LHCb Upgrade II
Detector and Physics Prospects

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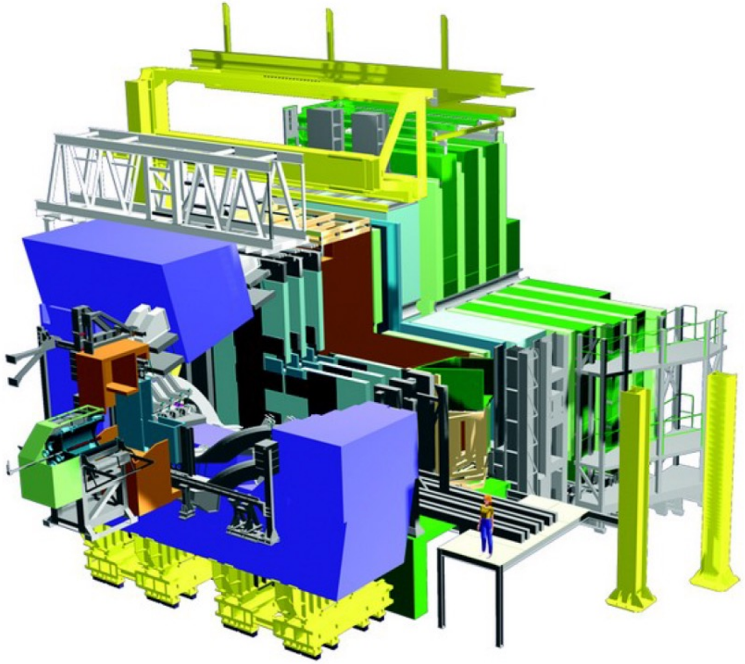
for the LHCb collaboration

15 January 2024

The 2024 International Workshop on

Future Tau Charm Facilities

The LHCb collaboration



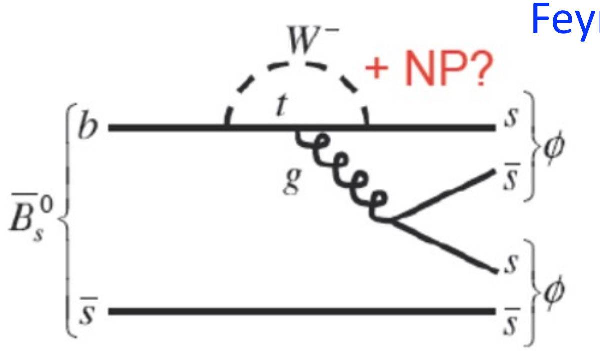
- As of today, more than 1600 members from 98 institutes in 22 countries
  - Including 1100 authors
- 700 collaboration-wide papers so far, using data from LHC runs 1 and 2

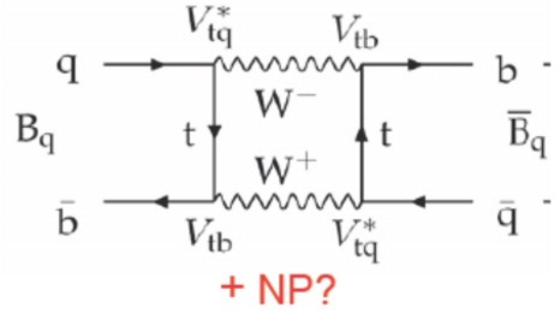
Groups currently involved in LHCb from China

- Full member institutes
  - Center for High Energy Physics, Tsinghua University, Beijing
  - Institute Of High Energy Physics (IHEP), Beijing
  - School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing
  - University of Chinese Academy of Sciences, Beijing
  - Institute of Particle Physics, Central China Normal University, Wuhan, Hubei
- Associated institutes
  - School of Physics and Electronics, Hunan University, Changsha City, associated to Wuhan
  - Guangdong Provincial Key Laboratory of Nuclear Science, Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Institute of Quantum Matter, South China Normal University, Guangzhou, associated to Tsinghua
  - Lanzhou University, Lanzhou, associated to IHEP
  - School of Physics and Technology, Wuhan University, associated to Tsinghua
- Fraction of LHCb members and authors from Chinese institutes: 12%
  - Third largest national component, after UK and Italy

Loop diagrams and new physics amplitudes

Feynman diagrams with closed loops within: new-physics virtual particles can circulate





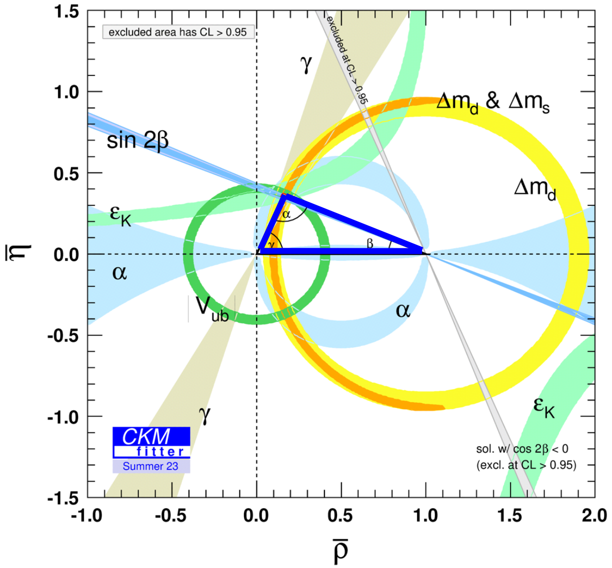
$$A = A_0 \left[c_{SM} \frac{1}{M_W{}^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

- General decomposition of a transition amplitude in terms of couplings and scales
- Must know the Standard Model contribution precisely, otherwise it could hide small new-physics effects → need to go to high precision measurements of observables that can be calculated in the Standard Model with the smallest possible uncertainty
- New-physics virtual particles of arbitrarily large mass can enter loops in Feynman diagrams and produce observable effects → the existence of particles with much larger masses than the energy made available by LHC could be unveiled
- LHCb main focus on such “indirect” new physics searches

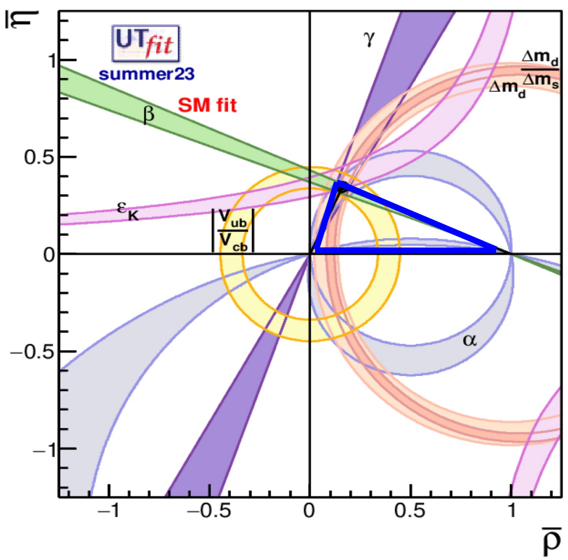
Consistency of global CKM fits

- Each coloured band defines the allowed region of the apex of the unitarity triangle according to the measurement of a specific process

http://ckmfitter.in2p3.fr



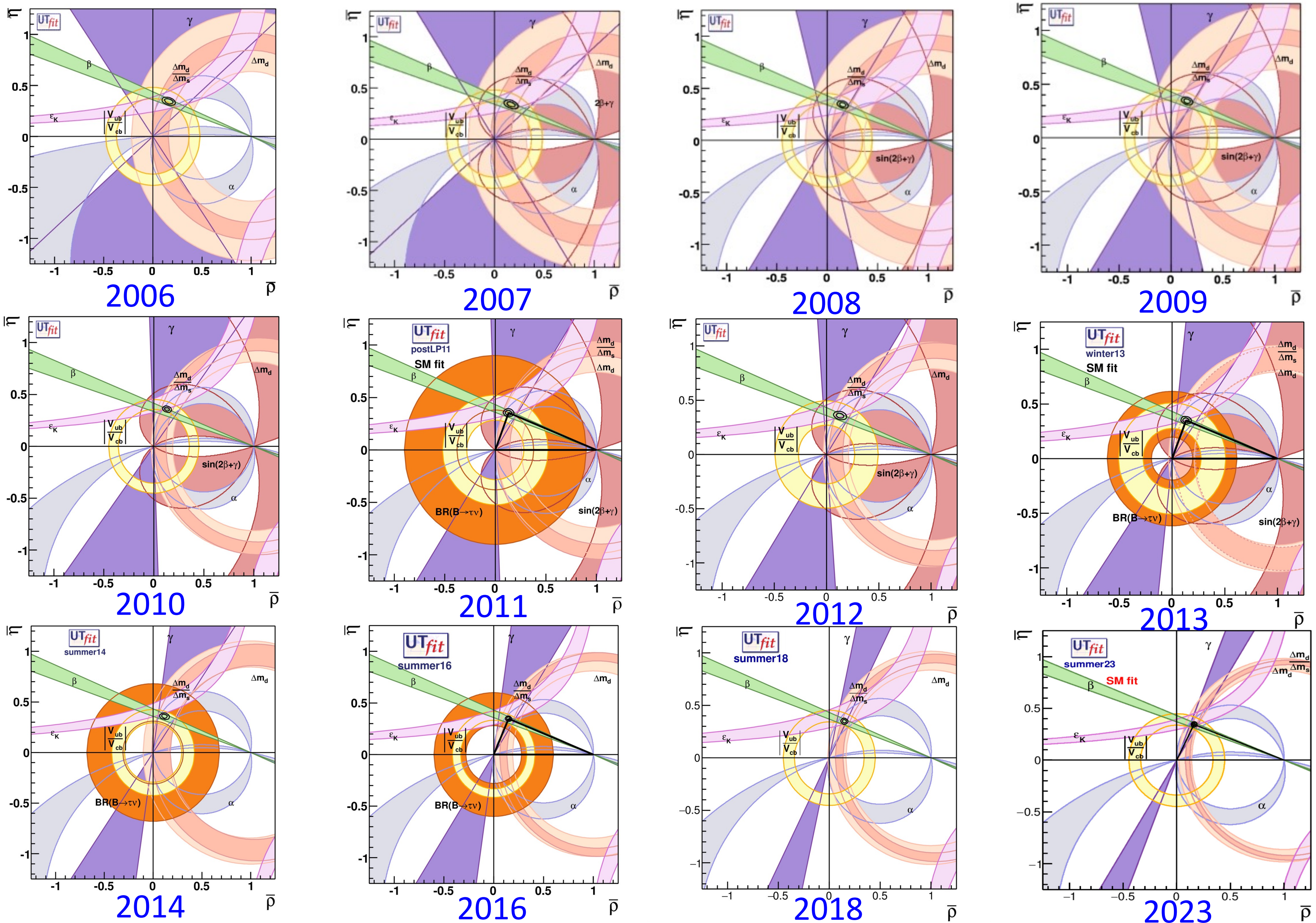
http://www.utfit.org



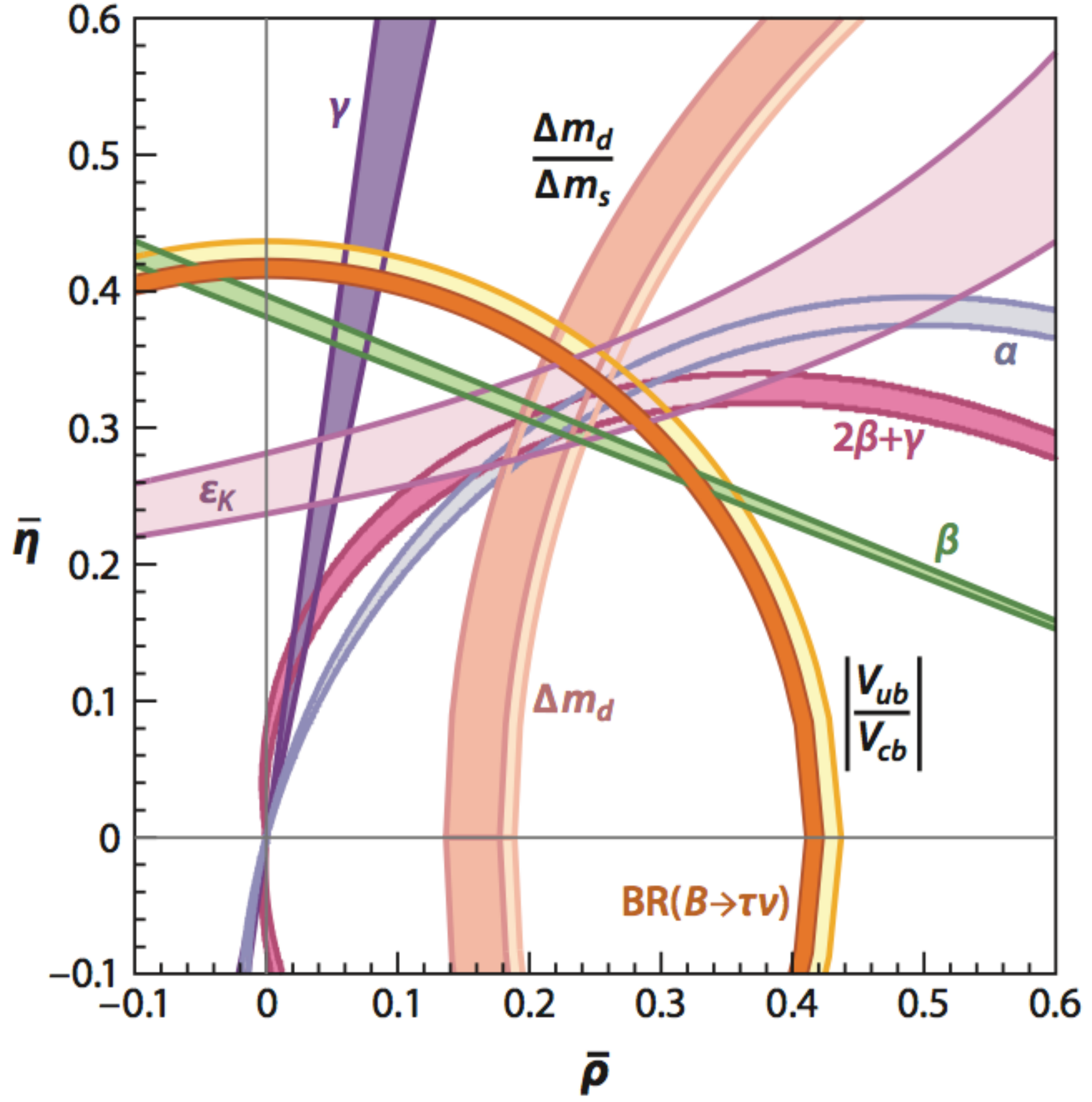
- Tremendous success of the CKM paradigm!
  - All of the available measurements agree in a highly profound way to the current level of precision
  - In presence of new physics affecting the measurements, the various contours would not cross each other into a single point
- The quark flavour sector is generally well described by the CKM mechanism, but there's still room for new physics contributions at the ~10% level

Long journey to reach here...

