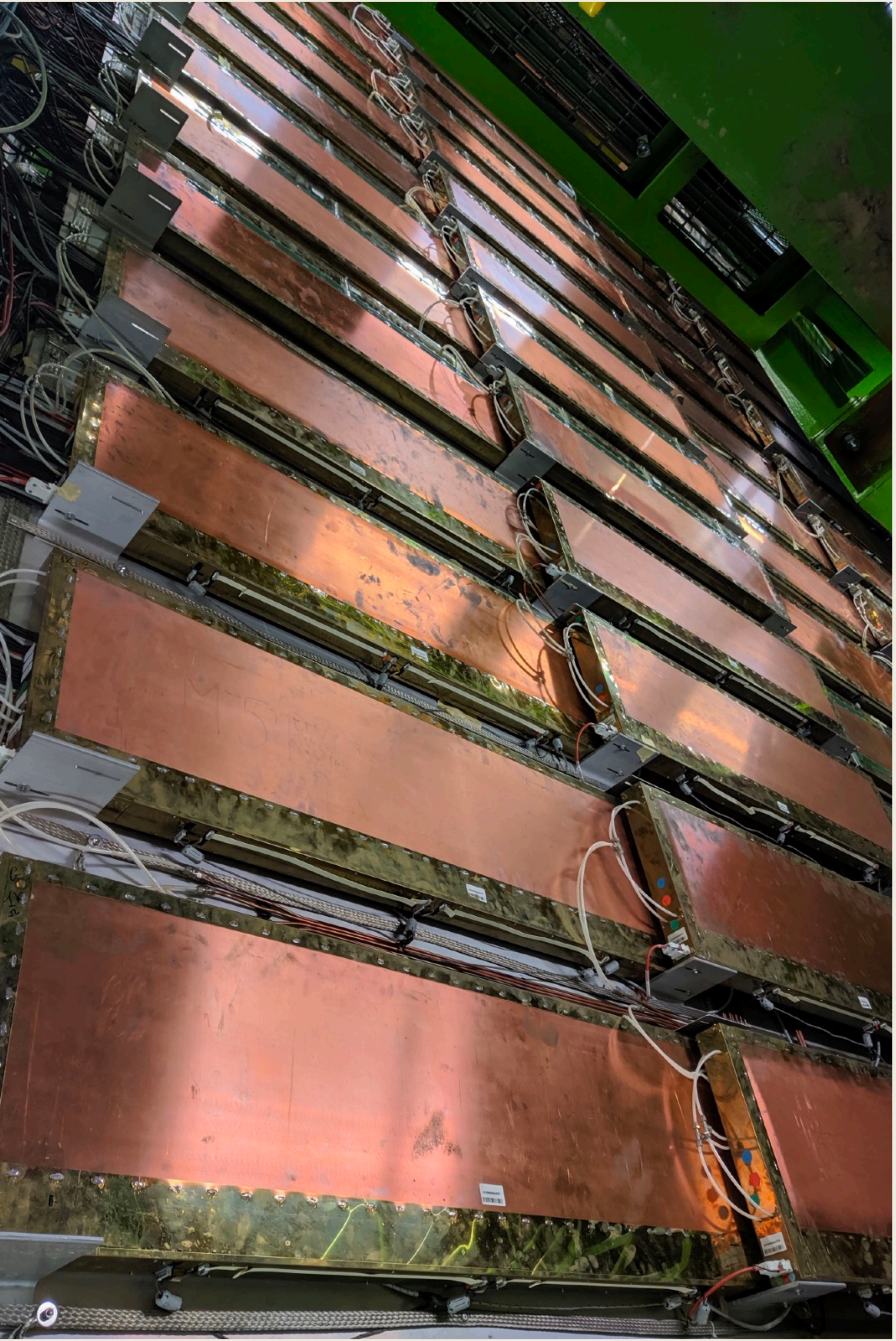

LORENZO PAOLUCCI (ON BEHALF OF THE LHCB COLL.)

The LHCb Muon Detector Upgrades

ICHEP 2022, Bologna, Italy - 09/07/2022

Parallel Session on Operation, Performance and Upgrade (Incl. HL-LHC) of Present Detectors

LHCb

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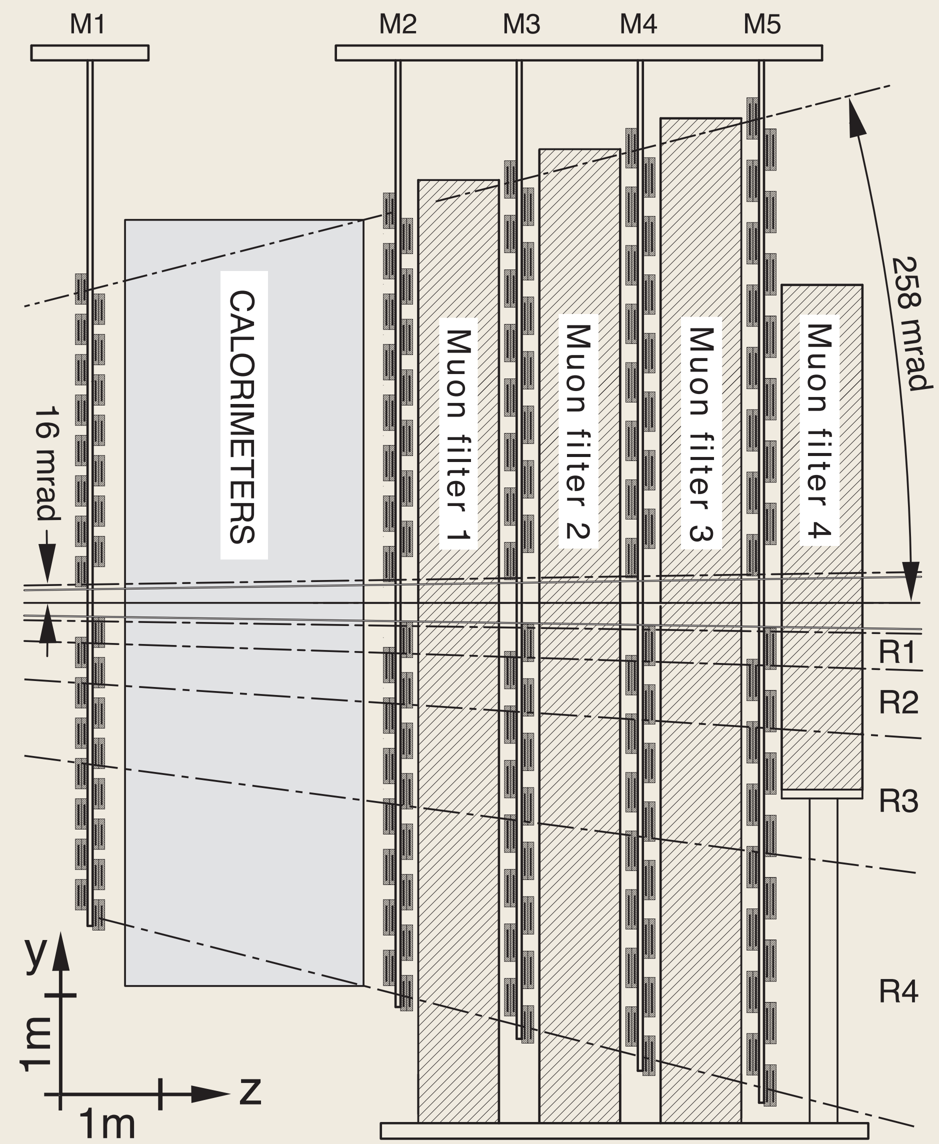
The Muon system of the LHCb Detector

- Composed of five stations containing multi-wire-proportional-chambers (MPWC).
- Stations alternate with iron filters.
- Detects high p_T muons, providing information for trigger, PID and tracking.
- As many physics channels are identified by a clear muon signature, its performance is crucial for the success of LHCb.



