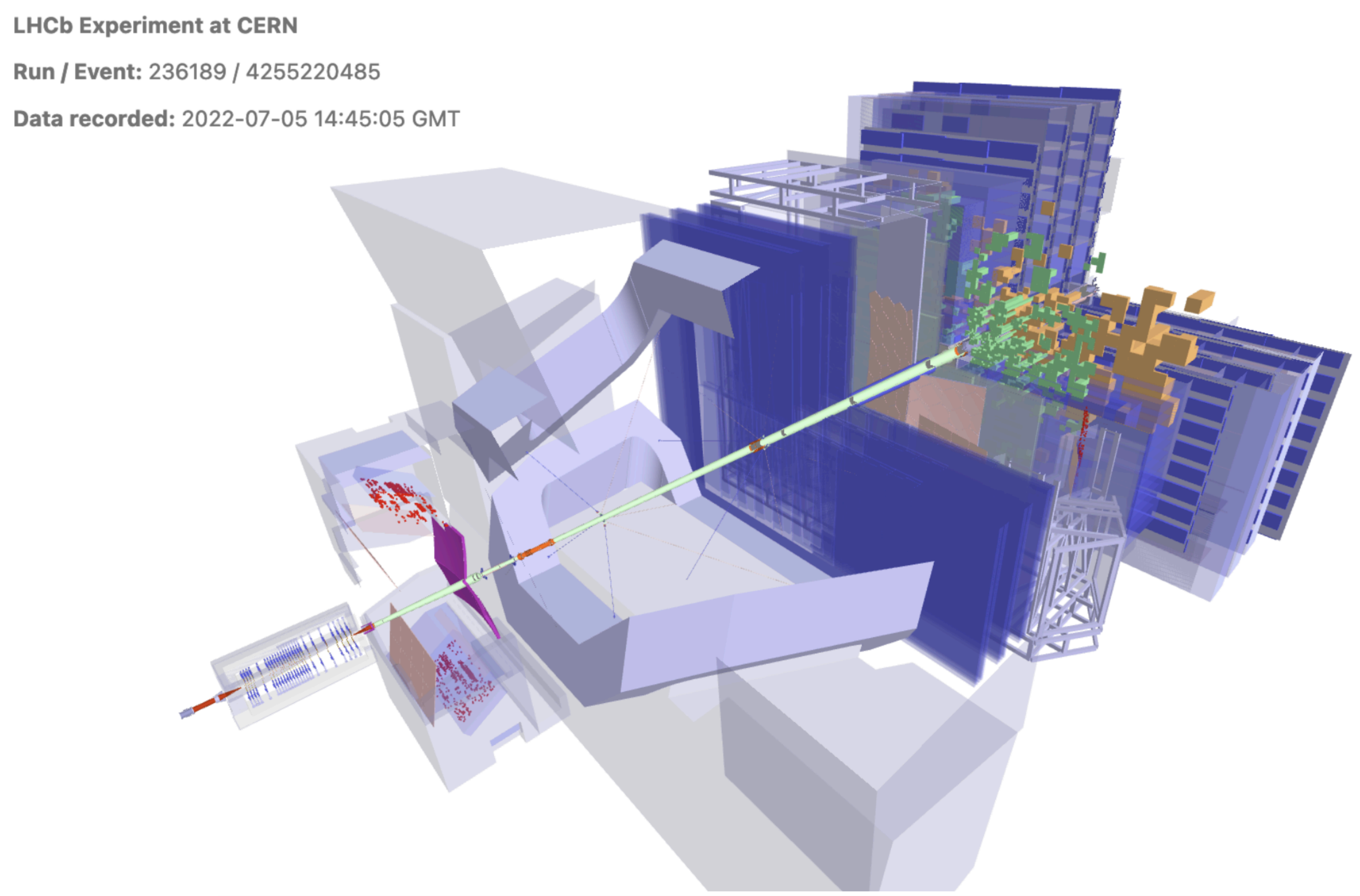


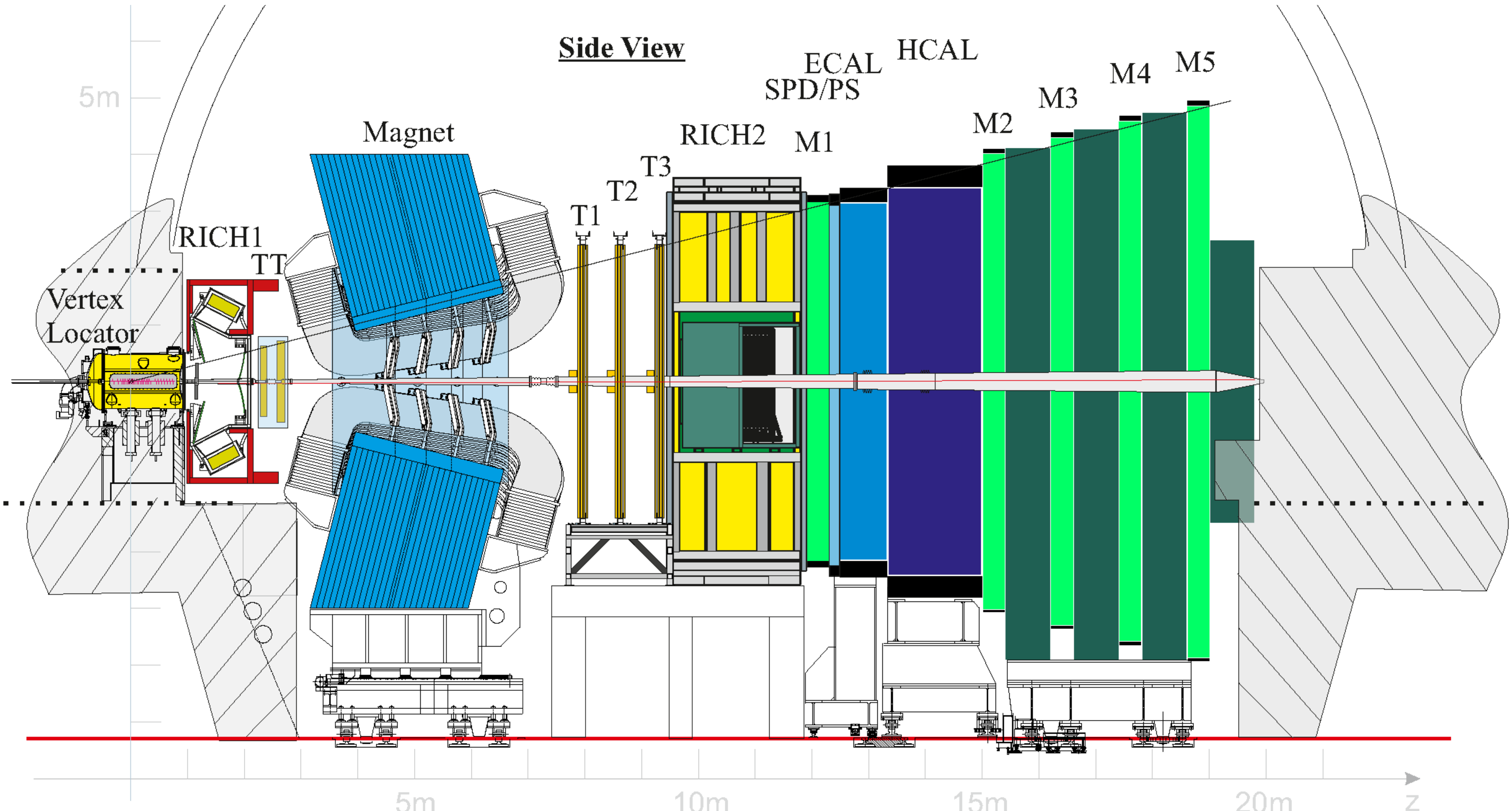
The LHCb Upgrade and Run 3

Federico Alessio, Preema Pais
CERN

LHCb Starterkit
December 01, 2022

The LHCb Detector

Single-arm spectrometer instrumented in the forward ($2 < \eta < 5$) region, designed to study decays of beauty and charm hadrons



The LHCb Detector

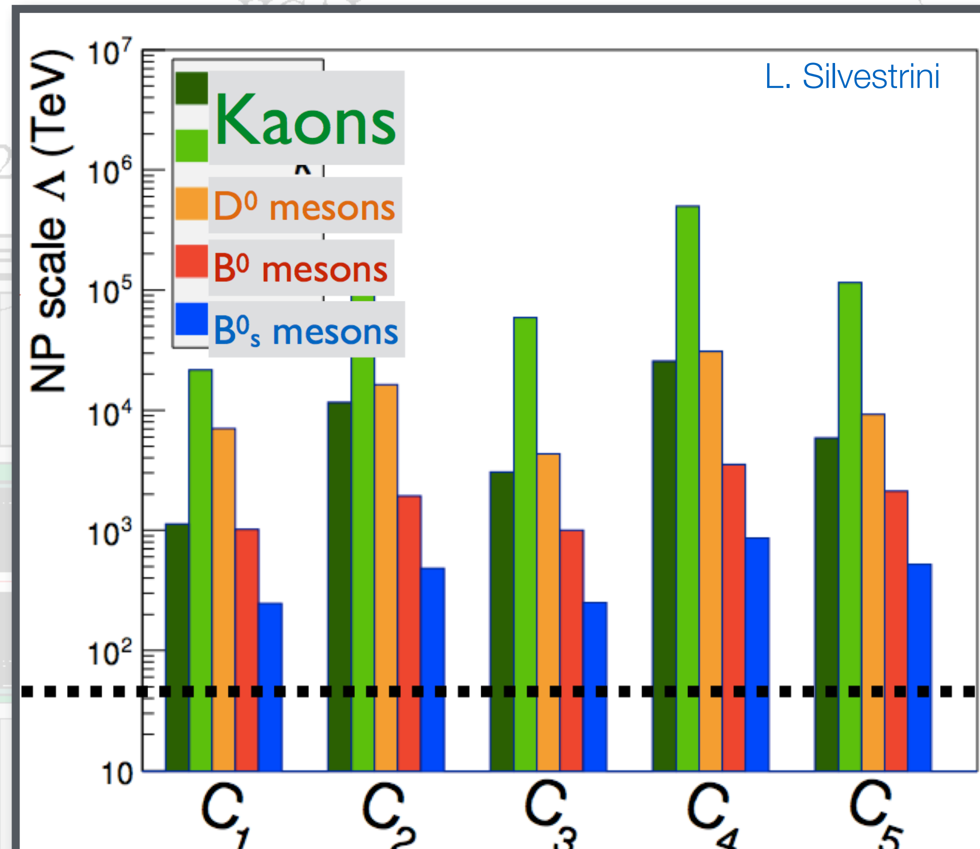
Single-arm spectrometer instrumented in the forward (2 < η <5) region, designed to study decays of beauty and charm hadrons

Studies of heavy quark hadrons can be excellent probes to search for NP and high energy scales, sources of CPV

LHCb physics program complementary to ATLAS, CMS, Belle-II

Requirements:

- Precision primary and secondary vertex reconstruction, efficient tracking
- Excellent particle identification
- Efficient trigger

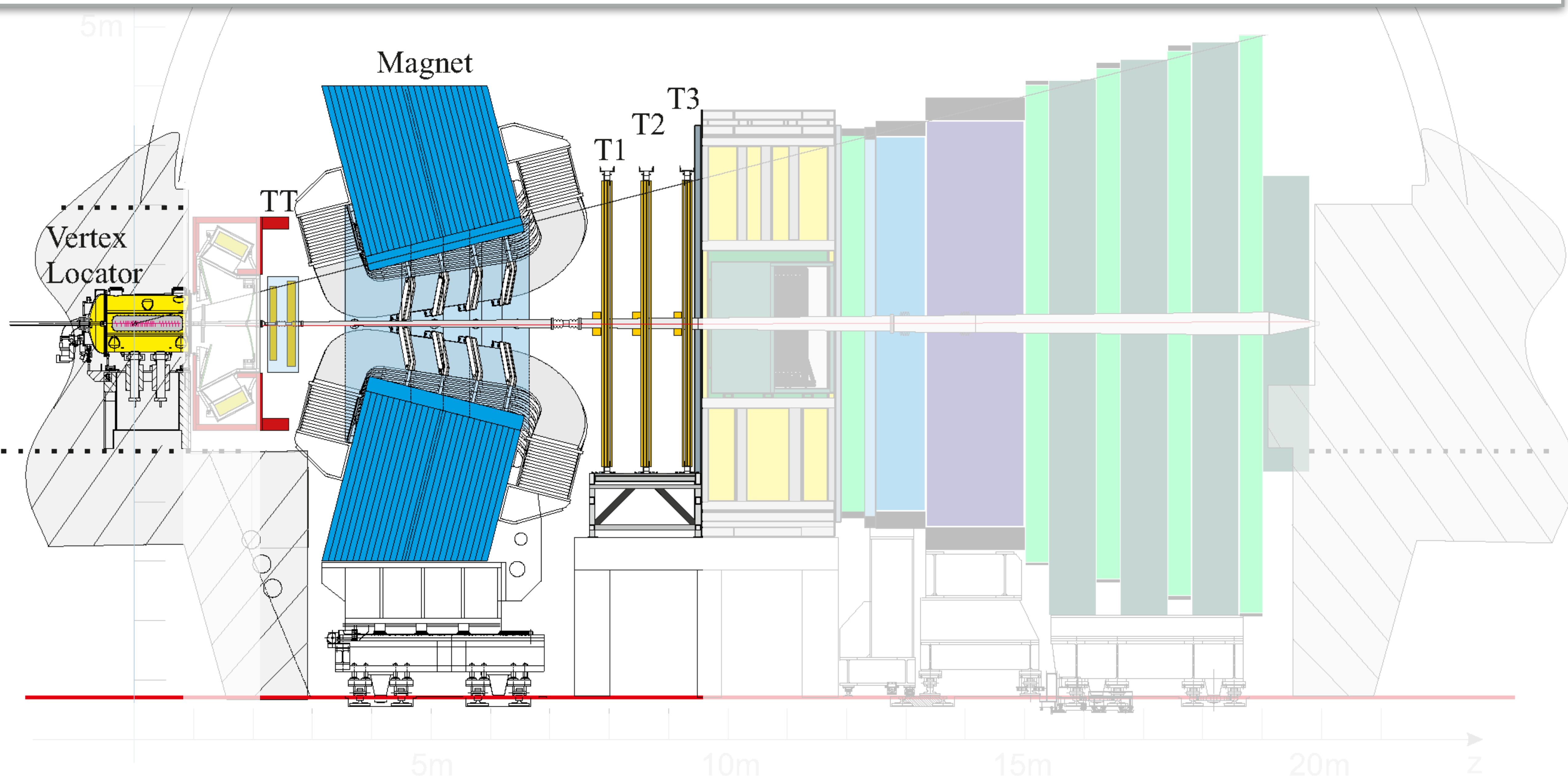


LHC direct searches

THE LHCb DETECTOR

Tracking system (Runs 1 and 2):

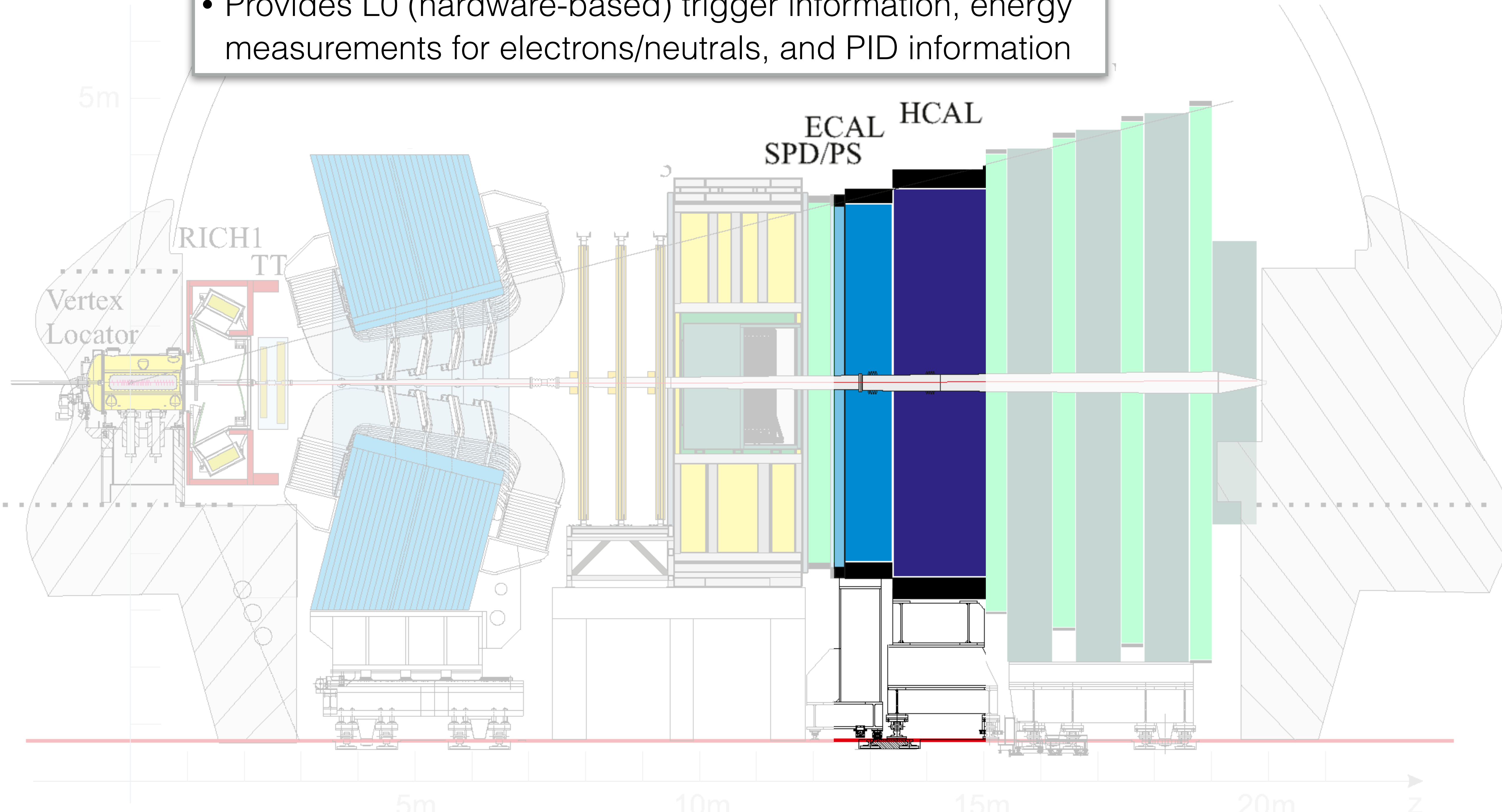
- **Vertex Locator (VELO)** for precision reconstruction + separation of primary, secondary vertices
- **Silicon Tracker (ST)**, consisting of:
  - Four-layer silicon strip **Tracker Turicensis (TT)** upstream of magnet
  - Silicon strip **Inner Tracker (IT)** in the innermost region of tracking stations (T1-T3) downstream of magnet



