.00096}_{-0.00068}$ rad  CKMfitter group

  $-2\beta_s^{SM} = -0.0370 \pm 0.0010$ rad  UTfit collaboration

- LHCb is well placed to approach such precision limit
Owing to very fast $B_s^0 - \bar{B}_s^0$ oscillations ($\Delta m_s \approx 17.77 \text{ ps}^{-1}$) two critical parameters need to be known very precisely, to attain the mrad precision at the LHC:
- $B_s^0/\bar{B}_s^0$ flavor tagging efficiency and dilution at $t=0$
- time resolution $\sigma_t$, better than $2\pi/\Delta m_s \approx 350 \text{ fs}$

LHCb has significantly improved flavor tagging since 2011, by refining both the opposite side (OS) muon/electron/kaon/multiplicity) and the same side (SS) kaon tagging.

<table>
<thead>
<tr>
<th>Category</th>
<th>$\varepsilon_{\text{tag}} (%)$</th>
<th>$D^2$</th>
<th>$\varepsilon_{\text{tag}} D^2 (%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS-only</td>
<td>11.35</td>
<td>0.078</td>
<td>0.88 ± 0.04</td>
</tr>
<tr>
<td>SSK-only</td>
<td>42.57</td>
<td>0.032</td>
<td>1.38 ± 0.30</td>
</tr>
<tr>
<td>OS&amp;SSK</td>
<td>23.84</td>
<td>0.104</td>
<td>2.47 ± 0.15</td>
</tr>
<tr>
<td>Total</td>
<td>77.76</td>
<td>0.061</td>
<td>4.73 ± 0.34</td>
</tr>
</tbody>
</table>

Large control samples of $B^+ \rightarrow J/\psi K^+$ and $B^0_s \rightarrow D_s^- \pi^+$ are respectively used.
TIME RESOLUTION AT LHCb

With $\sigma_t \approx 45$ fs, the oscillation amplitude is damped by factor $\exp \left(-\sigma_t^2 \Delta m_s^2 / 2\right)$ ($\approx 0.7$ LHCb).

A prompt sample of $B_s^0 \rightarrow J/\psi K^+K^-$ events, selected at the primary $pp$ vertex (zero decay time), is used to calibrate the effective decay-time resolution, by correlating it (11 subsets) with the estimated per-event decay-time uncertainty: $\sigma_{\text{eff}}(\delta_t) = b_0 + b_1 t$

The single Gaussian $\sigma_{\text{eff}} = \sqrt{-2/\Delta m_s^2} \ln D$ is obtained from a 3-Gaussian fit, convolved as $P(t) = \varepsilon(t) \left(\Gamma(t') \otimes R(t-t')\right)$ with an analytical distribution $\Gamma(t)$ times a calibrated acceptance function $\varepsilon(t)$.

An averaged single-Gaussian resolution is obtained of $\sigma_{\text{eff}} = 45.54 \pm 0.04 \pm 0.05$ fs for the $B_s^0 \rightarrow J/\psi K^+K^-$ simple.
AMPLITUDE ANALYSIS OF CP-EIGENSTATES

- The 3 VV helicity amplitudes $B_s^0 \to J/\psi \phi(K^+K^-)$ may also interfere with a $S(K^+K^-)=0$ scalar during the $B_s^0 - \bar{B}_s^0$ oscillation process:

  \[
  \mathcal{A} = \sum A_i = A_0 + A_\parallel + A_\perp + A_S \\
  \bar{\mathcal{A}} = \sum \frac{q}{p} \bar{A}_i = \sum \lambda_i A_i = \sum \eta_i \lambda_i e^{-i\phi^i_s A_i} \\
  \lambda_i \equiv \frac{q}{p} \bar{A}_i \\
  \phi^i_s \equiv -\arg(\eta_i \lambda_i)
  \]

- The flavor-tagged, time-convolved, background subtracted distributions are ML analysed

\[
\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt \ d\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega)
\]

\[
h_k(t|B_s^0) = \frac{3}{4\pi} e^{-\Gamma t} \left( a_k \cosh \frac{\Delta \Gamma t}{2} + b_k \cosh \frac{\Delta \Gamma t}{2} + c_k \cos(\Delta m t) + d_k \sin(\Delta m t) \right)
\]

\[
h_k(t|\bar{B}_s^0) = \frac{3}{4\pi} e^{-\Gamma t} \left( a_k \cosh \frac{\Delta \Gamma t}{2} + b_k \cosh \frac{\Delta \Gamma t}{2} - c_k \cos(\Delta m t) - d_k \sin(\Delta m t) \right)
\]

- $\phi_s$, $\Delta \Gamma_s = \Gamma_L - \Gamma_H$, $\Gamma_s - \Gamma_d$ ($\Gamma_s = \Gamma_L + \Gamma_H$)/2 are the most precise data today, along with a similar precision simultaneous measurement by ATLAS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_s$ [rad]</td>
<td>$-0.083 \pm 0.041 \pm 0.006$</td>
</tr>
<tr>
<td>$</td>
<td>\lambda</td>
</tr>
<tr>
<td>$\Gamma_s - \Gamma_d$ [ps$^{-1}$]</td>
<td>$-0.0041 \pm 0.0024 \pm 0.0015$</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ [ps$^{-1}$]</td>
<td>$0.0773 \pm 0.0077 \pm 0.0026$</td>
</tr>
<tr>
<td>$\Delta m_s$ [ps$^{-1}$]</td>
<td>$17.703 \pm 0.059 \pm 0.018$</td>
</tr>
<tr>
<td>$</td>
<td>A_\parallel</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$\delta_\perp - \delta_0$</td>
<td>$2.64 \pm 0.13 \pm 0.10$</td>
</tr>
<tr>
<td>$\delta_\parallel - \delta_0$</td>
<td>$3.062^{+0.082}_{-0.074} \pm 0.037$</td>
</tr>
</tbody>
</table>
CURRENT STATUS OF $\phi_s^{cc}$ MEASUREMENTS

