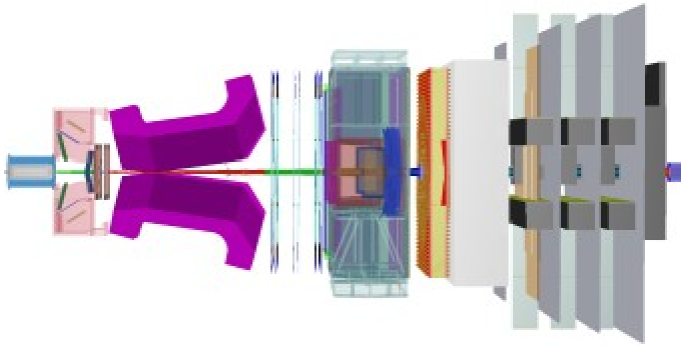
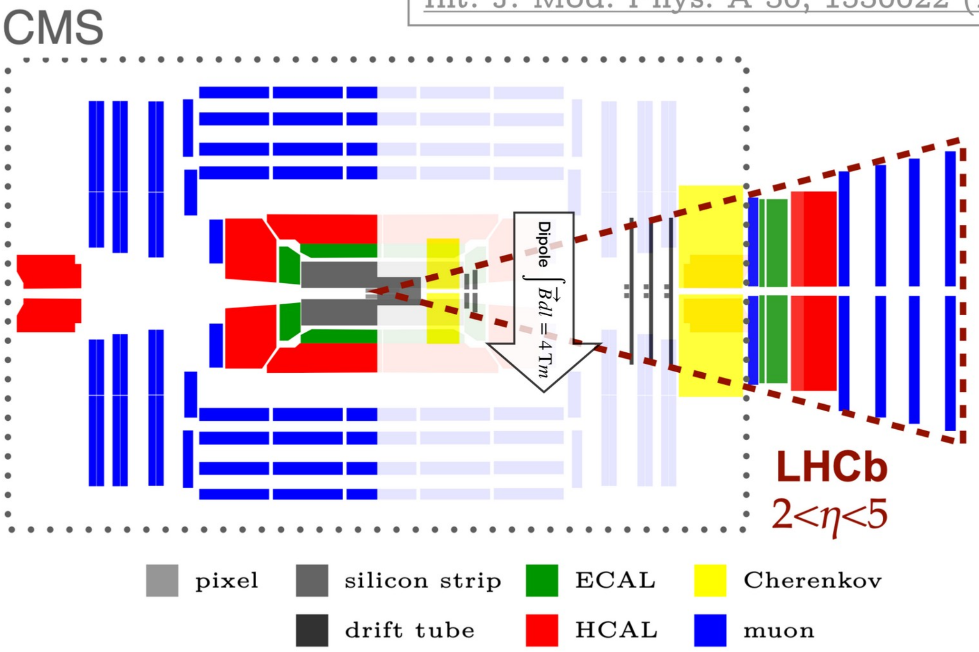


The LHCb experiment upgrade II

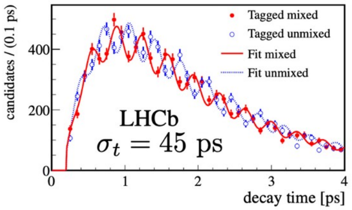
E. Santovetti
Università di Roma Tor Vergata e INFN

The LHCb detector

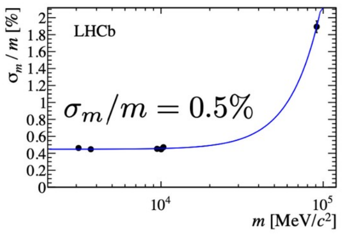
Int. J. Mod. Phys. A 30, 1530022 (2015)



vertex reconstruction



mass resolution



Run1 :

$$\int_{2011}^{2012} \mathscr{L} = 3\mathrm{fb}^{-1}, \ \sqrt{s} = 7 - 8\mathrm{TeV}$$

Run2 :

$$\int_{2015}^{2018} \mathscr{L} = 6\mathrm{fb}^{-1}, \ \sqrt{s} = 13\mathrm{TeV}$$

The LHCb Upgrade I

Run3 (on-going) (Upgrade I):

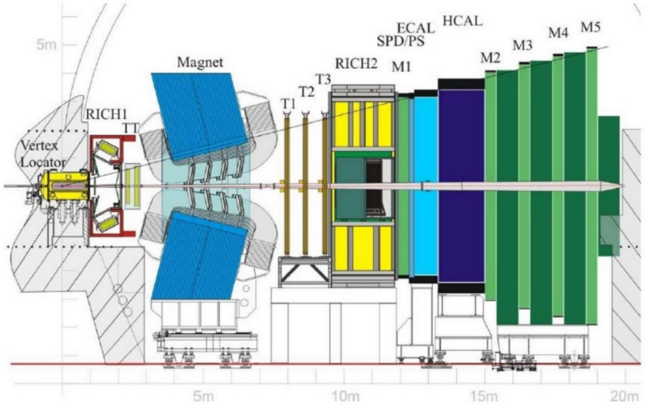
up to $50\,\mathrm{fb}^{-1}, \ \sqrt{s} = 13\mathrm{TeV}$

- Exploit large $\sigma_{pp\to b\bar{b},c\bar{c}}$ in $\eta \in [2,5]$ at LHC pp collisions
- Unique capabilities in forward region with fully flexible software triggers (since Run3) in real time.
  - Channels studied from $\mathscr{B} \sim \mathscr{O}(10^{-10}) - \mathscr{O}(1)$
- Very broad physics program in flavour (and not only) aiming at precision measurement for indirect NP signature finding. But also rare-decays, QCD, EW-physics, heavy-ion....

