LHCb Highlights and Perspectives

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on behalf of the LHCb Collaboration

- Selected recent physics results
- Upgrade I at the starting line!

LHCP, 16th May 2022
Celebrating “LHCb-original”!

LHCb was originally for CP violation and $b$- $c$-hadron rare decays…

… but it achieved also much more: exotic spectroscopy, heavy ions, fixed target programme, EW precision physics

Today recent results on

- CP violation in $B$ decays and $D^0$ mixing, Lepton Flavour Universality
- Spectroscopy, Heavy ions and fixed target
**CKM angle $\gamma$**

- $B^{\pm} \to DK^{\pm}$ decays, with $D \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$
  
  CP asymmetry measured in 4 bins of $D$ phase space, $D$ decay params. from CLEO-c/BESIII

- **Result from Run1/2 data (9 fb$^{-1}$):**
  
  $$\gamma = (54.8^{+6.0}_{-5.8} \text{ (stat)} \pm 0.6 \text{ (syst)}^{+6.7}_{-4.3} \text{(ext)})^\circ$$

  *2nd best result from single mode*

  (best result from $D \to K_S^0\pi^+\pi^-$, unc. $\pm 5.2^\circ$ [JHEP 02 (2021) 169])

- **In good agreement with latest LHCb average**
  
  $$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$

  [JHEP 12 (2021) 141]

*Run 2 target of 4° being surpassed!*
$B^0_{sL}$ and $B^0_{sH}$ mass (and $\sim$CP) eigenstates: direct measurement of their lifetimes can be compared with SM expectation and/or what is obtained from direct measurement of $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ in $B^0_s \to J/\psi\phi$ decays.

New lifetime measurement of $B^0_s \to J/\psi\eta$ CP-even final state, hence pure “short”-living $B^0_{sL}$, on full Run 1+2:

$$\tau_L = (1.452 \pm 0.014_{\text{stat}} \pm 0.007_{\text{syst-uncorr}} \pm 0.002_{\text{syst-corr}})$$

- Precision comparable with best results available
- Overall coherent picture!

LHCb-PAPER-2022-010 in preparation
Mixing parameter $y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$ related to the lifetime difference between $D^0$ mass eigenstates

$y$ is accessible via the lifetime difference btw $D^0 \to K^-\pi^+$ and $D^0 \to f$ ($f = \pi^+\pi^-, K^+K^-$)

$$\frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to f)} - 1 = y_f^CP - y_{K\pi}^CP \simeq y(1 + \sqrt{R_D})$$

100M events available on Run 2

Combining $\pi^+\pi^-$ and $K^+K^-$ we get:

$$y_{CP}^{} - y_{K\pi}^{} = (6.96 \pm 0.26_{\text{stat}} \pm 0.13_{\text{syst}}) \times 10^{-3}$$

four times better than previous world average (already dominated by LHCb)

2202.09106
**LFU in \( b \rightarrow c \ell \nu \)**

**Intriguing tension in**

\[
R(D^{(*)}) = \frac{\mathcal{B}(B^0 \rightarrow D^{(*)} - \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{(*)} - \mu^+ \nu_\mu)}
\]

- Tree-level process, sensitive to NP coupling preferentially to 3\(^{\text{rd}}\) generation
- Possible connection with \( b \rightarrow s l^+ l^- \) anomalies

**LHCb** can access also baryonic modes \( \rightarrow 1^{\text{st}} \) observation of

\( \Lambda_b^0 \rightarrow \Lambda_c^+ \tau \nu \)

using Run 1 data

**Ratio** \( R(\Lambda_c) \) with muonic mode:

\[
R(\Lambda_c) = 0.242 \pm 0.026_{\text{stat}} \pm 0.040_{\text{syst}} \pm 0.059_{\text{ext}}
\]

**PRL 128 (2022) 191803**
**LFU in $b \rightarrow s\ell\ell$**

\[ R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)} \]

3.1σ below SM

Nat. Phys. 18 (2022) 277

**Update with full Run 2 ongoing**

More modes, including $D_{(s)}^+ \rightarrow \pi^+\phi(\ell^+\ell^-)$, and more $q^2$ bins will be also added

**Most recent measurements with full Run 2 on** $B^0 \rightarrow K_S^0\ell^+\ell^-$ and $B^0 \rightarrow K^+(K_S^0\pi^+)\ell^+\ell^-$

Results in agreement with SM (≈ 1.5σ below) and previous results from Belle

[2110.09501](https://arxiv.org/abs/2110.09501) (in memory of S. Stone)

Run 3 data will be crucial to clarify the picture on $b \rightarrow s\ell\ell$ anomalies

\[ R_H = \frac{\mathcal{B}(H_s\mu\mu)}{\mathcal{B}(H_see)} \]
LHCb is a general purpose detector in the forward region!

First measurement of the $Z \rightarrow \mu^+\mu^-$ angular coefficients and differential cross section in the forward region with Run 2 data

$2203.01602$

$2112.07458$

First measurement of $m_W$ in the forward region with 1.7 fb$^{-1}$

$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theo}} \pm 9_{\text{PDF}}$ MeV

$JHEP 01 (2022) 36$

Great potential for reducing the systematic uncertainty for an LHC combination (and compare with CDF)
First observation of a doubly charmed tetraquark $T_{cc}^+$ in $D^0 D^0 \pi^+$ mass spectrum, consistent with $c c \bar{u} \bar{d}$

Very narrow state, slightly below $D^*+D^0$ threshold

$$\delta m_{BW} = -273 \pm 61 \pm 5^{+11}_{-14} \text{keV}/c^2,$$
$$\Gamma_{BW} = 410 \pm 165 \pm 43^{+18}_{-38} \text{keV},$$

Increased interest for $T_{bc}$, $T_{bb}$ as possible first stable exotic states!

need Run 3&4 statistics
Heavy ions and QCD

1) Nuclear PDFs: LHCb probes unprecedented $x$ range in $pPb$ collisions with its forward coverage

Charged particle nuclear modification factor in $pPb$ collisions at 5 TeV

LHCb: $R_{pPb}$

Constraints on the nuclear PDFs from LHCb measurements on charm production

2205.03936

2) Hadronization mechanisms:

Strangeness enhancement at high multiplicity observed by ALICE

Nat. Phys. 13 (2017) 535

LHCb: $B_s^0/B^0$ ratio vs multiplicity $\rightarrow$ evidence of an increasing trend at low $p_T$ (coalescence?)

