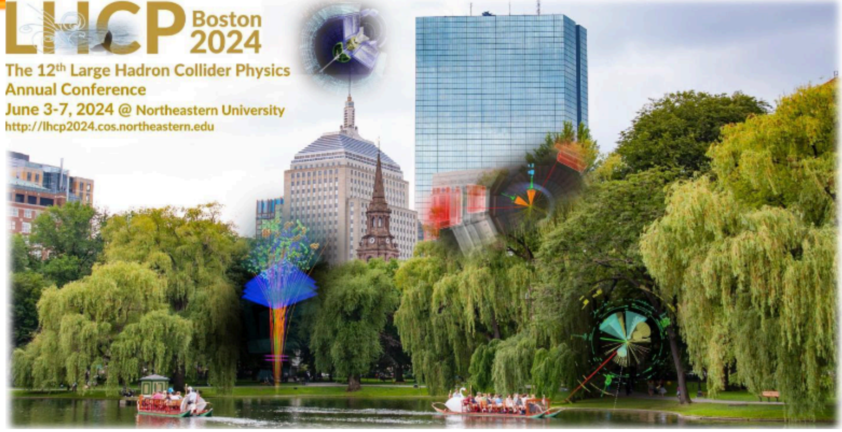
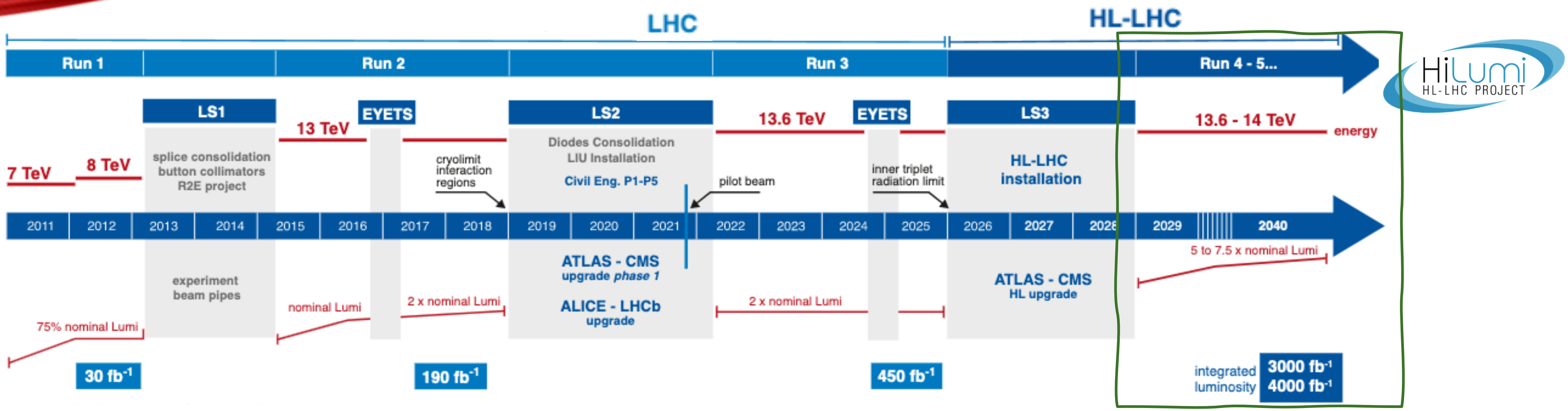


