LHCb upgrades

Pobednik the Victor, Kalemegdan park

Fabio Ferrari on behalf of the LHCb collaboration
University of Bologna and INFN

11th Edition of the Large Hadron Collider Physics Conference
Belgrade, 22th - 26th May 2023

Outline

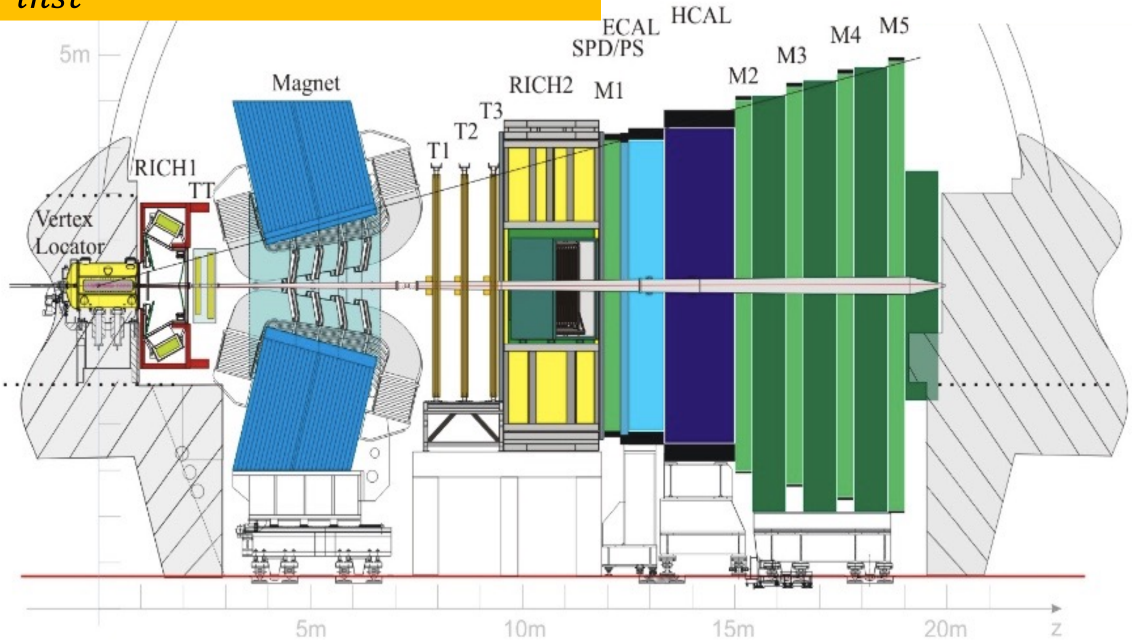
- LHCb in Run 1 and 2: what has been achieved so far
- LHCb Upgrade I (Run 3 and 4): what we are accomplishing
  - Motivations
  - New detector technologies
  - Commissioning
- LHCb Upgrade II (Run 5 and 6): what we dream of at the HL-LHC
  - Prospects
- Conclusions

The LHCb detector

2008 *JINST* **3** S08005

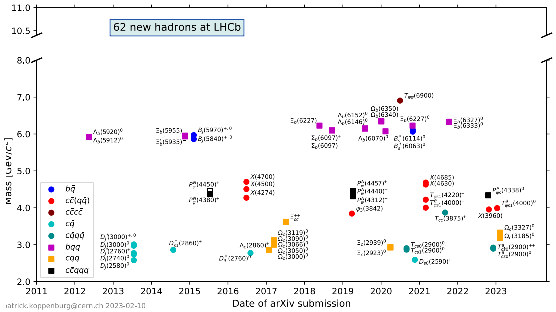
Single-arm forward spectrometer dedicated to beauty and charm decays

$L_{inst} = 2 - 4 \cdot 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

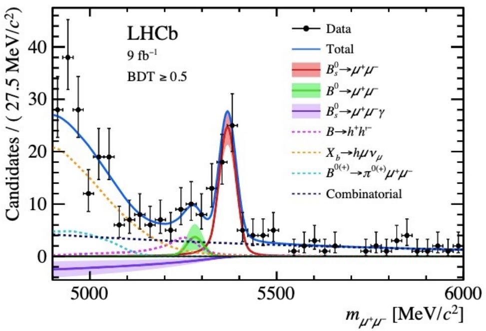


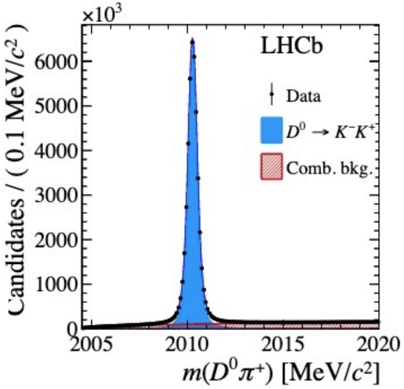
- Decay-time resolution: 45 fs for $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^- \pi^+$
- Very good momentum resolution: Δp/ p = 0.5% at < 20 GeV/c to 1.0% at 200 GeV/c
- Excellent PID capabilities: Kaon ID ~ 95 % for ~ 5 % π→K mis-id probability
- Good ECAL resolution: 1 % + 10 %/ √(E[GeV])
- Very good muon ID: Muon ID ~ 97 % for 1-3 % π→μ mis-id probability

LHCb: a history of success

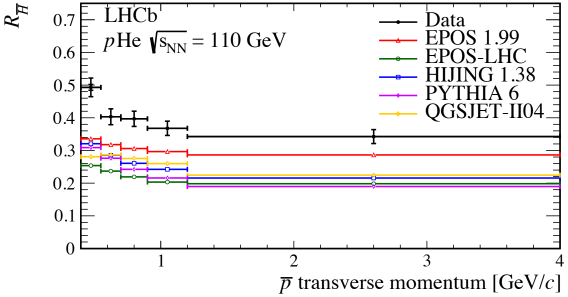


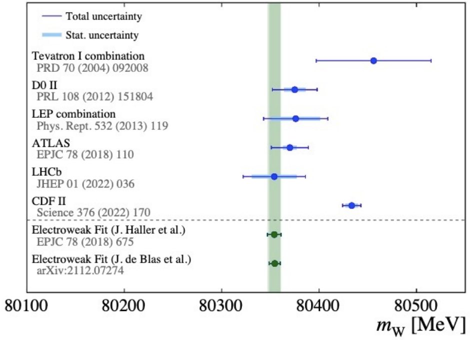
- More than 600 papers
- Series of significant discoveries
  - Rare decays
  - Spectroscopy
  - CPV in charm and beauty





- Physics program well beyond what originally planned
  - Fixed target
  - Heavy ions
  - Dark sector
  - Electroweak

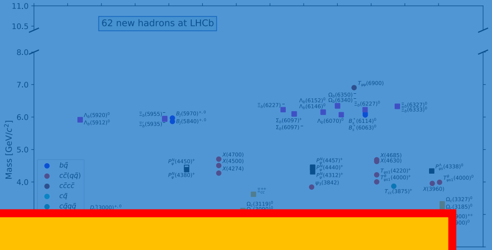


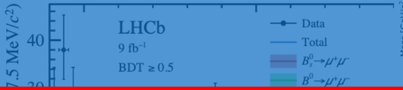


LHCb-PAPER-2021-007
LHCb-FIGURE-2021-001
LHCb-PAPER-2019-006
LHCb-PAPER-2022-006
LHCb-FIGURE-2022-003

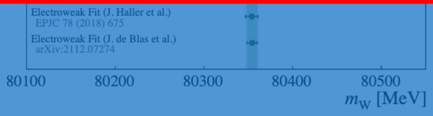
LHCb: a history of success

- More than 600 papers
- S
- P





LHCb can be considered as a general purpose detector in the forward region!

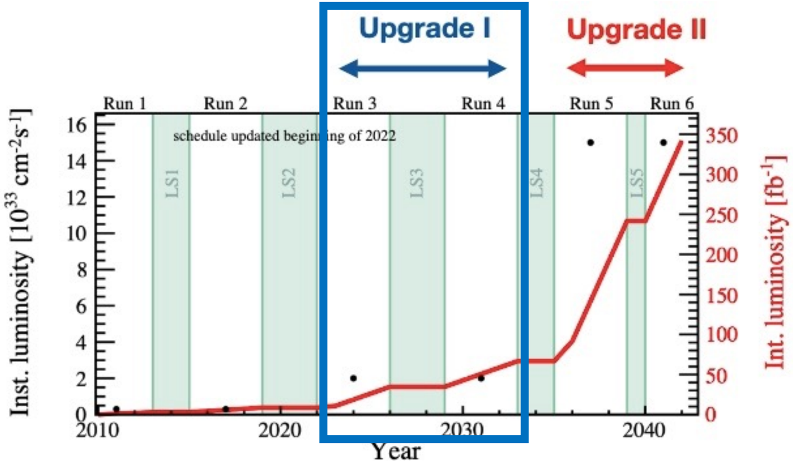


007
-001
006
LHCb-PAPER-2022-006
LHCb-FIGURE-2022-003

Motivations for LHCb Upgrade I

- New Physics still hiding somewhere, no direct observations yet
  - Flavour physics can probe energy scales well beyond the reach of current (and future) accelerators
- Physics program limited by LHCb, not by LHC
- More precision needed to push current measurements downt to SM precision
  - BR($B_s^0 \to \mu\mu$) down to 10% of SM
  - CKM angle γ down to 1^o
  - $2\beta_s$ to precision < 20% SM value
  - Charm CPV below 10^{-4}