THE LHCb DETECTOR

Calorimetry

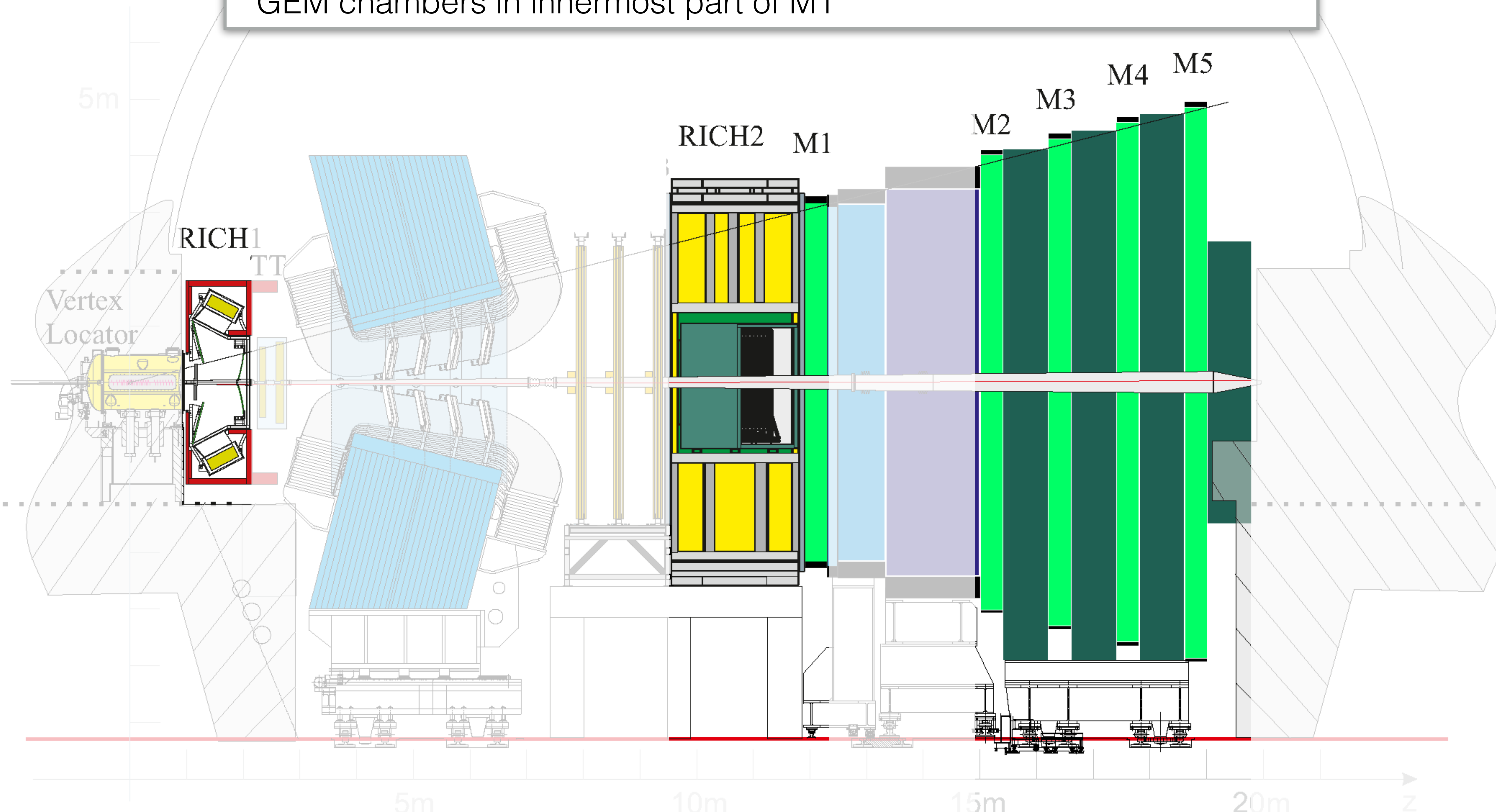
- Located ~12.5 m from the interaction point
- Four sub-detectors: SPD, PS, ECAL, HCAL
- Provides L0 (hardware-based) trigger information, energy measurements for electrons/neutrals, and PID information



THE LHCb DETECTOR

Particle Identification

- Ring Imaging Cherenkov detectors for pion, kaon identification
- Muon Spectrometer: Five stations of multi-wire proportional chambers, GEM chambers in innermost part of M1



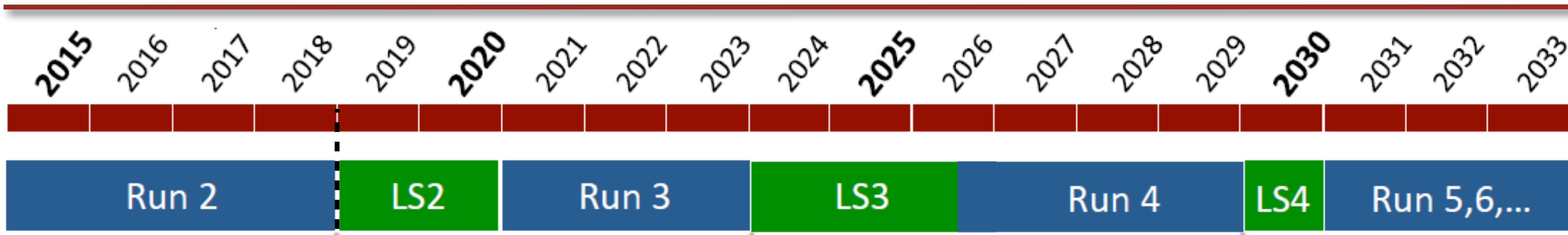
Why Upgrade?

Many LHCb results currently limited by statistical uncertainties

Observable	Current LHCb	σ(stat)/σ(sys)	Largest source of systematic
EW Penguins			
R_K	$0.745 \pm 0.090 \pm 0.036$	2.5	Mass shape & trigger eff
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$	2.2	MC correction & residual bkgd
CKM tests			
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$	3	Δm_s, time res, tagging, det asymmetry
γ, all modes	$(^{+5.0}_{-5.8})^\circ$	-	
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04	8	Decay time: bias and efficiency
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad	8	Angular efficiency
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad	8	Decay time resolution
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad	5	Acceptance (angular and time)
a_{sl}^s	33×10^{-4}	1.3	Track reco asymmetry
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6%	0.5	External BR(Λ_c)
$B_s^0, B^0 \to \mu^+\mu^-$			
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90%	6	f_d/f_s
$\tau_{B_s^0 \to \mu^+\mu^-}$	22%	9	Decay time acceptance
$S_{\mu\mu}$			
$b \to c\ell^-\bar{\nu}_l$ **LUV studies**			
$R(D^*)$	0.026	1	MC sample size
$R(J/\psi)$	0.24	1	F($B_c \to J/\psi$) form factor
Charm			
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4}	2.7	Mass model
A_Γ ($\approx x \sin\phi$)	2.8×10^{-4}	2.8	Contribution from sec $b \to D^*X$ decays
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4}	2	Contribution from sec $b \to D^*X$ decays

Physics Case for an LHCb Upgrade II, CERN-LHCC-2018-027

LHCb Upgrade I



$L = 4 \times 10^{32}$ $cm^{-2}s^{-1}$

~1.1 interactions per bunch crossing

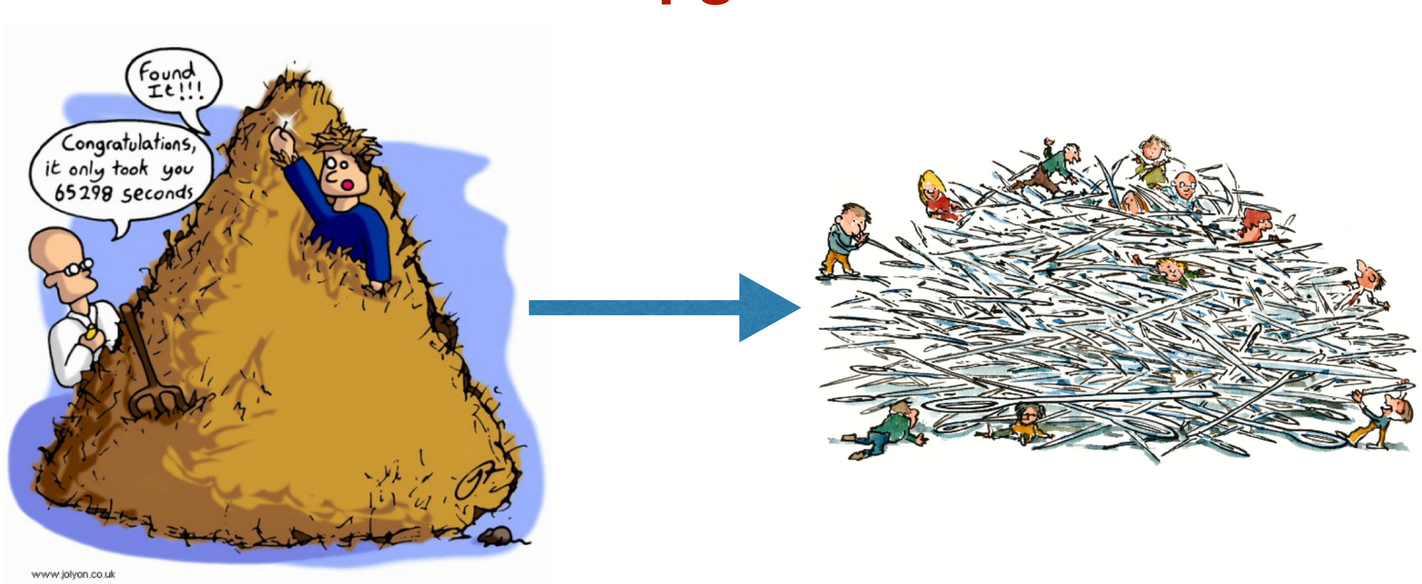
~9.5 fb^{-1} expected (2011-2018)

$L =$ **$1\text{-}2 \times 10^{33}$** $cm^{-2}s^{-1}$

~**5** interactions per bunch crossing

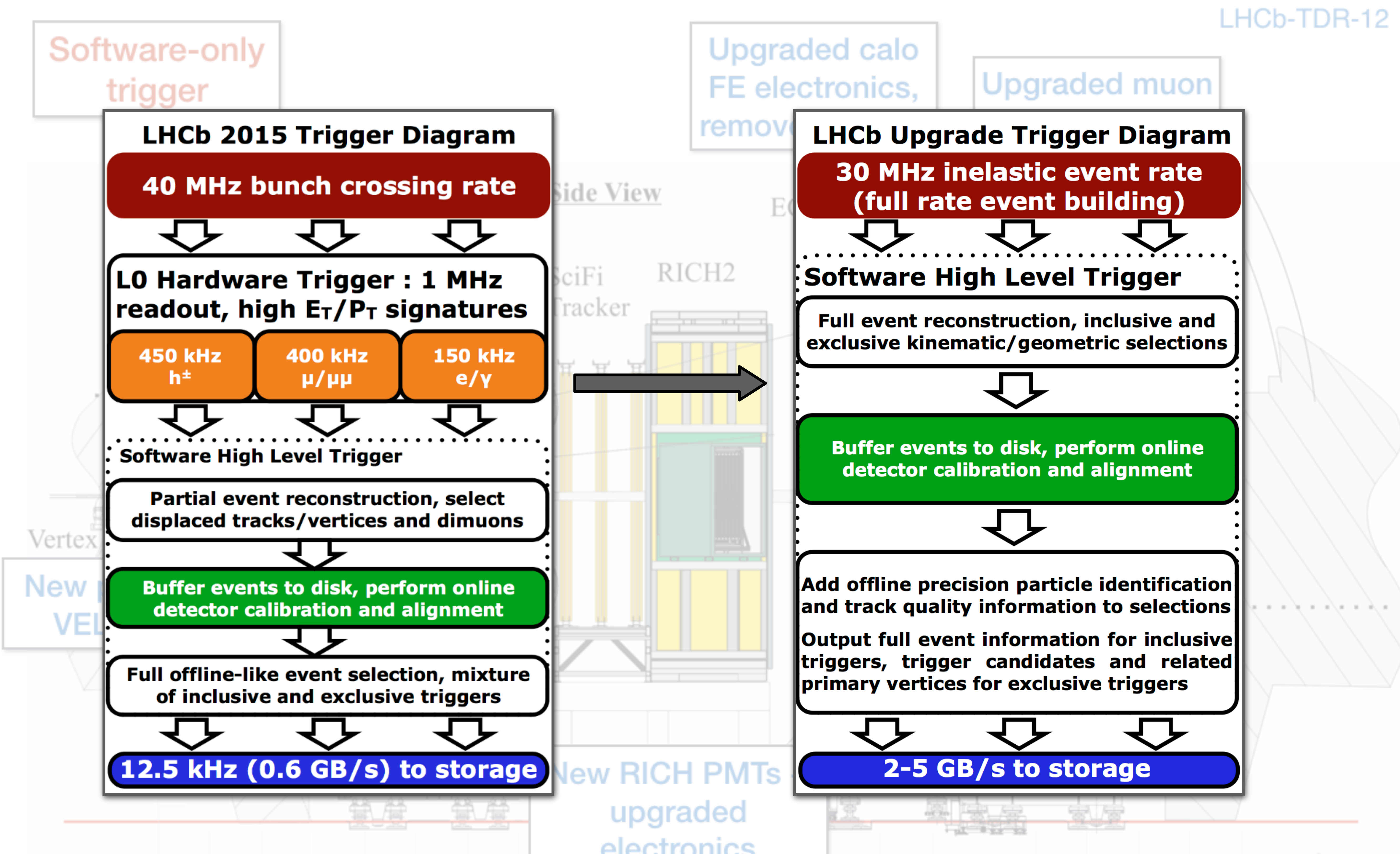
~50 fb^{-1} expected (Runs 3-4)

LHCb Upgrade I



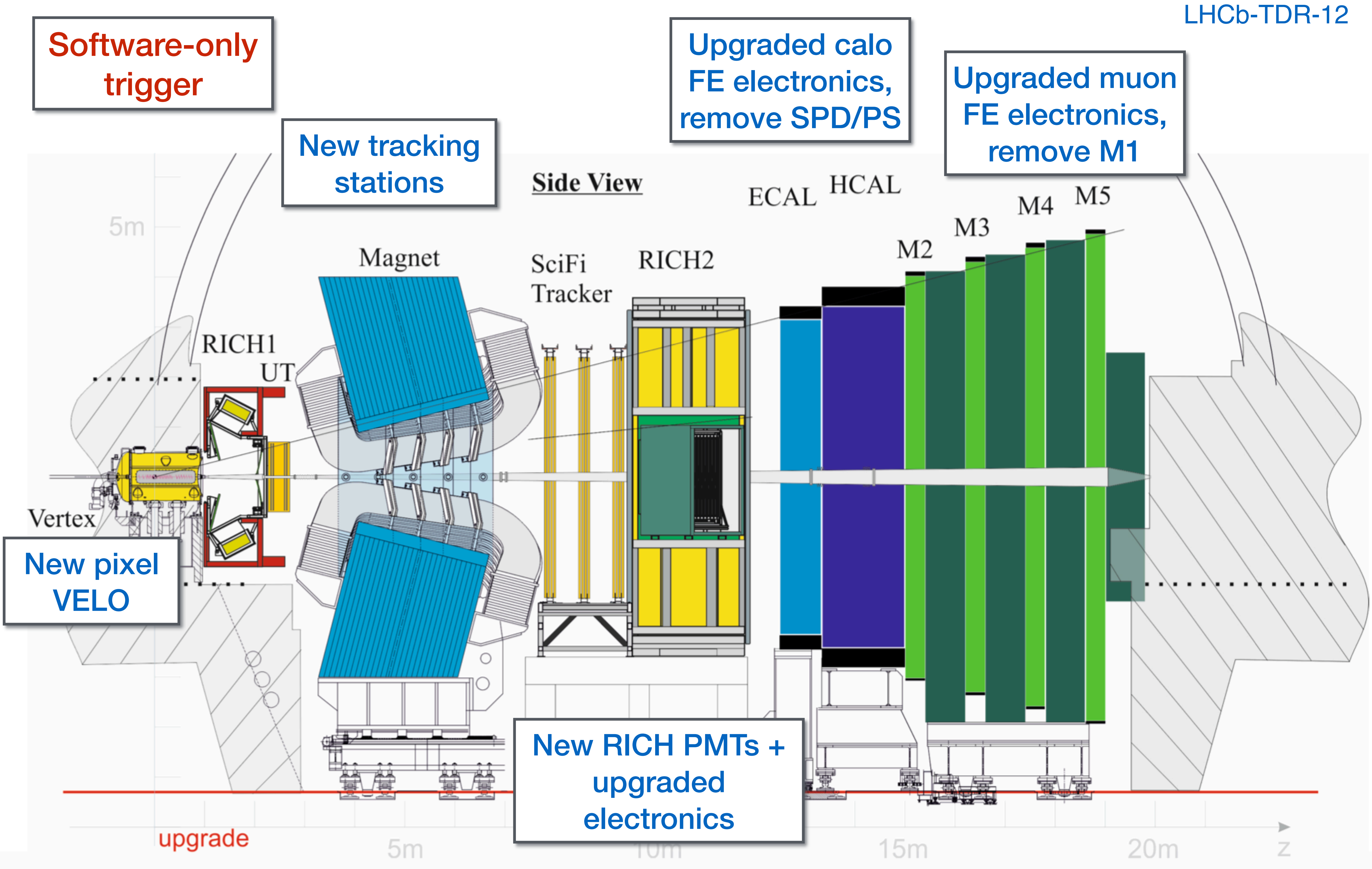
- Primary challenges after LS2:
  - Take advantage of higher luminosity (current L0 hardware trigger limits data-taking rate)
  - Sub-detectors will need to handle increased occupancy (factor 5 increase in number of interactions per bunch crossing)
    - Radiation damage also a concern

LHCb Upgrade I

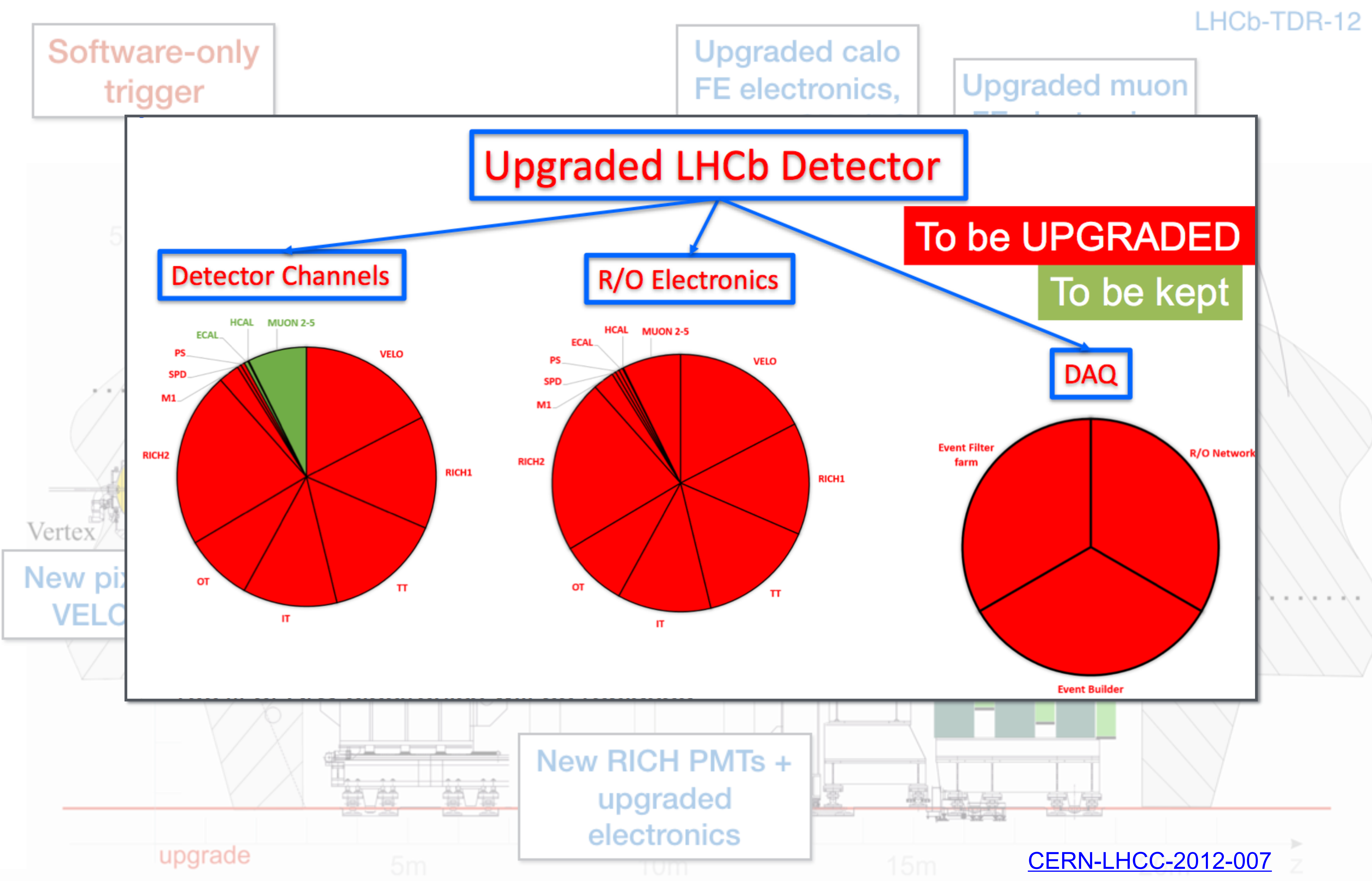


CERN-LHCC-2012-007

LHCb Upgrade I



LHCb Upgrade I



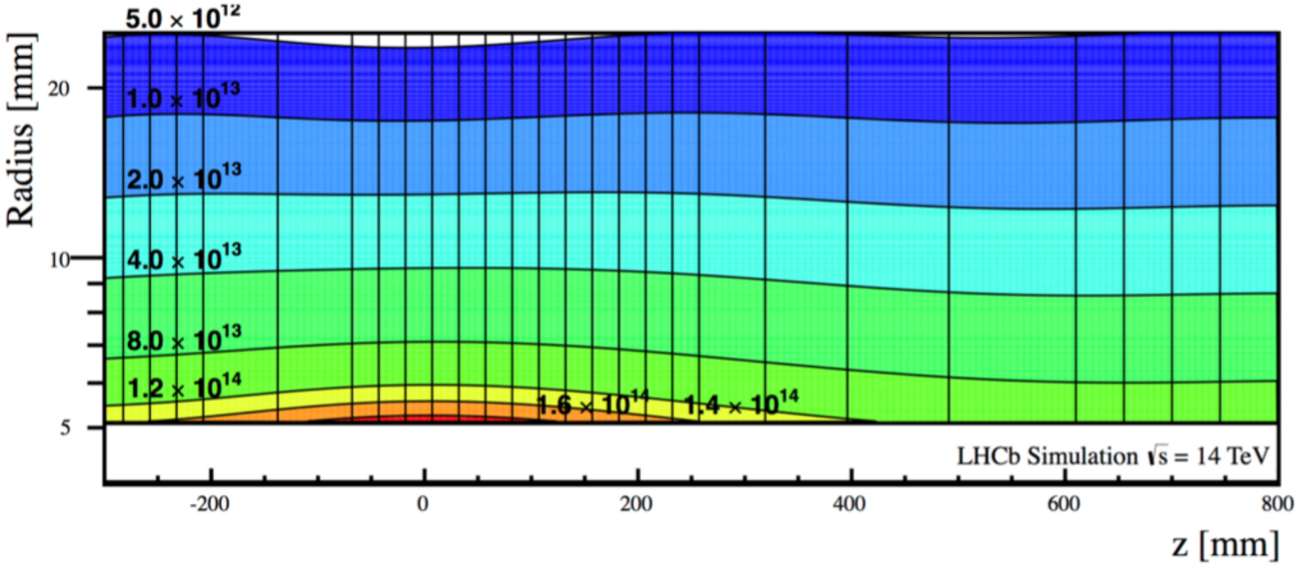
VERTEX LOCATOR

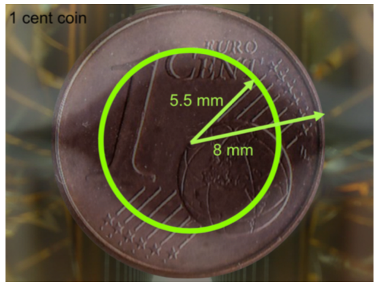
VELO challenges in Run 3:

