Highlights of Rare Decays and Lepton Flavor Universality

Yangheng Zheng
University of Chinese Academy of Sciences
Dec. 23, 2017
The Third China LHC Physics Workshop
Nanjing University
Many new results since last CLHCP meeting!

- Introduction
- Selected highlight results in
  - Lepton Flavor Universality
    - \( b \rightarrow s l^+l^- \Rightarrow R(K), \ R(K^{*0}) \)
    - \( B^0 \rightarrow D^* \tau \nu \Rightarrow R(D^*), \ B_c \rightarrow J/\psi \tau \nu \Rightarrow R(J/\psi) \)
  - Rare decays
    - \( B_{(s)} \rightarrow \mu \mu, \ B_{(s)} \rightarrow e\mu \)
    - \( \Lambda_b \rightarrow p h \mu \mu \)
    - \( D^0 \rightarrow hh \mu \mu \)
    - \( \Lambda_c \rightarrow p \mu \mu \text{ (submitted on Dec. 21)} \)
    - \( K_S \rightarrow \mu \mu \)
- Summary
Test of Lepton Flavor Universality

✧ SM features: LFU $\Rightarrow$ equal electroweak coupling to $e$, $\mu$, and $\tau$. differ only due to their mass

✧ However, some deviations

✧ LEP: \[
\frac{2\sigma(W \rightarrow \tau \nu_\tau)}{\sigma(W \rightarrow e \nu_e) + \sigma(W \rightarrow \mu \nu_\mu)} \quad 2.8\sigma \text{ above SM [arXiv:0511027]}
\]

✧ B-factories & LHCb: \[
R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} - \tau^+ \nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)} - e^+ \nu_e)} \quad (\ell = \mu, e)
\]

a combined $4.1\sigma$ above SM [HFLAV]

✧ LHCb rare decay: \[
R_{K^{(*)}} = \frac{\mathcal{B}(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow K^{(*)} e^+ e^-)}
\]

$2.6\sigma$ below SM [PRL, 113, 151601 (2014), JHEP 08 (2017) 055]

✧ Possible BSM scenarios: leptoquarks, new heavy vector bosons, $H^\pm$, ...

✧ Measurements of ratios of these B branching ratios

✧ Theoretically clean: cancellation of QCD effects

✧ Experimentally clean: cancellation of efficiency and reconstruction effects
Motivation: $R(K^{(*)})$, $R(D^{(*)})$, $R(J/\psi)$

- FCNC $b \to sll \Rightarrow R(K^{(*)}) \equiv \mathcal{B}(B \to K^{(*)}\mu^+\mu^-)/\mathcal{B}(B \to K^{(*)}e^+e^-)$
  - Forbidden at the tree level
  - Very sensitive to NP contributions in the loops

- Tree Level $b \to c\tau\nu \Rightarrow R(X_c) \equiv \mathcal{B}(B \to X_c\tau^+\nu_\tau)/\mathcal{B}(B \to X_c\mu^+\nu_\mu)$
  - $X_c = D^{(*)}$, $J/\psi$
  - Abundant semileptonic decay
  - Very well known in SM
  - Possible NP coupling mainly to the 3rd family

Forbidden at the tree level

Very sensitive to NP contributions in the loops

Tree Level $b \to c\tau\nu \Rightarrow R(X_c)$

$X_c = D^{(*)}$, $J/\psi$

Abundant semileptonic decay

Very well known in SM

Possible NP coupling mainly to the 3rd family
LHCb: A Forward Spectrometer

Optimized for beauty and charm physics at large pseudorapidity (2<\(\eta\)<5)

✧ Advantages:

✧ Excellent vertexing, tracking and PID
✧ Trigger also on low momentum hadrons
✧ Enormous data sample from LHC high \(b\bar{b}\) and \(c\bar{c}\) cross sections
✧ All type of \(b\) and \(c\)-hadrons, including \(B_c\) and \(\Lambda_b\)

✧ Challenges:

✧ Missing neutrinos → unconstrained kinematics
✧ High track multiplicity → significant amount of background
✧ High particle momenta → significant Bremsstrahlung for electrons
Test of LFU with $B^0 \rightarrow K^{*0} l^+ l^-$