➡ **LHCb Upgrade I**



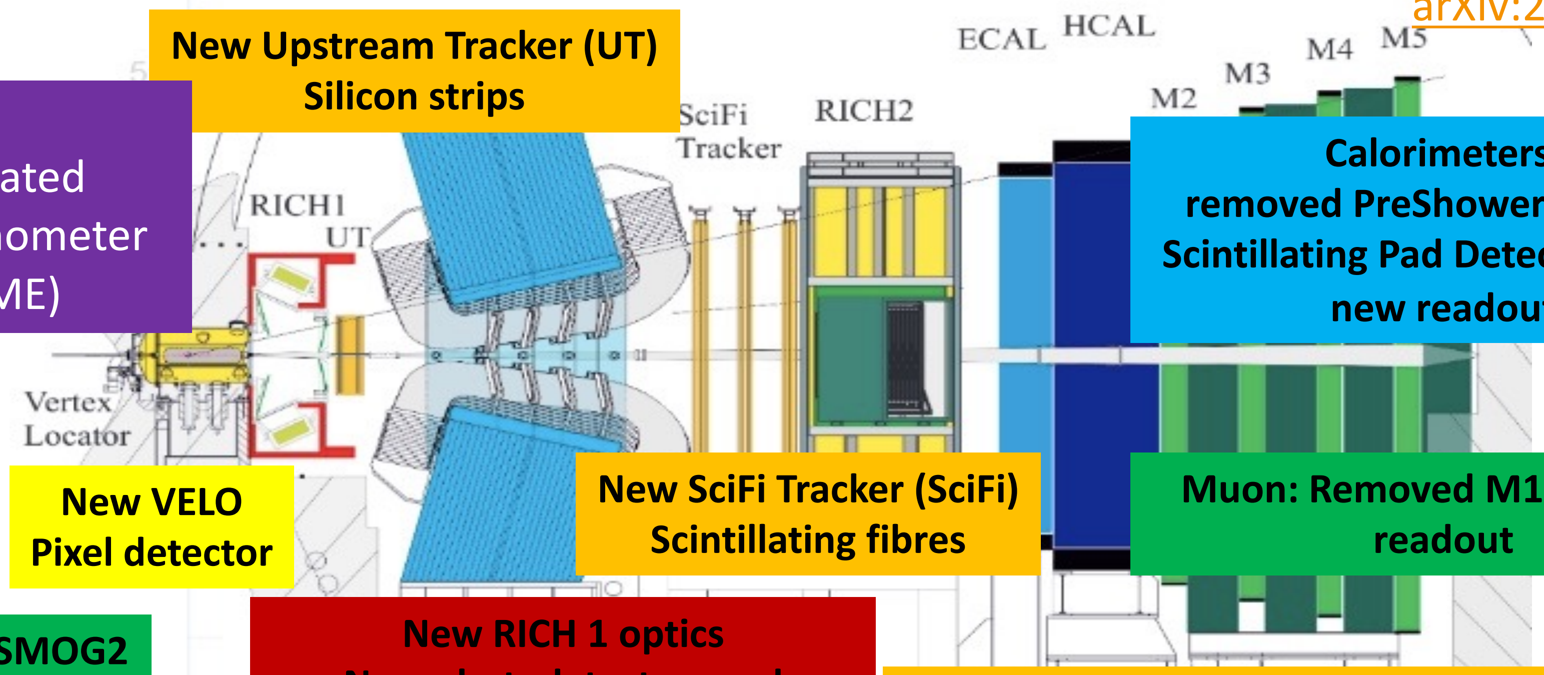
The LHCb detector – Run 3-4

Check G. Cavallero talk for more details on LHCb Run 3 performance

A brand new detector!

CERN-LHCC-2012-007

arXiv:2305.10515



New Upstream Tracker (UT)
Silicon strips

New dedicated luminometer (PLUME)

Calorimeters:
removed PreShower (PS) and Scintillating Pad Detector (SPD), new readout

New VELO Pixel detector

New SciFi Tracker (SciFi)
Scintillating fibres

Muon: Removed M1 and new readout

New SMOG2 system

New RICH 1 optics
New photodetectors and readout for RICH 1 and 2

$L_{inst} = 2 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (x5 w.r.t. Run 1)

The LHCb detector – Run 3-4

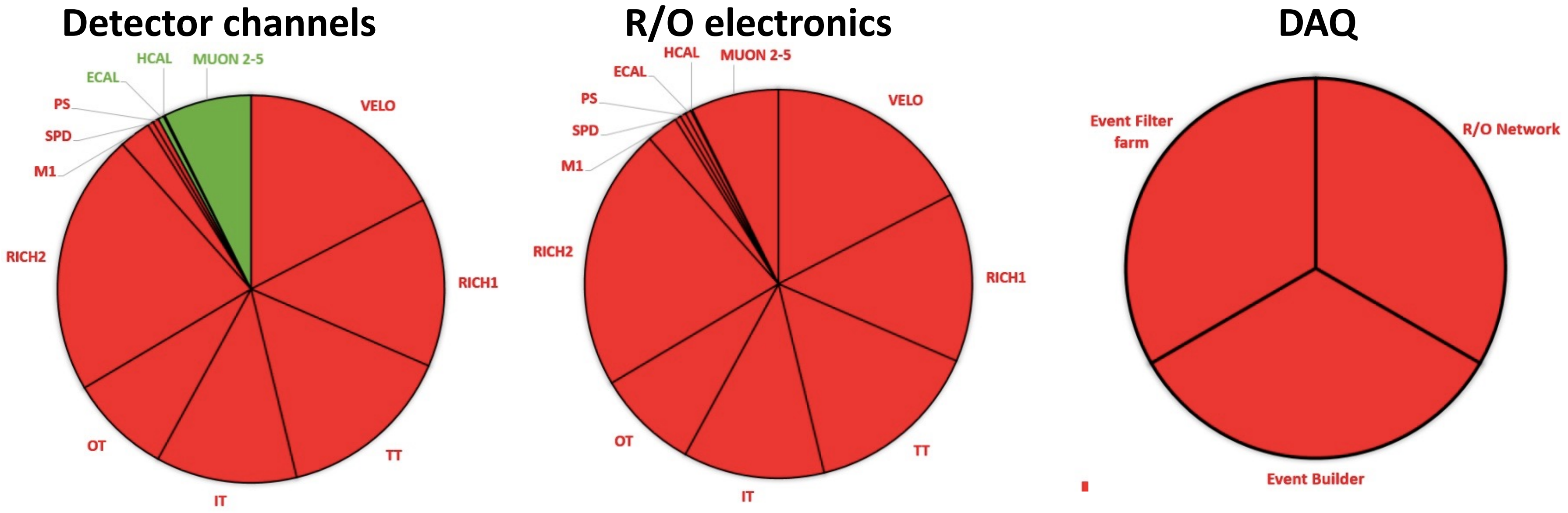
A brand new detector!

CERN-LHCC-2012-007

arXiv:2305.10515

To be upgraded

To be kept

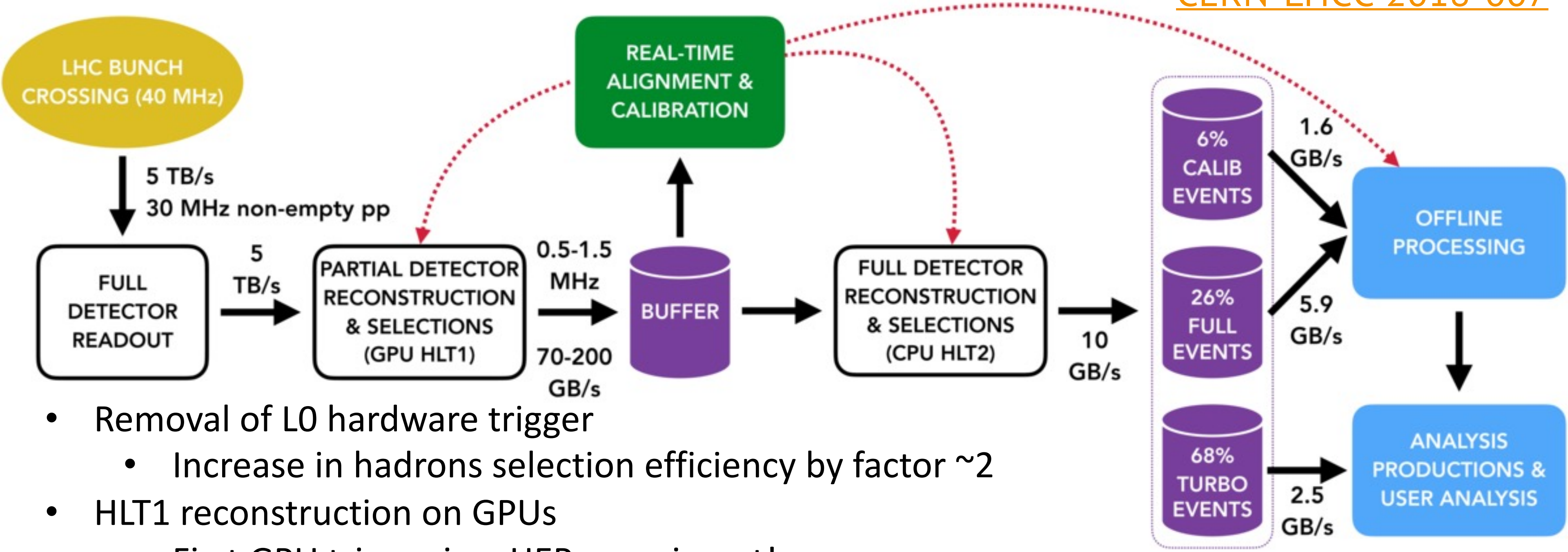


Upgrade I is a BIG upgrade for LHCb

Data processing and trigger

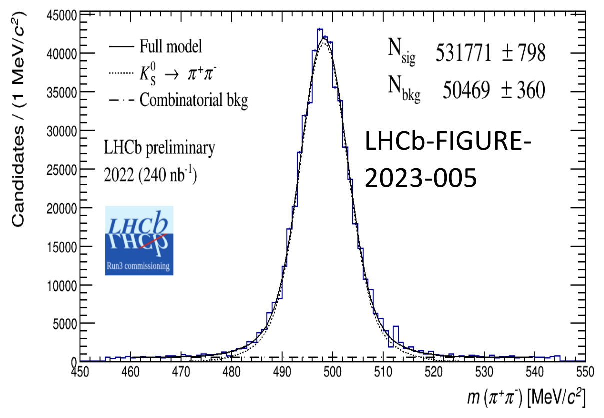
Check M. Fontana talk for more details about online reconstruction and trigger

