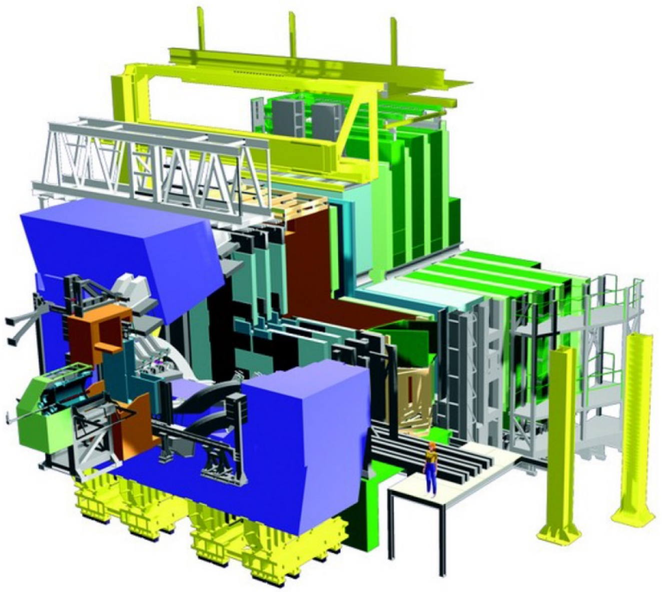
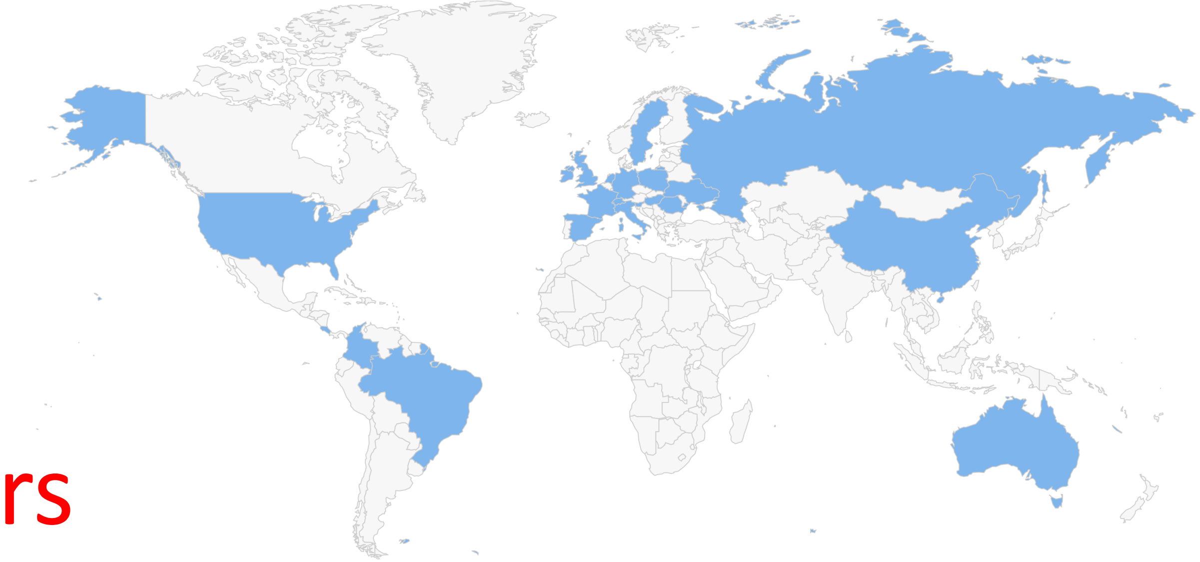
LHCb towards the 2040s

Vincenzo Vagnoni (INFN Bologna and CERN)

12th February 2024, LHCb Starterkit

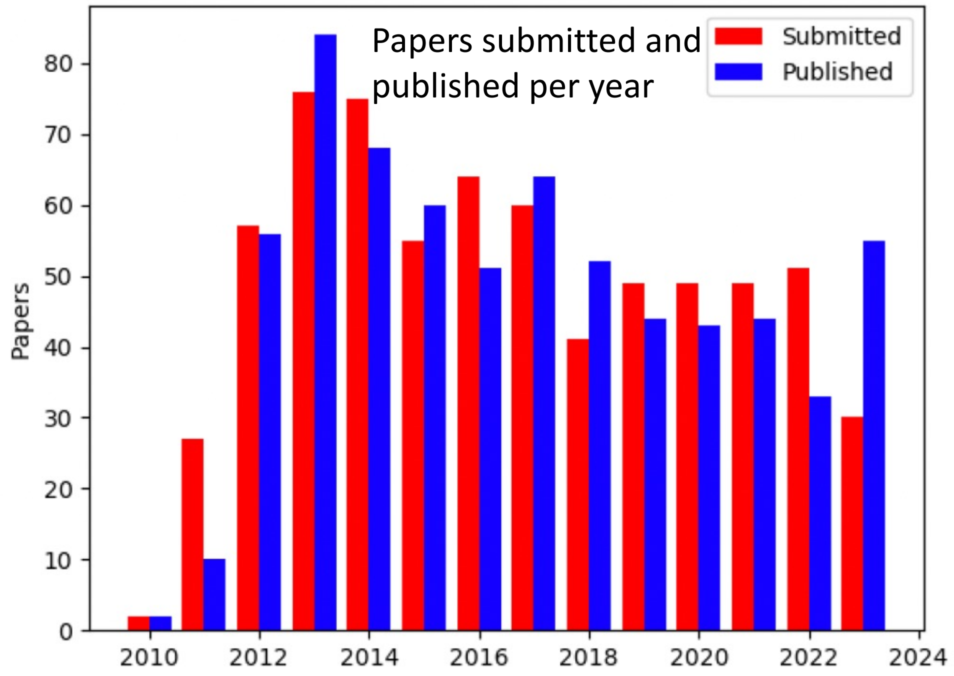
LHCb collaboration

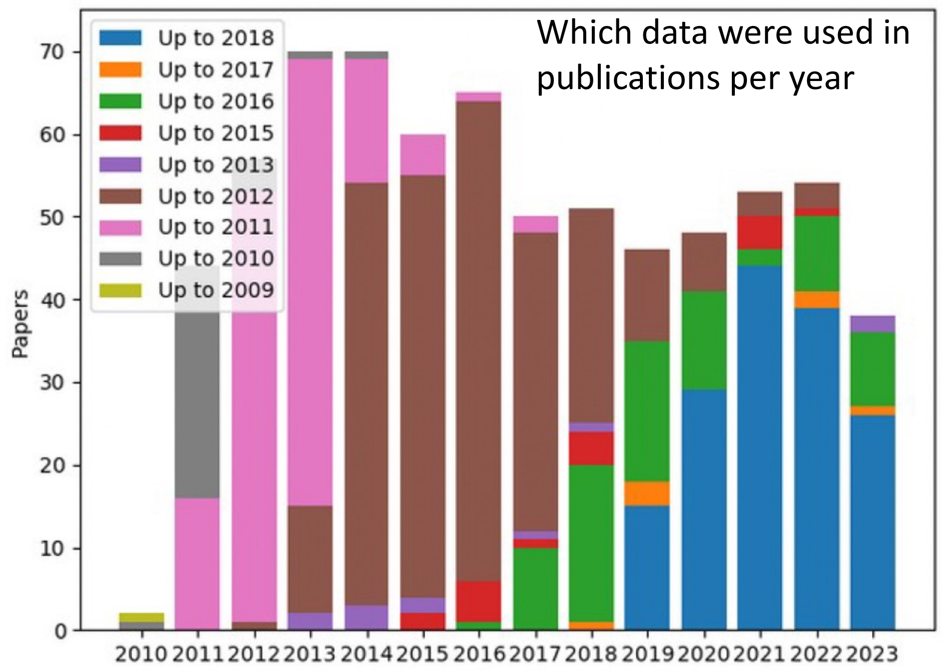




- As of today, 1650 members from 98 institutes in 22 countries
- Including about 1100 authors
    - About 1 x ALICE, 0.37 x ATLAS, 0.47 x CMS (source INSPIRE)

More on LHCb numbers

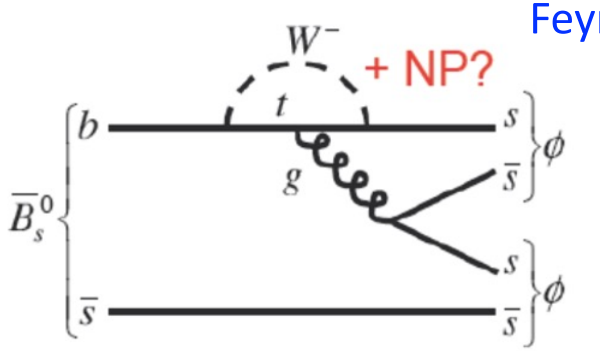


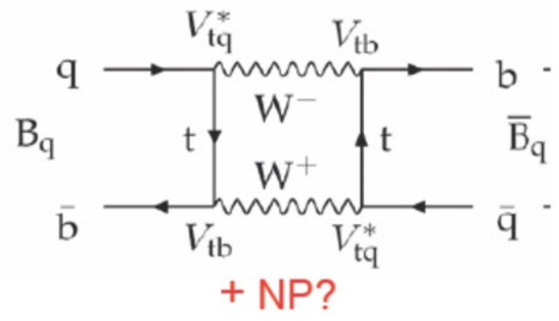


- 700+ papers submitted by LHCb so far
    - About 1.5 x ALICE, 0.56 x ATLAS, 0.56 x CMS (source INSPIRE)
- Or in terms of today's collaboration sizes
    - About 1.5 x ALICE, 1.5 x ATLAS, 1.2 x CMS (source INSPIRE)

Loop diagrams and new physics amplitudes

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





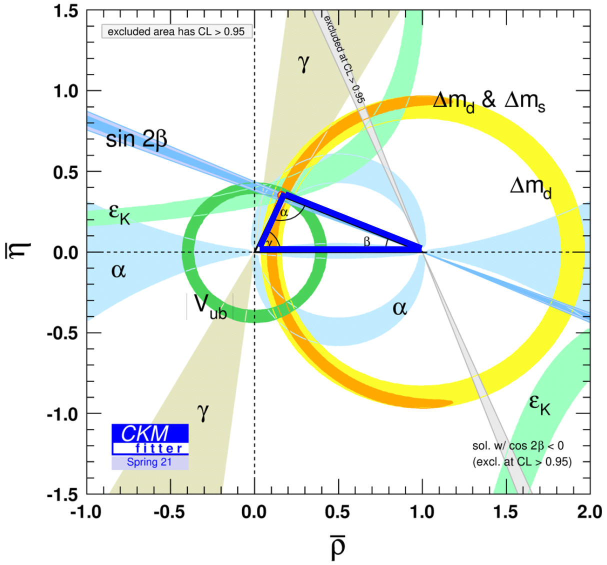
$$A = A_0 \left[c_{SM} \frac{1}{M_W^{\,2}} + c_{NP} \frac{1}{\Lambda^2} \right]$$

