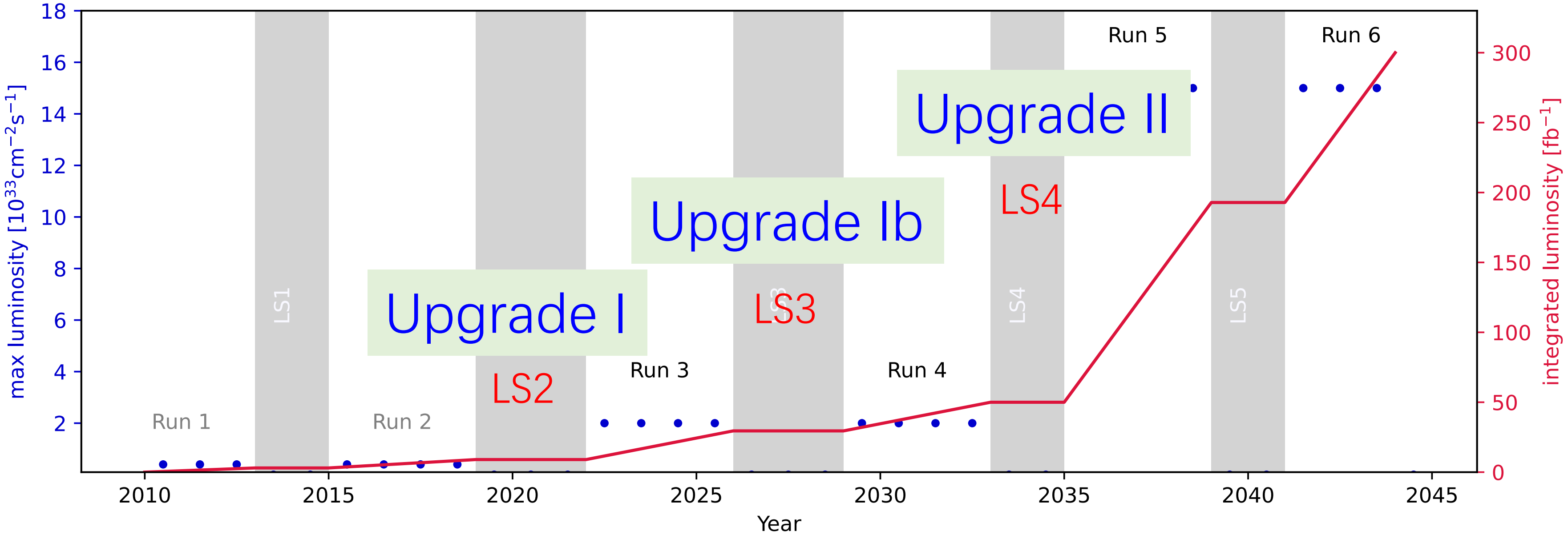
PEKING UNIVERSITY

The 9th China LHC Physics Workshop (CLHCP2023)
15-20 Nov 2023, Shanghai

LHCb Upgrades



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北京大学物理学院

2023.11.17

Contents

The born of LHCb

LHC-B

CERN/LHCC 95-5
LHCC/ I 8
25 August 1995

Last update
28 March 1996

LETTER OF INTENT

A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation

In colliding mode instead of fixed-target

Abstract

The LHC-B Collaboration proposes to build a forward collider detector dedicated to the study of CP violation and other rare phenomena in the decays of Beauty particles. The forward geometry results in an average 80 GeV momentum of reconstructed B-mesons and, with multiple, efficient and redundant triggers, yields large event samples. B-hadron decay products are efficiently identified by Ring-Imaging Cerenkov Counters, rendering a wide range of multi-particle final states accessible and providing precise measurements of all angles, α, β and γ of the unitarity triangle. The LHC-B microvertex detector capabilities facilitate multi-vertex event reconstruction and proper-time measurements with an expected few-percent uncertainty, permitting measurements of B_s-mixing well beyond the largest conceivable values of x_s. LHC-B would be fully operational at the startup of LHC and requires only a modest luminosity to reveal its full performance potential.

… dedicated to the study of CPV and other rare phenomena in the decays of Beauty particles.

… precise measurements of the CKM angles…

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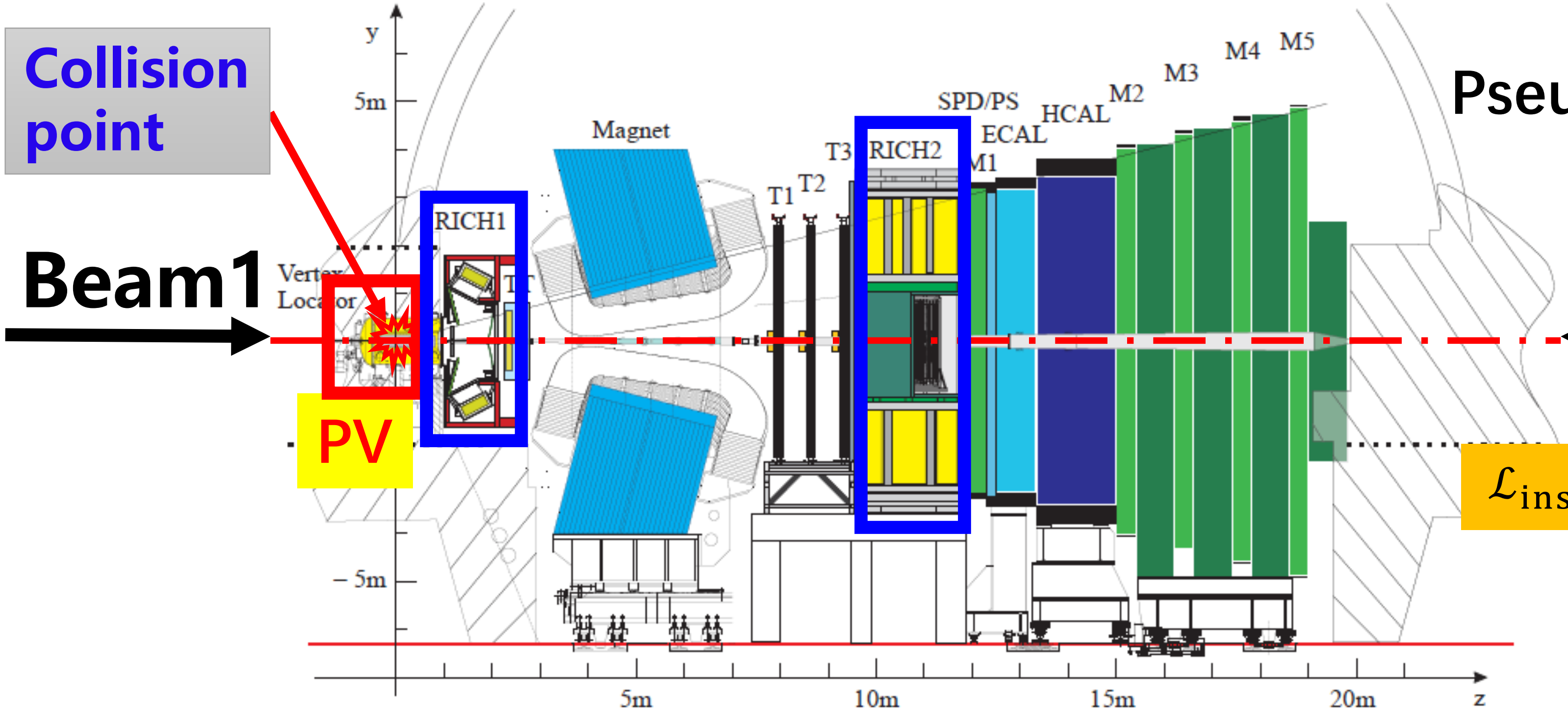
JINR, Dubna, Russia
E.N. Kozarenko, I.E. Kreslo, V. Tyukov

The LHCb detector

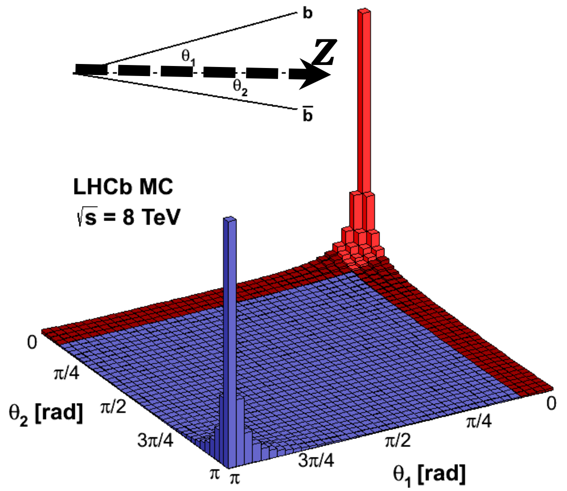
JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30 (2015) 1530022



Pseudorapidity coverage
$2 < \eta < 5$

$\mathcal{L}_{\text{inst}} = (2-4)\times10^{32}\ \text{cm}^{-2}\text{s}^{-1}$

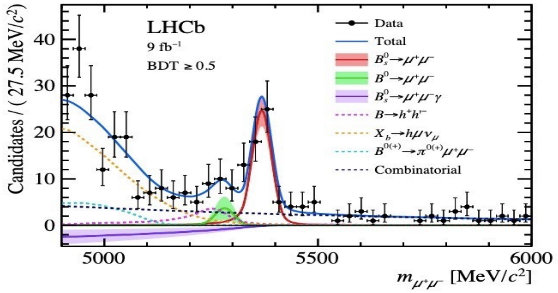
Vertex:	$\sigma_{\text{IP}} = 20\ \mu\text{m}$
Time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ (5 – 100 GeV/c)
Mass :	$\sigma_m = 8\ \text{MeV}/c^2$ for $B \to J/\psi X$ (constrained $m_{J/\psi}$)
Hadron ID:	$\varepsilon(K\to K) \sim 95\%$ mis-ID $\varepsilon(\pi\to K) \sim 5\%$
Muon ID:	$\varepsilon(\mu\to\mu) \sim 97\%$ mis-ID $\varepsilon(\pi\to\mu) \sim 1-3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E\ (\text{GeV})}$



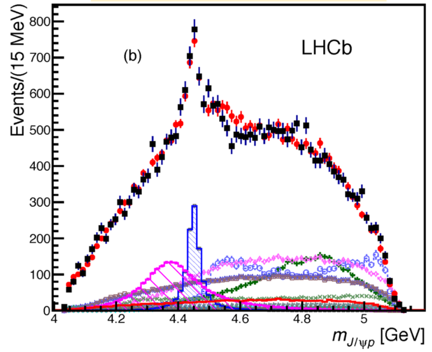
LHCb: a history of success

- ➢ 686 papers, 52093 citations
- ➢ Series of significant discoveries
  - Rare decays
  - CPV in charm and beauty
  - Spectroscopy
- ➢ Physics program well beyond designed
  - Fixed-target
  - Heavy-ions
  - Dark sector
  - Electroweak

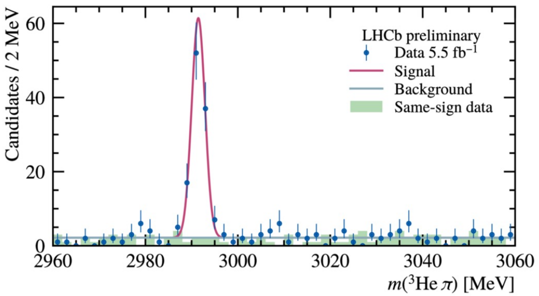
$B_s^0 \to \mu^+\mu^-$



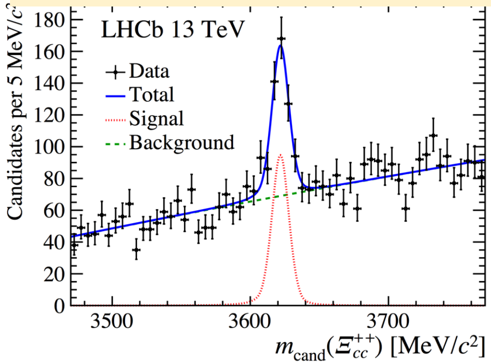
pentaquarks



${}^3_\Lambda H \to He\pi^-$

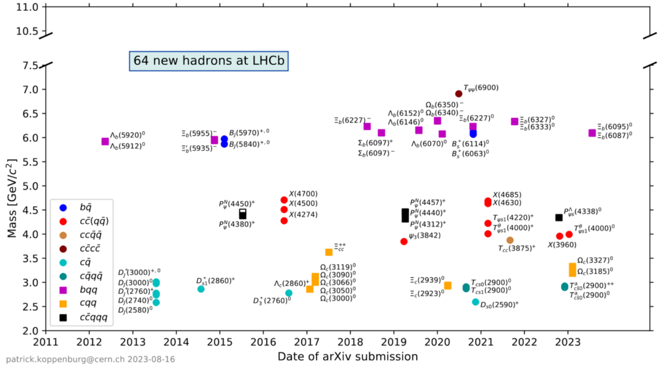


Doubly-charmed hadron

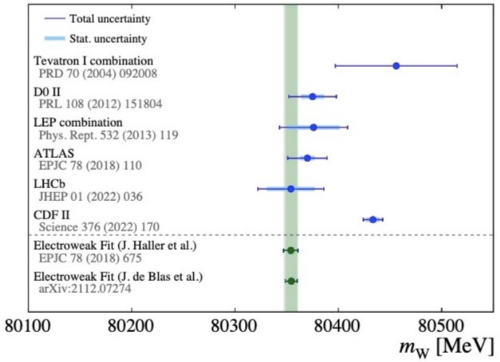


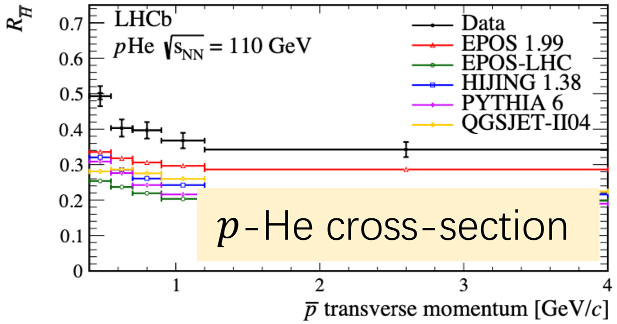
CPV in charm

https://www.nikhef.nl/~pkoppenb/particles.html



W mass



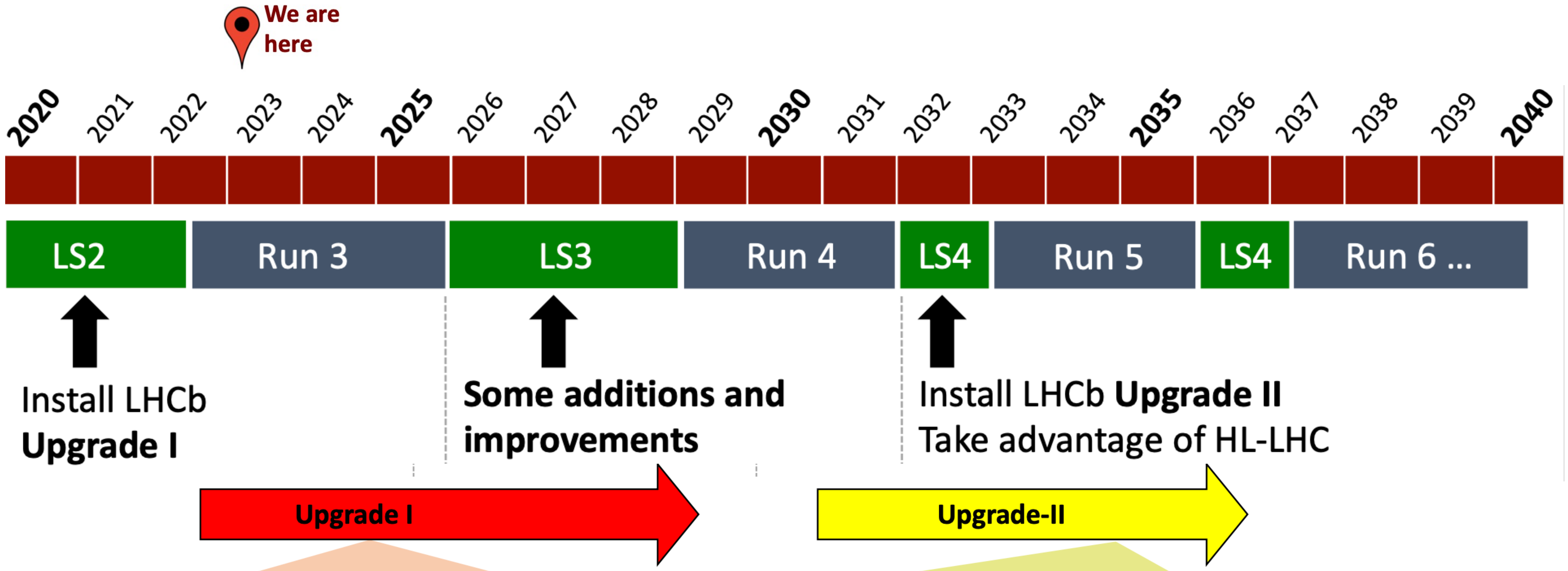


p-He cross-section

Contents

- Introduction: the past
  - LHCb in Run 1&2
- LHCb Upgrade 1: the present
  - Run 3&4
- LHCb Upgrade II: the future
  - Run 5&6 …
- Summary

LHCb Upgrades (-2040)



$\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$ **(5×)**

5.5 visible interactions / crossing

Accumulate **50 fb^{-1}** total

Freshly installed!!

