Highlights from the LHCb experiment

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Katharina Müller
on behalf of the LHCb collaboration
Physik Institut, University of Zurich
LHCb detector

forward arm spectrometer for precision measurements (2<\eta<5)

- good vertex and impact parameter resolution ($\sigma(\text{IP}) = 15 \pm 29/\text{p}_T \ \mu\text{m}$)
- excellent momentum resolution ($\sigma(m_B) \sim 25 \text{ MeV}/c^2$ for 2-body decays)
- excellent particle ID (\mu ID 97\% for $(\pi \rightarrow \mu)$ misID of 1-3\%)
- stable running conditions constant $\mu$
- trigger on small $p_T$ and low mass objects
- real time analysis alignment and calibration fully automated

LHCb has recorded about 9 $fb^{-1}$ of pp collisions
1 $fb^{-1}$ @ 7 TeV – Run 1
2 $fb^{-1}$ @ 8 TeV – Run 1
6 $fb^{-1}$ @ 13 TeV – Run 2

plus various datasets of proton-lead, lead-lead collisions as well as fixed target datasets: pNe, pHe, pAr, PbAr

→ LHCb a multipurpose detector in the forward region
• $A_f$ in $D^0 \to K^+K^-, \pi^+\pi^-$ [LHCb-CONF-2019-001]
History of CP violation

- CPV in Kaons and B mesons is well established – both are down type quarks
- charm contains an up-type quark
- SM predicts it to be at $10^{-3} - 10^{-4}$ level
- LHC is a charm factory, with billions of charm decays in LHCb
Observation of CP violation in charm

charm decays allow CP violation to be probed in the up-sector → complementary to studies in K and B systems

expected to be very small in the SM (10^{-3} - 10^{-4} level), but theory predictions are not very precise (large long distance effects)
time dependent CP asymmetries

\[ A_{CP}(f; t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(D^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(D^0(t) \to f)} \]
sensitive to

- direct CP-violation \((a_{CP}^{dir})\)
- indirect CP-violation \((a_{CP}^{indir})\)
  (CP-violation in mixing or in the interference between mixing and decay)
Observation of CP violation in charm

full Run 2 data 5.9 fb$^{-1}$
count how many $D^0$ and anti-$D^0$ decay into $\pi^+\pi^-$ and $K^+K^-$ should be equal if matter = antimatter

experimentally: easier to measure (time integrated) difference in CP asymmetry:

$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

- many systematics cancel at first order
- initial flavour of D meson tagged by charge of $\pi$ in prompt decays ($D^{*+} \rightarrow D^0\pi^+$), and by the muon charge in secondary production ($B^0 \rightarrow D^0\mu^-X$)
Observation of CP violation in charm

Run 2 result:
\[ \Delta A_{\text{CP}} = (-18.2 \pm 3.2 \text{ (stat)} \pm 0.9 \text{ (syst)}) \times 10^{-4} \]  
\[ \Delta A'_{\text{CP}} = (-9 \pm 8 \text{ (stat)} \pm 5 \text{ (syst)}) \times 10^{-4} \]  

\( \pi \)-tag compatible with previous LHCb result and world average

combination with Run 1 result
\[ \Delta A_{\text{CP}} = (-15.4 \pm 2.9) \times 10^{-4} \]

\( \rightarrow \) 5.3 \( \sigma \) difference from 0

\( \rightarrow \) roughly compatible with SM predictions

WA dominated by LHCb uncertainties of SM predictions larger than data

\( \rightarrow \) new window opened to investigate matter-antimatter asymmetry
Oscillations of charm mesons in $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

neutral flavoured mesons can oscillate between their particle and antiparticle states

$\rightarrow$ the physical mass eigenstates are linear combinations of the weak eigenstates

$|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\bar{D}^0\rangle$

with masses $m_1$ and $m_2$ and decay widths $\Gamma_1 + \Gamma_2$

mixing parameters $x \equiv (m_1 - m_2)c^2/\Gamma$ and $y \equiv (\Gamma_1 - \Gamma_2)/\Gamma$ ($\Gamma = (\Gamma_1 + \Gamma_2)/2$)

$x$ determines the oscillation rate

$x$ is very small for charm mesons but $x$ and CPV can be enhanced by the presence of new particles beyond the SM.

