LHCb Upgrade II

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on behalf of LHCb Collaboration

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LHCC-2021-012
LHCb upgrades

Physics programme limited by detector, and NOT by the LHC, so there’s a clear case for an ambitious plan of upgrades

Upgrade II

- Detector installation during LS4 (2033)

- \( L_{\text{peak}} = 1.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \)

- \( L_{\text{int}} = \sim50 \text{ fb}^{-1} \) per year, \( \geq300 \text{ fb}^{-1} \) during Run 5 & 6

Potentially the only general purpose flavour physics facility in the world on this timescale

*European Strategy Update 2020*  “The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited”
Search for New Physics

Increase of precision in flavour physics will allow to probe mass scales not accessible directly at LHC

Need huge statistics, low systematic uncertainties and precise SM predictions
Physics case: a few examples

LHCb Upgrade II will test the CKM paradigm with unprecedented accuracy

CP violation in charm

...and much more: rare decays, LFU tests, spectroscopy, EW precision, dark sector, heavy-ion and fixed target

A general purpose detector in the forward region!

Only planned facility with a realistic possibility to observe CPV in charm mixing

Physics case discussed in LHCC-2018-027
Upgrade II: approval steps so far

**EoI**

- LHCC-2017-003
  - Detector design and technology options
  - R&D program and schedule
  - Cost for baseline, options for descoping
  - National interests

**Physics case**

- LHCC-2018-027

**Accelerator study**

- CERN-ACC-2018-038

CERN Research Board  September 2019

“The recommendation to prepare a framework TDR for the LHCb Upgrade-II was endorsed, noting that LHCb is expected to run throughout the HL-LHC era.”
The approval process (LHCC)

Multiple steps, based on what has been done for ATLAS/CMS phase 2:

1.1 Letter of Intent: overall description of the upgrade programme, with discussion of physics notation and performance, detector elements, plan for R&D, technologies

“LHCb has fulfilled this step with the submission of the EoI, the Physics case document and the FTDR, all very favourably review by LHCC”

1.2 Scoping Document: estimated cost scenarios (baseline and descoped) with analysis of physics performances, person-power and funding profiles, project organisation and milestones, list of TDRs and project schedule; the document will be complemented by a money matrix (country vs sub detectors) to be agreed with Funding Agencies (will be kept confidential)

“It is recognised that the LHCb Upgrade FTDR already includes some elements foreseen for the Scoping Document, such as selected descoping options with a brief description of the corresponding cost reduction and the expected impact on the physics programme, and indications of national interests in detector system”

We plan to produce the Scoping Document within the next 2 years
Strong interest from the scientific community in our physics case → collaboration size doubled during last decade and keeps growing

The next target of the Scoping Document will certainly help in clarifying the contours of new participations

We need to accommodate/mitigate the consequences of Russian invasion of Ukraine and planned end-date for Russian participation
Timeline and constraints

- LS4 duration of 2 years will be fully needed for Upgrade II installation

- Mitigation: anticipate the LHCb detector infrastructure work to LS3

- LS3 would be also optimal to carry on the needed infrastructure modifications to the LHC (e.g. shielding wall to protect cryo equipment)
Preparation work during LS3

**LHCb detector infrastructure:**
- Facilities/buildings for detector cooling, assembly, clean room, storage
- Additional shielding for Muon detector in place of HCAL
- New platforms for ECAL FE electronics
- Refurbishment of underground infrastructure for the online system
- Power distribution, safety systems

Limited-size detector consolidations also proposed, which will bring some physics benefits already in Run 4 while anticipating features of the Upgrade II

Limited size, carried on independently of the Upgrade II approval discussion, but cost accounted as part of Upgrade II for reused elements
The detector challenge for Upgrade II

Targeting same performance as in Run 3, but with pile-up ~40!

Same spectrometer footprint, innovative technology for detector and data processing

Key ingredients:
- granularity
- fast timing (few tens of ps)
- radiation hardness (up to few $10^{16} n_{eq}/cm^2$)

Run 3: pile-up ~6
Upgrade II: pile-up ~40

VErtex LOcator (VELO)

~2000 tracks
~6 cm
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Extensive R&D campaign ongoing to face the huge technological challenges, with the support of many institutes and funding agencies

The developments needed to face the harsh experimental conditions of HL-LHC in the forward direction will represent a bridge towards projects based at future accelerators

A few recent results will be discussed in the next slides…
**VELO: 4D tracking with precision timing**

**Pile-up suppression**

Each hit in VELO time-stamped with 50 ps resolution → 20 ps per track

**Pixel requirements:** 55μm pitch, time reso 50 ps, extreme lifetime fluence $6 \times 10^{16} n_{eq}/cm^2$

**R&D**

Excellent timing performances achieved with 3D-trench silicon sensors after irradiation $2.5 \times 10^{16} n_{eq}/cm^2$

4D tracking Timepix4 telescope, to test at full rate future tracking devices over large ASIC area

$\sigma_{eff} = 10.3$ ps @ 150V
Hybridized Timespot1 ASIC, 32x32 pixels, 55μm pitch