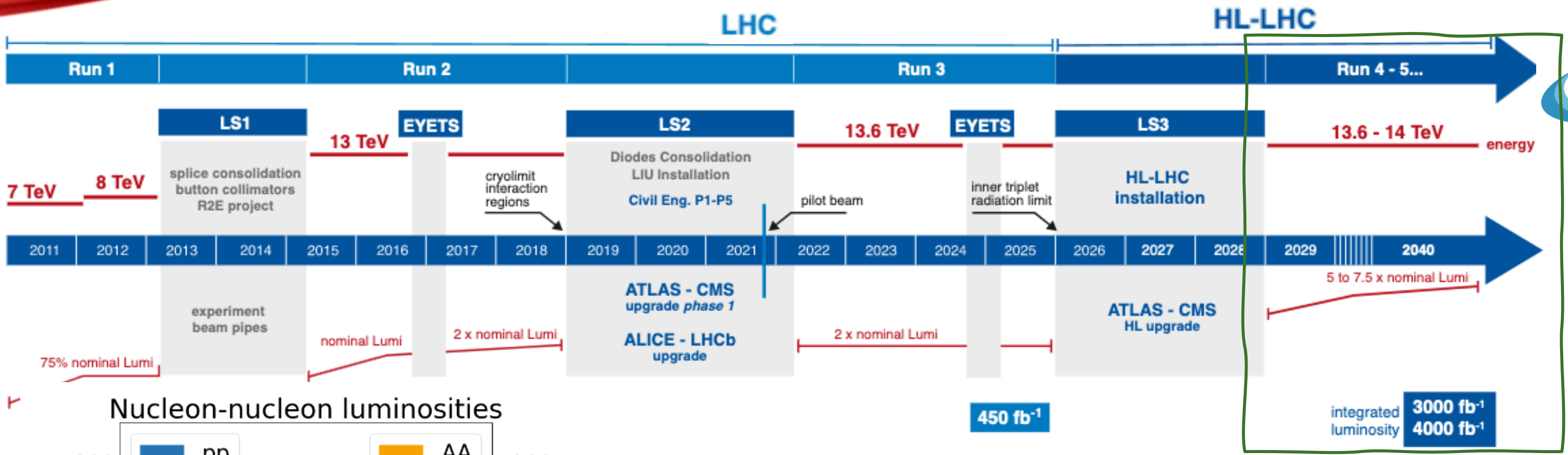

# On-detector particle identification at the HL-LHC

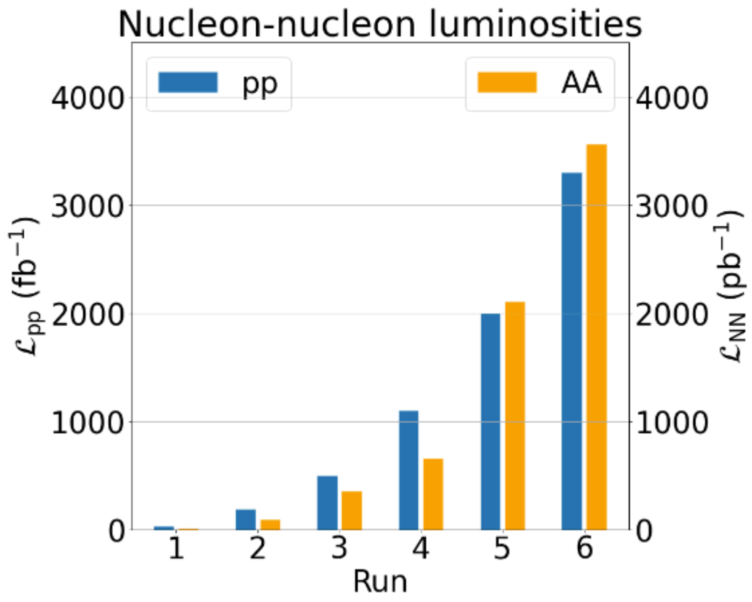
Stefania Bufalino
INFN and Politecnico of Torino
On behalf of the LHC Collaborations

# HL-LHC an amazing opportunity



# HL-LHC an amazing opportunity




Data taking foreseen until 2041:

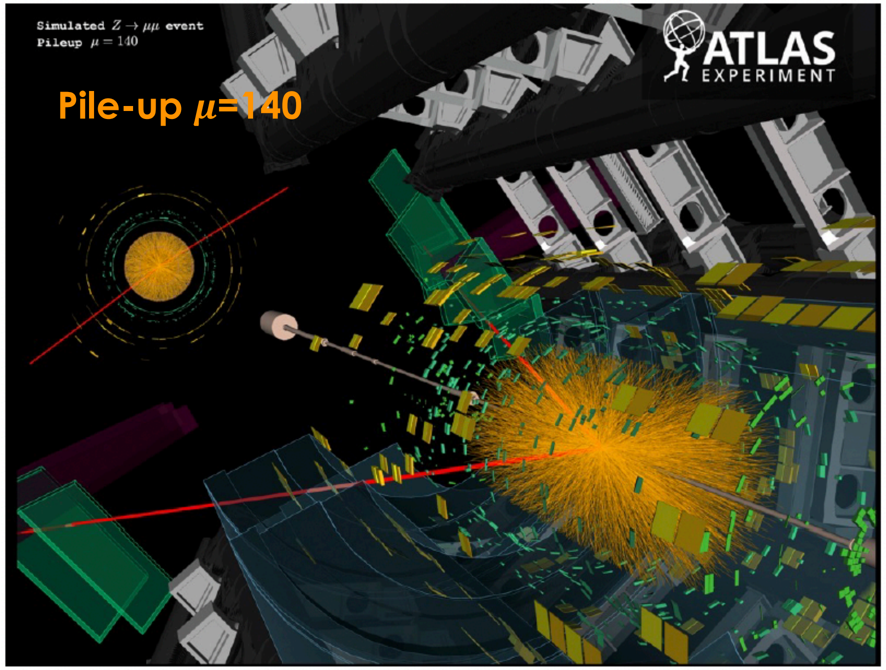
- expected integrated luminosity of **3 ab$^{-1}$ in pp**
- **higher luminosities for ions** mitigate space charge effects (SPS & LEIR), e.g. with lighter species
- **instantaneous luminosity** increased of a factor 3-4
- **peak leveled** pile-up of up to 200 compared to 60 in the current run!

