Flavor anomalies at LHCb

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on behalf of the LHCb collaboration

(Re)interpreting the results of NP searches at the LHC,
May 14th–16th 2018, CERN
Many interesting topics I won’t have time to cover here...

- $\phi_s$, $B^0_{(s)} \rightarrow \mu^+\mu^-$, radiative penguins, CPV in charm, ...
- Dark photon and LLP searches. See also LHCb scenario and CODEX-$b$ talks at LLP workshop to follow.

LHCb Public results page is our Data portal

The LHCb Public results

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<td>Observation of the decay $\Lambda_b^0 \rightarrow \Lambda_c^+ p p \pi^-$</td>
<td>PAPER-2018-005 arXiv:1804.09617 [PDF]</td>
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**NP HUNTING STRATEGY IN b-PHYSICS**

- Multi-scale problem: QCD, hadronic form-factors, Electroweak, NP.

\[ \Lambda_{\text{QCD}} \quad m_B \quad m_{W,t,H} \quad \Lambda_{\text{NP}} \]

\[ 0.2 \text{ GeV} \quad 5 \text{ GeV} \quad 100 \text{ GeV} \quad \gtrsim \text{ TeV} \]

- Effective Field Theory: separate long and short distance scales. SM + a basis of dim-6 local operators, \( O_i \) and Wilson coefficients \( C_i \)

  \[ \mathcal{H}_{\text{eff}(6)}^{\text{SM}} = -\frac{4G_F V}{\sqrt{2}} \sum_i C_i^{\text{SM}} O_i \]
  \[ \mathcal{H}_{\text{eff}(6)}^{\text{NP}} = \sum_i \frac{C_i^{\text{NP}}}{\Lambda_{\text{NP}}^2} O_i, \quad \Delta F = 1 \]

- Sensitive to \( \Lambda_{\text{NP}} \gtrsim \text{ TeV} \) scale thru’ \( C_i \). Need precision measurements.
**Operators for Charged and Neutral Currents**

**Charged current (SL tree-level):**

\[ b \rightarrow \{u, c\} \ell^- \bar{\nu}_\ell, \, \ell \in \{e, \mu, \tau\} \]

\[ V = \{V_{cb}, V_{ub}\}, \, \Lambda_{NP} \sim 1 \text{ TeV} \]

\[ O_{V_{L,R}} = (\bar{c}\gamma^\mu P_{L,R} b)(\bar{\ell}\gamma_\mu P_L \nu_\ell) \]

\[ O_{S_{L,R}} = (\bar{c} P_{L,R} b)(\bar{\ell} P_L \nu_\ell) \]

\[ O_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}\sigma_{\mu\nu} P_L \nu) \]

**Neutral FCNC (EWP loop-sup.).**

\[ b \rightarrow s \gamma_{pol}, \, b \rightarrow s \ell^+ \ell^-, \, \ldots \]

\[ V \sim \frac{\alpha}{4\pi} V_{ts} V^*_{tb}, \, \Lambda_{NP} \sim 10-100 \text{ TeV} \]

\[ O_{7\gamma}^{(\prime)} = \frac{m_b}{e} (\bar{s}\sigma^{\mu\nu} P_{R(L)} b) F_{\mu\nu} \]

\[ O_{9V}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma_\mu \ell) \]

\[ O_{10A}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma_\mu \gamma_5 \ell) \]
**Operators for charged and neutral currents**

- **Charged current (SL tree-level):**
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- **Neutral FCNC (EWP loop-supp.):**
  \[ b \rightarrow s \gamma_{\text{pol}}, \ b \rightarrow s \ell^+ \ell^-, \ldots \]
  \[ V \sim \frac{\alpha}{4\pi} V_{ts}^* V_{tb}, \ \Lambda_{NP} \sim 10-100 \text{ TeV} \]
  \[ O^{(7\gamma)} = \frac{m_b}{e} (\bar{s} \sigma^{\mu\nu} P_R(L) b) F_{\mu\nu} \]
  \[ O^{(9_V)} = (\bar{s} \gamma_\mu P_{L(R)} b)(\bar{\ell} \gamma_\mu \ell) \]
  \[ O^{(10_A)} = (\bar{s} \gamma_\mu P_{L(R)} b)(\bar{\ell} \gamma_\mu \gamma_5 \ell) \]

