Upgrade II of the muon detector at LHCb

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on behalf of the LHCb collaboration

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09/07/2025

index

- The LHCb experiment:
  physics objectives and the Upgrade II perspective

- The muon detector *today*
  - μ-ID/misID performance

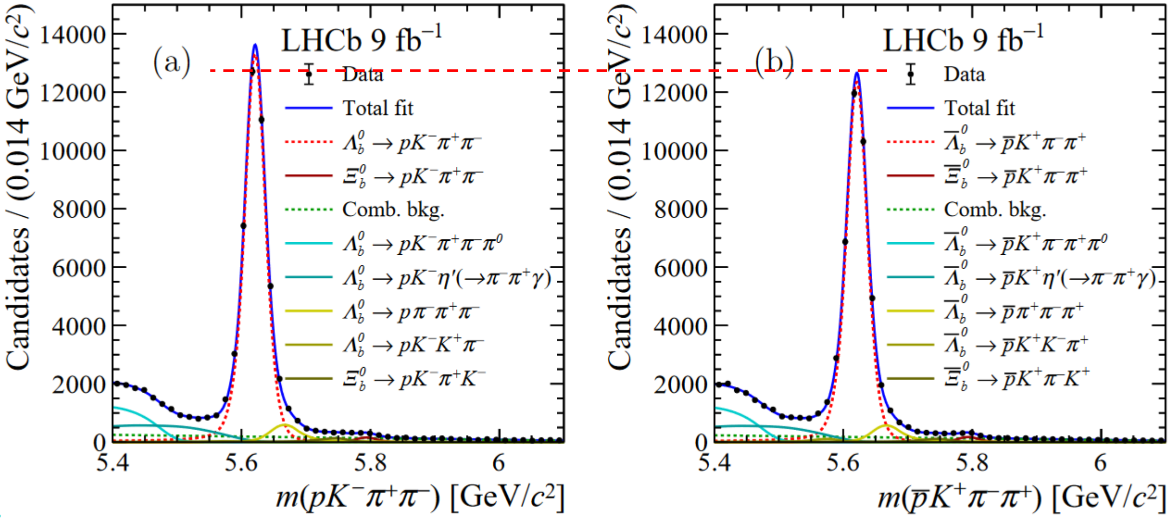
- The Upgrade II of the muon detector
  - The shielding
  - G-RWELL
  - New readout scheme
  - FATIC

LHCb physics objectives

Designed for CP violation and rare decays studies in the beauty flavour quark sector

CPV

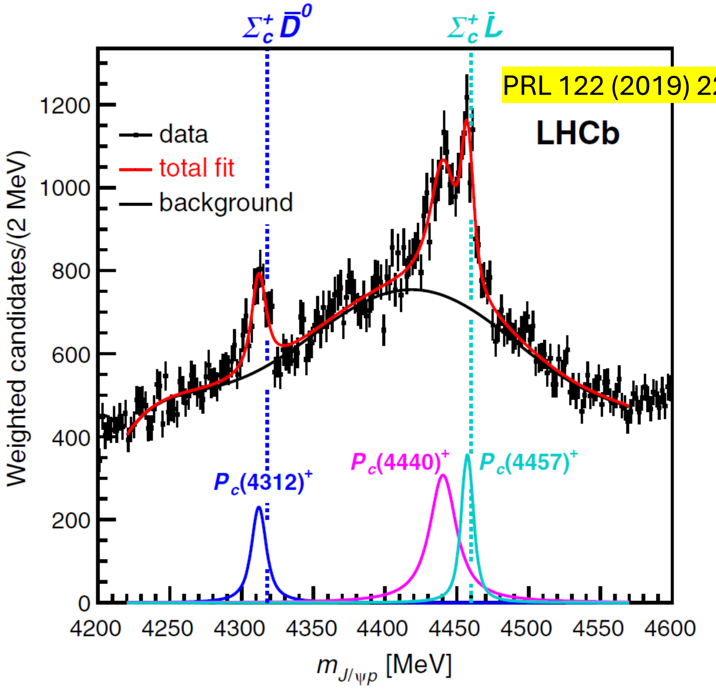
First CPV evidence (3.1σ) for baryons



ARXIV: 2503.16954

SPECTROSCOPY

New 5-quark P_c^+ state is observed, triggered by $\mu^+\mu^-$



PRL 122 (2019) 222001

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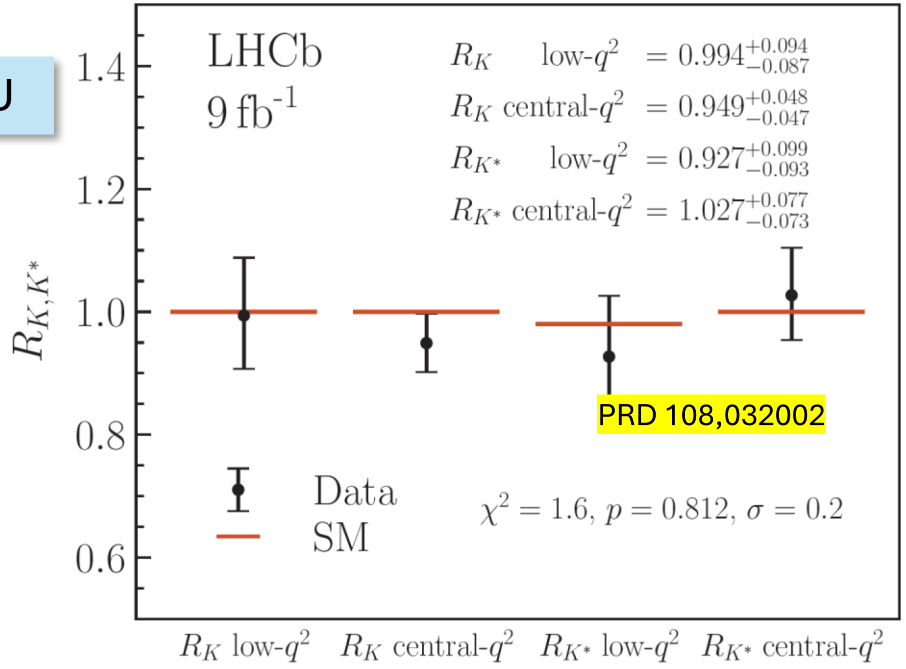
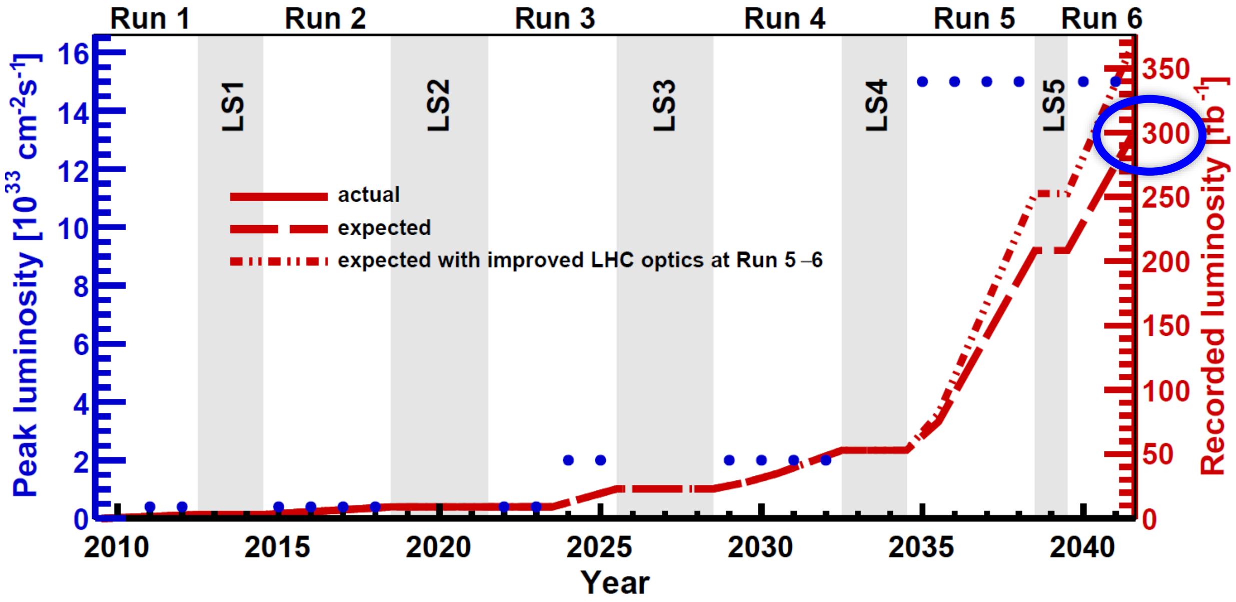


PRD 108,032002

High luminosity era

- Several hints of new physics (BSM) exist
- Absence of evidences suggests any New Physics is likely beyond the mass scale accessible at LHC.
- **Precision flavour physics measurements** would allow subtle effects of new particles on SM processes.



The **LHCb Upgrade II** is the key to achieving this goal, profiting of the future **LHC high luminosity era** ($L = 1 \cdot 10^{34}\ cm^{-2}s^{-1}$).

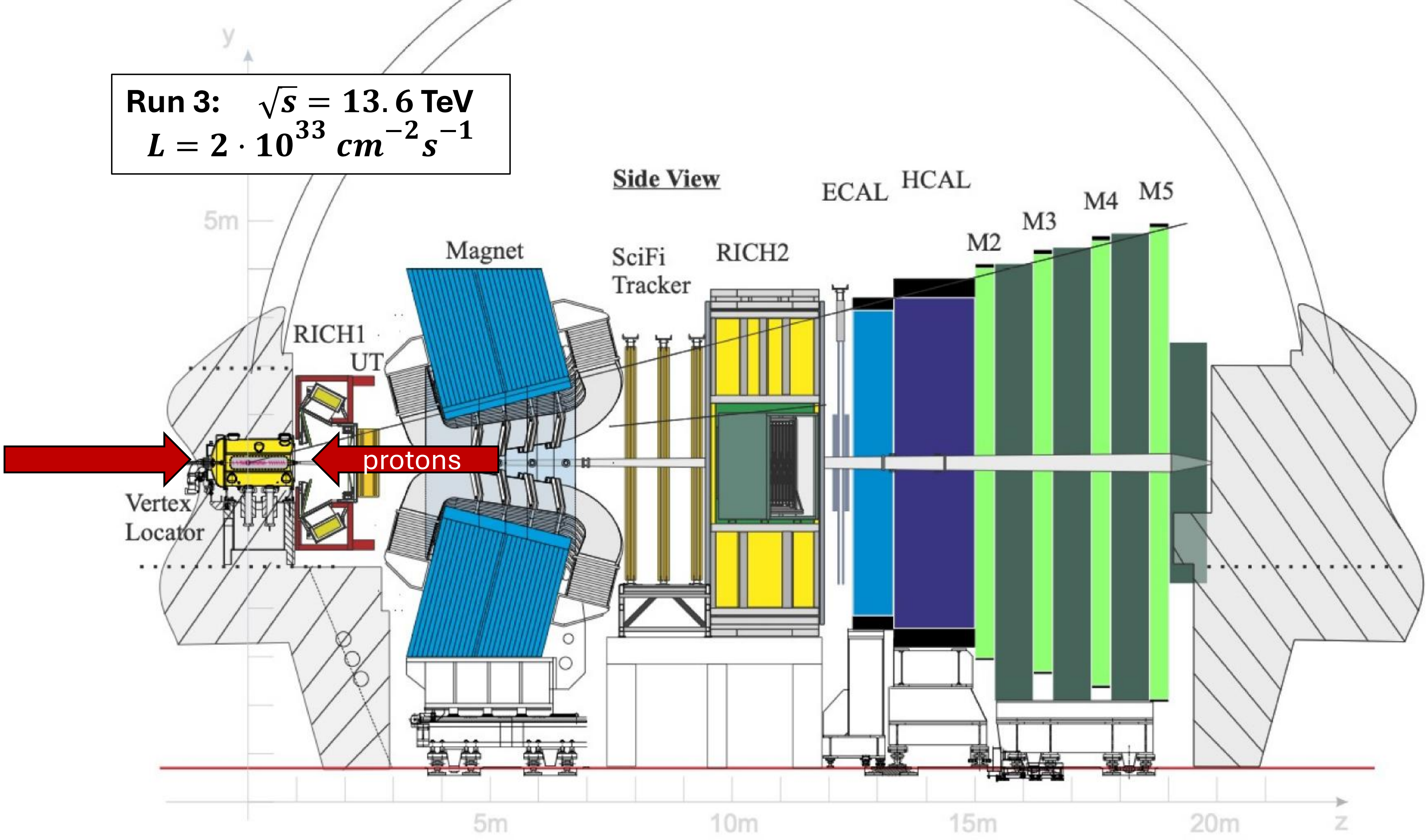
Anticipated uncertainties*:

[CERN/LHCC 2024-010 LHCb TDR 26]

Observable	Current LHCb (up to 9 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests			
γ ($B \to DK$, *etc.*)	2.8°	0.8°	0.3°
ϕ_s ($B^0_s \to J/\psi\phi$)	20 mrad	8 mrad	3 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	2%	1%
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 ($D^0 \to K^0_S\pi^+\pi^-$)	18×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare decays			
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	69%	27%	11%
$S_{\mu\mu}$ ($B^0_s \to \mu^+\mu^-$)	—	—	0.2
$A^{(2)}_{\mathrm{T}}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	0.043	0.016
$S_{\phi\gamma}(B^0_s \to \phi\gamma)$	0.32	0.062	0.025
$\alpha_\gamma(\Lambda^0_b \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	0.097	0.038

