LHCb Upgrades

Mark Tobin
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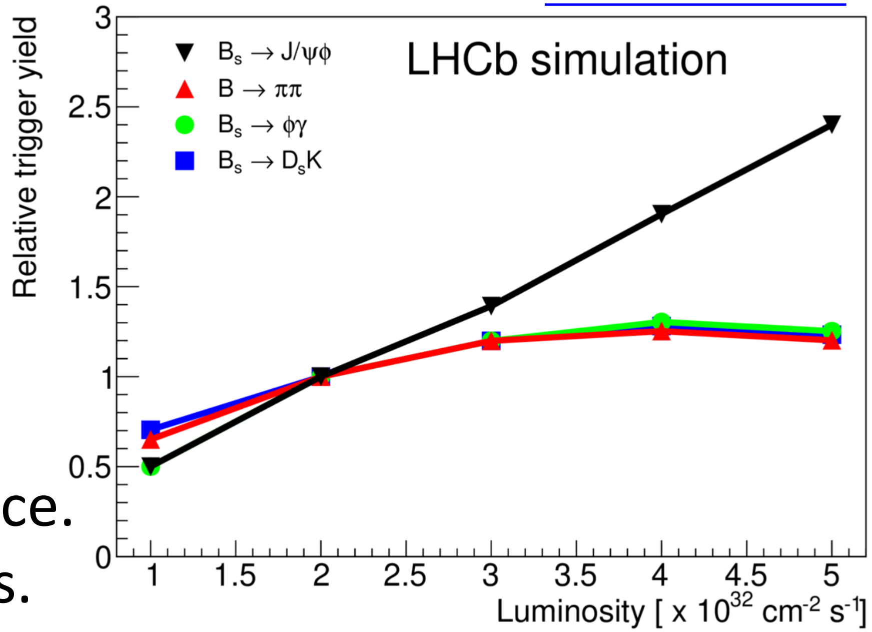
Chinese Academy of Sciences & CERN
On behalf of the LHCb collaboration

Why upgrade?

- Dedicated heavy flavour experiment at LHC.
  - No observation of New Physics in LHC Runs 1 & 2.
- Many measurements are statistically limited.
  - More data to further challenge theoretical predictions.
  - Precision tests with very rare decays (BR < 10^{-9}).
- Limited by Level-0 hardware trigger.
  - Maximum rate is 1.1 MHz.
- Higher luminosities:
  - Trigger yield saturates.
  - Harder cuts on E_T and p_T.
  - No real gain in statistics.
- Higher occupancy.
  - Degraded detector performance.
  - Radiation damage of detectors.

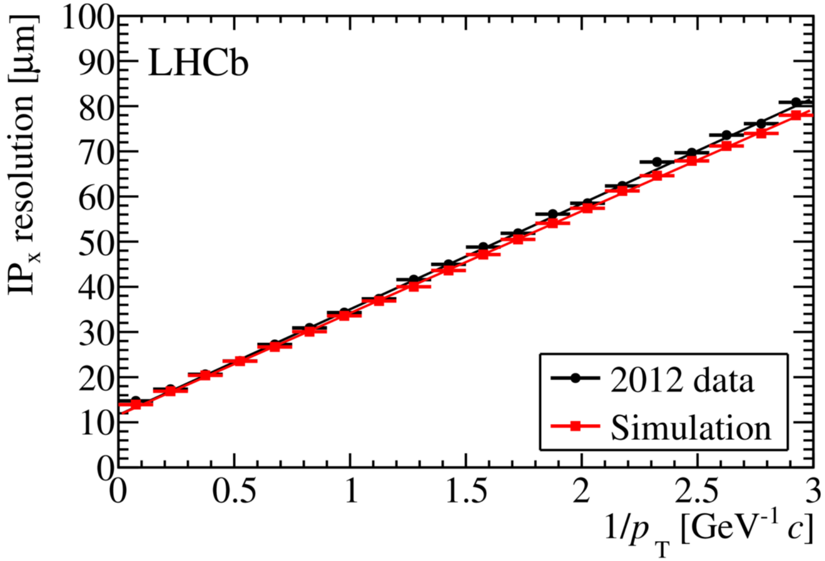
arXiv:2305.10515v1

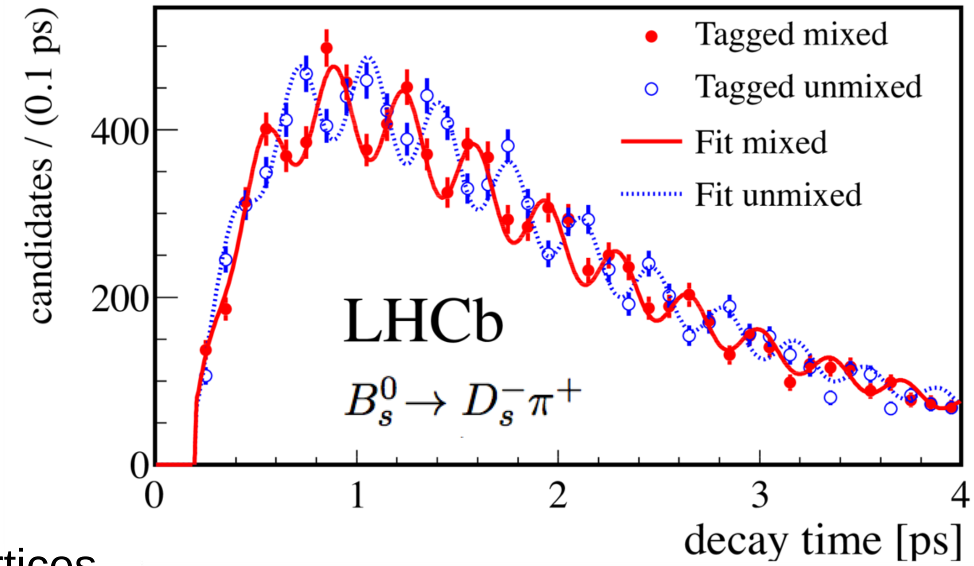


Replace detectors and read out full detector at 40 MHz

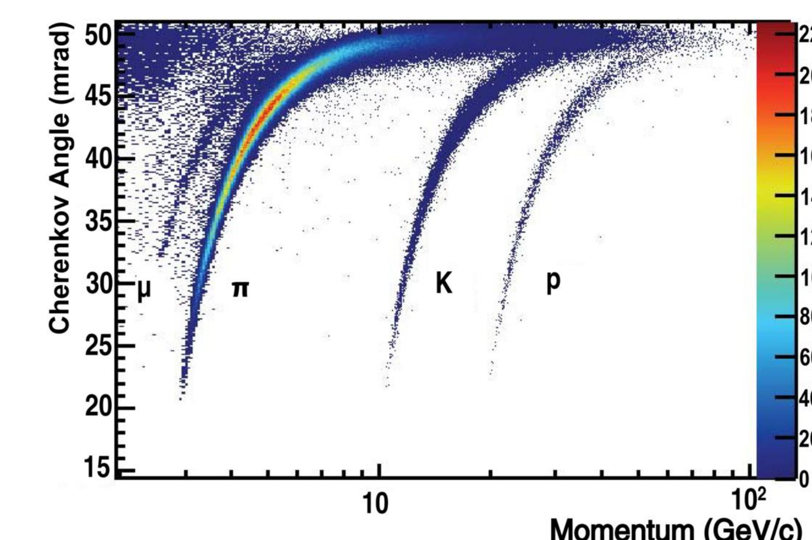
Int. J. Mod. Phys. A 30, 1530022 (2015)

Detector Performance



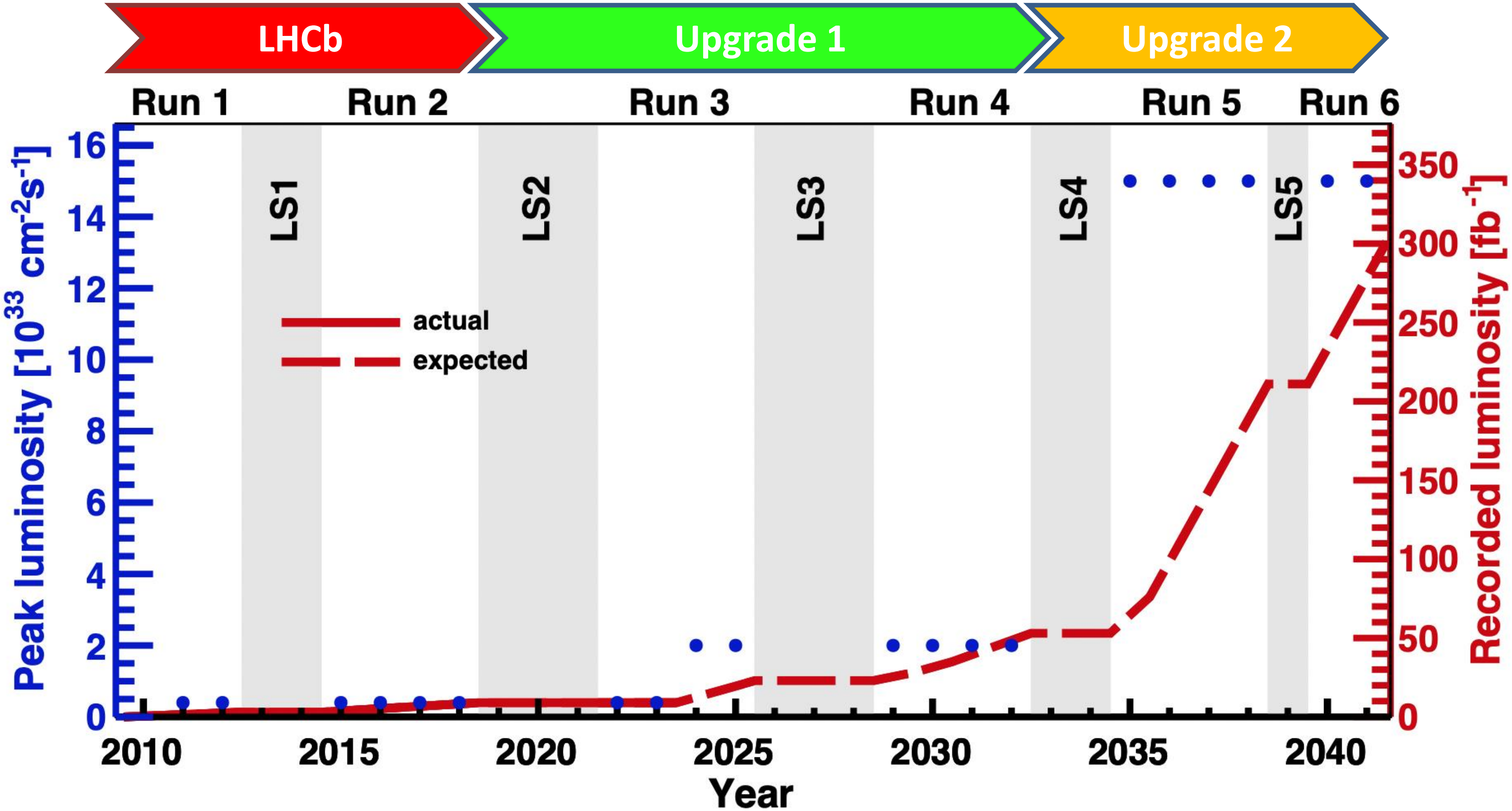


- Separation of primary and secondary vertices.
  - Impact parameter resolution: (15 +29/p_T[GeV]) μm.
- Proper time resolution.
  - Decay time resolution: ~45 fs ($B_s \to J/\psi\phi$ & $B_s \to D_s\pi$).
- Excellent momentum resolution:
  - Δp / p = 0.5% (<20 GeV) to 1.0% (200 GeV).
- Particle Identification:
  - Separation between γ, $e^\pm$, $mu^\pm$, π, K, p.
- Trigger Selection:
  - Efficient trigger for leptonic and hadronic final states.
  - Fast reconstruction of primary and secondary vertices



Run 1&2 performance is benchmark for Upgrades

Goal



$L_{inst.} = 4 \times 10^{32}\ cm^{-2}s^{-1}$ → $L_{inst.} = 2 \times 10^{33}\ cm^{-2}s^{-1}$ → $L_{inst.} = 1.5 \times 10^{34}\ cm^{-2}s^{-1}$

$\mu \approx 1$ | $\mu \approx 5$ | $\mu \approx 40$

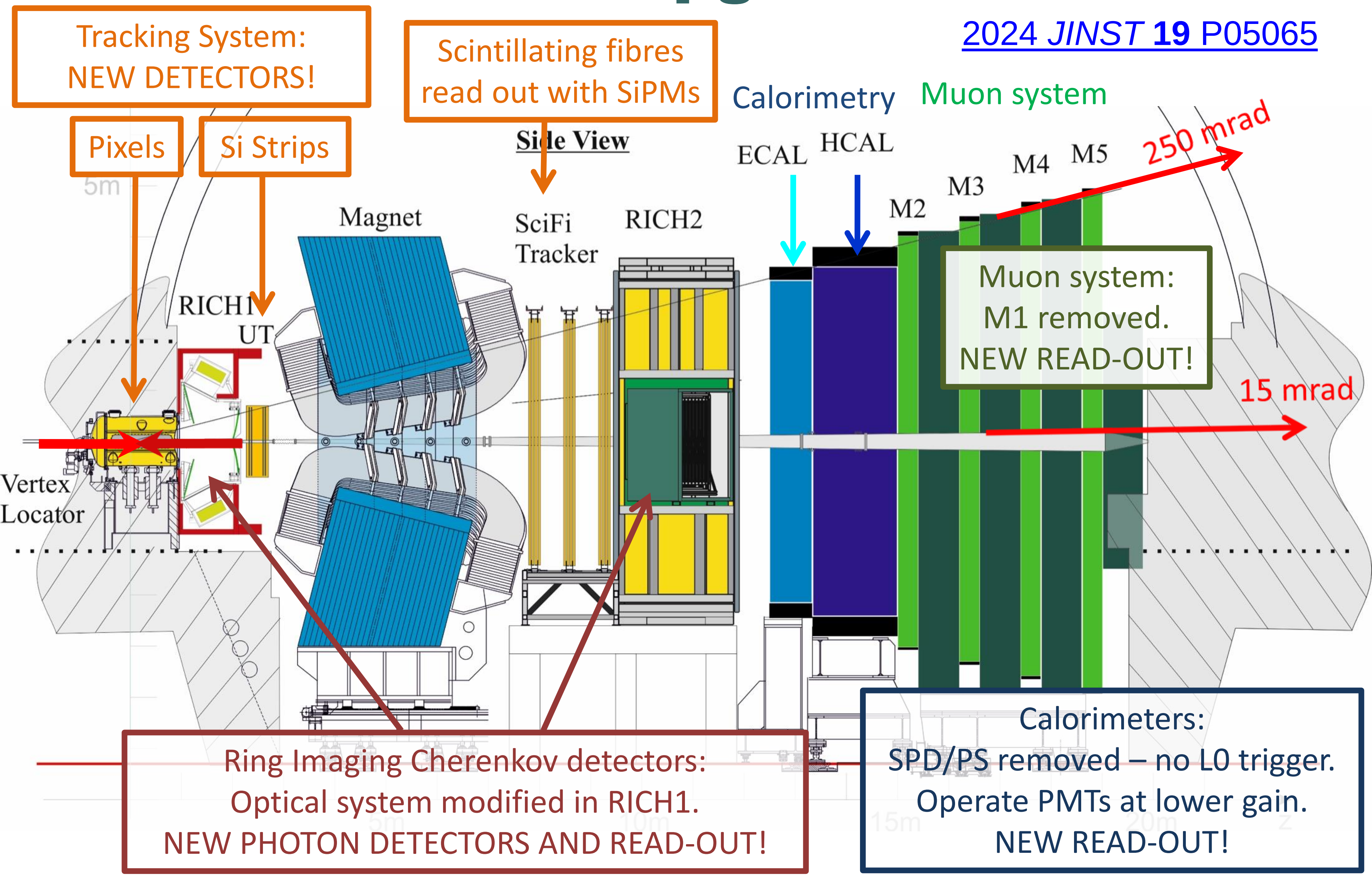
9 fb^{-1} | 50 fb^{-1} | 300 fb^{-1}

1. CERN-LHCC-2008-007
2. CERN-LHCC-2011-001
3. CERN-LHCC-2012-007
4. CERN-LHCC-2013-021
5. CERN-LHCC-2013-022
6. CERN-LHCC-2014-001
7. CERN-LHCC-2014-016
8. CERN-LHCC-2018-007
9. CERN-LHCC-2018-014
10. CERN-LHCC-2019-005
11. CERN-LHCC-2020-006
12. CERN-LHCC-2021-002