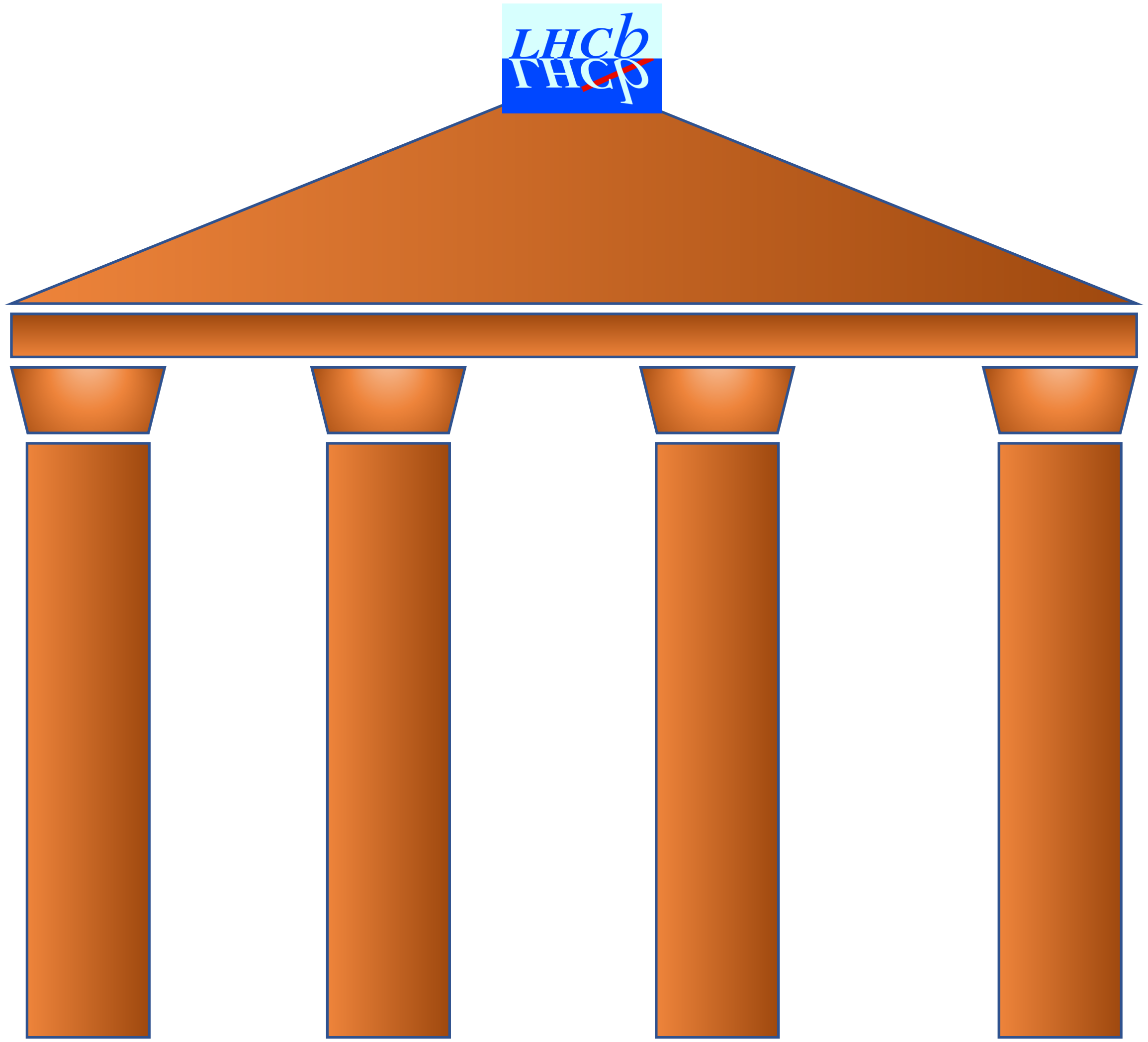
From 2010 onwards with crucial LHCb contributions



Dream new physics scenario for the unitarity triangle (for illustration only)



The LHCb physics pillars at design time



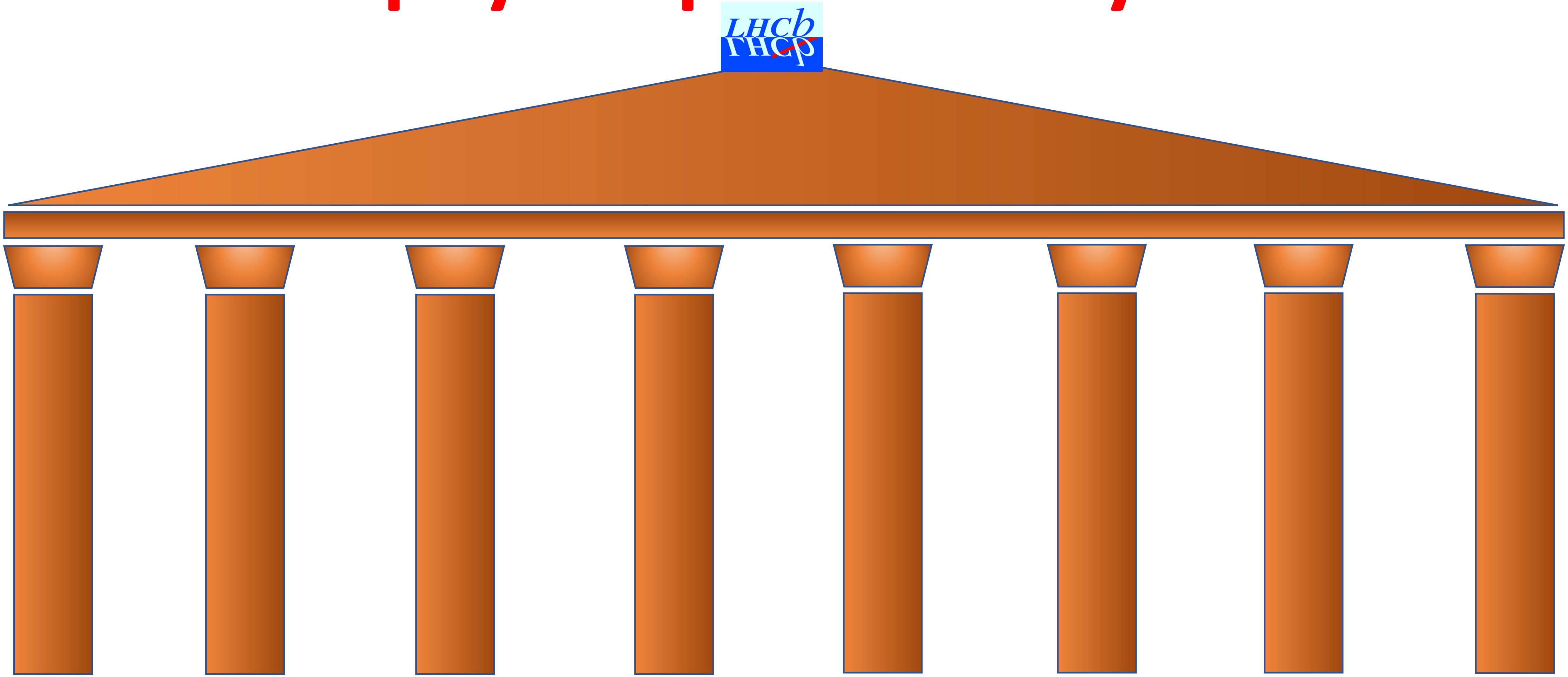
CP Violation in beauty

Rare decays in beauty, charm (and strange)

CP Violation in charm

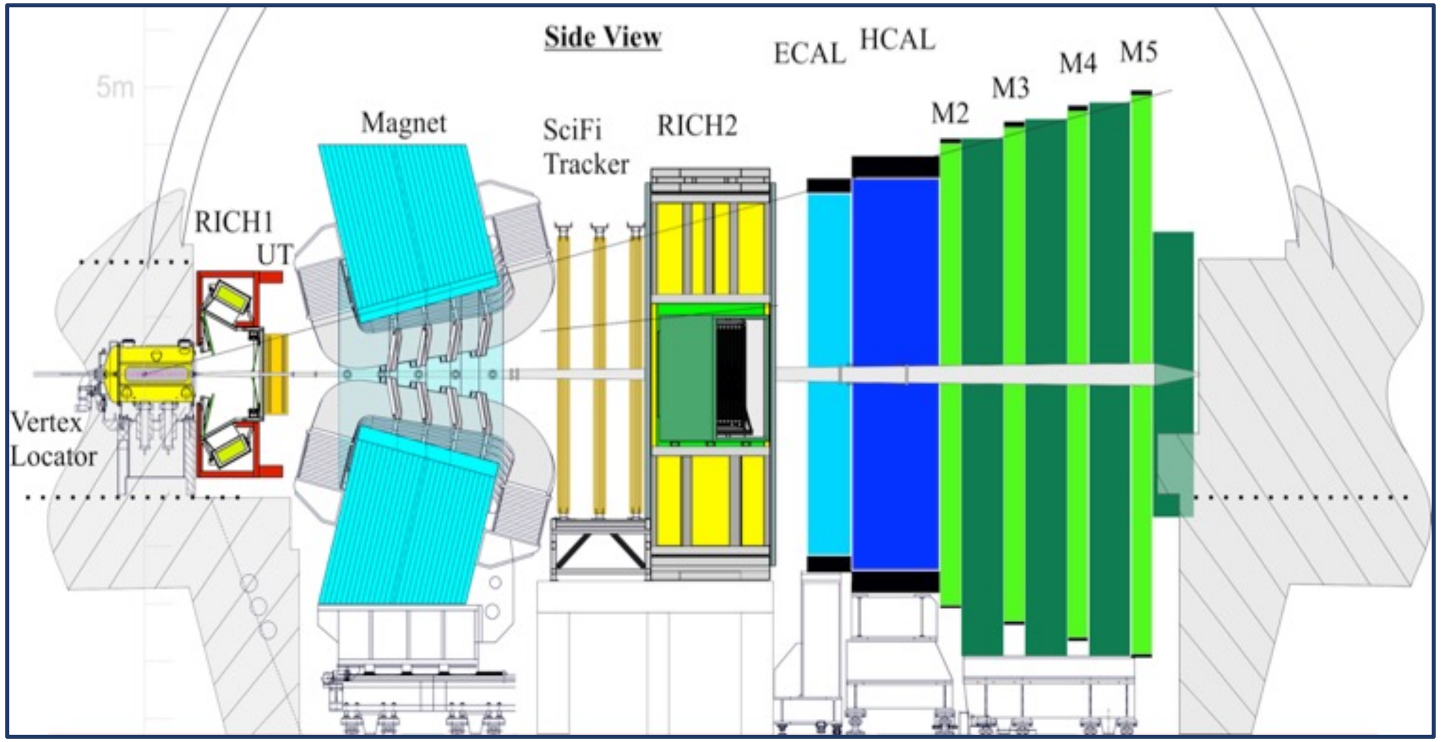
Heavy flavour production and spectroscopy