2204.13042
**Interpretation of** $\bar{p}/p$ **data from PAMELA and AMS-02 requires precise knowledge of** $\bar{p}$ **cross-section in cosmic rays collisions with interstellar medium.**

First measurement of prompt $\bar{p}$ production in $pHe$ collisions at 110 GeV using SMOG injection system performed during Run 2

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**New:** measurement of detached $\bar{p}$ component from anti-hyperons decays

\[ R_H = \frac{\sigma(pHe \rightarrow \bar{H}X \rightarrow \bar{p}X)}{\sigma(pHe \rightarrow \bar{p}_{\text{prompt}}X)} \]

Predictions underestimate this ratio
LHCb Upgrade I at the starting line!

Major upgrade of all subdetectors, target $L_{\text{peak}} = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, pile-up $\sim 5$

- Pixel detector VELO with silicon microchannel cooling 5 mm from the beam
- New RICH mechanics, optics and photodetectors
- New silicon strip upstream tracker UT detector
- New SciFi tracker with 11,000 km of scintillating fibres
- New electronics for Muon and Calorimeters

This is a NEW detector at the LHC!

Being completed on-budget and near schedule

All subdetectors readout at 40 MHz, fully software trigger
The new VELO

- Pixel detector 5 mm from the beam, with innovative micro channel cooling
- Test of first-half disrupted by omicron wave in December 2021, installed in March and now being commissioned
- Cooling leak delayed second half, transported at CERN end of April and installed last Friday, in time for 2022 data taking

FULL VELO IN: critical milestone!!!
**RICH1 and RICH2**

Unique particle identification system, key for success of physics programme

- **RICH1**: new mirrors with increased focal length, to halve the occupancy
- **RICH1/2**: new photodetectors MaPMTs with increased granularity and 40 MHz readout

**Installation successfully completed in February, detector commissioned and now in data taking**

**RICH1: MaPMTs installed upper side**

**RICH2: first rings acquired during LHC october test**

**RICH1: pixel map**
Scintillating Fibre Tracker

Cost-effective large scale downstream tracker based on 12 large planes equipped with scintillating fibres

Installation successfully completed in February

• All electronics and services connected

• Commissioning being finalised
Present detectors are capable to stand the increased luminosity of Run3/4

**Shashlik calorimeters**

- PMT gain reduced to stand the higher occupancy
- new front-end electronics with improved S/N and 40 MHz readout

**Muon stations**

- 4 walls equipped with MWPCs, and interleaved with iron filters
- front-end electronics upgraded for 40 MHz readout, granularity increased on first station to reduce occupancy

*Detectors in global data taking*
Luminometer and SMOG2

Crucial systems are also ready to operate just at the entrance of the VELO

**PLUME luminometer**

- quartz tablets + PMTs for online+offline per-bunch luminosity measurement

*Detector installed and included in DAQ*

**SMOG2 gas target**

- New storage cell for the gas upstream of the nominal IP
- Gas density increased by up to two orders of magnitude → much higher luminosity
- Gas targets: He, Ne, Ar + possibly H₂, D₂, N₂, Kr, Xe

*Simultaneous p-p and p-gas data taking possible!*
68 staves with silicon strips and integrated cooling, arranged in 4 planes

- fast $p_T$ determination for track extrapolation → reduce ghost track, and improve trigger bandwidth
- long-lived particles decaying after VELO ($K_S$, $\Lambda$)

Detector assembly ongoing at surface, to be ready for detector installation later in year

- services in the cavern completed, first stave mounted

Not essential for early physics operation
Run 3 trigger revolution

L0 hardware has been removed, a full software trigger will process 30 MHz of inelastic collisions → factor of ~10 expected in hadronic yields at Run 3

30 MHz of inelastic collisions will be reduced to ~1 MHz by the HLT1 (tracking/vertexing and muon ID) running on GPUs

- achieved with ~200 cards
- room to expand to ~500 cards when porting more reco/selection functionalities into HLT1
Planning for Upgrade II

**Upgrade II**

- $L_{\text{peak}} = 1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- $L_{\text{int}} = \sim 300 \text{ fb}^{-1}$ during Run 5 & 6
- Fully exploit the HL-LHC for flavour physics

**Framework TDR approved by LHCC**

- Targeting same detector performance as in Run 3, but with pile-up $\sim 40!$
- New detector technologies (e.g. precision timing, low-cost monolithic pixels) pathfinder for future projects beyond the LHC
- Subdetector TDRs at beginning of LS3

New collaborators welcomed!
Summary

**LHCb Upgrade I**: largest CERN particle physics detector project since LHC completion

Despite pandemic, is being completed on-budget and near schedule

**Significant physics results**: world-best measurements on CKM angle $\gamma$ and $D^0$ mixing, LFU measurements under-way, world-class measurements in spectroscopy, EW precision physics and QCD

Farewell to “LHCb-original" detector: more than 600 papers published so far, many more to come with ongoing analyses on Run 2 data!

**LHCb Upgrade II project is taking shape**: Framework TDR delivered, R&D setting the path to detector TDRs