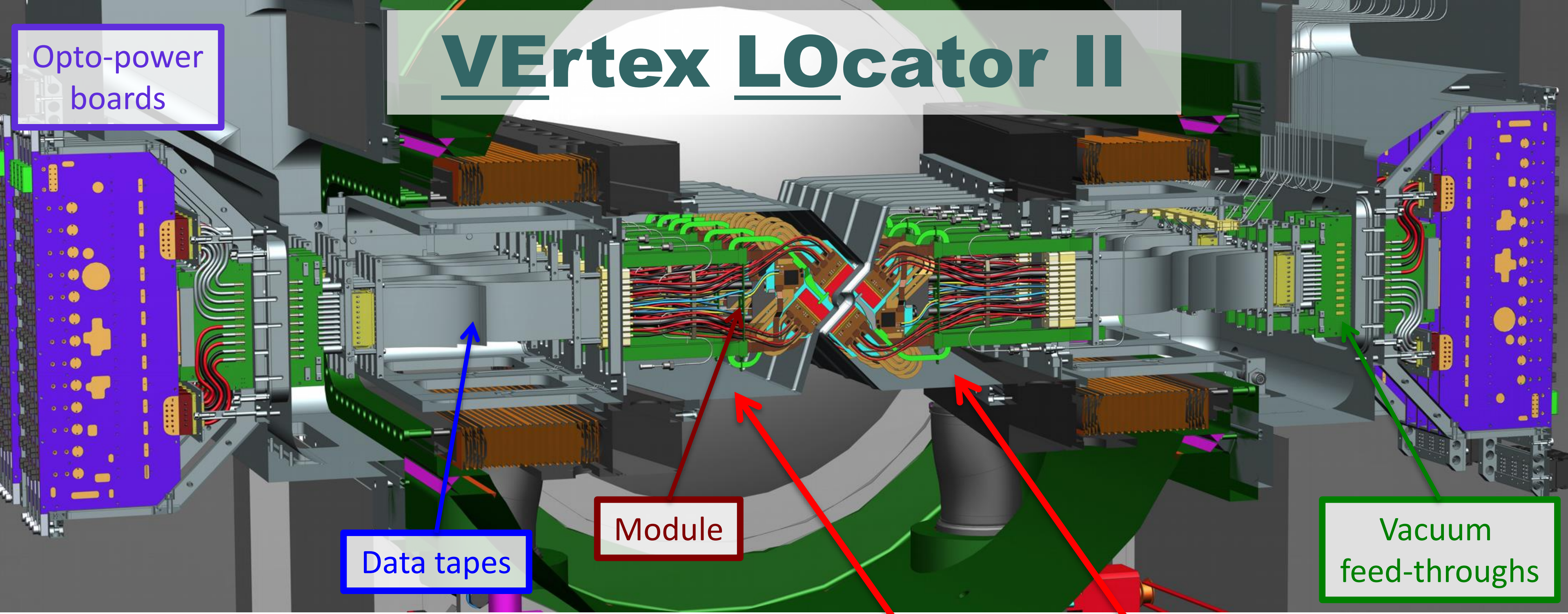
RUN 3 & 4

LHCb Upgrade I

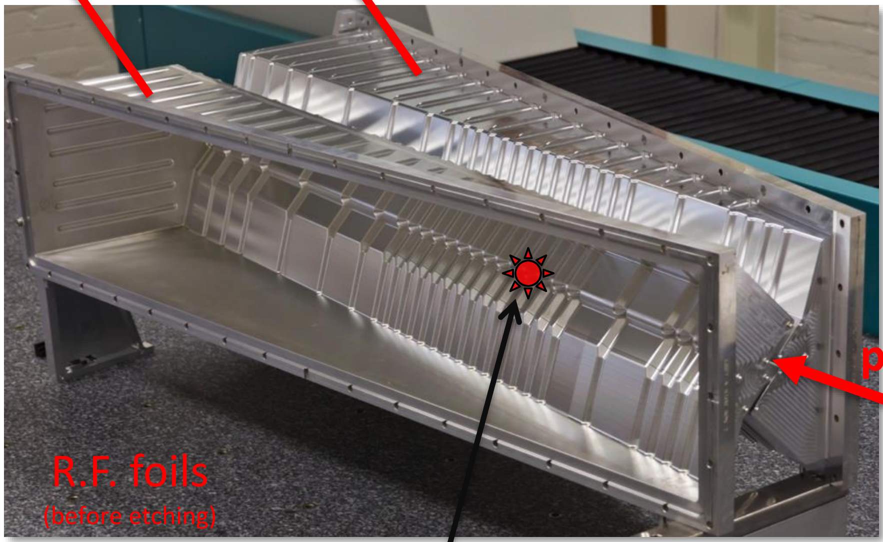
2024 *JINST* **19** P05065



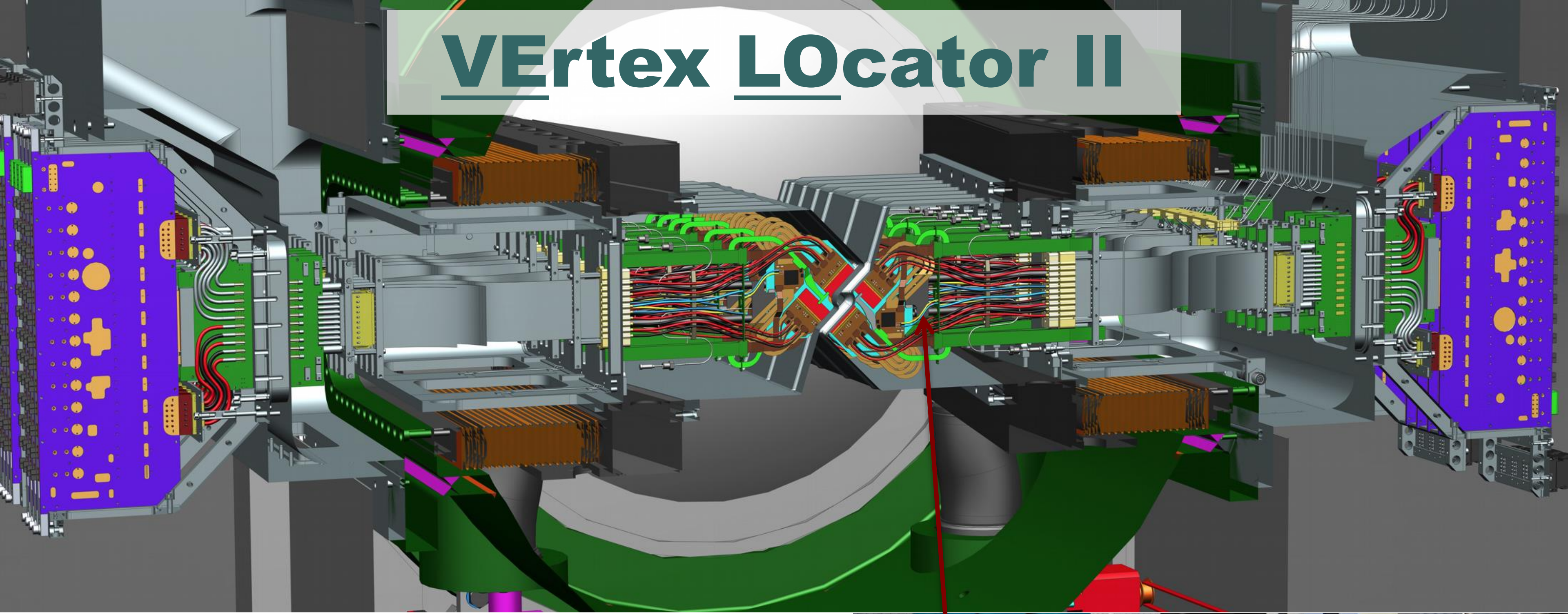
VErtex LOcator II



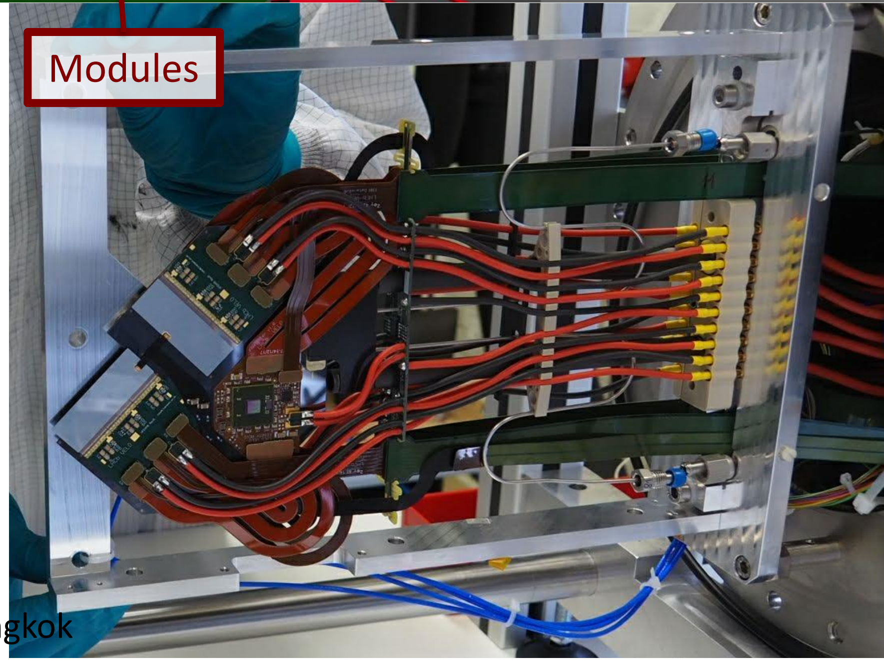
- Two retractable halves
  - 3.5 mm from beam when closed.
  - First measurement: 8.1 → 5.1 mm.
- Operates in secondary vacuum.
  - Aluminium R.F. foils separate detector from beam vacuum: 300 → 150 µm.
  - Milled to 250 µm thick then chemically etched to 150 µm.
- 52 hybrid-pixel modules.
  - 41M pixels covering total area ~ 1.2 m^2.



VErtex LOcator II

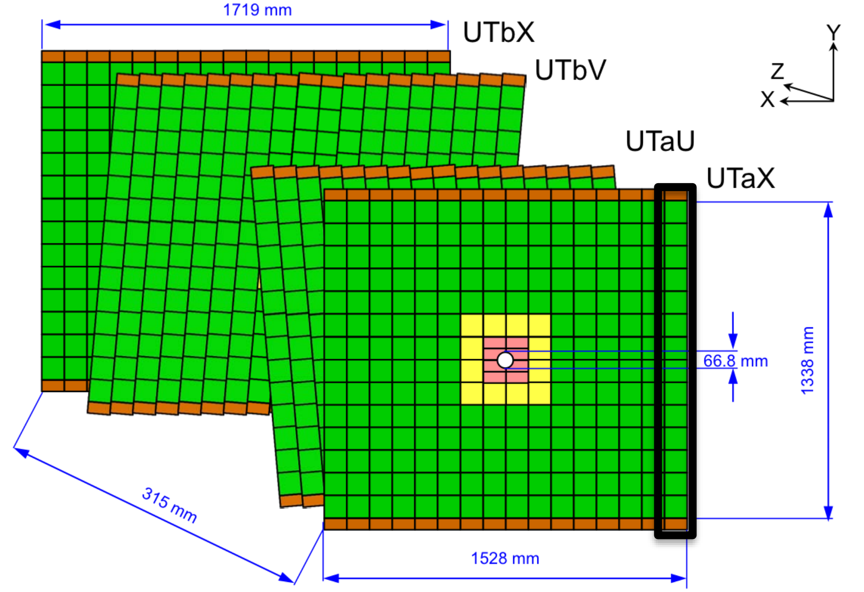


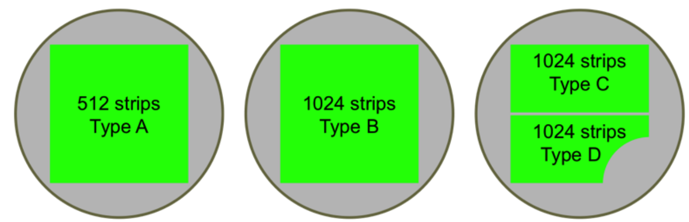
- Hybrid pixel detector.
  - 200 µm n-on-p sensor tiles.
- New read-out ASIC (VeloPix).
  - 256x256 pixel array (55 µm x 55 µm)
  - 12 per module.
- Evaporative CO_2 cooling in silicon micro-channel substrates (T < −20°C).
- High bandwidth:
  - 20 Gbit/s in hottest ASICs with ~ 3 Tbit/s overall.
- Non-uniform irradiation:
  - $8 \times 10^{15}\ n_{eq}$ / cm^2 which falls as ~ $r^{-2.1}$.

