The LHCb upgrade: status and progress

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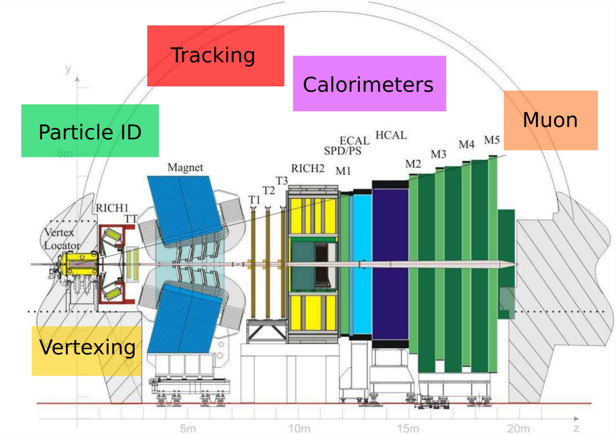
on behalf of the LHCb collaboration

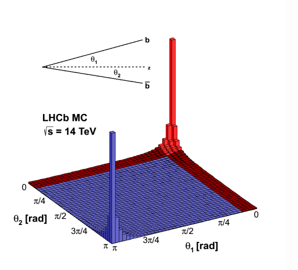
Flavour Physics and CP Violation 2019

The LHCb experiment

General purpose single arm forward spectrometer
($2 < \eta < 5$, 4% of solid angle)

[J. Instrum. 3 (2008) S08005]





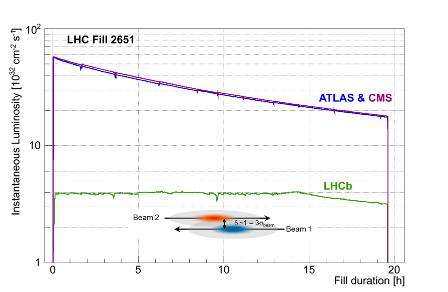
LHCb physics:

- rare b and c hadron decays
- CP-violation in b sector
- CKM parameters
- indirect search for NP
- spectroscopy
- electroweak physics

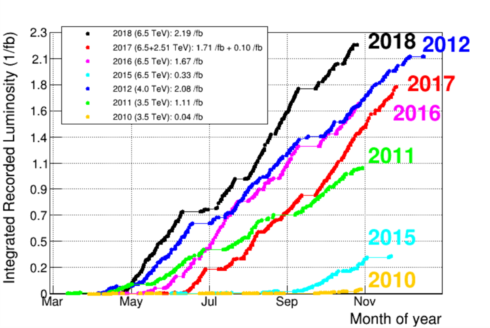
Unprecedented collection of bottom and charm hadrons
Very successful physics programme!

The LHCb performance

- LHCb designed to run at lower luminosity than ATLAS and CMS
- mean number of interactions per bunch crossing ~ 1
- pp beams displaced to reduce the instantaneous luminosity: $\mathscr{L} \sim 4 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- twice the design value



Run 2 ended in 2018: excellent performance!



- $\sim$ 3 fb^{-1} of pp collisions at 7-8 TeV in Run 1
- $\sim$ 6 fb^{-1} of pp collisions at 13 TeV in Run 2
- $\sim$ 9 fb^{-1} reached at the end of Run 2

Why upgrade?

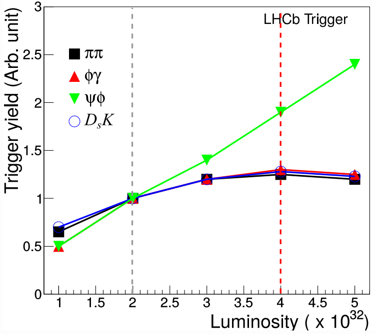
Type	Observable	Current precision	LHCb 2018	**Upgrade** (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.10 [139]	0.025	0.008	$\sim$0.003
	$2\beta_s(B_s^0 \to J/\psi f_0(980))$	0.17 [219]	0.045	0.014	$\sim$0.01
	a_{sl}^s	6.4×10^{-3} [44]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\overline{K}^{*0})$	–	0.13	0.02	<0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [44]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	$<$0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [68]	0.025	0.008	0.02
	$s_0 A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [68]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [77]	0.08	0.025	$\sim$0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [86]	8 %	2.5 %	$\sim$10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim$100 %	$\sim$35 %	$\sim$5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	$\sim$10–12° [252, 266]	4°	0.9°	negligible
	$\gamma(B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	0.8° [44]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [44]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

Eur. Phys. J. C (2013) 73:2373

Need to increase the precision to reach theoretical uncertainty $\Rightarrow$ search for NP