The LHCb apparatus

Run 3: $\sqrt{s} = 13.6$ TeV
$L = 2 \cdot 10^{33}\ cm^{-2} s^{-1}$



The Muon Detector

Run 3: $\sqrt{s} = 13.6$ **TeV**
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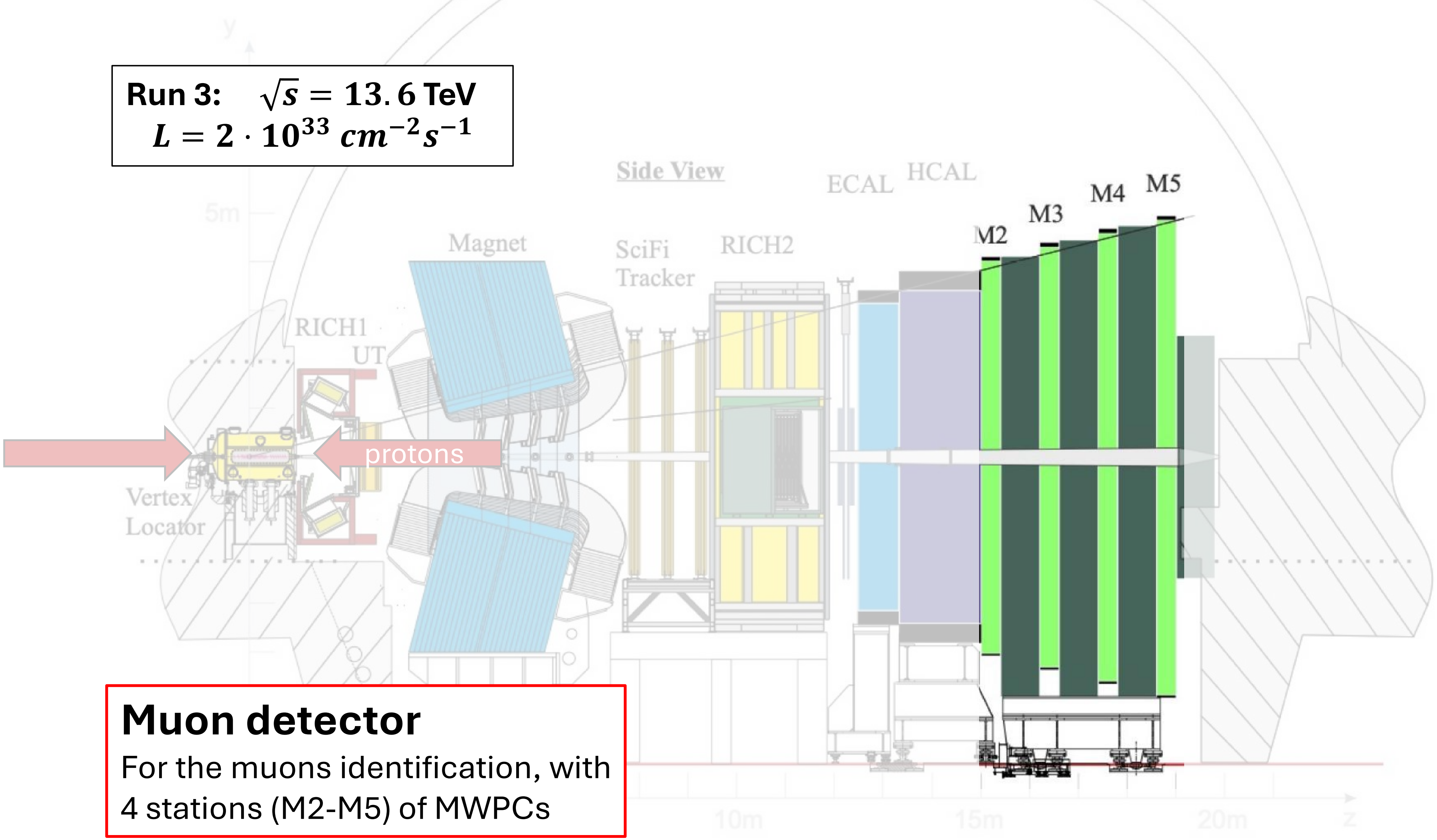
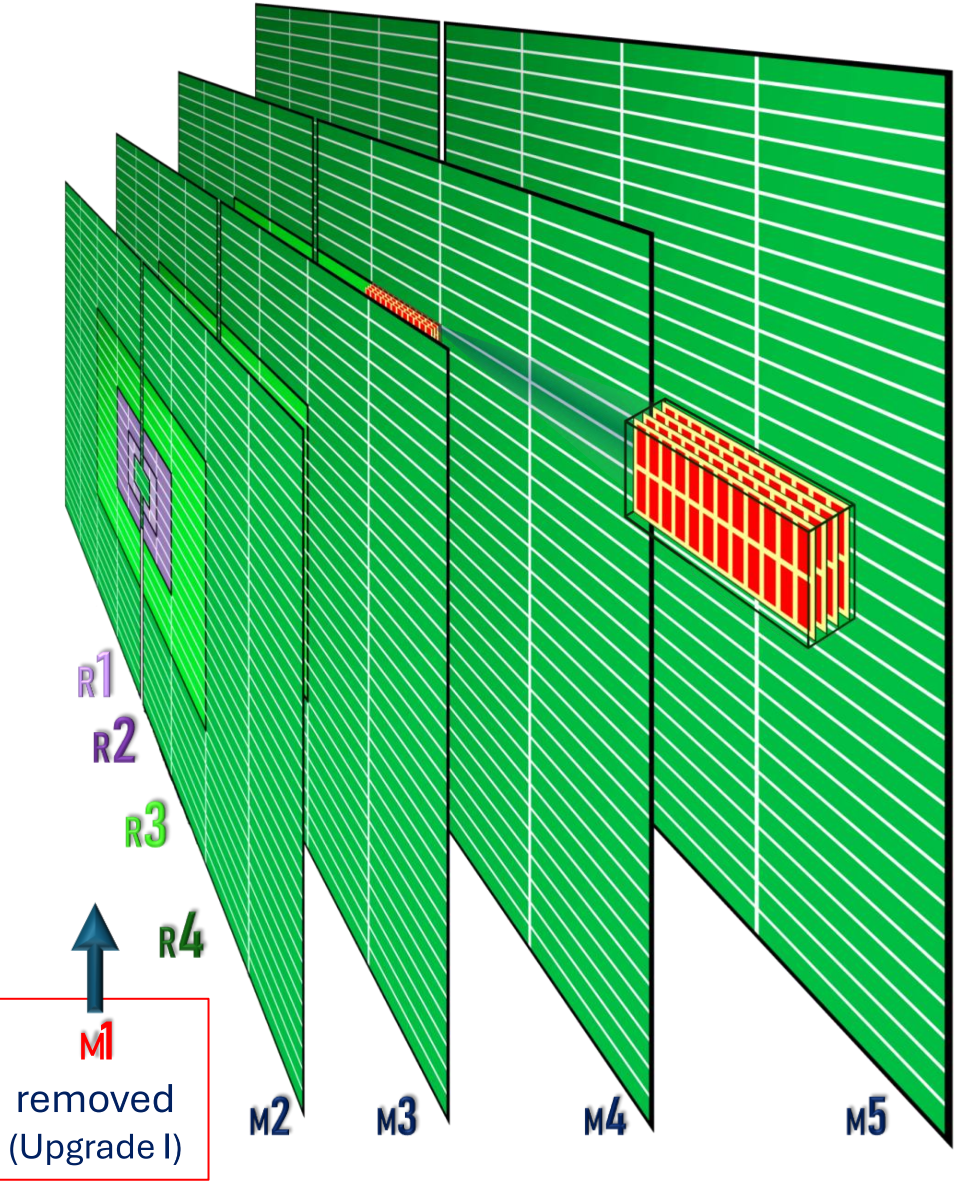


Muon detector

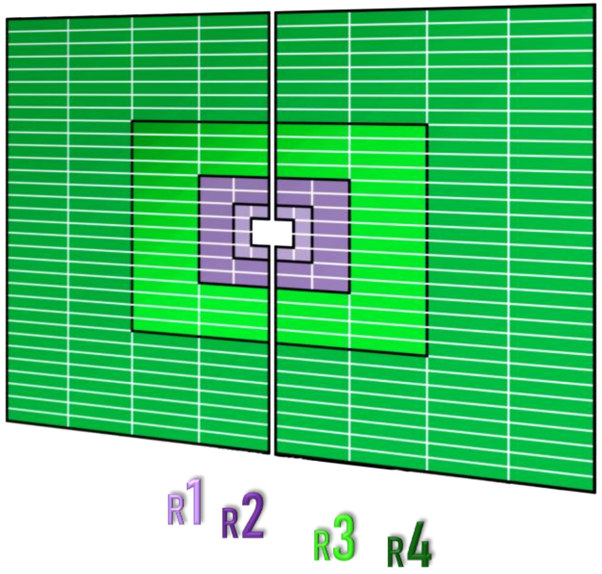
For the muons identification, with 4 stations (M2-M5) of MWPCs

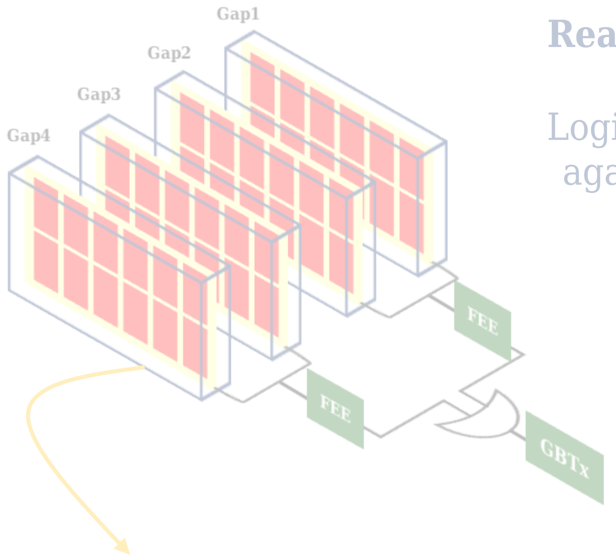
The Muon Detector



4 stations (M2-M4) of 4 gaps MWPCs, defining 4 regions (R1-R4).

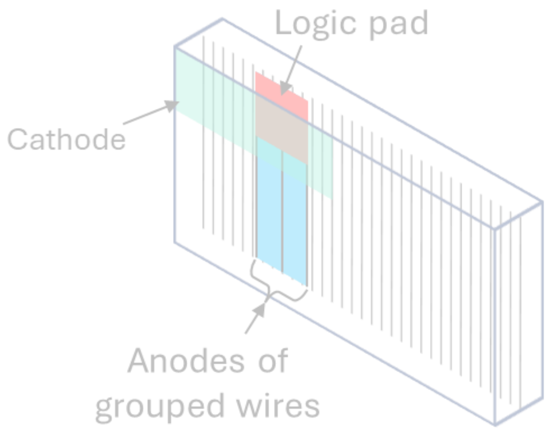
Iron absorbers, 80 cm thick, between the stations.





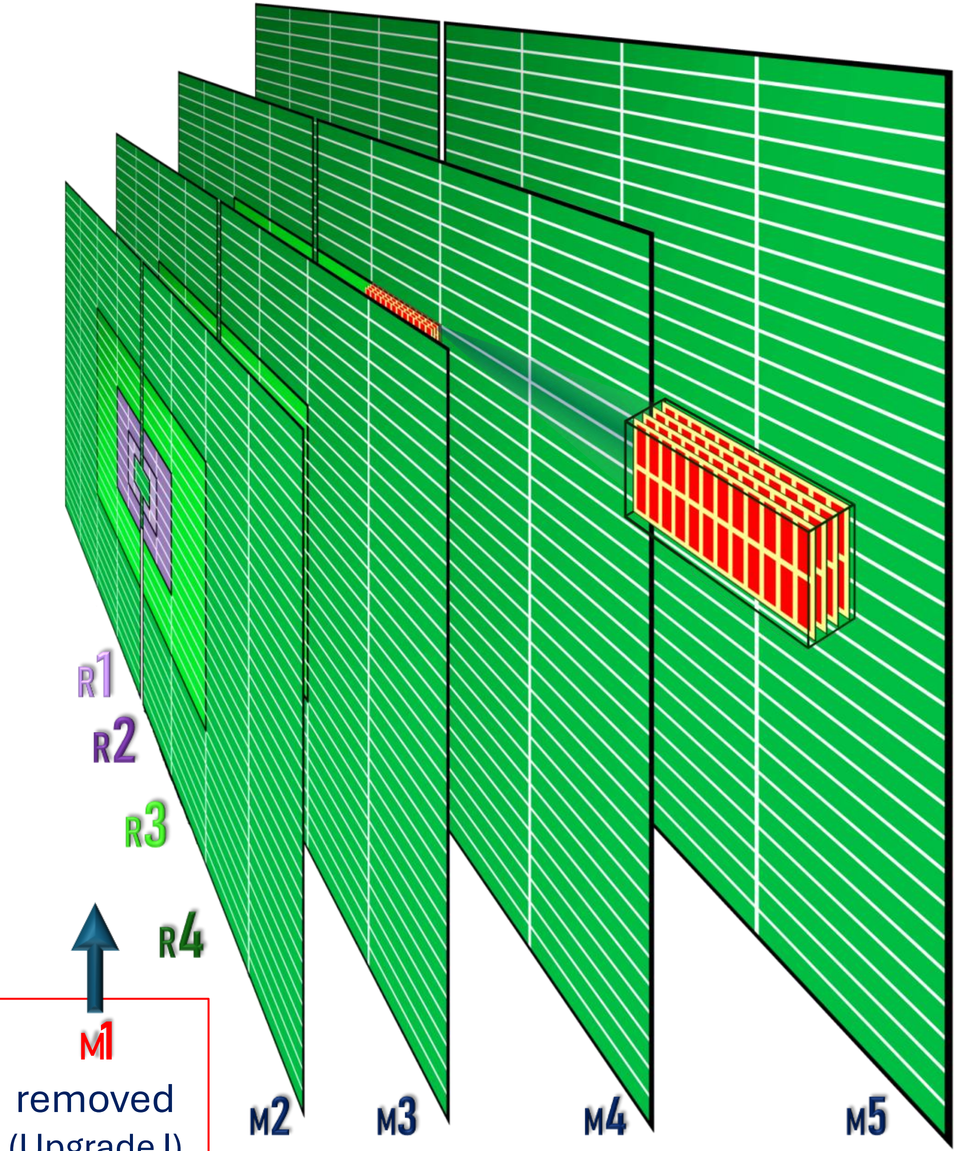
Readout scheme of chambers

Logical OR of bi-gap, again implemented at FEE level



For each gap, logical pads (red) from logical AND of grouped wires and cathodic pads