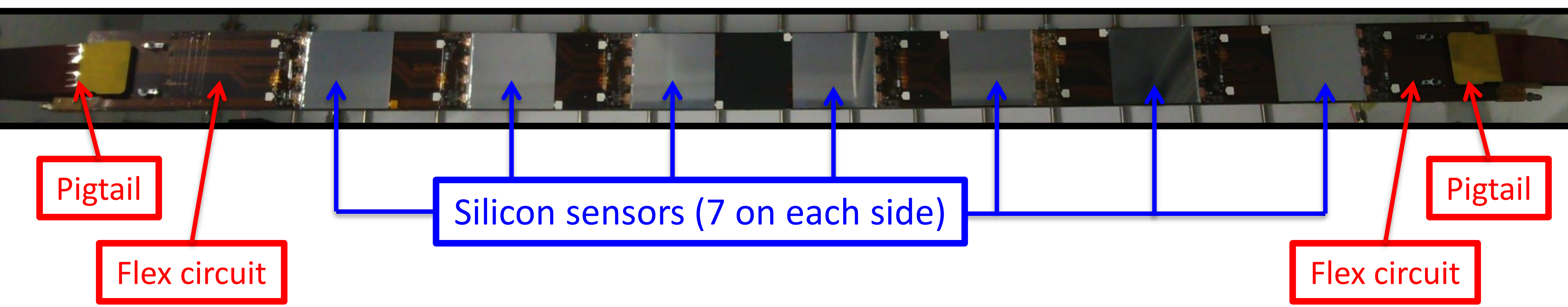


Upstream Tracker

- Silicon micro-strip detector.
  - Four layers (x, u, v, x) upstream of magnet.
  - Finer granularity in x & y, closer to beam.
- Four types of sensors.
  - n- and p-type with 512 or 1024 strips.
  - 320/250 µm thick; 187.5/93.5 µm pitch.
- Modules mounted on double-sided staves.
  - 68 staves / 968 sensors.
  - Bi-phase CO_2 cooling pipe integrated in stave.
- New read-out ASIC (SALT).
  - 128 channels with 6-bit ADC.
  - Pedestal & common-mode subtraction, zero-suppression.
  - Output up to 6 SLVS e-links per ASIC.
  - 1048 4-asic read-out sectors = 4192 ASICs.
- Read-out electronics mounted on detector frame.

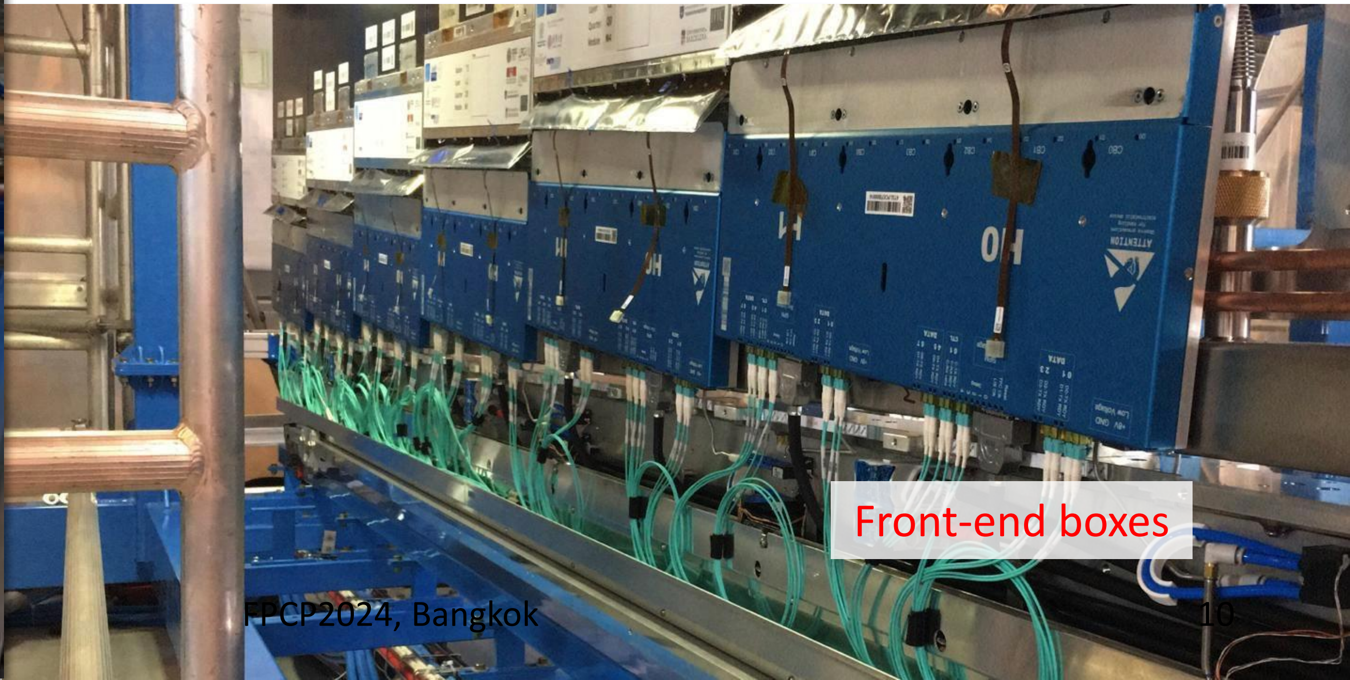






Scintillating Fibre Tracker

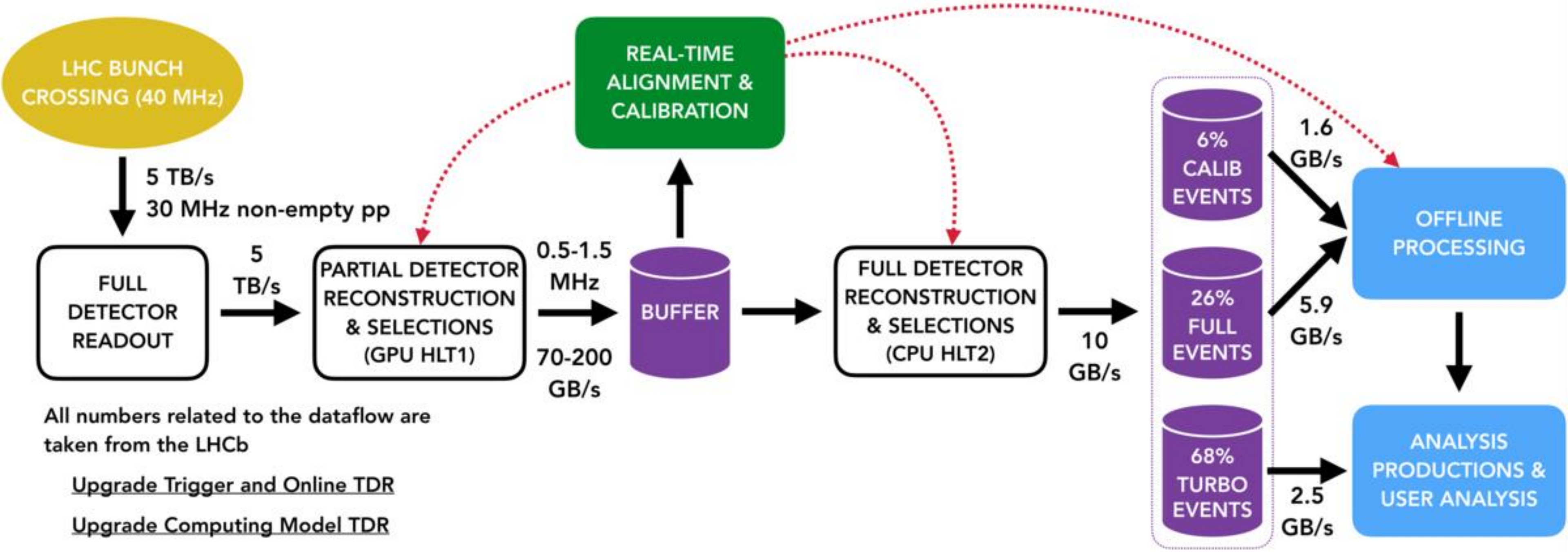
- Scintillating fibres read out with SiPMs.
  - 2.4 m long, 250 μm diameter, 6 layers of fibres in module.
  - 12 detection planes – 3 × (x, u, v, x).
- SiPMs outside acceptance.
  - 128 channels with width 250 μm
  - Require cooling to −40°C (neutron radiation).
- New ASIC for read-out (PACIFIC).
  - 64 channels, 130 nm CMOS (TSMC).
  - ADC with three hardware thresholds.
- Clustering on FPGA board in front-end box.



Comput. Phys. Commun. **208** 35-42
Run 2: 2019 *JINST* **14** P04013
GPU: Comput Softw Big Sci 4, 7 (2020)
TURBO: 2019 *JINST* **14** P04006

LHCb-FIGURE-2020-016

Data Processing



- RTA is integral part of DAQ chain in upgrade data processing.
  - HLT1 reconstruction runs on GPUs in event builder network.
  - Offline reconstruction in HLT2 à la Run 2.
- TURBO model for exclusive selections.
  - High-level physics objects directly from the HLT

Commissioning

2022

- Dedicated to (sub-)detector commissioning.

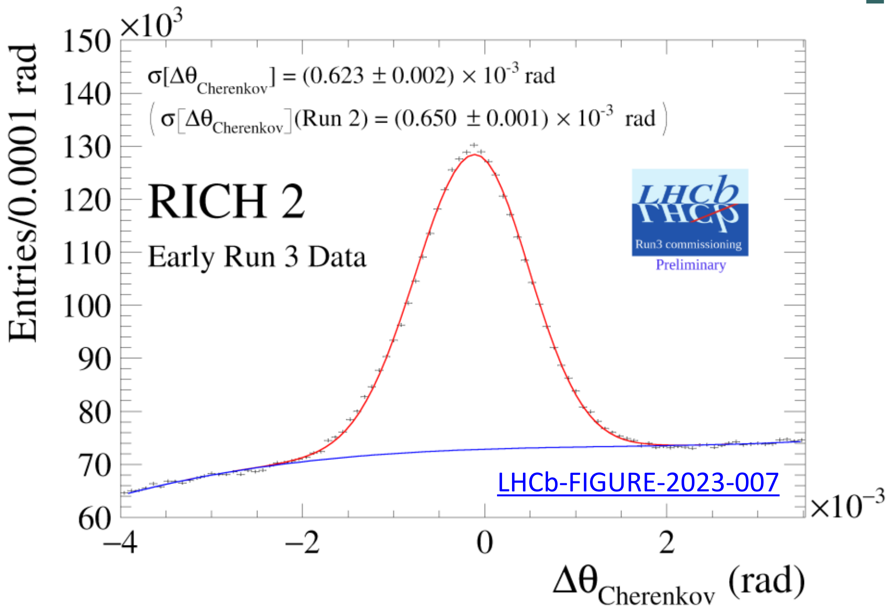
2023

- UT installed during YETS (Year End Technical Stop)
  - Dedicated time required for commissioning at start of year.
  - Desynchronisation problems in read-out electronics.
- Vacuum incident in VELO in January.
  - Loss of control in LHC vacuum protection system.
    - Differential pressure of 200 mbar between primary and secondary vacuum
  - R.F. foil sustained permanent plastic deformation.
    - Replacement foils prepared for installation during YETS.
- Data collected with VELO partially closed.

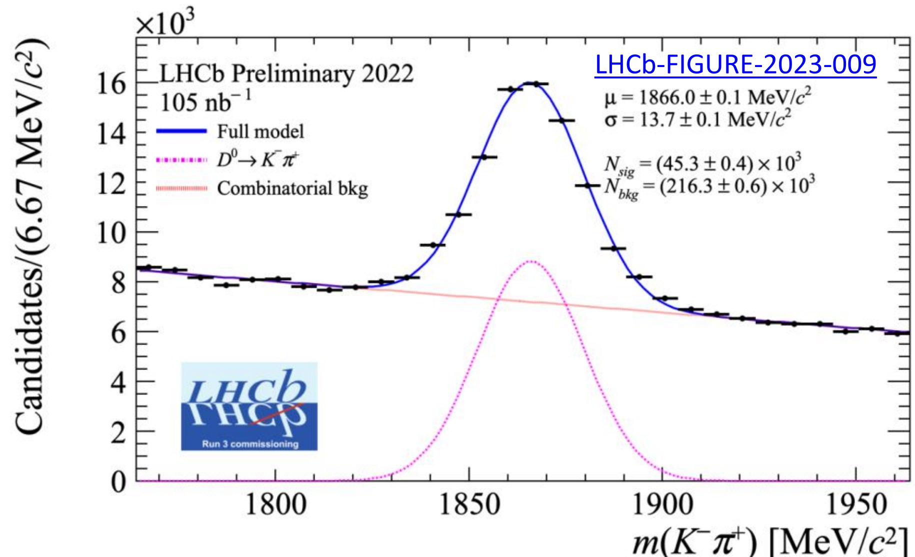
2024

- Re-installation & re-commissioning of VELO
- Commissioning of UT & integration into trigger.
- Aim to collect ~ 7 fb^{-1} .