# HL-LHC challenges

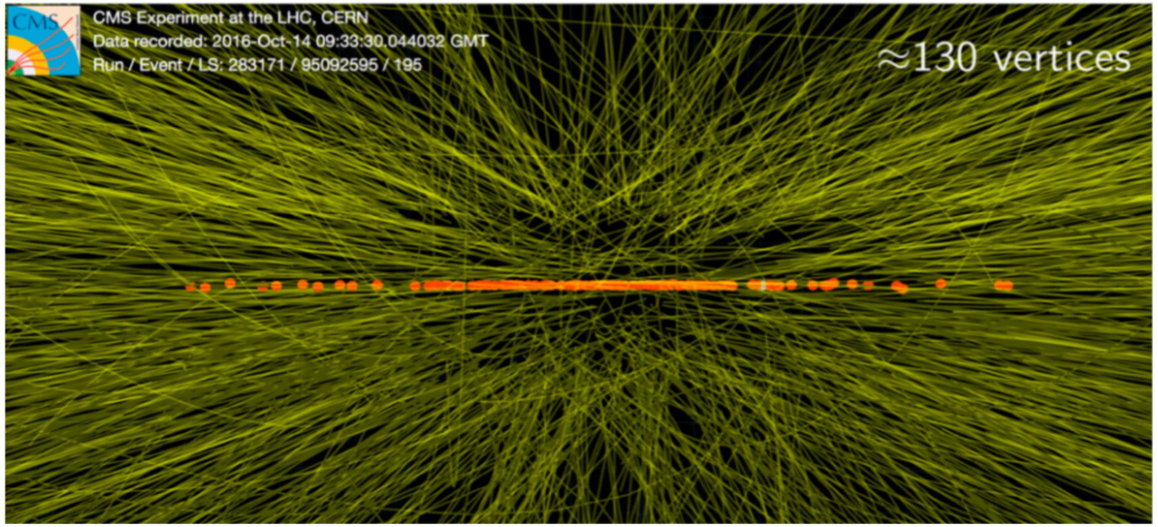
The HL-LHC will have about x3 instantaneous and x10 integrated luminosity, requiring detector upgrades to

- deal with **enhanced pileup interaction** and **radiation damage** levels
- improve the experiment for better discovery potential and measurement precision