Detector configuration in Run 1-2

A. A. Alves Jr. et al. Performance of the LHCb muon system.

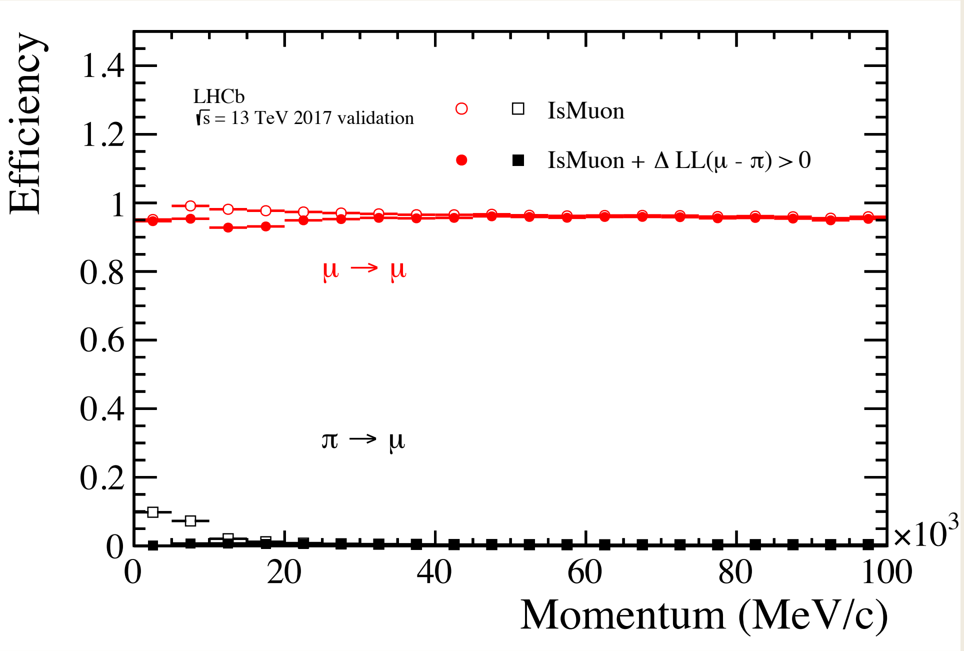
Performance of the Muon system in Run 1-2 (2011-2018)

- The Muon detector has performed very well in Run 1-2 at an instantaneous luminosity up to $4 \cdot 10^{32}$ cm^{-2}s^{-1} (twice the design value).
- After nine years of operation, no significant ageing has been observed.
- Detection efficiency > 99% across the detector.
- High Muon PID efficiency ~97%.

	R1	R2	R3	R4
M1	$98.66^{+0.07}_{-0.07} \pm 0.08$	$99.37^{+0.04}_{-0.04} \pm 0.08$	$99.70^{+0.02}_{-0.04} \pm 0.06$	$99.85^{+0.01}_{-0.08} \pm 0.02$
M2	$99.68^{+0.03}_{-0.07} \pm 0.04$	$99.78^{+0.02}_{-0.04} \pm 0.05$	$99.79^{+0.02}_{-0.06} \pm 0.02$	$99.80^{+0.02}_{-0.22} \pm 0.01$
M3	$99.35^{+0.05}_{-0.04} \pm 0.05$	$99.79^{+0.02}_{-0.02} \pm 0.04$	$99.85^{+0.01}_{-0.03} \pm 0.01$	$99.86^{+0.01}_{-0.14} \pm 0.01$
M4	$99.62^{+0.03}_{-0.09} \pm 0.07$	$99.89^{+0.01}_{-0.01} \pm 0.03$	$99.65^{+0.03}_{-0.05} \pm 0.03$	$99.72^{+0.03}_{-0.17} \pm 0.01$
M5	$99.64^{+0.05}_{-0.07} \pm 0.10$	$99.82^{+0.02}_{-0.04} \pm 0.04$	$99.90^{+0.02}_{-0.07} \pm 0.12$	$100.0^{+0.00}_{-0.46} \pm 0.1$

Above: detection efficiency measured in Run 1 (with statistical and systematic uncertainties).

Below: Muon PID efficiency vs candidate's momentum, measured in 2017.

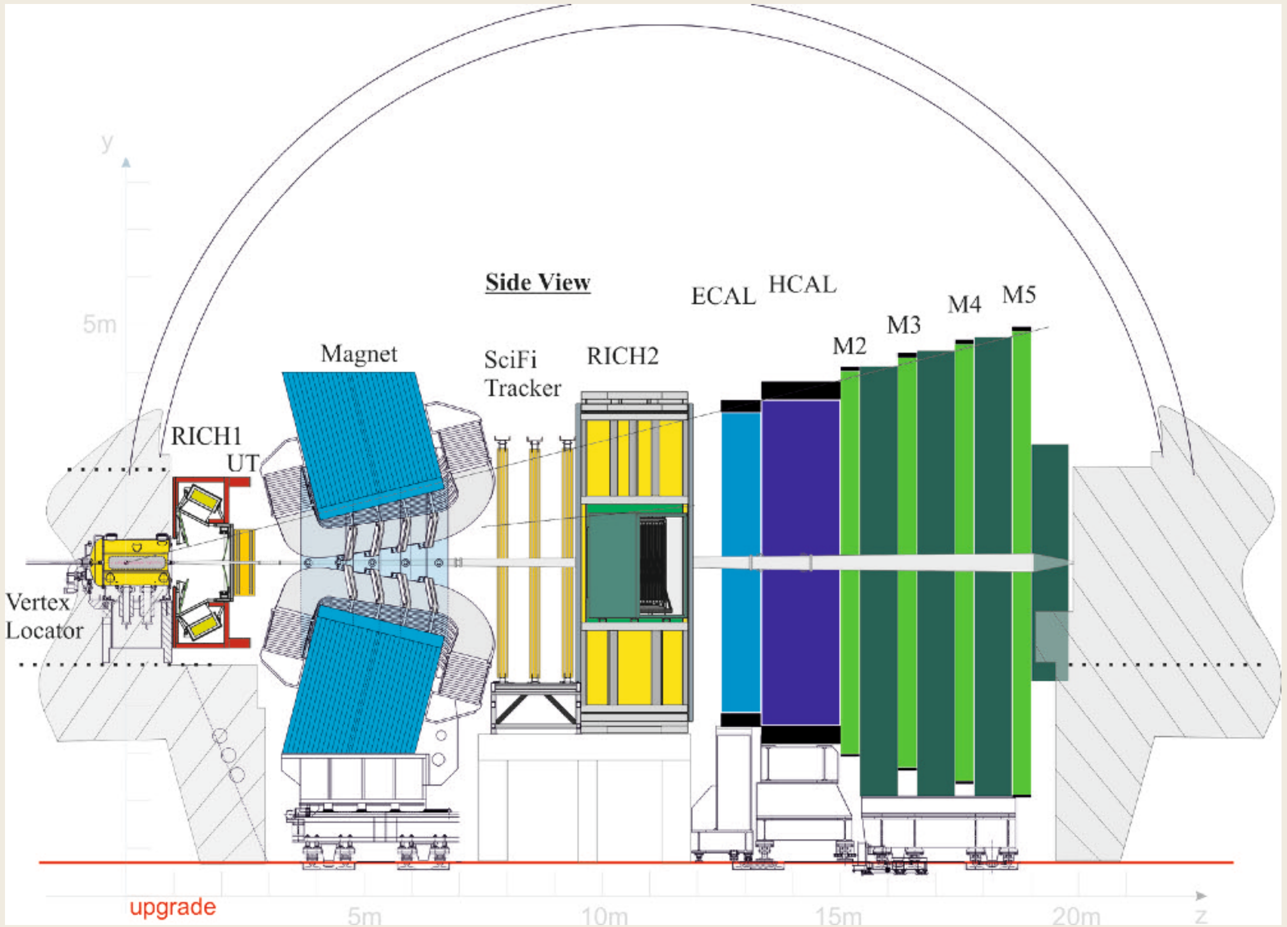


A. A. Alves Jr. et al. Performance of the LHCb muon system.

LHCb Upgrade I (2022-2032)

LHCb Upgrade I (1/2)

- Goal: to increase the statistical power of the collected data, for precision studies of the hinted New Physics anomalies.
- Increased luminosity by a factor of 5, up to $2 \cdot 10^{33}$ cm^{-2}s^{-1}.
- Readout rate increased from 1 MHz to bunch crossing rate of 40 MHz.
- Switch to a purely software trigger (more inclusive).