CPV can occur in the mixing $\rightarrow$ oscillation rates differ for mesons and antimesons

LHCb Run 1, decay: $D^0 \rightarrow K_S^0 \pi^+ \pi^+$
yields: prompt 1.3M, secondary 1M candidates
Oscillations of charm mesons in $D^0 \to K_S^0 \pi^- \pi^+$

model independent approach (bin-flip method)

→ most precise determination of CP averaged normalized mass difference $x=(m_1-m_2)c^2/\Gamma$ by a single experiment

$x_{\text{CP}} = [2.7 \pm 1.6 \pm 0.4] \times 10^{-3}$

$y_{\text{CP}} = [7.4 \pm 3.6 \pm 1.1] \times 10^{-3}$

if CP symmetry in mixing and interference is conserved:

$x_{\text{CP}} = x$, $y_{\text{CP}} = y$

$x_{\text{CP}} = (3.9^{+1.1}_{-1.2}) \times 10^{-3}$ new world average

→ new world average provides first evidence of mass difference between the neutral charm mesons

Measurement of CPV parameter $A_\Gamma$ in $D^0 \to K^+K^-$, $\pi^+\pi^-$

$A_\Gamma$ probes CPV in mixing and interference

$$A_{CP}(f,t) \approx A_{CP}^{\text{decay}} - A_\Gamma(f) \frac{\langle t \rangle_f}{\tau_D}$$

SM predictions: $\approx 3 \times 10^{-5}$ [arXiv:1812.07638]

$A_\Gamma$ required input to measure CPV in decay from $\Delta A_{CP}$

→ measure time dependent CP asymmetry

$$A_\Gamma(K^+K^-) = (1.3 \pm 3.5 \pm 0.7) \times 10^{-4}$$

$$A_\Gamma(\pi^+\pi^-) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4}$$

combined with previous LHCb result

$$A_\Gamma(\pi\pi + KK) = (0.9 \pm 2.1 \pm 0.7) \times 10^{-4}$$

$$\Delta A_\Gamma = A_\Gamma(KK) - A_\Gamma(\pi\pi) = (-8.6 \pm 5.0 \pm 0.5) \times 10^{-4}$$

analysis based on 2 fb$^{-1}$ Run 2 data, still 4 fb$^{-1}$ to be analysed, statistically limited

→ need Upgrade II to reach sensitivity of SM
Precision in beauty – covered in more detail in Johannes’ talk

- Combination of $\gamma$ measurements [LHCb-CONF-2018-002]
- $B_s$ mixing phase $\Phi_s$ [arXiv:1903.05530, arXiv:1906.08356]
- Phase $\Phi_{sss}$ in $B_s \rightarrow \phi \phi$ decays [LHCb-PAPER-2019-019]
Combination of $\gamma$ measurements

tension (2σ) between $B^+$ and $B_s^0$ results

tension (2σ) between direct measurements and indirect constraints from UT

LHCb: new measurement in $B^0 \rightarrow DK^{*0}$ ($D \rightarrow K\pi$, $KK$, $\pi\pi$) [arXiv:1906.08927]

HFLAV from UT (CKM fitter) $\gamma=(71.1^{+4.6}_{-5.3})^\circ$

$\gamma=(65.8^{+1.0}_{-1.7})^\circ$

$\gamma=(74.0^{+5.0}_{-5.8})^\circ$
B_s mixing phase $\Phi_s$ from $B_s \rightarrow J/\psi$ KK and $B_s \rightarrow J/\psi\pi\pi$ measure the phase difference between the two processes.

SM prediction $\Phi_s = -36.8^{+9.6}_{-6.8}$ mrad (CKM Fitter)

highly sensitive to NP contributions

LHCb uses two channels:

$B_s \rightarrow J/\psi$ KK and $B_s \rightarrow J/\psi\pi\pi$

high yield, clean signature

→ very high precision measurements

flavour tagging from decay of other $b$ hadrons in the event analysis part of Run 2 (2 fb$^{-1}$) combined with Run 1

$\Phi_s = (-41 \pm 25)$ mrad (still 4 fb not analysed)

HFLAV combination: $\Phi_s = (-55 \pm 21)$ mrad

[arXiv: 1903.05530]
[arXiv: 1906.08356]
Measurement of CP violation in $B_s \rightarrow \Phi \Phi$

Enhanced sensitivity to NP since decay is dominated by penguin loop

SM prediction $|\Phi_s^{sss}| < 20$ mrad


time dependent angular analysis, 2 fb$^{-1}$ Run 2

$\Phi_s^{sss} = -73 \pm 115 \pm 27$ mrad

$|\lambda| = -0.99 \pm 0.05 \pm 0.01$

(LHCb preliminary)
Test of lepton flavour universality

test of LFU in various B decays with leptons in the final state

**Charged current (Semileptonic decays)**
tree-level decays $b \rightarrow c l \nu$, testing third generation
BR of few %, precise prediction in SM

$$R(D^{(*)}) = \frac{BR(B \rightarrow D^{(*)} \tau \bar{\nu}_\tau)}{BR(B \rightarrow D^{(*)} \mu \bar{\nu}_\mu)} = 0.252 \pm 0.003 \text{ (SM)}$$

