LHCb: Large Hadron Collider beauty experiment

1260 members from 78 institutes in 18 countries
LHC experiment dedicated to flavor physics
Designed to study CPV and new physics in rare b and c decays
Nowadays a general purpose experiment for physics in forward region
Flavour physics

A precision tool for new physics discovery
Flavour physics

- Flavour physics studies the problems related to the existence of different species of elementary matter particles:
  - 6 known types of quarks (grouped in 3 generations)
  - 6 known types of leptons (grouped in 3 generations)

- Why 3 generations?
- What is the origin of the peculiar mass hierarchy?

- Unraveling the flavour mysteries gives access to fundamental problems in modern physics

Mass of quarks in MeV/c^2
Drawing not in linear scale!!
• New particles can contribute to the loop e.g. in rare flavour-changing neutral current processes, modifying the amplitudes

• Indirect search approach: precise measurements of such decays may reveal the effect of new physics!

• This is the main mission of LHCb
The LHCb experiment

**Vertex Detector**
- Reconstruct vertices
- Decay time resolution: 45 fs
- IP resolution: 20 μm

**Dipole Magnet**
- Bending power: 4 Tm

**RICH detectors**
- K/π/p separation
- $\varepsilon(K \rightarrow K) \sim 95\%$
- mis-ID $\varepsilon(\pi \rightarrow K) \sim 5\%$

**Tracking system: TT and OT**
- Momentum resolution
- $\Delta p/p = 0.5\% - 1.0\%$
  
  (5 GeV/c – 100 GeV/c)

**Muon system**
- $\mu$ identification $\varepsilon(\mu \rightarrow \mu) \sim 97\%$
- mis-ID $\varepsilon(\pi \rightarrow \mu) \sim 1-3\%$

**Calorimeters (ECAL, HCAL)**
- Energy measurement
- $e/\gamma$ identification
- $\Delta E/E = 1\% \oplus 10\%/\sqrt{E(GeV)}$

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[IJMPA 30 (2015) 1530022]
[JINST 3 (2008) S08005]
2018 LHCb run

LHCb operations and performance
Detector operations in 2018

- Reached 8.0 fb\(^{-1}\) Run 1 + Run 2
- ~1 fb\(^{-1}\) collected in 2018

- The LHCb performance is excellent
2018 the last year for LHCb... as we know it now!...

...Going to install a major upgrade in a few months...
Selected recent physics results
Measurements of CKM matrix parameters

The foundations of experimental flavour physics
In the SM, flavour changing weak interactions between quarks are encoded in the CKM matrix.

The CKM matrix is unitary, and reduces to three rotations and one phase.

Phase gives rise to CP violation.

$$
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
= \begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3 (1 - \rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
$$

Using the properties of unitary matrices:

$$0 = 1 + \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} + \frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}$$

“Most open” triangle, others are possible.
Unitarity Triangle tests

- The Unitarity Triangle is particularly interesting in the b-quark sector and it provides many observables that severely constraint the SM: the triangle MUST “close” within the SM!
- Angles related to CP violation
- A precise measurement of these observables is one of the most powerful weapons to challenge the SM!
- Flavour physics experiments are pursuing a systematic program to measure such observables.
Meson oscillations at work

Time dependent CP asymmetries

- Measurement of CP violation in $B^0 \rightarrow D^+\pi^-$ decays
- Measurement of CP asymmetry in $B^0_{(s)} \rightarrow h^+h^-$ decays
Measurement of CP violation in $B^0 \rightarrow D^+\pi^-$ decays

- Time dependent asymmetries in this channel are sensitive to $|\sin(2\beta + \gamma)|$
- Obtain $\beta$ from external measurements.
- Can be used to constrain $\gamma$ (or, using $\gamma$ as input, to obtain penguin-free measurement of $\beta$)

Large signal sample but low sensitivity, will be important for the LHCb upgrades
CP violation in $B^0_{(s)} \rightarrow h^+h^-$

