LHCb Upgrades

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AGH-UST

ON BEHALF OF THE LHCB COLLABORATION

9TH EDITION OF THE LARGE HADRON COLLIDER PHYSICS CONFERENCE, 7-12 JUN 2021, ONLINE

LHCb historical view…

LHCb before Run 1

LHCb after Run 2 (a lot of radiation damage too…)

Run 3 / 4 LHCb

Outlook

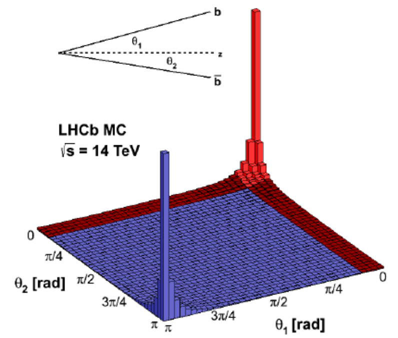
- ❑ LHCb experiment: story so far…
- ❑ Motivation for upgrade
- ❑ General overview of the schedule
- ❑ **Upgrade I** - hardware
- ❑ Software Trigger – data processing masterpiece to be…
- ❑ Summary

Upgrade II physics case – see talk by Francesca Dordei

Upgrade II detector – see talk by Silvia Gambetta

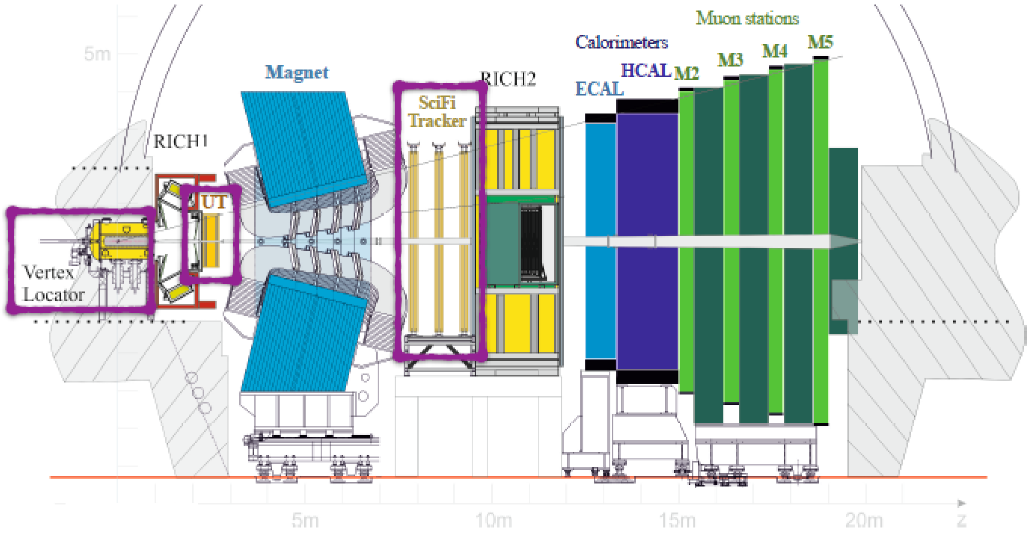
See also talk by our Spokesperson Chris Parkes

Large Hadron Collider **beauty**



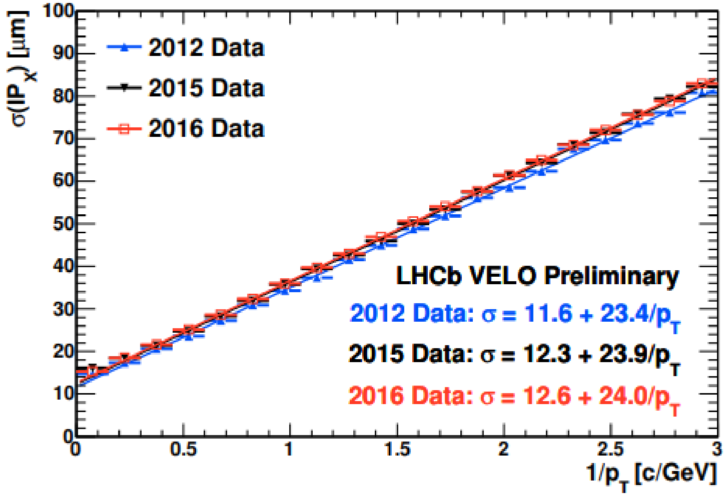
- After Run 1 and Run 2 LHCb proved to be the **General-Purpose Forward Detector**
  - a single arm spectrometer – not your typical geometry for a collider based experiment!
  - fully instrumented in the pseudo-rapidity range of $(2 < \eta < 5)$
  - can register up to 40% of all heavy quarks with only 4% of the solid angle coverage!
  - very precise measurements in beauty and charm sector and New Physics search
  - excellent performance in Run 1 and Run 2:
    - momentum resolution $\frac{\Delta p}{p} \sim \mathbf{0.5\%}$ **@20 [GeV]**
    - impact parameter resulution ~ $\mathbf{15 + \frac{29}{p_T}}$ **[μm]**
    - time resolution $\sigma_t \sim$ **45 [fm]** for $B_s \to J/\psi\varphi$
  - In time, the physics programme has been extended to cover exclusive processes, QCD studies, Electro-weak physics, direct NP searches and heavy ion physics

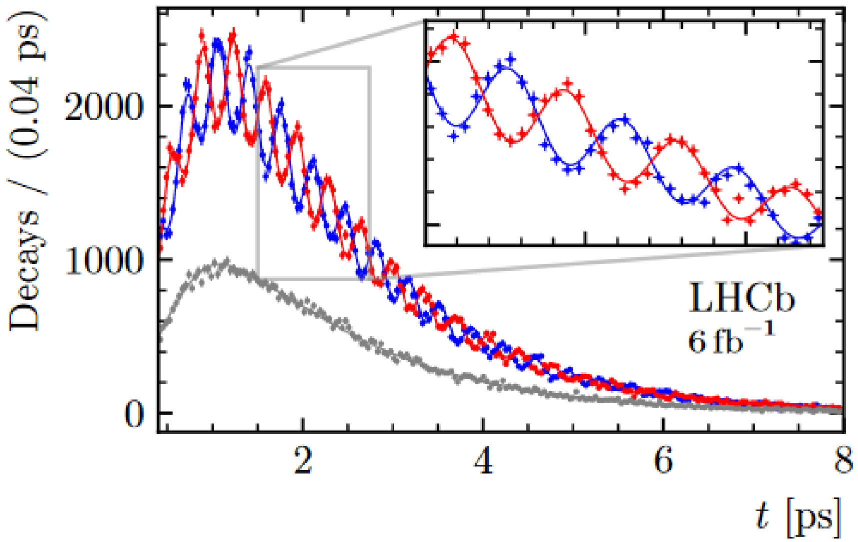
Int. J. Mod. Phys. A30 (2015) 1530022

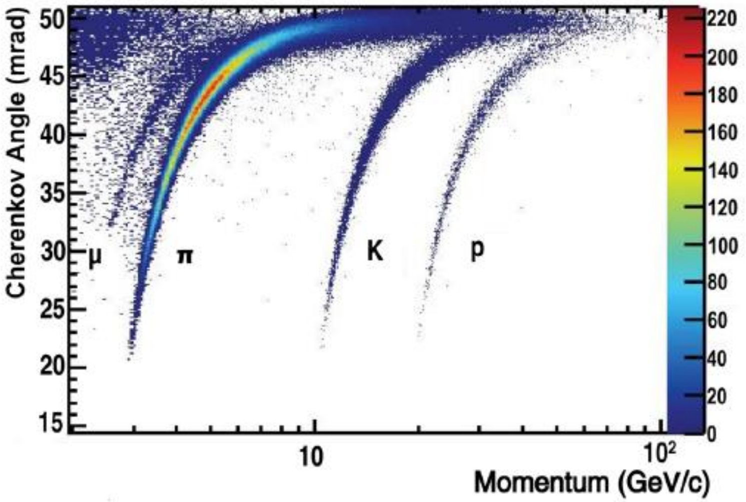


LHCb performance

Int. J. Mod. Phys. A 30, 1530022 (2015)
LHCb-PROC-2018-020
https://arxiv.org/abs/2104.04421 (2021)







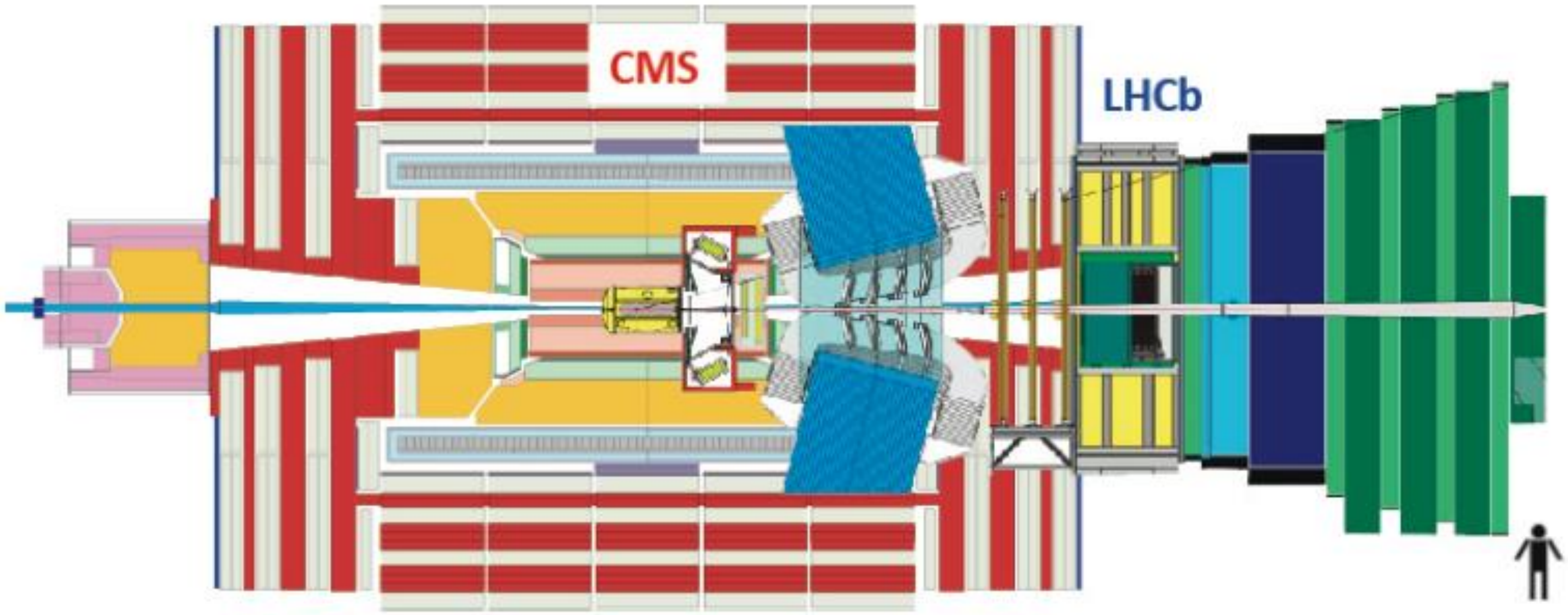
- Geometrical Impact parameter resolution
- **Separation of the primary and secondary vertices**

- Lifetime resolution
- **Can resolve fast $B_s - \overline{B}_s$ oscillations**

- Excellent particle identification
- **Separation between charged chadrons, $\gamma, e^{\pm}, \mu^{\pm}$**

LHCb detector

- Non typical geometry, but a typical composition…

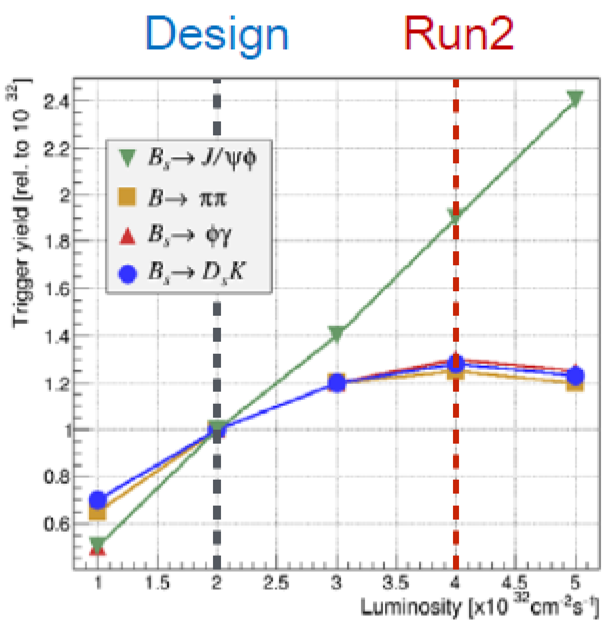


Motivation for LHCb upgrade(s) / 1

- No „smoking-gun" evidence for NP in direct searches yet… SM is still in control
- **Parameter space of most popular BSM is shrinking**! Still, taking into account „available" data till the end of HL-LHC **we just collected a tiny bit (~5%)**
- Some **intriguing hints of NP** in non-direct approach
  - **Flavour anomalies**: $b \to s l^+ l^-$ ($B_d^0 \to K^{*0} l^+ l^-$), $R(K)$ and $R(K^*)$
  - **Possible lepton flavour universality violation**: $B_d^0 \to D^* l^+ l^-$, $R(D^*)$
  - No „discovery significance" but the observed anomalies seem to indicate tension with the SM
- Clear need for more data! Many measurements are statistics limited – challenge theory
  - $\boldsymbol{BR(B_s \to \mu^+\mu^-)}$ push down the precision to $\sim 10\%$ of the SM prediction
  - **CMK γ angle** down to $\sim 1^{\text{o}}$
  - Probe **CPV in charm** sector below 10^{-4}