**Neutral currents (Rare decays)**
$b \rightarrow sll$
forbidden at tree-level in the SM
→ FCNC only at loop level → BR $10^{-7} \div 10^{-6}$

theoretically clean

$$R(K^{(*)}) = \frac{BR(B \rightarrow K^{(*)} \mu \mu)}{BR(B \rightarrow K^{(*)} e e)} = 1 \pm \frac{O(10^{-3})}{\text{neglect lepton mass}} \pm \frac{O(10^{-2})}{\text{QED}}$$

[EPJ C76 (2016) 8, 440]
Test of lepton universality: $R_K$ and $R_{K^*}$

test the LFU in FCNC decays $b \rightarrow s l^+ l^-$

Run 1 result: old results for $R(K)$ and $R(K^*)$

$$R(K^*) = \frac{BR(B \rightarrow K^{(*)} \mu \mu)}{BR(B \rightarrow K^{(*)} e e)} = 1 \pm O(10^{-3}) \pm O(10^{-2})$$

- neglect lepton mass
- QED

References:
- PRL 113, 151601 (2014)
- JHEP 08 (2017) 055
New measurement of $R(K)$

new measurement re-analysing Run 1 data and adding $\sim 2 \text{ fb}^{-1}$ of Run 2 data

$$R(K) = \frac{BR(B \rightarrow K \mu \mu)}{BR(B \rightarrow K e e)}$$

electrons are difficult to measure at LHCb: trigger, Bremsstrahlung …
New measurement of $R(K)$

Reduce systematic effects: normalise to $B \rightarrow KJ/\psi \rightarrow \mu\mu$ to measure double ratio

$$R(K) = \frac{BR(B \rightarrow K \mu\mu)}{BR(B \rightarrow K J/\psi(\rightarrow e e))} \frac{BR(B \rightarrow K e e)}{BR(B \rightarrow K J/\psi(\rightarrow \mu\mu))}$$

Signal

$1.1 < q^2 < 6 \text{ GeV}^2$

Normalisation
New measurement of $R(K)$

$$R(K) = 0.846^{+0.060}_{-0.054} \text{(stat)}^{+0.016}_{-0.014} \text{(syst)}$$

compatible with the SM at 2.5 $\sigma$
→ better precision but central value closer to the SM

→ need more data: inclusion of 2017+2018 data will double the statistics

other measurements in preparation: $R(pK)$, $R(K^*)$ and other decay channels
Search for Lepton flavour violating decays

$B^0_{(s)} \rightarrow \tau^\pm \mu^\mp$ [arXiv:1905.06614]

BR in SM highly suppressed: $\sim 10^{-54}$

can be strongly enhanced in NP models:

up to $O(10^{-8} - 10^{-5})$

$B(B_s \rightarrow \tau \mu) = 3.4 \times 10^{-5}$ @ 90% CL (first limits)

$B(B^0 \rightarrow \tau \mu) = 1.2 \times 10^{-5}$ @ 90% CL (best limits)

$B^+ \rightarrow K^+ \mu^\pm e^\mp$ [LHCB-PAPER-2019-022]

NP models including leptoquarks, extended gauge boson models or CP violation in the neutrino sector predict branching fractions $10^{-8} - 10^{-10}$

search in full Run 1 dataset, no signal observed

$B(B^+ \rightarrow K^+ \mu^+ e^-) = 7.0 \times 10^{-9}$ @ 90% CL

$B(B^+ \rightarrow K^+ \mu^- e^+) = 7.1 \times 10^{-9}$ @ 90% CL

$\rightarrow$ limits improved by more than one order of magnitude

• Observation of a new state in DD mass spectrum [JHEP 07 (2019) 035]

• New resonances in the $\Lambda^0_b\pi^+\pi^-$ spectrum [LHCb-PAPER-2019-025]