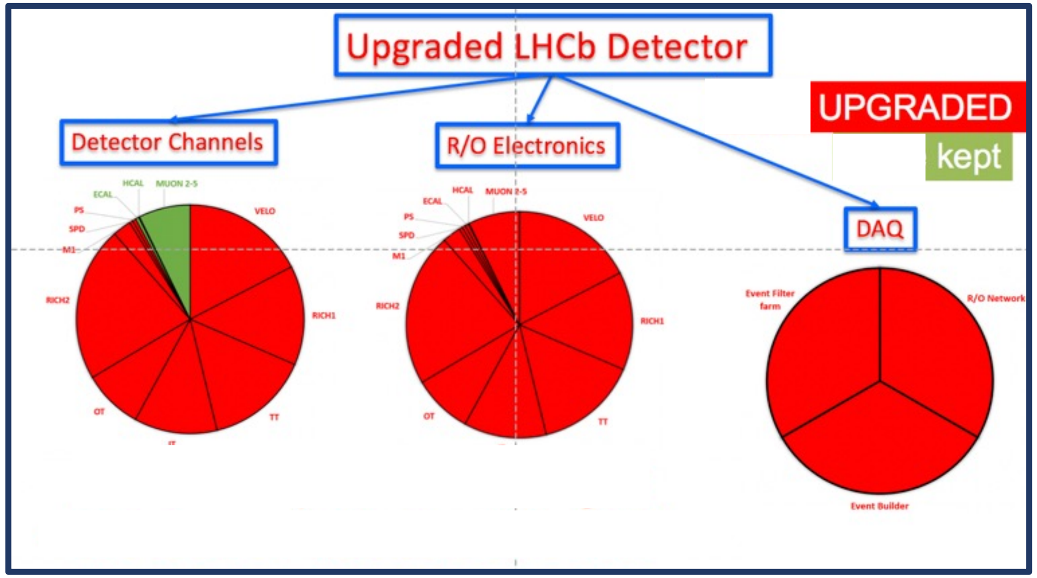
The LHCb physics pillars today



Current detector: LHCb Upgrade I

- All sub-detectors read out at 40 MHz for a fully software trigger with GPU based first level

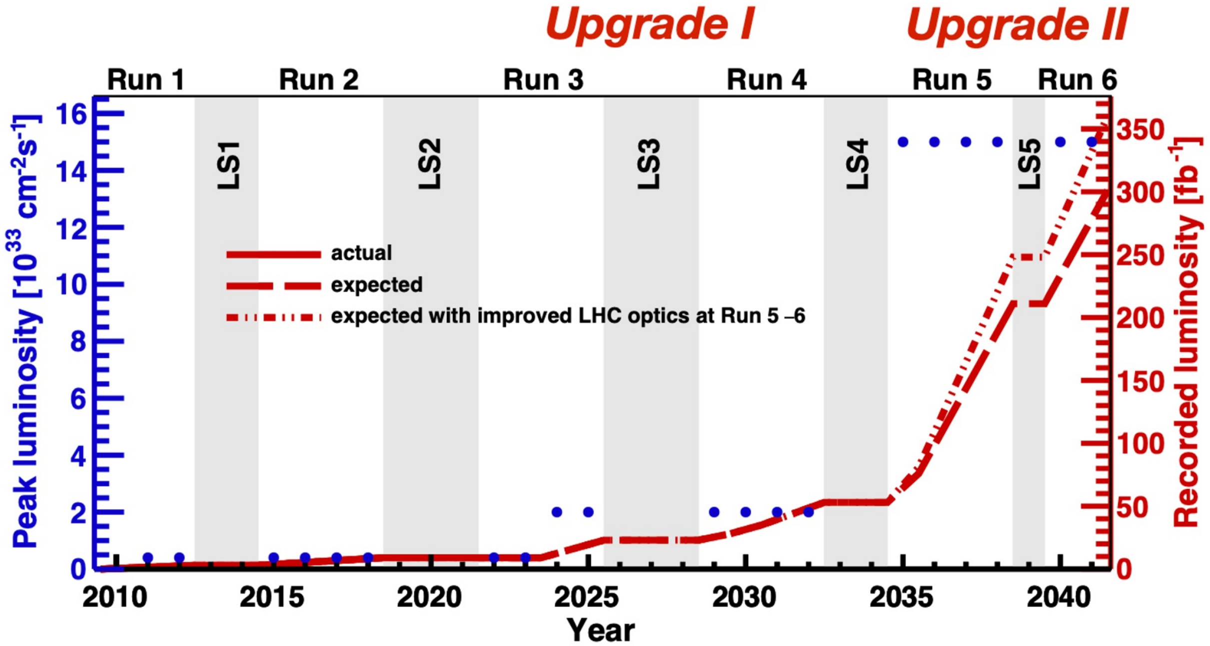




- Pixel detector VELO with silicon microchannel cooling 5 mm from LHC beam
- New RICH mechanics, optics and photodetectors
- New silicon strip upstream tracker detector
- New SciFi tracker with 11,000 km of scintillating fibres
- New electronics for muon and calorimeter systems

Why a new upgrade: LHCb Upgrade II

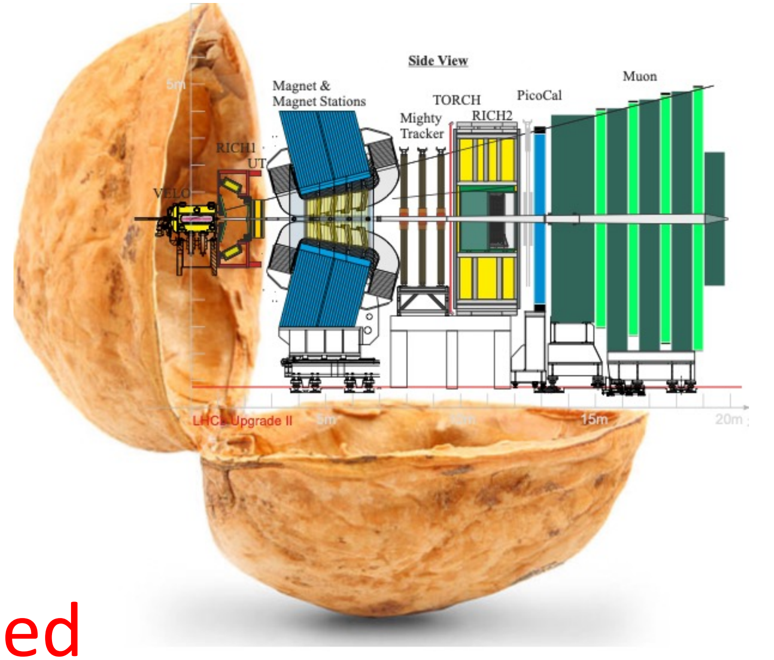
- European Strategy Update 2020: "The full physics potential of the LHC and the HL-LHC, including the study of flavour physics, ... should be exploited"
- Upgrade I was designed to collect 50 fb^{-1} by end of Run 4, but there is the opportunity to operate the experiment until the end of HL-LHC
  - With this in mind, the Upgrade II detector is being designed to accumulate the maximum possible integrated luminosity



- The proposed baseline is to achieve 50 fb^{-1} per year, with peak luminosity of 1.5×10^{34} $cm^{-2}s^{-1}$, and reach at least 300 fb^{-1} at the end of Run-6
- That will allow for unprecedented samples and a compelling physics programme

LHCb Upgrade II in a nutshell

- Unique scientific programme with BSM discovery potential with unprecedented sensitivity for *B* and *D* physics
- Furthermore, broad programme on spectroscopy, EWK precision measurements, top and Higgs physics, dark sector searches, heavy ions and fixed target, all made with a unique and fully instrumented forward acceptance

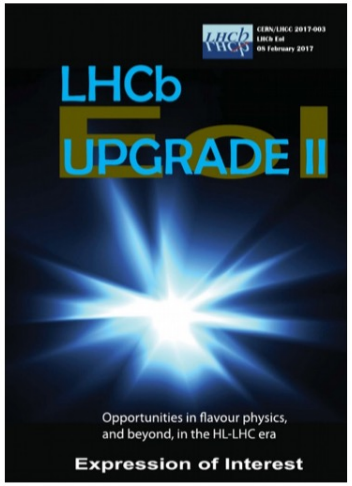


- Besides the luminosity increase and the necessary detector modifications to allow for higher multiplicity and radiation damage, it is also proposed to add further sub-detectors to expand the original programme
- Technology-wise, it provides an exciting technology roadmap with novel detectors and electronics

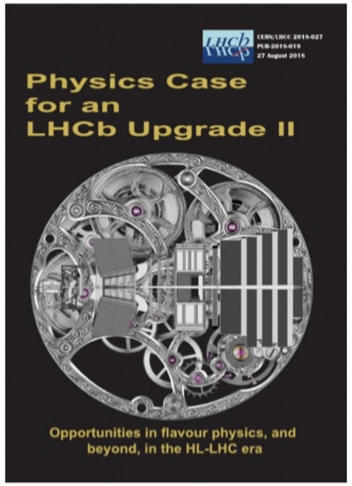
LHCb Upgrade II: advanced design phase

	LHC era			HL-LHC era	
	Run 1	Run 2	Run 3	Run 4	Run 5/6
LHCb $\int\mathcal{L}dt$	3 fb^{-1}	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}

- Framework TDR published in 2022, following EoI and an extensive Physics Case document in previous years
- Now working on a Scoping Document to be submitted to the LHCC in September 2024, with preliminary results in April, and then will move towards the sub-detector TDRs, to be ready in 3 years