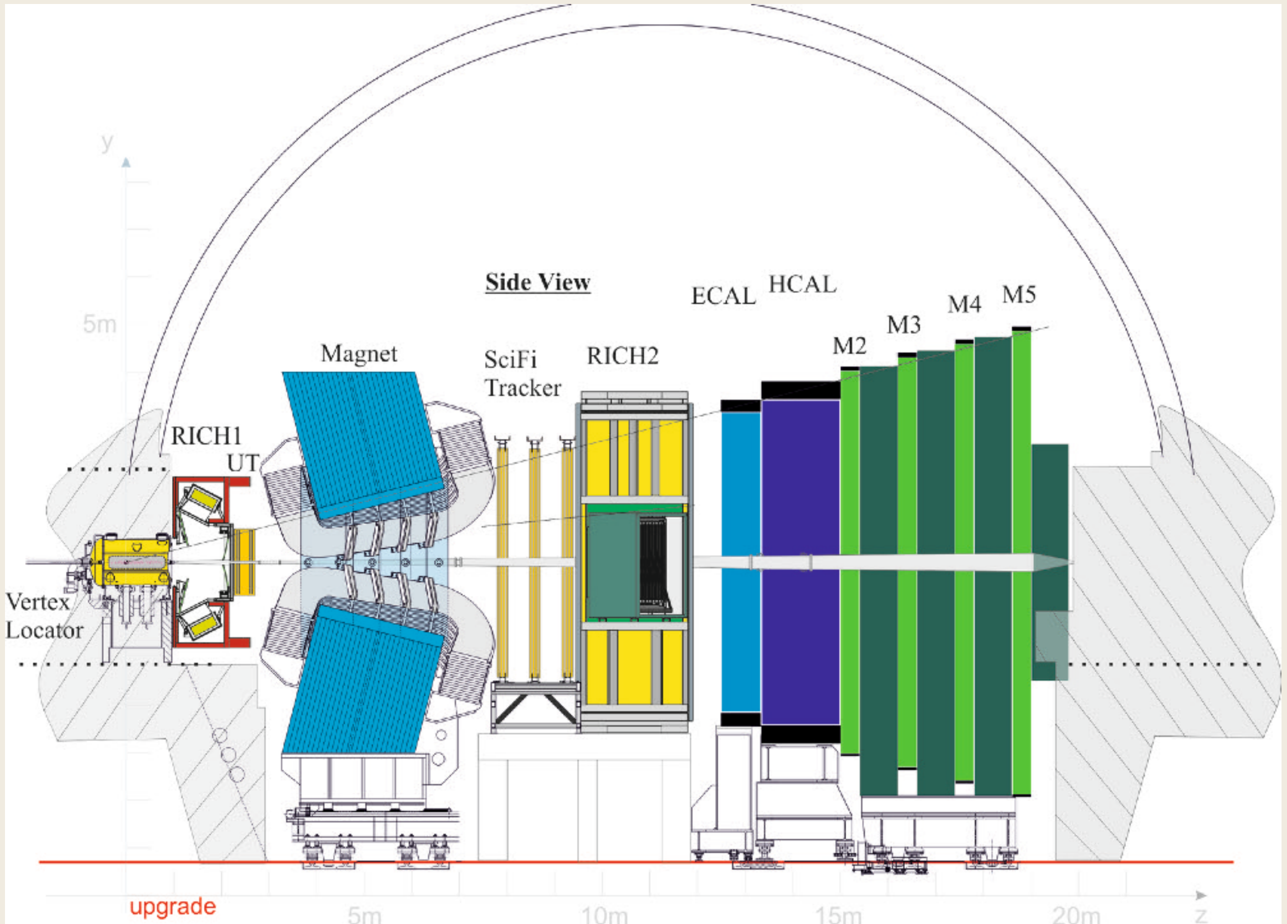
LHCb after Upgrade I

LHCb Coll. Letter of Intent for the LHCb Upgrade

LHCb Coll. Physics case for an LHCb Upgrade II

LHCb Upgrade I (2/2)

- To sustain the higher pileup and readout rates:
  - A new and improved Vertex Locator.
  - A new scintillating fibre tracker.
  - New Upstream Tracker, and upgraded RICH 1-2.
  - New Front-End (FE) electronics for all sub-detectors and upgrade the DAQ network.



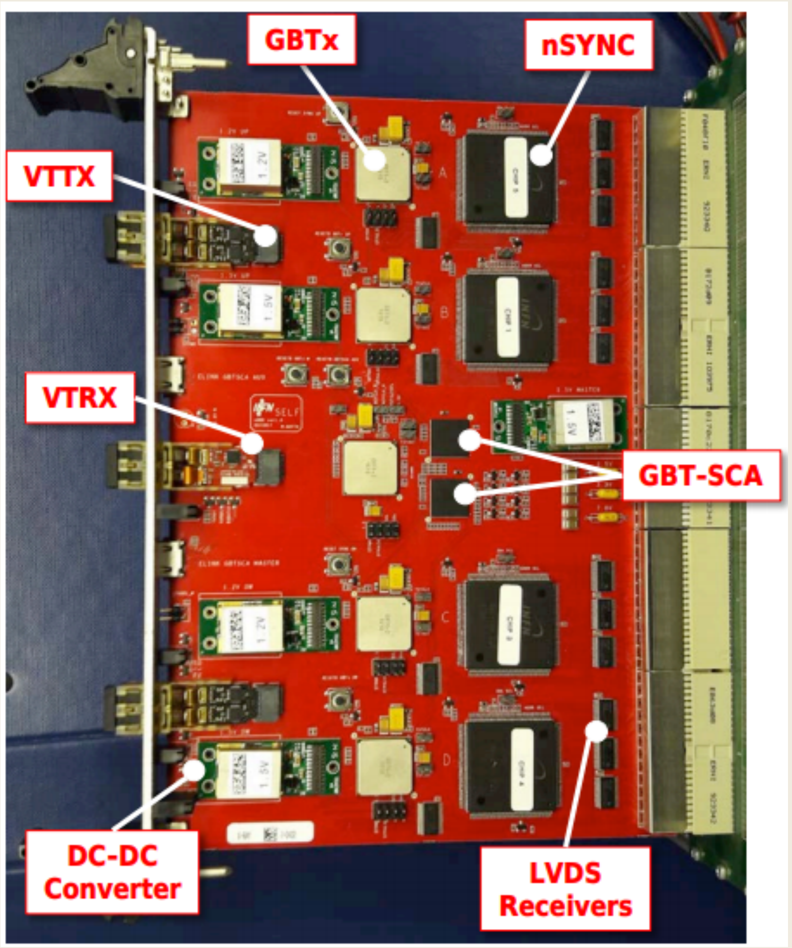
LHCb after Upgrade I

LHCb Coll. Letter of Intent for the LHCb Upgrade

LHCb Coll. Physics case for an LHCb Upgrade II

The Muon system in Upgrade I

- M1, only used for L0 trigger purposes, has been removed.
- To cope with the 40 MHz readout rate, Off-Detector Electronics (ODEs) have been upgraded.
- The ODEs are equipped with nSYNCs ASIC which:
    - Transmit digital signals from FEs;
    - Measure hit arrival times;
    - Align hits from same collision.

