Introducing LHCb

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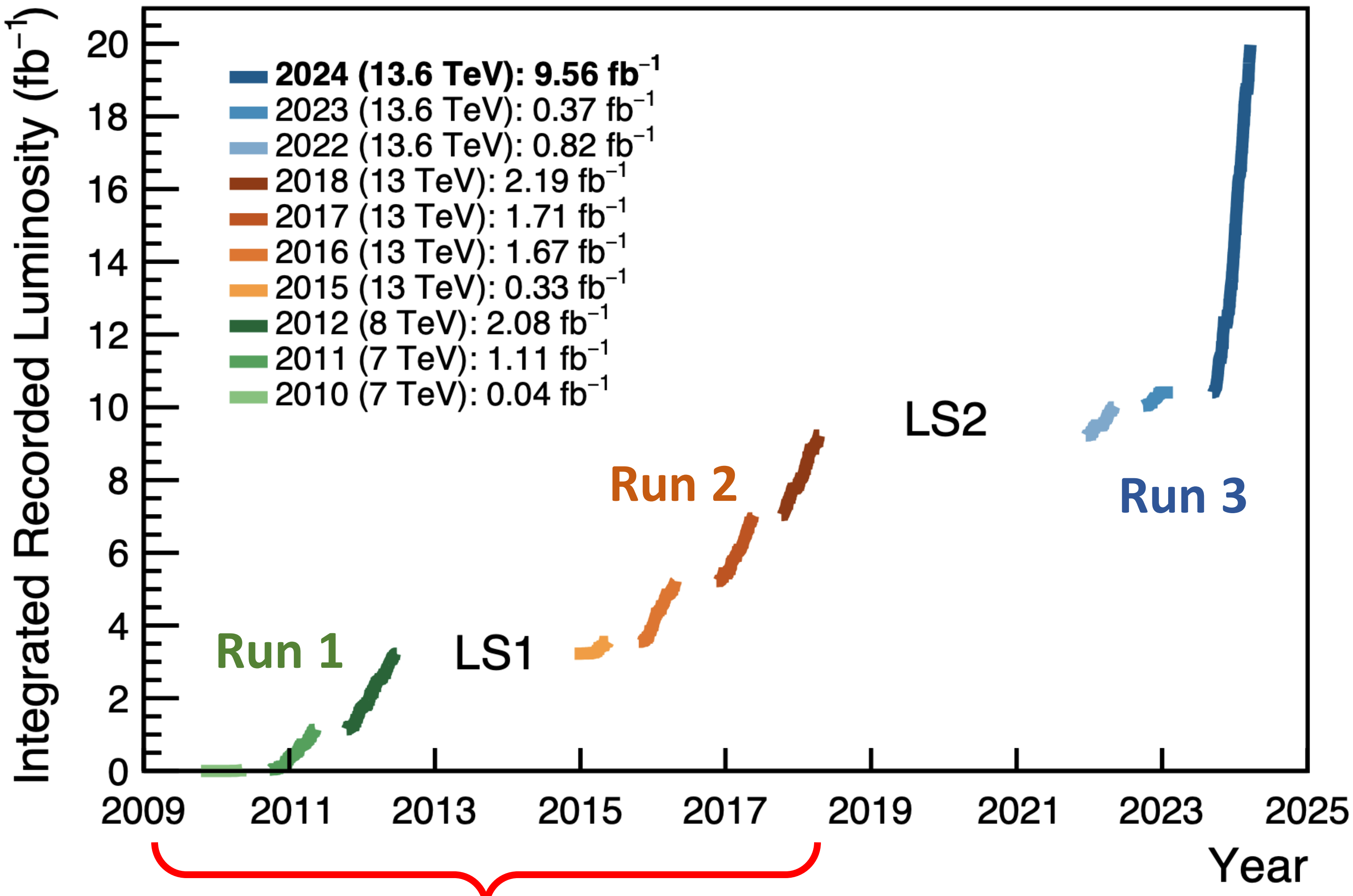
25th November 2024, LHCb Starterkit

The birth of the LHCb experiment

- When the constructions of the BaBar and Belle detectors were being scrutinised for approval, three distinct proposals for a dedicated *b*-physics experiment at the LHC were put forward, so-called COBEX, GAJET, and LHB
  - GAJET and LHB were both based on fixed targets, the former working with a gas target placed inside the LHC beam pipe and the latter exploiting an extracted LHC beam
  - COBEX was instead proposed to work in proton-proton collider mode
- The three groups of proponents were asked to merge and submit to the LHC Experiments Committee (LHCC) a proposal for a single collider-mode experiment, then called LHCb
- LHCb was designed to exploit the potential for heavy-flavour physics at the LHC by instrumenting the forward region of proton-proton collisions, to take advantage of the large beauty cross section in the forward (or backward) LHC beam direction
- The LHCb experiment was approved in 1998 and started taking data with the start-up of LHC in 2009

LHCb phases

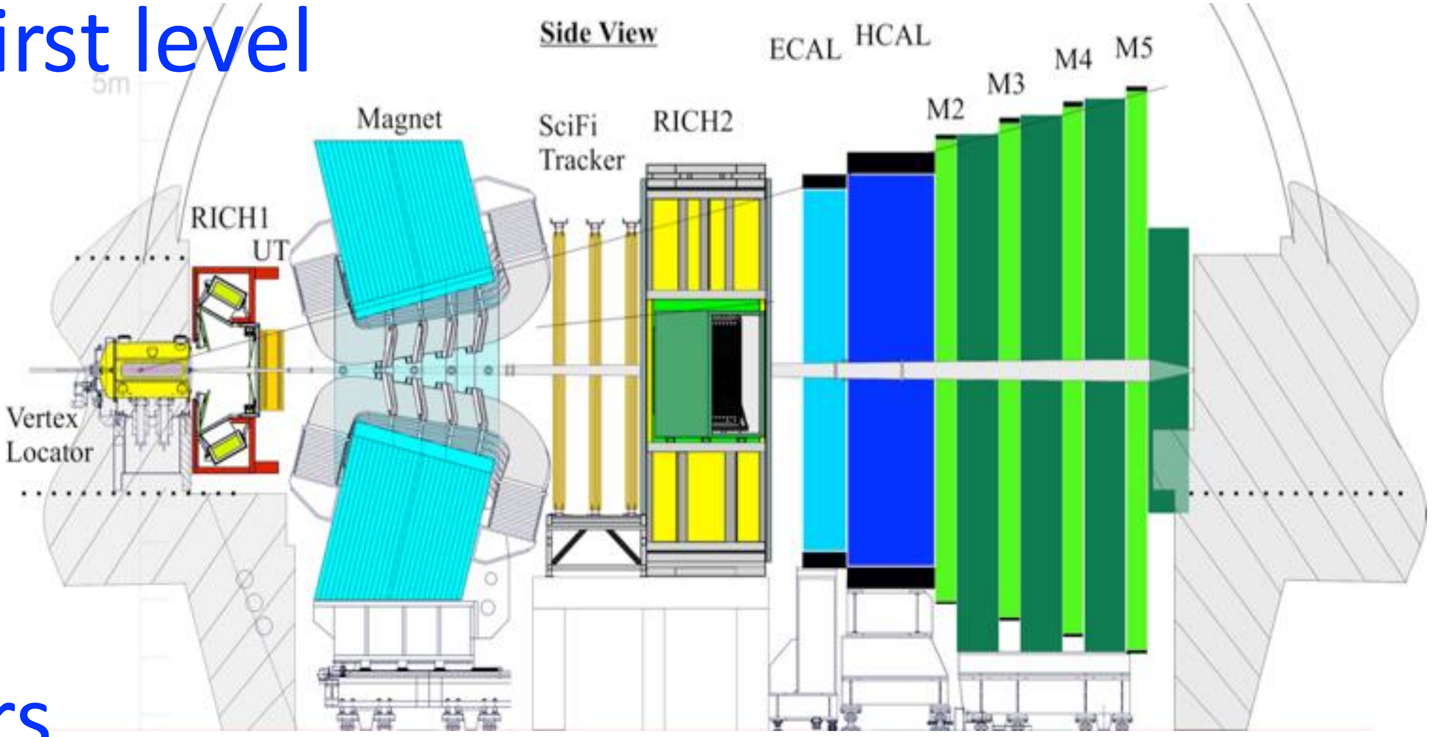
LHCb Upgrade I detector



First LHCb detector

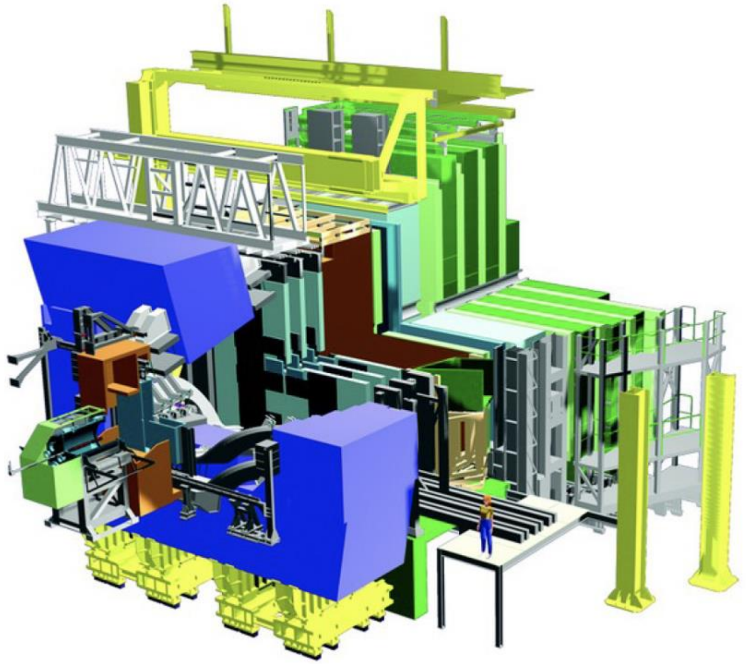
LHCb Upgrade I detector

- 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



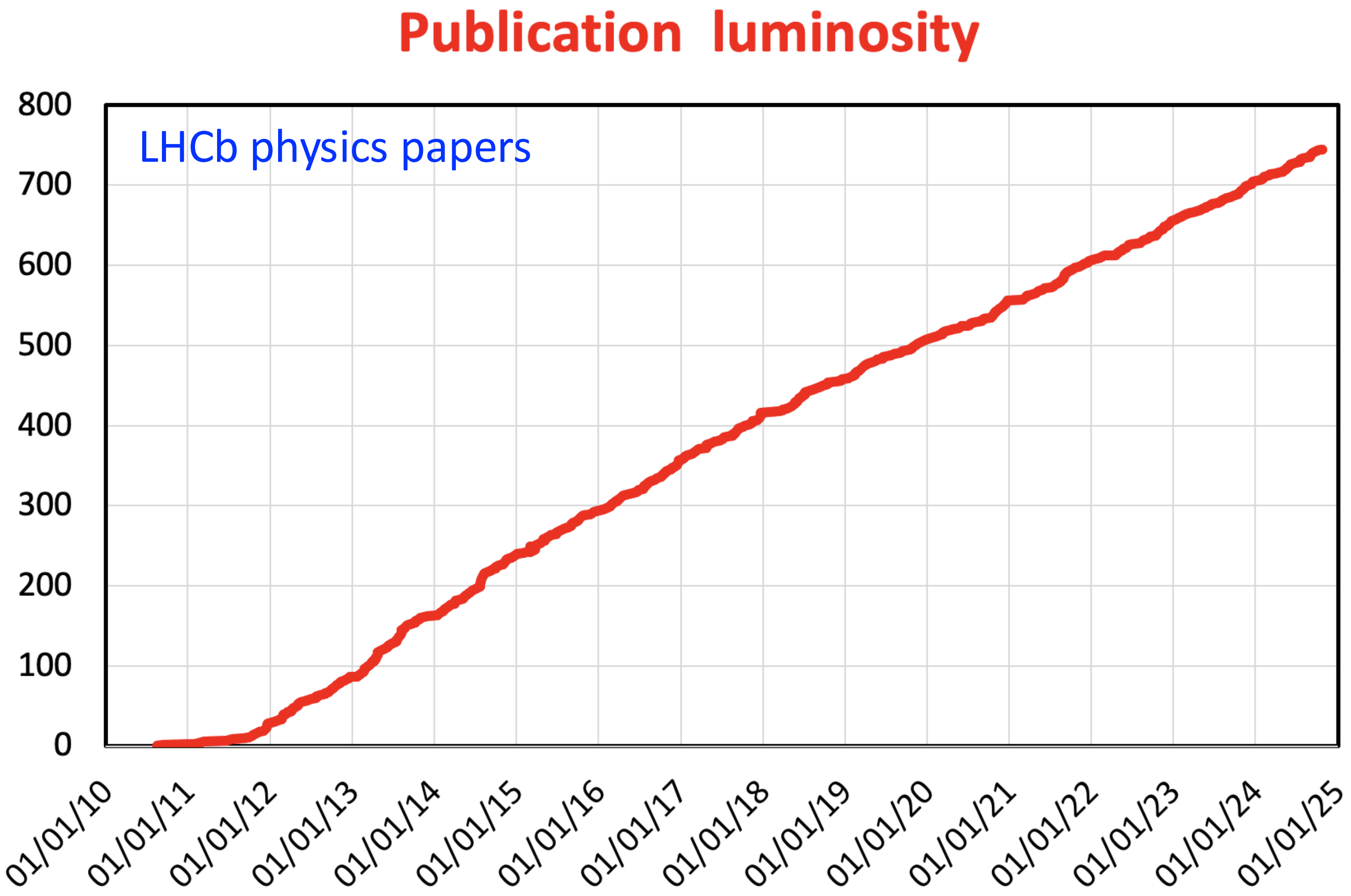
- New silicon-strip upstream tracker detector (UT)
- New SciFi tracker with 11,000 km of scintillating fibres
- New electronics for muon and calorimeter systems

LHCb collaboration today



- As of today, 1784 members and 1161 authors, continuing to grow at a steady pace