- Combined analysis of the branching fractions and CP asymmetries in $B^0_{(s)} \rightarrow h^+h^-$ allows to constrain $\gamma$
- Sensitive to direct CPV in decay through $C_f$

$$A_{CP}(t) = -C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t) + A^{T}\Gamma \sinh(\frac{\Delta \tau_{d,s} t}{2})$$

- Measure 4.0$\sigma$ deviation of $(C_{KK}, S_{KK}, A^{\Delta \Gamma}_{KK})$ from (0, 0, -1) no-CPV expectation;
- Strongest evidence of CPV in $B^0_S$ system to date
- 1st determination of $A^{\Delta \Gamma}_{KK}$

$C_{\pi+\pi^-} = -0.34 \pm 0.06 \pm 0.01$
$S_{\pi+\pi^-} = -0.63 \pm 0.05 \pm 0.01$
$C_{K^+K^-} = 0.20 \pm 0.06 \pm 0.02$
$S_{K^+K^-} = 0.18 \pm 0.06 \pm 0.02$
$A^{\Delta \Gamma}_{K^+K^-} = -0.79 \pm 0.07 \pm 0.10$
$A^{B^0}_{CP} = -0.084 \pm 0.004 \pm 0.003$
$A^{B^0}_{CP} = 0.213 \pm 0.015 \pm 0.007$
Quest for precision

Time integrated CP asymmetries

- A precise measurement of CKM angle $\gamma$
- Combination of LHCb measurements of $\gamma$
Measurement of $\gamma$ using $B^+\rightarrow DK^+$ with $D \rightarrow K_S h^+ h^-$ decays

- Same $B^\pm \rightarrow (D^0 \rightarrow K^0_S h^- h^+)K^\pm$ final state accessible with $D^0$ and $\bar{D}^0$
- Divide up the Dalitz space into symmetric bins chosen to optimise sensitivity to $\gamma$

- Fit Dalitz plot to determine $x_\pm$ and $y_\pm$
- Combining with Run 1 determines $\gamma = (80^{+10}_{-9})^\circ$
- Most precise determination of $\gamma$ from a single channel!

More details in the talk by Jörg Marks on August 10th
Combination of LHCb measurements of $\gamma$

**LHCb Average - [LHCb-CONF-2018-002]**

$$\gamma = (74.0^{+5.0}_{-5.8})^\circ$$

- $B^0$ decays
- $B^0$ decays
- $B^+$ decays
- Combination

**World Average (HFLAV) - [Spring update]**

$$\gamma = (73.5^{+4.2}_{-5.1})^\circ$$

Indirect constraints are:

$$\gamma = (65.3^{+1.0}_{-2.5})^\circ \ (\sim 2\sigma)$$

Comparison between $B_s^0$ and $B^+$ initial states $\sim 2\sigma$

Slight tensions to be monitored as the precision on $\gamma$ improves
Rare decays, a window on new physics

$D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ decays
**D⁰→h⁺h⁻μ⁺μ⁻ decays**

- Rare charm decays very sensitive to new physics contributions
  - Unique laboratory to probe FCNCs in the up-type quark sector
- Rarest charm decay ever observed, BR ~O(10⁻⁷ - 10⁻⁶) [PRL 119 (2017) 181805]
- Now looking for CP asymmetries!

![Graphs showing data and fit for D⁰ and D̅⁰ decays](image)

All measured asymmetries compatible with zero
Is Nature blind to lepton flavour?