The LHCb detector evolution

Past

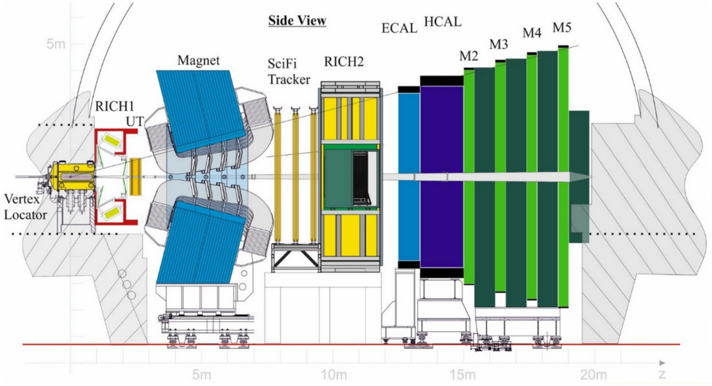
Run I + Run II (2011-2018)



Physics case grown and matured

Present

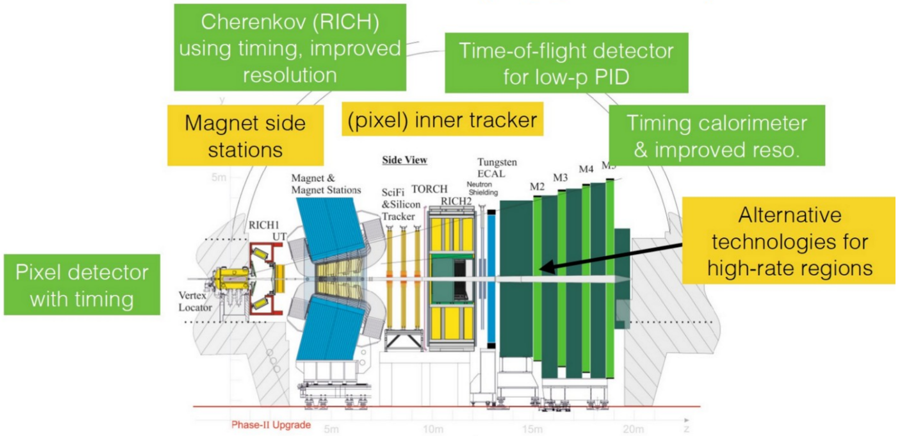
Run III/IV (Upgrade I)



Full software trigger and upgraded sub-detectors/read-out to benefit of higher luminosity

Future

Run V/VI (Upgrade II)



Add timing/improve sub-detetectors and operate at even higher luminosity (HL-LHC)

The LHCb experiment Physics program

- **Precision measurement in the flavour sector**

CP Violation in charm and beauty decays

V_{CKM} matrix element

Neutral meson oscillations†

EW physics in forward direction†

- **Rare decays and sensitivity to high-energy NP**

Rare b/c decays

Lepton flavor universality tests

- **Leave no stones unturned : low energy NP & Dark Sector†**

Search for exotic new particles: axions, dark photons, dark sector

†not covered in this talk

The LHCb experiment Physics program

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Rare b/c decays

Lepton flavor universality tests

- **Leave no stones unturned : low energy NP & Dark Sector**

Search for exotic new particles: axions, dark photons, dark sector

But also

QCD†

Spectroscopy†

Heavy Ion†

†not covered in this talk

High precison measurements with Upgrade II

Ingredients for high precision with heavy flavour

High production rate → Large data sample → Selection efficiency → Resolve signal ability

- b/c production cross section at LHC is enormous
- Be able to collect maximum possible by end of HL-LHC
- Go beyond the $\sqrt{(N)}$ scaling in precision with acceptance and capabilities of detector
- In flavour physics and for LHCb: p-resolution, vertexing and hadrons (π, K, p) separation
- Approximately$3 \times 10^{11} (5 \times 10^{12})/\text{fb}^{-1}$ b(c)-hadrons

Matched only by ATLAS and CMS — *Channel dependent*

- (e, μ, p, π, K) : LHCb unique and superior to any other experiment considering all charged stable final states. Decays with μ, ATLAS & CMS competitive
- One or more γ, π^0 or ν: Belle II competitive (or superior)

High precison measurements with Upgrade II

Ingredients for high precision with heavy flavour

High production rate	Large data sample	Selection efficiency	Resolve signal ability
b/c production cross section at LHC is enormous	Be able to collect maximum possible by end of HL-LHC	Go beyond the $\sqrt(N)$ scaling in precision with acceptance and capabilities of detector	In flavour physics and for LHCb: p-resolution, vertexing and hadrons (π, K, p) separation