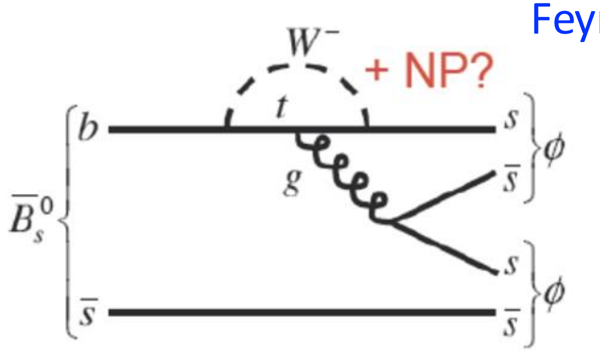
LHCb publication rate

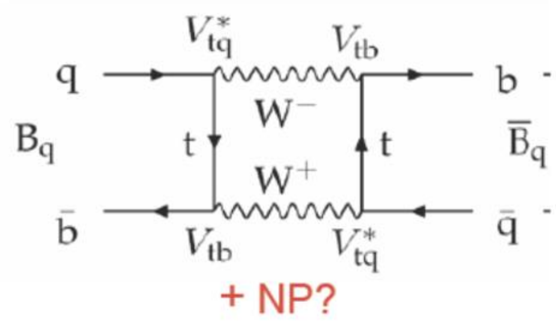


- 750 physics papers produced by LHCb as of today
- The number of papers continues to increase in a linear fashion over time, and we haven't yet started to publish with Run-3 data

Loop diagrams and new physics amplitudes

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





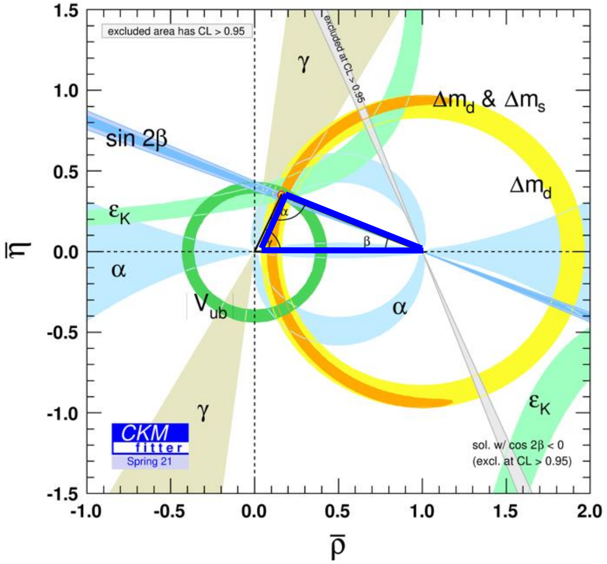
$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

- 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 possible 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

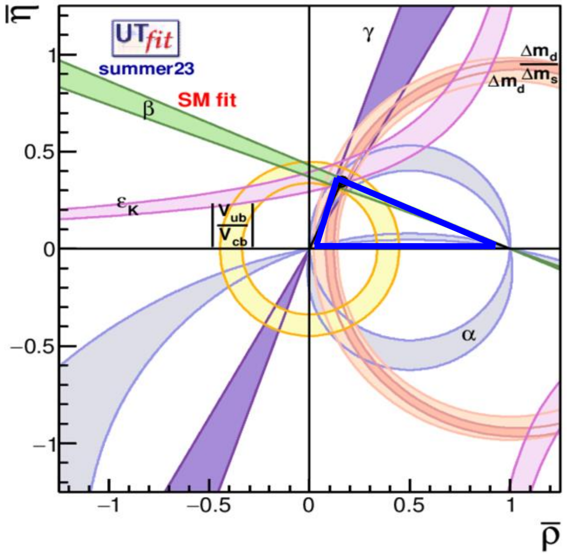
Consistency of global CKM fits

- 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

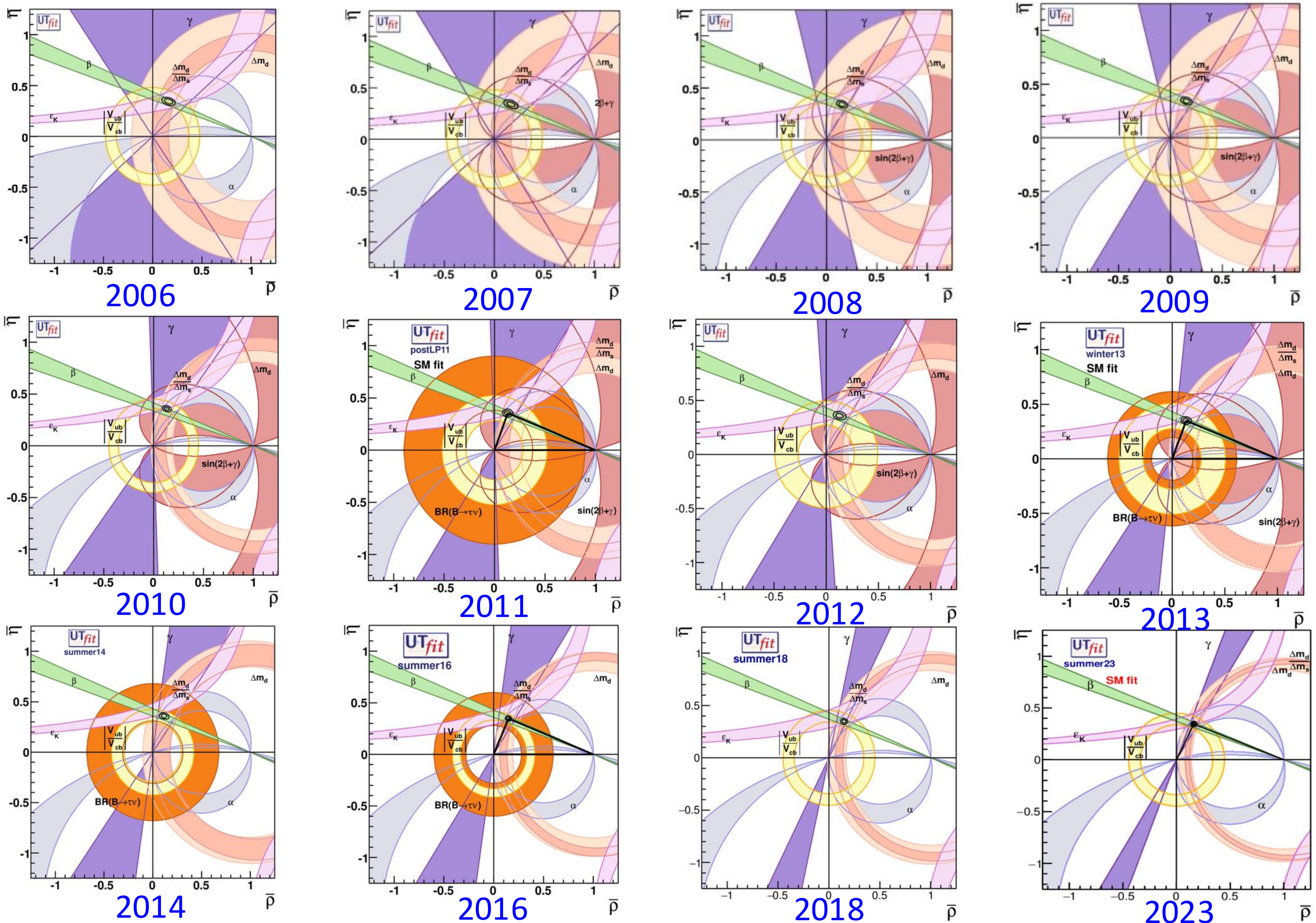


http://www.utfit.org

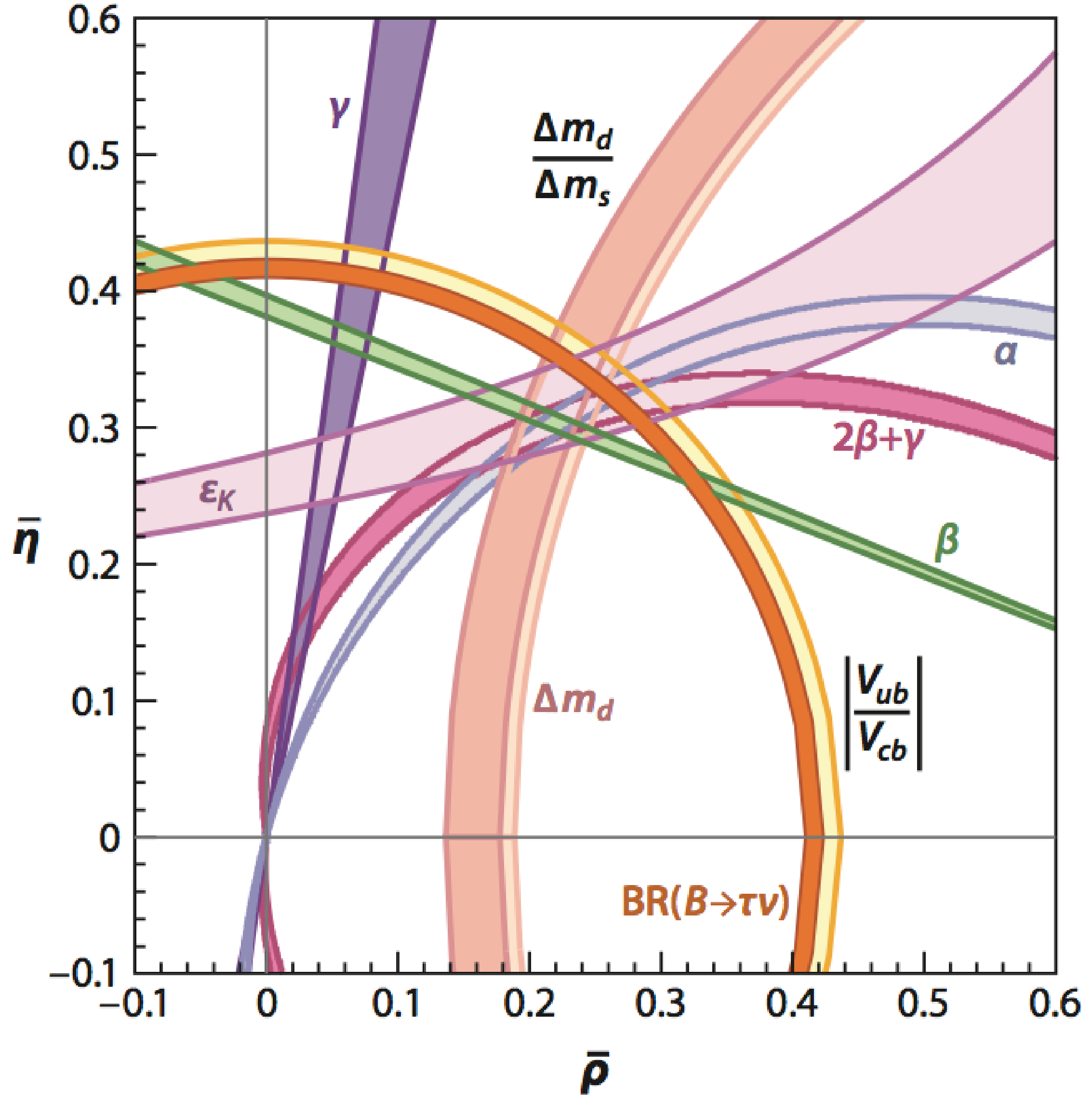


- Tremendous success of the CKM paradigm!
  - All of the available measurements agree in a highly profound way to the current level of precision
  - In presence of new physics affecting the measurements, the various contours would not cross each other into a single point
- The quark flavour sector is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