**SM is (almost) purely left-handed**
**B^0 \rightarrow K^* \mu^+ \mu^- ANGULAR ANALYSIS**

\[
\frac{d\Gamma}{dq^2 d\Omega} = \frac{9}{32\pi} \sum_{i=1}^{17} J_i(q^2)f_i(\theta_l, \theta_K, \phi)
\]

- \( J_i \) are bilinears of the transversity amplitudes \( A_0^{L,R}, A_{\perp}^{L,R}, A_{\parallel}^{L,R}, A_S^{L,R} \)

- Both short- and long-distance parts enter the amplitudes:

\[
A_{\perp}^{L(R)} \sim \left\{ \left[ (C_9^{\text{eff}} + C_9'^{\text{eff}}) \mp (C_10^{\text{eff}} + C_10'^{\text{eff}}) \right] \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} (C_7^{\text{eff}} + C_7'^{\text{eff}}) T_1(q^2) \right\}
\]

- Reduced FF uncertainties at LO: \( P_5' = \frac{J_5}{\sqrt{J_{1c}(1 - J_{1c})}} \), [1303.5794]
Status of $P'_5$ anomaly

Experiments:

  JHEP02(2016)104 (full Run1)
- Belle: JHEP02(2016)104

SM Theory (among many):

- DHMV: 1407.8526
- ASZB: 1411.3161, 1503.05534 (different treatment of the hadronic part)

- $2.8 \sigma$ and $3.0 \sigma$ local deviations with DHMV in two $q^2$ bins. $3.4 \sigma$ global discrepancy. Confirmation by Belle.
NP or “brown muck” aka QCD?

- $\Delta C_{9\mu} = C_{9\mu}^{NP} < 0$ from a tree-level $Z_\mu'$ would explain the anomaly. [Altmannshofer’14, Crivellin’15,...]

- Nasty issue for EWP: $\bar{c}c$ poles in the physical $q^2$ region (SL doesn’t have this). Mimics $\Delta C_{9\mu}$.
**Non-factorisable power corrections**

- **SL** and EWP $O_{7,9,10}$ factorizes into $H_\mu L^\mu$. Allows FF formalism.

- Additional EWP 4-quark operators $O_{1-6}$ factorizes only at $m_b \to \infty$ and $q^2 < 4m_c^2$ $c\bar{c}$ threshold.

- Perturbative corr: $C_9^{\text{eff}} = C_9 + Y_{\text{pert}}(q^2)$, plus a long distance part.

- For each helicity amplitude $A_{\lambda \in \{0, \pm\}}$, additional power correction:
  $$h_{\lambda}(q^2) = h_{\lambda}^{(0)} + q^2 h_{\lambda}^{(1)} + q^4 h_{\lambda}^{(2)}$$

- $h_{\lambda}(q^2)$ can accommodate the data, but undesirably large (> 100%) corrections.
Introduction: EFT for flavor physics

$h_\lambda(q^2)$: DATA-DRIVEN APPROACHES AT LHCb - I

- Unbinned ML fits to data w/ external inputs as Gaussian constraints.
- $C_9^{NP}$ can’t have $q^2$ dependence. $h_\lambda(q^2)$ same for $e/\mu$ cases.

1) [1709.03921] Assume $h_\lambda$ is a sum of relativistic Breit Wigners from \{\rho^0, \phi, J/\psi, \psi(2S), \psi(3770), \psi(4040), \psi(4160)\} with floating strong phases. Entire $q^2$ range.