Doubly charmed baryons

ground states: $\Xi_{cc}^{++}$ (ccu), $\Xi_{cc}^+$ (ccd) and $\Omega_{cc}^+$ (ccs)
only $\Xi_{cc}^{++}$ discovered so far, search ongoing for $\Xi_{cc}^+$ and $\Omega_{cc}^+$

first observed by LHCb in decay: $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ final state $\Lambda_c^+ K^- \pi^+ \pi^+$ [Phys. Rev. Lett. 121 162002 (2018)]
$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\text{(stat)} \pm 0.27 \text{(syst)} \pm 0.14 \text{(}\Lambda_c^+) \text{ MeV/c}^2$

weakly decaying: $\tau(\Xi_{cc}^{++})= 0.256+0.024 -0.022\text{(stat)} \pm 0.014\text{(syst)} \text{ ps}$ [PRL 121 (2018) 052002]
no signal found for: $\Xi_{cc}^{++} \rightarrow D^+ (\rightarrow K^- \pi^+ \pi^+) pK^\pi^+$ [arXiv:1905.02421]

$313\pm33$
Observation of a new state in DD mass spectrum

full Run1+Run2 dataset

→ new narrow state observed in the invariant mass spectra of D^0D^0 and D^+D^-

\[ M_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12 \text{ MeV}/c^2 \]
\[ \Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35 \text{ MeV} \]

narrow width → likely to be \( \psi_3(1^3D_3) \) \( J^{PC} = 3^{--} \)

→ first observation of a spin-3 charmonium state

In addition: first observation of prompt hadroproduction of \( \chi_{c2}(3930) \) and \( \psi(3770) \)
New resonances in the $\Lambda_{b}^{0}\pi^{+}\pi^{-}$ spectrum

Full Run1+Run2 dataset
→ two new resonances in $\Lambda_{b}^{0}\pi^{+}\pi^{-}$ spectrum

- high mass state:
  decays via intermediate $\Sigma_{b}$ and $\Sigma_{b}^{*}$
- low-mass state: decays $\Sigma_{b}$ suppressed.

mass and mass-splitting are in very good agreement with expectation for $\Lambda_{b}(1D)$-doublet

\[
m(\Lambda_{b}(6152)) = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16 \text{ MeV}
\]

\[
M(\Lambda_{b}(6146)) = 6146.15 \pm 0.33 \pm 0.22 \pm 0.16 \text{ MeV}
\]

\[
\Gamma(\Lambda_{b}(6152)) = 2.11 \pm 0.81 \pm 0.32 \text{ MeV}
\]

\[
\Gamma(\Lambda_{b}(6146)) = 2.90 \pm 1.28 \pm 0.28 \text{ MeV}
\]
Observation of new pentaquark states

first pentaquarks observed by LHCb four years ago using $\Lambda_b \rightarrow J/\psi Kp$

$\rightarrow$ narrow $P_c(4450)^+$, broader $P_c(4380)^+$

large theoretical interest in understanding the nature of the new states

tightly bound vs loosely bound molecular states

Observation of new pentaquark states

Update with full Run 2 statistics, 246'000 candidates

→ new peak at $P_c(4312)^+$ (7.3σ)

→ broad $P_c(4450)^+$ resolved as two narrow states (5.4σ): $P_c(4440)^+$ and $P_c(4457)^+$

minimal quark content $duucc$

narrow and close to $\Sigma_c^+D^0$ and $\Sigma_c^+D^{*0}$ ([$duc$][$uc$]) mass thresholds

→ extremely important result to shed light on the nature of these exotic states
Heavy ion and fixed target

- b-hadron production in proton-lead collisions  [Phys. Rev. D99 052011 (2019)]
- Charm production in fixed target collisions  [PRL 122 (2019) 132002]
Production of $B^0$, $B^+$ and $\lambda_b$ in proton-lead collisions at 8.16 TeV with exclusive decay modes:

- first measurement of beauty hadron production at $p_T < \text{mass of the hadrons in the forward region}$

- input for fits of the nuclear PDFs
- fragmentation models in nuclear environment.

**Graphs:**

1. **LHCb $R_{\text{eff},y}$**
   - $\sqrt{s_{NN}} = 8.16$ TeV
   - $B^0/B^+$ and $\Lambda_b/B^0$
   - $2 < p_T < 20 \text{ GeV/c}$

2. **LHCb $R_{\text{tot},0}$**
   - $\sqrt{s_{NN}} = 8.16$ TeV
   - $B^0/B^+$ and $\Lambda_b/B^0$
   - $p_T, 2.5 < y < 3.5$
Charm production in fixed target collisions

Unique opportunity for measurements in fixed target mode
first measurement of J/ψ and D⁰ production in
dHe @86.6 GeV pAr @110.4 GeV
→ sensitive to large Bjorken-x, up to x=0.37 for D⁰

D⁰ good agreement in rapidity shapes → no evidence for
significant contribution of valence-like intrinsic charm
LHCb is transforming

- charm
- beauty
- spectroscopy
- heavy ion
- fixed target
- upgrade
LHCb upgrade – upgrade I