$\mathcal{L} = 1.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ **(7.5×)**

41 visible interactions / crossing

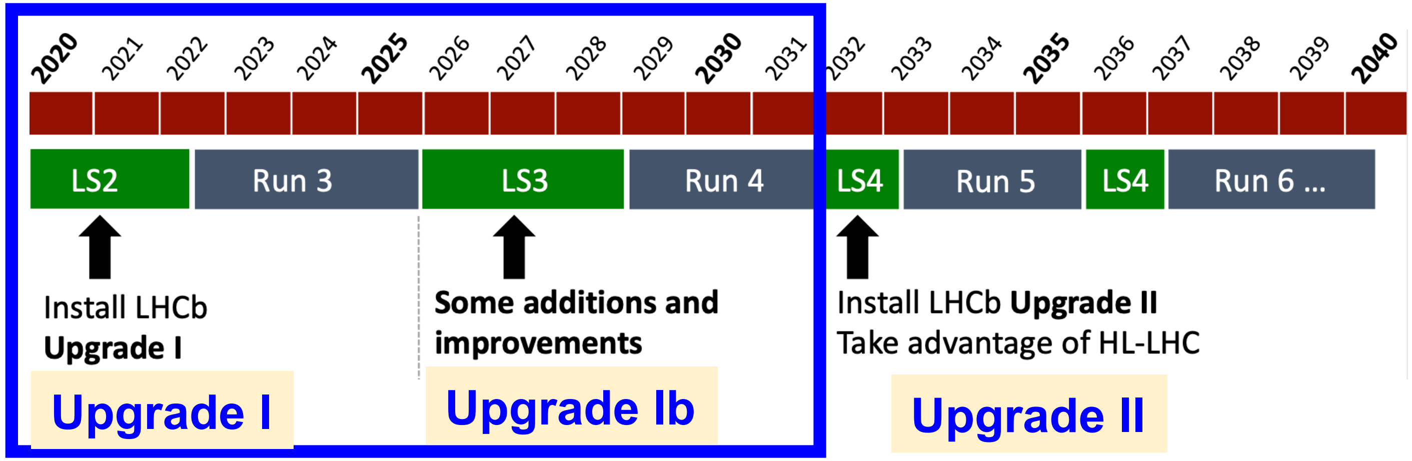
Accumulate **300 fb^{-1}** total

Design & R&D phase

LHCb Upgrade I: motivations

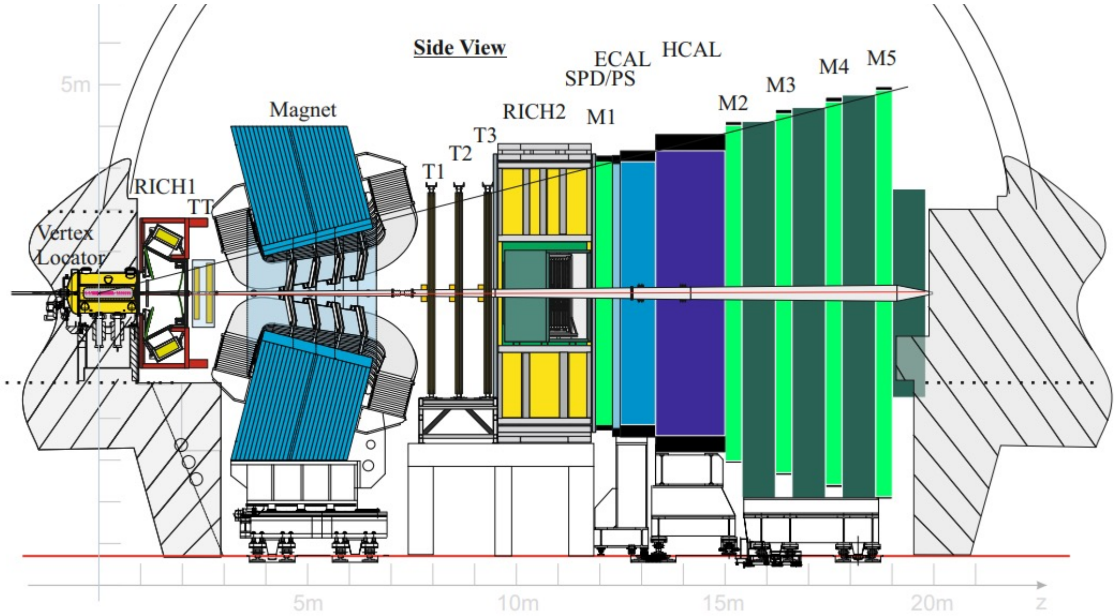
- New Physics
  - Flavour physics can probe energy scales well beyond the reach of current and foreseen accelerators
- Physics program limited by LHCb instead of the LHC
- Necessary to push current measurements down to SM precision
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ down to 10% of SM
  - CKM angle γ down to $1°$
  - $2\beta_s$ to precision $< 20\%$ of SM value
  - Charm CPV down to 10^{-4}

LHCb Upgrade I

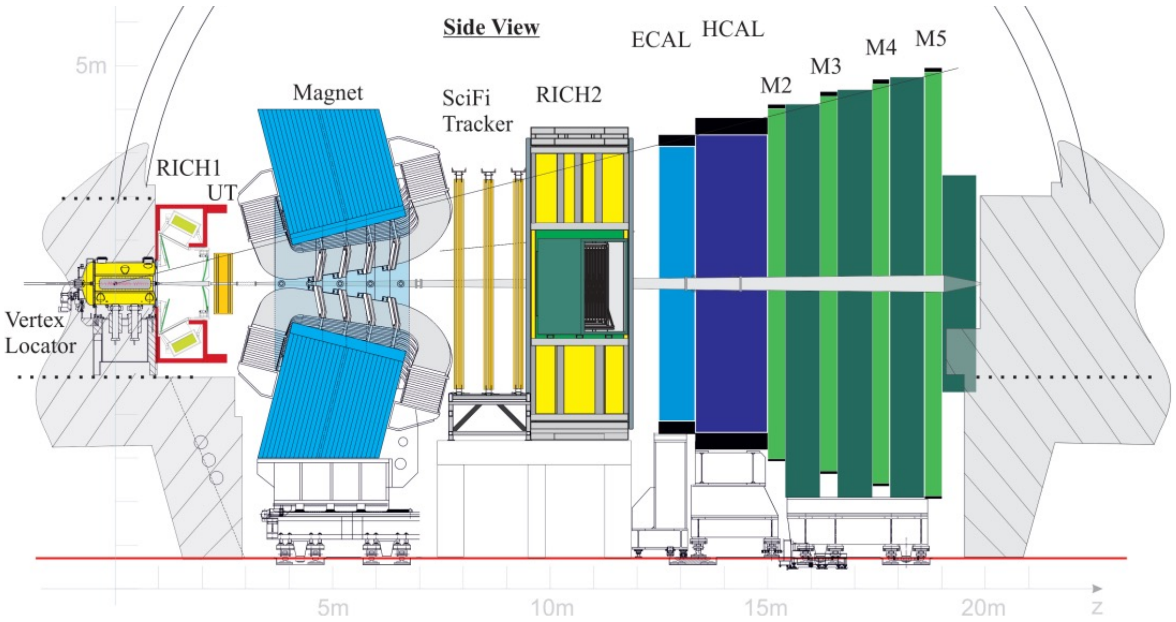


What's the difference?

LHCb



LHCb Upgrade I



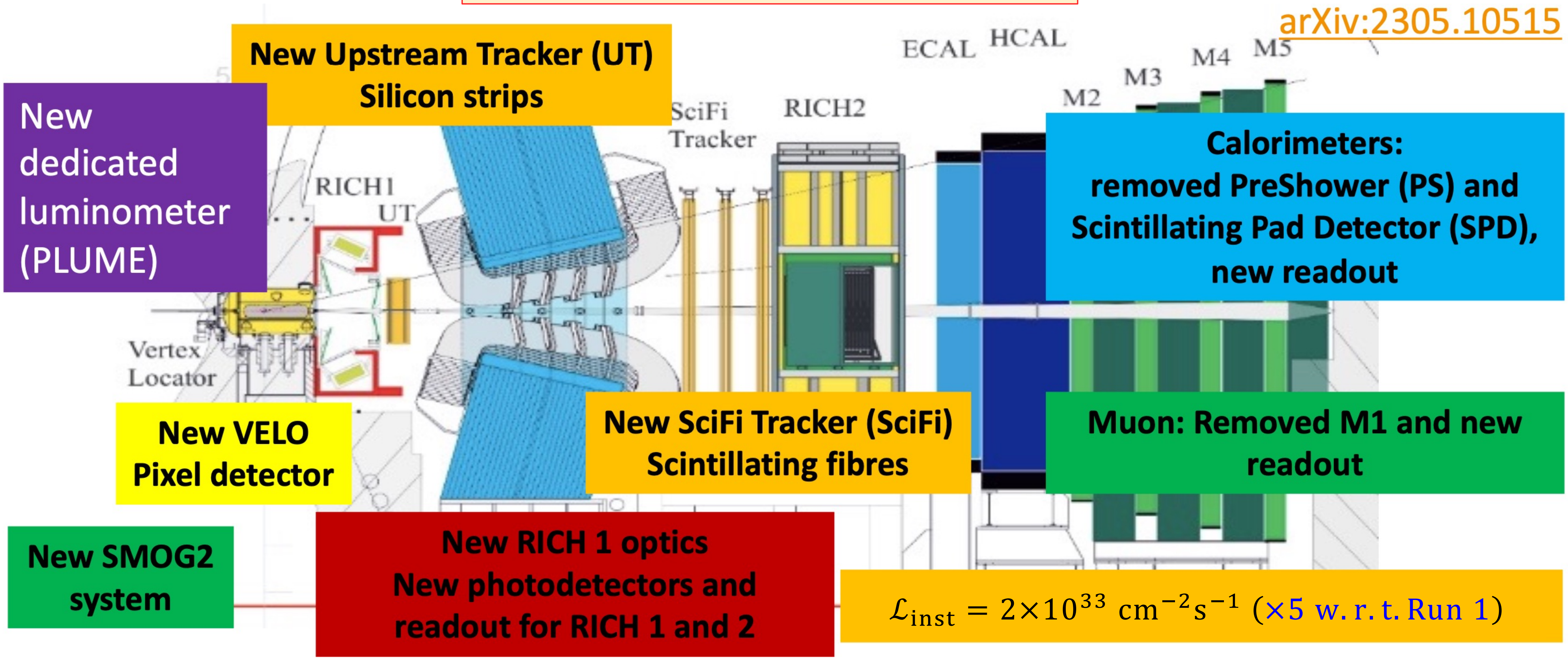
Almost the same?

LHCb Upgrade I: Run 3&4

A brand new detector!

CERN-LHC-2012-007

arXiv:2305.10515



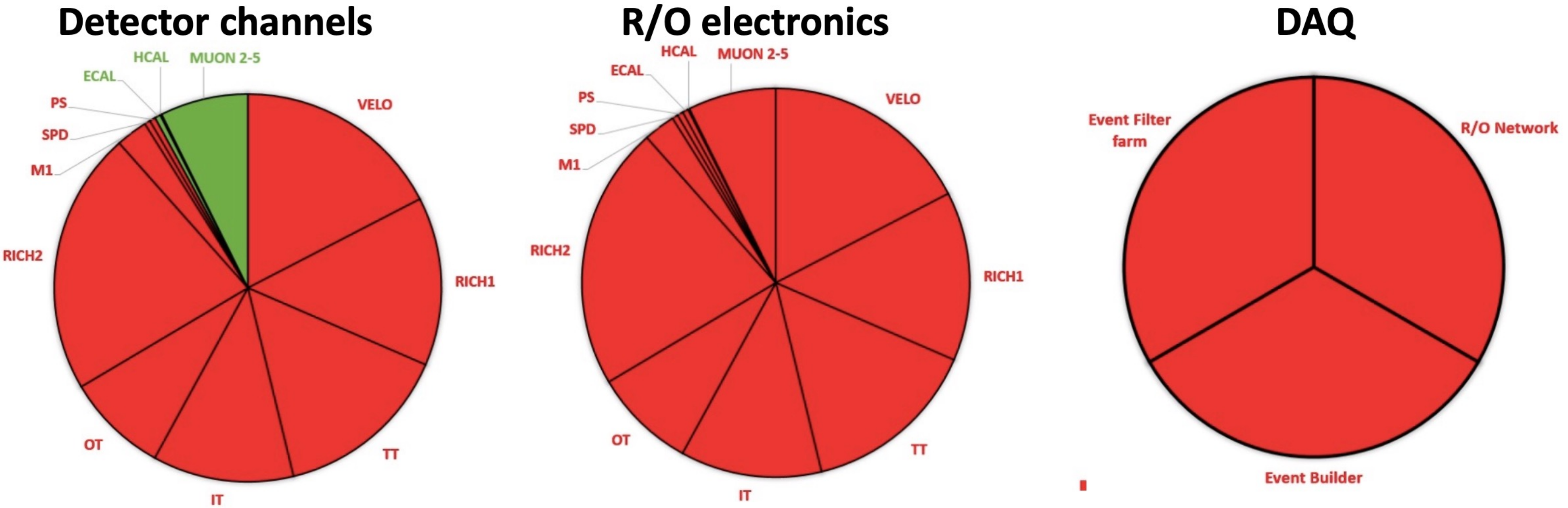
$\mathcal{L}_{\text{inst}} = 2\times10^{33}\ \text{cm}^{-2}\text{s}^{-1}$ ($\times5$ w.r.t. Run 1)

LHCb Upgrade I: Run 3&4 (cont.)

A brand new detector!