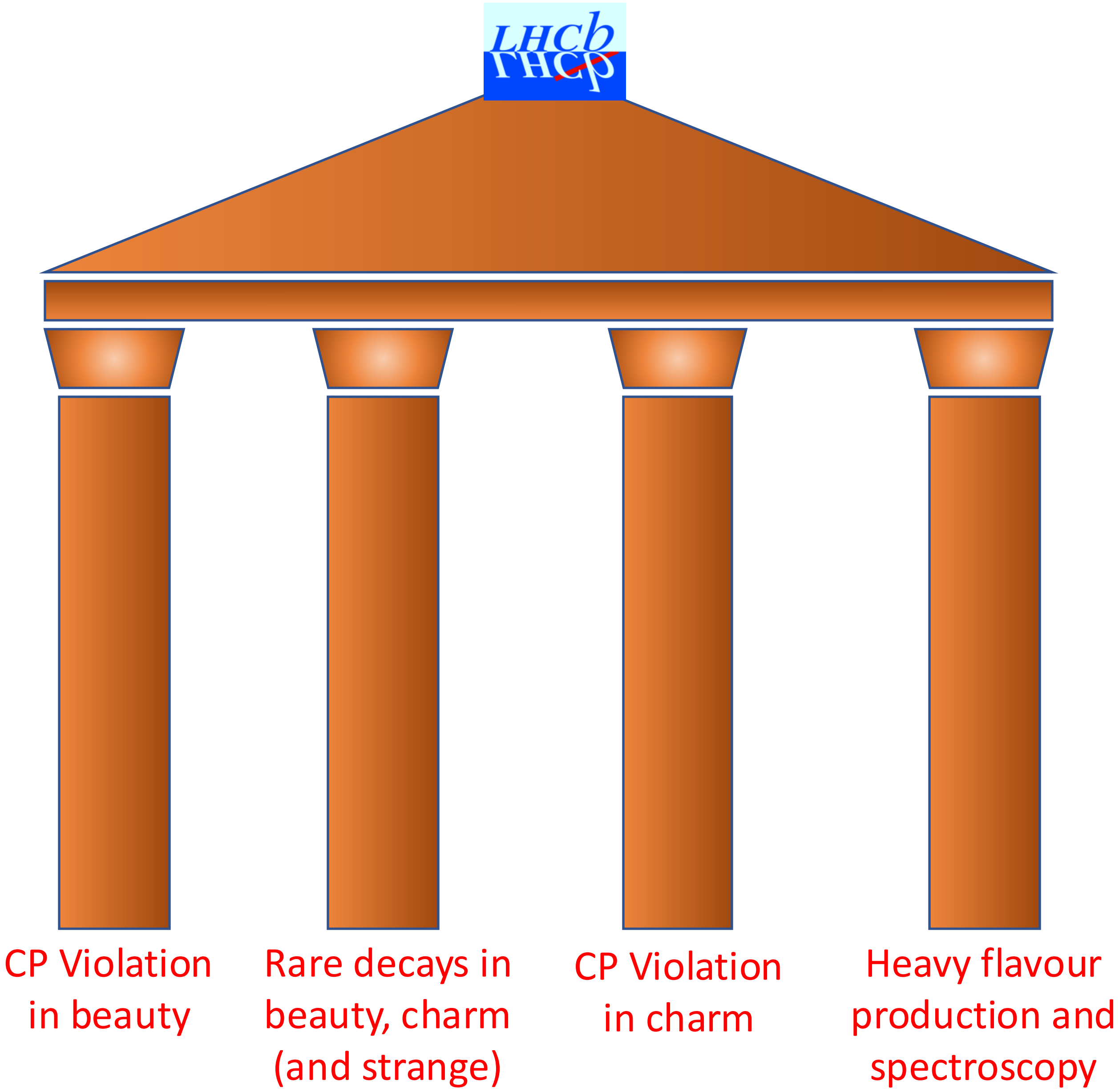
Long journey to reach here…



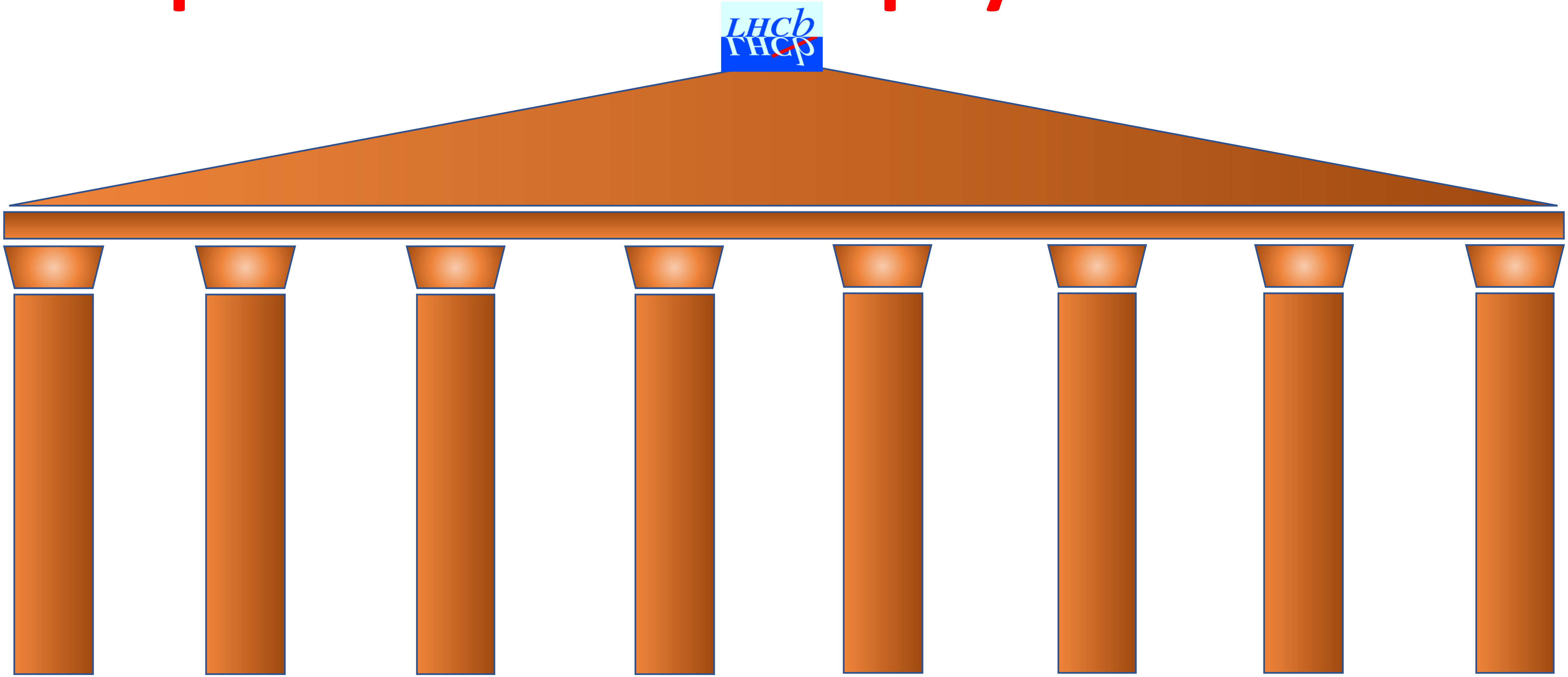
Dream new physics scenario for the unitarity triangle (for illustration only)



The pillars of the LHCb physics



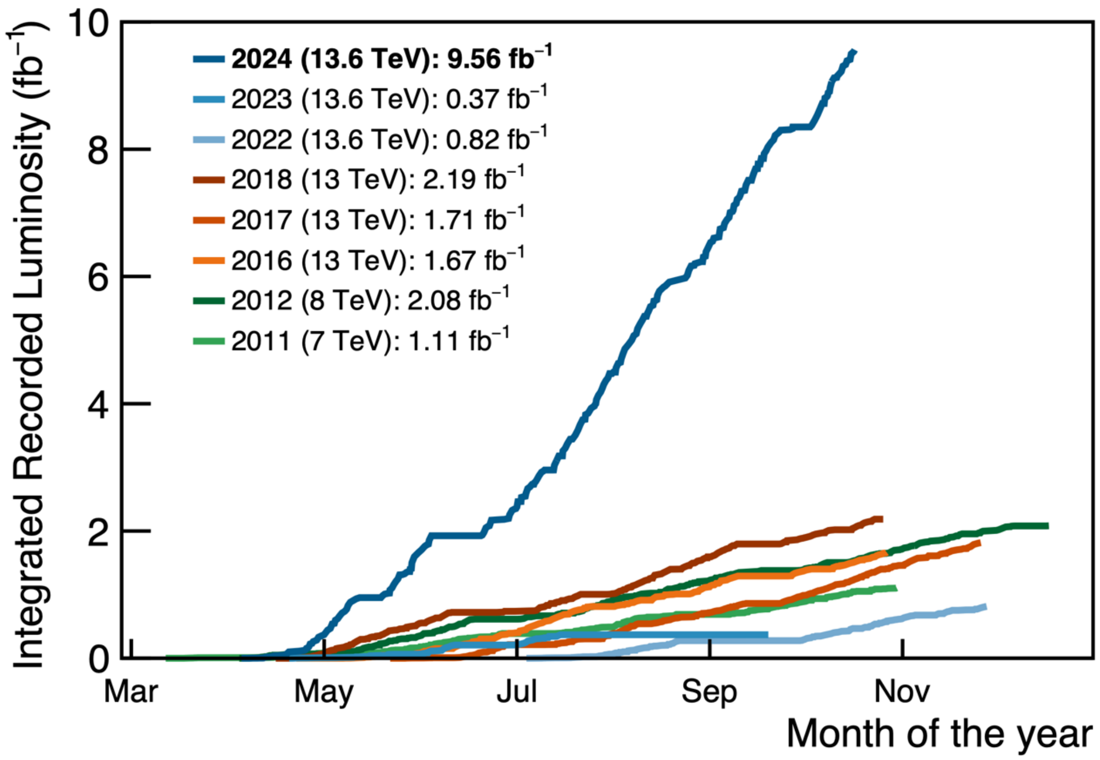
The pillars of the LHCb physics



2024 data taking

This year's 13.6 TeV *pp* data taking

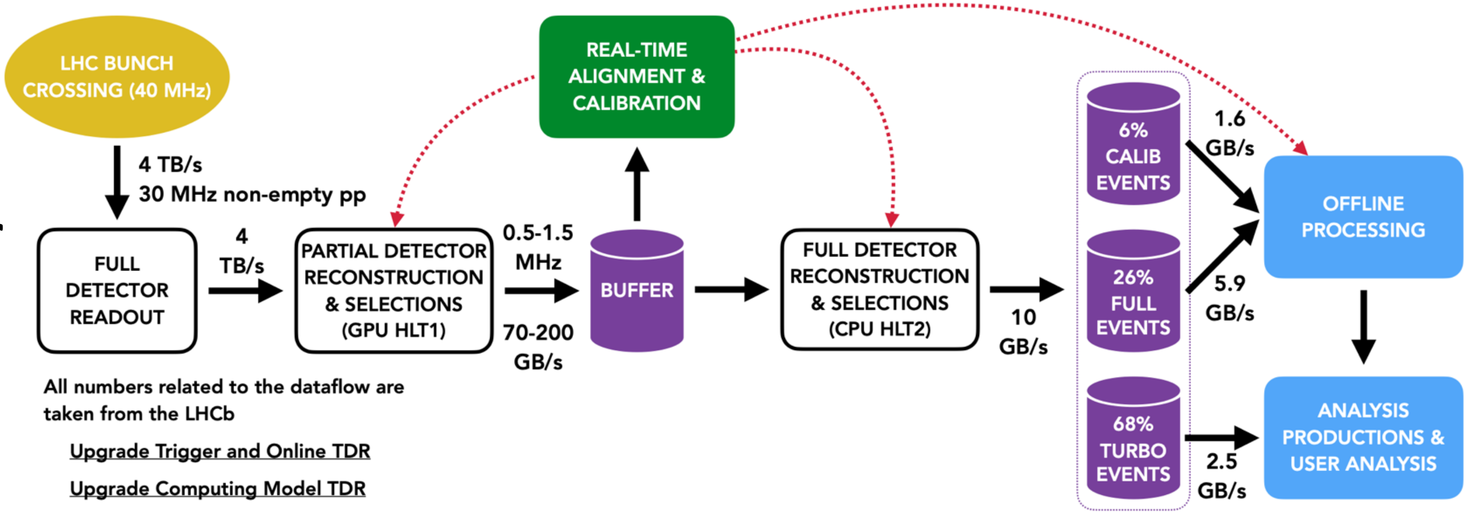
- Extremely successful data taking in 2024!
- All subdetectors have been taking data and participated to the trigger
- Total integrated luminosity: 9.56 fb^{-1}
  - The total integrated luminosity in Run-1 and Run-2 was 9 fb^{-1}

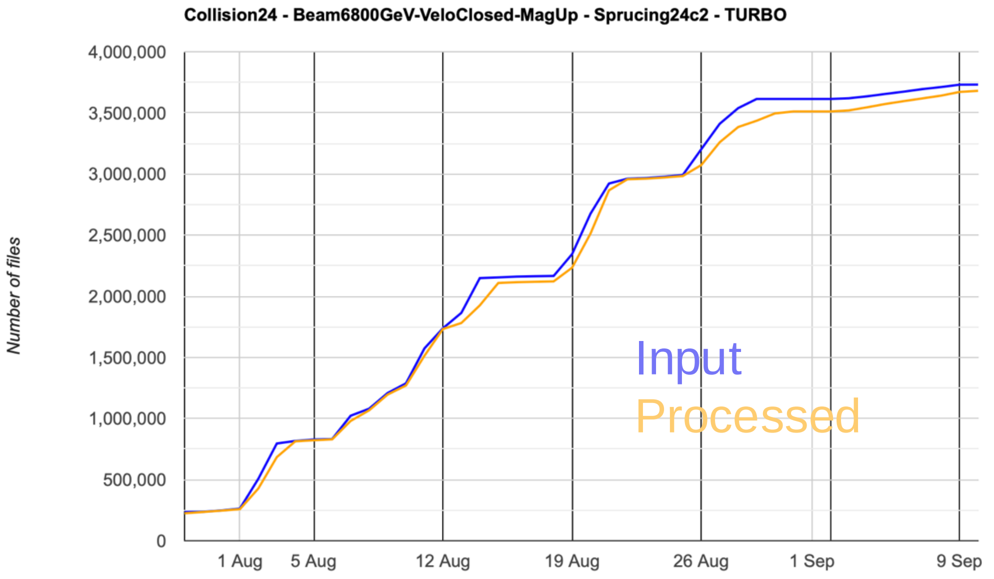


- Not only we surpassed in a single year the integrated luminosity of previous years all together, but with did it with a more efficient trigger, in particular for hadronic charm and beauty decay modes
  - Trigger efficiency x2 or even more, depending on the modes!

Real-time analysis

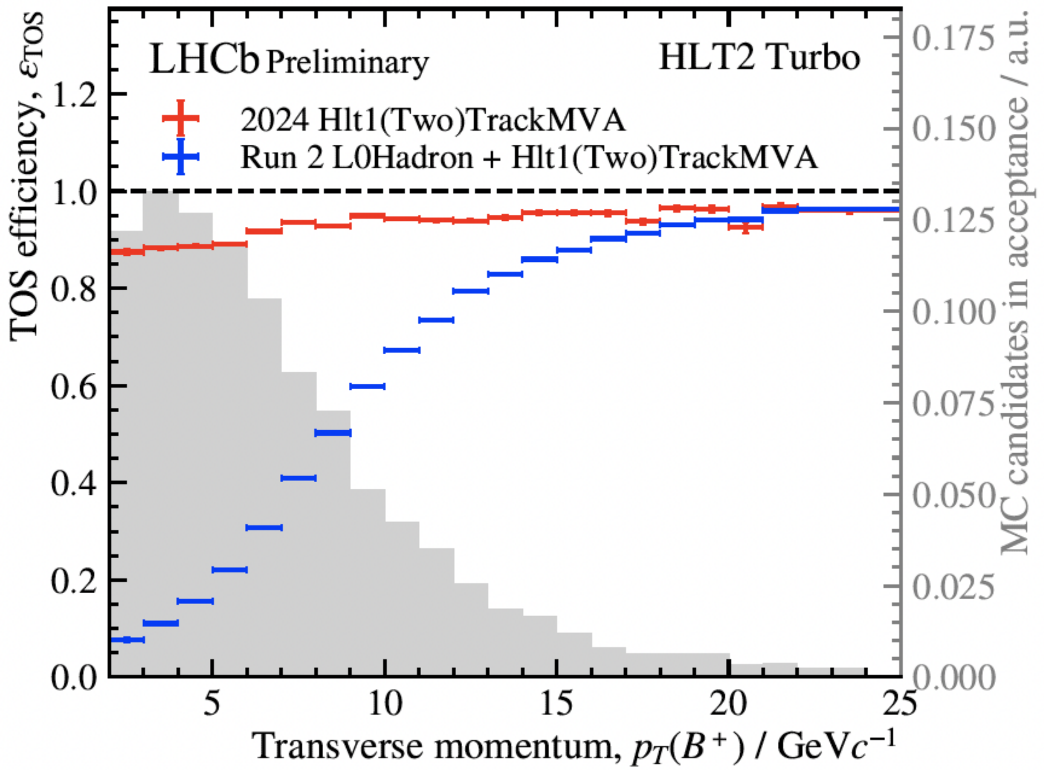
- Fully software trigger
  - Entire detector read out at full LHC rate with no trigger layer on custom electronics
- First level trigger (HLT1) made with ~500 GPUs
- Second level trigger (HLT2) running on a large CPU-based computing farm
- All data are made available offline for analysts almost in real time → LHCb users can analyse data taken a few days earlier
- First time in HEP!