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Matched only by ATLAS and CMS *Channel dependent*

European Strategy Update 2020

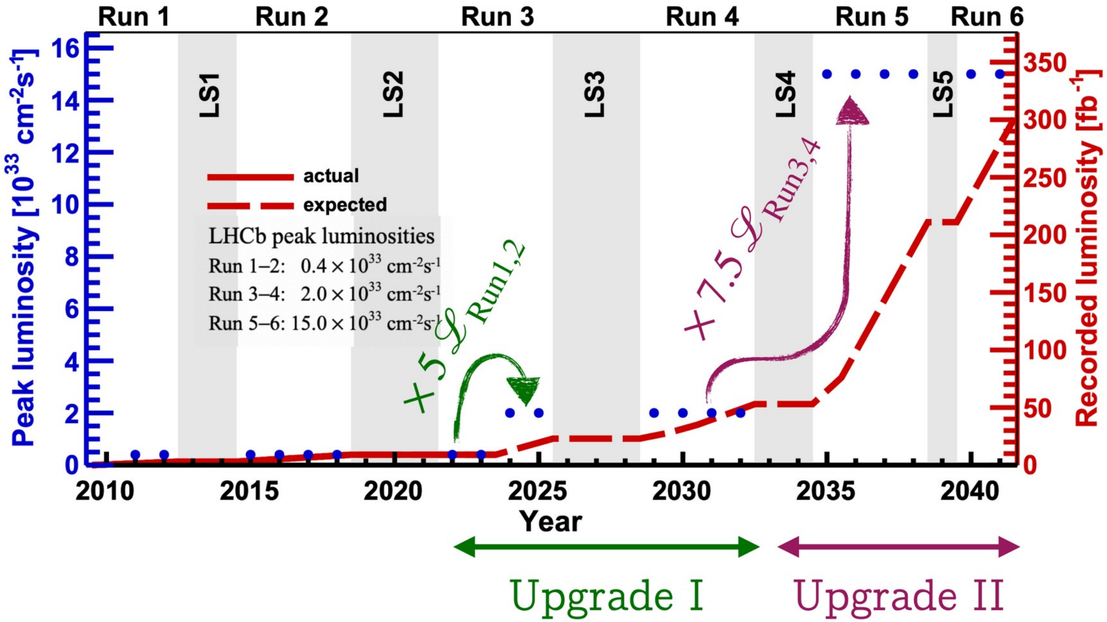
"The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited"

Luminisity increase

	Run 2	Run 3	Run 4	Run 5	Run 6
Total LHCb recorded luminosity at end of each Run [fb^{-1}]	9	23	53	211	300

$50(25)\,\frac{\mathrm{fb}^{-1}}{\mathrm{year}}\,(1^{st}\,\mathrm{year})\oplus$

$\varepsilon_{\mathrm{data-taking}} = 90\,\%$

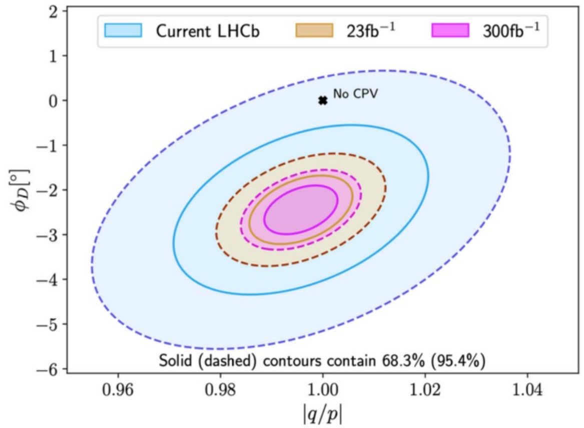


- Opportunity to operate until end of HL-LHC
- Upgrade II designed to reach up to 300 fb^{-1} by end of Run6