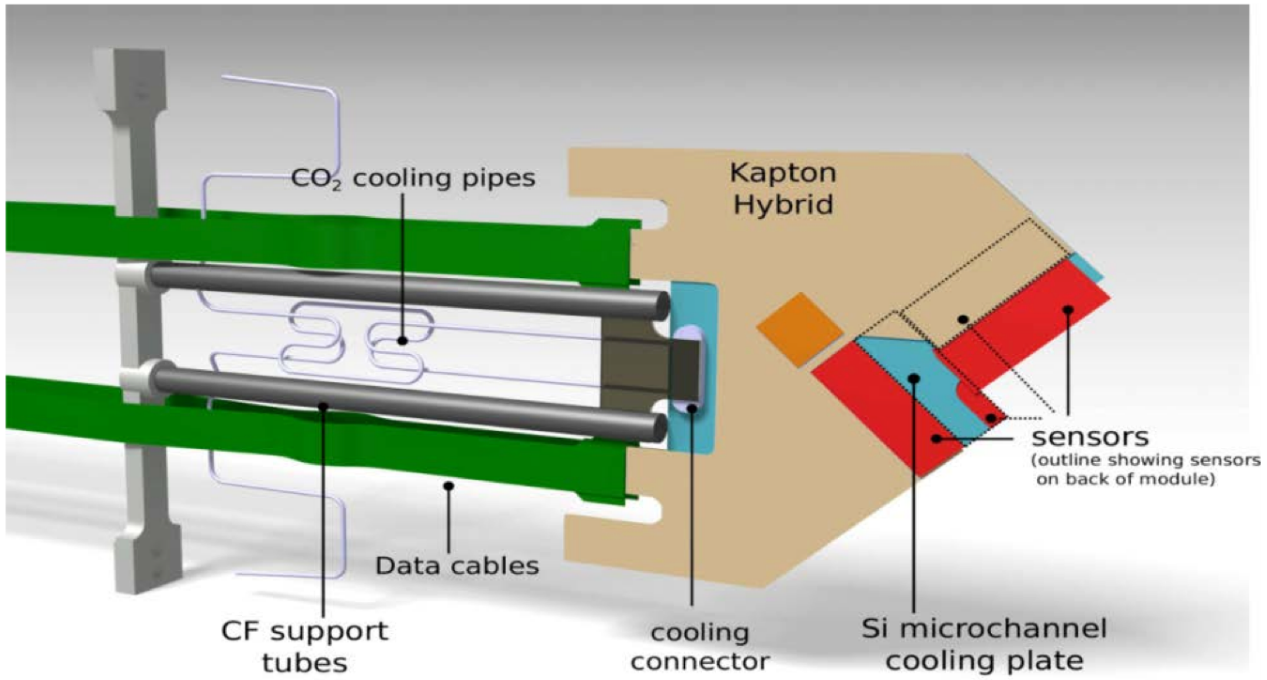
- Retain high vertex and track reconstruction efficiency with ~ 5x increase in interactions per bunch crossing
- Increased radiation (order of magnitude higher than current doses), highly non-uniform

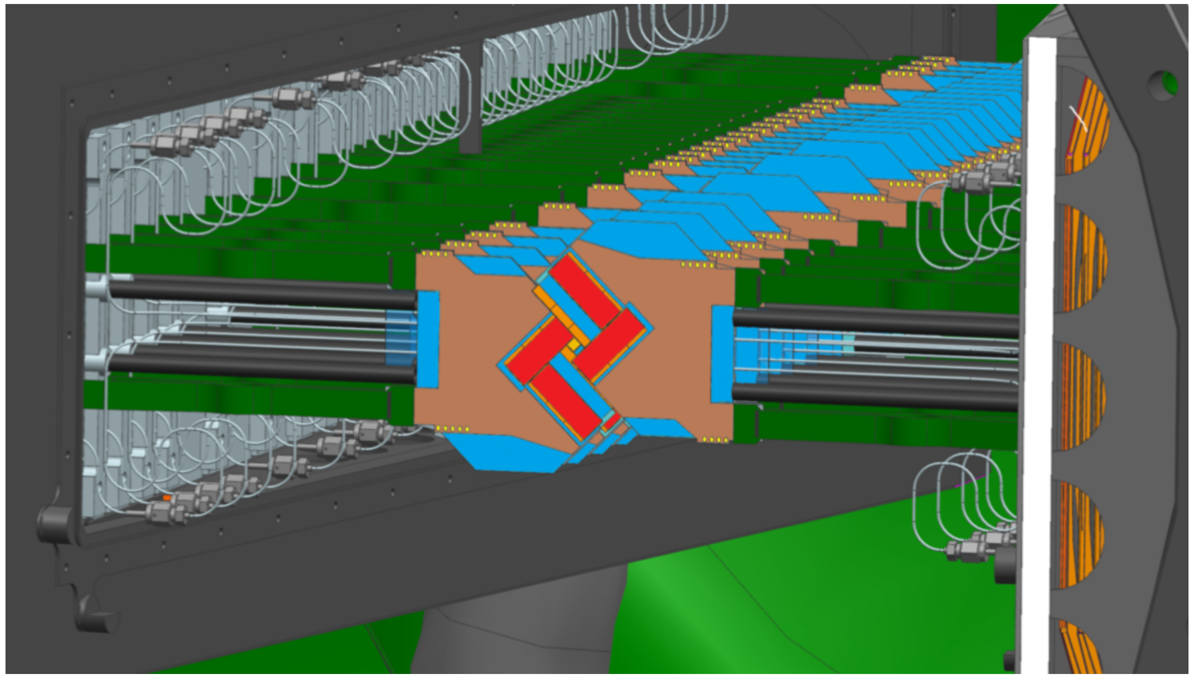
- Use silicon hybrid pixels
- 52 modules, two retractable halves
  - Innermost sections ~5.1 mm from beam pipe
  - 4 silicon sensors per module, 55 μm x 55 μm

LHCb-TDR-12





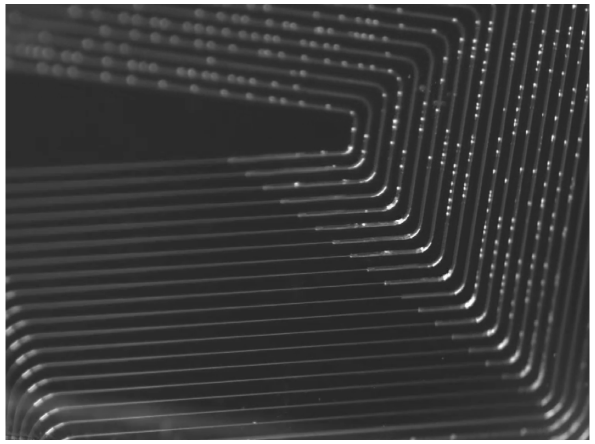




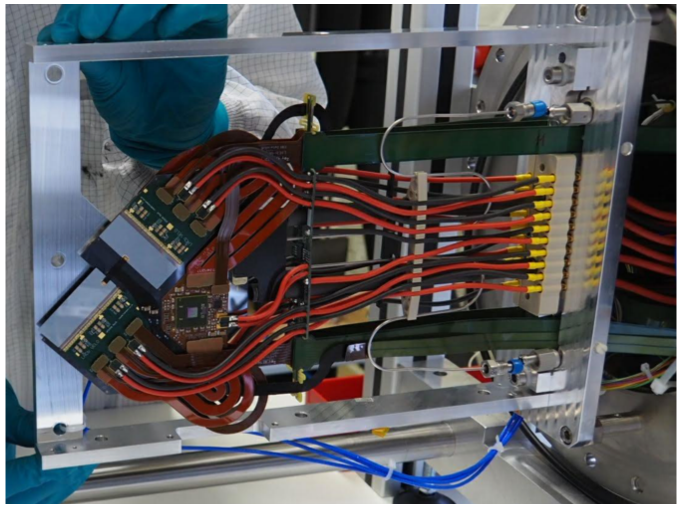
Vertex Locator

LHCb-TDR-12

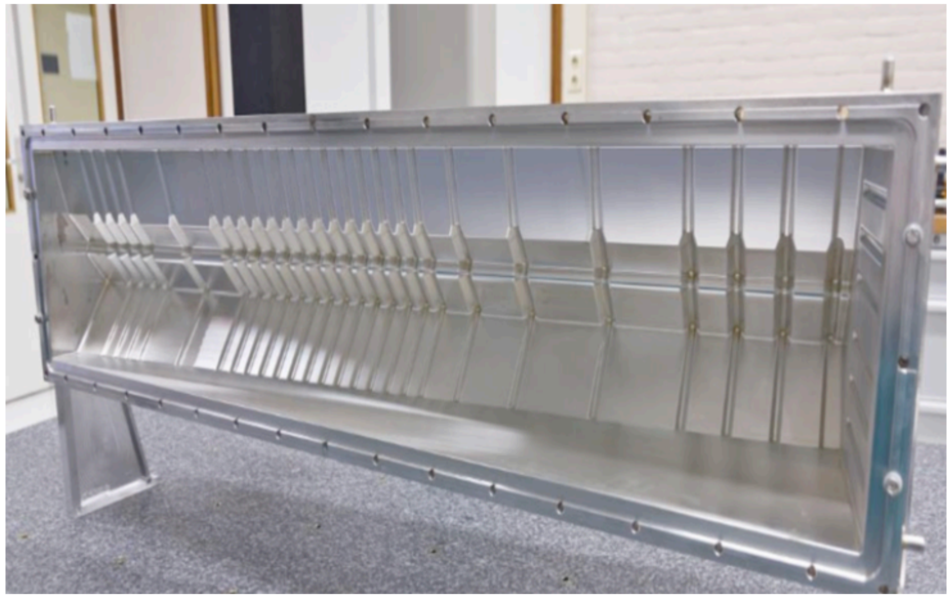
- Sensor+readout electronics mounted on cooling substrate
  - Sensor temperature maintained at -20 C, novel technique of evaporated CO_2 cooling in substrate micro-channels
  - Minimal material within acceptance



- Pixel VELO ASIC front-end readout chip
  - 3 chips bump-bonded to each sensor
  - Triggerless binary readout
  - Up to 800 MHits/s/ASIC



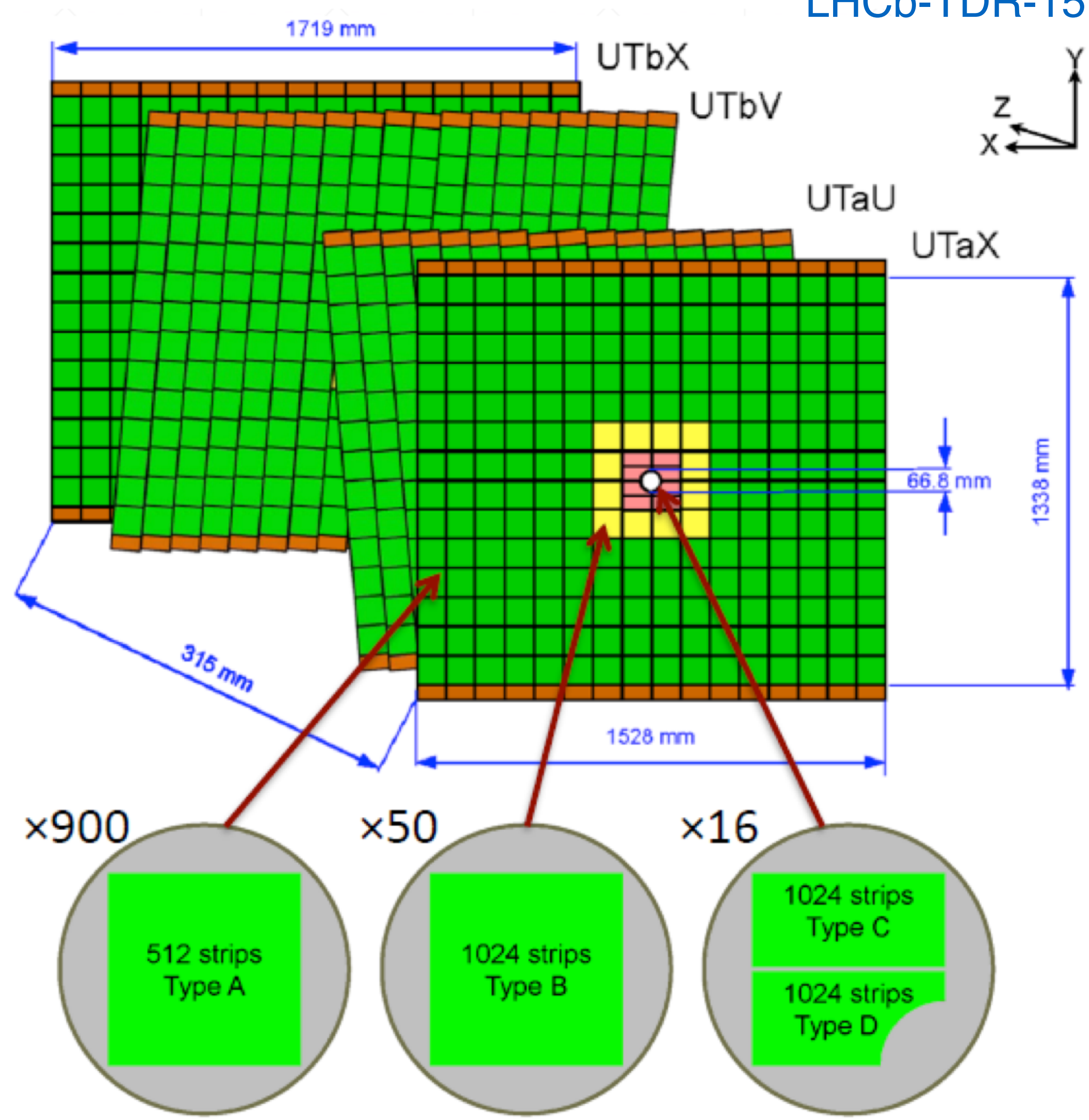
- VELO operates in secondary vacuum, separated from primary vacuum by 1.1 m long thin RF foil
  - New foil thinned to 250 μm
  - Withstands pressure variations of 10 mbar



UPSTREAM TRACKER

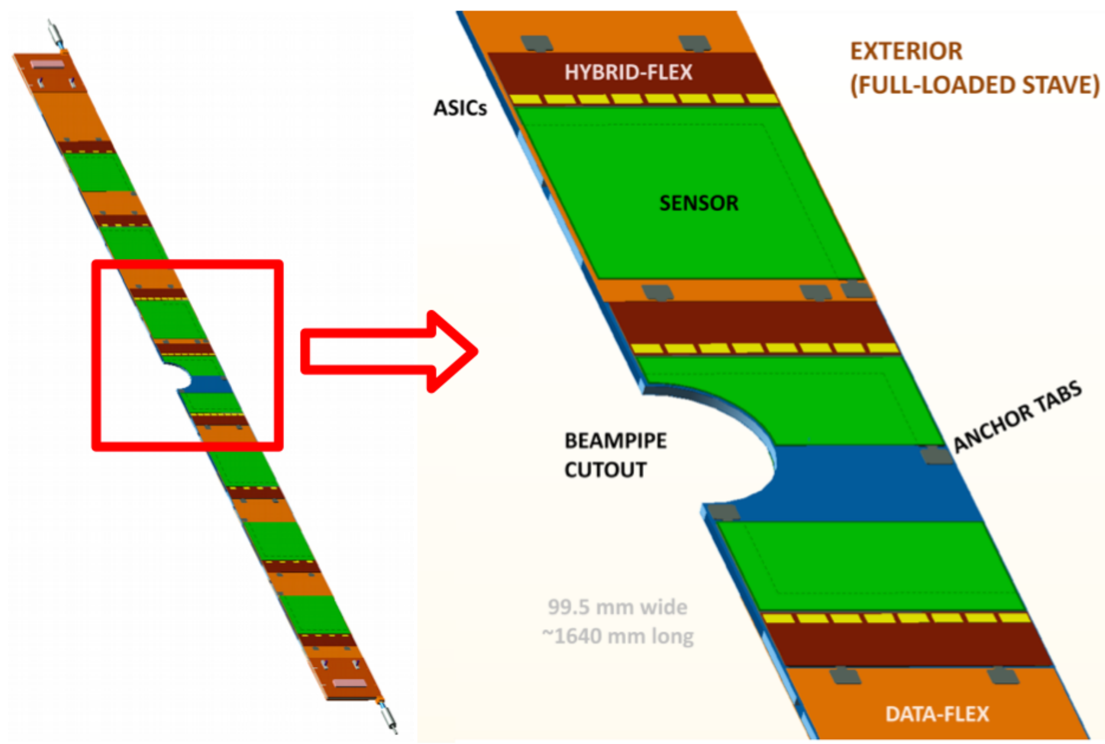
- Four-layer silicon strip detector
  - Finer granularity than TT, innermost sensors closer to beam pipe
  - Inner layers tilted by a stereo angle (±5%)
- Four different types of sensors
- Mounted to lightweight staves (10 cm wide, 1.6 m long)
- Novel readout chip (SALT ASIC)

