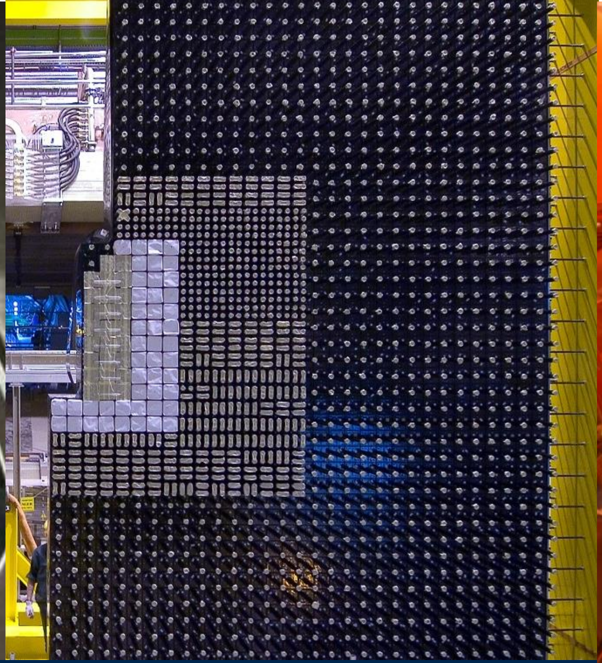
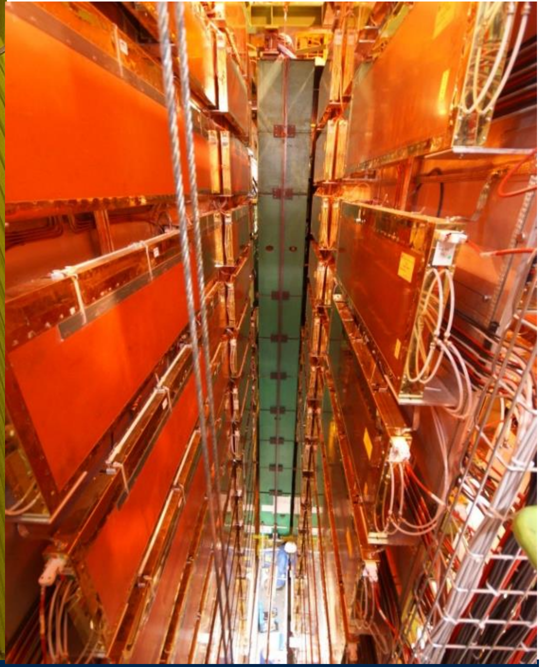




Instrumentation for PID in the HL-LHC LHCb

E. Picatoste

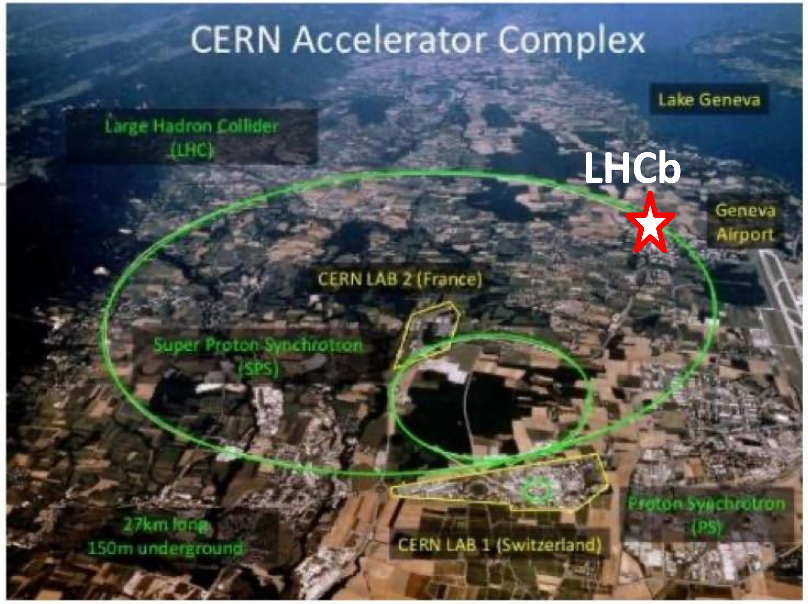
ICCUB – Universitat de Barcelona

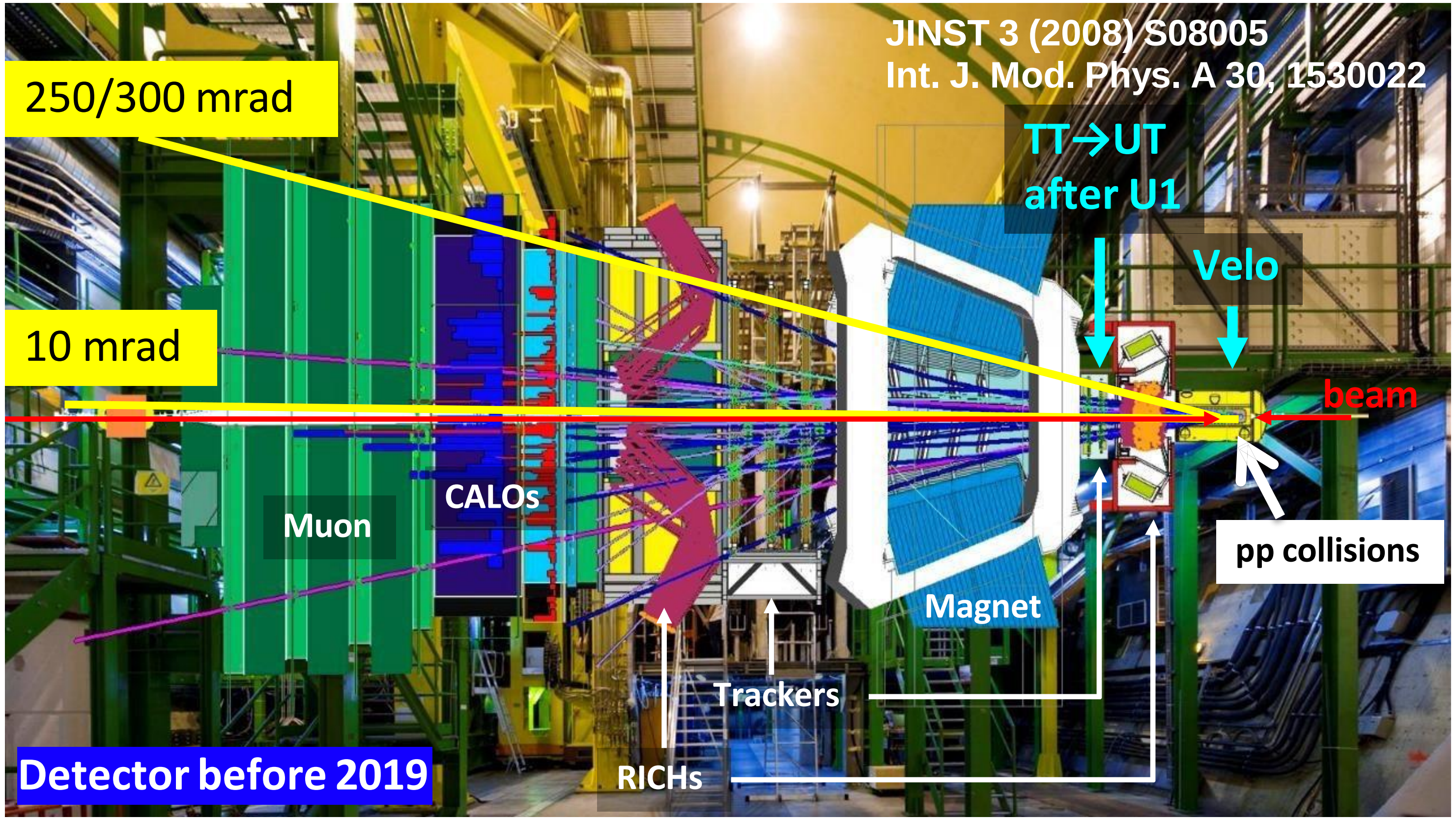
TIDPAN 2026

Taller de instrumentación y Detectores en Física de Partículas, Astropartículas y Nuclear

16/06/2026

LHCb: a forward spectrometer @ LHC



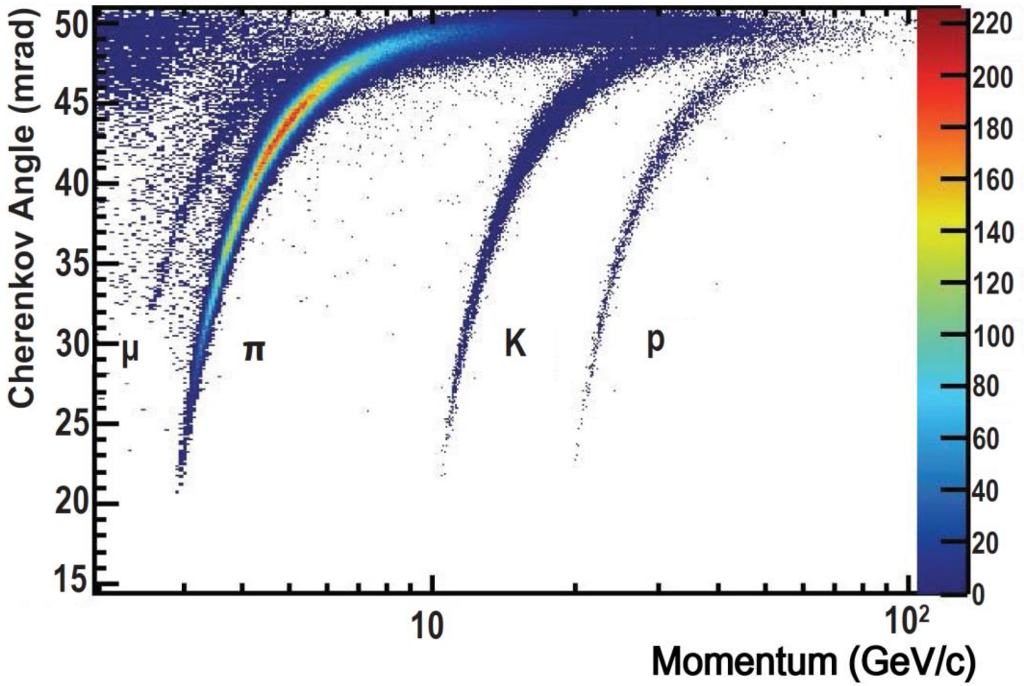


Main physics goal

► To study b & c sectors on CPV, rare decays, new physics...

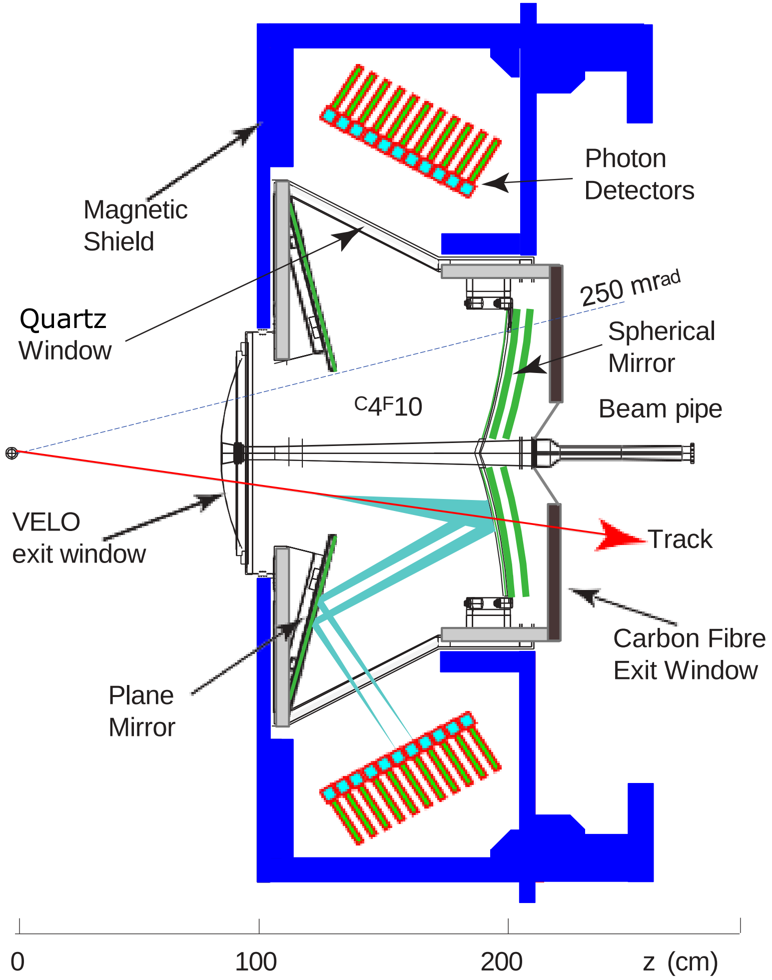
The Ring Imaging Cherenkov detectors

- Excellent PID for charge hadrons by using the Cherenkov effect
- RICH 1: 1 to 60 GeV using C_4F_{10}
- RICH 2: 15 to 100 GeV using CF_4

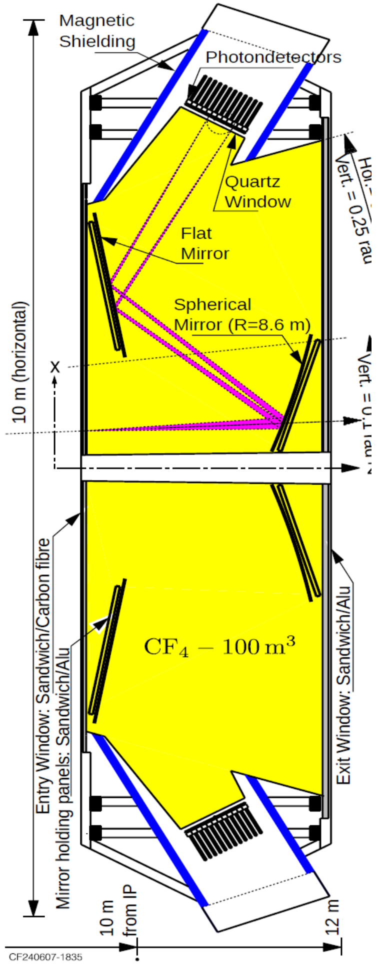


[Int. J. Mod. Phys. A 30 (2015) 15300223]

RICH 1

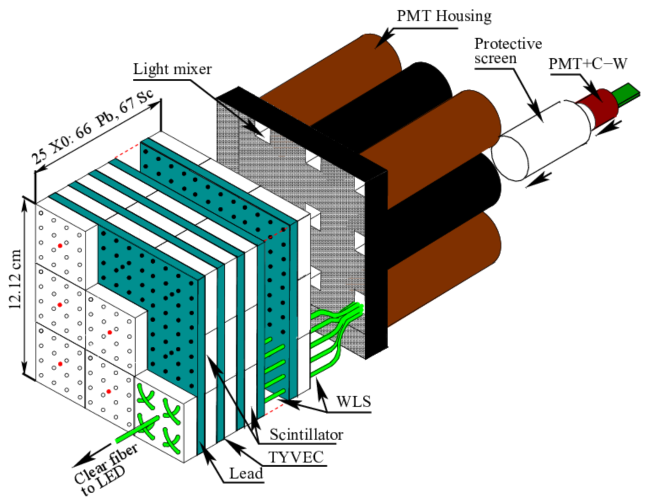


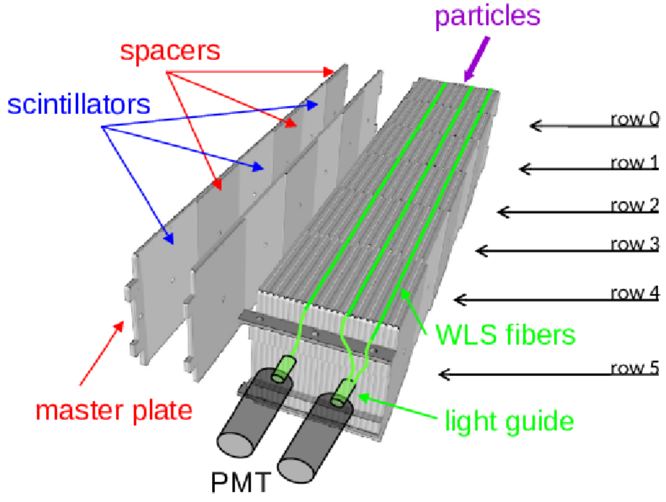
RICH 2



The Calorimeters

- Sampling calorimeters with scintillator tiles alternated to Pb/Fe spacers
- Measurement of energies and position of the e.m. and hadronic showers
- PID for photons, electrons and hadrons (neutral and charged)



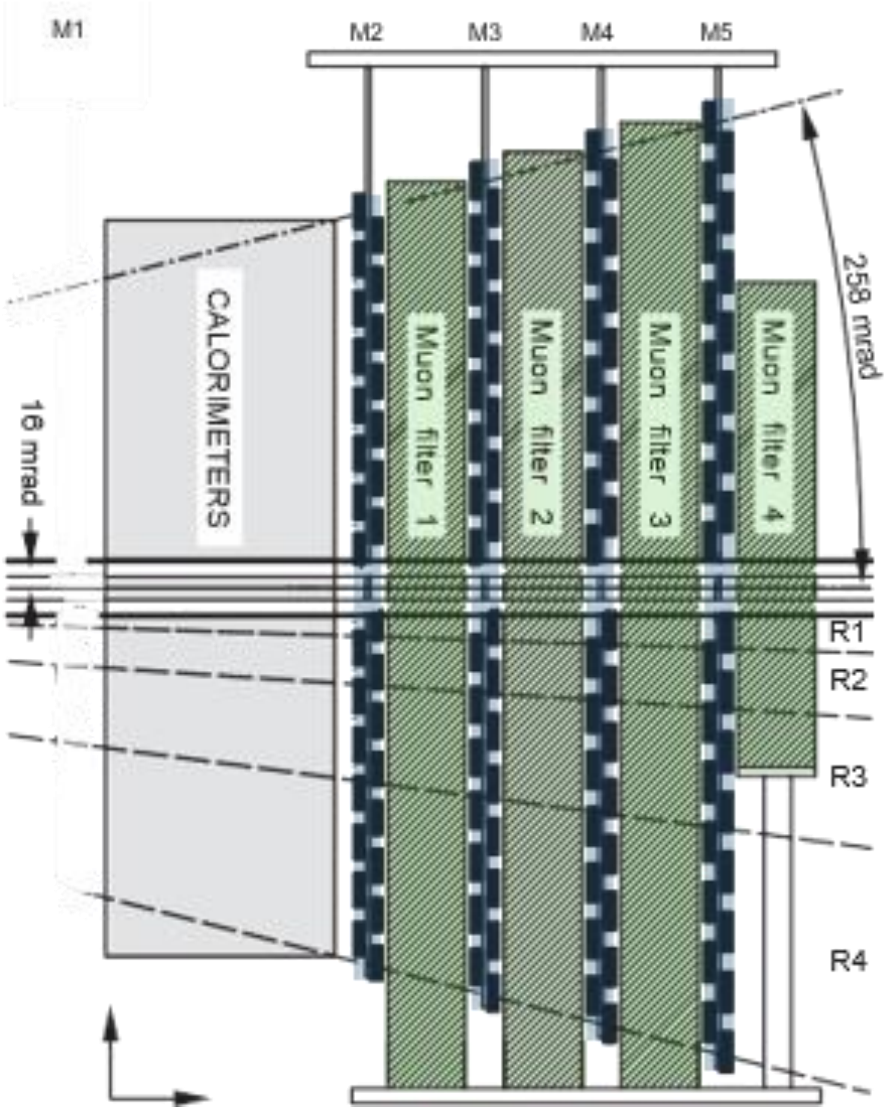


[LHCb-DP-2020-001]

The Muon System

- Four stations with Multi-Wire Proportional Chambers (MWPC) interleaved by thick iron ”filters”

- Hits around the track extrapolation provide performant muon ID criteria (IsMuon)



[JINST 3 (2008) S08005]

LHCb Upgrades

Upgrade I (U1), started in LS2

$\mathcal{L}_{max}$~ 2×10^{33} $cm^{-2}s^{-1}$

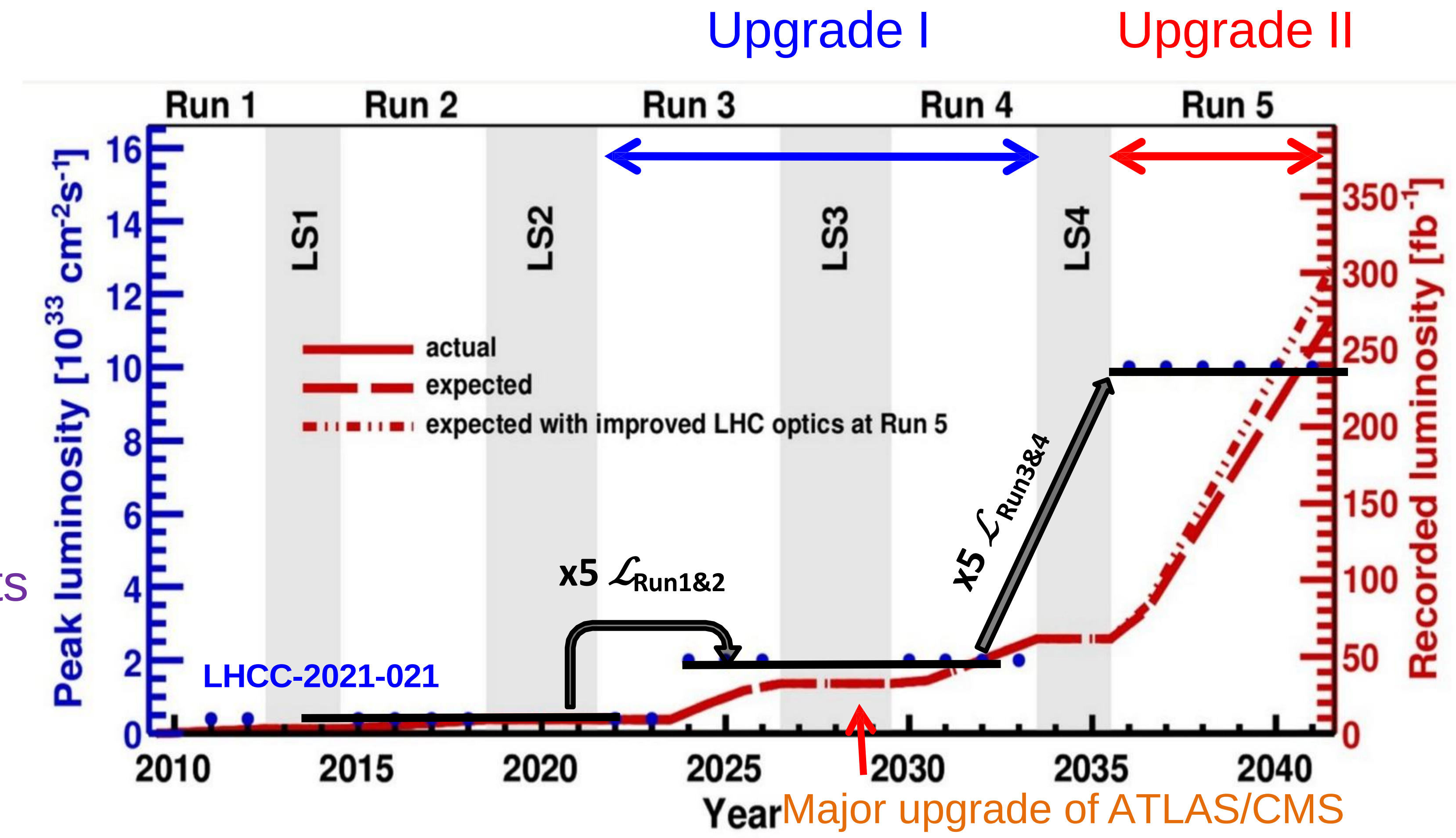
$\mathcal{L}_{int}$~ 50 fb^{-1}

Upgrade II (U2), starts in LS4

$\mathcal{L}_{max}$~ 1×10^{34} $cm^{-2}s^{-1}$

$\mathcal{L}_{int}$~ 250 - 300 fb^{-1}

Some smaller detector consolidation and enhancements in LS3 (2026)

