LHCb upgrades

Elisabeth Maria Niel
on behalf of the LHCb collaboration

12th Large Hadron Collider Physics Conference - LHCP

Boston, 3-7 June 2024

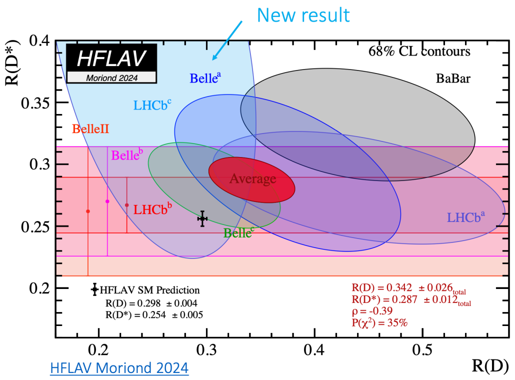
Motivation for LHCb upgrades

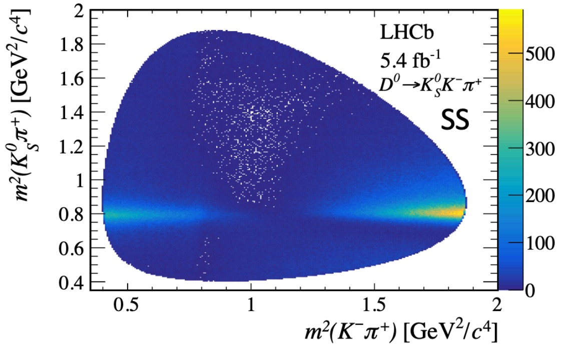
LHCb has been very successfull during Run 1 and 2
probing the Standard Model with precision measurements, discovery of CP violation in the charm sector, new exotics states, EW physics and unique fixed-target results!

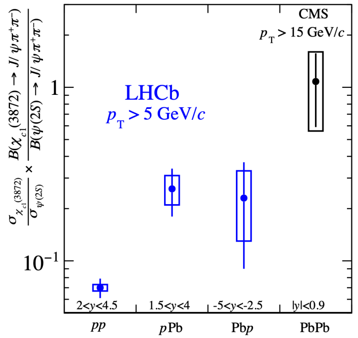
Yet no clear observation of New Physics effects!

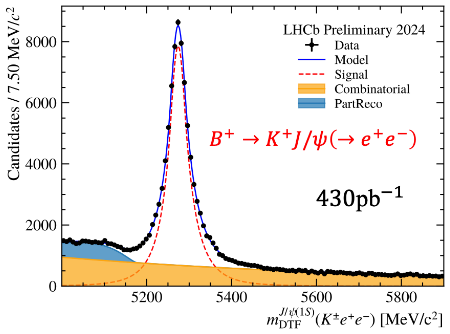
Some measurements are statistically limited!

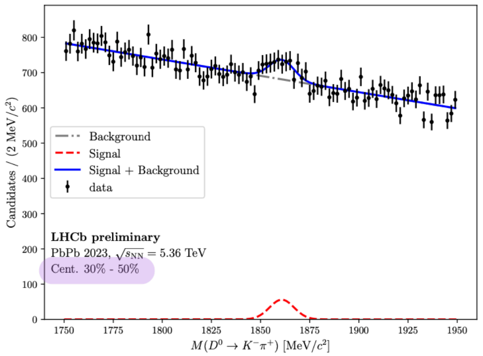
We need more data to further challenge theoretical predictions











LHCb-PAPER-2024-007

LHCb-PAPER-2024-011

LHCB-FIGURE-2024-007

LHCb-FIGURE-2023-030

LHCb-PAPER-2023-026

On the menu of LHCP 2024

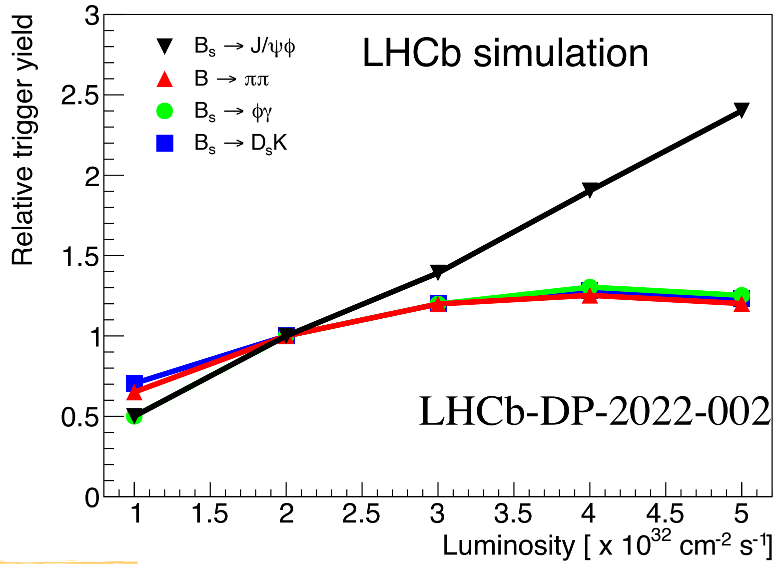
- M. Artuso LHCb status and overview
- E. Smith Experimental status of b->sll and b->cln
- F. Gallego Rare & forbidden decays
- L. Hartmann Anomaly detection
- G. Pietrzyk Flavor anomalies
- M. K. Wilkinson Time independent CPV at LHCb
- P. Gandini Heavy Flavor spectroscopy
- T. Martin Precision QCD (LHCb, Atlas, CMS)
- M. Ramos Pernas Electroweak Measurements
- B.R. Delaney Axion searches
- Louis Henry - HLNs@LHCb
- V.Tisserand Opportunities in heavy flavour physics at the HL-LHC experiments

Motivation for LHCb upgrades

Limits of LHCb experiment in Run 1-2

$L_{inst} = 4 \times 10^{32} cm^{-2} s^{-1}$, direct increase of luminosity not possible
saturation of trigger (and detectors)

- Hardware trigger L0:
    1. Maximum allowed output rate 1.1 MHz
    2. Hard cuts on transverse momentum and energy
- Aging of the detector due to radiation damage



Profite from a higher luminosity only possible by removing the L0 trigger

Upgraded detector :

- all software trigger reconstructing events in real-time!
- higher instantaneous luminosity $L_{inst} = 2 \times 10^{33} cm^{-2} s^{-1}$

Complete **renewal of the LHCb detectors** & **readout electronics**
read events at 40 MHz LHC bunch crossing rate

LHCb Upgrade I

Overall major upgrade, >90 % of detector channels!