CERN-LHCC-2012-007
arXiv:2305.10515

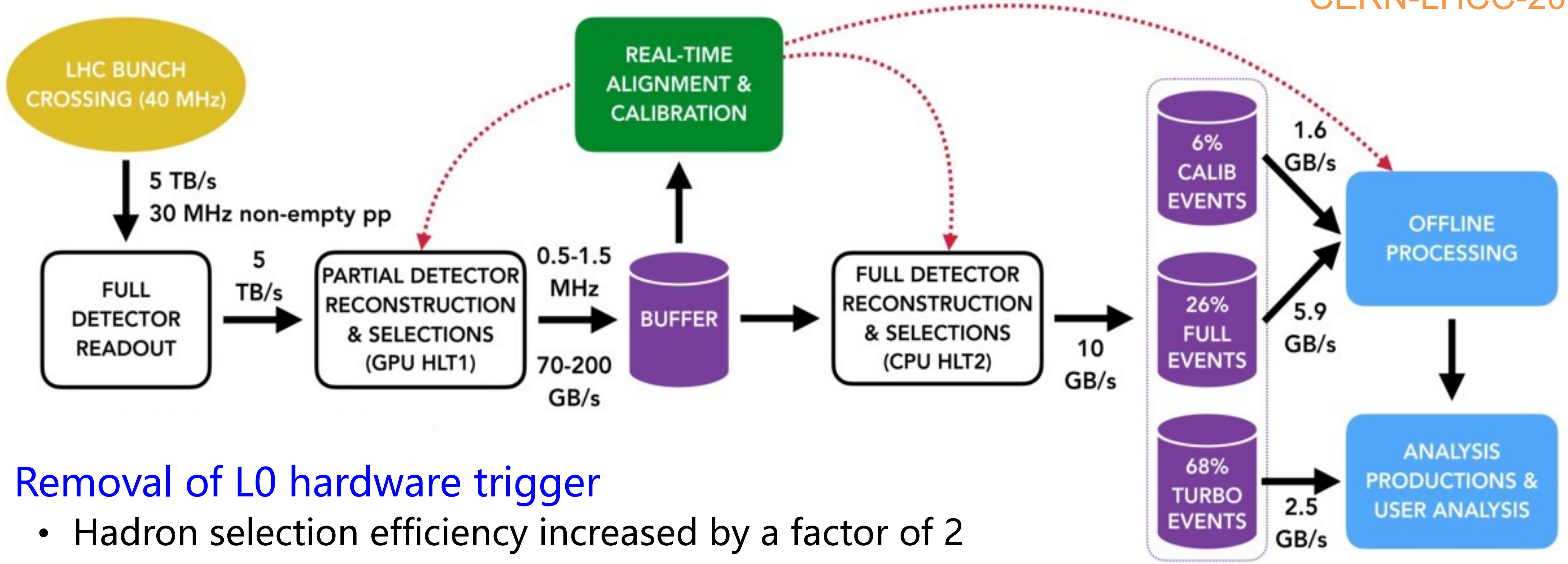
To be upgraded
To be kept



a BIG upgrade for LHCb

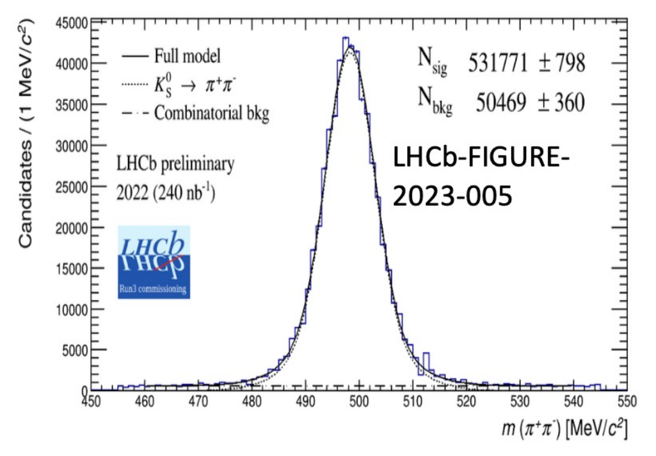
LHCb Upgrade I: Data processing and trigger

CERN-LHCC-2018-007

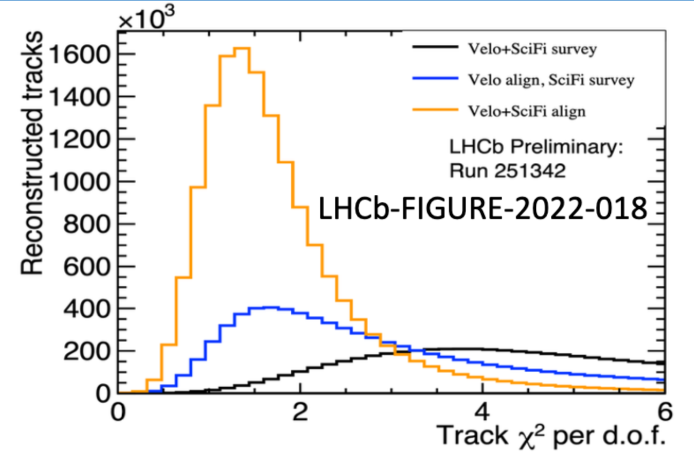


- Removal of L0 hardware trigger
  - Hadron selection efficiency increased by a factor of 2
- HLT1 reconstruction on GPUs
- Real time alignment and calibration
- Offline quality reconstruction in HLT2

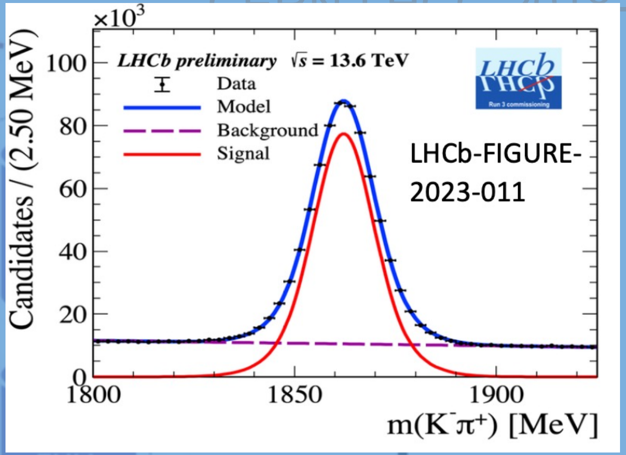
LHCb Upgrade I: Data processing and trigger (cont.)



K_S^0 candidates directly by HLT1



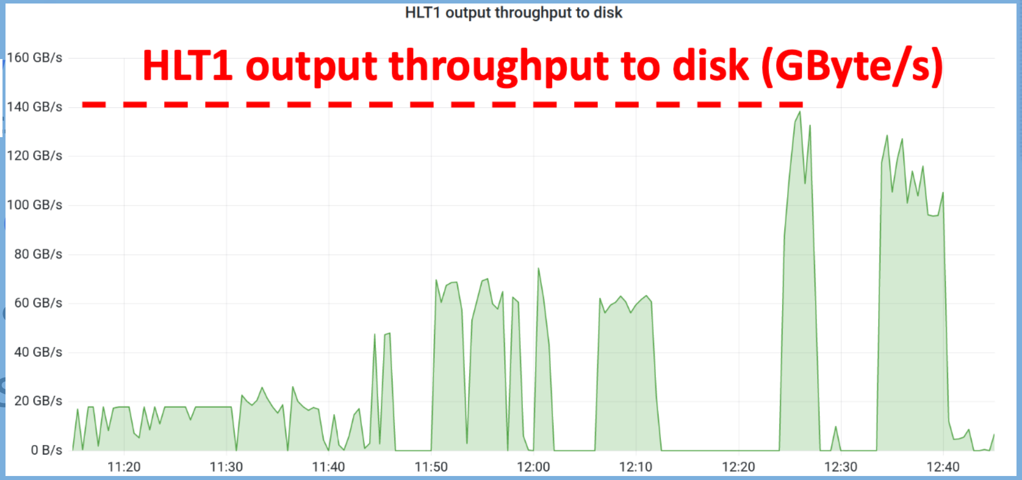
Improvements of distribution of χ^2/ndof for long tracks after alignment



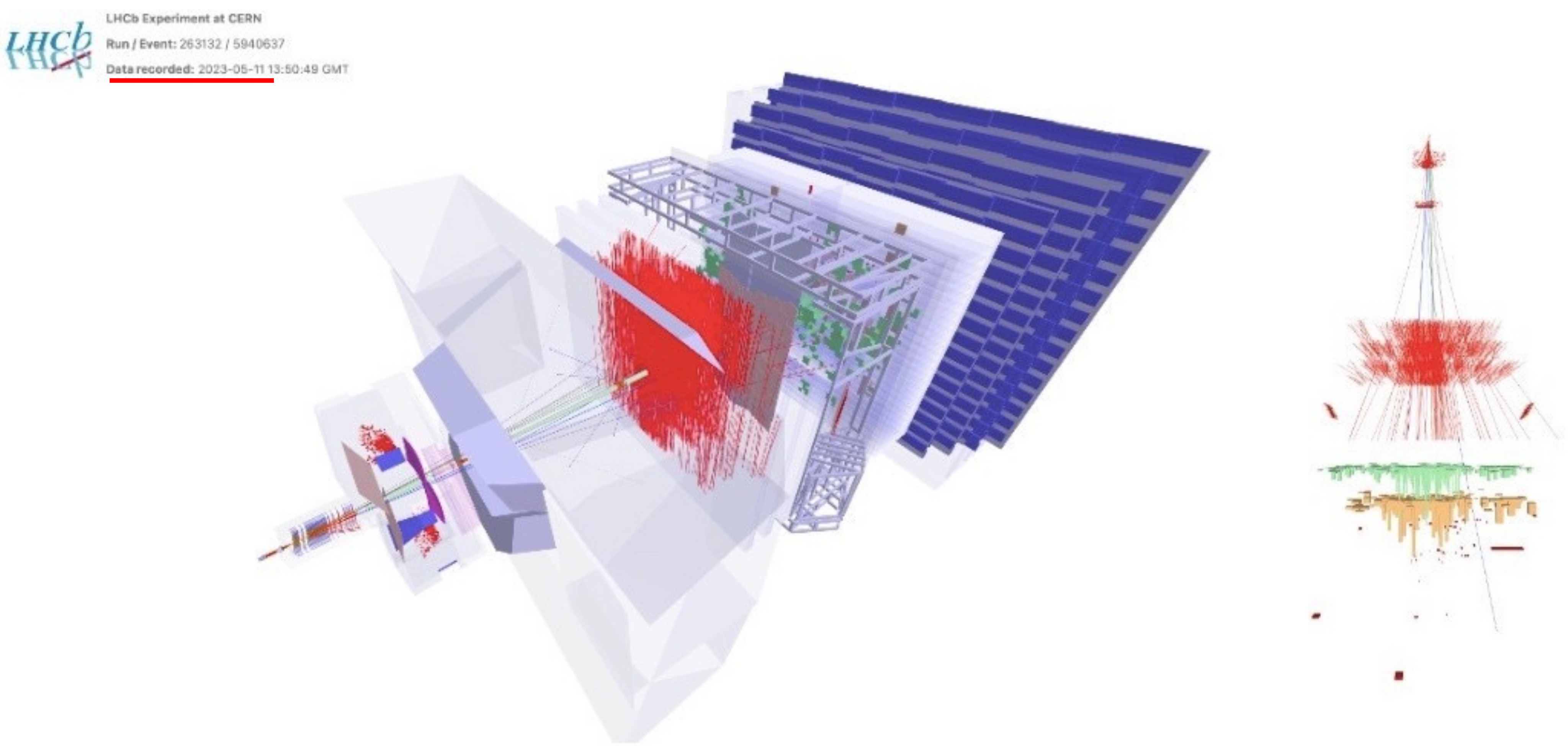
D^0 candidates by HLT2

- Removal of
  - Hadron selection e
- HLT1 reconstruction
- Real time alignment
- Offline quality recons

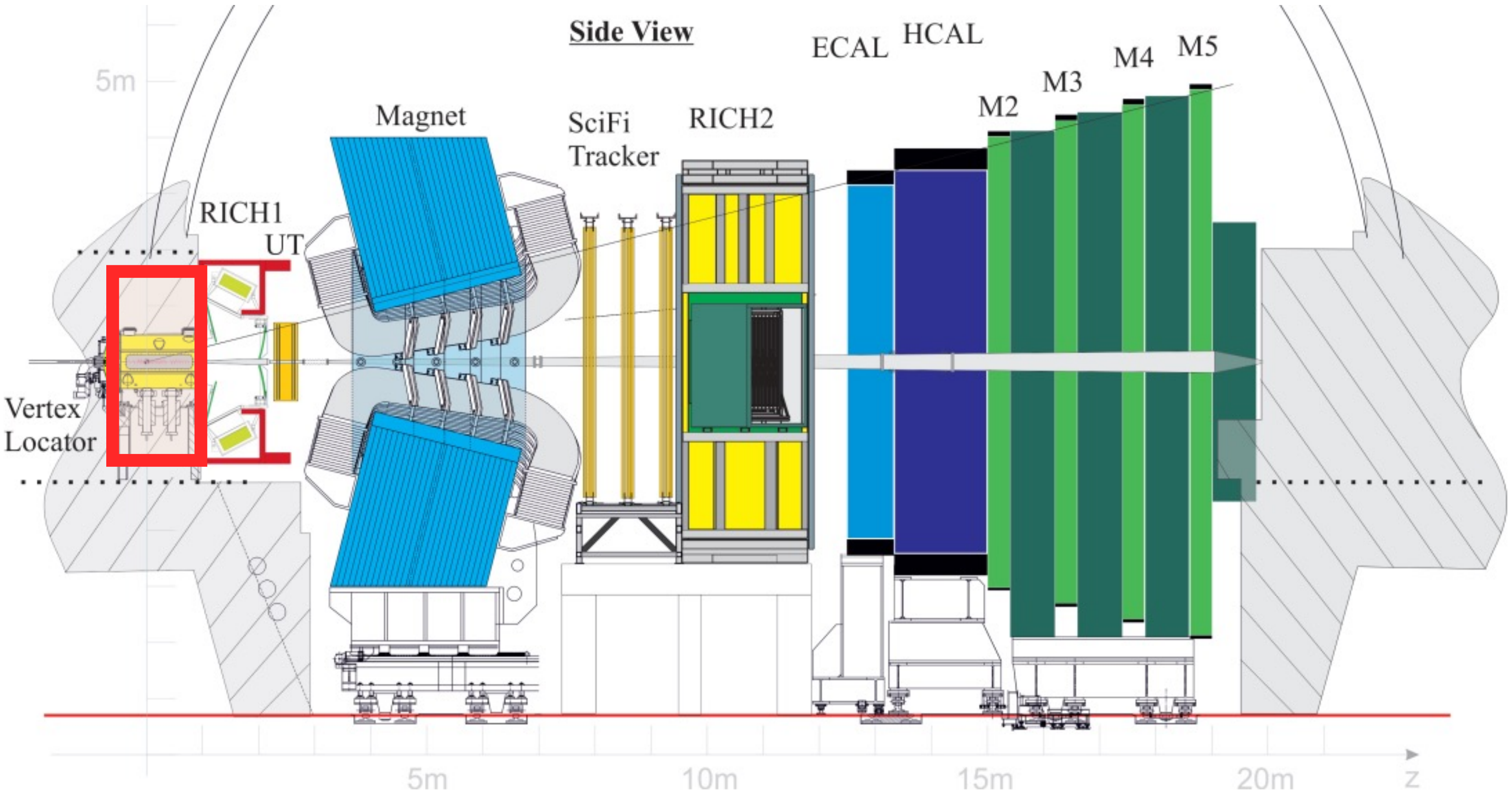
140 GB/s



Event display at 2023: Run 3



LHCb Upgrade I: VELO



Silicon micro-strip → Silicon pixel

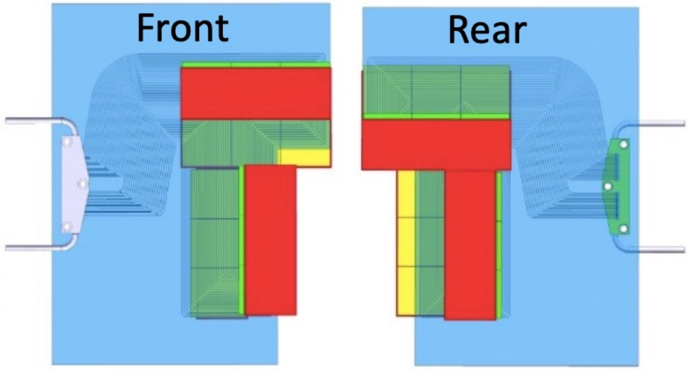
LHCb Upgrade I: VELO

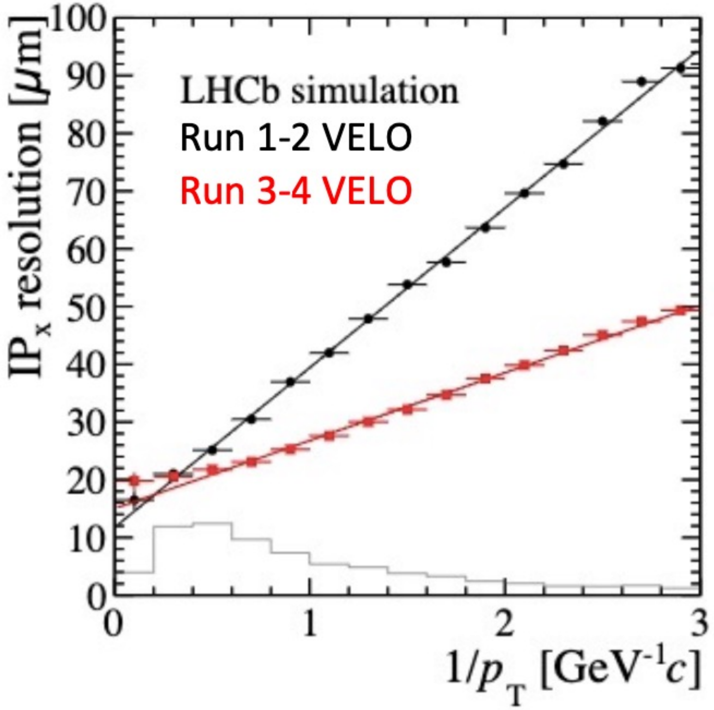
CERN-LHCC-2013-021

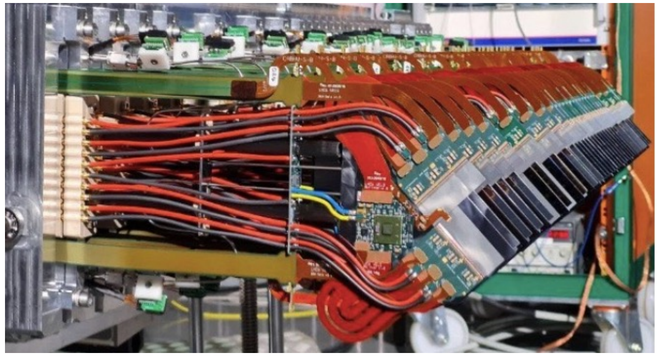
- 52 modules for a total of 41M pixels
  - Area: $1.2\ \mathrm{m}^2$