CERN-LHCC-2018-007

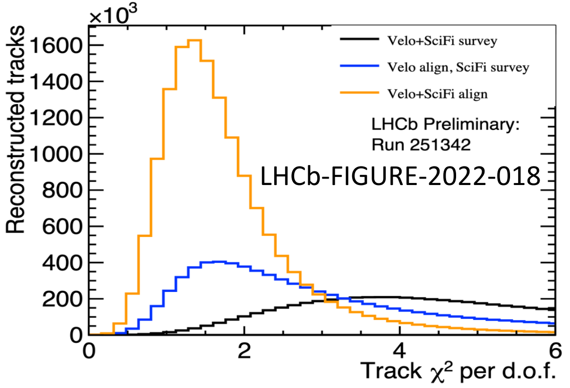


- Removal of L0 hardware trigger
  - Increase in hadrons selection efficiency by factor ~2
- HLT1 reconstruction on GPUs
  - First GPU trigger in a HEP experiment!
- Real time alignment and calibration
- Offline quality reconstruction in HLT2

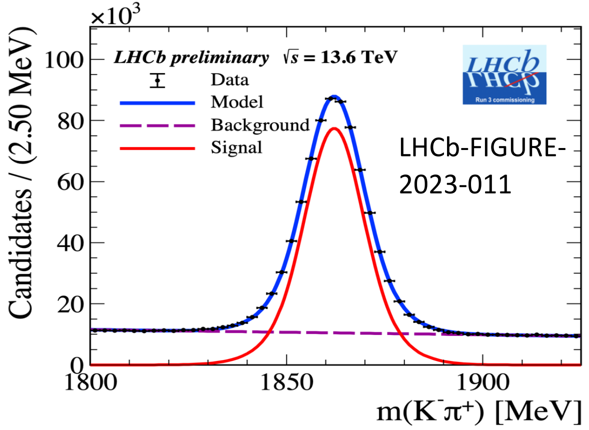
Check M. Fontana talk for more details



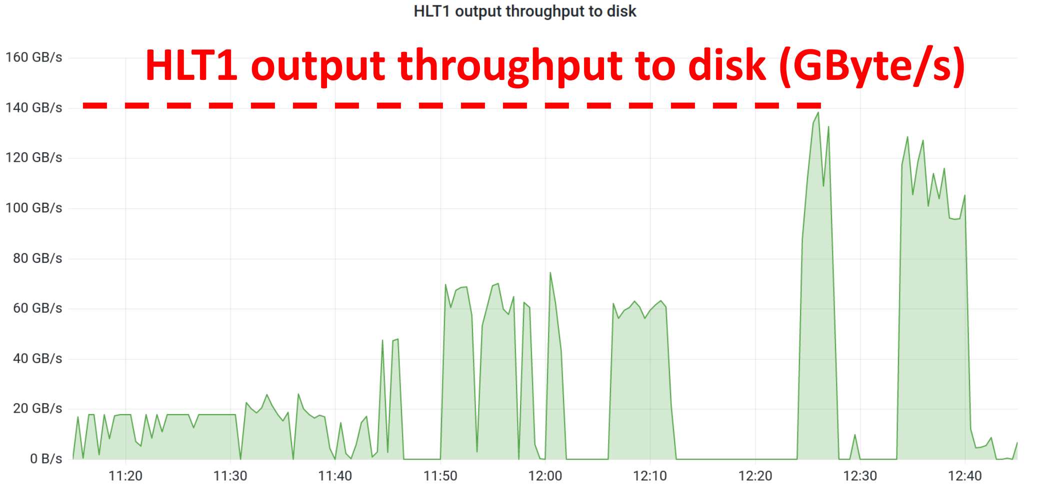
K_S^0 candidates reconstructed directly in HLT1



Distribution of χ^2 per degree of freedom for long tracks improves after alignment procedure



D^0 candidates reconstructed by HLT2



DETECTOR READOUT

ULL ENTS

5.9 GB/s

8% RBO ENTS

2.5 GB/s

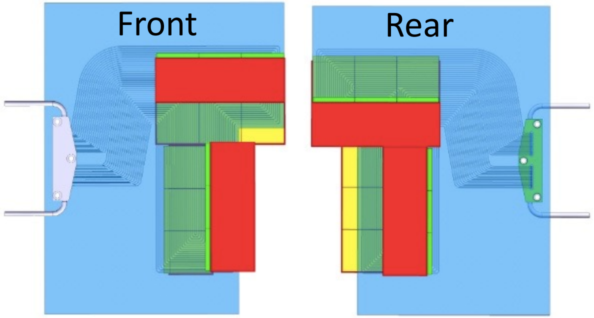
ANALYSIS PRODUCTIONS & USER ANALYSIS

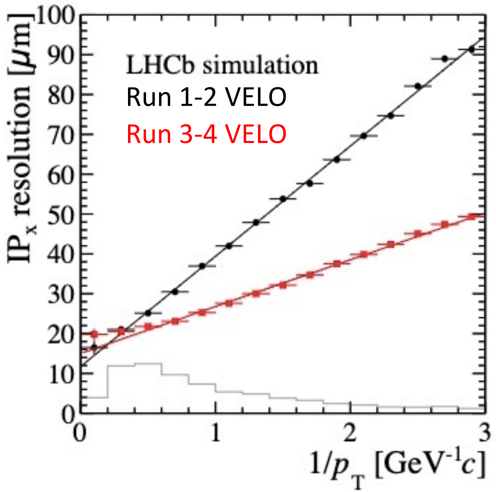
- Removal of L0 h
  - Increase in
- HLT1 reconstruc
  - First GPU tr
- Real time alignm
- Offline quality re

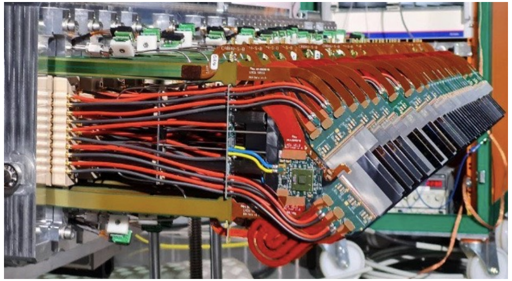
VELO

CERN-LHCC-2013-021

- 52 modules for a total of 41M pixels
  - Area ~ 1.2 m^2
- Two movable halves → get as close as 3.5 mm to the beam to improve IP resolution
  - Separation from primary vacuum achieved with 150 μm thick RF foil
- Silicon substrate built with micro channels that will carry CO_2 for evaporative cooling
  - Designed to cool a load of up to 30W from each module
- New ASIC VeloPix, ~20 Gbit/s in hottest ASIC and total of ~2 Tbit/s



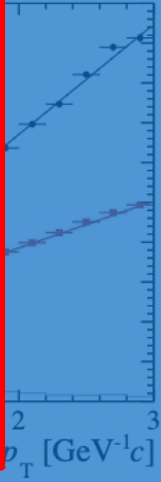




VELO

CERN-LHCC-2013-021

- 52 modules
  - Area ~ 1.2
- Two movab
  improve IP
  - Separati
- Silicon subs
  for evapora
  - Designed
- New ASIC V
  Tbps



- On 10th January 2023 an incident happened due to a failure of the LHC vacuum system of the VELO
- RF foils have suffered plastic deformation and have to be replaced (YETS 2023/24), but no damage on detector modules and cooling
- Physics programme of 2023 is significantly affected, commissioning of Upgrade I systems can proceed as planned
- Final checks to be performed in June technical stop and running configuration decided

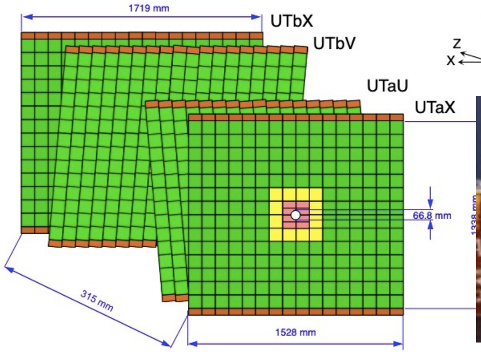
Vacuum

Upstream Tracker (UT)

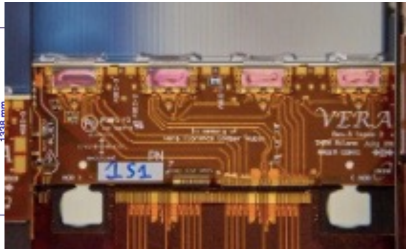
CERN-LHCC-2014-001

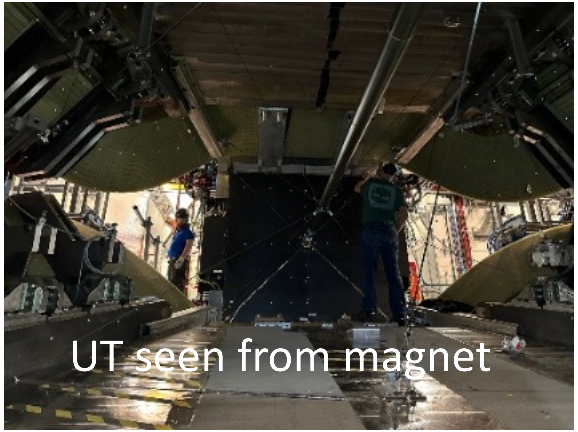
- Silicon micro-strip detector
  - Four layers (aX,aU,bV,bX)
  - Increasing granularity getting closer to the beam
- Different sensors for different regions
  - 250 μm thickness
  - Pitch: ~ 95-190 μm
  - Sensors mounted on staves (both sides)
  - Maximum occupancy: < 1%
- Sensors need to be kept below -5° C
  - Bi-phase CO^2 cooling pipe integrated in stave
- UT installed before cavern closure in 2023 → commissioning ongoing!