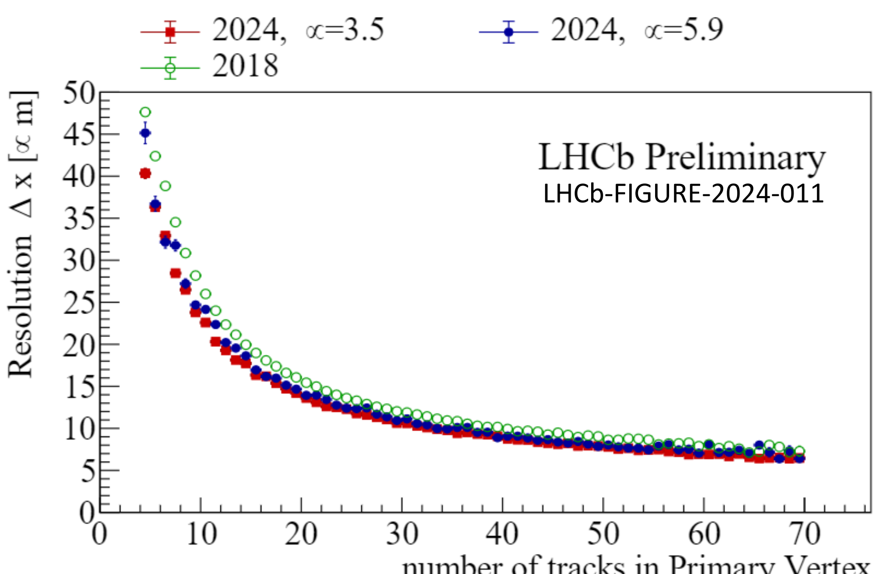
Detector performance



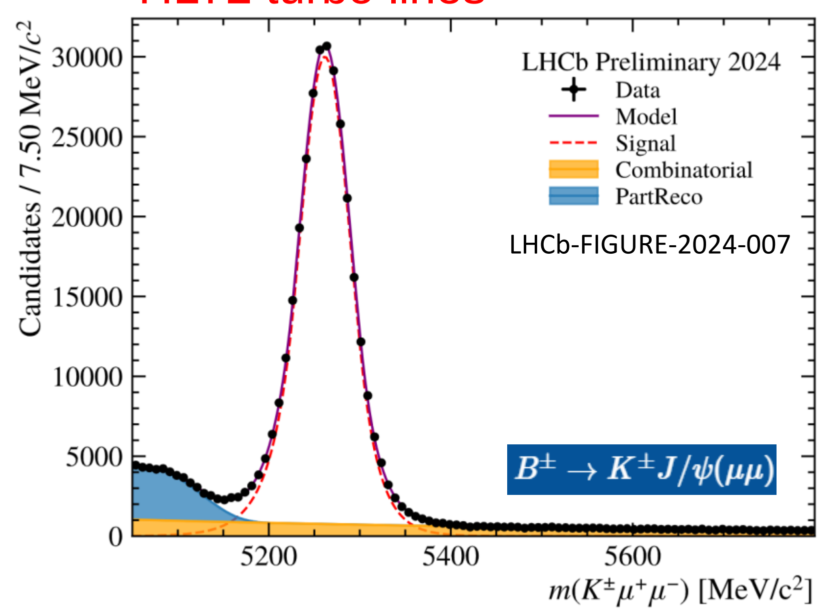
D0 reconstruction direct from HLT1



Resolution on PV & Δθ better than Run 2



HLT2 turbo lines



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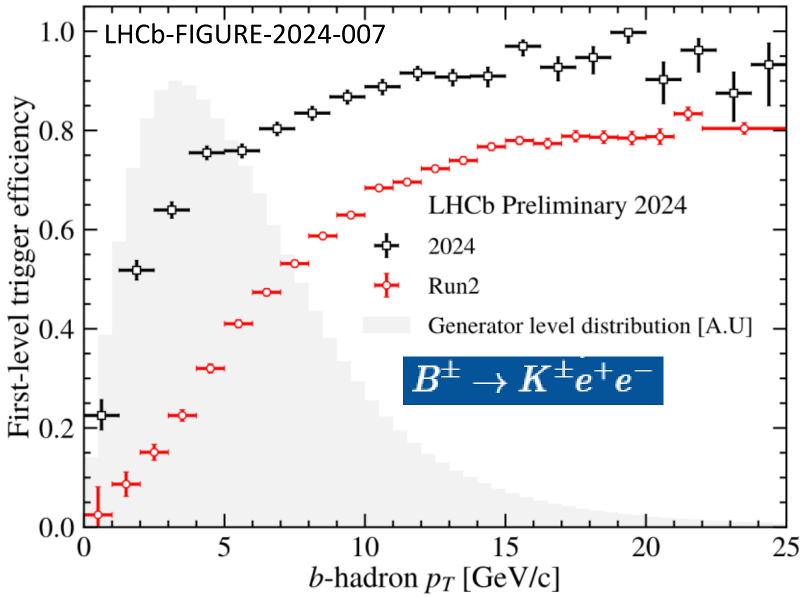
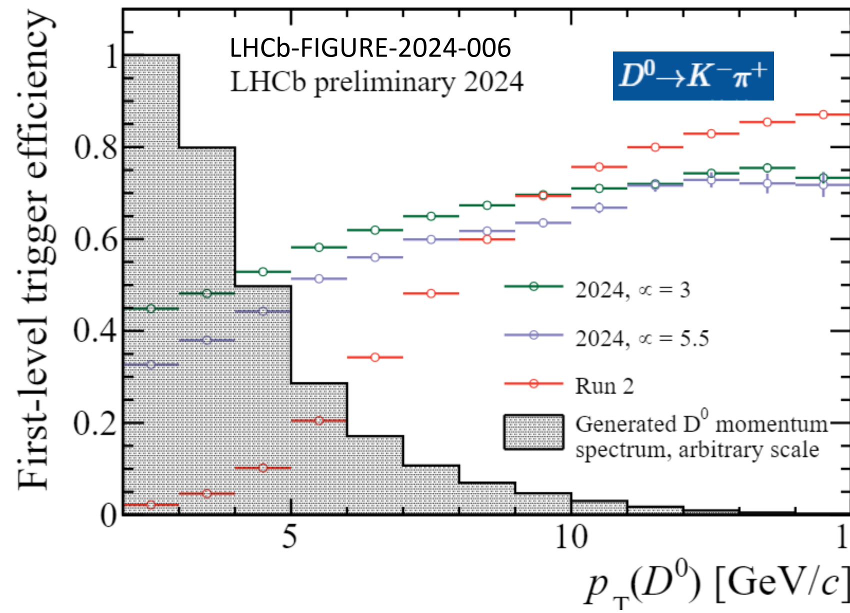
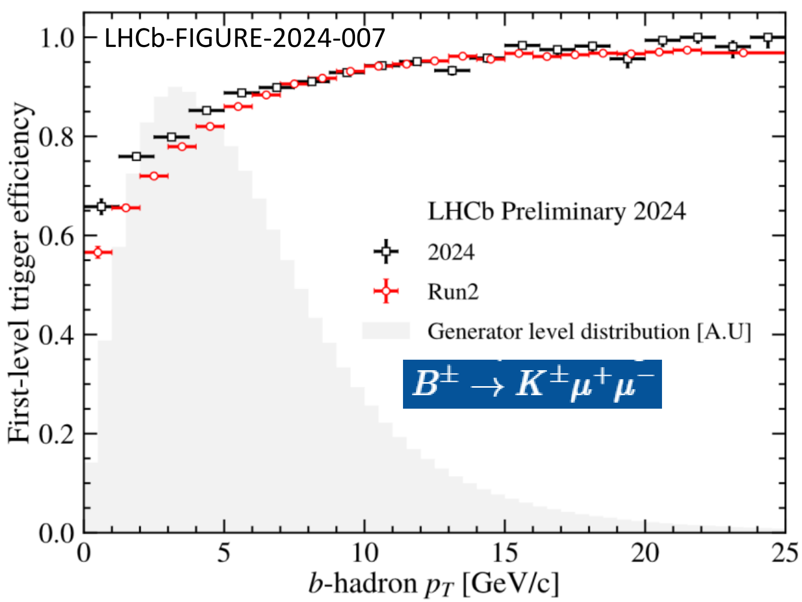
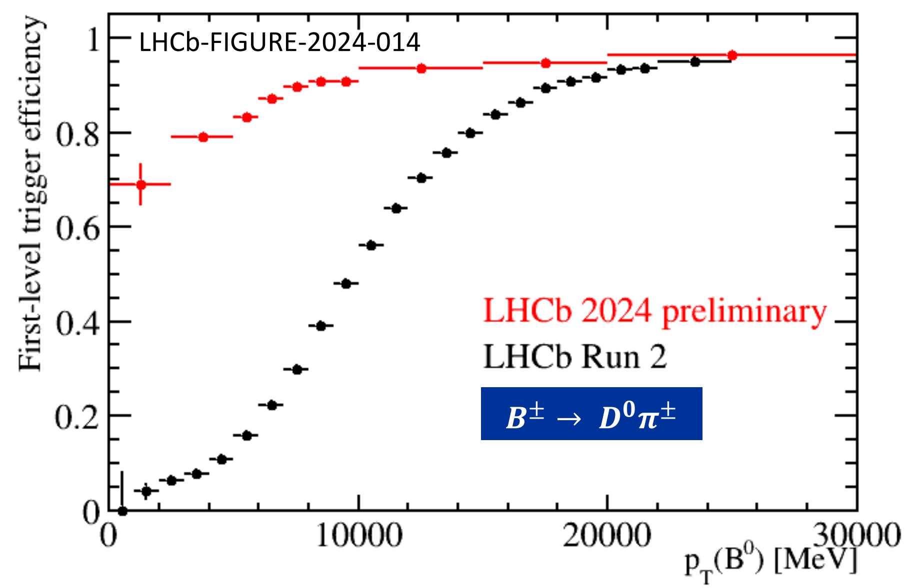
Trigger Efficiency

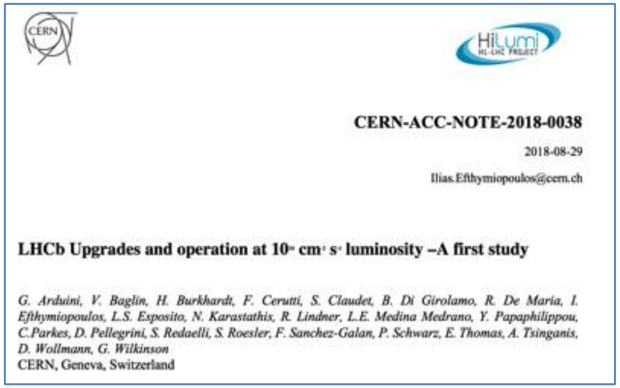








1. CERN-LHCC-2017-003
2. CERN-LHCC-2018-027
3. CERN-LHCC-2021-012
4. CERN-LHCC-2023-005



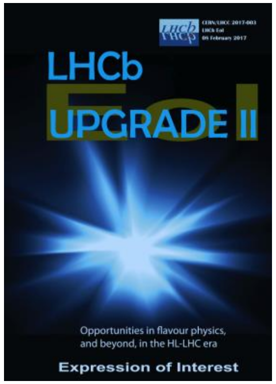
CERN-ACC-NOTE-2018-0038

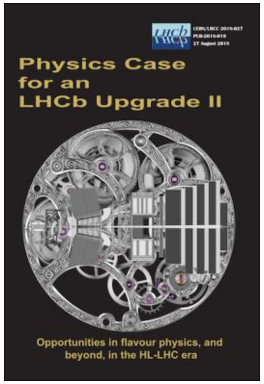
2018-08-29

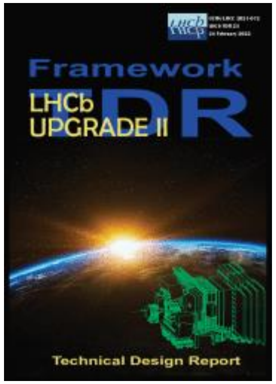
Ilias.Efthymiopoulos@cern.ch

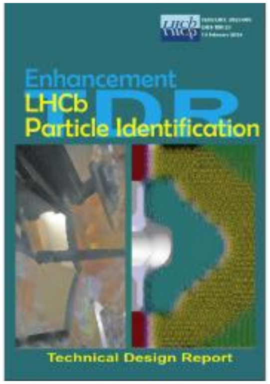
LHCb Upgrades and operation at 10^{34} cm^{-2} s^{-1} luminosity – A first study

G. Arduini, V. Baglin, H. Burkhardt, F. Cerutti, S. Claudet, B. Di Girolamo, R. De Maria, I. Efthymiopoulos, L.S. Esposito, N. Karastathis, R. Lindner, L.E. Medina Medrano, Y. Papaphilippou, C.Parkes, D. Pellegrini, S. Redaelli, S. Roesler, F. Sanchez-Galan, P. Schwarz, E. Thomas, A. Tsinganis, D. Wollmann, G. Wilkinson
CERN, Geneva, Switzerland









RUN 5 & 6

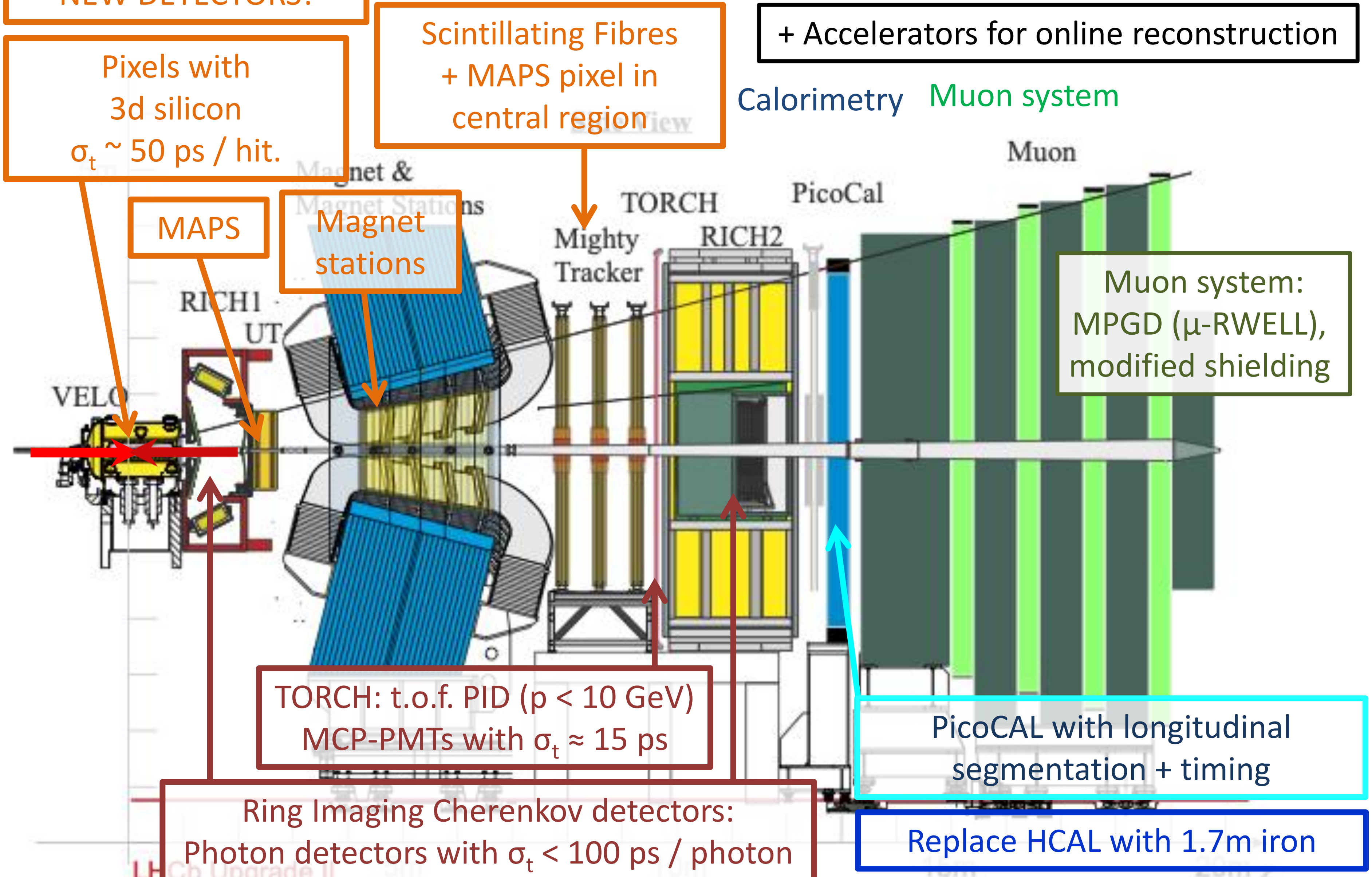
"The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited."

European Strategy Update 2020

LHCb Upgrade II

Tracking System:
NEW DETECTORS!