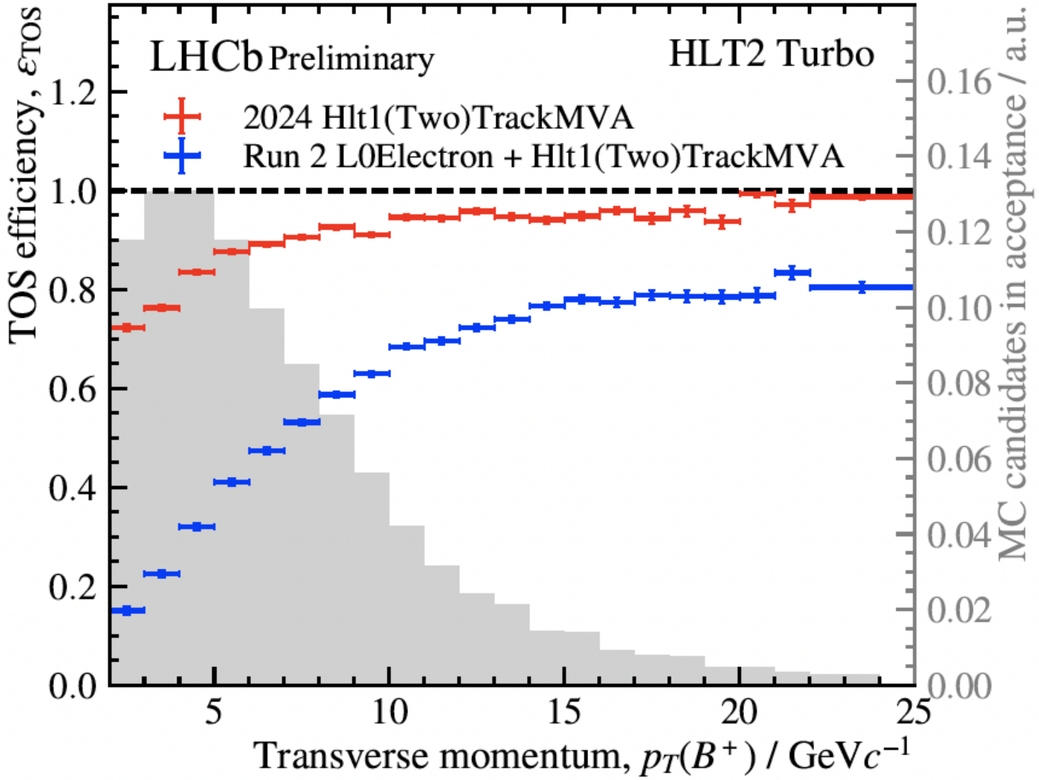


2024 trigger (on signal) efficiency

$B^+ \to D^0\pi^+$



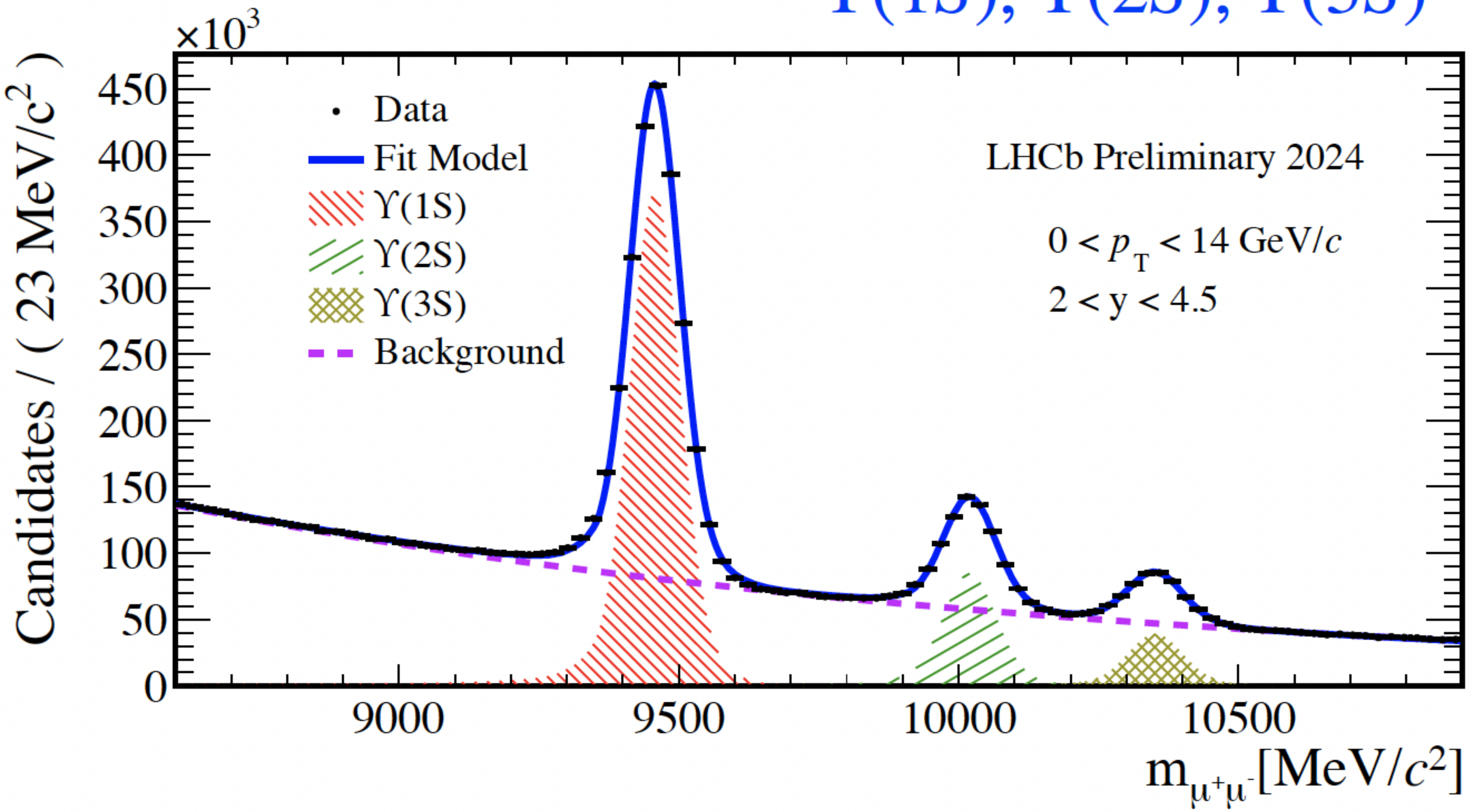
$B^+ \to J/\psi(\to e^+e^-)K^+$



- Run 3 (red) vs Run-2 (blue) → Large gain in efficiency thanks to the removal of the hardware trigger that was cutting low-p_T tracks in Run-2
- One of the central goals of LHCb Upgrade I

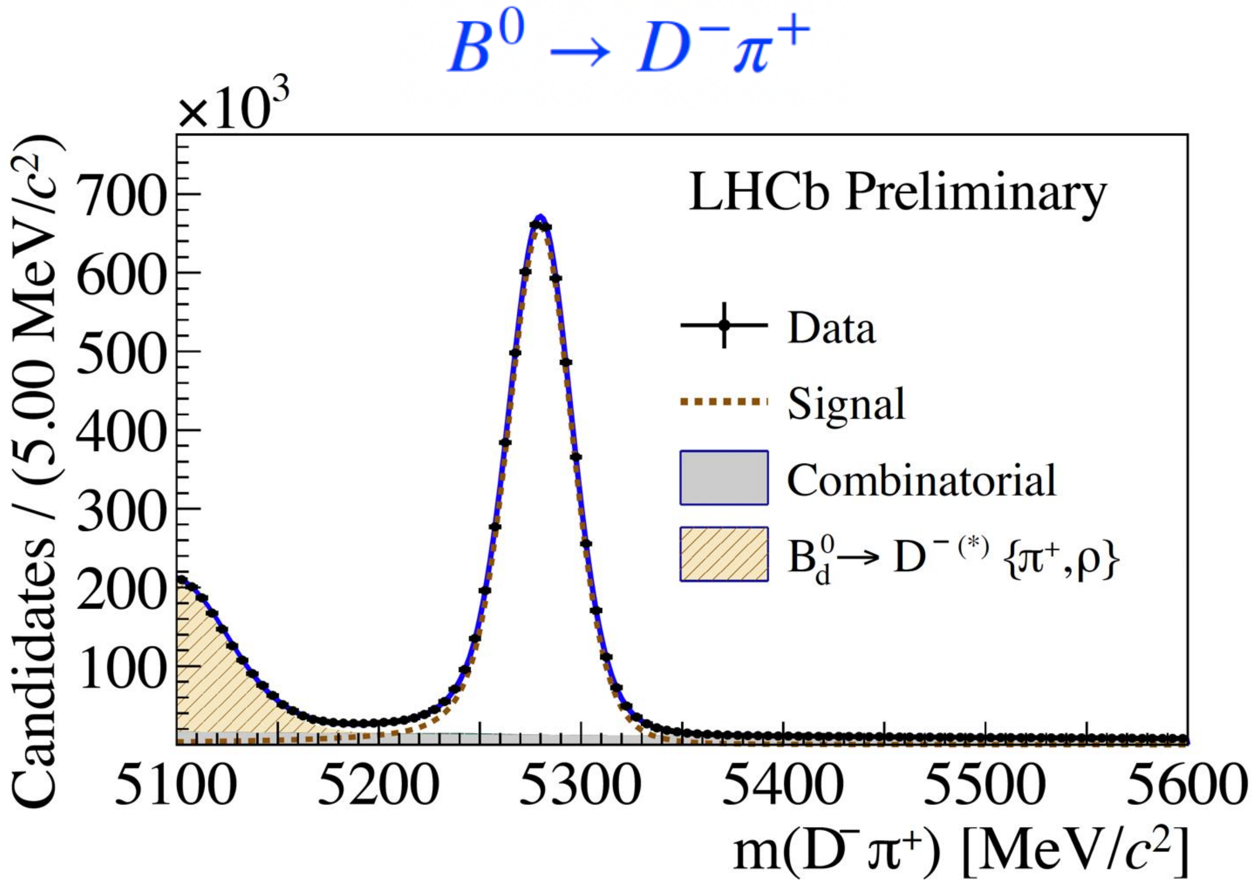
A look at 2024 data: dimuon final states

$\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$



- Alignment quality approached Run-2 level, with excellent mass resolutions!

A look at 2024 data: hadronic *B* decays

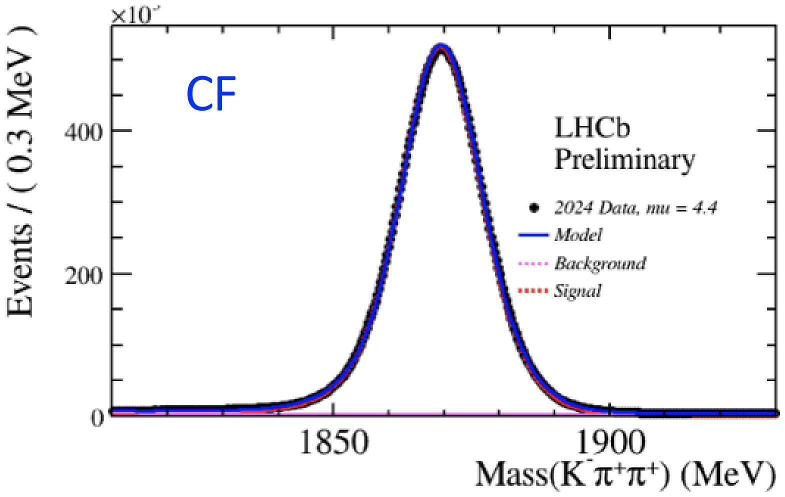


- In this example, 5.8 million reconstructed decays in 5.3 fb^{-1}, corresponding to 1.1 x 10^6 decays per fb^{-1} in 2024
  - To be compared with about 0.36 x 10^6 decays per fb^{-1} in Run-2

A look at 2024 data: 3-body charm decays

- With charm hadronic decays we gain likewise beauty, again thanks to the removal of the hardware trigger

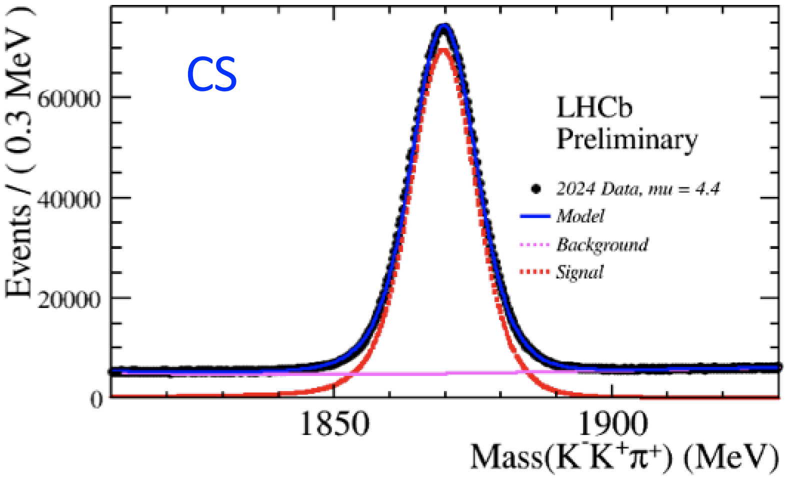
$D^+ \to K^-\pi^+\pi^+$



yield/pb^{-1}= 1.84×10^6

($\times$ 2.8 Run2)