- Recap on tests of lepton flavour universality in $B$ decays
- New avenues: $b \rightarrow d \ell^+ \ell^-$, the partners of $b \rightarrow s \ell^+ \ell^-$ transitions
Tests of lepton flavour universality

- Lepton flavour universality can be checked in several B meson decays involving leptons in the final state

- Two main classes of decays have been studied:
  - Semileptonic $B^0 \rightarrow D(\star)^{-} l^{+} \nu -$ tree level decay
  - $b \rightarrow s l^{+} l^{-}$ decays e.g. $B^0 \rightarrow K(\star)^{0} l^{+} l^{-} -$ FCNC decays

- Observables:

\[ R(D^*) = \frac{BF(B \rightarrow D^* \tau \nu)}{BF(B \rightarrow D^* \mu \nu)}_{SM} = 0.252 \pm 0.003 \]

\[ R(K^{(*)}) = \frac{BF(B \square K^{(*)} e^+ e^-)}{BF(B \square K^{(*)} e^+ e^-)}_{SM} \sim 1 \]

More details in the talk by Lars Eklund on August 10th

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Tests of lepton universality: semitauonic decays - $R(D^*)$

• Latest measurement from LHCb look at final states $\tau \rightarrow \pi^+ \pi^- \pi^+ \nu$...

• ...and also to the $B_c$ sector: $R(J/\psi) = BF(B_c \rightarrow J/\psi \tau \nu)/BF(B_c \rightarrow J/\psi \mu \nu)$

• Combined $R_D$, $R_{D^*}$ deviate from SM by $\sim 4\sigma$
  (http://www.slac.stanford.edu/xorg/hflav/semi/fpcp17/RDRDs.html)

• New combined $R_D$ and $R_{D^*}$ measurement well under way

• Great potential at LHCb to study other modes with $B_s$, $B_c$, $\Lambda_b$ decays
Tests of lepton universality: semitauonic decays - $R(D^*)$

Results are internally consistent and 4σ from SM prediction

- BaBar had. tag: $0.332 \pm 0.024 \pm 0.018$
- Belle had. tag: $0.293 \pm 0.038 \pm 0.015$
- Belle sl.tag: $0.302 \pm 0.030 \pm 0.011$
- Belle (hadronic tau): $0.270 \pm 0.035 \pm 0.027$
- LHCb: $0.336 \pm 0.027 \pm 0.030$
- LHCb (hadronic tau): $0.285 \pm 0.019 \pm 0.029$

Average: $0.304 \pm 0.013 \pm 0.007$

S. Fajfer et al. (2012): $0.252 \pm 0.003$

Δχ² = 1.0 contours
- $R(D)=0.300(8)$ HPQCD (2015)
- $R(D)=0.299(11)$ FNAL/MILC (2015)
- $R(D^*)=0.252(3)$ S. Fajfer et al. (2012)

[arXiv:1708.08856]
Tests of lepton universality: $R(K)$ and $R(K^*)$

Test the LFU in electroweak penguin decays (e.g. the class of FCNC decays $b \rightarrow s l^+ l^-$):

- Results for $R(K)$ and $R(K^*)$:

  ~2-2.5 $\sigma$ away from SM with potential to become 4-5 $\sigma$ in few years


- Updates for $R_K$ and $R_{K^*}$ being worked out
- New unexplored channels will be also measured, like $B_s \rightarrow \phi^* l^+ l^-$ ($R_{\phi^*}$) and others
- Upcoming updates based on Run 1 + ~2 fb$^{-1}$ Run 2
Evidence for the decay $B^0_s \rightarrow \bar{K}^*(892)^0 \mu^+\mu^-$

- Look to measure the branching fraction of the rare decay
  - ★ Heavily suppressed $b \rightarrow d\ell$ transition - SM expectation for BR $O(10^{-8})$

- Measured BR of $O(10^{-8})$, consistent with SM

- Counterpart of the $b \rightarrow s \ell\ell$ transitions
  - ★ setting the ground work for angular analysis and study of LFUV with upgraded LHCb

38±12 signal events 3.4$\sigma$ significance
A benchmark for QCD: spectroscopy

• New results on $\Xi_{cc}^{++}$ and $\Omega_c^0$
• Observation of a new $\Xi_b^-$ resonance
New results from charmed baryons: $\Xi_{cc}^{++}$

Discovered by LHCb in the channel $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ [PRL 119 (2017) 112001]