LHCb has added other $B_s^0$ decays: $J/\psi \pi\pi$, $\psi(2s)\phi$, $D_s^+D_s$ all sensitive to $\phi_s^{cc}$

$$\phi_s = -0.041 \pm 0.025 \text{ rad},$$
$$|\lambda| = 0.993 \pm 0.010,$$
$$\Gamma_s = 0.6562 \pm 0.0021 \text{ ps}^{-1},$$
$$\Delta\Gamma_s = 0.0816 \pm 0.0048 \text{ ps}^{-1}$$

Both main players yet to analyse full Run2. Some tension on absolute $B_s^0$ lifetime, and $\Delta\Gamma_s$

LHCb result:

$$\phi_s = -41 \pm 25 \text{ mrad}$$

begins to deviate from zero, but on the same side as the SM prediction: $-37 \pm 1 \text{ mrad}$

accumulated CP-asymmetry per oscillation cycle ($2.4\sigma$)
Copious signal, $\phi \rightarrow K^+ K^-$, subject in SM is to the same CKM phase as $B_s^0 \rightarrow J/\psi \phi$: $\phi_s^{ss} = -2\beta_s$.

However, lowest order involves *penguin* $b \rightarrow ss\bar{s}$ diagrams, with potential contributions from NP particles from loops. Entirely similar *tagged* angular and time analysis, with 4 helicities: $A_0, A_{||}, A_\perp$ (CP-odd), $A_S$

$$\phi_s^{ss} = -0.073 \pm 0.115 \text{ (stat)} \pm 0.027 \text{ (syst)} \text{ rad},$$

$$|\lambda| = 0.99 \pm 0.05 \text{ (stat)} \pm 0.01 \text{ (syst)}.$$

Helicity dependent amplitudes have also been explored:

$$\phi_{s,||} = 0.014 \pm 0.055 \text{ (stat)} \pm 0.011 \text{ (syst)} \text{ rad},$$

$$\phi_{s,\perp} = 0.044 \pm 0.059 \text{ (stat)} \pm 0.019 \text{ (syst)} \text{ rad}.$$

Triple products are T-odd observables, a complementary search for CPV without flavor tagging or time analysis.

With 5.0 fb$^{-1}$ (2011-2016), results are consistent with the hypothesis if CP conservation in $b \rightarrow s s\bar{s}$ transitions.
CP-VIOLATING OBSERVABLES IN $B_s \rightarrow \phi \gamma$

- Time-dependent CP-asymmetries have been measured by LHCb for $B_s^0 \rightarrow \phi (K^+K^-) \gamma$ radiative decays, with $3 \text{ fb}^{-1}$ ($7+8 \text{ TeV}$)
  \[ P(t) \propto e^{-\Gamma_s t} \{ \cosh(\Delta \Gamma_s t/2) - A^\Delta \sinh(\Delta \Gamma_s t/2) + \zeta C \cos(\Delta m_s t) - \zeta S \sin(\Delta m_s t) \} \]

- $A^\Delta$ sensitive to right-handed currents in $b \rightarrow s \gamma$ transition (penguins) and small in the SM ($\propto A_L A_R$ photon amplitudes)
  arXiv:0802.0876

- $B^0 \rightarrow K^{*0} \gamma$ used as proxy for time acceptance calibration (single exponential)

- Measured parameters compatible with SM expectation within $(1.3, 0.3, 1.7)\sigma$, respectively:
  \[ S_{\phi \gamma} = 0.43 \pm 0.30 \pm 0.11 \]
  \[ C_{\phi \gamma} = 0.11 \pm 0.29 \pm 0.11 \]
  \[ A^\Delta_{\phi \gamma} = -0.67^{+0.37}_{-0.41} \pm 0.17 \]
CP violation in $c$
LHCb has discovered a non zero \textit{charmed} time integrated CP-violating asymmetry:

\[
\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = -(15.4 \pm 2.9) \times 10^{-4}
\]

\[
A_{CP}(f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)}
\]

R. Aaij et al. PRL 122, 211803 (2019)

Model independently, we know to \(\mathcal{O}(10^{-6})\):

\[
A_{CP}(f) \approx a_{CP}^{\text{dir}}(f) \left( 1 + \frac{\langle t \rangle_f}{\tau_{D^0}} y_{CP} \right) - \frac{\langle t \rangle_f}{\tau_{D^0}} A_{\Gamma}
\]

effective \(\Gamma(CP = +1)\) different from \(\Gamma(D^0)\)

LHCb has also performed a \textit{time analysis} \(A_{CP}(t)\) to determine \(A_{\Gamma}\) and elucidate whether the CP-violating \(D^0/\bar{D}^0\) mixing (modulus or phase) is responsible

LHCb-CONF-2019-001 April, 2019

In addition an updated measurement of \(y_{CP}\) has been issued to accurately perform the correction to \(a_{CP}^{\text{dir}}\), using \textit{un}tagged \textit{se}mileptonic \(B\)-decays

R. Aaij et al. PRL 122, 011802 (2019)
LHCb has used 6 fb\(^{-1}\) at pp \(\sqrt{s}=13\) TeV, with CP\(=+1\) eigenmodes \(D^0 \rightarrow K^+K^-\), \(\pi^+\pi^-\) (44 million \(D^0 \rightarrow K^+K^-\) decays). Both \(D^*+(\rightarrow D^0 \pi^+)\) and semileptonic taggings were used.

R. Aaij et al. PRL 122, 211803 (2019)

The difference \(A_{CP}(KK) - A_{CP}(\pi\pi)\) is chosen because detector and production CP-asymmetries largely cancel. Not unrelated, \(A_{CP}(KK) = -A_{CP}(\pi\pi)\) is predicted from exact SU(3) symmetry. The outcome is then:

\[
\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = -(15.4 \pm 2.9) \times 10^{-4}
\]

By using \(y_{CP} = (5.7 \pm 1.5) \times 10^{-3}\) and \(-A_{f} = (-2.8 \pm 2.8) \times 10^{-4}\) \(\approx a_{CP}^{\text{ind}}\) (see next) we get:

\[
\Delta a_{CP}^{\text{dir}} = (-15.6 \pm 2.9) \times 10^{-4}
\] or \(A_{CP}\) PRIMARY SENSITIVE TO DIRECT CPV

The result is consistent with, although at the upper end of, SM expectations \(10^{-4} - 10^{-3}\). Beyond the SM, the CPV rate could be enhanced. Present understanding does not allow more precise predictions, due to the difficulty of long-range strong interactions.
SEARCH FOR TIME DEPENDENT CPV IN CHARMS

- Tagged D(2010)$^{*+} \to D^0 \pi^+$ decays are employed for time analysis of CP-asymmetries. Kinematic weighing is used for detector-induced asymmetries, with $D^0 \to K^- \pi^+$ as calibration.

