XII International Conference
on New Frontiers in Physics
10-23 July 2023, OAC, Kolymbari, Crete, Greece

The Muon Detector of the LHCb experiment at Upgrade II

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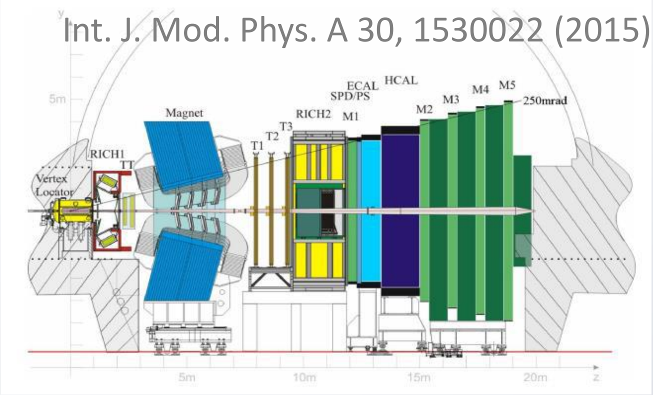
Outline

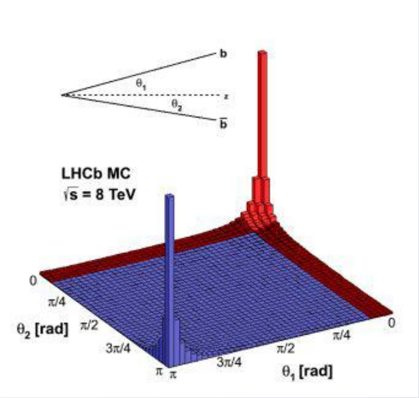
- The Large Hadron Collider beauty
- LHCb performance in LHC Run1 and 2
- LHCb Upgrades
- The Muon System and its future upgrade

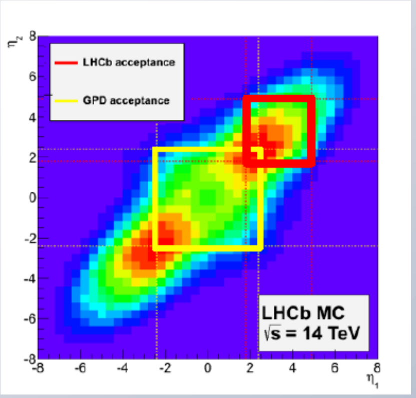
The Large Hadron Collider beauty

a dedicated b-physics experiment at LHC originally designed for a precise test of the SM and search of New Physics beyond it through the study of very rare decays of b-(and c) hadrons

Int. J. Mod. Phys. A 30, 1530022 (2015)







Extended physics program to QCD, EW, direct searches and heavy ion runs → Dedicated talk, C. De Angelis, Jul 14, 2023

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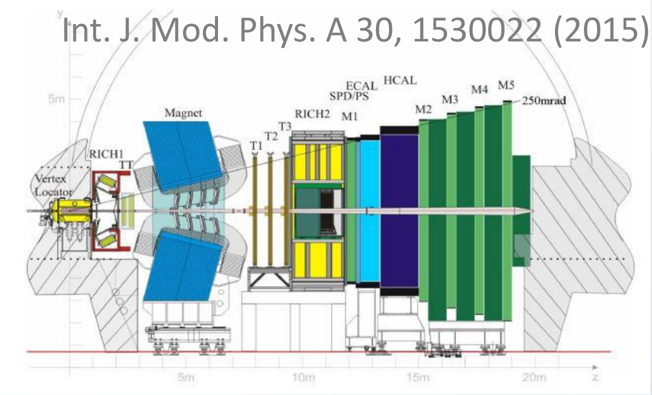
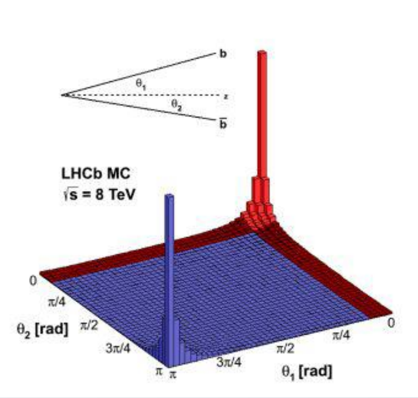
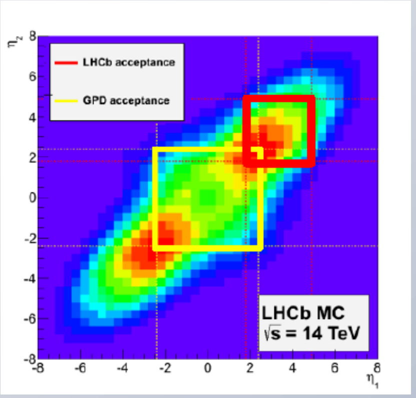
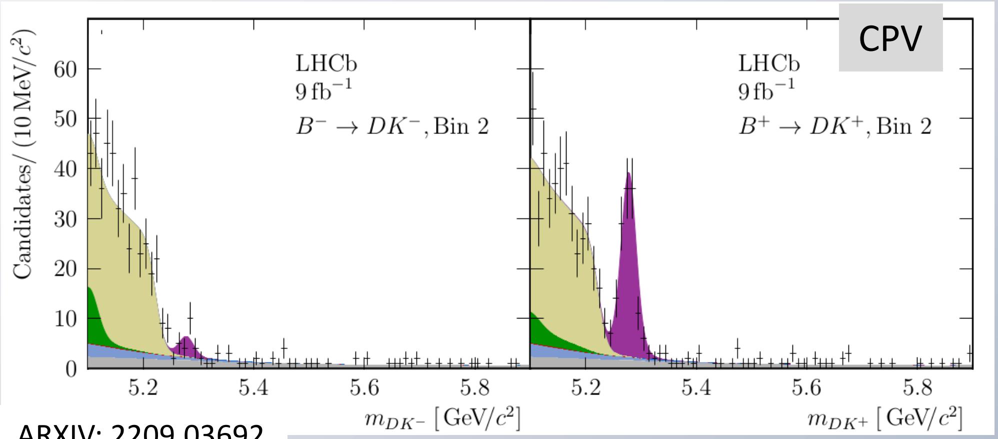