- 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
- Unfortunately, we cannot work with free quarks and we must deal with composite hadrons → low-energy QCD is at work in many cases (LQCD very relevant)
- However, the plus is that 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
- An it is not only question of loops: new physics could also manifest itself in tree-level decays

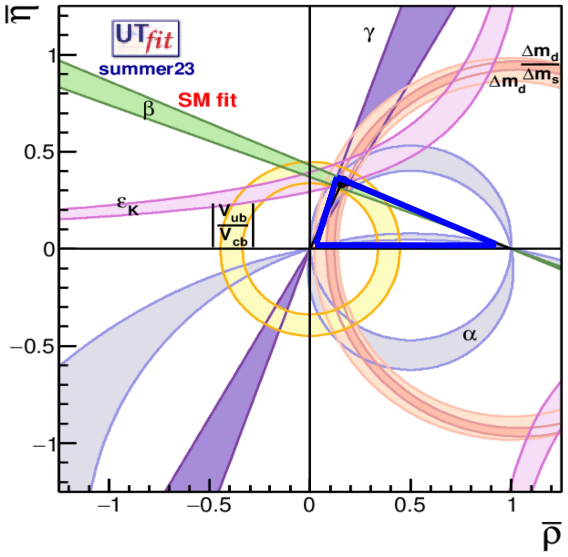
Consistency of global CKM fits

- 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

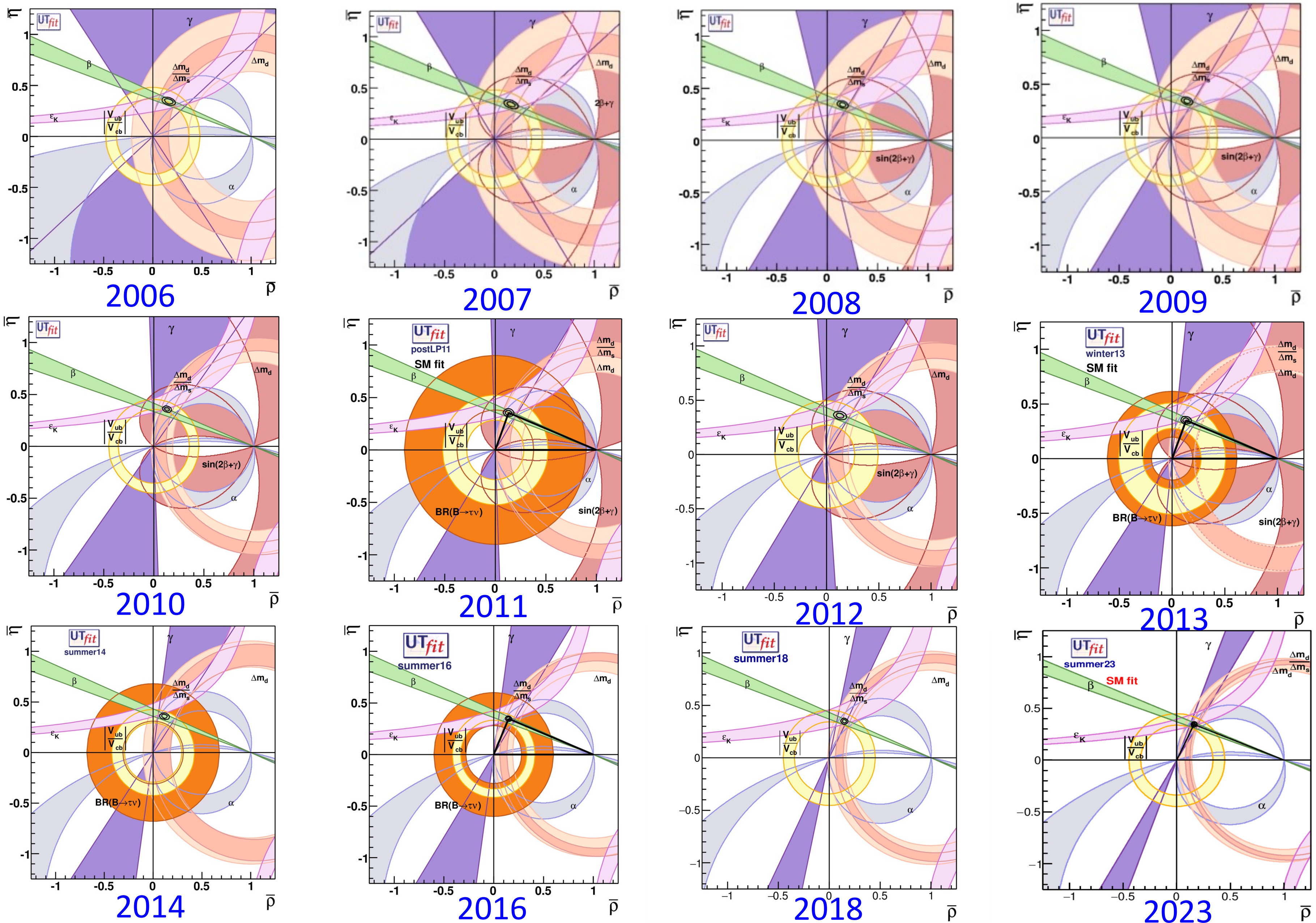


http://www.utfit.org

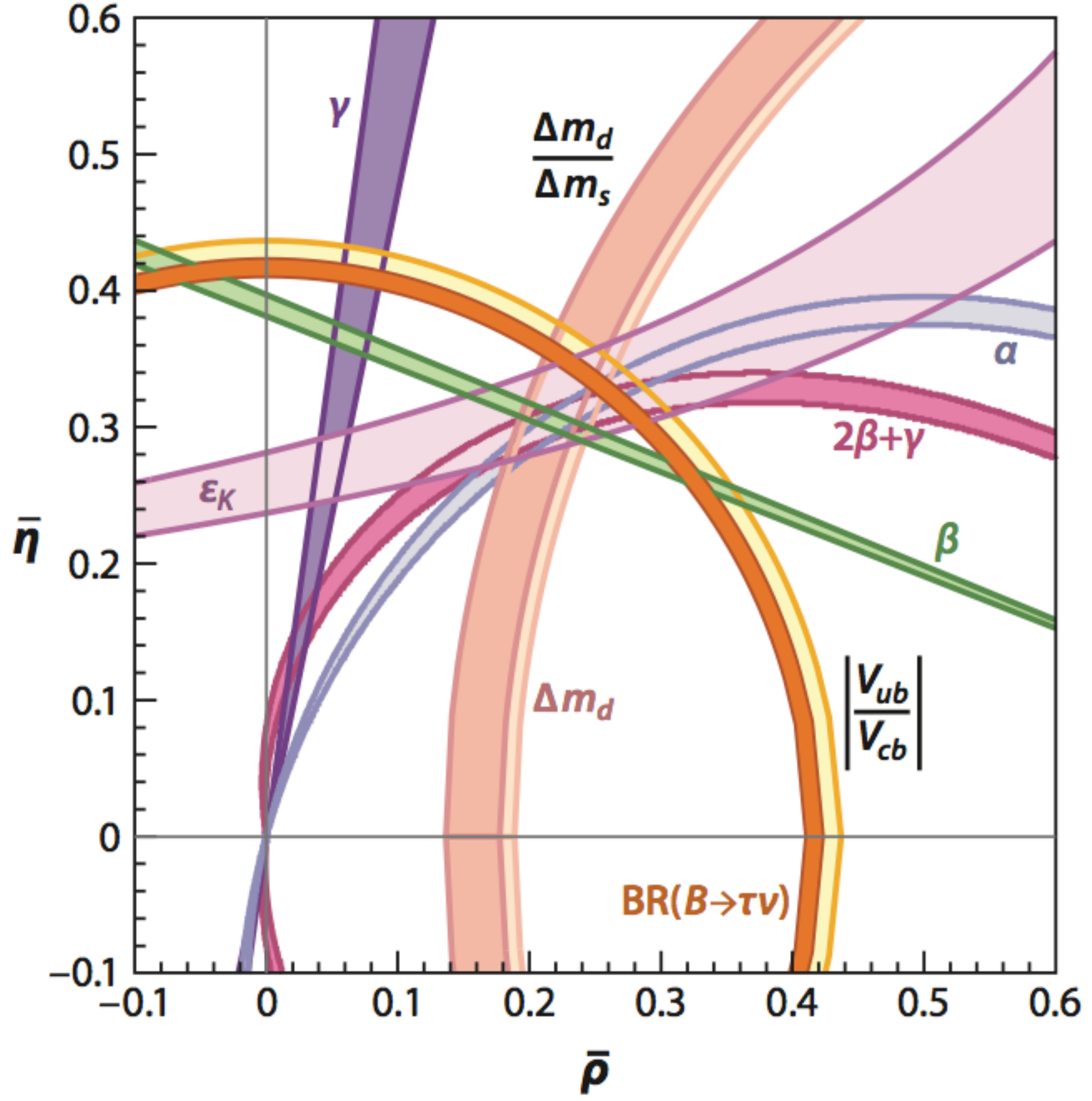


- Tremendous success of the CKM paradigm!
  - All of the available measurements agree in a highly profound way to the current level of precision
  - In presence of new physics affecting the measurements, the various contours would not cross each other into a single point
- The quark flavour sector is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

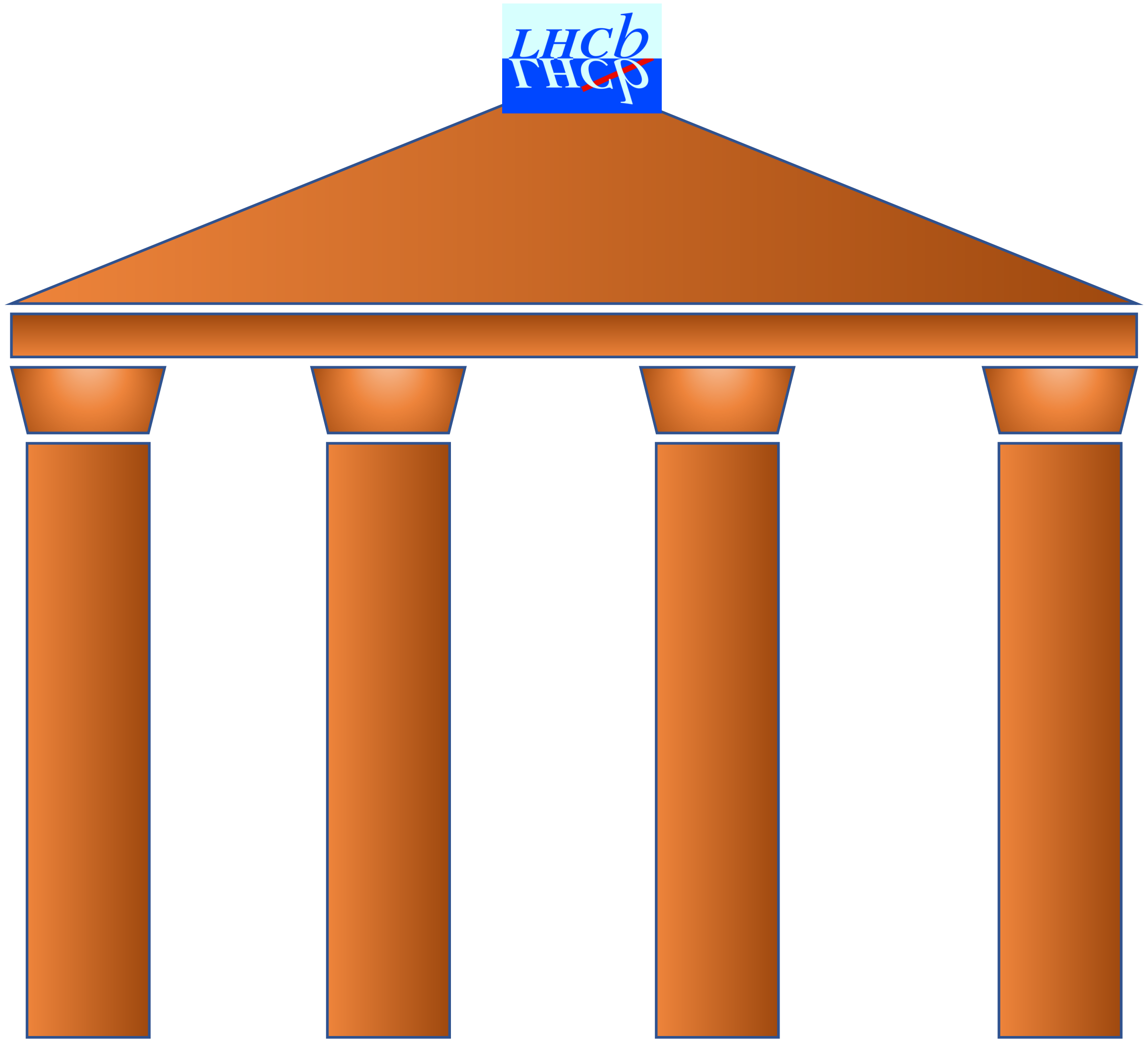
Long journey to reach here...