Completely new readout system for the full detector

LHCb-DP-2022-002
LHCb-TDR-12

Fully software trigger

PLUME & SMOG2

New pixel VELO

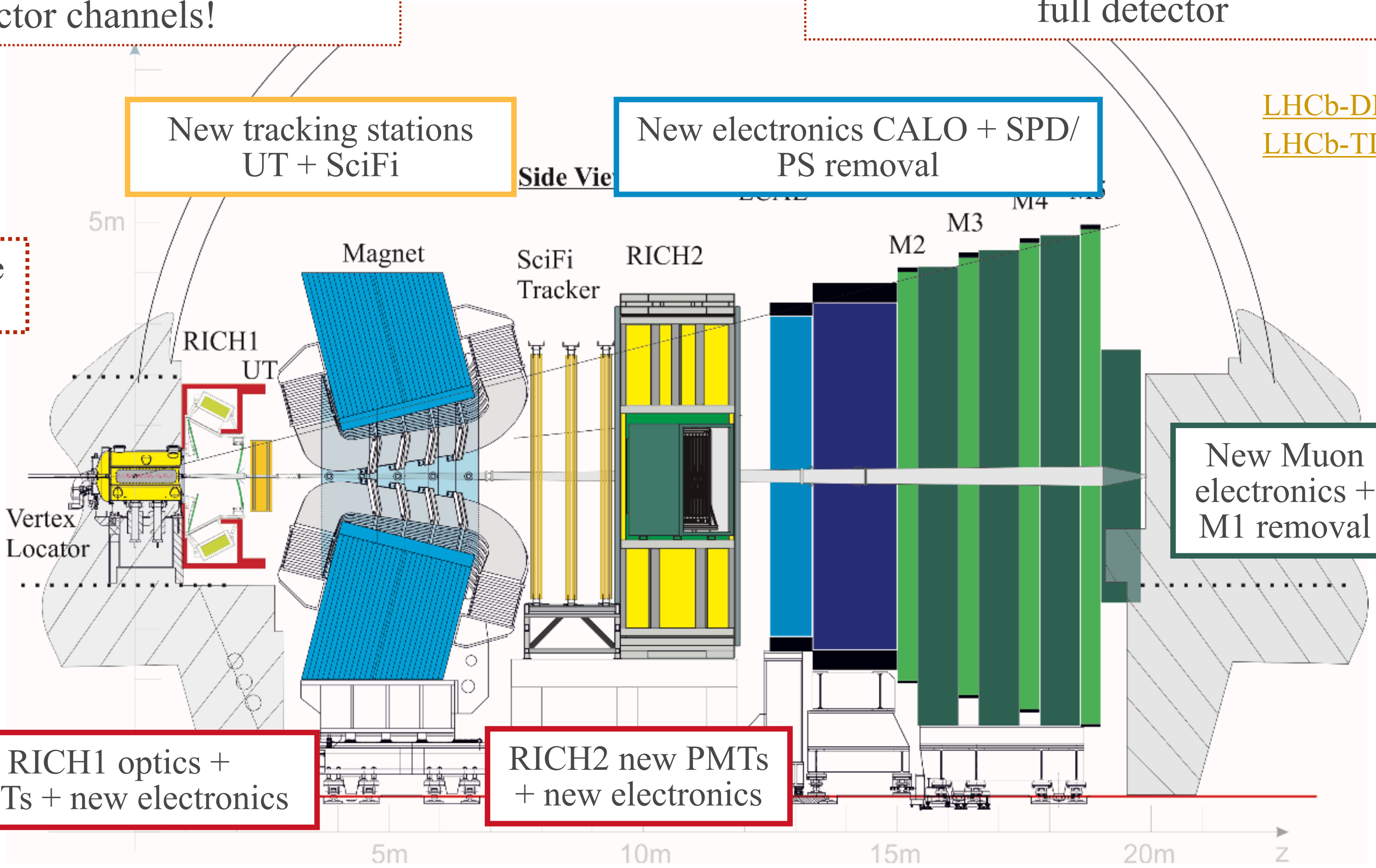
New tracking stations UT + SciFi

New electronics CALO + SPD/ PS removal

New Muon electronics + M1 removal

New RICH1 optics + new PMTs + new electronics

RICH2 new PMTs + new electronics



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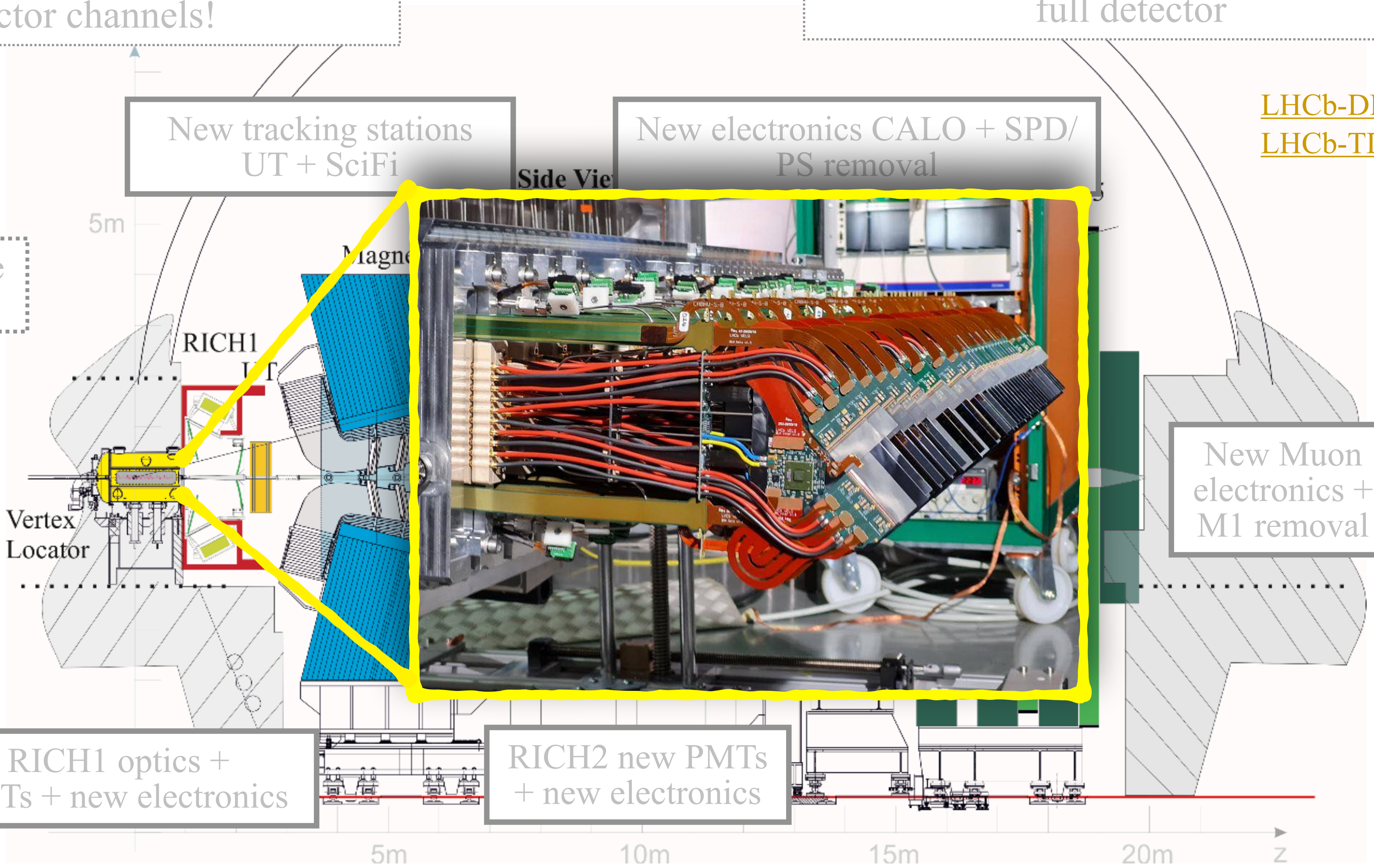
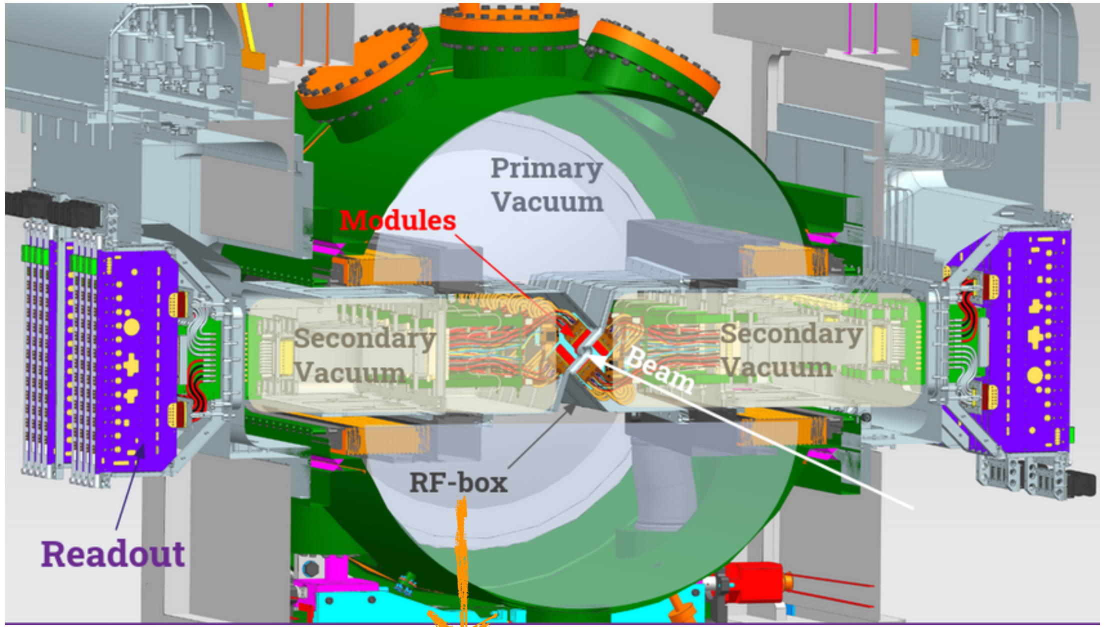


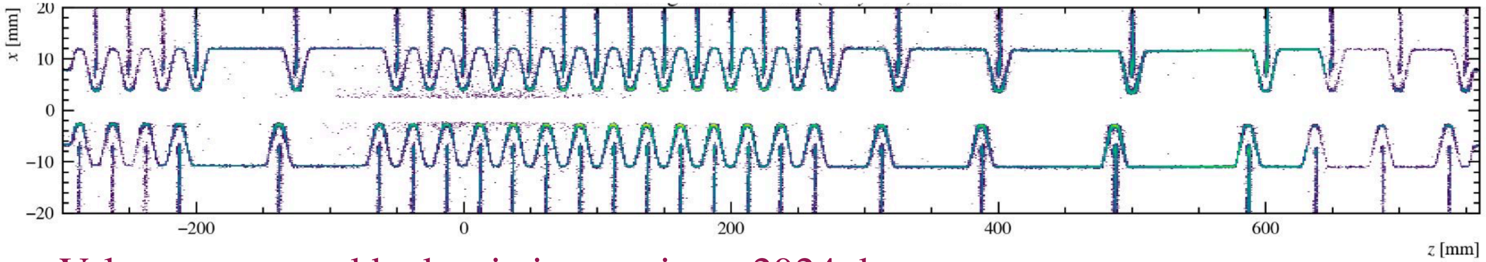
VELO

GOAL: location of interaction vertices, displaced decay vertices and the distances between them

- Two retractable halves, 3.5 mm from beam → better IP resolution
- Pixelated hybrid silicon with microchannel cooling CO_2
- New ASIC VeloPix, total of ~2 Tbit/s T. Poikela et al 2017 JINST 12 C01070
- Operates in secondary vacuum: allumininium 150 μm foils separate the detector from the beam vacuum
- 2024 news: after the LHC vacuum volume incident Jan. 2023
  - ✦ RF box replacement successful!
  - ✦ VELO operating at nominal gap



LHCB-TDR-013

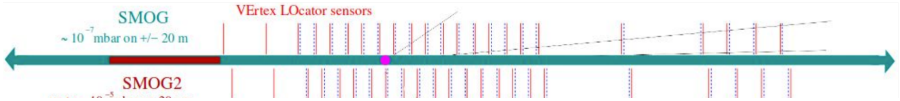


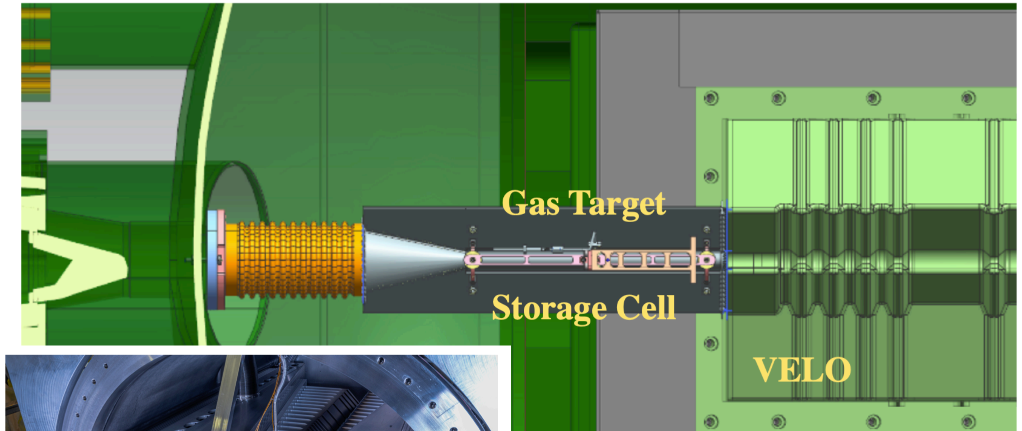
Velo recontructed hadronic interactions, 2024 data