Extended physics program to QCD, EW, direct searches and heavy ion runs

a few examples …



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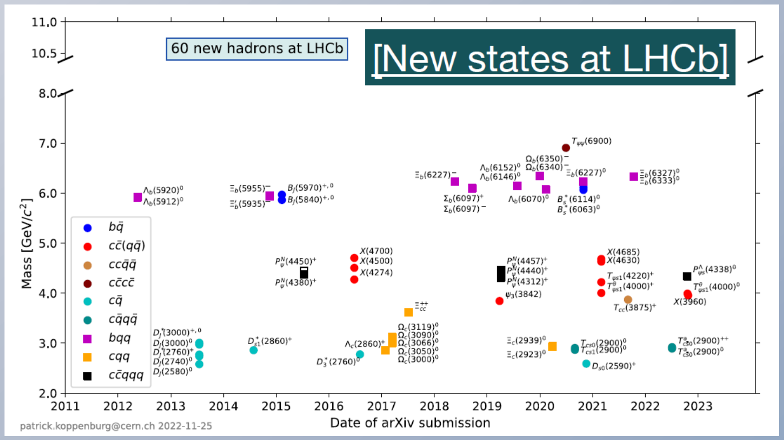
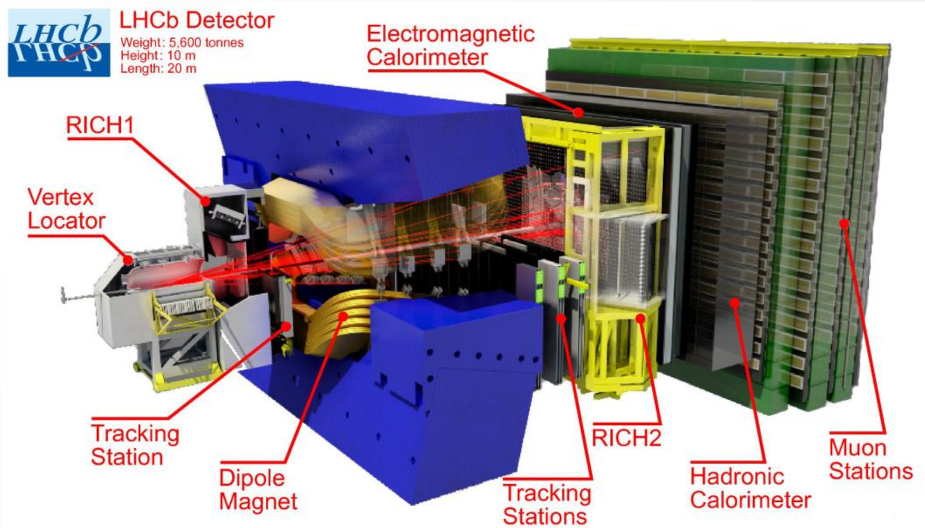


https://www.nikhef.nl/~pkoppenb/particles.html

LHCb performance in LHC Run 1 and 2

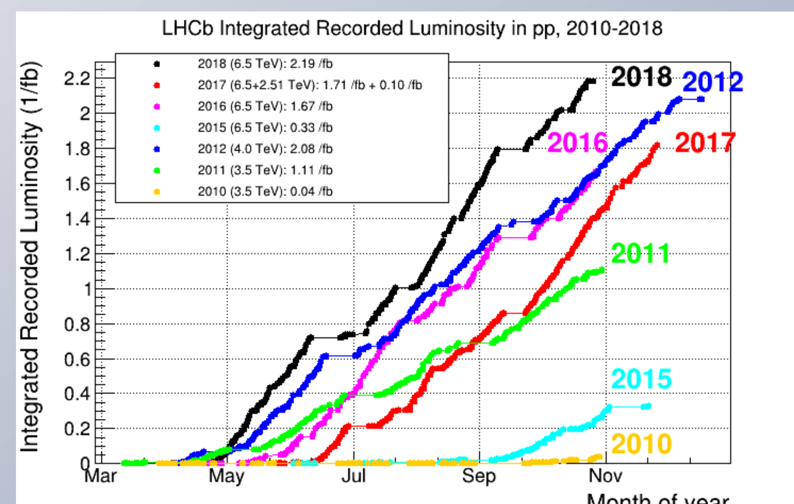


Excellent detector performance in Run1 and 2 of LHC:

- running at 2x design luminosity, 9 fb-1 collected in total
- ~ 1.5 interactions/bunch crossing

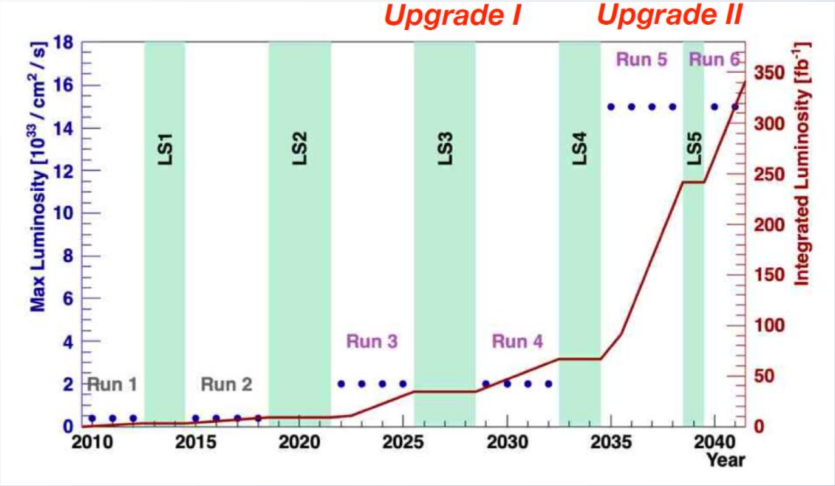
- $\boldsymbol{\Delta p/p} \sim \mathbf{0.5}$% below 20 GeV/c, ~ 1% at 200 GeV/c
- impact parameter resolution IP ~ $(\mathbf{15}+\ \mathbf{29}\boldsymbol{pT}$[GeV]) $\boldsymbol{\mu m}$
- decay time resolution $\boldsymbol{\sigma_t} \sim \mathbf{45}$ fs for $Bs \rightarrow J/\psi\varphi$
- PID efficiency (mis ID prob.): e ~ 90% (e→h ~ 5%),

  k ~ 95% (π→ K ~ 5%), μ ~ 97% (π→μ 1-3%)



Upgrading LHCb

beyond Flavor Physics, from exploration studies to precision studies

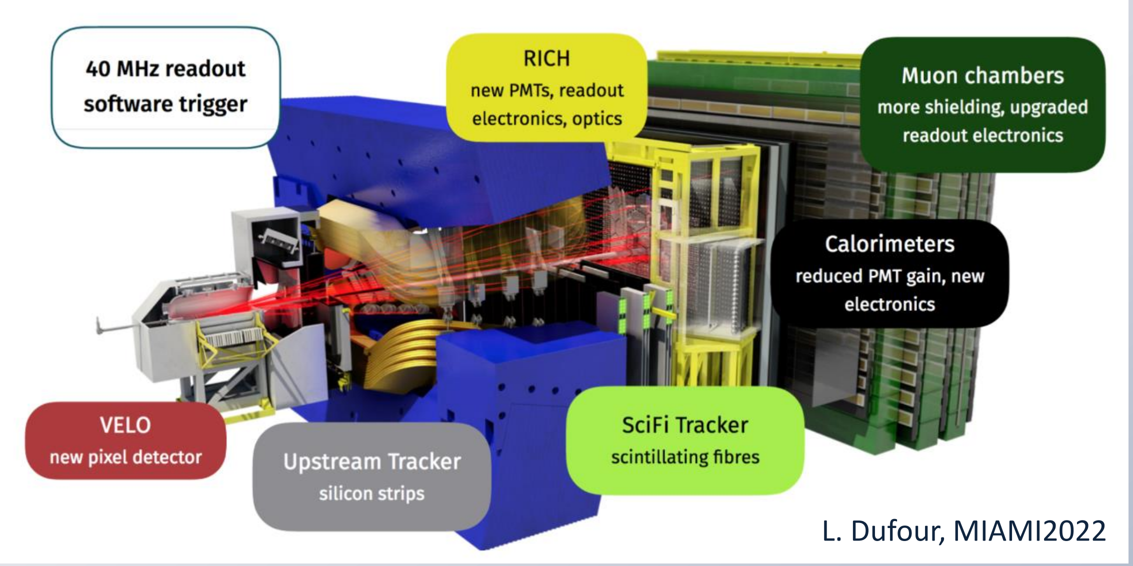


Observable	Current LHCb (up to $9\,\text{fb}^{-1}$)	Upgrade I ($50\,\text{fb}^{-1}$)	Upgrade II ($300\,\text{fb}^{-1}$)
CKM tests			
γ ($B \to DK$, *etc.*)	4°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	2%	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	7×10^{-4}	3×10^{-4}
Charm			
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-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%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—	—	0.2
$A_{\text{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	0.043	0.016
A_{T}^{Im} ($B^0 \to K^{*0}e^+e^-$)	0.10	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	0.097	0.038
Lepton Universality Tests			
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	0.005	0.002