The Muon Detector



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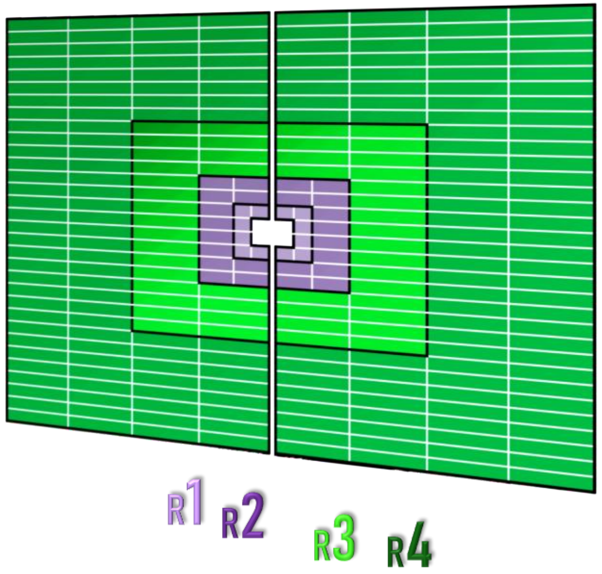

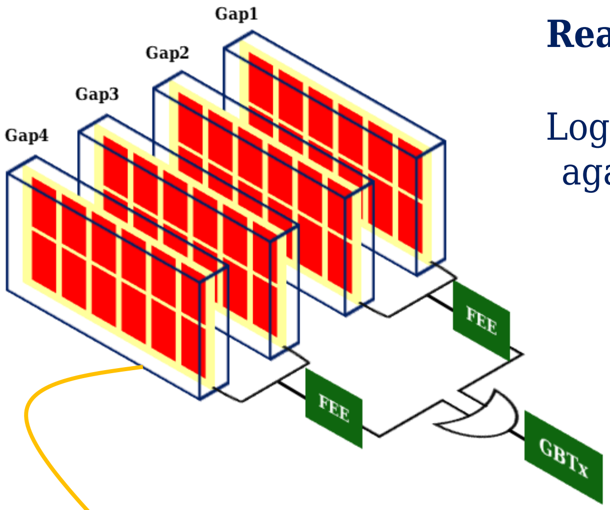

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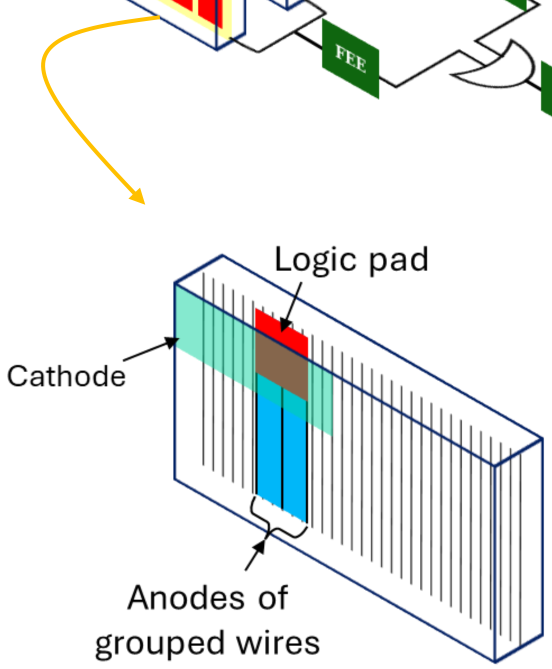

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Muon identification

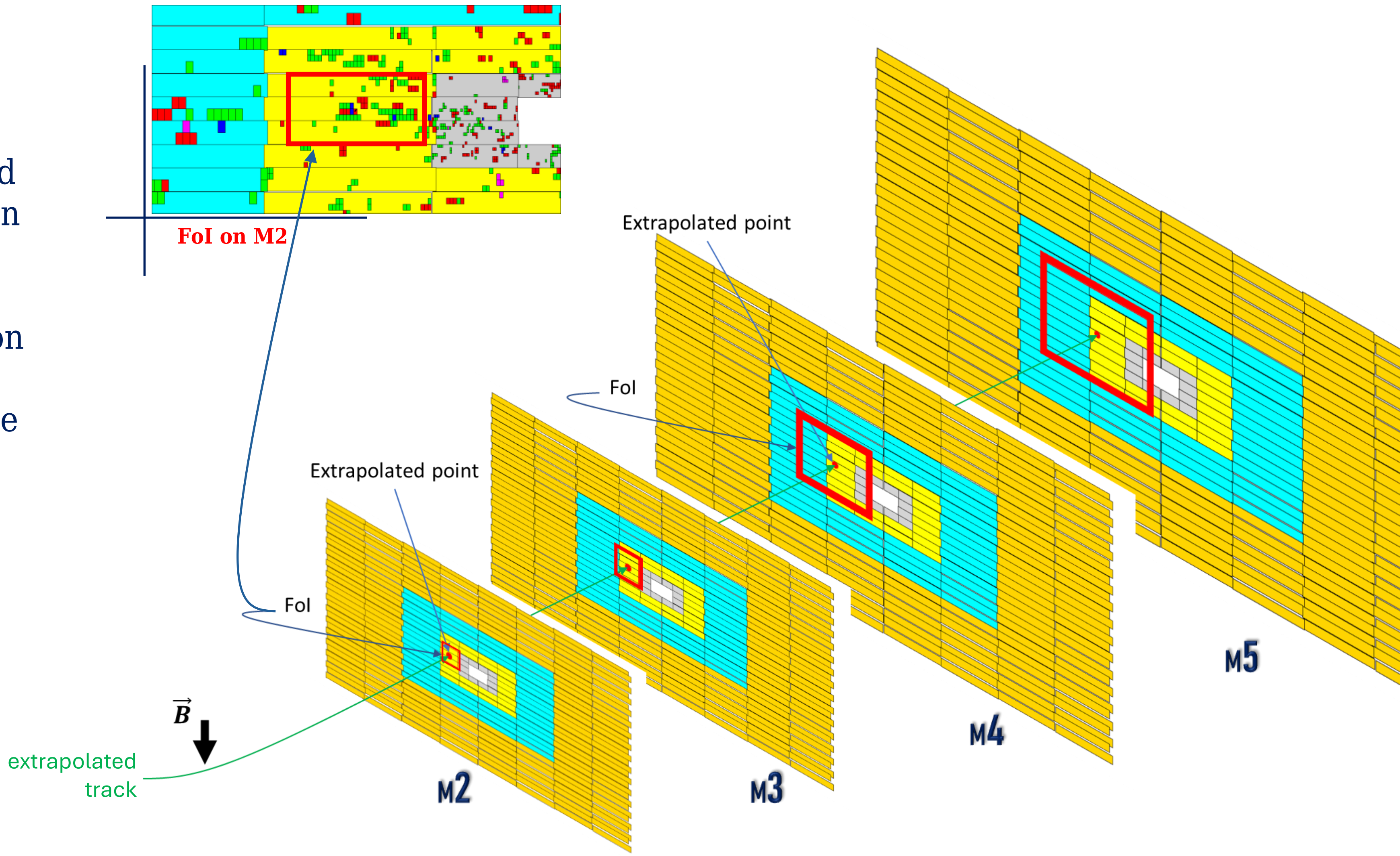
IsMuon, for the muons identification in Run3 at HLT1:

1. Open a Field of Interest (FoI) around the extrapolated track, depending on the momentum

2. Hit search in each FoI in each station

3. Check fired stations according to the track momentum:

p [GeV/c]	Track is a muon (isMuon)
$p < 3$	false
$3 < p < 6$	M2 & M3
$6 < p < 10$	M2 & M3 & (M4 || M5)
$p > 10$	M2 & M3 & M4 & M5

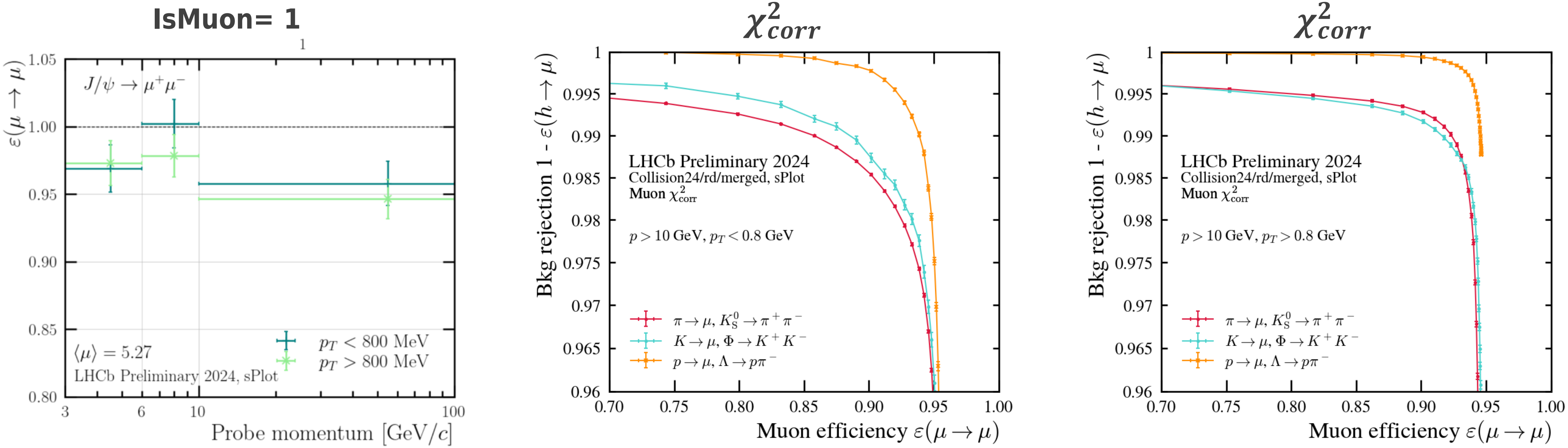


Muon misidentification

A further step in Run3 (at HLT1) for the mis-ID: **the χ^2_{corr} algorithm**.

Very efficient for muons mis-identification reduction,
accounting for hit position correlation between the stations due to multiple scattering

[JINST 15 (2020) T12005]



Data: rd_ap_2024 (AnalysisProduction!1670),
Block 7-8, FillNumbers 10196-10232

sPlot method: used for background subtraction

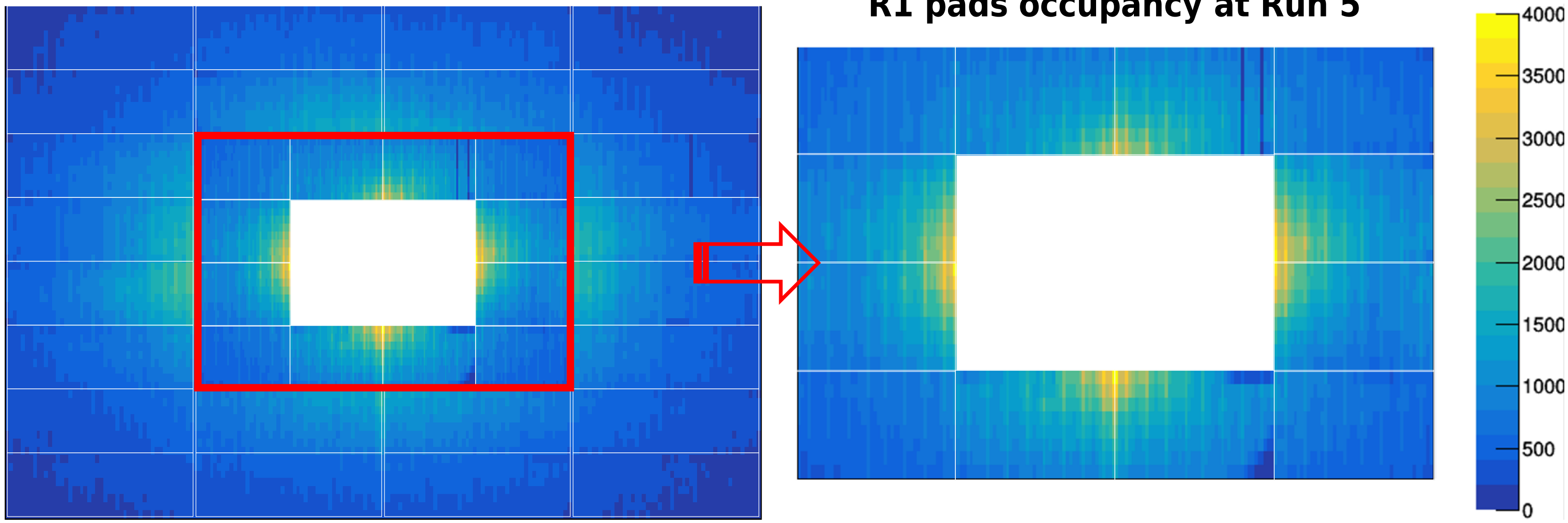
The expected rates at U2

LHC Run 3 data ($L = 2.0 \times 10^{33}\ cm^{-2}s^{-1}$) are used for particle rates extrapolation at Run 5 luminosity: $\boldsymbol{L = 1.0 \times 10^{34}\ cm^{-2}s^{-1}}$

Strong non-uniformity in the same chamber.