UT layers sketch



Zoom on sensor + hybrid



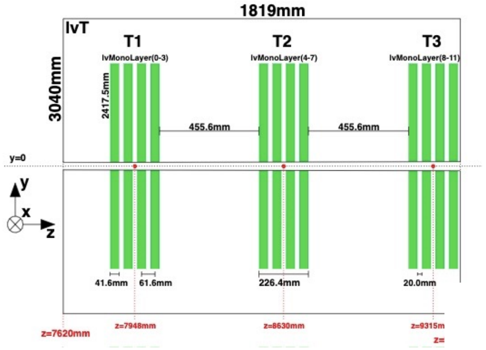


Scintillating fibres tracker (SciFi)

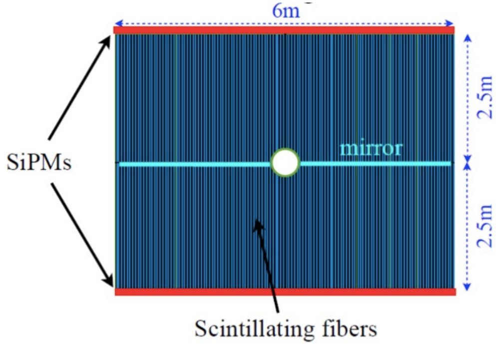
CERN-LHCC-2014-001

- Brand new detector based on scintillating fibres
  - Three stations with four detection layers each, 6 fibres / layer
  - Fibres diameter and length: 250 μm / 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 -40º C to reduce rate of dark counts
- New ASIC, 64 channels 130 nm CMOS
  - Clusterisation of hits implemented in FPGA after signal digitisation

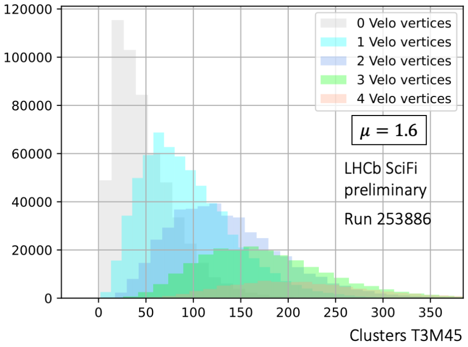
Side view sketch of SciFi

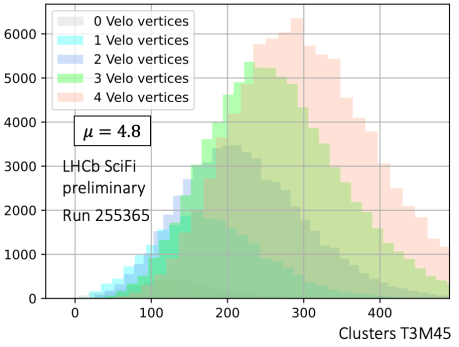


Front view sketch of SciFi



LHCb-FIGURE-2023-012



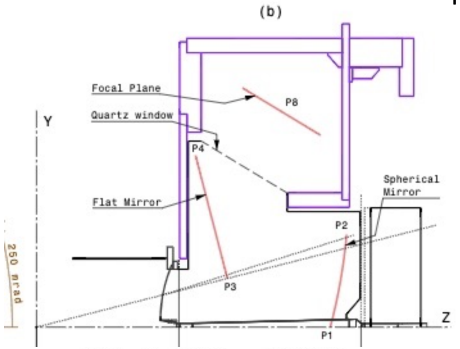


RICH 1 and 2

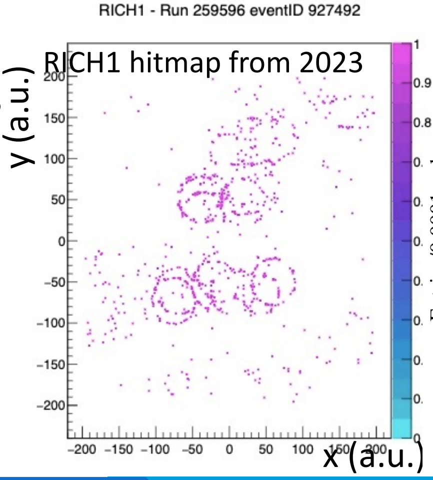
CERN-LHCC-2013-022

- Preserve excellent performance achieved in Run 1 and 2
  - RICH1 with C_4F_{10} and RICH2 with CF_4
  - Particle identification for momenta between 2.6 ad 100 GeV/c
- Replace Hybrid Photon Detectors (HPDs) with Multianode PMTs (MaPMTs) in RICH1 and RICH2
  - 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 and 2 performance already better than in Run 1 and 2!

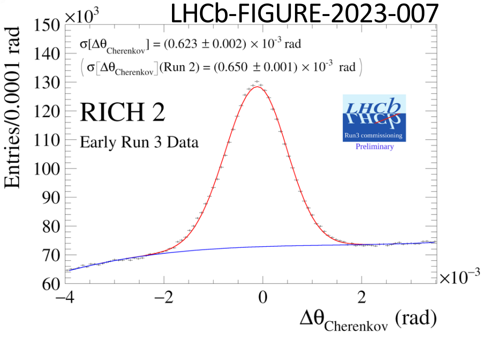
Scheme of new mirrors setup



RICH1 hitmap from 2023



LHCb-FIGURE-2023-007

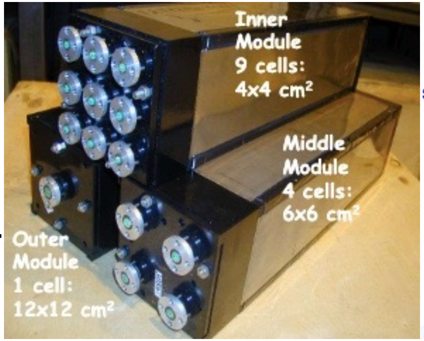


ECAL and HCAL

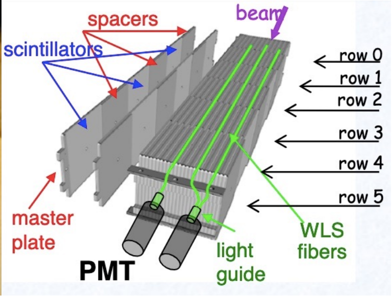
CERN-LHCC-2013-022

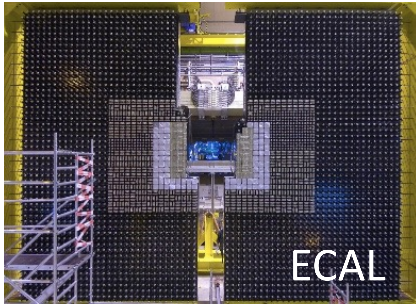
- Present detector kept unchanged
  - ECAL: Shashlik modules (lead + scintillator) for a total of 25 X_0
  - HCAL: TileCal modules (iron + scintillator)
- PS/SPD detectors removed
  - No need anymore for fast inputs to L0 hardware trigger
- PMT gain reduced by a factor 5 to increase lifetime of detector
  - 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

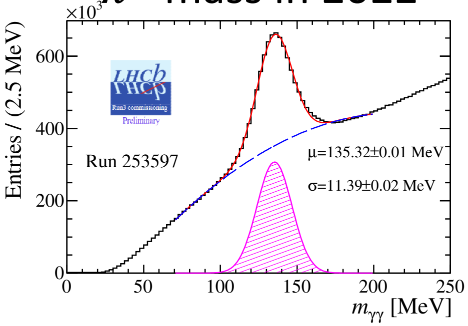


HCAL module





π^0 mass in 2022

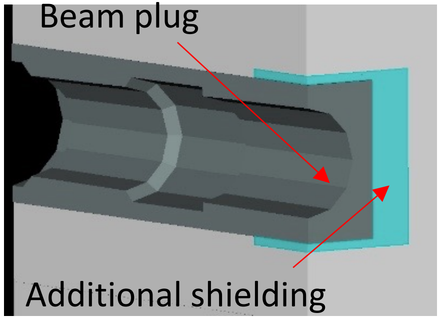


LHCb-FIGURE-2022-019

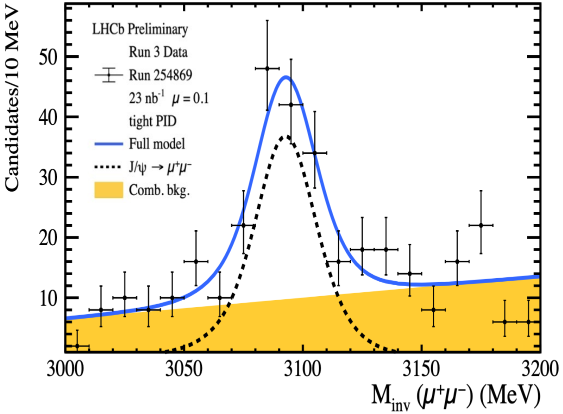
MUON

[CERN-LHCC-2013-022]

- Present MUON detector kept as it is
  - 4 layers (M2-M5) of Multi-Wire Proportional Chambers (MWPCs)
- Remove first layer (M1) with GEMs, since L0 trigger level has been removed
- Install additional shielding around beam-pipe to 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-FIGURE-2023-002