- Now the measurement of $A_T$ is largely insensitive to time-independent detection and production asymmetries, so $KK$ and $\pi\pi$ analyses can be separated.

\[
A_T(K^+K^-) = (1.3 \pm 3.5 \pm 0.7) \times 10^{-4} \\
A_T(\pi^+\pi^-) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4}
\]

- $A_T$ is channel independent when decay phases are neglected, so a combined value (2011-2016) is meaningful:

\[
A_T(K^+K^- + \pi^+\pi^-) = (0.9 \pm 2.1 \pm 0.7) \times 10^{-4}
\]

- No evidence for CP violation in mixing or interference.

\[
A_T(f) \approx -x\phi_f + y \left[ \left( \frac{q}{p} \right) - 1 \right]
\]
MEASUREMENT OF CHARM-MIXING PARAMETER $y_{CP}$

R. Aaij et al. PRL 122, 011802 (2019)

- In time analysis with $D^0$–$\bar{D}^0$ mixing, the effective decay widths (CP-even) $\Gamma(K^+K^-/\pi^+\pi^-)$ may differ from $\Gamma(D^0)$:
  \[ y_{CP} = \frac{\Gamma_{CP^+}}{\Gamma} - 1 \]
  CP conservation $\iff y_{CP} = y$

- LHCb has searched for CPV in mixing by requiring $D^0$ mesons to originate from semileptonic decays of $B^-$ or $\bar{B}^0$: $\bar{B}^0 \to D^0 \mu \bar{\nu} X$, and studying the time dependent RATIO between $D^0 \to K^+K^-/\pi^+\pi^-$ and $D^0 \to K^-\pi^+$ signal yields

\[ y_{CP} = (0.57 \pm 0.13 \pm 0.09) \times 10^{-2} \]

\[ 2y_{CP} \approx \left( \frac{|q|}{|p|} + \frac{|p|}{|q|} \right) y \cos \phi - \left( \frac{|q|}{|p|} - \frac{|p|}{|q|} \right) y \sin \phi \]

\[ |D_{1,2} \equiv p|D^0\rangle \pm q|\bar{D}^0\rangle \quad x \equiv (\Delta m)/\Gamma \quad y \equiv \Delta \Gamma/2\Gamma \]

- $y_{CP}$ is the most precise to date single experiment, being consistent with the w. a. mixing parameter $y = (0.62 \pm 0.07)\%$, hence no evidence for CPV in $D^0$–$\bar{D}^0$ mixing.
NEW CHARM AVENUE

The CP violation picture in the quark sector is now set for precision studies. Is the $\mathcal{O}(10^{-3})$ CPV found in charm the ultimate confirmation of Kobayashi-Maskawa theory, or a hint of new physics?

Direct CPV in charm seems difficult to grasp, for challenging hadronic calculations with SM prediction $\mathcal{O}(10^{-3}-10^{-4})$. But indirect CPV in $A_{\Gamma}$ is predicted in the SM to be $A_{\Gamma} \approx 3 \times 10^{-5}$, offering a great window of opportunity for NP: its smallness may be turned into an advantage after all.

Future measurements at HL-LHC (LHCb Upgrade II) will certainly improve the picture:

A. Cerri et al. CERN-LPCC-2008-06 arXiv: 1812.07638

<table>
<thead>
<tr>
<th>Sample ($\mathcal{L}$)</th>
<th>Tag</th>
<th>Yield $K^+K^-$</th>
<th>$\sigma(A_{\Gamma})_{K^+K^-}$</th>
<th>Yield $\pi^+\pi^-$</th>
<th>$\sigma(A_{\Gamma})_{\pi^+\pi^-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1–2 (9 fb$^{-1}$)</td>
<td>Prompt</td>
<td>60M</td>
<td>0.013%</td>
<td>18M</td>
<td>0.024%</td>
</tr>
<tr>
<td>Run 1–3 (23 fb$^{-1}$)</td>
<td>Prompt</td>
<td>310M</td>
<td>0.0056%</td>
<td>92M</td>
<td>0.0104%</td>
</tr>
<tr>
<td>Run 1–4 (50 fb$^{-1}$)</td>
<td>Prompt</td>
<td>793M</td>
<td><strong>0.0035%</strong></td>
<td>236M</td>
<td><strong>0.0065 %</strong></td>
</tr>
<tr>
<td>Run 1–5 (300 fb$^{-1}$)</td>
<td>Prompt</td>
<td>5.3G</td>
<td><strong>0.0014%</strong></td>
<td>1.6G</td>
<td><strong>0.0025 %</strong></td>
</tr>
</tbody>
</table>
LEPTON UNIVERSALITY anomalies in CC
LEPTON UNIVERSALITY IN CHARGED CURRENTS

- Very large data samples at LHCb, started and envisaged:

  \[ B \left\{ q \rightarrow W^+ \tau^+ \nu_\tau, \bar{b} \rightarrow D^{(*)} \right\} \]

  \[
  R(H_c) = \frac{\mathcal{B}(H_b \rightarrow H_c \tau \nu_\tau)}{\mathcal{B}(H_b \rightarrow H_c \mu \nu_\mu)}
  \]

  \[
  H_b = B^0, B^{(c)}, \Lambda_b, B_s \ldots
  \]

  \[
  H_c = D^*, D^0, D^+, D_s, \Lambda_c^{(*)}, J/\psi \ldots
  \]

- Clean observables: hadronic uncertainties and \(|V_{cb}|\) cancel out in the ratio. New operators may challenge universality:

  \[
  (p_z)_B = \frac{m_B}{m(D^* \mu)} (p_z)_{D^* \mu}
  \]