+ Accelerators for online reconstruction



OUTLOOK

arXiv:1808.08865

Physics Reach

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	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1	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 $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad	14 mrad	–	4 mrad	22 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad	39 mrad	–	11 mrad	Under study
a_{sl}^s	33×10^{-4}	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6%	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90%	34%	–	10%	21%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22%	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ **LUV studies**					
$R(D^*)$	0.026	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4}	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4}	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4}	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}	–

** Taken from Physics case for an LHCb Upgrade II (CERN-LHCC-2018-027)*

CKM Measurements

LHC-B

LETTER OF INTENT

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

1995

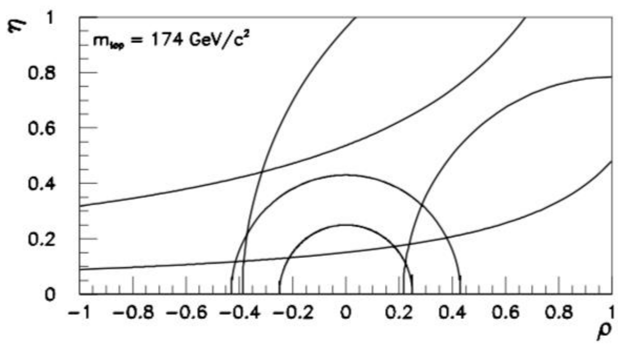
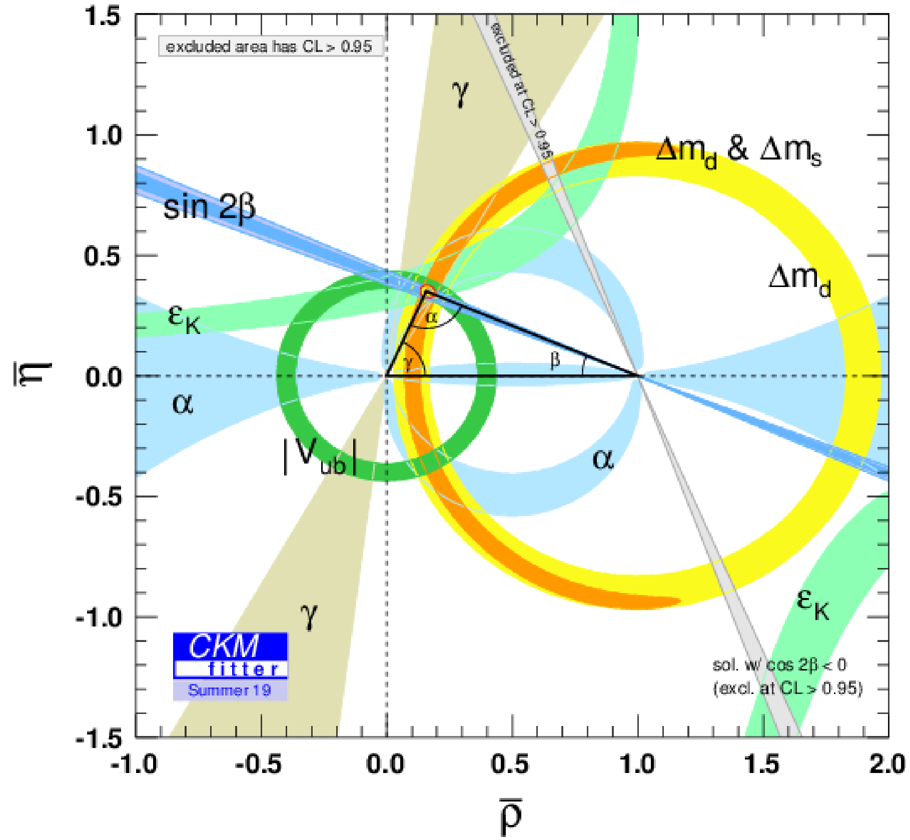


Figure 2.1: Limits on the CKM parameters (1σ) ρ and η for $m_t = 174$ GeV. The annular region cen-

2019



$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Matrix is unitary: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \qquad \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \qquad \gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

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CKM Measurements

LHC-B

LETTER OF INTENT

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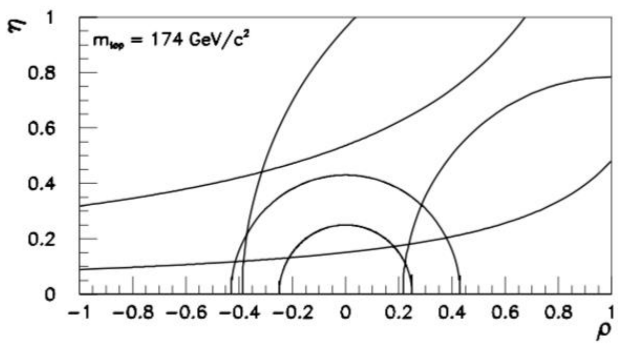
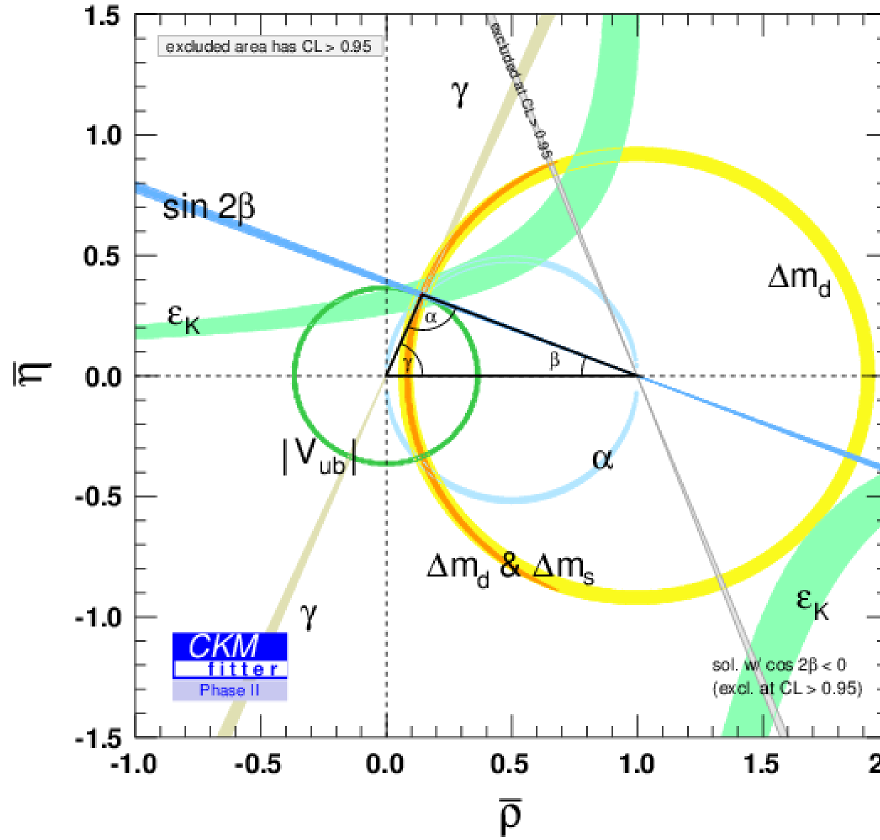


Figure 2.1: Limits on the CKM parameters (1σ) ρ and η for m_t = 174 GeV. The annular region cen-

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Phase 2



LHCb (300 fb^{-1}), Belle-II (50 ab^{-1})
ATLAS & CMS (3000 fb^{-1})

arxiv:1812.07638

$\sigma_\gamma \approx 5°$ (2019) → 1° (Phase 1) → 0.35° (Phase 2)

Summary

CONCLUSIONS

Summary

- New detector installed during LS2!
  - Higher luminosity, higher data rates, etc.
  - Finer granularity, improved acceptance.
- Commissioning progressing well.
  - Excellent performance with early data.
  - Upstream Tracker installed during YETS 2022/23.
  - VELO vacuum incident in 2023.
  - Working towards operation at nominal conditions.
- Plans for Upgrade 2 are advancing fast.
  - R&D in new detectors, finalising sub-detector designs.
    - Timing information is crucial to resolve primary vertices.
  - Preparing *scoping document* for LHCC.


Chula
22ND CONFERENCE ON FLAVOR PHYSICS AND CP VIOLATION
Chulalongkorn University
Bangkok, Thailand
27 - 31 May 2024
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F. Bianchi (Torino)
R. Briere (Carnegie Mellon)
J. Brod (Cincinnatti)
T. Browder (Hawaii)
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Y. Yan (SUT)
Do you spot something strange in the poster?
See picture description in the Indico page.
indico.cern.ch/e/FPCP2024

ขอบคุณ

MORE?

BACK UP

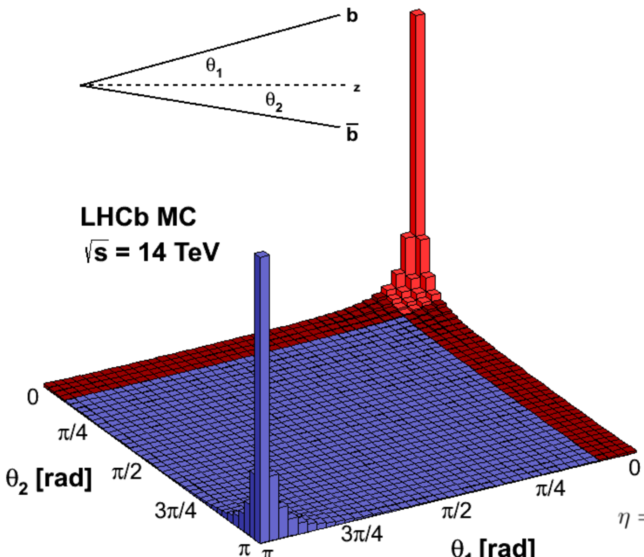
Why LHCb?

- Dedicated heavy flavour experiment at LHC.
  - Measure CP-violation in *b*- and *c*-sector.
  - Study rare *b*- and *c*- hadron decays.
  - Exploit forward production of *b*-pairs with low angle.

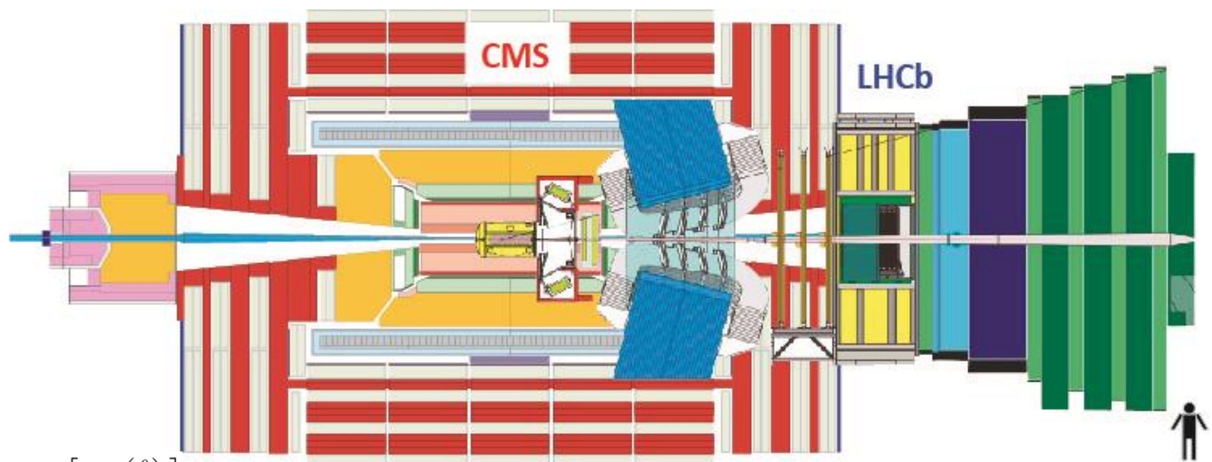
✧ ***Indirect searches for New Physics.***

- Physics program in Runs 1 & 2 was much much more.
  - Electroweak, QCD, direct searches, heavy ions.

✧ ***General Purpose Detector in forward region.***



$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



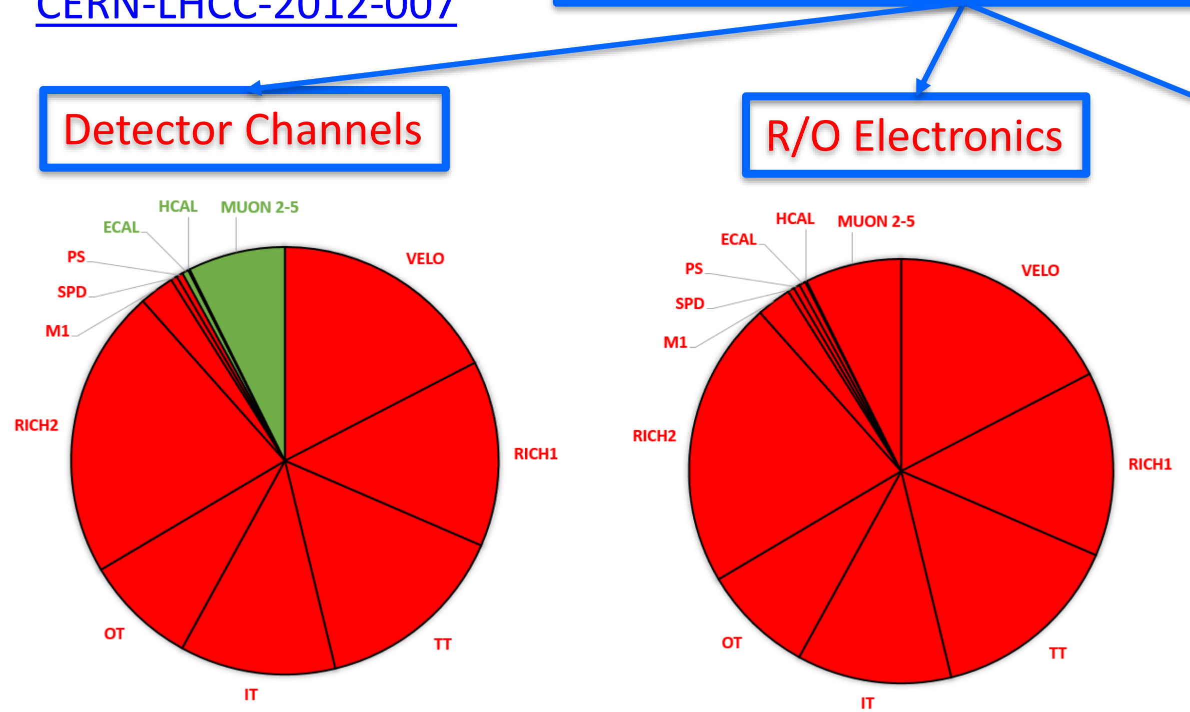
$2 < \eta < 5$

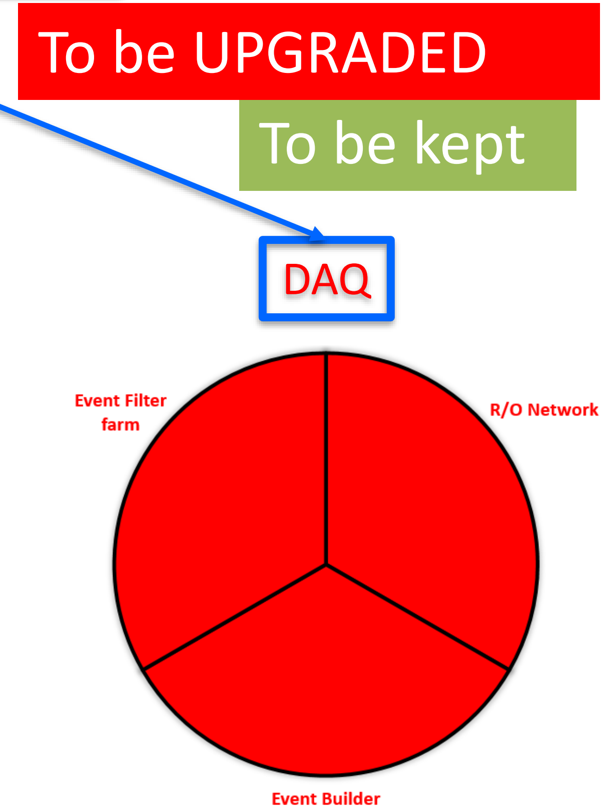
RUN 3 & 4

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Upgraded LHCb Detector

CERN-LHCC-2012-007



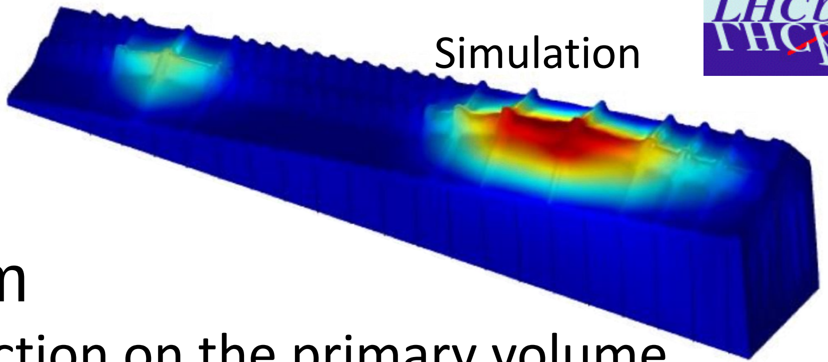


Conditions:

- Luminosity: 2×10^{33} cm^{-2}s^{-1} (inst.), 50 fb^{-1} (int.)
- 5.2 visible interactions / crossing.