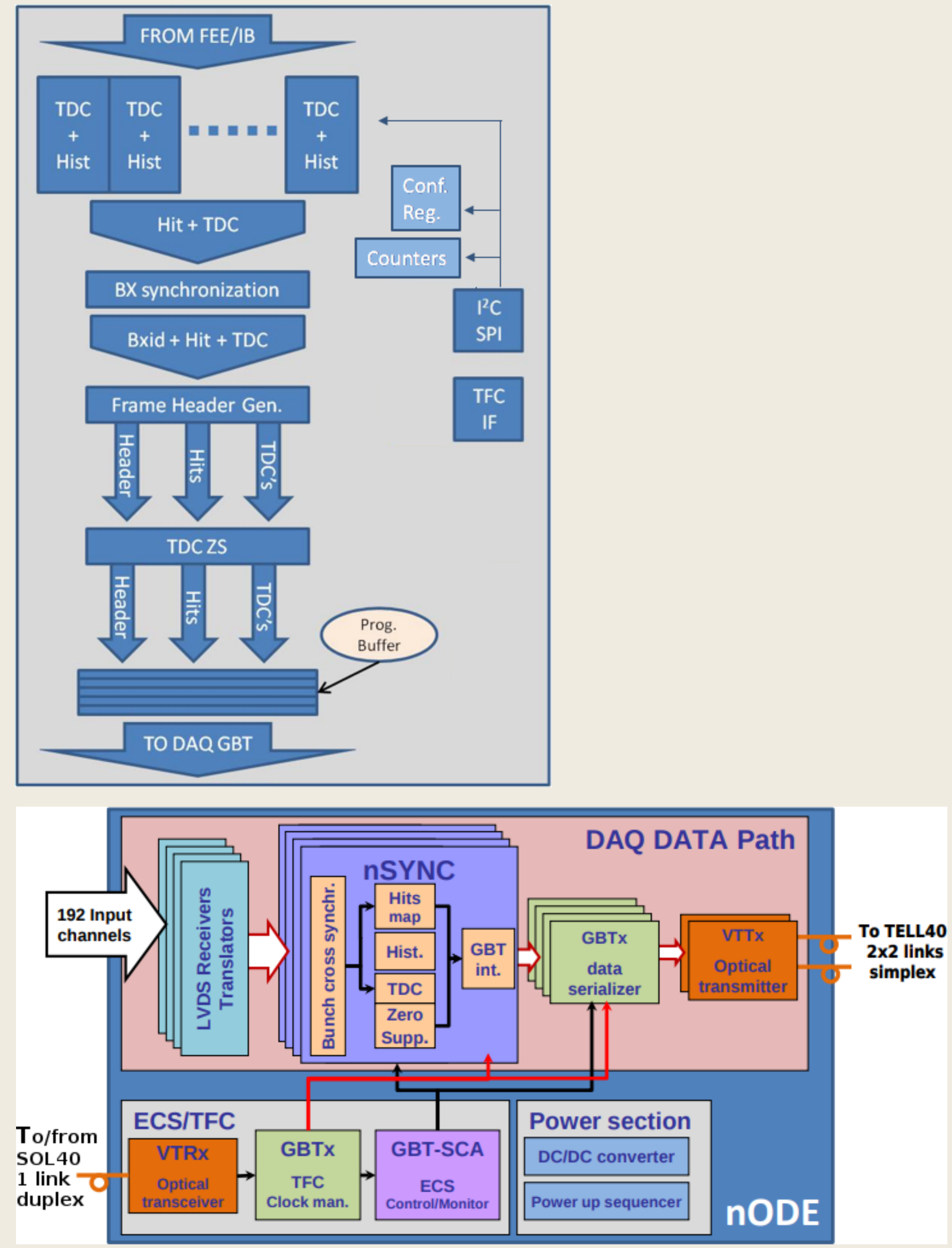


Picture of a new ODE (nODE) board, equipped with nSYNC chips.

S. Cadeddu et al. The nSYNC ASIC for the new readout electronics of the LHCb Muon Detector Upgrade

The nSYNC and nODEs architectures

- Each nSYNC receives 48 digital signals from FEs.
- Arrival time measured with Time-to-Digital Converters (TDC), as a phase difference with respect to the master clock.
- nODEs handle and distribute the master clock, and transfer data processed by nSYNCs to the DAQ.
- They also handle chip configuration and power.



nSYNC and nODE architectures.

D. Brundu A new readout electronics for the LHCb Muon Detector Upgrade

Using the Muon system as a Luminosity monitor (1/2)

- Achieving high precision in physics results requires good knowledge of the luminosity $\mathcal{L}$ at the LHCb interaction point.
- New methods to measure luminosity for Run 3:
  - Probe for LUminosity MEasurement (PLUME);
  - Sub-detector counters:

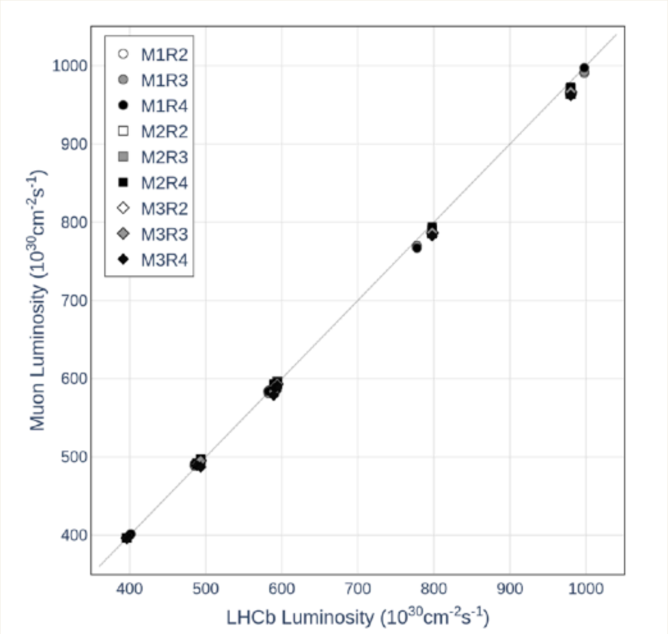
See also the talk "Luminosity at LHCb in Run 3" by E. Graverini

$$\mathcal{L} \propto \frac{\mu_{visible}}{\sigma_{visible}}$$

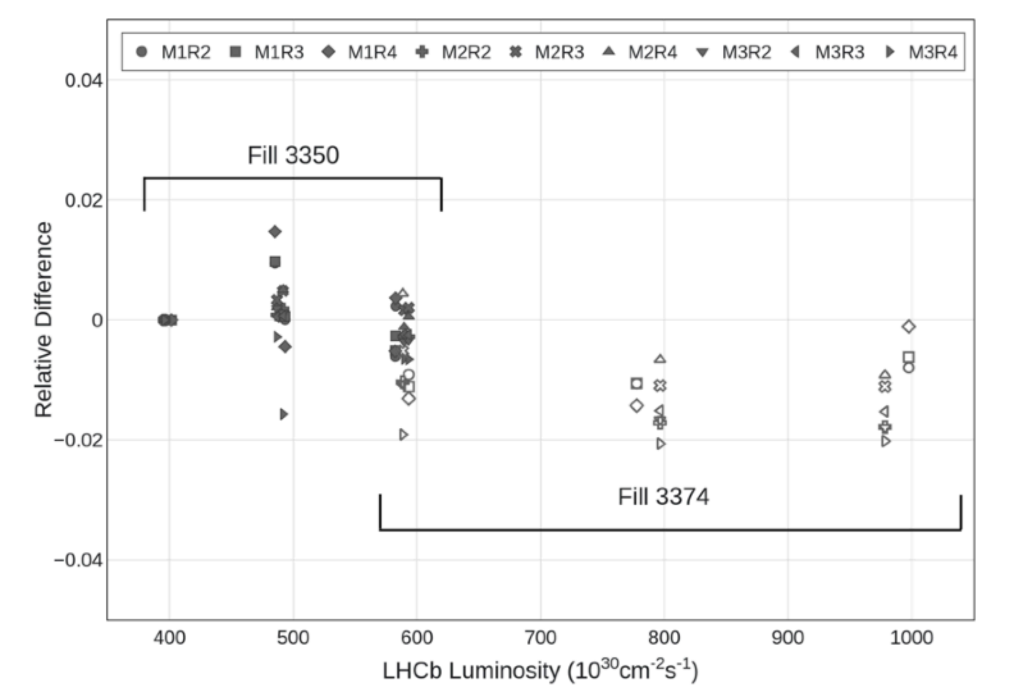
$\mu_{visible}$: #visible p-p interactions $\longrightarrow$ counters (hits, tracks, clusters, etc.).