- Similar to $R(K)$
- Double ratio to minimize uncertainties
  - $R(K^{*0}) \equiv \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi(\rightarrow \mu^+ \mu^-))} / \frac{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi(\rightarrow e^+ e^-))}$
- Measured in two $q^2$ bins $[0.045 - 1.1]$ and $[1.1 - 6]$ GeV$^2$/c$^4$, with $K^{*0} \rightarrow K^+ \pi^-$
- Challenges are again trigger and Bremsstrahlung due to differences between $\mu$ and $e$
- Fit mass in low and central $q^2$ bins
- Simultaneous fit to $J/\psi$ and non-resonant channels
Test of LFU with \( R(K), R(K^{*0}) \)

- Ratios of branching fractions are powerful tests of LU as experimental systematics are reduced and theoretical uncertainties largely cancel.
- Extremely challenging due to differences in the way muons and electrons “interact” with the detector.

Compatibility with the SM prediction(s)
- \( R(K) \) 2.6σ
- \( R(K^{*0}) \) low-\( q^2 \) 2.1-2.3σ
- \( R(K^{*0}) \) central-\( q^2 \) 2.4-2.5σ

JHEP 08 (2017) 055
**LFU with** $B^0 \rightarrow D^* \tau \nu (\tau \rightarrow 3\pi \nu_\tau)$

- **R**($D^*$) \( \equiv \frac{B(B^0 \rightarrow D^* - \tau^+ \nu_\tau)}{B(B^0 \rightarrow D^* - 3\pi)} \times \frac{B(B^0 \rightarrow D^* - 3\pi)}{B(B^0 \rightarrow D^* - \mu^+ \nu_\mu)}, \)

  \( \tau^+ \rightarrow 3\pi (\pi^0) \nu_\tau \)

- Signal and normalization modes chosen to have the same final state

- **Main backgrounds**
  - $B^0 \rightarrow D^* 3\pi X$ (BR $\sim 100 \times$ signal)
    (Suppressed by requiring $\tau$ vertex)
  - $B^0 \rightarrow D^* D_s X$ (BR $\sim 10 \times$ signal)

- **BDT used to suppressed the remaining background**

- **Results**
  - Templates extracted from simulation and data control samples
  - $N(B^0 \rightarrow D^* - \tau^+ \nu_\tau) = 1300 \pm 85$

- **Dominant systematics:** size of simulation samples and external BR

---

Submitted to PRL (arXiv:1708.08856)
Generalization of $R(D^*)$ to $B_c^+$ decays

$$R(J/\psi) \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$

Theoretical prediction: $R(J/\psi) \in [0.25, 0.28]$ ($B_c^+$ decay form factors unconstrained experimentally)


Reconstruct signal with $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$

Main background: $b \to J/\psi + \text{mis-ID hadron}$

3D template binned fit

- Template distribution derived from control samples or simulations

Main systematics: Form factor and size of simulation sample

Analysis of $\tau \to 3\pi \nu_\tau$ is ongoing.

$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$

~2 $\sigma$ above SM
Summary of $R(D)$, $R(D^*)$ and $R(J/\psi)$

- $R(D)$ has been measured by Belle and BaBar
- Theoretical prediction
  \[ R(D) = 0.300 \pm 0.008 \text{ [HPQCD, PRD 92, 054510 (2015)]} \]

- Combination of LHCb, Belle and BaBar: 4.1\sigma wrt SM!

All $R(D^*)$ and $R(J/\psi)$ measurements lie above SM predictions
Anomalies in Rare Decays

Intriguing anomalies in rare decays of b-hadrons emerged in recent years.

\[ \text{JHEP 06 (2014) 133} \]

\[ \text{JHEP 09 (2015) 179} \]

\[ P^1 \]

\[ q^2 \text{ [GeV}^2/c^4] \]

\[ dB/dq^2 \text{ [10}^{-8} \times c^4/\text{GeV}^2] \]

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

\[ B_s \rightarrow \phi \mu\mu \]

\[ 3.3\sigma \text{ form SM} \]

• JHEP 02 (2016) 104
• ATLAS-CONF-2017-023
• PRL 118 (2017)
arXiv:1710.02846
Angular analysis: $B^0 \rightarrow K^{*0}\mu^+\mu^-$