[LHCB-TDR-12]

Upgrade strategy



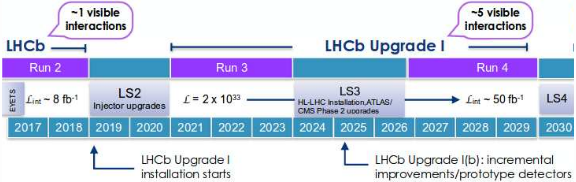
- LHC will increase luminosity
- Level-0 hardware trigger very efficient for dimuon events
- for hadronic channels trigger yield saturates with increasing luminosity
- detectors will start to degrade because of radiation
- physics programme limited by the detector

Strategy:

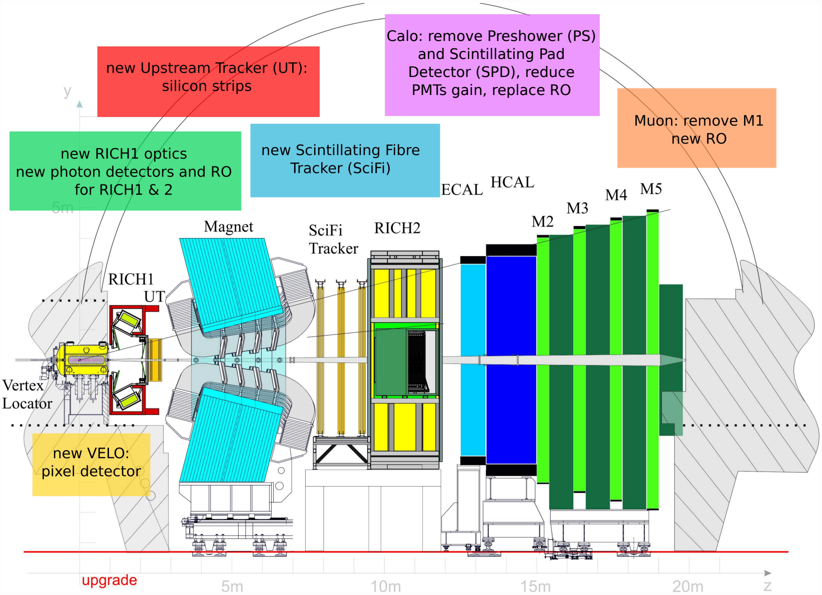
- remove 1MHz L0 bottleneck
- increase readout rate to 40MHz
- fully software trigger
- run at $\mathscr{L} \sim 2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

- need to cope with pile up
- need to cope with high occupancy and higher radiation
- new detector front-end electronics

$\Rightarrow$ upgrade detector during LS2



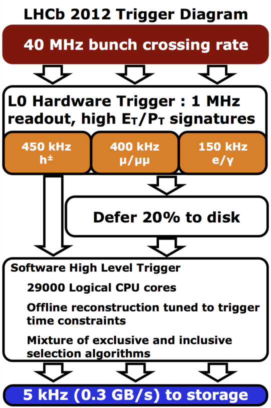
The LHCb Upgrade



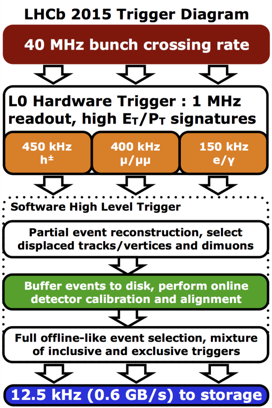
aim to reach 50 fb^{-1} [LHCB-TDR-12]

Trigger Upgrade

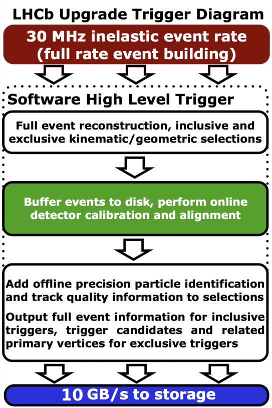
Run 1



Run 2



Run 3 & 4



- first-level hardware trigger

- first-level hardware trigger
- HLT and real time calibration

- first-level trigger removed
- fully software flexible trigger

after the upgrade we will operate the highest bandwidth DAQ built so far

[LHCB-TDR-016]