$\sigma_{visible}$: effective cross section $\longrightarrow$ measured with Van Der Meer scans.

Using the Muon system as a Luminosity monitor (2/2)



- For the Muon system $\mu_{visible} \propto N_{hits}$
- Linearity of response studied using old runs acquired at various luminosities.
- Relative difference with reference Lumi is of $< 2\,\%$.
- Systematic effects still under study.



Above: $\mathcal{L}_{Muon}$ plotted against the reference $\mathcal{L}_{LHCb}$.

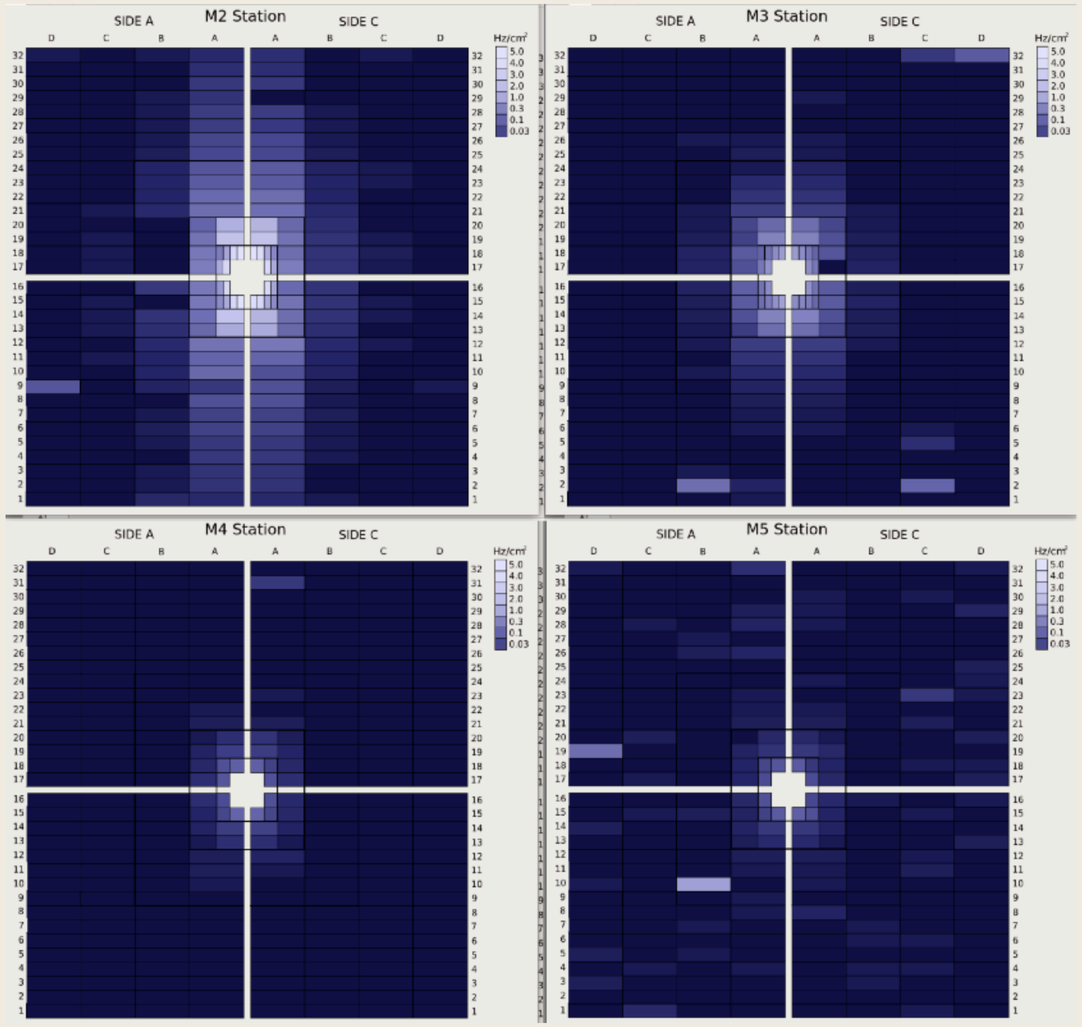
Below: Relative difference of the lumi as measured only using some regions of the detector, as a function of the reference luminosity.

Pietro Albicocco et al. A method based on Muon System to monitor the LHCb luminosity.

Run 3 Commissioning phase

The October 2021 Beam Test

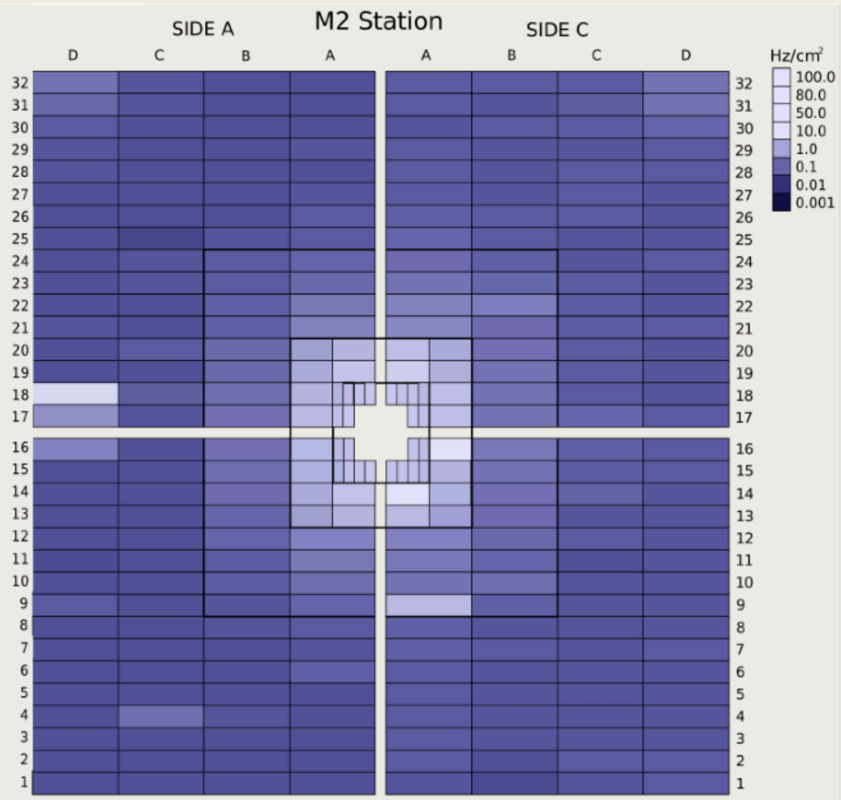
- Stable beams at 450 GeV.
- First time Muon system run in “global", along with rest of LHCb.
- First "coarse" time alignment with LHC clock.
- Test was fundamental for debugging and testing DAQ and control system, ahead of the 2022 commissioning.
- Luminosity counter also tested.



Hit rate maps for the four Muon stations, for data collected during the October beam test.