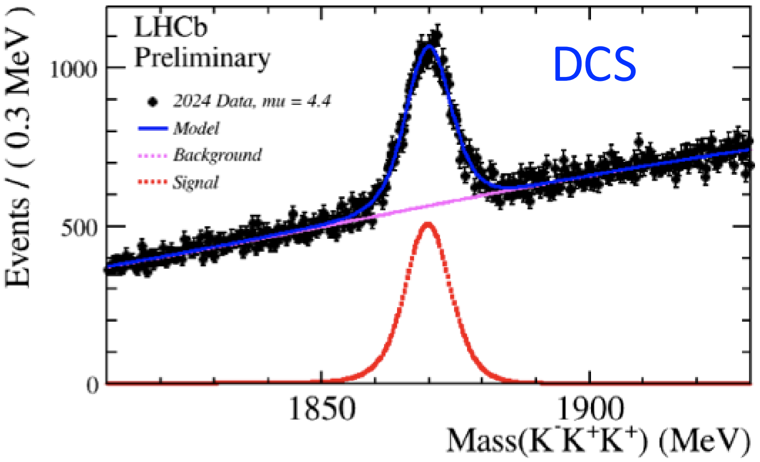
$D^+ \to K^-K^+\pi^+$



yield/pb^{-1}= 1.97×10^5

($\times$ 3.2 Run2)

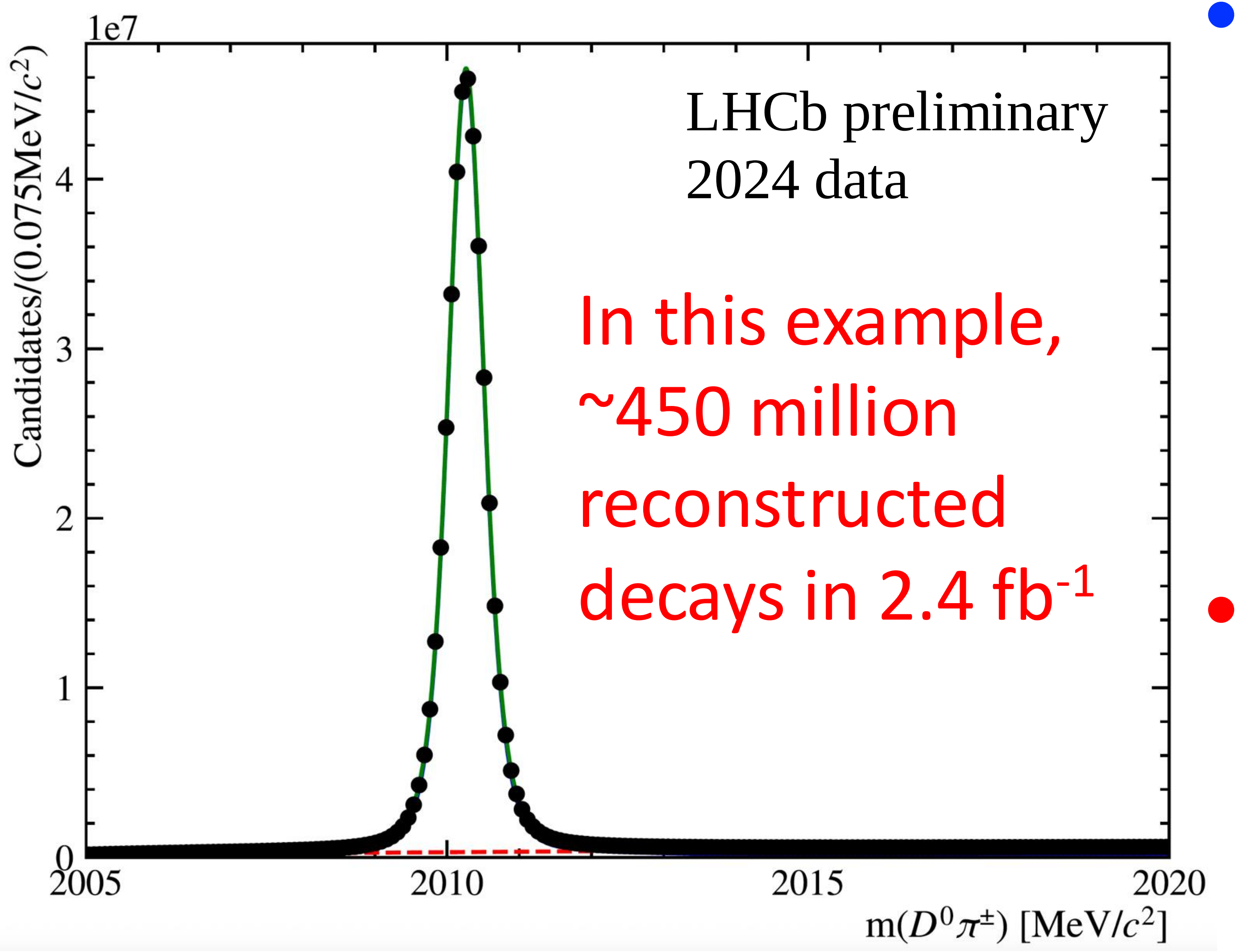
$D^+ \to K^-K^+K^+$



yield/pb^{-1}= 1.03×10^3

($\times$ 2.5 Run2)

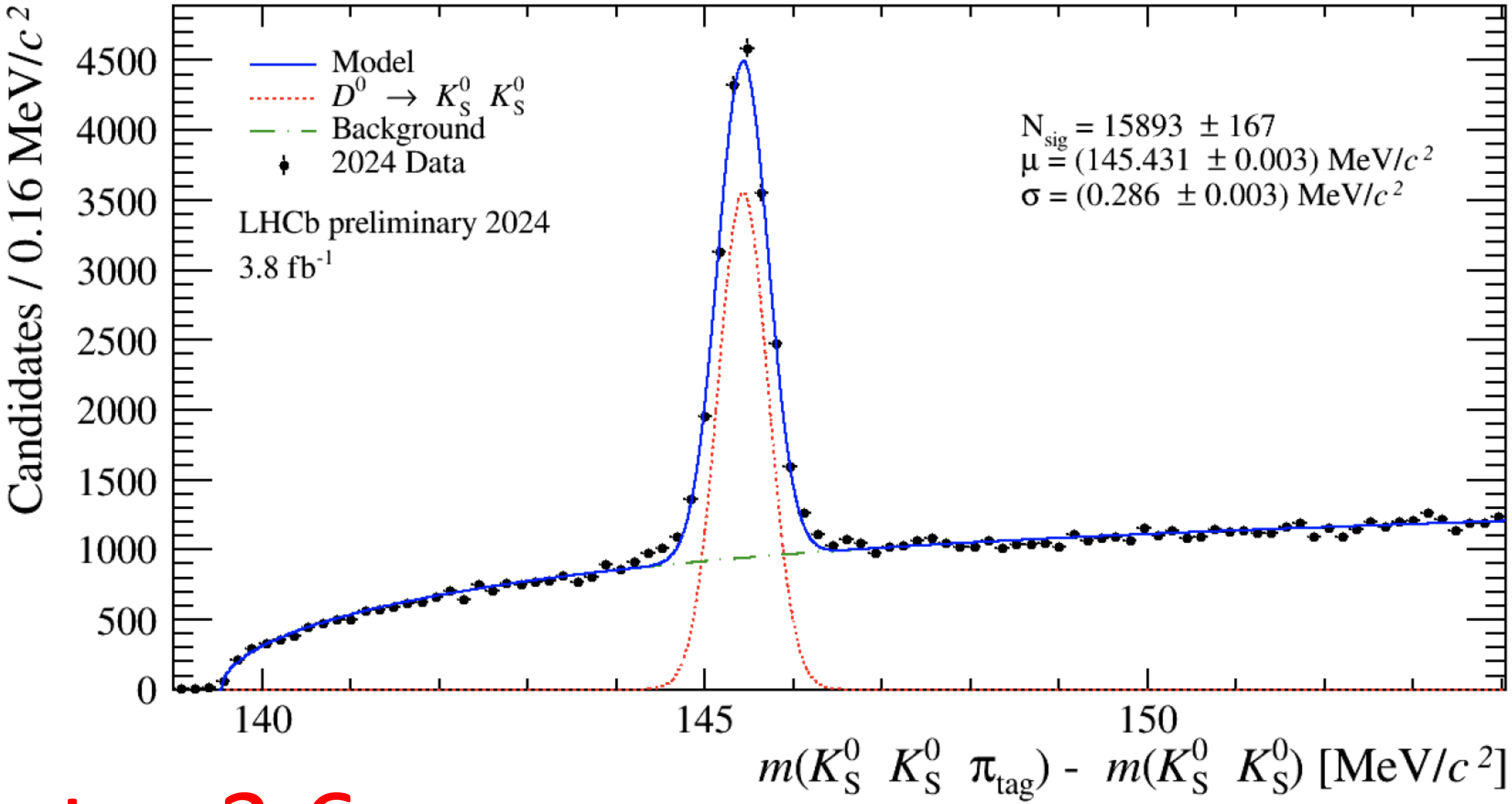
A look at 2024 data: $D^* \to D^0(\to K\pi)\pi$



- About 190 x 10^6 decays per fb^{-1} in 2024
  - To be compared with 85 x 10^6 decays per fb^{-1} in Run-2
- Exciting prospects for charm *CP* violation and mixing measurements in Run-3!

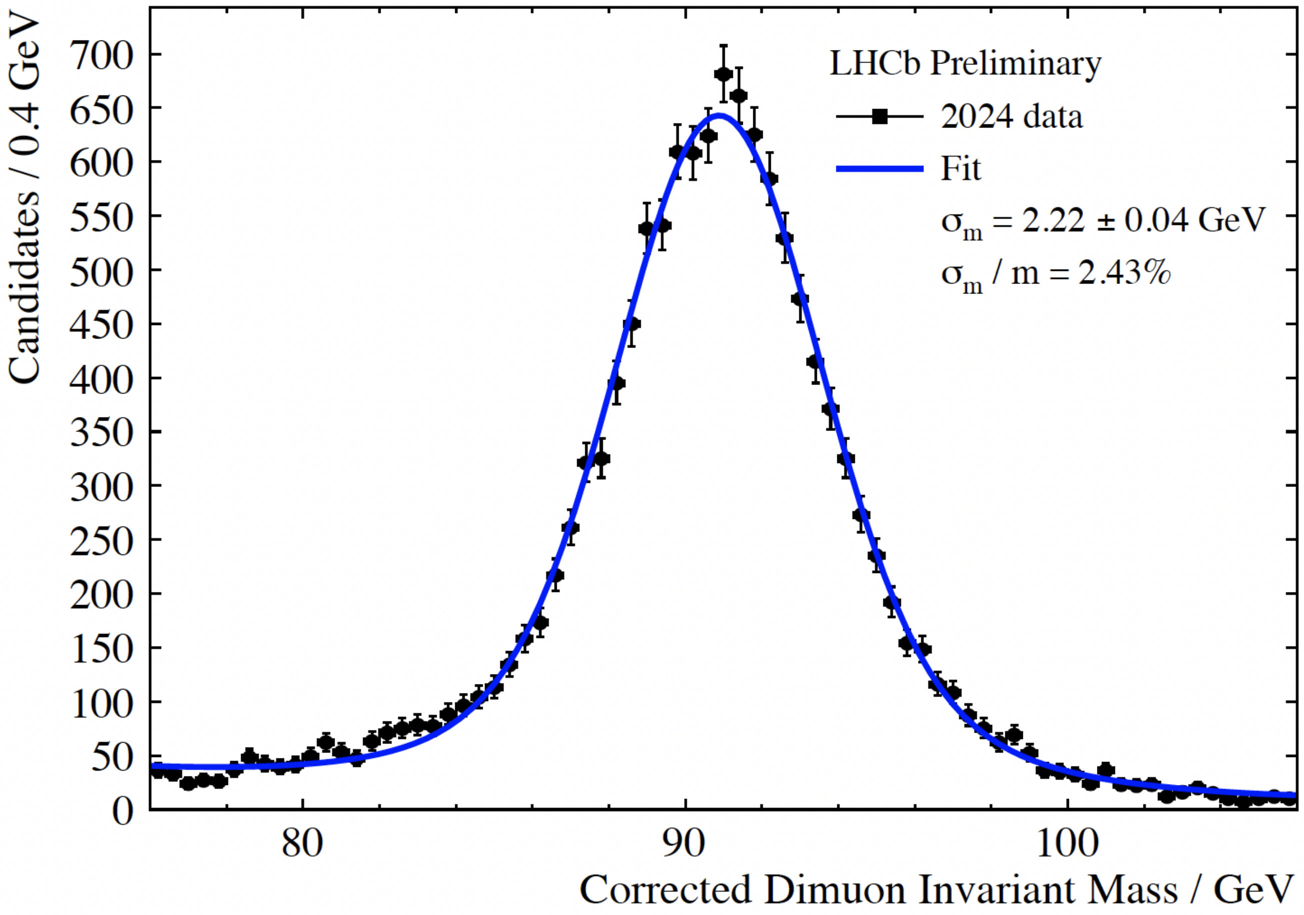
A look at 2024 data: $D^* \to D^0(\to K_S K_S)\pi$

- Also in this case, signal yield per unit luminosity significantly increased when compared with Run-2: about a factor 3.6, thanks to a dedicated K_S track trigger line in HLT1 for the first time



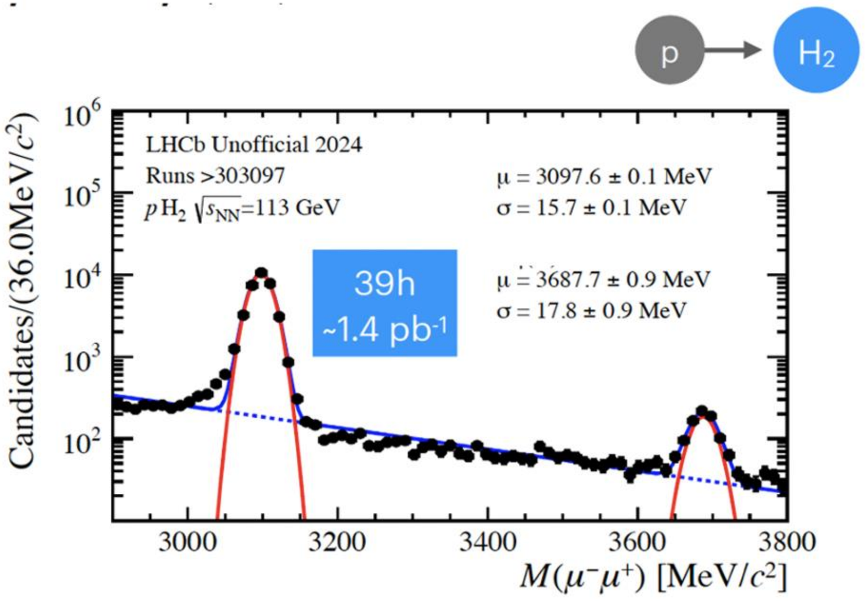
A look at 2024 data: $Z^0 \rightarrow \mu^+\mu^-$