Pads occupancy at Run 5 of M2 R1-R2, most irradiated

R1 pads occupancy at Run 5



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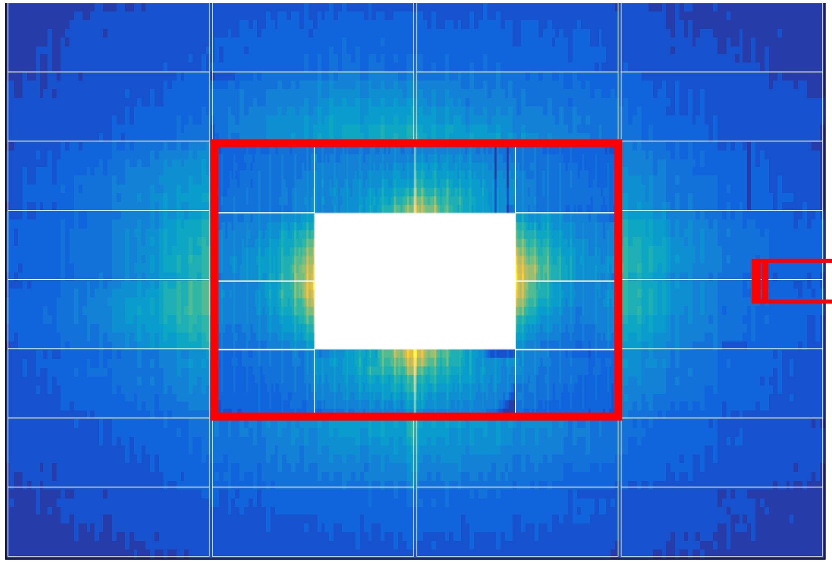
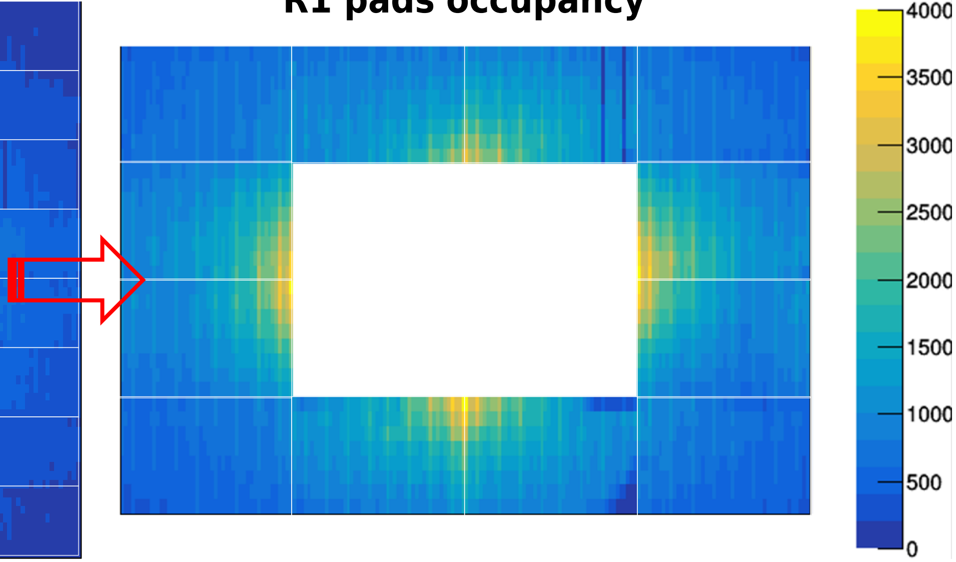


R1 pads occupancy



Maximum rate value: $\cong 1.3\ \mathrm{MHz/cm^2}$

$\cong$ 2 times the maximum average measured rates in M2R1 chamber.

Maximum rates (M2) in **Run 3**:
L = $2.0 \times 10^{33}\ cm^{-2}\ s^{-1}$

$R1_{max}$:	91	kHz/cm^2
$R2_{max}$:	30	kHz/cm^2
$R3_{max}$:	4.8	kHz/cm^2
$R4_{max}$:	1.7	kHz/cm^2

Maximum per region of the average rates in chambers

kHz/cm^2	R1	R2	R3	R4
M2	660.9	153.5	25.9	9.3
M3	219.8	38.2	4.7	1.6
M4	184.4	22.6	3.2	0.8
M5	155.6	13.2	2.9	2.2

The Muon Detector Upgrade II

Targeting same performance as usual

- ***Challenges* of the present detector in the future high luminosity *(rates)* era:**
  - **Efficiency loss** ← FEE dead time
    pads granularity very low for the expected rates (~1 MHz/cm^2)
  - **misID enhanced** ← High pile-up from background
    limited reduction of background hits

- ***Necessary "solutions"*:**
  - **Reduction of hit rates in the detector**
  - **Increase pads granularity**
  - **Background hits discrimination from signals (μ)**

- **Appropriate shielding**, in place of HCAL calorimeter, for background rate reduction
- **In R1-R2** (~1 MHz/cm^2 at Run 5):
  - ✓ New high performance detectors with granularity and rate capability improvement
- **In R3-R4** (rates ≤ 50 kHz/cm^2):
  - ✓ Reuse of most of the present **MWPCs**
- **A new readout scheme in all regions**, for background reduction and a new **FE electronics**

[LHCb-U2-FTDR]

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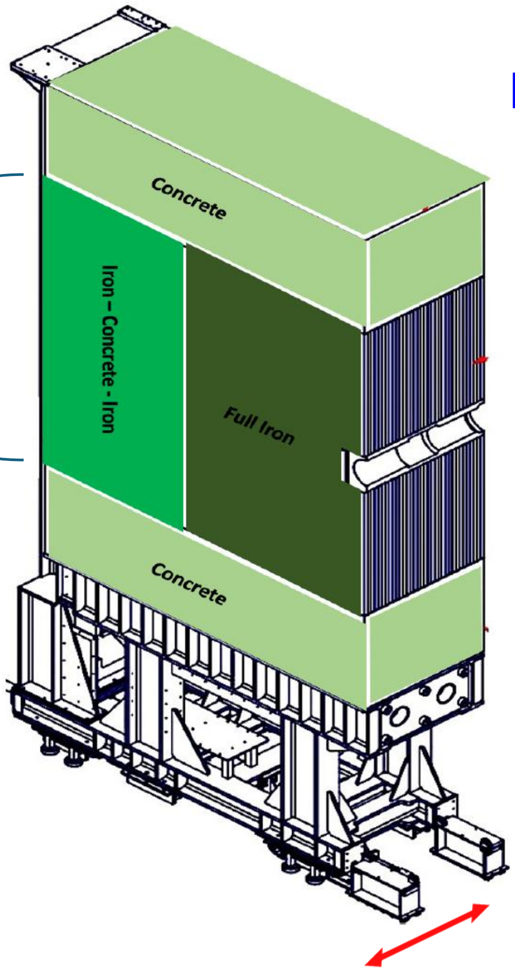
[LHCb-U2-FTDR]

Shielding

A shielding **in place of the HCAL** system is proposed at Upgrade II.

[LHCB-INT-2019-008]

iron-concrete-iron-NeutronAbsorber ($6.2\ \lambda_I$), acting on M2M3R4



Iron-NeutronAbsorber ($10.1\ \lambda_I$), acting on M2M3R1-R3

concrete-NeutronAbsorber ($4\ \lambda_I$), acting on M2M3R4

Shielding effects on the background rate, according to simulation:

		rates reduction
M2	R1	-30%
	R2	-40%
	R3	-60%
	R4	-40%
M3	~	-10%

Further studies are ongoing, optimising materials choice, in order to maintain the HCAL

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[LHCb-U2-FTDR]

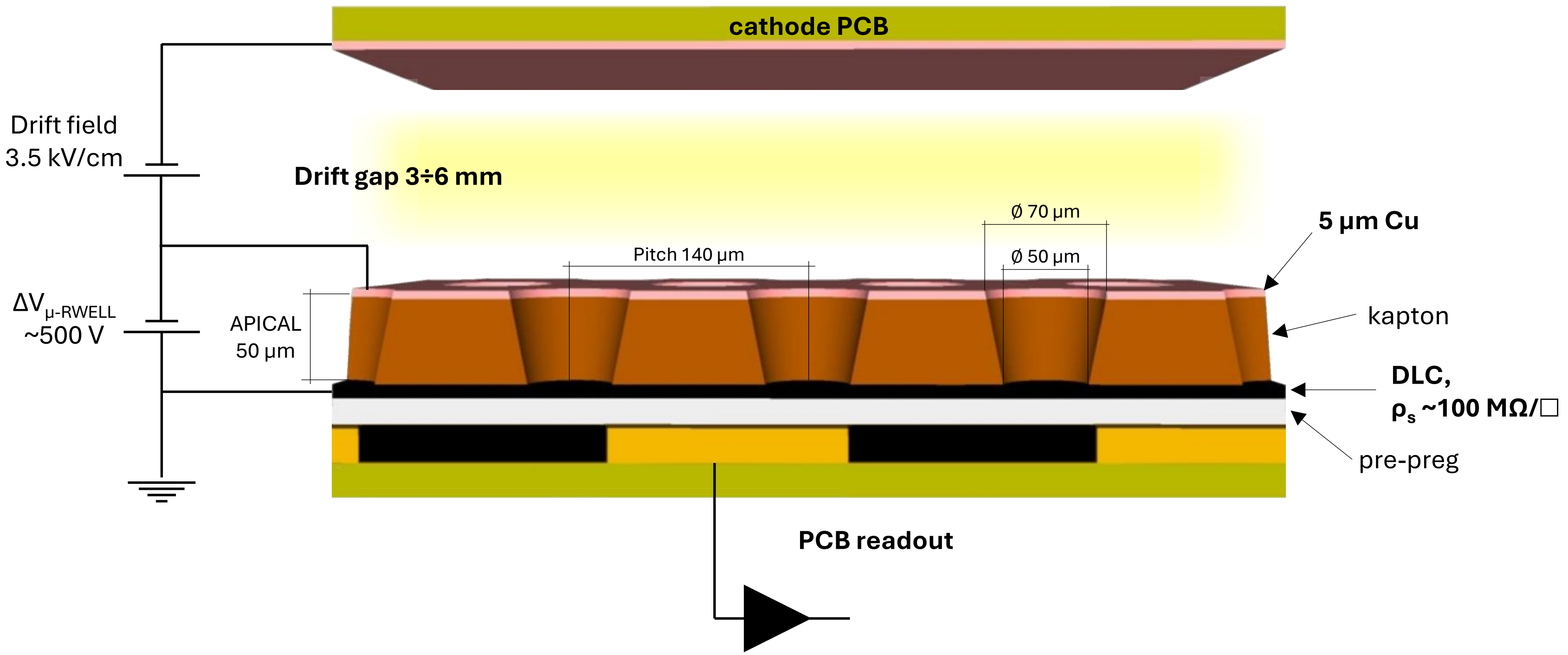
Detectors for inner regions R1-R2

Evolution of the μRWELL technology:

MicroPattern Gas detector (MPGD) consisting of:

- cathodic plane
- Gaseous drift region
- μRWELL:
  - well foil (copper + kapton)
  - resistive layer
- Pad readout

G. Bencivenni et al., The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD, 2015 JINST 10 P02008



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- Pad readout

Ionisation from drift region is amplified in wells, generating an avalanche. Discharges are suppressed by the resistive layer.