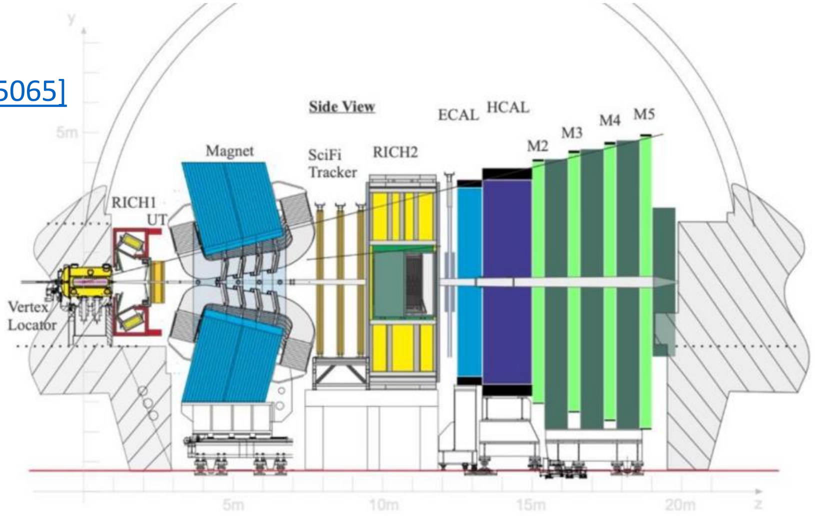


Major upgrade of ATLAS/CMS
LHCb also plan enhancements

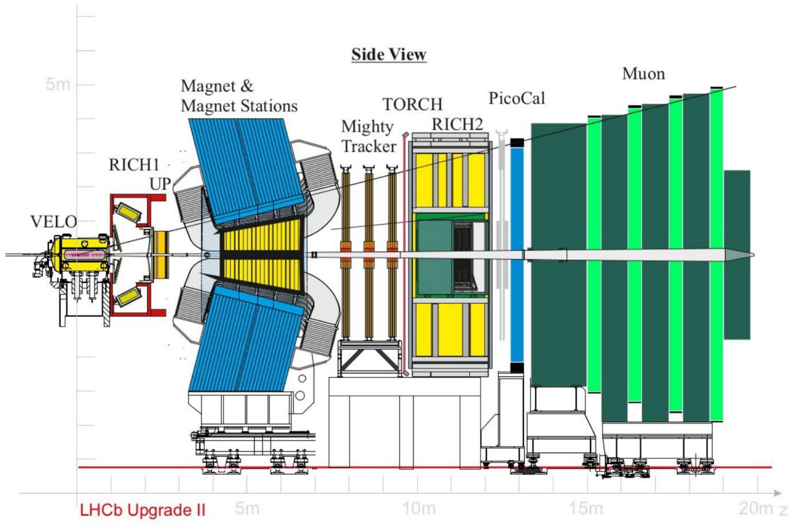
LHCb in Upgrade II

- Same performances as Run 3, with a pile-up of 40 instead of 5

[JINST19 (2024) P05065]



Run 3

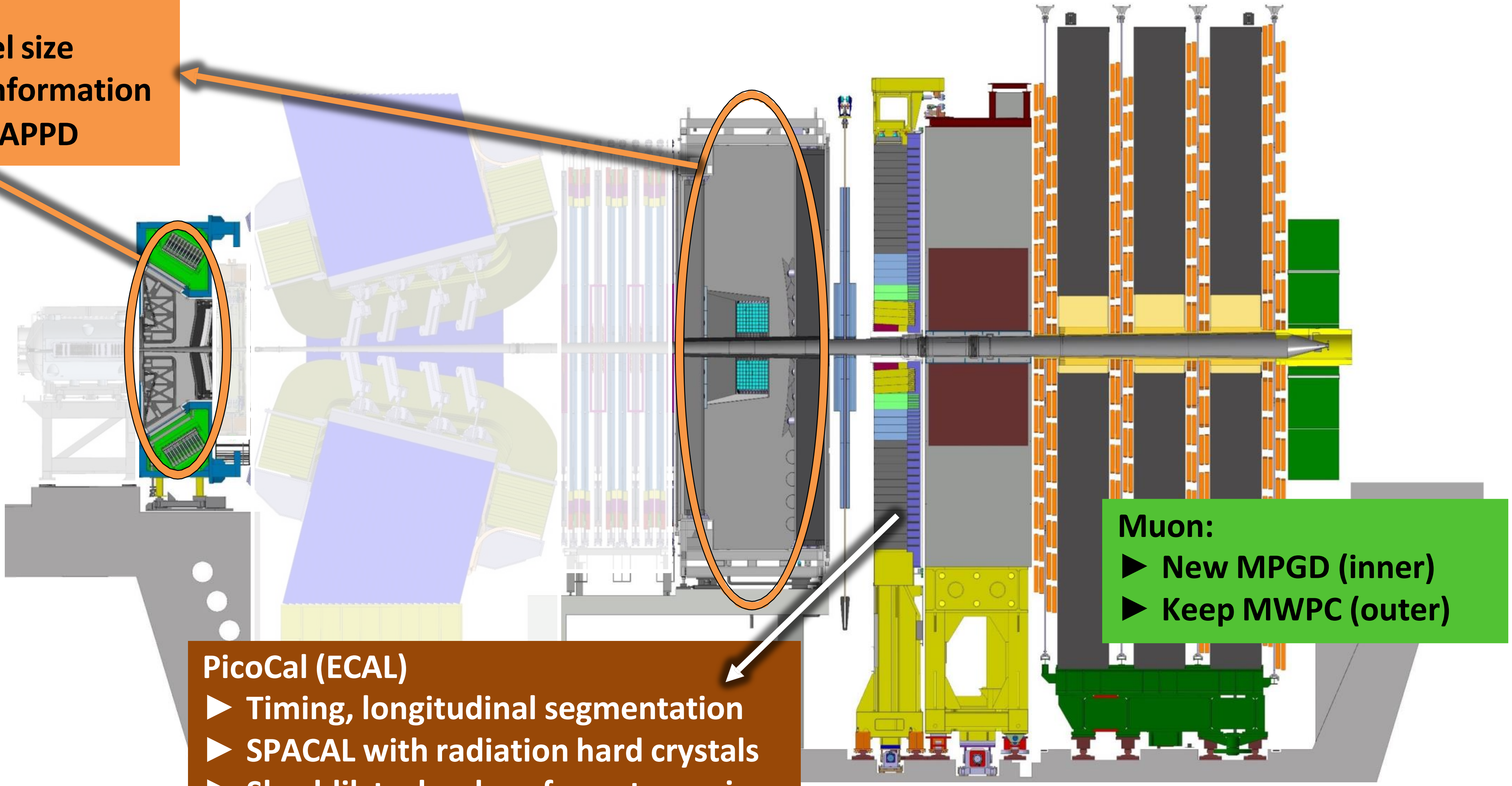


Run 5

- Same geometry for the detector with innovative technologies for sub-detectors and data processing
- Main elements:
  - Increase granularity
  - Add timing measurement (resolutions up to 10-50 ps, in VELO, RICH, ECAL)
  - Radiation hardness (up to 10^{16} neq/cm^2)
  - Data rate: 200 Tbit/s

LHCb PID system in Upgrade II

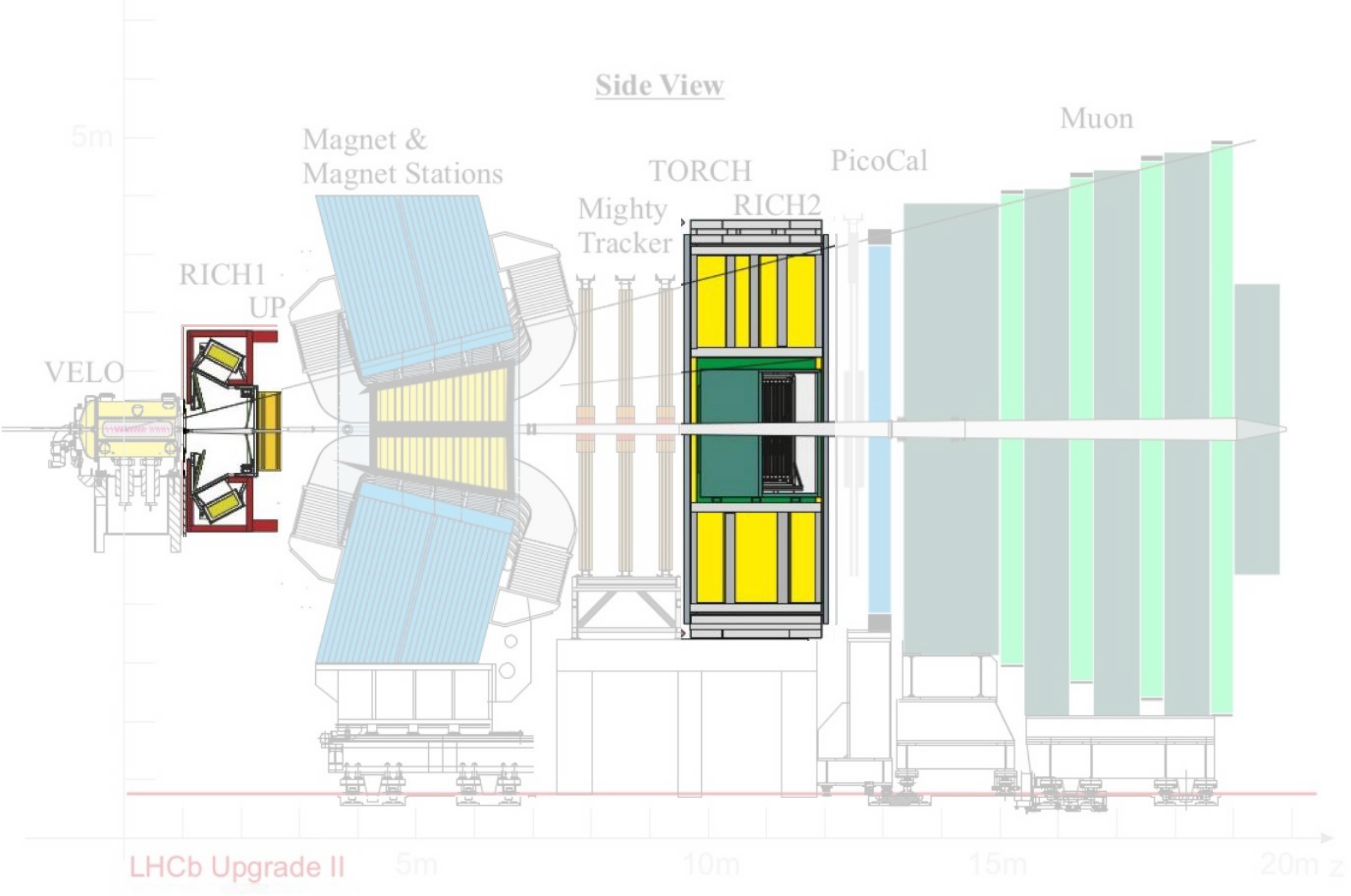
RICH 1, RICH2:
- ▶ Reduced pixel size
- ▶ Add timing information
- ▶ SiPM, MCP, LAPPD



Muon:
- ▶ New MPGD (inner)
- ▶ Keep MWPC (outer)

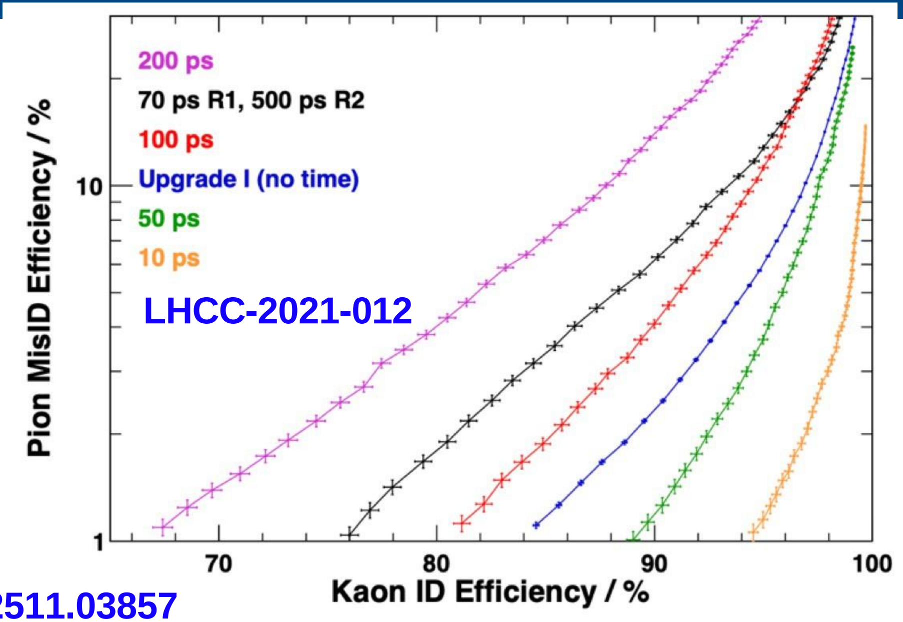
PicoCal (ECAL)
- ▶ Timing, longitudinal segmentation
- ▶ SPACAL with radiation hard crystals
- ▶ Shashlik technology for outer region

The RICH System

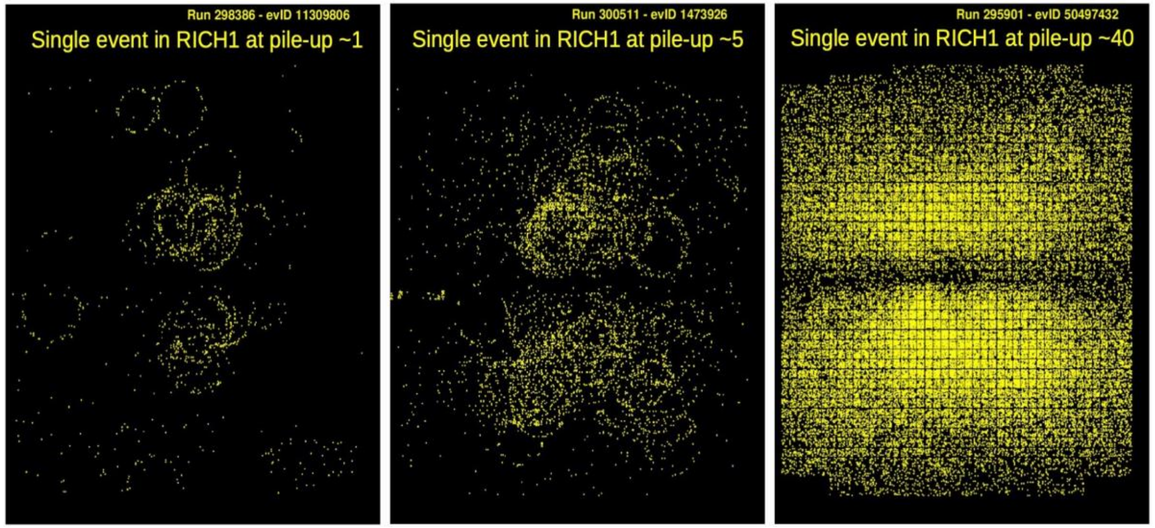


RICH detectors with better timing

- High-Lumi RICH occupancy increase by an order of magnitude
- RICH 1&2 will maintain same geometry, reduce pixel size
- Photon detector options: SiPM, MCP, LAPPD. MAPMT may be backup for low occupancy area
- 100ps required resolution to maintain Run 3 PID performance
- LS3 Enhancements for Run 4: Readout upgrade (FastRICH) with same detector technology
- Upgrade II for Run 5: New detector technology compatible with FastRICH readout



arXiv:2511.03857

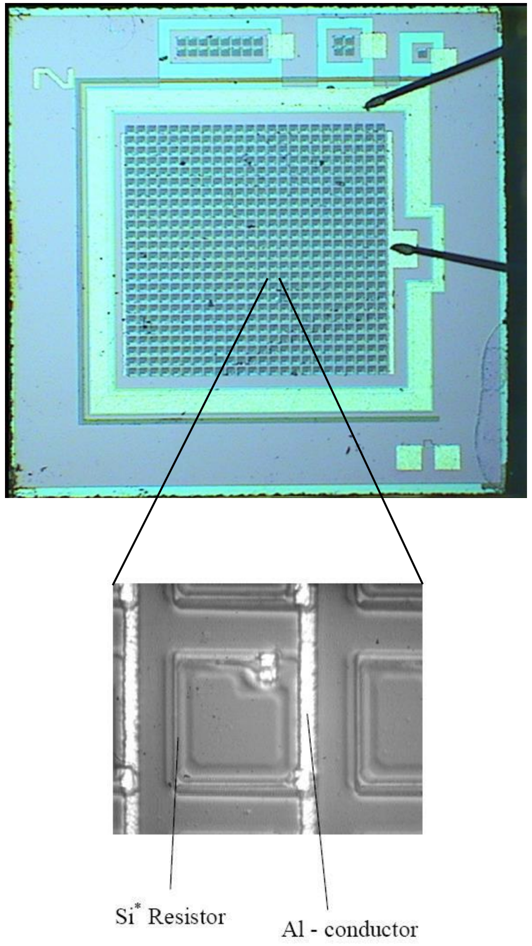


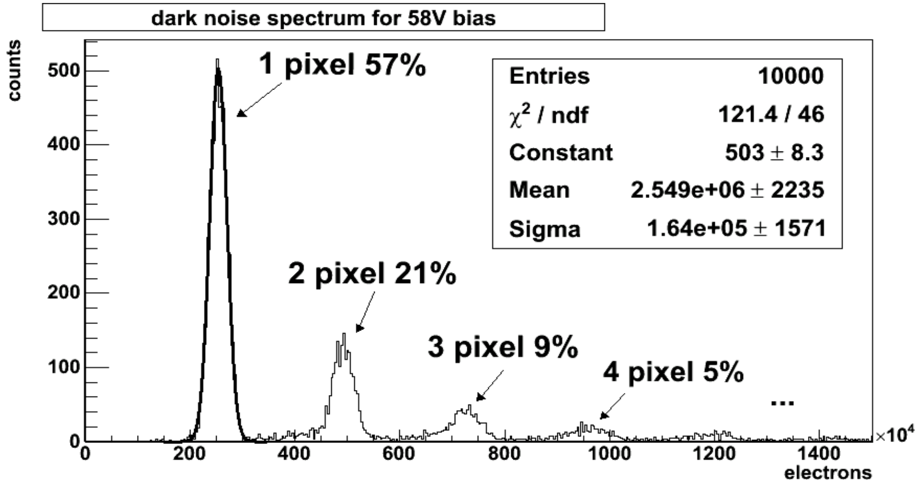
Upgrade	Photon Detector	FE ASIC	Time Resolution	TimeStamp Precision
I	MAPMT	CLARO	~ 150 ps	3.125 ns
I.b*	MAPMT	FastRICH	~ 150 ps	25 ps
II	SiPM, MCP LAPPD	FastRICH	< 100 ps	25 ps

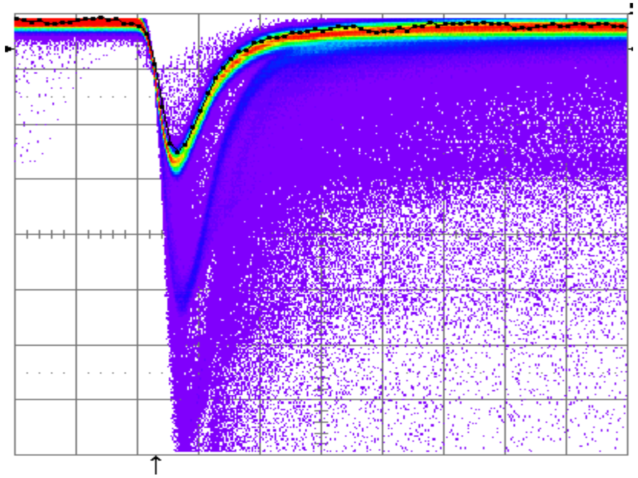
* LS3 enhancement

SiPM sensors

- A SiPM is a matrix of Geiger-mode APD pixels connected in parallel
- The gain is in the range of 10^5 to 10^7
  - Single photoelectrons produce a signal of several mV on a 50 Ω load
  - An amplifier is needed
- Dark count rates of 100 kHz to 10 MHz/mm2 @25°C
  - Increased by defect states due to production
  - Strong function of overbias voltage (trigger probability)







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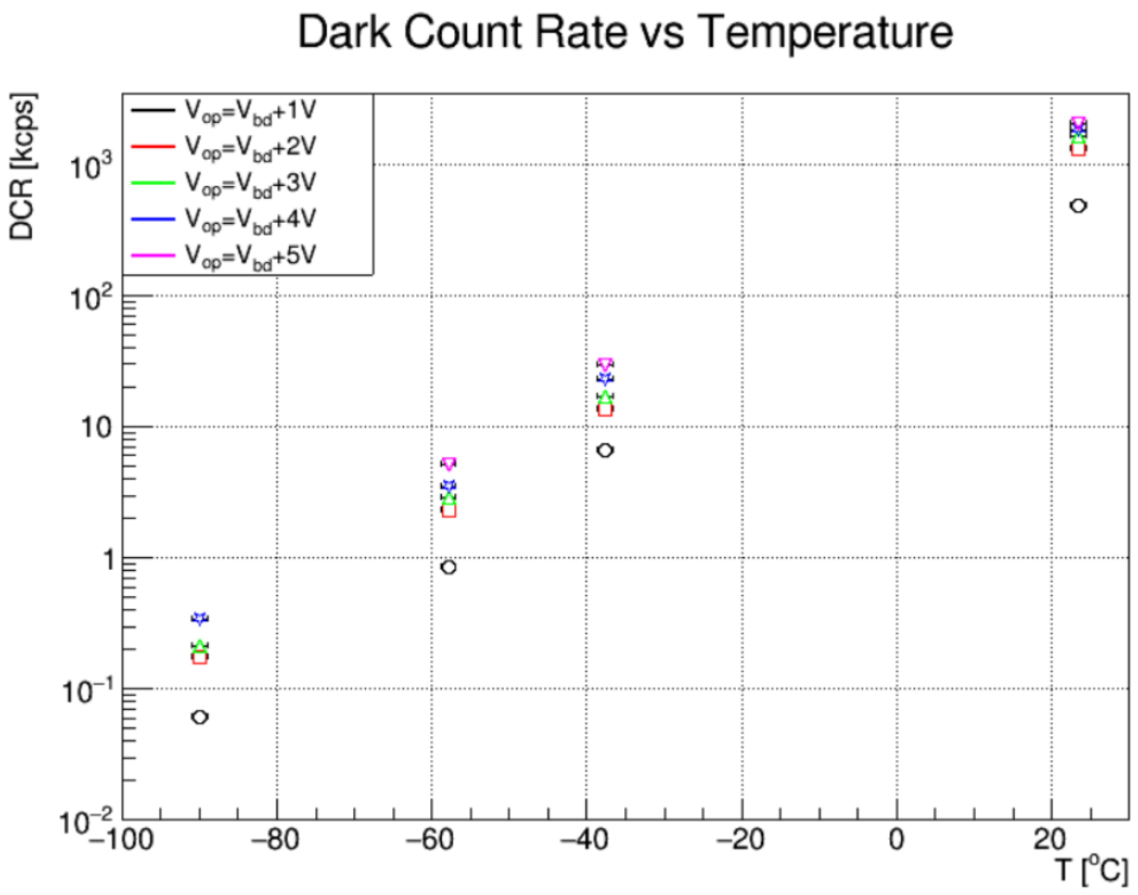
SiPM Advantages and DCR Mitigation

- Advantages of SiPMs:
  - Smaller pixel size than current MaPMTs (3mm × 3mm)
  - Very good time resolution
  - Higher photon detection efficiency

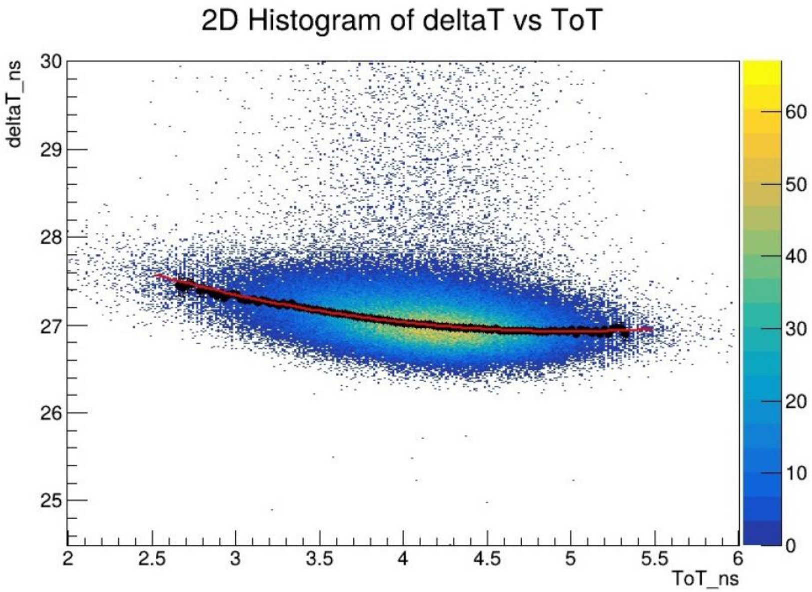
- High Dark Count Rate (DCR) mitigation strategies:
  - **Cooling**: can reduce DCR, which is temperature dependent
  - **Annealing**: heating the SiPMs can partially recover radiation-induced damage in the silicon lattice and thus reduce the DCR
  - **Measurement of photon arrival time**: the introduction of time bins, in addition to the spatial pixel bins, contributes significantly to suppressing the DCR contribution.