Challenge:

- Install and commission a brand new detector & read-out during LS2!
- Maintain current reconstruction performance in harsher environment.
- Read out the complete detector at 40 MHz → full software trigger.
- Run HLT1 reconstruction on GPUs in event builder servers.



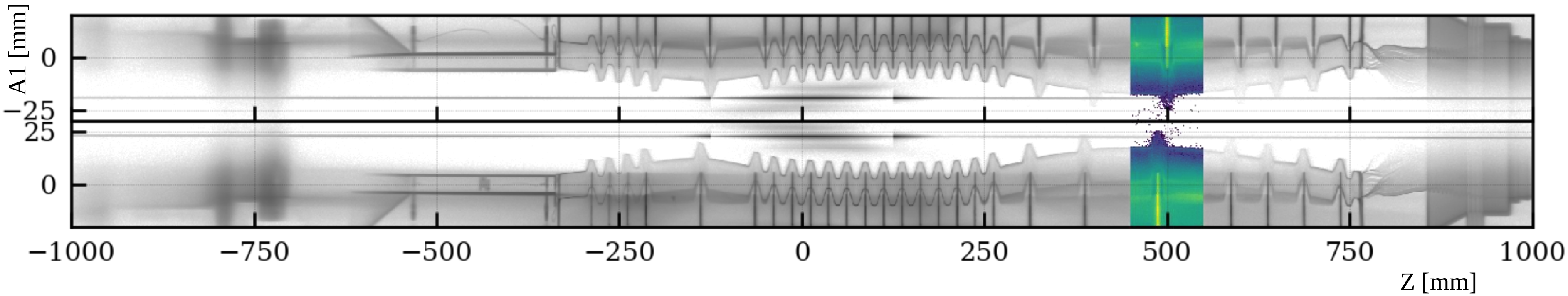
RF-box incident

January 2023

- LHC vacuum protection system
  - Loss of control led to a pumping action on the primary volume.
  - ΔP between secondary and primary vacuum was too high.
- RF-box sustained permanent plastic deformation.
- VELO modules were unharmed.
- Deformation of the RF box was assessed with a tomography.

YETS 2024

- Replacement foils prepared during 2023
- Damaged foils replaced during YETS 2024

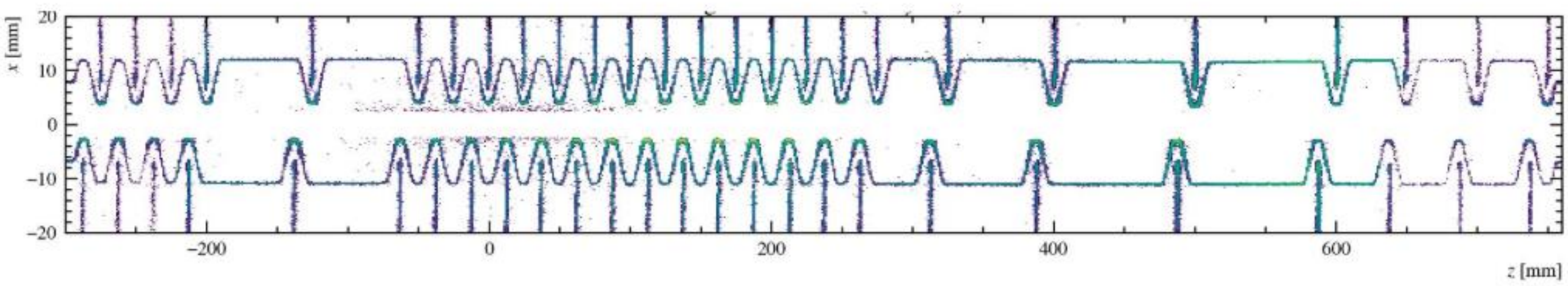


VELO in 2024

LHCb Status Report @ 158th LHCC Meeting

- Performances
  - >99% optical links active
  - hit efficiencies higher than 98%
  - operation at nominal conditions stable

Selfie of the new RF-box and VELO modules with reconstructed hadronic interaction vertices



Institute of High Energy Physics Chinese Academy of Sciences

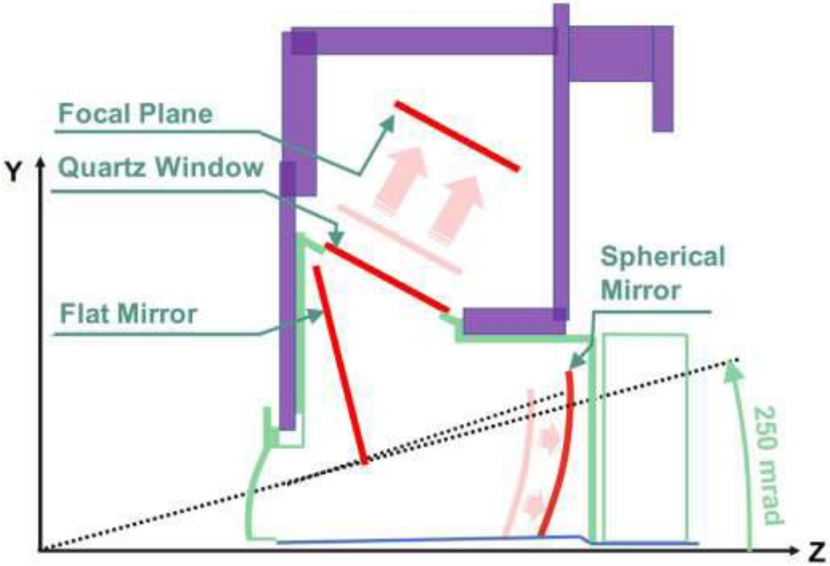
Particle ID

Cherenkov detectors:

- RICH 1: C_4F_{10} (10 – 65 GeV/*c*).
  - Replace everything (mirrors, gas enclosure, quartz windows).
- RICH 2: CF_4 (15 – 100 GeV/*c*).
- Replace Hybrid Photon Detectors (HPDs) with Multi Anode Photomultiplier Tubes (MaPMTs).
- New 8-channel read-out ASIC (CLARO).

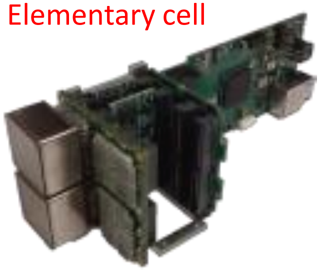
Calorimeters & Muon System

- Remove unnecessary detectors.
- Replace read-out electronics.

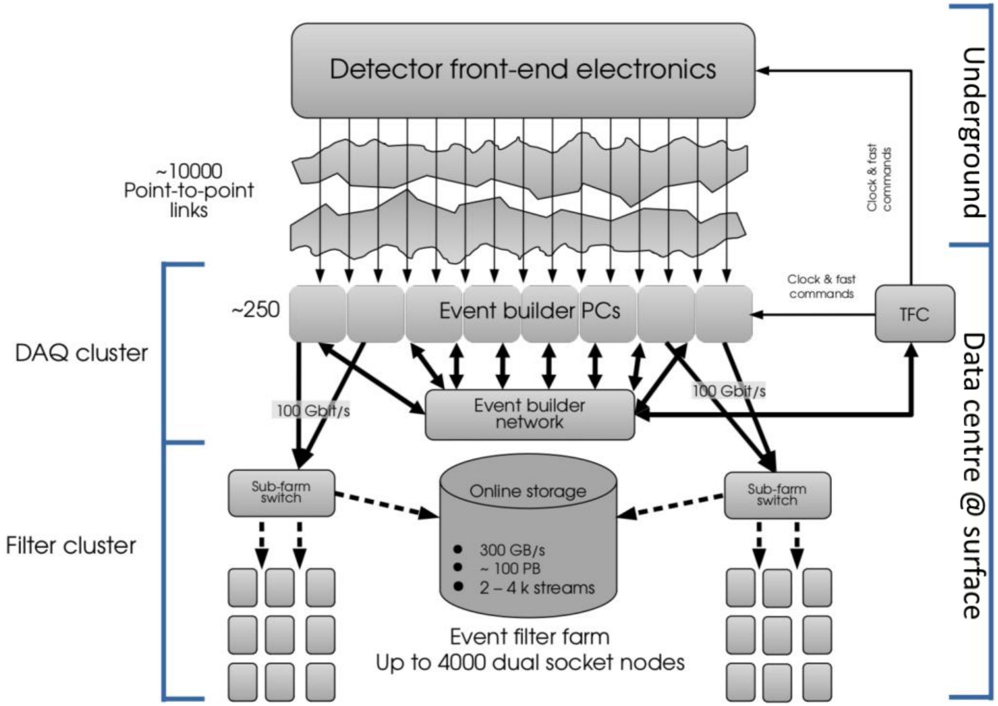


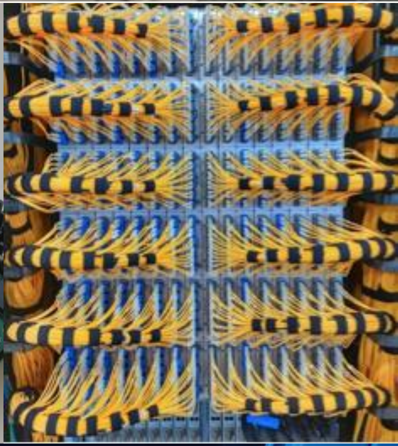
MaPMTs (Hamamatsu)

Elementary cell



Online

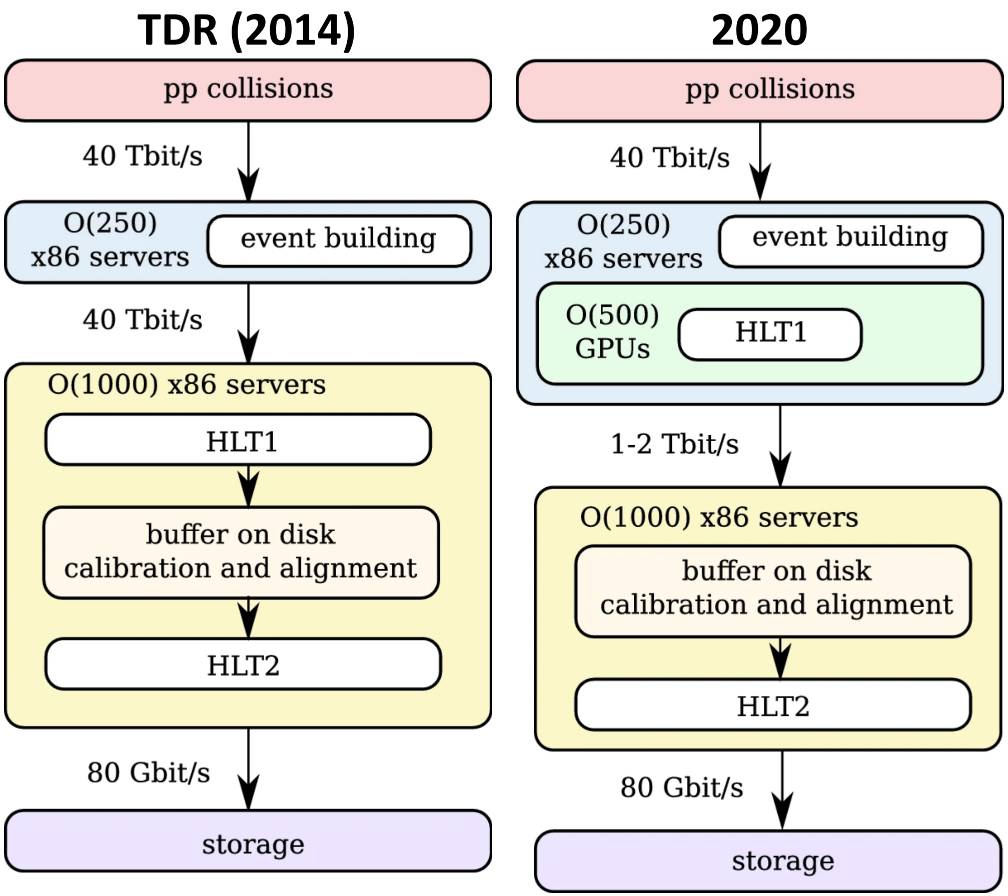




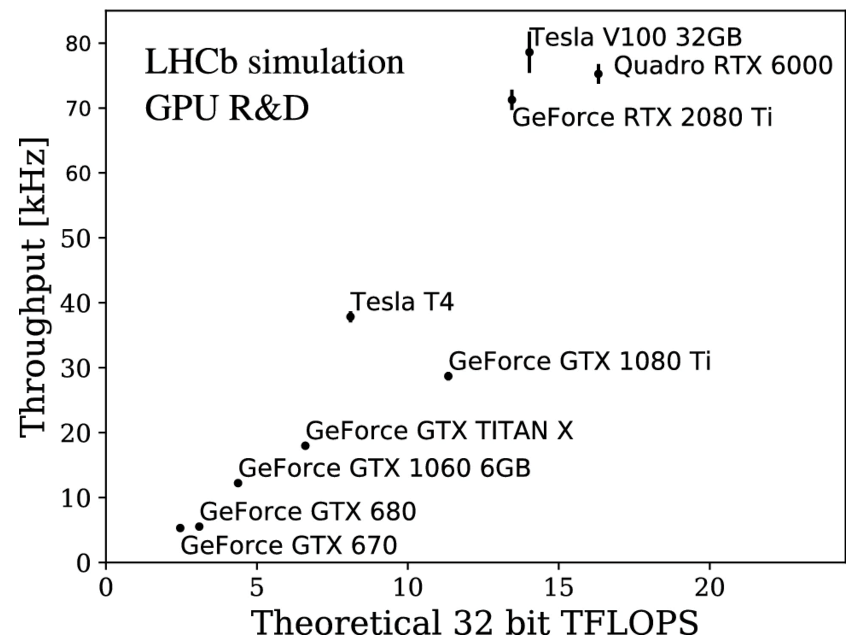
- Data centre on surface.
  - Event Filter Farm and Event Builder network.
- Long distance optical fibres.
  - 19008 fibers installed (0.25% broken).
- Common read-out boards (PCIe40).
  - Large FPGA with 1.15M cells.
  - 48 bi-directional links (10 Gbit/s).
  - Three flavours of firmware.
- GPUs in event builder PCs.