- Give access to many different observables sensitive to NP

\[
\frac{1}{d\Gamma/dq^2 dq^2 d\cos \theta_L d\cos \theta_K d\phi} = \frac{9}{8\pi} \left\{ \frac{2}{3} \left[ (F_S + A_S \cos \theta_K) (1 - \cos^2 \theta_L) \ight.ight.
\]
\[
+ A_S^5 \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta_L} \cos \phi \left. \right] \right. + (1 - F_S) \left[ \frac{1}{2} (F_L \cos^2 \theta_K (1 - \cos^2 \theta_L)
\right.
\]
\[
+ \frac{1}{2} (1 - F_L) (1 - \cos^2 \theta_K) (1 + \cos^2 \theta_L)
\]
\[
+ \frac{1}{2} P_1 (1 - F_L) (1 - \cos^2 \theta_K) (1 - \cos^2 \theta_L) \cos 2\phi
\]
\[
+ 2 P_5' \cos \theta_K \sqrt{F_L (1 - F_L) \sqrt{1 - \cos^2 \theta_K \sqrt{1 - \cos^2 \theta_L} \cos \phi}} \left. \right\}
\]

- The systematic uncertainties ⇒ affecting BR measurements

- These observables ⇒ constraints to the BRs in global fits

- Construct observables with reduced form-factor dependence (e.g. $P_5'$)

Submitted to PLB
arXiv:1710.02846

JHEP 02 (2016) 104

PRL 118 (2017) 111801
Observation of $B_s \to \mu\mu$, search for $B^0 \to \mu\mu$

- Branching fractions are predicted in the SM with small uncertainties $\Rightarrow$ sensitive to NP effects
- Combined fit to Run-1 data by CMS and LHCb
  - First observation of $B_s \to \mu\mu$ (6.2$\sigma$, SM at 1.2$\sigma$)
  - 3.0$\sigma$ excess of $B^0 \to \mu\mu$ (SM at 2.2$\sigma$)
- New measurement adds 1.4 fb$^{-1}$ of Run-2
  - First observation by single experiment of $B_s \to \mu\mu$ (7.8$\sigma$)
  - $\mathcal{B}(B_s \to \mu\mu) = (3.0 \pm 0.6 \pm 0.3) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu\mu) < 3.4 \times 10^{-10}$@95%CL(1.2$\sigma$ excess)
- First measurement of $B_s$ effective lifetime
  - $\tau(B_s \to \mu\mu) = 2.04 \pm 0.44 \pm 0.05$ ps
- Still large uncertainty, but important proof of concept for the future
Search for $B_{(s)} \to e\mu$

- Hints of LU violation could be associated to LF violation and enhance $\mathcal{B}(B_{(s)} \to e\mu)$ up to $10^{-11}$
  [MPLA 32 (2017) 1730006]

- Search on 1 fb$^{-1}$ of Run-1 data
  [PRL 111 (2013) 141801]

- No excess of signal wrt background is observed

- New search on full Run-1 data
  - World’s best limits (2-3x improvement)
  - $\mathcal{B}(B_s \to e\mu) < 6.3 \times 10^{-9}$ @ 95% CL
  - $\mathcal{B}(B^0 \to e\mu) < 1.3 \times 10^{-9}$ @ 95% CL
  - Best upper limits, better than previous LHCb result by a factor of ~2.5
Decays such as $b \rightarrow s l^+ l^-$ and $c \rightarrow u l^+ l^-$ have an overwhelming contribution from long-distance processes, through intermediate vector resonances in the dimuon spectrum.

Unlikely that NP could show up in the branching fraction.