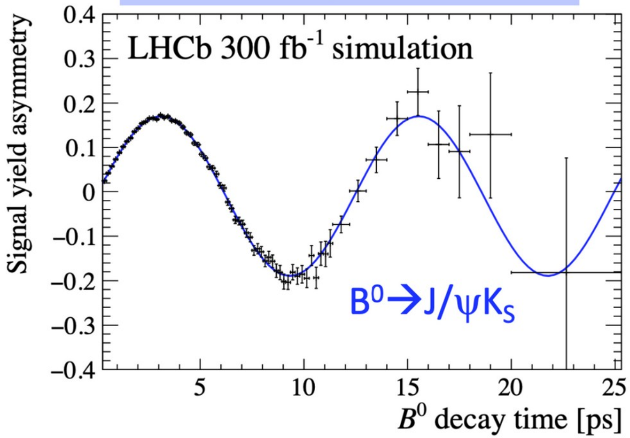
LHCb Upgrade II Physics case

With 300 fb^{-1}

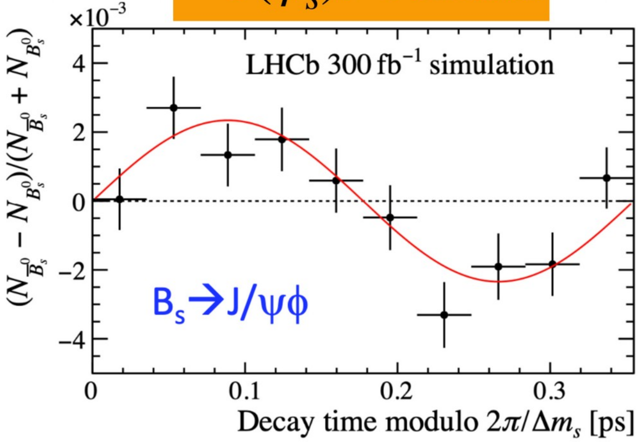
- $\sigma(\text{Charm CPV}) : \mathcal{O}(10^{-5})$