Motivation for LHCb upgrade(s) / 2

- The current detector is **severely limited by its hardware trigger** layer (a.k.a. L0)
  - The **maximum available rate** of events is 1.1 MHz
- To keep up with evolution of other LHC experiments need to go up with the luminosity
  - Current system would just saturate
  - Harder cuts on both E_T (transverse Energy - calorimeter) and p_T (transverse momentum – tracking)
  - Serious loses for hadronic channels
- **Much higher pile-up** (up to ~ 5 primary vertices per bunch crossing, $\mathcal{L} = 2 \times 10^{33}\ [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$)
  - Tracking super difficult with the Run 1/2 design
  - Radiation damage not manageable for Run 1/2 technologies



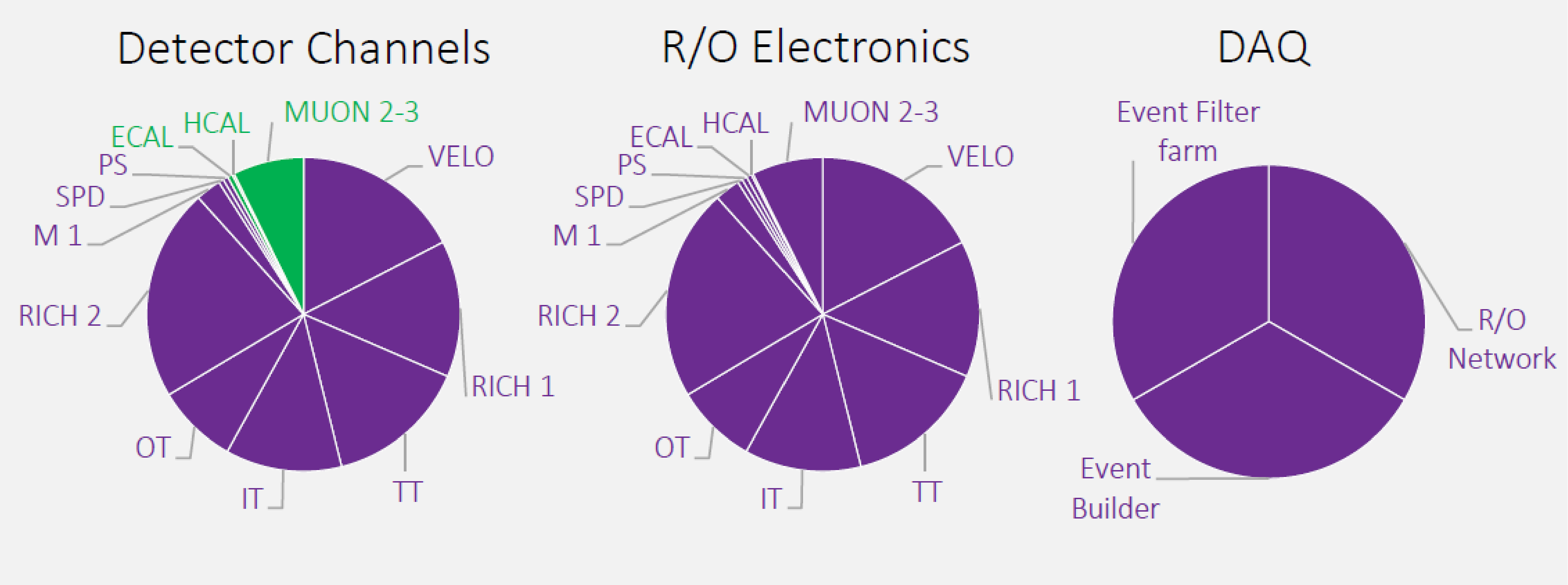
Motivation for LHCb upgrade(s) / 3

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1	0.031	0.032	0.008
$R_\phi,\ R_{pK},\ R_\pi$	–	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
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
$a_{\rm sl}^s$	33×10^{-4}	10×10^{-4}	–	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6%	3%	1%	1%
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90%	34%	–	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22%	8%	–	2%
$S_{\mu\mu}$	–	–	–	0.2
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **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}

arXiv:1808.08865

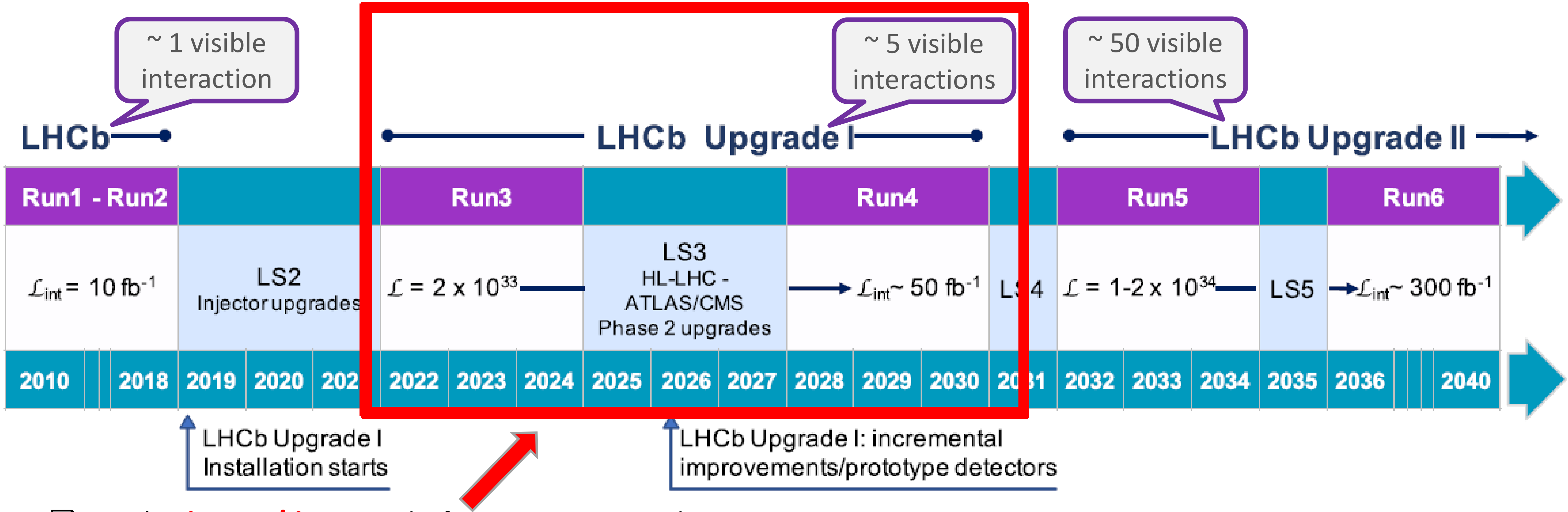
Upgrade scope and timeline / 1

CERN-LHCC-2012-007



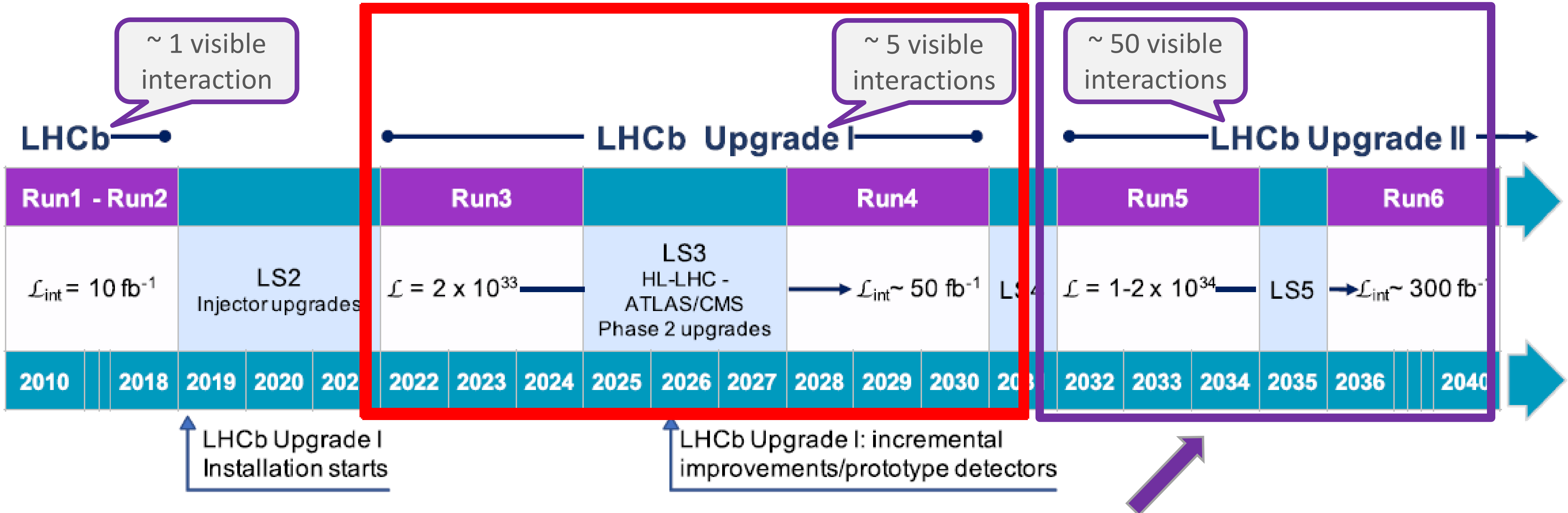
What to keep and what to upgrade… Major upgrade!

Upgrade scope and timeline / 2



- LHCb **Phase-I/Ib** upgrade for LHC Run 3 and Run 4
  - Full software trigger and readout at the LHC clock speed of 40 MHz
  - Replace tracking system and PID
  - Consolidate PID, tracking and ECAL during LS3

Upgrade scope and timeline / 3



- LHCb **Phase-II** upgrade, installation in LS4, operation beyond Run 4
  - New radiation hard technologies for tracking
  - Add timing to cope with $\mathcal{L} \sim 1.5 \times 10^{34}$ [cm^{-2}s^{-1}]