CERN-LHCC-2017-003

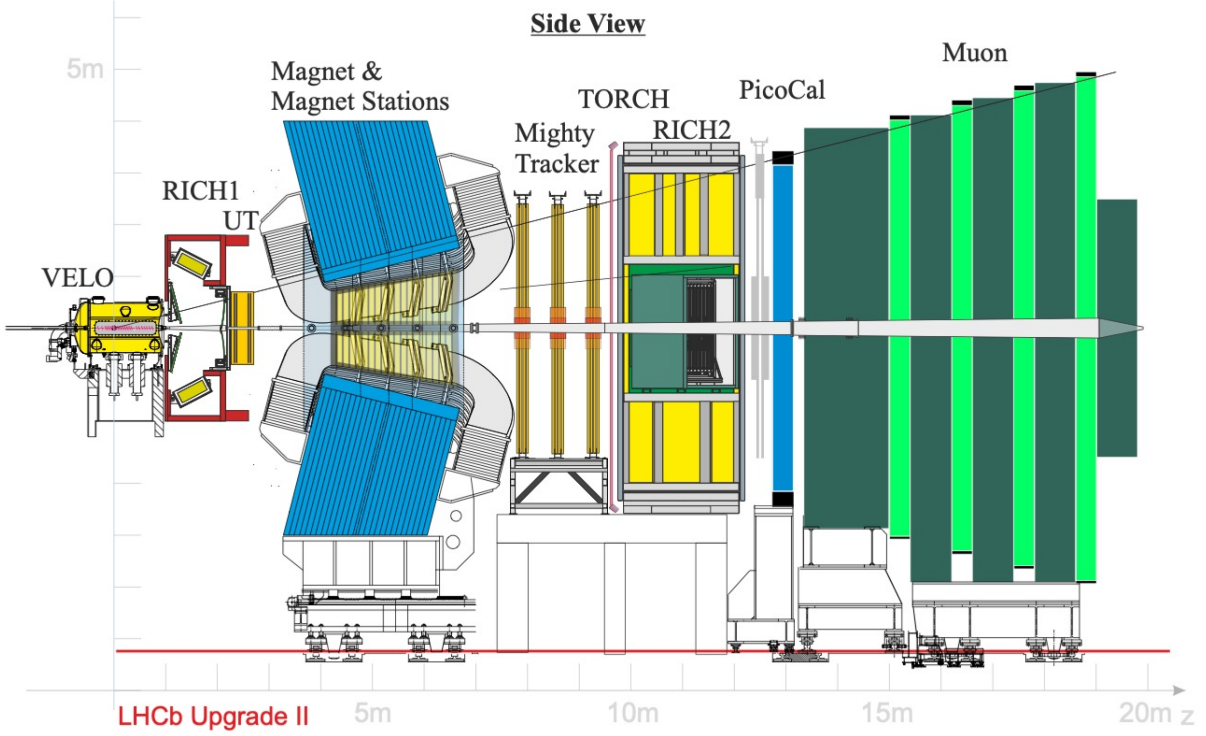


CERN-LHCC-2018-027
arXiv:1808.08865

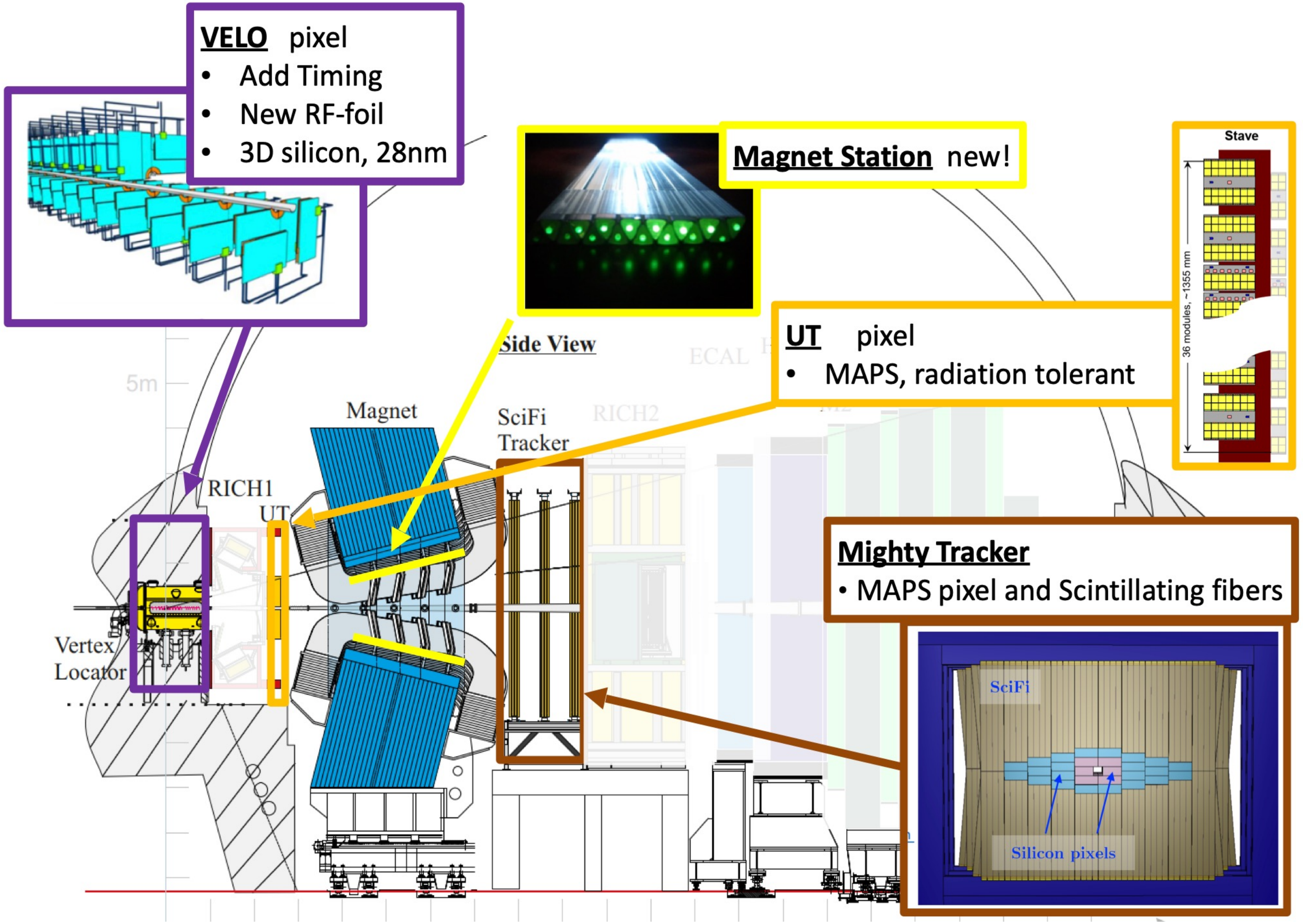
CERN-LHCC-2021-012

The LHCb Upgrade II detector

- Targeting the same performance, or even better in certain areas, as in Run 3, but with an increased pile-up of a factor 7
- Same footprint of the spectrometer, but with innovative technology for sub-detectors and data processing
- Key ingredients
  - High granularity
  - Fast timing
    - Few tens of ps per hit
  - Radiation hardness
    - Up to few 10^{16} neq/cm^2



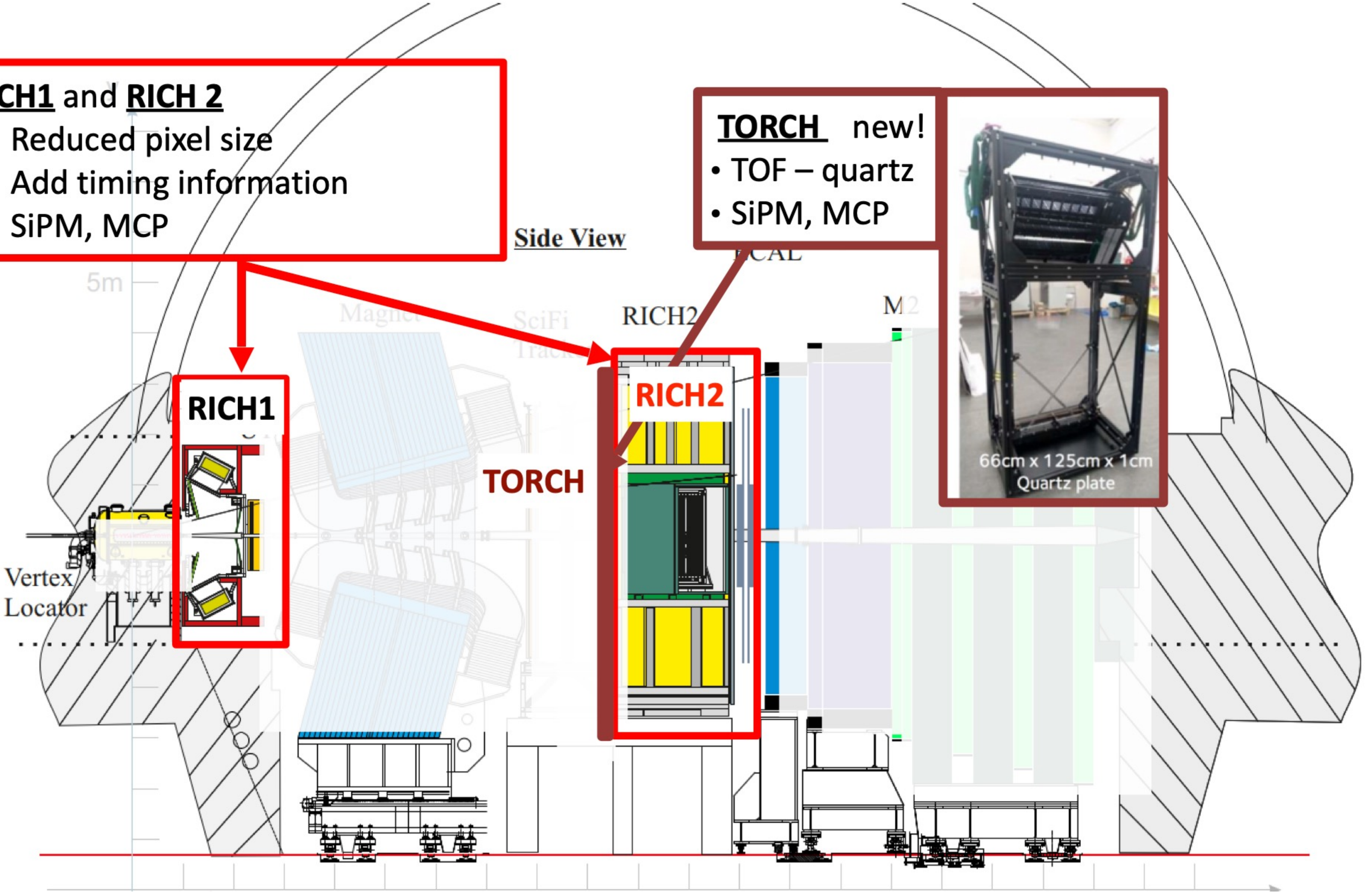
New tracking detectors



New PID detectors

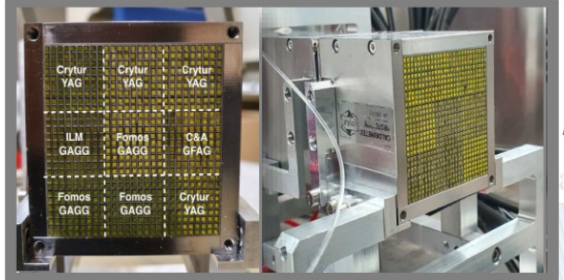
RICH1 and **RICH 2**
- Reduced pixel size
- Add timing information
- SiPM, MCP

TORCH new!
- TOF – quartz
- SiPM, MCP

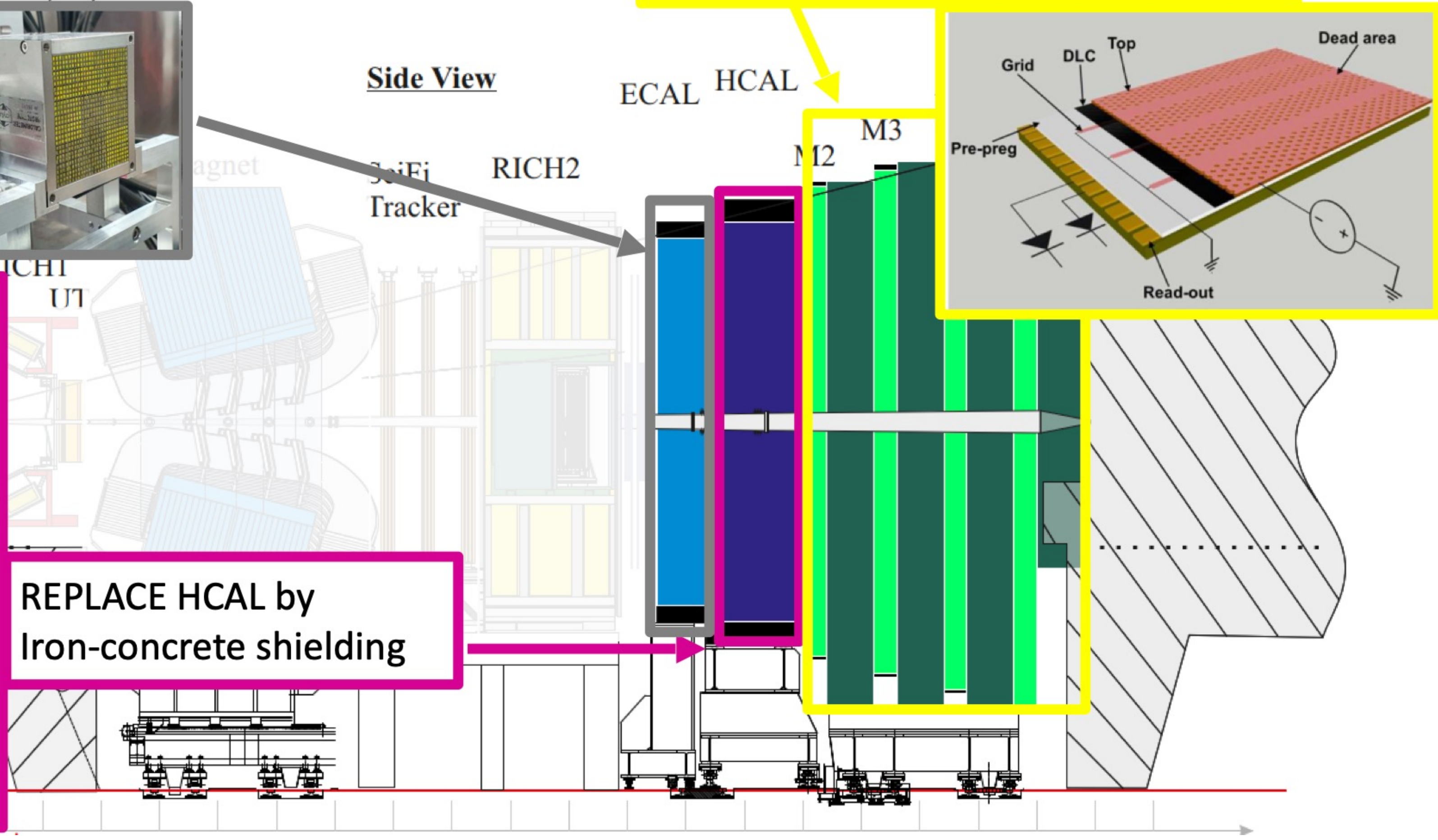


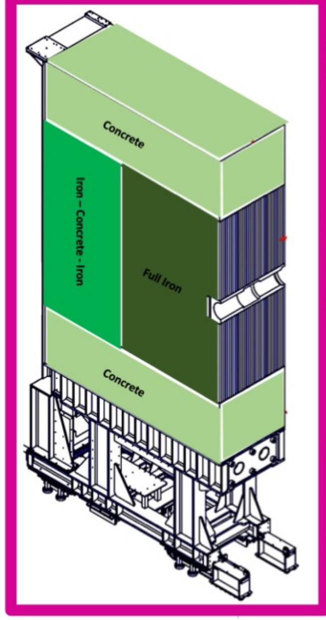
New PID detectors

ECAL
- Space & time, longitudinal segmentation
- SPACAL with radiation hard crystals



Muon
- μRWELL for inner regions
- MWPC for outer regions (recycles)