  18% resolution on B momentum

- Generic difficulty at hadron colliders, due to missing neutrinos, partially solved by rest-frame approximation:
MUONIC R(D*)


\[
R(D^*) = \frac{\Gamma (\bar{B}^0 \to D^{*+} \tau^{-}(\mu^- \bar{\nu}_\mu \nu_\tau) \bar{\nu}_\tau)}{\Gamma (\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu)}
\]

3D fit to the data uses
\[
(m_{\text{miss}}^2, E_\mu^*, q^2 = (p_B - p_D)^2)
\]

\[
R(D^*) = 0.336 \pm 0.027 \pm 0.030
\]

The result is \(1.2\sigma\) above the SM \(0.252 \pm 0.003\)
HADRONIC $R(D^*)$

Separation between $B$ and $3\pi$ vertex ($\Delta z > 4\sigma_{\Delta z}$) crucial to achieve the required rejection of $B \rightarrow D^* 3\pi X$

External knowledge of critical branching fractions is used ($B \rightarrow D^* 3\pi$, BaBar+Belle+LHCb)

$R(D^*- ) = 0.291 \pm 0.019$ (stat) $\pm 0.026$ (syst) $\pm 0.013$ (ext)

The result is $\sim 1\sigma$ above the SM $0.252 \pm 0.003$
**LFU IN R(J/ψ) FROM B_c DECAYS**

- New version of R(D*), charmed B-meson B_c⁺:
  \[
  R(J/ψ) = \frac{\mathcal{B}(B_c^+ \rightarrow J/ψτ^+ν_τ)}{\mathcal{B}(B_c^+ \rightarrow J/ψμ^+ν_μ)}
  \]

- B_c⁺→J/ψ(μ⁺μ⁻)μ⁺ν_μ is used as normalization

- Form factors not constrained from B-factories

- Measurement from 3D fit (m_{miss}², t_B, Z (q², E_μ*))

\[R(J/ψ) = 0.71 ± 0.17 \text{ (stat)} ± 0.18 \text{ (syst)} \text{ above SM prediction by } 2\sigma \text{ (0.25–0.28)}\]

---

R. Aaij et al. PRL 120 (2018) 121801
R(D) and R(D*) COMBINATION

Not in average:

World average for R(D) and R(D*) 3.1σ from the SM

New R(D) and R(D*) measurements by Belle
arXiv:1904.08794
LEPTON universality and anomalies in FCNC
THE $b \rightarrow s \, \mu \mu$ PROCESSES

\[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C'_i O'_i) + \text{h.c.} \]

- These rare processes are \textit{forbidden} at tree level in the SM, because neutral currents ($Z^0, \gamma$) do not change flavour. They receive \textit{calculable} loop contributions that are \textit{small}.

- These contributions are in SM normalized by the couplings of the Higgs/Yukawa sector ($V_{\text{CKM}}$), determined from other processes.

- Beyond the SM, \textit{new heavy particles} may contribute, altering the chiral couplings.

\[
\begin{align*}
O_7 & = \frac{e}{16\pi^2} m_b \bar{s} \sigma^{\mu\nu} (1 + \gamma_5) F_{\mu\nu} b \quad \text{[real or soft photon]} \\
O_9 & = \frac{e^2}{16\pi^2} \bar{s} \gamma_{\mu} (1 - \gamma_5) b \, \bar{\ell} \gamma^\mu \ell \quad \text{[Z/hard \gamma…]} \\
O_{10} & = \frac{e^2}{16\pi^2} \bar{s} \gamma_{\mu} (1 - \gamma_5) b \, \bar{\ell} \gamma^\mu \gamma_5 \ell \quad \text{[Z]} \\
O'_{7,9,10} & \rightarrow \text{chirally-flipped} \ (1+\gamma_5)(…)
\end{align*}
\]
SENSITIVITY $d\Gamma(b \to s\mu\mu)/dQ^2$ SPECTRUM

Photon pole enhancement (absent in pseudoscalar $B \to K \ell^+\ell^-$)

Form-factors from LCSR calculations

$C_7^{(7)}$ and $C_9^{(7)}$ interference

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

Long distance contributions above $c\bar{c}$ threshold

Form-factors from Lattice QCD

$q^2$ Dimuon mass squared
ANGULAR ANALYSIS OF $B \rightarrow K^{*0}\mu\mu$

- Rare $b \rightarrow s \mu^+\mu^-$ decays are only allowed in the SM by calculable electroweak penguin and box diagrams, open to new heavy particles ($Z'$, extra H...)

- Angular observables in $B^0 \rightarrow K^{*0}(K^+\pi^-) \mu^+\mu^-$ are characterized by 6 amplitudes: 3 $K^{*0}$ helicities and 2 $\mu^+\mu^-$ chiralities (L,R)

  $$A_{0,||,\perp}^{L,R}$$

- The full set of 9 (CP-averaged) observables was analyzed by LHCb in 2013 arXiv:1304.6325 (1 fb$^{-1}$), as function of $q^2(\mu^+\mu^-)$, showing statistical agreement with the SM predictions in all of them, except this particular observable:

  $$P_5' = \sqrt{2} Re \left( A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*} \right) / \sqrt{F_L(1 - F_L)}$$

  $$F_L = |A_0^L|^2 + |A_0^R|^2$$

  which showed a significant discrepancy ($3.7\sigma$)

- Since then, a great deal of attention has been devoted to this anomaly, both theoretically and experimentally (Belle, CMS, ATLAS)
CURRENT STATUS OF K*\(^0\)\(\mu\mu\) ANOMALY

- Global significance is 3.4 \(\sigma\), despite recent CMS results. Note the measurements show consistency with one another. The Belle result includes muons and electrons.