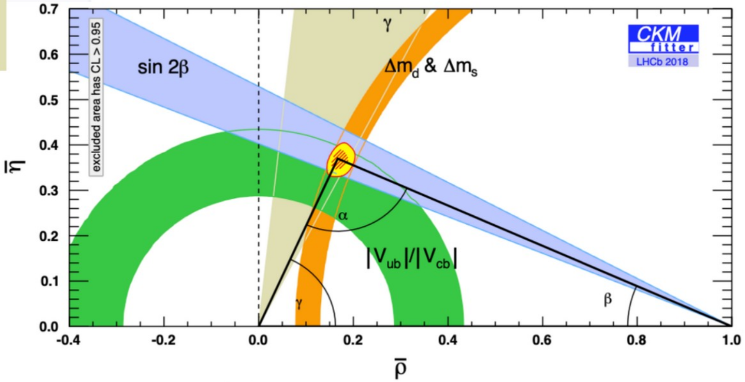
- $\sigma(\sin(2\beta)) : 0.003$

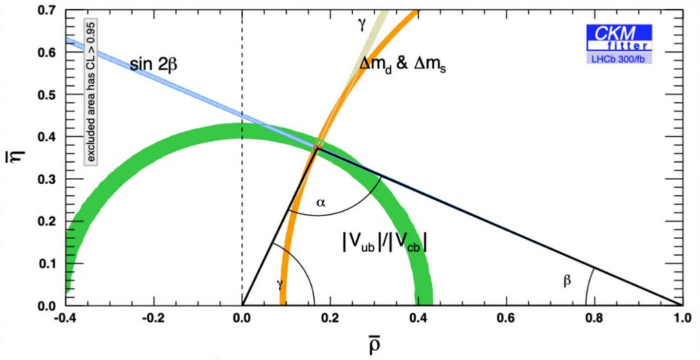


- $\sigma(\phi_s)$: 4 mrad

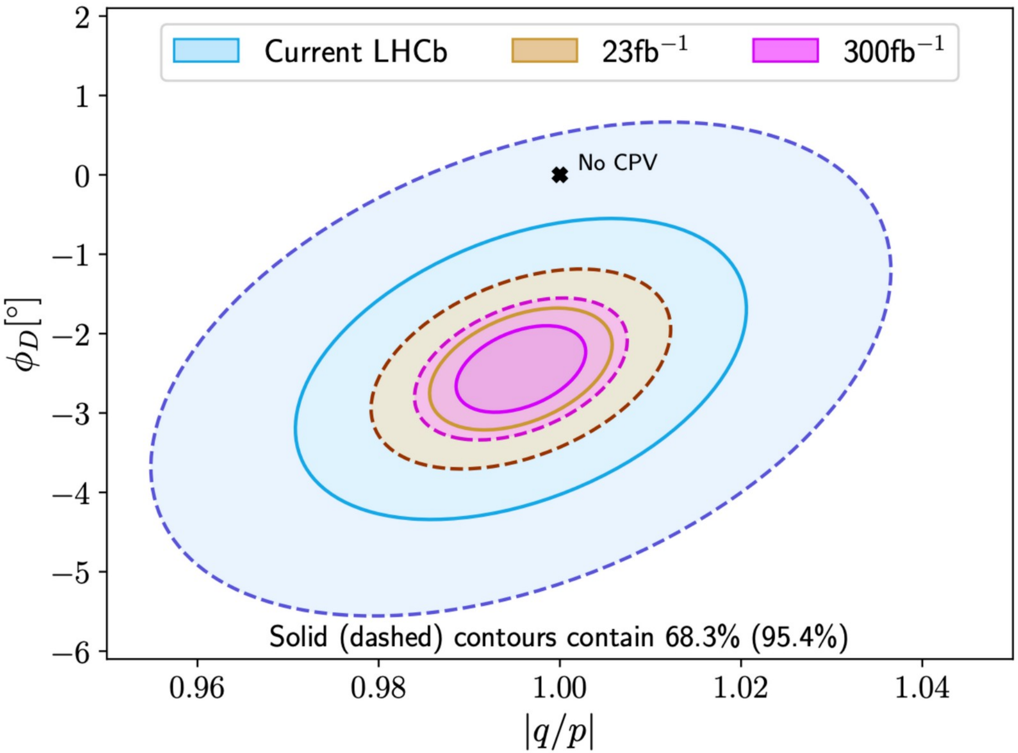


- $\sigma(\gamma) : 0.4°$





Charm CP violation



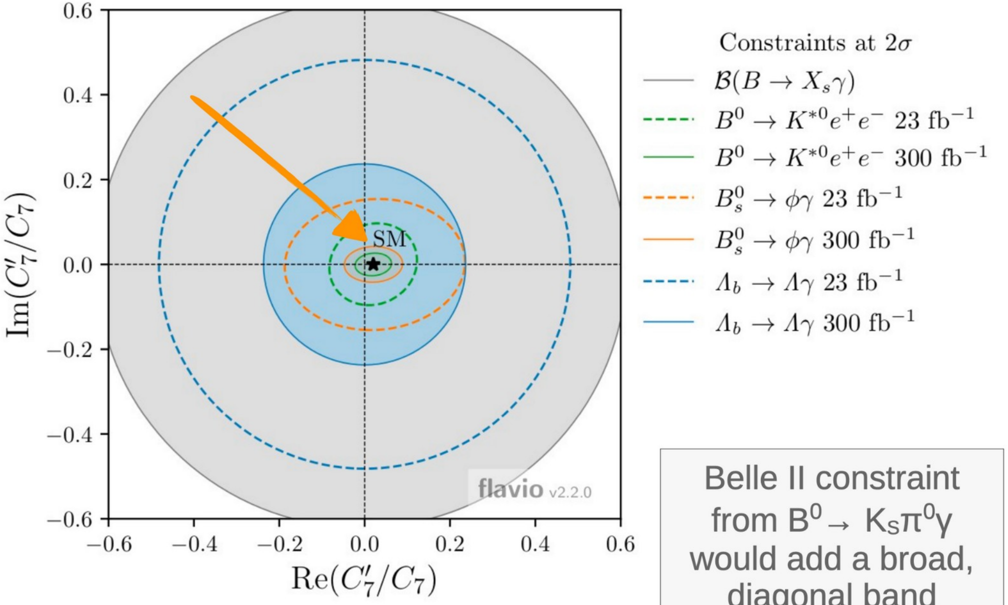
Is ΔA_{CP} SM or BSM?

- Need more measurements to over-constrain theory parameters
- Beginning to resolve separate contributions from $D \to K^+K^-(\pi^+\pi^-)$ to ΔA_{CP}, but still rely on theory to test SM prediction.
- LHCb Upgrade II uniquely can provide measurements of A_Γ for $D \to K^+K^-$ & $\pi^+\pi^-$ and pin down these parameters.

LHCb U2 has capability to reach 10^{-5} level of precision needed to understand CP violation in charm

Search for “right-handed” interactions

- Why does the SM weak interaction have a V-A structure?
  - i.e only LH weak currents
- Unique, high precision methods to search for RH currents in
  - $B^0 \to K^{*0}\gamma$ angular distribution
  - $B_s^0 \to \phi\gamma$ decay-time distribution
  - $\Lambda_b \to \Lambda\gamma$ polarisation



Belle II constraint from $B^0 \to K_S\pi^0\gamma$ would add a broad, diagonal band

LHCb U2 can study SM extensions with RH currents at this level of precision (2/3 methods unique to LHCb)

Why an Upgrade II for LHCb?

- <u>Beside CPV in B, Upgrade II of LHCb</u>
  - Unique place to reach 10^{-5} precision needed to understand CP violation in charm (is ΔA_{CP} SM or BSM?)
  - SM extensions with RH currents? [several $b \to s\gamma$ methods unique to LHCb]
  - Spectroscopy (unrivaled), QCD
  - Rare decays & LFU-test tree
  - But also fixed target collisions (SMOG)
  - Complementary region of parameter space in heavy ion, Long-Lived searches/Dark sector, EW sector....

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05
CKM tests				
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°
γ, all modes	3° [167]	1.5°	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.013 [609]	0.011	0.005	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	20 mrad [44]	14 mrad	–	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad
$a_{\rm sl}^s$	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%
$B_s^0, B^0 \to \mu^+\mu^-$				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%
$S_{\mu\mu}$	–	–	–	0.2
$b \to c\ell^-\bar{\nu}_l$ LUV studies				
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002
$R(J/\psi)$	0.24 [220]	0.071	–	0.02
Charm				
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}
A_Γ $(\approx x \sin\phi)$	2.9×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}

From CERN-LHCC-2018-027
With some edits for current LHCb

THIS PHYSICS can be done only with a future upgrade of LHCb (Upgrade II) operating at the HL-LHC

Granular/Rad-Hard/Timing detectors [pile-up mitigation]
Technology not yet available in most cases, important R&D ongoing/needed

Detector/Physics interplay

Need efficiency tracking, robust reconstruction of decay vertices, excellent charged hadrons, leptons ID

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EW Penguins				
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007
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✓ Best calorimetry