Comput Softw Big Sci 4, 7 (2020)

HLT1 on GPUs



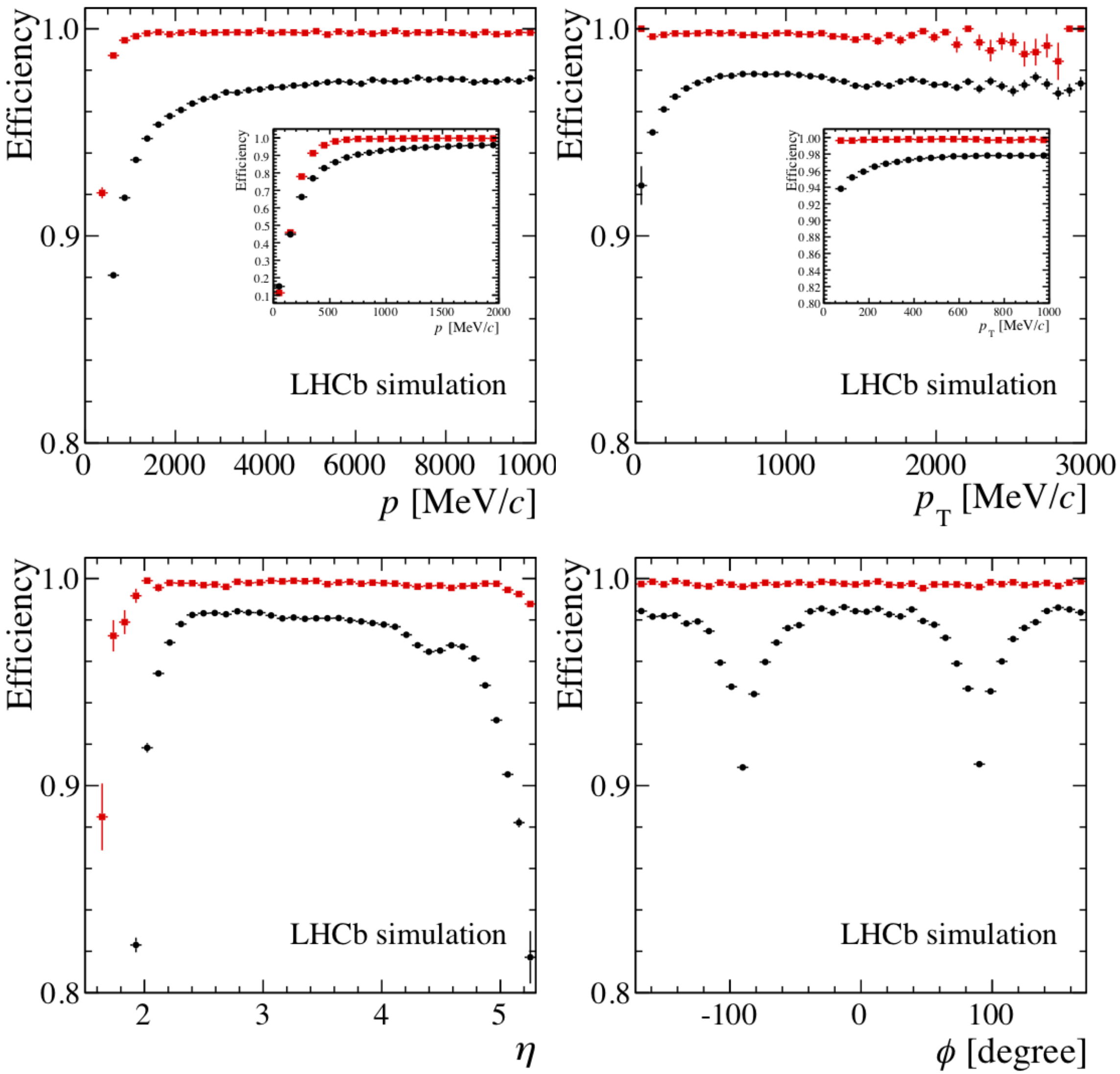
Three good GPU candidates

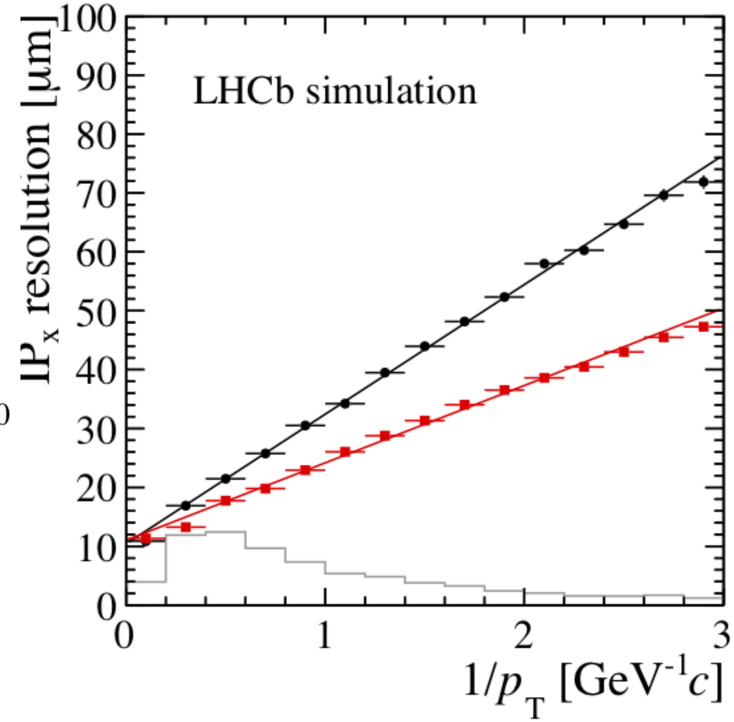


- Each event builder server has two GPU slots = 500 GPUs.
- HLT1 ***must*** run at visible collision rate (30 MHz).
  - Minimum throughput rate per GPU is 60 kHz.

CERN-LHCC-2013-021

Expected Performance





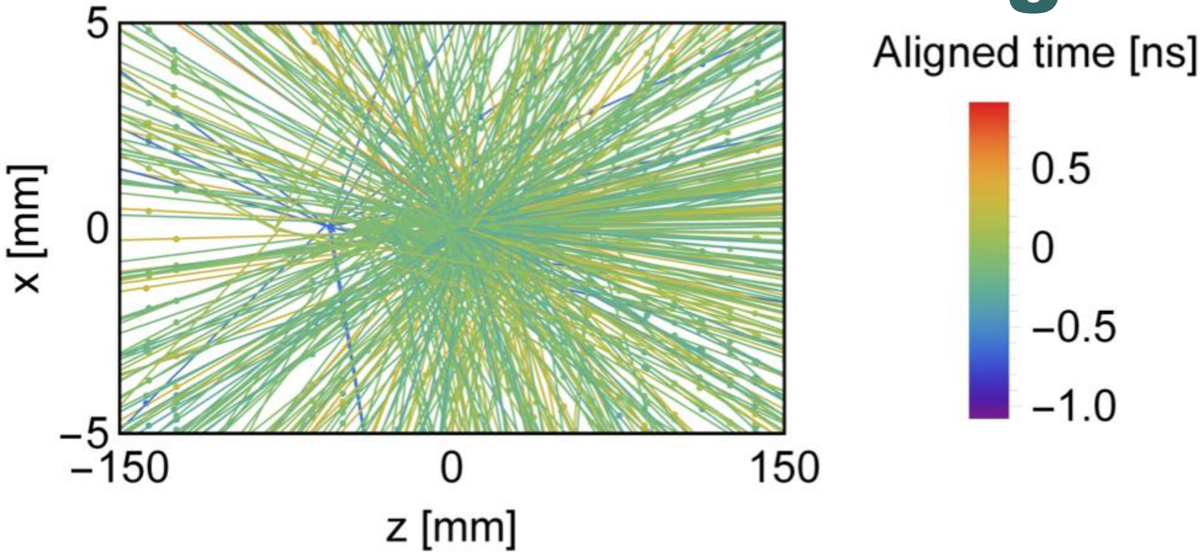
- Original VELO (strips)
- New VELO (pixels)

RUN 5 & 6

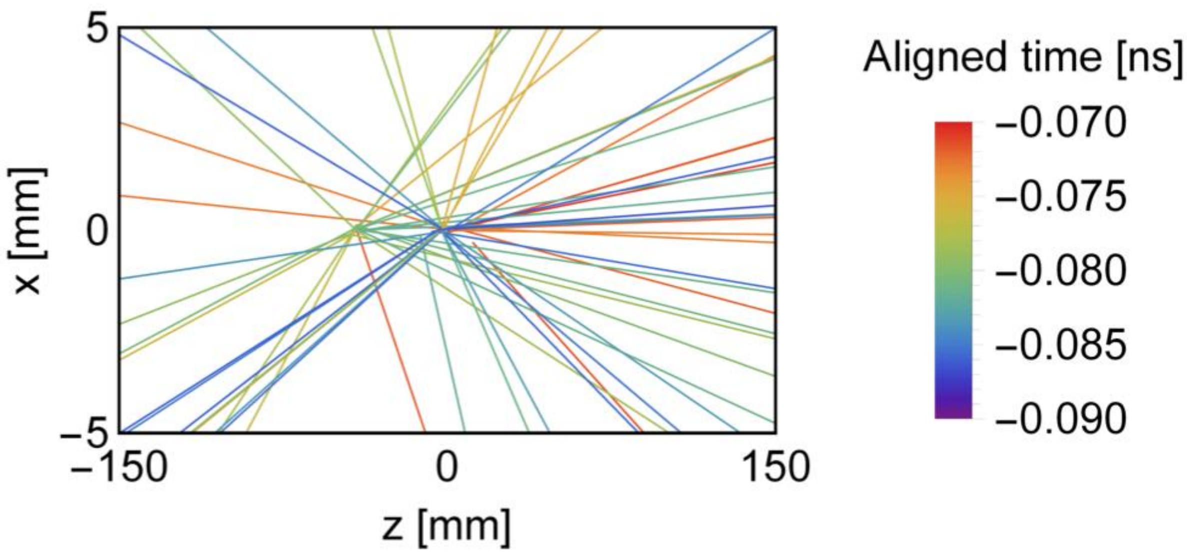
Timing

CERN-LHCC-2021-012

Simulated event with 42 PVs



No timing information

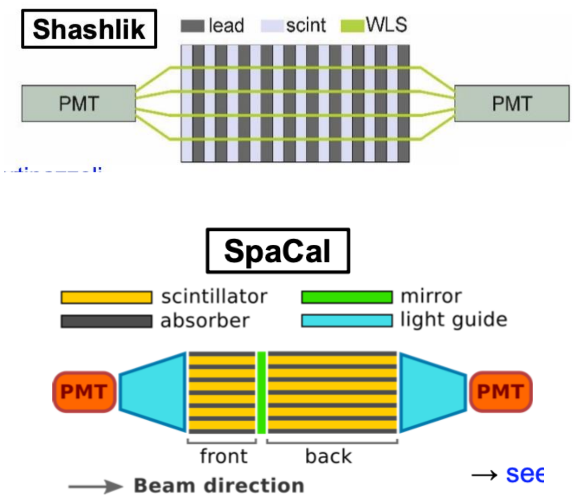


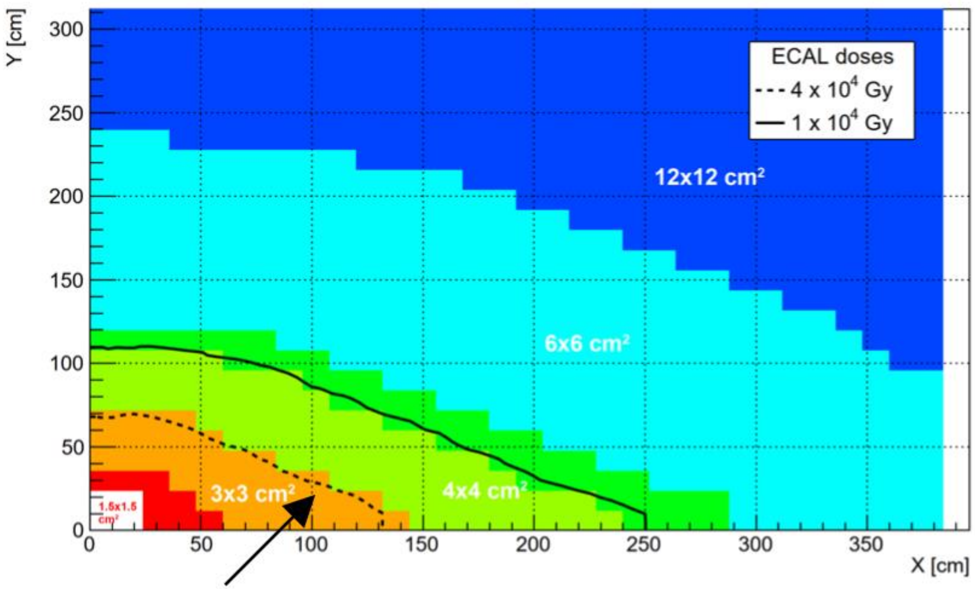
Require 20 ps window

Timing information will be crucial to resolve primary vertices

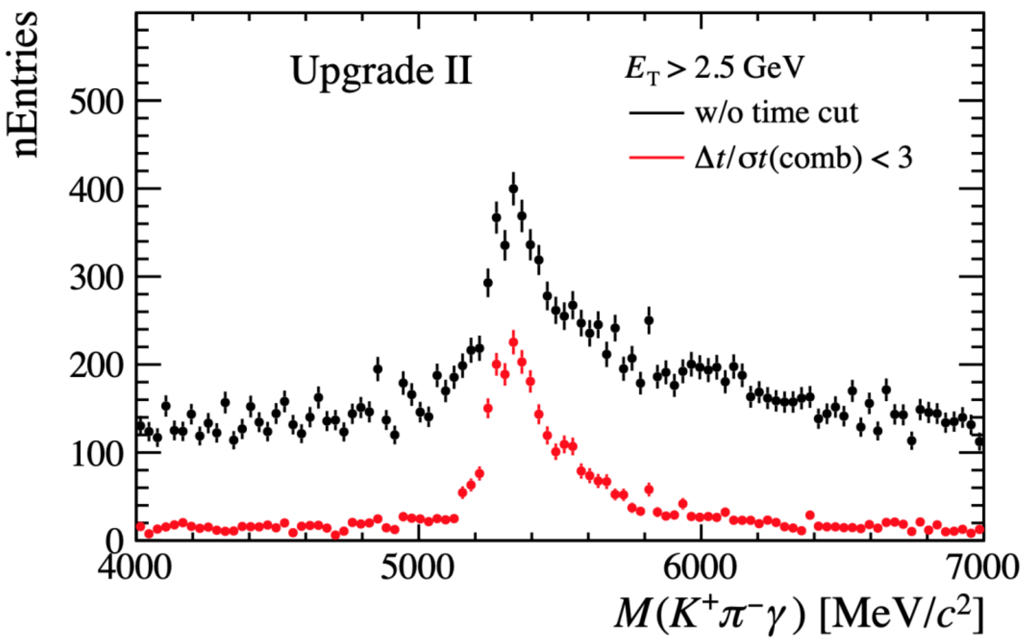
ECAL

[CERN-LHCC-2021-012]