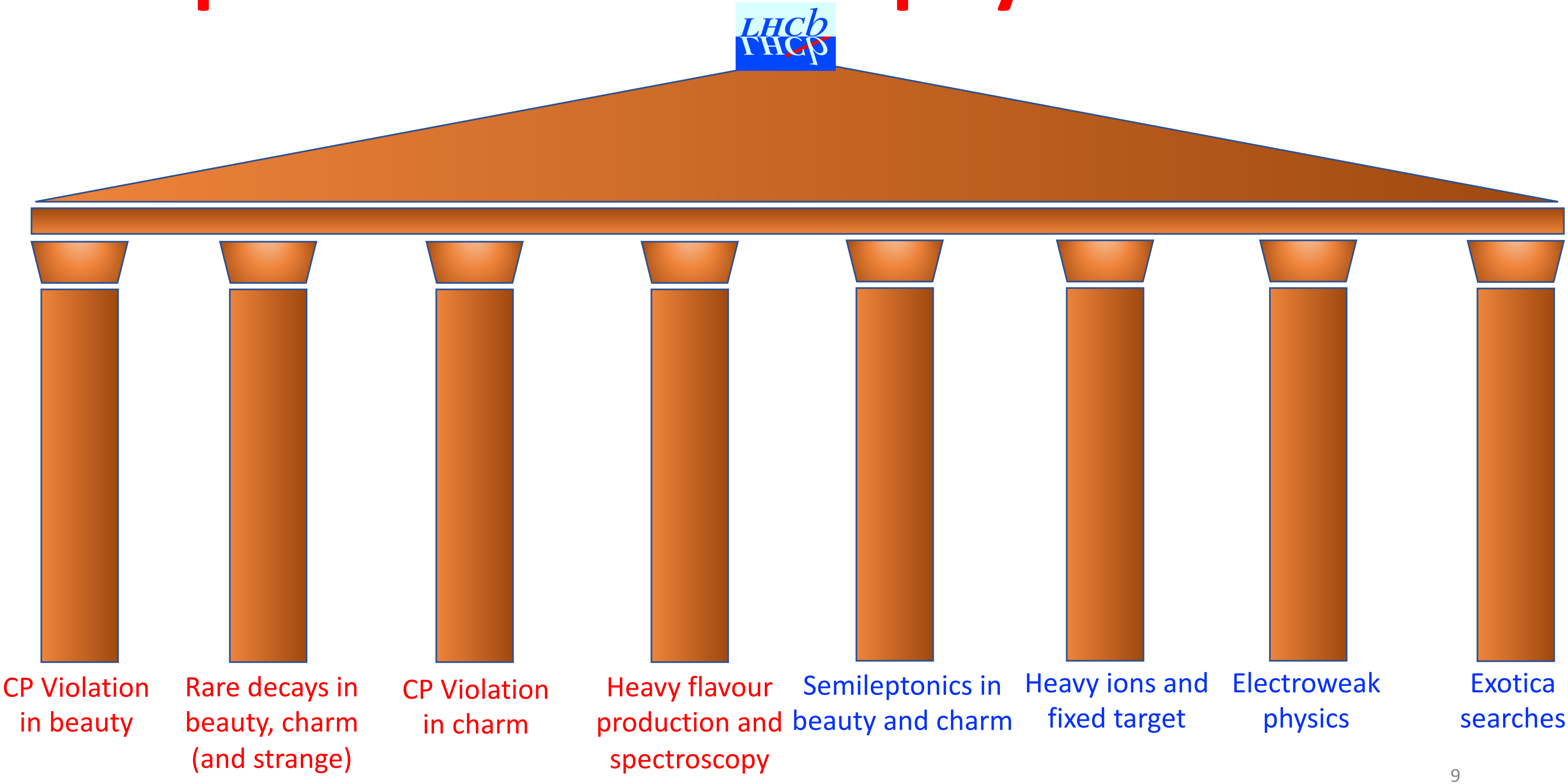
Dream new physics scenario for the unitarity triangle (for illustration only)