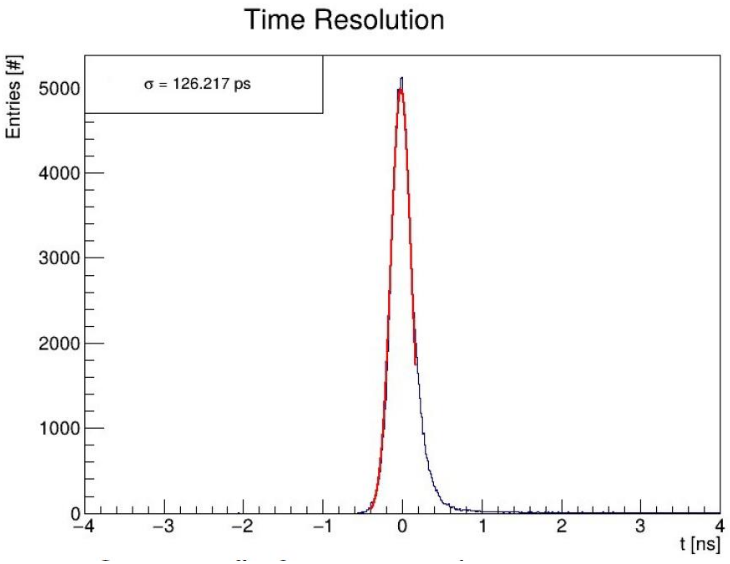
SiPM Time Resolution

- SiPM characterization: the device is illuminated with a pulsed laser in a light-tight environment.
- Two quantities are recorded:
  - The **Time of Arrival (ToA)** of the SiPM signal, relative to the laser trigger.
  - The **Time over Threshold (ToT)** of the SiPM, with respect to the threshold of the measurement instrument.
- A time walk correction is applied to the 2D ToA vs ToT plot
- The peak in the ToA projection is fitted with a Gaussian

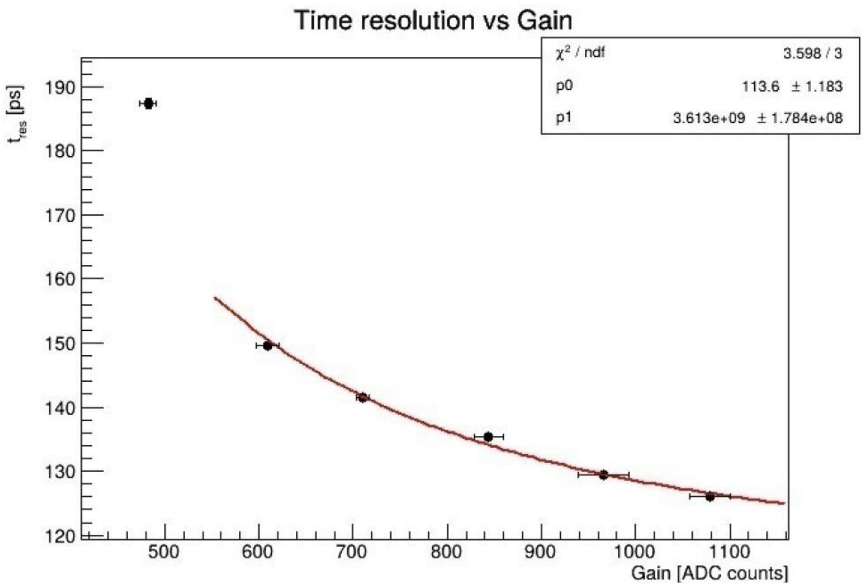
[PD 2025 poster]



Time walk correction



Gaussian fit for time resolution estimation



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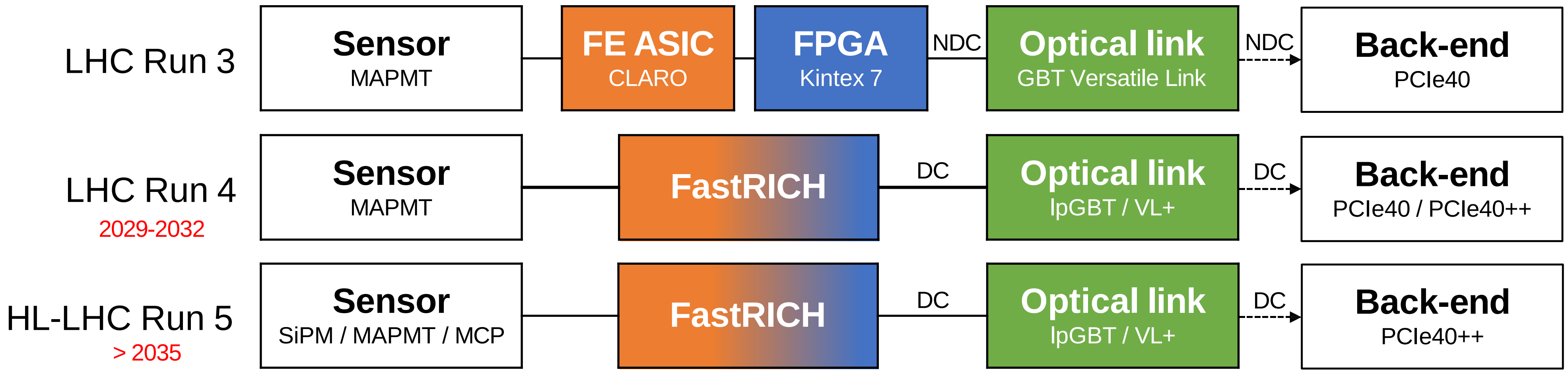
RICH Upgrade II Electronics Chain

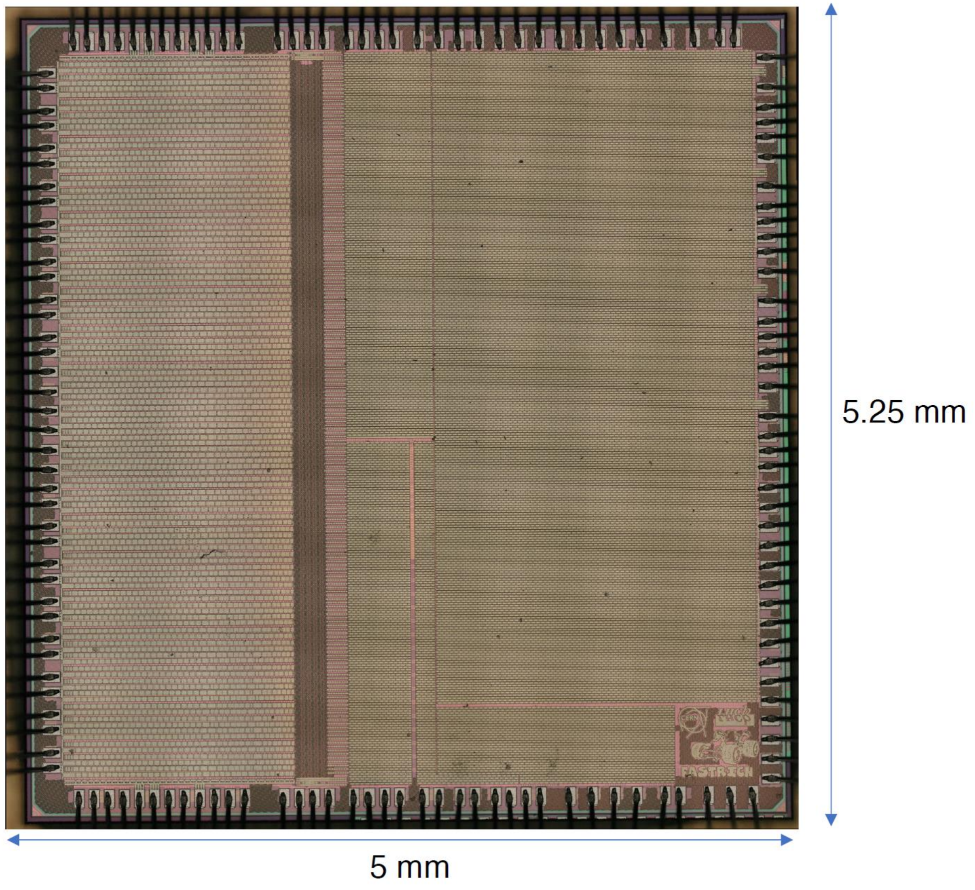


- New **FastRICH** ASIC by CERN-EP-ESE and the University of Barcelona with strong input from the RICH group.
- The ASIC is tailored for high flexibility and compatible with MAPMTs (LS3 enhancements) and Upgrade II photon sensors.
- **Time resolution**: TDC with ~ 25 ps time bins.
- **Power consumption**: ~ 8 mW per channel in 16-channel ASIC.
- **Radiation hardness** for ~ 10^{13} n_{eq}/cm^2 and ~ 5 kGy
- **Readout rate**: 40 MHz

RICH Upgrade II: FastRICH ASIC

- 16 Channels, **triggerless readout**, with Time of Arrival (ToA) acquisition via Leading Edge (LED) or Constant Fraction (CFD) discriminators, **configurable hardware shutter**, **40MHz** readout
- ToA: **24.41ps (gate)** or 97.64ps (no gate) bins, ToT: 390.625ps bins
- Sensor Coupling: MaPMT, SiPM and MCP
- Data encoding: AURORA 64b/66b
- **Radiation hard design**: triple modular redundancy (TMR) for configuration and enclosed layout transistors (ELT) for analogue blocks.

FastRICH Die



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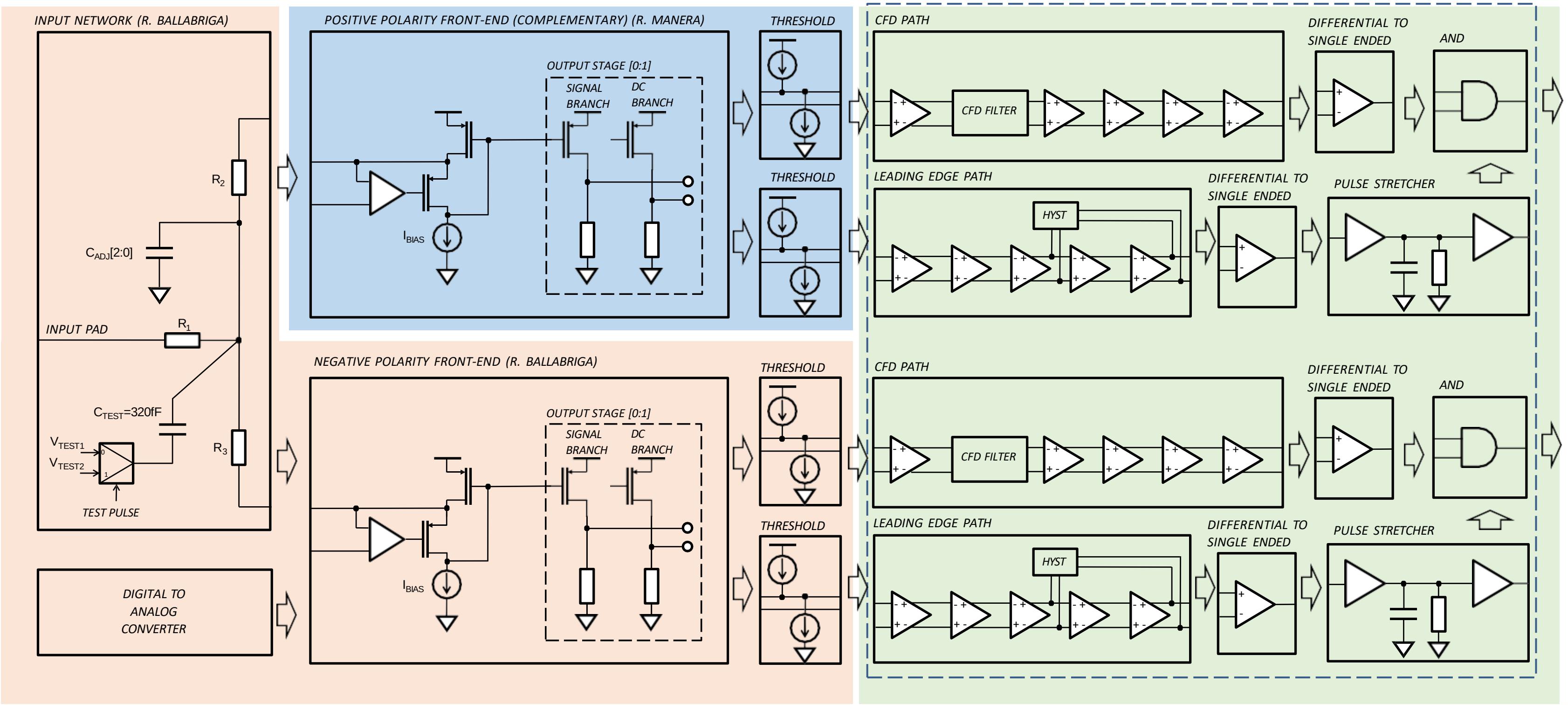
RICH Upgrade II: FastRICH architecture

- Input network with high dynamic range: 50 µA to few mA for MAPMT, SiPM or MCP coupling.
- Test pulse DAC for testing purposes.
- Positive or negative polarity signal processing.
- Novel Constant-Fraction Discrimination (CFD) to reduce throughput (no ToT information).
- Optional leading-edge path without recovery time (~15 ns for CFD).
- Logic blocks can be switched on/off for optimal power consumption.



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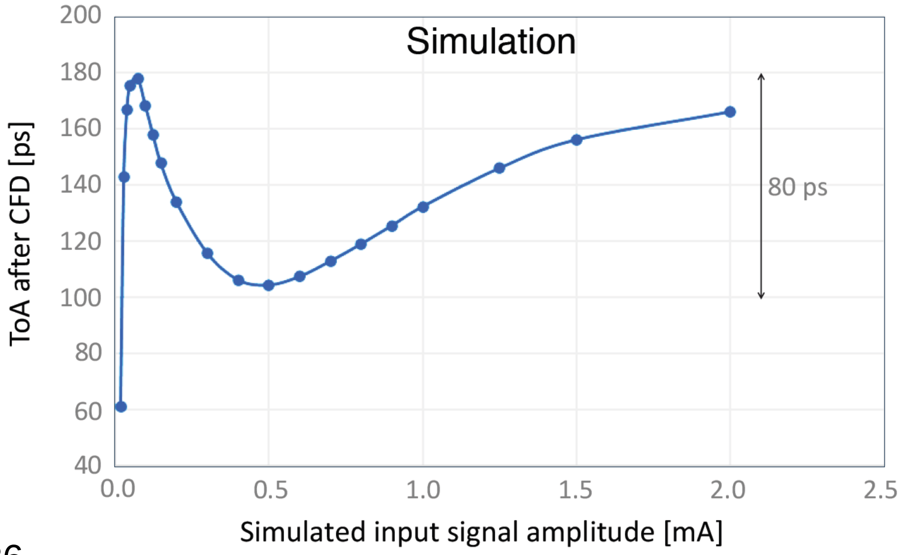
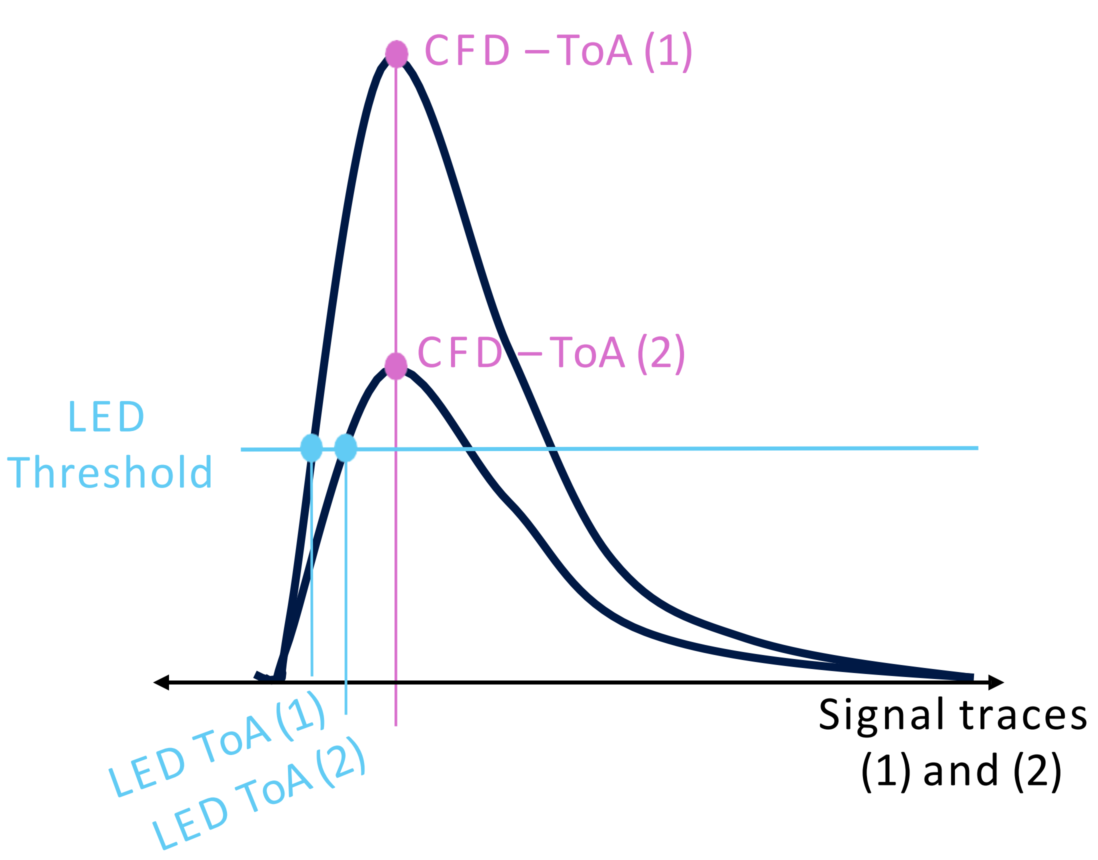
RICH Upgrade II: FastRICH ASIC time meaqsurement

- Front-end configurable between **Constant-Fraction Discrimination (CFD)** or **Leading-Edge Discrimination (LED)** with 390 ps LSB **Time-over-Threshold (ToT)** measurement.

- Simulated residual time walk of the CFD
  - with a worst-case residual of ~ 80 ps
  - For SiPMs, the (residual) time walk is expected to be negligible.

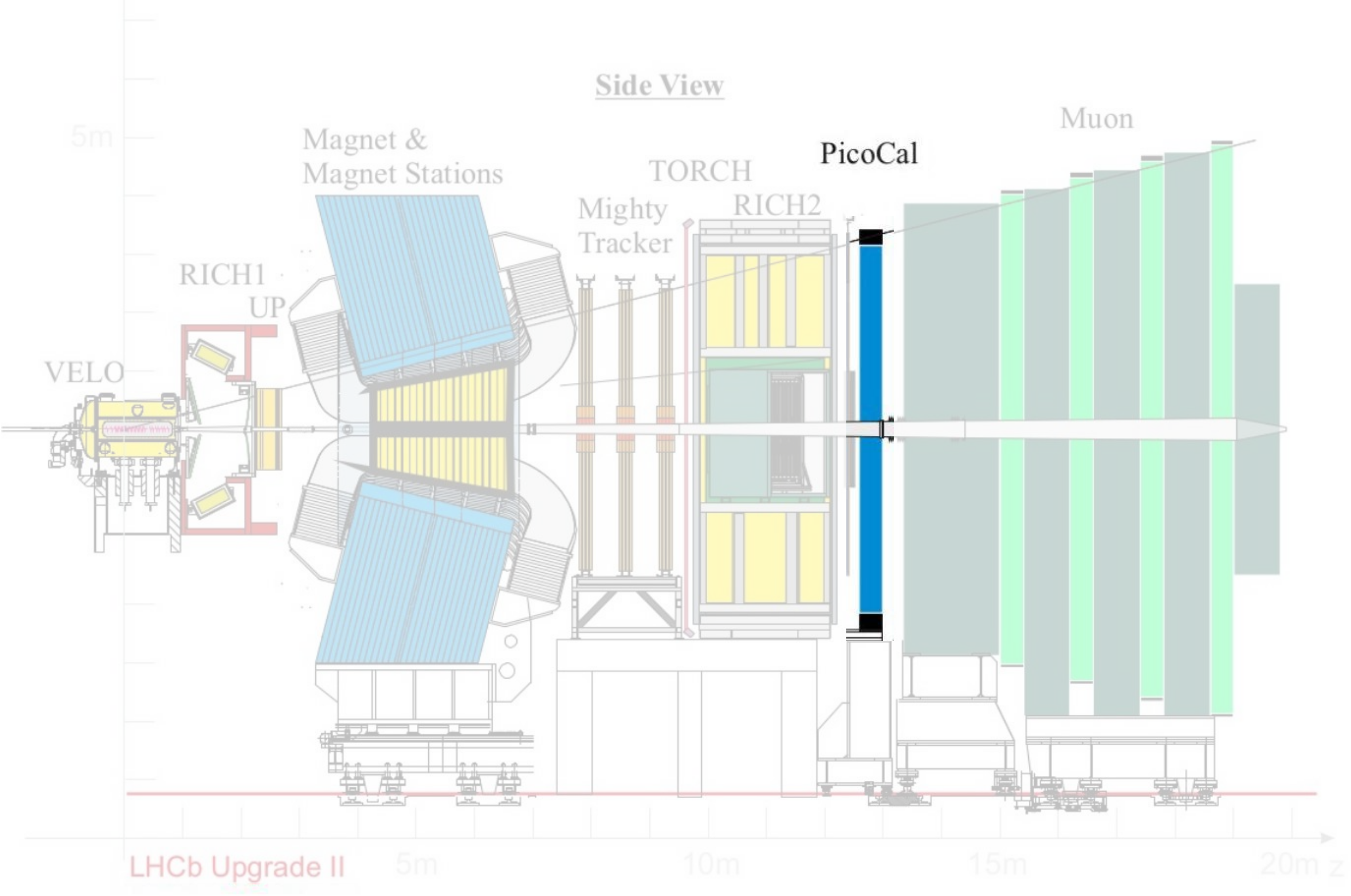


Example of two different signal traces

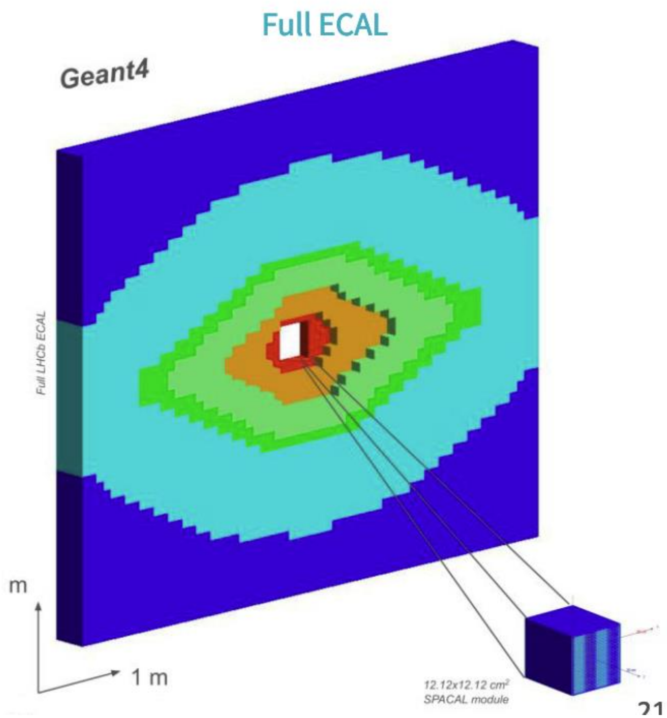


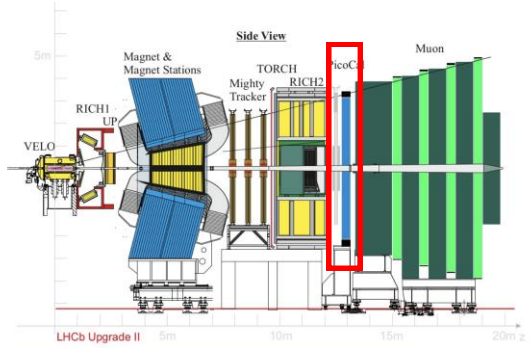
✓ CFD corrects Time of Arrival (ToA) timewalk