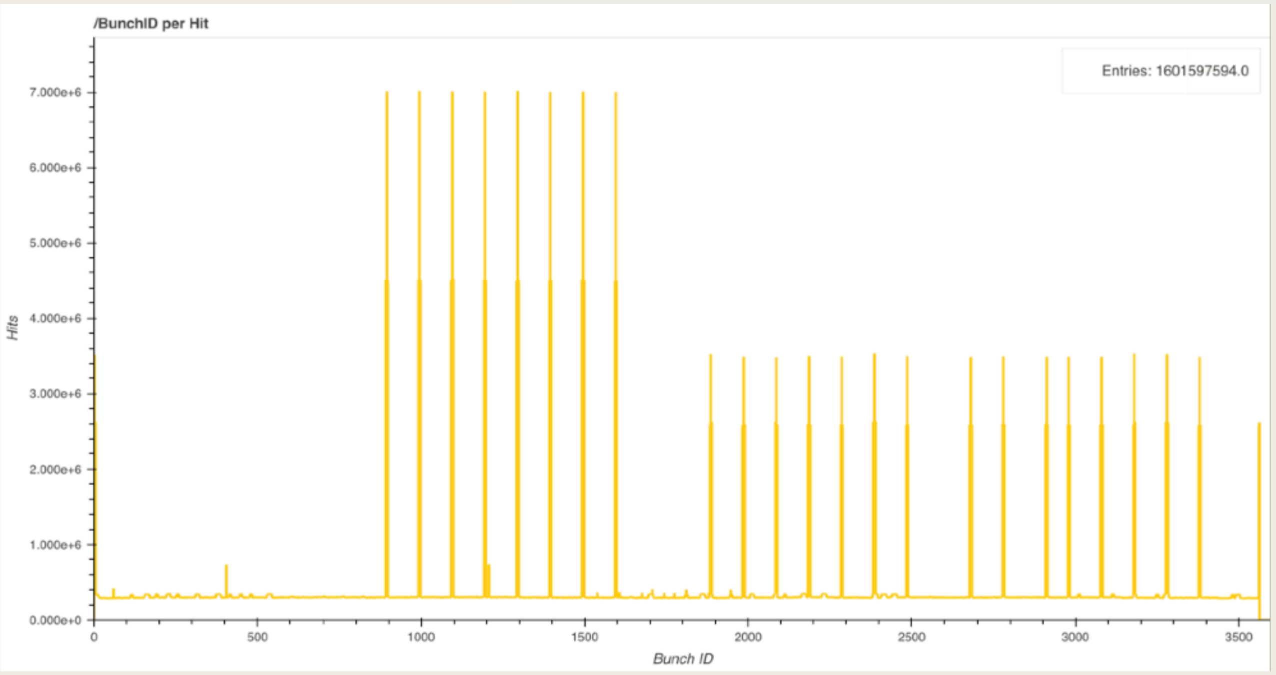
Ongoing commissioning

- Final stretch of commissioning with beams has begun in March.
- “Cosmic runs” to deal with issues encountered in October.
- Finally, on 5th July first collisions at 6.8 TeV.
- Muon system smoothly running.
- Now focusing on finer time alignment of the detector, and ironing out smaller issues.



Above: Hit map for M2 at 6.8 TeV.

Below: Activity plot of colliding bunches, as seen by the Muon system



Upgrade II (2033 onwards)

The future: Upgrade II

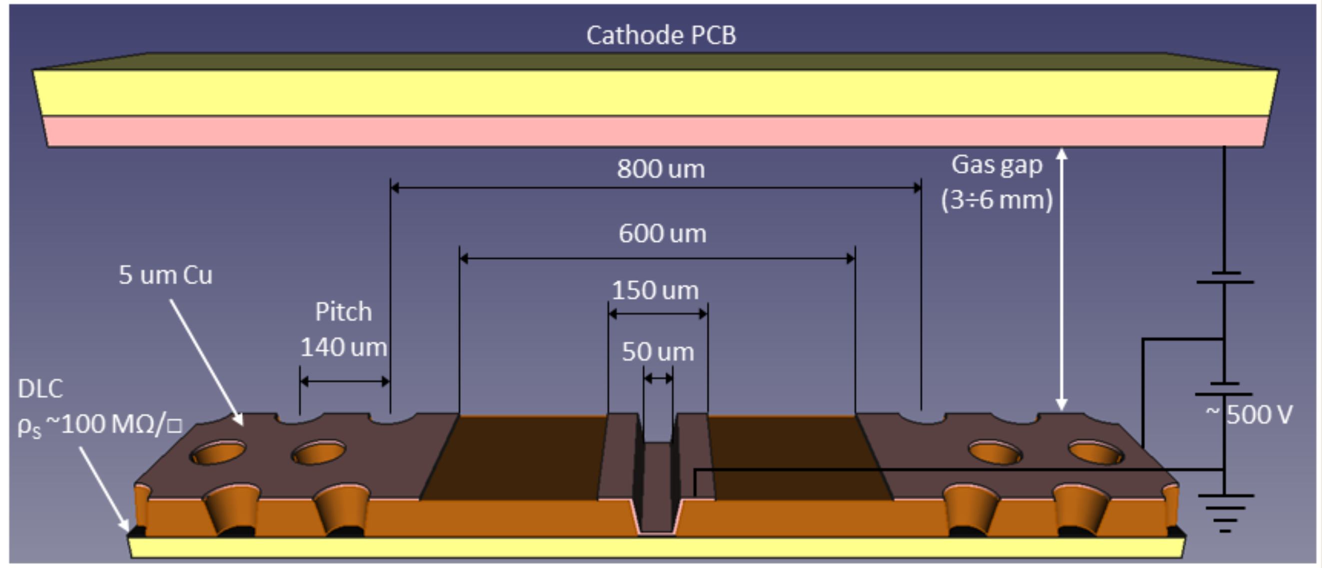
- Planned for Run 5 of LHCb, operating at $\mathcal{L} \sim 1.5 \cdot 10^{34}$ cm^{-2}s^{-1}.
- Expected factor of 10 increase in hit rates across the Muon system.
- The inner most regions of the detector will have to be replaced and upgraded.
- The readout scheme will also be redesigned to optimise performance and reduce backgrounds.

Technical Design Report for LHCb Upgrade II

LHCb Coll. Physics case for an LHCb Upgrade II

Inner regions: μ-RWell detector

- The current chamber and readout configuration would have very high occupancies and dead time inefficiencies.
- Improved shielding can reduce the rates slightly.
- For the most-inner region of the Muon system (highest rates), new Micro-Pattern Gaseous Detector, μ-RWell.
- R&D is ongoing, see dedicated talk by G. Morello for more details.



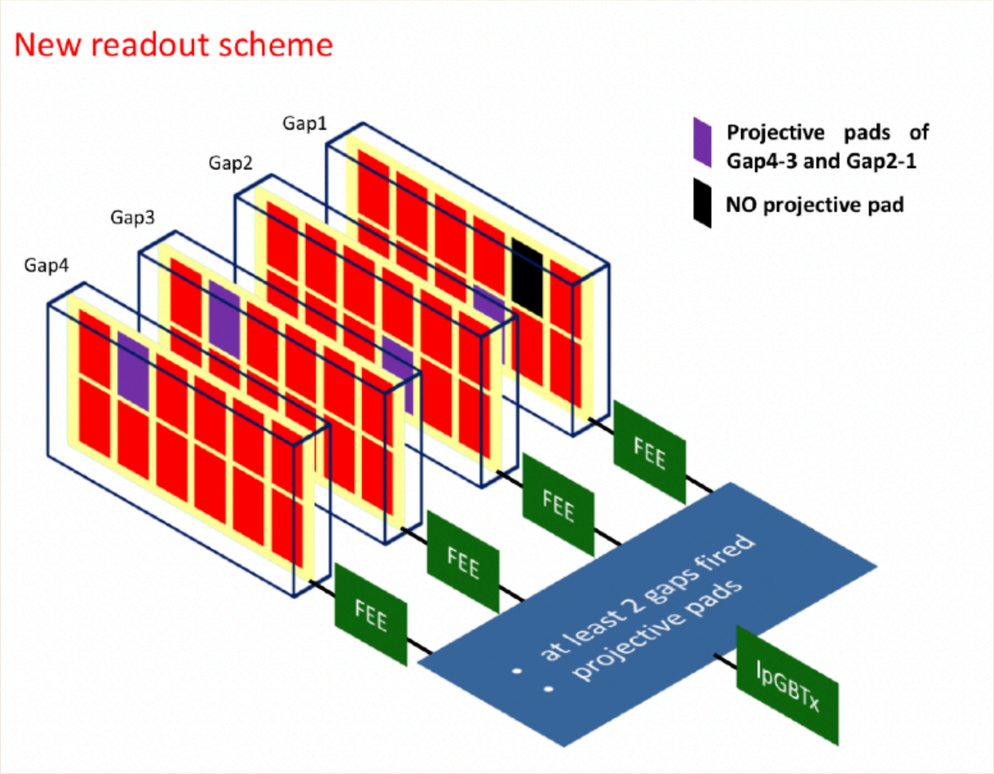
Design for the proposed μ-RWell detector.

