Physics at LHCb

Status of the experiment
Selection of Physics
Future plans

On behalf of the LHCb collaboration

May 8, 2018
Hassan Jawahery
University of Maryland
The LHCb Detector
A Single Arm Spectrometer at LHC

Acceptance: 2 < $\eta$ < 5

$\sigma_{\text{inel}} \approx 70-80 \text{ mb}$
$\sigma_{cc} \approx 6 \text{ mb (7 TeV)}$
$\sigma_{\tau} \approx 80 \mu\text{b (7 TeV)}$
$\sigma_{bb} \approx 280 \mu\text{b (7 TeV)}$
$\sigma_{bb} \approx 500 \mu\text{b (14 TeV)}$

$b\bar{b}$ peaked forward or backward with $\approx 25\%$ in detector acceptance

Access to all species of $B$ hadrons

LHCb Status

- Operates at Inst Luminosity ~$4 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
  - Beam separation is adjusted to keep the luminosity constant.
- In Run 2, mean number of visible collisions/beam-crossing ~1.1
- Recorded Luminosity ~ 7 fb$^{-1}$
Some measures of the power of the Spectrometer

[Graph showing candidates against mass (MeV)]

Excited $\Omega_c$ (css)

LHCb

$\pi^\pm K^\mp$

Full fit

Background

Feed-downs

$\Xi_c$ sidebands

[Candidates / (1 MeV)]

$3000 \quad 3100 \quad 3200 \quad 3300$

$m(\Xi_c^+ K^-)$ [MeV]

B$_s^0$ oscillation

[Graph showing decay time vs. number of candidates]
LHCb covers a very broad spectrum of physics, from Flavor to EW, DM search, QCD, pA...
Comments on three key areas

- New Physics search via CKM meterology
- New Physics search in FCNC processes: Observation of $B \rightarrow \mu^+\mu^-$
  Precise measurements of $B \rightarrow K^{(*)} l^+l^-$
- Tests of Lepton Flavor Universality
Continue to sharpen the CKM picture

L. Wolfenstein Parameterization of CKM matrix (1983)

\[
\begin{pmatrix}
1 - \frac{1}{2} \lambda^2 & \lambda & A \lambda^3 (\rho - i \eta) \\
-\lambda & 1 - \frac{1}{2} \lambda^2 & A \lambda^2 \\
A \lambda^3 (1 - \rho - i \eta) & -A \lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
\]

All CPV effects governed by a single parameter - the complex phase of CKM - \( \eta \)
Continue to sharpen the CKM picture

The picture may be modified by the presence of New Physics (NP)

Observables involving
$B^0 \leftrightarrow \bar{B}^0$ oscillation
Bring in sensitivity to New Physics

NP free measurements - tree level processes: $V_{ub}$ & $\gamma$
With careful set up of the initial and final states

\[ B_d \rightarrow J/\psi \ K^0_s \quad \text{::} \quad \beta \propto \arg(V_{td}^*) \sim 24^\circ \]

\[ B_s \rightarrow J/\psi \ K^+K^- \quad \text{::} \quad \phi_s \propto \arg(V_{ts}^*) \sim 1^\circ \]
Measurement of \( \beta = \arg\left(-\frac{V_{cd}V_{cb}^{*}}{V_{td}V_{td}^{*}}\right) \)

Measured to high accuracy at the B factories. LHCb is already competitive with Run 1 data.