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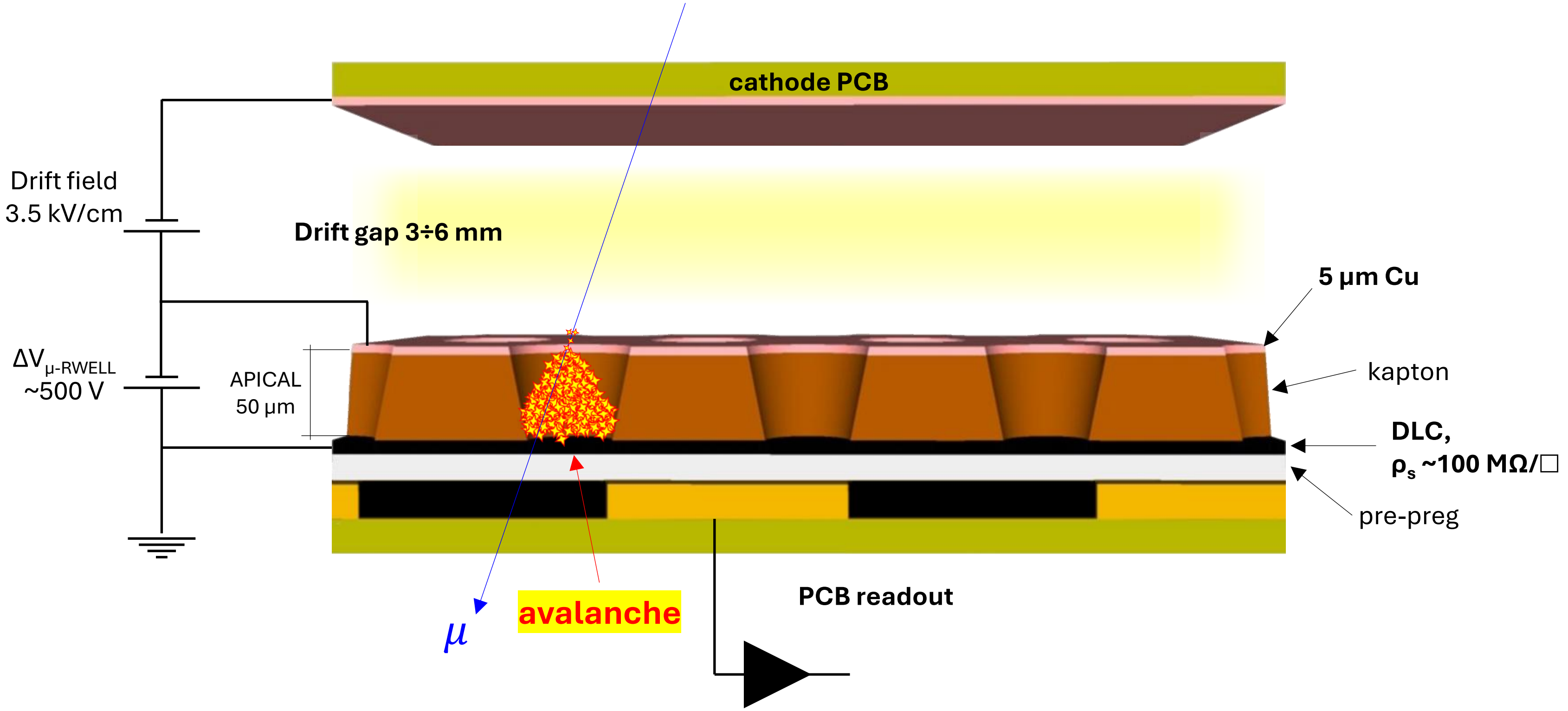
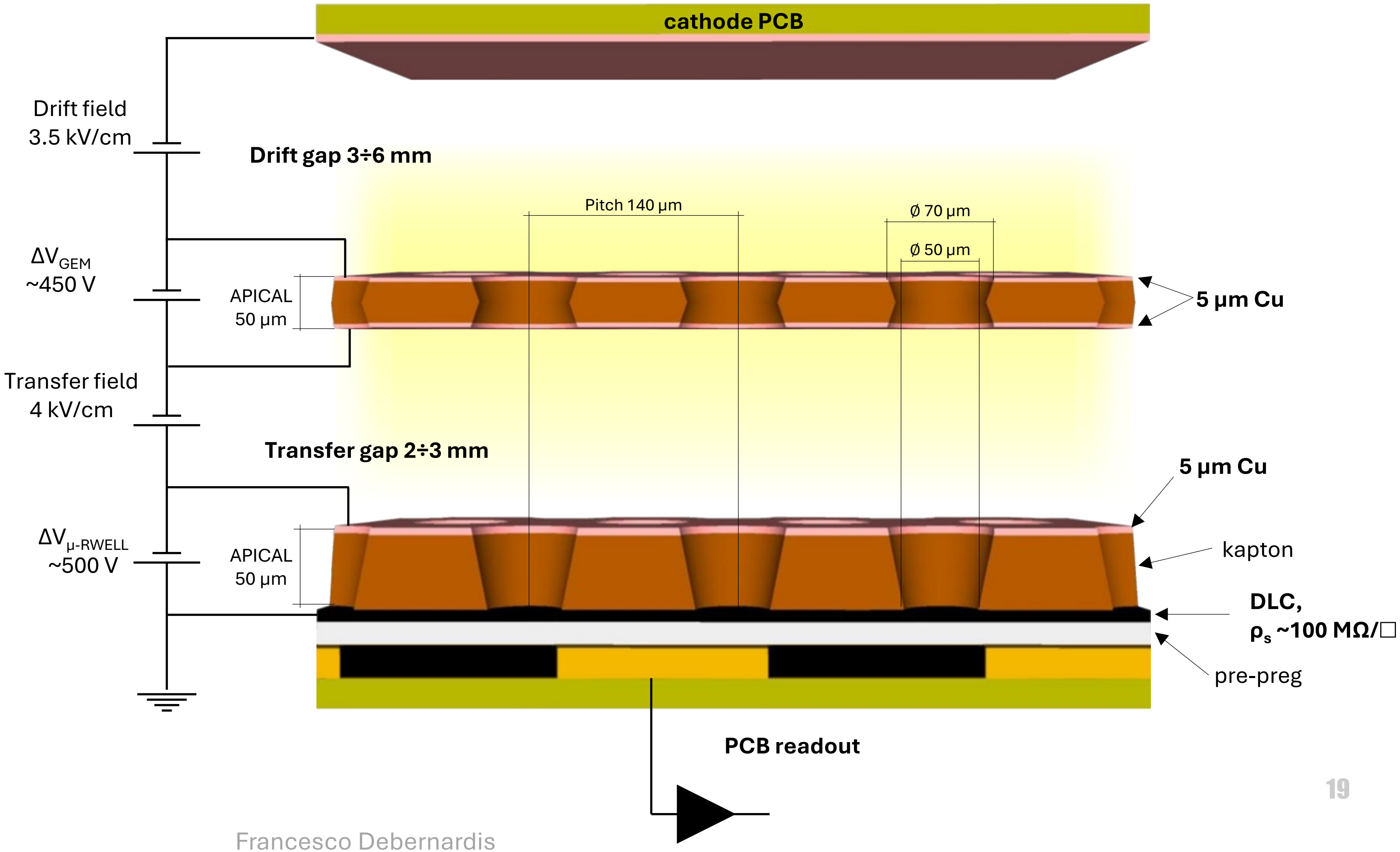


The G-RWELL

a GEM foil added
in the μRWELL drift region

The **G-RWELL** consists of:

- cathodic plane
- Gaseous <u>drift region</u>
- GEM foil
- Gaseous <u>transfer region</u>
- μRWELL



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a GEM foil added in the μRWELL drift region

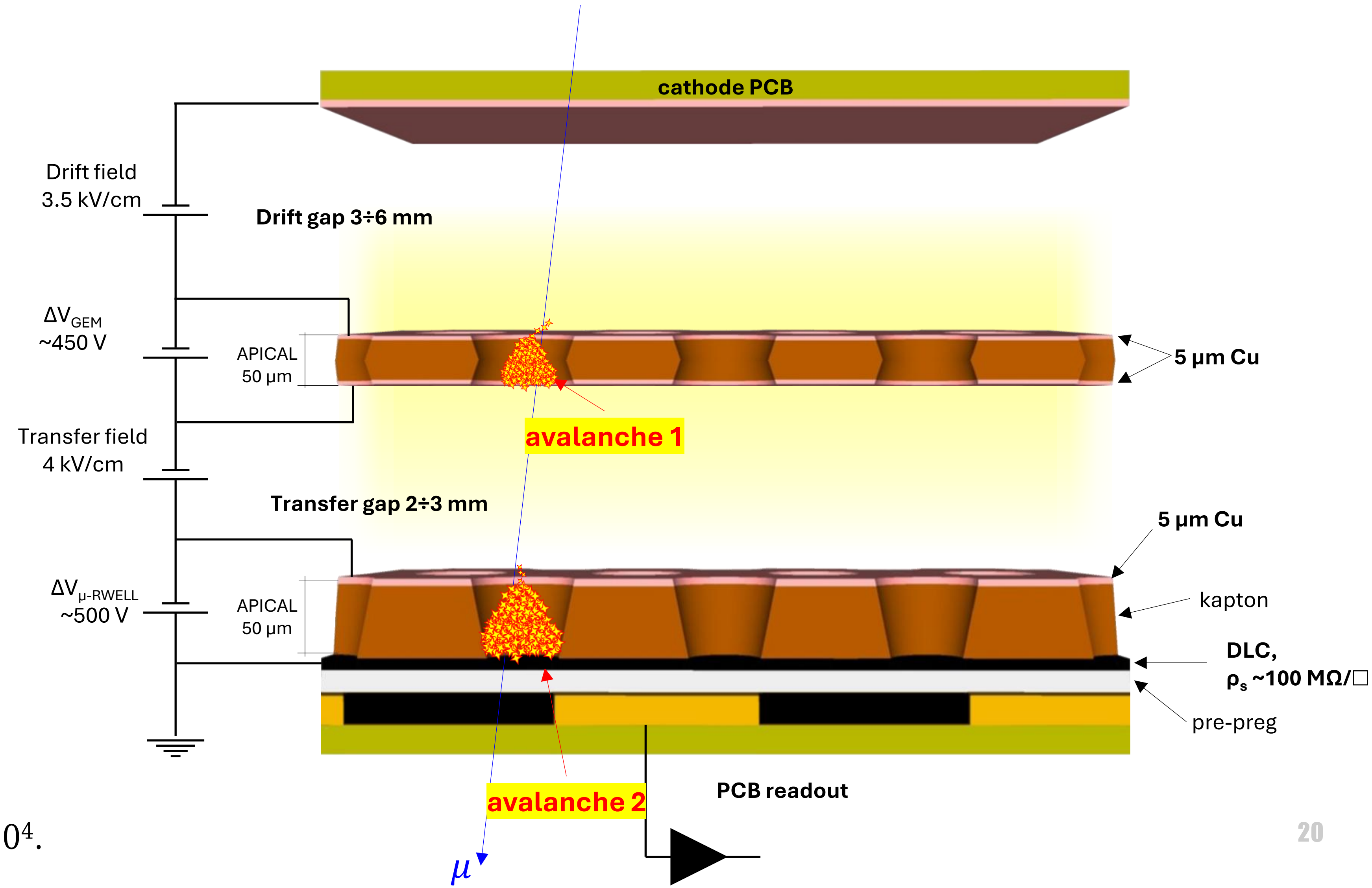
The **G-RWELL** consists of:

- cathodic plane
- Gaseous drift region
- GEM foil
- Gaseous transfer region
- μRWELL

Two amplification stages in very stable operation:

- Pre-amplification at GEM stage
- Amplification at μRWELL stage

Gas gains significanly greater than 10^4.

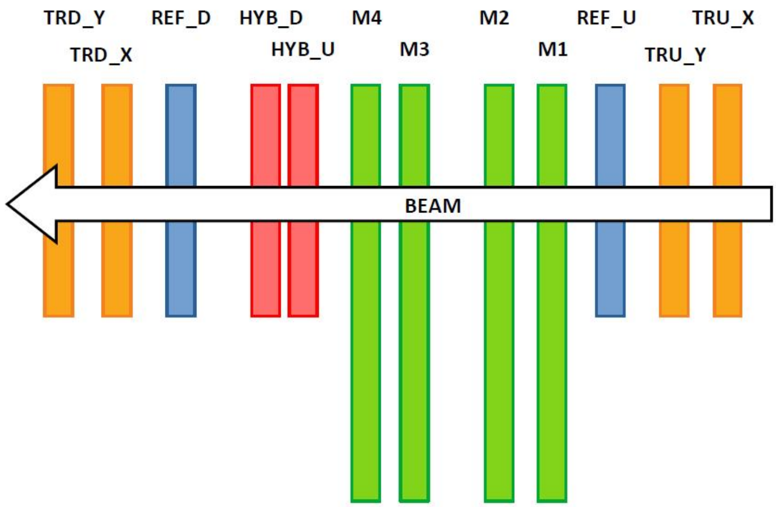


The G-RWELL

A tested technology!
(TB November 2024)

A rich setup of 12 detectors, including both **μRWELL and G-RWELL** has been tested.

A new FEE (**FATIC3**, see below) has been used, with a dedicated software for data analysis.

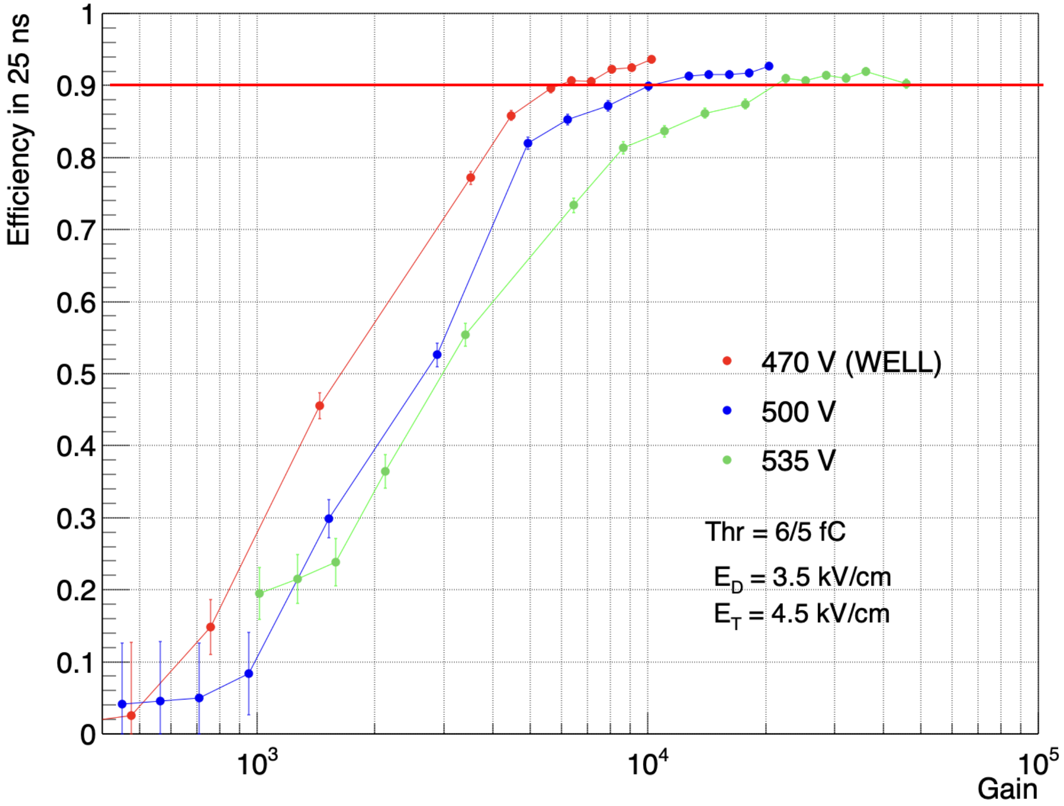


FEE: **16 FATIC3** FEE boards
Trackers: 10×10cm^2 - 1.2mm strip R/O (Capacitive Sharing)
Reference: 10×10cm^2 - 9×9mm^2 pad R/O
HYBRID: 10×10cm^2 - 9×9mm^2 pad R/O
M2R1: 30×25cm^2, instrumented 15×13cm^2 - 9×9mm^2 pad R/O
Gas MIXTURE: $Ar/CO_2/CF_4$ = 45/15/40
TB area: PS-T10 w/ 5 GeV muons