https://cds.cern.ch/record/2776420/files/LHCB-TDR-023.pdf

LHCb upgrade I

- Increased luminosity up to $2*10^{33}$ cm^{-2} s^{-1} (5x)
- ~ 5 visible interactions/bunch crossing
- ~ 50 fb^{-1} expected in Run 3&4



https://arxiv.org/abs/2305.10515 , CERN-LHCC-2011-001

Major upgrade of the detector + purely software trigger with read out rate at 40 MHz

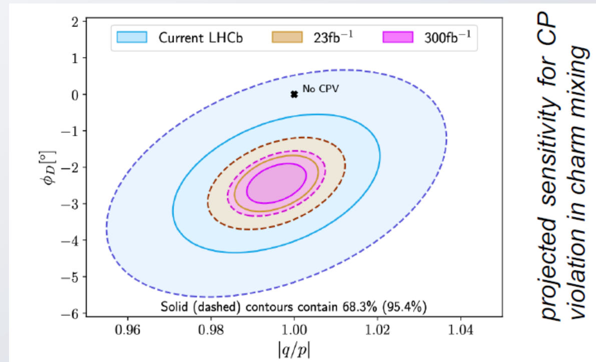
Partial reconstruction and selection to reduce data flow from 40 Tb/s to 1-2 Tb/s in HLT1(GPUs)
Detector alignment and calibration in real time
Full reconstruction with offline quality in real time in HLT2

Now taking data!

The future of LHCb

LHCC-2021-012

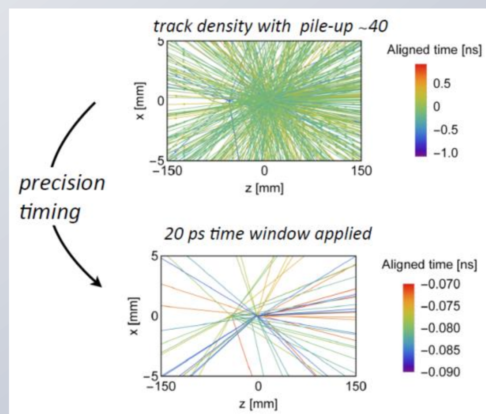
Unprecedented potential for heavy-flavour at the HL-LHC, but not only…



projected sensitivity for CP violation in charm mixing

Excellent technology case (granularity, timing, rad hard, ..)!

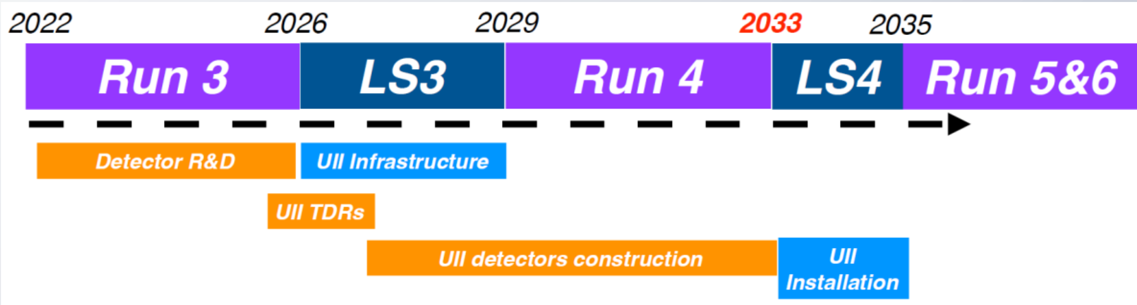
Extensive R&D campaign will be a bridge towards projects based at future accelerators



M. Palutan, LHCC May 30th 2023
https://cerncourier.com/a/lhcb-looks-forward-to-the-2030s/

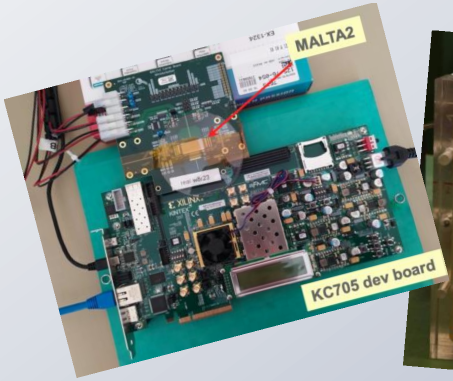
LHCb upgrade II

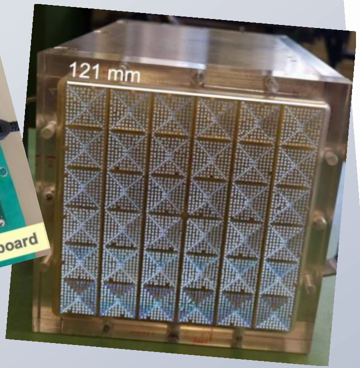
- L_{peak} = 1.5*10^{34} cm^{-2} s^{-1}
- ~ 40 visible interactions/bunch crossing
- ~ 300 fb^{-1} expected in Run 5&6