Upgrade scope and timeline / 4

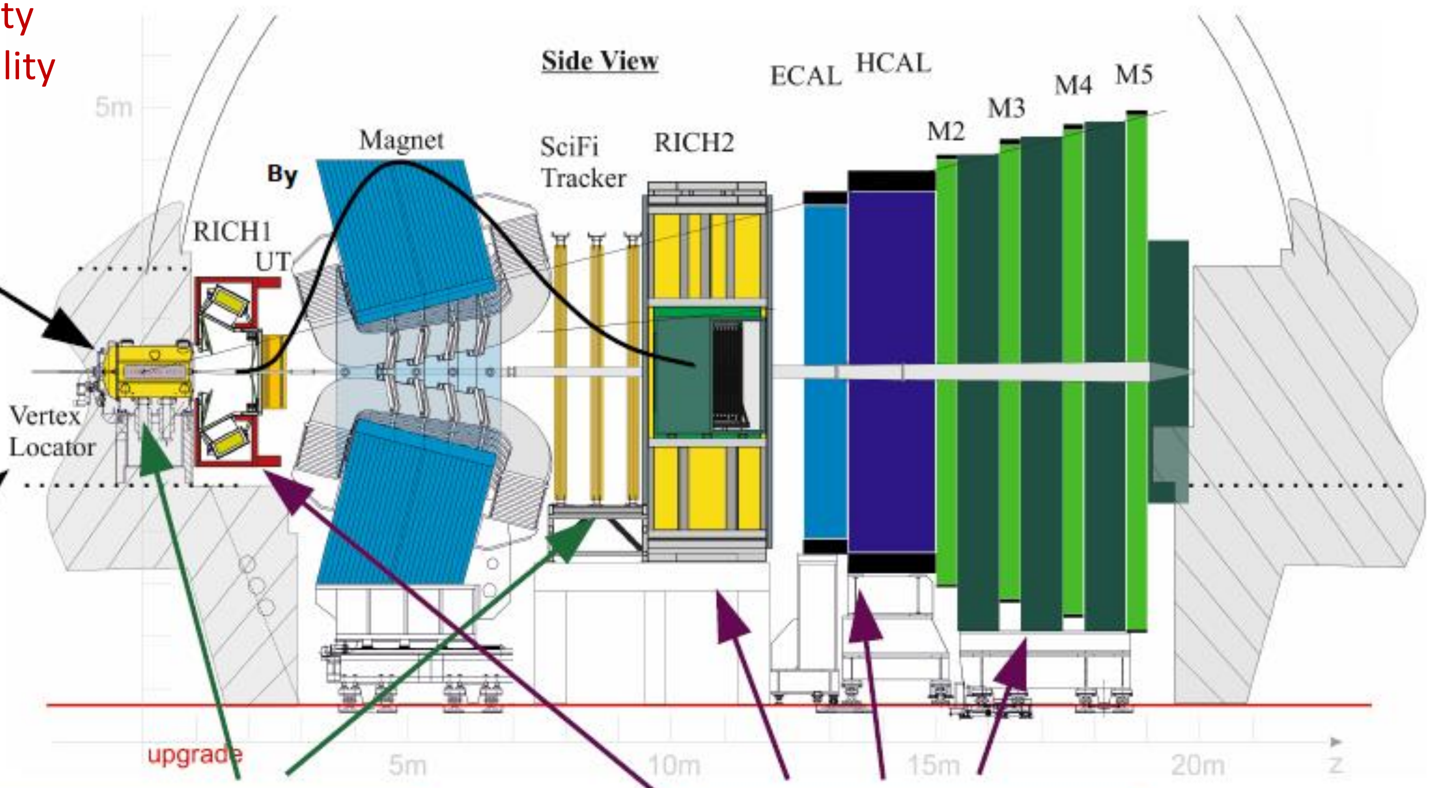
Kaon ID ~ 95 % for ~ 5 % π→K mis-id probability
Muon ID ~ 97 % for 1-3 % π→μ mis-id probability

Precise vertex measurements

Impact parameter resolution:
(15 +29/pT[GeV]) μm

Decay time resolution: ~45 fs

Excellent decay time resolution

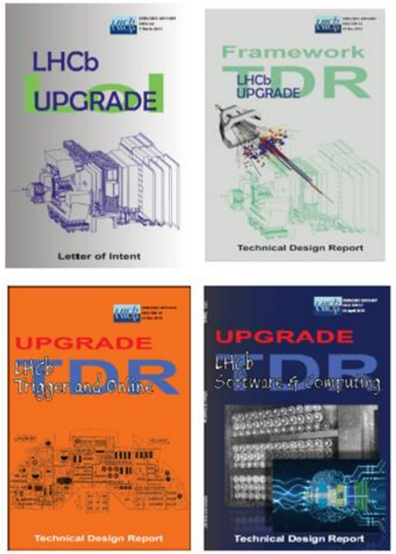


Δ p / p = 0.5 % at low momentum to 1.0% at 200 GeV/c

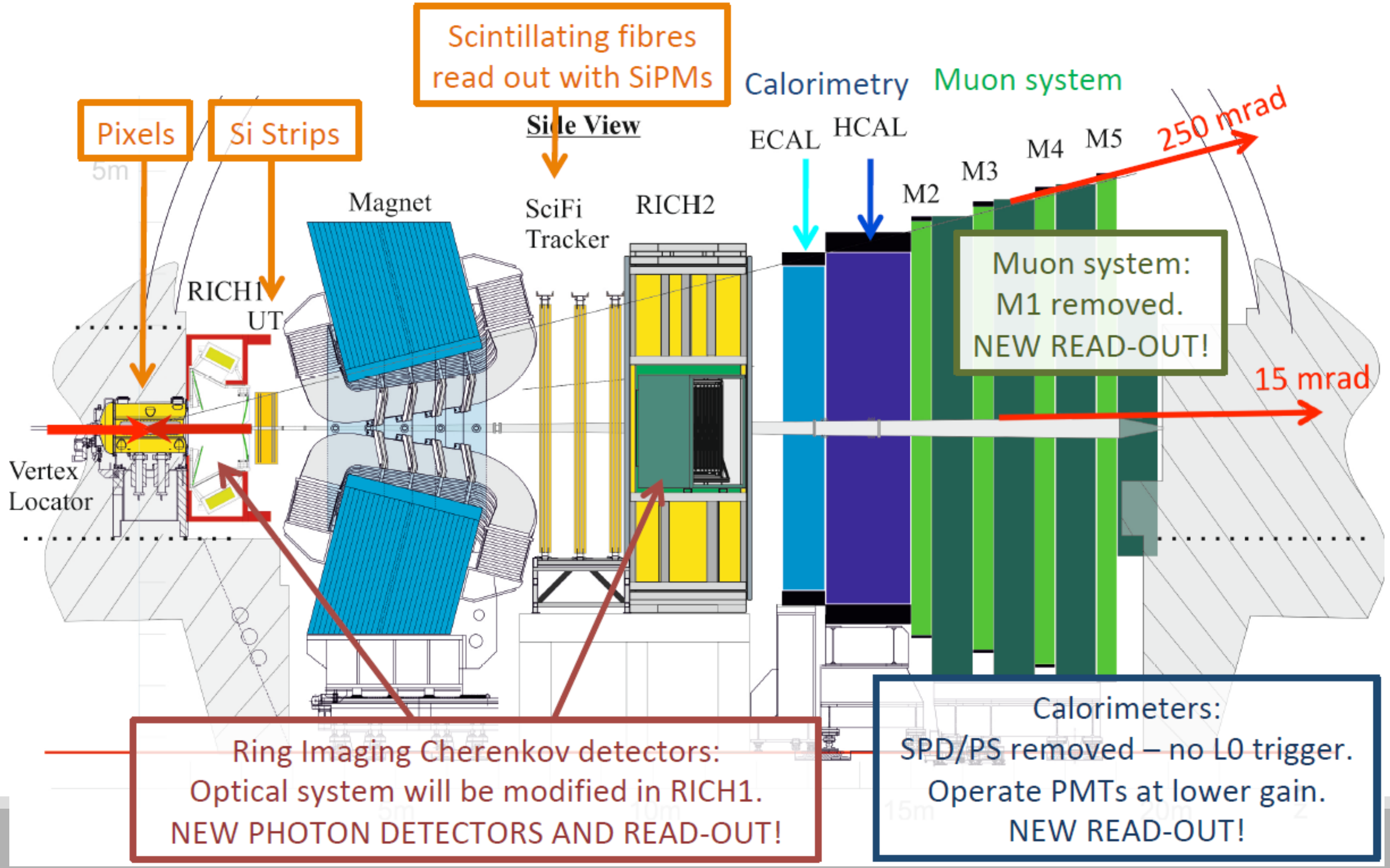
Excellent momentum resolution

Excellent particle identification

Upgrade scope and timeline / 5



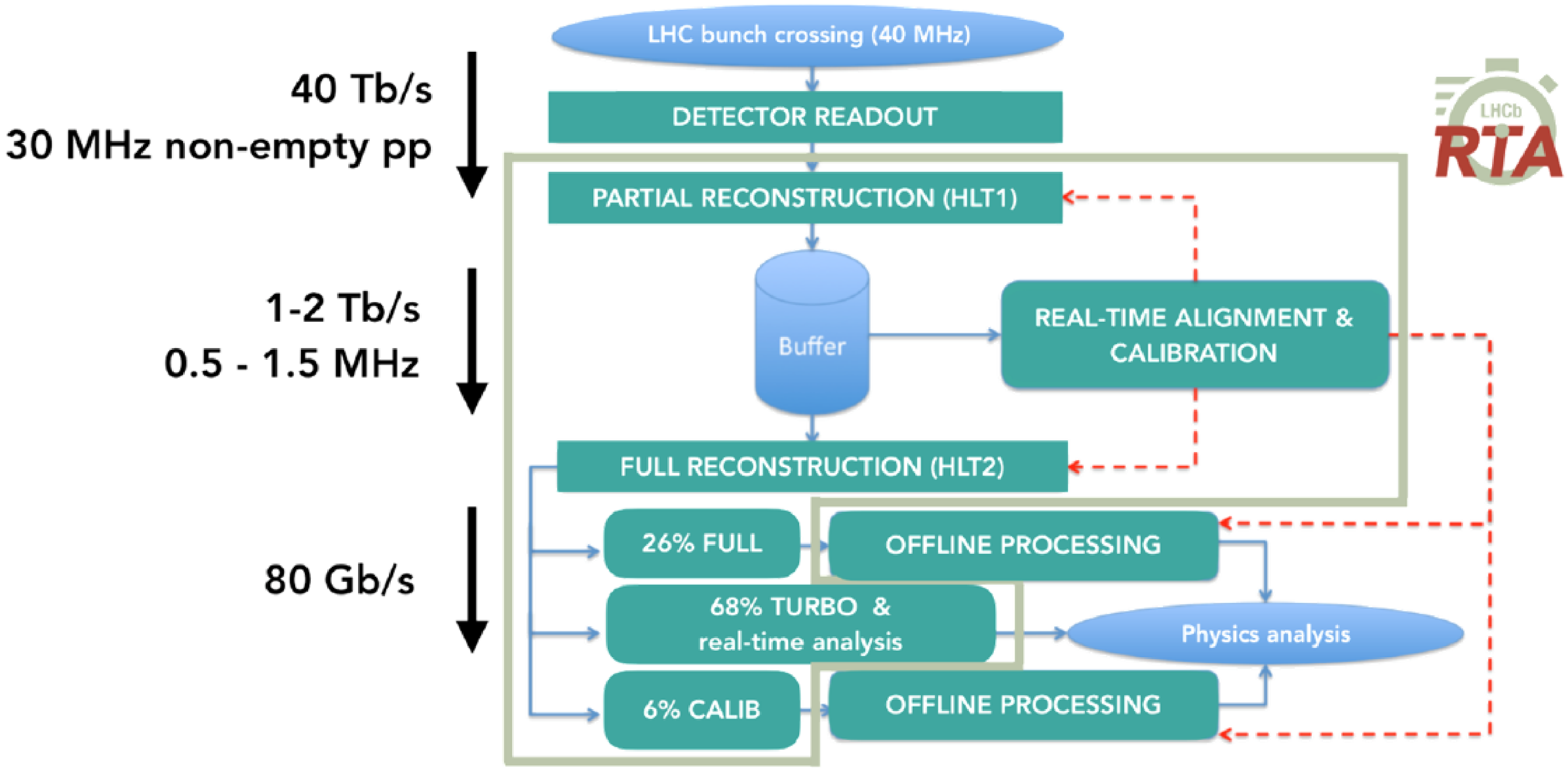
CERN-LHCC-2011-001
CERN-LHCC-2012-007
CERN-LHCC-2014-016
CERN-LHCC-2018-007