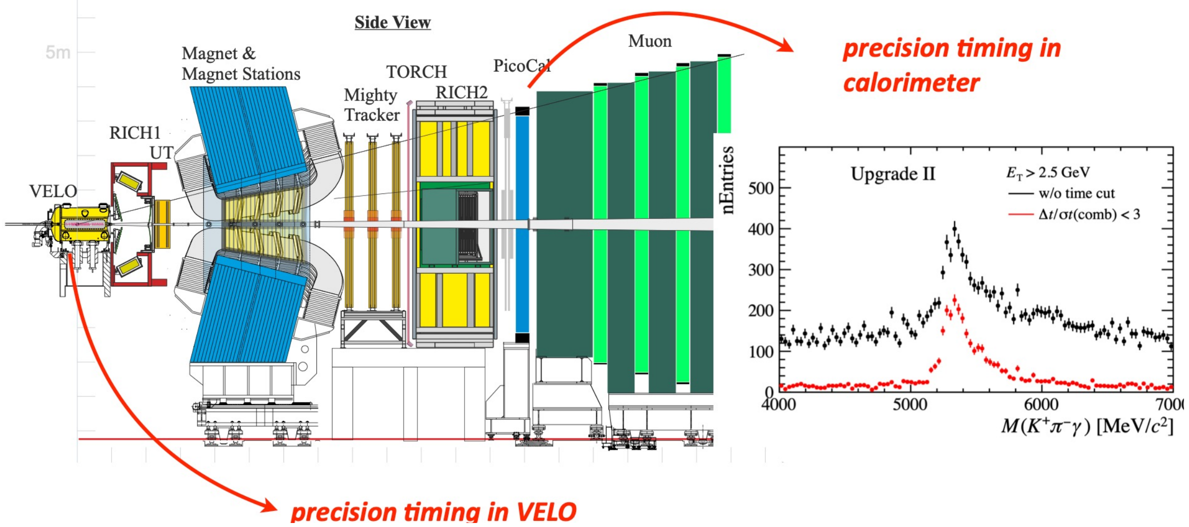


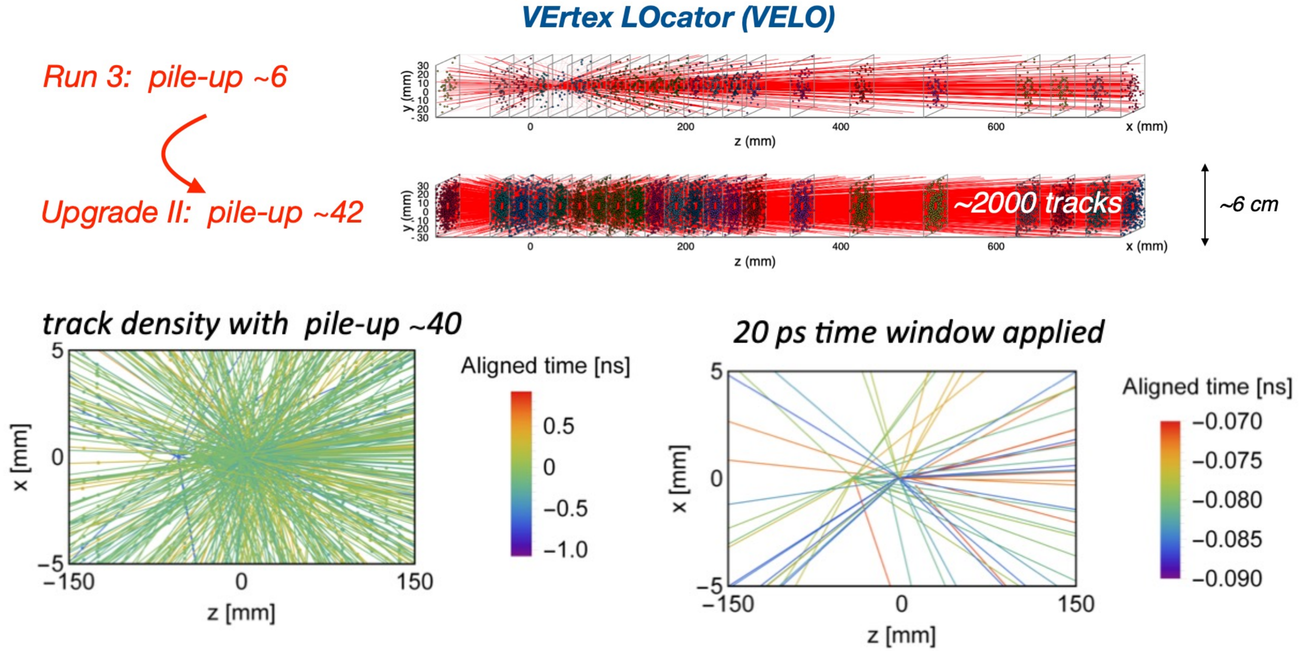


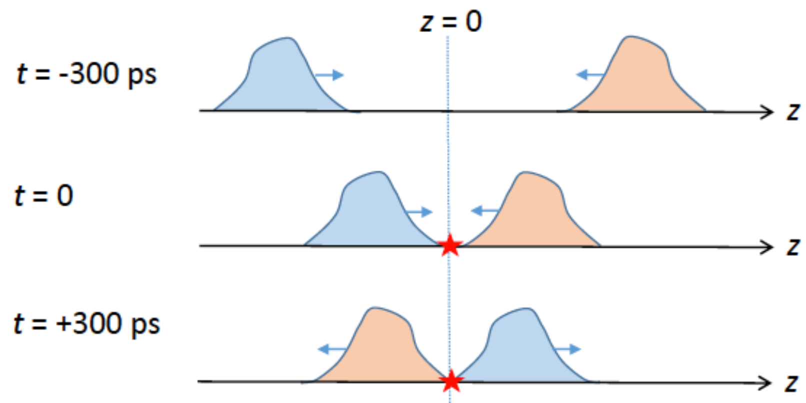
REPLACE HCAL by
Iron-concrete shielding

The importance of precision timing

- Timing capability with a resolution of a few tens of picoseconds is a key to reduce background and associate signal decays to correct p-p primary vertices







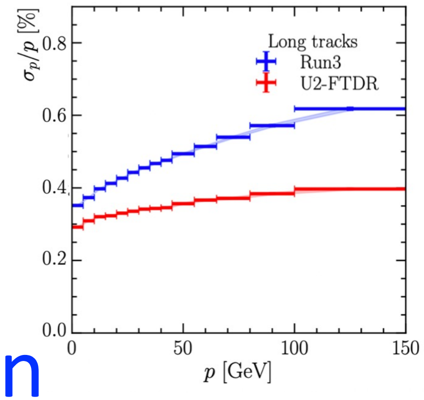
Example: interactions happening are at same *z* but separated by 300 ps in time

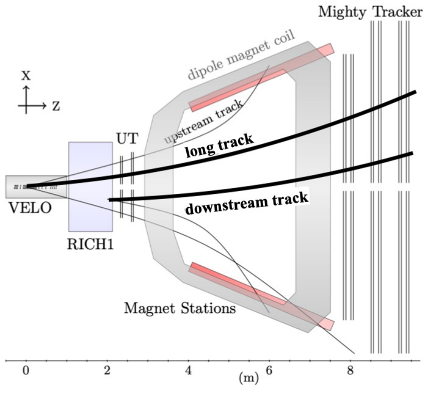
- The programme requires strong R&D on sensors, already ongoing, and dedicated efforts for the design of new FEE ASICs and related electronics

Beyond Upgrade I performance

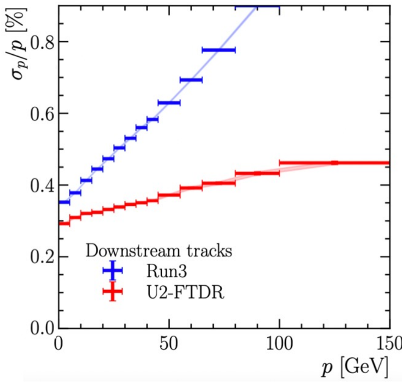
- Besides upgrading to cope with the increased pile-up, introducing pixel detectors in tracking stations upstream (UT) and downstream (Mighty Tracker) of the magnet, to improve substantially momentum resolution

*Momentum resolution for **long tracks** at **Run 3** and **Upgrade II***





*Momentum resolution for **downstream tracks** at **Run 3** and **Upgrade II***



- Furthermore, additional detector features will be introduced to improve phase space coverage
  - Magnet side stations to reconstruct slow pions from charm events which, in the present detector, are swept away from the magnetic field
  - Time of flight detector (TORCH), to improve PID of low momentum protons, kaons and pions with respect to using only the RICH

Baseline costs and Scoping Document

- The Framework TDR of 2022 described the baseline detector and cost
- Before proceeding to the sub-detector TDR phase, we will provide a Scoping Document, with estimated cost scenarios (baseline and descoped), and with the analysis of physics performances in the various scenarios

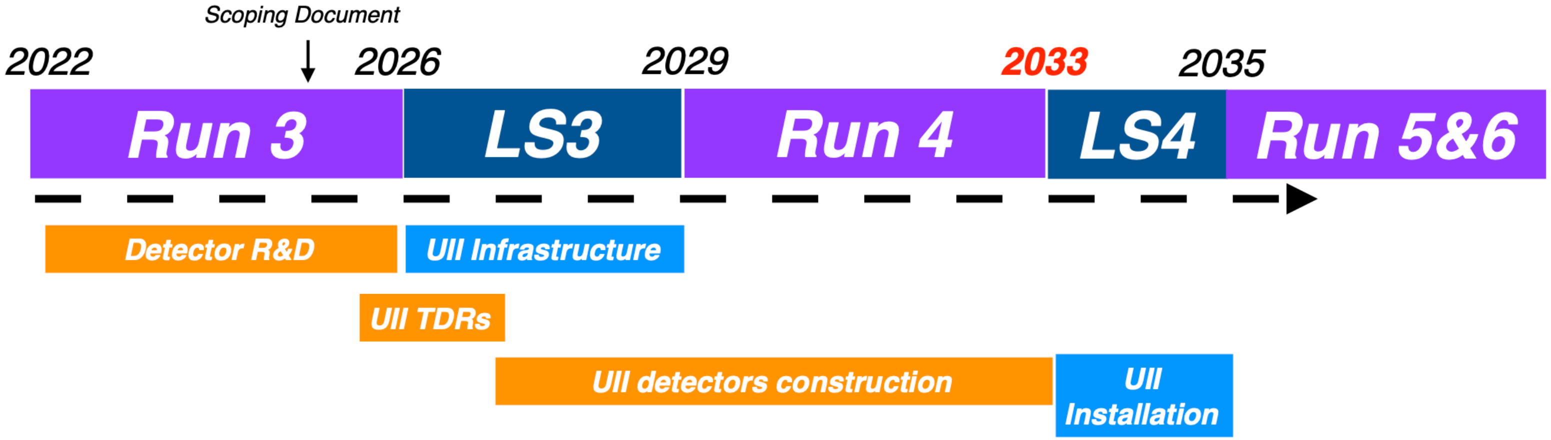
Detector	Baseline (kCHF)
VELO	14800
UT	8900
Magnet Stations	2300
MT-SciFi	22400
MT-CMOS	19500
RICH	15600
TORCH	9900
ECAL	34800
Muon	7100
RTA	17400
Online	8900
Infrastructure	13500
Total	175100

Scoping strategy

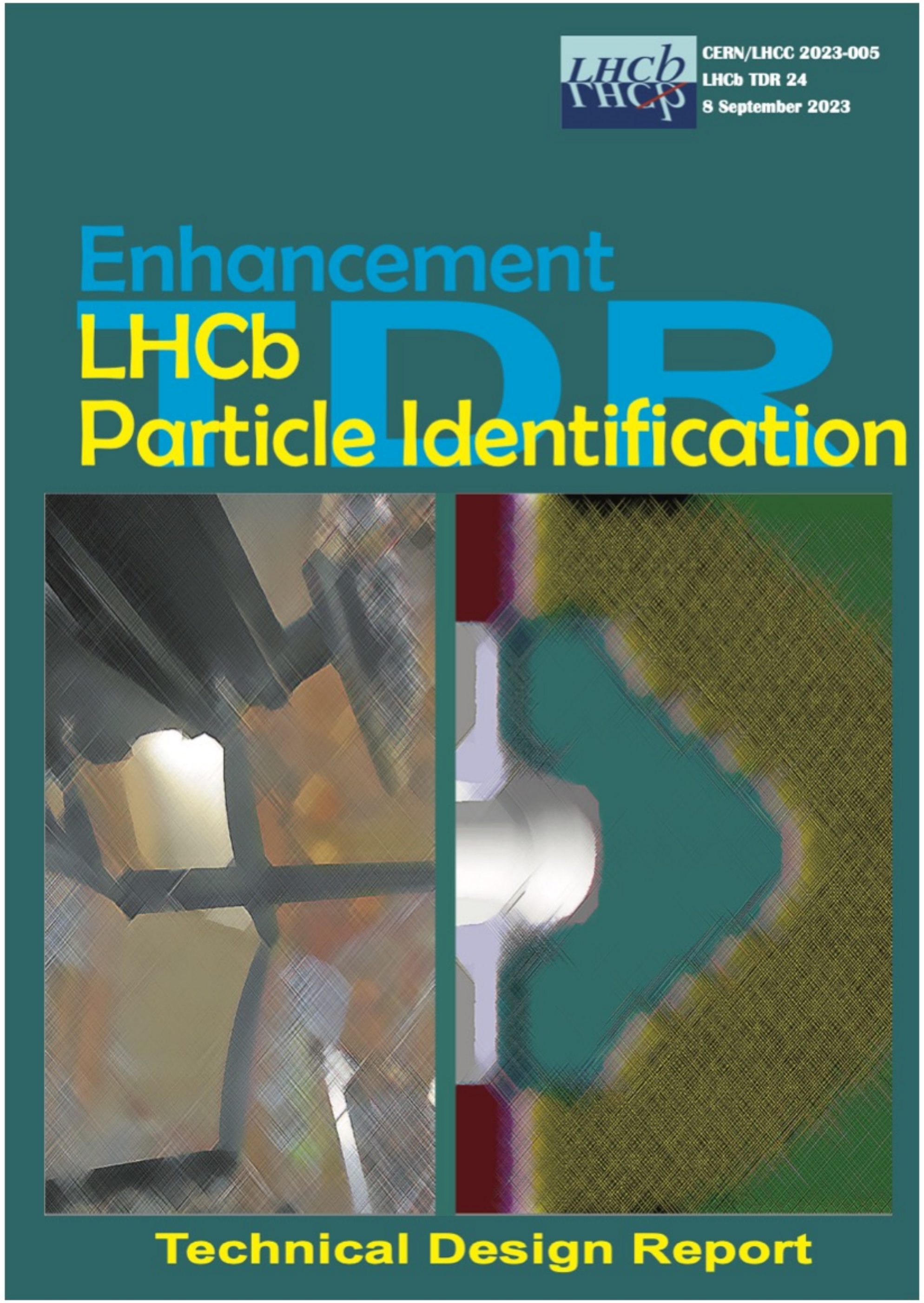
- The intention is to present scenarios at approximately 100% / 85% / 70% of FTDR baseline cost (175 MCHF)
- Main directions
  - Reduce peak luminosity
    - Discussing with accelerator experts to optimise optics and levelling scheme
  - Reduce acceptance
    - Innermost region most challenging (rates, radiation hardness)
    - Outermost region requires large area coverage for smaller gain in acceptance
  - Reduce subdetector performance
- Full simulation framework in place to provide accurate physics performances in the various scenarios