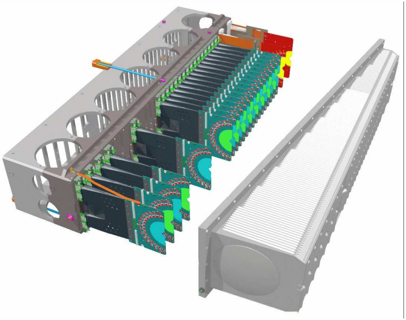
VELO detector

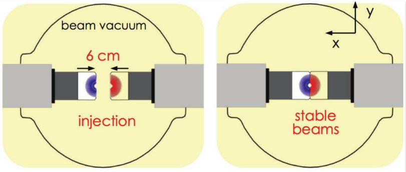
Current detector

- semi-circular modules, silicon strip sensors
- two retractable halves separated from the LHC vacuum by RF foil
- closest active strip at 8.2 mm from beam line
- one interaction per bunch crossing
- $\sigma_{IP} \sim 20\mu m$ for high p_T tracks

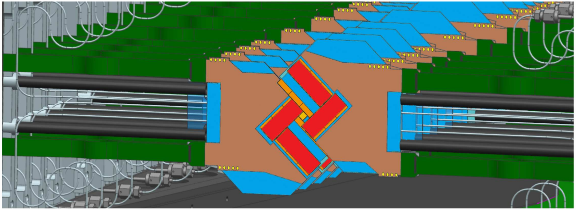
Requirements and upgrade challenges:

- ~ 5 interactions per bunch crossing
- measure impact parameter (IP) to high precision
- high tracking efficiency
- tolerance to high dose ($8 \times 10^{15} n_{eq} cm^{-2}$): 10 times the current VELO and highly non-uniform





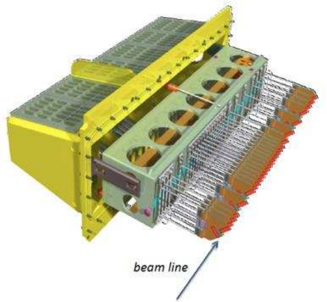
VELO Upgrade

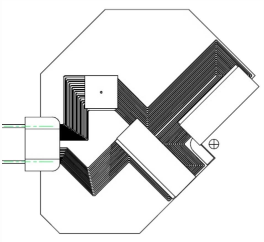


- hybrid pixel sensors, higher granularity (55μm pixel size)
- first sensor closer to the beam: 5.1mm
- reduced thickness for RF foil
- microchannel two-phase CO_2 cooling system (sensors at -20°C against radiation damage)
- improved IP resolution
- DAQ capable of handling $\sim$40 Tb/s

intense testbeam campaign to validate sensors and radiation tolerance

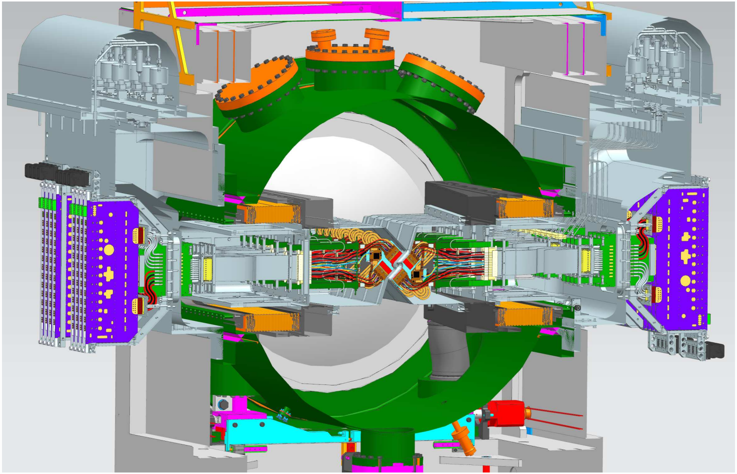
- charge collection
- charge collection efficiency
- spatial resolution

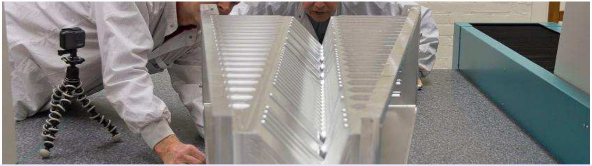




[LHCB-TDR-013]