Going on right now!
remove the hardware trigger → all detectors read out at 30 MHz

New tracking systems
VELO, UT, SciFi

Calorimeters & Muons
New readout

RICH
new optics and photodetectors

→ this will be a new detector at LHCb

[CERN-LHCC 2014-001]
[CERN-LHCC 2014-016]
[CERN LHCC 2013-021]
[CERN-LHCC 2013-022]
LHCb upgrade – work in progress

- Remove old VELO
- Remove beam pipe
- Dismantling muon station
- UT stave
- VELO test setup
- VELO RF boxes
- Event builder prototype
- RICH test stand
And looking further – upgrade II

- 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
- Physics case document released [CERN-LHCC-2018-027]
- Green light from LHCC to proceed to TDRs (expected ~late 2020)
Conclusion and outlook

Plenty of interesting results still coming from LHCb Run1-2

LHCb upgrade opens the door to many improvements in precision, so interesting times are ahead!

LHCb has a bright future

- Tensions on lepton flavour universality will be clear in a few years
- Sensitivity to NP in many interesting channels, more will open with upgraded detector
- Precision measurements of SM parameters
- Heavy Ion and fixed target physics programme has much to add
Backup
Observation of a new state in DD mass spectrum

Full Run1+Run2 dataset

New narrow state observed in the invariant mass spectra of $D^0\bar{D}^0$ and $D^+D^-$

$\chi_c(3930) = 3921.9 \pm 0.6 \pm 0.2 \text{ MeV}/c^2$

$\Gamma_{\chi_c(3930)} = 36.6 \pm 1.9 \pm 0.9 \text{ MeV}$

→ first observation of prompt hadroproduction of $\chi_c(3930)$
Tagging flavour of charmed meson

two independent ways

$A_{\pi\text{-tagged}}(f) \approx A_{CP}(f) + A_D(\pi) + A_P(D^*)$.

Semileptonic tag

$A_{\mu\text{-tagged}}(f) \approx A_{CP}(f) + A_D(\mu) + A_P(B)$.
New combination of $\gamma$ measurements

Combination of many tree level determinations

Using frequentist treatment

<table>
<thead>
<tr>
<th>$B$ decay</th>
<th>$D$ decay</th>
<th>Method</th>
<th>Ref.</th>
<th>Dataset</th>
<th>Status since last combination</th>
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<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-$</td>
<td>GLW</td>
<td>[14]</td>
<td>Run 1 &amp; 2</td>
<td>Minor update</td>
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<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-$</td>
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<td>[15]</td>
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<td>TD</td>
<td>[26]</td>
<td>Run 1</td>
<td>New</td>
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$^1$ Run 1 corresponds to an integrated luminosity of 3 fb$^{-1}$ taken at centre-of-mass energies of 7 and 8 TeV. Run 2 corresponds to an integrated luminosity of 2 fb$^{-1}$ taken at a centre-of-mass energy of 13 TeV.

Run 2 measurements with 2 fb$^{-1}$ (4 fb$^{-1}$ yet to be included)

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

Detector Channels

R/O Electronics

To be UPGRADED

To be kept

«This is a new detector at the LHC»
Oscillations of charm mesons in $D^0 \to K^0_S \pi^- \pi^+$

Model independent approach (bin-flip method)
Data is binned in Dalitz coordinates
binning scheme: approximately constant strong-phase differences
measure the yield ratio $R_{bj}^\pm$ between $-b$ and $b$ in bins of decay time

Observation of new pentaquark states

246’000 candidates
→ new peak at $P_c(4312)^+$ (7.3$\sigma$)
→ broad $P_c(4450)^+$ resolved as two narrow states (5.4$\sigma$): $P_c(4440)^+$ and $P_c(4457)^+$

$m>1.9$ GeV remove $\lambda^*$

Reweighted to enhance signal
LHCb – a multipurpose detector in the forward region

- Indirect searches for New Physics at the multi-TeV scale
decays of beauty and charm hadron
CP violation

- Understanding the details of QCD
Heavy flavour production, pentaquark states,
double heavy states, top physics, jets …

- Quark gluon plasma, cold nuclear effects in heavy ion collisions
Heavy flavour production in p-Pb collisions, fixed target collisions
Doubly charmed baryons

Search for: $\Xi_{cc}^{++} \rightarrow D^+ (\rightarrow K^-\pi^+\pi^+) pK\pi^+$

no signal found $\rightarrow \mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow D^+ pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^-\pi^+\pi^+)} < 1.5 \times 10^{-2} \text{ at } 90\% \text{ CL}$

LHCb 13 TeV

+Data
-Background