The pillars of the LHCb physics

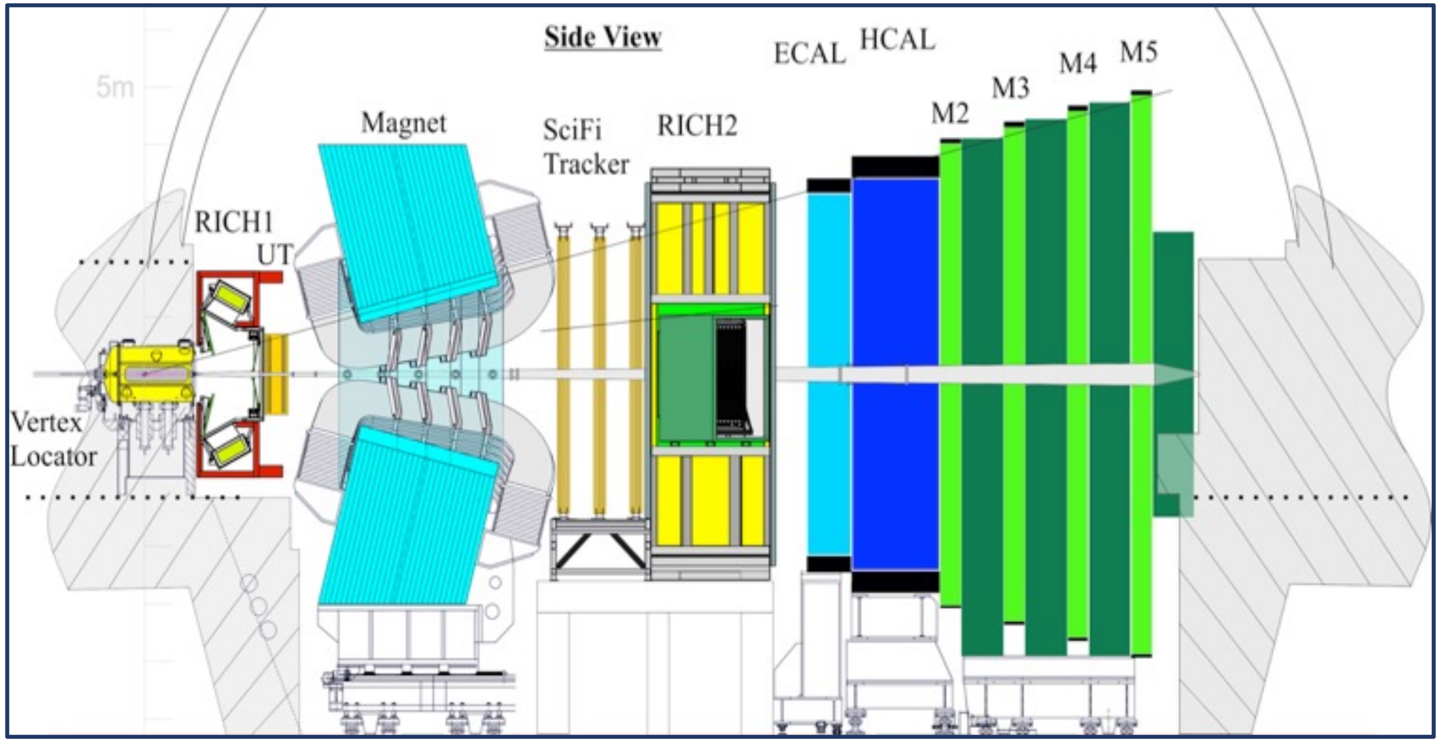


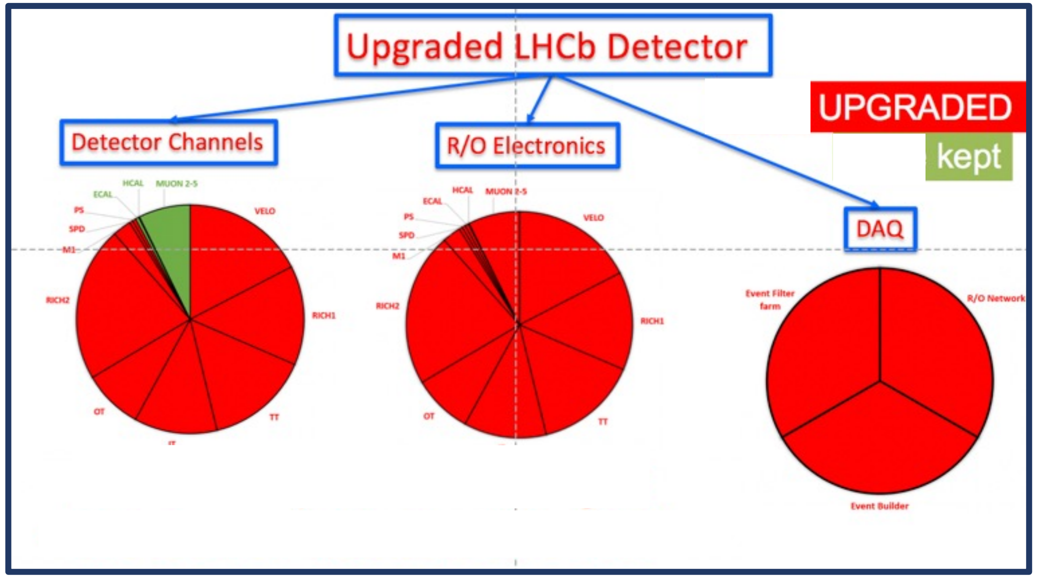
The pillars of the LHCb physics



The present detector: Upgrade I

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

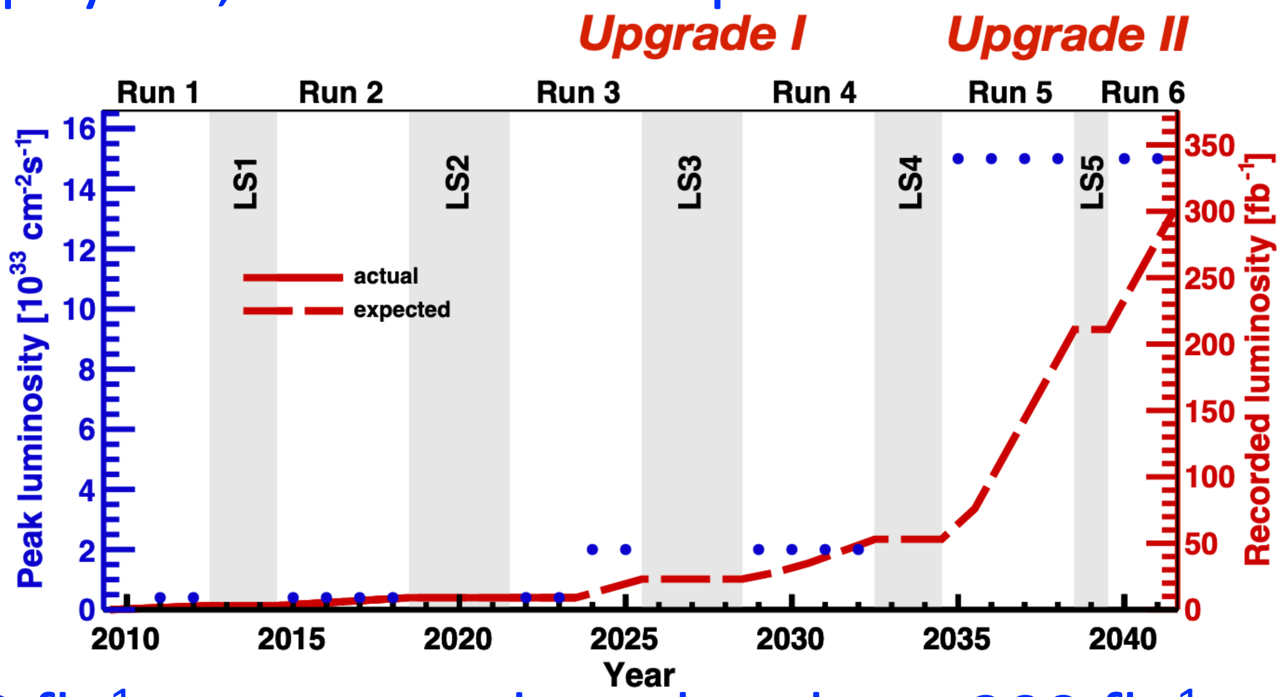




- Pixel detector VELO with silicon microchannel cooling 5 mm from LHC beam (…)
- New RICH mechanics, optics and photodetectors
- New silicon strip upstream tracker detector
- New SciFi tracker with 11,000 km of scintillating fibres
- New electronics for muon and calorimeter systems

The future: 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



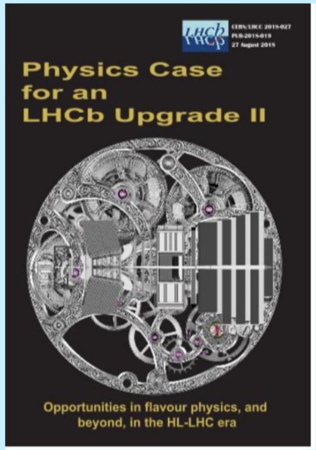
- The proposed baseline is to achieve 50 fb^{-1} per year and reach at least 300 fb^{-1} at the end of Run-6
- That will allow for unprecedented samples and a compelling physics programme

Upgrade II: approval steps so far

Eol

LHCC-2017-003

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."

LHCC-2021-012

FTDR approved on March 2022

- Detector design and technology options
- R&D program and schedule
- Cost for baseline and options National interests

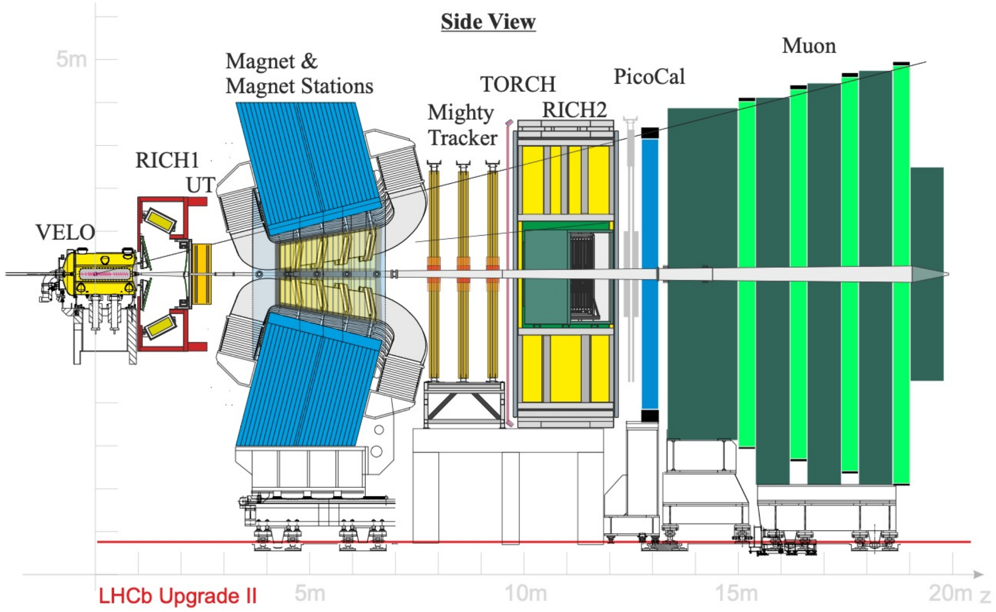
"The **LHCC recommends** that LHCb continue the R&D necessary to complete technical design reports on the proposed schedule, …"

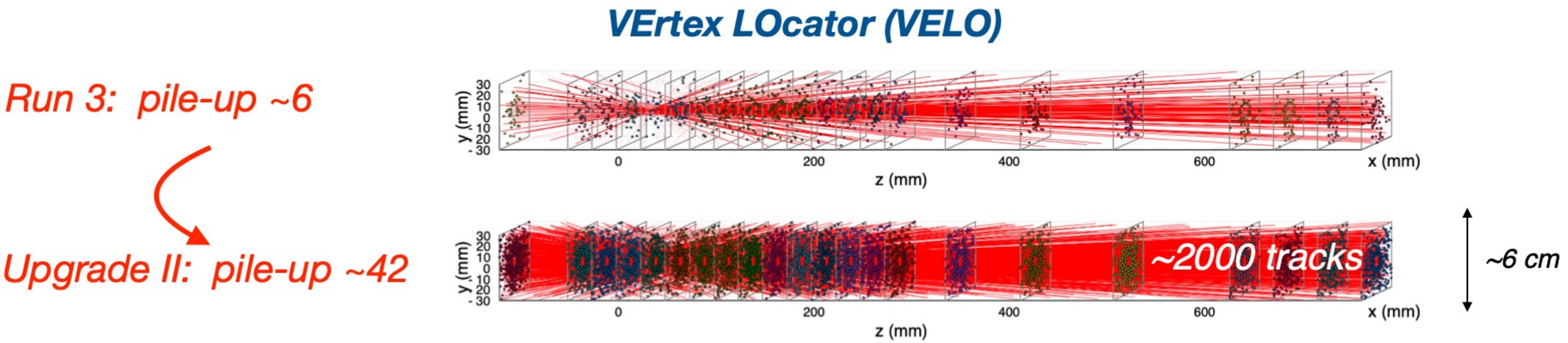
"The **LHCC recommends** the continued investigation of descoping and other cost-saving possibilities. …"

"The **LHCC recommends** that a well-defined process to establish the financial envelope prior to the preparation of TDRs be set up and notes that close coordination with funding agencies will likely be required in this process.

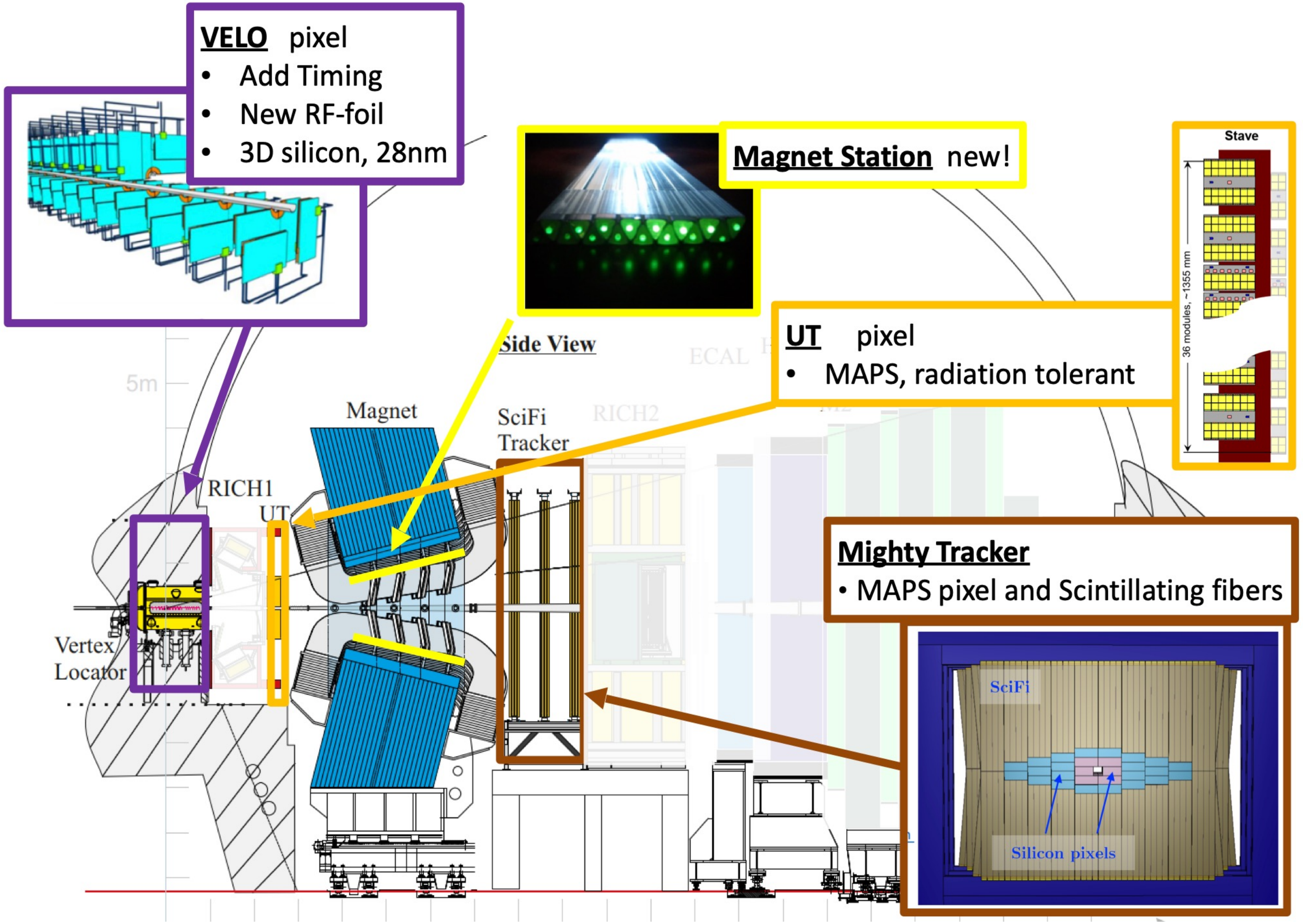
The new detector

- 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)
  - Radiation hardness (up to few 10^{16} neq/cm^2)