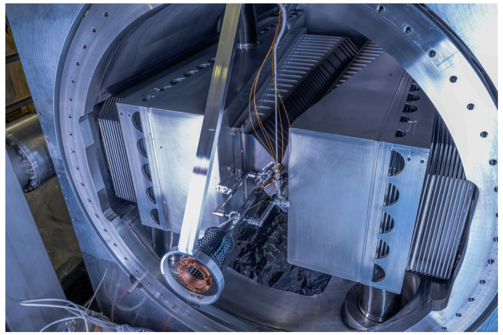
System for Measuring Overlap with Gas - SMOG

- ✦ Upgraded SMOG system, storage cell + dedicated Gas Feed System
- ✦ Upstream nominal IP at [-500,-300] mm, gas density increased of 2 order of magnitude ⟶ higher luminosity
- ✦ Gas target possible: $H_2,\ D_2,\ He,\ N_2,\ O_2,\ Ne,\ Ar,\ Kr,\ Xe$
- ✦ Separated luminous region from *pp* ⟶ simultaneous data-taking

Reaction	DAQ time	Non coll. bunches	Lumi (nb^{-1})	Decays	SMOG yields	Scale factor	SMOG2 proj. yields
pAr	18 h	684	~ 2	$D^0 \to K^-\pi^+$	6450	62	400 k
				$D^+ \to K^-\pi^+\pi^+$	975		60 k
				$D_s^+ \to K^-K^+\pi^+$	131		8 k
				$D^{*+} \to D^0\pi^+$	2300		140 k
				$\Lambda_c^+ \to pK^-\pi^+$	50		3 k
				$J/\psi \to \mu^+\mu^-$	500		30 k
				$\psi(2S) \to \mu^+\mu^-$	20		1.2 k
pHe	84 h	648	7.6	$J/\psi \to \mu^+\mu^-$	500	19.6	10 k
				$\psi(2S) \to \mu^+\mu^-$	20		0.4 k

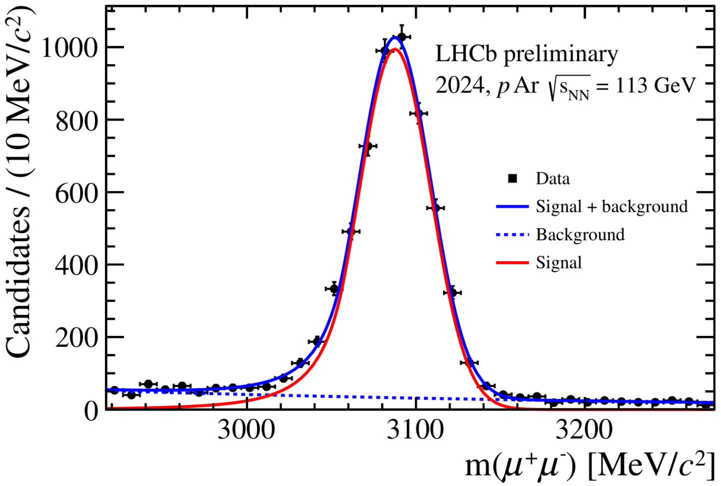




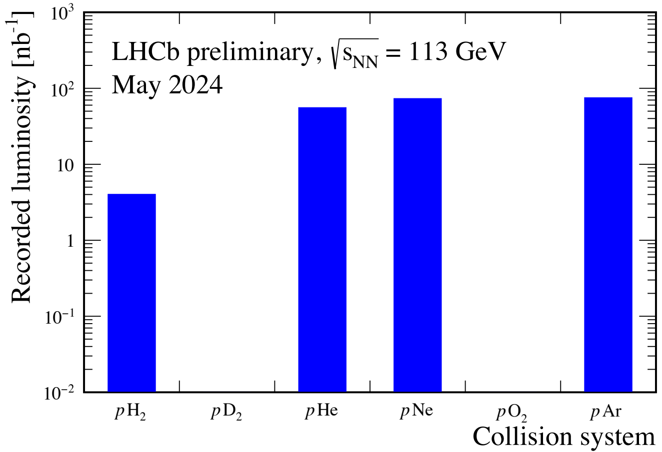


CERN-LHCC-2019-005

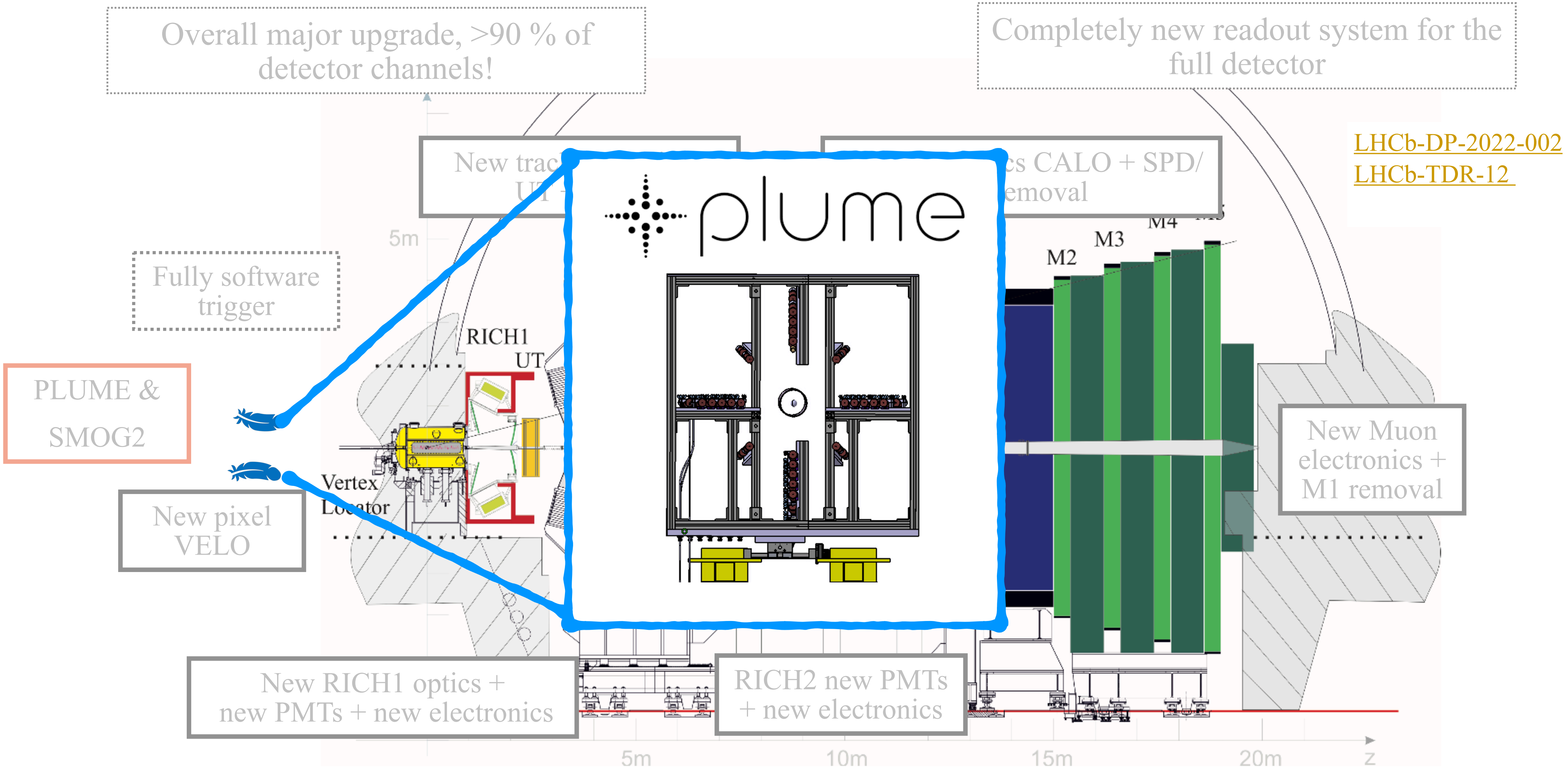
LHCB-TDR-020



LHCB-FIGURE-2024-005



LHCb Upgrade I: PLUME luminometer

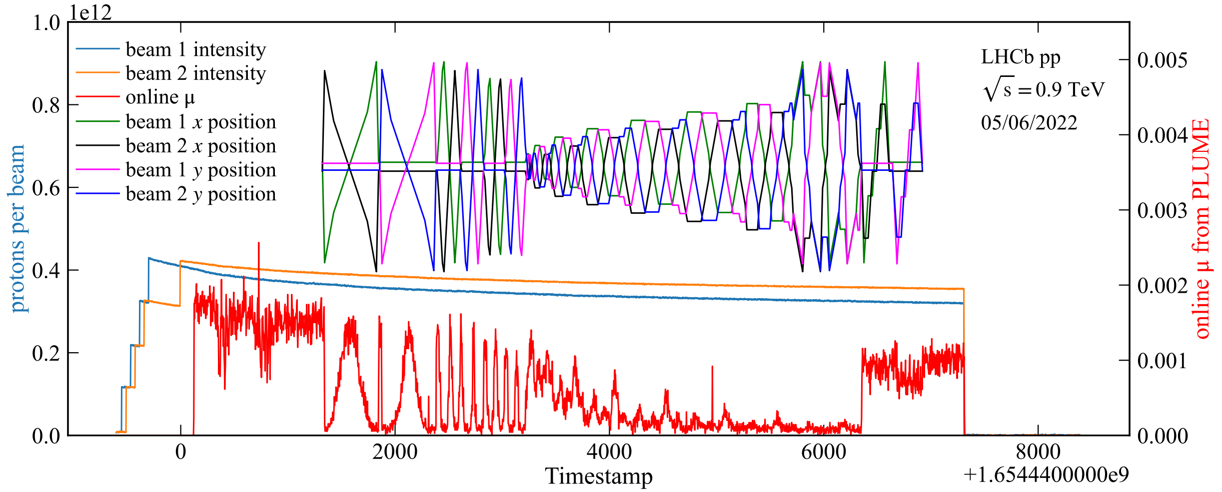


A new LHCb luminometer

- ✦ Cross-shaped hodoscope composed by 48 PMTs, installed upstream of the VELO

Detect Cherenkov light from particles impinging on quartz tablet glued to the PMTs window

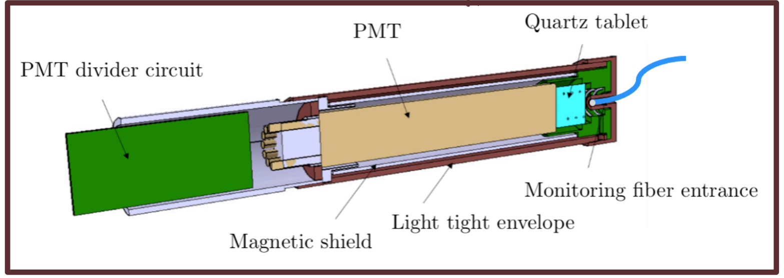
- ✦ Measure rates every 3 seconds and compute luminosity
- ✦ Provide real-time feedback to the LHC to level the luminosity at IP8 and luminosity measurement per bunch crossing!
- ✦ 10 % precision for online luminosity measurement
- ✦ Used for levelling of luminosity, key for stable operation of the detector!