Silicon pixel detector

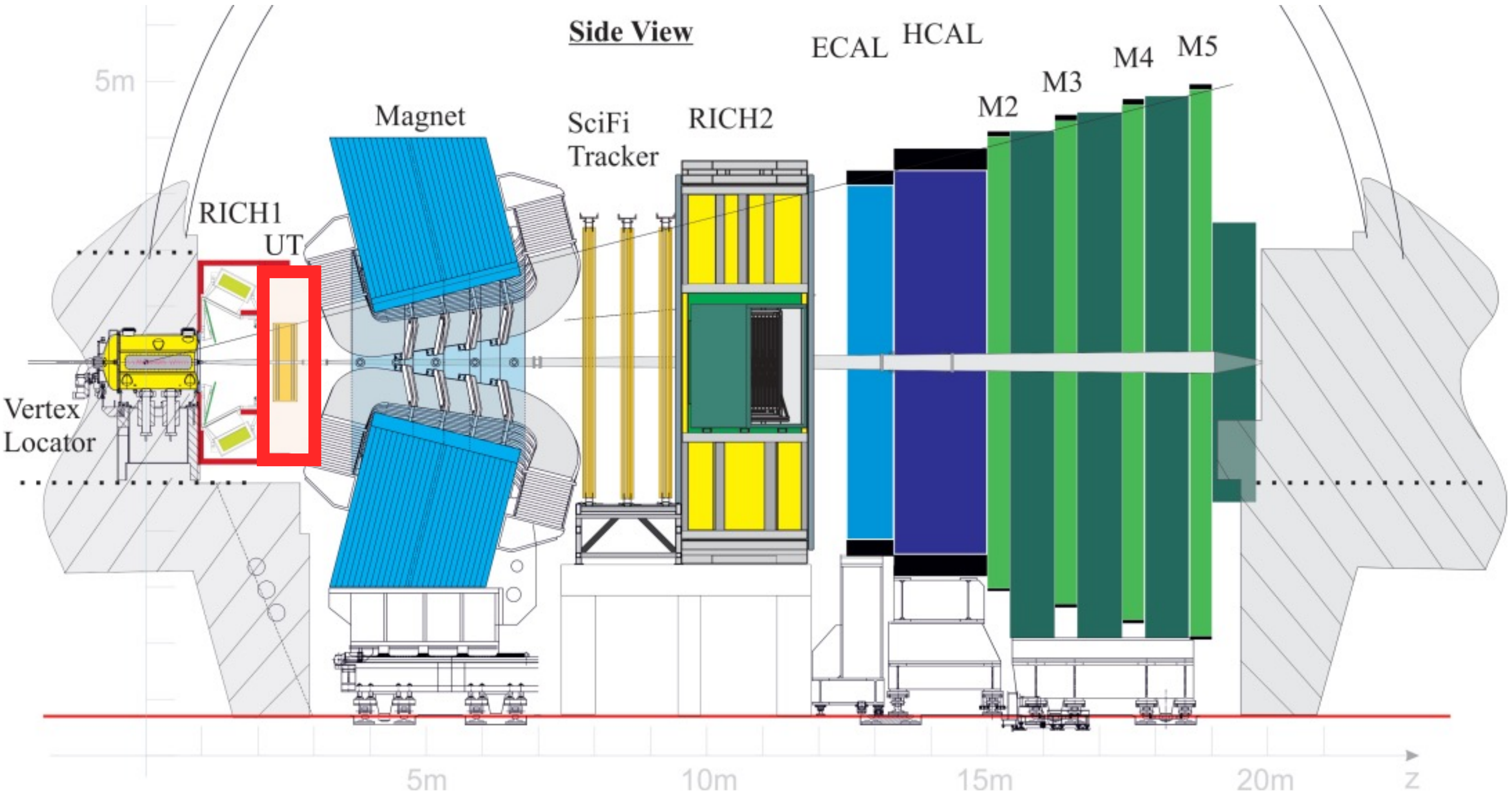
- Two movable halves → as close as $3.5\ \mathrm{mm}$ to the beam to improve σ_{IP}
  - Separation from primary vacuum achieved with $150\ \mu\mathrm{m}$ thick RF foil
- Silicon substrate with micro channels carrying CO_2 for evaporative cooling
  - Designed to cool a load of up to 30W from each module
- New ASIC VeloPix, $\sim 20\ \mathrm{Gbit/s}$ in hottest ASIC and total of $\sim 2\ \mathrm{Tbit/s}$







LHCb Upgrade I: Upstream Tracker (UT)



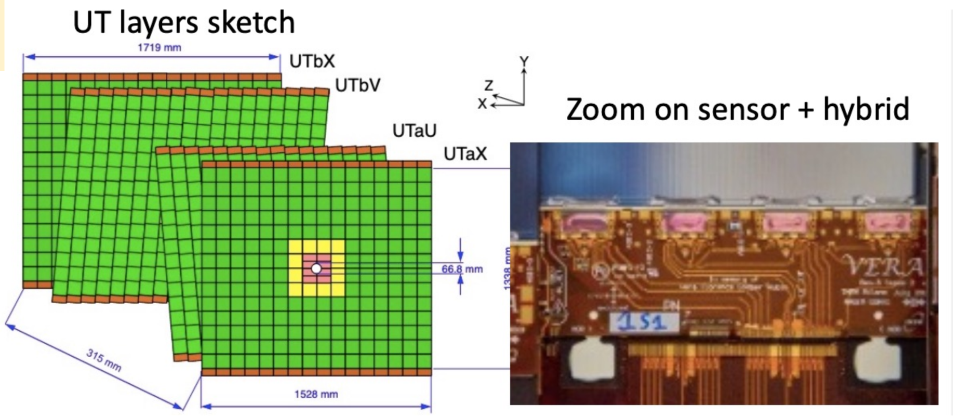
Silicon micro-strip → Silicon micro-strip, but …

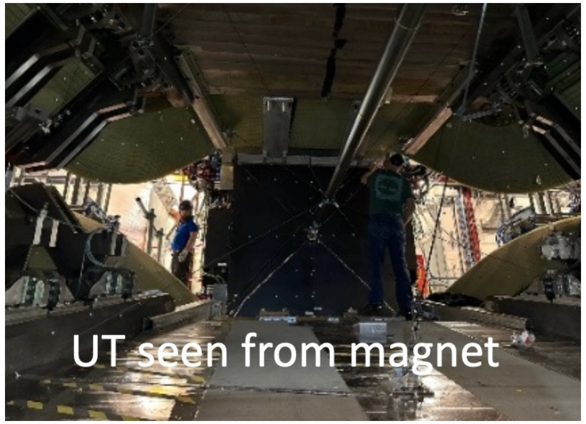
LHCb Upgrade I: UT

CERN-LHCC-2014-001

Silicon micro-strip detector

- Two layers → four layers (aX,aU,bV,bX)
- Increasing granularity getting closer to beam
- Different sensors for different regions
  - $250\ \mu m$ thickness
  - Pitch: $\sim 95 - 190\ \mu m$
  - Sensors mounted on staves (both sides)
  - Maximum occupancy: < 1%
- Sensors need to be kept below $-5℃$
  - Bi-phase CO_2 cooling pipe integrated in stave
- UT installed before cavern closure in 2023 → commissioning ongoing!

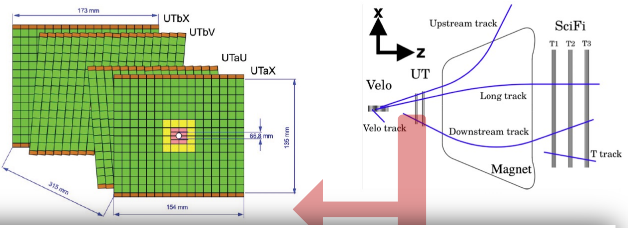


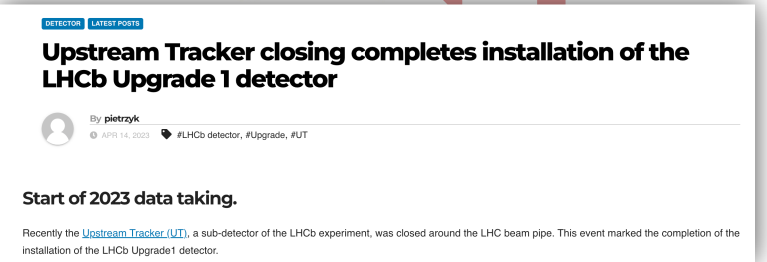


Upgrade I: UT at China

Chinese groups contributed to **UT installation**, ensuring LHCb Upgrade I completion in time (IHEP/HNU/CCNU/THU/SCNU/LZU)

Completion of: a stave / A-side / C-side





DETECTOR LATEST POSTS

Upstream Tracker closing completes installation of the LHCb Upgrade 1 detector

By pietrzyk

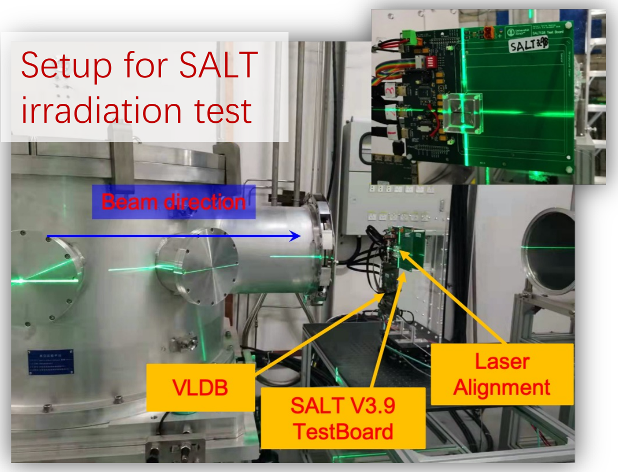
APR 14, 2023 #LHCb detector, #Upgrade, #UT

Start of 2023 data taking.

Recently the Upstream Tracker (UT), a sub-detector of the LHCb experiment, was closed around the LHC beam pipe. This event marked the completion of the installation of the LHCb Upgrade1 detector.

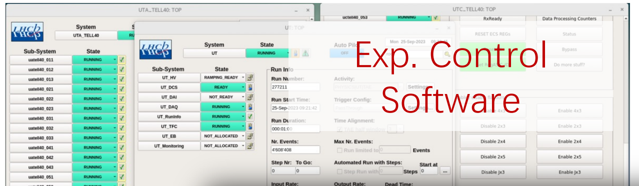
Lead development in control and safety monitoring software (IHEP)

Performed **key radiation tests for SALT chip using Chinese facilities** during pandemic (IHEP/HNU)

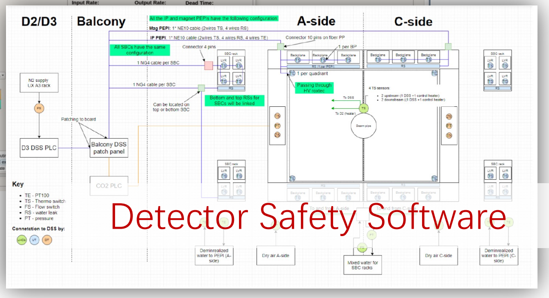


Test at CSNS (Dongguan)

Test at CIAE (Beijing)

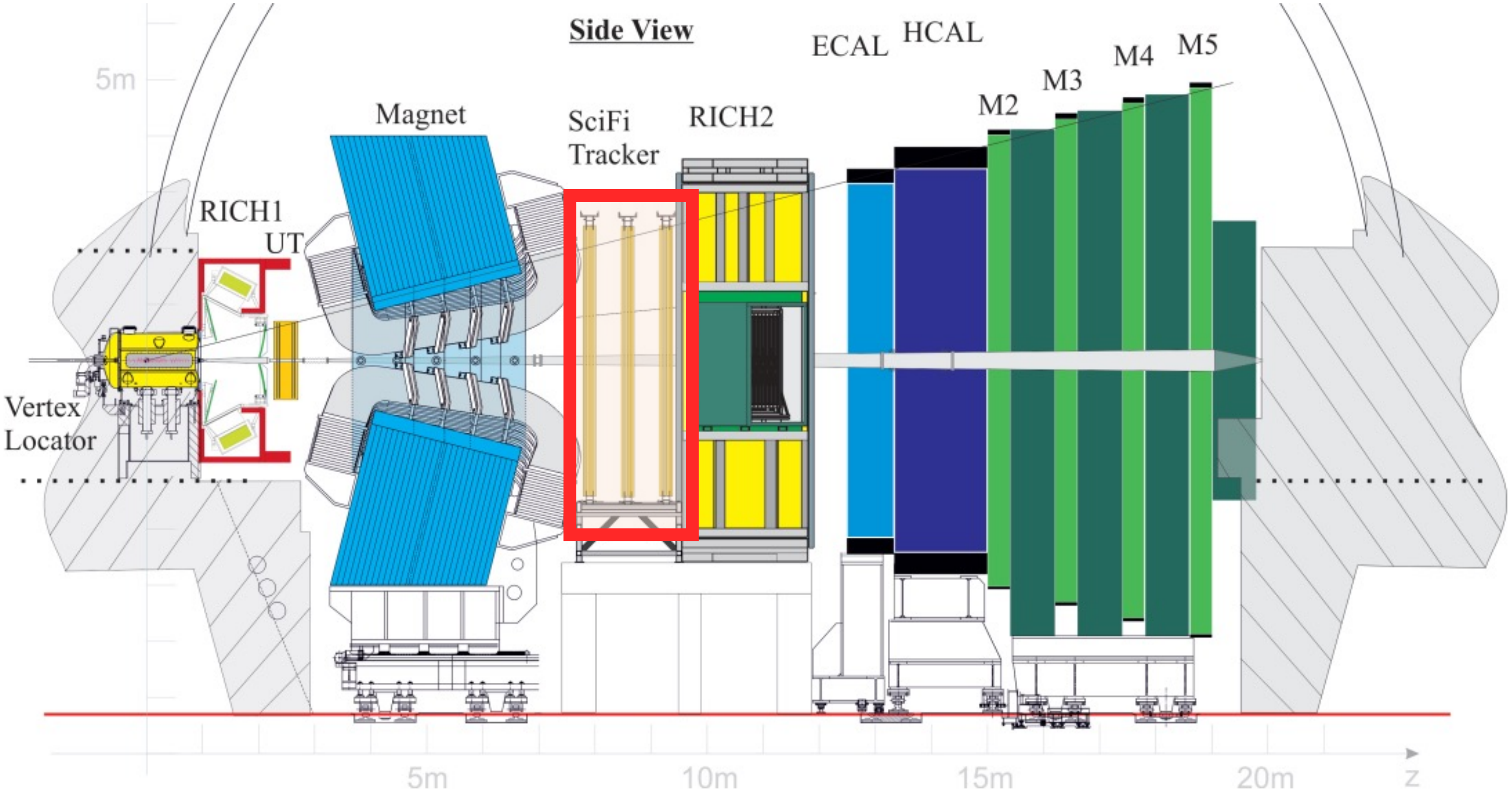


Exp. Control Software



Detector Safety Software

LHCb Upgrade I: Scintillating fibres tracker (SciFi)