The Electronic Calorimeter (PicoCal)



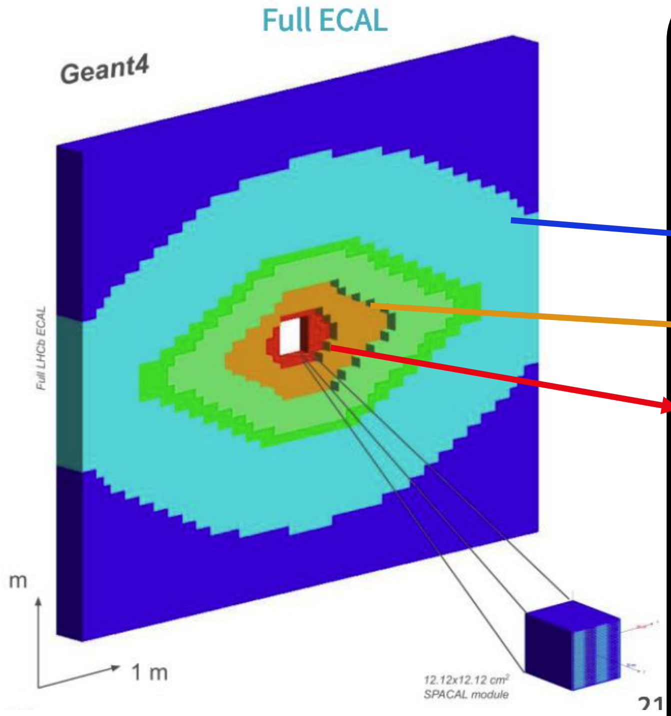
The Calorimeter System in Upgrade II (PicoCal)





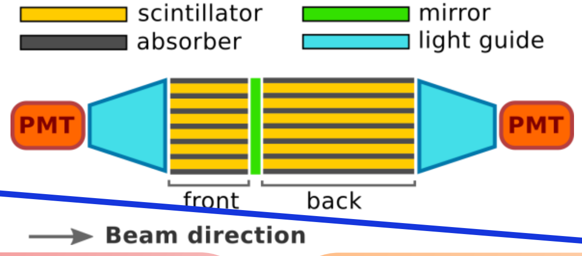
- Ongoing R&D to produce modules that allow
  - Precise time measurement
  - Energy resolution of $\sigma(E) / E \approx 10\% / \sqrt{E} \oplus 1\%$
- Reorganize the ECAL zones in rhombic shapes to follow better radiation and cell occupancies
  - Increased granularity in the central region with denser absorber
- Add longitudinal segmentation at shower maximum to improve time resolution
  - Useful also for particle identification: separation electron/hadron

Electronic Calorimeter: SpaCal Technology

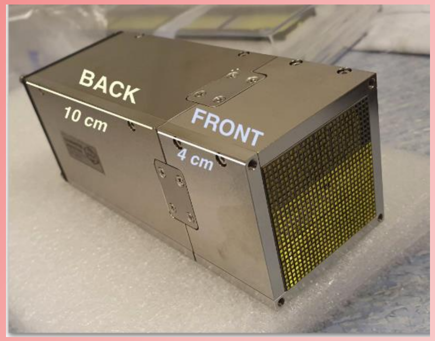


Middle
$1.0 \times 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
<u>PicoCal</u>
40 SpaCal-W
408 SpaCal-Pb
2864 Shashlik
double R/O
30,976 channels

SPACAL

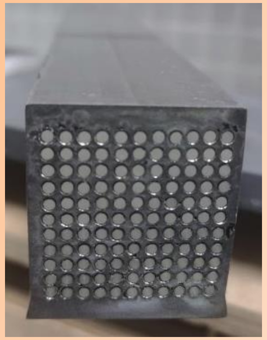


SPACAL-W



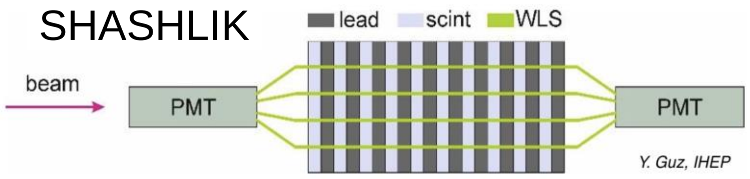
- W absorber, crystal fibers (GAGG, gadolinium aluminum gallium garnet)
- Large tolerance to radiations and small Molière radius
- **Cell size 1.5x1.5 cm²**

SPACAL-Pb

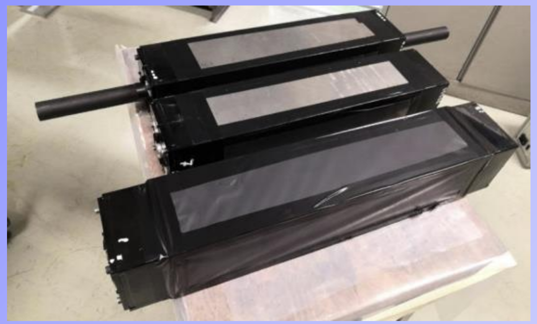


- Pb absorber, polystyrene fibres
- Cell sizes
  - 3x3 cm²
  - 4x4 cm²

SHASHLIK

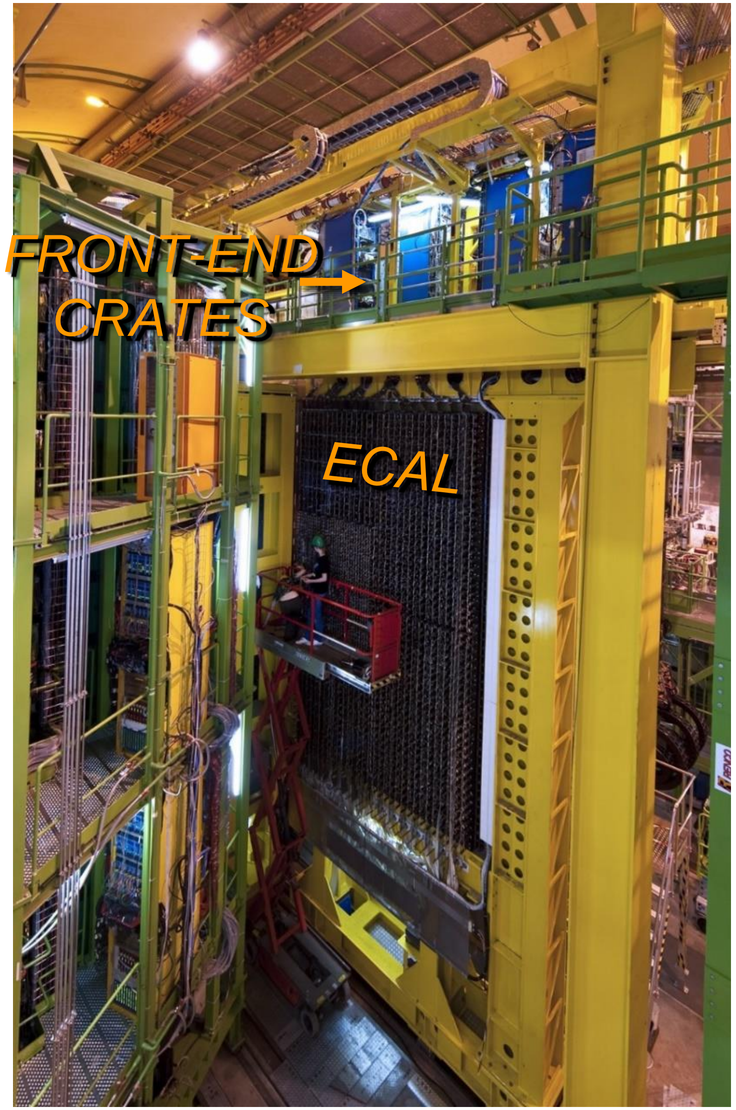


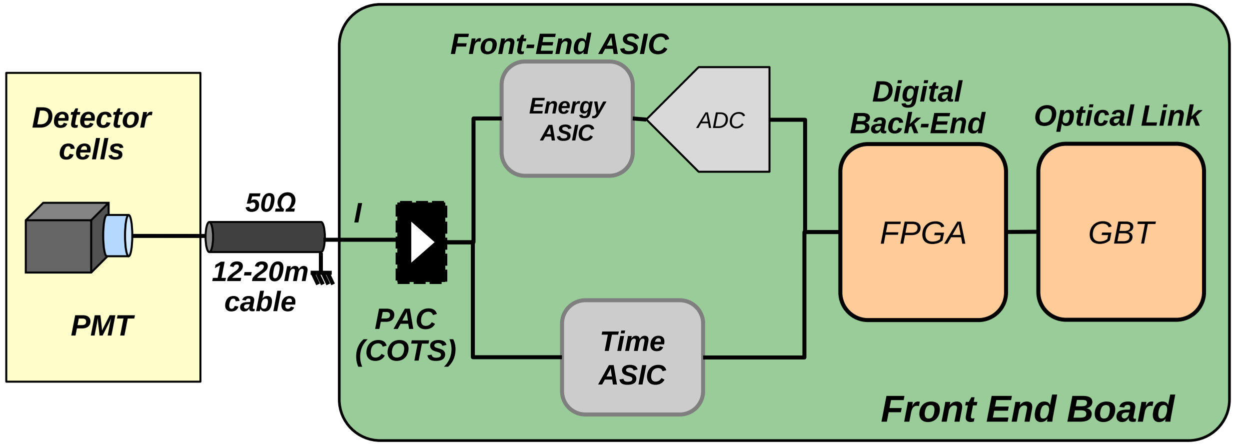
SHASHLIK



- Pb absorber, scintillator, YS4 fibres
- Current modules: outer region
- Cell sizes
  - 4x4 cm²
  - **6x6 cm²**
  - **12x12 cm²**

PicoCal readout architecture



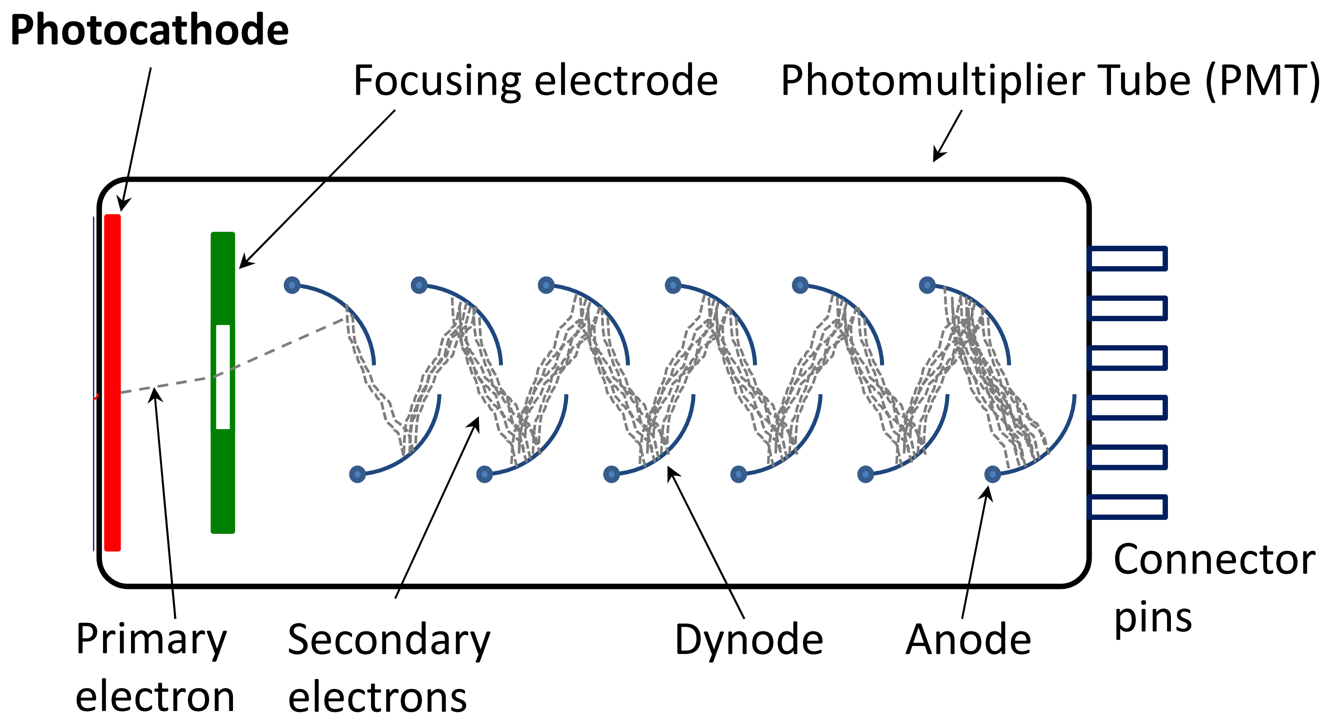


- Photodetectors readout solution follows the same scheme as in current ECAL:
  - PMT sensors near modules
- Signal conditioner circuit (COTS) to compensate cable attenuation, improve SNR, and reduce spill-over effort designed by IFIC
- ASIC/chipset in TSMC 65 nm with separate energy and timing paths.
  - Energy ASIC (ICECAL65) designed by UB, UPC and IFIC.
  - Timing ASIC (SPIDER) designed by IJCLab, LPC and IP2I and SUBATECH.

Photomultiplier Tubes

- A **Photomultiplier Tube** (PMT) light into a measurable electrical signal.
  - Gain $<10^8$

- Main Applications: Particle Physics, Medical Imaging (PET), Spectroscopy and Radiation Security.

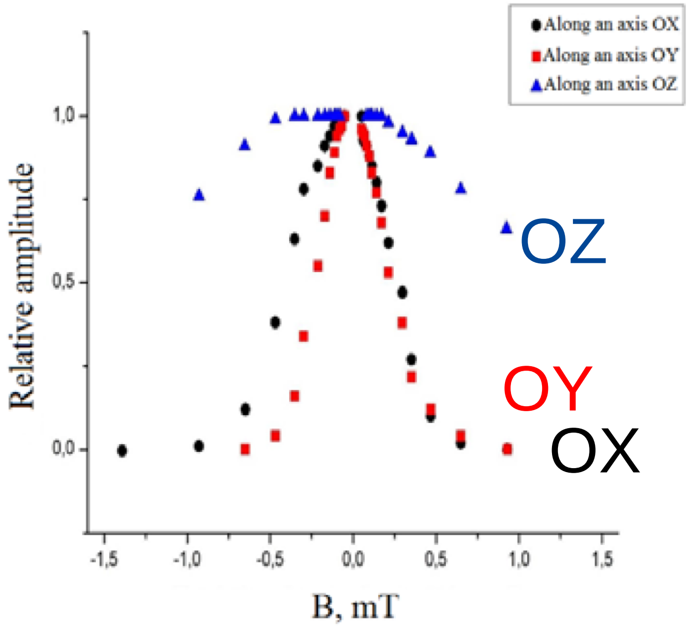


PMT: magnetic field effects

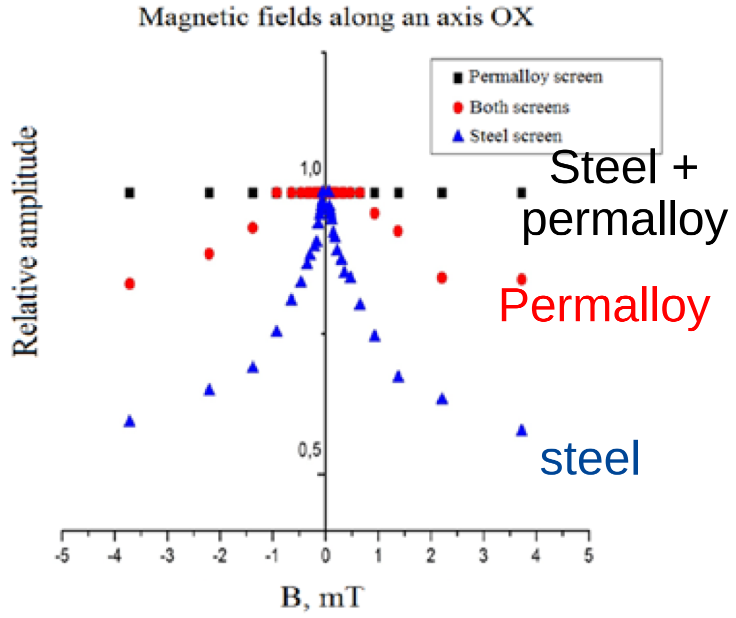
- The PMTs operate in proximity to the LHCb's powerful dipole magnet
- Strong magnetic fields → degrade PMT electron collection efficiency and gair
- Use of shielding
  - Steel screen
  - Permalloy

Dependence of the relative output pulse amplitude of the PMT HAMAMATSU R7899-20

No shielding



Shielding

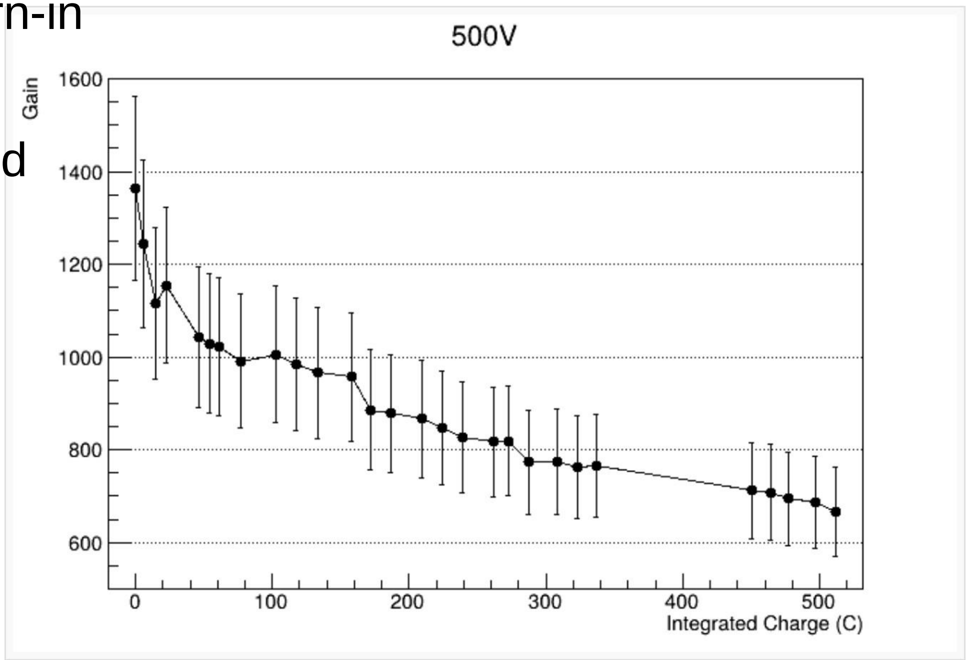


[Paper]

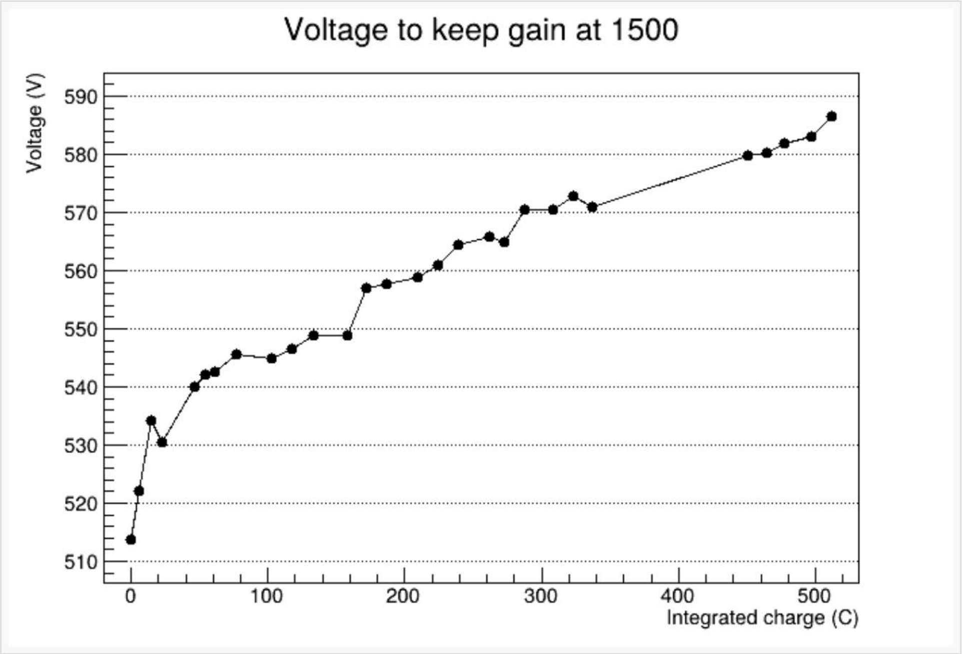
PMT ageing

- Extended operation and accumulated anode charge → decrease in gain and quantum efficiency
  - Gain Fatigue: The amplification factor of the dynode chain drops over time
  - Photocathode Degradation
  - Anode Charge: ageing is directly tied to the total integrated charge
- How we can cope with it
  - Pre-ageing or burn-in
  - Increase HV
  - Partially recovered after stop time