- Method shown to work for Run I
  \[ B^+ \rightarrow K^+ \mu^+ \mu^- \] [EPJC(2017)77:161]

- For $K^*$, complicated by exotics in $J/\psi \pi$ and $K \pi$ S-wave
$h_\lambda(q^2)$: DATA-DRIVEN APPROACHES AT LHCb - II

2) [JHEP11(2017)176] Unbinned fit to $q^2 \in [0.1, 8]$ GeV$^2$.
   - Power corrections: $A_\lambda \rightarrow A_\lambda \times (1 + a_\lambda + b_\lambda \frac{q^2}{6})$

3) [1707.07305] Use analyticity to control $h_\lambda(q^2)$ in $q^2 < m_{\psi(2S)}^2$.
   - “$z$-expansion” with $J/\psi$ and $\psi(2S)$ poles removed:

   $$h_\lambda = \frac{1 - zz_{J/\psi}}{z - z_{J/\psi}} \frac{1 - zz_{\psi(2S)}}{z - z_{\psi(2S)}} \mathcal{F}(z) \left[ \sum_{i=0}^{N} a_i z^i \right]$$

   - Extract $a_i$ from fit to data.
3) (cont.) Only theory connection is LCSR calculation in the unphysical $q^2 < 0$ region (Khodjamirian’10).

- Issues: $|z_{\text{max}}| \sim 0.5$ is not truly small. Is the truncation error for expansion always under control?
BF’s systematically lower than SM

\[ B_+^0 \rightarrow \phi \mu^+ \mu^- \]

JHEP09(2015)179

\[ \Lambda_b \rightarrow \Lambda \mu^+ \mu^- \]

JHEP06(2015)115

\[ B^0 \rightarrow K^* \mu^+ \mu^- \]

JHEP11(2016)047

JHEP06(2014)133:

\[ B^+ \rightarrow K^+ \mu^+ \mu^- \]

LHCb

\[ B^0 \rightarrow K^0 \mu^+ \mu^- \]

LHCb

\[ B^+ \rightarrow K^{*+} \mu^+ \mu^- \]

LHCb
Higher resonances for $b \rightarrow s\ell^+\ell^-$ results

- Higher $K^*$ resonances region in $B^0 \rightarrow K^+\pi^-\mu^+\mu^-$ also probed.

Angular analysis reveals a surprisingly suppressed $D$-wave $K_2^*(1430)$. At odds with other experiments in the $m_{K\pi} \sim 1430$ MeV region.

- $f_2(1525) \rightarrow K^+K^-$ tensor in $B_s \rightarrow K^+K^−\mu^+\mu^−$ being searched as well. The two modes can be connected by $SU(3)$. 

![Graphs showing resonances and angular analysis results]
**Rare $b \to d$ FCNC Transitions**

- For $b \to d$, two interfering amplitudes from $t/u$ quark in the loop.
- $V_{ub}V_{ud}^*$ and $V_{tb}V_{td}^*$ both are $\propto \lambda^3$ and have a relative phase.
- Excellent place to probe CKM structure of NP. SM is suppressed.

$N_{\text{sig}} \sim 92$

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

JHEP10(2015)034

$B^0_s \to K^* \mu^+ \mu^-$

1804.07167

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

JHEP04(2017)029
Lepton Flavor Universality (LFU) in SM

- Standard Model: three generations of leptons \( \{e, \mu, \tau\} \) couple universally to the electroweak bosons. Only difference is in their mass.

**Semi-tauonic:**

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

Tree-level and \( R(D^{(*)}) < 1 \) with large \( \tau-\mu \) mass difference

**Electroweak penguins:**

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

Loop-level and \( R(K^{(*)}) \sim 1 \) upto small \( e-\mu \) mass difference
**LFU Run I Measurements**

**Semi-tauonic:**
- Global $\sim 4.1\,\sigma$ tension w/ SM

**Electroweak penguins:**
- $2.1 - 2.6\,\sigma$ tension w/ SM

**New $R(J/\psi)$ in $B_c^+ \rightarrow J/\psi\ell^-\bar{\nu}_\ell$**

(From PRL120, 121801(2018)) within $2\,\sigma$ of SM
Many different global fits incorporating different $b \to s\ell^+\ell^-$, $b \to s\gamma$ measurements.