LHCb: JHEP 02 (2016) 104  
Belle: PRL 118 (2017) 111801  
ATLAS: JHEP 10 (2018) 047  
CMS: PLB 781 (2018) 517

- The \(P'_5\) observable is one of a set of so-called form-factor free observables that can be measured. SM DHMV: S. Descotes-Genon et al. JHEP 01 (2013) 048  
various other LHCb branching fraction measurements in $b \to s \mu\mu$ processes have reported a similar behavior in the $0<q^2<6$ GeV$^2$ region.
THE $R_H$ OBSERVABLES FOR $\mu/e$

- Lepton universality has been tested by comparing the rates $B \rightarrow H \mu^+\mu^-$ to $B \rightarrow H e^+e^-$:

$$R_H[q_{\text{min}}^2, q_{\text{max}}^2] = \frac{\int_{q_{\text{min}}^2}^{q_{\text{max}}^2} dq^2 \frac{d\Gamma (B \rightarrow H\mu^+\mu^-)}{dq^2}}{\int_{q_{\text{min}}^2}^{q_{\text{max}}^2} dq^2 \frac{d\Gamma (B \rightarrow He^+e^-)}{dq^2}}, \quad q^2 = m^2(l^+l^-) \quad H = K, K^*, \phi \cdots$$

- These are flavour-changing neutral current processes of the form $b \rightarrow s l^+l^-$, with amplitudes involving loop diagrams

- They provide clean probes of New Physics, for two reasons:
  - new interactions may render non-universal couplings to $\mu$ and $e$
  - hadronic uncertainties as form factors, cancel in the SM ($R_H=1$), with QED corrections at $\sim \%$ level

JHEP 07 (2007) 040, EPJC 76 (2016) 8, 440
**μ⁺μ⁻ VERSUS e⁺e⁻ MEASUREMENT**

- Photon-bremsstrahlung is accounted for
- Upper cut of 6 GeV chosen to reduce $J/\psi$ background
- Reconstruction efficiency for $e^+e^-$ about 5 times smaller than for $\mu^+\mu^-$

LHCb: JHEP 08 (2017) 055 (3 fb⁻¹)
$R_{K^*} \text{ is measured as a double ratio}$

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+\mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+\mu^-))} / \frac{\mathcal{B}(B^0 \rightarrow K^{*0} e^+e^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+e^-))}$$

R. Aaij et al. JHEP 08 (2017) 055 (3 fb$^{-1}$)
SOME CHECKS ON $R_{K^*}$

R. Aaij et al., JHEP 08 (2017) 055

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-))}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-))} = 1.043 \pm 0.006 \pm 0.045$$

- very important independent test: when the same method is applied to $J/\psi$ events, no deviation from unity is observed.
- insensitive to kinematics ($p_T, \eta$ of $B^0$ meson), and track multiplicity

$$R_{\psi(2s)} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \psi(2s) (\rightarrow \mu^+ \mu^-))}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-))} / \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \psi(2s) (\rightarrow e^+ e^-))}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-))}$$

Compatible with 1 at 1$\sigma$ (2%)

- If no correction is made to simulation, <5% change to efficiency ratio
**$R_{K^*}$ RESULT**

Comparison with SM predictions

![Graph comparing $R_{K^*}$ with SM predictions](image1)

Comparison with Belle & BaBar

![Graph comparing $R_{K^*}$ with Belle & BaBar](image2)

**Comparison with SM predictions**

- **BIP**: arXiv:1605.07633
- **CDHMV**: arXiv:1510.04239, 1605.03156, 1701.08672
- **JC**: arXiv:1412.3183

**Comparison with Belle & BaBar**

- **Belle**: arXiv:1904.02440 (711 fb$^{-1}$) new result
- **BaBar**: PRD 86 (2012) 032012
- **Belle**: PRL 103 (2009) 171801

\[
R_{K^*} = \begin{cases} 
0.66^{+0.11}_{-0.07} \text{ (stat)} \pm 0.03 \text{ (syst)} & \text{for } 0.045 < q^2 < 1.1 \text{ GeV}^2 \quad 2.1-2.3 \sigma \\
0.69^{+0.11}_{-0.07} \text{ (stat)} \pm 0.05 \text{ (syst)} & \text{for } 1.1 < q^2 < 6.0 \text{ GeV}^2 \quad 2.4-2.5 \sigma 
\end{cases}
\]
NEW MEASUREMENT OF $R_K$

---

**LHCb has performed a thorough update of $R_K$ measurements, with 5 fb$^{-1}$:**

- re-optimized analysis of Run 1 (3 fb$^{-1}$)
- Added 2015&2016 Run 2 datasets (2 fb$^{-1}$)

**Electron/muon reconstruction assessment, in the non resonant region, follows similar strategy as for the $R_{K^*}$ measurement**

**Simultaneous fit performed over the $\mu\mu$ and ee nonresonant candidates, using $J/\psi$ as essential calibration tool: partial reconstruction background in $Kee$ mainly from $B^0 \rightarrow K^{*0} e^+e^-$**

---

R. Aaij et al. 122 (2019) 191801
R_K ANALYSIS CHECKS

- Efficiencies computed from simulation, calibrated with several control channels selected from data

- Numerous cross-checks to ensure good understanding of efficiencies, in particular \( r_{J/\psi} = 1 \):

\[
    r_{J/\psi} = \frac{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow \mu^+ \mu^-))}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow e^+ e^-))} = 1.014 \pm 0.035 \text{ (stat + syst)}
\]

- Kinematics of \( J/\psi (\ell^+ \ell^-) \) resonant and nonresonant pairs do overlap considerably in the laboratory frame, which facilitates calibration

\[
    R_K = 0.846^{+0.060}_{-0.054} \text{ (stat)}^{+0.014}_{-0.016} \text{ (syst)}
\]

Compatible with SM expectation at 2.5 \( \sigma \)

R. Aaij et al., PRL 122 (2019) 191801
SUMMARY OF LEPTON UNIVERSALITY IN $b \to s \ell^+ \ell^-$

- Ratios of muons/electrons extremely well predicted in the SM ($R_K$)
  - Hadronic uncertainties $O(10^{-4})$  
    JHEP 07 (2007) 040
  - QED uncertainties $O(10^{-2})$  
    EPJC 76 (2016) 8, 440

$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)} \overset{\text{SM}}{\approx} 1$$

- $B^+ \to K^+ \ell^+ \ell^-$
  - LHCb 2.5 $\sigma$
  - Any statistically significant deviation from 1 indicates New Physics