Gain



Correction voltage

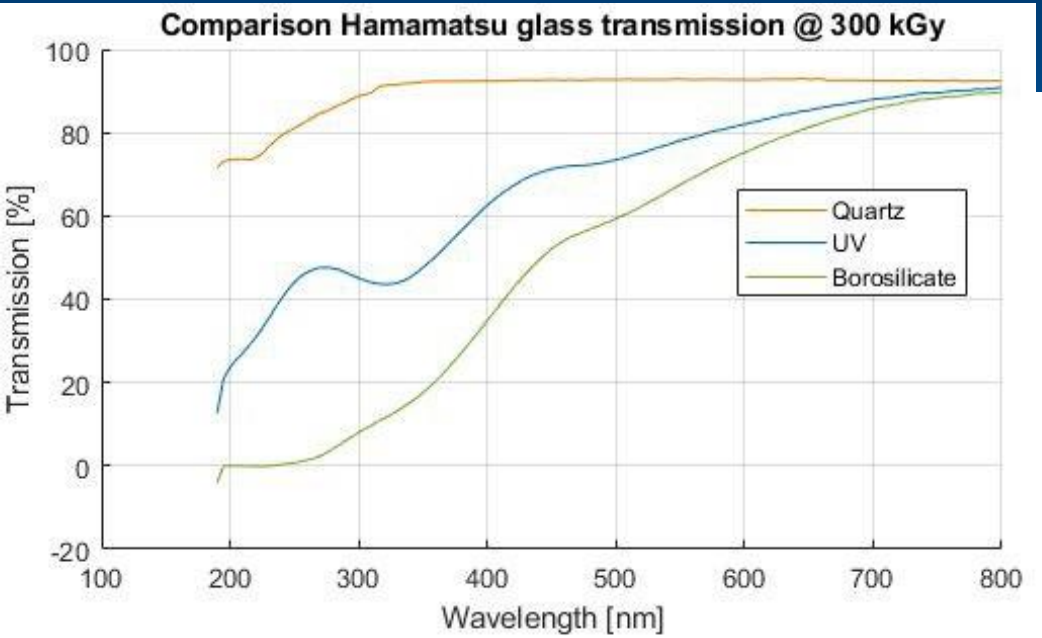


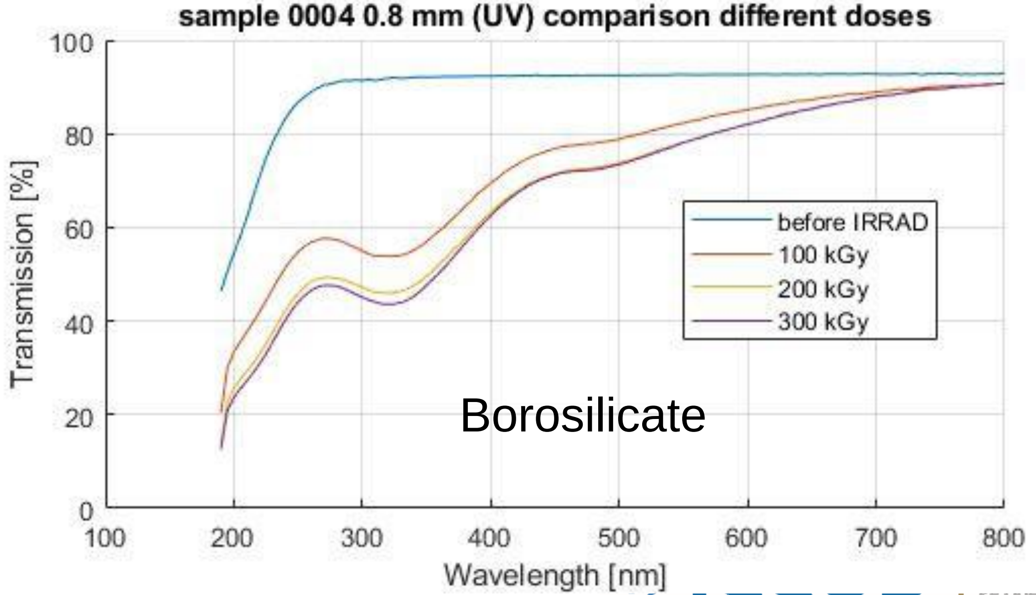
PMT radiation effects

- Irradiated PMTs present problems with the entrance window transparency

- Proposed PMTs for PicoCal could use quartz, UV or borosilicate windows

- Quartz transparency degrades the least, but it is more expensive

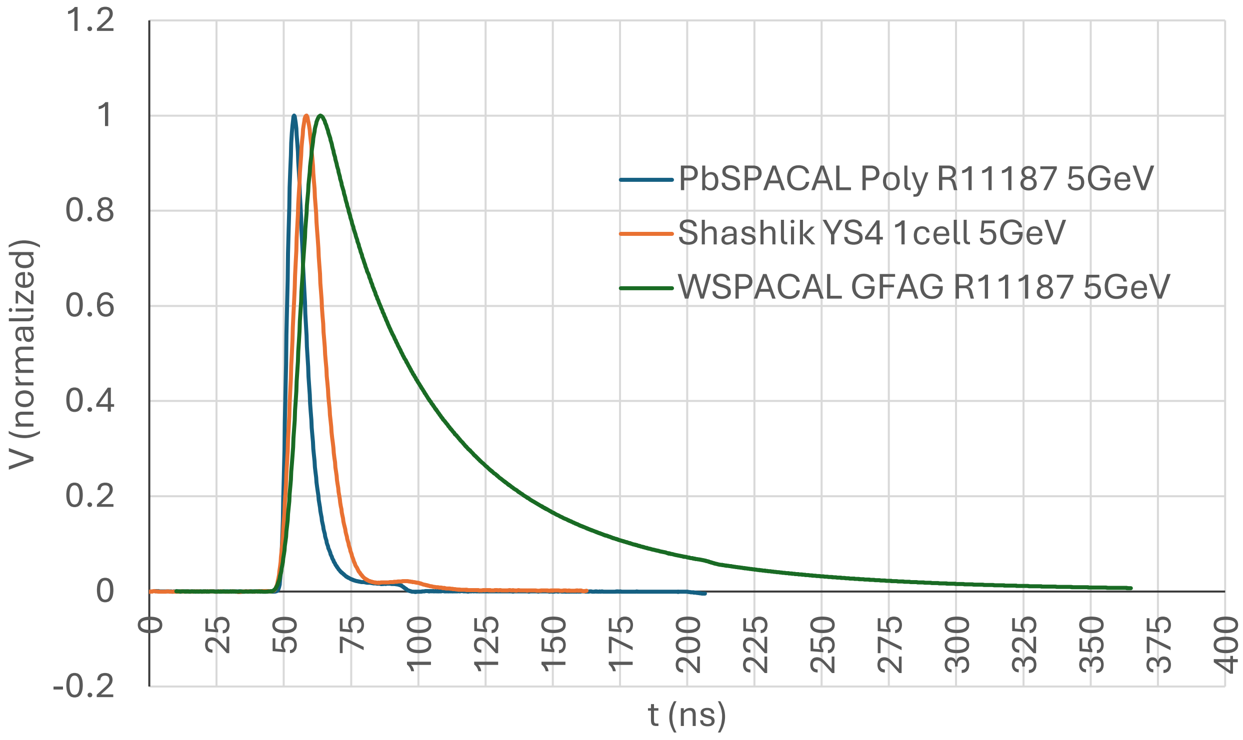




PicoCal Electronics Requirements

- Energy resolution = $\frac{\sigma(E)}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 1\%$
- Time resolution = 15 ps RMS for entire chain at high energy (ET > 1 GeV)
- Energy measurement in the range ET = 0 to 40 GeV @ 40 MHz
- Time measurement in the range ET = 50 MeV to 5 GeV
  - With occupancy (ET > 50 MeV) below 50%
  - Possibility to record 8 consecutive events
- Radiation tolerance: 400 kRad at end of Run 5

Normalized PMT pulse shapes for SpaCal and Shashlik channels



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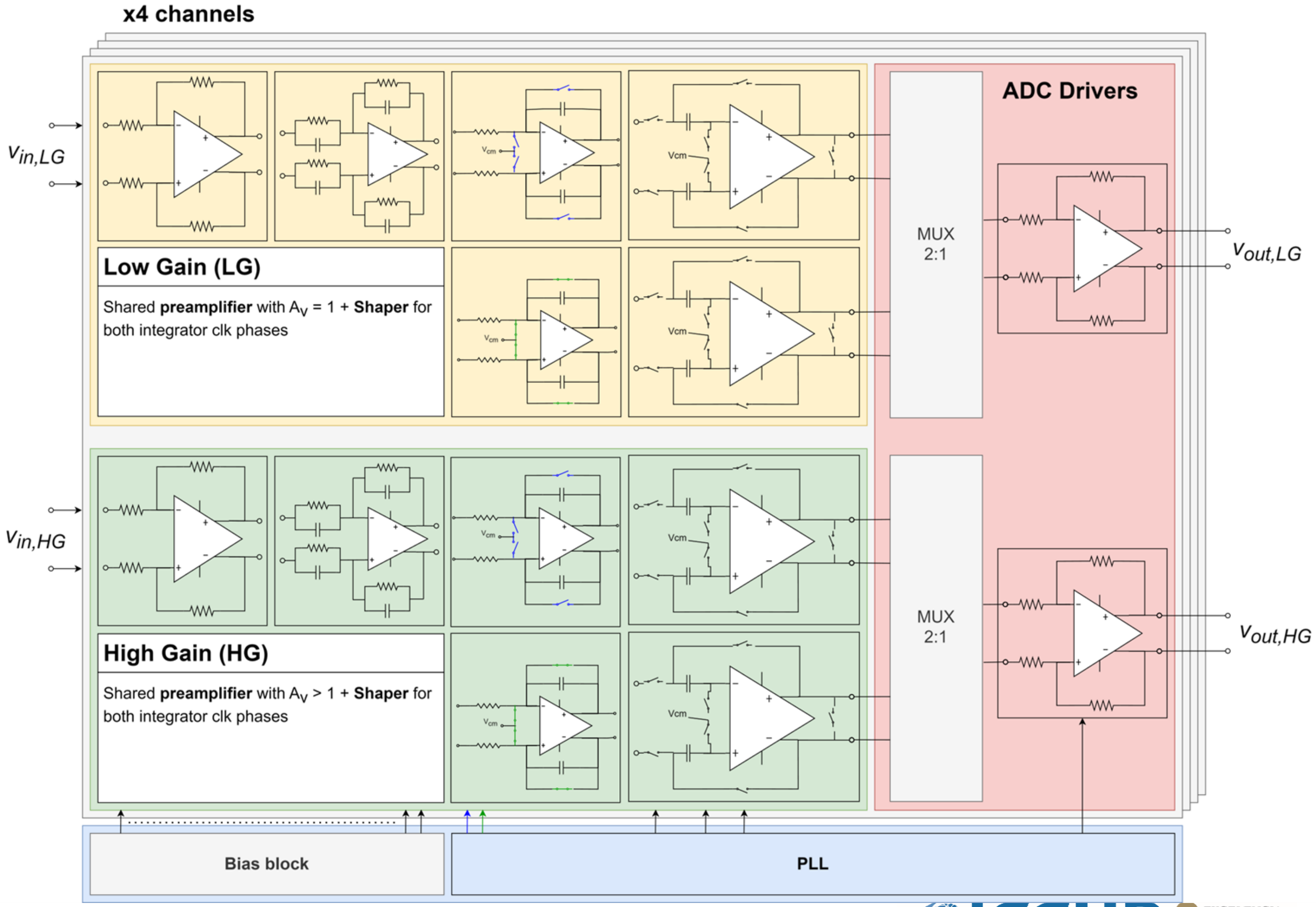
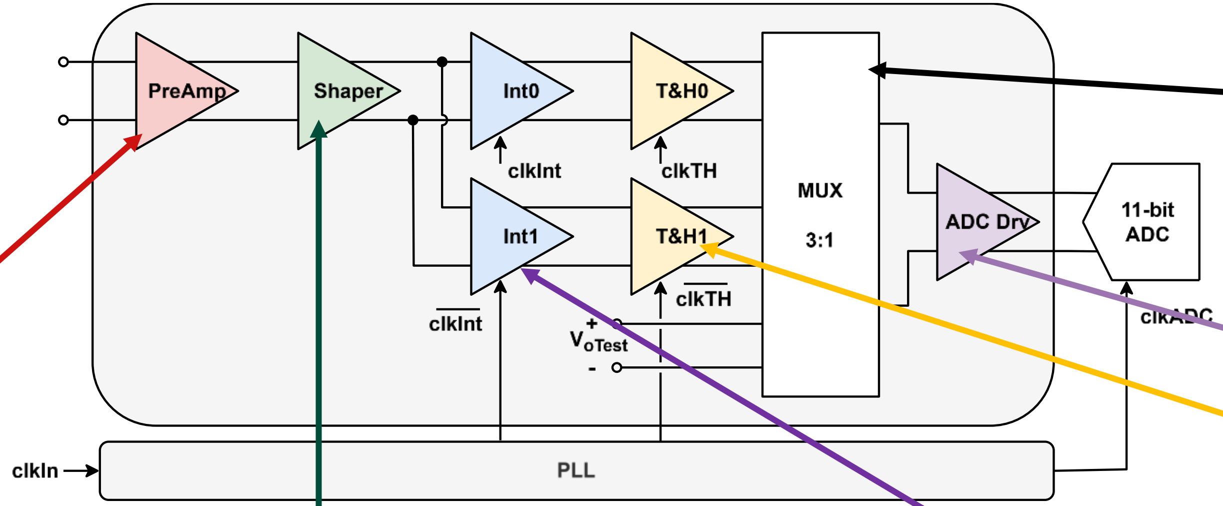
PicoCal Energy Measurement ASIC: ICECAL65

- TSMC 65nm **4- or 8-channel ASIC**
- Dynamic range 1 V
  - Noise/1LSB at ~ 500 μV
  - **Two-gain system** and **11-bit** resolution for optimal SNR
- Continuous readout at 40 MHz
  - No deadtime
  - **Time-interleaved double channel** scheme for integrator recovery
  - **Fully differential** to improve noise rejection.
  - **Clocks** individually generated per channel using a **PLL**.
- Power consumption < 50 mW/channel.
- Measure digitized with an **external ADC. On-chip ADC is under development** for the second run.



PicoCal Energy Measurement ASIC: ICECAL65

- Analog channel stages based in a fully differential operational amplifier
- 4 channels
- External ADCs
- Channel independent syncronization



MUX

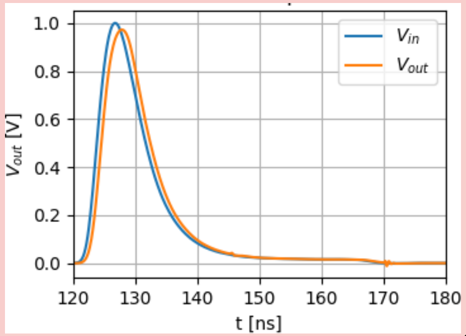
- Select correct sub-channel
- Debug mode

ADC Driver

- ADC driver needed to cope with the I/C parasitics and the ADC input capacitance

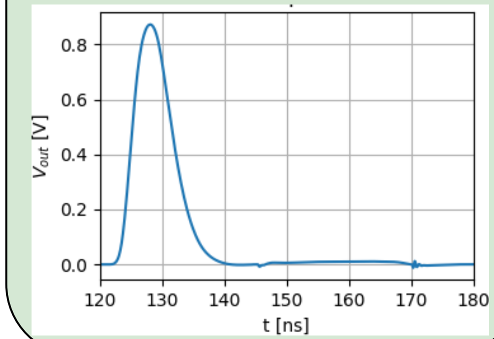
Pre-Amp

- HG and LG adjustment
- Two-gain system for 11+1 bits precision.
- Integration error < 1 %



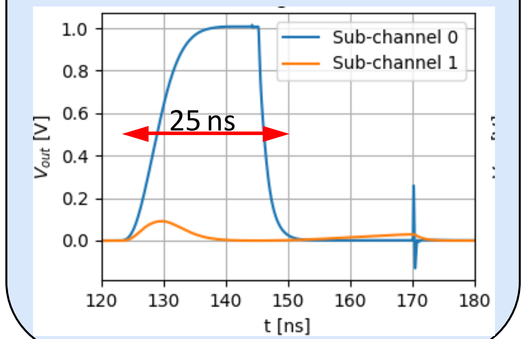
Shaper

- Reshape input signal within 25ns window
- Adjustable RC to cope with channel technology and PVT variations



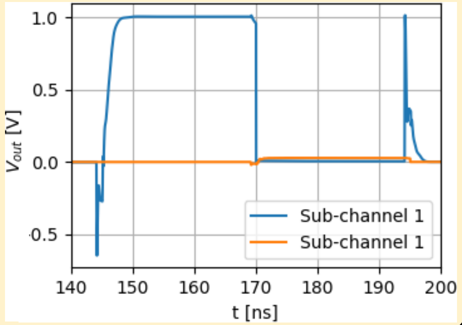
Integrator

- Continuous readout with no deadtime.
- Tunable C for gain adjustment.



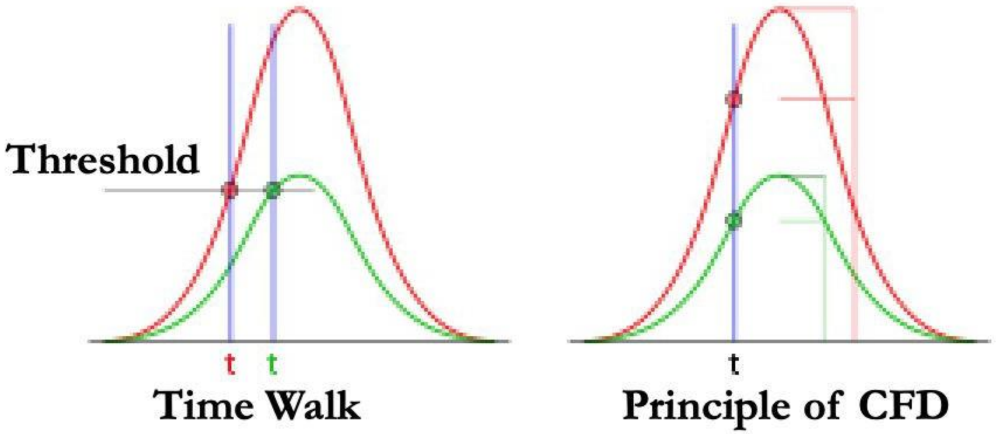
T&H

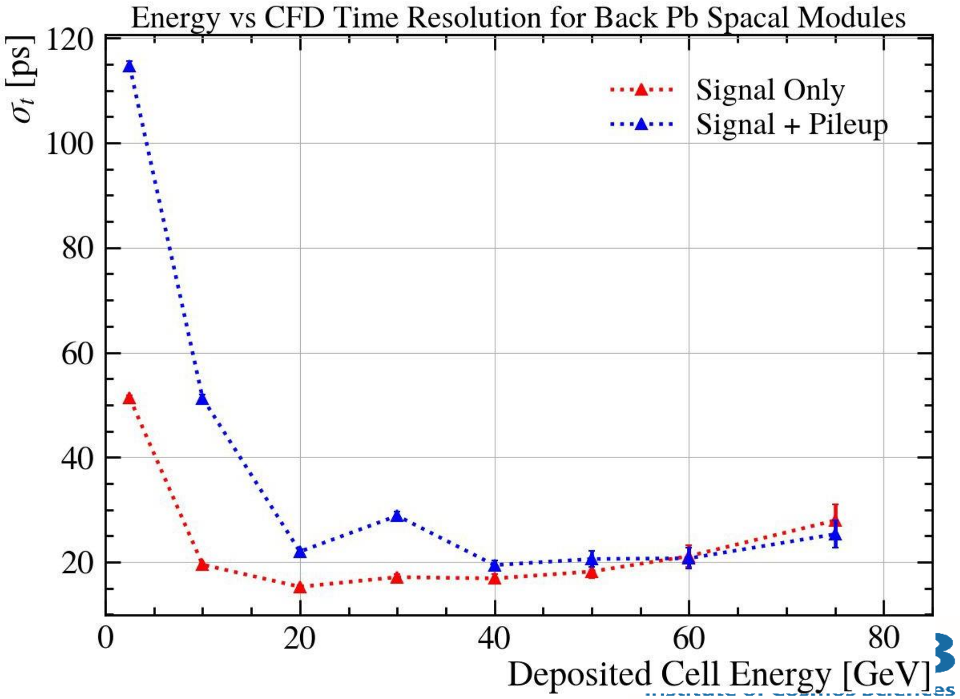
- Bottom-sampling technique.
- Transient noise < 500 µV.
- Linearity error < 1% for input signals up to 1V



PicoCal Time Measurement ASIC: Timestamping

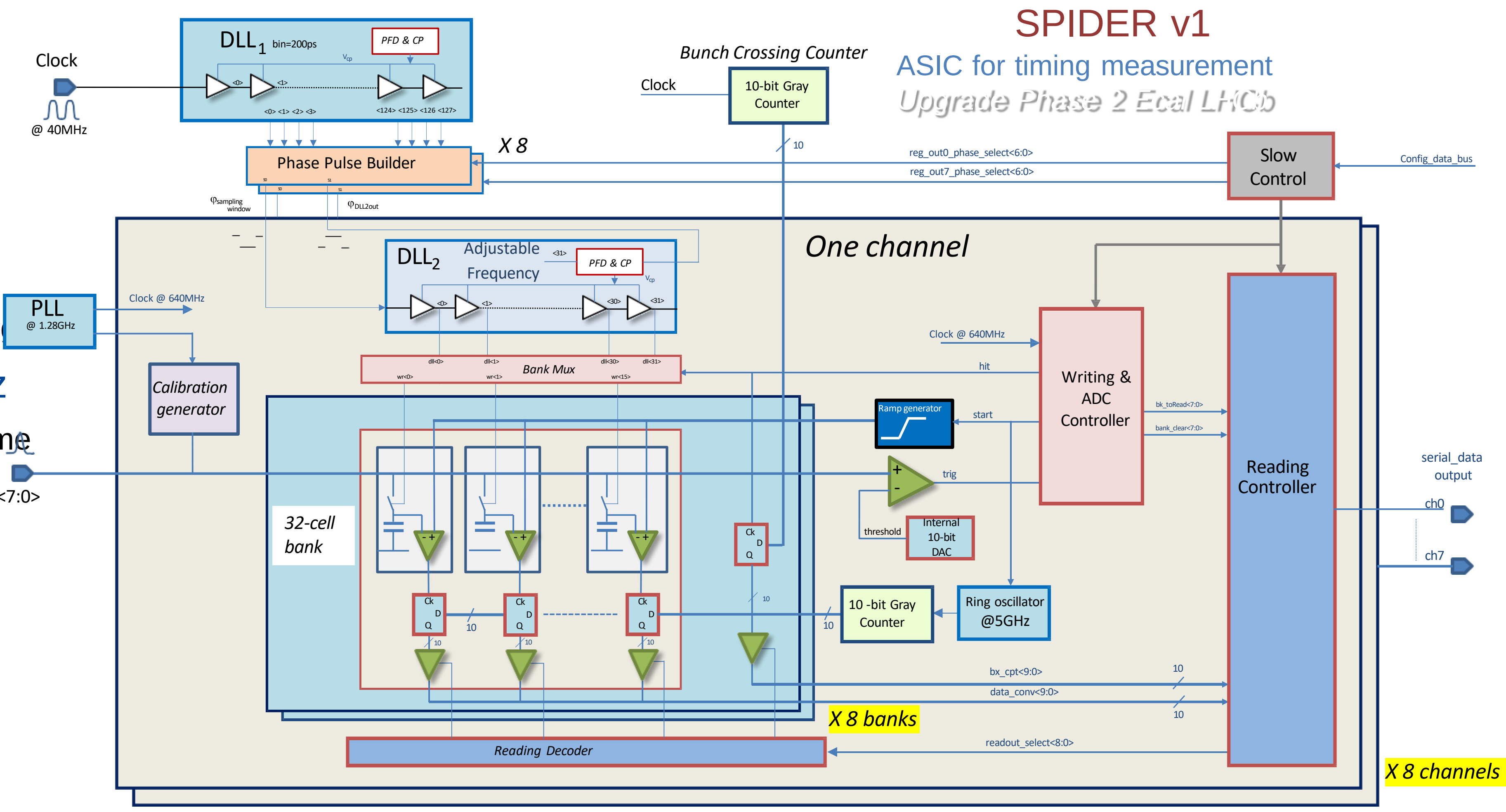
- **Timestamping** is a regularized determination of the time of arrival of a pulse with respect to a standard time reference
- Primary goal is to determine the timestamp of signals with **tens of picoseconds of resolution**
- Several methods exist for timestamping analog signals
  - Fixed threshold, fitting, template matching, optimal filtering, analog/digital constant fraction discrimination (CFD), machine learning
- **Jitter** is the time variation of an individual measurement from the expected value
- **Timewalk** is the dependence of the timestamp on the amplitude of a pulse
  - Can be corrected





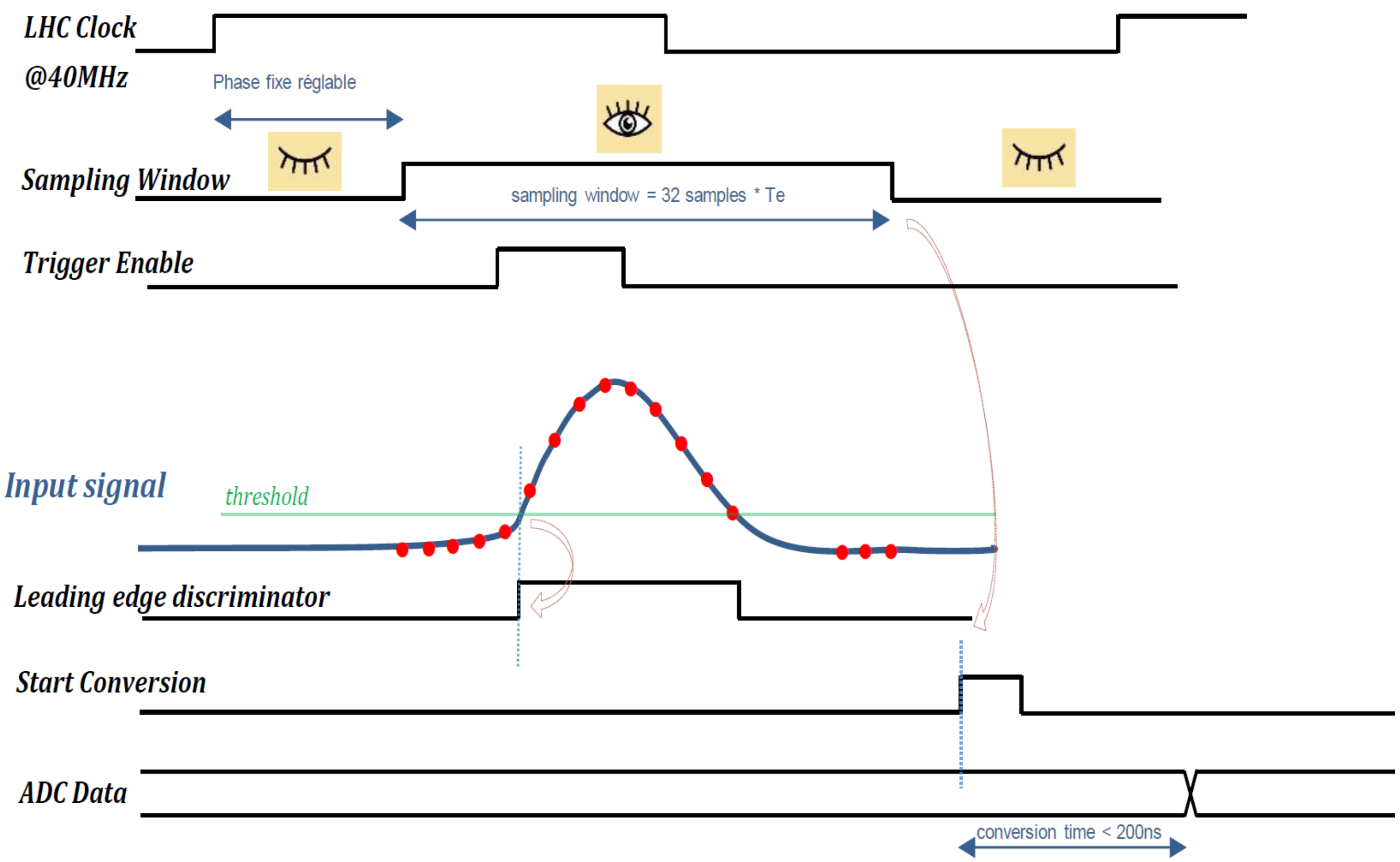
PicoCal Time Measurement ASIC: SPIDER architecture