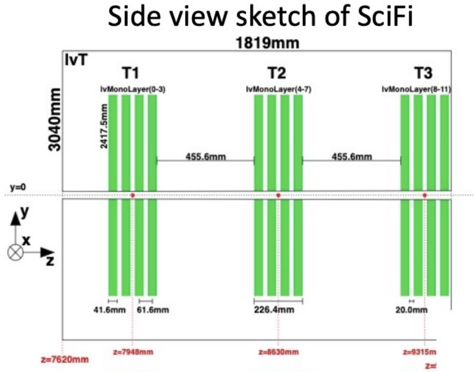


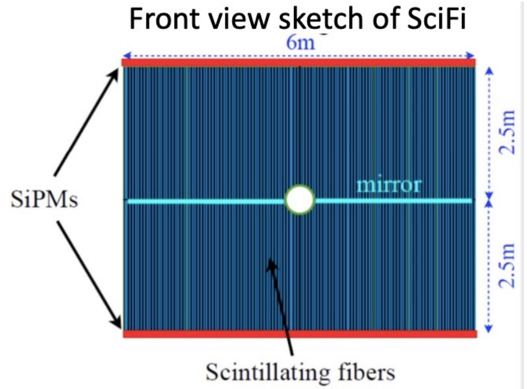
straw-tube drift chambers+Silicon micro-strip → Scintillating fibres tracker

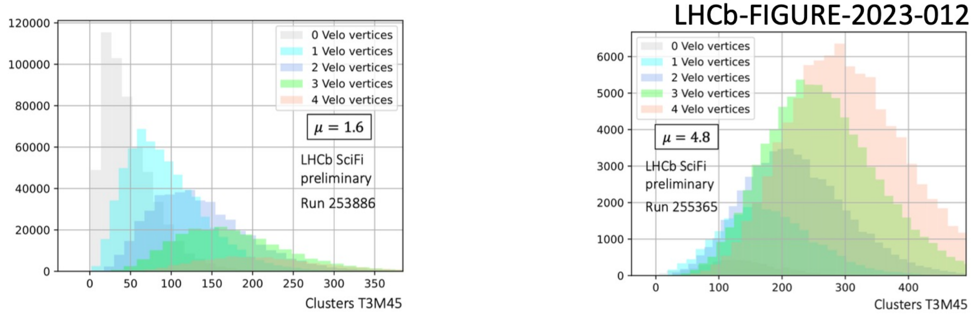
LHCb Upgrade I: SciFi

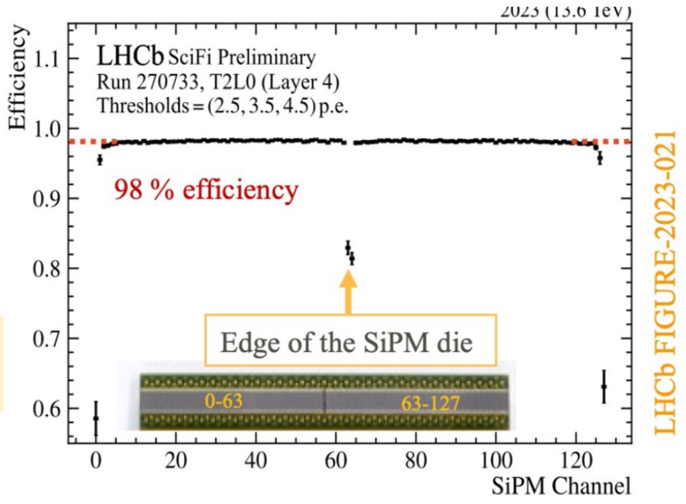
- Brand new detector with scintillating fibres
  - Three stations with four detection layers each, 6 fibres / layer
  - Fibres diameter and length: $250\ \mu m$ / $2.4\ m$
  - Decay-time constant: $2.8\ ns$
  - Produced in total 12000 km of fibres
- Light detected by SiPMs installed at one end of the fibres
  - Temperature $-40°C$ to reduce dark counts
- New ASIC, 64 channels $130\ nm$ CMOS
  - Clusterisation of hits implemented in FPGA after signal digitisation

Good performance in 2023

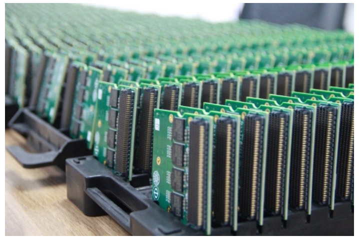






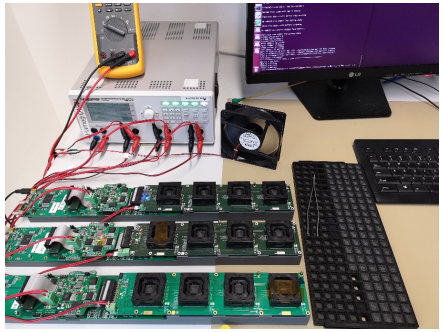


LHCb Upgrade I: SciFi at China



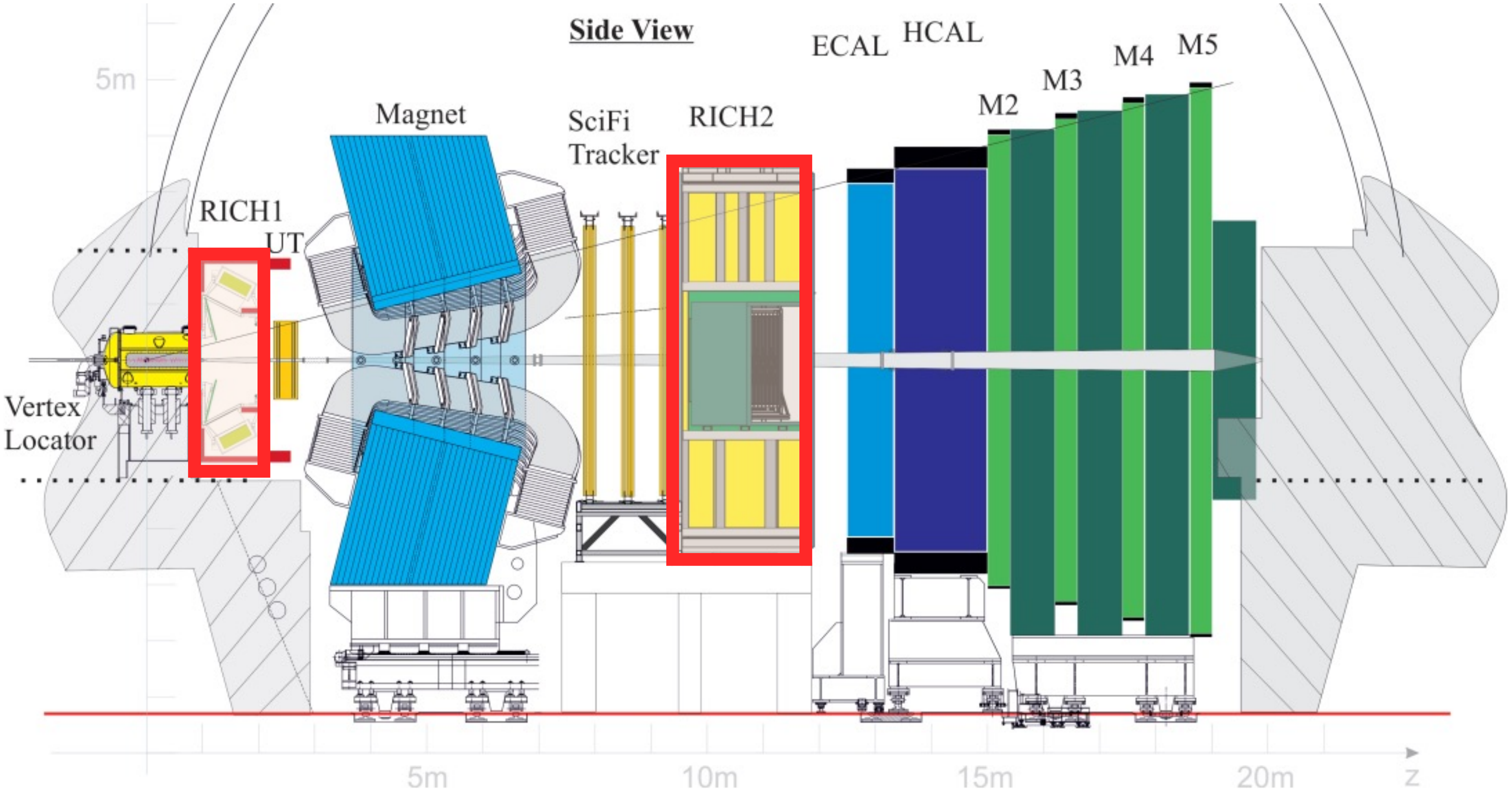
QA System for readout ASICs & the Front-End Board

SciFi: 524,000 SiPM channels
SciFi readout ASIC (PACIFIC): a 64-channel SiPM readout



- **LHCb SciFi China Group (Tsinghua U):**
  - **Co-design the ASIC Frontend Board (with Heidelberg)**
  - **Manufacture all 2,528 ASIC Boards (64,168 channels in total)**
  - **Test 1/2 of ASIC Boards and all the chips**
  - **11 setups of Quality Assurance System for ASICs & boards for LHCb**

LHCb Upgrade I: Rich 1&2



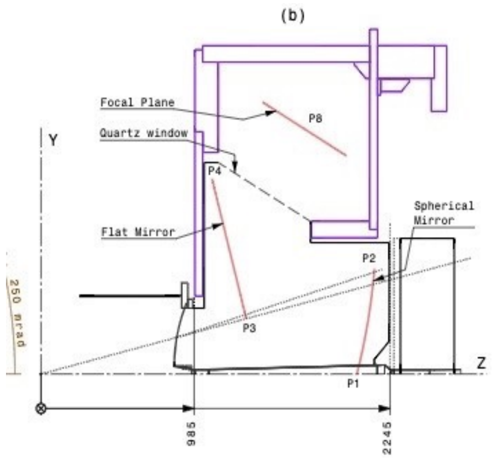
New optics, new PMTs, new readout

LHCb Upgrade I: RICH 1&2

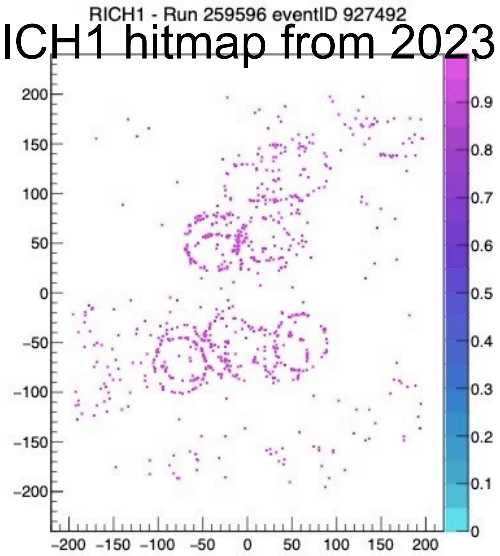
- Preserve excellent performance in Run 1&2
  - RICH1 with $\mathrm{C_4F_{10}}$ and RICH2 with $\mathrm{CF_4}$
  - PID for momenta between 2.6 and 100 GeV/c
- Replace Hybrid Photon Detectors (HPDs) with Multianode PMTs in RICH1&2
  - 26.2 or 52 mm^2 area with 64 pixels
- Change curvature of RICH1 spherical mirrors to reduce occupancy on PMTs
  - factor 2 less
- New radiation hard and fast readout ASIC developed (CLARO)
- RICH 1&2 performance already better than in Run 1&2!

CERN-LHCC-2013-022

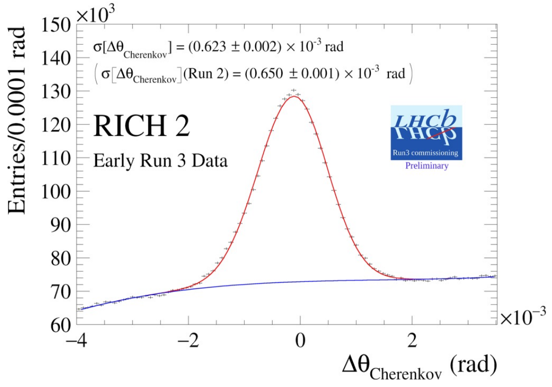
Scheme of new mirrors setup



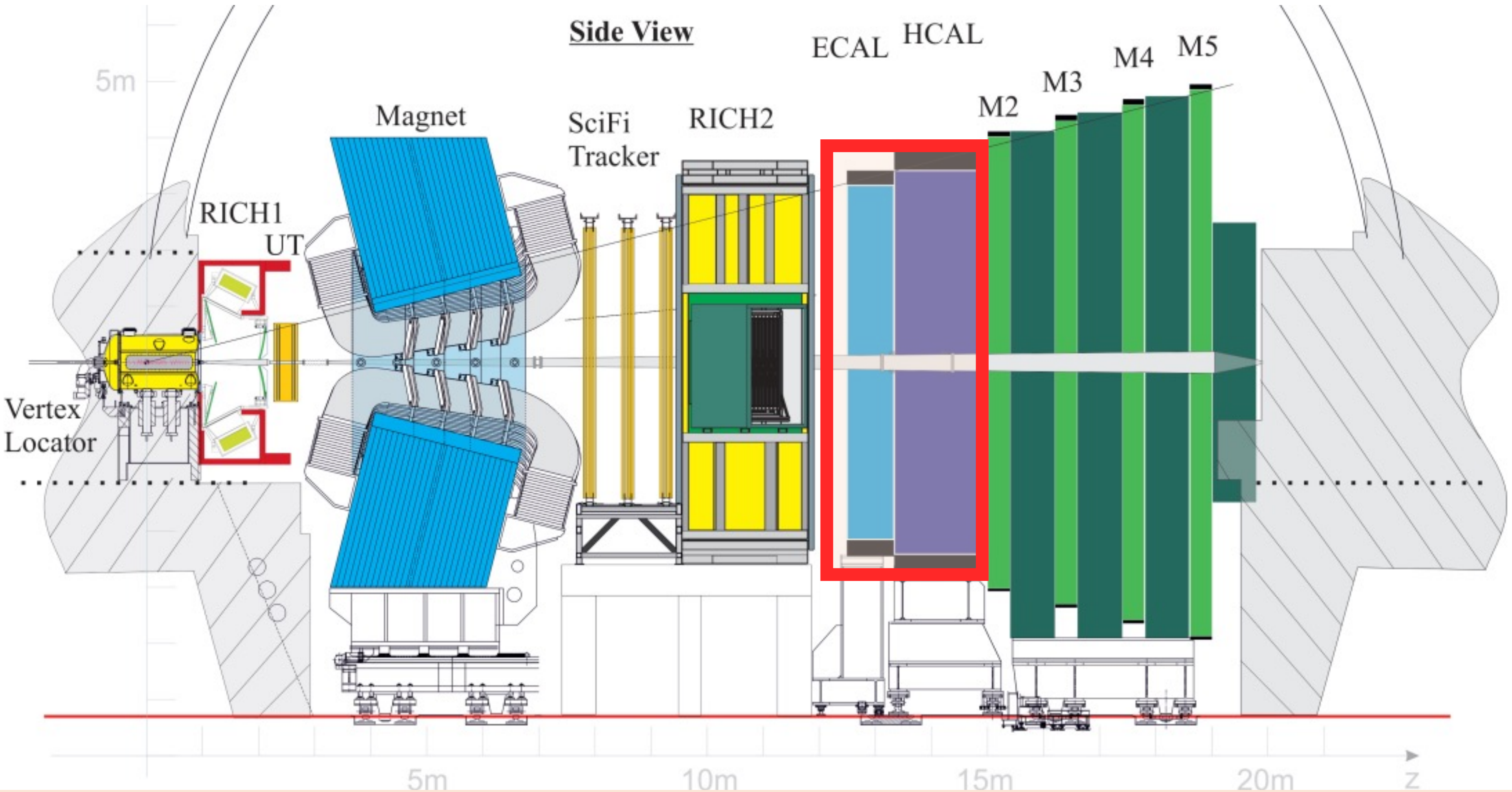
RICH1 hitmap from 2023



LHCb-FIGURE-2023-007



LHCb Upgrade I: ECAL&HCAL



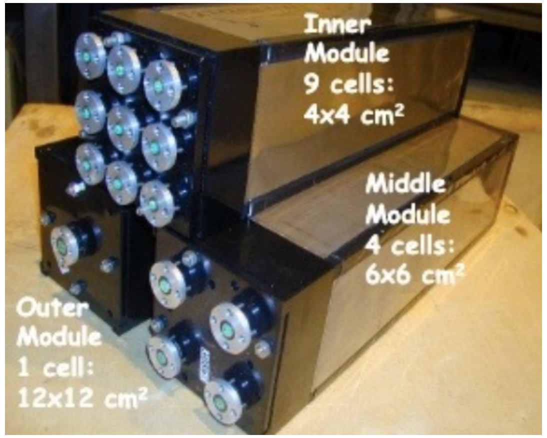
new readout, Preshower (PS) and Scintillating pad detector (SPD) removed