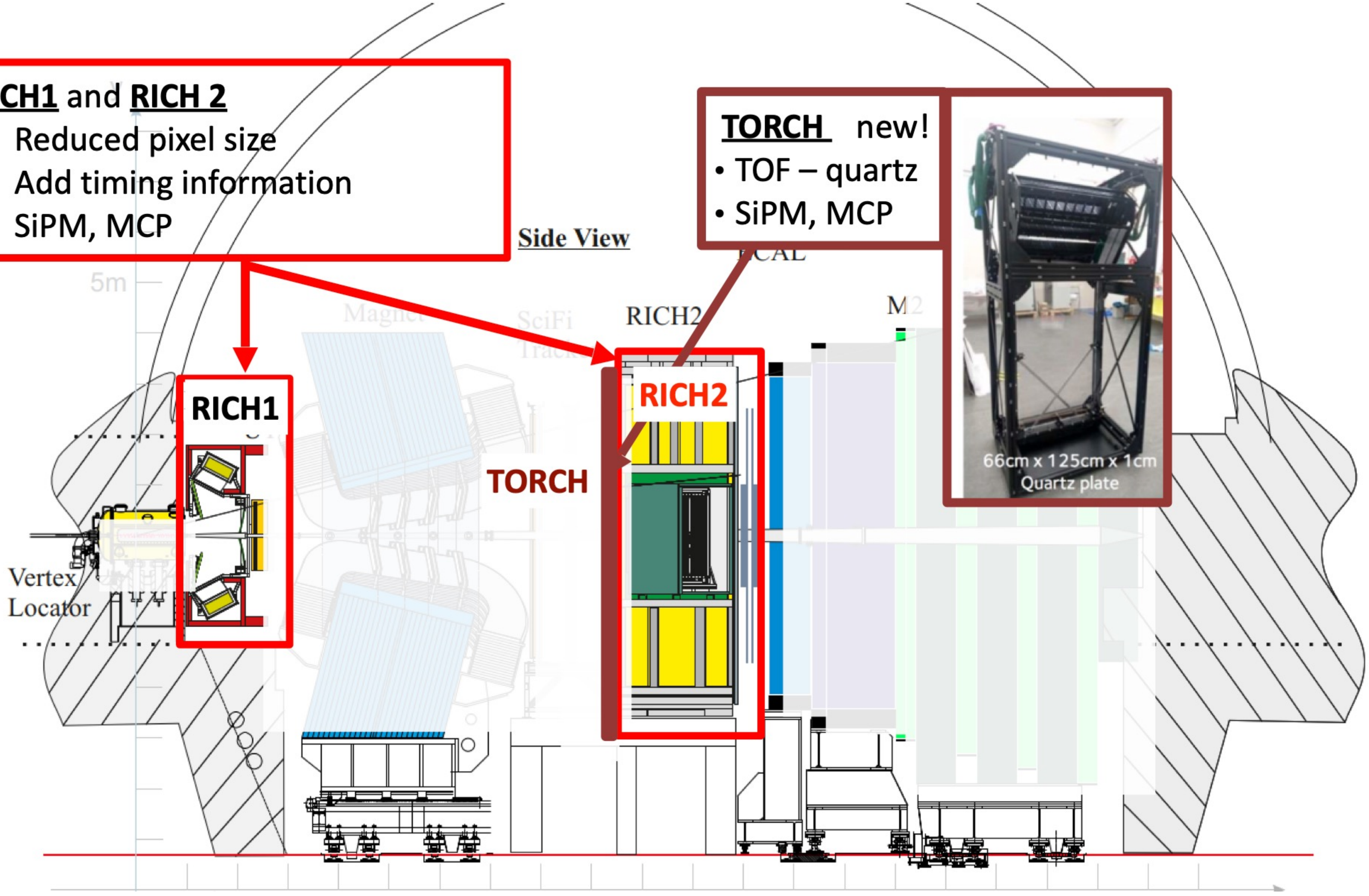
New tracking detectors



New PID detectors

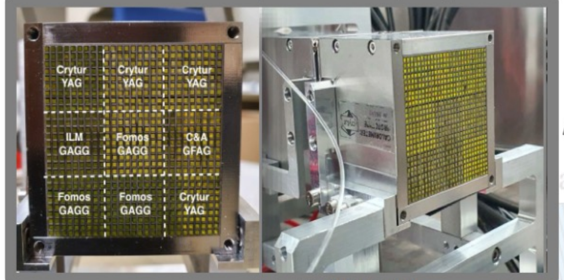
RICH1 and **RICH 2**
- Reduced pixel size
- Add timing information
- SiPM, MCP

TORCH new!
- TOF – quartz
- SiPM, MCP

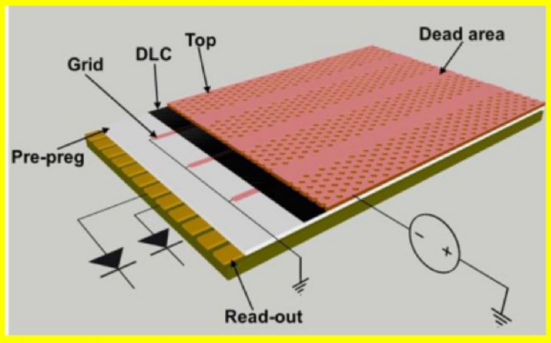


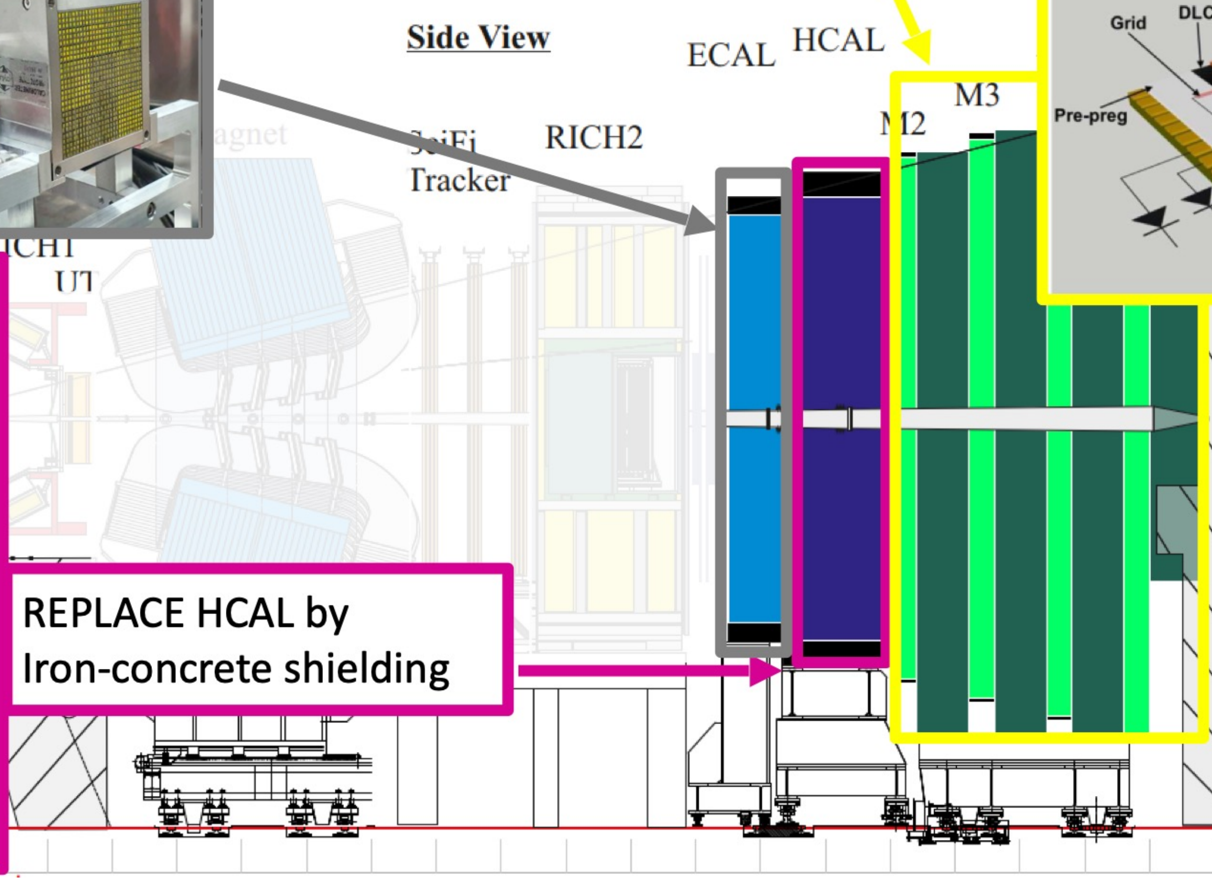
New PID detectors

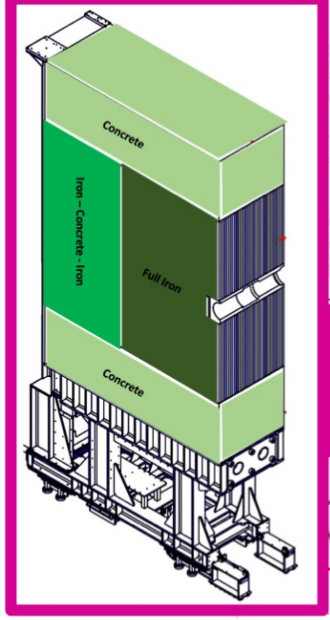
ECAL
- Space & time, longitudinal segmentation
- SPACAL with radiation hard crystals