CERN-LHCC-2013-021
CERN-LHCC-2013-022
CERN-LHCC-2018-014
CERN-LHCC-2014-001

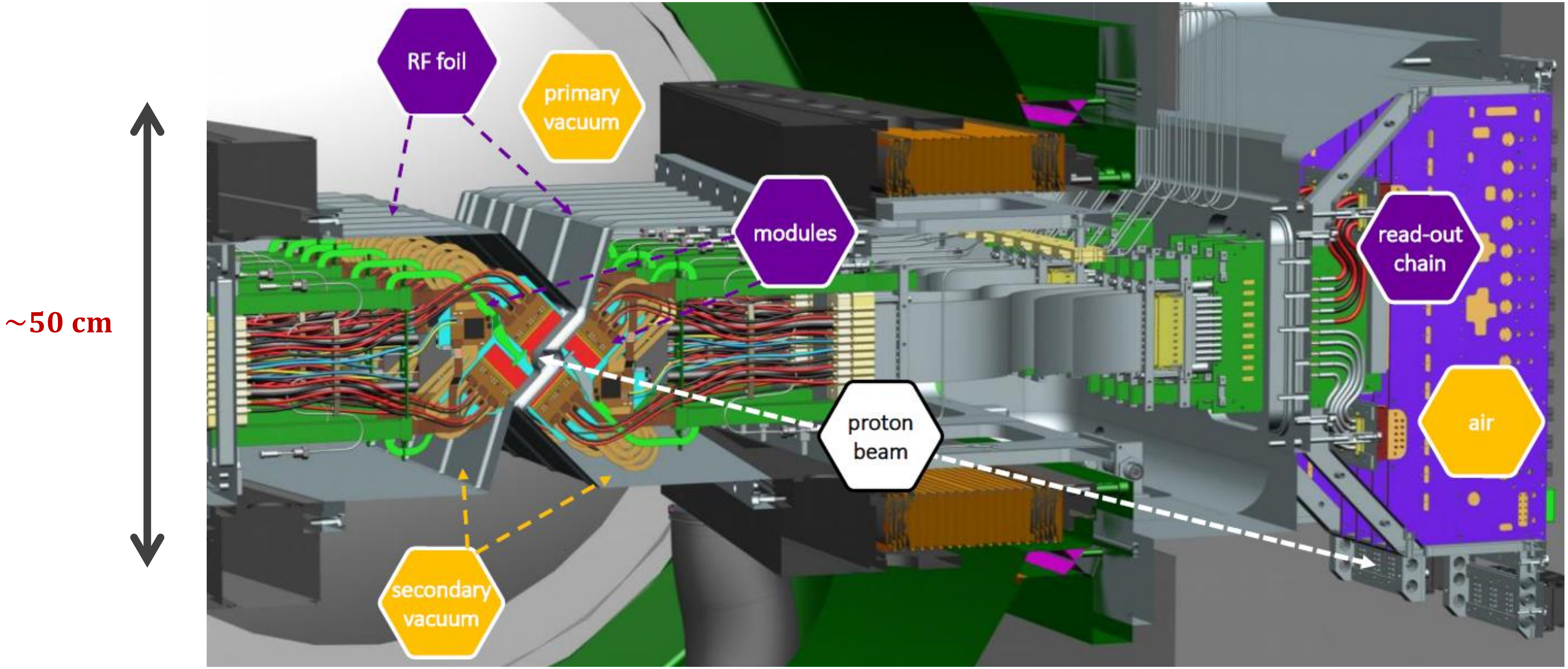
Overview of the data flow

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



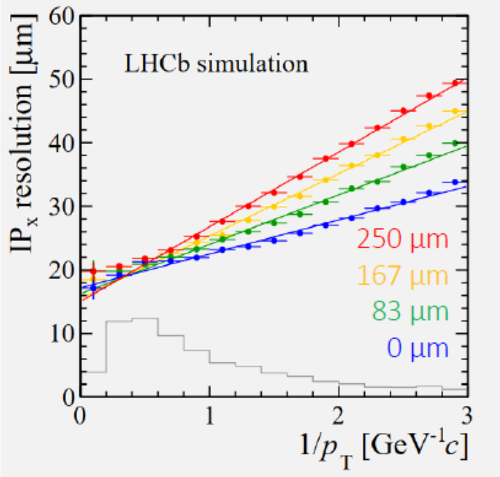
- Split the software trigger into two stages
  - HLT1 full real-time processing using GP-GPUs
  - HLT2 offline processing similar to Run 2 (more on this later on)
  - TURBO model for signals selection: save only high-level objects used to trigger the event (small fraction of the full events)
  - Do it right!
  - Processed data volume similar to that for ATLAS/CMS after their respective major upgrades!

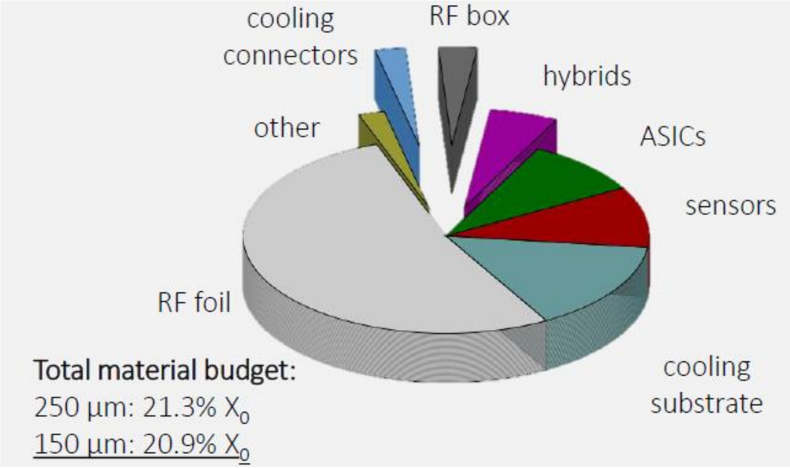
Pixel Vertex Locator (VELO) / 1



Pixel Vertex Locator (VELO) / 2

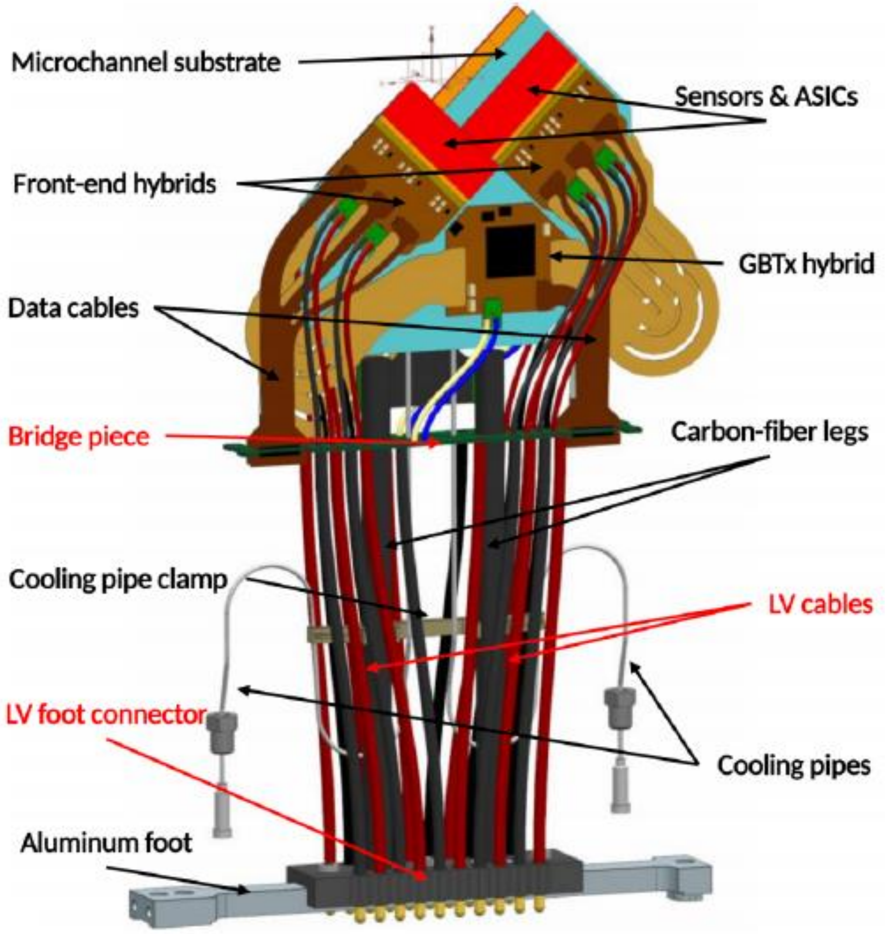
- Built with **two retractable halves**
- Closest to the proton beam @LHC just 3.5 mm when stable beams
- **First active pixels @5.1 mm**
- Secondary vacuum tank
  - Aluminium R.F. foil made for each half to separate it from the machine vacuum
  - Milled from one block to 250 μm then etched down by another 100!
- The whole detector made of **52 hybrid-pixel modules**
  - **$\sim$41 Mpixels covering $\sim 0.12\ \mathrm{m}^2$**

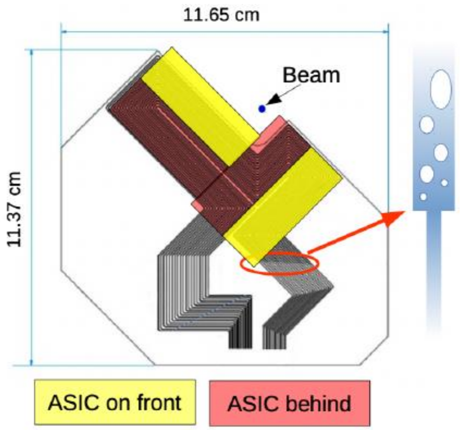


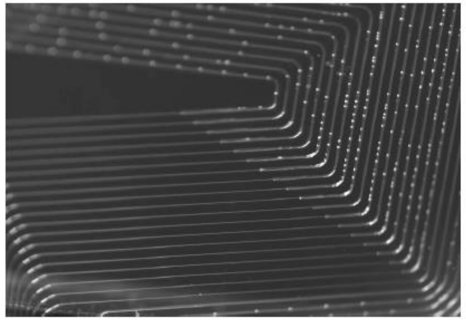


Pixel Vertex Locator (VELO) / 3

- Hybrid pixel detector with **n-on-p 200 μm thick silicon sensors**
- **New readout ASIC** (VeloPix)
  - Based on TimePix3 design
  - 256×256 array with square pixels 55×55 μm
- State-of-the-art **microchannel cooling** with evaporative CO_2
  - Down to $\sim -20^oC$
- Data rate ~3 Tbit/s with the hottest ASICs @20 Gbit/s
- Highly un-uniform irradiation

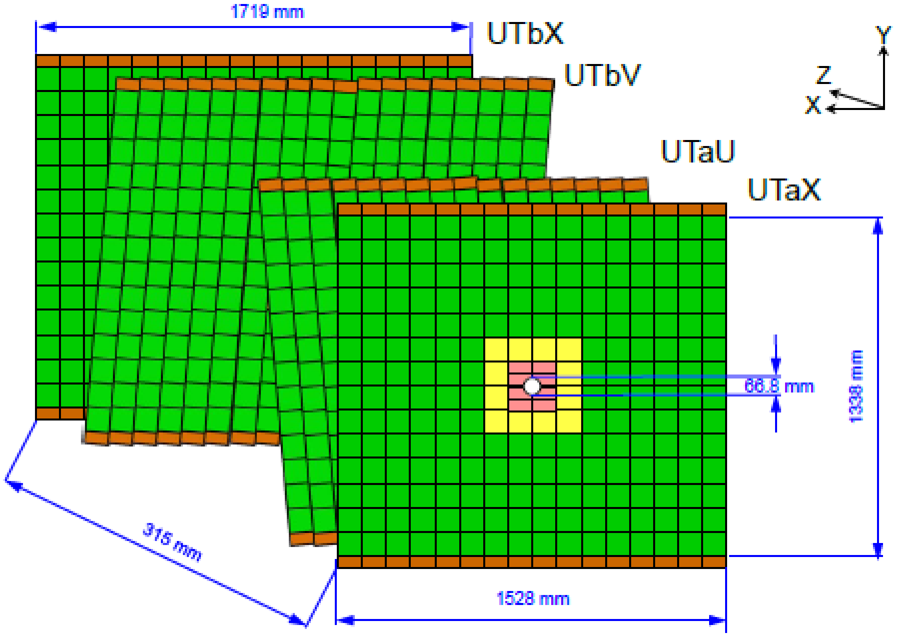


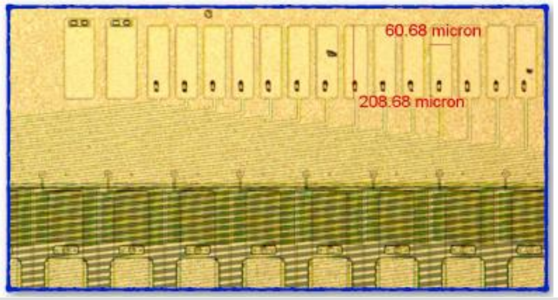




Upstream Tracker (UT) / 1

- Placed upstream to the VELO detector before the warm dipole magnet
- **4 layers of silicon micro-strip sensors** with the geometry similar to Run 1/2 tracker
  - Each vertical plane has a stereo counter part that provides second coordinate
- **40 MHz readout thanks to new SALT ASIC** capable of sophisticated on-detector data processing
- Finer granularity with fine pitch close to the beam, sensors featuring embedded pitch adapters
- Larger coverage thanks to the sensors with **round cut-outs** („touching” the beam pipe)