@ 12 μW on AFE

μ=22.6 [ps]
σ=5.5 [ps]

μ=42.6 [ps]
σ=18.2 [ps]

Layout below is the oscillator-core of in-pixel TDC, with comparison to previous generation (Timepix4), massive size reduction in 28nm → pixel size feasible
Tracker: DMAPs and Scintillating Fibres

Monolithic Active Pixel Sensors in the inner region
- low-cost commercial process, low material budget
- first rad-hard application for a large tracker at LHC
- pixel size $50 \times 150 \mu m^2$, fluences $6 \times 10^{14} n_{eq}/cm^2$ (and 5 times more in the UT)

Scintillating fibres in the outer region
- radiation-hard fibres
- micro-lens enhanced SIPMs

SciFi R&D: Cryogenic cooling with clear fibre interface
- Test setup operational spring 2023
- Long Kapton flex PCB produced – no problems observed
- Clear fibre interface development ongoing
- SiPM operation at 77K (LN2), less than 5KW total power expected, LN2 cooling system
- Close contact with Cern cryo group
- Feed though development ongoing, only thermal vacuum needed
SciFi R&D on Microlens-enhanced SiPM array

**Goal:** Increase detection efficiency, reduce noise and extend radiation tolerance of SciFi

- Prototypes for μ-Lens implementation, 10ch and 128ch (new)
- Cryo operation tests with SciFi in 2023
- New irradiation tests and operation at LN2 temperature

- µ-Lens implemented on 10ch custom device
- µ-Lens spherical and cylindrical patterns
- µ-Lens characterisation
- µ-Lens / cryo optimised SiPMs by FBK (summer 2022)
DMAPs R&D: results after irradiation

**Successful testbeam with irradiated AtlasPix3.1 sensor** (early predecessor of MightyPix design for LHCb)

- After irradiation technology works best at \( \leq -10 ^\circ C \) operation temperature
- For MightyPix1 we expect improved neutron tolerance above \( 1 \cdot 10^{14} \text{ MeV} n_{eq} \)
- For MightyPix1 (expected in December) we also expect better time resolution (~3ns)

**MightyPix1 prototype submitted**
ECAL with timing

**Goal:** achieve energy resolution and reconstruction eff. as in Run 1&2, with much higher pile-up and radiation up to 1 MGy

**Requires:** granularity, precision timing

**Different technologies in different regions:** SpaCal/Shashlik for inner/outer regions

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**R&D on SpaCal: time resolution**

Excellent time resolution achieved with W + crystal-fibres (GAGG)

Excellent time resolution achieved with Pb + Polystyrene fibres
Excellent time resolution achieved also with Shashlik modules (present technology); in particular, single vs double readout is explored, as an option for reducing the readout channels.

**Double-sided readout (CERN SPS 2021)**

![Graph showing time resolution vs energy for double-sided readout](image)

- 20 ps

**Single-sided readout (CERN SPS 2022)**

![Graph showing time resolution vs energy for single-sided readout](image)

- 20 ps

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3D printing techniques explored, with very good results in terms of surface smoothness.

**R&D on SpaCal: tungsten absorber**

- 3D printed W-absorber
- 1x1 mm² holes
- 500 µm wall thickness

Recently used at DESY & SPS (SpaCal-W/Polystyrene)

3D printed W-absorber

in collaboration with EOS (Germany)
RICH with timing

New design with improved Cherenkov angle resolution (0.1-0.2 mrad) and timing capability (tens of ps) expected to recover Run 3 performance

- SiPM good candidate for high-granularity and time resolution, front-end with 65nm CMOS

R&D on new READOUT with timing capability

Presently testing the RICH elementary cell equipped with both MaPMTs and SiPMs and FastIC ASICs + external TDC

Design well advanced for future FastRICH ASICs with on-board TDC and qualified for radiation
**TORCH and MUON**

**R&D on TORCH time-of-flight**

- **full module**
- **half-module proto**

Half module prototype 66x125x1 cm³, 2 out of 11 MCP-PMTs

Test photon counting, time resolution and reconstruction algorithms

**R&D on μRWell for MUON**

micro-pattern gas detector technology for the high rate region (≥MHz/cm²)

DLC sputtering machine for realisation of base-material for these detectors just arrived at CERN (co-fund CERN/INFN)
Conclusions

LHCb has fulfilled the first step of the approval for the Upgrade II project with a lot of documentation produced, the EoI, the Physics Case Document, and the framework TDR, all very favourably reviewed by the LHCC.

There’s now a clear strategy proposed by the LHCC to give final approval to the project (same as ATLAS/CMS): next step is a Scoping Document, coming within then next 2 years, to decide on the detector scenario which has best chances to be realised.

R&D phase is now in full steam

Goal is to identify solutions for all of the sub-systems: many results are already available, which represent state-of-the-art in the technology sectors of interest, and constitute a path-forward for future applications.

This phase will be crucial to guide the choices for optimising the cost/performance ratio.

We warmly thank all of the laboratories and funding agencies for their support.