Talk on ATLAS Upgrade by Y. Okumura onJune 6th




One such collision every 25 ns at HL-LHC



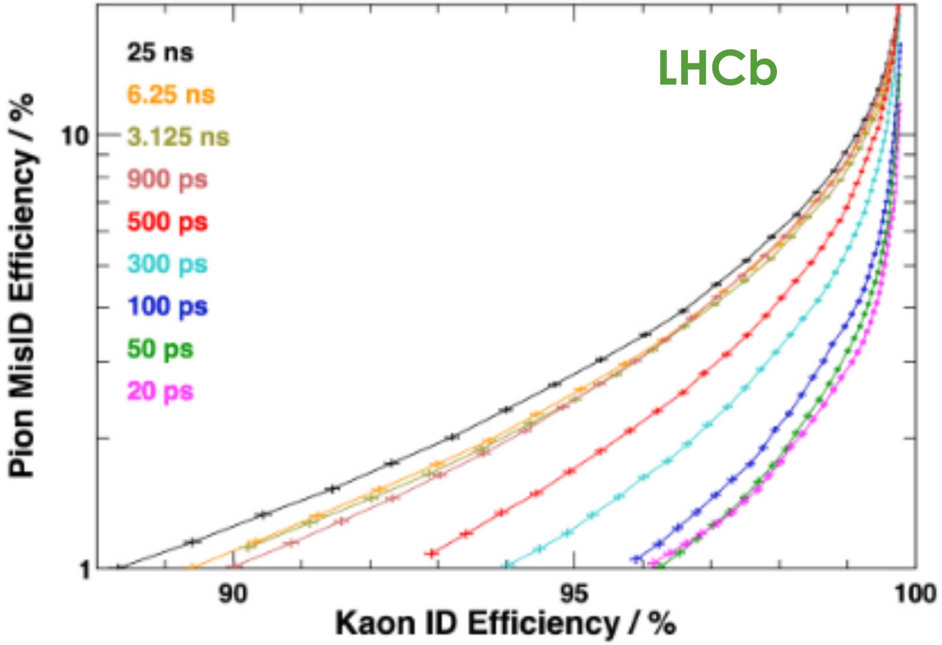

Talk on CMS Upgrade by T. Fernandez on June 6th

Strategy
4D track and vertex reconstruction with per-particle precise timing

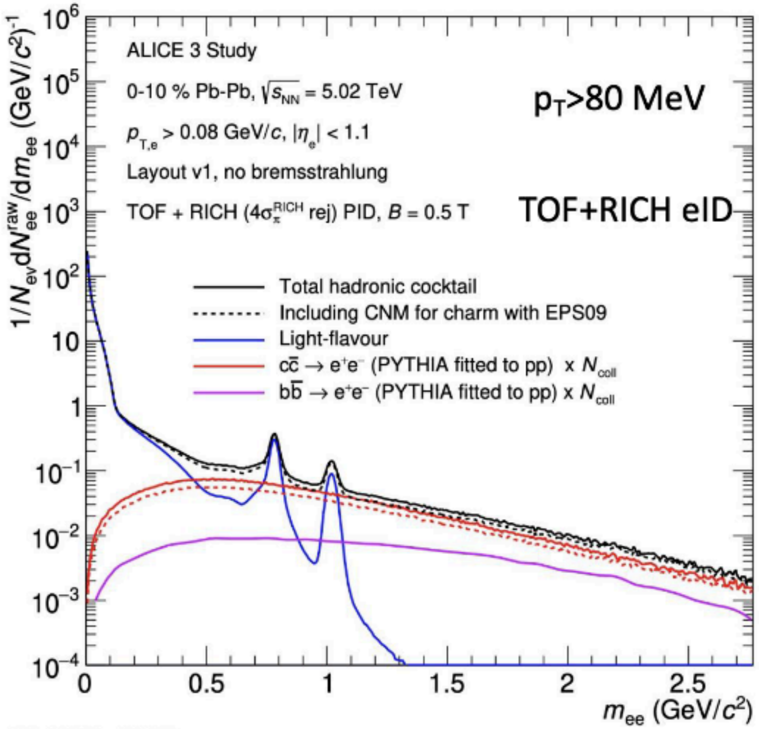
# HL-LHC challenges

## Physics programme limited by the detectors

- Use of timing is a key strategy to overcome challenges
- Improvement of **Particle IDentification** capabilities is **crucial for physics reach**