LHCb-FIGURE-2022-012

CERN-LHCC-2021-002

LHCB-TDR-022



Elementary detection module

LHCb Upgrade I: Upstream Tracker

Overall major upgrade, >90 % of detector channels!

Completely new readout system for the full detector

LHCb-DP-2022-002
LHCb-TDR-12

New tracking stations UT + SciFi

New electronics CALO + SPD/ PS removal

Fully software trigger

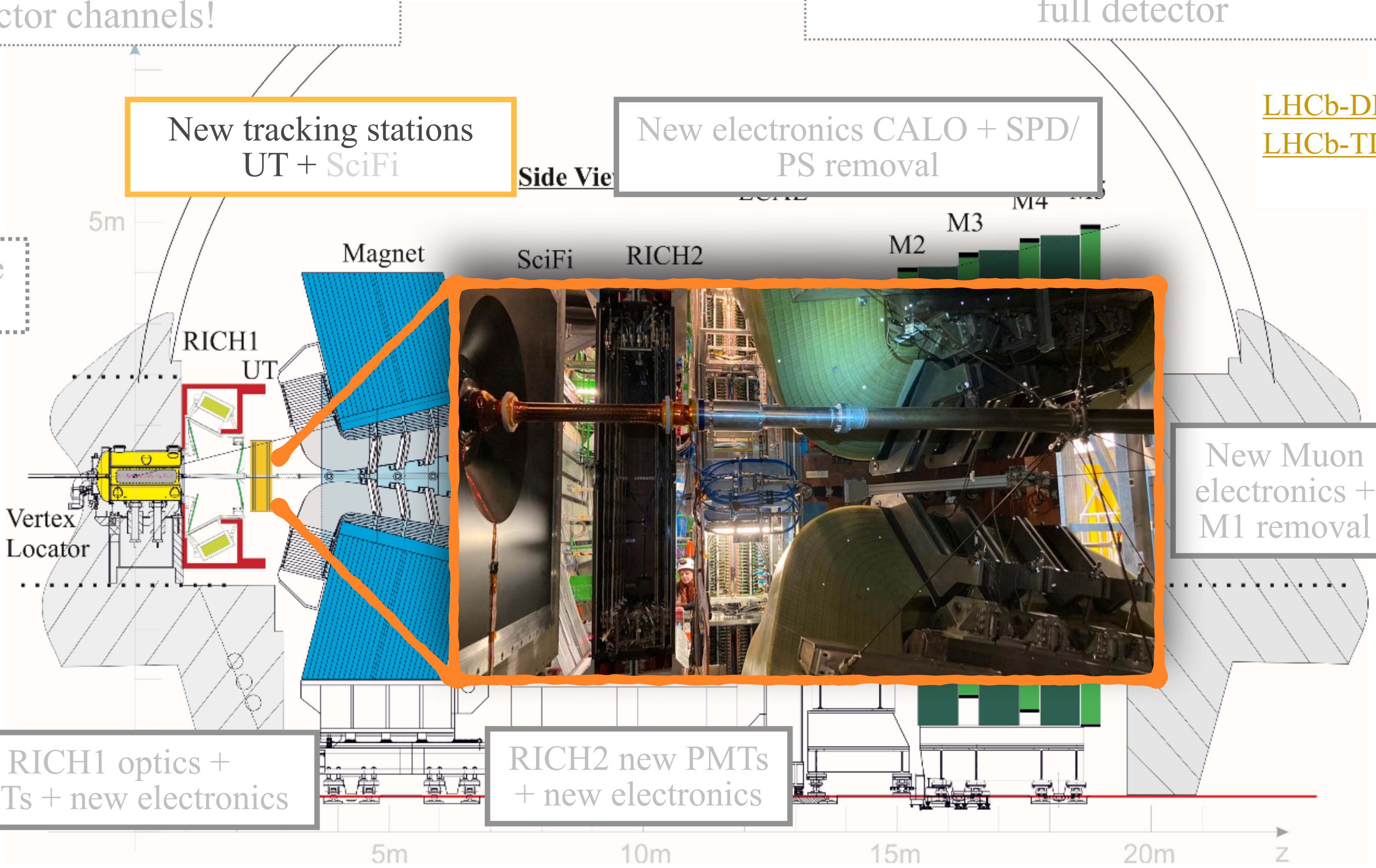
PLUME & SMOG2

New pixel VELO

New Muon electronics + M1 removal

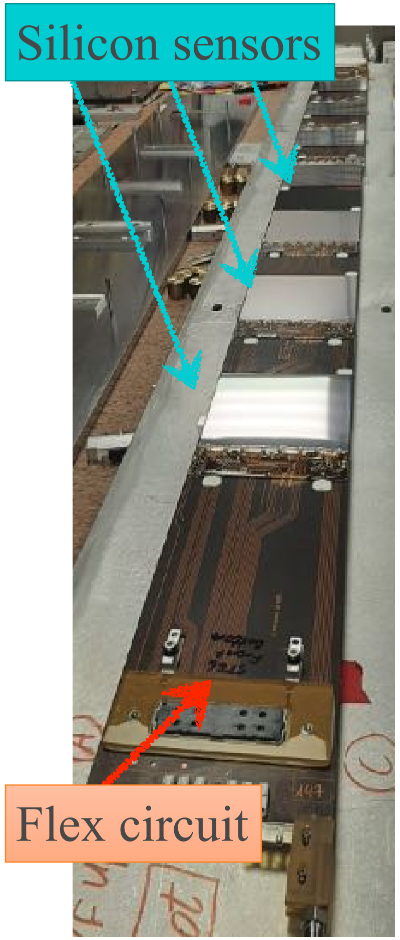
New RICH1 optics + new PMTs + new electronics

RICH2 new PMTs + new electronics

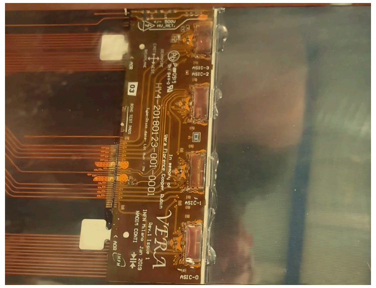


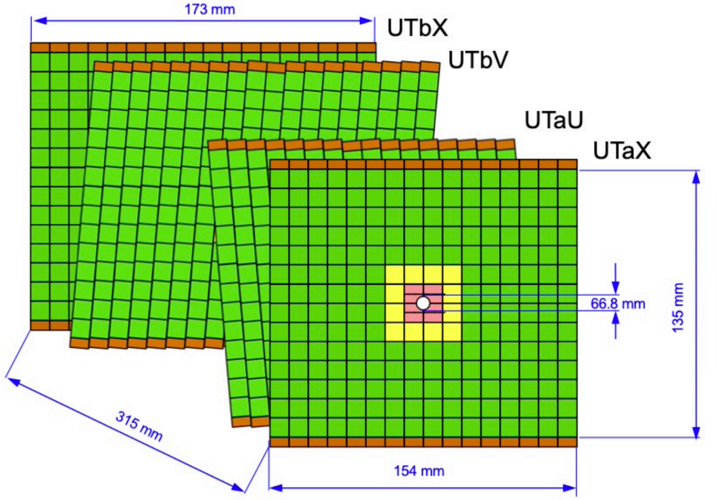
Upstream Tracker

GOAL: first determination of the track momentum (precision ~ 15%)



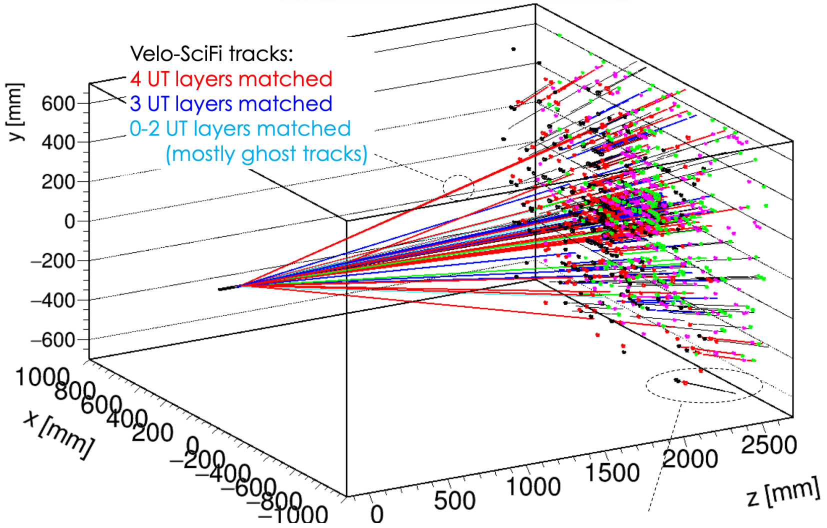
- ✦ Silicon micro-strip detector
  - ◆ Four layers upstream the magnet
  - ◆ Increasing granularity getting closer to the beam
- ✦ Different sensors for different regions : 250/320 μm thickness, pitch: ~ 95/190 μm
- ✦ Sensors mounted on staves (both sides) with bi-phase CO_2 cooling ($< -50^0$C)
- ◆ New read-out ASIC (SALT) Sensors 2022, 22(1), 107
- ◆ Integration in the data chain well advancing!