Remarkable consistency: BF, angular, $R(K^{(*)})$ all point to $\Delta C^\mu_9 \sim -1$. 

Altmannshofer et al. 1703.09189
Altmannshofer et al. 1704.05435
Global fits

\[ b \rightarrow c\tau^- \bar{\nu}_\tau \] STATUS

- The most obvious one (charged Higgs), consistently disfavored

- Vector-like $\epsilon_{V_L} \sim 0.13$ (Grinstein) more viable.

- Could be good news since this should also affect $e/\mu$ modes where things are measurable

- Caveats: $\tau$'s are hard, $D^{**}$ backgrounds, ...

![Graph showing model prediction and data points for $R(D^*)$ as a function of $\tan(\beta)/m_{H^+}$ (GeV$^{-1}$).]
$|V_{ub}| - |V_{cb}|$ TENSIONS AND FF’S FOR $R(D^*)$

- Long known tension in the CKM parameters $|V_{ub}|$ and $|V_{cb}|$: inclusive and exclusive methods don’t agree. $\sim 3\sigma$ discrepancy.

- Same FF’s for $|V_{cb}|$ extraction from $\bar{B} \rightarrow D^* \ell^- \bar{\nu}_\ell$ enter $R(D^*)$

- FF parameterization (CLN) too constrained. Error budget underestimated (factor of $\sim 3$).

- Belle/BaBar data being re-analyzed with model-independent (BGL) FF [1702.01521, 1703.06124, 1703.08170, 1707.09509]
**FF SHAPE IN $\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu}$**

PRD96, 112005(2017)

- **FF shape** for a baryonic $b \to c$ transition for the first time.

- Reasonable agreement with unquenched lattice.

- Full angular analysis not possible for SL decays. **Resolution** not good enough due to missing $\nu$. 
The path ahead for LHCb...


- Many more $R(X)$, asymmetry measurements. TD-CPV in $B_s \rightarrow \phi \mu^+ \mu^-$, $B^0 \rightarrow K_S^0 \rho^0 \gamma$, ...

- Major upgrade in LS2.
- Consolidation in LS3.
- 50/fb by 2030. Phase II upgrade for HL-LHC, aiming for 300/fb.
**Our friendly competitors at SuperKEKB**

- First $e^+e^-$ collisions in Belle II on 26th April, 2018, after 7 years of preparation!
- $\sim 1.1/\text{ab}$ of $B\bar{B}$ at Belle+$\text{Babar}$. Aim for $50/\text{ab}$ at Belle II by 2024

- Different background, systematics. Entangled $B\bar{B}$ pairs, excellent flavor tagging, neutrino program, ...

- While, LHCb has large boost, access to all $b$-hadron species.

**Excellent overlap + complementarity between LHCb and Belle II**
If these flavor anomalies survive LHCb Run III and Belle II, strong motivation for a 100 TeV FCC-hh.
Backup slides
$q^2$ DEPENDENCE

large $K^*$
recoil (LCSR)

$E_{K^*} \text{ [GeV/c}^2\text{]}^2$

$J/\psi$

$\psi(2S)$

$K^*$ at rest
(lattice)

OPE

broad $c\bar{c}$
resonances

LHCb vetos

$|\mathcal{O}_{7\gamma}|$, pole

$|\mathcal{O}_{7\gamma} - \mathcal{O}_{9V}|$
interference

$|\mathcal{O}_{7\gamma}|$, pole

QCDF

$q^2 \text{ [GeV}^2/c^4\text{]}$
The LHCb Detector components
Phase II upgrade reach