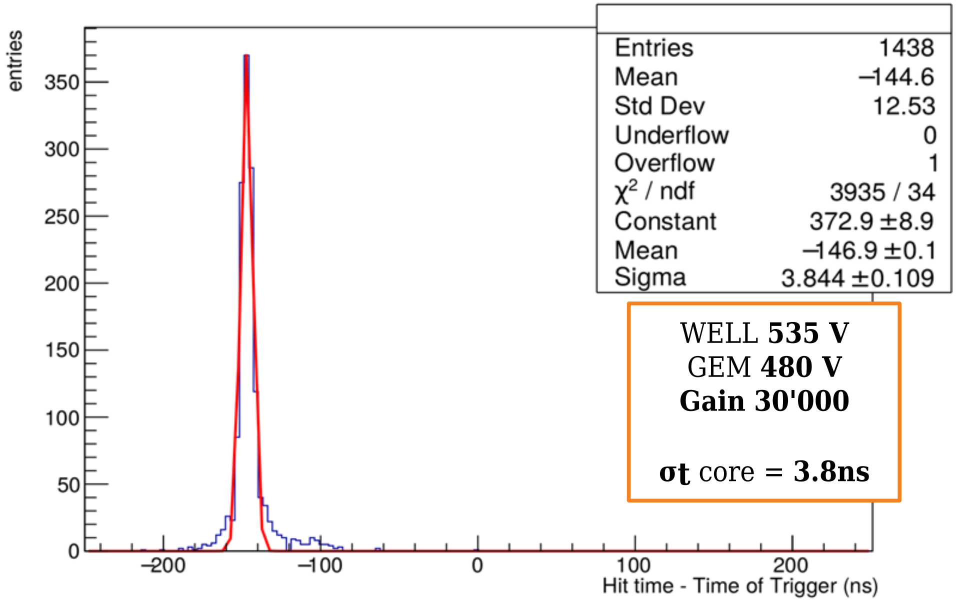
...with very promising results

The G-RWELL performance

...with very promising results



An efficiency of 90% within 25 ns for a single gas gap is achieved at a gas gain of 10^4, which is to be considered well within safe detector operational limits.



The time resolution of a G-RWELL is as good as 3.8 ns.

Further analysis on the data from the test beam is still ongoing

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[LHCb-U2-FTDR]

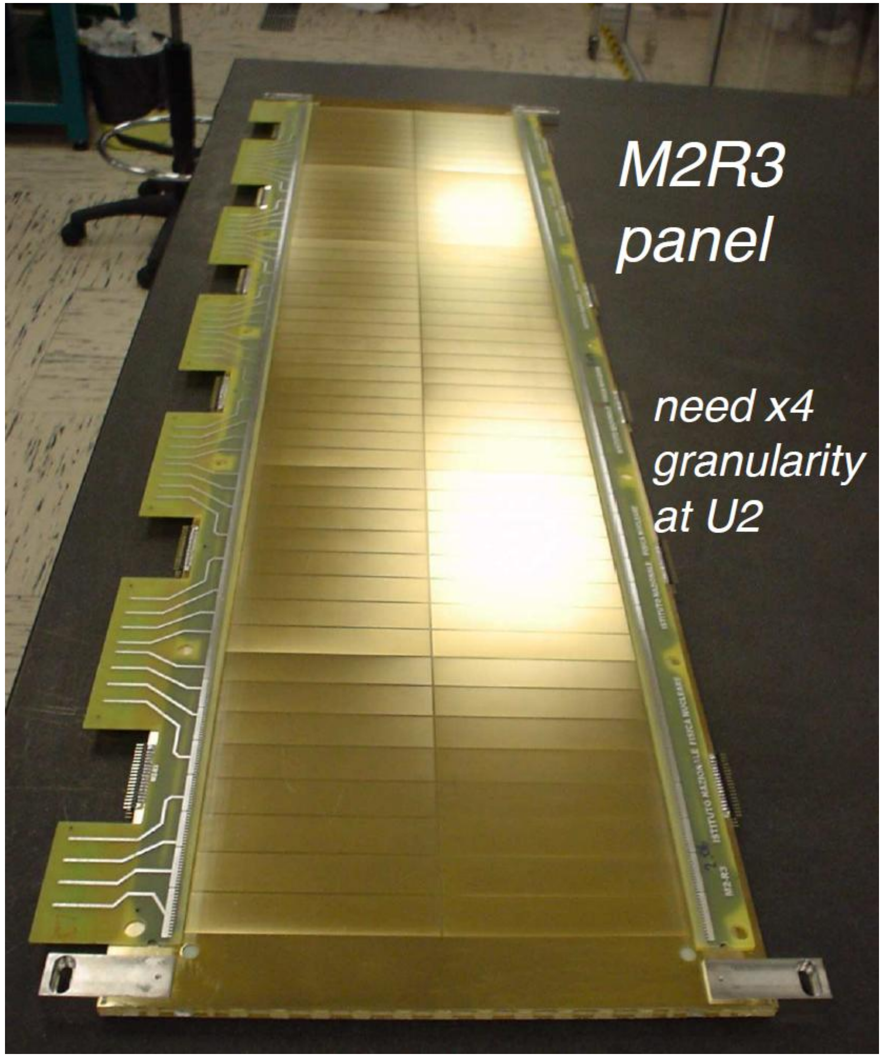
Outer regions R3-R4

R3-R4
(960 chambers: ~364 m^2, 94% of the area, rates ≲ 50 kHz/cm^2)

- Keep all of the R4 **MWPCs** (~768) and a large fraction of R3: aging effects not expected during Run 5-6 in outer regions, based on M1R2 chambers, showing no sign of efficiency loss at the end of Run 2 [JINST 14 (2019) P11031]

- Readout of MWPCs at their full granularity: with only anodes or cathodes, no pads grouping to form logic pads

- Propose to replace M2R3 & M3R3 chambers (96): to rebuild with higher granularity.



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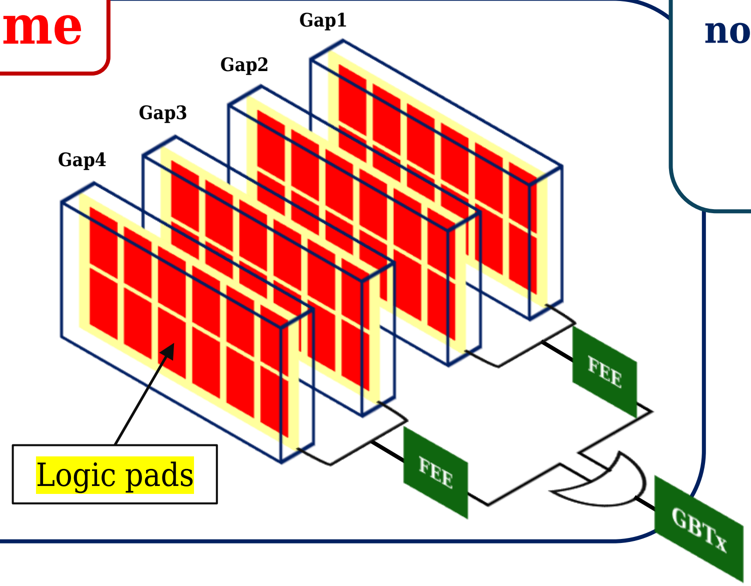
[LHCb-U2-FTDR]

The new readout scheme

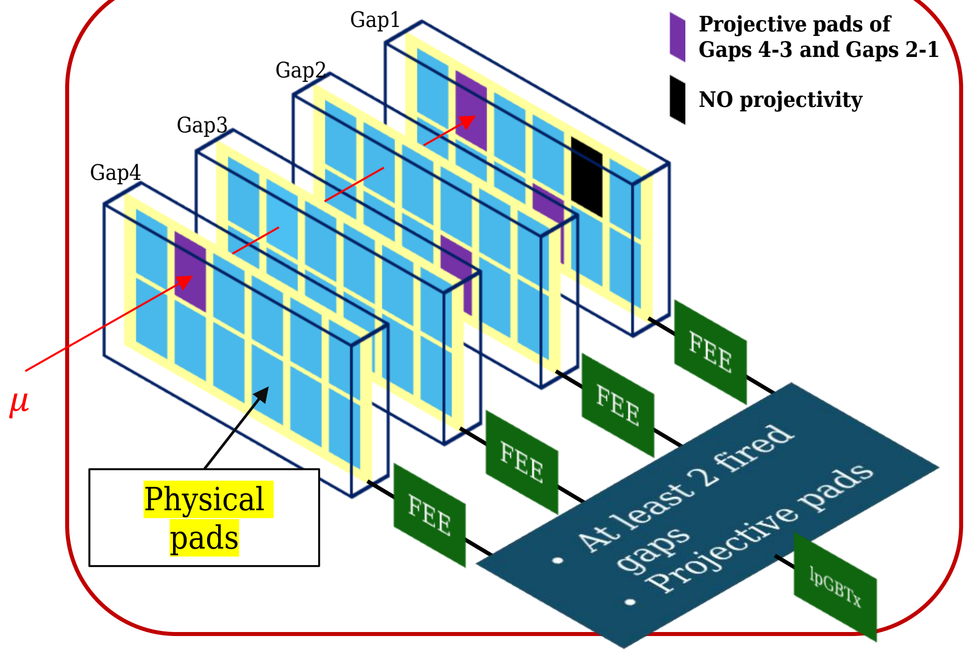
Present readout scheme

If one charged particle crosses one single gap, the chamber signal is generated



hits from background **not penetrating more than one gas gap** represent the largest bkg component

New readout scheme



- Separate readout per gap, requiring:
  - signal in at least 2 gaps at the same bunch crossing
  - At least two projective pads fired in the gaps

The new readout scheme

Effect on the μ-ID efficiency ?

The new readout scheme will <u>reduce the background</u> by a large factor:

$2 \div 4$ (depending on region/station)

at the cost of small <u>efficiency loss for muons</u> detection: (*-1 % per station*).

Further studies are ongoing aiming to reducing the muon efficiency loss, with clustering algorithms to be implemented.

Pads size planned for the Upgrade II

Comparison between:

- Present pads size of MWPCs
- G-RWELL pads size (red) with higher granularity
- New MWPCs with higher granularity (blue)

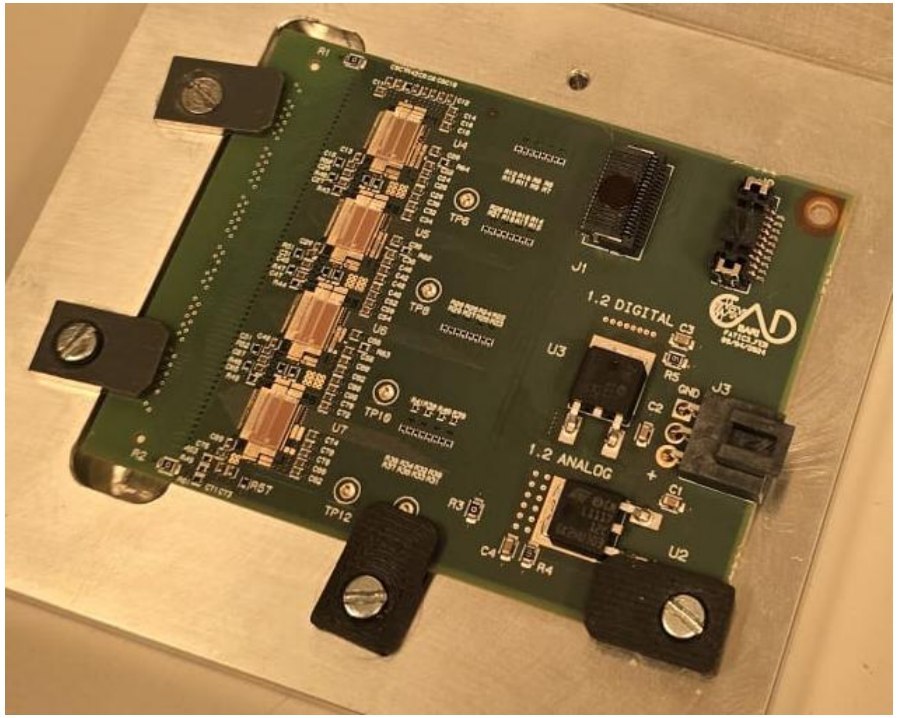
[mm²]	M2	M3	M4	M5
R1	$38 \times 31 \rightarrow$ **9×9**	$41 \times 34 \rightarrow$ **10×10**	$29 \times 36 \rightarrow$ **11×10**	$31 \times 39 \rightarrow$ **12×11**
R2	$76 \times 31 \rightarrow$ **9×18**	$82 \times 34 \rightarrow$ **10×19**	$58 \times 73 \rightarrow$ **11×21**	$62 \times 77 \rightarrow$ **12×22**
R3	$25 \times 125 \rightarrow$ **25×31**	$27 \times 135 \rightarrow$ **27×34**	58×145	62×155
R4	50×250	54×270	58×290	62×309

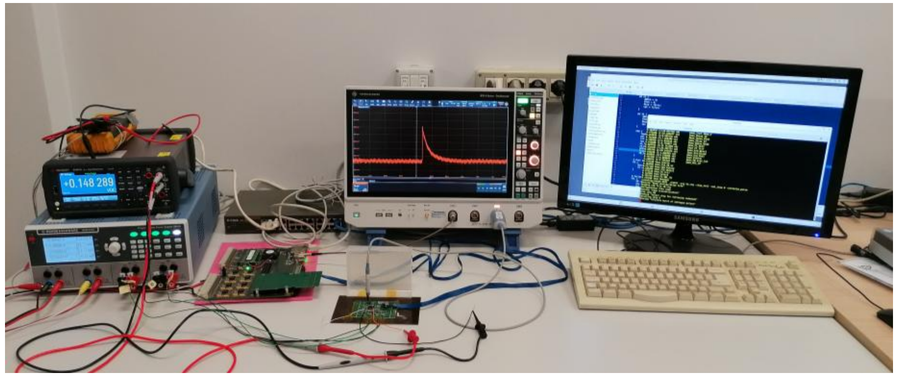
The FATIC

The FATIC is a new FEE under development at INFN-Bari, aiming to sustain the high rates (~1 MHz/cm^2) expected at Run 5-6, in innermost regions.