LHCb Upgrade I: ECAL&HCAL

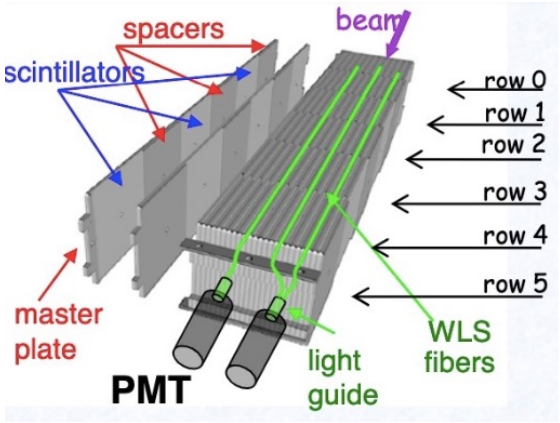
CERN-LHCC-2013-022

- Present detector kept unchanged
  - ECAL: Shashlik modules (lead + scintillator) for a total of $25X_0$
  - HCAL: TileCal modules (iron + scintillator)
- PS/SPD detectors removed
  - No need for fast inputs to L0 hardware trigger
- PMT gain reduced by a factor 5 to increase lifetime of detector
  - Compensated by an equal increase in the electronic amplifier gain
- Front-End electronics redeveloped
  - Trigger-less readout
  - Cope with increased instantaneous luminosity
- Some ECAL inner modules will be replaced already in LS3 to test Upgrade II prototypes in Run 4

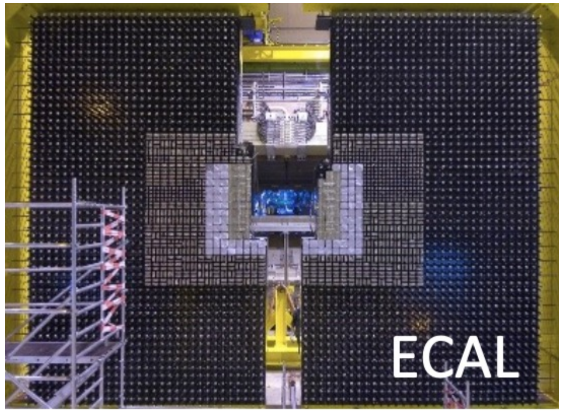
Shashlik modules



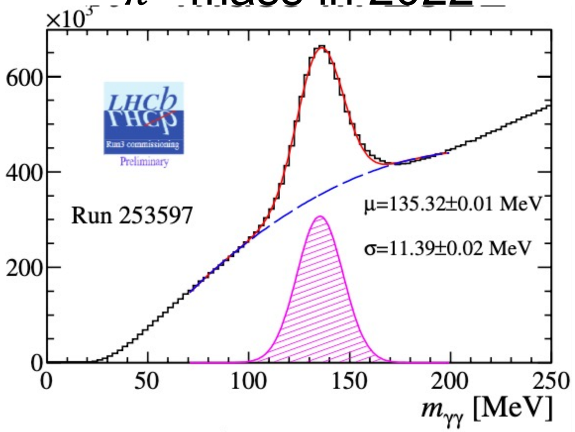
HCAL module



RICH1 hitmap from 2023

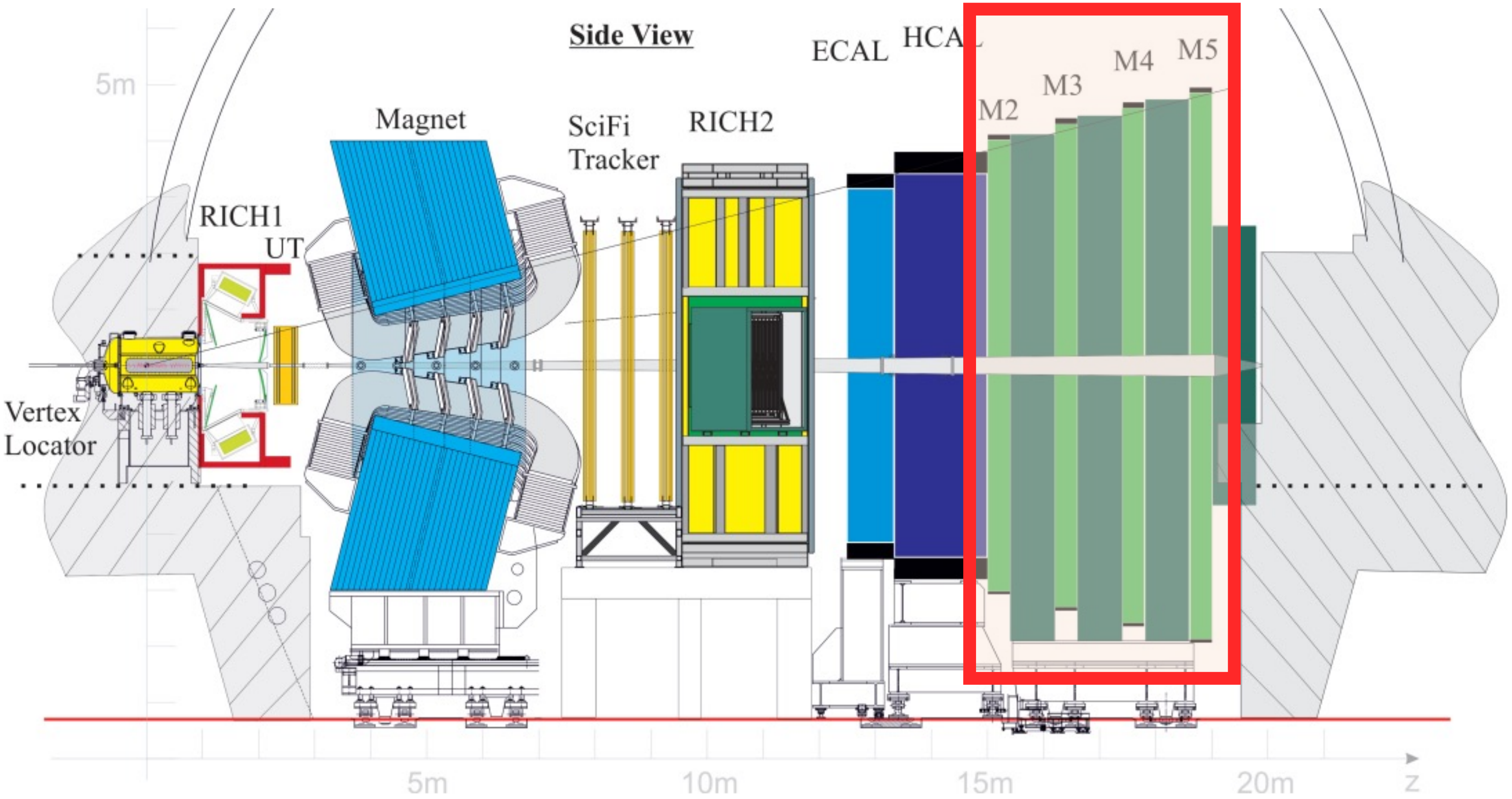


π^0 mass in 2022



LHCb-FIGURE-2022-019

LHCb Upgrade I: MUON

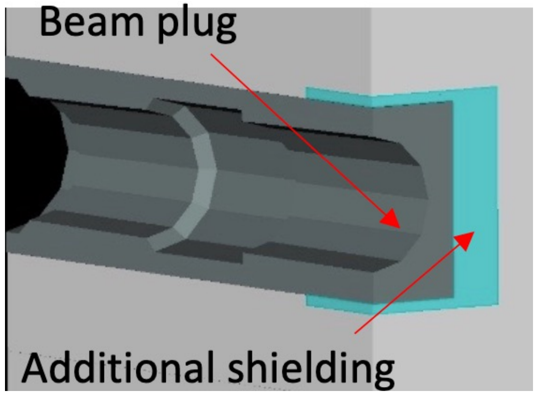


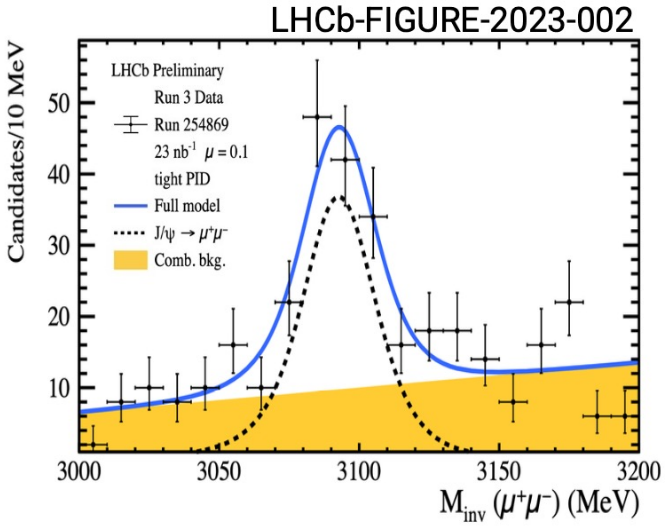
new readout, M1 removed

LHCb Upgrade I: MUON

CERN-LHCC-2013-022

- Remove first layer (M1) with GEMs of present MUON detector
  - since L0 trigger level has been removed
  - The 4 layers (M2-M5) of Multi-Wire Proportional Chambers (MWPCs)
- Install additional shielding around beampipe
  - reduce particle flux in M2 inner region
- Redesign electronics to cope with 40 MHz trigger-less readout
- R&D to replace inner parts of M2 and M3 with more granular detectors (triple GEMs/MWPCs)



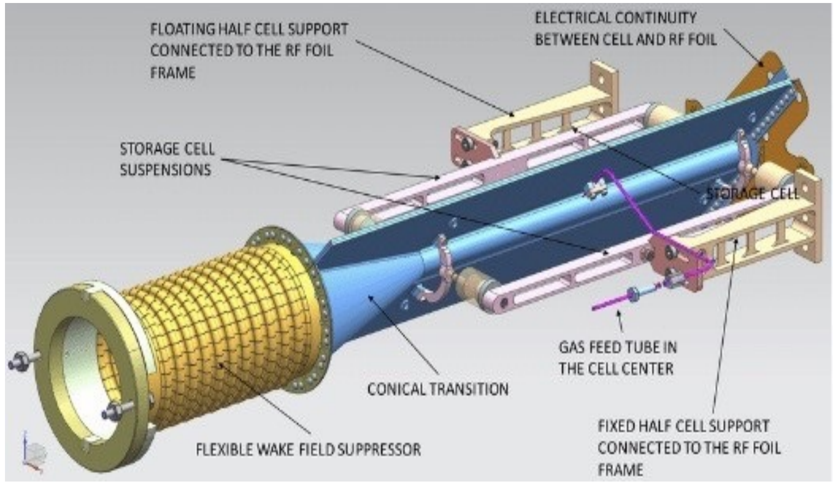


LHCb Upgrade I: SMOG2

CERN-LHCC-2019-005

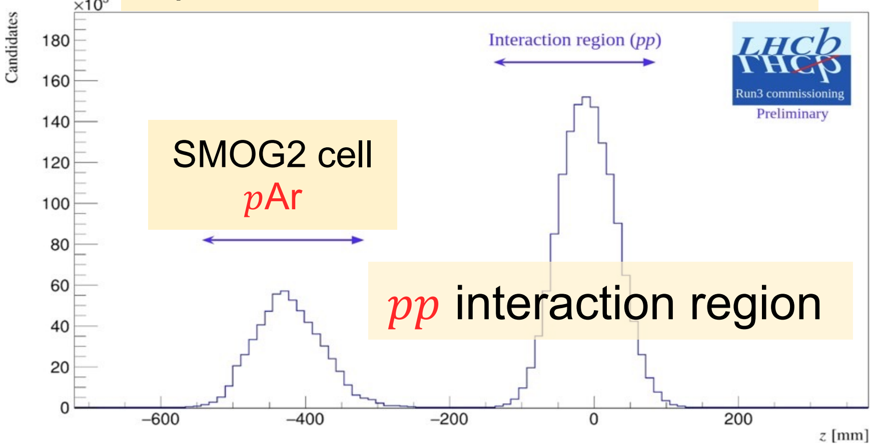
- Allows to inject different gases in LHCb IP
  - Fixed-target physics, in parallel with pp data taking
  - Gas cell upstream of VELO → pp and p-gas vertices easily distinguishable
- Increase interaction rate by orders of magnitude compared with previous SMOG
  - 20-100 times of collected sample size

Sketch of the gas cell



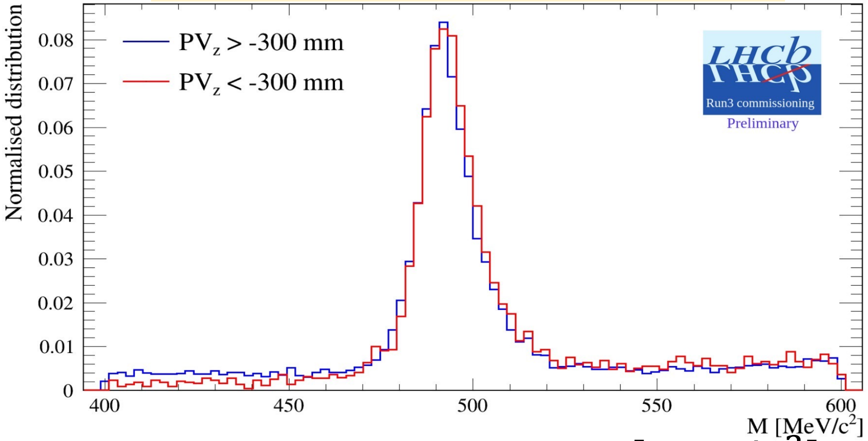
Shashlik modules

z position of reconstructed vertices



z [mm]

K_S^0 reconstructed in pp and pAr



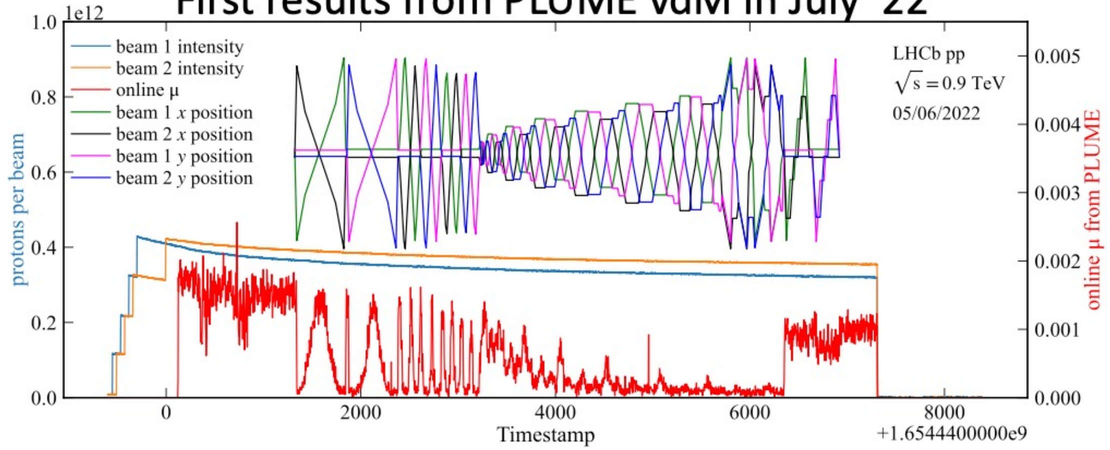
M [MeV/c^2]