50 VELO-SciFi tracks, 2024

UT can help reduce ghost tracks



LHCb Upgrade I: Scintillating Fibre Tracker

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PLUME & SMOG2

New pixel VELO

New tracking stations UT + SciFi

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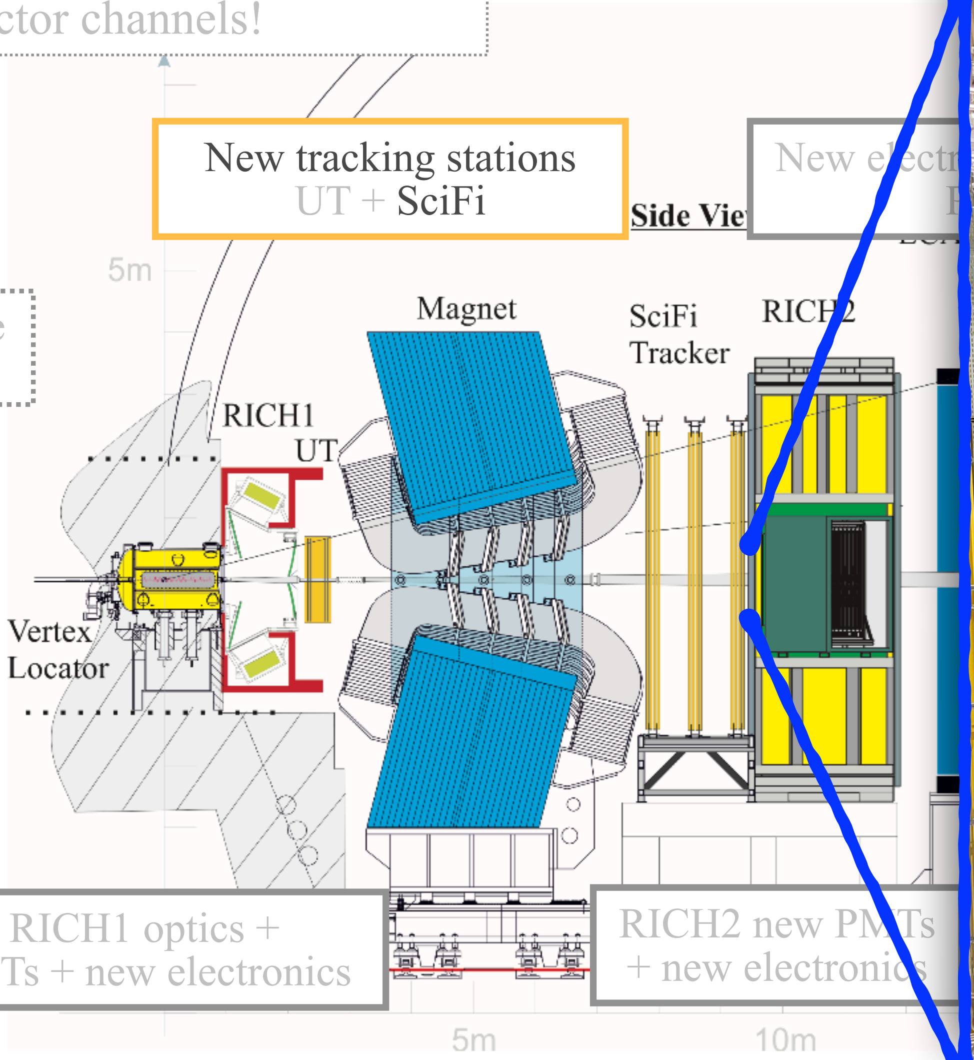
RICH2 new PMTs + new electronics



P-2022-002

DR-12

Scintillating Fibre Tracker - SciFi

GOAL: measure particle trajectories with a spatial resolution of $< 100 \mu m$

Scintillating fibers readout by SiPMs

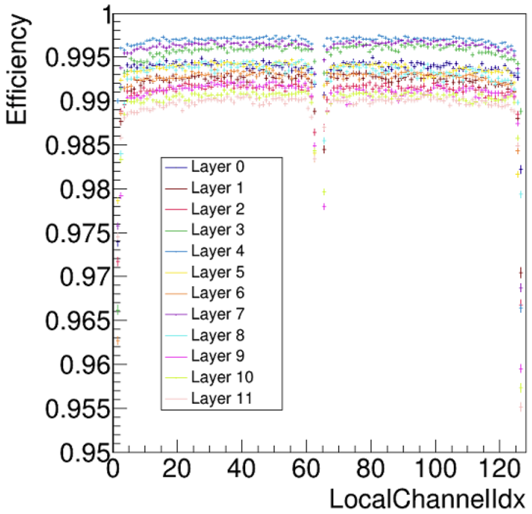
- Amplitude each channel proportional to the number of detected photons
- Clustering in FPGA with 3 different tunable thresholds

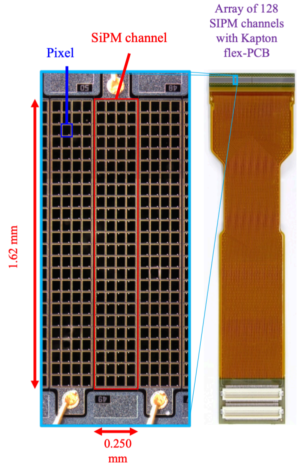
✦ New readout ASIC PACIFIC [A Comerma et al 2013 JINST 8 C01048]

✦ Radiation tolerant: 35 kGy near the beam pipe, $6 \times 10^{11} n_{eq}/cm^2$ at SiPMs

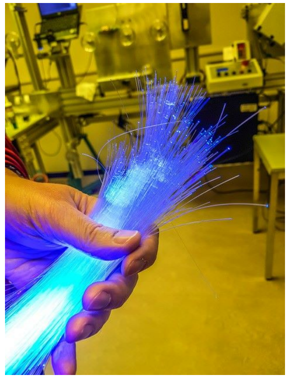
✦ Noise cluster rate: < 10 % of signal → cooled to -40 C

Status 2024: high efficiency achieved with low thresholds

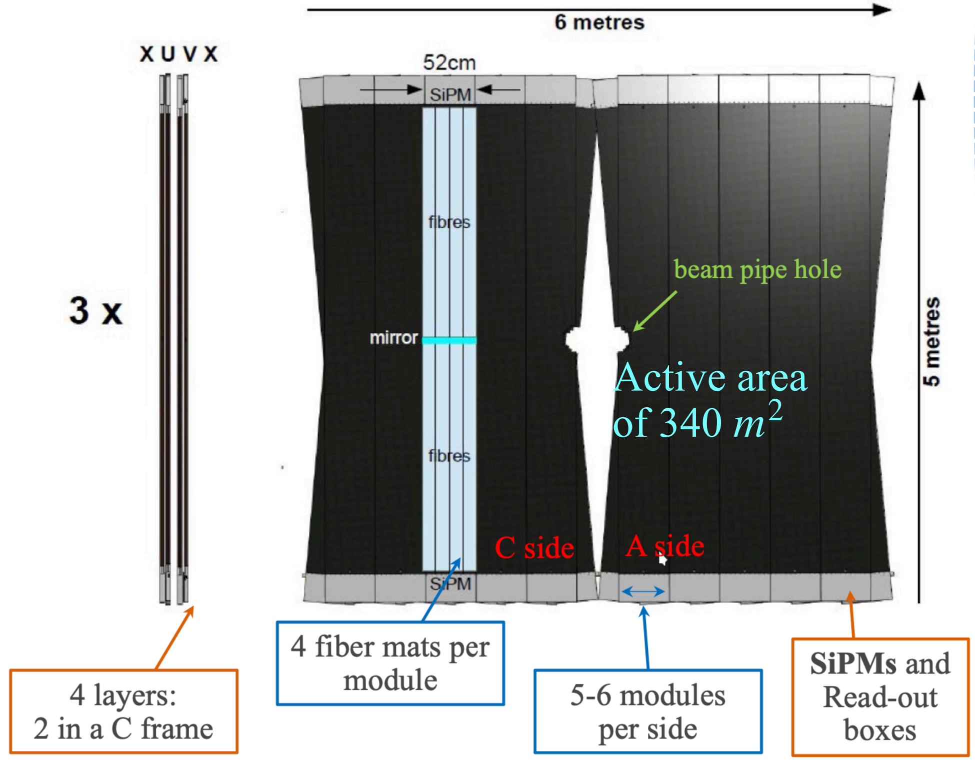


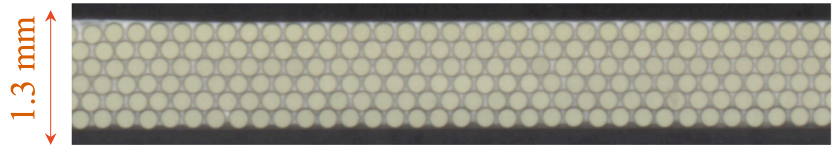


C.Trippl poster



SciFi station





Cross section of a fiber mat

LHCb Upgrade I: Ring-Imaging Cherenkov - RICH

Overall major upgrade, >90 % of detector channels!