But the richer dynamics allows to investigate $A_{CP}, A_{FB}$ which can be up to a few percent in some NP scenarios.
Observation of $\Lambda_b \to p\ell\mu\mu$

✧ Occurs at loop level, $b \to d$ CKM suppressed
✧ Suppression not necessarily present in BSM

✧ Search on Run-1 data
  ✧ First observation of $\Lambda_b \to pK\mu\mu$
  ✧ $\Delta A_{CP} = (-3.5 \pm 5.0 \pm 0.2) \times 10^{-2}$
  ✧ $a_{CP}^{T-\text{odd}} = (1.2 \pm 5.0 \pm 0.7) \times 10^{-2}$

\[ C_T = \frac{p_{\mu^+} \cdot (p_\pi \times p_K^-)}{N(C_T > 0) - N(C_T < 0)} \]
\[ A_T = \frac{A_T^0 - \bar{A}_T^0}{2} \]

✧ First observation of $b \to d$ transition in a baryonic decay at $5.5\sigma$
  ✧ $\mathcal{B}(\Lambda_b \to p\pi\mu^+\mu^-) = (6.9 \pm 1.9 \pm 1.1 \pm 1.3) \times 10^{-8}$
Observation of $D^0 \rightarrow h^+h^-\mu^+\mu^-$

- Short-distance $\mathcal{B}_{SM}(D^0 \rightarrow X\mu\mu) \sim O(10^{-9})$
- Long-distance $\mathcal{B}_{SM}(D^0 \rightarrow XV[\mu\mu])$ up to $O(10^{-6})$
  [PRD 83 (2011) 114006]
- BSM could enhance $\mathcal{B}(D^0 \rightarrow X\mu\mu)$

- Using 2/fb LHCb made the first observation
- Measure differential and total BF (normalized to $D^0 \rightarrow K^+\pi[\mu^+\mu^-]_{\rho/\omega}$) [PLB 757 (2016) 558-567]
- Total branching fractions: ($\mathcal{B}$ integrated over full $q^2$)
  - $\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$
  - $\mathcal{B}(D^0 \rightarrow K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$
- Rarest observed Charm decays!
- Compatible with SM predictions [JHEP 04(2013)135]
- Statistics is enough to perform first asymmetry measurements!
Observation of $\Lambda_c \rightarrow p\mu^+\mu^-$

- $c \rightarrow ull$ transitions less explored than $b \rightarrow sll$
- Short-distance $B_{SM}(\Lambda_c \rightarrow p\mu\mu) \sim O(10^{-9})$
- Long-distance $B_{SM}(\Lambda_c \rightarrow pV[\mu\mu])$ up to $O(10^{-6})$
- BSM could enhance $B(\Lambda_c \rightarrow p\mu\mu)$

- Search on Run-1 data
  - 3 $q^2$ regions: a) short-distance, b) $\phi$, c) $\omega$
  - First observation of $\Lambda_c \rightarrow p\omega$ at $5\sigma$
  - Total branching fractions: ($B$ integrated over full $q^2$)
    - $B(\Lambda_c \rightarrow p\omega) = (7.6 \pm 2.6 \pm 0.9 \pm 3.1) \times 10^{-6}$
    - $B(\Lambda_c \rightarrow p\mu^+\mu^-) < 7.68 \times 10^{-8} @90 \, CL$
Search for $K_S \to \mu\mu$

- Dominated by long-distance
  \[ \mathcal{B}_{SM}(K_S \to \mu\mu) = (5.0 \pm 1.5) \times 10^{-12} \text{ [JHEP 01 (2004) 009]} \]
- New light scalars could increase $\mathcal{B}(K_S \to \mu\mu)$ by $O(10)$
- Search on 1 fb$^{-1}$ of Run-1 data [JHEP 01 (2013) 090]
- New search on Run-1 data
- World’s best limits (10x improvement)
- $\mathcal{B}(K_S \to \mu\mu) < 1 \times 10^{-9} \text{ @ 95\% CL}$
Summary and future perspective

- Exciting time for LFU tests with the anomalies:
  - Charged current $b \rightarrow c\tau\nu$, $4.1\sigma$ tension in $R(D) - R(D^*)$ when combining BaBar, Belle and LHCb results. $2\sigma$ discrepancy observed by LHCb in $B_c \rightarrow J/\psi \tau\nu$
  - FCNC $b \rightarrow s l^+l^-$, notably $R(K)$ and $R(K^{*0})$
- Rare decays are particularly sensitive probes for BSM physics
- Intriguing set of anomalies in rare decays of $b$-hadrons observed in the recent years
- If taken together these probably represent the largest "coherent" set of BSM effects in the present data
- LHCb Run 2 (2015-2018) $\cong$ Run 1 $\times$ 3. Then, Upgrade, Run 3, 4 and 5 until 2035!
Thank you
Backup slides