- TSMC 65nm, VDD 1.2V
- 8 self-triggering channels
- Clock distribution & DLLs
- Memory cell
- Multi-bank system
  - Derandomization buffer
  - 8 banks of 32 cells, sequencing lo
- 10-bit Wilkinson ADC @5 GHz
  - Fast counter to limit conversion time (max 200 ns for 10 bits i-e 8 LHC periods, for 800 mV signals)
- PLL and DAC + buffer for calibrations
- Serial readout interface
  - Digital buffers
  - Up to 2.56 Gb/s on each channel



PicoCal Time Measurement ASIC: Waveform Sampling

- Swift Pipelined Digitizer for Electromagnetic Readout (SPIDER)
  - 8-channel* sampler-digitizer ASIC for synchronous signals in high-rate conditions
- **Analog signal sampling** in a configurable time window, adjustable by 200ps steps
  - Sampling period adjustable from 50ps to 600ps
- Sampling region of 32 samples -readout typically restricted to 8 samples
- **Self-triggered digitization** on 10 bits
  - Voltage range 0 - 800mV
  - Time resolution target: <15ps on 160 - 800mV



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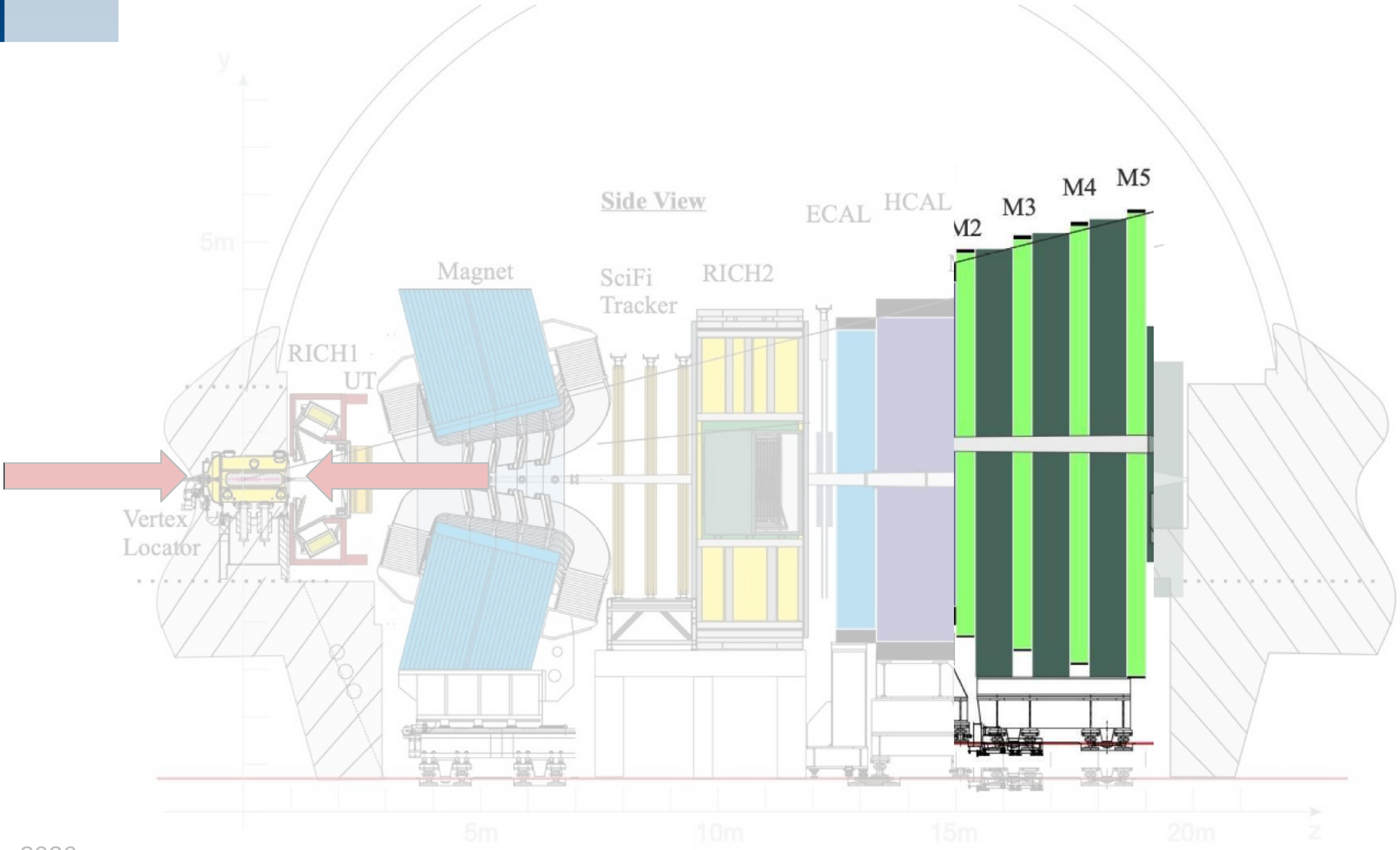
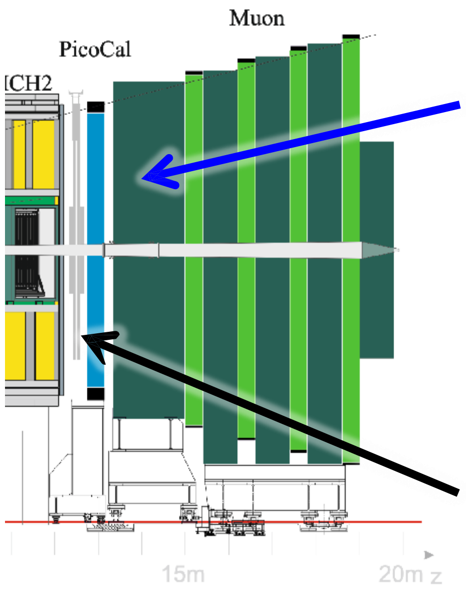
The Muon System



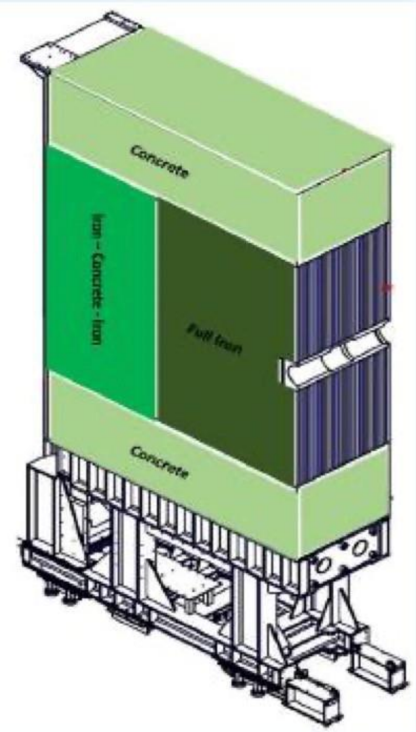
Muon Detector

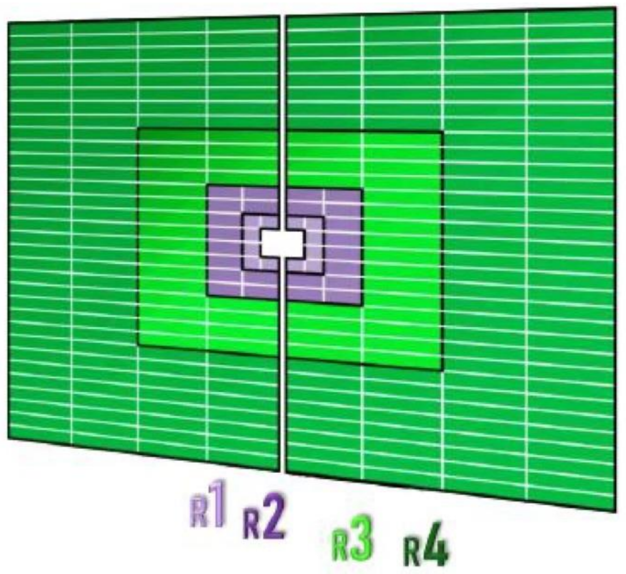


HCAL replaced with Iron/concrete shield

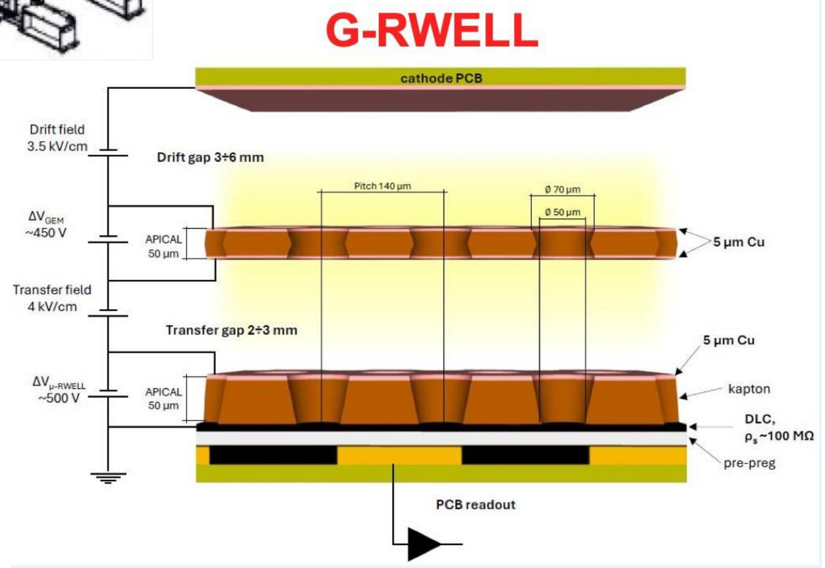
SPD/PS/M1 already removed in Upgrade I

Shielding to protect electronics against slow neutrons

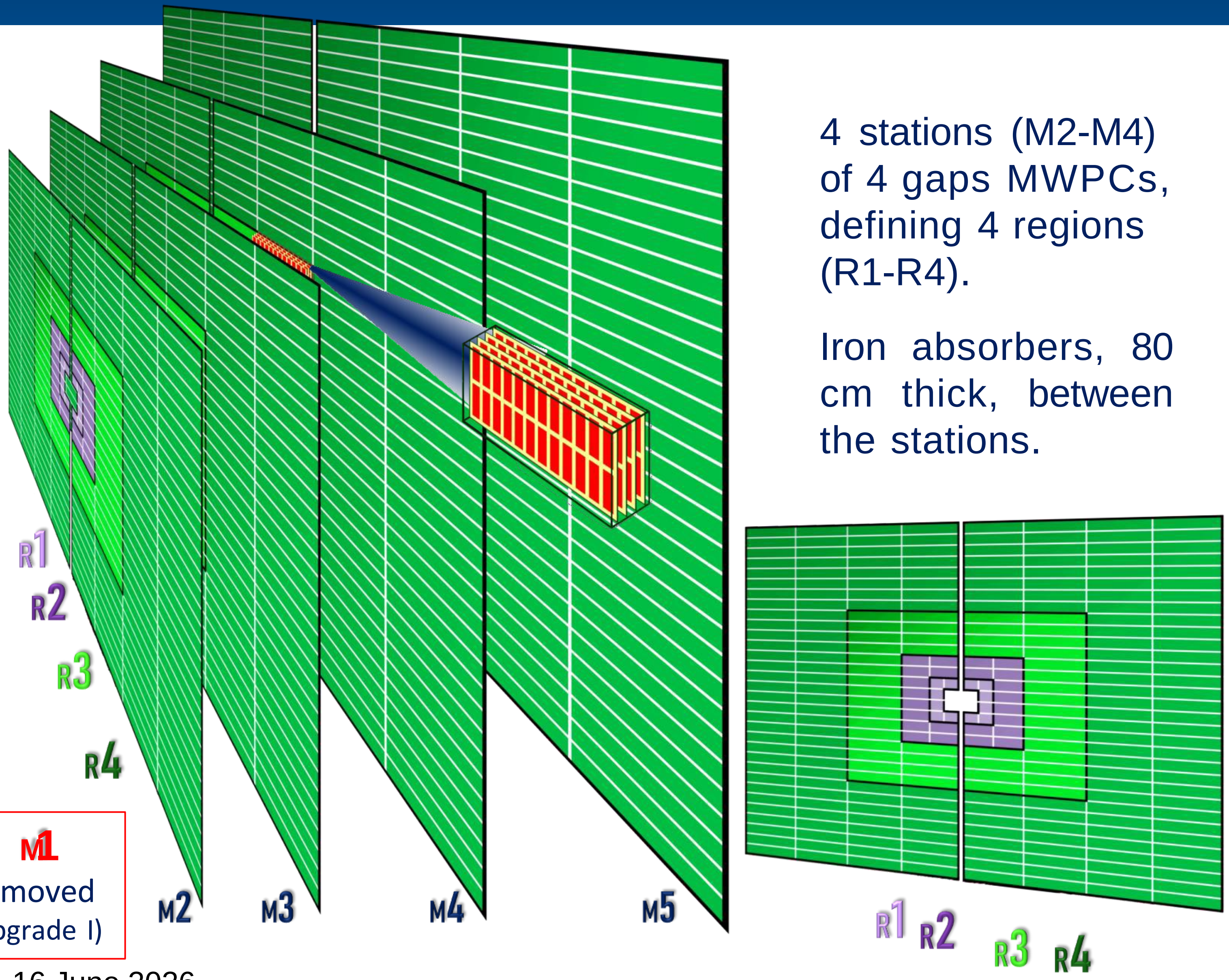




- Novel G-RWELL for inner-most region (R1, R2)
- Reuse existing MWPC in outer region (R3, R4)
- New readout scheme in all regions, for background reduction and a new FE electronics
- Additional shielding (4 $\lambda_I \rightarrow$ 10 λ_I) to be installed in front of Muon detector



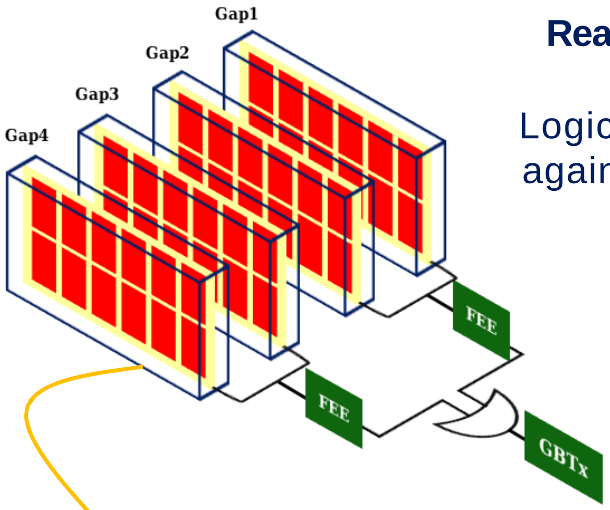
The Muon Detector



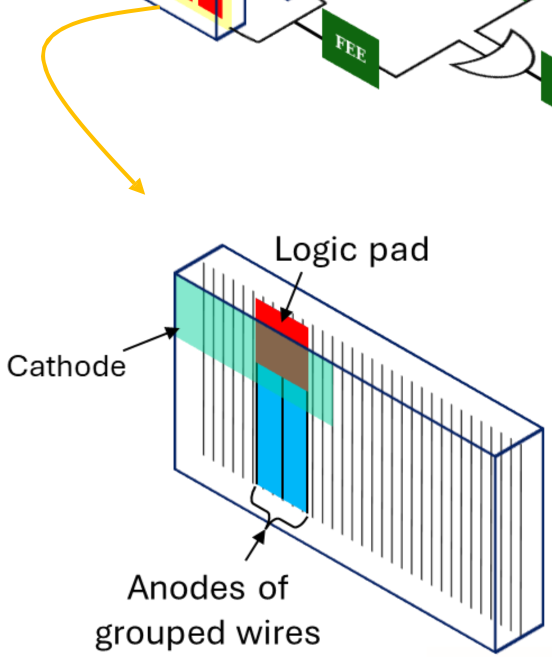
M1 removed (Upgrade I)

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



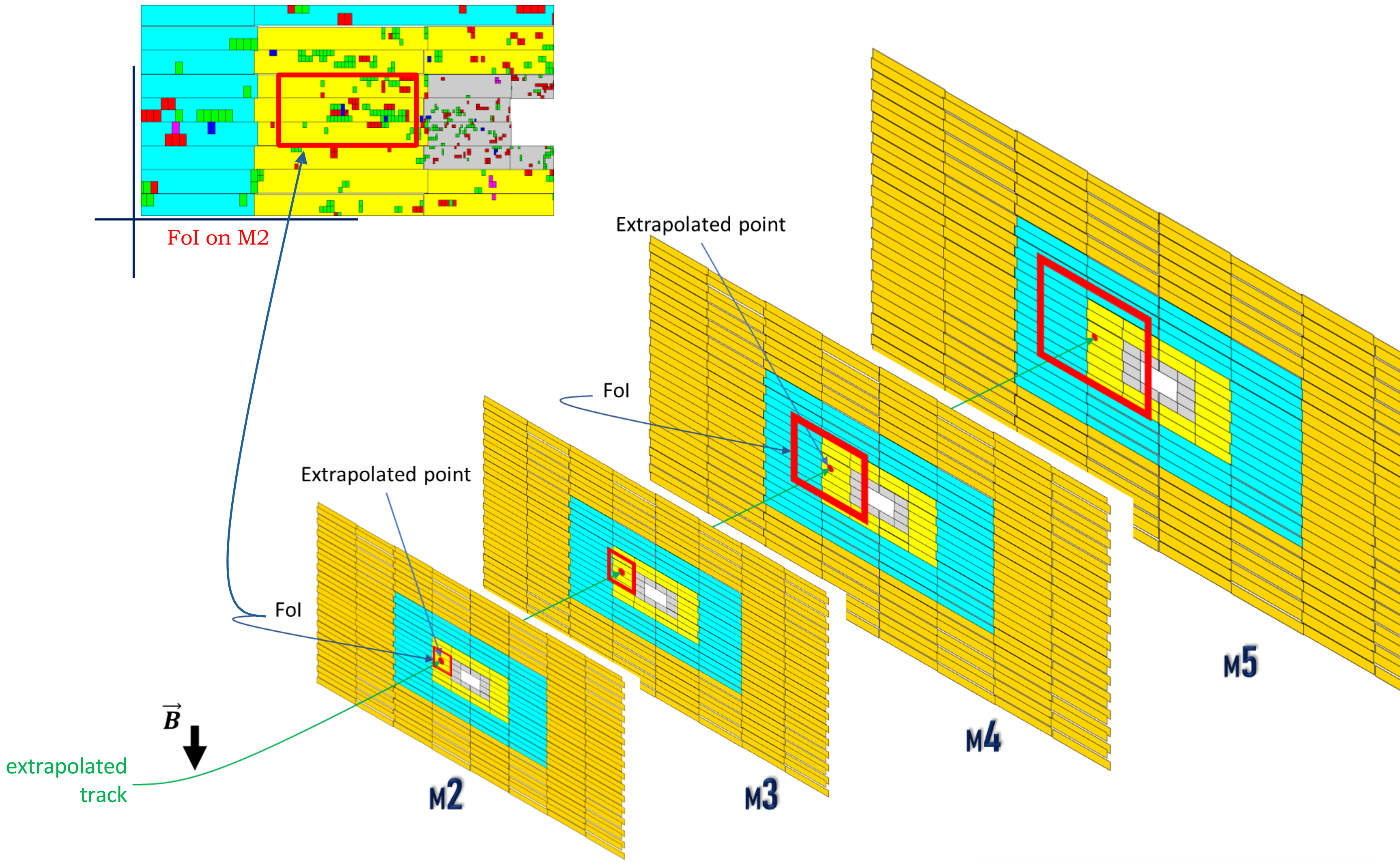
For each gap, logical pads (red) from logical AND of grouped wires and cathodic pads

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



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The Muon Detector Upgrade II

- *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/cm2)
  - **misID enhanced** ← High pile-up from background limited reduction of background hits

- Targeting same performance as in Runs 1 to 3

- *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**

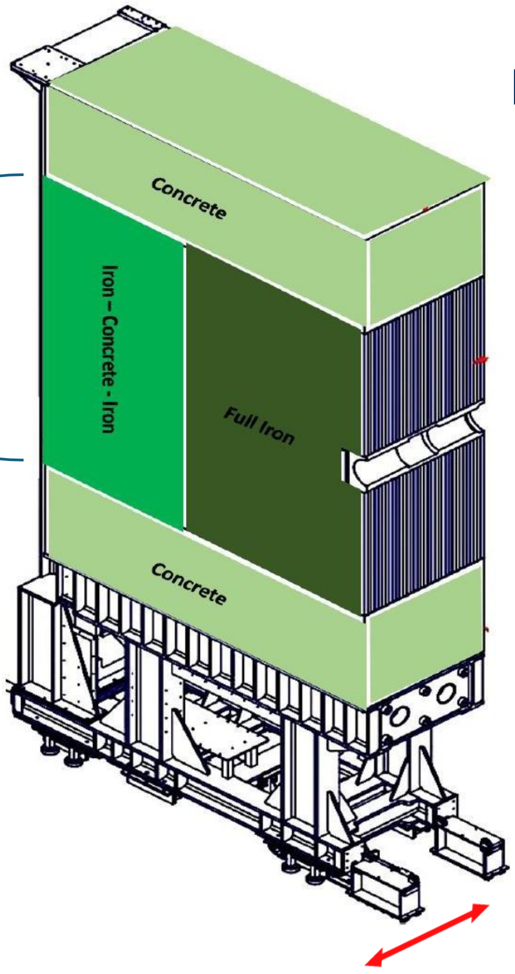
[LHCb-U2-FTDR]