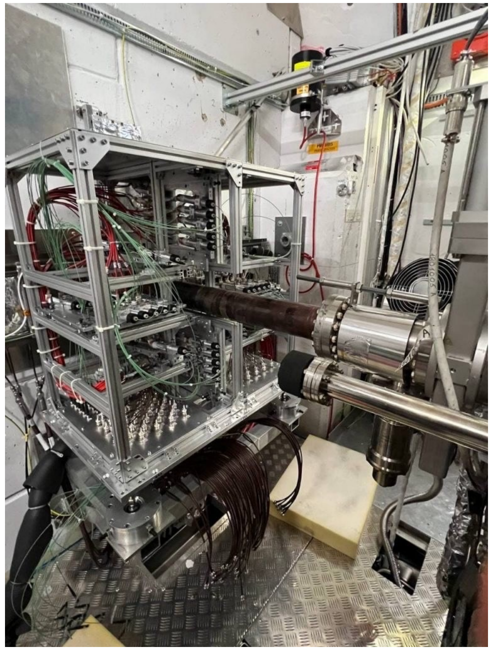
LHCb Upgrade I: PLUME

CERN-LHCC-2021-002

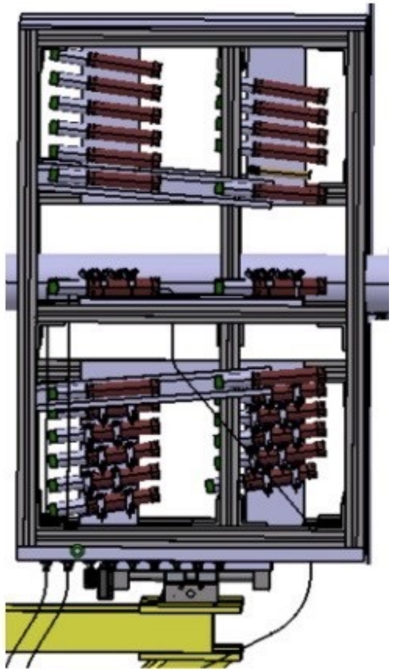
- Cross-shaped hodoscope composed by 48 PMTs, installed upstream of the VELO
  - Detect Cherenkov light from particles impinging on a quartz tablet glued to the PMTs window
- Measure rate of coincidences every 3 sec and compute lumi with logZero method
  - Provide real-time feedback to the LHC to level the luminosity at IP8

First results from PLUME vdM in July ‘22





Lateral view sketch



z [mm]

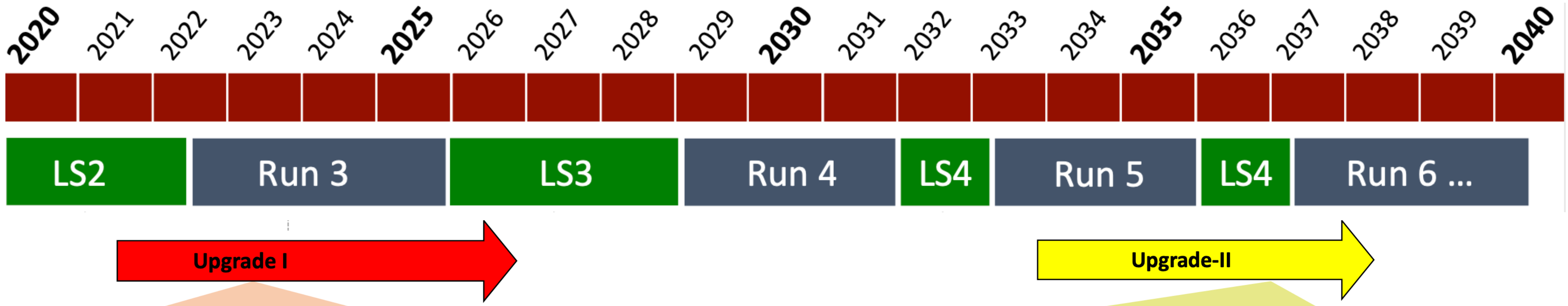
Contents

- Introduction: the past
  - LHCb in Run 1&2
- LHCb Upgrade 1: the present
  - Run 3&4
- LHCb Upgrade II: the future
  - Run 5&6…
- Summary

To fully exploit potential provided by HL-LHC

- Upgrade Ib: partly upgrade central parts of ECAL, SciFi, et al
- Upgrade II: fully upgrade

Challenges



$\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$ **(5×)**

5.5 visible interactions / crossing

Accumulate **50 fb^{-1}** total

Freshly installed!!

$\mathcal{L} = 1.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ **(7.5×)**

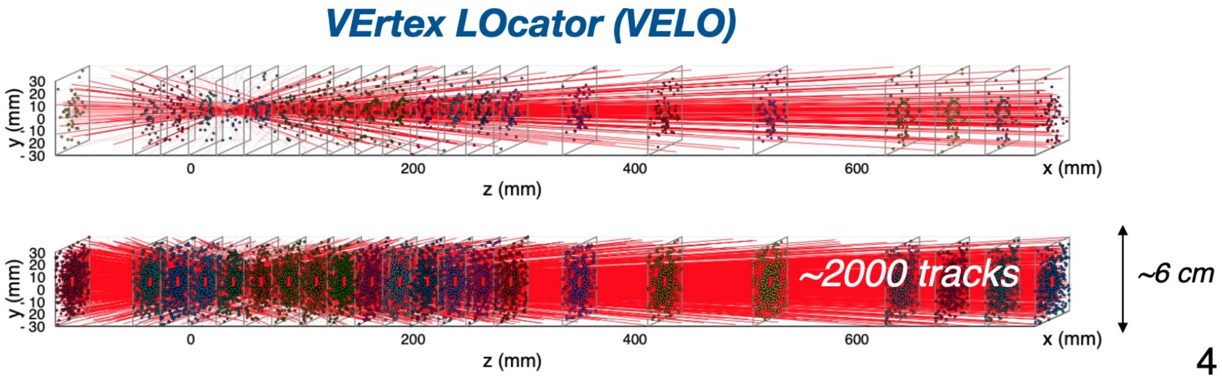
41 visible interactions / crossing

Accumulate **300 fb^{-1}** total

Design & R&D phase

Run 3: pile-up ~6

Upgrade II: pile-up ~40



High pile-ups

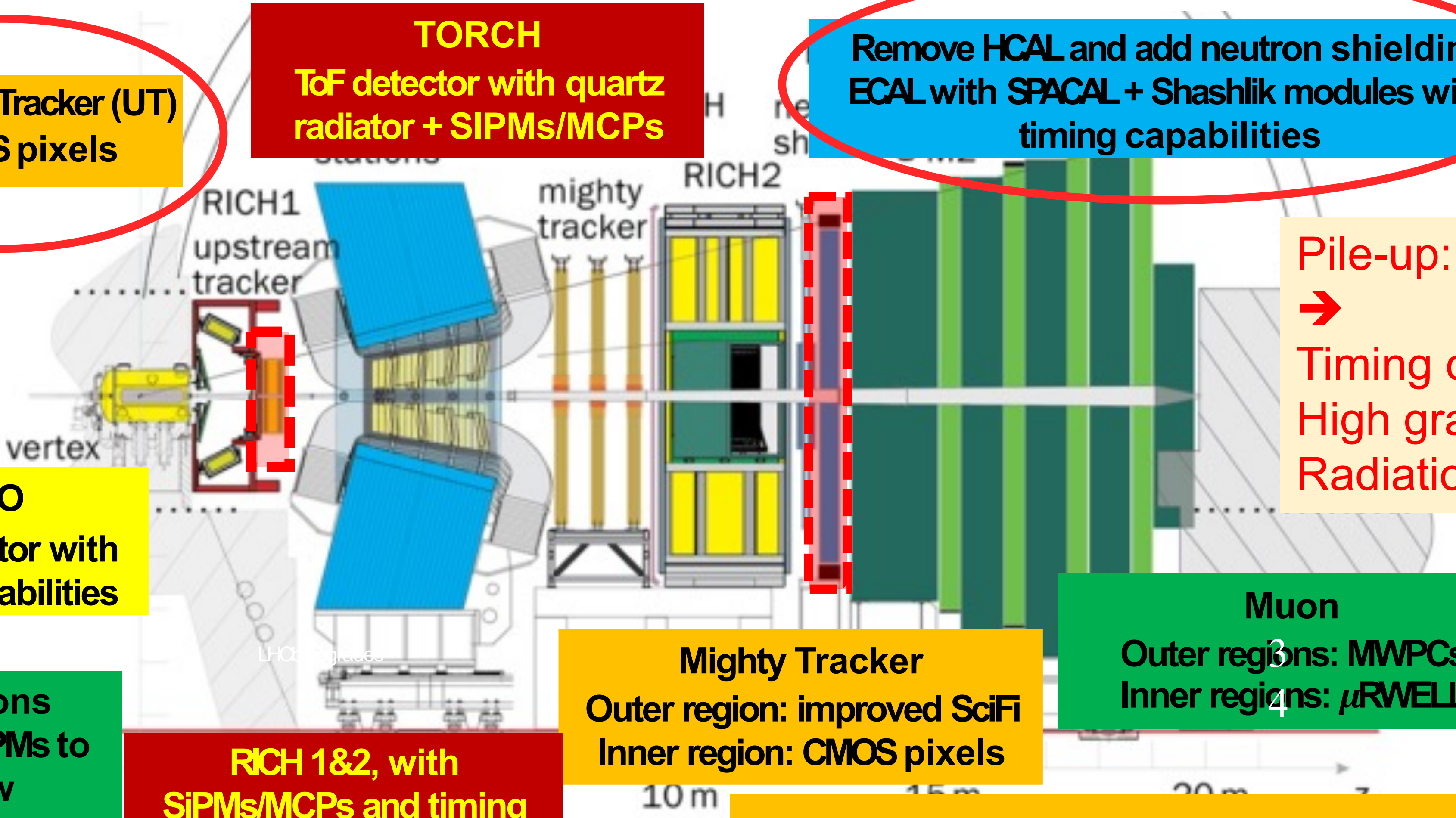
Radiation hardness

…

LHCb Upgrade II: a plan for Run 5&6

CERN-LHCC-2021-012

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

Pile-up: ~ 40
➔
Timing capabilities
High granularity
Radiation hardness

VELO
Pixel detector with timing capabilities

Magnet Stations
Scintillators + SiPMs to improve low momentum acceptance

RICH 1&2, with
SiPMs/MCPs and timing capabilities

Mighty Tracker
Outer region: improved SciFi
Inner region: CMOS pixels

Muon
Outer regions: MWPCs
Inner regions: μRWELL

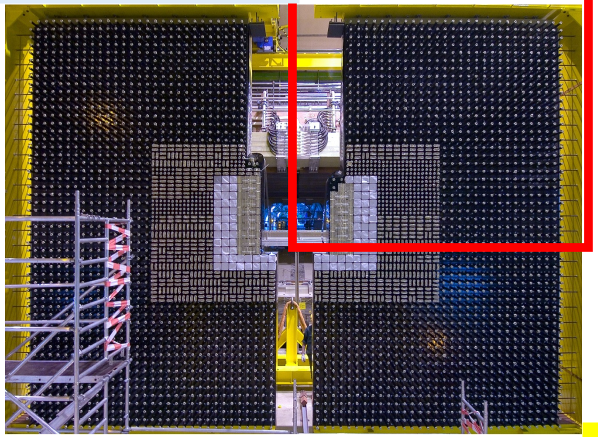
$\mathcal{L}_{\text{inst}} = (1-2)\times10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ ($\times(5-10)$ w.r.t. Run 3)

LHCb Upgrade Ib+II at China: ECAL

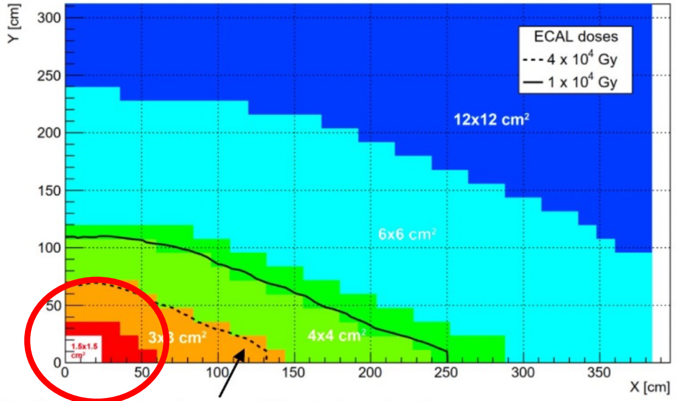
- Requirement: to operate up to $\mathcal{L} = 1.5\times10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
  - Keep current energy resolution: $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$
  - Sustain radiation doses up to 1 MGy
  - Mitigate high occupancy and pile-up

High granularity
Time resolution of $\mathcal{O}(10)$ ps

Current ECAL



New layout for Ib/II

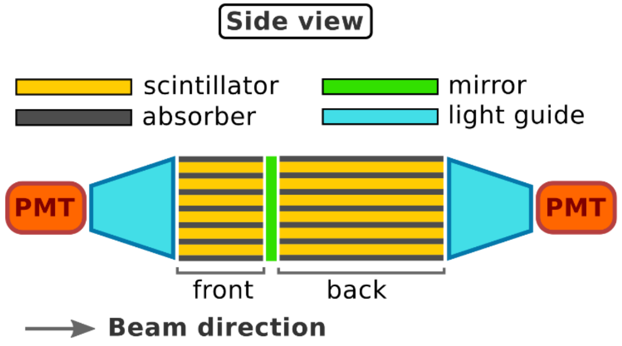


Radiation limit of current Shashlik technology

Inner region

Spaghetti Calorimeter (SPACAL)

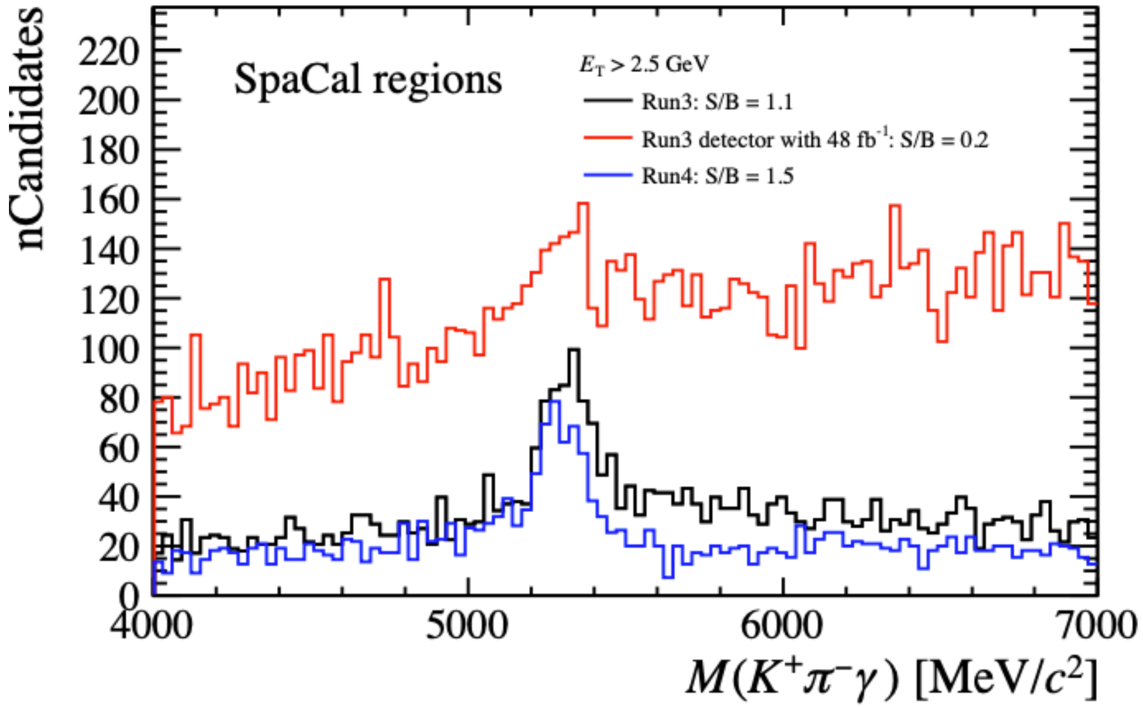
SPACAL-W (tungsten) for the most inner region