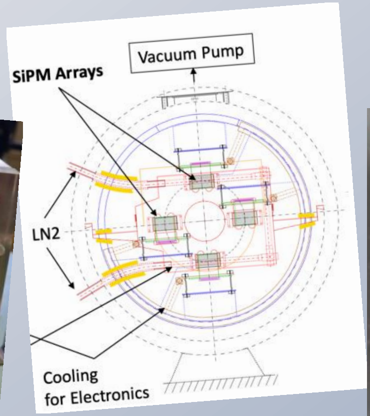


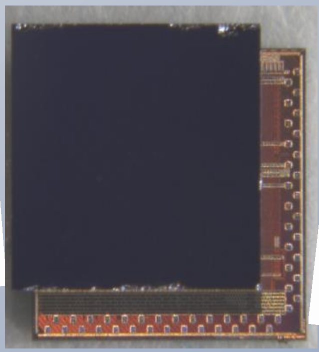
major change of the detector during LS4, to sustain the expected instantaneous luminosity

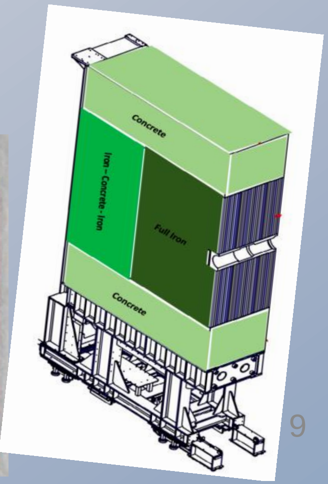
many R&D activities on-going for tracking, PID detectors and preparation of infrastructures





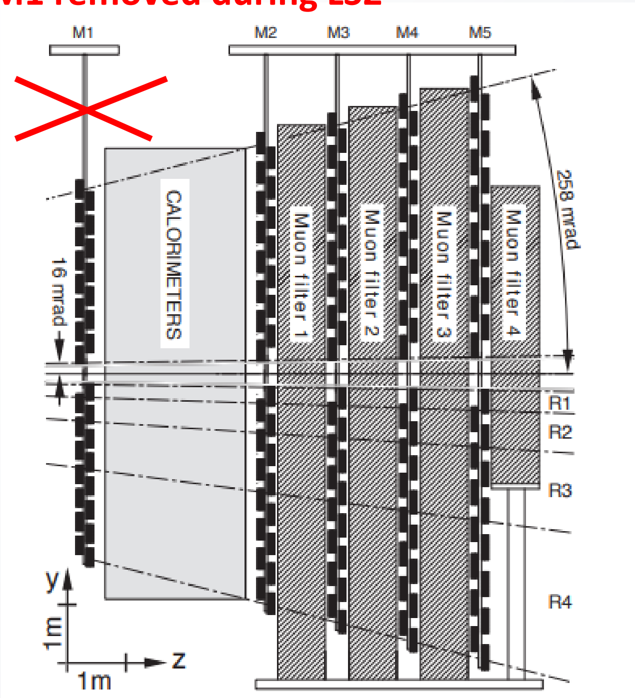


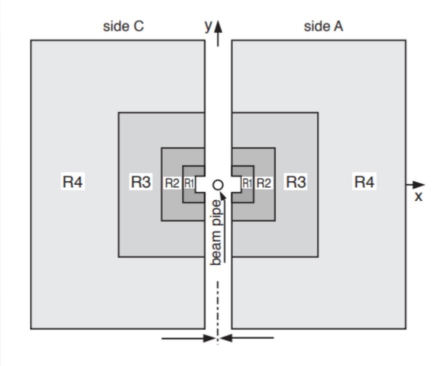




The current LHCb Muon System

M1 removed during LS2





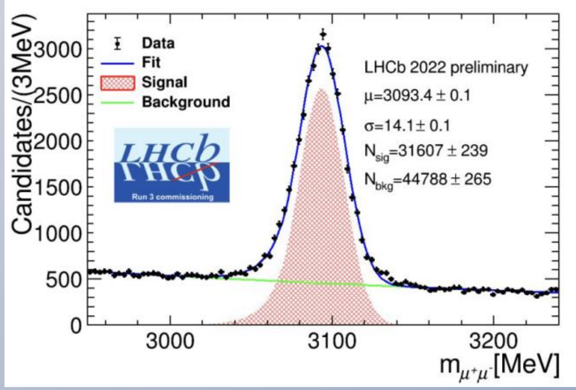
MWPC gas mixture:
Ar/CO2/CF4 (40/55/5)

four stations equipped with 4-gap multi-wire-proportional chambers alternated with iron absorbers.