LHCb Upgrade II timeline

- We are committed to present a realistic plan, fully compatible with the HL-LHC schedule and its planned end in 2041



- Key points
  - All detector components fully ready at beginning of LS4 (2033)
  - Introduce some crucial Upgrade II enhancements already in LS3
  - Anticipate some detector and infrastructure work to LS3
- LS4 duration of 2 years: optimised installation plans
  - Less than 1 year of commissioning
  - Lessons learned from original LHCb and its Upgrade I (and ATLAS/CMS phase 2) to be put in place



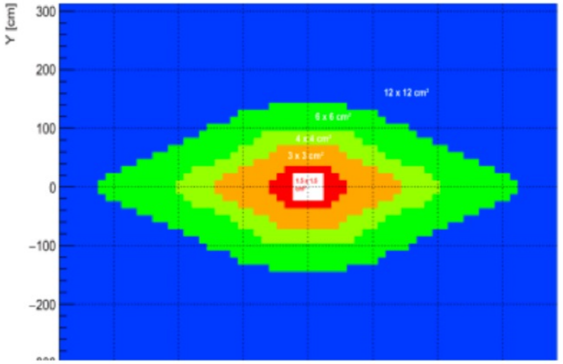
Detector enhancements at LS3: ECAL and RICH

- Duration of LS3 (2026-2028) also offers the opportunity to lay the foundation of Upgrade II on the detector side, and to strengthen its performance during Run 4, where the majority of Upgrade I data will be collected
- Main requirements: limited size, bring physics benefits already in Run 4, anticipate features of the Upgrade II
- TDR for ECAL and RICH enhancements submitted to LHCC in September 2023
- The review is still ongoing and it is expected to be concluded on February 2024

LS3: ECAL inner modules

Strong involvement from Chinese groups!

- Innermost region needs replacing after Run 3 due to radiation damage → propose to install new SpaCal modules, that will be reused at Upgrade II
- In addition: rearrangement of existing modules into occupancy-motivated rhombus shape
- Stepping stone in view of Upgrade II → early stage production and installation of new modules for the Upgrade II calorimeter

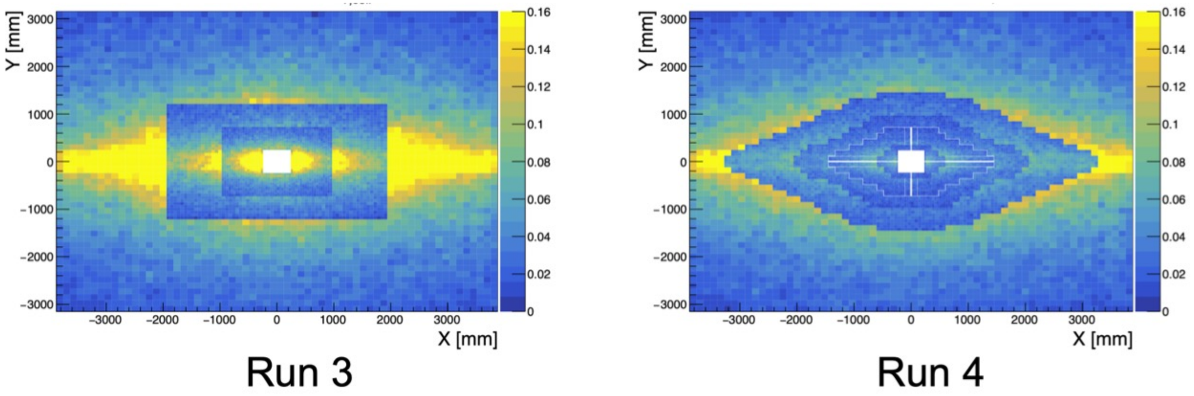


No longitudinal segmentation

Cell size:	Modules:
2 x 2 cm²	32 *new* SpaCal-W modules
3 x 3 cm²	144 *new* SpaCal-Pb modules
4 x 4 cm²	176 existing modules in rhombic configuration
6 x 6 cm²	448 existing modules in rhombic configuration
12 x 12 cm²	2'512 existing modules in rhombic configuration

Occupancy at $L_{int} = 2 \times 10^{33}\ cm^{-2}s^{-1}$

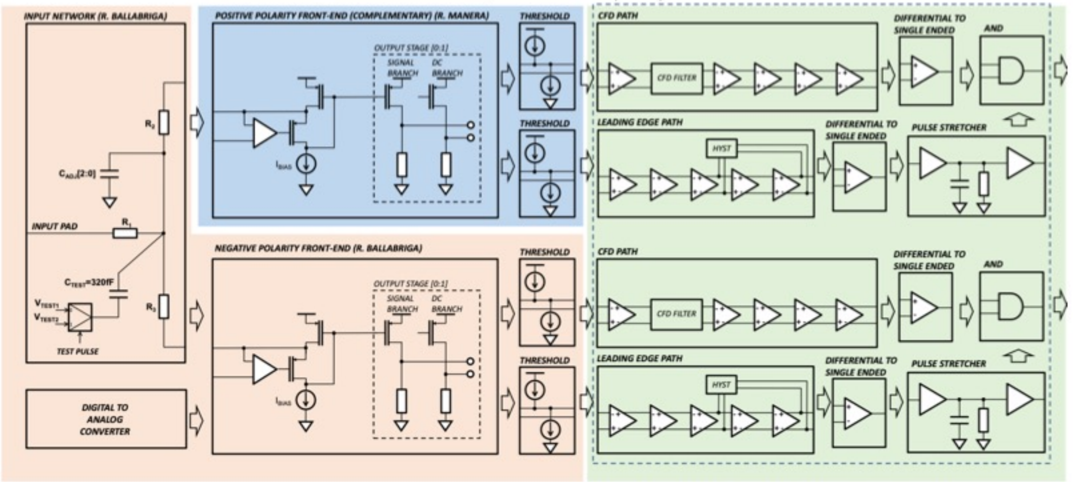
- Great benefit expected from reducing the average occupancy
- Option to introduce timing as well in innermost cells (if new front-end electronics based on analog memories ready)

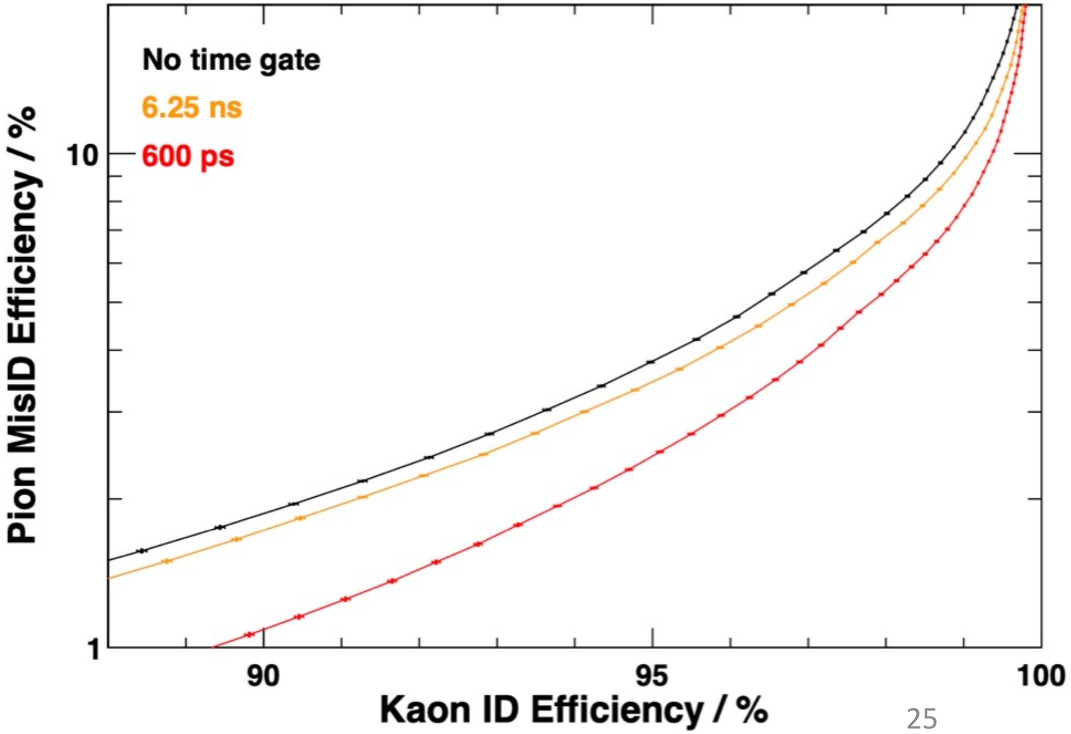


LS3: RICH with precise timing

- New front-end readout electronics including FastRICH ASIC, capable of time-stamping photon hits with ~25 ps resolution → possibility to apply a narrow time window gate and reduce background
  - Main limitation will remain at Run 4 from MaPMT photodetectors ($\sigma \sim 150$ ps)
- The planned 600 ps time gate will bring a significant gain in PID performances
- Design of FastRICH ASIC almost finalised, with submission expected very soon
- Stepping stone in view of Upgrade II
  - Early stage design and production of the first version of the Upgrade II RICH ASIC
  - Deploy and commissioning of precision timing in our detector, in advance of Run 5

FastRICH (CMOS 65 nm)

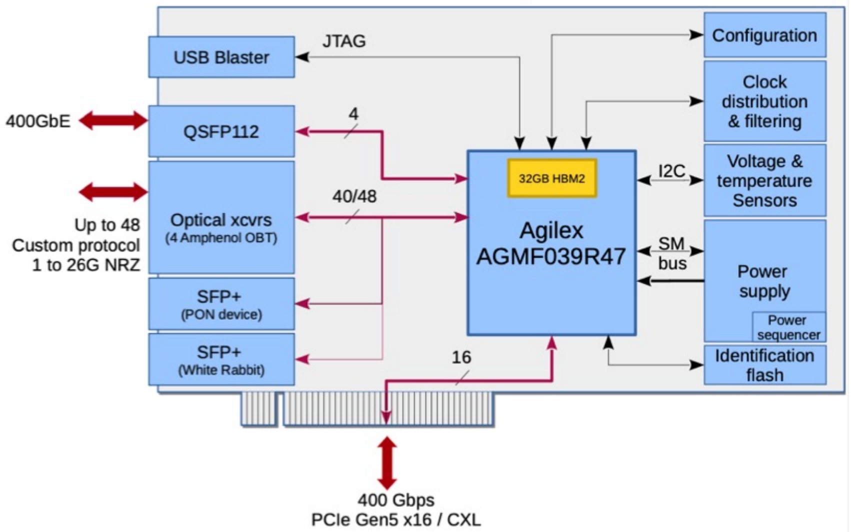




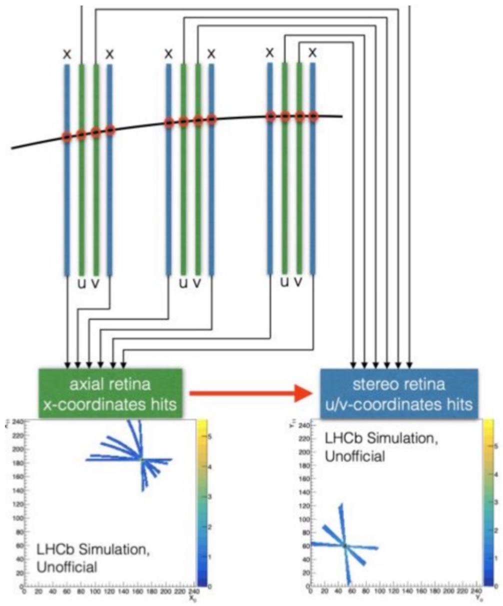
LS3: opportunities for online

- PCIe400: new readout board with 400 Gb/s
  - Run 5 prospect: fundamental development to keep pace with technology evolution (FPGA, links)
- Downstream tracking with FPGA (RETINA)
  - Event reconstruction primitives (clusters, tracks) found by FPGA immediately available to event building, freeing CPU resources for other tasks
  - LS3 proposal: realise a downstream tracking unit using hits from SciFi at 30 MHz→ clear benefit for downstream K_S and long-lived particle searches
  - Run 5 prospect: realise a truly integrated system of FPGA+GPU+CPU+... that makes best use of specialised hardware
- Targeting a TDR to be submitted in February 2024
  - Will also include a brief description of the Online infrastructure refurbishment