LHCb-TDR-15

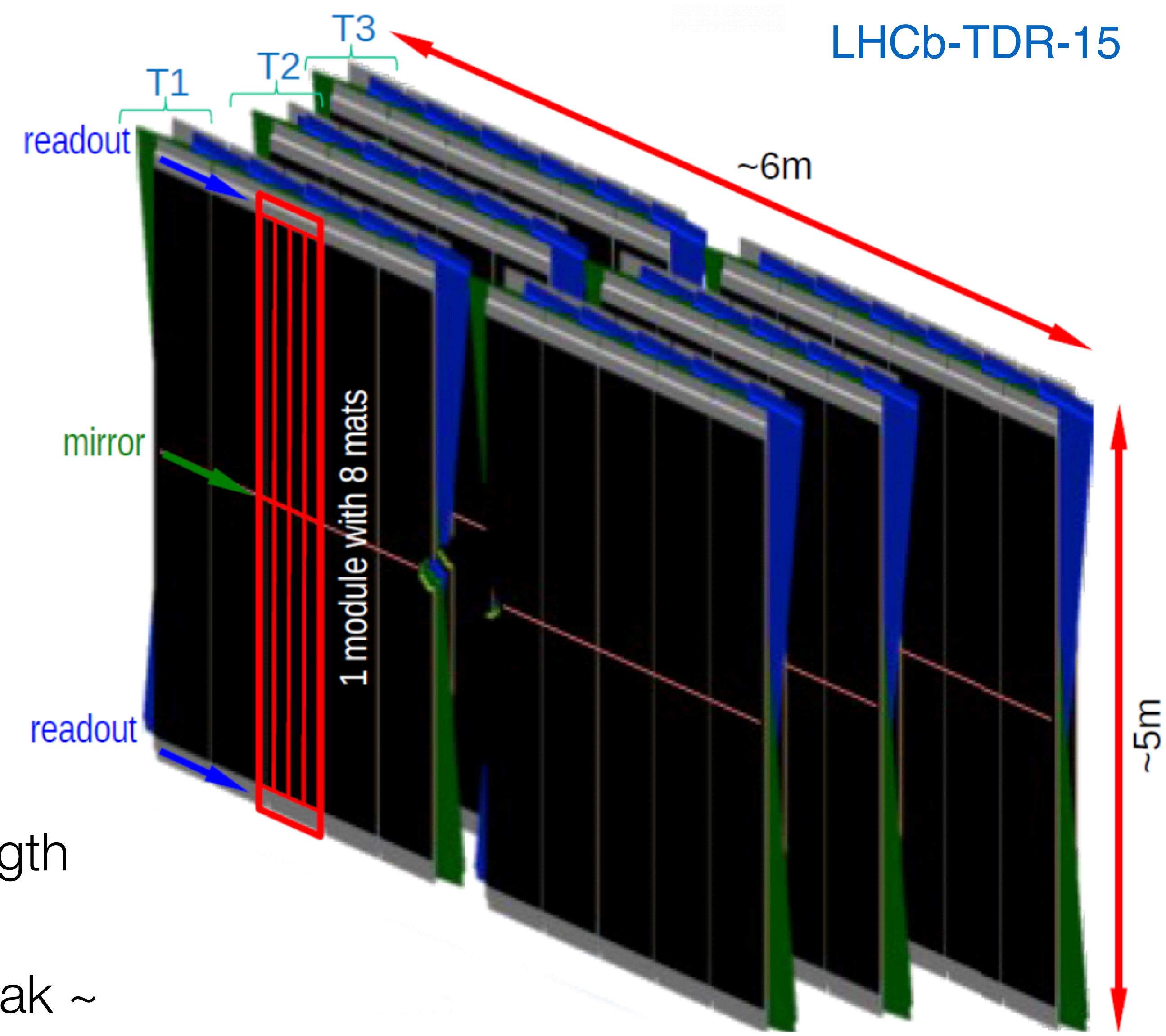


320 µm thick, p-in-n, 190 µm pitch

250 µm thick, n-in-p, 80 µm pitch

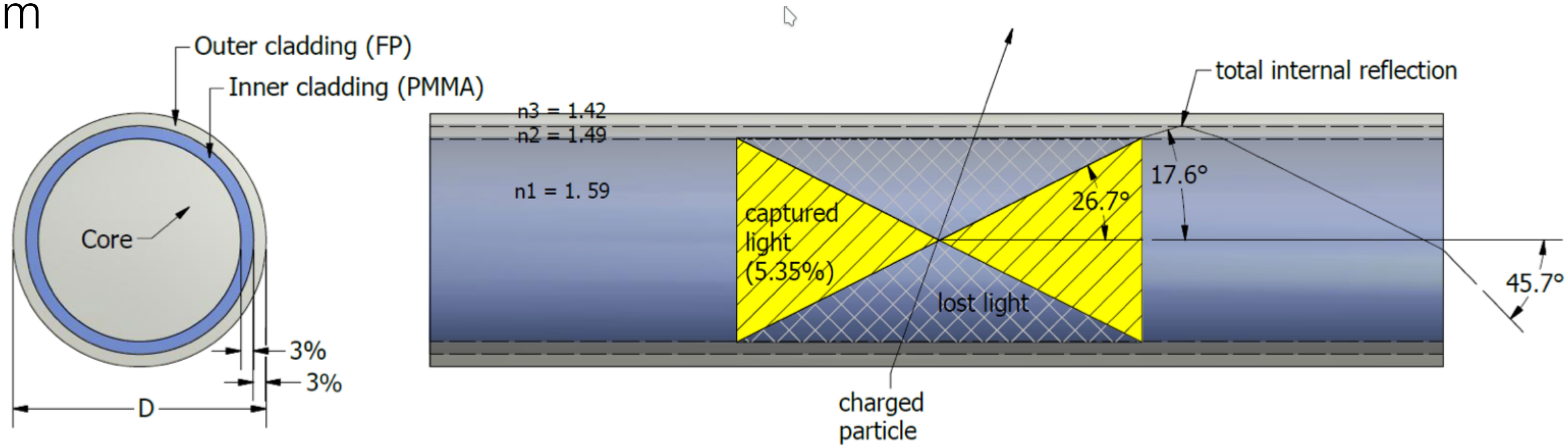


Scintillating Fiber Tracker



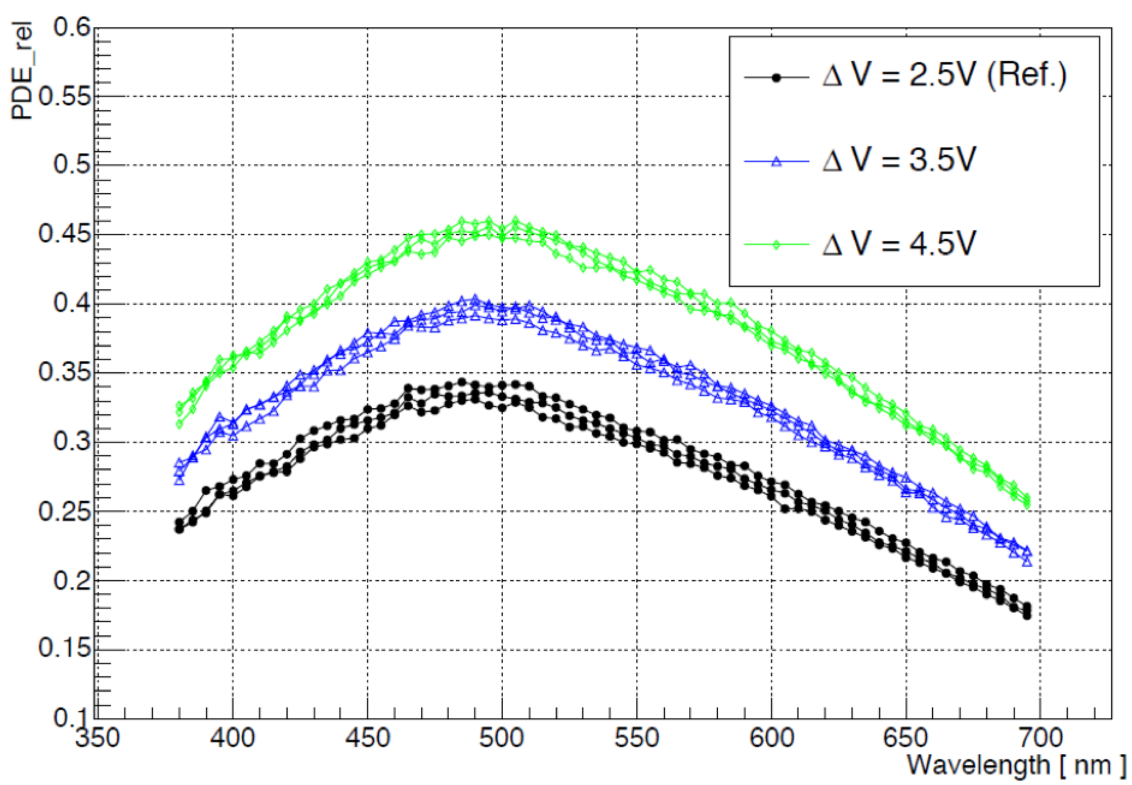
- 3 x 4 layers of scintillating fiber mats
  - Each mat with 6 layers of fibres
  - 8 mats assembled into a module
  - 11,000 km of fibres in total
- Coverage up to 3m from the beam pipe

- Fibres manufactured by Kuraray (Japan)
  - Double-clad plastic scintillating fibre
  - Core: polystyrene base + activator + wavelength shifting dye
  - Attenuation length ~ 3.5m, light emissions peak ~ 450 nm

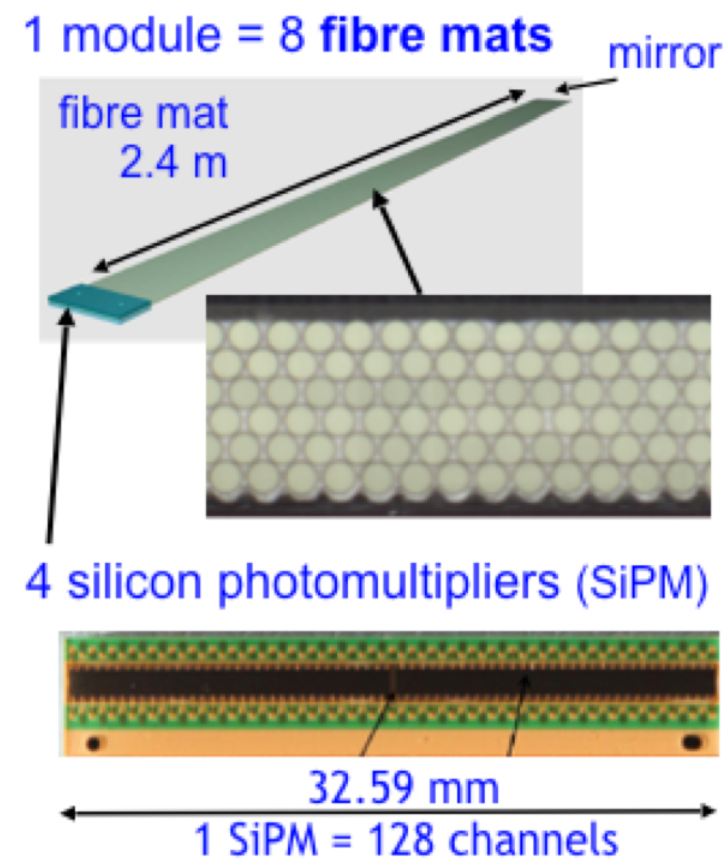


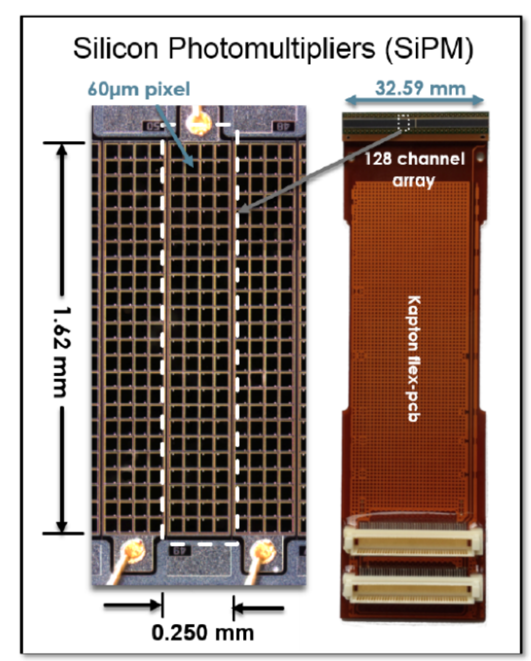
Scintillating Fiber Tracker

- Fibre readout provided by silicon photo-multipliers
  - 128-channel SiPM arrays, channel size 250 um
  - Cooled to -40°C to minimise dark count rate after high irradiation
- Photon detection efficiency ~ 45%
- SiPM signal processed by custom 64-channel PACIFIC ASIC chip
  - Zero suppression + clustering on FPGAs (clusterisation boards)



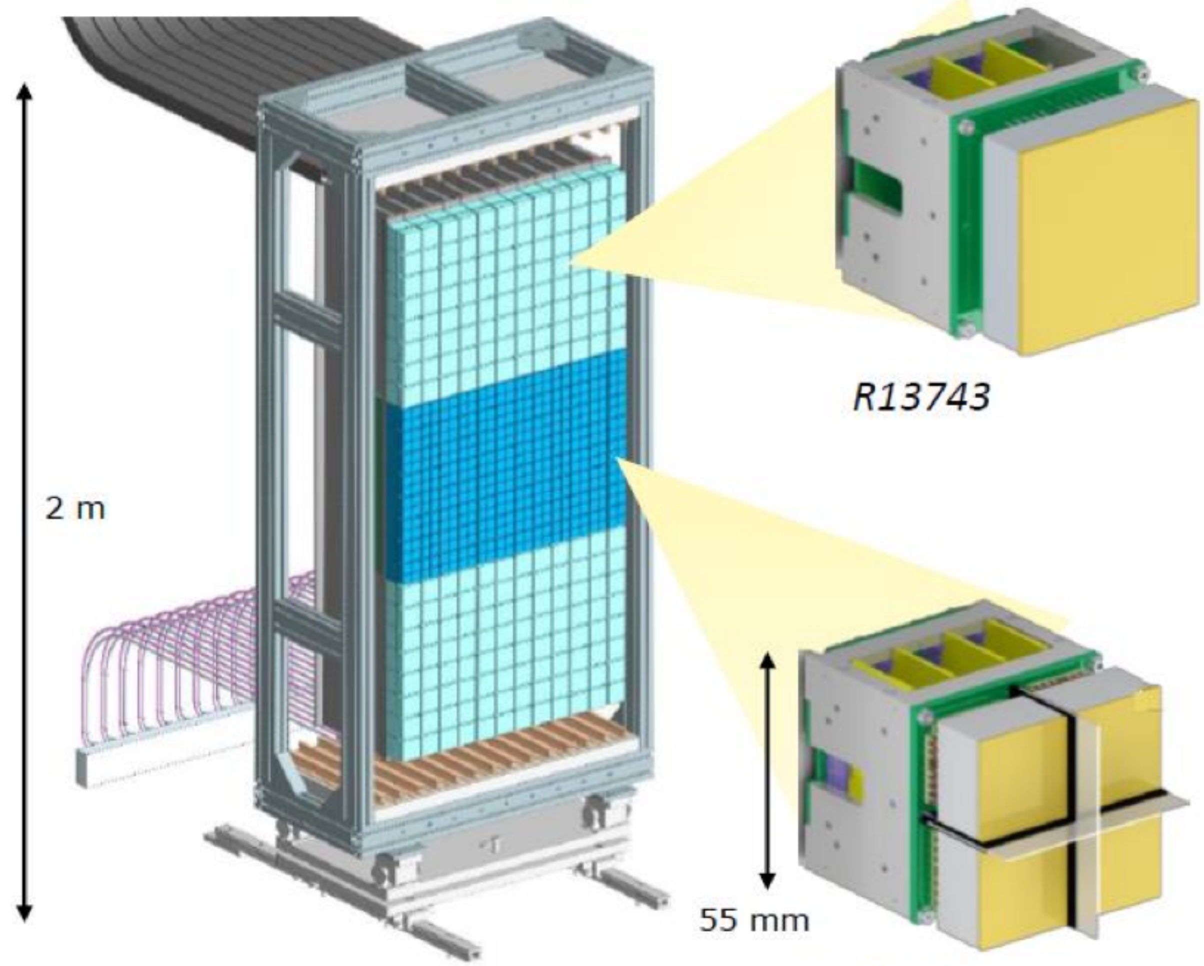
LHCb-TDR-15

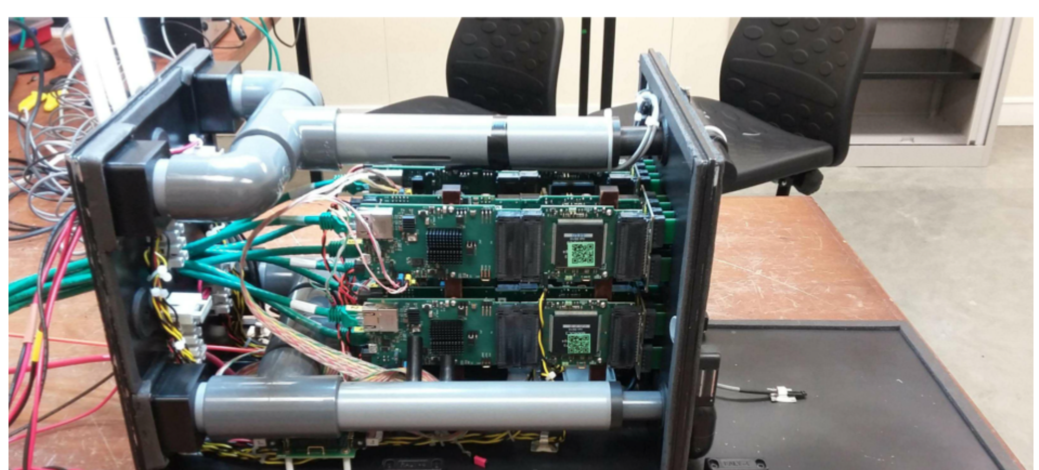




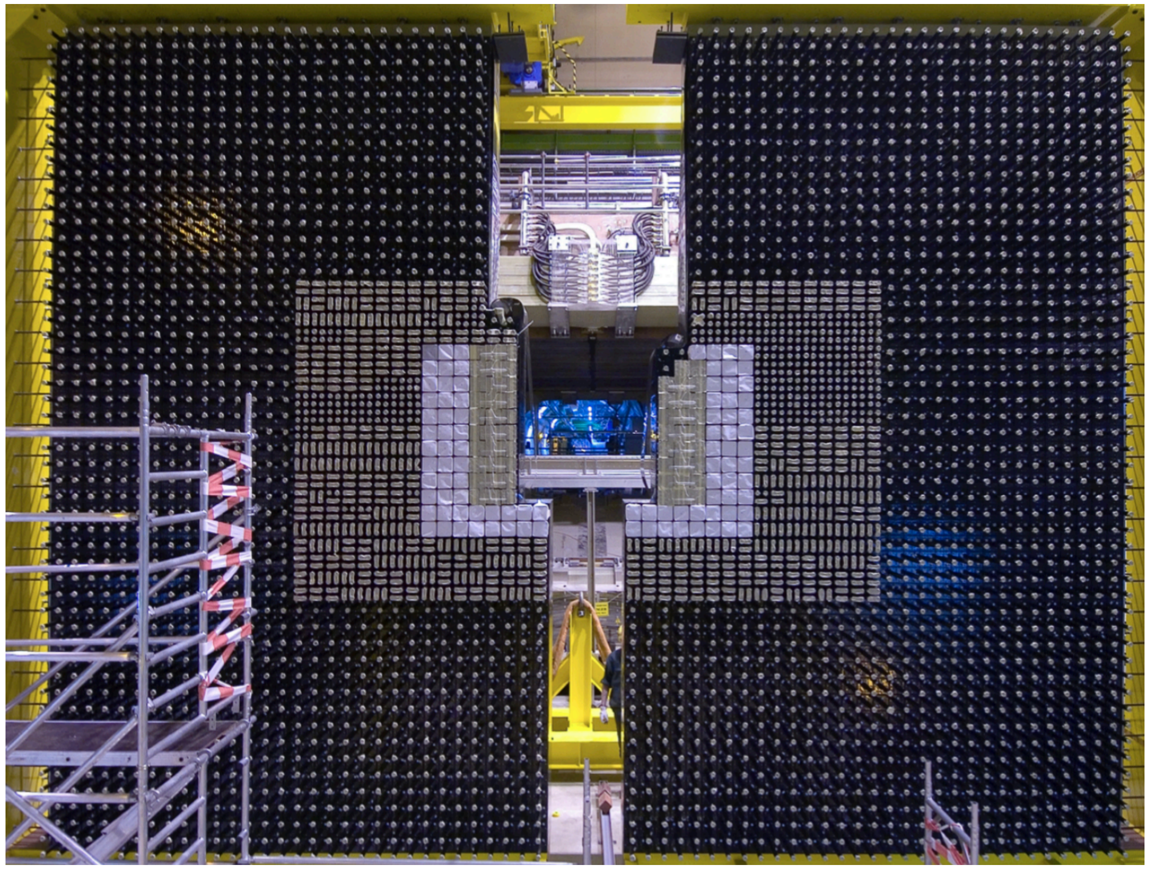
RICH Detectors

- New glass flat mirrors for RICH1 (better photon yield)
  - Focal plane, optics modified to increase size of Cherenkov rings
- Photo-detectors to be upgraded
  - Two types of multi-anode photomultiplier tubes (MaPMTs) with finer granularity
- Readout electronics updated to allow for data-taking at 40 MHz
- Single photon angular resolution improved by 50% (RICH1) , 20% (RICH2)





CALORIMETRY + MUON DETECTORS



- Run 1-2 calorimeters will be kept for Run 3
  - Front-end electronics rebuilt
  - SPD/PS removed
- PMT gain reduced by a factor of 5 to reduce degradation
- To compensate, the front-end gain is increased by the same factor
  - Custom low-noise FE ASIC developed
- Reconstruction improved for higher occupancy environment