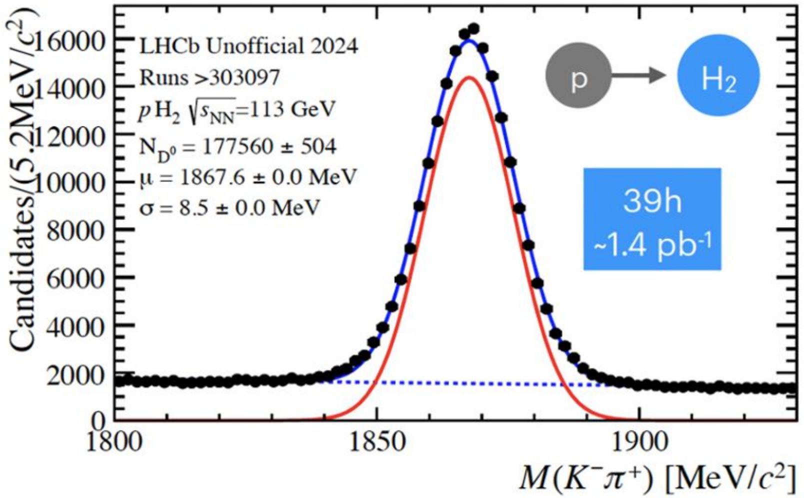
- Very clean peak with high purity and efficiency
- In the high-p_T sector LHCb is also well on track with Run-3 data

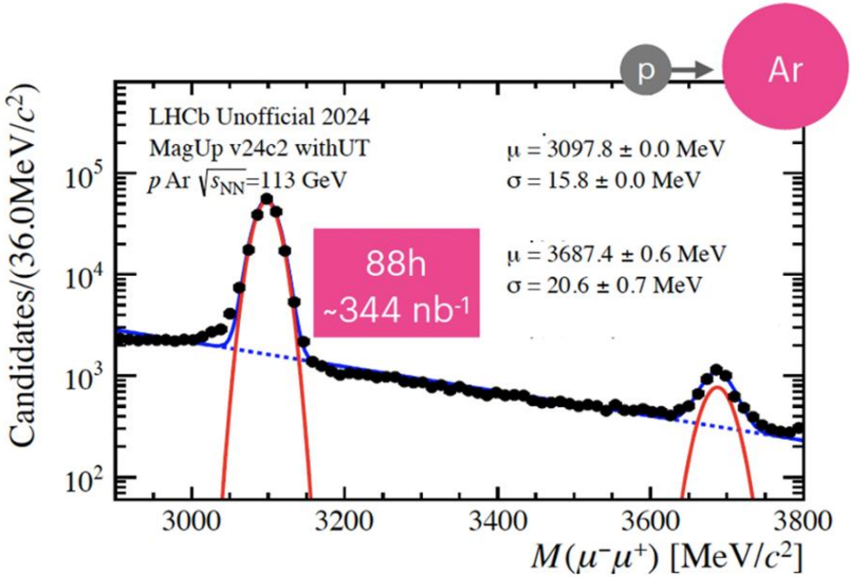


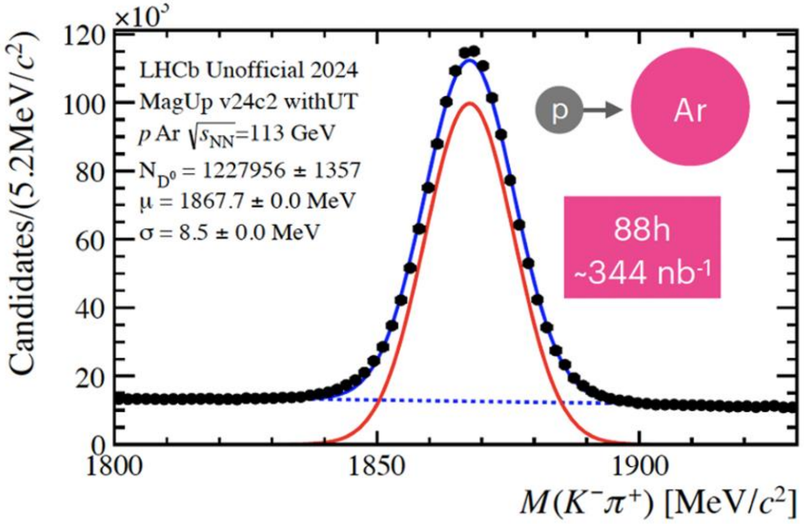
A look at 2024 data: fixed-target physics

- Fixed-target programme at the LHC is a unique feature of LHCb
  - *p*-gas (Pb-gas) collisions now running in parallel with *pp* (Pb-Pb)
- In this example, charmonium and open charm production in pH_2 and pAr collisions









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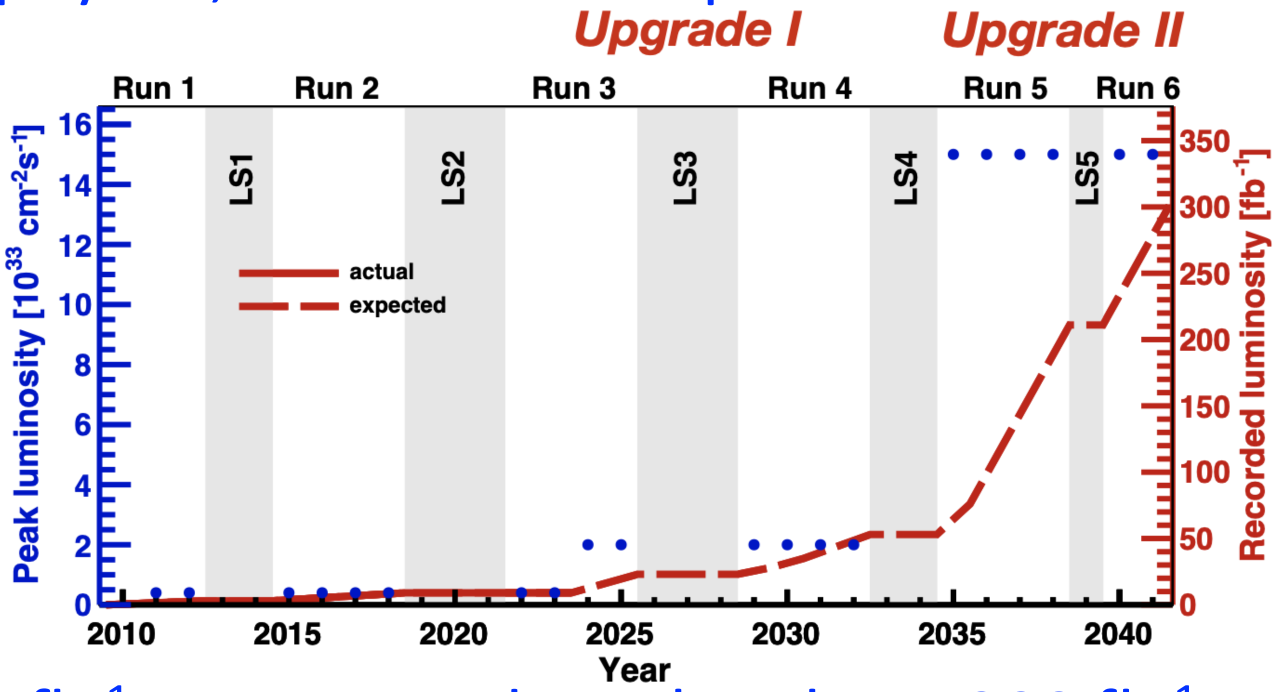
2024 Pb-Pb run

- This year for the first time we have been taking Pb-Pb collision data with the nominal LHCb Upgrade I detector (closed VELO, UT included)
- The Upgrade I detector is much more capable of making measurements with Pb-Pb collisions, due to the higher granularity of its tracking detectors, especially the VELO
  - Can reach much lower centrality than the first LHCb detector, covering the 100%-30% centrality range
- Furthemore, commencing this year we got a ~70% increase in instantaneous luminosity, mostly thanks to the an increase in the number of colliding bunches at the LHCb interaction point
- The run ended over the last weekend, so we are now entering the Year End Technical Stop (YETS)

Future upgrades

The future: LHCb Upgrade II

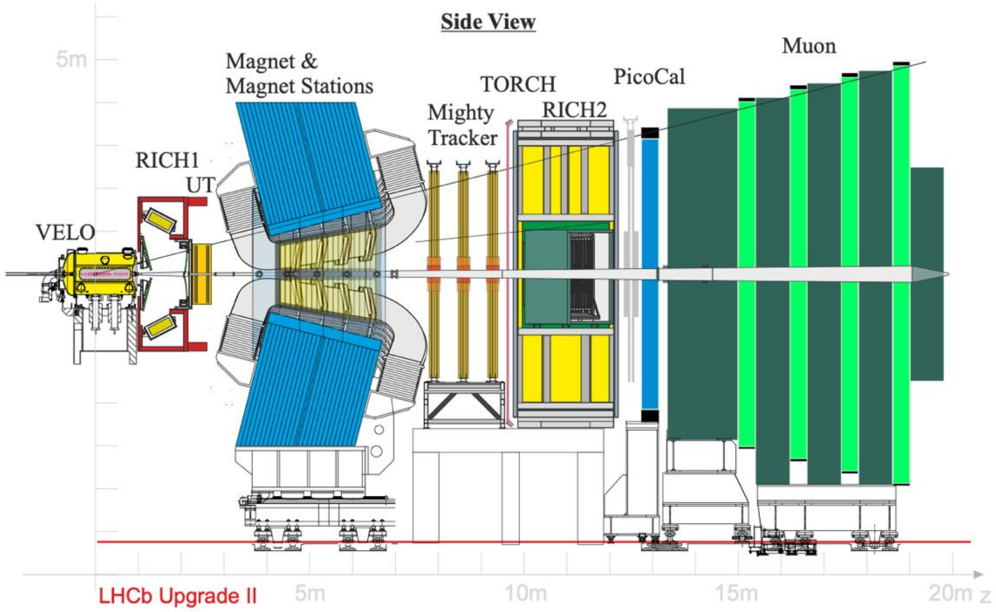
- European Strategy Update 2020: "The full physics potential of the LHC and the HL-LHC, including the study of flavour physics, ... should be exploited"
- Upgrade I was designed to collect 50 fb^{-1} by end of Run 4, but there is the opportunity to operate the experiment until the end of HL-LHC
  - With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

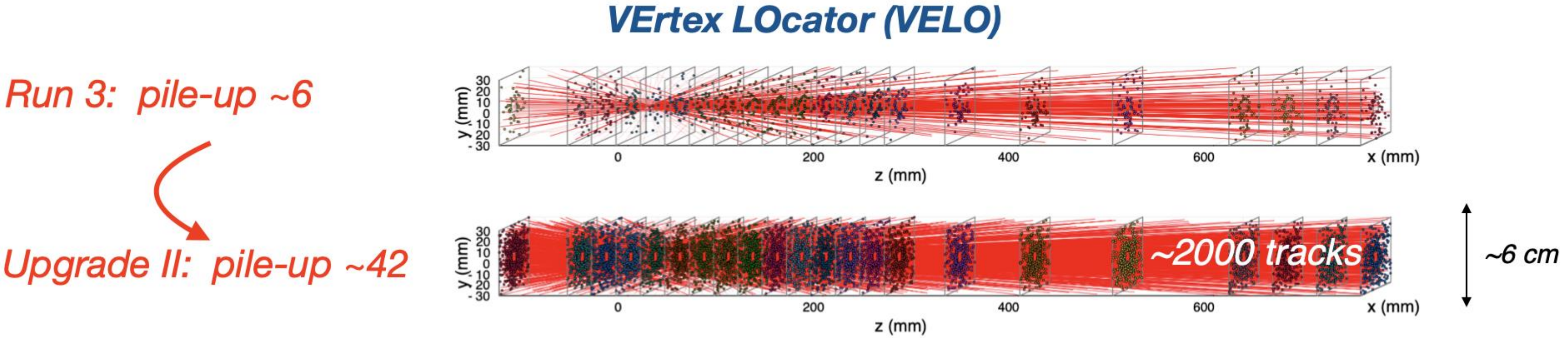


- The proposed baseline is to achieve 50 fb^{-1} per year and reach at least 300 fb^{-1} at the end of Run-6
- That will allow for unprecedented samples and a compelling physics programme

The LHCb Upgrade II detector

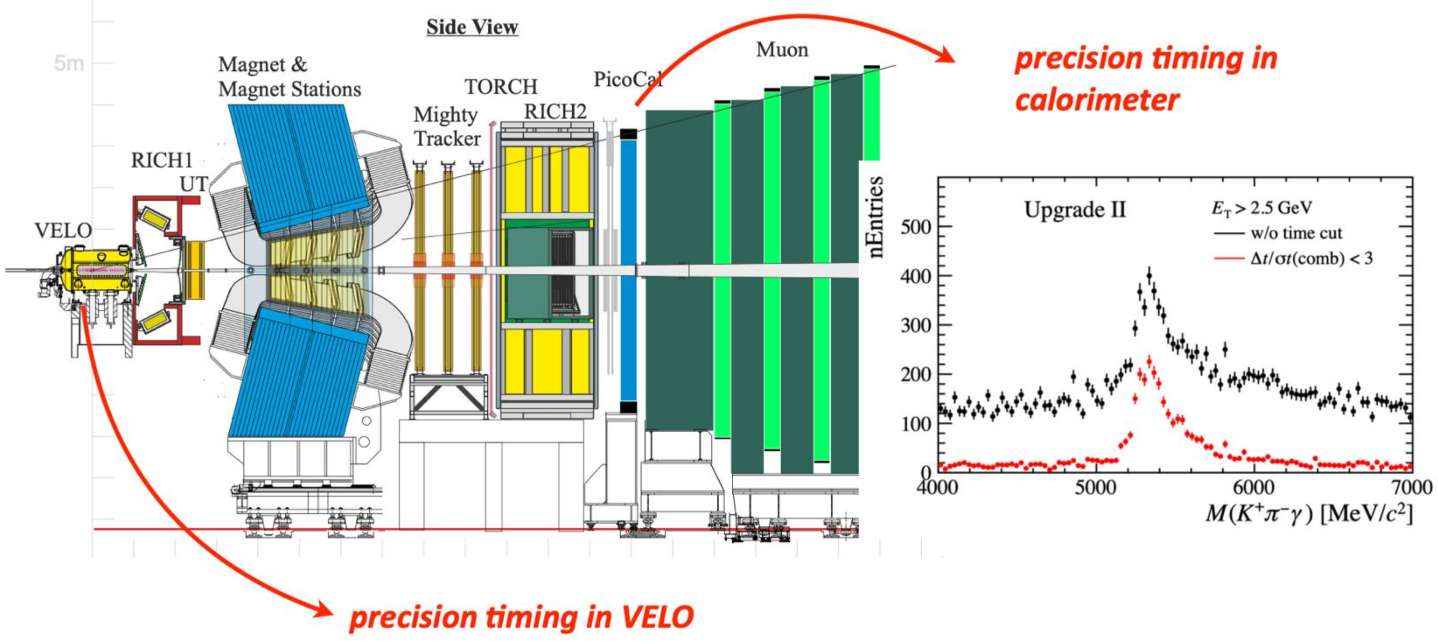
- Targeting the same performance, or even better in certain areas, as in Run 3, but with an increased pile-up of a factor 7
- Same footprint of the spectrometer, but with innovative technology for sub-detectors and data processing
- Key ingredients
  - High granularity
  - Fast timing (few tens of ps)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