The latest version, the **FATIC 3**:
successfully used to readout all the chambers in the test beam (November 2024) for G-RWELL technology performance study.

- Main features:
    - 32 channels with programmable polarity, gain and peaking time
    - Charge and time measurements
    - dead time of ~1 usec





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    - 32 channels with programmable polarity
    - Charge and time measurements
    - dead time of ~1 usec

A new specific version for LHCb (**FATIC4**) is under development in order to reduce the **dead time to ~100 nsec**.

Conclusion

- Strategy against high rates: the shielding
- Inner Region with G-RWELL: R&D is well advanced
- Replacement of small part of detectors for the outer regions with higher granularity MWPCs
- Design of the new FEE: intermediate version (FATIC3) is ready and tested. Almost final version (FATIC4): 2026

Thank you a lot for your attention

Francesco Debernardis
INFN Bari
on behalf of the LHCb collaboration

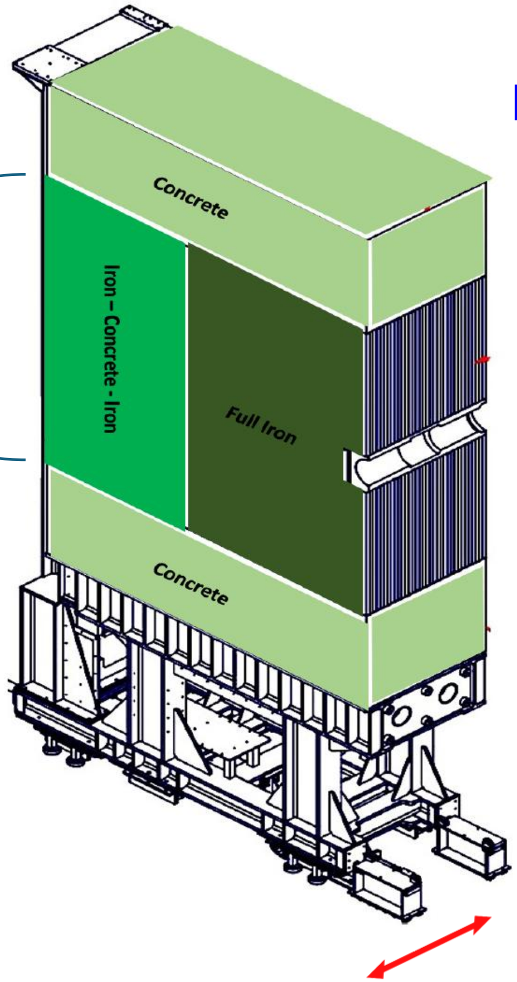
EPS-HEP Conference,
07-11 July 2025
Palais du Pharo, Marseille, France

BACKUP

Shielding

A shielding **<u>in place of the HCAL</u>** system is proposed at Upgrade II.

[LHCB-INT-2019-008]



148+5 cm

iron-concrete-iron-Borotron* (6.2 λ_I), acting on M2M3R4

Iron-Borotron* (10.1 λ_I), acting on M2M3R1-R3

concrete- Borotron* (4 λ_I), acting on M2M3R4

*Borotron: Polyetilen+Boron(5%)

Shielding effects on the background rate, according to simulation:

		rates reduction
M2	R1	−30%
	R2	−40%
	R3	−60%
	R4	−40%
M3	R1	−5%
	R2	−10%
	R3	−15%
	R4	−5%

Further studies are ongoing, optimising materials choice, in order to maintain the HCAL

The G-RWELL

Benefits:

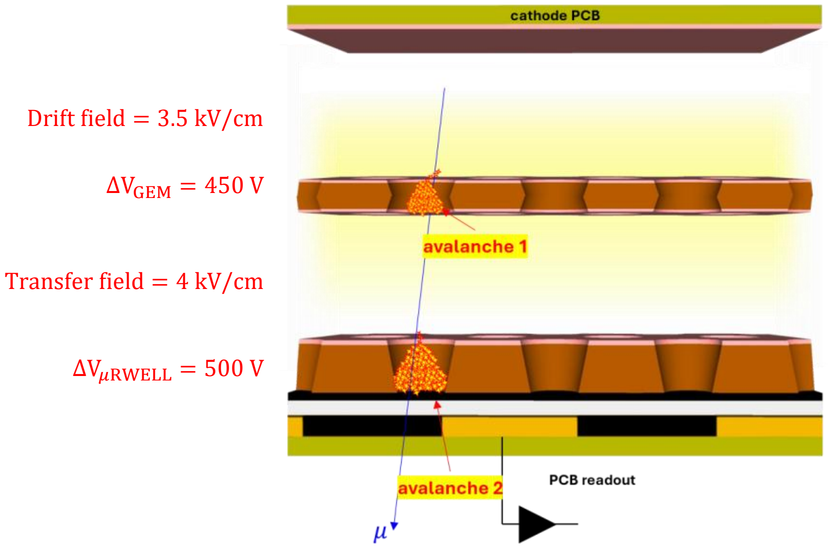
High gas gains ($>10^4$)
in **very stable operation:**

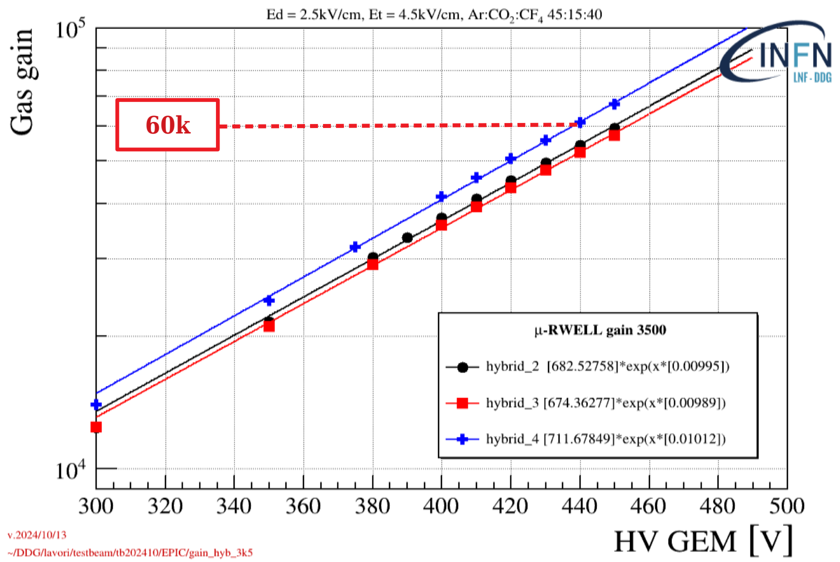
- ~ 500 V working point for wells
- ~ 4 kV/cm working point for drift/transfer

Signal spread less than 1 mm²
thanks to the highly resistive layer, allowing for higher pad granularity w.r.t present MWPCs.

↓

G-RWELLs can be used for inner regions R1-R2





Expected requirements at high luminosity:

- Rates up to 1.3 MHz/cm² on detector single gap
- Rates up to 800 kHz per electronic channel
- Single gap efficiency ~90% within a BX (25 ns)

Shielding

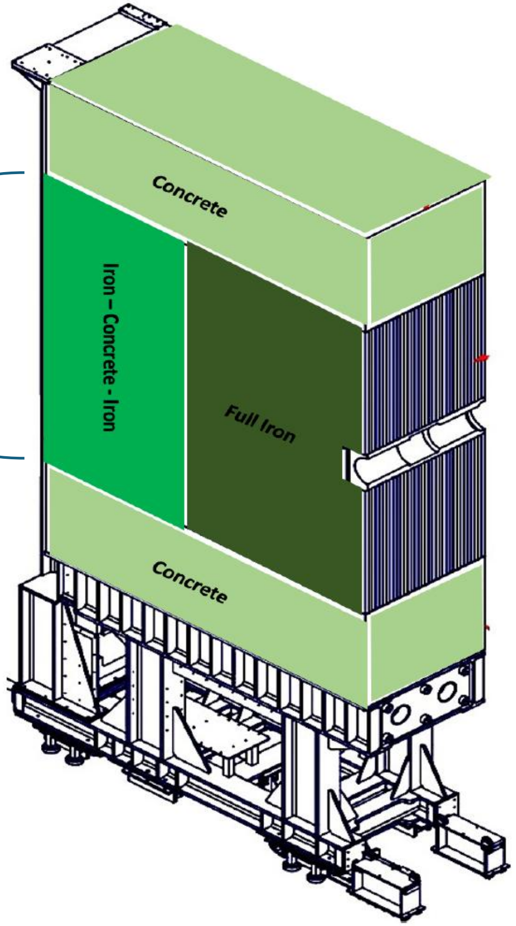
A shielding in place of the HCAL system is proposed at Upgrade II.

The shielding acts on background rate reduction in M2 and M3 stations:

		rates reduction
M2	R1	−30%
	R2	−45%
	R3	−55%
	R4	−55%
M3	R1	−20%
	R2	−23%
	R3	−25%
	R4	−30%

[LHCB-INT-2019-008]

iron-concrete-iron-Borotron* ($6.2\ \lambda_I$), acting on M2M3R4



Iron-Borotron* ($10.1\ \lambda_I$), acting on M2M3R1-R3

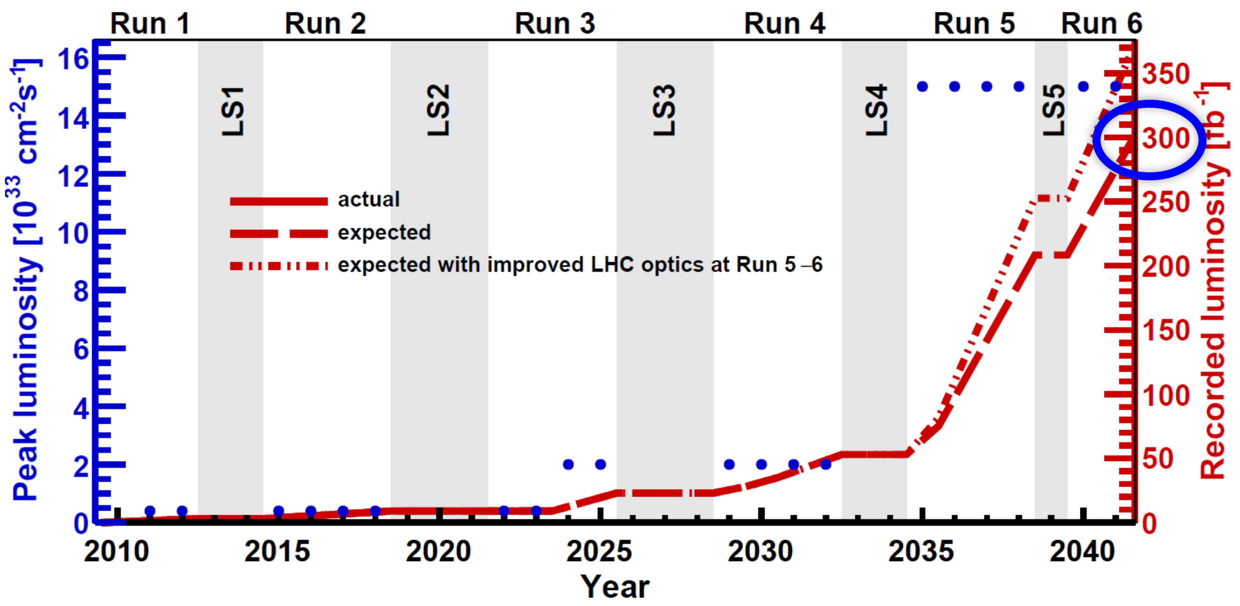
concrete- Borotron* ($4\ \lambda_I$), acting on M2M3R4

Studies on the Borotron effects on muon chambers are ongoing: layers installed on 2 chambers.

***Borotron**: Polyetilen+Boron(5%)

High luminosity era

- Several hints of new physics (BSM) exist [...]
- Absence of evidences suggests any New Physics is likely beyond the mass scale accessible at LHC.
- **Precision flavour physics measurements** would allow subtle effects of new particles on SM processes.



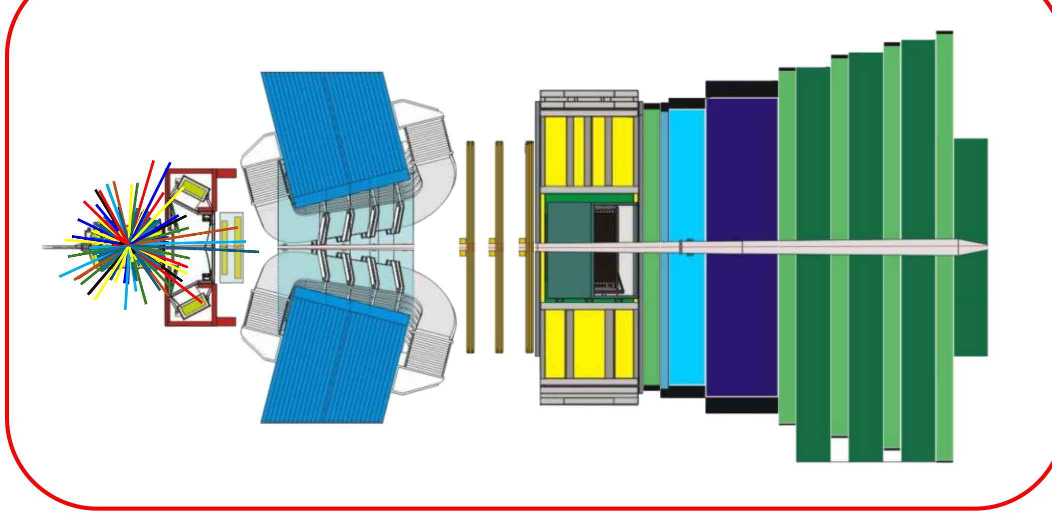
Anticipated uncertainties:

Upgrade I projections are given both with the data sample available after Run 3 (23 fb^{-1}) and with that after Run 4 (50 fb^{-1}). Uncertainties are extrapolated assuming that systematic uncertainties will not becoming limiting (see Ref. [6] for further discussion).