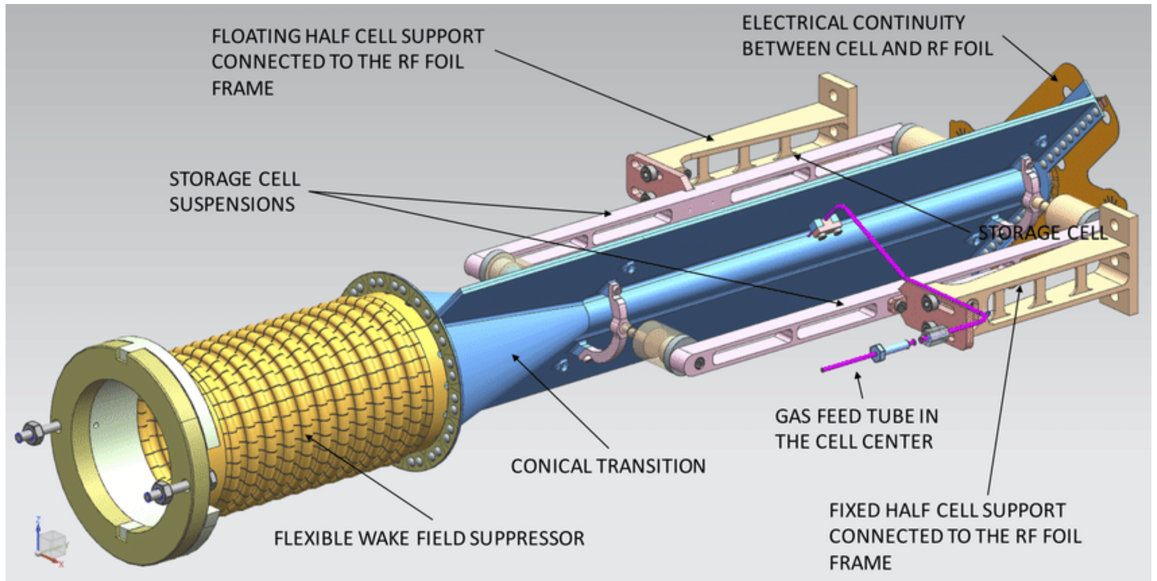
- Muon detector electronics also upgraded during LS2
- First GEM layer to be removed
- 36 new PAD chambers to be installed in inner region

SMOG2

CERN-LHCC-2019-005

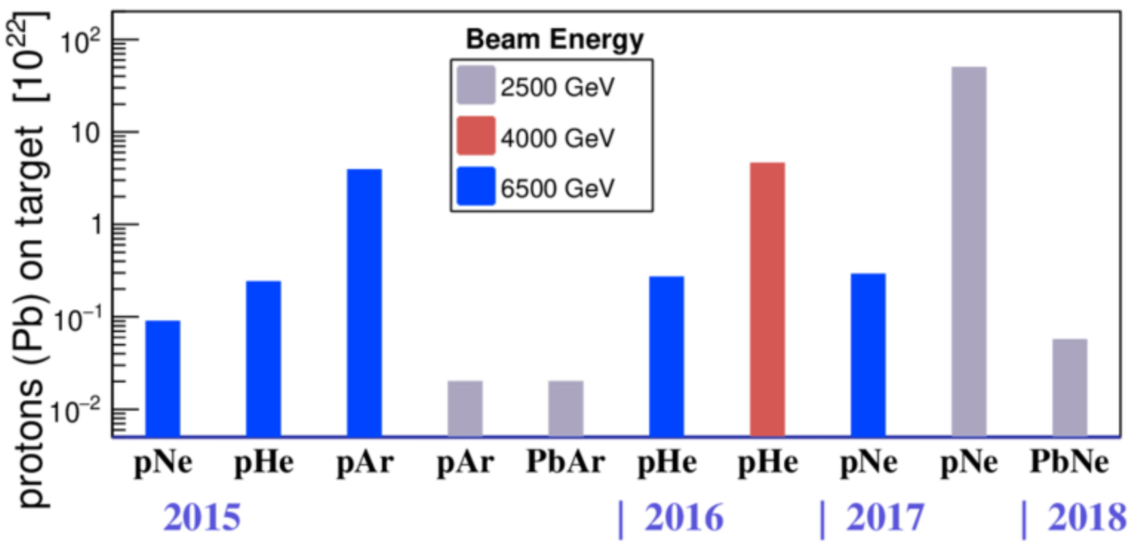
New SMOG2 system installed to inject various gas species in the LHCb IP

- Fixed Target physics at the LHC collider: in // with pp data taking
- Gas cell attached to VELO, displaced p-gas IP for easy distinction from pp data

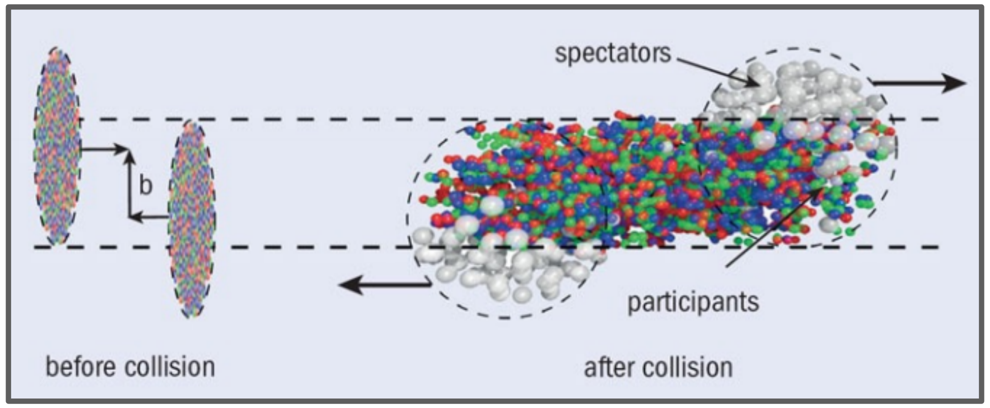


Physics program spans:

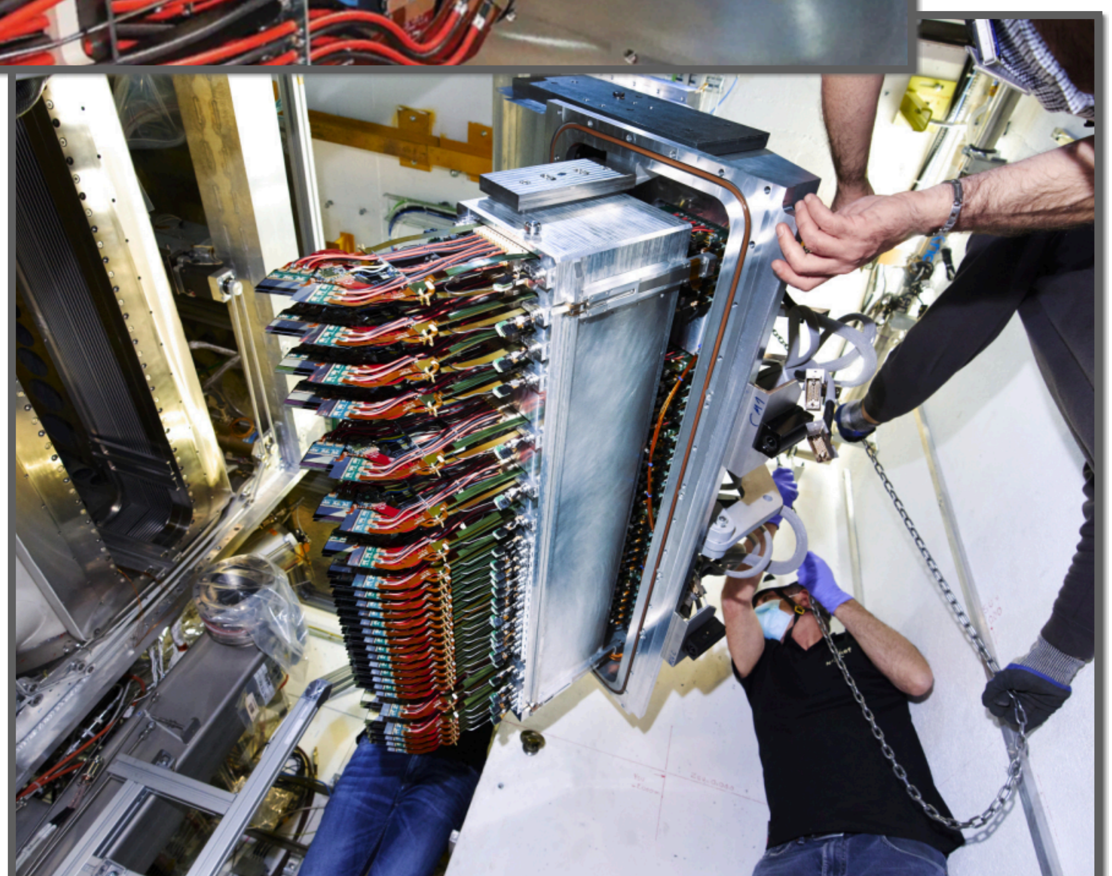
- anti-proton production
- Central exclusive production
- X(3872)/ψ(2S)
- ψ(2S) / J/ψ
- Strangeness production
- Λc -> pKπ

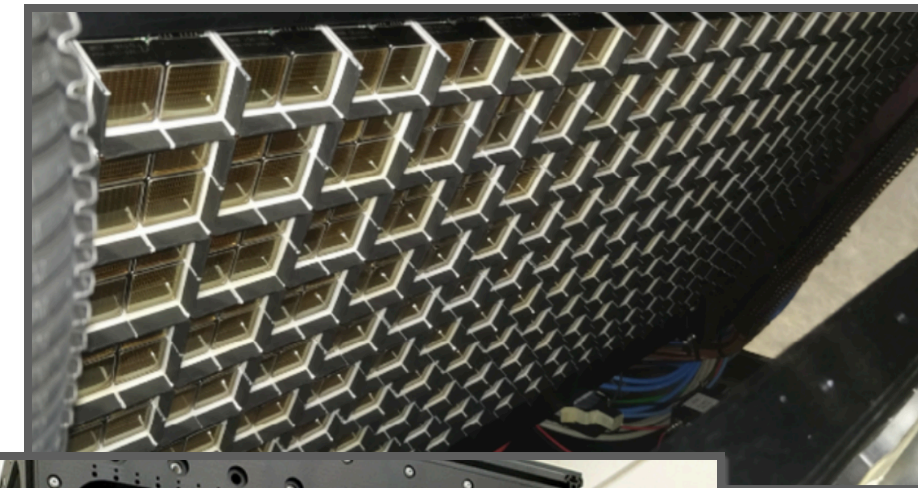


+ LHCb participation in Heavy Ion runs
(PbPb and pPb data taking)

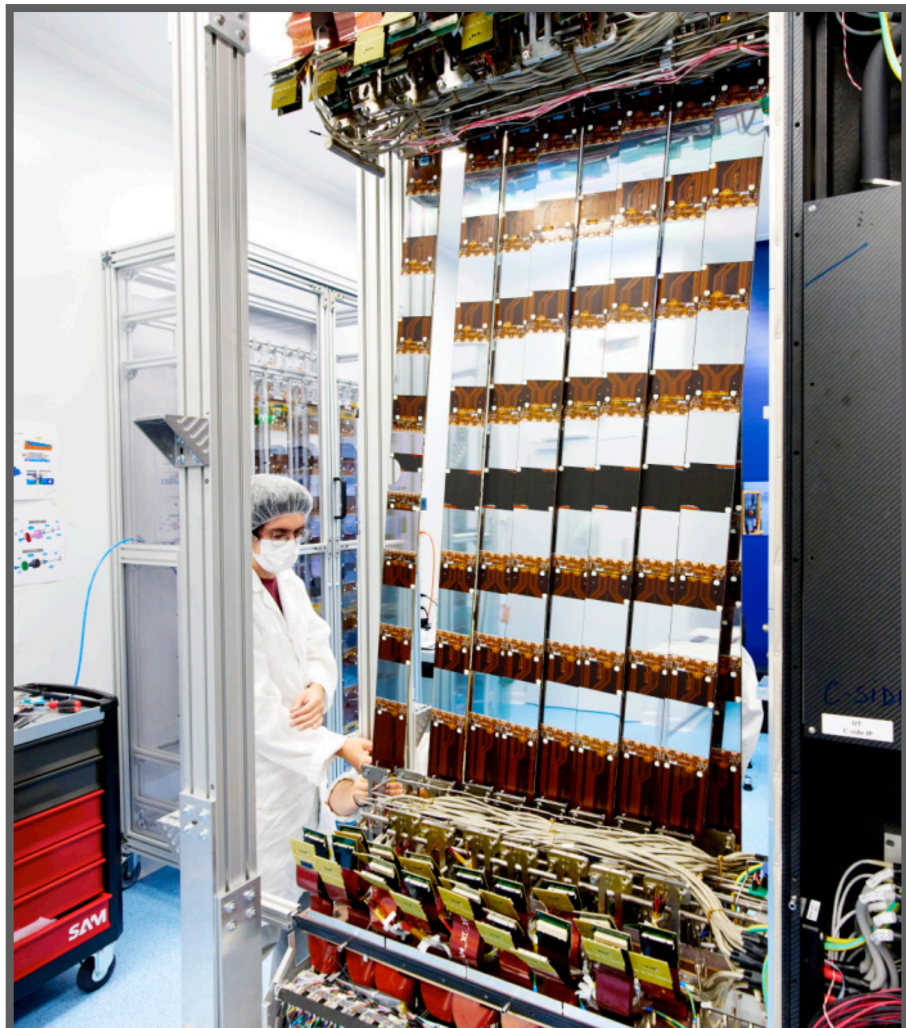


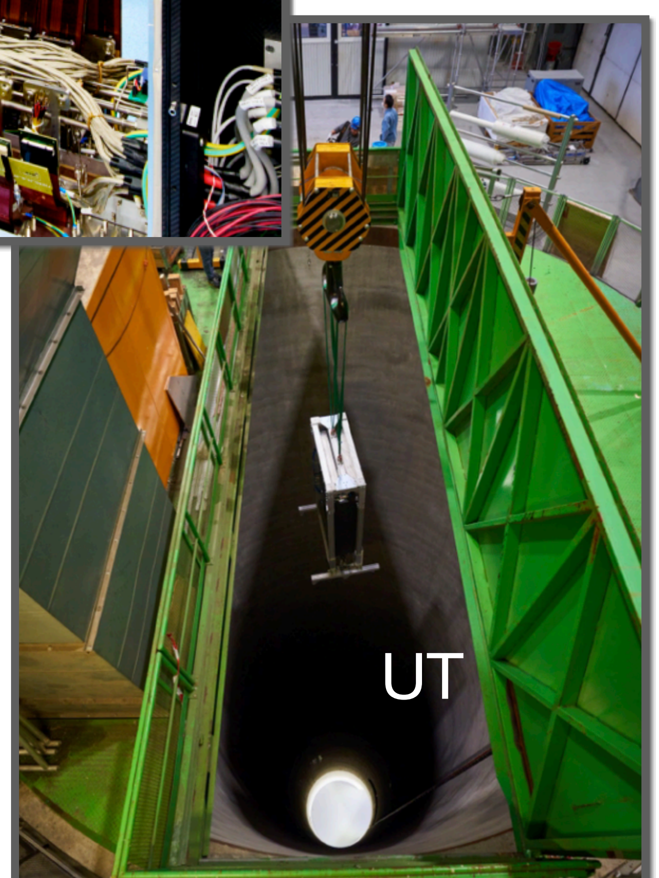
Upgrade I Assembly and Installation Highlights