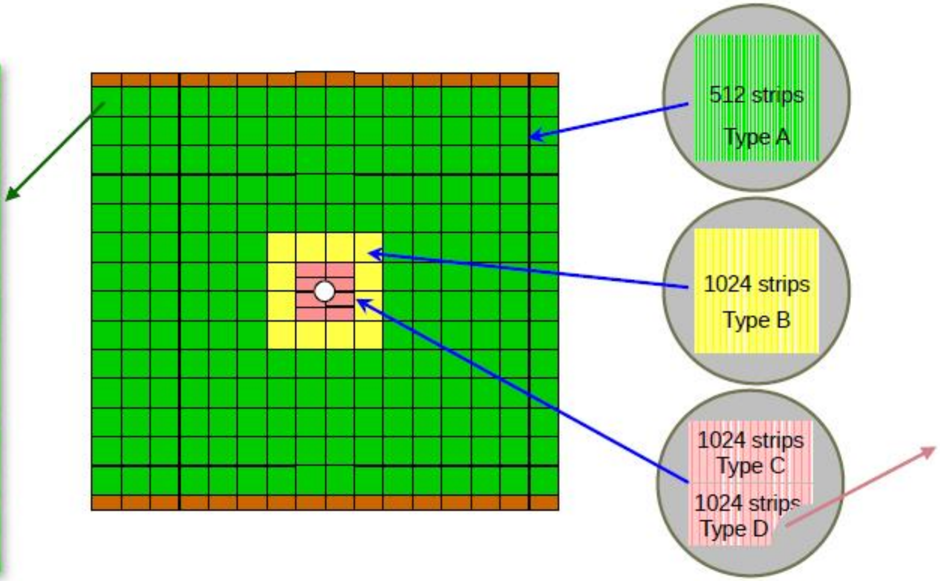


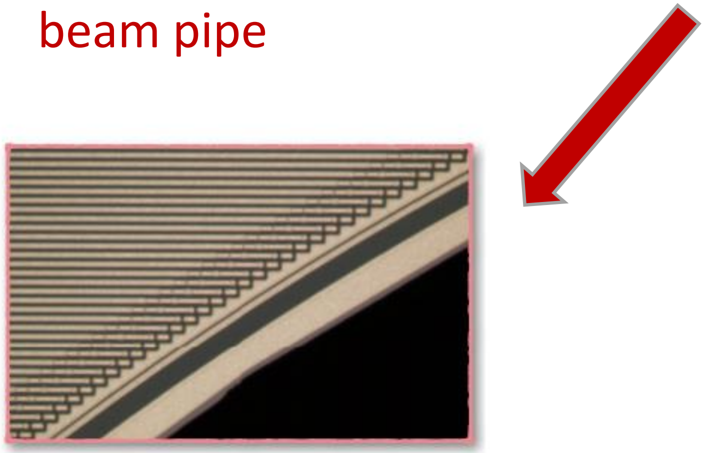


Upstream Tracker (UT) / 2

Sensor	Type	Pitch	Length	Strips	# sensors
A	p-in-n	187.5 μm	99.5 mm	512	888
B	n-in-p	93.5 μm	99.5 mm	1024	48
C	n-in-p	93.5 μm	50 mm	1024	16
D	n-in-p	93.5 μm	50 mm	1024	16

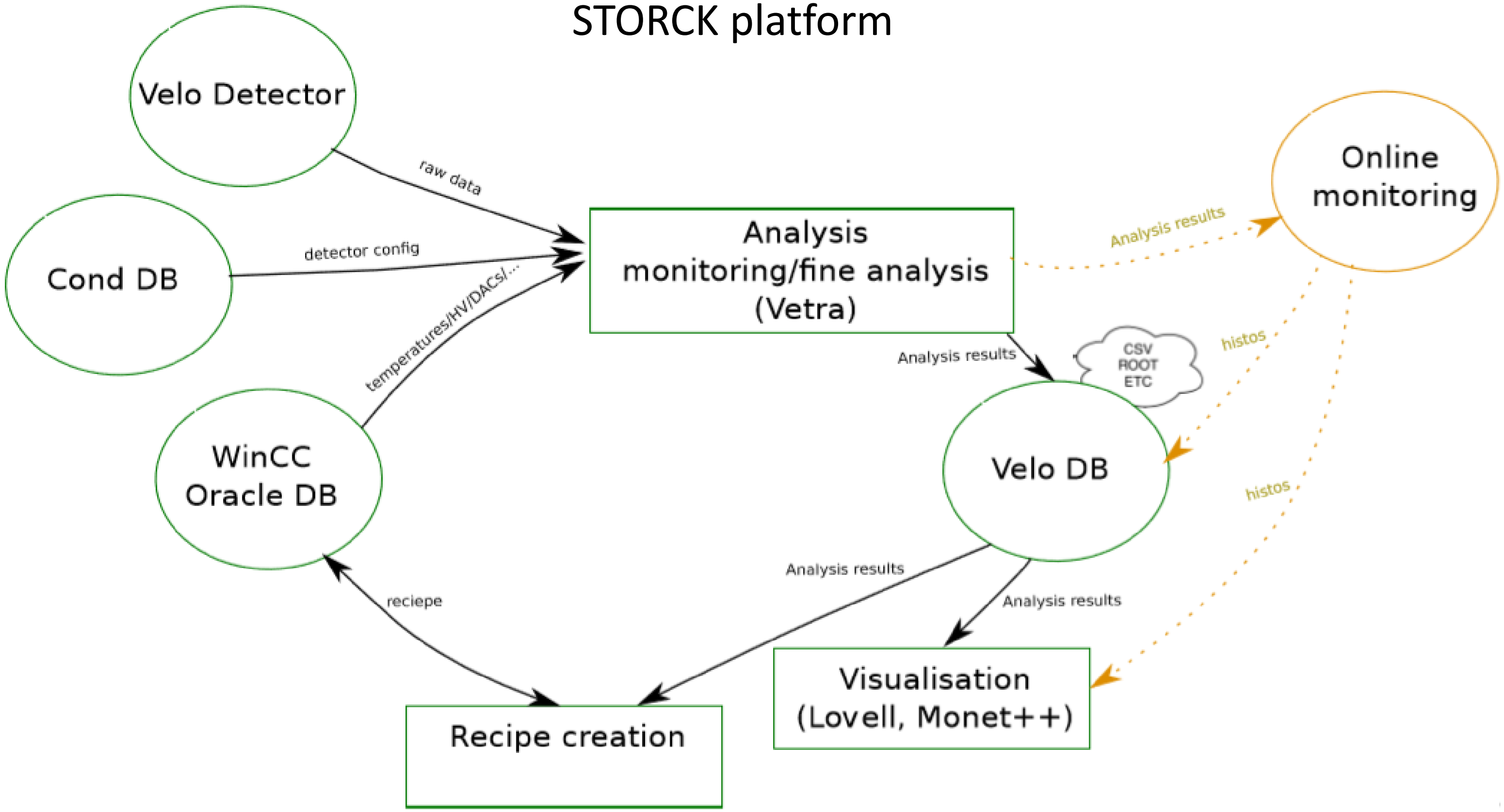
- 4 types of silicon sensors with different granularities (cost optimisation)
  - **Outer region with p-in-n sensors** with 187.5 μm pitch
  - **Inner region with n-in-p sensors** (more radiation hard) with 93.5 μm pitch
  - Complex readout scheme
- Circular cut-out for sensors closest to the beam pipe



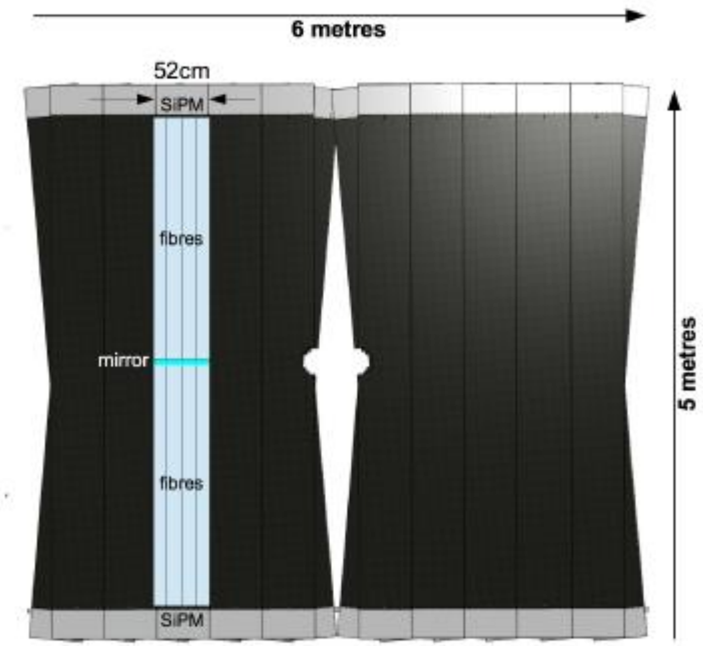


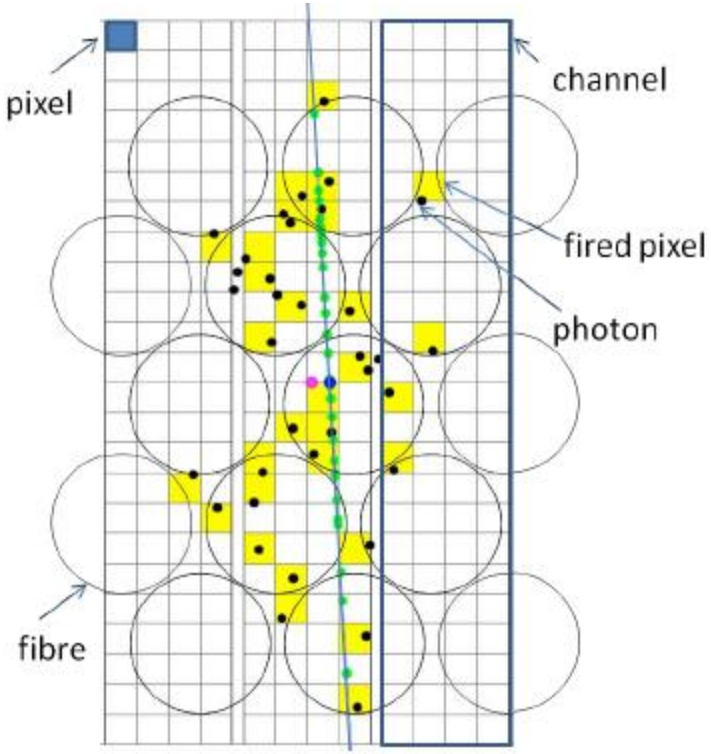
Robust software for silicon detectors

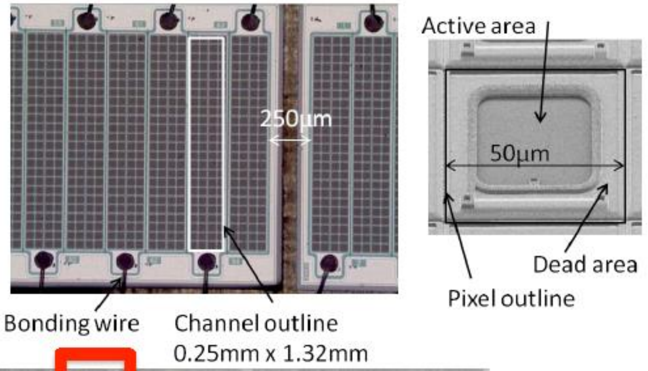
STORCK platform

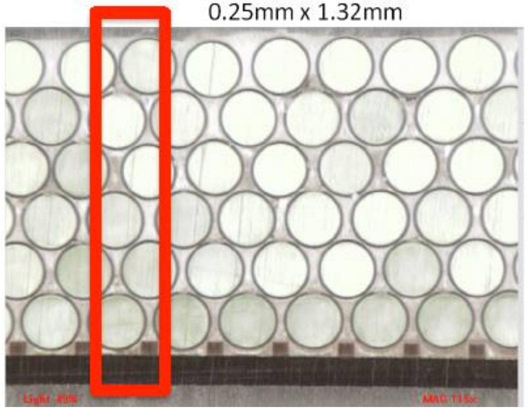


Scintillating Fibre Tracker (FT) / 1









- Large area tracker placed after the magnet
- **Novel technology with active scintillating fibres** – called SciFi…

Scintillating Fibre Tracker (FT) / 1

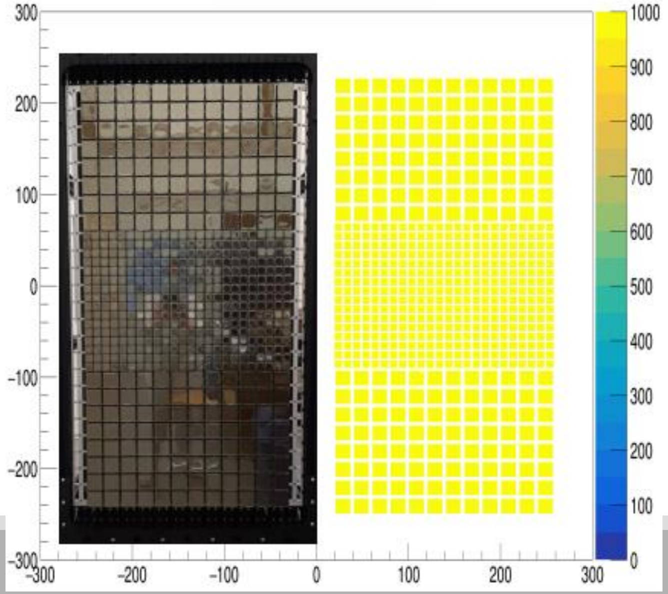
- Scintillating fibres readout with SiPMs
  - The whole detector made of 3 stations and 12 active layers (each station arranged in a similar manner to the UT detector (x, u, v, x)
  - 2.4 m long fibres, 250 μm diameter, **more that 10 000 km of scintillating fibre in total!**
- SiPMs outside acceptance
  - Each with 128 individual channels
  - Sensitive to radiation damage (neutron fluence) need to be placed in cold boxes and cool down to about $-40^{o}\mathrm{C}$
- Dedicated ASIC (PACIFIC) for on-detector readout
  - 64 channels, 130 nm CMOS
  - clusterisation done on FPGA boards

Particle Identification system (PID) / 1

- **Cherenkov detectors**
  - RICH 1: C_4F_{10} (momentum coverage 10 – 65 GeV/c)
  - change pretty much everything (including new readout electronics and new photon detectors)
  - New detector mechanics
  - New mirrors, gas enclosure and quartz windows
  - Installation is progressing

  - RICH 2: CF_4 (momentum coverage 15 – 100 GeV/c)
  - Replace HPDs (Hybrid Photon Detectors) with Anode Photomultiplier Tubes
  - New 8 channel read-out ASIC (CLARO)
  - Installation of both sides of the detector already completed!