- $B^0 \to K^{*0} \ell^+ \ell^-$
  - 2.1-2.5 $\sigma$

Belle new result ($K^{*0} + K^{*+}$): arXiv: 1904.02440

LHCb: JHEP 08 (2017) 055  
LHCb: PRL 113 (2014) 151601  
BaBar: PRD 86 (2012) 032012  
Belle: PRL 103 (2009) 171801
$B_{(s)}^0 \rightarrow \mu^+\mu^-$  GOLDEN CHANNEL

$B_{(s)}^0 \rightarrow \mu^+\mu^-$ is the cleanest exclusive $b \rightarrow s \ell^+\ell^-$ process, strongly constraining the scalar (S), pseudoscalar (P), and $C_{10} \mu^\prime$ operators, beyond the SM. All QCD effects encapsulated in a decay constant: $f_{B_s} = 230.7(1.3)$ MeV from lattice QCD RBC–UKQCD collab. arXiv: 1311.0276, HPQCD, Fermilab Lattice and MILC collab.

All LHC experiments have contributed to establishing the $B_s \rightarrow \mu^+\mu^-$ signal:

ATLAS collab. JHEP 04 (2019) 098  (latest, next)

By exploiting $\Delta \Gamma_s \neq 0$, LHCb has accessed the effective $B_s$ lifetime ($y_s \equiv \tau_{B_s} \Delta \Gamma/2$)

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s}}{1 - y_s^2} \left[ \frac{1 + 2 A_{\Delta \Gamma}^{\mu^+\mu^-} y_s + y_s^2}{1 + A_{\Delta \Gamma}^{\mu^+\mu^-} y_s} \right]$$

Even if hardly constrained so far, a future measurement of $A_{\Delta \Gamma}^{\mu^+\mu^-} \neq +1$ (SM), would unveil NP scenarios for P, S operators
\[ B_{(s)}^{0} \rightarrow \mu^{+}\mu^{-} \text{ UPDATE} \]

- Latest measurement by ATLAS adds to the earlier results by LHCb and CMS. Because \( B^0 \) and \( B^{0s} \) masses are close, some maximum likelihood unfolding is needed, that takes into account the resolution properties of each experiment.

- Combined probabilities have been evaluated J. Aebischer et al., arXiv:1903.10434, and some tension appears with respect to the SM predictions, defined by:

\[
\begin{align*}
\text{BR}(B_s^0 \rightarrow \mu^+\mu^-)_{\text{SM}} &= 3.67 \pm 0.15 \times 10^{-9} \\
\text{BR}(B^0 \rightarrow \mu^+\mu^-)_{\text{SM}} &= 1.14 \pm 0.12 \times 10^{-10}
\end{align*}
\]

- Interesting future complementarity, since LHCb and ATLAS/CMS seem to be measuring different linear combinations of BR’s.

**B_{s}^{0} \rightarrow \mu^{+}\mu^{-}  FUTURE SCOPE**

1. Latest LHCb and ATLAS results have reached $\sim 25\%$ uncertainty on $\mathcal{B}(B_{s} \rightarrow \mu^{+}\mu^{-})$.

2. Low-$p_T$ of dimuon triggers and mass resolution will define the performance at HL–HE LHC, for $B_{s,d} \rightarrow \mu^{+}\mu^{-}$ analysis.

3. At LHCb, improved tracking and muon shielding will ensure non degraded performance with increasing pileup. The CMS inner tracker detector at HL–LHC will result in improved $B_{s}/B_{d}$ separation.

4. The estimated experimental sensitivity at HL–LHC is close to the uncertainty of current SM theory prediction (dominated by $f_{B_{s}}$).

---

**Table:**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Scenario</th>
<th>$B(B_{s}^{0} \rightarrow \mu^{+}\mu^{-})$ (stat + syst. %)</th>
<th>$B(B^{0} \rightarrow \mu^{+}\mu^{-})$ (stat + syst. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>23 fb$^{-1}$</td>
<td>8.2</td>
<td>33</td>
</tr>
<tr>
<td>LHCb</td>
<td>300 fb$^{-1}$</td>
<td>4.4</td>
<td>9.4</td>
</tr>
<tr>
<td>CMS</td>
<td>300 fb$^{-1}$</td>
<td>12</td>
<td>46</td>
</tr>
<tr>
<td>CMS</td>
<td>3 ab$^{-1}$</td>
<td>7</td>
<td>16</td>
</tr>
<tr>
<td>ATLAS</td>
<td>Run 2</td>
<td>22.7</td>
<td>135</td>
</tr>
<tr>
<td>ATLAS</td>
<td>3 ab$^{-1}$ Conservative</td>
<td>15.1</td>
<td>51</td>
</tr>
<tr>
<td>ATLAS</td>
<td>3 ab$^{-1}$ Intermediate</td>
<td>12.9</td>
<td>29</td>
</tr>
<tr>
<td>ATLAS</td>
<td>3 ab$^{-1}$ High-yield</td>
<td>12.6</td>
<td>26</td>
</tr>
</tbody>
</table>
Some recent interpretations: J. Aebischer et al. [1903.10434], M. Algueró et al. [1903.09578]

- Data strongly prefer a solution with NP pointing at $C_9 = - C_{10}$
- Fits able to discriminate an additional LF-Universal shift in $C_9$
- Shift can be generated by 4-fermion operators (above EW scale), in particular a semi-tauonic operator (loop induced), also accounting for $R_D, R_{D^*_s}$ data

NP context: vector leptoquark, $Z'$ models with vector-like quarks ...

Prospects for LU Tests in $R_{HS} (b \to s \ell^+ \ell^-)$

- Precision in $R_{K(*)}$ expected to be comparable for Belle II and LHCb at the end of the former data taking (2025).
- For LHCb, significantly higher efficiencies for $e$ and $\mu$ channels will be achieved from suppression of the hardware trigger bottleneck (after 2021). However larger pile-up in Upgrade II may increase backgrounds. Belle II precision is expected to be statistics dominated.

- New possibilities for LFU in $b \to s \ell \ell$ arise from $R_\phi$ and $R_{pK}$, due to the large production cross-sections. $R_\phi$ particularly interesting, free of backgrounds from higher hadronic resonances $h \to \phi$.
- If no change in current central values of $R_{K(*)}$, both Belle II and LHCb will be able to confirm LU violation with $> 5\sigma$ by 2025.

