Highlights from the LHCb Experiment

Nico Serra (Universität Zürich) on behalf of the LHCb collaboration

XIX Lomonosov Conference on Elementary Particle Physics

22nd-28th August — Moscow State University
Flavour Physics at LHCb

- Searches for new CP Violation sources:
  - B-hadron decays
  - Open Charm

- Flavour Anomalies and related measurements:
  - Rare Decays
  - Semileptonic Decays

- LHCb does much more, for example:
  - Dark Sector Searches:
    - Searches for Dark Scalars, Dark Photons, ...
  - Spectroscopy:
    - First observation of various new states, e.g. Pentaquarks
  - ...

Talk by Francesca Dordei (24/8 at 16.10)

This talk
The LHCb Detector JINST 3 (2008) S08005

- $b\bar{b}$ produced predominantly forward and backward
- Displacement between primary (PV) and secondary (SV) vertexes one of the main discriminating variable
- Run 1 LHCb collected 1+2 fb$^{-1}$ of data in 2011+2012
- Run 2 LHCb collected 6 fb$^{-1}$ of data between 2015 and 2018 (roughly twice b-meson per fb$^{-1}$ due to increased $\sqrt{s}$ )
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Rare Decays
Use an effective operator approach, similar to Fermi theory of weak interaction
Effective Hamiltonian

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

Local operators
\[ \langle f | O_i | i \rangle \text{ Long distance QCD} \]

New Physics can contribute to different WCs depending on its Lorentz structure

\[ \mathcal{O}_9^{(*)} \propto \left( \bar{s} \gamma_\mu P_{R(L)} b \right) \left( \bar{\ell} \gamma^\mu \ell \right) \]

\[ \mathcal{O}_7^{(*)} \propto \left( \bar{s} \sigma_{\mu\nu} P_{R(L)} b \right) F_{\mu\nu} \]

\[ \mathcal{O}_{10}^{(*)} \propto \left( \bar{s} \gamma_\mu P_{R(L)} b \right) \left( \bar{\ell} \gamma^\mu \gamma_5 \ell \right) \]

\[ \mathcal{O}_P^{(*)} \propto \left( \bar{s} P_{R(L)} b \right) \left( \bar{\ell} \gamma^\mu \gamma_5 \ell \right) \]

\[ b \rightarrow s \gamma \]

\[ B \rightarrow K^{(*)} \ell \ell \]

\[ B_{(s)}^0 \rightarrow \ell^+ \ell^- \]
$B^0 \rightarrow K^* (\rightarrow K^+ \pi^-) \mu^+ \mu^-$

This decay is described by 3 angles ($\theta_l, \theta_K, \phi$) and the di-muon invariant mass squared ($q^2$)

This is analogous to the orbitals in atoms, i.e. the spectroscopy allows you to infer about atomic potential

\[
\frac{1}{\Gamma} \frac{d^3(\Gamma + \Gamma)}{d\cos \theta_l \, d\cos \theta_K \, d\phi} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_l \right. \\
- F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + \\
\sqrt{F_L (1 - F_L)} P_5' \sin 2\theta_K \sin \theta_l \cos \phi + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi + \\
S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \left. \right]
\]
$B^0 \rightarrow K^* (\rightarrow K^+ \pi^-) \mu^+ \mu^-$
Measurement of $P_{5'}$

- Discrepancy first observed in 2013 with $1\text{fb}^{-1}$
- Confirmed consistent result in 2016 with $3\text{fb}^{-1}$
- Analysis with Run 2 dataset ongoing
ATLAS, CMS and Belle also measured this quantity

The discrepancy in $P_5'$ wrt SM can be interpreted as NP in either $C_9$ or $C_9/10$ simultaneously
A Coherent Pattern?

- Data consistently below SM predictions
- Large theory uncertainty due to form factors

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Theory Uncertainty

- Both $P_5'$ and the branching ratios discrepancy can be explained with the same shift in $C_9$ or $C_{9/10}$
- Charm loop contribution is essentially a correction to $C_9$ not possible to compute this contribution reliably

- Long debate on the community if the relatively large effect we see is NP or can be attributed to charm loop
- Charm loop can be considered as the sum of the tails of all resonances + open charm

See talk by J. Matias 24/8 at 15.25
LFU in Rare Decays

\[
\begin{align*}
\bar{b} & \rightarrow \mu^+ \mu^- \\
\bar{b} & \rightarrow e^+ e^- \\
\end{align*}
\]

\[= 1.00 \pm 0.01\]

Electron emit bremsstrahlung photons spoiling \(q^2\), invariant mass and momentum resolutions:
- More complicate and difficult J/ψ veto
- Harder trigger, reconstruction, PID, smaller efficiency wrt muons
LFU in Rare Decays