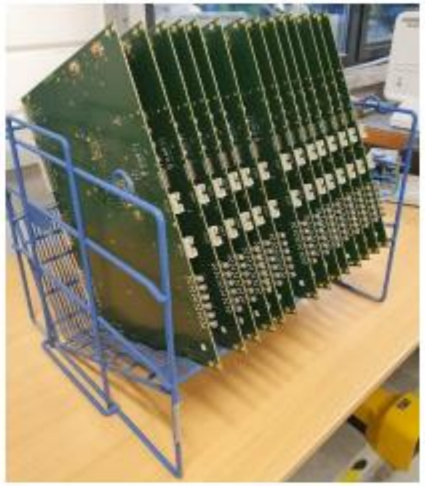
MaPMT columns



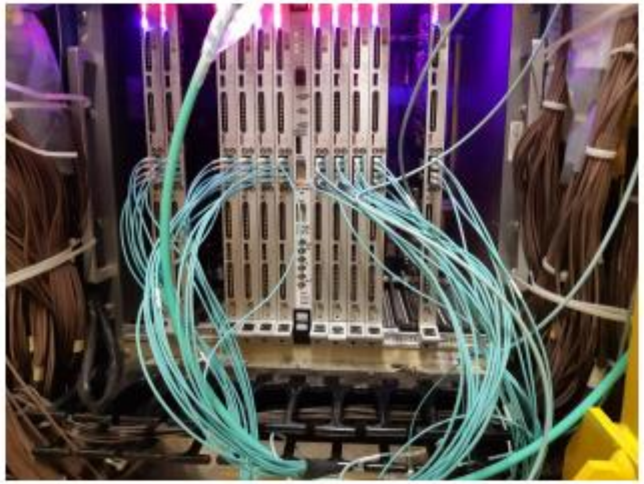
RICH2 pixel map

Particle Identification system (PID) / 2

- **Calorimeters (Hadronic and Electromagnetic)**
  - Technology
  - **HCAL** – Shashlik 25 X_0 Pb + scintillator
  - **ECAL** – Fe + scintillator
  - LHCb Upgrade I – PS/SPD removed (multiplicity counters removed)
  - PMT gain reduced (factor of 5), electronics updated for trigger-less readout
- **Muon System**
  - The current system will be kept, 4 layers (M2-M5) of multi-wire proportional chambers (MWPC)
  - FE electronics redeveloped – trigger-less readout
  - Layer M1 (GEM detector) removed

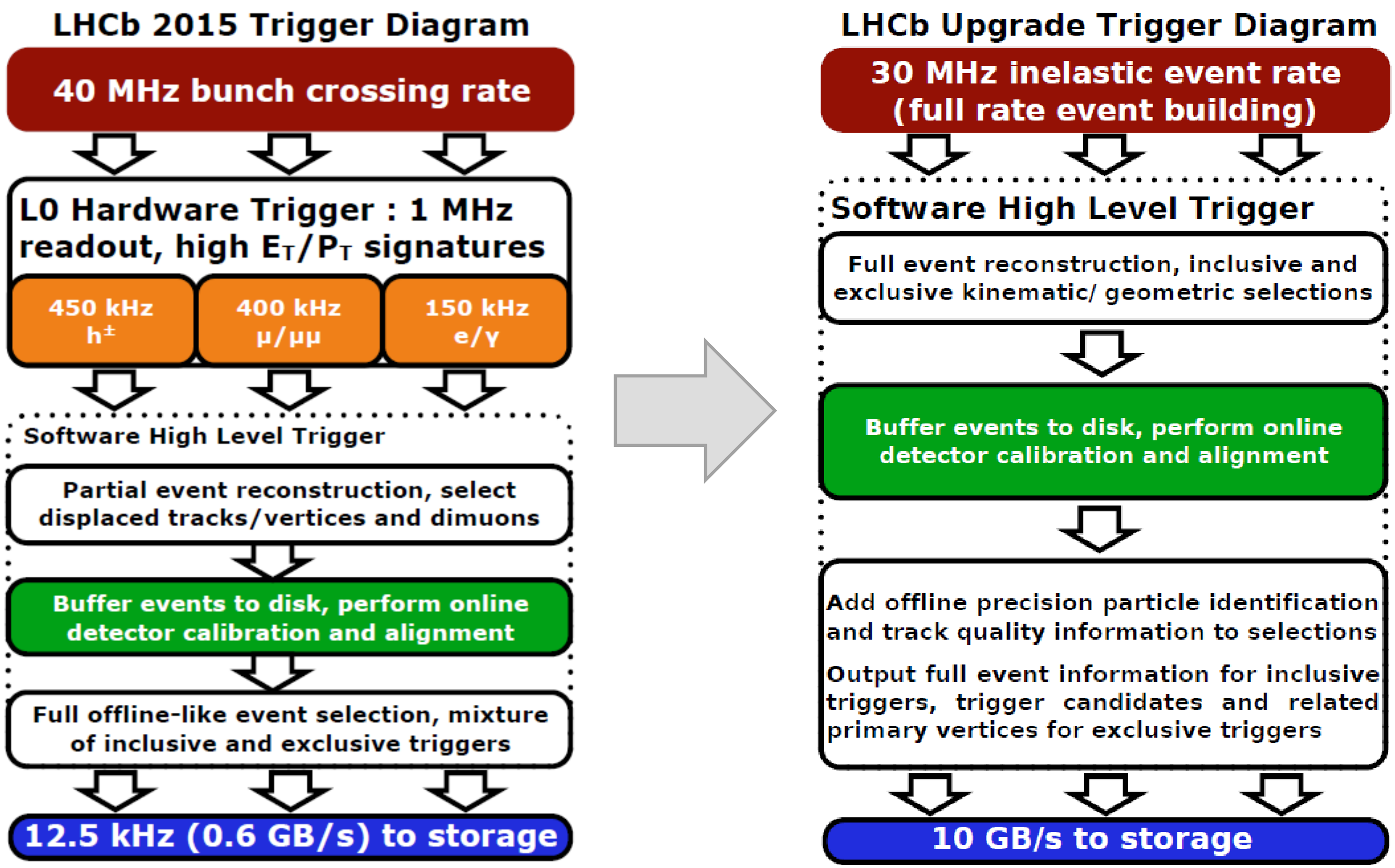


Control electronics boards



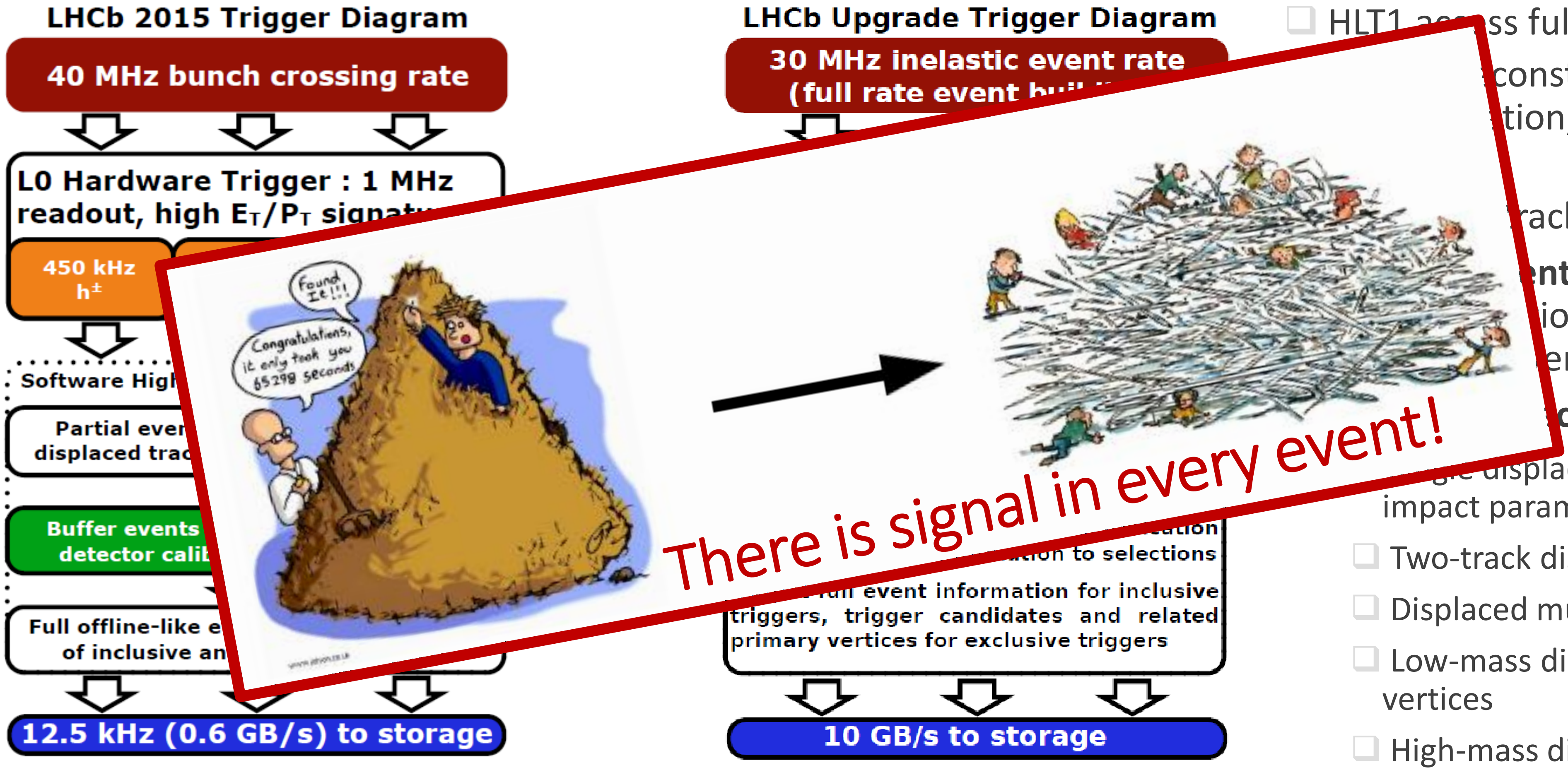
Crates being installed

Software trigger (HLT) Run 2 → Run 3 / 1



- HLT1 access full detector information
  - **VELO** reconstruction with clusterisation, tracking and vertex fitting
  - **UT & FT** track reconstruction
  - **Global event reconstruction** with Full bidirectional Kalman filter and secondary vertices
  - **Physics selections**
    - Single displaced (in terms of large impact parameter) tracks
    - Two-track displaced vertices
    - Displaced muons
    - Low-mass displaced two-muon vertices
    - High-mass dimuons