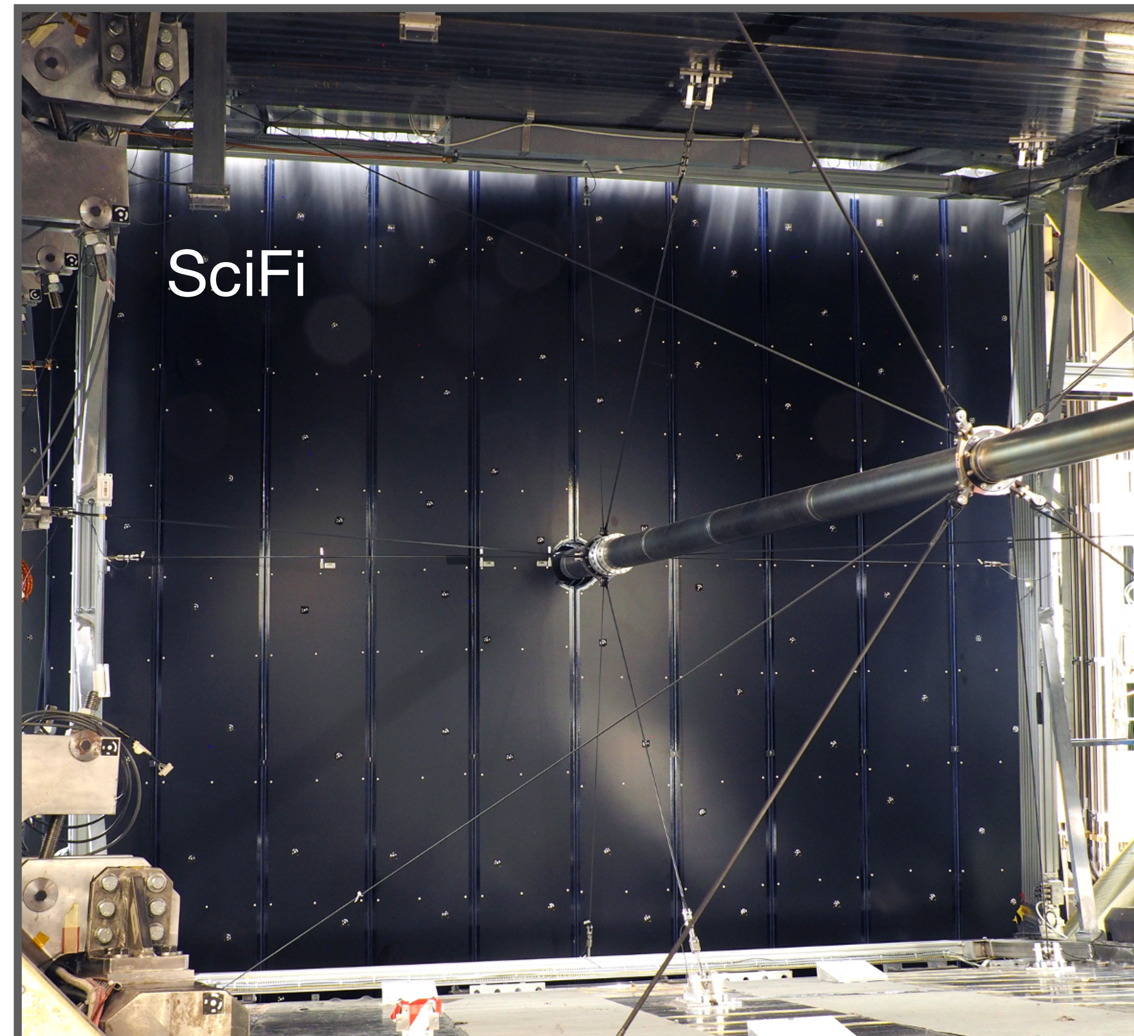


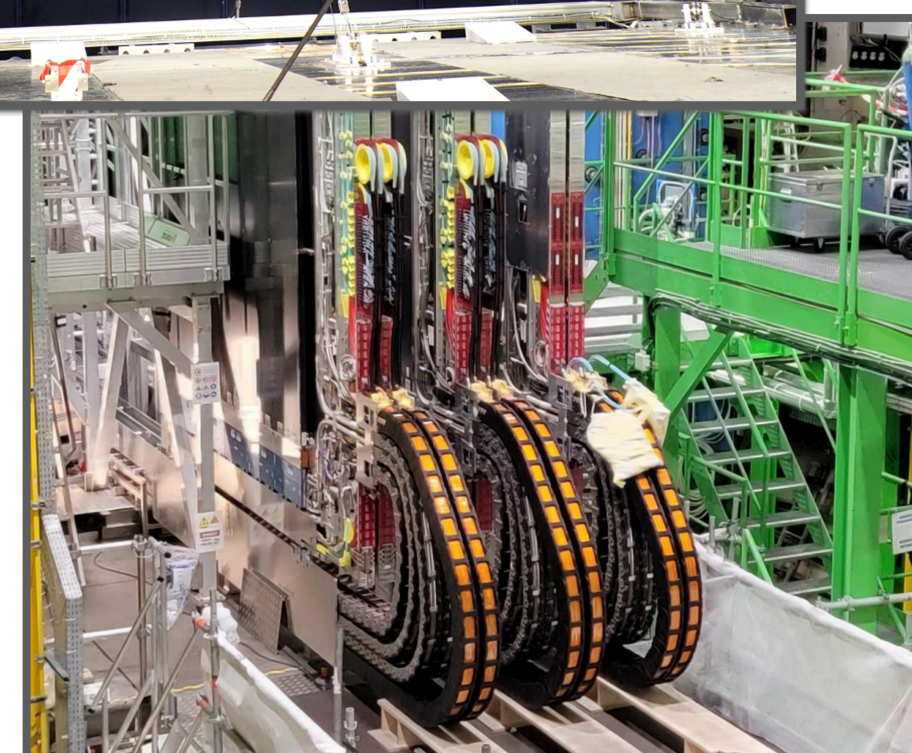


UPGRADE I ASSEMBLY AND INSTALLATION HIGHLIGHTS





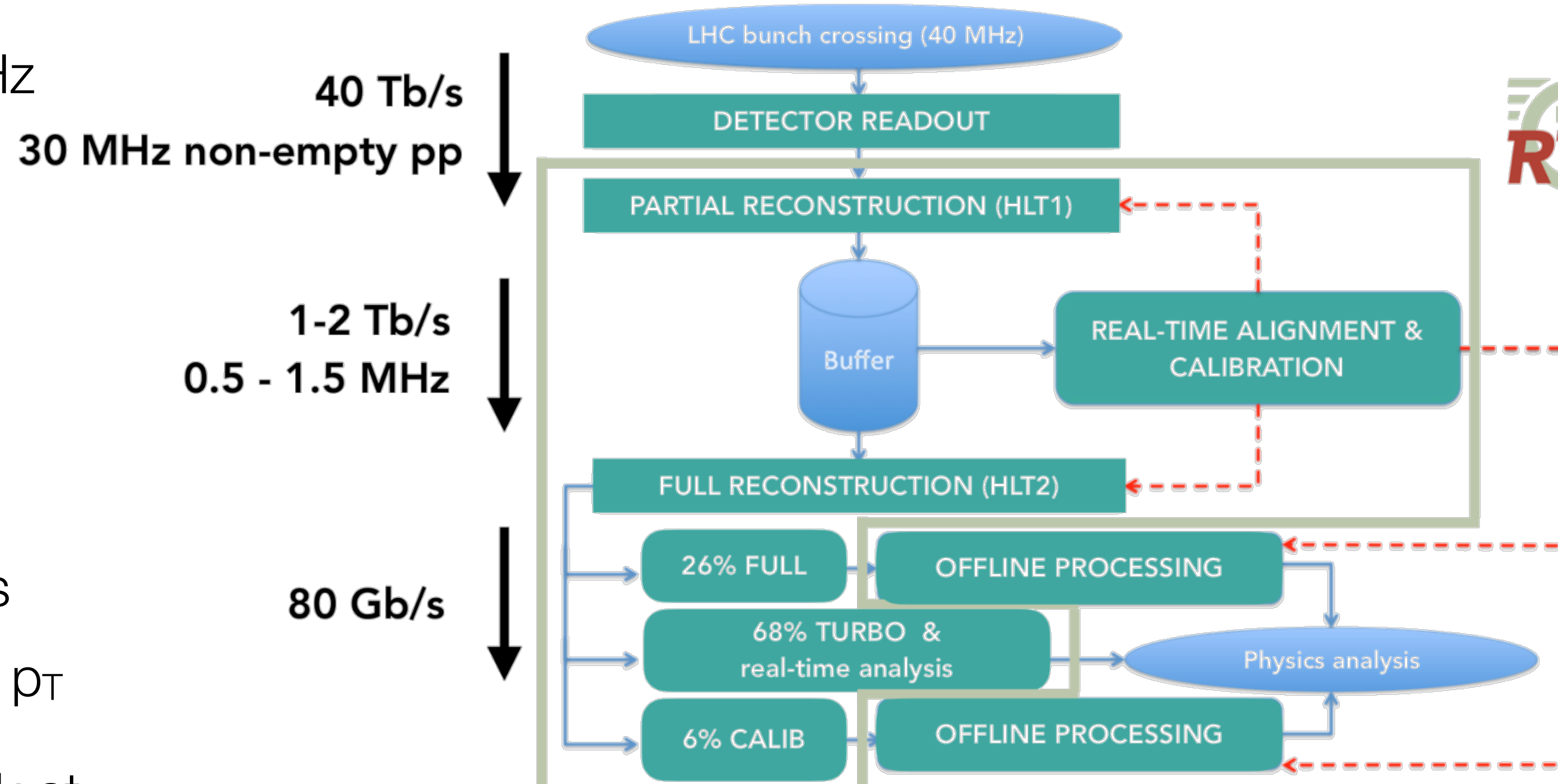




REAL-TIME DATA PROCESSING

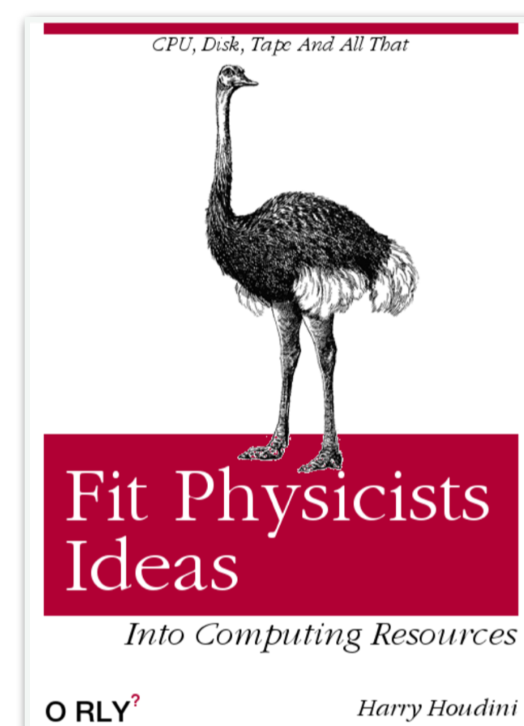
[CERN-LHCC-2018-007]

- Software-only trigger in the upgrade
- Must fully process events at 30 MHz
  - Information needed from all sub-detectors at initial trigger stage
- Events stored in buffer, for online alignment, calibration
- Will be able to trigger on signatures with large impact parameters, high p_T
- Event sized reduced to write to disk at 2-5 Gb/s



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

- Order of magnitude increase in data to storage, without a corresponding change in offline computing resources
- Move towards Turbo model in Run 3
  - Implemented for a few channels in Run 2
  - Save only HLT reconstructed output to offline (no RAW data)

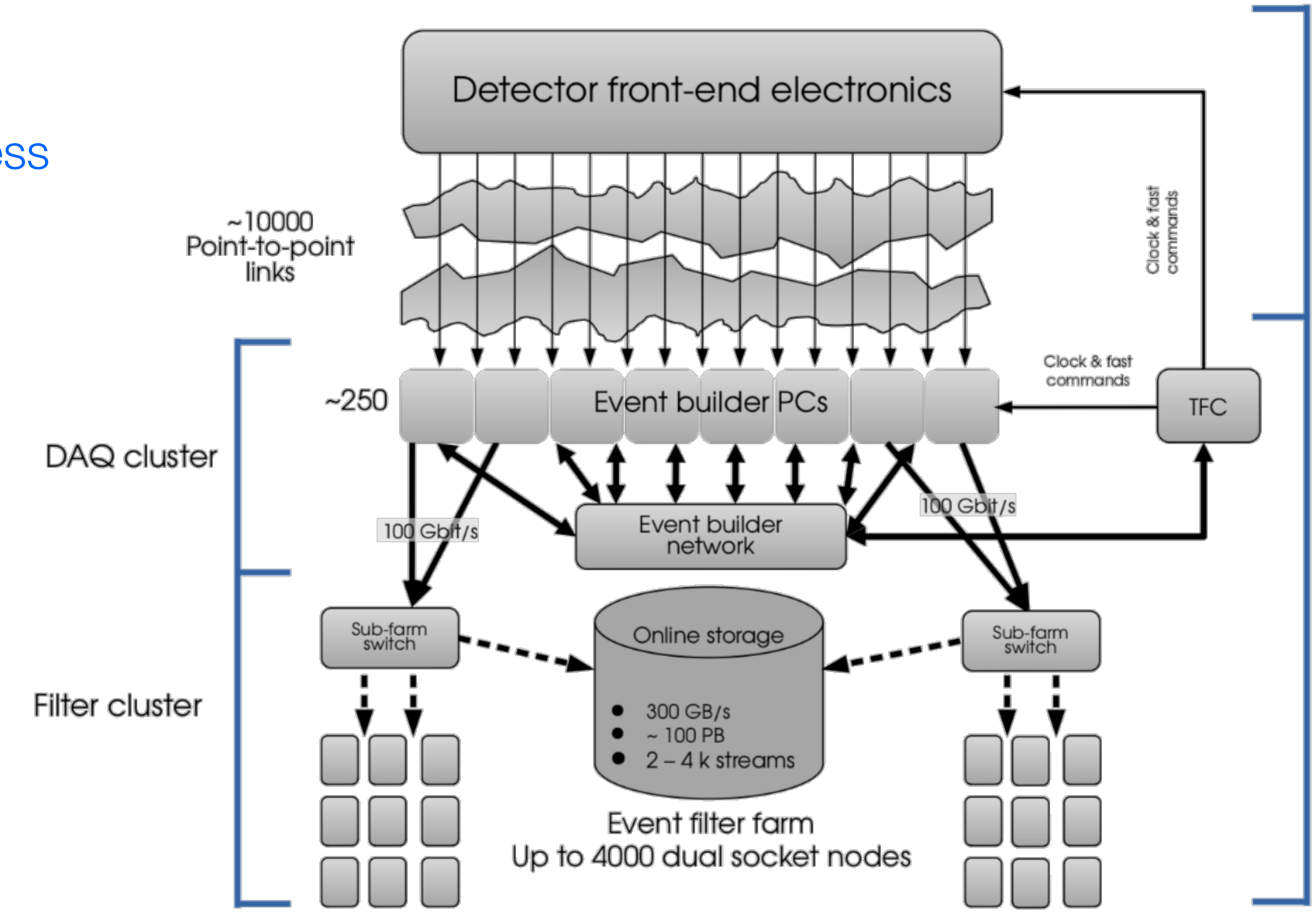


TRIGGERLESS READOUT

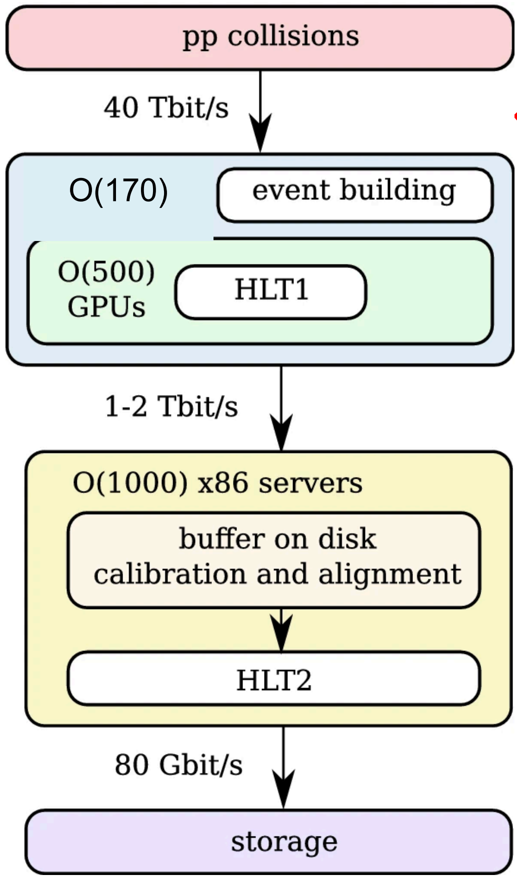
Remove the first-level hardware trigger

- Accept all LHC bunch crossing: trigger-less Front-End electronics!

- Back-End electronics on surface in data center
- ~19000 long distance optical fibers (99.75% yield)
- Common Back-End boards (PCIe40)
  - ✓ Large FPGA and optical links (48 x 10 Gbps)
- Total effective bandwidth of 32 Tbps



HLT1 With GPUs



[CERN-LHCC-2020-006](#)

[LHCB-TDR-016](#)

3 GPUs+PCIe40 card / EB server

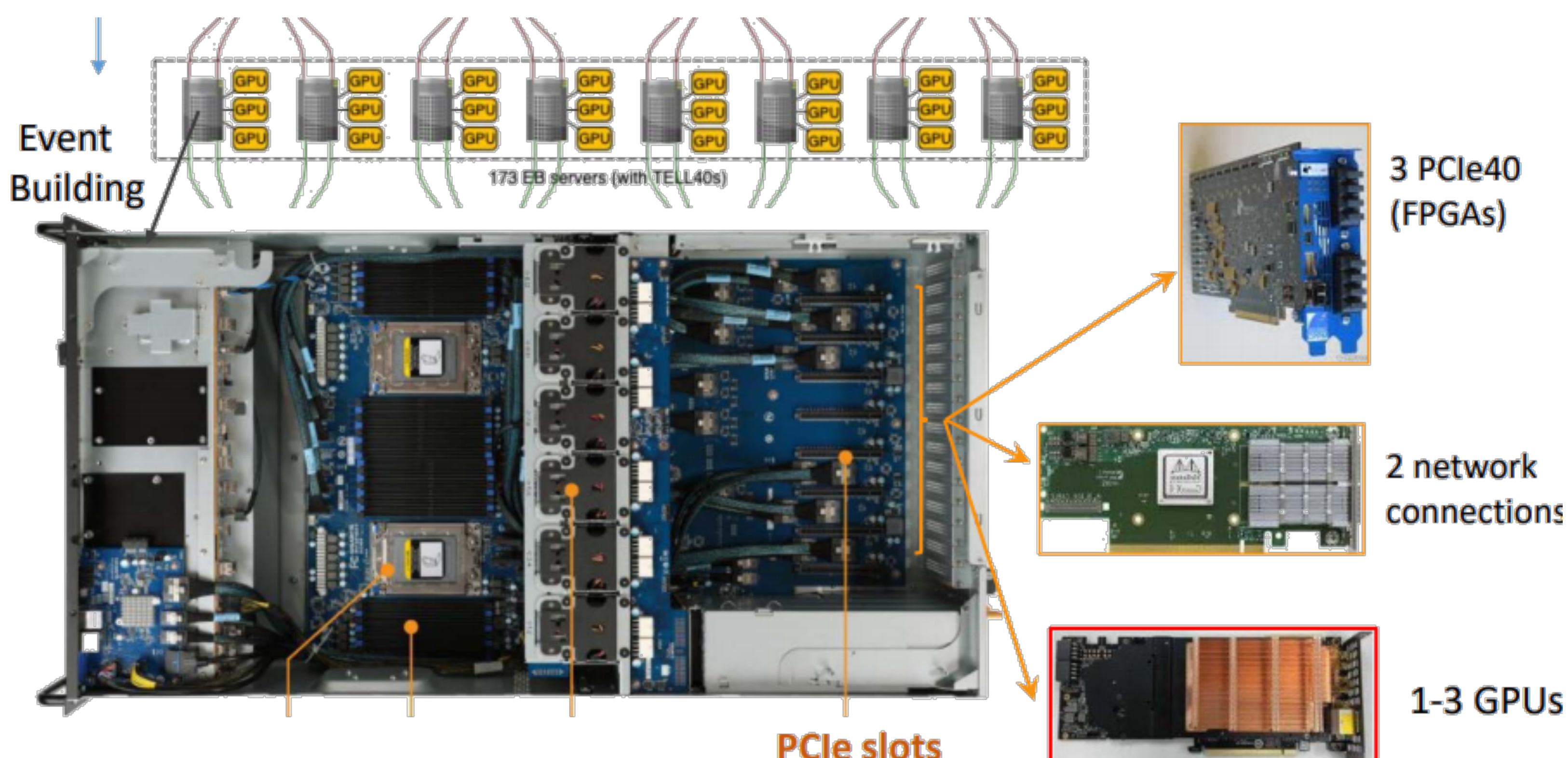
HLT1 runs at visible collision rate

~30 MHz

✓ 60 kHz per GPU

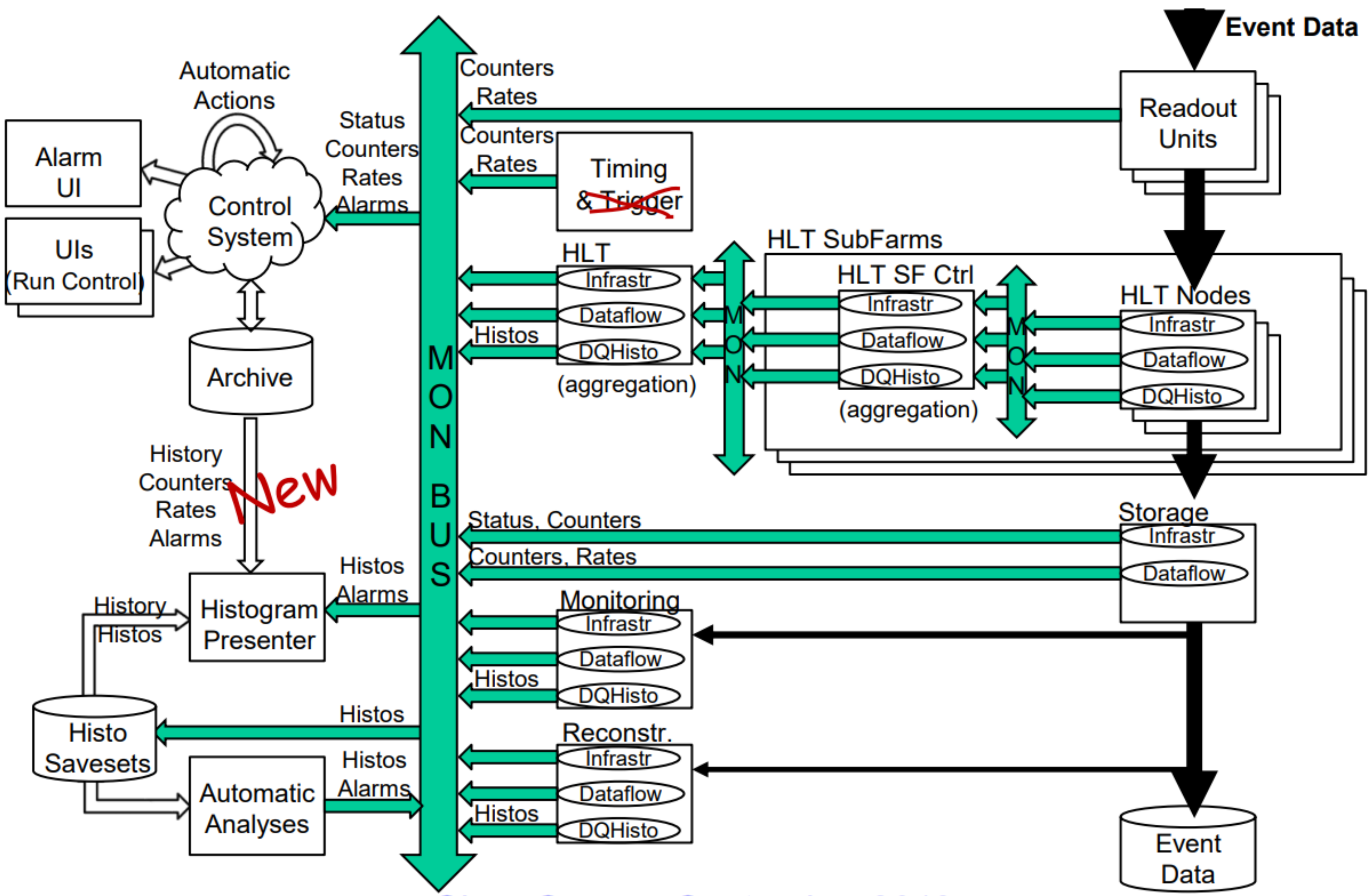
[Allen](#) project for fully software trigger on GPUs

- Implemented on C++, CUDA and python
- Running also for CPU and HIP (AMD, experimental)
- It can run standalone
- Continuously improving



Complex system that aggregates information from many different sources

- Provide output to the LHCb control room, to the experts, to the run control
- Fundamental in automatizing the LHCb readout system and control



Data-taking with the Upgrade LHCb Detector

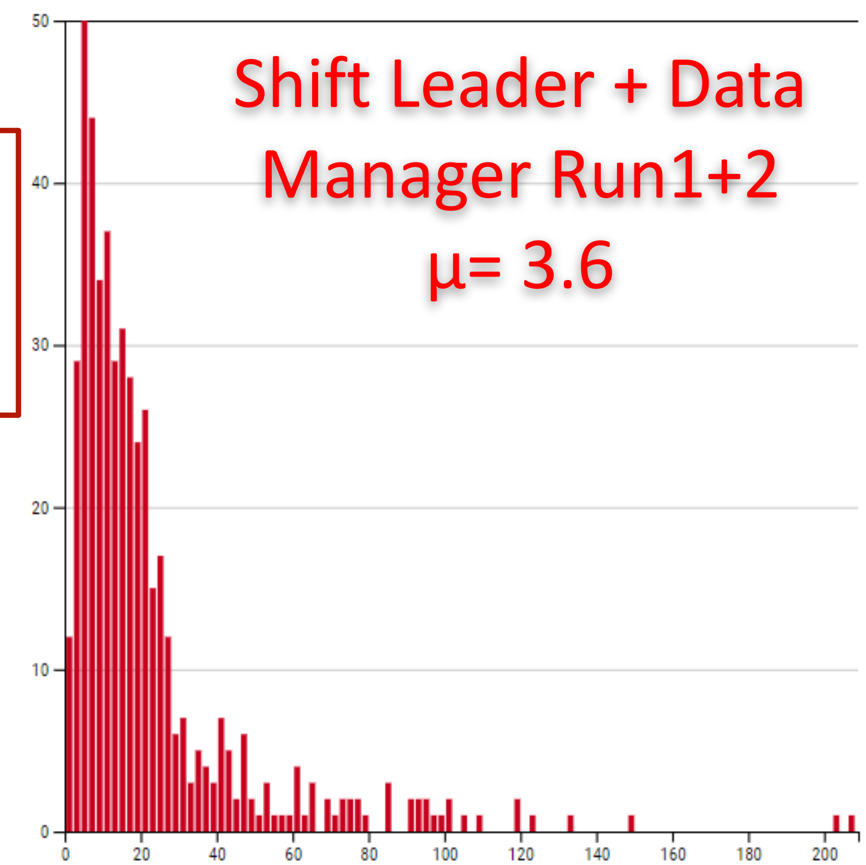
DATA-TAKING IN RUN 3

(Good) data taking in LHCb relies on the contributions of the entire Collaboration