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Cb-DP-2022-002

Cb-TDR-12

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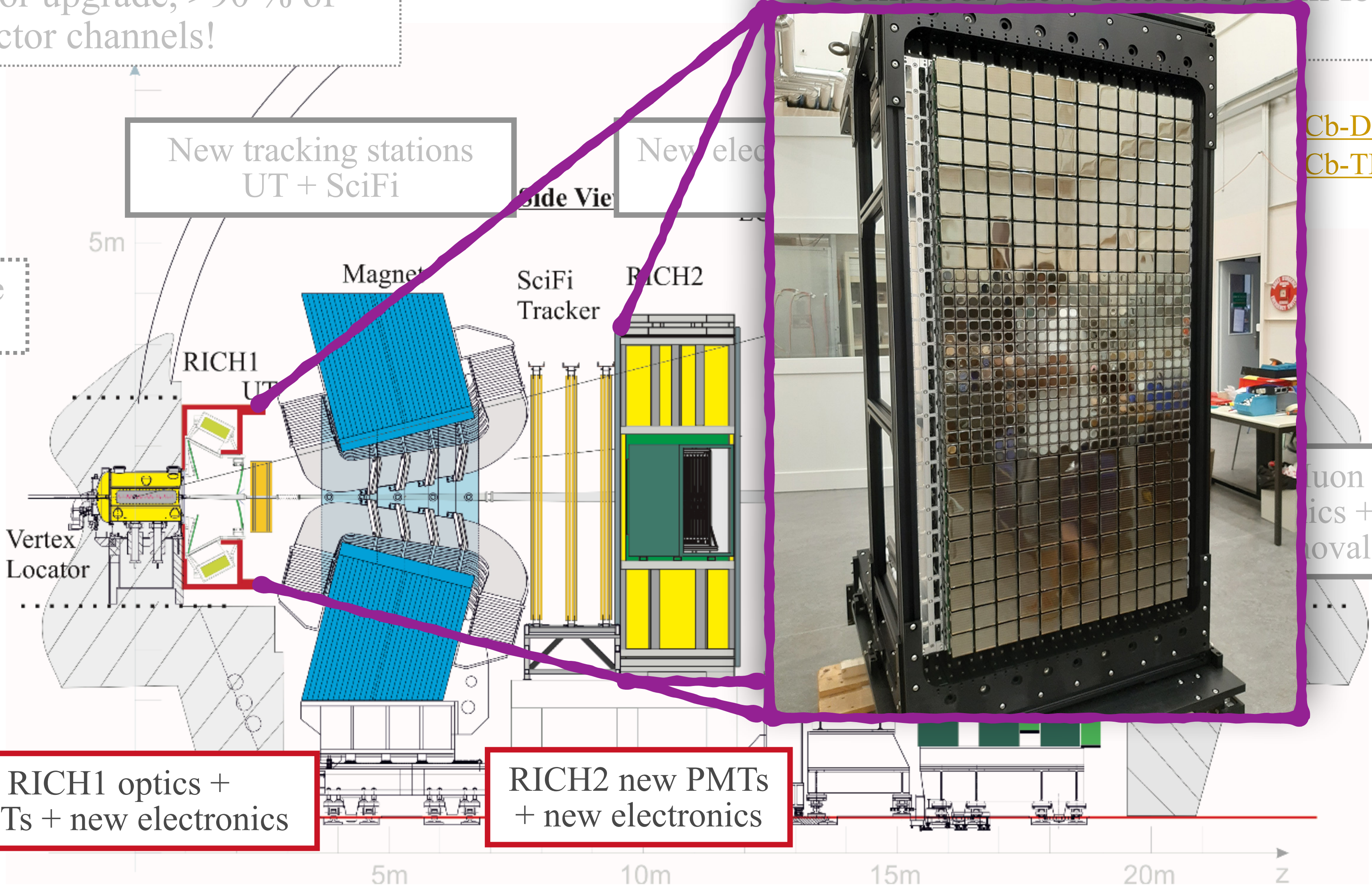
New elec

uon ics + oval



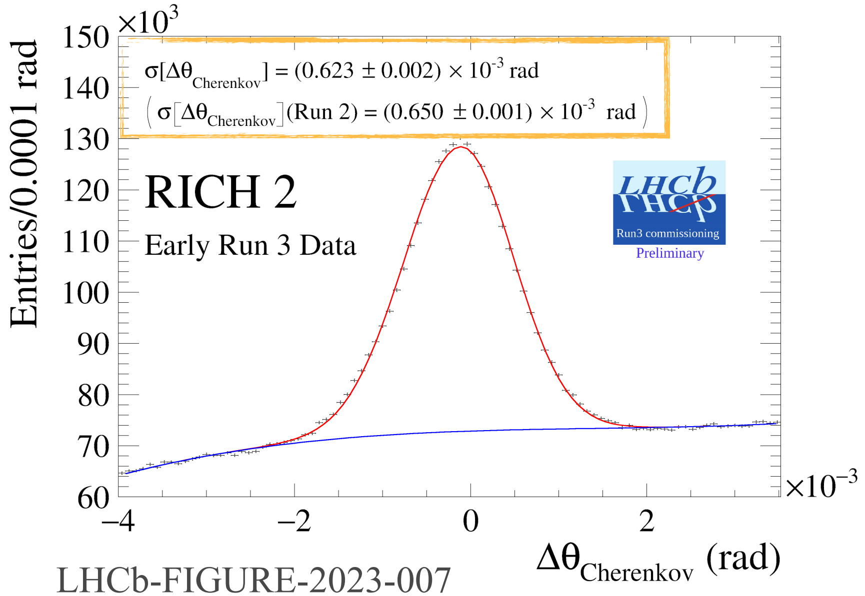
New RICH1 optics + new PMTs + new electronics

RICH2 new PMTs + new electronics

Ring-Imaging Cherenkov - RICH

GOAL: charge hadrons identification for momenta 2.6 -100 GeV/c

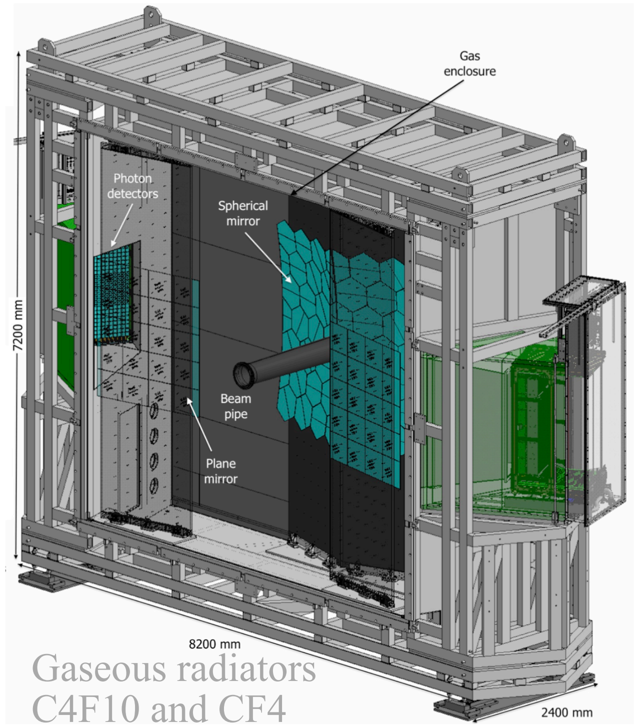
- ✦ Overall layout and concept of the RICH system unchanged:
  Cherenkov photons reflected outside the LHCb acceptance using spherical and planar mirrors
- ✦ Preserve excellent performance achieved in Run 1 and 2
- ✦ Replace Hybrid Photon Detectors (HPDs) with Multianode PMTs (MaPMTs)
- ✦ Change curvature of RICH1 spherical mirrors to reduce occupancy on PMTs (factor 2 less)
- ✦ New radiation hard and fast readout ASIC developed (CLARO) M. Baszczyk et al 2017 JINST 12 P08019



LHCb-FIGURE-2023-007

2024: RICH 1 and 2 performance already better than in Run 1 and 2!

See dedicated PID talk by M. Atzeni PID at LHCb



Gaseous radiators C4F10 and CF4

MaPMTs (Hamamatsu)

Real Time Software trigger

CERN-LHCC-2018-007

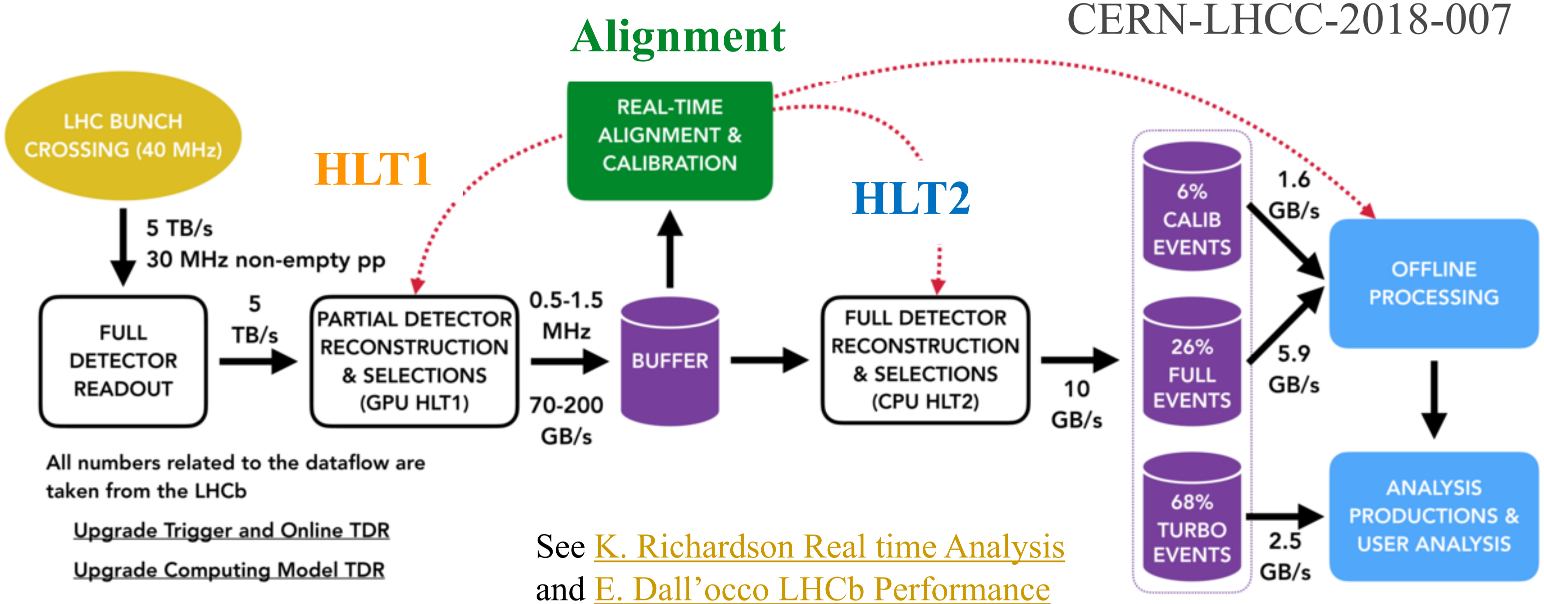
Removal of hardware trigger, moved to fully software trigger.