[CERN/LHCC 2024-010 LHCb TDR 26]

Observable	Current LHCb (up to 9 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests			
γ ($B \to DK$, *etc.*)	2.8°	0.8°	0.3°
ϕ_s ($B_s^0 \to J/\psi\phi$)	20 mrad	8 mrad	3 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	2%	1%
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
$A_T^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	0.043	0.016
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	0.097	0.038

Excellent LHCb performance at Run 1-2 (Run 3 ongoing)

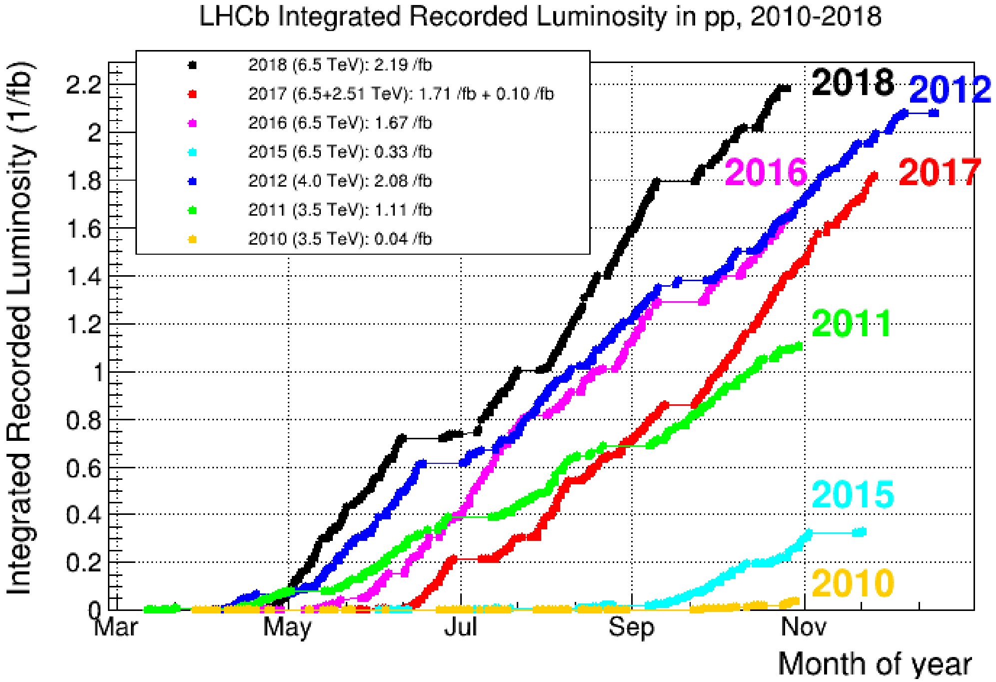


- Pulse resolution:
  $\Delta p/p \sim 0.5\%$ upt a 20 GeV/c
  $\Delta p/p \sim 1\%$ at 200 GeV/c

- Impact parameter resolution:
  $\mathrm{IP} \sim (15 + 29/\ pT\ [\mathrm{GeV}])\ \mu\mathrm{m}$

- Decay time resolution:
  $\sigma_t \sim 45\ fs$ for $B_s \rightarrow J/\psi\ \varphi$

- PID efficiency (mis-ID prob.):
  $e \sim 90\%\ (e \rightarrow h \sim 5\%)$,
  $K \sim 95\%\ (\pi \rightarrow K \sim 5\%)$
  $\mu \sim 97\%\ (\pi \rightarrow \mu \sim 1 \div 3\%)$



RUN 1
(2010-2012)
$3\ fb^{-1}$

RUN 2
(2015-2018)
$6\ fb^{-1}$

The χ^2_{corr} accounts for correlations via a covariance matrix V

[JINST 15 (2020) T12005]

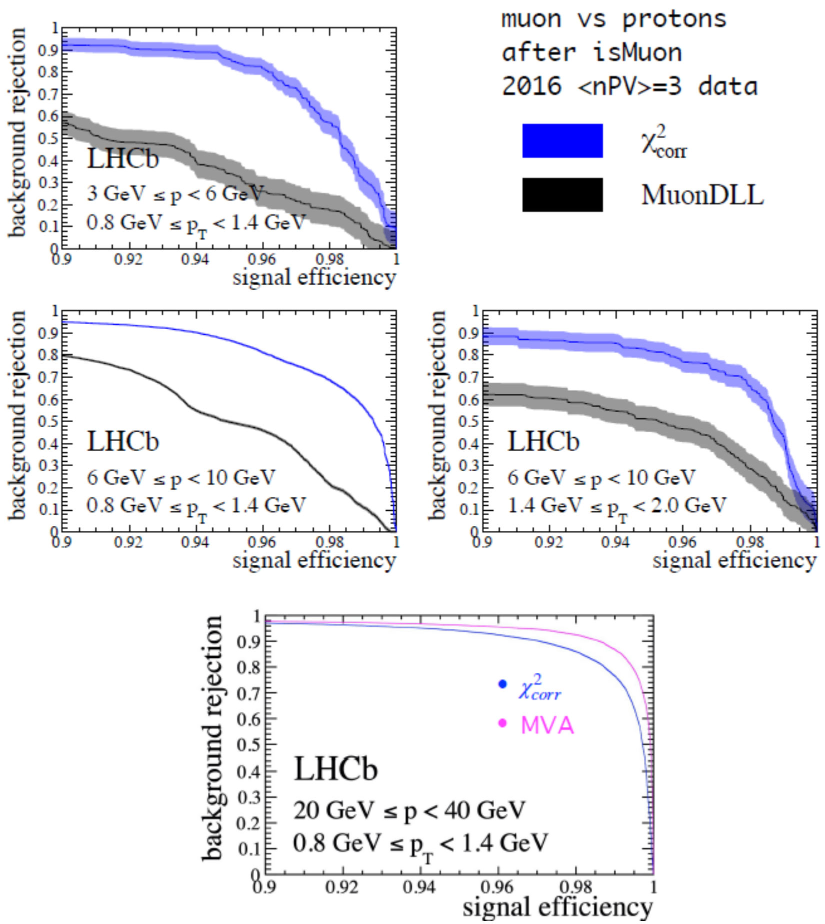
$$\chi^2_{corr} = \delta\vec{x}^T V_x^{-9} \delta\vec{x} + \delta\vec{y}^T V_y^{-9} \delta\vec{y}$$

Wich is made by the sum of the spatial residuals

$$V_{jj}^{RES} = \sigma^{+}_{RES_j} \qquad \sigma_{RES_j} = pad^{j}_{x^4 y}/\sqrt{12}$$

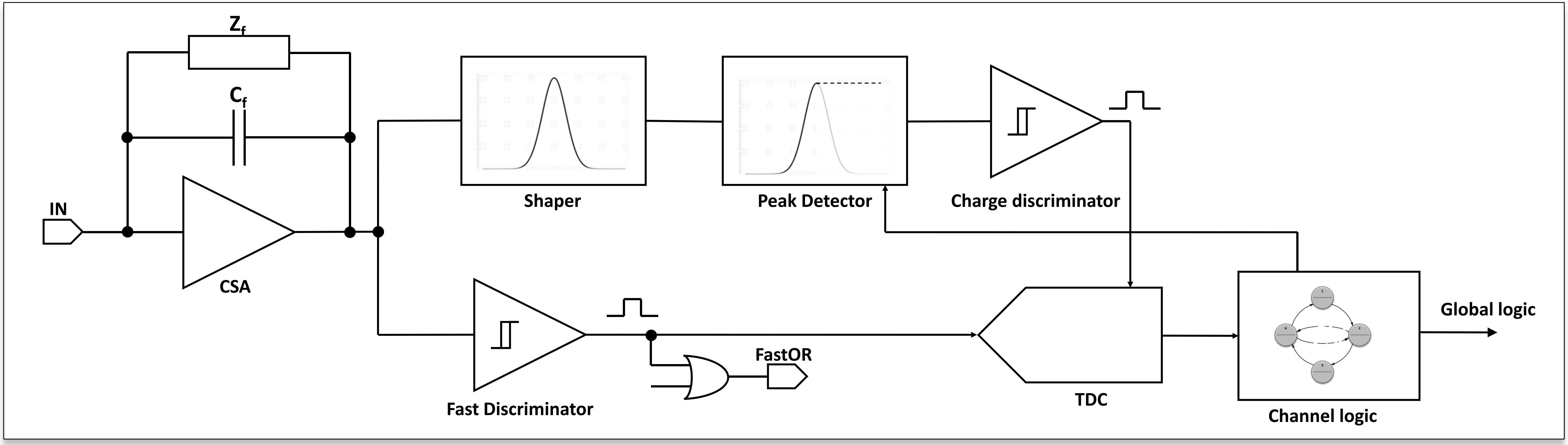
And the matrix of MS deviations caused in the absorbers crossing:

$$V_{jk}^{MS} = \sum_{z_i < z_j {}^4 z_k} (z_j - z_i)(z_k - z_i)\,\sigma^{+}_{MS^4 i} \qquad \sigma_{MS^4 i} = 13.6\,\frac{MeV}{\beta c p}\, q\sqrt{\Delta z_i / X_8}$$



χ^2_{corr} gives much better performance on high-multiplicity data on top of the isMuon selection across the whole momentum spectrum. It allows $O(10)$ misID reduction with respect the IsMuon only selection

FATIC3 - Channel block diagram



Charge Sensitive Amplifier:

- Input signal polarity: positive & negative
- Recovery time: adjustable
- Programmable Gain: 10 mV/fC, 50 mV/fC

Shaper:

- Peaking time: 25 ns, 50 ns, 75 ns, 100 ns

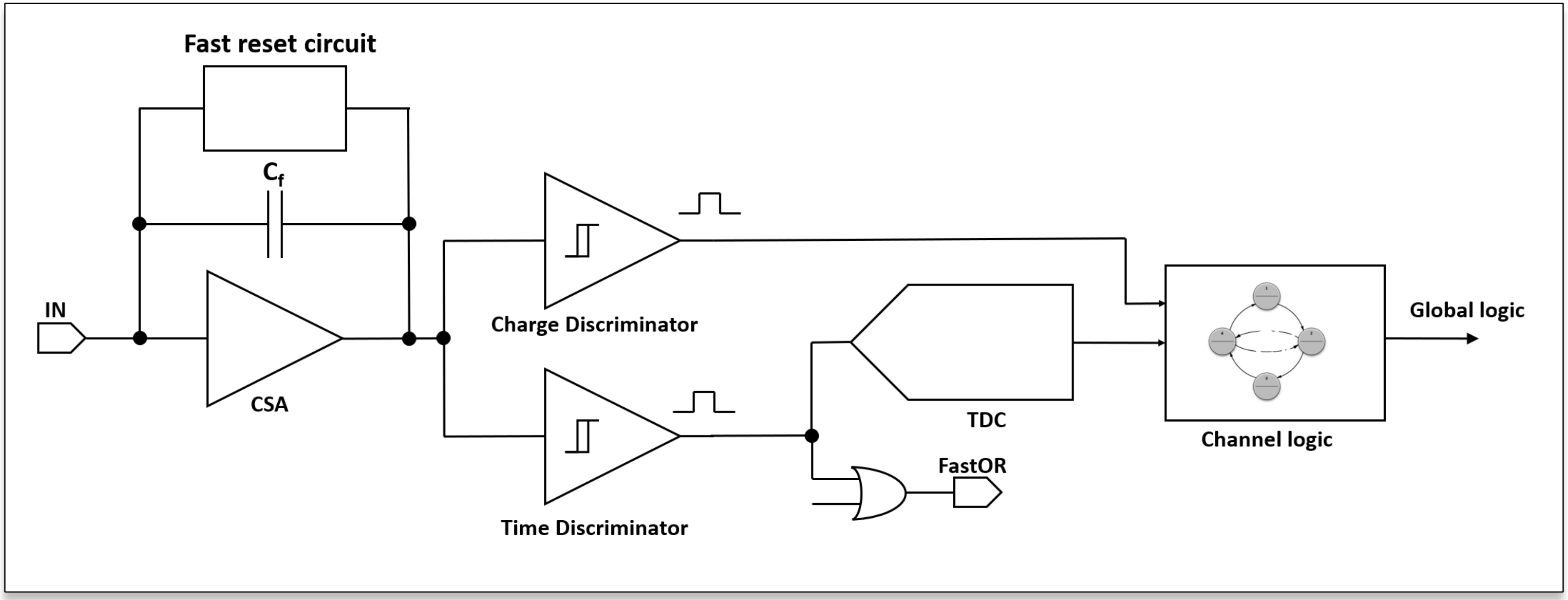
Timing branch:

- ✓ Measures the arrival time of the input signal
- ✓ Time jitter: 400 ps @ 1 fC & 15 pF (Fast Timing MPGD)

Charge branch:

- ✓ Acknowledgment of the input signal
- ✓ Charge measurement: dynamic range > 50 fC, programmable charge resolution

FATIC4 - Channel block diagram



Charge Sensitive Amplifier:
- Input signal polarity: positive & negative
- Fixed Gain: 7 mV/fC
- Recovery time: adjustable
- **Fast recovery: < 100 ns**

Time Discriminator:
- ✓ Measures the arrival time of the input signal
- ✓ **Measure of Time Over Threshold**

Charge branch:
- ✓ Acknowledgment of the input signal
- ✓ Filter noise
- ✓ Charge discrimination threshold: ≤ 50 fC