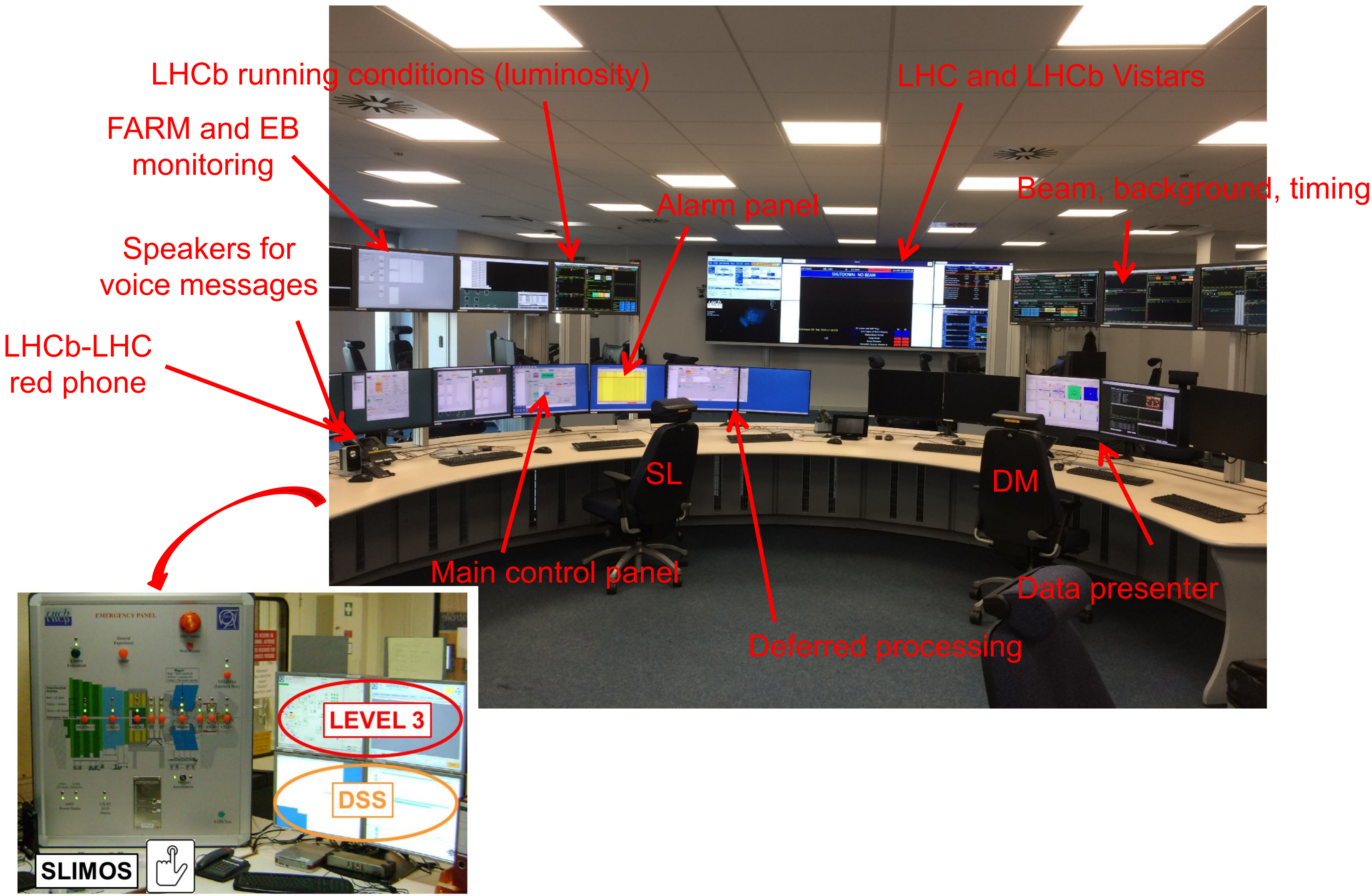
- Central shifters roles have always played an important role in our success
    - It also includes the so-called sub-detector piquet getting calls 24/7
- They rely on a “volunteering” paradigm
    - No formal quota to be reached -> just accounting and monitoring
    - Small number of shifts required per year -> no need to be an expert, system highly automatized
    - Quite successful approach: in Run1 and Run2 we had ~450 unique shifters and piquet trained

Taking a central shift is the best way to take active part in our physics successes regardless of what your competence / work domain is!

It is also the best way to get involved directly!



THE LHCb CONTROL ROOM



LHCb Control room Shifters

Shift Leader (SL): responsible for safety (SLIMOS), supervision of activities, supervision of control system and experiment conditions, contact with experts and piquets, contact with EICs

- Shift Leader must be physically in the CR to manage the access system, guide the firemen if needed, access with piquet if needed, push “real buttons” if needed, write information to the logbook, makes sure information are propagated at shift change
- Shift Leader is a role with more “responsibility” but no technical knowledge required

Data Manager (DM): responsible for monitoring the quality of data, replaces SL if needed

- Data Manager must be physically in CR due to the “2 people rule” at CERN
- Data Manager has practically no “direct responsibility”: excellent role for early PhD or newcomer

✓ SL and DM have to follow a one half-day training + one shadow shift (if 1st shift ever)
  - Training can be remote + extensive Twiki with instructions on how to operate LHCb

✓ SL and DM are generally non-experts LHCb members
  - SL are required to “know more” about LHCb

✓ SL and DM shifts are self-assignable, with schedule validated and supervised by Run Coordinator(s)
  - On average, asks to have ~3 shifts / year / author_trained
  - Gaps normally taken by people based at CERN or experts or Run Coordinators
  - Every day, 3 shifts/day, 8h/shift (6.30-14.30 / 14.30-22.30 / 22.30-6.30)

LHCb On-call Piquets

Run Chief(s): Assists the Run Coordinator(s) in the daily operations of LHCb by running the Run Meeting, go to LHC morning meeting and have executive decision power (with RCoord).

- Normally a "senior" (experience with LHCb commissioning/operations) individual, expert in LHCb
- Can be 1 or 2 people at the same time, for one or two weeks according to availability
  - have to be available 24/7 for the period in charge
  - follow a few hour training with Run Coordinator to be "enabled" to the role
- At the beginning of Run3, the Run Chiefs will be taken by the pool of commissioning coordinators and commissioning "activists" at the pit
  - over time, plan to increase the pull of Run Chiefs as more people will rotate

Sub-system piquet: in charge for about one week, first contact person for a specific sub-system, reports at Run Meeting and at specific sub-system meetings

- Direct line of contact between Shift Leader and sub-systems during data taking
- Have to be available 24/7: answer the phone at any time, but does not need to be physically in the CR, but should be in the "region" to access if needed
- Entirely managed by sub-system coordinators (training, assignment and supervision included).
  - Generally people taken by the pool of institutes collaborating to a sub-system

DQCS Shifts

Data Quality, Computing and Simulation Shifter: new role in view of Run3, merge the piquet role of Data Quality Piquet, Computing Shifter and Simulation Shifter

- Improve communication, central shifter from Collaboration, meaningful shifter role
  - Allow acquire knowledge on all aspects of LHCb offline data processing

- Three tasks, similar in modus operandi, different in scope
  1. Monitor the quality of the data through the Data Quality monitoring tools
     - ✓ "look at DQ plots" and report/flag any anomaly via JIRA tasks
  2. Monitor production issues in the computing domain
     - ✓ Monitor WLCG tools and report/flag any anomalies via dedicated tracking system
  3. Monitor simulation Quality of MC productions
     - ✓ Verify SimDQ plots and report/flag any anomaly via JIRA to MC experts and relevant PA WG
     - ✓ Check LHCbPR plots and report/flag discrepancies via JIRA to MC developers

- Different needs throughout the year
  - DQ task mostly needed during data taking or around data taking periods
  - Computing and simulation tasks needed all year long

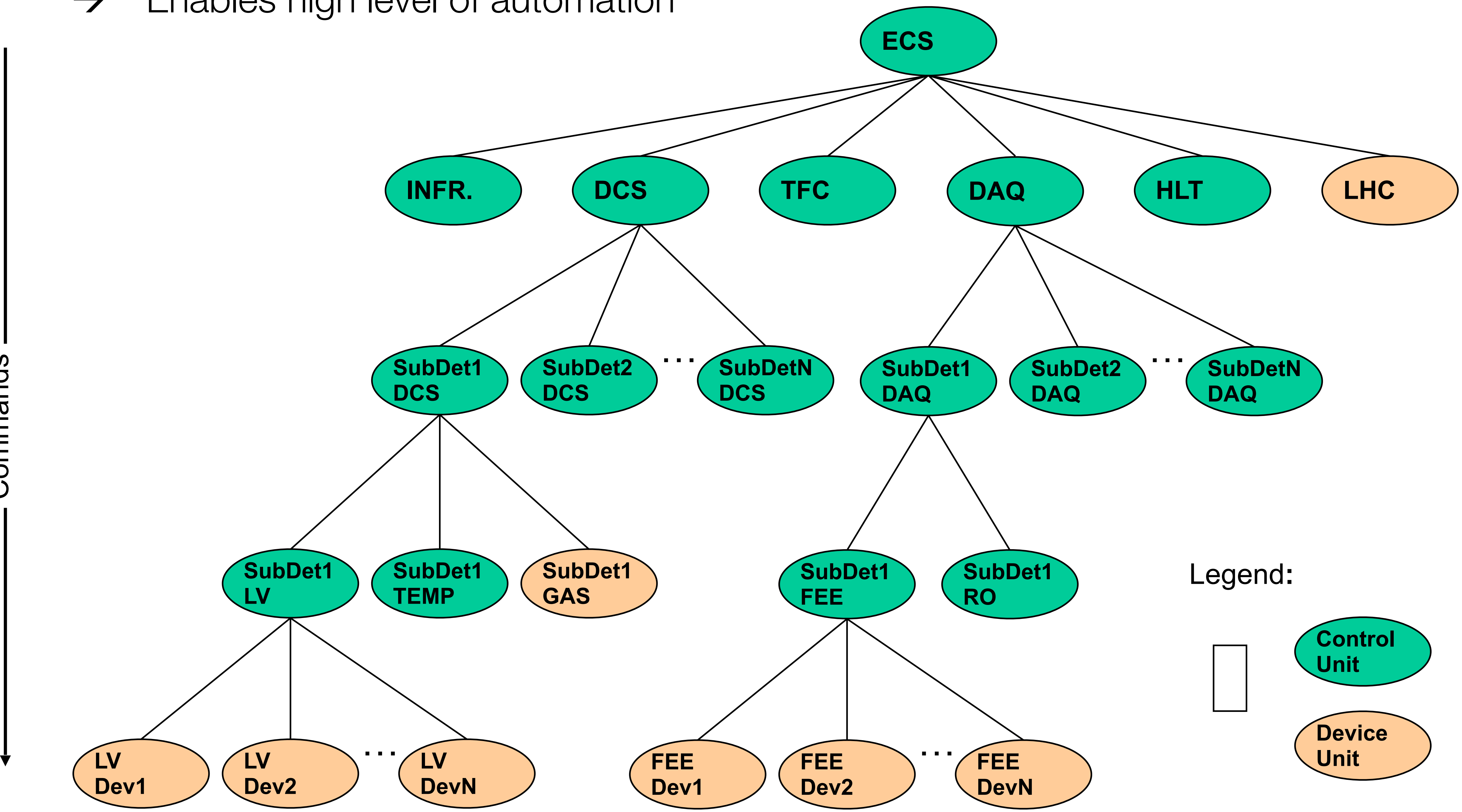
- Day shift, 8 h/day, ~8.30am - ~5.30pm (can be remote)

- Assignment of shifts done on a Self-Assignment basis

LHCb Control System

Hierarchical control system - can reach any device in the experiment from two single panels

→ Enables high level of automation

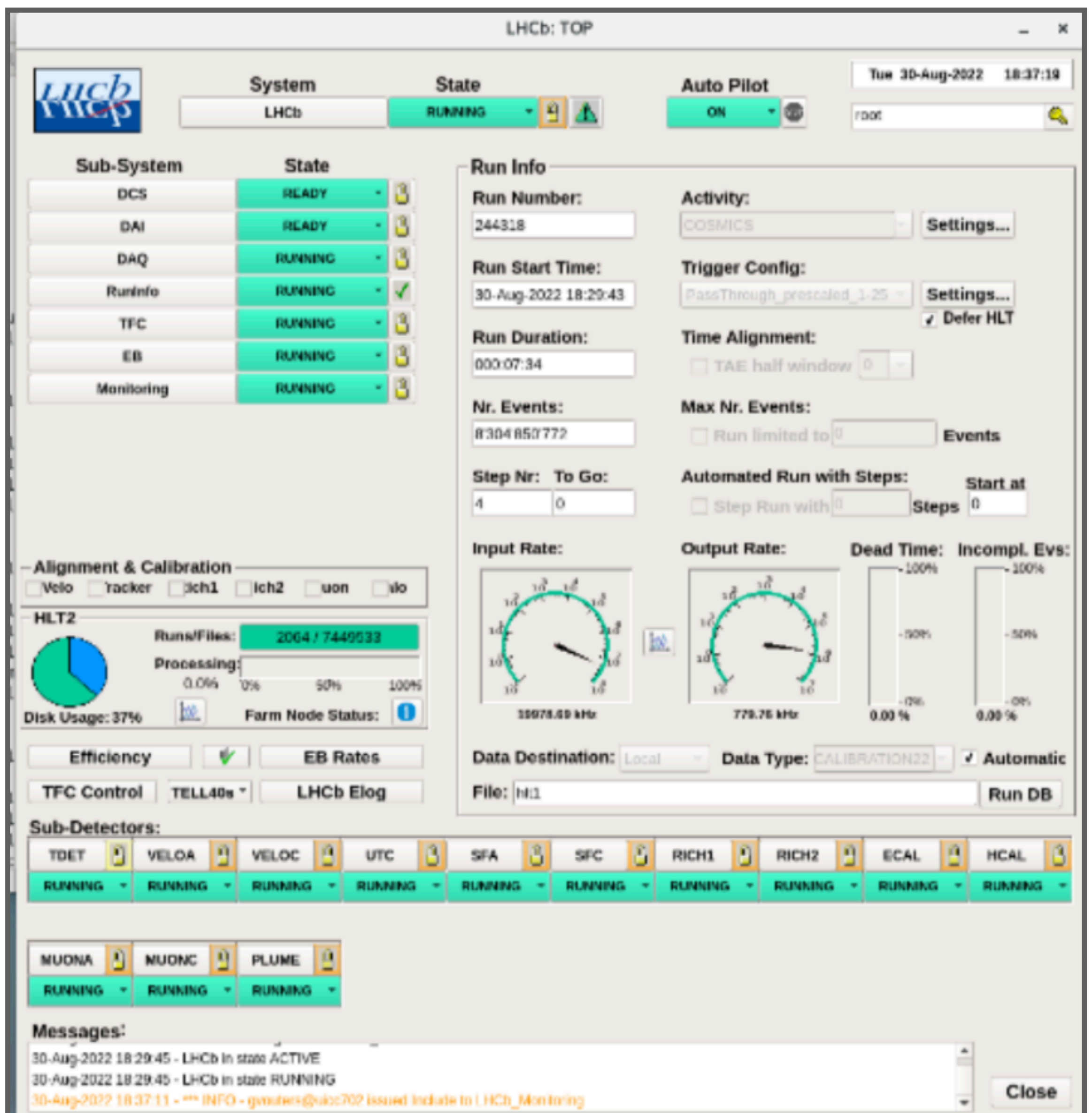


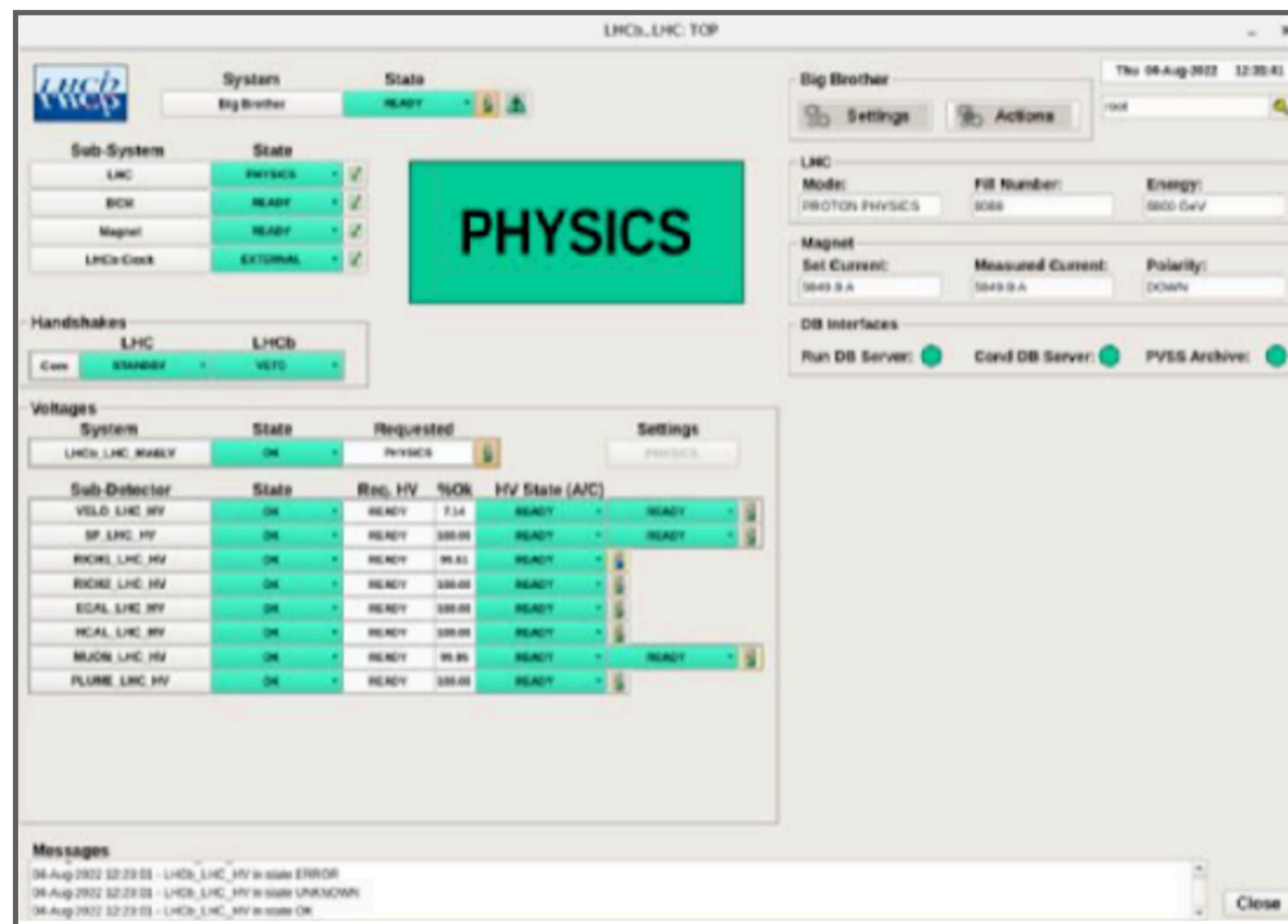
LHCb Run Control

The LHCb control system (ECS) is highly automatized

- HV/LV panel (called BigBrother) checks the LHC state, picks a corresponding ACTIVITY, and automatically adjusts HV/LV states

- The RunControls AutoPilot follows the procedure to start a run based on the ACTIVITY
  1. ACTIVITY loads a set of electronics, HLT recipes, configure all devices and checks they are ok, and then starts taking data
  2. Produce alarms, voices, messages, automatic entry to logbook, SMS