In the SM, lepton flavor violation (LFV) may only occur from loop diagrams with neutrino oscillations (strong $m_{\nu}^2$ suppression), unobservable at future facilities.

A presumptive breaking of lepton universality (LU) by the weak anomalies in CCs and FCNCs reinforces the importance of LFV searches, as LU violation usually implies LFV as well. S.L. Glashow, D. Guadagnoli, K. Lane, PRL 114, 091801 (2015)

LHCb has searched for $B_{(s)} \to \tau^+ \mu^-$ and $B^+ \to K^+ \mu^- e^+$ decays, with Run 1 data.

SEARCH FOR $B_{(s)}^{+} \rightarrow \tau^{+} \mu^{-}$

- $\tau^{-} \rightarrow \pi^{-} \pi^{+} \pi^{-} \nu_{\tau}$ vertex detached from PV, good B-mass resolution, despite $\nu_{\tau}$ (2-fold ambiguity). $B^{0} \rightarrow D^{-} (\rightarrow K^{+}\pi^{-}\pi^{-}) \pi^{+}$ provides normalisation. Same sign $\tau^{+}\mu^{+}$ serves as background proxy.

- First measurement for the $B_{s}$ meson, and factor $\sim 2$ improvement wrt to BaBar result for $B^{0}$. Very significant constraint to 3-site Pati-Salam model

<table>
<thead>
<tr>
<th>Mode</th>
<th>Limit</th>
<th>90% CL</th>
<th>95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{s}^{0} \rightarrow \tau^{\pm} \mu^{\mp}$</td>
<td>Observed</td>
<td>$3.4 \times 10^{-5}$</td>
<td>$4.2 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>Expected</td>
<td>$3.9 \times 10^{-5}$</td>
<td>$4.7 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B^{0} \rightarrow \tau^{\pm} \mu^{\mp}$</td>
<td>Observed</td>
<td>$1.2 \times 10^{-5}$</td>
<td>$1.4 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>Expected</td>
<td>$1.6 \times 10^{-5}$</td>
<td>$1.9 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Peaking simulated sample $B_{s} \rightarrow D_{s} (\mu\bar{\nu}) \pi\pi\pi$ before and after full selection criteria
SEARCH FOR $B^+ \rightarrow K^+ \mu^- e^+$

- LHCb has also searched for the LF violating decay $B^+ \rightarrow K^+ \mu^\pm e^\mp$, using $3 \text{ fb}^{-1}$.
- Displaced 3 charged tracks vertex, with well identified $K, e, \mu$ are required
- Normalisation is provided by $B^+ \rightarrow K^+ J/\psi \rightarrow \mu^- \mu^- / e^+ e^+$, accurately described in the analysis
- Current limits are improved by an order of magnitude, posing important constraints on leptoquark, extended gauge boson models, or CP violation in neutrino sector

<table>
<thead>
<tr>
<th>$\mathcal{B}/10^{-9}$</th>
<th>90% C. L.</th>
<th>95% C. L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow K^\pm \mu^- e^\mp$</td>
<td>6.3</td>
<td>8.2</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^\pm \mu^+ e^-       $</td>
<td>5.7</td>
<td>7.6</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+ \mu^+ e^-       $</td>
<td>5.7</td>
<td>7.6</td>
</tr>
</tbody>
</table>

LHCb-PAPER-2019-022, preliminary

1(2) signal events observed after unblinding, respectively, in agreement with background-only hypothesis

Muon normalisation channel

Electron normalisation channel, one brems. photon recovered
RESULTS and OPPORTUNITIES in low-$P_T$ TRIGGERS
SEARCH FOR $K_{s}^{0} \rightarrow \mu^{+}\mu^{-}$

- The SM prediction for $K_{s}^{0} \rightarrow \mu^{+}\mu^{-}$ is very strongly suppressed and dominated by long-distance contributions, which can be constrained using the observed $K_{s}^{0} \rightarrow \gamma\gamma$ and $K_{s}^{0} \rightarrow \pi^{0}\gamma\gamma$ leading to the prediction $\mathcal{B}(K_{s}^{0} \rightarrow \mu^{+}\mu^{-}) = (5.0 \pm 1.5) \times 10^{-12}$ Isidori, Unterdorfer, JHEP 01 (2004) 009.

- LHCb trigger system not originally prepared for the very low-$p_{T}$ s-quark physics, but drastic improvements took place for Run 2. F. Dettori, D. Martinez Santos, J. Prisciandaro, LHCb-PUB-2017-023

- LHCb with 3 fb$^{-1}$ has obtained the world’s best upper limit (overall improvement factor $\sim$ 30)

$$\mathcal{B}(K_{s}^{0} \rightarrow \mu^{+}\mu^{-}) < 0.8 (1.0) \times 10^{-9} \text{ at } 90\% (95\%) \text{ CL.}$$

- $K_{s}^{0} \rightarrow \pi^{+}\pi^{-}$ decays provide normalization and constitute the main background source, along with combinatorial random matchings. Dedicated multivariate classifiers are used to strongly suppress both backgrounds.
SEARCH FOR $\Sigma^+ \rightarrow p \mu^+ \mu^-$

LHCb collaboration, PRL 120 (2018) 221803

- The HyperCP collaboration, H. Park et al. PRL 94 (2005) 021801 reported evidence of $B(\Sigma^+ \rightarrow p \mu^+ \mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$ and observed 3 candidates $X^0 \rightarrow \mu^+ \mu^-$ at nearly the same mass $m_{\mu\mu} = 214.3 \pm 0.5 \text{ MeV/c}^2$

- Such particle was subject to several BSM interpretations, including a light pseudoscalar Higgs boson X.He, J. Jandeau, G. Valencia, PRL 98 (2007) 081802

- Despite the insufficient $p_T$ of $\Sigma^+$ decays to pass the LHCb trigger, the $\Sigma^+ \rightarrow p \mu^+ \mu^-$ signal is partially acquired independently of the signal (TIS), and so is the normalization channel $\Sigma^+ \rightarrow p\pi^0$ used in this analysis

- The decay fraction is seen $B(\Sigma^+ \rightarrow p \mu^+ \mu^-) = (2.2^{+0.9+1.5}_{-0.8-1.1}) \times 10^{-8}$ compatible with the SM predictions

- A scan is steps of $\sigma_{\mu\mu}$ was made and no significant signal was found consistent with an intermediate particle, with limit:
  
  $B(\Sigma^+ \rightarrow pX^0(\rightarrow \mu^+ \mu^-)) < 1.7 \times 10^{-8} \text{ (95\%CL)}$
PROSPECTS FOR K-PHYSICS AT LHCb

- The LHCb prospects for searching $K_s^0 \rightarrow \pi^+\pi^-$ decays are excellent.