The Muon Detector UII: Shielding

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

[LHCB-INT-2019-008]

iron-concrete-iron-NeutronAbsorber (6.2 λ_I), acting on M2M3R4



148+5 cm

Iron-NeutronAbsorber (10.1 λ_I), acting on M2M3R1-R3

concrete-NeutronAbsorber (4 λ_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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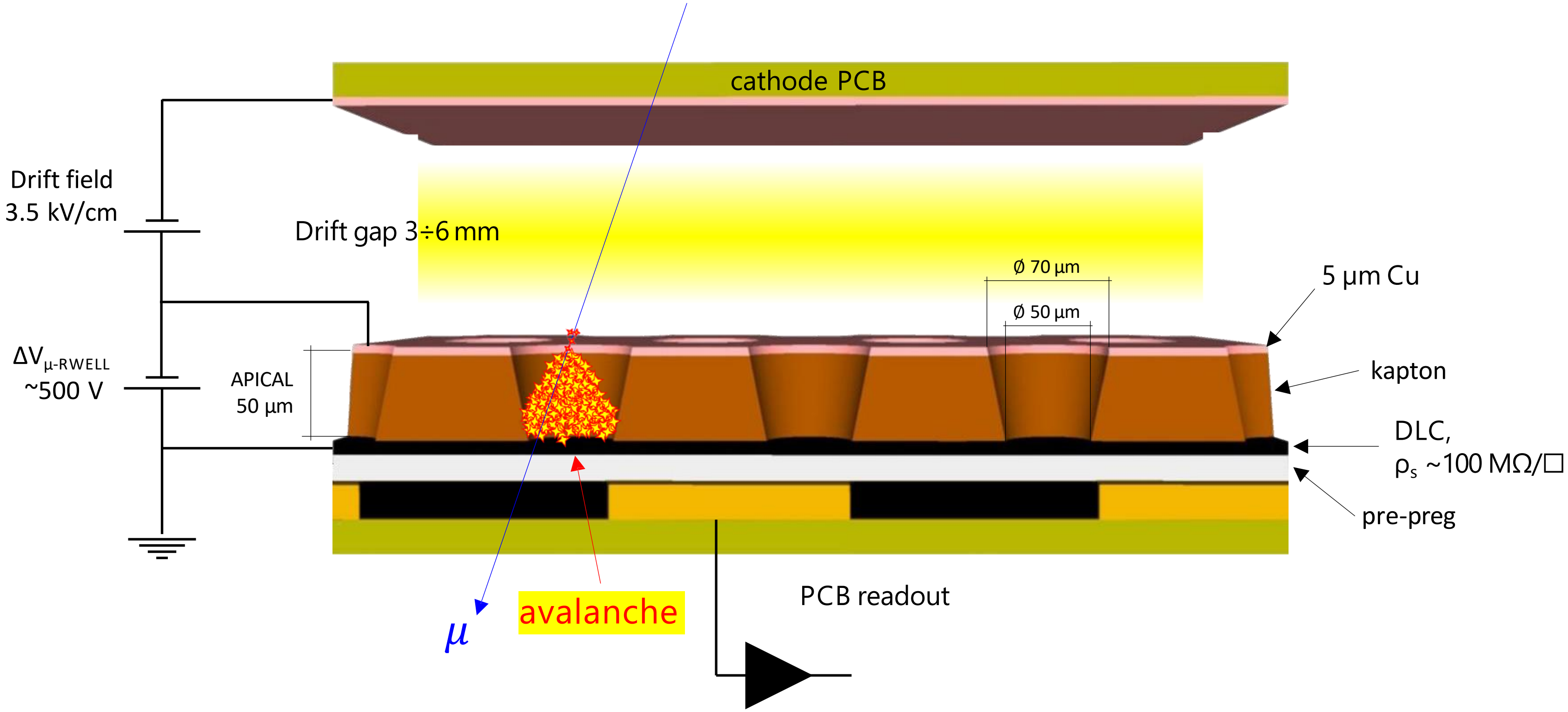
The Muon Detector UII: inner regions R1-R2

μRWELL technology:

- MicroPattern Gas detector (MPGD) consisting of:
  - cathodic plane
  - Gaseous drift region
  - μRWELL:
    - well foil (copper + kapton)
    - resistive layer
  - Pad readout

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

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

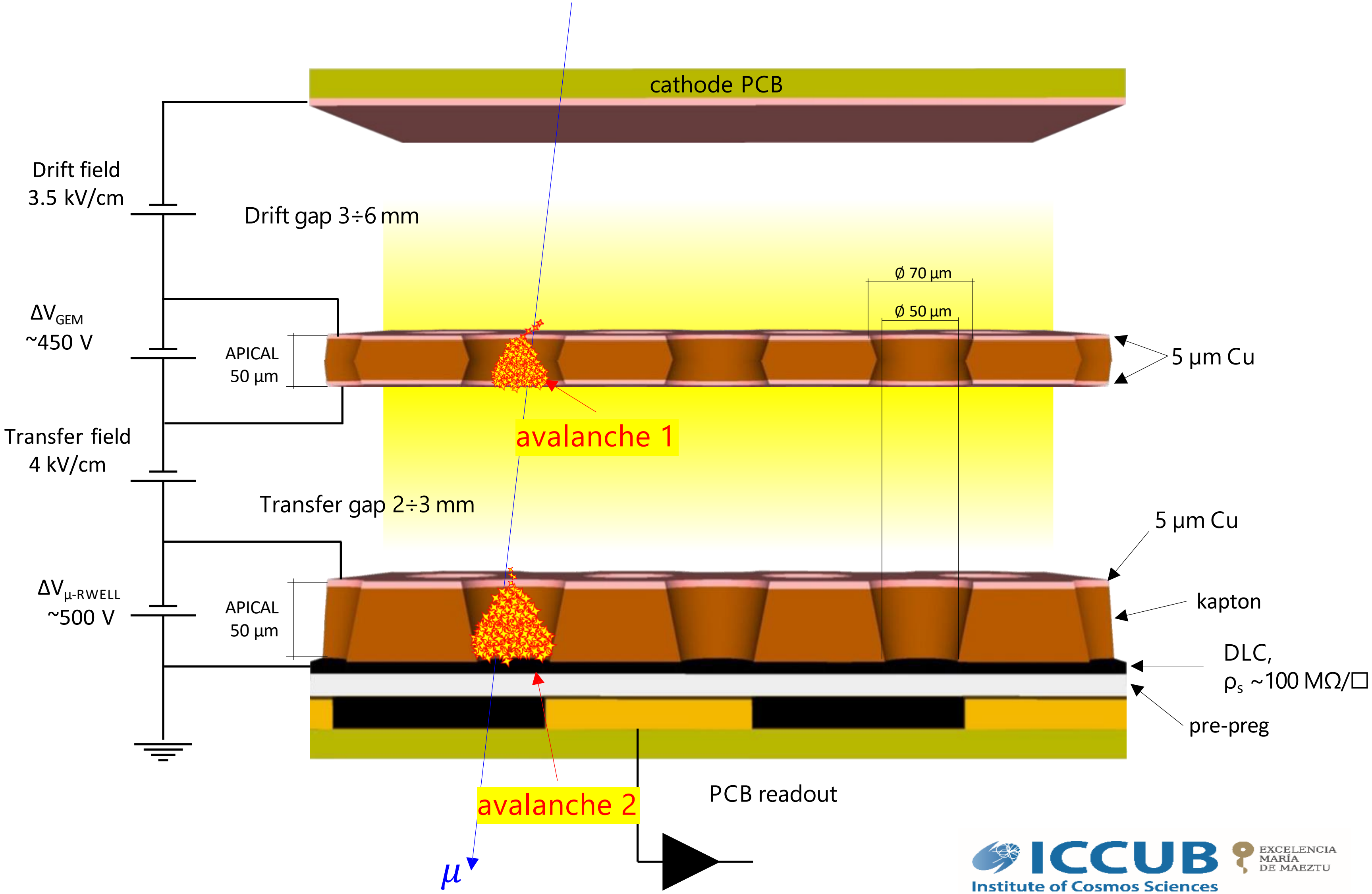


The Muon Detector UII: inner regions R1-R2

G-RWELL technology:

- 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 104.



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  - Gaseous drift region
  - GEM foil
  - Gaseous transfer region
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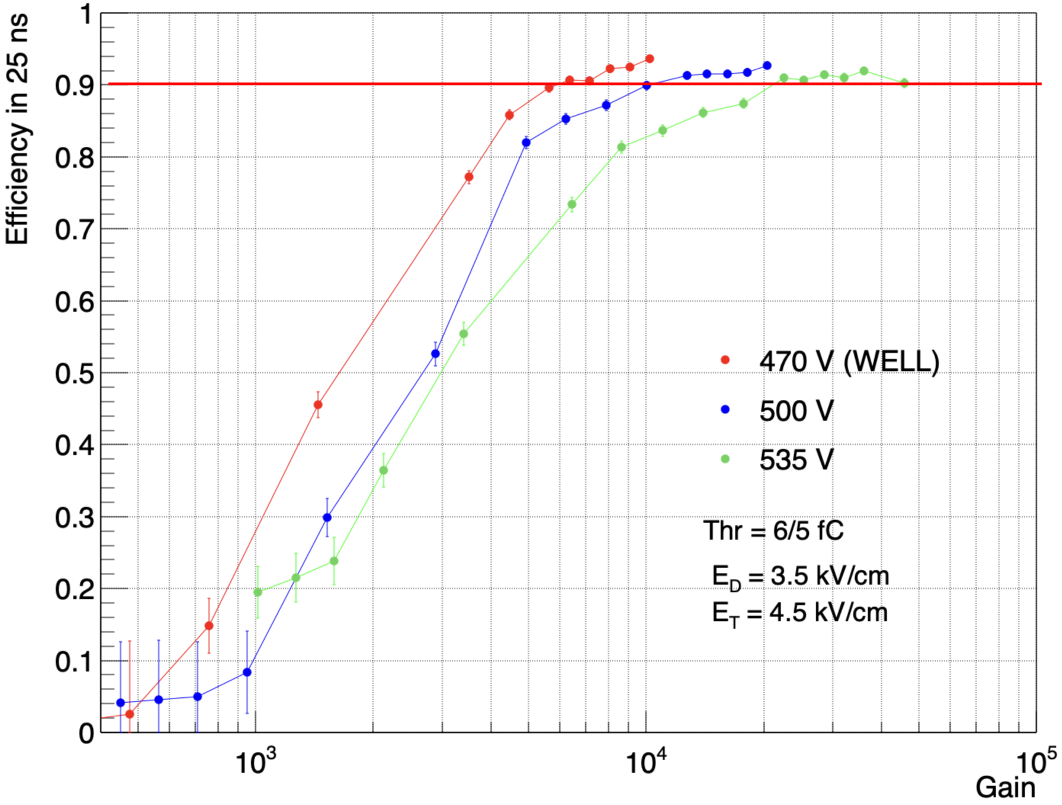


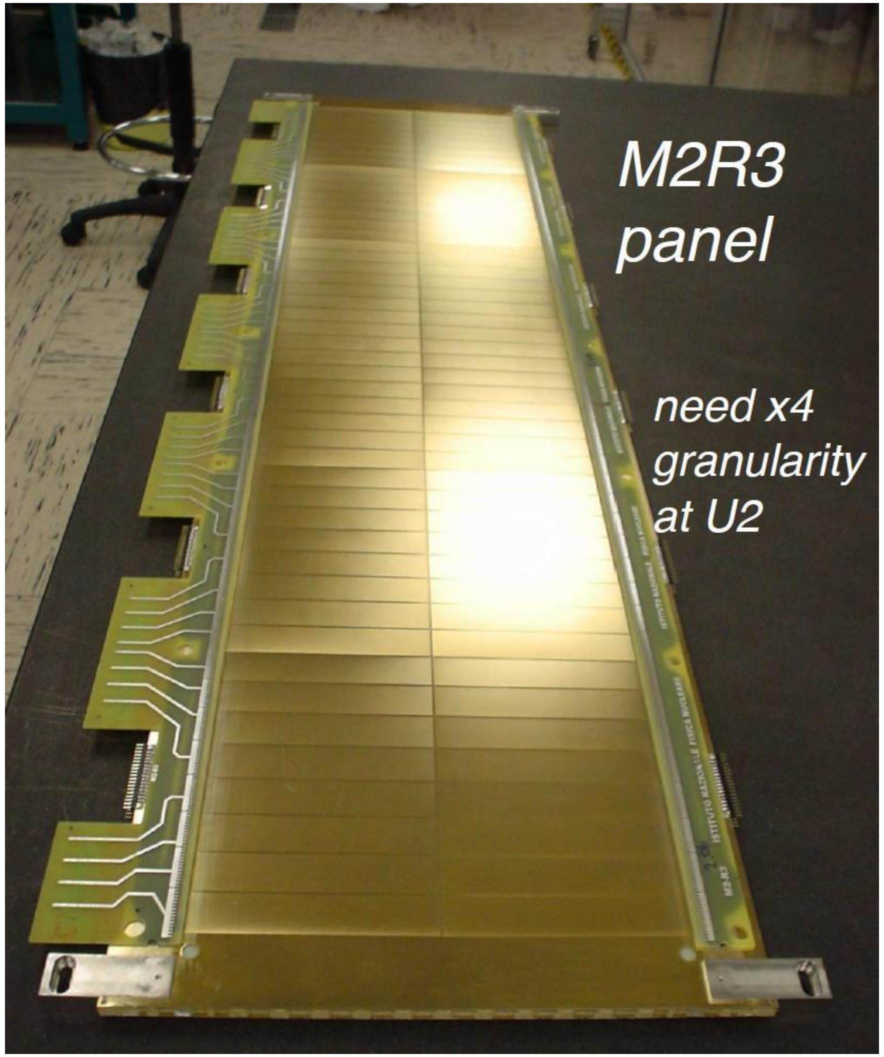
An efficiency of 90% within 25 ns for a single gas gap is achieved at a gas gain of 10^4, which is to be considered well within safe detector operational limits.

The Muon Detector UII: outer regions R3-R4

In R3-R4 (rates ≤ 50 kHz/cm^2):

Reuse of most of the present MWPCs

- 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



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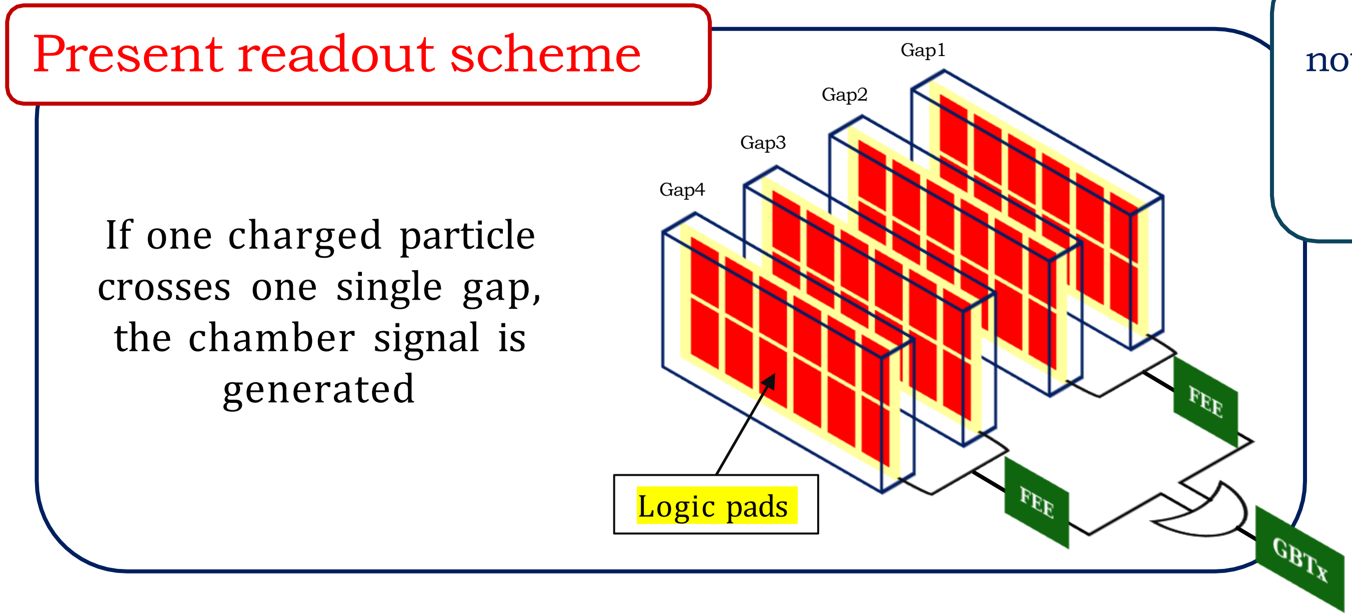
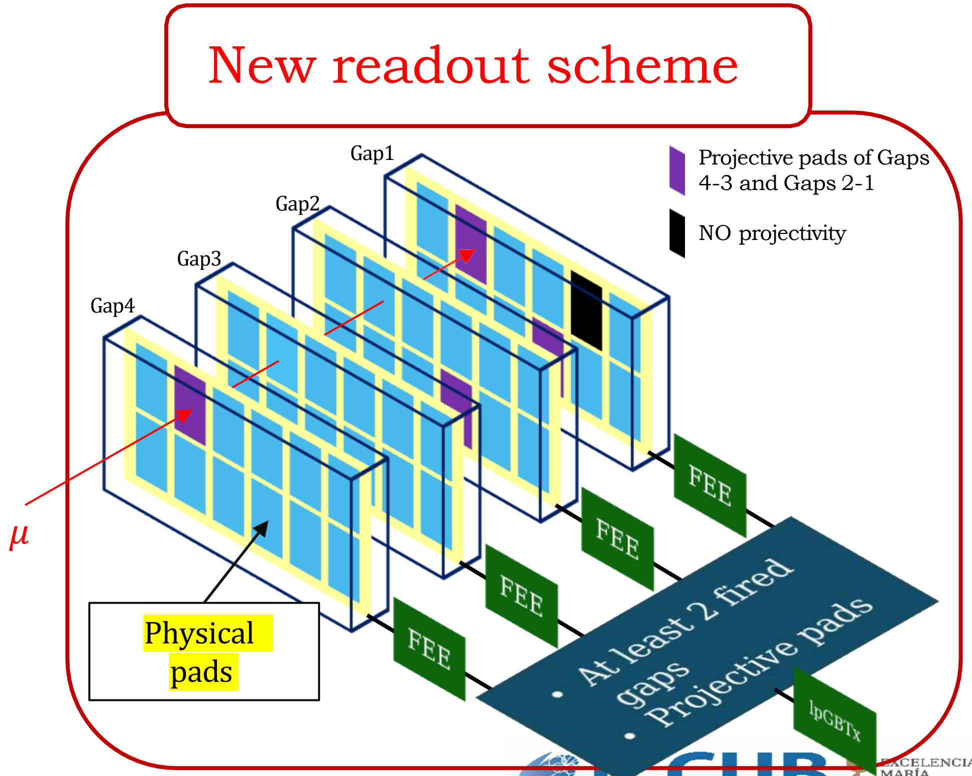
The Muon Detector UII: background reduction



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



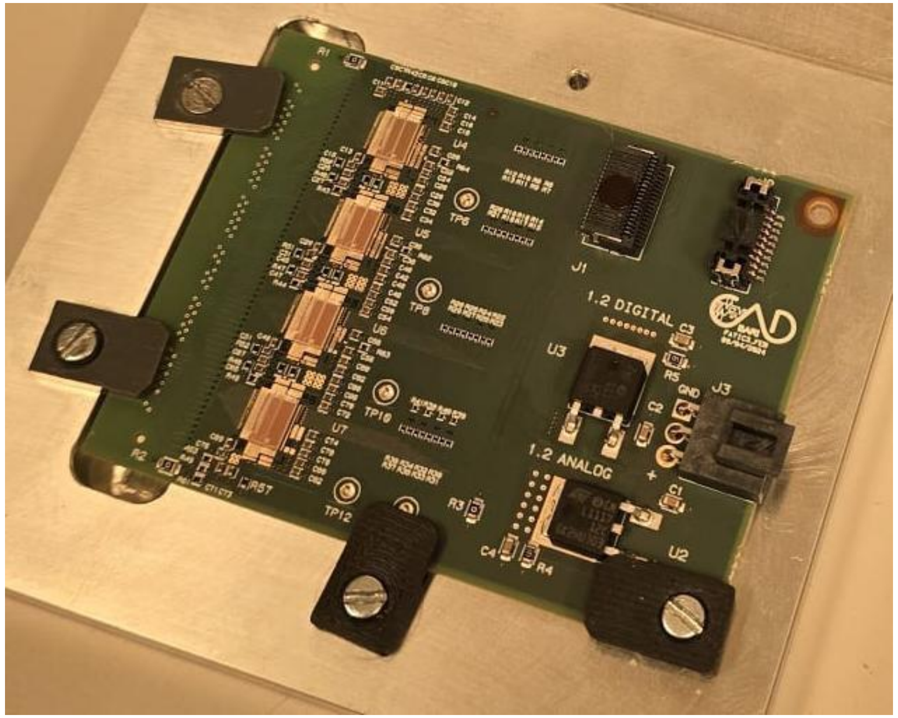
- A new readout scheme in all regions, for background reduction and a new FE electronics
- Separate readout per gap, requiring:
  - signal in at least 2 gaps at the same bunch crossing
  - At least two projective pads fired in the gaps
- First studies show a factor 2 to 4 of background reduction

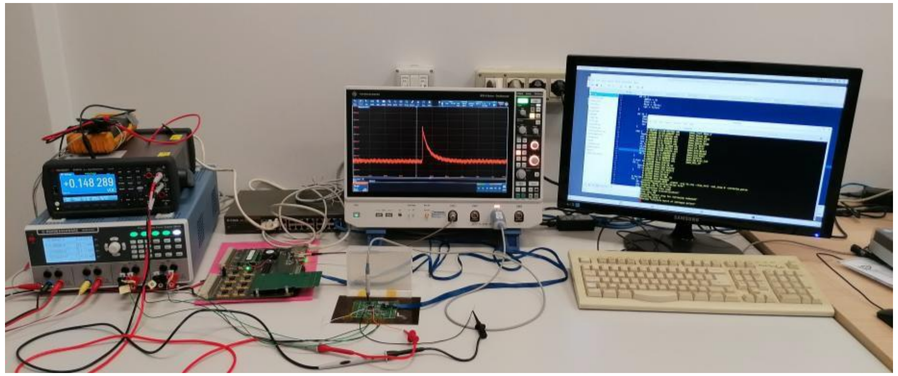
The Muon Detector UII: the FATIC FEE

- 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 FATIC3:
  - 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

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





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Summary

- LHCb PID:
  - RICH → charge hadrons by using the Cherenkov effect
  - Calo → photons, electrons and hadrons (neutral and charged)
  - Muon → track extrapolation provide performant muon ID
- HL-LHC conditions require an increase of granularity, timing and radiation hardness
- The RICH plan to use SiPM and FastRICH with time stamping
- The Calo is developing a new SpaCal channels with increased granularity for energy and timing measurements with ICECAL65 and SPIDER
- The Muon detector will update the MicroPattern Gas detector with a new FATIC and add a new shielding

Thanks for your attention

Grant PID2022-138172NB-C43 funded by MICIU/AEI/ 10.13039/501100011033, as appropriate, by the "European Union NextGenerationEU/PRTR" and by Generalitat de Catalunya.