**World Average**
\[ \beta = (22.2 \pm 0.7)^\circ \]

Most precisely measured element of the CKM Unitarity Triangle.
Combining LHCb results:

\[ \phi_s = 2 \text{arg}\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \]

LHCb measurements dominate:

\[ B_s^0 \rightarrow J/\psi K^+ K^- \quad \varphi - \text{region} \]
\[ B_s^0 \rightarrow J/\psi K^+ K^- \quad \text{High-mass region} \]
\[ B_s^0 \rightarrow J/\psi \pi^+ \pi^- \]
\[ B_s^0 \rightarrow \psi (2S) K^+ K^- \]

Summer 2017

\[ \phi_s^{J/\psi hh} = 0.001 \pm 0.037 \]
\[ \Delta \Gamma_s = 0.0813 \pm 0.0081 \]
\[ \Gamma_s = 0.6588 \pm 0.0026 \]

SM

\[ \varphi_s^{\phi \phi} = -0.0370 \pm 0.0006 \quad \text{rad} \]
\[ \Delta \Gamma_s = 0.088 \pm 0.020 \quad \text{ps}^{-1} \]
Measurement of  $\gamma = \arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$

Yet another interferometer: tree level processes $b\rightarrow c$ & $b\rightarrow u$

$$A[B^- \rightarrow (D^{(*)} \rightarrow f)\pi^-] = A_c A_f e^{i(\delta_c + \delta_f)} + A_u A_f e^{i(\delta_u + \delta_{f^*} - \gamma)}$$

Final state “f” is common to $D$ & $\bar{D}$

Analysis updates involve several new channels & some includes Run 2 data

$\gamma = (76.8^{+5.1}_{-5.7})^\circ$
All is well with the CKM picture at \( O(10\%) \) level:

- Direct CKM fit:
  - \( \beta = (22.2 \pm 0.7)° \)
  - \( \gamma = (76.2^{+4.7}_{-5.0})° \)
  - \( -2\beta_s = -0.021 \pm 0.031 \)

- CKM fit:
  - \( \alpha = (87.6^{+3.5}_{-3.3})° \)
  - \( \beta = (23.74^{+1.13}_{-0.98})° \)
  - \( \gamma = (65.9^{+0.96}_{-2.54})° \)
  - \( -0.0370 \pm 0.0006 \)
Status of CKM (2018)

All is well with the CKM picture at $O(10\%)$ level:

\[
\frac{\alpha}{\beta} = \left(87.6^{+3.5}_{-3.3}\right)^\circ
\]

\[
\beta = (22.2 \pm 0.7)^\circ
\]

\[
\gamma = \left(76.2^{+4.7}_{-5.0}\right)^\circ
\]

\[-2\beta_s = -0.021 \pm 0.031\]

Is there room for New Physics?

CPV sources beyond SM?
New Physics Through Mixing

Through new loop diagrams in mixing

\[ M^0(t) \]
All is well with the CKM picture at $O(10\%)$ level:

For New Physics through Mixing

Constraint on NP/SM amplitude
See (arXiv: 1309.2293)

$M_{12} = M_{12}^{SM} \times (1 + \Lambda e^{2i\phi})$

$A_{NP} < 0.3A_{SM}$

$\Lambda_{NP} > 10^3$ TeV
For $c \sim 1$
Search for New Physics footprint in other FCNC Processes

A key probe of NP in B decays
Observables: Rate, CPV, polarization of $\gamma$

$SM : Br(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9}$
PRL 112, 101801

Finally seen (LHCb & CMS) – consistent with SM – sets severe constraints on BSM

Recent precise measurements from LHCb show interesting hints of deviations from SM – including tests of Lepton Flavor Universality
Observation by LHCb & CMS Run -1
consistent with SM

\[ \text{ATLAS: } \text{Br}(B_s^0 \rightarrow \mu^+\mu^-) = (9.0^{+1.1}_{-0.8}) \times 10^{-9} \]
\[ \text{Br}(B_s^0 \rightarrow \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \]
\[ \text{Br}(B_s^0 \rightarrow \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10} \]

\[ \text{SM: } \text{Br}(B_s^0 \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9} \]

[arXiv:1411.4413]

PRL 112, 101801

#19
$B \rightarrow \mu^+ \mu^-$

LHCb observation with Run1+ 1.4 fb$^{-1}$ of Run 2

$\text{BR}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$

7.8 $\sigma$

PRL 118, 191801 (2017)

$\text{SM} : \text{BR}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9}$

PRL 112, 101801
Several observables sensitive to New Physics extracted from differential rates.