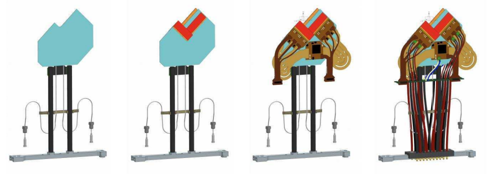
Few highlights





250μm of thickness vacuum tight

Few highlights

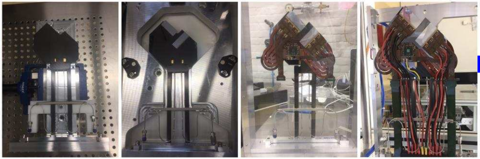


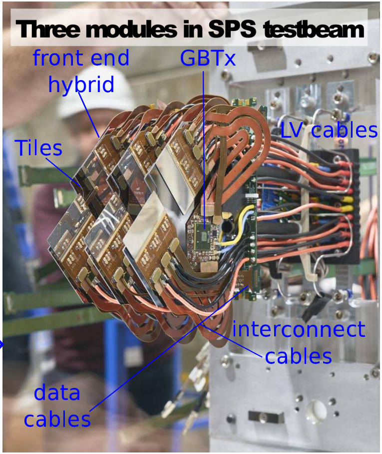
Mechanical Construction

Precision tile placement to 10 μm

Flex circuit placement

wire bonding and HV/LV/data cable attachment





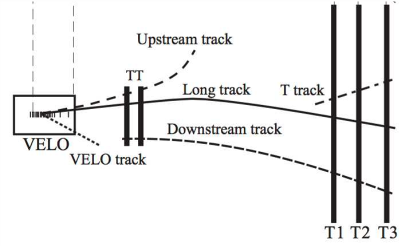
Current tracking system

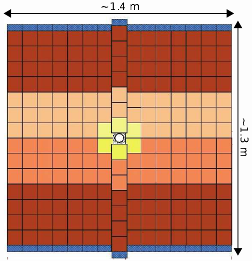
TT

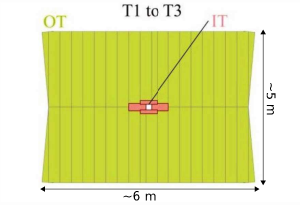
- 4 planes of silicon strips, crucial to detect tracks originated outside the VELO
- Insufficient radiation hardness for upgrade
- Readout of consecutive strips incompatible with high occupancy
- Front-end electronics non easily replaceable

IT and OT

- inner tracker: 4 planes of silicon strips in high η region
- outer tracker: 4 planes of straw tubes in the low η region
- incompatible with high occupancy

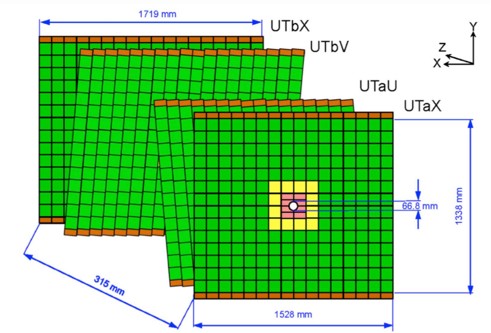


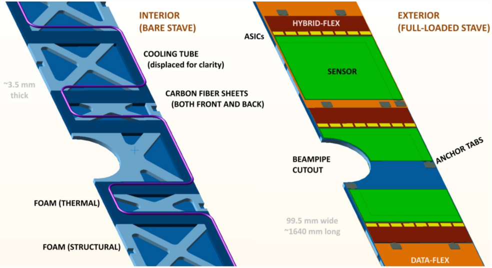




- reconstruct long tracks combining signal from VELO
- downstream tracks for the reconstruction of long lived particles

Tracking Upgrade: Upstream Tracker (UT)

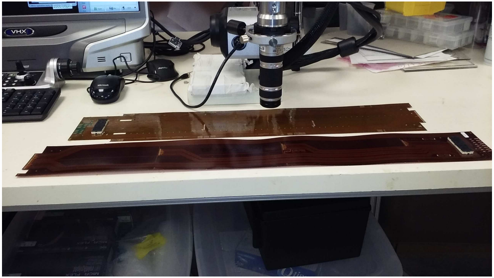


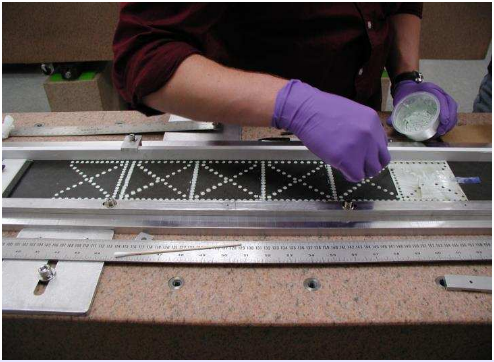


[LHCB-TDR-015]

- Reconstruct particles decaying after the VELO
- Reconstruct low-momentum tracks deflected out of the T-acceptance
- 4 planes of silicon strip as for TT
- Finer segmentation: from $183\mu m \times 10cm$ to $95\mu m \times 4.9cm$, $95\mu m \times 9.7cm$, $190\mu m \times 9.7cm$
- Better coverage, no gaps
- Lower material budget
- Higher radiation hardness
- Front-end in the active area, close to sensors: better signal to noise ratio
- intense campaign of testbeams to validate the custom developed front-end chip