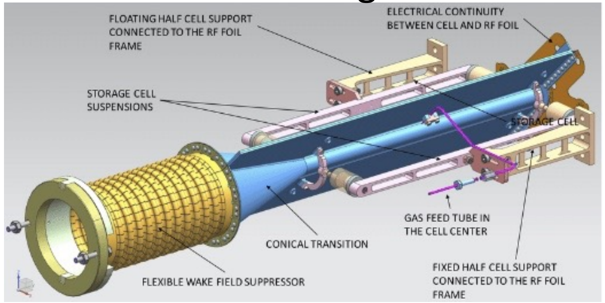


SMOG 2

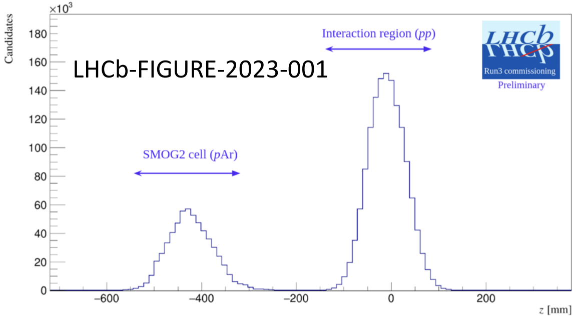
Check G. Graziani and O. Boente talks for more details about SMOG2 and physics results
CERN-LHCC-2019-005

- SMOG2 allows to inject different gases in LHCb IP
  - Fixed target physics, in parallel with p-p data taking
  - Gas cell upstream of VELO → p-p and p-gas vertices easily distinguishable
- Increase interaction rate by orders of magnitude compared to previous SMOG
  - x20-100 collected statistics

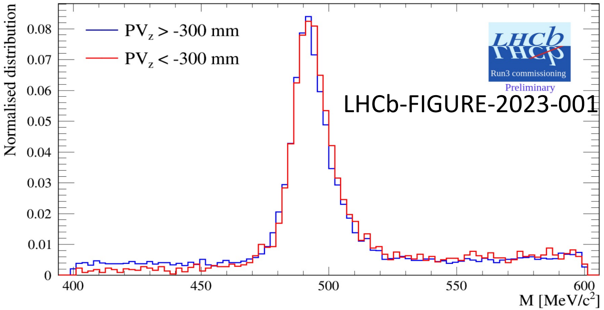
Sketch of the gas cell



Distribution of reconstructed vertices for pp and pAr



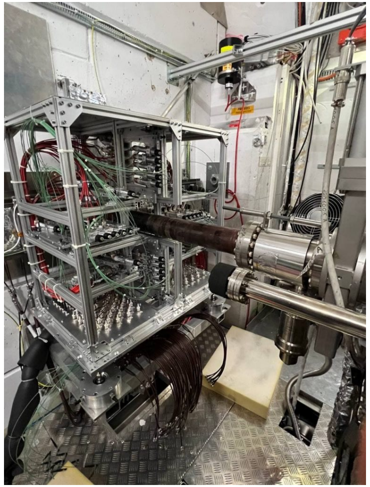
K_S^0 reconstructed in pp and pAr collisions



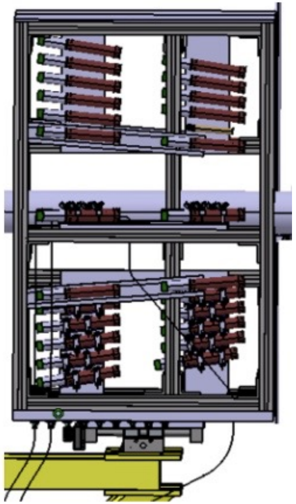
PLUME

CERN-LHCC-2021-002

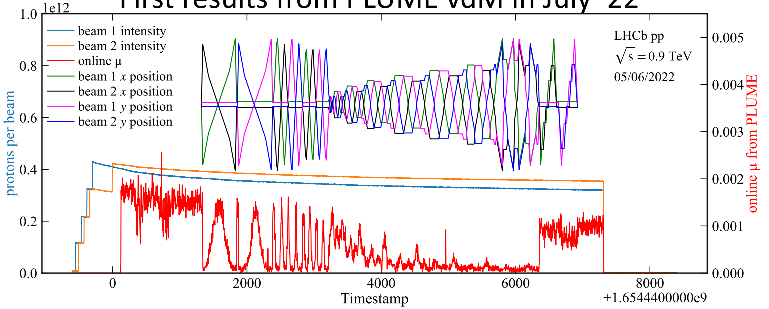
- Cross-shaped hodoscope composed by 48 PMTs, installed upstream of the VELO
  - Detect Cherenkov light from particles impinging on a quartz tablet glued to the PMTs window
- Measure rate of coincidences every 3 seconds and compute luminosity with logZero method
  - Provide real-time feedback to the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