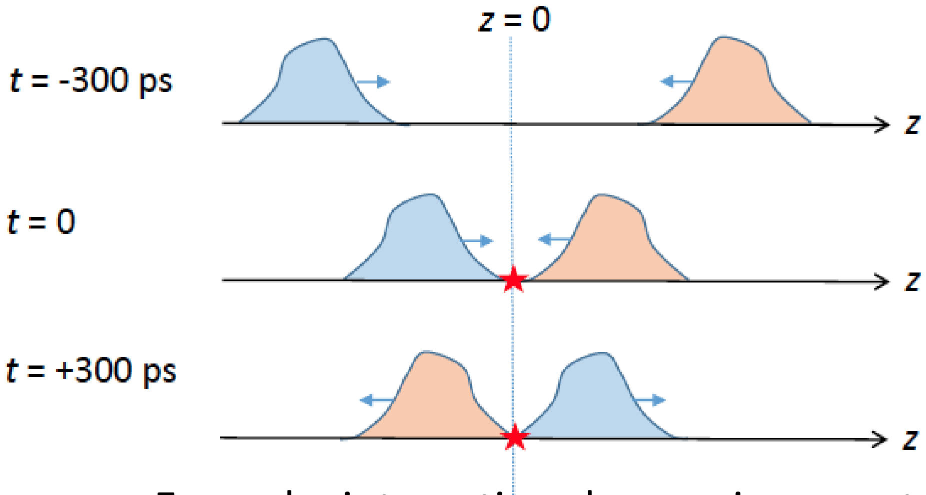




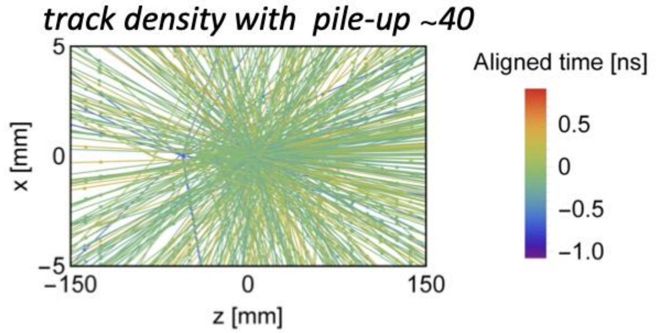
The importance of precision timing

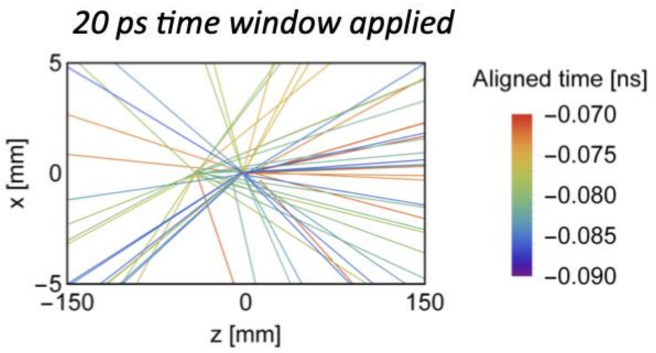
- Timing capability with a resolution of a few tens of picoseconds is a key to reduce background and associate signal decays to correct p-p primary vertices





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



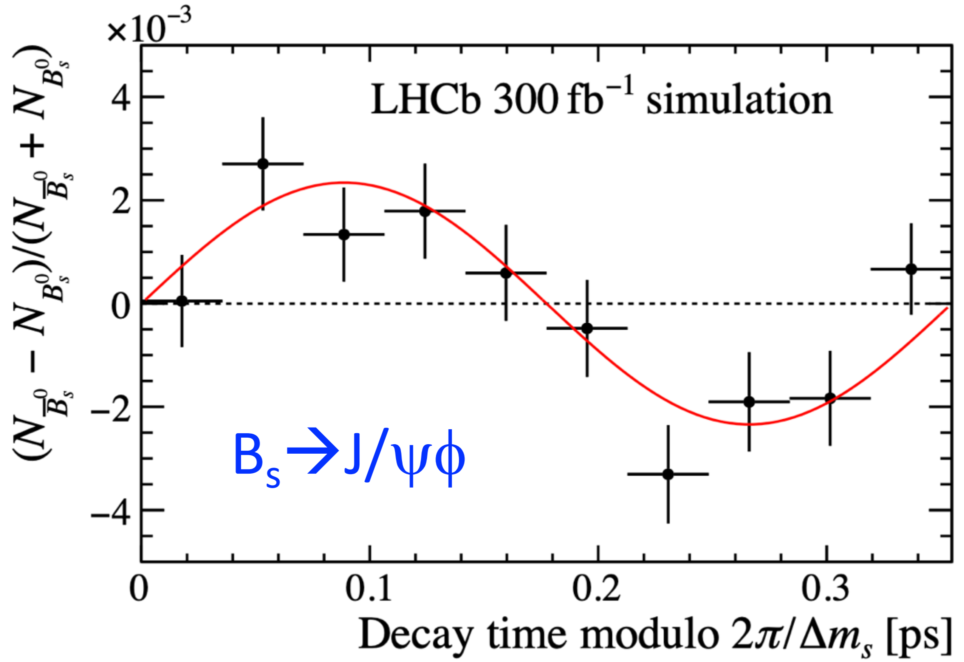


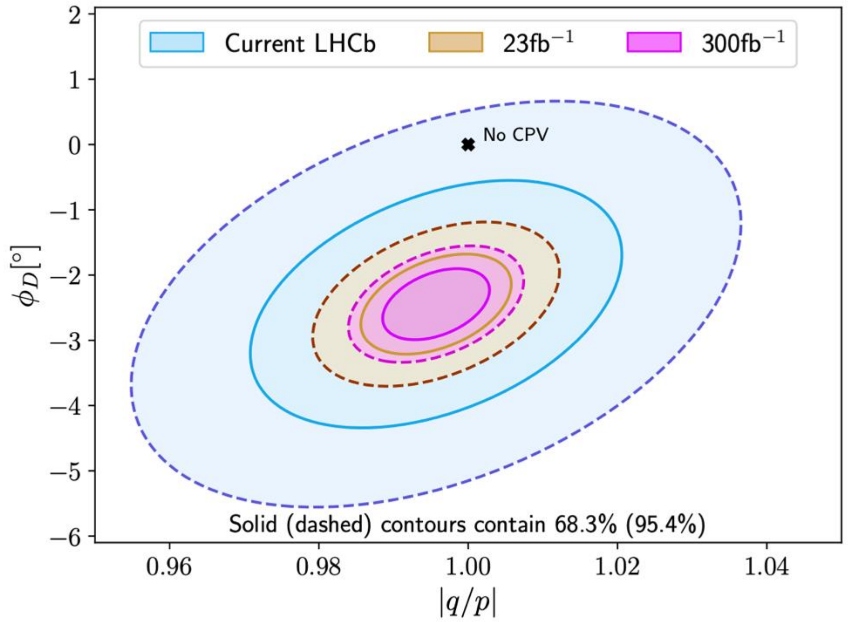
The programme requires strong R&D on sensors, already ongoing, and dedicated efforts for the design of new FEE ASICs

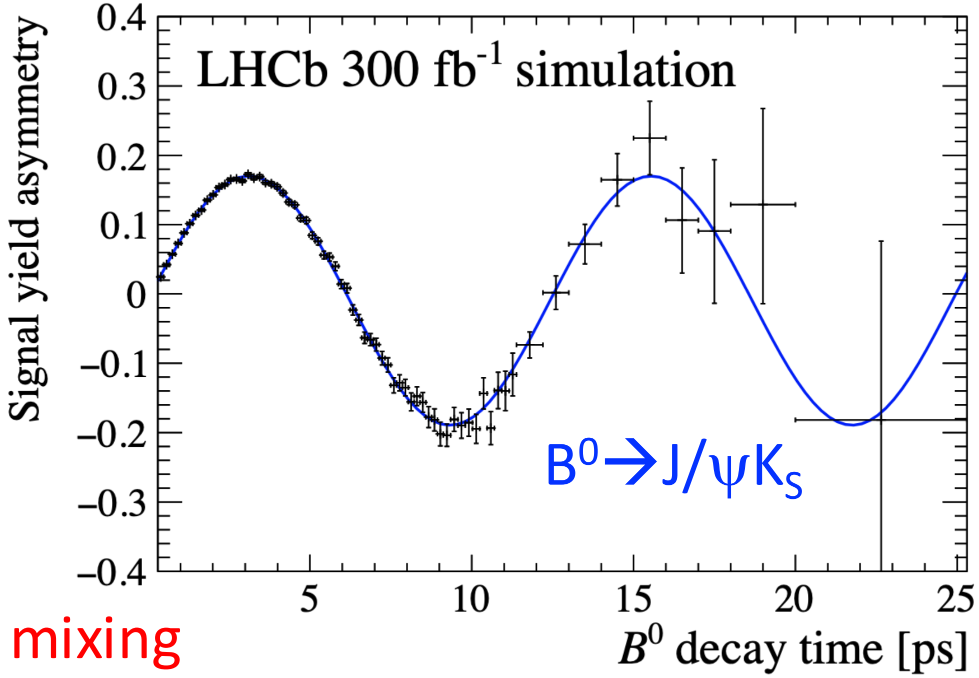
LHCb Upgrade II Physics Case: *CP* violation

- $\sigma(\gamma)$: 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



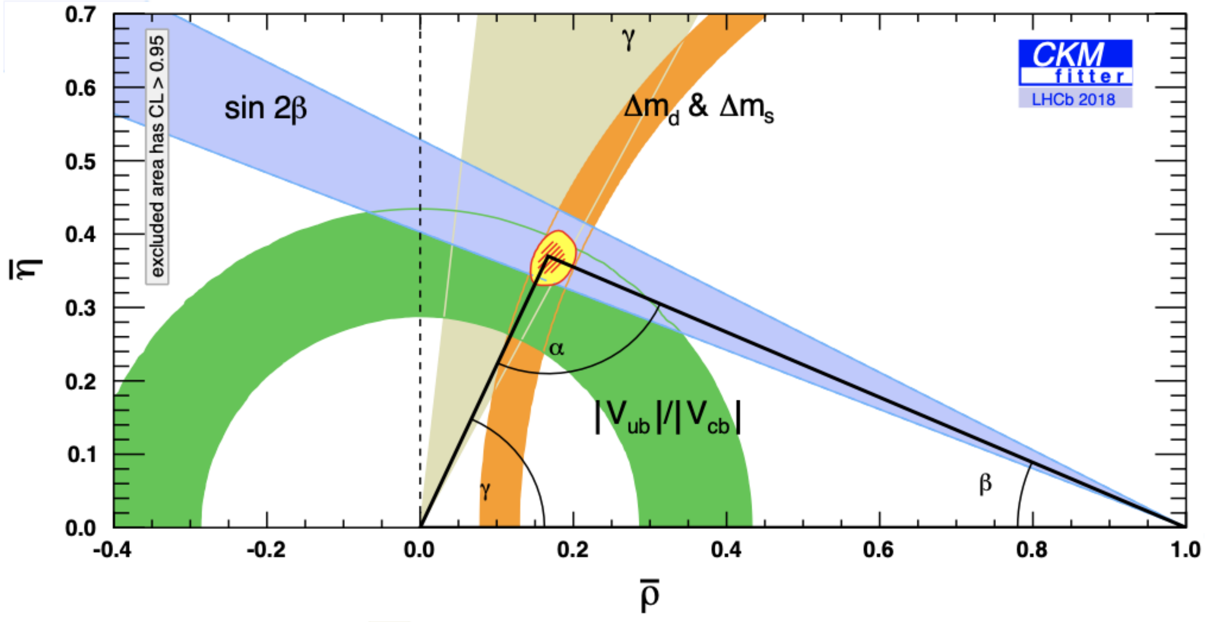


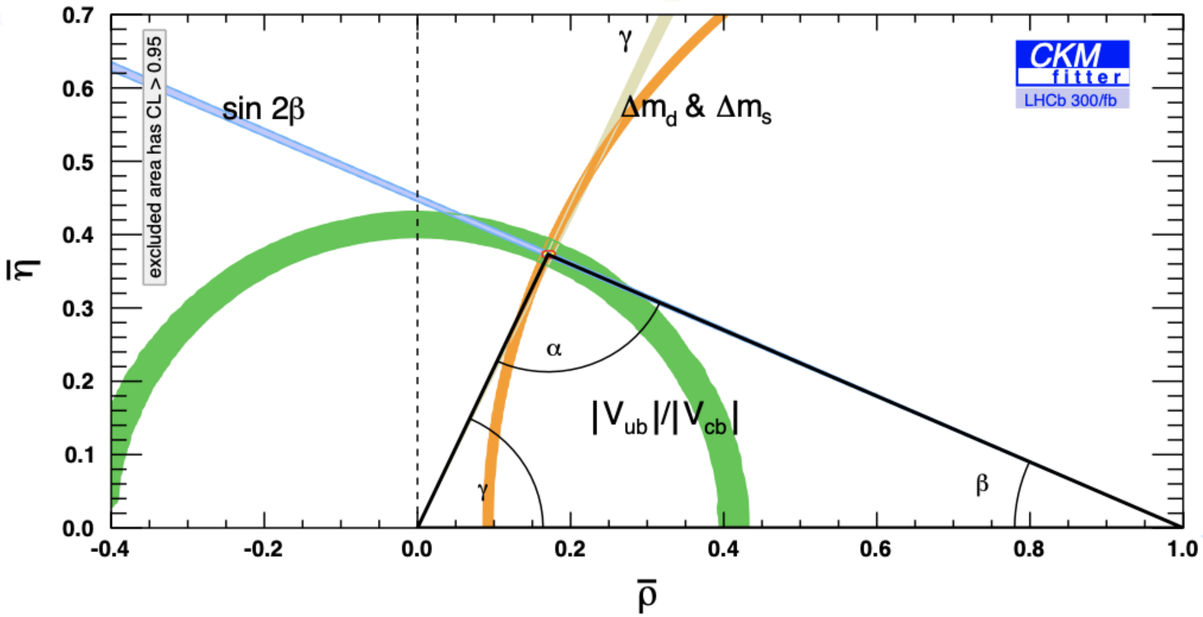


LHCb Upgrade II is the only planned facility with a realistic possibility to observe *CP* violation in charm mixing