Radiation damage mechanisms on electronics

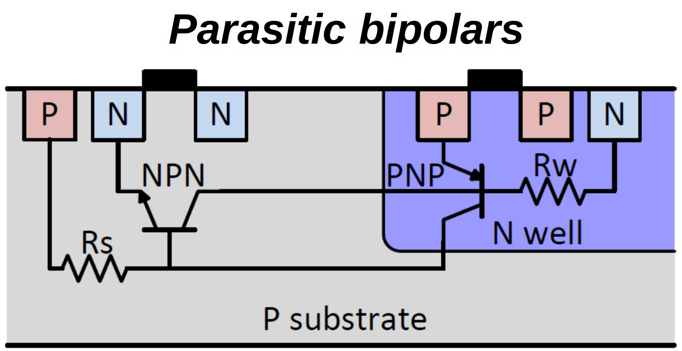
- Cumulative effects: relatively low dose rate or flux in a long time
  - Ionization damage (TID)
    - Charge carriers released by the energy absorbed in the insulating layers (mostly Silicon oxide); build-up parasitic electric field changing electrical characteristic of the devices
  - Displacement damage
    - Incident particle transfer enough energy to the Si atom to displace it from its site in the crystal lattice; change of electrical property of the Si

Radiation damage mechanisms on electronics

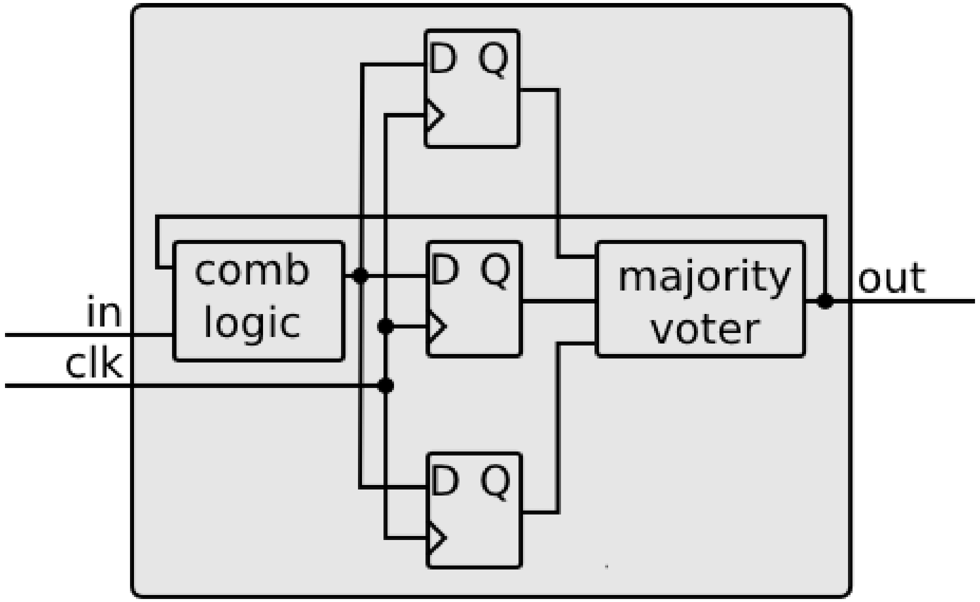
- Single Event Effects (SEE): Huge amount of charge deposited in the very short time by heavy ion (hadronic interaction induced by protons, pions or neutrons) or alpha particle
  - Single event upset (SEU)
    - The deposited charge is sufficient to flip the value of a digital signal
    - Normally refer to bit flips in memory circuits (RAM, Latch, flip-flop)
  - Single event latchup (SEL)
    - Parasitic bipolar transistors that can be triggered by a locally deposited charge to generate a kind of short circuit between the power supply and ground
    - SEL may be limited to a small local region or may propagate to affect large parts of the chip
  - Single event gate rupture (SEGR) or burnout (SEB): important for power transistors
    - Destructive failures of power MOSFET transistors in high power applications

Radiation damage mitigation techniques

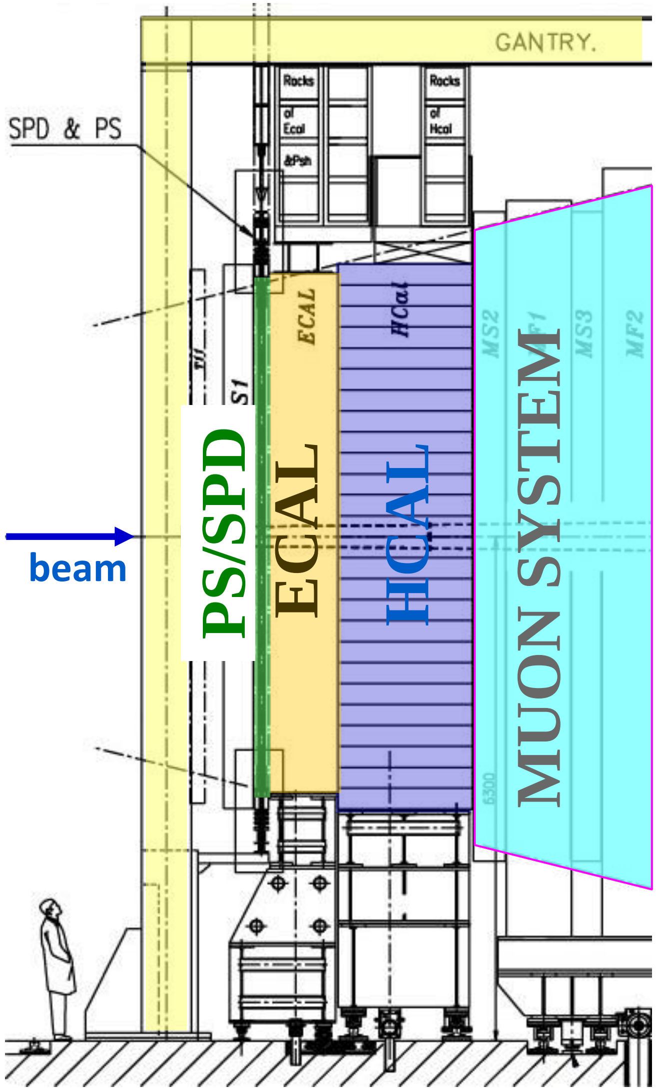
- Guard rings to prevent SEL at layout level



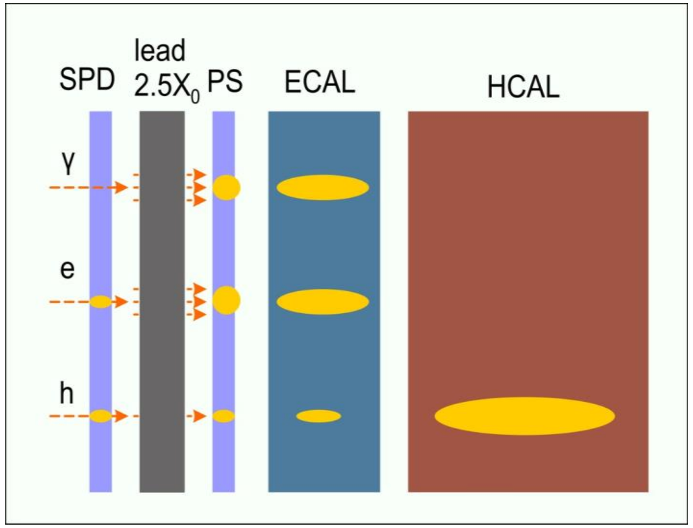
- Mitigate SEU with Triple Modular Redundancy (TMR)



The Calorimeters



- Solid angle coverage 300x250 mrad
- Distance from interaction point ~12.5 m
- Four sub-detectors: SPD, PS, ECAL, HCAL
- Based on scintillator/WLS (with PMTs)



- L0 trigger on high p_T, e±, π^0, γ, hadron
- Precise energy measurement for e± and γ
- Particle identification: e±/γ/hadron, and contributes to Muon ID (HCAL)

[LHCb-DP-2020-001]

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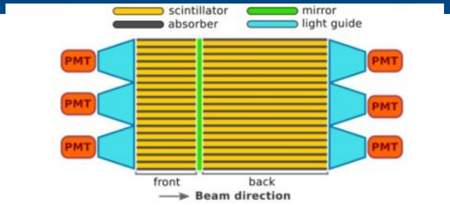
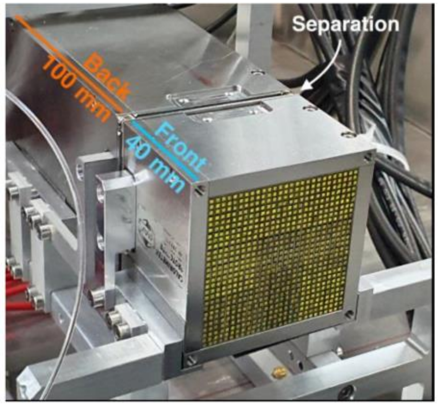
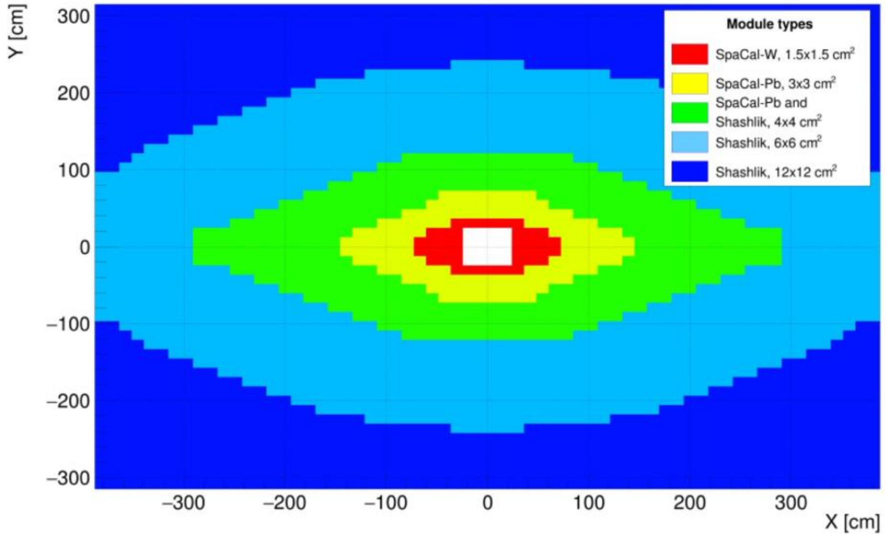
Calorimetry with precision timing

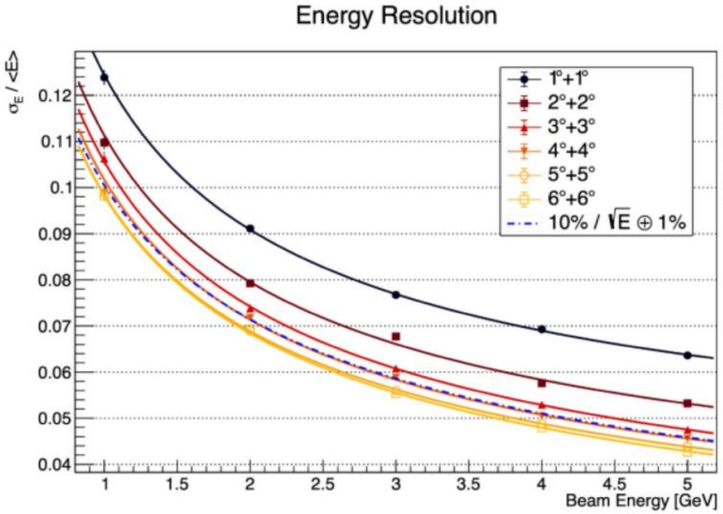
- Improve efficiently the performance at high luminosity
- Re-organize ECAL zones to follow radiation & occupancy map
- Baseline: combination of technologies for different regions starting from inner-most
  - SpaCal W/ GAGG fibers
  - SpaCal Pb / Plastic fibers
  - Shashlik / WLS fibers

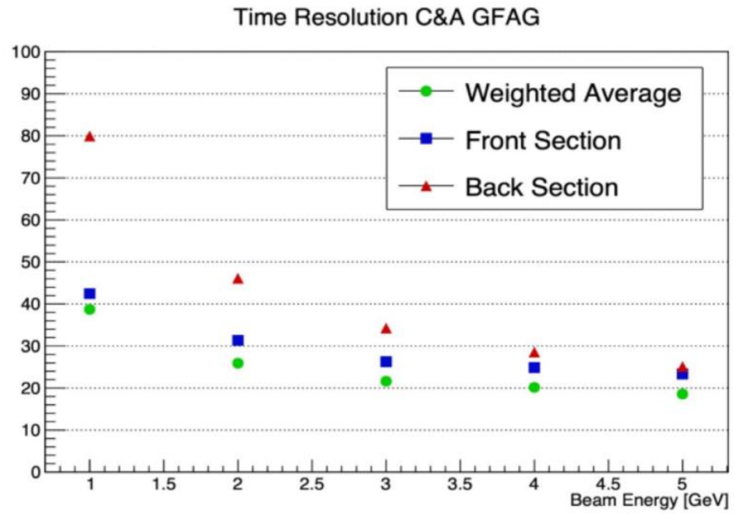


Cell size [cm^2]	Module type	Modules	Cells
1.5×1.5	SpaCal-W with GAGG fibers	40	5120
3×3	SpaCal-Pb with plastic fibers	136	4352
4×4	SpaCal-Pb with plastic fibers	272	4896
	Shashlik with WLS fibers	176	3168
6×6	Shashlik with WLS fibers	448	3584
	Shashlik with new tiles and WLS fibers	896	7168
12×12	Shashlik with WLS fibers	1344	2688
Sum		3312	30976









The Muon Detector Expected rates at Upgrade II

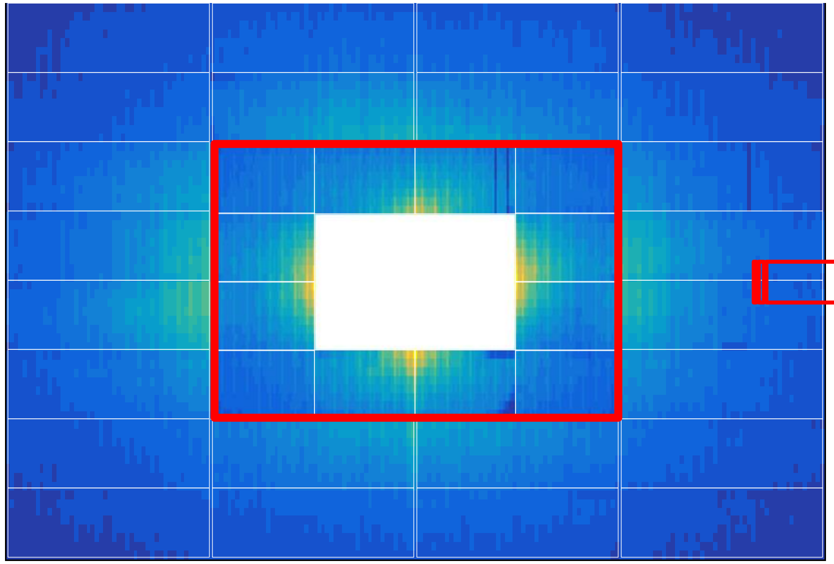
LHC Run 3 data

(L = 2.0 × 10^{33} $cm^{-2}s^{-1}$) are used for particle rates extrapolation at Run 5 luminosity:

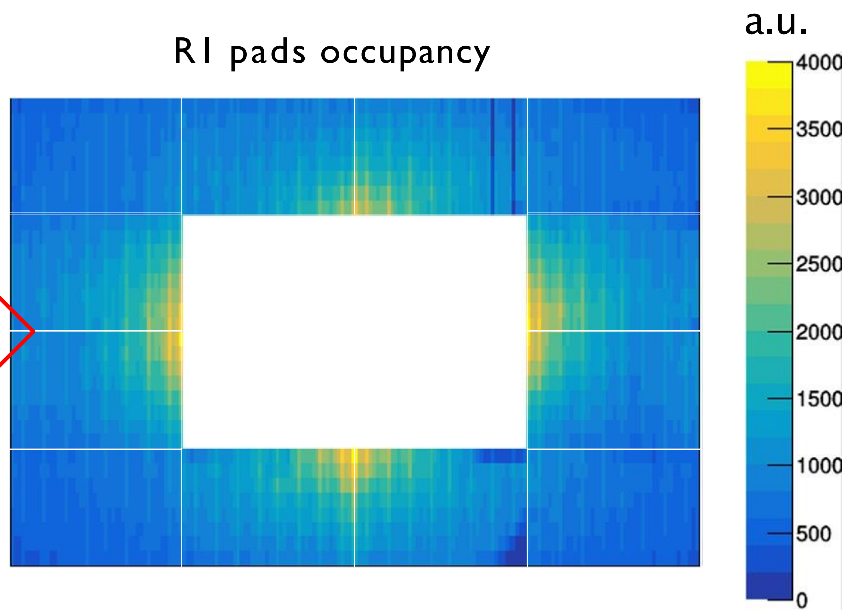
$\boldsymbol{L = 1.0 \times 10^{34}\ cm^{-2}s^{-1}}$

Strong non-uniformity in the same chamber.

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



R1 pads occupancy



Maximum rate value: ≅ 1.3 MHz/cm²

≅ 2 times the maximum average measured rates in M2R1 chamber.

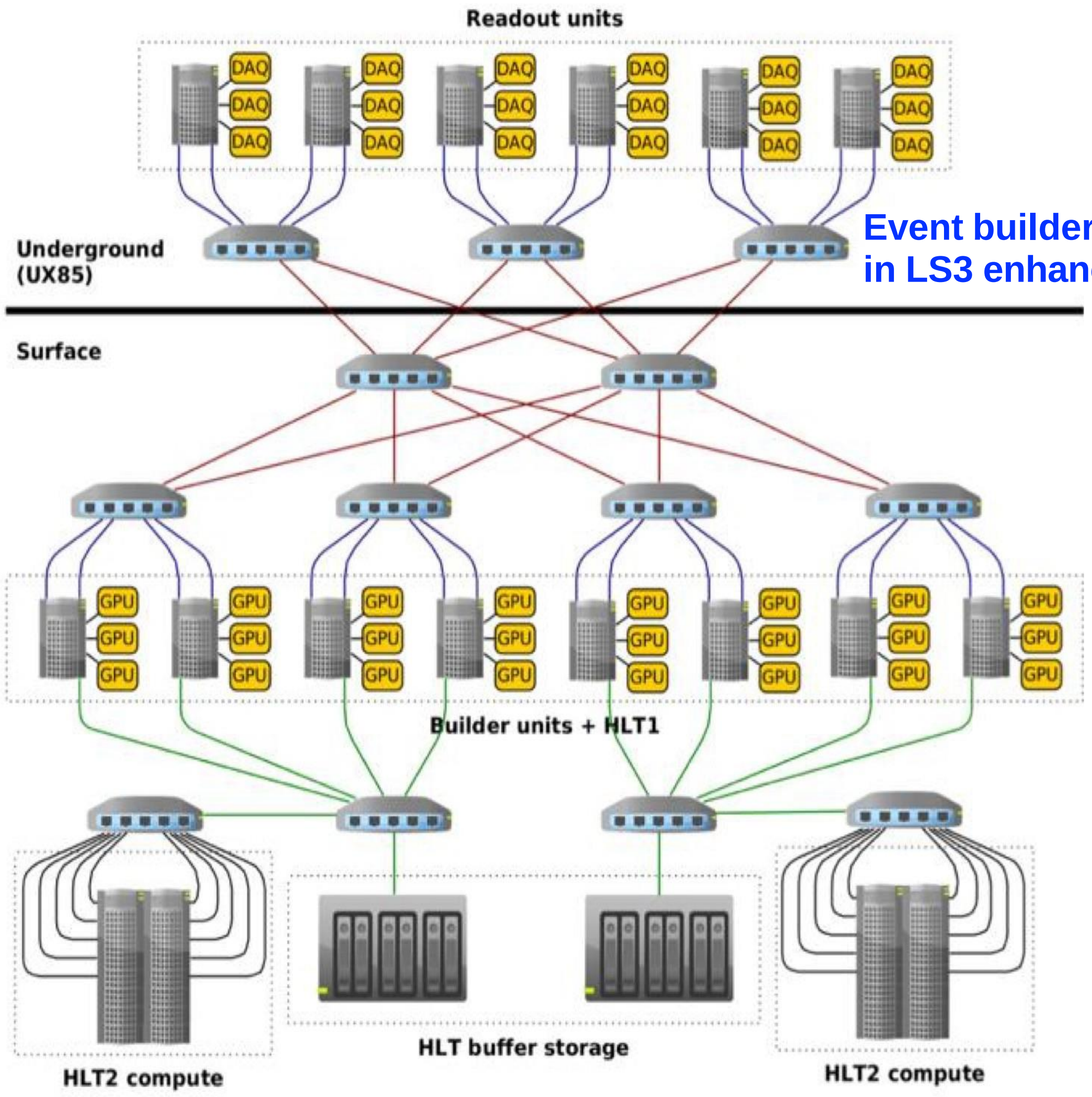
Maximum rates (M2) in Run 3:
L = 2.0x10³³ cm⁻² s⁻¹

$R1_{max}$:	91	kHz/cm²
$R2_{max}$:	30	kHz/cm²
$R3_{max}$:	4.8	kHz/cm²
$R4_{max}$:	1.7	kHz/cm²

Maximum per region of the average rates in chambers

kHz/cm²	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

Online and Offline

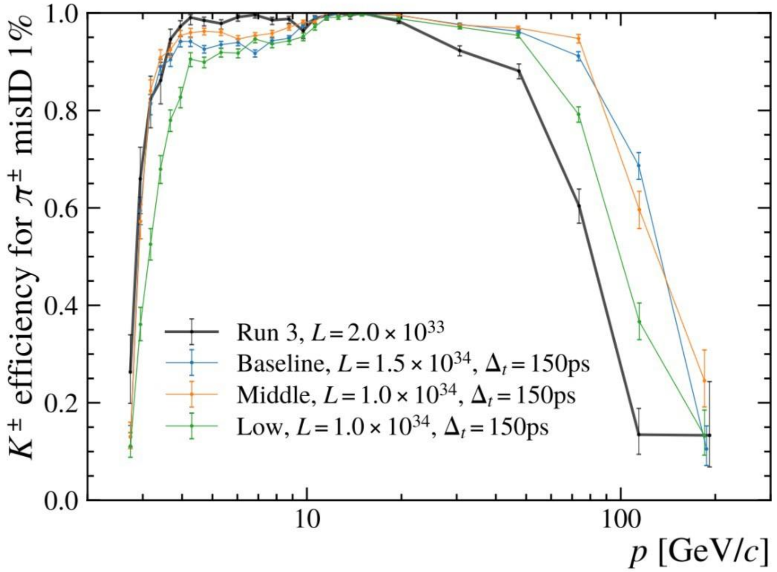


Event builders in UX85 in LS3 enhancement

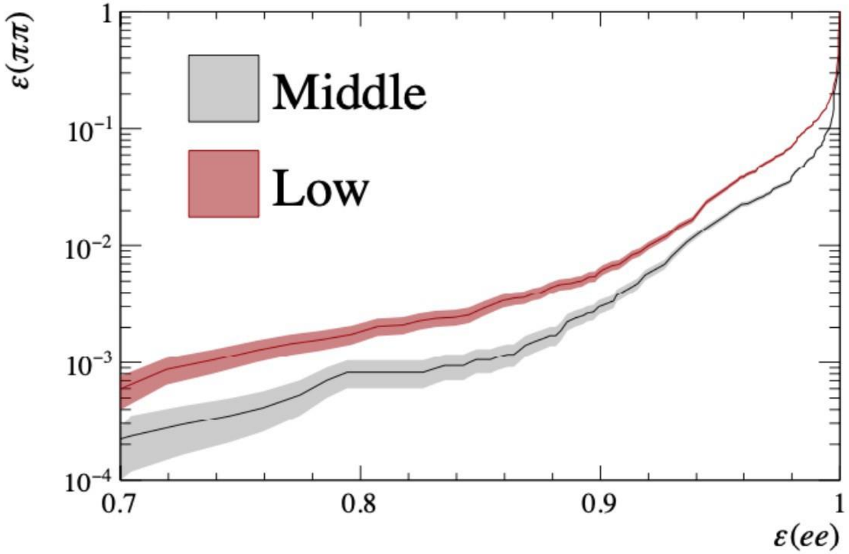
- ► Novel trigger system for Upgrade I
  - □ Fully software trigger
  - □ HLT1 based on GPUs, HLT2 on CPUs
- ► Similar concept planned for Upgrade II
  - □ Expected data throughput for real time analysis is ~ 200 Tb/s, (~ 5x ATLAS or CMS after L0 at HL-LHC)
  - □ Further exploitation of hybrid architectures: CPU, GPU, FPGA …
- ► Offline computing requirements are significant
  - □ Software R&D match requirement to prospective resources
  - □ Issues in Run 5 are similar to ATLAS & CMS Run 4
  - □ Coordination with WLCG and the HEP

PID performances

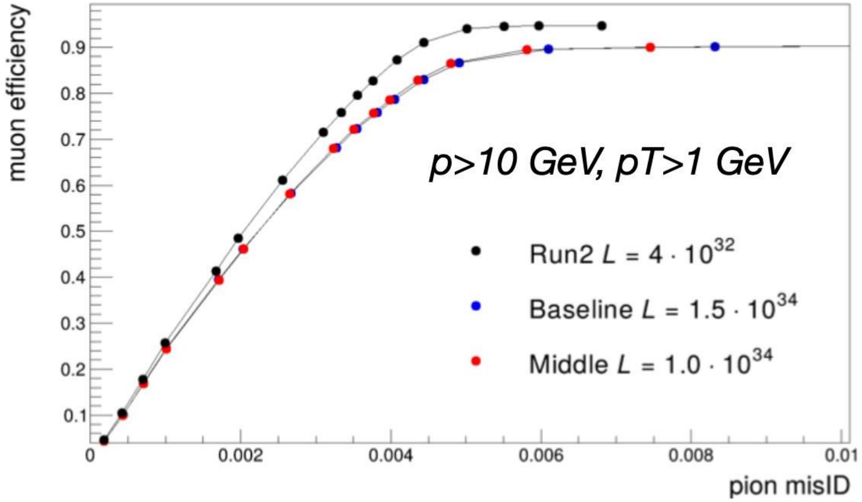
Kaon ID (RICH)



Electron ID (PicoCal): mis-id rate of $B^0 \rightarrow K^{*0}\nu^+\nu^-$ as a function of $B^0 \rightarrow K^{*0}e^+e^-$ selection efficiency



Muon ID (Muon)



[LHCb Upgrade II Scoping Document]

- RICH PID close to Run 3 efficiencies, low momentum region affected in Low scenario
- Electron ID is affected by removal of PicoCal longitudinal segmentation in Low scenario
- Muon ID not yet at Run 2 performances: optimization of shielding in front of detector will improve performances

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