- Consistent with a weakly decaying object, but lifetime left for later study
- Revisit 1.7 fb$^{-1}$ sample of Run 2 data, using $\Lambda_b^0 \to \Lambda_c^+ K^- \pi^+ \pi^+$ control mode to measure the $\Xi_{cc}^{++}$ lifetime with respect to that of $\Lambda_b^0$
- Lifetime result:
  $$\tau(\Xi_{cc}^{++}) = (256^{+24}_{-22} \pm 14) \text{ fs}$$

- Confirms that $\Xi_{cc}^{++}$ is a weakly decaying baryon.
- Also, $\Xi_{cc}^{++}$ “rediscovered” in another decay channel: $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$
- Measured mass is:
  $$m(\Xi_{cc}^{++}) = 3620 \pm 1.5 \text{ (stat)} \pm 0.4 \text{ (syst)} \pm 0.3(\Xi_c^+) \text{ MeV/c}^2$$

arXiv:1807.01919, Run 2, 1.7 fb$^{-1}$
New results from charmed baryons: Lifetime of $\Omega_c^0$

- Fit the ratio
  \[ \frac{\tau_{\Omega_c^0}}{\tau_{D^+}} = \frac{\tau_{\Omega_c^0}}{\tau_{D^+}} \]
  from decay time distributions of $D^+$ and $\Omega_c^0$ and obtain $\tau(\Omega_c^0)$ from the well known $\tau(D^+)$

- Use a sample of $\Omega_b^0 \rightarrow \Omega_c^0 (\rightarrow pK^+\pi^+) \mu\nu X$; $B \rightarrow D^+ (\rightarrow K^-\pi^+\pi^+)\mu\nu X$

- Results
  \[ \frac{\tau_{\Omega_c^0}}{\tau_{D^+}} = 0.258 \pm 0.023 \pm 0.010 \]
  \[ \tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2 \text{ fs} \]

- The measured lifetime is ~4 times larger and inconsistent with the PDG average $69 \pm 12$ fs (Chin. Phys.294 C40 (2016) 100001)

- This measurement places the $\Omega_c^0$ baryon as having the second largest lifetime of charmed baryons
Observation of a new $\Xi_b^{**-}$ resonance

- Seen both in fully hadronic and semileptonic decays
- $J^P$ not yet measured
- Use fully hadronic decays to determine mass and width
Not only flavour

*Heavy ion and fixed target physics*
Charm production in fixed-target mode at LHCb

- First publication on heavy flavour production in fixed-target mode at LHCb

- Charm production measurements in LHCb acceptance constrain proton charm quark PDF at high x

- Production of J/ψ and D⁰ mesons is studied in 4 TeV pHe and 6.5 TeV pAr

- LHCb fills the gap between lower c.m. energy experiments and RHIC

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A look to the future

The LHCb upgrades
The experimental scenario

LHCb may be the only large-scale flavour physics experiment operating in the HL-LHC era.

*LHCb has submitted an expression of interest for an Upgrade II aiming at 300 fb$^{-1}$ to be installed in LS4

LHCb may be the only large-scale flavour physics experiment operating in the HL-LHC era.
The LHCb upgrade I in a snapshot

All sub-detectors read out at 40 MHz for a **fully software trigger**

- New PIXEL vertex detector (VELO)
- New RICH optics and photodetectors
- New silicon upstream tracker (UT)
- New scintillating fibre tracker (SciFi)
- New electronics for muon and calorimeter systems
LHCb upgrade I: final rush towards installation

- Detector construction in full swing, **installation starts in 6 months**!
Upgrade II

*LHCb Upgrade II: the ultimate exploitation of LHC for flavour physics*
• Aim to **fully exploit** HL-LHC for flavour physics and other opportunities in the forward direction

• Aim to collect > 300 fb$^{-1}$ at $L = 2 \times 10^{34}$, $x10$ with respect to Upgrade I

• Consolidate in LS3, Major upgrade in LS4

• Expression of Interest issued in 2017

• Feasibility study performed by LHC experts

• Physics case in preparation
Conclusions and outlook
Conclusions and outlook

• 2018 run going very well

• LHCb continues to provide a wealth of excellent physics results

• The march towards the upgrade I is continuing
  ★ All subsystems progressing - crucial steps forward in critical projects
  ★ Schedule is tight, working hard to be ready for LHC Run 3!