Precise measurements from LHCb dominate this channel, including tests of Lepton Flavor Universality:
Some intriguing results

First full angular analysis of $B \to K^{(*)} \mu^+ \mu^-$ performed with LHCb Run 1 data:

[JHEP 02 (2016) 104]

Overall compatibility of LHCb results with SM $\sim 3.4 \sigma$
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Tests of Lepton Flavor Universality in $B \to K^{(*)} l^+ l^-$

$$R_H = \frac{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2} \, dq^2}{\int \frac{d\Gamma(B \to He^+e^-)}{dq^2} \, dq^2}$$

Within SM: $R_{K^{(*)}} = 1$

LHCb

$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$

Within 2.6 $\sigma$ of SM

PRL 113, 151601

$R_{K^*} = 0.660^{+0.110}_{-0.070} \pm 0.024$ low-$q^2$

$R_{K^*} = 0.685^{+0.113}_{-0.069} \pm 0.047$ high-$q^2$

Within 2.1-2.3 $\sigma$ & 2.4-2.5 $\sigma$ of SM

JHEP 08(2017)055
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JHEP 08(2017)055
Tests of Lepton Flavor Universality (2)

The key observables:

\[ R(D^{(*)}) = \frac{B(\bar{B} \rightarrow D^{(*)}\tau\bar{\nu})}{B(\bar{B} \rightarrow D^{(*)}\mu\bar{\nu})} \]

\[ R(J/\psi) = \frac{B(B_c^+ \rightarrow J/\psi\tau^+\bar{\nu})}{B(B_c^+ \rightarrow J/\psi\mu^+\bar{\nu})} \]

In SM, decays to \( \mu \) & \( \tau \) differ only due to their mass differences

- These are theoretically very “clean”; computed in HQFT or LQCD
- Form-Factor Uncertainties largely cancel

\[ R(D) = 0.300 \pm 0.008 \quad \text{H. Na et al., (LQCD)} \]

\[ R(D^*) = 0.252 \pm 0.003 \quad \text{S. Fajfer et al (HQET)} \]

\[ R(J/\psi) = 0.25 - 0.28 \]

Uncertainties partly due to scalar form factors- helicity suppressed contributions that are negligible for \( e \) & \( \mu \) channels
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Hints of deviation from these predictions first seen by BaBar

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Uncertainties partly due to scalar form factors- helicity suppressed contributions that are negligible for e & \( \mu \) channels
$\bar{B} \rightarrow D^{*-} \tau^{+} \nu_{\tau}$

$\tau \rightarrow \mu \nu \nu$

$R(D^*) = 0.336 \pm 0.027 \text{ (stat) } \pm 0.030 \text{ (syst)}$

Within 2.1 $\sigma$ of SM

PRL 113, 111803

$R(D^*) = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$

Within 1 $\sigma$ of SM

PRL 120, 171802

$R(J/\psi) = 0.71 \pm 0.17 \text{ (stat) } \pm 0.18 \text{ (syst)}$

Within 2 $\sigma$ of SM

PRL 120, 121802
Several Intriguing results: away from SM in the same direction.

No single measurement is yet at or beyond 3 sigma away from SM

Too early to consider LFU in serious trouble

Several theoretical scenarios- e.g. models with leptoquarks- can accommodate the data.

4.1 σ tension with LFU/SM
Future
Toward precision Flavor Physics - O(1%): CKM and Rare Decays & much more

Last century

2001

Today

2025+

Constraint on NP/SM amplitude
See (arXiv: 1309.2293)

~20-30%
Experimental Landscape

<table>
<thead>
<tr>
<th>LHC</th>
<th>Period of data taking</th>
<th>Maximum $\mathcal{L}$ [cm$^{-2}$s$^{-1}$]</th>
<th>Cumulative $\int \mathcal{L} dt$ [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase-1 Upgrade</td>
<td>3 &amp; 4 2021–2023, 2026–2029</td>
<td>$2 \times 10^{33}$</td>
<td>50</td>
</tr>
<tr>
<td>Phase-2 Upgrade</td>
<td>5 → 2031–2033, 2035 →</td>
<td>$2 \times 10^{34}$</td>
<td>300</td>
</tr>
</tbody>
</table>