Radiation limit of current Shashlik technology

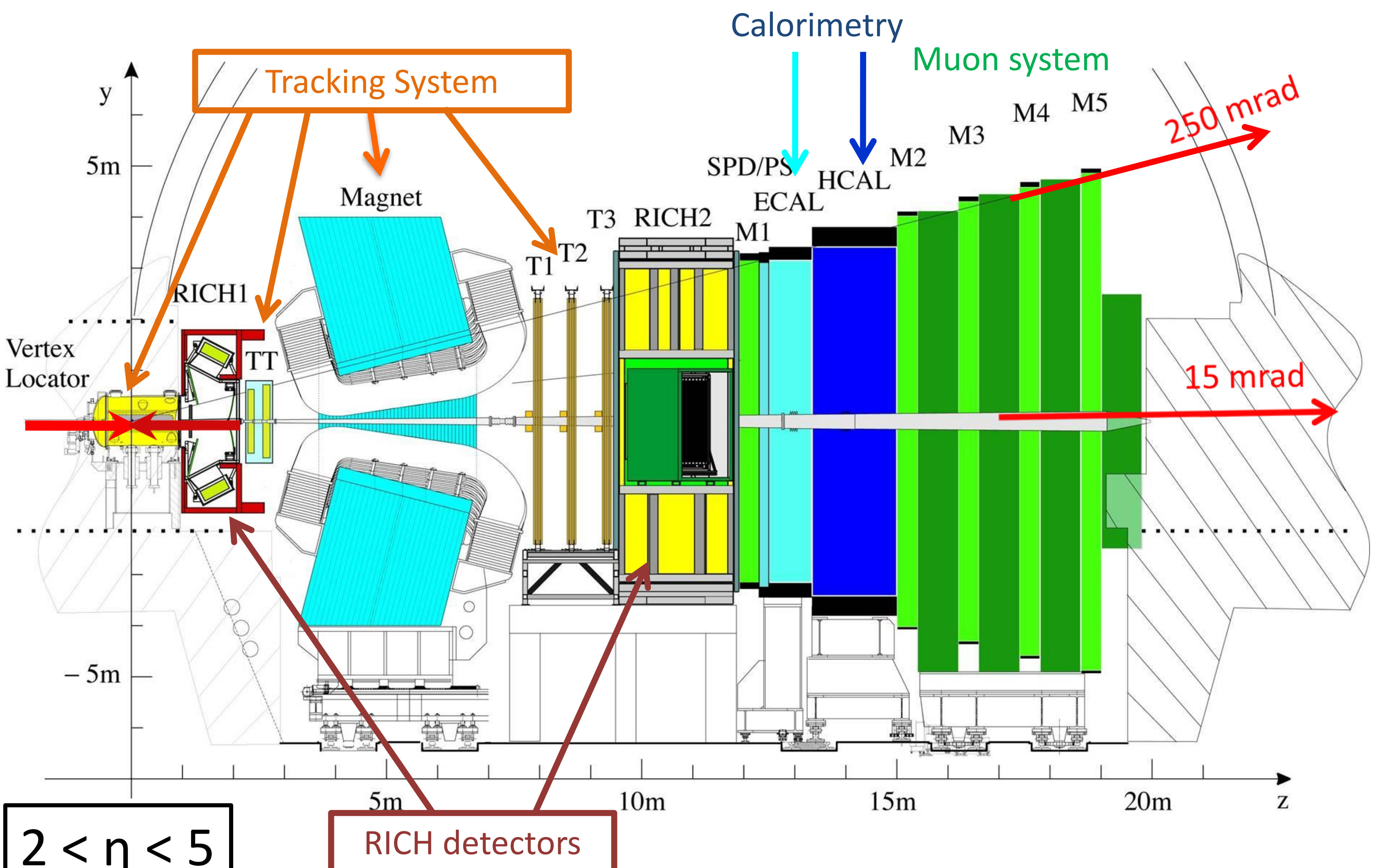


Timing information improves resolutions and supprezsses background

RUN 1 & 2

2008 JINST 3 S08005

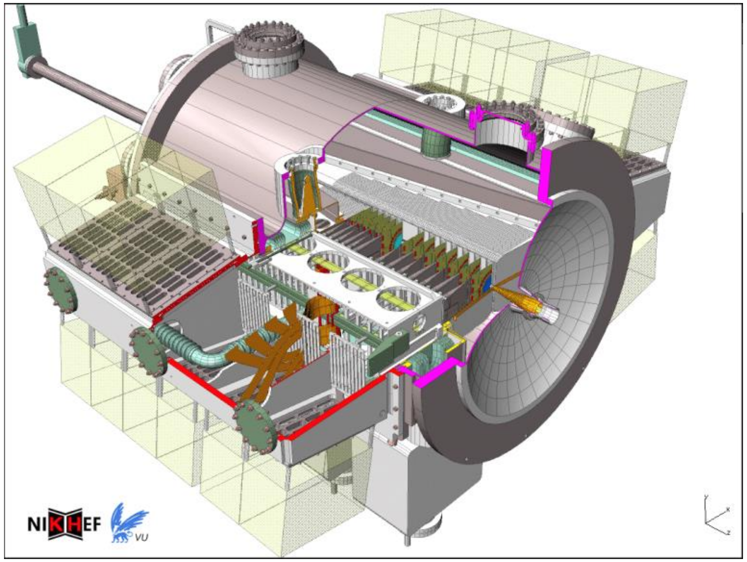
LHCb detector



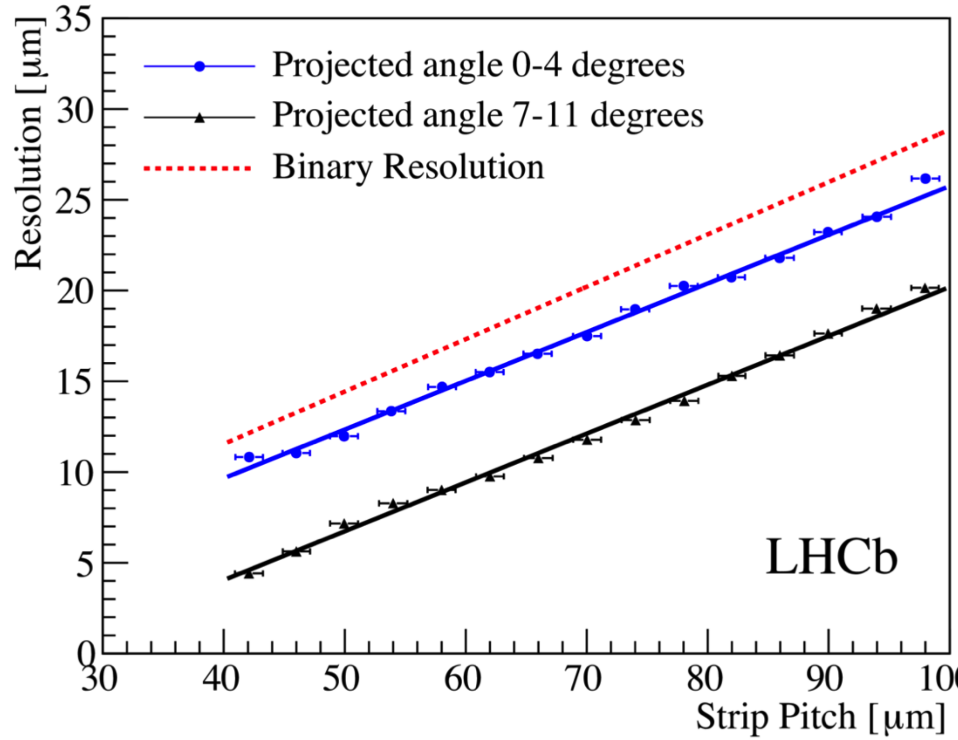
$2 < \eta < 5$

VErtex LOcator (VELO)

Int. J. Mod. Phys. A 30, 1530022 (2015)
2014 JINST 9 P09007

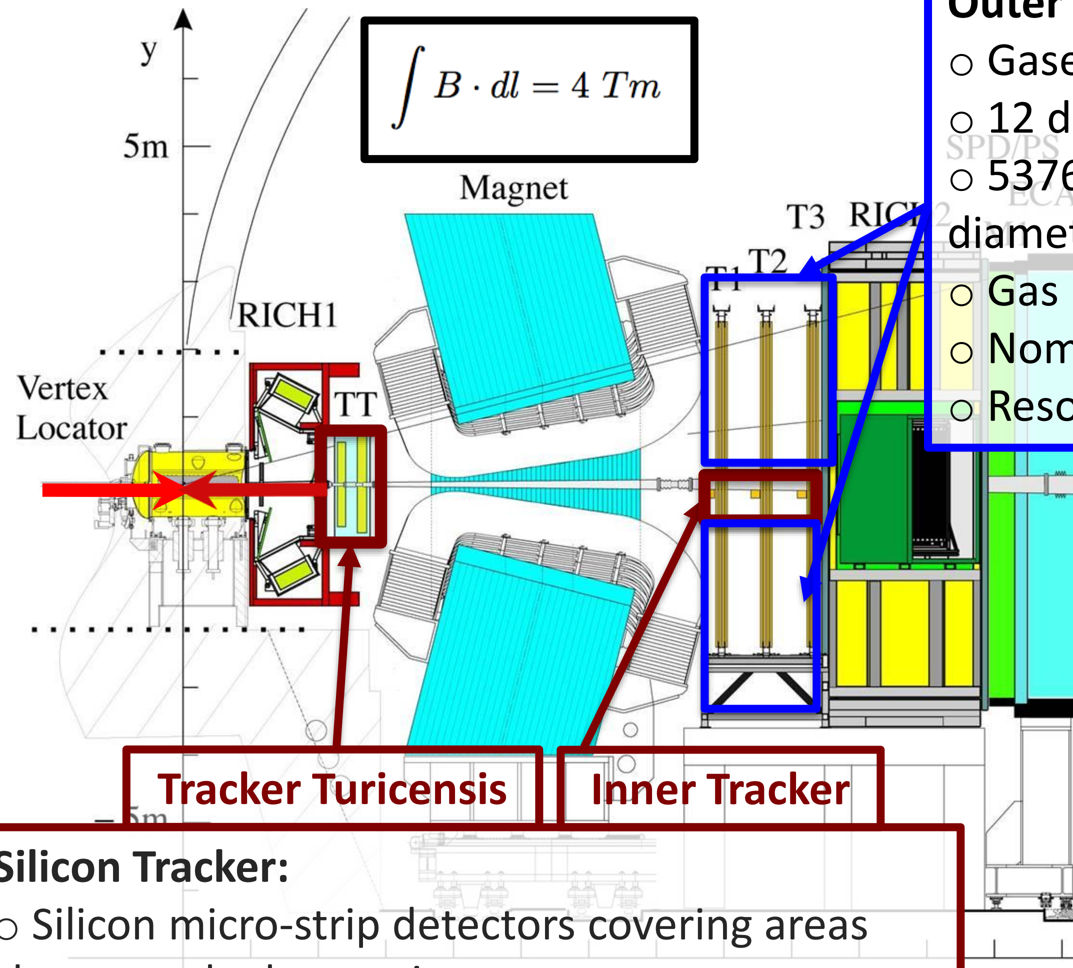


- Two retractable halves
  - 5 mm from beam when closed.
  - 30 mm during injection.
  - First measurement at 8.13 mm.
- Operated in secondary vacuum.
  - 300 µm aluminium foils separates detector from beam vacuum.
- 21 R-Φ modules per half.
  - Silicon microstrip sensors.
  - Pitch: 38 – 101 µm.

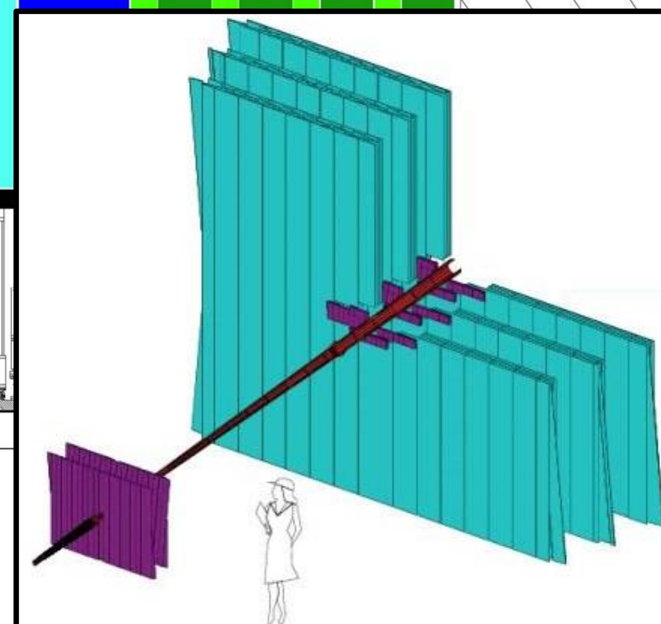


- Hit resolution measured from unbiased residuals of cluster to track.
- Projected angle is the angle between track and strip in plane perpendicular to the track.
- Best resolution: 4 µm!

LHCb Tracker



Outer Tracker:
- ○ Gaseous straw tube detector.
- ○ 12 detection layers (~ 4 x 6 m^2).
- ○ 53760 straw tubes (2.4 m long, 4.9 mm diameter).
- ○ Gas mixture: $Ar/CO_2/O_2$ (70%/28.5%/1.5%).
- ○ Nominal operating voltage is 1550 V.
- ○ Resolution ≈ 200 µm.



Silicon Tracker:
- ○ Silicon micro-strip detectors covering areas closest to the beam pipe.
- ○ Pitch: 183 µm (TT), 198 µm (IT).
- ○ Thickness: 500 µm (TT), 320/410 µm (IT)
- ○ Strips up to 37 cm long.
- ○ Resolution ≈ 50 µm.

2019 JINST 14 P04006

LHCb Trigger (Run 2)