Electron emit bremsstrahlung photons spoiling $q^2$, invariant mass and momentum resolutions:
- More complicate and difficult J/ψ veto
- Harder trigger, reconstruction, PID, smaller efficiency wrt muons
- Critical aspect in these analyses is the double ratio with the corresponding J/ψ modes

$$= 1.00 \pm 0.01$$
LFU in Rare Decays

\[ R(K^+) = \frac{\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \rightarrow K^+e^+e^-)} \]

\[ \times \frac{\mathcal{B}(B^+ \rightarrow K^+J/\psi(\rightarrow e^+e^-))}{\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)} \]

Ratio of efficiency determined with simulation using control channels:
- B-momentum kinematics, Tracking Efficiency,
- Particle Identification
- Trigger calibration
- Calibration of \( q^2 \) distribution and invariant mass
LFU in Rare Decays

\[ R(K^+) = \frac{\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-) \mathcal{B}(B^+ \rightarrow K^+J/\psi(\rightarrow e^+e^-))}{\mathcal{B}(B^+ \rightarrow K^+e^+e^-) \mathcal{B}(B^+ \rightarrow K^+J/\psi(\rightarrow \mu^+\mu^-))} = \frac{\int_{6.0 GeV^2}^{1.1 GeV^2} \frac{d\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)}{dq^2}}{\int_{6.0 GeV^2}^{1.1 GeV^2} \frac{d\mathcal{B}(B^+ \rightarrow K^+e^+e^-)}{dq^2}} = 0.846^{+0.060}_{-0.054}(\text{stat})^{+0.016}_{-0.014}(\text{syst}) \]

- 1.9 sigmas compatibility between Run1 and Run2
- Combined dataset 2.5 sigmas from SM predictions

Run1 + 2fb^{-1} (out of 6fb^{-1}) of Run2 (2015/2016)

\[
R_{K \text{ Run 1}}^{\text{new}} = 0.717^{+0.083+0.017}_{-0.071-0.016}; \quad R_{K \text{ Run 2}} = 0.928^{+0.089+0.020}_{-0.076-0.017}, \\
R_{K \text{ Run 1}}^{\text{old}} = 0.745^{+0.090}_{-0.074} \pm 0.036 \quad (\text{PRL113}(2014)151601),
\]
Discrepancy with respect to the SM, numerically consistent with the $b \rightarrow s \mu \mu$

Surprising result at low $q^2$, would expect this part to be dominated by the photon contribution, but large statistical error still

Compatibility with SM 2.2-2.4σ (low-$q^2$) 2.4-2.5σ (central-$q^2$)

Only 3fb$^{-1}$ of Run1 used for this analysis

Already 6 fb$^{-1}$ of Run2 available
\[ B_{s,d} \rightarrow \mu^+ \mu^- \]

- \( B_{s,d} \rightarrow \mu^+ \mu^- \) branching ratio sensitive to scalar and pseudo-scalar contributions, which lift helicity suppression

- No large enhancement, but still precise measurement of this decay sensitive to \( C_{10} \)

\[ BR(B_s \rightarrow \mu^+\mu^-) \propto |C_{10} - C_{10}'|^2 \]

- **LHCb** First observation (7.8\( \sigma \)) by a single experiment **PRL 118 (2017) 191801**

- **CMS PRL 111 (2013) 101804** to be updated with **CMS PAS BPH-16-004** (presented at Lepton-Photon 2019)

- **ATLAS JHEP 04 (2019) 098**

- Branching ratio of \( B_s \rightarrow \mu^+ \mu^- \) in agreement within about 2\( \sigma \) with predictions

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

\[ BR(B_s \rightarrow \mu^+\mu^-)_{SM} = (3.65 \pm 0.23) \times 10^{-9} \]

\[ BR(B^0 \rightarrow \mu^+\mu^-)_{SM} = (1.06 \pm 0.09) \times 10^{-10} \]
Wilson Coefficient Fits

J Matias et al., Portoz 2019 & 1903.09578

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D. Straub Moriond EW 2019 & 1903.10434
Searches for LFV

• Most New Physics models explaining the flavour anomalies predict visible branching fractions for LFV decays


• We searched for the decay \( B^+ \rightarrow K^+ e^+ \mu^- \)
  with Run 1 dataset, observing no signal and setting the upper limits

\[
\begin{align*}
\text{BR}(B^+ \rightarrow K^+ \mu^- e^+) & \leq 7.0 \times 10^{-9} @90\% \text{ CL} \\
\text{BR}(B^+ \rightarrow K^+ \mu^+ e^-) & \leq 7.1 \times 10^{-9}
\end{align*}
\]

• improvement by more than 1 order of magnitude

LHCB-PAPER-2019-022-002
Searches for LFV

- For several BSM models $B \to \mu\tau$ is a strong constraint
- Status before spring 2019:
  - $\text{BR}(B^0 \to \tau^+\mu^-) < 2.2 \times 10^{-5}$ [BaBar PRD77(2008)091104]
  - $B_s \to \tau^+\mu^- :$ no limit yet