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



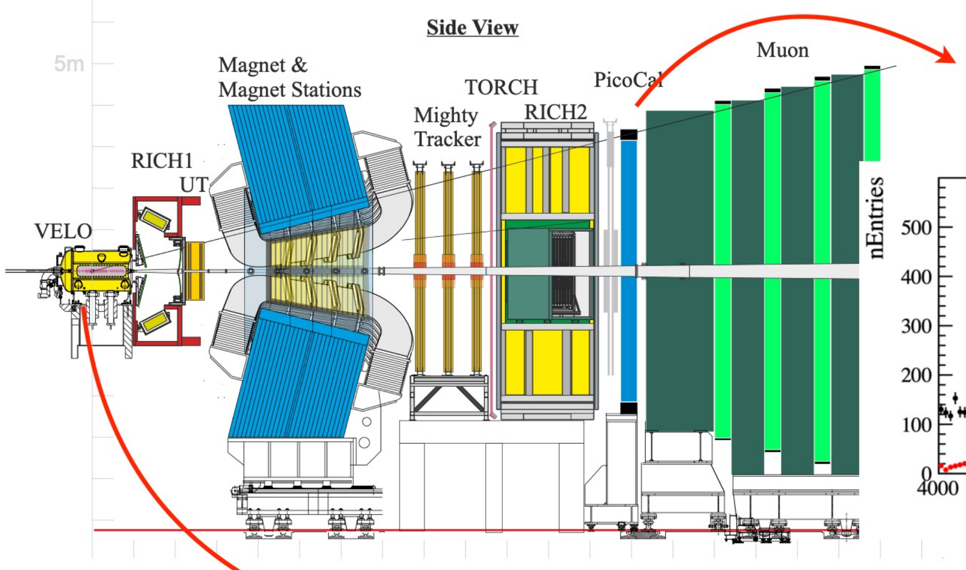




REPLACE HCAL by
Iron-concrete shielding

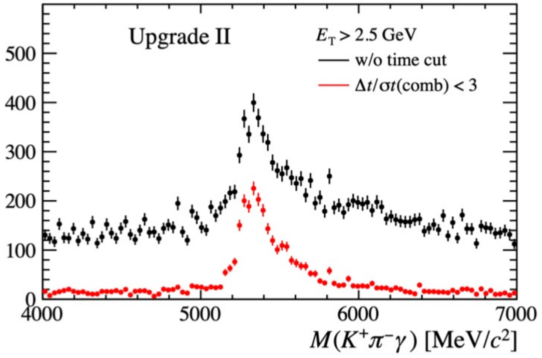
The importance of precision timing

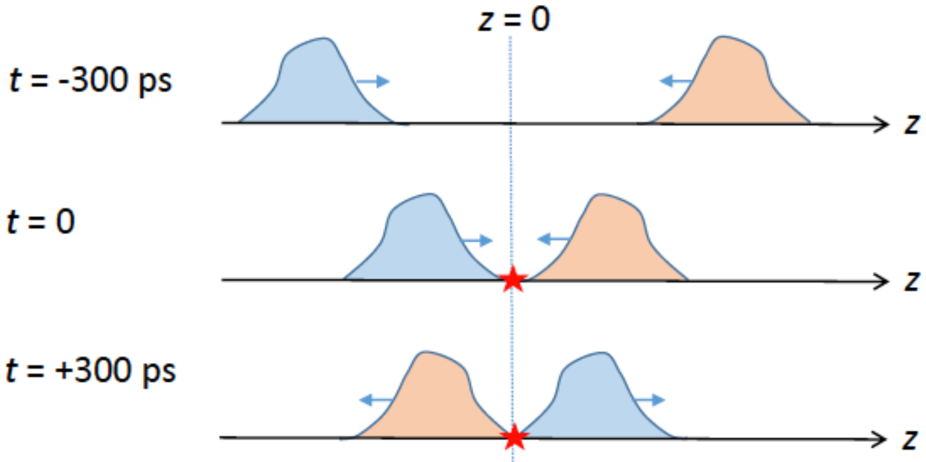
- Timing capability with a resolution of a few tens of picoseconds is a key to reduce background and associate signal decays to correct p-p primary vertices



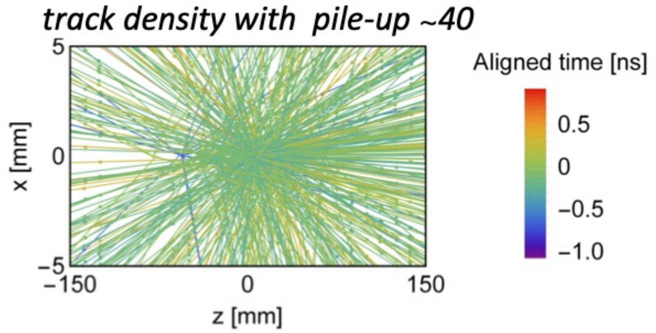
precision timing in calorimeter

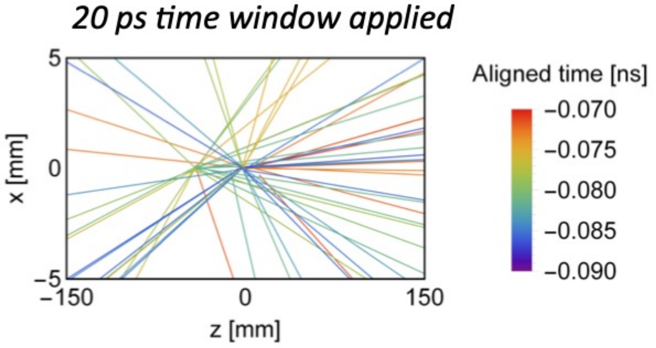
precision timing in VELO





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



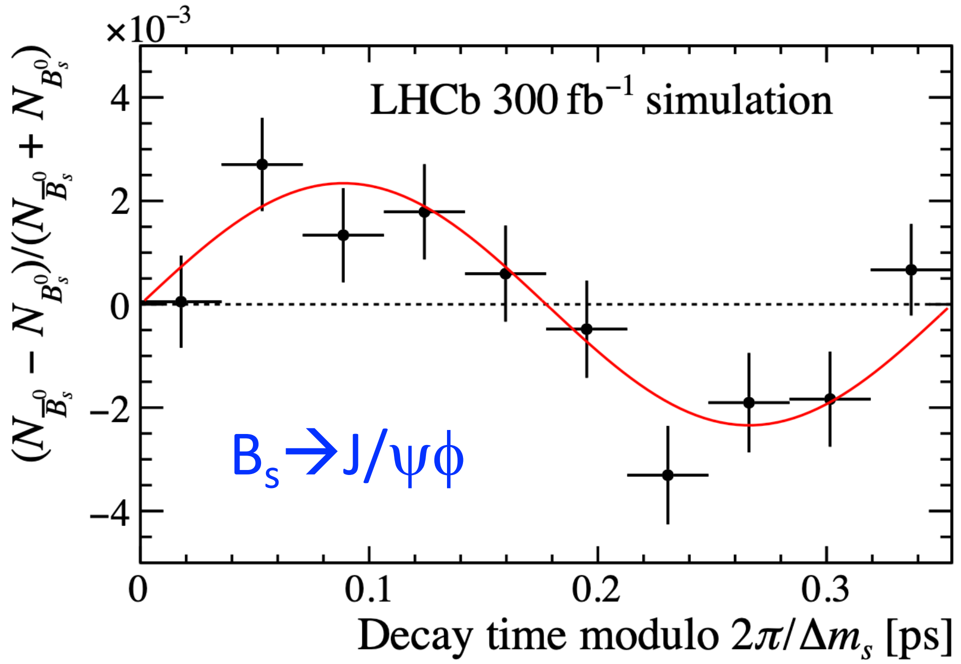


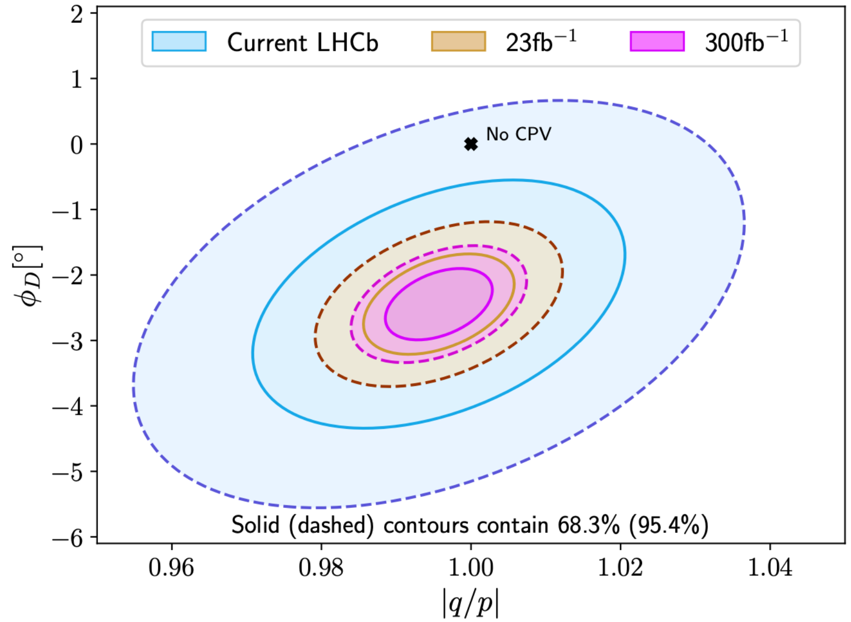
The programme requires strong R&D on sensors, already ongoing, and dedicated efforts for the design of new FEE ASICs

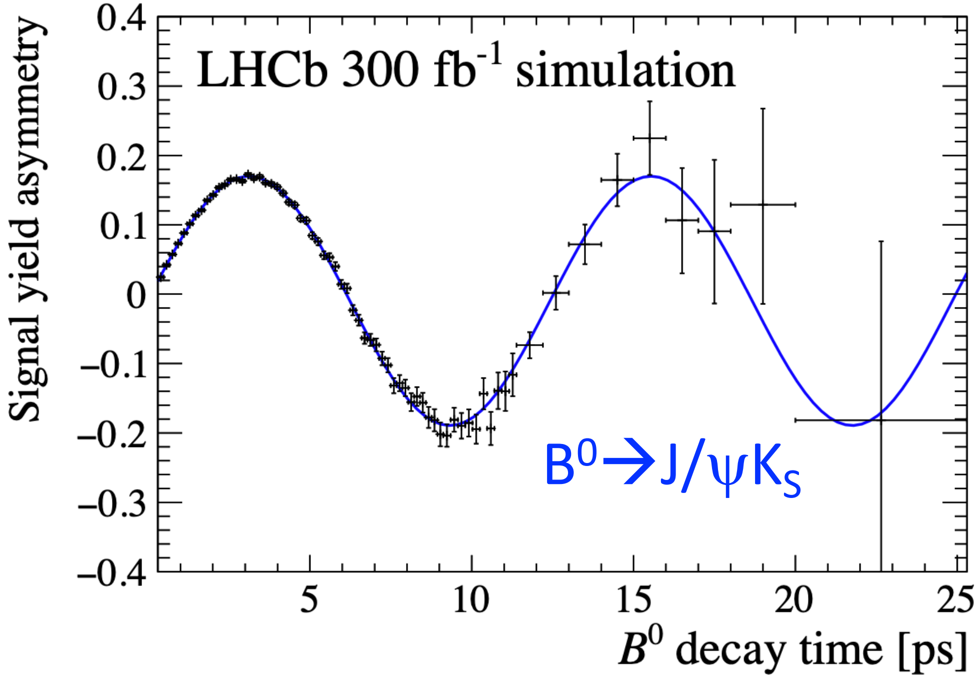
LHCb Upgrade II Physics Case: CP violation