Software trigger (HLT) Run 2 → Run 3



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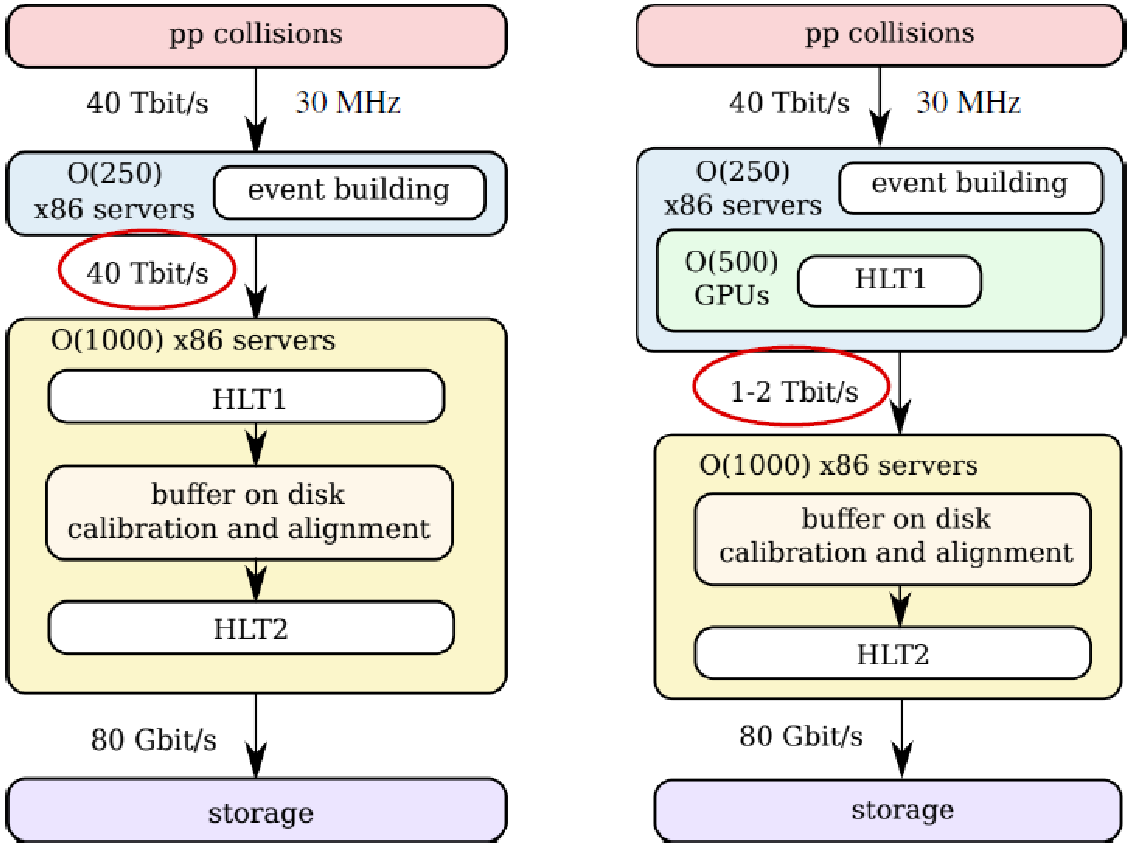
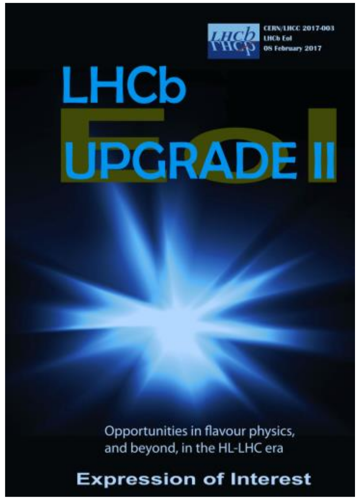
LHCb Software trigger goes GPU



- Trigger event selection exibits **„natural" data parallelism** – could be exploited using massively parallel GP-GPUs
- LHCb RAW event size about 100 kB
- GPU used for producing selection decision
- The HLT1 data stream can be processed using **~500 top-shelf GP-GPU cards**
- Physics performance with simulated data **exceeds by far the TDR proposal regarding full CPU trigger**

Summary

- **LHCb Upgrade I** (Run 3/4, beyond 2022) is a very challenging project – we are building effectively a new detector!
- Despite COVID-19, that made the installation schedule extremely difficult, its impact is being continuously assessed
- All sub-detector projects at peak production mode
- **Upgrade Ib** (consolidation plans, LS3 2025 - 2027) improvements in the detector setup
  - Magnet tracker inside LHCb magnet
  - TORCH detector for precise timing
- Upgrade II
  - New technologies are necessary for precise tracking – need to develop new radiation hard silicon structures
  - Framework TDR should come along this year!



BACK UP

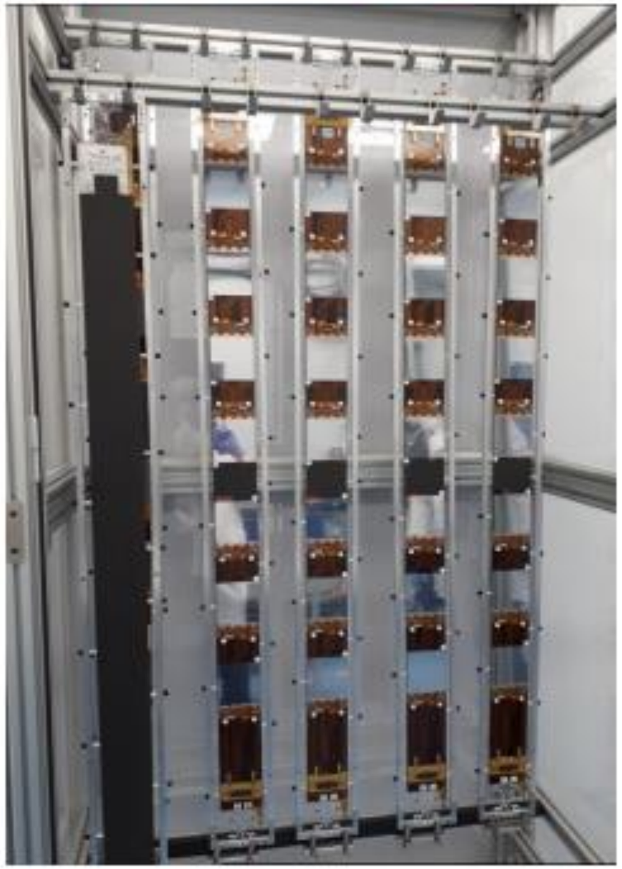
VELO status

- More than 50% of the VELO modules are ready

UT status

- UT modules: most of the 4 chip hybrids passed quality checks, can be used for the detector
- 16 8 chip modules produced and being tested
- Detector staves – close to half of them are complete

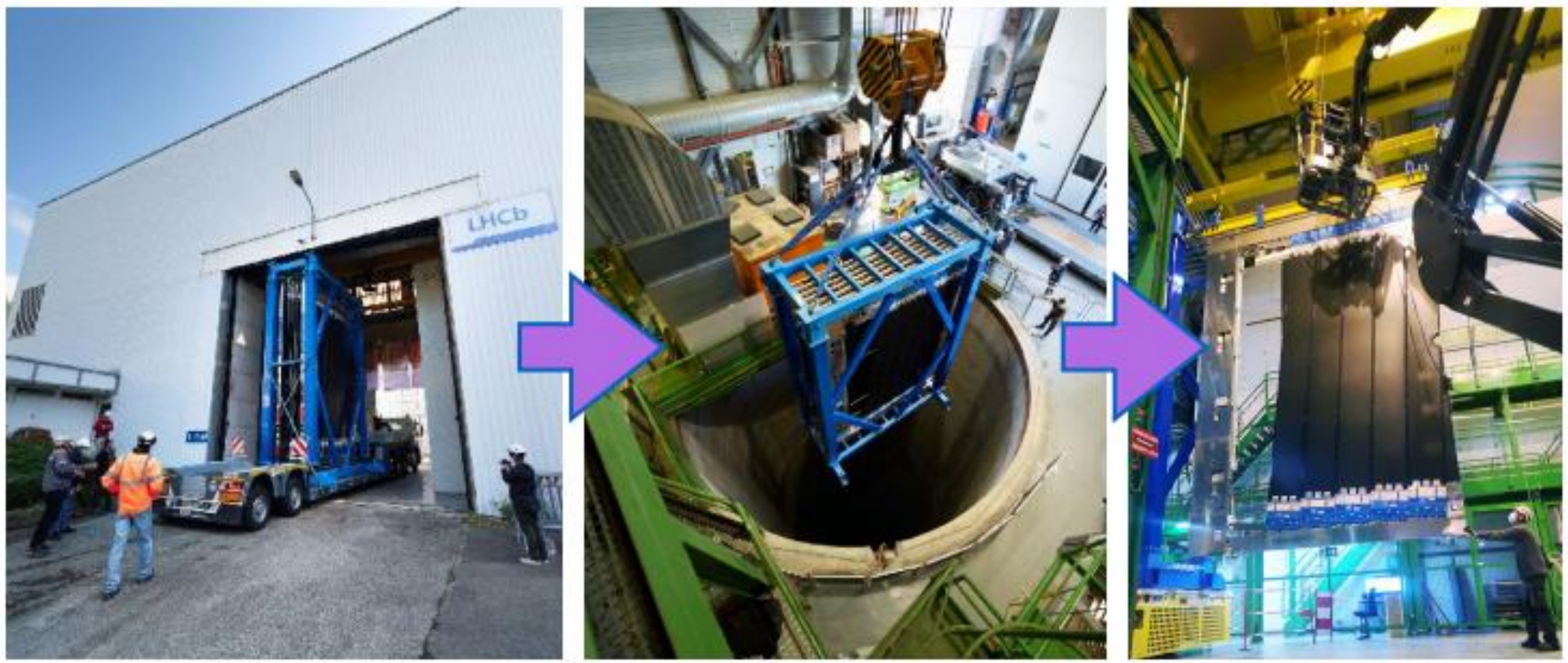
staves stored at CERN



UT box assembly

Fibre Tracker status

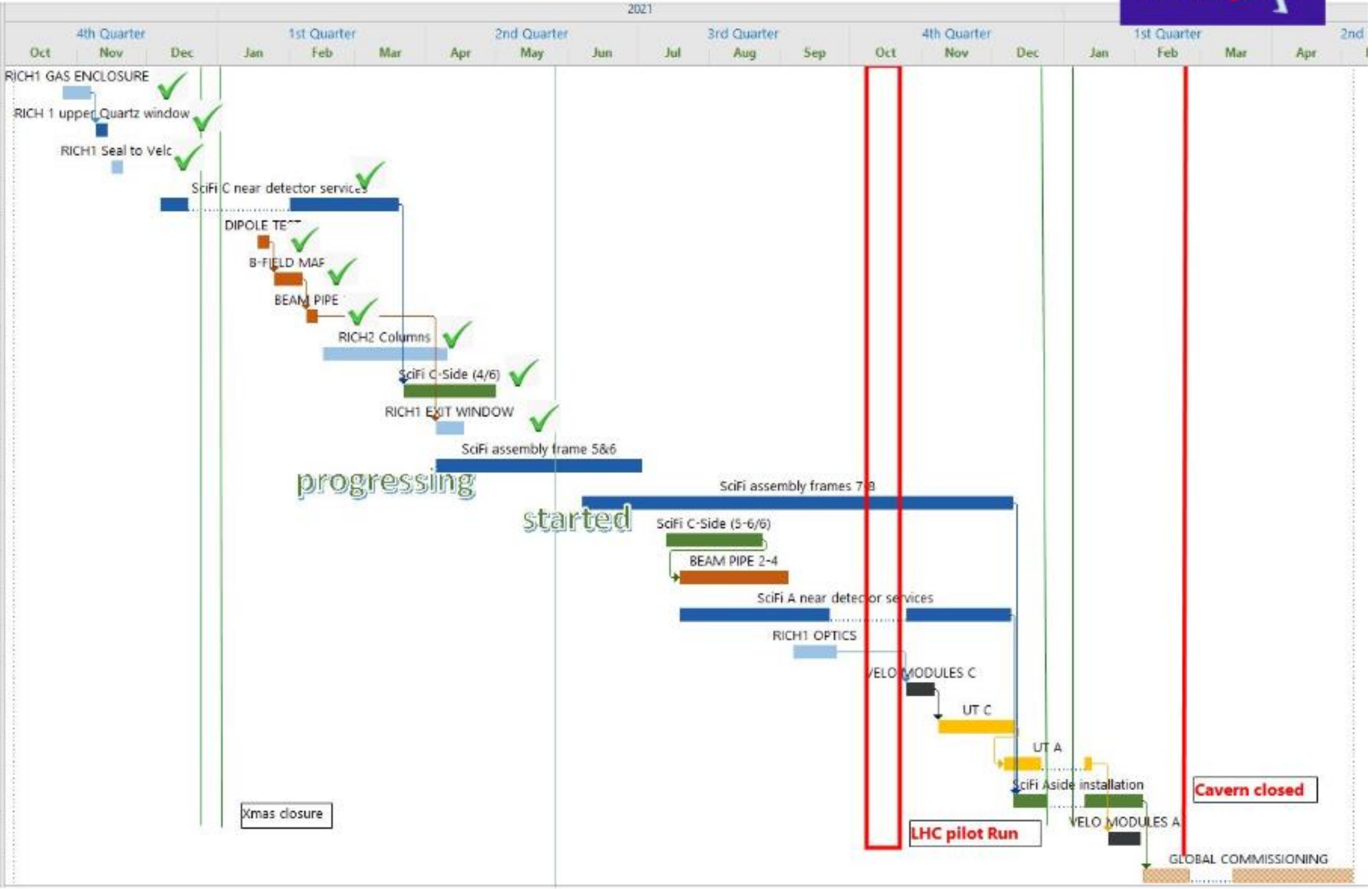
First C-frames transported and installed at the pit!