PCIe400 layout



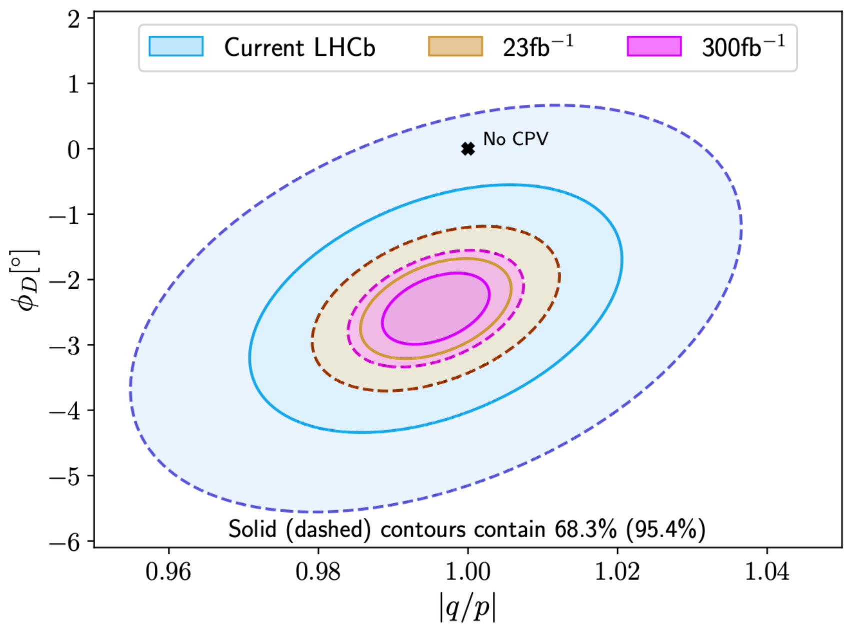
Downstream tracking with RETINA

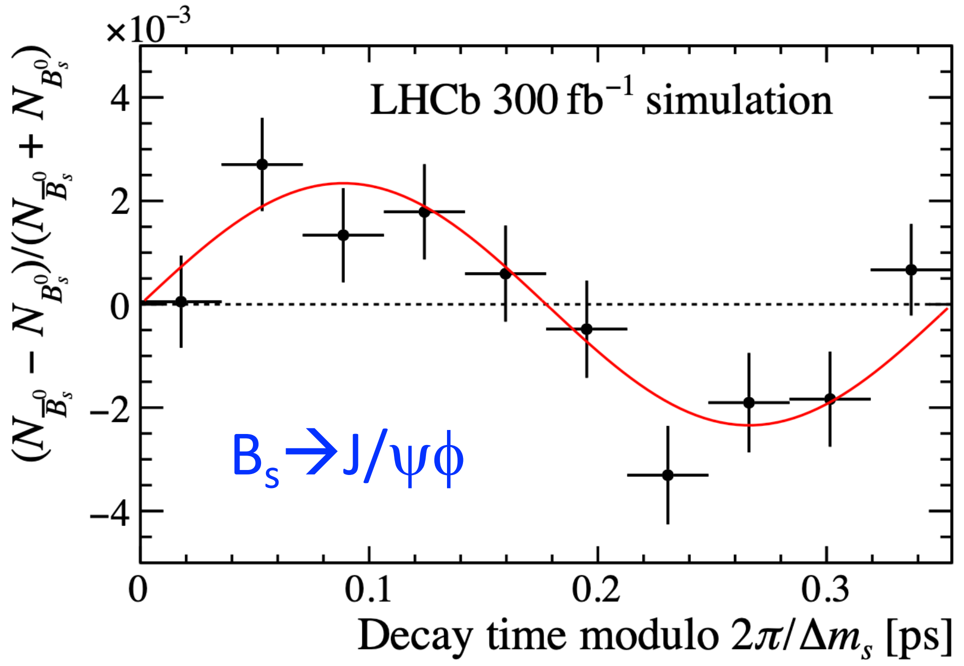


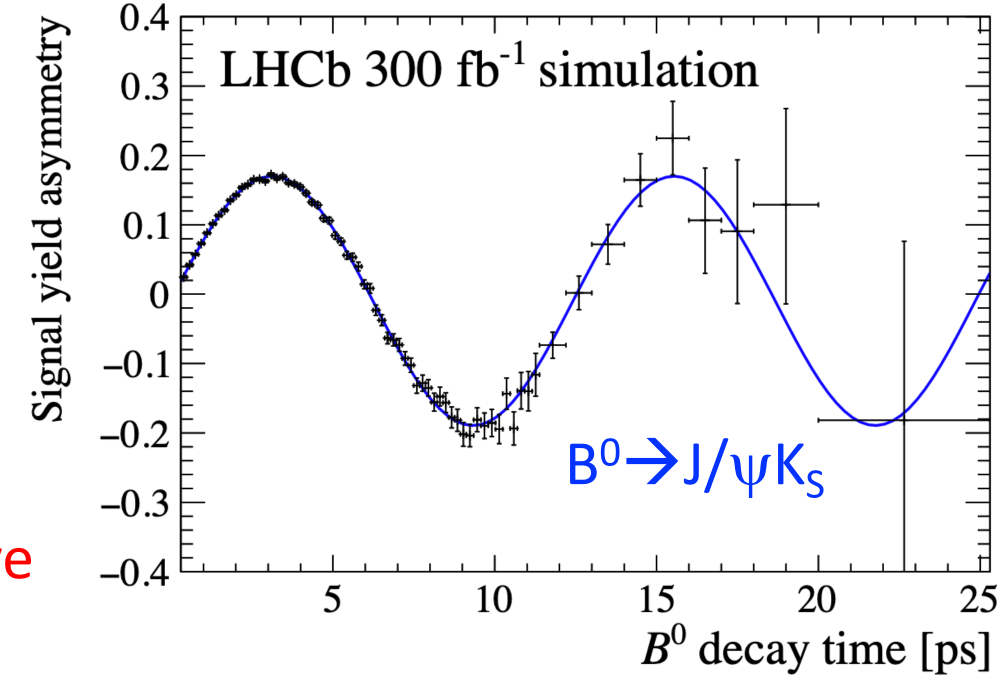
LHCb Upgrade II Physics Case: CP violation

- $\sigma(\gamma)$: 0.4°
- $\sigma(\varphi_s)$: 4 mrad
- $\sigma(\sin 2\beta)$: 0.003
- σ(Charm CPV): $O(10^{-5})$

Impressive precision on CP violation phases

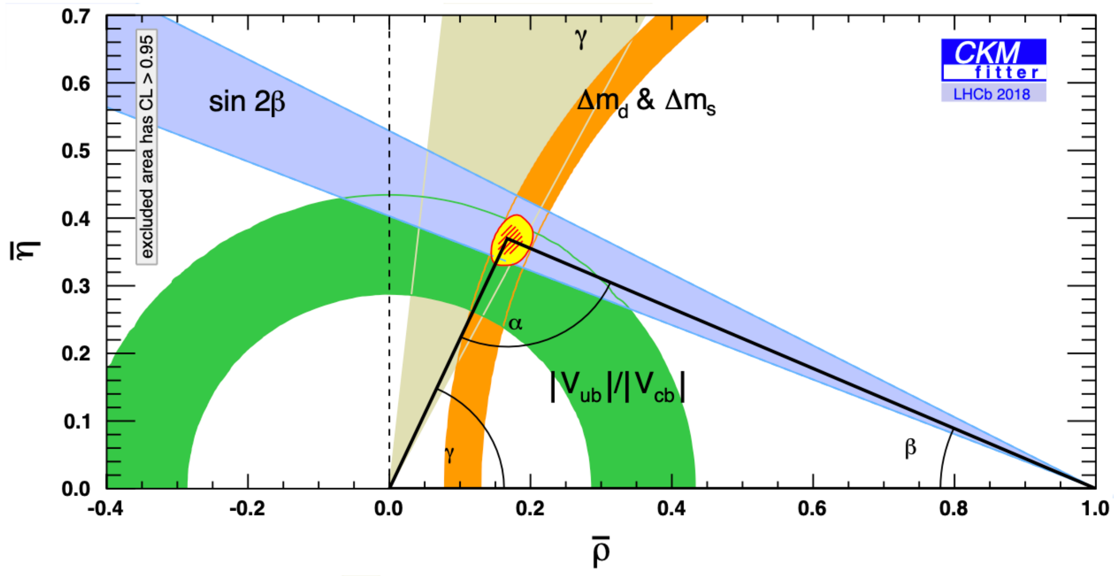




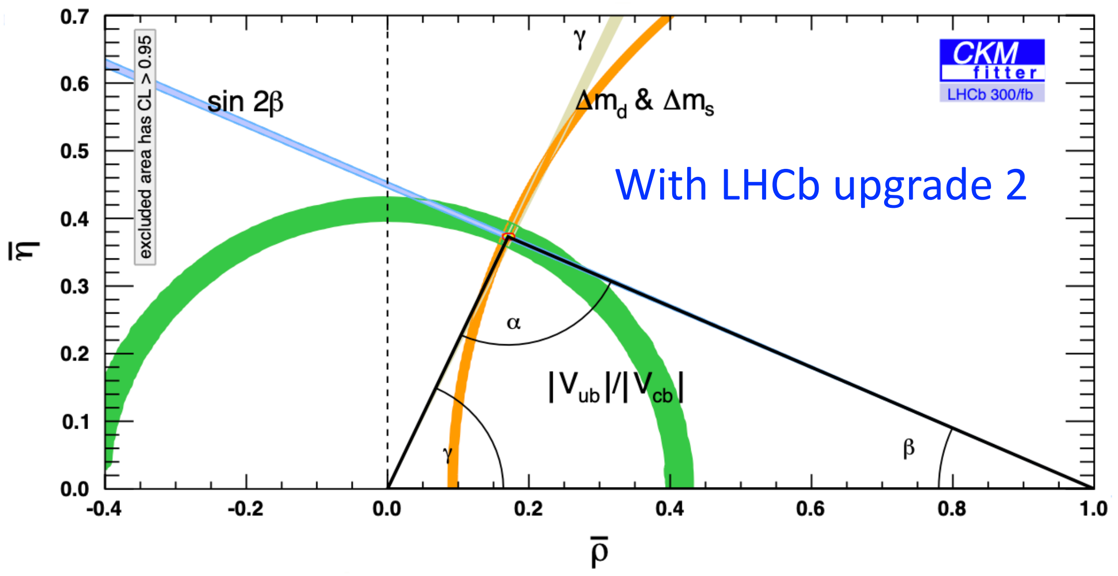


LHCb Upgrade II has a realistic possibility to observe CP violation in charm mixing

Evolution of Unitarity Triangle precision



Status with data up to 2018



Projection after Upgrade II

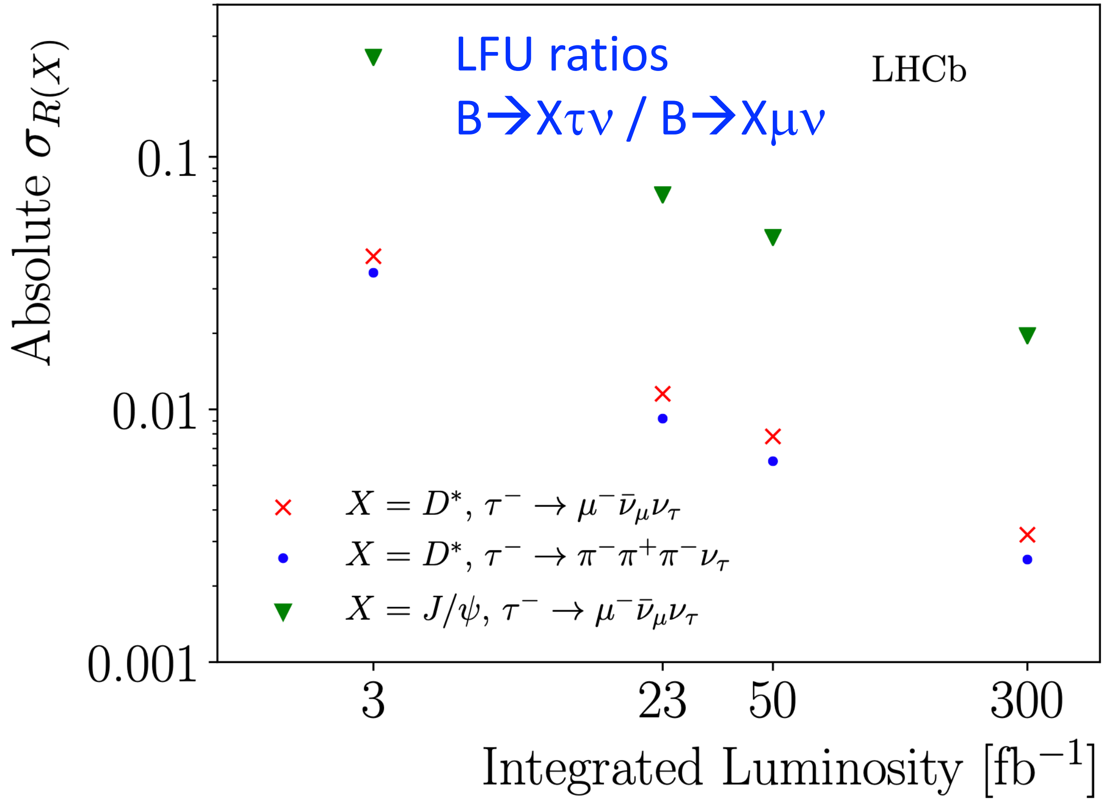
- Upgrade II will push the frontier of flavour precision physics to unprecedented levels, trying to break the Standard Model with indirect measurements
- Permit tree-level observables (SM benchmarks) to be assessed against loop contributions (new physics sensitive)