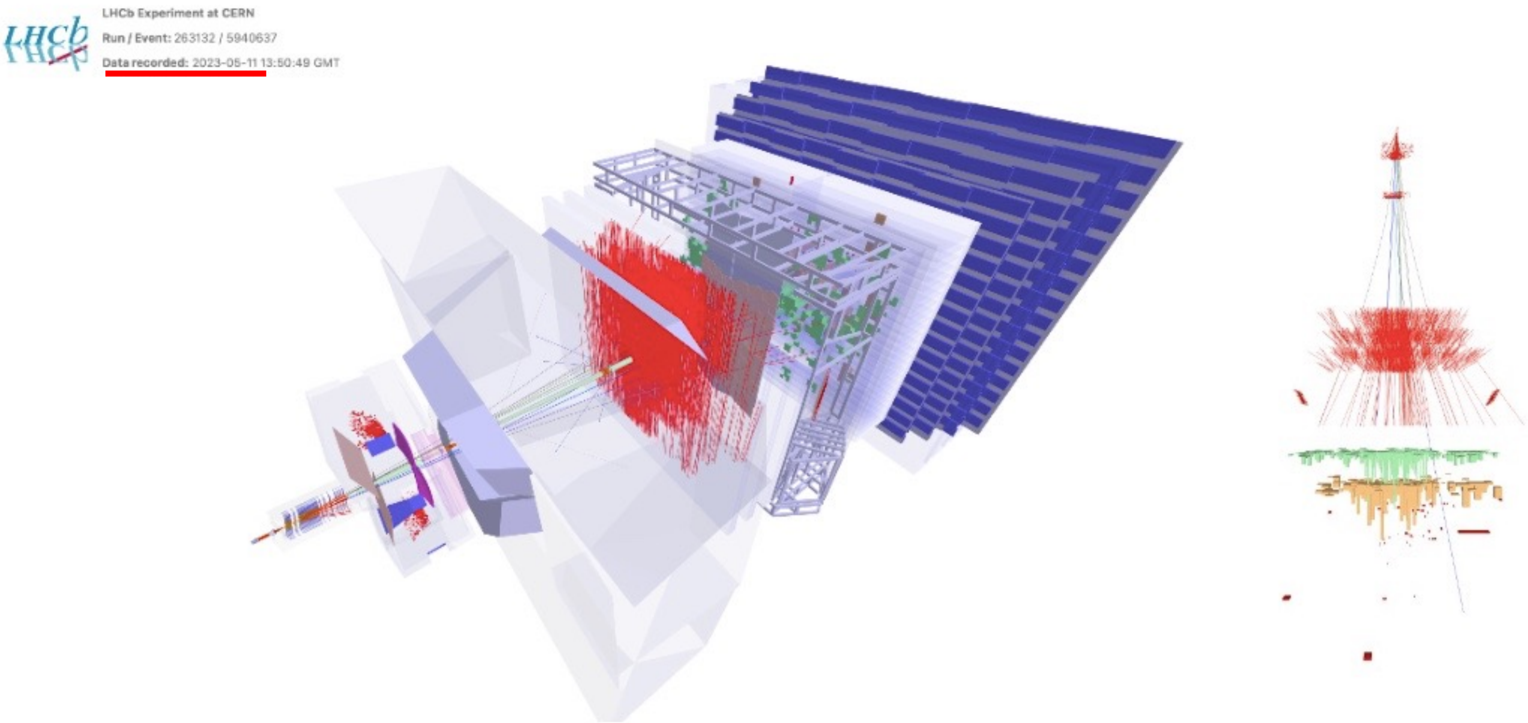
Lateral view sketch



First results from PLUME vdM in July '22



Event display from 2023

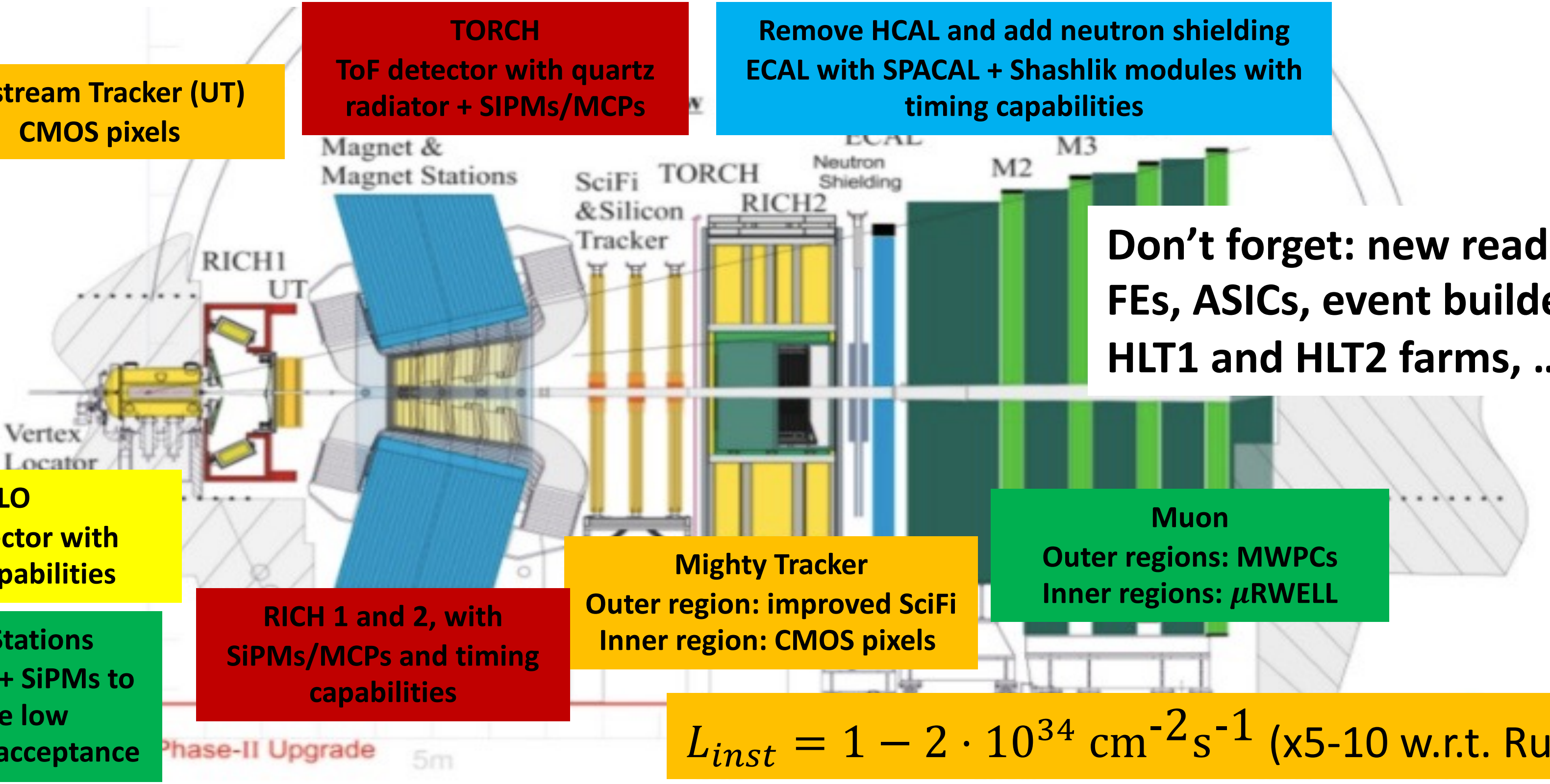


Run 3 is happening and the LHCb detector is ready to face it

The LHCb detector – 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

Don't forget: new readout, FEs, ASICs, event builders, HLT1 and HLT2 farms, ….

VELO
Pixel detector with timing capabilities

Magnet Stations
Scintillators + SiPMs to improve low momentum acceptance

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

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

Muon
Outer regions: MWPCs
Inner regions: μRWELL

$L_{inst} = 1 - 2 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (x5-10 w.r.t. Run 3)

The LHCb detector – Run 5-6

CERN-LHCC 2021-012

The ultimate flavour physics experiment at the HL-LHC

TORCH

Remove HCAL and add neutron shielding

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

dout,

ders,

....

timing capabilities

Magnet Stations
Scintillators + SiPMs to improve low momentum acceptance

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

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

Outer regions: MWPCs
Inner regions: μRWELL

Phase-II Upgrade

$\mathcal{L}_{inst} = 1 - 2 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (x5-10 w.r.t. Run 3)

Prospects for Upgrade I and Upgrade II

*: Run 1 and 2

- Collect 50 fb^{-1} by the end of Run 4 and 300 fb^{-1} by the end of Run 6
  - Collected 9 fb^{-1} during Run 1 and 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 fb^{-1})		Upgrade I (23 fb^{-1})	(50 fb^{-1})	Upgrade II (300 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%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	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
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	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

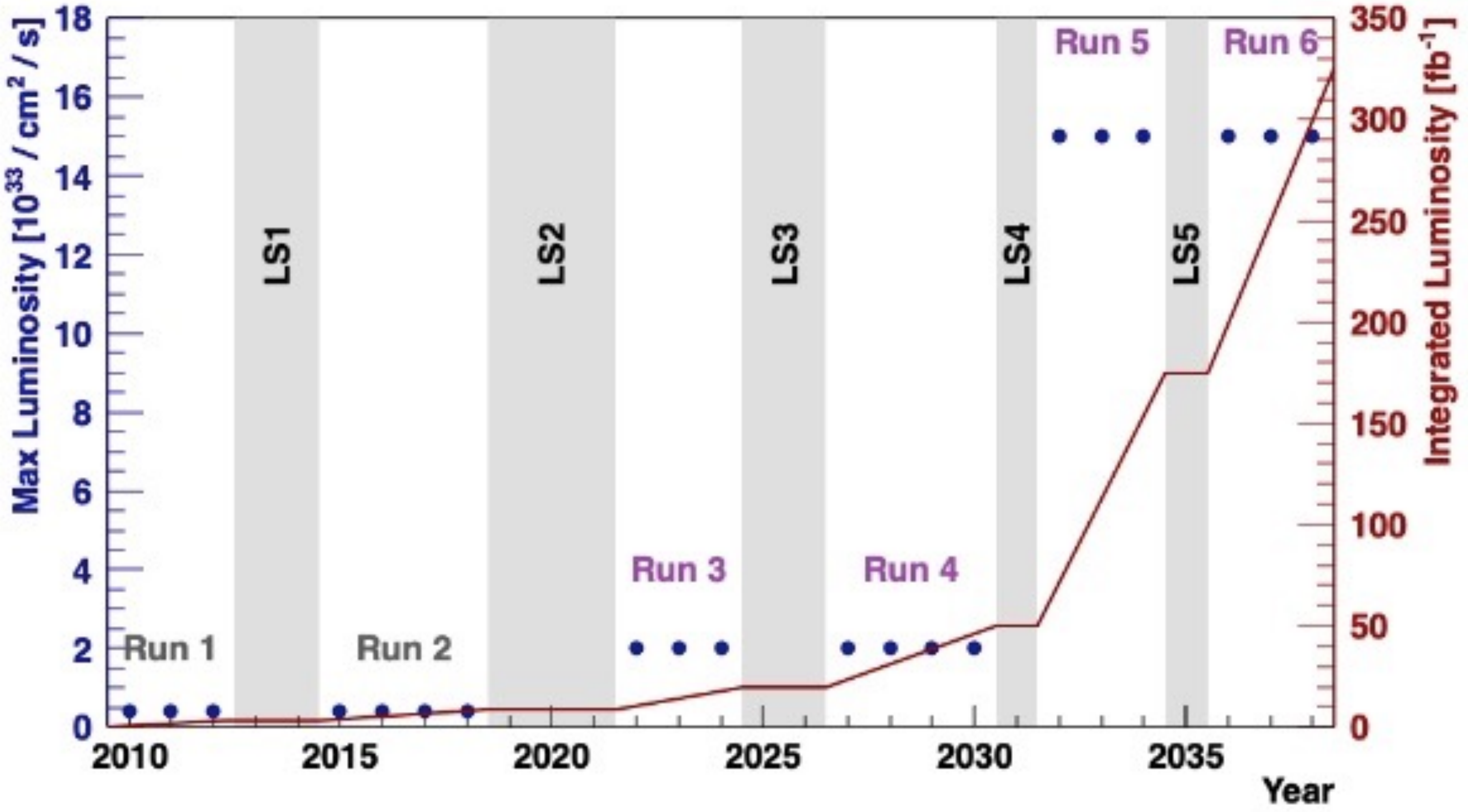
CERN-LHCC 2021-012

Conclusions

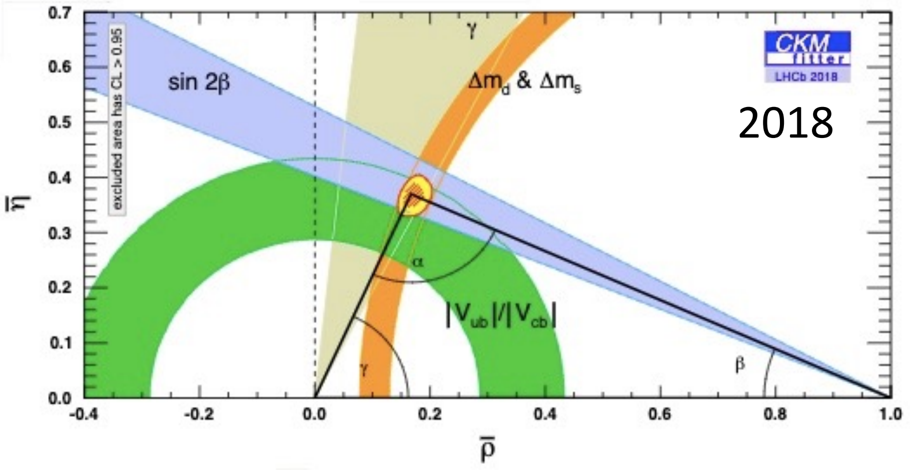
- The LHCb experiment completed it’s first decade of operations
  - Very successful operation lead to first class results
  - Physics programme expanded well beyond original expections
- The LHCb detector underwent its first major upgrade during LS2 → brand new detector
  - Removal of L0 hardware trigger
  - High-level software trigger running at 30 MHz on GPUs
  - New trackers (VELO, UT, SciFi)
  - Upgraded RICH 1 and 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)
- Commissioning phase is proceeding at full steam, even after the unfortunate VELO incident
  - Trying to squeeze out everything we can from the data we are collecting → stay tuned!