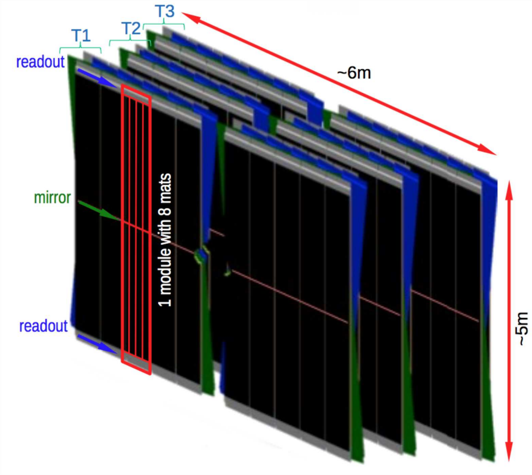
Few highlights

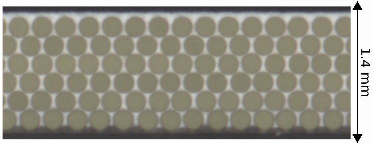




- QA of flex cables
- assembly of staves
- tests of the sensor+asic+readout

Tracking Upgrade: Scintillating Fibre Tracking

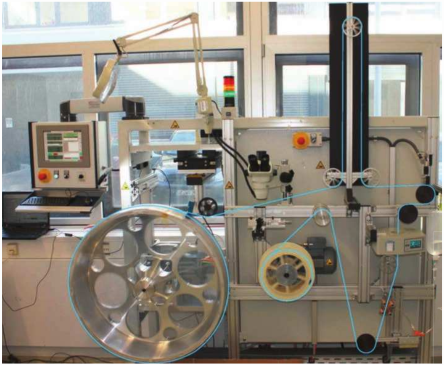


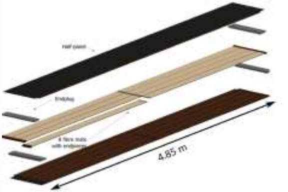


- Scintillating fibres mats transport signal outside the the acceptance volume
- 2.5m long fibres with diameter of $250\mu m$
- Each mat composed by 6 layers of fibres
- Signal readout by SiPMs at $-40°$C
- Homogeneous coverage with high granularity
- Spatial efficiency better than $70\mu m$
- Single hit efficiency $> 99\%$

[LHCB-TDR-015]

Few highlights



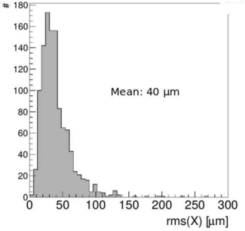


- quality assurance of fibres to identify defects and impurities (∼12000 km)
- winding of fibre mats and module assembly completed
- fibre mats connected to cold box containing SiPMs

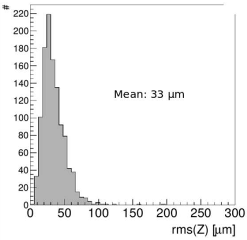
Few highlights

first full frame being assembled with fibre mats modules, SiPMs cold box, readout electronics, mechanics, services

measure of straightness of fibre mats in modules



measure of flatness of fibre mats in modules

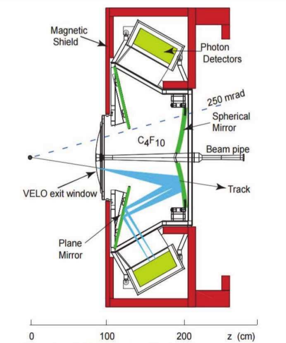


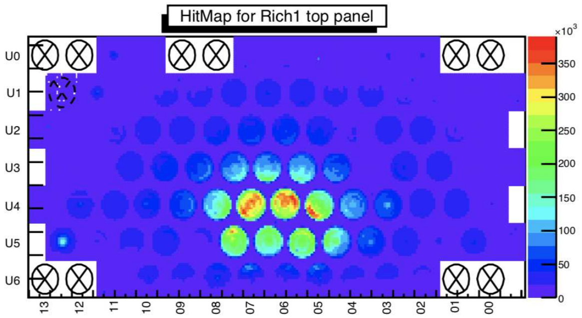
RICH

Two RICH detectors

- RICH1: upstream, 2GeV/c - 40GeV/c over 25mrad - 300mrad
- RICH2: downstream, 30GeV/c - 100GeV/c over 15mrad - 120mrad

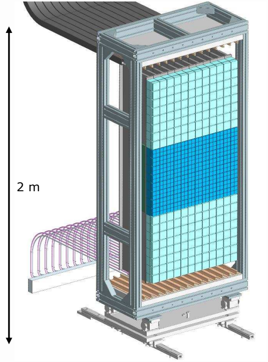
Excellent PID performance!