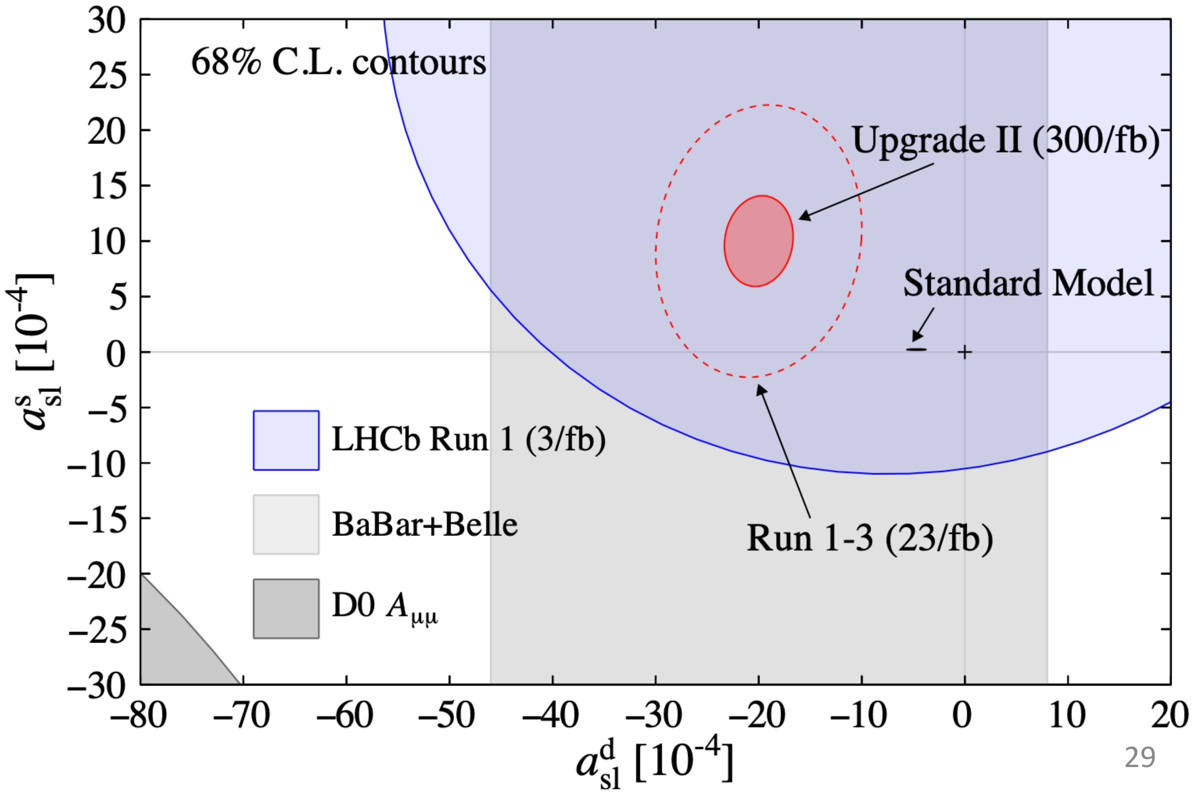
LHCb Upgrade II Physics Case: semileptonics

- Semileptonic sector is another key laboratory for new physics searches
- Very strong impact from Upgrade II

Semileptonic asymmetries $a_{\rm sl}^d$ and $a_{\rm sl}^s$

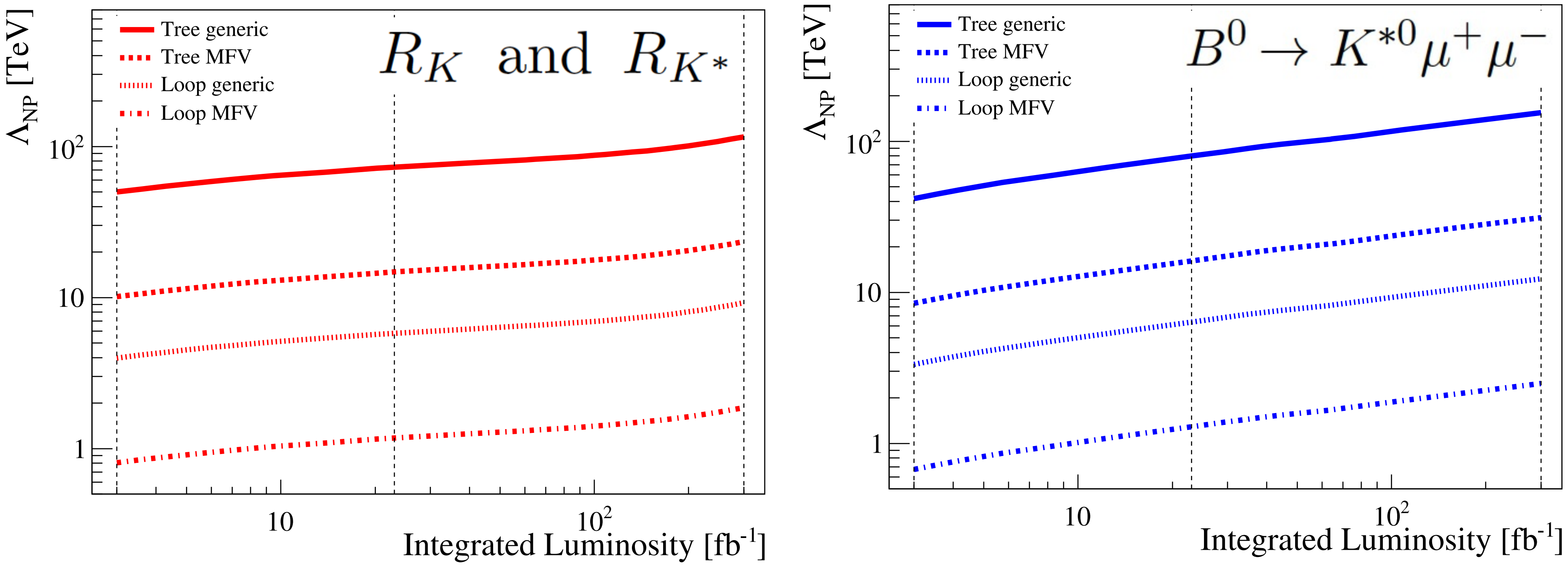
Sample ($\mathcal{L}$)	$\delta a_{\rm sl}^s [10^{-4}]$	$\delta a_{\rm sl}^d [10^{-4}]$
Run 1 (3 $\rm fb^{-1}$)	33	36
Run 1-3 (23 $\rm fb^{-1}$)	10	8
Run 1-3 (50 $\rm fb^{-1}$)	7	5
Run 1-5 (300 $\rm fb^{-1}$)	3	2
Current theory	0.03	0.6





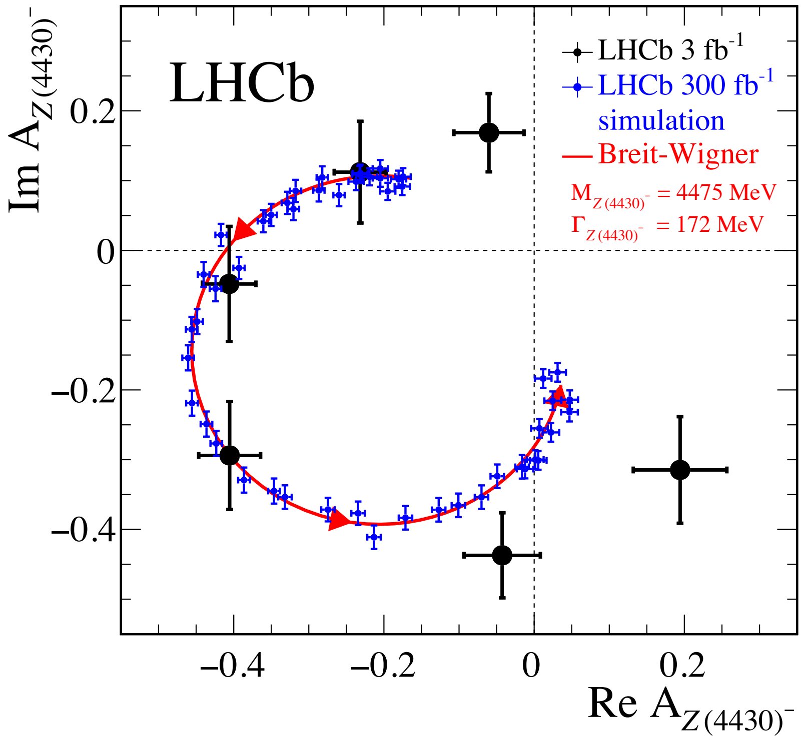
LHCb Upgrade II Physics Case: rare decays

- Although hints for new physics in b→sl⁺l⁻ transitions have been largely reabsorbed, this is still interesting physics with strong discovery potential at Upgrade II statistics, also imposing relevant constraints on new physics models

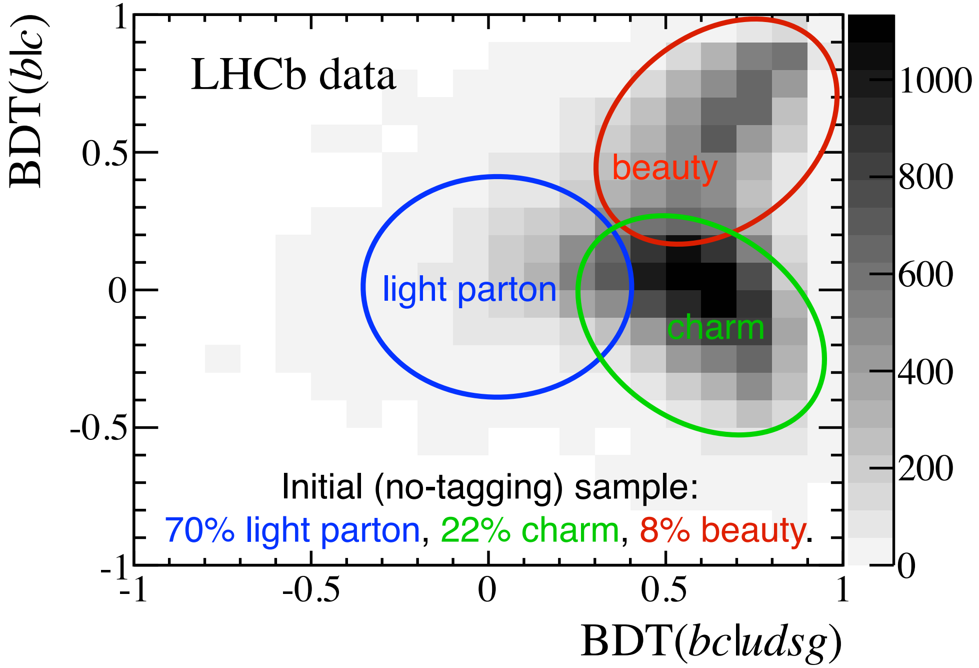


- EFT approach → generic new physics scale probed exceeds 100 TeV
- Concerning B→μμ → 11% precision on B^0 / B_s ratio of branching fractions
- Besides b→sl⁺l⁻, LHCb Upgrade II will have access also to rarer b→dl⁺l⁻ transitions

LHCb Upgrade II Physics Case: other opportunities



- General purpose facility
  - Unique forward acceptance, particularly relevant for heavy ion and fixed-target physics (injecting gas on the proton beam line)
- 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

Summary Table for Upgrade II sensitivities on some key flavour observables

Observable	Current LHCb (up to 9 fb^{-1})	Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests				
γ ($B \to DK$, *etc.*)	4°	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	3%	2%	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm				
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—	—	—	0.2
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	0.060	0.043	0.016
$A_{\mathrm{T}}^{\mathrm{Im}}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	0.148	0.097	0.038
Lepton Universality Tests				
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	0.007	0.005	0.002

Upgrade I will not saturate precision in many key observables ⇒ Upgrade II will fully realise the flavour-physics potential of the HL-LHC

LHCb Upgrade II Physics Case: key messages

- Host of theoretically clean (or clean-ish) observables that will not be limited by systematics (ϕ_s, γ, $\sin 2\beta$, $R_K(*)$, $B \rightarrow \mu\mu$, …)
- New physics scale probed will increase by a factor ~2 compared with pre-HL-LHC
- Widen the set of observables under study to search and characterise new physics ($b \rightarrow sll$, $b \rightarrow dll$, $b \rightarrow cl\nu$, …)
- Strong programme beyond flavour exploiting unique acceptance
    - Higgs physics, spectroscopy, electroweak, dark sector, heavy ions, fixed target

Closing remarks

- We have a once-in-a-lifetime opportunity to optimise the design of what will be a remarkable experiment, with unique capabilities to achieve the best possible heavy flavour-physics results (and more) from the HL-LHC
- Scoping Document is the next step in the project approval process
  - We will provide preliminary results in April 2024, with full study and document delivery in September 2024
- Then in 3 years we will have to proceed to the sub-detectors TDRs
- Precious experience from our Upgrade I (and more to come from ATLAS/CMS Phase II upgrades) to design, construct and commission Upgrade II on schedule
  - Timely construction of the detector components
  - Anticipation of infrastructure work during LS3
  - LS3 detector enhancements
- Now's a good time for interested groups to get involved in the design and construction of the new detector