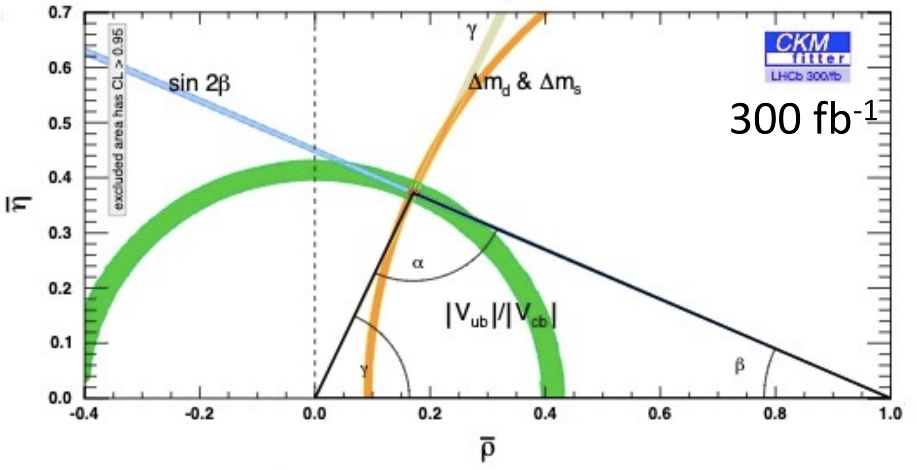
Backup

Luminosity vs year

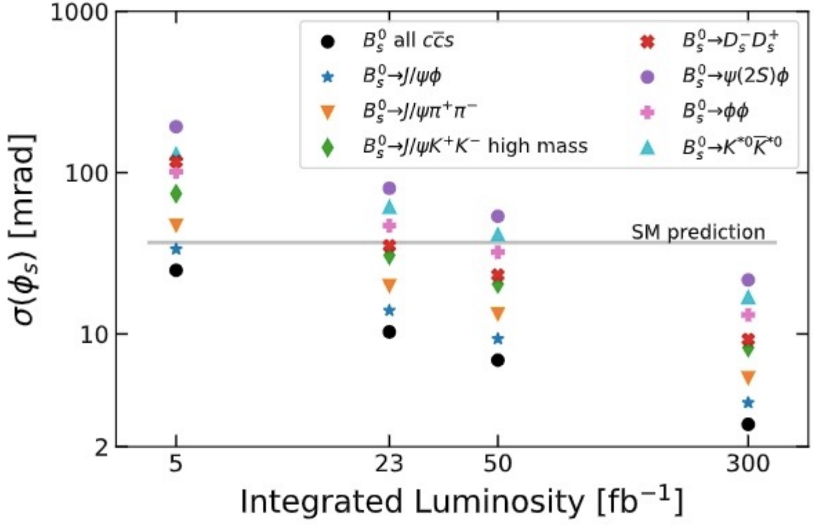


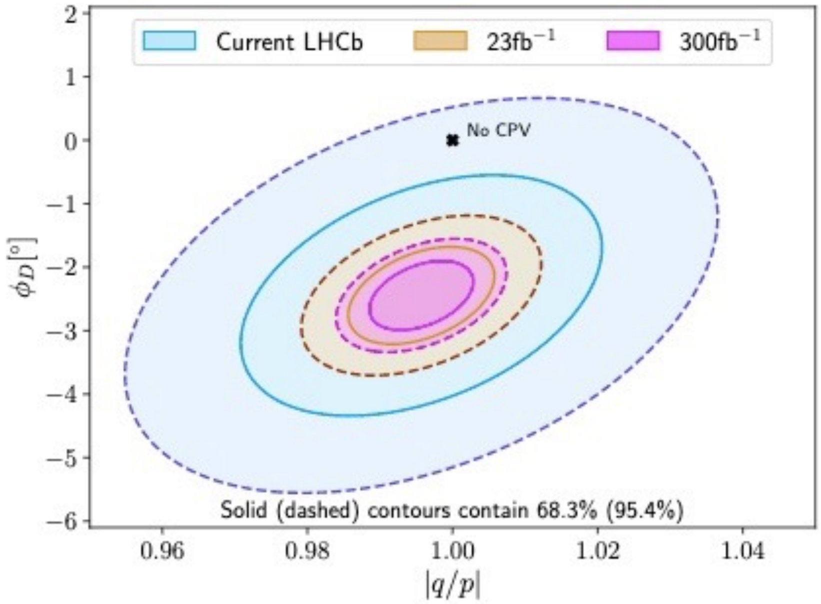
CKM picture - Prospects





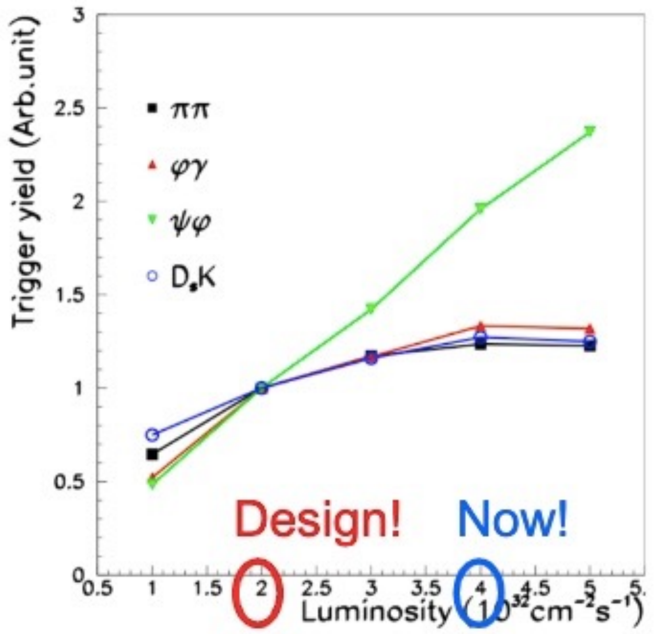
ϕ_s and CPV in charm mixing - Prospects





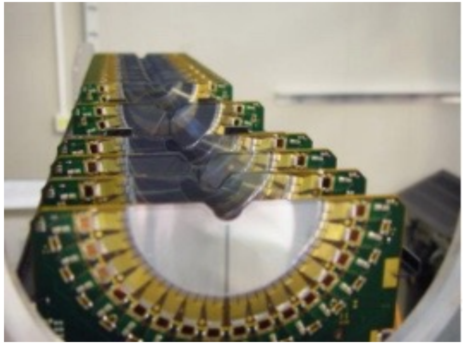
L0 hardware trigger

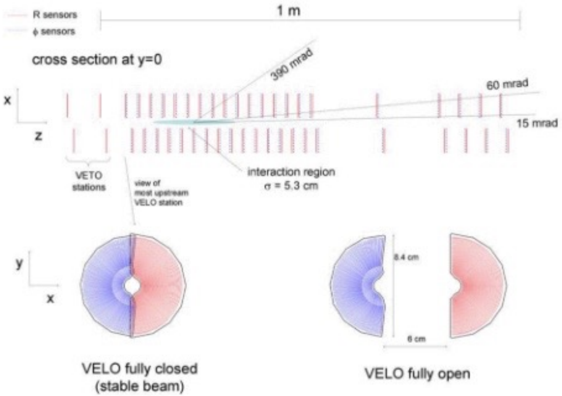
- LHCb Run 1-2 L0 trigger less efficient for hadrons wrt muons
  - Factor ~ 2 lower efficiency with Run 3 conditions
  - Loss of efficiency due to p_T and E_T cuts needed to keep total output bandwidth lower than 1.1 MHz (actual limit)
- At higher luminosities, loss even more important
  - Waste luminosity while not retaining amount of data
- Redesign trigger and readout to cope with 30 MHz input rate
  - Fully software trigger: flexible
  - Reconstruct higher level quantities to improve trigger efficiency and S/B



VELO – Run 1 and 2

- Silicon strips measuring the r and ϕ coordinates of the hits
- Movable device, from 50 mm (fully open) to 5.5 (mm) fully closed
  - Improve IP resolution, accetpance
  - Fully automatic system
- Total fluence: 4 x 10^{14} neq /cm^2
- Total number of channels 170k
- Excellent performance, reliable, cluster efficiency >99.5% best hit resolution down to <4μm

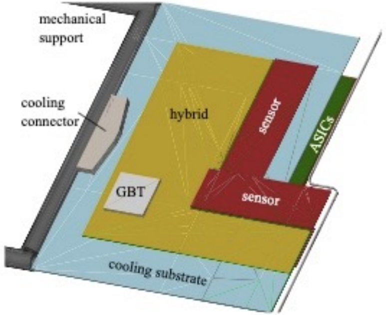




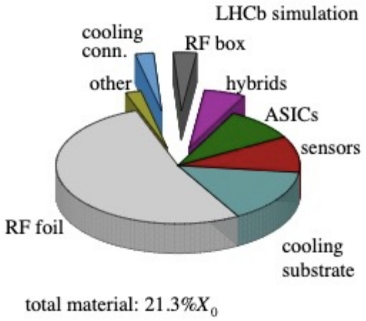
VELO – Run 3 and 4

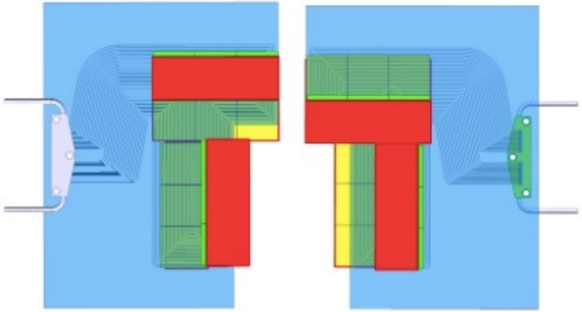
- Pixel detector
  - Thinner sensors (300 μm → 200 μm)
- Move closer to beam wrt Run 1 and 2
- New RF foil
  - Reduce material budget before first hit ($4.6\%\ X_0 \rightarrow 1.7\%\ X_0$)
- New ASIC (VeloPix)
  - Based on Medipix/TimePix
  - 256x256 (55 μmx 55 μm)
  - 12 per module
- Extremely high data rates