Unitarity Triangle improvements after Upgrade II

LHCb Upgrade II will test the CKM paradigm with unprecedented accuracy





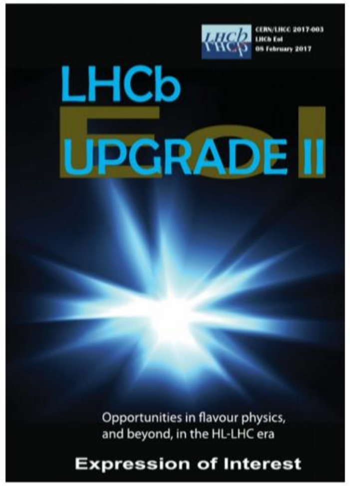
Two independent measurements of triangle apex: ($\Delta m_d/\Delta m_s$, sin 2β)   and (V_{ub} , γ)

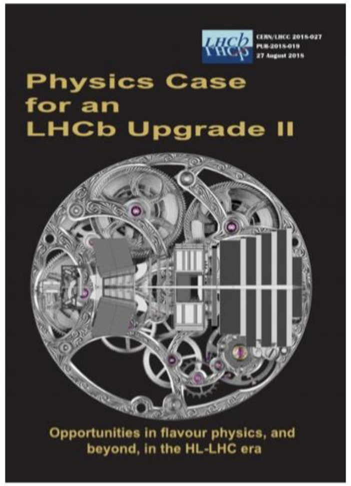
Both pairs require Upgrade 2 for statistics (sin 2β and γ) and time for theory improvements ($\Delta m_d/\Delta m_s$ and V_{ub})

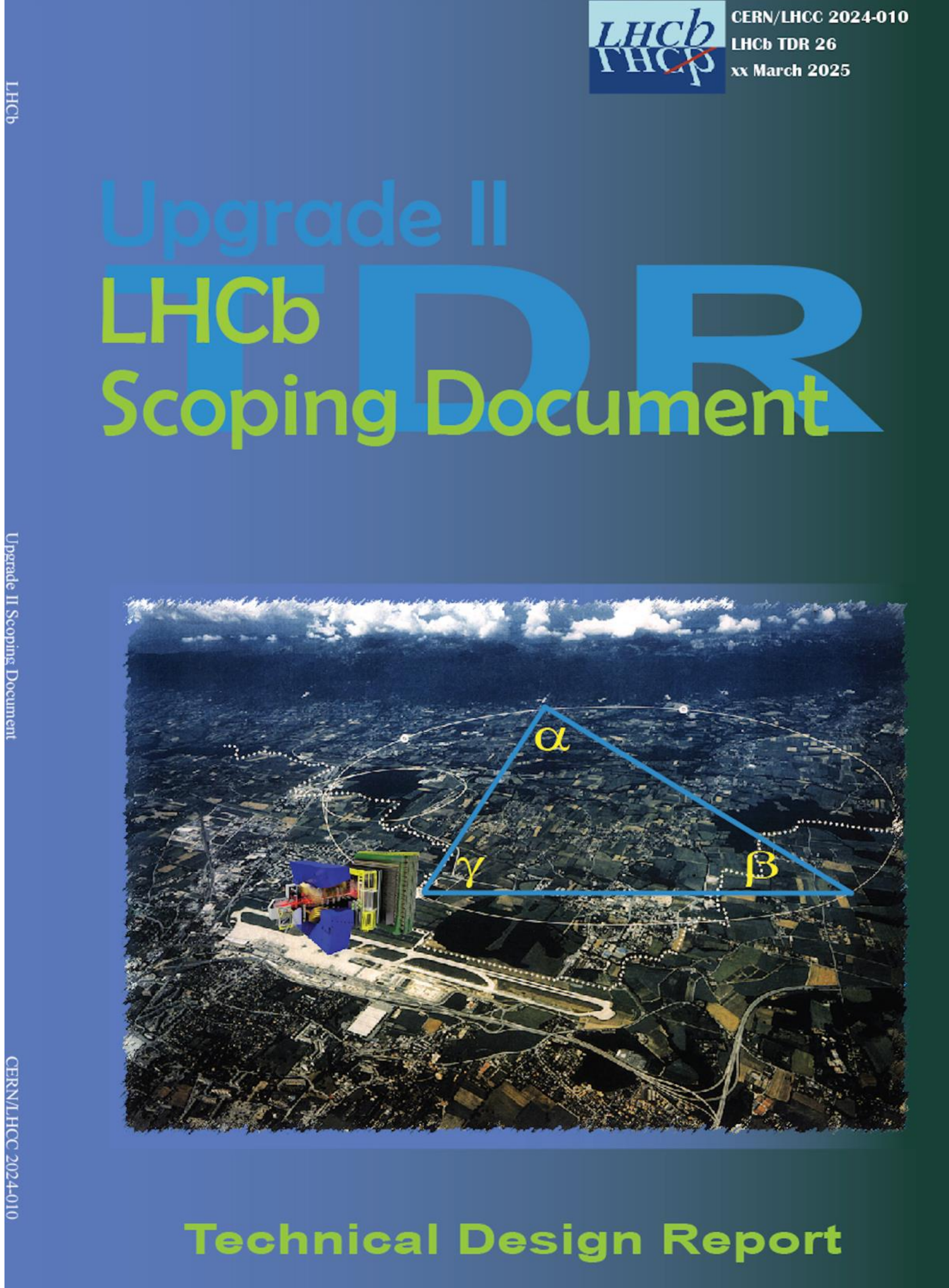
- Permit tree-level observables (SM benchmarks) to be assessed against loop contributions (new physics sensitive)

LHCb Upgrade II Scoping Document

- Following the Expression of Interest (LHCC-2017-003), the Physics Case Document (LHCC-2018-027) and the Framework TDR (LHCC-2021-012), all already reviewed and recommended for approval by the LHCC, LHCb has now submitted for review to the LHCC the Upgrade II Scoping Document







Scoping scenarios

	Baseline	Middle	Low
$\mathcal{L}_{\text{peak}}$ ($10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$)	1.5	1.0	1.0
	(kCHF)	(kCHF)	(kCHF)
VELO	16672	15906	13753
UP	8077	7719	6887
Magnet Stations	2592	2234	0
Mighty-SciFi	21767	21273	17388
Mighty-Pixel	15993	11642	11060
RICH	21450	18415	14794
TORCH	12508	8756	0
PicoCal	27607	27607	21584
Muon	9785	8266	8266
RTA	18800	11700	9500
Online	11800	9467	8993
Infrastructure	14463	13284	12430
Total	181514	156269	124655

- Three scenarios differing in peak luminosity, physics potential, cost and complexity
- TDRs within 2026, construction phase 6 years + 1 contingency, to be ready for installation in LS4

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-LHCC-2024-010
LHCb-TDR-026
September 2, 2024

LHCb Upgrade II Scoping Document

LHCb collaboration

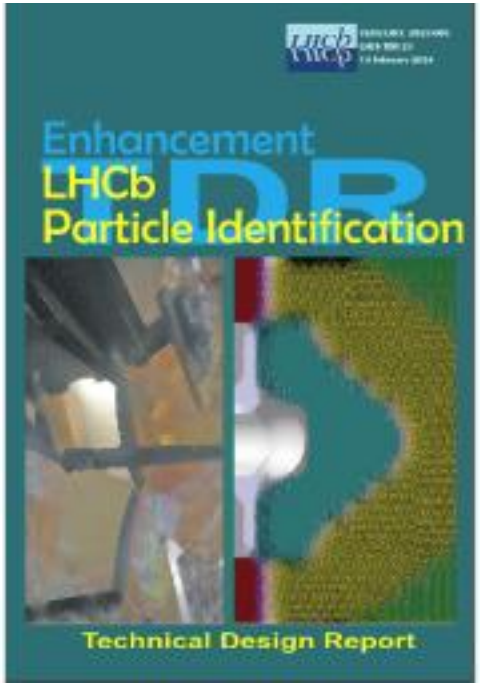
Abstract

A second major upgrade of the LHCb detector is necessary to allow full exploitation of the LHC for flavour physics. The new detector will be installed during long shutdown 4 (LS4), and will operate at a maximum luminosity of $1.5 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$. By upgrading all subdetectors and adding new detection capability it will be possible to accumulate a sample of $300\,\text{fb}^{-1}$ of high energy *pp* collision data, giving unprecedented and unique discovery potential in heavy flavour physics and other areas. The baseline LHCb Upgrade II detector has been presented in a Framework Technical Design Report that was approved in 2022. Here, updates are presented alongside scoping options with reduced detection capability and operational luminosity. The costs and physics performance of each scenario are discussed, and an overview of the project management plans is presented.

Intermediate step: LS3 enhancements

- Both TDRs on LS3 enhancements for ECAL, RICH, the PCIe400 readout board, and the Downstream Tracker on FPGAs have been approved
- These enhancements will enable improved performances for neutral particle reconstruction in the ECAL, for particle identification in the ECAL and RICH, and higher efficiency in long-lived particle reconstruction during Run-4
- Very importantly, we will also test precision timing, to be ready for measuring timestamps with O(10) ps precision in the LHCb Upgrade II

CERN-LHCC-2023-005

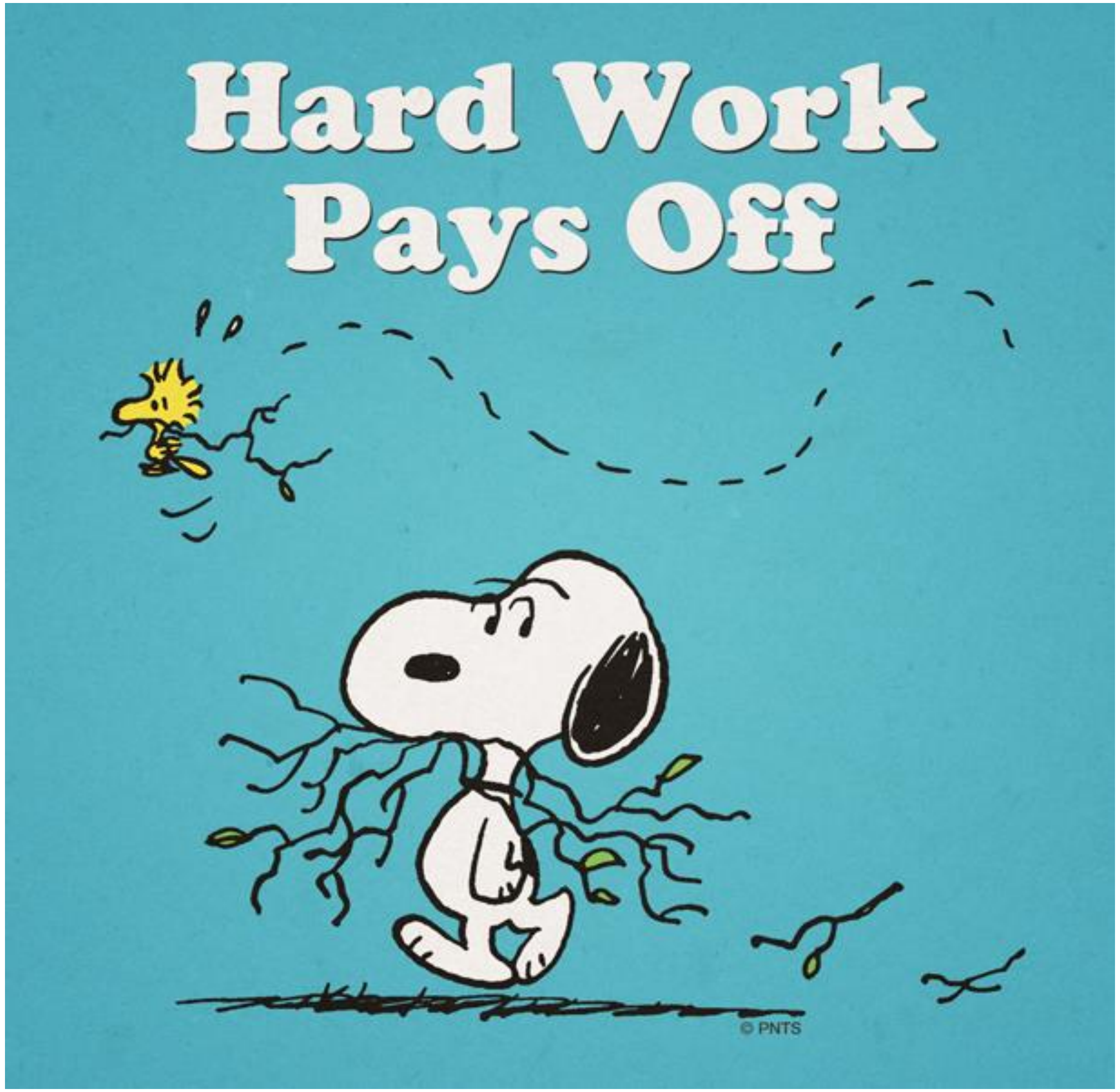


CERN-LHCC-2024-001

Conclusion

Lots to do!

- Very exciting period ahead → we have now a large data sample from Run-3 to be analysed for the first time
  - And many more data are coming in the 2025/26 runs!
- Lots of work to do on
  - Data Analysis
  - Operations
  - Detector R&D
  - Software development
  - …



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