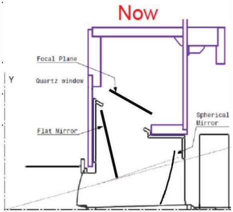


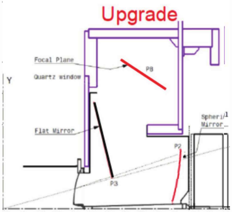
- Charged particles produce Cherenkov radiation focused on Hybrid Photon Detectors (HPD) plane
- HPDs equipped with embedded FE electronics, 1MHz readout
- need to change photon detectors in order to move to 40 MHz readout
- need to design new RICH1 optics in order to cope with high peak occupancy

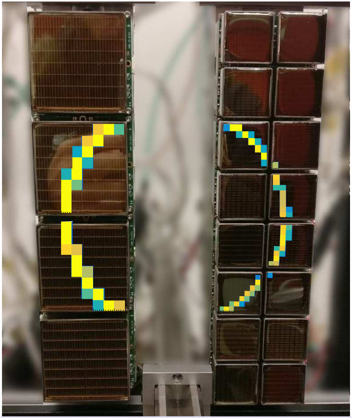
RICH Upgrade



- Replace HPDs with Multi-anode Photomultipliers (∼3000 units), finer granularity
- New external readout (CLARO asic)
- RICH1 focal plane and optics modified to increase size of Cherenkov rings
- intense testbeam campaign to validate new photon detectors and readout now in production

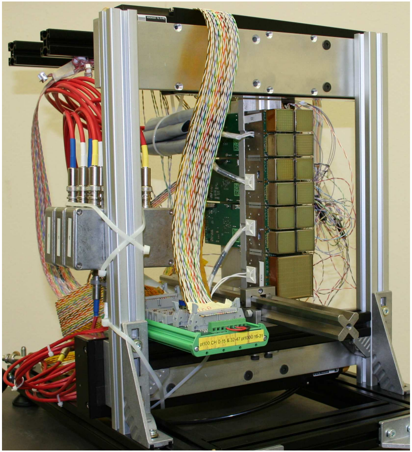


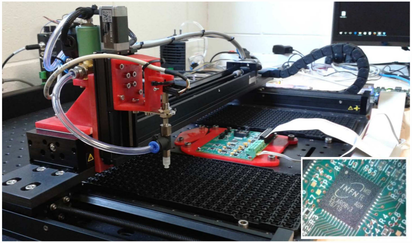


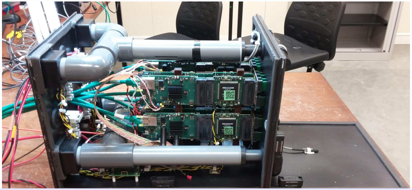


[LHCB-TDR-014]

Few highlights



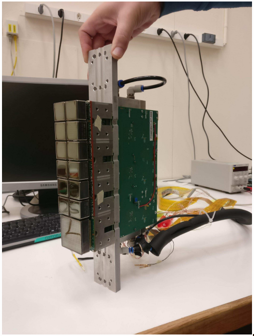




- Quality Assurance of MaPMTs completed
- CLARO production qualified
- photon detector opto-electronics chain tests on going

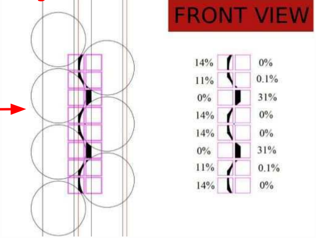
Few highlights

Photon Detector Module installed in RICH 2 during last winter shutdown and operated with collisions in 2018

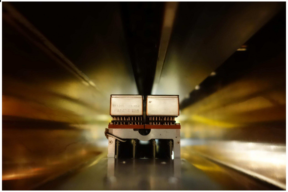


Cherenkov light through the HPD columns

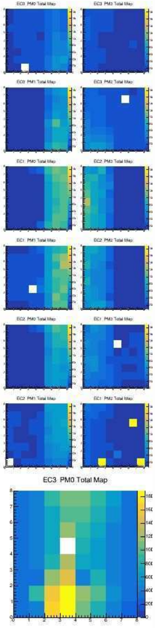
Idea



Installation



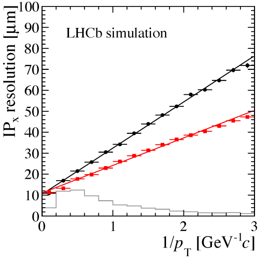
First collisions



- **Prototype adapted from test beams**
- **Pre-production components**
- **Ready for testing in real environment**