As many physics channels are identified by a clear μ signature, its performance is crucial for the success of LHCb.

Excellent performance in Runs 1 and 2:

- Detection efficiency > 99% in all regions
- Muon ID efficiency ~ 97%
- No significant ageing

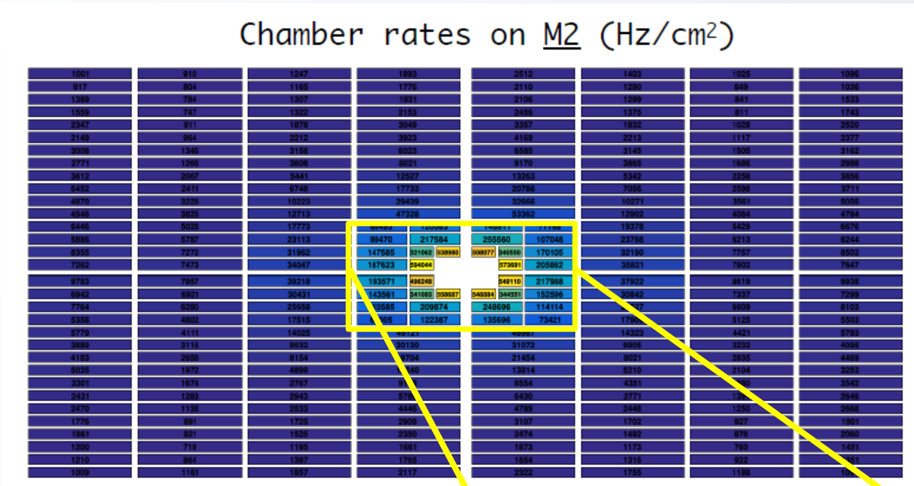


Run3 commissioning, J/Psi → μμ@HLT2

The future Muon System

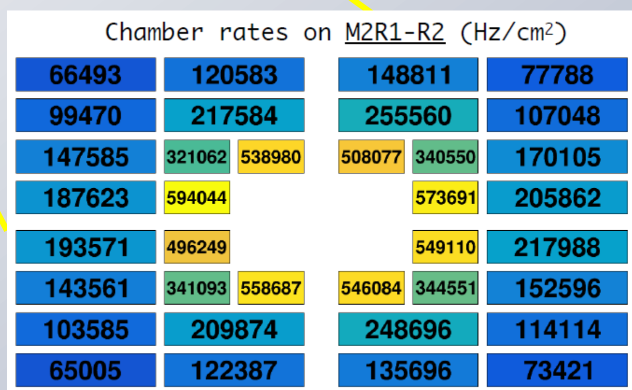
Challenge: maintain current sub-detector performance at U2

rate expected @U2 extrapolating from rates measured in Run 3



Limiting factors:
FEE deadtime for muon efficiency, high misID due to increased combinatorial rate & particle flux

Three "handles" to solve it, **under study**:
improved granularity, new electronics and additional shielding in front of M2



The future Muon System

Baseline option (under study)

- Inner regions (R1-R2): µRWells
- Outer regions (R3-R4): MWPCs at their full granularity

Increased number of channels and new FEE across the whole detector

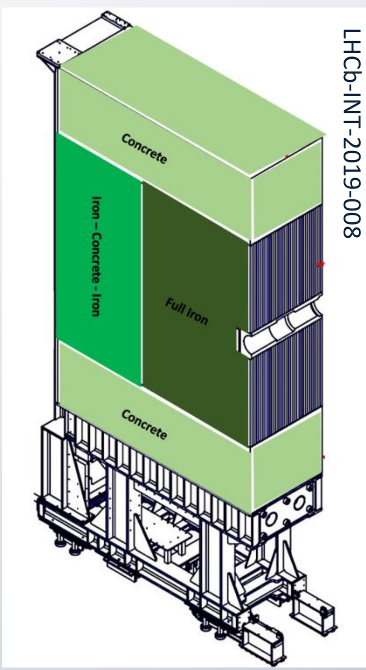
MUON U2 detector granularity

	# of chambers	Pad size cm×cm
M2R1	12	0.9×0.9
M2R2	24	0.9×1.8
M3R1	12	1.0×1.0
M3R2	24	1.0×1.9
M4R1	12	1.1×1.0
M4R2	24	1.1×2.1
M5R1	12	1.2×1.1
M5R2	24	1.2×2.2
M2R3	72	2.5×12.5
M2R3n	40	2.5×6.3
M2R4	128	5×25
M3R3	64	2.7×13.5
M3R4	176	5.4×27.0
M4R3	48	5.8×14.5
M4R4	192	5.8×29.0
M5R3	48	6.2×15.5
M5R4	192	6.2×31.0
Total	1104	