- $\sigma(\gamma)$: 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



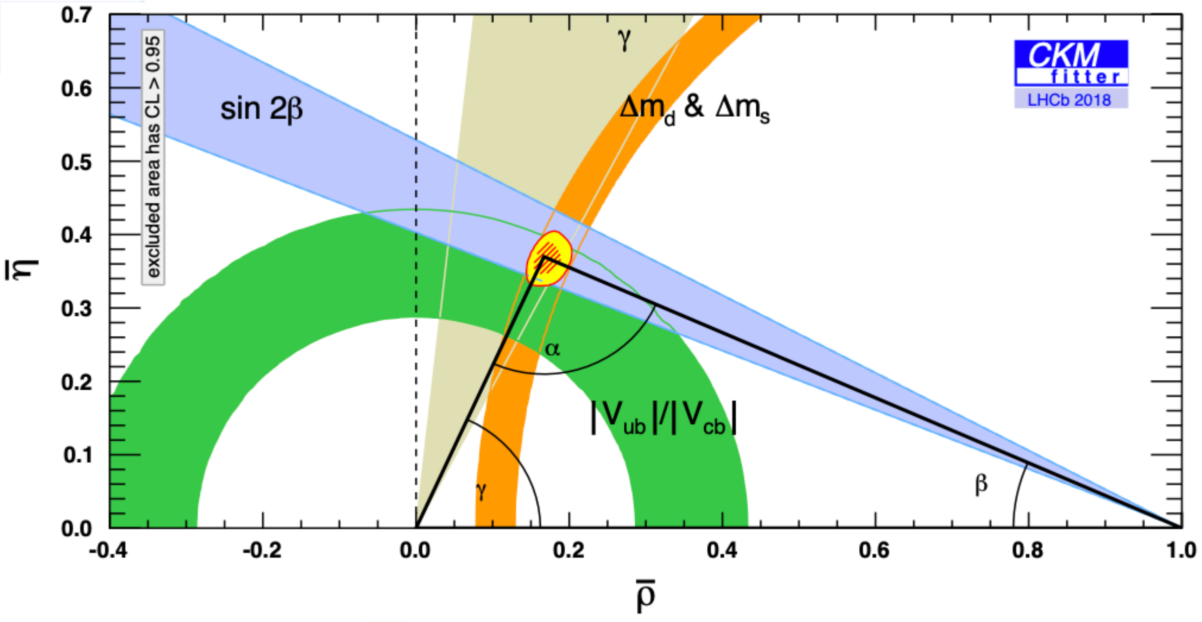


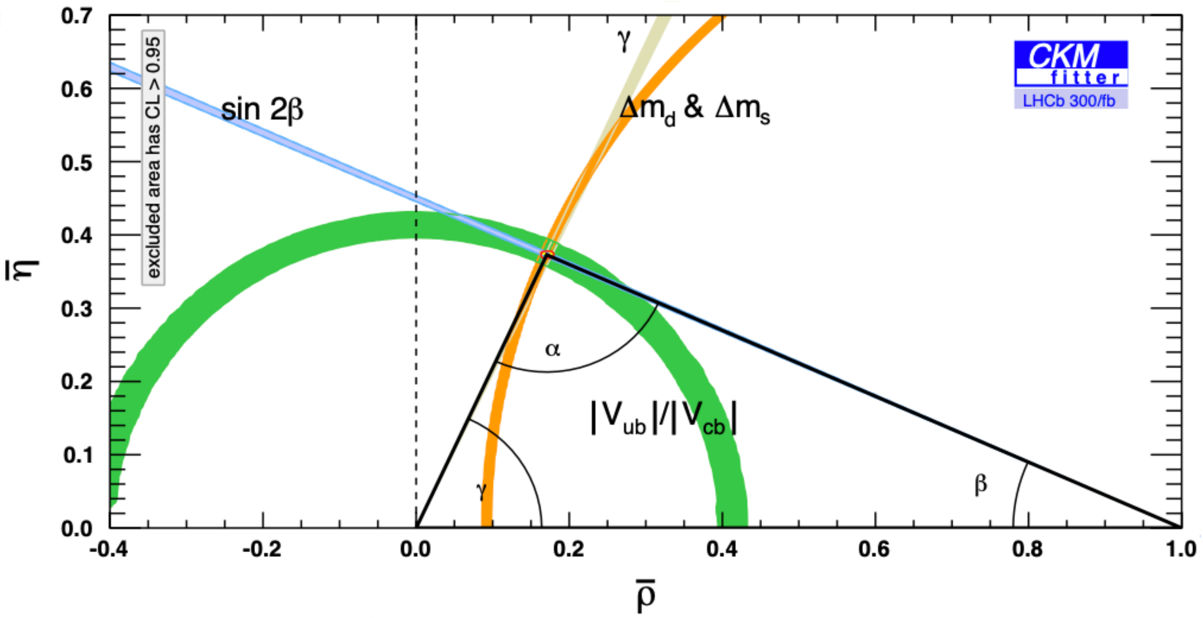


LHCb Upgrade II is the only planned facility with a realistic possibility to observe CP violation in charm

Unitarity Triangle improvements after Upgrade II

LHCb Upgrade II will test the CKM paradigm with unprecedented accuracy





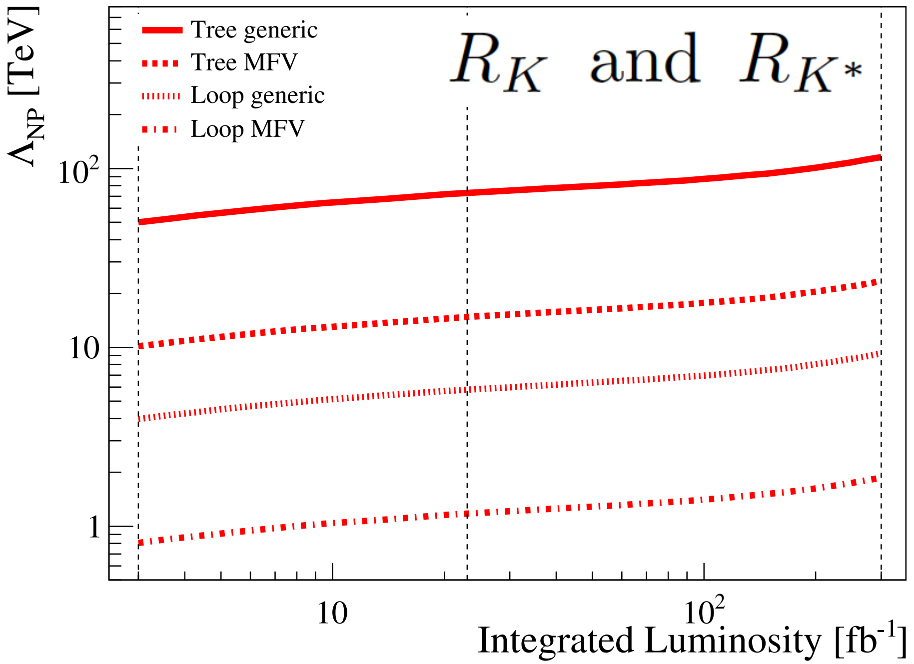
Two independent measurements of triangle apex: ($\Delta m_d/\Delta m_s$, sin 2β) and (V_{ub}, γ)

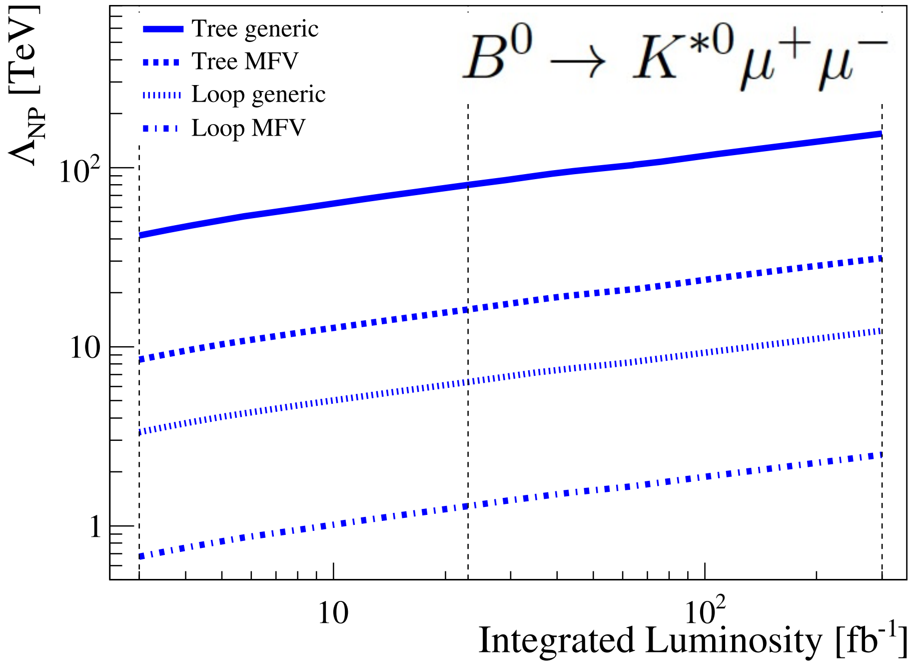
Both pairs require Upgrade 2 for statistics (sin 2β and γ) and time for theory improvements ($\Delta m_d/\Delta m_s$ and V_{ub})

- Permit tree-level observables (SM benchmarks) to be assessed against loop contributions (new physics sensitive)

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

W mass measurement

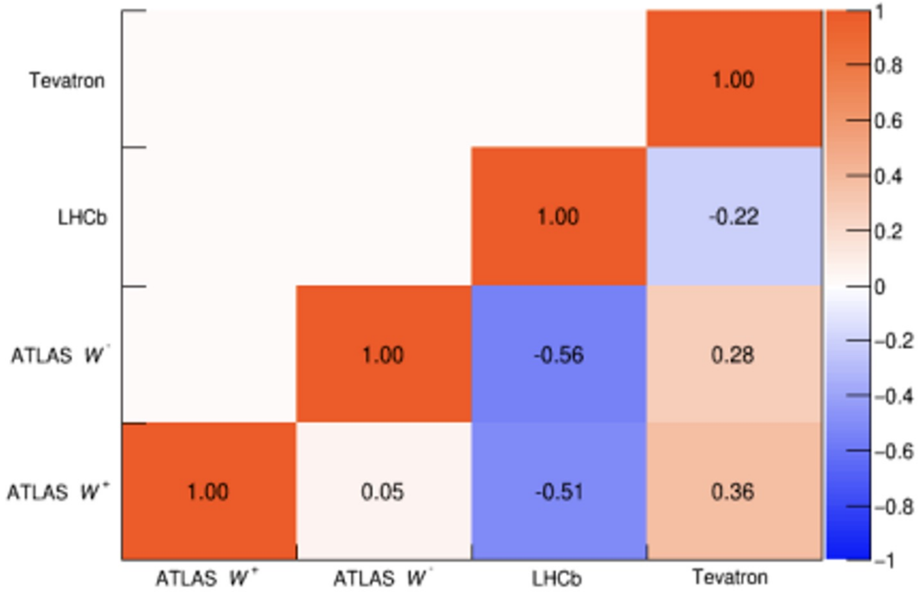
- Proof-of-principle measurement, based on q/p_T distribution in $W \to \mu\nu X$, using 2016 data presented in summer 2021 JHEP 01 (2022) 036