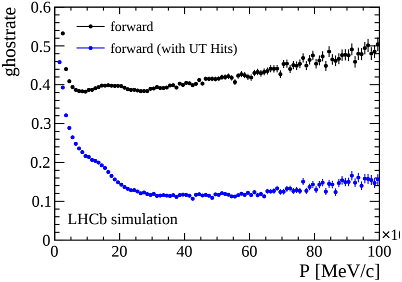
Performance of the upgraded LHCb

IP resolution for upgraded and current VELO

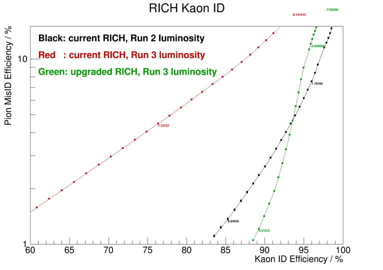


[LHCB-TDR-013]

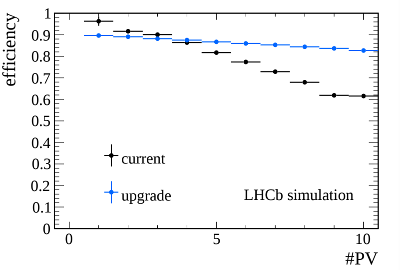
Tracking performance after upgrade



PID performance of the upgraded RICH



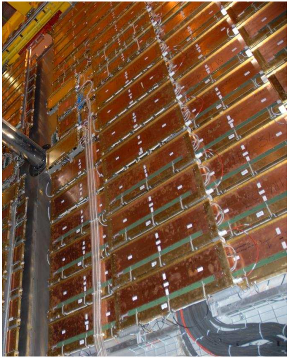
[S. Easo, talk at RICH2016]



[LHCB-TDR-015]

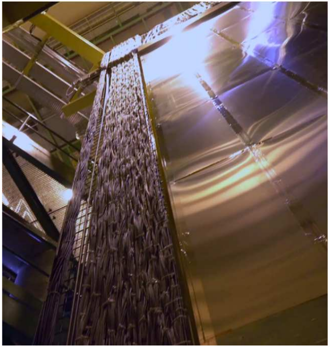
Current activities

M1 at the end of Run 2



M1 today

PS & SPD removal started



Intense activity to remove former LHCb detectors before starting installation

Weekly videos on LHCb activity posted here:

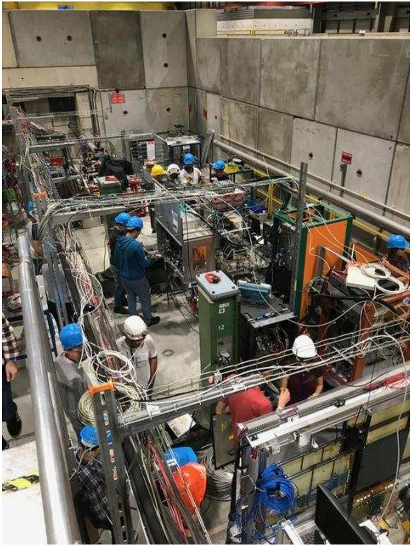
http://lhcb-media.web.cern.ch/lhcb-media/

LHCb upgrade: status

- very challenging programme
- project on schedule
- commissioning of each subdetector in assembly facilities
- global commissioning once installation of each subdetector starts

- integration testbeam in October 2018
- VELO, UT, RICH, CALO operated with upgrade DAQ and central trigger

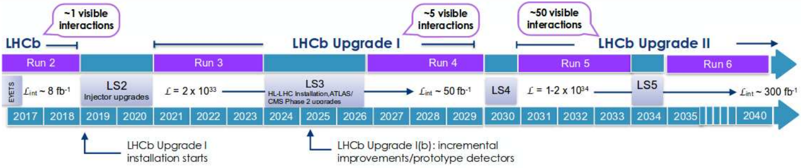
What's next?