µRWell (M2R1–M5R2)

MWPCs (M2R3–M5R4)

Possible replacement of HCAL with a shielding (under study)



- R1-R3: full iron, $10.1\lambda_I$
- Median plane: iron/concrete/iron sandwich, $6.2\lambda_I$
- Top and bottom: concrete, $4\lambda_I$

Negligible muonID efficiency loss

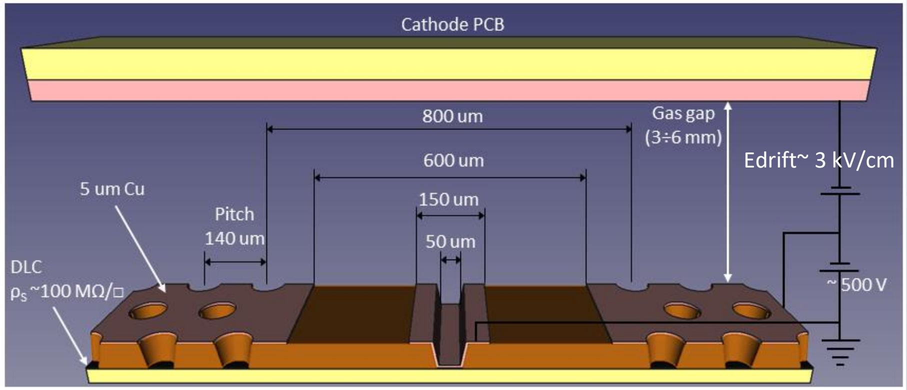
Maximum rate per region (black) and mitigation effect of the shielding (red)

Maximum chamber rate (kHz/cm²)				
	M2	M3	M4	M5
R1	594.0 -> 344.5	274.5	203.5	232.7
R2	255.6 -> 79.2	64.2	34.1	39.0
R3	53.4 -> 19.2	8.9	6.2	8.9
R4	9.9	3.0	1.7	6.8

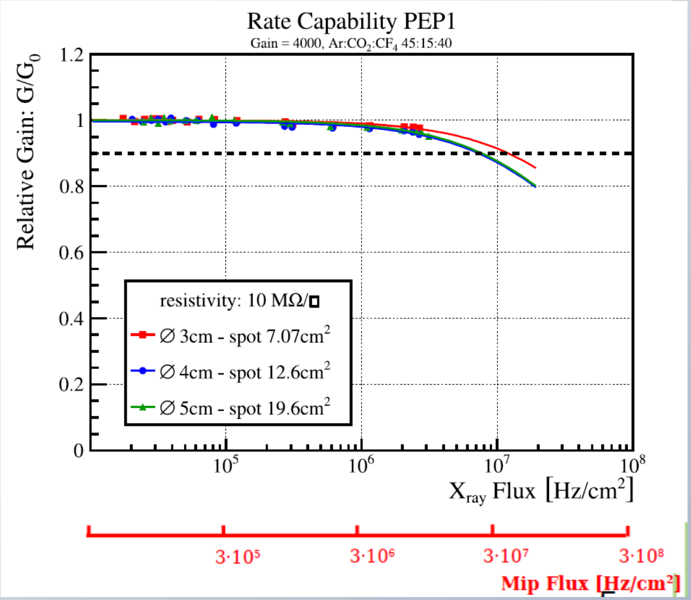
μRWELLs for the high rate inner regions

Current MWPC in R1-R2 → stack of 4 μRWELL gaps, size 30x25 to 74x31 cm^2

NIMA 1049 (2023) 168075, 2019-JINST 14 P05014, 2015-JINST 10 P02008



PEP: Patterning–Etching–Plating
- Single DLC layer ~100 nm-thick
- Grounding from top by Cu and kapton etching and plating
- scalable to larger size (prototype under test 10x10cm^2)



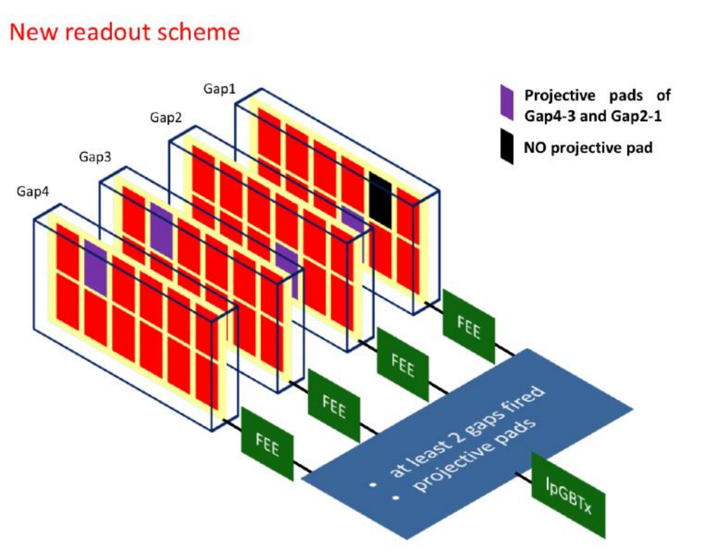
expected @U2, δ = 100ns

Maximum deadtime inefficiency % HCAL - μRWELL				
	M2	M3	M4	M5
R1	1.18	0.48	0.79	0.95
R2	1.22	0.32	0.31	0.41