G. Bencivenni et al. The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD

Upgrade for the Outer regions

- The MWPCs should be able to cope with the expected rates in the outer regions.
- To reduce inefficiency as much as possible, the FEs scheme will be upgraded to readout each MWPC plane separately.
- The granularity will be increased in some regions as well.
- A good fraction of the present chambers will be reused.

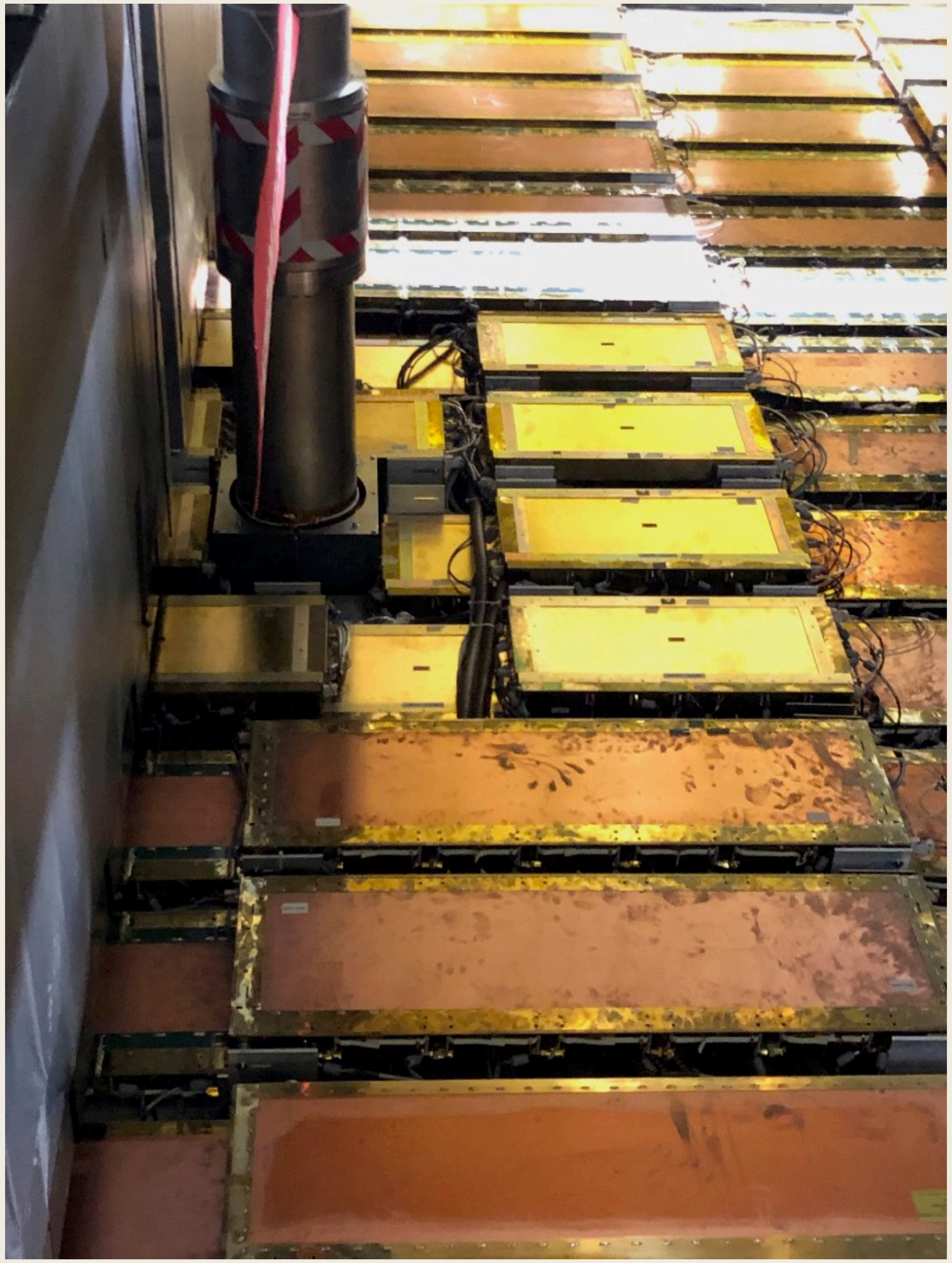
- Testing of the readout scheme is ongoing with simulation.



Possible new readout scheme for the outer regions. The 4 gaps in the MWPC can be read individually to greatly reduce background rates.

Conclusions

- The Muon system has performed exceptionally well in the first two Runs of LHCb.
- The electronics have now been upgraded fully. Chambers have been kept, having shown little to no ageing.
- LHCb Upgrade I is under commissioning and the Muon detector is projected to perform just as well for Run 3-4.
- In parallel, R&D is ongoing for Upgrade II, which will have to deal with even higher luminosities.

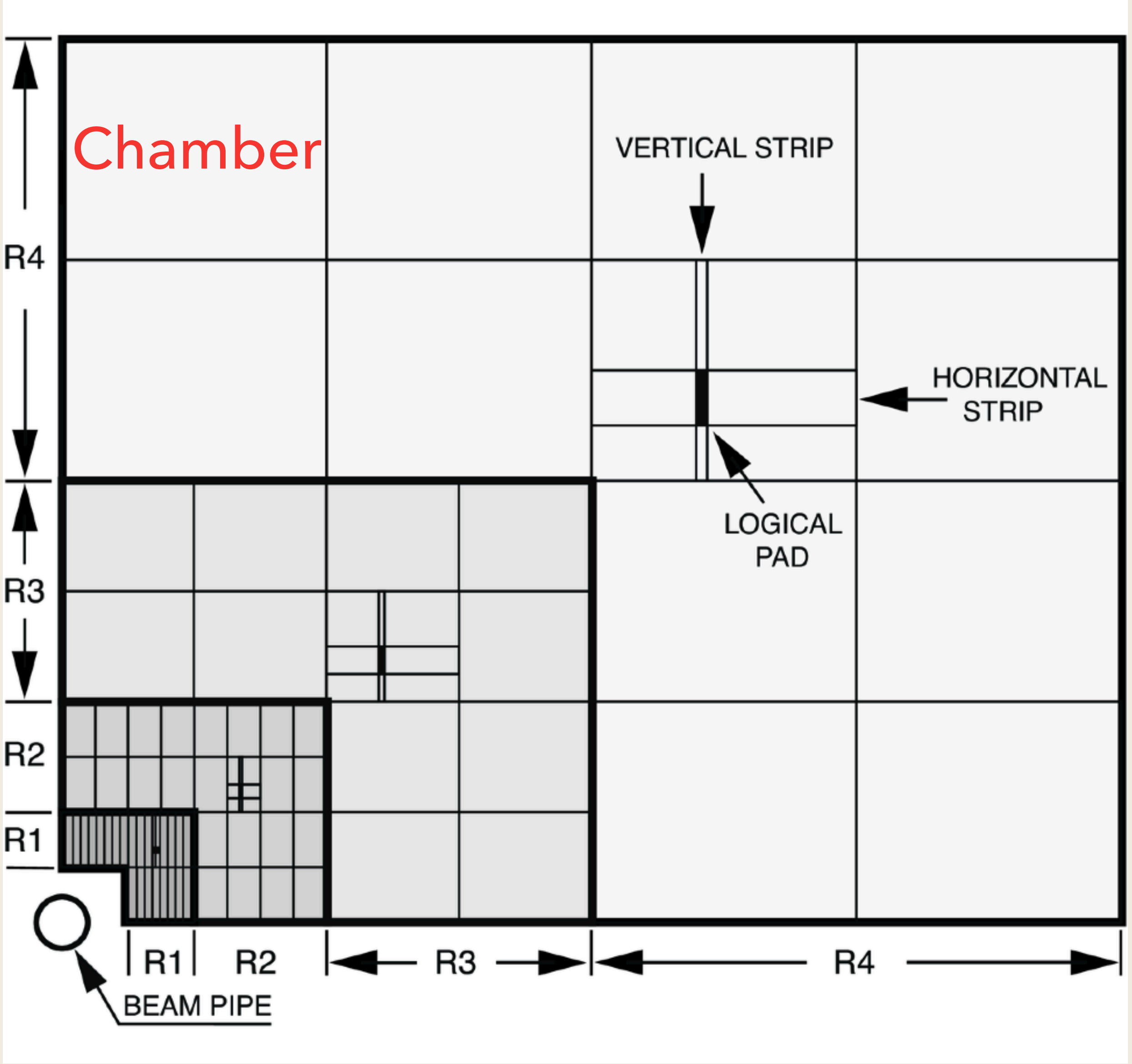


Thank you for your attention!