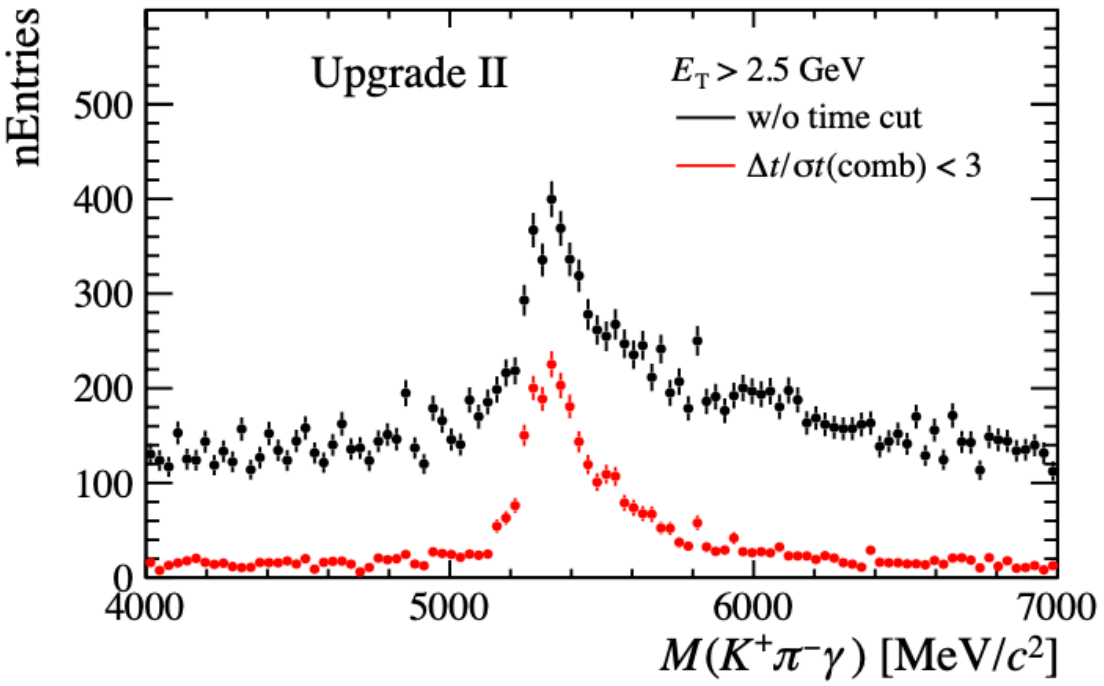
Physical benchmarking simulation

➢Example: $B^0 \to K^{*0}\gamma$

[LHCb-TDR-024]



[LHCb-TDR-023]

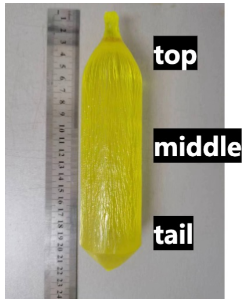


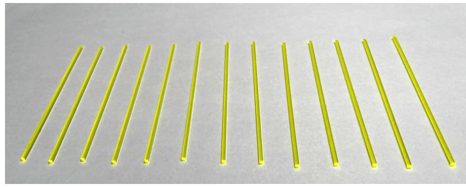
- Upgrade Ib ECAL has better performance than current ECAL
- Time resolution $\mathcal{O}(10)$ ps important to suppress the background

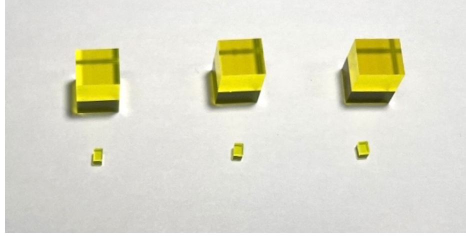
LHCb Upgrade Ib+II at China: **GAGG crystal**

➢ **R&D of fast Cerium-doped Gadolinium Aluminum Gallium Garnet (GAGG) crystal (< 25 ns) with SIPAT in Chongqing**

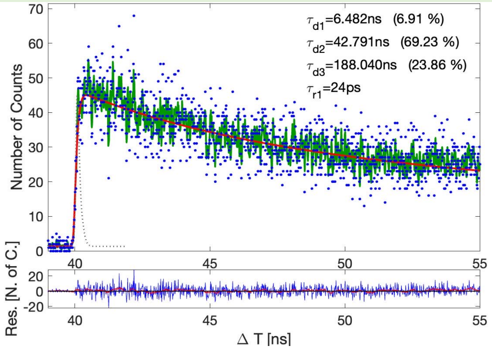
GAGG from SIPAT







Decay time measured at CERN



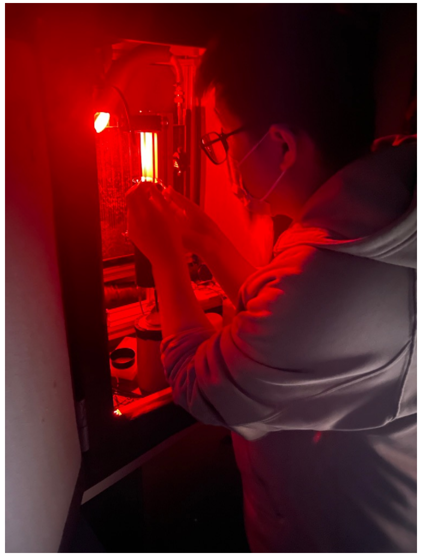
Decay time for different batches

Table 2: Scintillation rise time (τ_r), three decay times (τ_{d1}, τ_{d2}, τ_{d3}), and relative intensities of the corresponding

Batch1 Top2 #4424	62	9.2	6.2	54	68.7	267	25.1	49
Batch1 Top7 #4425	83	7.8	5.8	54	69.1	242	25.1	47
Batch1 Middle7 #4426	47	6.2	5.0	46	64.5	149	30.5	41
Batch1 Middle8 #4427	16	7.3	6.5	49	68.8	180	24.7	41
Batch1 Tail3 #4428	24	6.5	6.9	43	69.2	188	23.9	36
Batch1 Tail8 #4429	87	7.7	8.7	46	70.3	210	21.0	36
Batch2-ingot1 Top5 #4474	23	7.0	5.3	48	66.6	162	28.1	43
Batch2-ingot1 Top7 #4475	27	7.1	5.3	46	62.9	134	31.8	43
Batch2-ingot1 Middle1 #4476	28	6.4	6.7	47	70.5	172	22.8	37
Batch2-ingot1 Middle3 #4477	21	4.9	4.6	43	65.4	147	30.0	37
Batch2-ingot1 Tail6 #4478	26	5.4	6.7	42	70.5	206	22.9	33
Batch2-ingot1 Tail7 #4479	27	4.8	6.8	40	69.1	134	24.1	30
Batch2-ingot2 Top4 #4492	17	3.8	6.7	30	59.5	101	33.8	25
Batch2-ingot2 Top7 #4493	7	4.5	8.3	34	67.8	139	23.9	25
Batch2-ingot2 Middle2 #4494	21	5.0	8.6	36	69.1	134	22.4	26
Batch2-ingot2 Middle7 #4495	10	5.3	8.1	36	65.2	128	26.7	28
Batch2-ingot2 Tail5 #4496	11	3.6	8.8	29	66.0	124	25.3	20
Batch2-ingot2 Tail6 #4497	10	4.1	10.4	30	67.6	138	22.0	20

Decreasing

Measuring light yield



Decay times from 50 ns down to 25 ns, expect to finalise soon

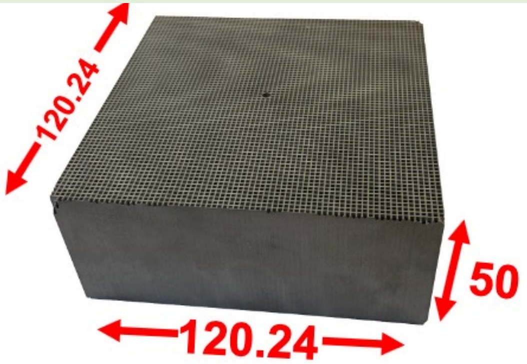
LHCb Upgrade Ib+II at China: **absorber**

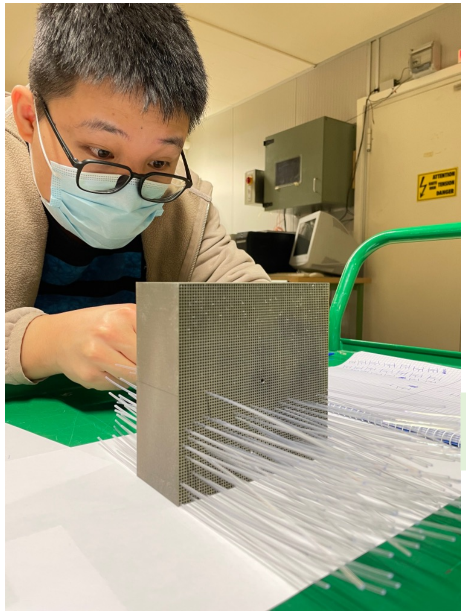
- 3D-print tunsten (W) absorber with LaserAdd in Zhuhai

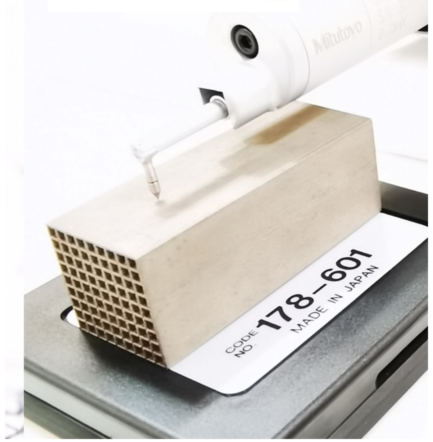
Module size: $121 \times 121 \times 5\ \mathrm{mm}^3$
5180 square holes of $1.2 \times 1.2\ \mathrm{mm}^2$

Small modules printed by LaserAdd

Full-size module printed by LaserAdd





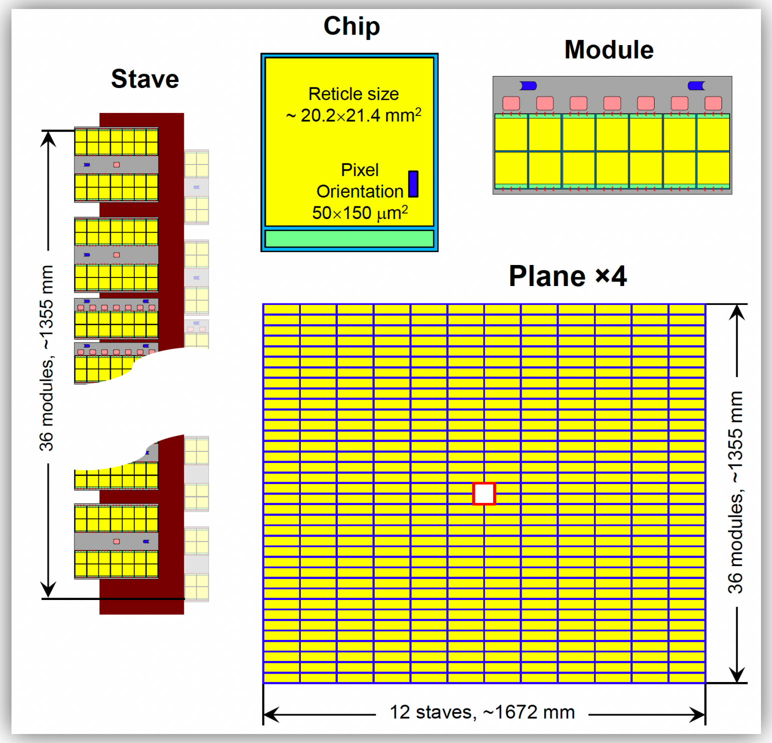


Roughness measurement at PKU

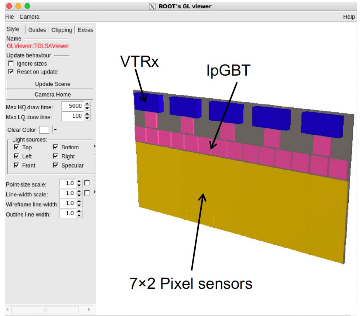
Similar quality as EOS produced in Germany

LHCb Upgrade 1b+II at China: **UT**

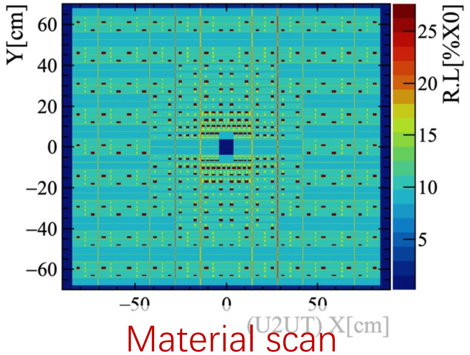
- ➢Leading the R&D for CMOS-based UT upgrade
- ➢Proposal of system design accepted in Framework TDR
- ➢Jianchun Wang (IHEP) appointed as UT deputy project leader for UII



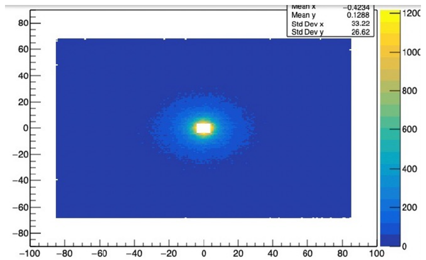
Design of CMOS-based UT upgrade



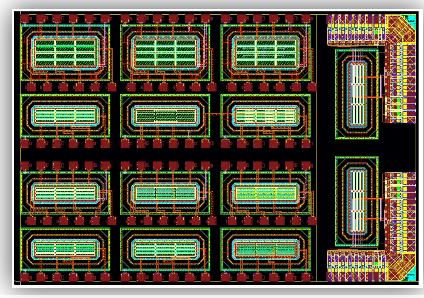
Detector modelling



Material scan



Simulation of hits in Run 5/6 condition



HVCMOS design for MPW using 55nm process

Prospects for Upgrade I and Upgrade II

CERN-LHCC-2021-012

- Collect $50\ \mathrm{fb}^{-1}$ by end of Run 4 and $300\ \mathrm{fb}^{-1}$ by end of Run 6
  - $9\ \mathrm{fb}^{-1}$ Collected in Run 1&2
- Aim at keeping same performance (or better) with Upgrades
- Several flagship measurements still statistically dominated and with uncertainty on predictions negligible compared to the experimental knowledge → great potential!

	Run 1-2		Run 3-4		Run 5-6
Observable	Current LHCb (up to $9\,\mathrm{fb}^{-1}$)		Upgrade I ($23\,\mathrm{fb}^{-1}$)	Upgrade I ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	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%	[29, 30]	3%	2%	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[37]	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%	[40, 41]	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	[52]	0.060	0.043	0.016
$A_{\mathrm{T}}^{\mathrm{Im}}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

Summary

- ➢ The past: A very successful operation leading to excellent results
  - Physics program expanded well beyond original expectation: heavy-ion, fix-target, EW, …
- ➢ The present: LHCb Upgrade I
  - A first major upgrade during LS2 → brand new detector
    - Removal of L0 hardware trigger
    - High-level software trigger running at 30 MHz on GPUs
    - New trackers (VELO, UT, SciFi)
    - Upgraded RICH 1&2 with new photodetectors and readout electronics
    - ECAL, HCAL and MUON upgraded with new readout electronics
    - New fixed-target system (SMOG2) to inject various gases
    - New dedicated luminometer (PLUME)
- ➢ The future: LHCb Upgrae Ib&II
  - Replace some parts close to beam for Upgrade Ib during LS3
  - A second major upgrade during LS4: timing, granularity, radiation resistance, …
  - Many R&D ongoing in China: ECAL, UT
    - GAGG crystal, 3D-print tungsten absorber, CMOS, …

Thanks!