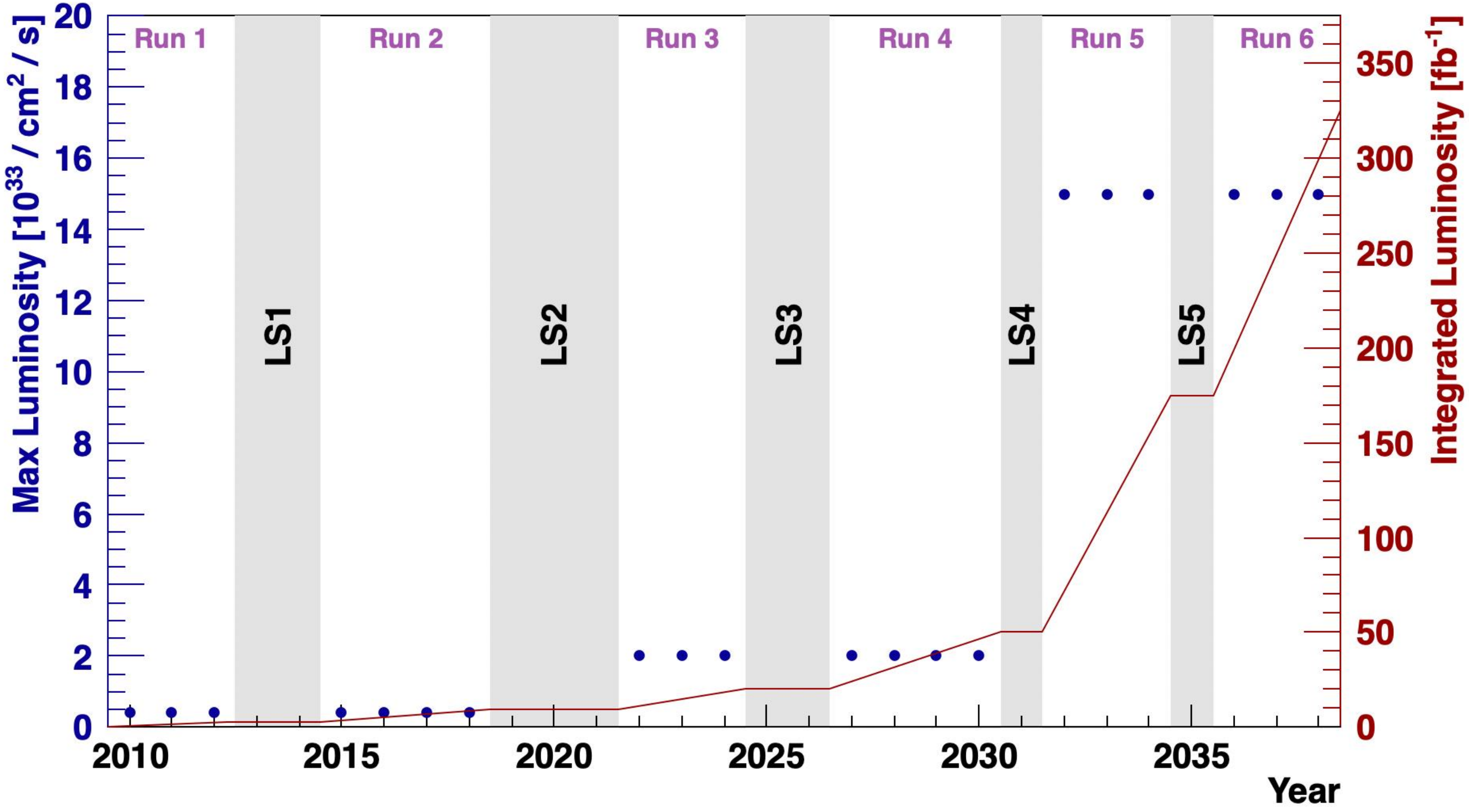
- Installation completed for one side of the detector!

Schedule

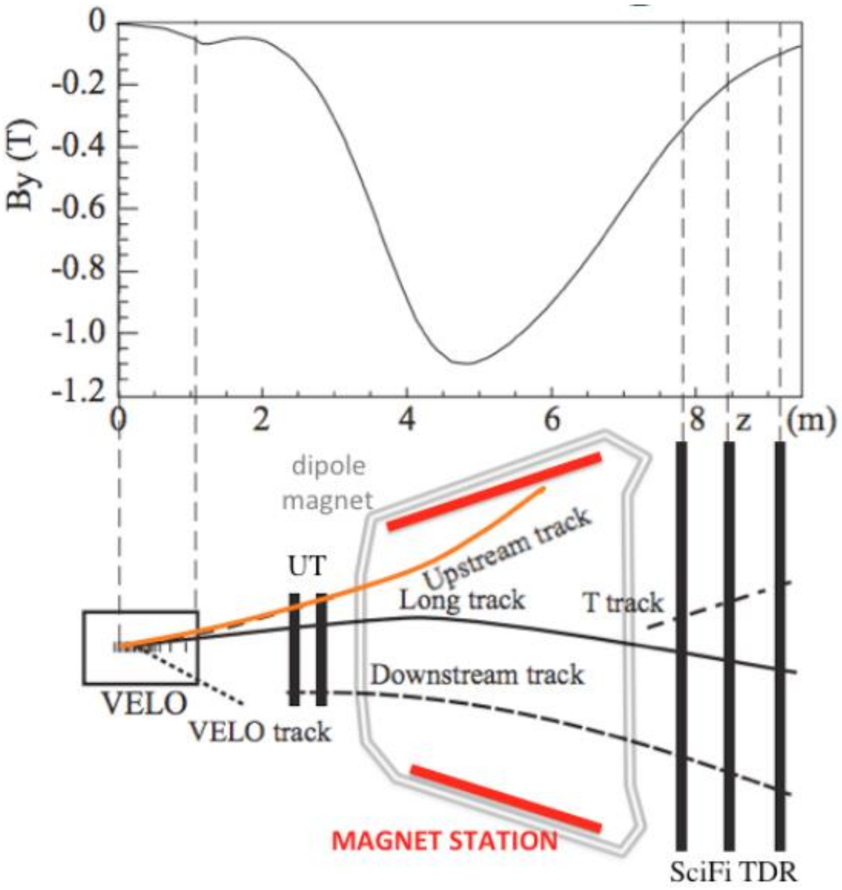
Task Name	Duration	Start
RICH1 GAS ENCLOSURE	2 wks	Mon 26/10/20
RICH 1 upper Quartz window	1 wk	Mon 09/11/20
RICH1 Seal to Velo	1 wk	Mon 16/11/20
SciFi C near detector services	9 wks	Mon 07/12/20
DIPOLE TEST	1 wk	Mon 18/01/21
B-FIELD MAP	2 wks	Mon 25/01/21
BEAM PIPE 1	1 wk	Mon 08/02/21
RICH2 Columns	8 wks	Mon 15/02/21
SciFi C-Side (4/6)	6 wks	Mon 22/03/21
RICH1 EXIT WINDOW	2 wks	Mon 05/04/21
SciFi assembly frame 5&6	13 wks	Mon 05/04/21
SciFi assembly frames 7-8	26.8 wks	Mon 07/06/21
SciFi C-Side (5-6/6)	6 wks	Tue 13/07/21
BEAM PIPE 2-4	7 wks	Mon 19/07/21
SciFi A near detector services	16 wks	Mon 19/07/21
RICH1 OPTICS	3 wks	Mon 06/09/21
VELO MODULES C	2 wks	Mon 25/10/21
UT C	5 wks	Mon 08/11/21
UT A	3 wks	Mon 06/12/21
SciFi Aside installation	6 wks	Fri 10/12/21
VELO MODULES A	2 wks	Thu 20/01/22
GLOBAL COMMISSIONING	52 days	Fri 04/02/22

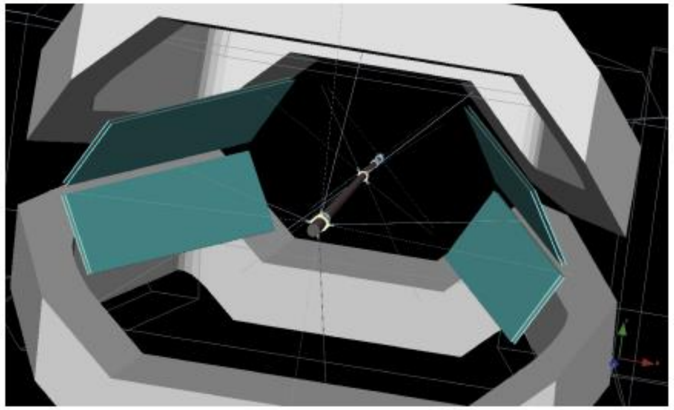


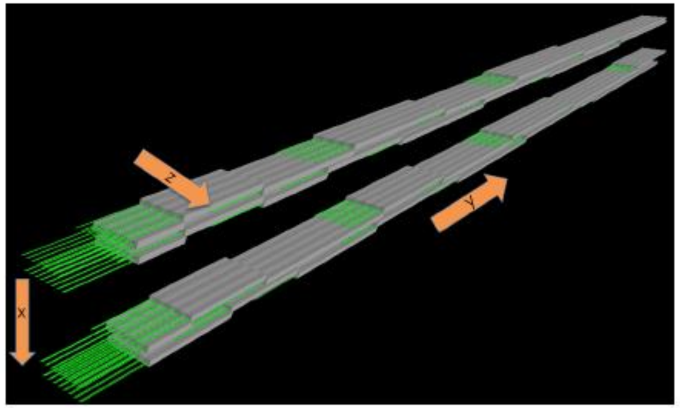
Run 3/4/5/6 luminosities for LHCb



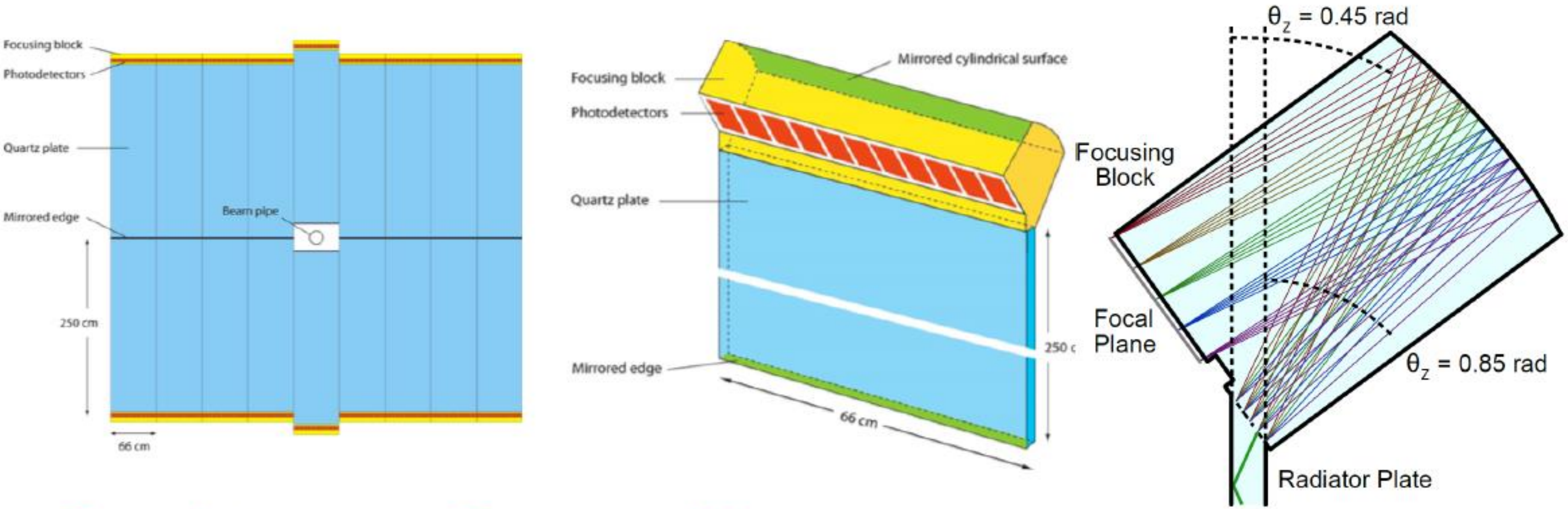
Magnet stations / Upgrade Ib







TORCH detector / Upgrade Ib



- Time Of internally Reflected CHerenkov light.
  - Large area time-of-flight detector.
  - Provide PID in momentum range 1 – 10 GeV/c.