- The theoretical prediction $\mathcal{B}(K_s^0 \rightarrow \mu^+\mu^-)_{SM} = (5.18 \pm 1.50_{LD} \pm 0.02_{SD}) \times 10^{-12}$ leaves room for small BSM contributions to interfere and compete with SM rate, such as leptoquark models (LQ), and MSSM.


- In LQ case, enhancements can reach up to the current limit, while for MSSM $\mathcal{B}(K_s^0 \rightarrow \mu^+\mu^-)$ can range within $[0.78, 35.00] \times 10^{-12}$.

- The full-software trigger, to operate at the Phase II of HL-LHC, will allow exploration of BF’s below $10^{-10}$. Provided $\varepsilon^{Trig} \approx 1$, LHCb could exclude BF’s down to the vicinity of the SM prediction.

  Estimated uncertainty on the sensitivity, due to model systematics, statistical subtraction of $K_L^0 \rightarrow \mu^+\mu^-$ background.

OTHER K-PHYSICS TOPICS AT LHCb UPGRADE

- At Run 2, LHCb trigger has provided access to muon $p_T$ as low as 80 MeV/c (minimum allowed by geometry and B-field), thus increasing trigger efficiency for $K_s^0 \rightarrow \mu^+\mu^-$, $K_s^0 \rightarrow \pi^0\mu^+\mu^-$, $\Sigma^+ \rightarrow p\mu^+\mu^-$, $K^+ \rightarrow \pi^+\mu^+\mu^-$, ..., $\times \mathcal{O}(10)$ LHCb-PUB-2017-023

- With a full-software trigger (L0 removed) $\varepsilon_{\text{Trig}} \approx \mathcal{O}(1)$ are attainable in the LHCb Upgrade (Phases I and II), for dimuons A.A. Alves Junior et al., JHEP 05 (2019) 048

- Two examples of LHCb prospective measurements A. Cerri et al. CERN-LPCC-2018-06 arXiv:1812.07638:
  - Tighter bounds on LFU can be set by improving the poorly known semimuonic hyperon decay BF’s ($\Lambda \rightarrow p\mu\bar{\nu}_\mu$, $\Xi^- \rightarrow \Sigma^0\mu\bar{\nu}_\mu$), since electron modes are already very well measured
  - Baryon-number and lepton-number violating decays (suppressed by $(m_W/\Lambda_{\text{GUT}})^4$) can be explored, beyond recently reported searches by CAS M. E. McCracken et al., PR D92 (2015) 072002, to reach sensitivities in $\Lambda \rightarrow hl$ modes of $\mathcal{O}(10^{-9})$
SEARCH FOR LOW–MASS AXION–LIKE PARTICLES

- \( f_a \) decay constants for axion-like particles (ALP) are favored, both theoretically and from DM searches, with ALP’s having \( \gamma \gamma \) and gg couplings. X. Cid Vidal et al. JHEP 1901 (2019) 113.

- LHCb has developed a low mass diphoton trigger, designed to look for the rare decay \( B_s^0 \rightarrow \gamma \gamma \) LHCb-PUB-2018-006, that motivates a dedicated LHCb search for \( \gamma \gamma \) resonances in the broader mass range \( m_{\gamma \gamma} \in [3, 20] \text{ GeV/c}^2 \)

- Axions acquire a significant longitudinal boost and no extra \( E_T \)-jets are needed. Decay widths \( \Gamma_{\gamma \gamma} \) and \( \Gamma_{gg} \) are very narrow, so that:

\[
(0.1\text{mm})^{-1} \ll \Gamma_{\gamma \gamma} + \Gamma_{gg} \ll m_{\gamma \gamma}^{\text{bin}}
\]

- LHCb sensitivity to \( f_a \) in \( \sigma (p p \rightarrow a) \), for expected \( \int \mathcal{L} dt \) values, is very complementary to that of ATLAS and CMS at higher masses

\[
\mathcal{L}_{\text{eff}} \supset \frac{N \alpha_3}{4\pi} \frac{a}{f} G_{\mu \nu} \tilde{G}^{\mu \nu} + \frac{E \alpha_{\text{em}}}{4\pi} \frac{a}{f} F_{\mu \nu} \tilde{F}^{\mu \nu}
\]
SUMMARY

- The LHCb experiment has successfully completed Run 1 and Run 2 (2010-2018) and collected nearly 9 fb$^{-1}$ of integrated luminosity, as originally conceived.

- A program of *precision* measurements of CP-violation in the b- and c-sectors has been carried out. CP-violation has been observed in the charm sector at the level $10^{-3}$, and ascribed to direct decay amplitudes. Searches for new physics will continue to even higher precision.

- Detailed investigations have been performed on LFU, both in charged currents and in flavor-changing neutral currents, and on weak anomalies and LF-violating decays. Studies will continue to elucidate whether amplitudes beyond the SM are required to understand the data.

- An Upgrade program is underway (Phase I), and the physics case has been made public for a Phase II, within a HL LHC, beyond 2030.

- QCD studies have not been discussed, where a very rich field of new measurements has been launched, both exotic and non exotic.
THANK YOU

LA GRAN VIA:

VISTA, MIRANDO AL ESTE, DESDE SU ENCUENTRO CON LA CALLE DE LA CORREDERA BAJA DE SAN PABLO.

(Proyecto del arquitecto municipal D. Carlos Velasco.)