Pile up

1.1
6
50
The LHCb upgrade: Trigger

High Luminosity running requires major changes to the LHCb trigger scheme

Saturation of yields with 1MHz L0 limit
Must raise $P_T$ cut to stay below 1 MHz

**Upgrade Trigger**

**New Trigger Approach:**
- Remove L0 (hardware) trigger
- Readout the detector at the 40 MHz LHC clock rate
- Move to a fully flexible software trigger

**major upgrade of LHCb detector required:**
- Replace all FE electronics & DAQ system
- Replace all Tracking sub-detectors
- Upgrade of RICH photo-detectors and optics
Upgrade-I

The assembly and installation to start in LHC LS2 – starting in 2019

Tracking system:
- New VELO (Si strip → Pixel)
- New upstream tracker (TT) (Si)
- New downstream tracker (Sci Fiber)

RICH 1 & RICH 2
- HPD → MaPMT
- New 40 MHz R/O
- RICH1: new optics
  remove aerogel

Calorimeter:
- New 40 MHz R/O
- Lower PMT gain to reduce anode current
- Remove SPD & PS

Muon System:
- Remove M1
- M2-5 fine for $1 \times 10^{33}$
- May need upgrade of inner region at $2 \times 10^{33}$
Further in Future: Upgrade-II

LHCb phase-1 Upgrade

2019 2021 2024 2027 2030

Run 2 LS2 Run 3 LS3 Run 4 LS4

LHCb

UPGRADE II

Opportunities in flavour physics, and beyond, in the HL-LHC era

Expression of Interest
Major challenges for LHC & LHCb at peak Luminosity of $2 \times 10^{34} / \text{cm}^2/\text{s}$:

- Current studies indicate $2 \times 10^{34}$ is possible with changes to IP optics ($\beta^*$ reduction) & shielding. Triplet lifetime may limit integrated Luminosity to $\sim 300 \text{ fb}^{-1}$.

- At Int/crossing $\sim 50$ (vs 1.1 now) & Track Multiplicity as high as 3500:
  - Will need a new tracking system & thinner pixels with finer granularity & time measurements in VELO
  - Improved PID & Calorimetry (with fine granularity - e.g. SiW)
  - Will need innovative solutions to enormous increase in data rate ( $>>$ ATLAS & CMS)

- Next: narrow the space of solutions and develop TDR
Expression-of-Interest submitted for LHCb Upgrade-II

- A comprehensive measurement programme of observables in a wide range of $b \to s l^+l^-$ and $b \to d l^+l^-$ transitions, many not accessible in the current experiment or Phase-I Upgrade, employing both muon and electron modes;

- Measurements of the $CP$-violating phases $\gamma$ and $\phi_s$ with a precision of $0.4^\circ$ and 3 mrad, respectively;

- Measurement of $R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$ with an uncertainty of 20%, and the first precise measurements of associated $B^0_s \to \mu^+\mu^-$ observables;

- A wide-ranging set of lepton-universality tests in $b \to c l^-\bar{\nu}_l$ decays, exploiting the full range of $b$-hadrons;

- $CP$-violation studies in charm with $10^{-5}$ precision.
Flavor physics remains one of the primary drivers of the search for the physics beyond SM, as most scenarios of New Physics are expected to leave a footprint in flavor processes.

The current data is consistent with the Standard Model, setting severe constraints on scenarios of New Physics, but many stones remain unturned.

There are some areas of tensions with SM, waiting for more precise measurements. Lepton Flavor Universality is under the microscope.

The next phase of the program (LHCb upgrades I & II)-together with Belle-II - will result in a much sharper picture of the physics of flavor- will resolve or solidify some of the current anomalies with potential to reveal solid evidence for new physics.