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

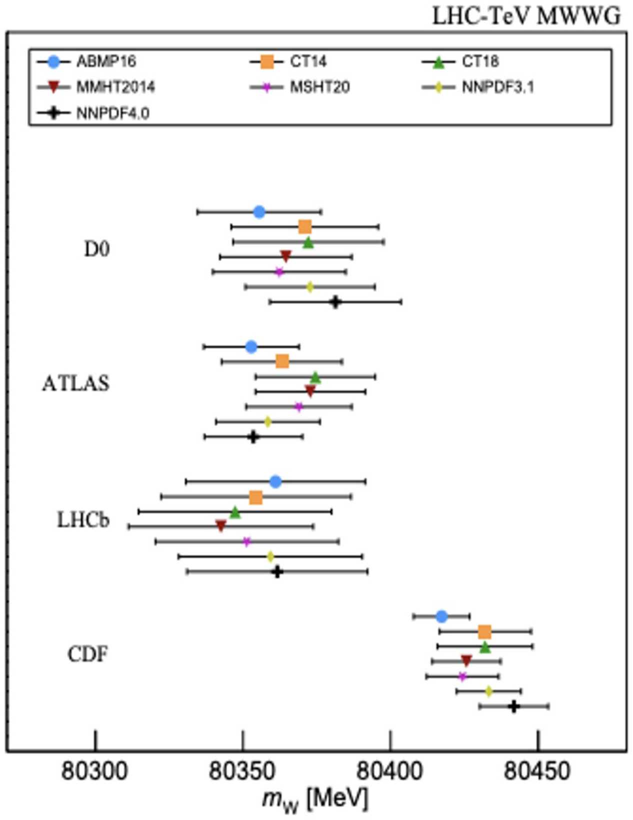
EPJC 75 (2015) 12, 601

- PDF uncertainties are partially anticorrelated for LHCb versus ATLAS and/or CMS
- A measurement from LHCb is relevant without necessarily matching the standalone precision of ATLAS/CMS

PDF correlations with MSHT20 PDF set

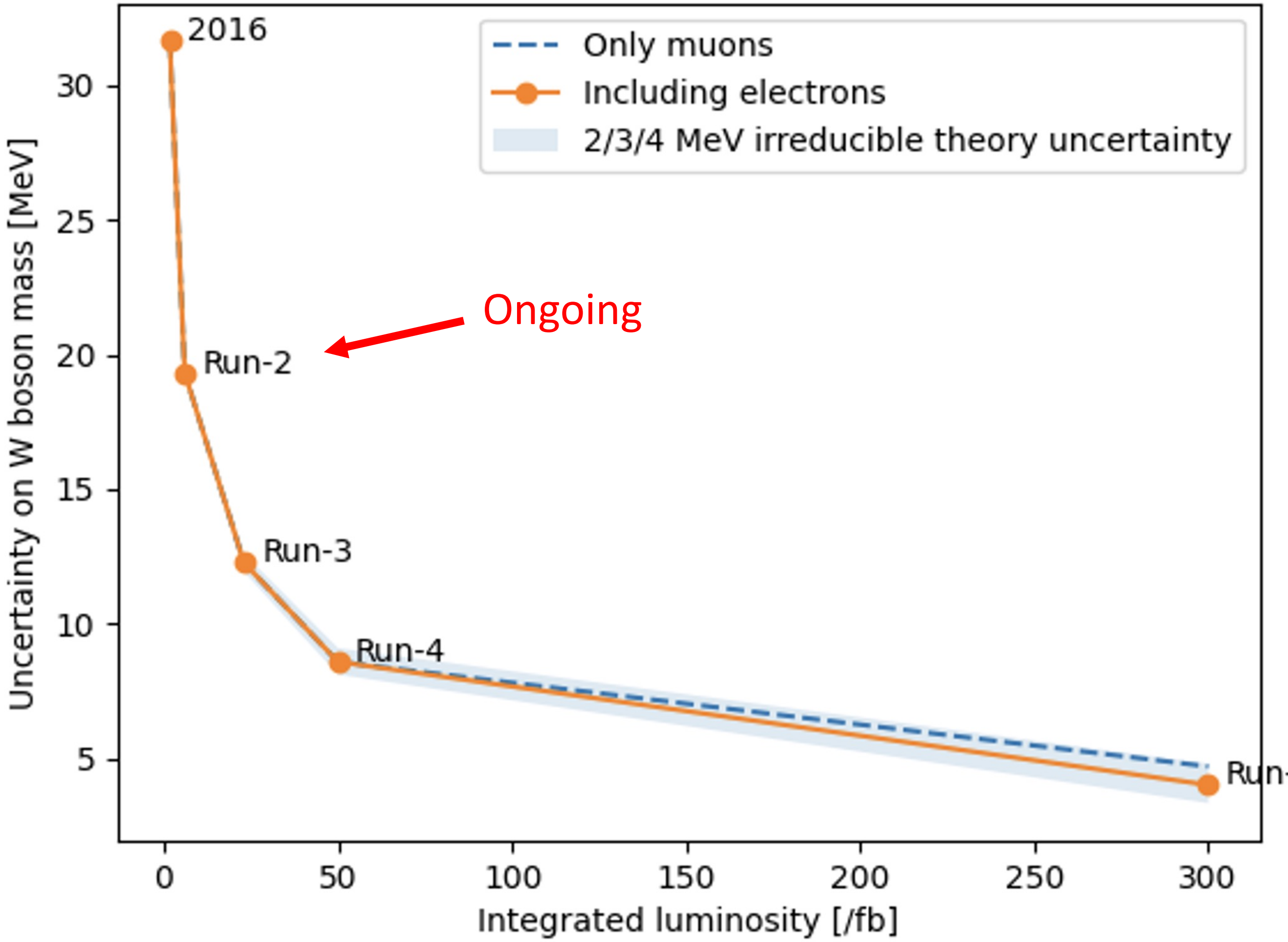


https://arxiv.org/abs/2308.09417



W mass prospects at LHCb

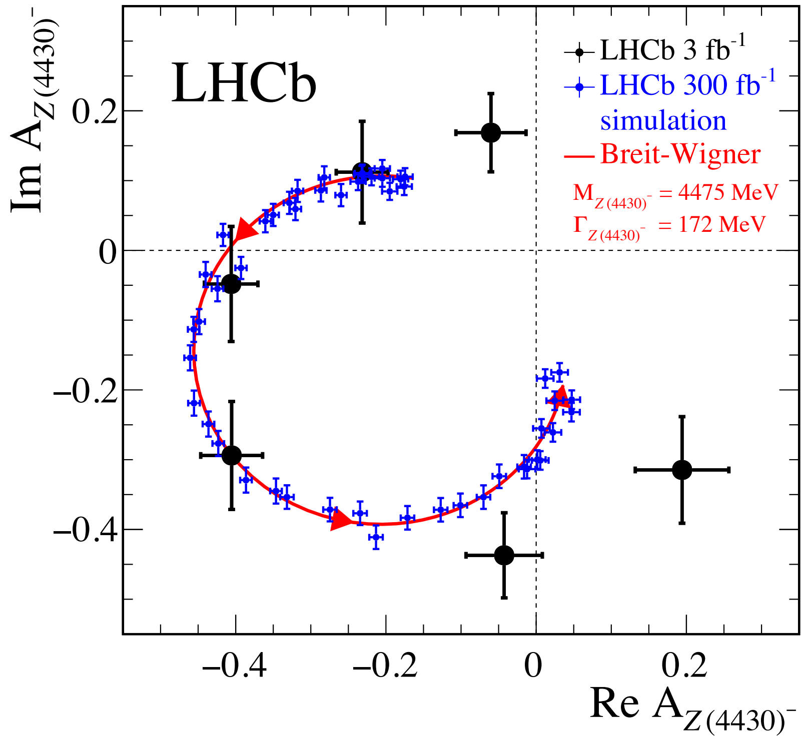
- On the basis of some assumptions and a simple extrapolation model
  - More details in backup slides



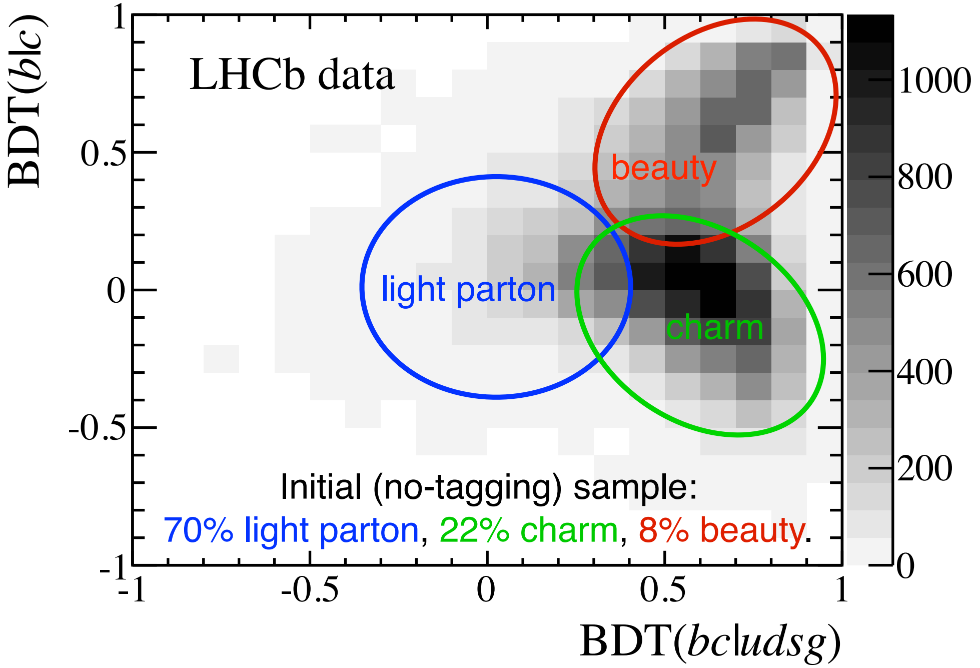
Courtesy of Mika Vesterinen

Upgrade II total uncertainty of 5 MeV or better, depending on the theory uncertainty

LHCb Upgrade II Physics Case: other opportunities



- General purpose facility
  - Unique forward acceptance
- 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

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, $\sin 2\beta$, $R_K(*)$, $B \to \mu\mu$, …)
- 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 ($b \to sll$, $b \to dll$, $b \to cl\nu$, …)
- Strong programme beyond flavour exploiting unique acceptance
  - Higgs physics, spectroscopy, electroweak, dark sector, heavy ions, fixed target

Lots to do!

- Data Analysis
- Operations
- Detector R&D
- Software development
- …

- Many thanks to the organisers, volunteers and participants!