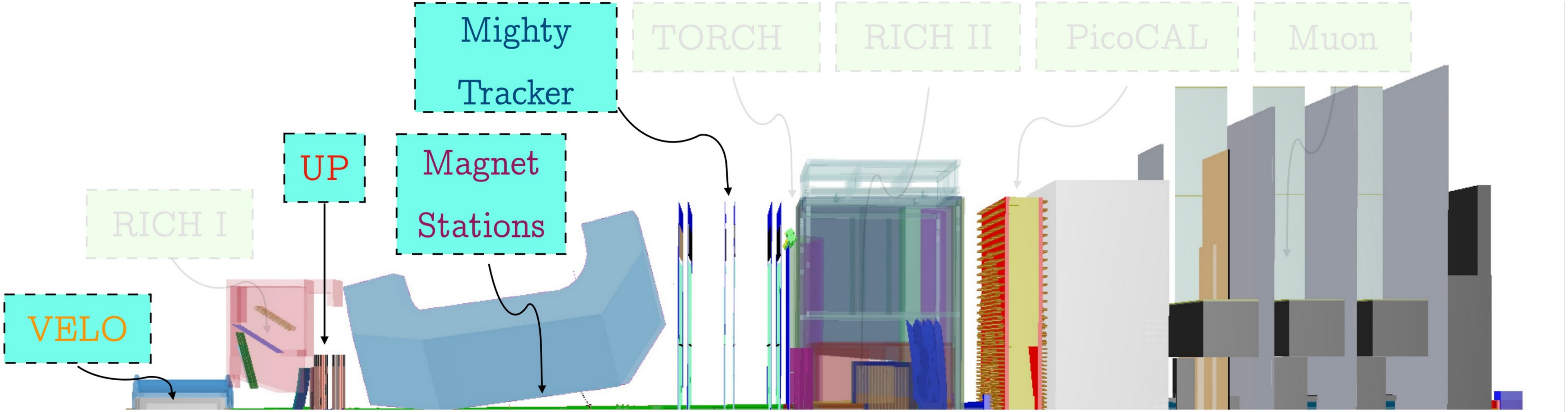
✓ Best charged hadron $K/\pi/p$ ID / Light detector

✓ μ ID & mass resolution

✓ Light detector

✓ Increase acceptance for low p_T

Tracking detectors at LHCb Upgrade II



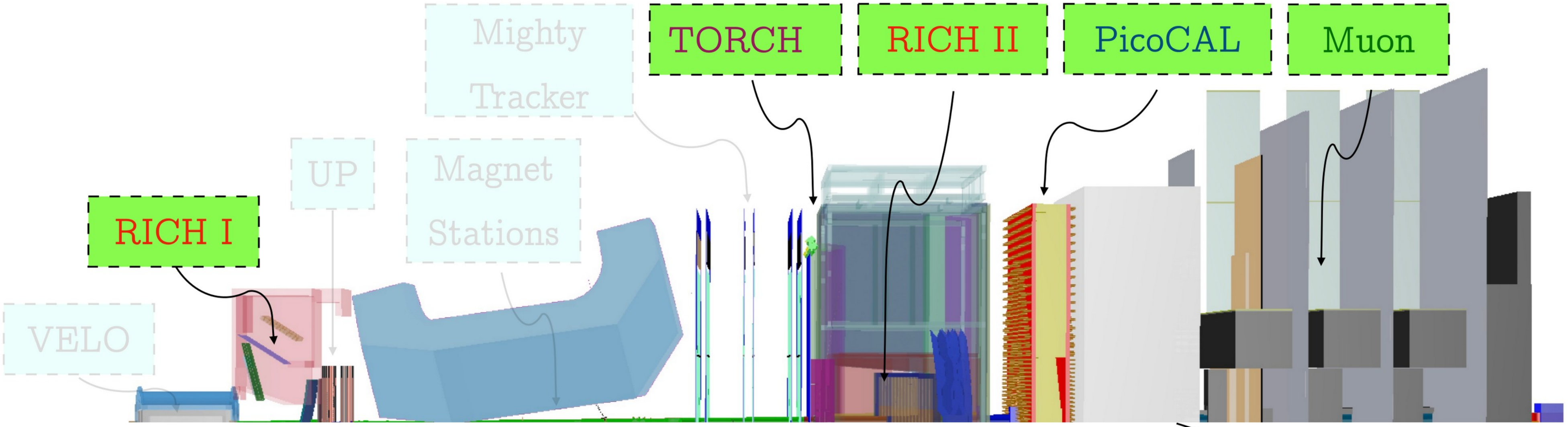
Tracking system

- VELO: pixel 3D silicon , per-hit time resolution 50 ps , ASIC 28nm
- UP: Depleted Monolithic Active Pixel Sensors (DMAPS) pixel
- Mighty Tracker: DMAPS pixel inner region, Scintillating Fibers for outer region
- Magnet Stations: scintillating slabs on side walls of magnet (low p tracks) [*NEW*]

Vertexing and tracking in high pile-up environment require granular, rad-hard and efficiencient trackers.