- We searched for these decays with Run 1 and using the decay $\tau \to 3\pi\nu$:
  \[
  \text{BR}(B^0 \to \tau^+\mu^-) \leq 1.2 \times 10^{-5} \quad \text{at 90\% CL}
  \]
  \[
  \text{BR}(B_s \to \tau^+\mu^-) \leq 3.4 \times 10^{-5}
  \]
- Improvement on $B^0$
- First result on $B_s$

arXiv:1905.06614
Semileptonic Decays
LFU with Semileptonic

$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)} \tau \nu)}{\mathcal{B}(B \to D^{(*)} \mu \nu)} = \frac{\text{Signal}}{\text{Normalization}}$

- B-factories exploit the fact that $B_{\text{sig}}$ momentum
- B-factories use the electron, muon and hadronic modes
- LHCb only uses $\tau \to \mu 2\nu$ and $\tau \to 3\pi \nu$
- B-factories have cleaner events, while LHCb larger statistics
LFU with Semileptonic

\[ B \rightarrow D^{*}\tau\nu \quad B \rightarrow D^{*}\mu\nu \]

\[
(\gamma\beta z)_B \simeq (\gamma\beta z)_{D^*}\mu \Rightarrow (p\tilde{z})_B = \frac{m_B}{m(D^*\mu)}(p\tilde{z})_{D^*}\mu
\]

- Fit of \( E^* \) and missing mass using template from the simulation tuned with data
- Background from \( B \rightarrow D^* D_{(s)} \) and from \( B \rightarrow D^{**}\ell\nu \) taken from control regions

LHCb simulation

Supplementary material PRL115(2015)111803

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22\textsuperscript{nd} - 28\textsuperscript{th} Aug 2019
LFU with Semileptonic

$$\tau \rightarrow \mu 2\nu$$
\[ R(D^*)_{\tau \rightarrow \mu 2\nu} = 0.336 \pm 0.027 \pm 0.030 \]

$$\tau \rightarrow 3\pi\nu$$
\[ R(D^*)_{\tau \rightarrow 3\pi\nu} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013 \]

SM Prediction average (HFLAV 2019)
\[ R(D^*)_{SM} = 0.254 \pm 0.05 \]
HFLAV Combinations

HFLAV2019

- Tension wrt SM predictions goes from 3.8σ (pre-Moriond 2019) to about 3σ (post-Moriond 2019)

Near Future

Rare Decays

- $R(K^*)$ measurement with full Run1+Run2 (only Run1)
- $R(K)$ measurement with full Run1+Run2 (only Run1 + 2015-2016)
- Measurement of other related decays $R(\phi)$, $R(K\pi\pi)$, $R(\Lambda^{(*)})$
- Measurement of non-LFU angular asymmetries in $B^0 \to K^*\ell^+\ell^−$ such as $\Delta P_{5'}$
- Measurement of $C_9^{\mu\mu} - C_9^{ee}$ and $C_{10}^{\mu\mu} - C_{10}^{ee}$ Phys. Rev. D 99, 013007 (2019)

Semileptonic Decays

- Measurement of $R(D^*)$ from LHCb still with Run1, but much better trigger efficiency for Run2

- Several measurements in the pipeline:
  - Simultaneous measurement of $R(D^*)$ and $R(D^0)$ with Run1 + Run2
  - Measurement of $R(D_s)$ with Run2
  - Measurement of $R(D^\pm)$ and $R(D^*)$ with Run2
  - Measurement of $R(\Lambda_c)$ with Run2

  Less feed-down background
LHCb Upgrade
LHCb Upgrades

- Upgrade of the LHCb detector during LHC LS2 (2019-20):
  - Change subdetector electronics to 40 MHz readout
  - All trigger decision software
  - Start data taking in 2021
  - Upgrade detector qualified to accumulate 50 fb$^{-1}$

In order to exploit the full potential of the LHC, it is natural to have a further major LHCb upgrade during LS4

The Upgrade II will allow to increase data sample from 50 fb$^{-1}$ to 300 fb$^{-1}$
LHCb Upgrades

Expected LHCb sensitivity with Upgrade II: \( \frac{\sigma(R(D^*))}{R(D^*)} \sim 1\% \)

Angular analysis of semi-tauonic decays allow to determine spin structure of potential NP contribution

[CERN-LHCC-2017-003]
[CERN-LHCC-2018-027]

Physics of the HL-LHC, WG 4 Flavour
[arxiv:1812.07638]
Conclusions

- Intriguing pattern of anomalies in rare and semi-leptonic decays, measured by LHCb, BaBar and Belle

- Still need much larger statistics to understand if these anomalies are a genuine sign of PBSM

- More results will come from LHCb Run2 analyses for both anomalies

- LHCb Upgrades will allow to further clarify the situation and if these anomalies are due to NP to disentangle between different scenarios
Let’s hope flavour anomalies do not have a disappointing finale
Thanks for the attention