• Looking into the far future:
  ★ Expression of Interest for future upgrades submitted
  ★ Preparing a physics case document
  ★ A lot of opportunities!
Thank you!
Overall status for CP violation in $B^0 \rightarrow \pi^+ \pi^-$

Courtesy of the Heavy Flavour Averaging Group

$\pi^+ \pi^- S_{CP}$ vs $C_{CP}$

BaBar
PRD 87 (2013) 052009
$-0.25 \pm 0.06 \pm 0.02$

Belle
PRD 89 (2013) 092003
$-0.33 \pm 0.06 \pm 0.03$

LHCb
LHCb-PAPER-2018-006
$-0.34 \pm 0.06 \pm 0.01$

Average
$-0.32 \pm 0.04$

HFLAV correlated average

$\pi^+ \pi^- S_{CP}$

BaBar
PRD 87 (2013) 052009
$-0.68 \pm 0.10 \pm 0.03$

Belle
PRD 89 (2013) 092003
$-0.64 \pm 0.08 \pm 0.03$

LHCb
LHCb-PAPER-2018-006
$-0.63 \pm 0.05 \pm 0.01$

Average
$-0.63 \pm 0.04$

HFLAV correlated average
top pair production at $\sqrt{s} = 13$ TeV

- tt production in LHCb acceptance: sizeable rates of $q$ anti-$q$ and $qg$ scattering, higher than in the central region, in addition to $gg$ fusion
- Potential interest to study FB production asymmetries
- 1st measurement of top production with Run 2 data
  - use high-momentum electrons, muons and $b$-jets
  - About 87% of selected events correspond to the signal process, highest purity measurement of top physics at LHCb to date
- Still statistically limited, but will not remain so for long

$$\sigma_{tt} = 126 \pm 19 \text{ (stat)} \pm 16 \text{ (syst)} \pm 5 \text{ (lumi)} \text{ fb}$$
An LHCb Upgrade is scheduled, with installation in 2019-2020 (LHC LS2) and first data-taking in Run 3 (2021-2023). The motivation is to take increased advantage of the huge rate of heavy-flavour production at the LHC.

1. **Full software trigger**
   - Allows effective operation at higher luminosity
   - Improved efficiency in hadronic modes

2. **Raise operational luminosity by factor five**
   to $2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
   - Necessitates redesign of several sub-detectors and overhaul of readout

- Huge increase in precision, in many cases to the theoretical limit, and the ability to perform studies beyond the reach of the current detector.
- Flexible trigger and unique acceptance also opens up opportunities in other topics apart from flavour (‘a general purpose detector in the forward region’)

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LHCb can operate in collider mode, fixed target mode or both in parallel!

- Collider mode: forward/backward coverage
- Fixed target mode: central and backward coverage with $\sqrt{s_{NN}}$ between SPS and RHIC
- $\gamma: 0.4^\circ$
- $\phi_s: 3$ mrad
- Charm CPV: $O(10^{-5})$
Physics Case – Rare Decays

- Wide range of $b \rightarrow s l^+l^-/d l^+l^-$ observables
- 10% precision on

$$R \equiv \frac{B(B^0 \rightarrow \mu^+\mu^-)}{B(B^0_s \rightarrow \mu^+\mu^-)}$$
Physics Case – Other Opportunities

- General purpose facility
  - unique forward acceptance
- LHCb has had transformative effect on spectroscopy
  - Many more discovery opportunities

- Potential for best Higgs to charm limits at LHC
- Unique sensitivity for BSM long-lived and dark sector particles