Backup

Muon detector geometry

- Four regions per station, with different granularity.
- Each chamber has both vertical and horizontal strips, which can be read out separately.
- The strips output binary "hit/not hit" information.
- The intersection of the strips define the "logical pad", i.e. the pixel.



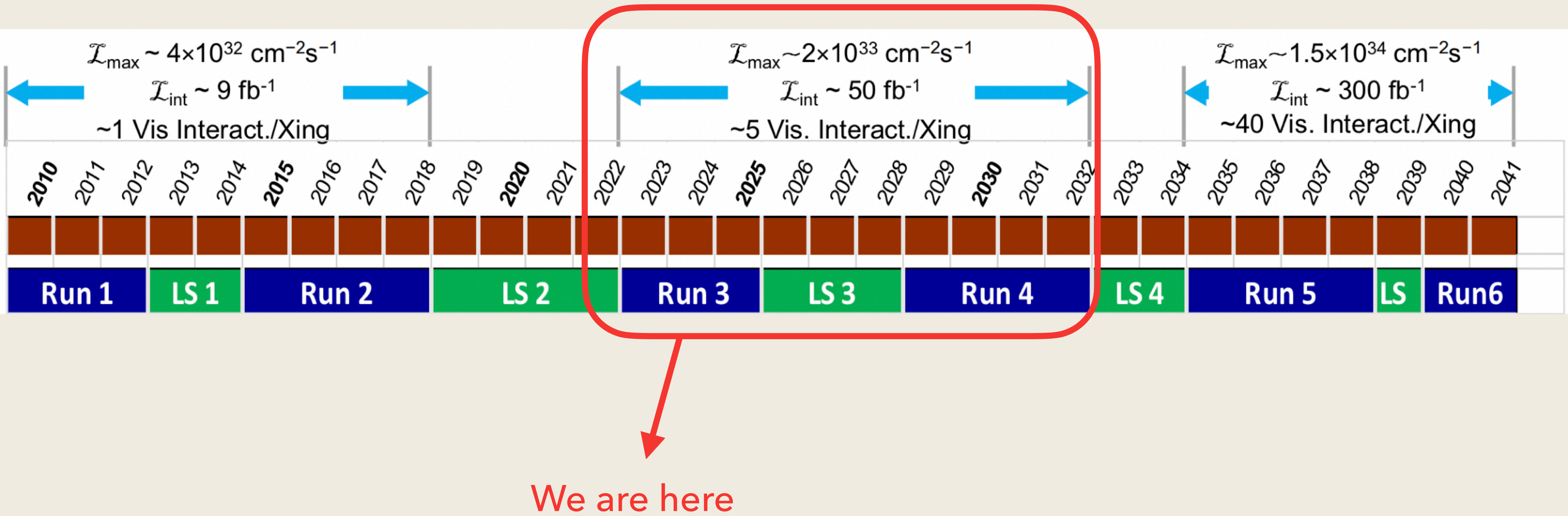
L. Anderlini et al. Muon Identification in Run 3

Muon PID variable: IsMuon

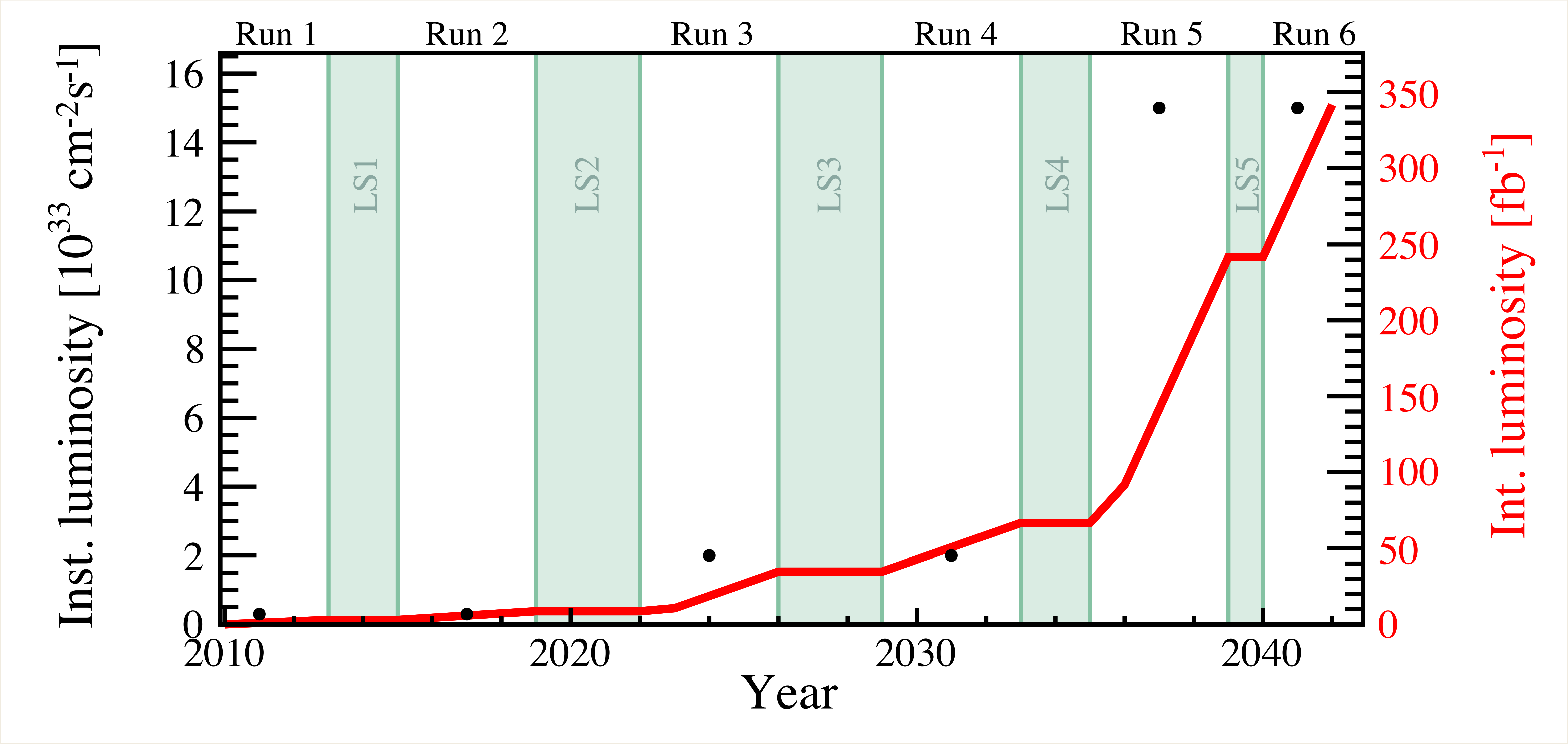
- Binary variable.
- Requires candidate to have at least one hit in two or more Muon stations (depending on the momentum).

Momentum range	Muon stations
$3\ \mathrm{GeV}/c < p < 6\ \mathrm{GeV}/c$	M2 and M3
$6\ \mathrm{GeV}/c < p < 10\ \mathrm{GeV}/c$	M2 and M3 and (M4 or M5)
$p > 10\ \mathrm{GeV}/c$	M2 and M3 and M4 and M5

LHCb Upgrade timeline



Luminosity projections



LHCb Physics reach in Upgrade I-II

Observable	Current LHCb (up to $9\,\mathrm{fb}^{-1}$)		Upgrade I ($23\,\mathrm{fb}^{-1}$)	Upgrade I ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
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_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{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
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\mathrm{T}}^{\mathrm{Im}}$ ($B^0 \to K^{*0}e^+e^-$)	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