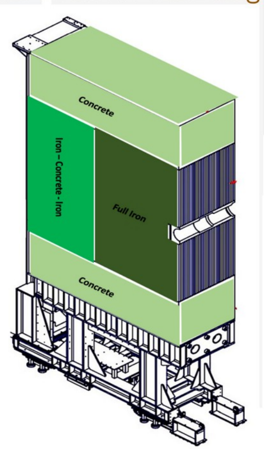
ps-timing information near interaction region crucial, ns-timing for BXID in UP and Mighty Tracker needed

PID detectors at LHCb Upgrade II



Particle ID

- RICH I and RICH 2: improve optics, reduce pixel size and per-photon timing information,(MCPs)
- TORCH (new!): time of flight quartz, SiPM, MCPs (as RICH read-out)
- PicoCAL to replace ECAL: space, energy and time using longitudinal segmentation
  - Current HCAL : replaces by iron-concrete shielding
- Muon: μRWELL in inner regions , MWPC for outer region (recycled)

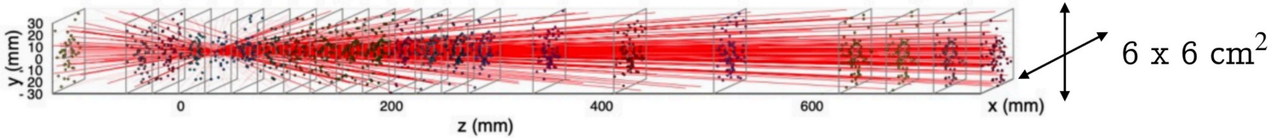


Particle identification of hadrons, muons, electrons, photons crucial for LHCb in a wide momentum range. PicoCAL and RICH need timing to cope with occupancy.

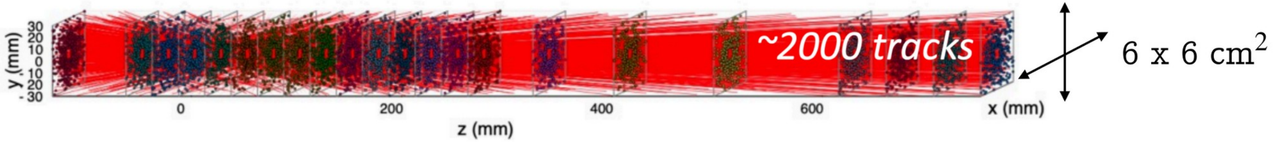
Operating LHCb at HL-LHC: need of timing detectors

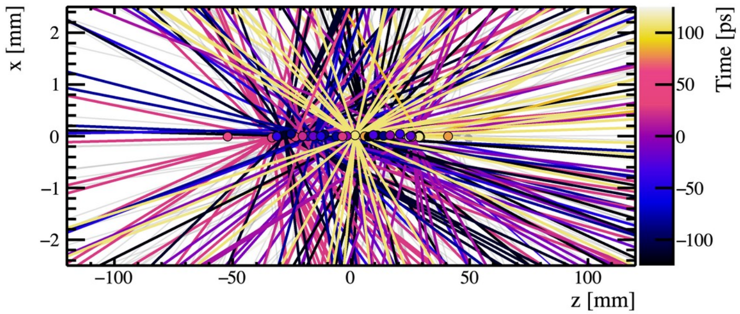
- Ensure PV finding/association of tracks/displacement signatures at the core of LHCb physics program
  - Including timing information is mandatory for VELO
  - Operate at $\mathscr{L}_{max} = 1.0 - 1.5 \times 10^{34}$ cm$^{-2}s^{-1}$ → occupancy/multiplicity and 4D detectors