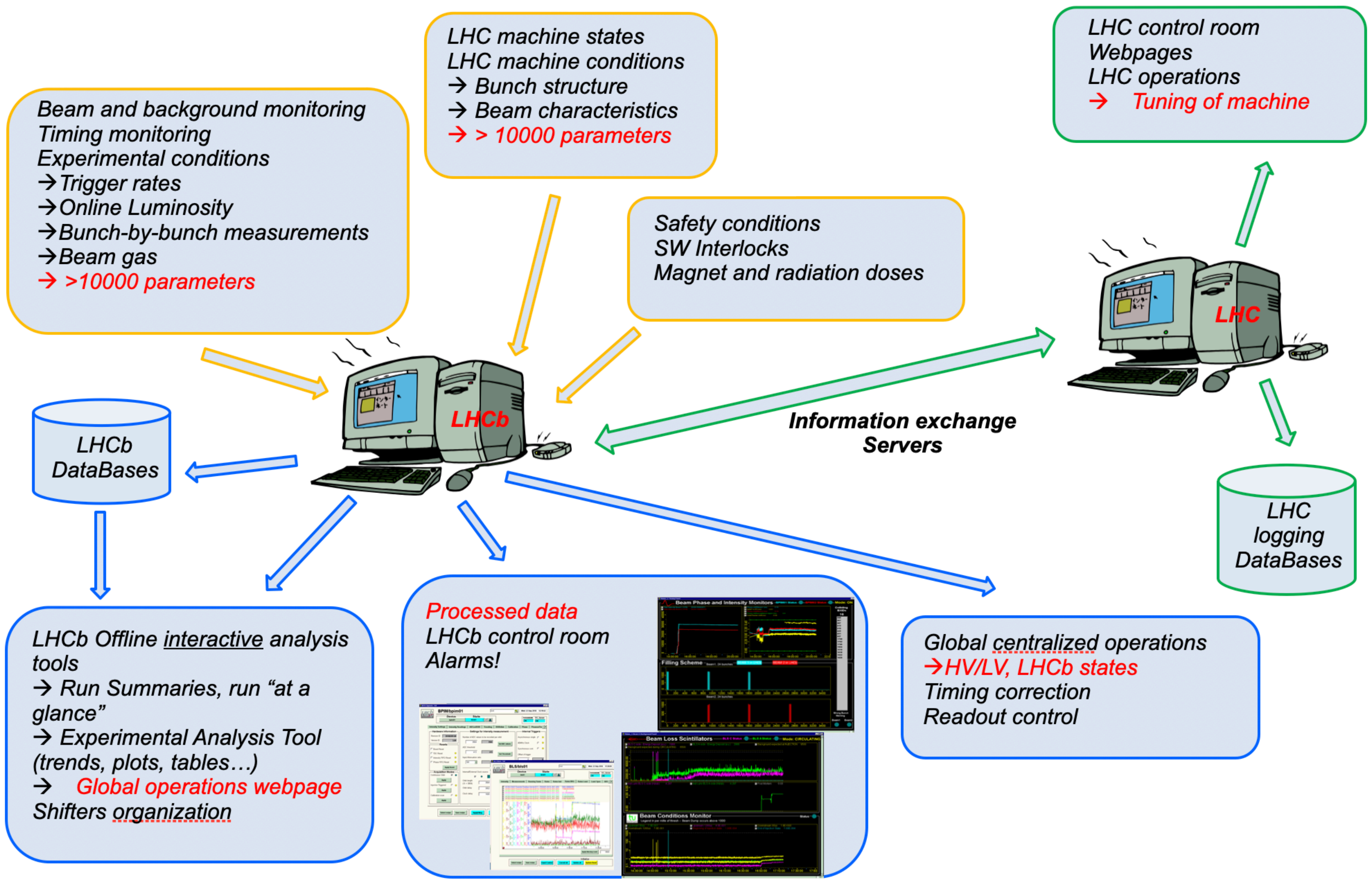


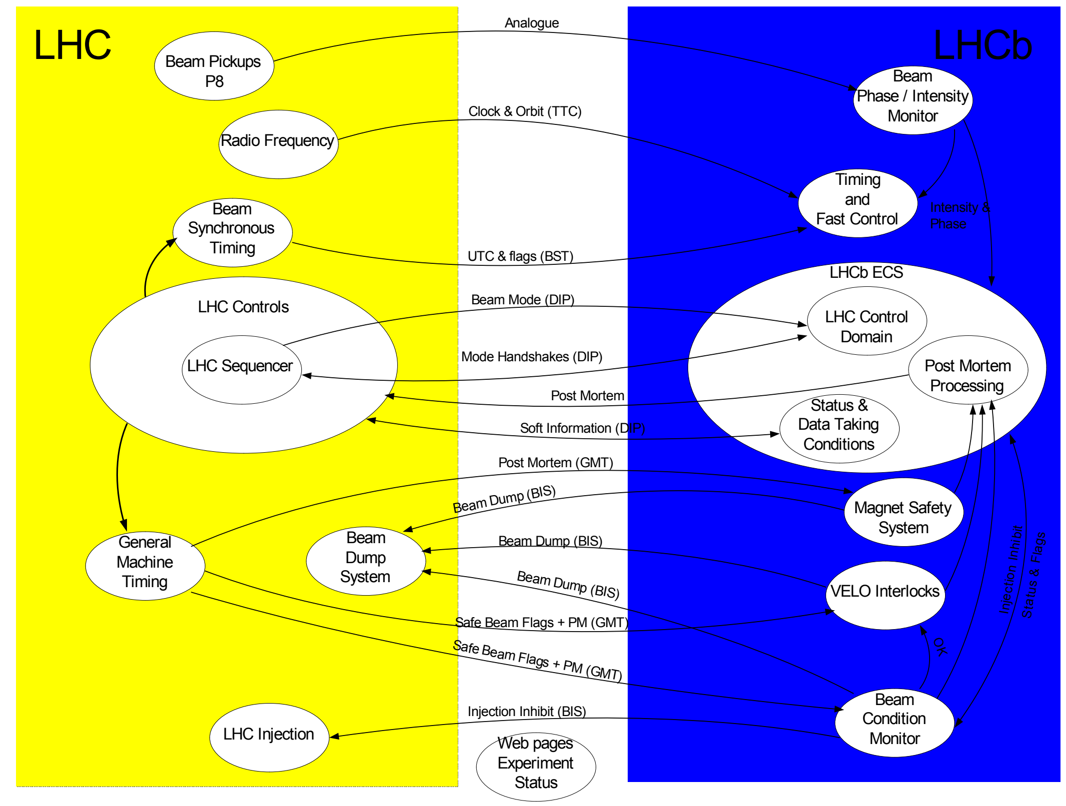


LHCb and the LHC

High interconnectivity between the accelerator and experiments

- Protection through fast beam extraction
- Automating and securing operational procedure
- Readout Control and Event Management





LUMINOSITY

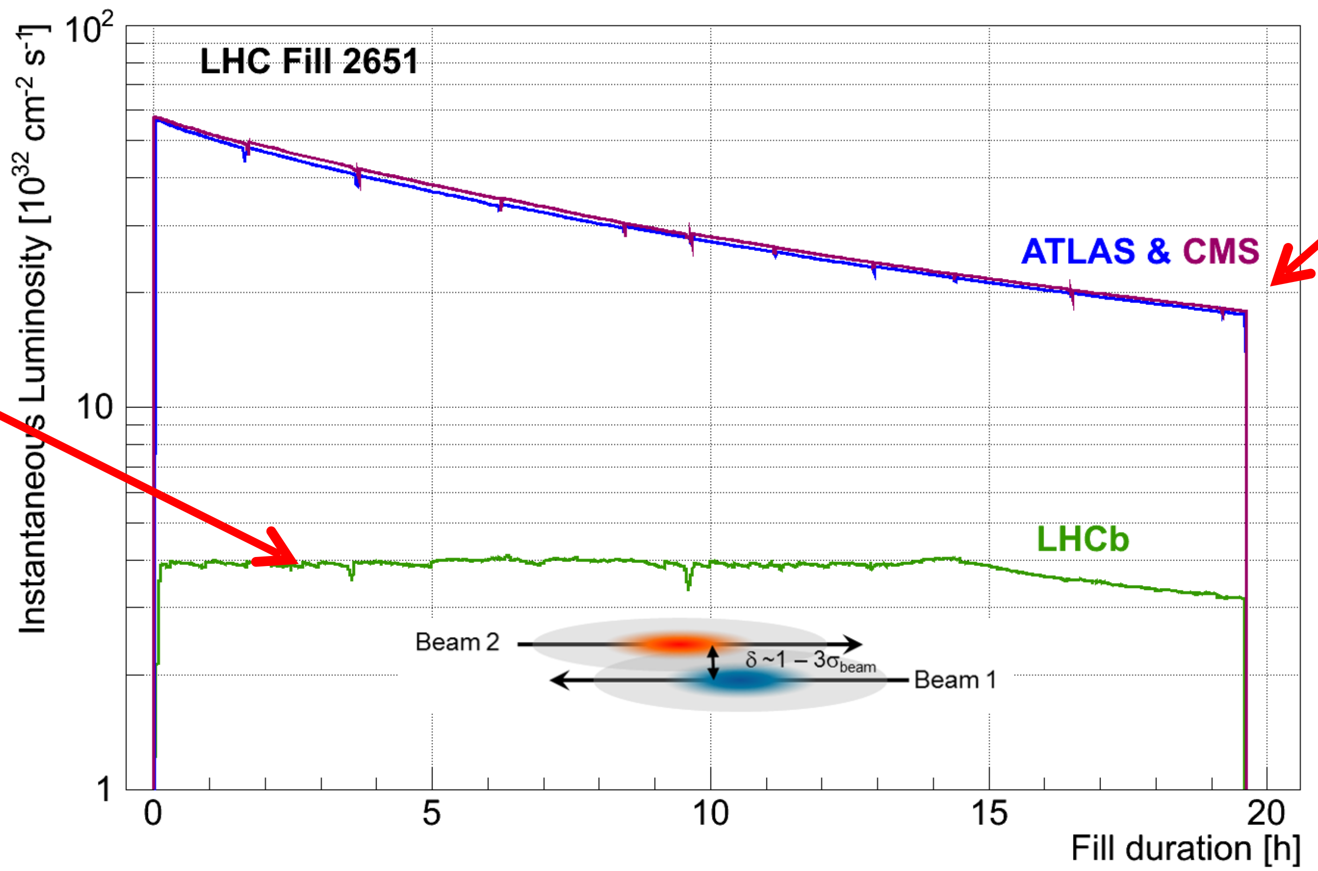
Measurement of how many collisions we get per second per cm²

$$L \approx \frac{N_b N_1 N_2 f_{bc}}{4\pi\sigma_x\sigma_y} \approx \frac{N_b N_1 N_2 f_{bc}}{4\pi\varepsilon\beta*} \text{ [cm}^{-2}\text{ s}^{-1}]$$

Nominal LHC luminosity is ~1-2 x 10^{34} $cm^{-2}s^{-1}$ with 25ns beams

- ATLAS and CMS are high-lumi experiment, reaching up to 1-2 x 10^{34} $cm^{-2}s^{-1}$
- LHCb is a mid-lumi experiment, running in the range of 2 x 10^{33} $cm^{-2}s^{-1}$
- ALICE is a low-lumi experiment, running in the range 10^{29} – 10^{31} $cm^{-2}s^{-1}$

LHCb lumi constantly leveled



ATLAS and CMS decay exponentially

MU, PILEUP AND NU

Instantaneous luminosity depends on beams population, given constant beam sizes

- ✓ better to have live quantities which are in terms of rate -> direct observable

μ (mu) = average number of visible pp interaction per bunch crossing

-> This is the only thing we can directly measure at the pit, so everything should be considered in terms of μ

$\mu = -\ln\left(P(0)\right)$ calculated from the number of empty events in a counter

$$L_{tot\_inst} = \frac{\mu * N_b * f}{\sigma_{xsection\_L0CALO}}$$

μ = 1.1 with $N_{bunches}$ = 2335 and L ~ 4.5 $\times 10^{32}$ cm^{-2} s^{-1}

pileup = average number of pp interaction in visible events

-> pileup is the zero suppressed mean of the Poissonian distribution for visible events

$$pileup = \frac{\mu}{1 - e^{-\mu}}$$

-> pileup = 1.65 for μ = 1.1

ν (nu) = average number of pp interaction per bunch crossing

-> only useful if to be compared with MC

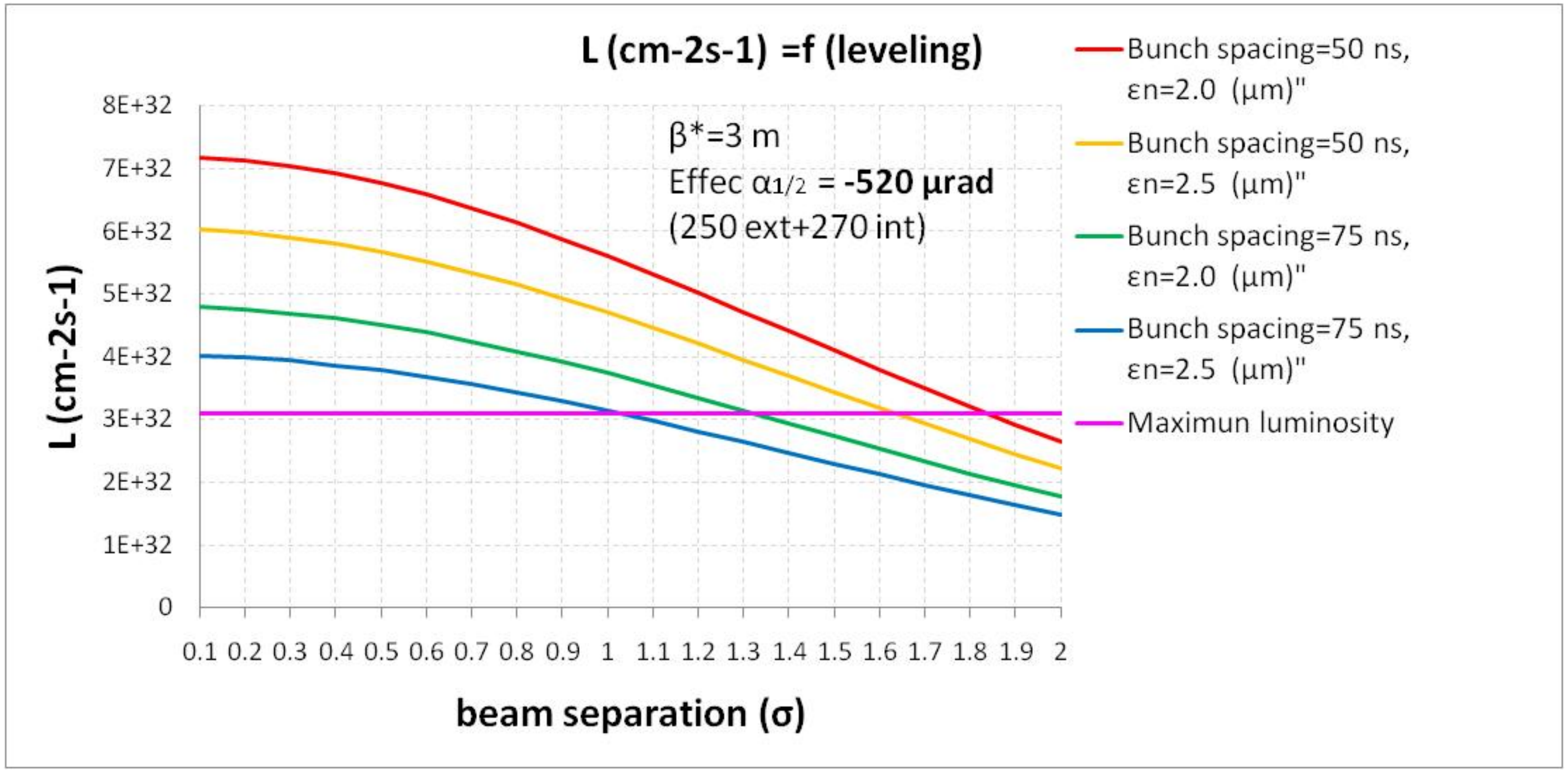
Luminosity Levelling

In LHCb, we optimize data taking to obtain homogenous dataset

→ Choose value of μ to be constant independently of bunch population and number of bunches

→ Level the luminosity to whichever value gives μ = 1.1

- ✓ Done by separating the beams in the plane perpendicular (V) to the crossing angle plane (H) until beams are “head-on” (i.e. no more V separation possible)
- ✓ Real-time application in the LHCb control room, controlled by the central LHCb control system that exchange life information with the LHC and “coordinate” the beams separation -> completely automated!



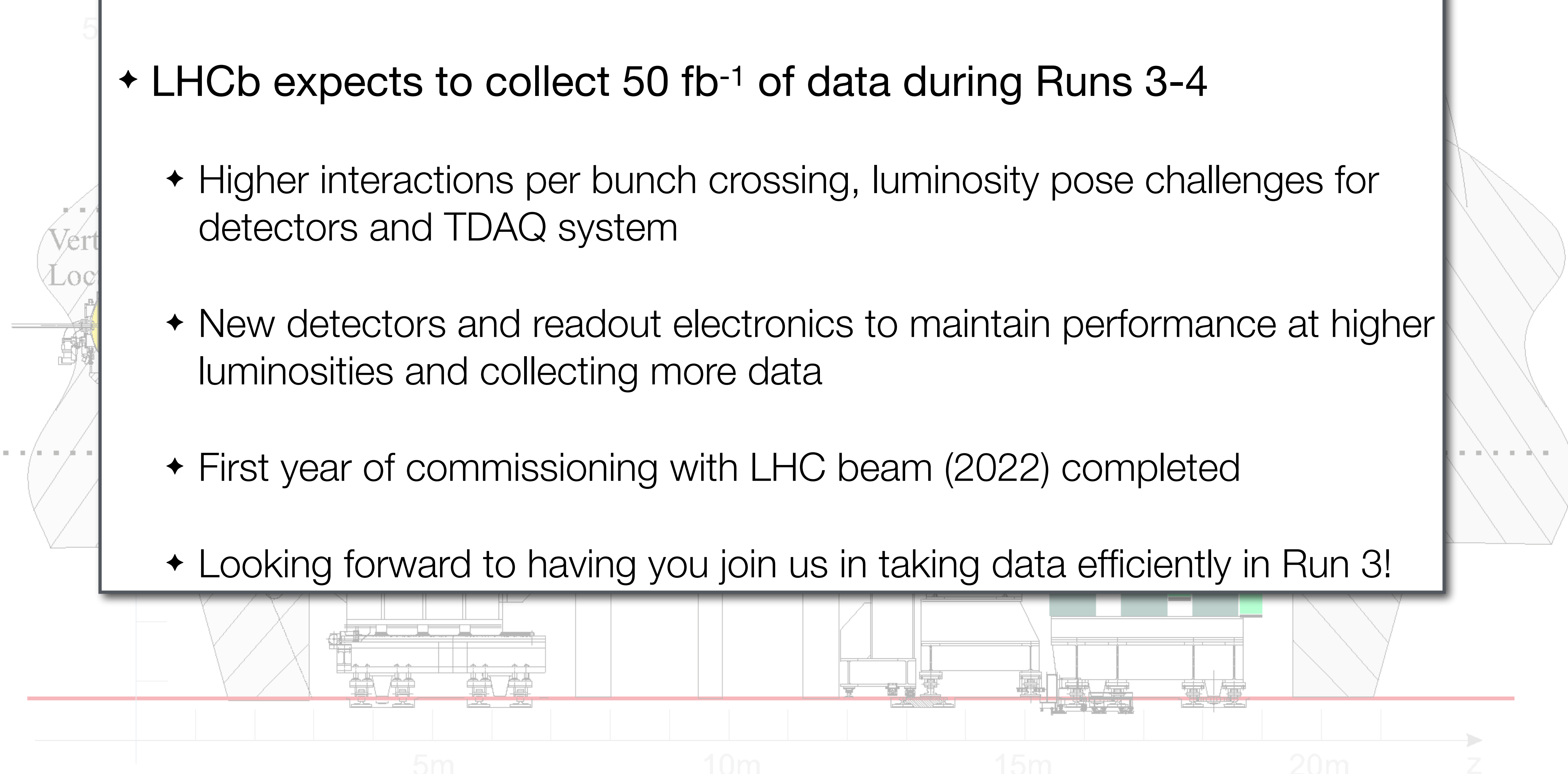
OPERATIONS IN 2022

First stable beams in Run 3! July 5, 2022

SUMMARY

- The LHCb experiment successfully completed its first decade of data taking in the LHC Run1 and Run2
  - Physics program extended well beyond beauty and charm sectors

- LHCb expects to collect 50 fb^{-1} of data during Runs 3-4
  - Higher interactions per bunch crossing, luminosity pose challenges for detectors and TDAQ system
  - New detectors and readout electronics to maintain performance at higher luminosities and collecting more data
  - First year of commissioning with LHC beam (2022) completed
  - Looking forward to having you join us in taking data efficiently in Run 3!




LHCb

BACKUP