LHCb data flow:

✦ **HLT1**: partial reconstruction data to buffer

✦ **HLT2** concurrent processing

- ➢ Intake 5 TB/s of raw data at 30 MHz
- ➢ Partial event reconstruction + coarse selections
- ➢ Reduce input rate by a factor of 30

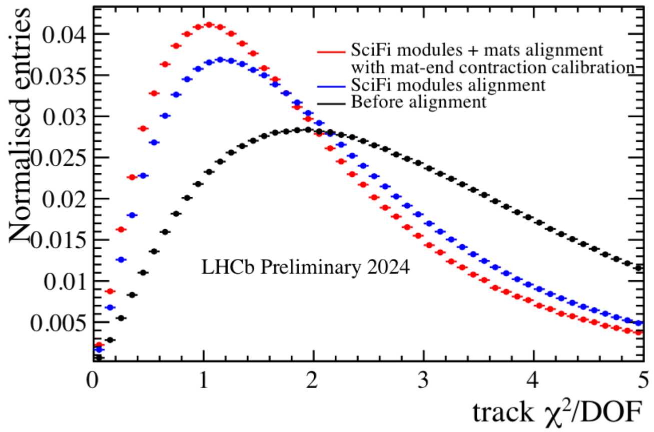


See K. Richardson Real time Analysis and E. Dall'occo LHCb Performance

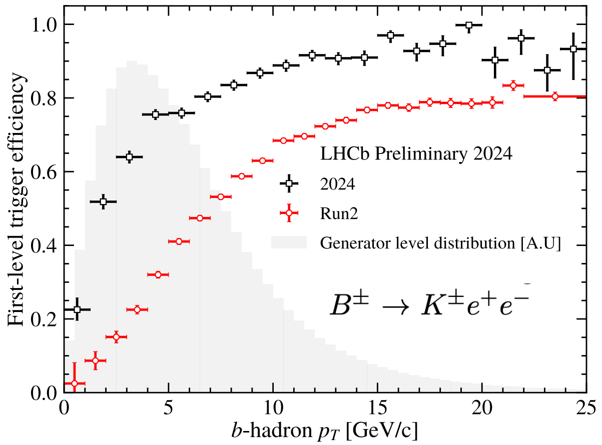
Alignment and calibration online

- ➢ Intermediate selected events in a buffer for online real time alignment
- ➢ Automatic update of alignment constants
- ➢ Monitor relevant quantities online, e.g. unbiased residuals

LHCb-FIGURE-2024-009

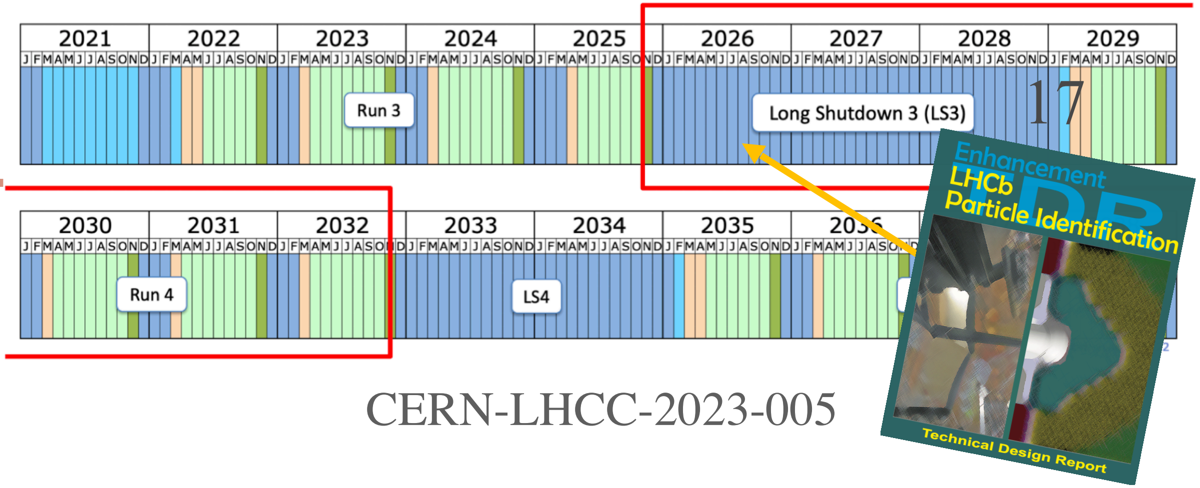


LHCb-FIGURE-2024-007



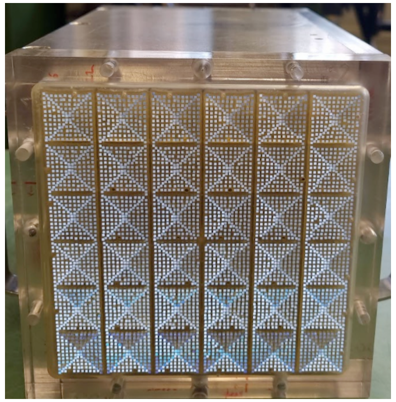
PID enhancement for Run 4

- ➢TDR: *LHCb particle identification enhancement during LS3*
- ➢Upgrade of RICH and ECAL

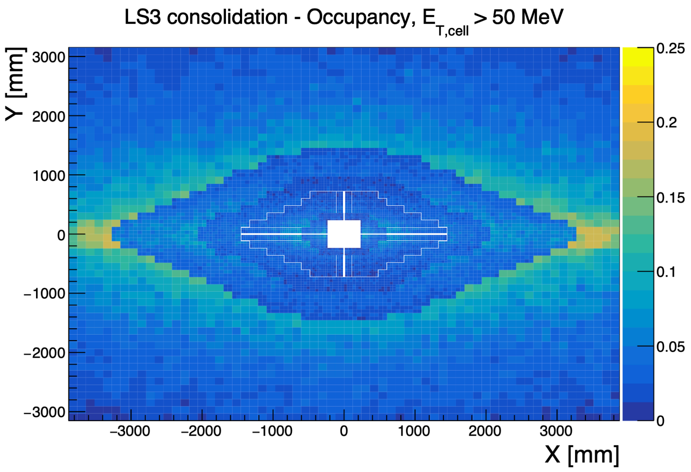


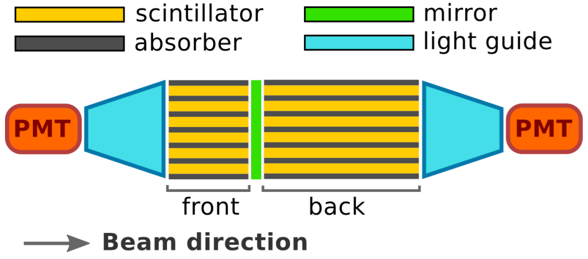
CERN-LHCC-2023-005

ECAL: detector modules have not been replaced during LS2



Prototype module



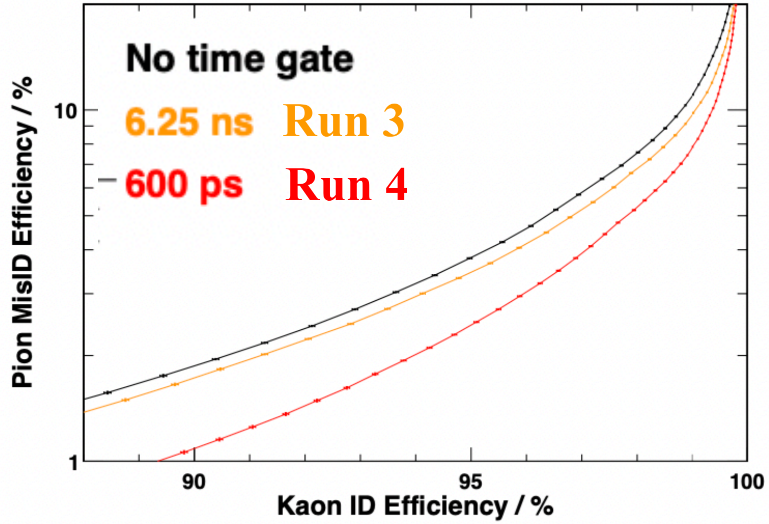


Innermost region needs replacing after Run 3

→plan to replace with new SpaCal modules (reused for Upgrade II)
→rearrange outer modules in a rhombic shape (following occupancy)

Poster: D. Manuzzi PicoCAL

RICH: new electronics time-stamping photon hits

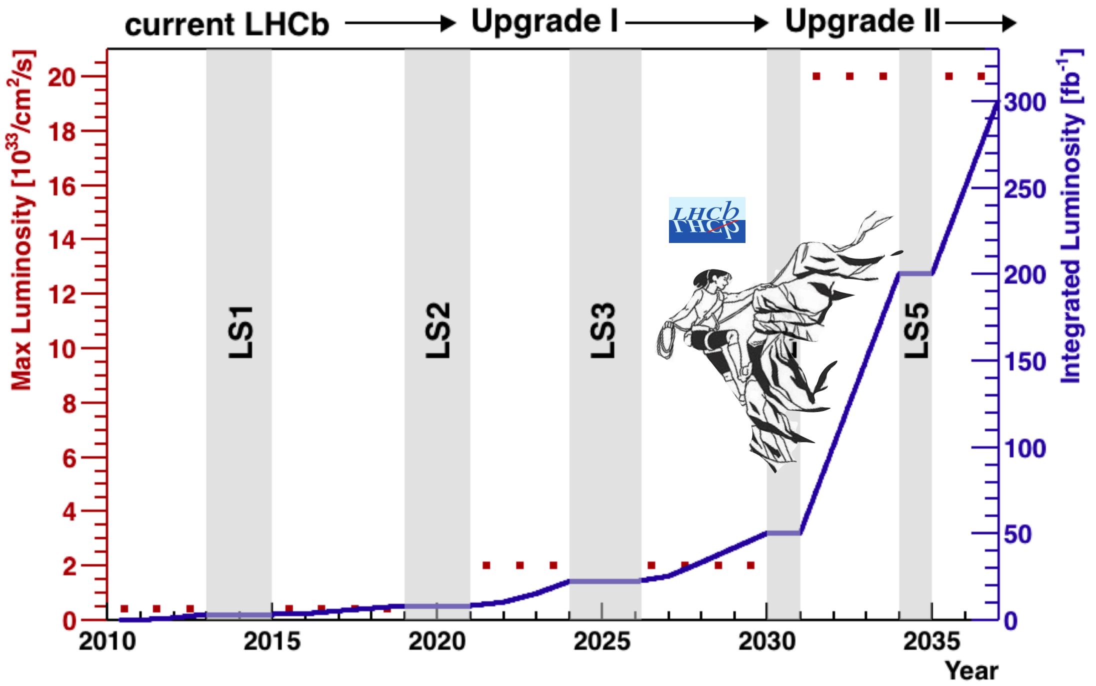


For Run 4 MaPMT photodetectors remains the major limitation for timing

High Lumi LHC for LHCb

"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."