- Run 3 (Upgrade I):
  - pile-up ~ 5

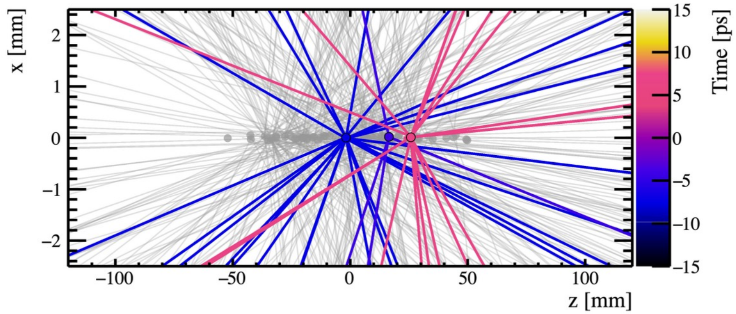


- Upgrade II:
  - pile-up ~ 40



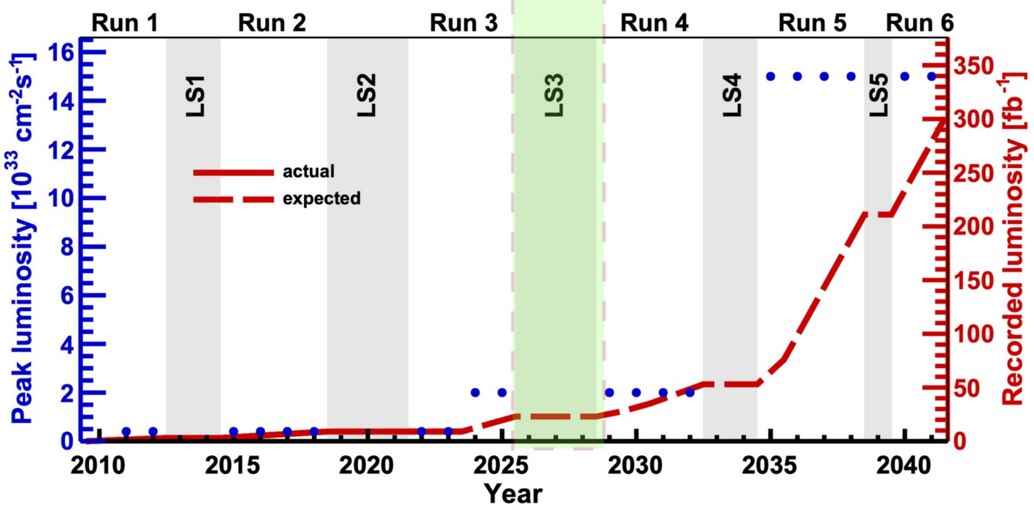


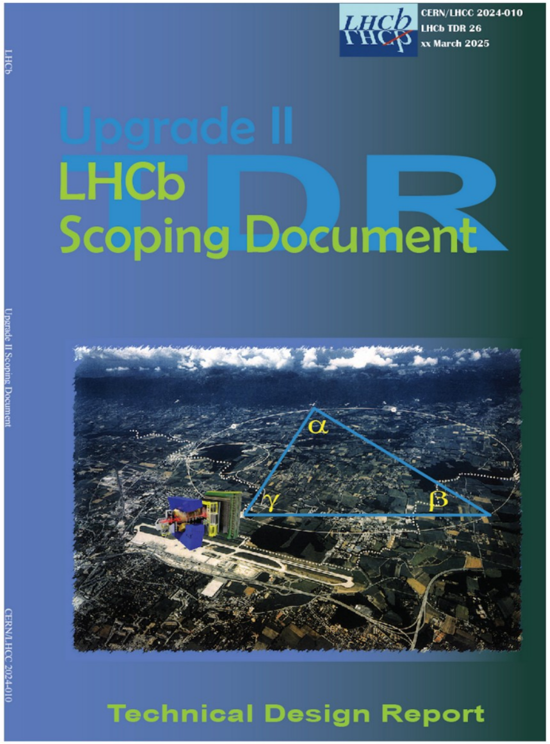
“Problem” complexity with no timing per track



“Problem” complexity with 20ps/track resolution

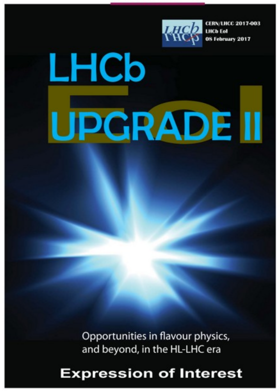
Road to Upgrade II (Scoping document)





- 2017

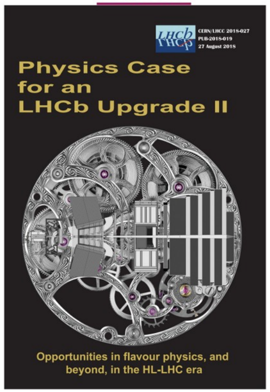
Expression of Interest



[LHCC-2017-003](#)

- 2018

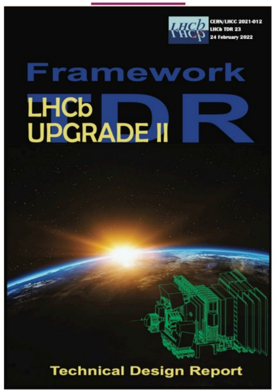
Physics Case



[LHCC-2018-027](#)

- 2021

Upgrade II FTDR



[LHCC-2021-012](#)

Accelerator studies: CERN-ACC-NOTE-2018-0038

Approved 03/2022

LHCb has now submitted for review to the LHCC the Upgrade II Scoping Document

Conclusions

- Flavour physics at hadron colliders is able to probe indirectly NP high energy scales
  - The LHCb experiment is and will keep shaping the landscape in the next years
  - Via multibody decays, time dependence, flavour tagging, amplitude analyses, complementarity of many different final states
  - Maximising current data output using novel techniques and pushing experiments beyond design
  - Synergy between experiments also critical in various measurements
- Interpretation of flavour results requires often better understanding of penguin amplitudes, form factors, hadronic uncertainties. Progresses are ongoing and should continue
- Run3 at LHCb has a powerful dataset on his way coming, *stay tuned*
  - 2024 has been crucial for realization and execution of full LHCb experiment Upgrade potential
- <u>Beyond Run3, a second upgrade planned</u>
  - Ambitious project with excellent prospects for physics and technology developments
  - <u>LHCb U2 Project is in its approval phase, perfect opportunity to contribute!</u>
  - Somewhat, U2 of LHCb is once-in-a-life project, (maybe the last-chance?) to push many flavour measurements to the ultimate precision.