LHCb Upgrade II

The collaboration submitted the Expression of Interest and a Physics Case to install a second upgrade of the LHCb detector [CERN-LHCC-2017-003] [CERN-LHCC-2018-027]

- install new detector for the beginning of Run 5
- operate at $\mathscr{L} \sim 1.5 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- mean number of interactions per bunch crossing: $\mu \sim 45$
- collect more than $300 \mathrm{fb}^{-1}$
- improve even more LHCb precision (even after first upgrade many measurements still limited by statistics)
- fully exploit HL-LHC

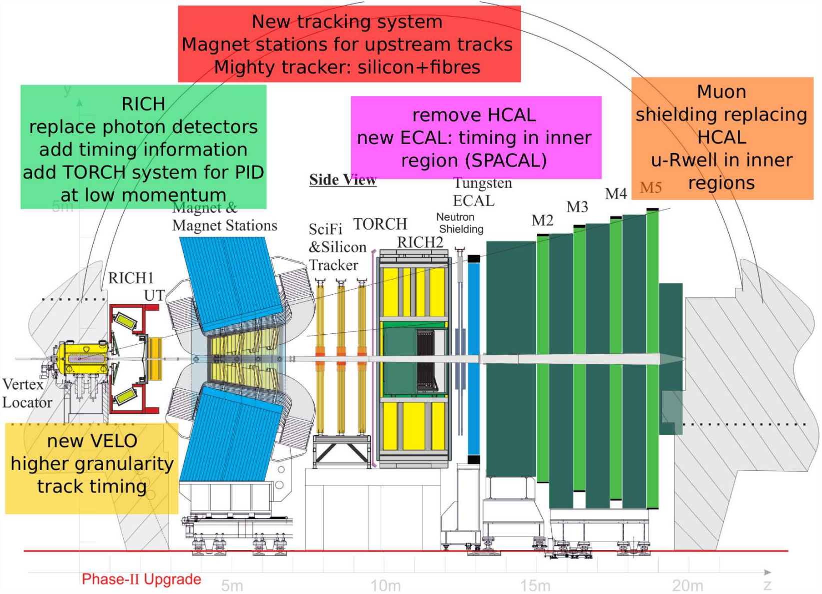


Why upgrade?

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [274]	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	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 [606]	0.011	0.005	0.003
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [44]	14 mrad	–	4 mrad
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
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%
$B_s^0, B^0 \to \mu^+\mu^-$				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%
$S_{\mu\mu}$	–	–	–	0.2
$b \to c\ell^-\bar{\nu}_l$ 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} [610]	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}

second upgrade to realise the flavour potential of HL-LHC

The LHCb Upgrade II



Adding timing is the key to cope with the pile-up!!!

Conclusions

LHCb completed the Run 2 data taking successfully operating above the design parameters and delivering high quality data

The LHCb upgrade is foreseen to collect 50 fb^{-1}

- very challenging project
- all subdetectors are progressing and production of components ongoing
- dismantling on former detectors well advanced and on schedule
- installation of services already ongoing
- installation of first new detector elements foreseen to start this summer
- operations foreseen in Run 3 and 4
- upgrade is mandatory to reach experimental precision of the order of theoretical uncertainties in many areas of the LHCb physics programme

The EoI and Physics Case for the LHCb upgrade II have been submitted

- project very technologically challenging
- aim to collect 300 fb^{-1} $\Rightarrow$ upgrade would allow to collect 100$\times$ more data and reach higher precision!
- the Upgrade II has been approved to proceed towards the framework TDR $\Rightarrow$ R&D is active across all subsystems! First testbeams already carried out!

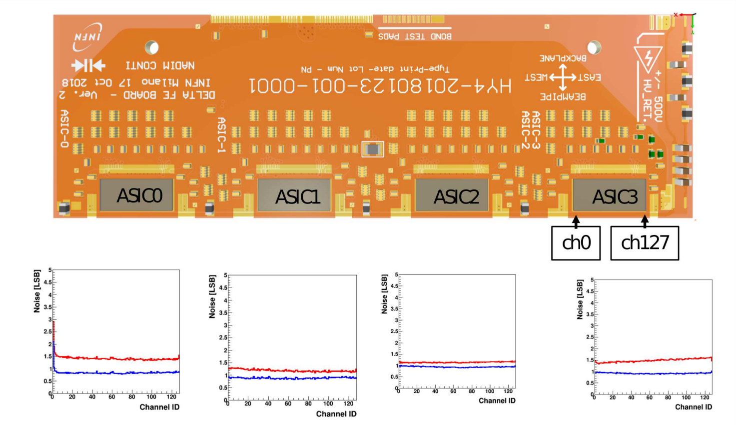
Thank you for your attention!

Extra slides

SALT chip status

Latest version of the SALT asic submitted and tested first standalone and then on hybrid

Extensive tests performed in three laboratories and on beam: non-zero suppressed mode, noise/gain studies, laser scans, test beam analysis...



output of the tests: specifications met

first stave assembled this week for full test