Upgrade for the outer regions

Baseline option under study:

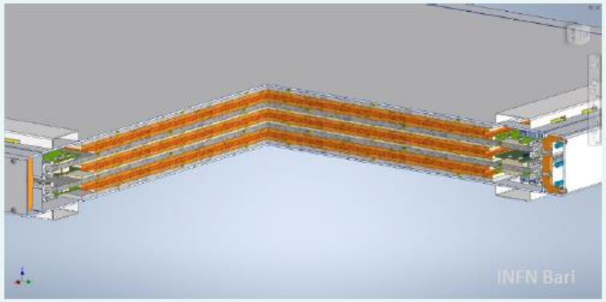
- Current MWPCs, at their full granularity
- The granularity will be increased in some regions as well.
- A good fraction of the present chambers will be reused.



Possible new readout scheme for the outer regions. The 4 gaps in the MWPC can be read individually to greatly reduce background rates, here requiring a majority 2/4 and projective fired pads.

Other detector options for the outer regions

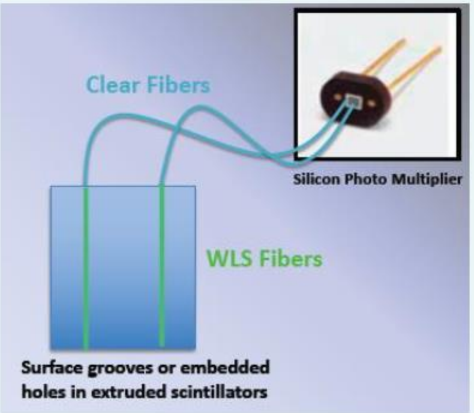
NEW GENERATION RPCs



Intense R&D activity ongoing:

- improve the rate capability (up to several kHz/cm^2) $\Rightarrow$ reduce electrode resistivity and thickness, reduce average charge per event
- study and optimize detector performance with eco-friendly gas mixtures

SCINTILLATING TILES



1-2 cm-thick tiles read out by WLS/clear fibers and SiPM

- Compact, easy-to-build solution
- Main drawback: radiation-induced SiPM damage $\Rightarrow$ adequate shielding against neutrons

Conclusion

The LHCb Upgrade II has been proposed to fully exploit the flavour physics opportunities of the High Luminosity era, probing a wide range of physics observables with unprecedented accuracy

As many physics channels are identified by a clear μ signature, the Muon System performance is crucial for the success of LHCb

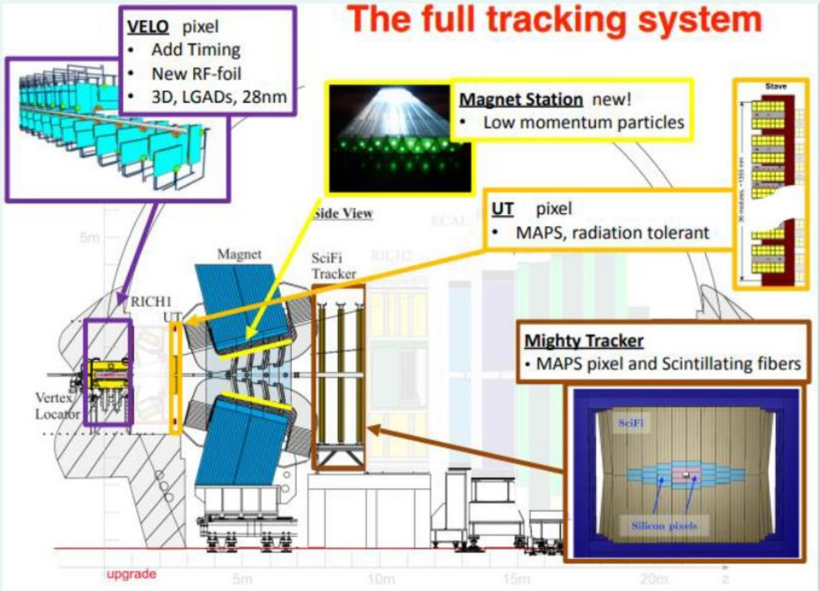
A new design for the Muon Detector is under study, in order to deal with the luminosity and readout rate increase while preserving its stable operation together with highly efficient μ detection capability.

An intense R&D activity on new technologies is currently ongoing heading to HL-LHC.

Backup

LHCb upgrade II

$\mathcal{L}_{peak} = 1.5 \times 10^{34}$ $cm^{-2}s^{-1}$ with ~ **40 visible interactions**
Expected to collect about 300 fb^{-1} in Runs 5+6



Detector challenge!

Key ingredients:
- improve granularity
- exploit timing
- radiation hardness

PID detectors