European Strategy Update 2020



Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\text{GeV}^2c^4)$	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	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
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	Under study [611]
a_{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%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **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 $(\approx x \sin\phi)$	2.8×10^{-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}	–

CERN-LHCC-2017-003
CERN-LHCC-2018-027
CERN-LHCC-2021-012
CERN-LHCC-2023-005

- ✦ In general, need more granular and radiation tolerant detectors, with timing capabilities, to mitigate effect of pile up
- ✦ Technology not available yet in most cases, important R&D effort needed

LHCb upgrade II

The ultimate flavour physics experiment at the HL-LHC

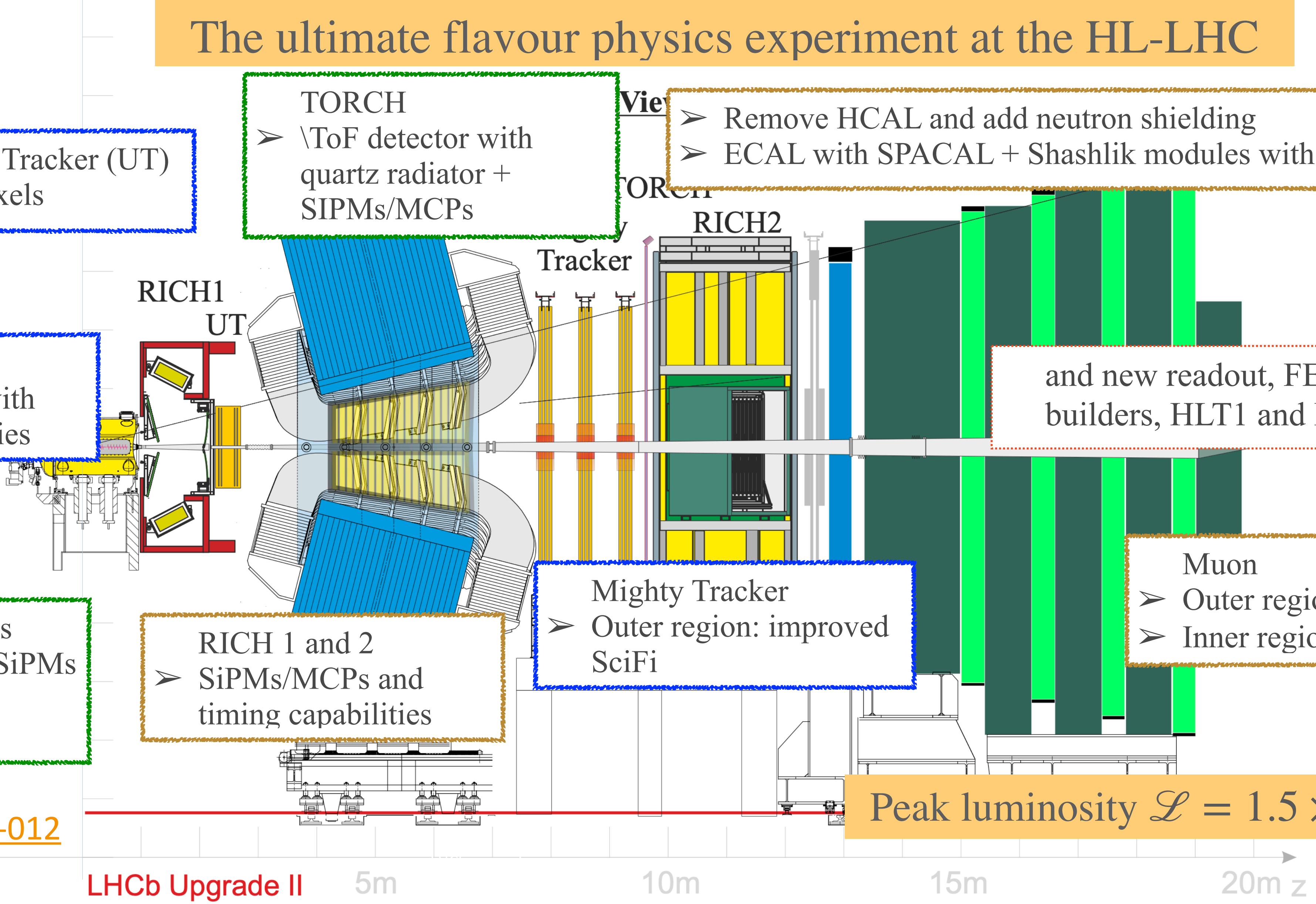
Upstream Tracker (UT)
- CMOS pixels

TORCH
- \ToF detector with quartz radiator + SIPMs/MCPs

- Remove HCAL and add neutron shielding
- ECAL with SPACAL + Shashlik modules with timing capabilities

VELO
- Pixel detector with timing capabilities

and new readout, FEs, ASICs, event builders, HLT1 and HLT2 farms, ….



Magnet Stations
- Scintillators + SiPMs to improve low momentum

RICH 1 and 2
- SiPMs/MCPs and timing capabilities

Mighty Tracker
- Outer region: improved SciFi

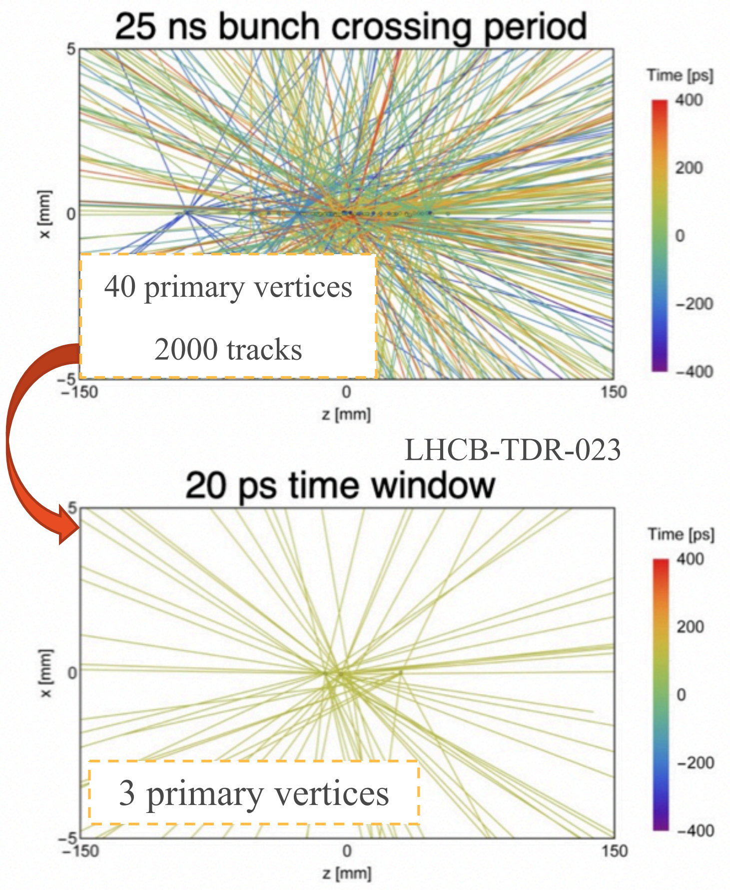
Muon
- Outer regions: MWPCs
- Inner regions: μRWELL

Peak luminosity $\mathscr{L} = 1.5 \times 10^{34} cm^{-2} s^{-1}$

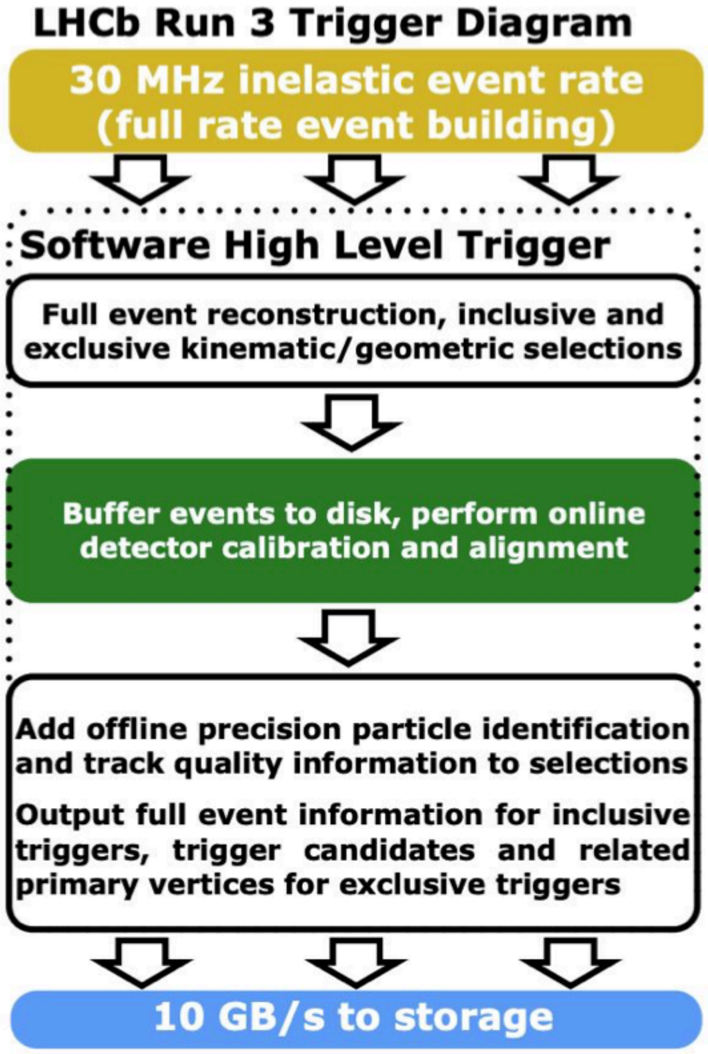
CERN-LHCC 2021-012

LHCb Upgrade II software trigger

Tracks in an Upgrade II collision



Slices of 20 ps would reduce the number of primary vertices



- ➢ Linear increase of HLT1 output rate
- ➢ Quadratic increase of HLT2 processing: harder reconstruction but also more events
- ➢ Plan: move main consumers (Track fit and RICH) of HLT2 to GPUs as well
- ➢ Timing reconstruction algorithms will have an impact on throughput

T. Evans Detectors with timing capabilities

→go to 50 GB/s

Conclusions

LHCb experiment, a story of success!

➢ First decade showed a physics program expanded **well beyond original expectations**

➢ New detector installed during LS2! **Major upgrade of the detector**
- Higher luminosity, higher data rates, etc
- Finer granularity, improved acceptance

➢ Calibration and operations progressing at full speed
- Excellent performance with early data
- Upstream Tracker integrating the trigger
- VELO vacuum incident in 2023 solved!
- Operation close to nominal conditions

➢ Plans for Upgrade 2 are advancing fast
  - ➢ First enanchement Upgrade Ib approved! (Run 4)
  - ➢ R&D in new detectors, finalising sub-detector designs
  - ➢ Preparing scoping document for LHCC