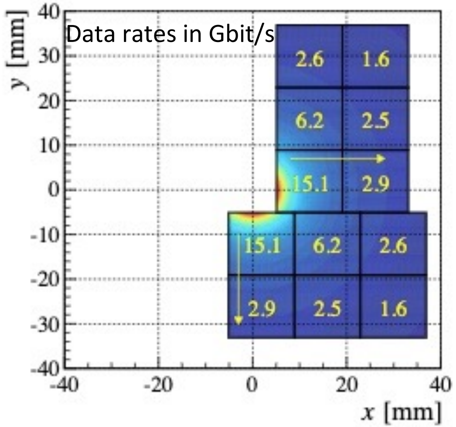
Module



Material budget from VELO in Run 3-4



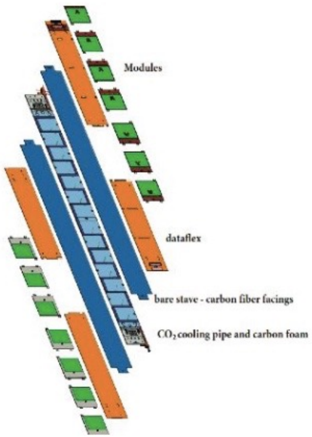


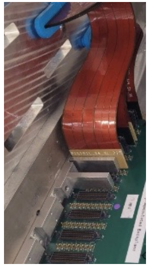


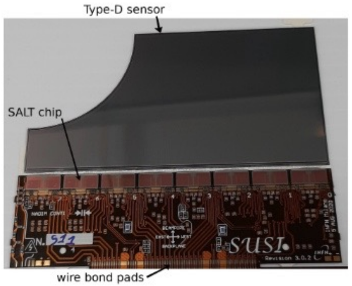
Upstream Tracker

- Maximum occupancy below 1% in innermost regions
- Fluences up to 4×10^{14} neq/cm^2 in the inner region
- Near-detector electronics outside acceptance
  - Distributes TFC&ECS signals
  - Collects serial data from ASICs (320 Mbps)
  - Transmits optical serial data via GBTx/VTTx(~4.8 Gbps)
  - Connected to stave via pigtail flex cables
- Full read-out chain validated in system test
- CO_2 cooling tests at −30°C

A complete stave, with an exploded view of all the elements

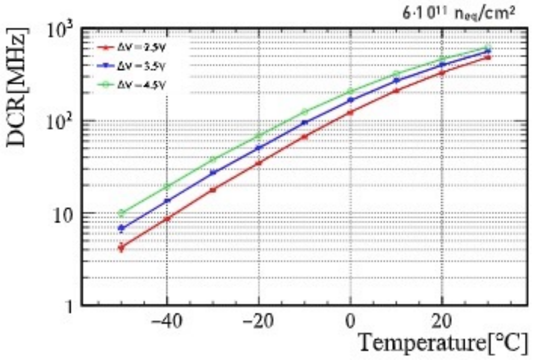


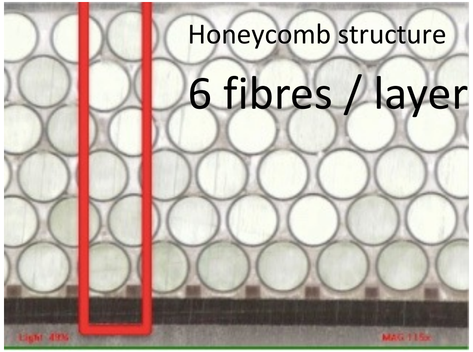




SciFi

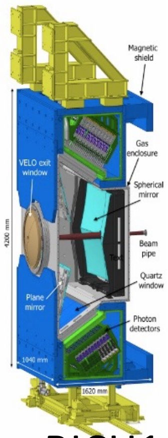
- Single hit reconstruction efficiency better than 99%, ~ 60 μm from test beams
- Less than 1% X_0 per layer (12x)
- 8000 photons per MeV of ionisation energy deposited, before irradiation → expect max. 40% loss at end of operation (inner regions)
- Expected total fluence: 6×10^{11} 1MeV neq/cm^2



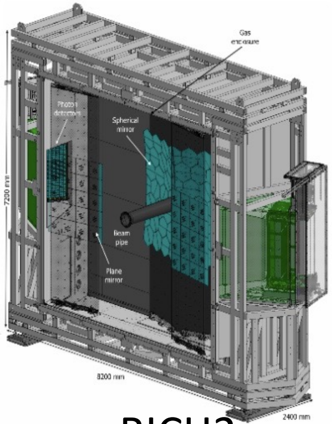


RICH – Run 3 and 4

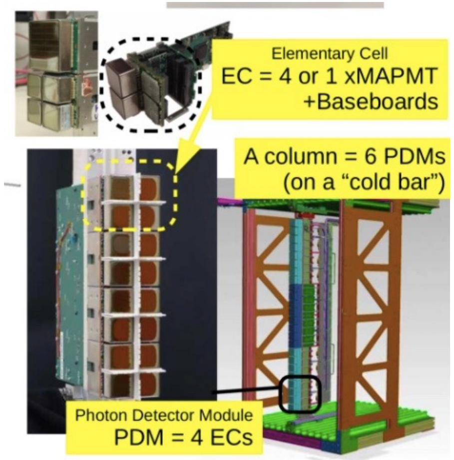
- Active area of MaPMTs: ~ 80%
- Average gain @ 1000V: > 1e6
- Quantum efficiency: 30% at 300 nm
- Dark count rate < 2.5 kHz/cm^2
- Occupancy: ~ 1 MHz / mm^2 in the innermost RICH1 regions
- Shielding around RICH1 PMTs to mitigate effect of residual LHCb magnetic field (~ 2 mT)
- Hamamatsu developed special series R13742 and R1374 complying with RICH requests



RICH1

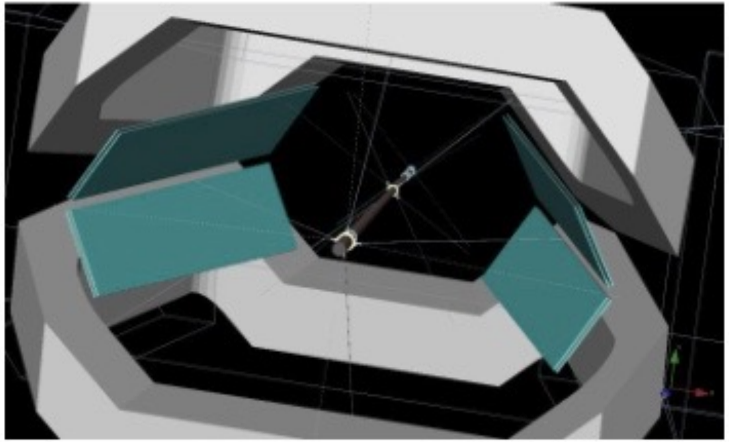


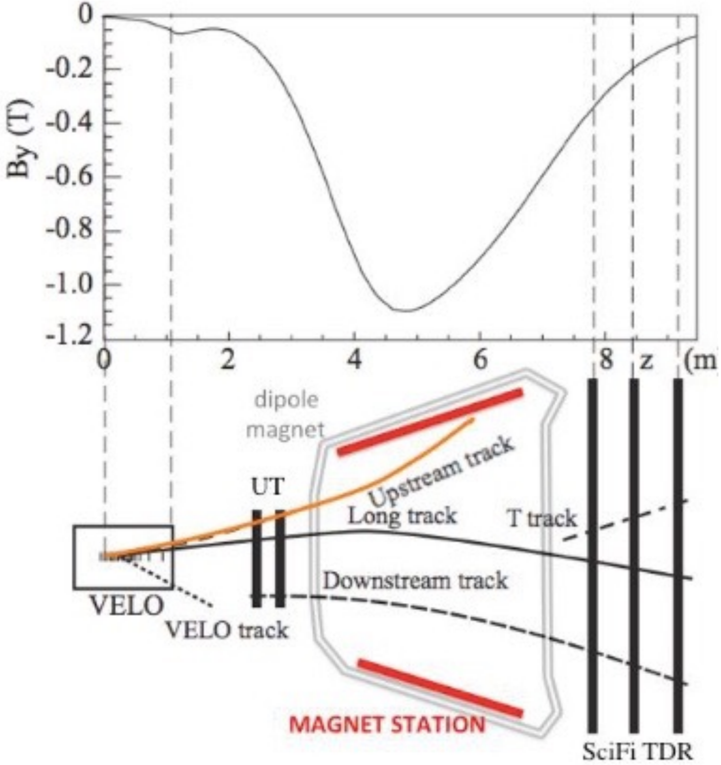
RICH2



Magnet tracking stations

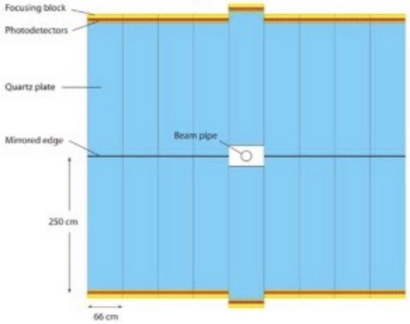
- Improve acceptance for low momentum tracks that would exit LHCb acceptance
- Scintillator bars read out with SiPMs outside acceptance
- Reuse existing SciFi electronics (ASIC, read-out boards, etc)

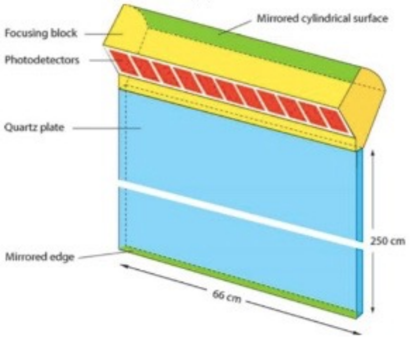




TORCH

- Time Of internally Reflected CHerenkov light
  - Large area time-of-flight detector
  - Provide PID in the momentum range 1-10 GeV/c
- Cherenkov light produced in quartz plates
  - Photons travel along the detector plane via total internal reflection
  - Focusing block focuses image on detection plane
  - Photodetectors: MCPs with 35 ps time resolution





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