### dielectrons: TOF + RICH

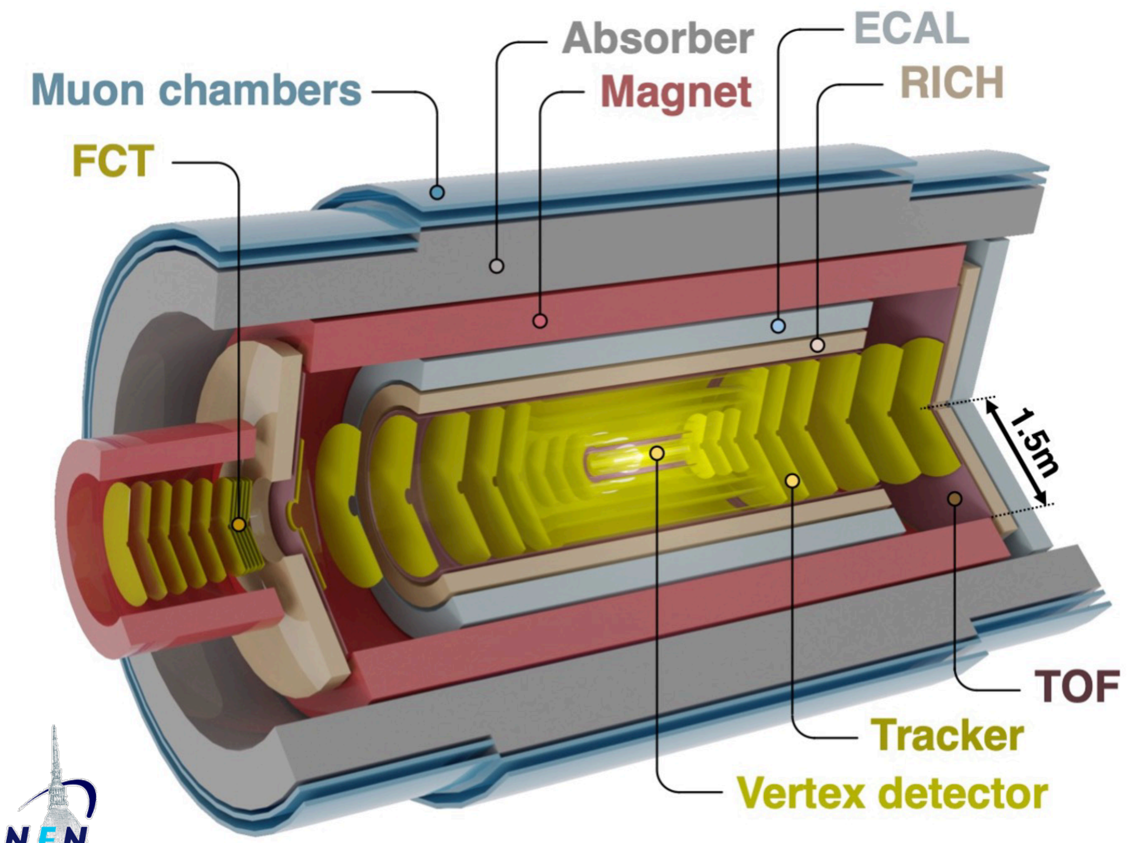


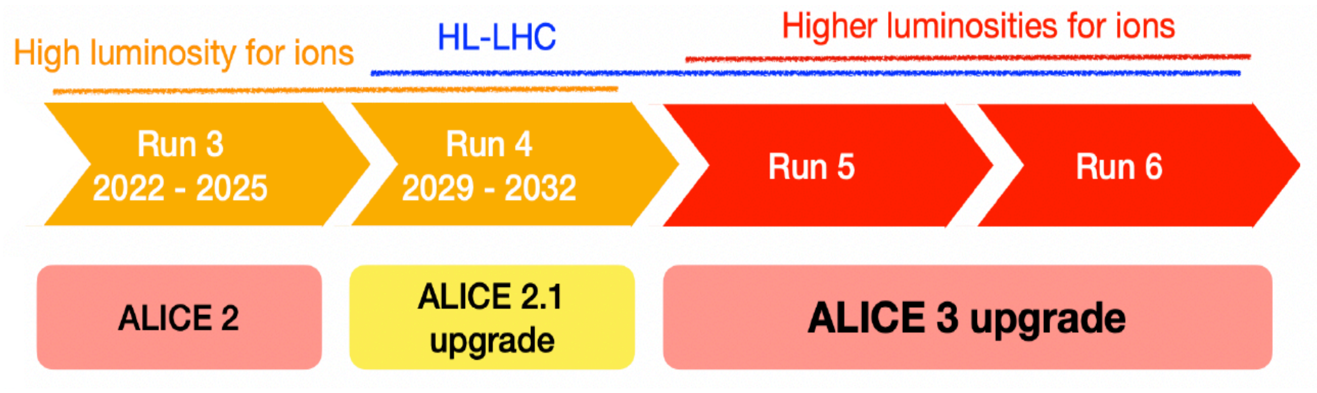

**ALICE 3**

**This talk:**
R&D strategies for PID detectors with focus on timing
→ ALICE 3 and LHCb

# The ALICE 3 upgrade

**ALICE main goal:** access the dynamics of the strongly interacting matter produced in heavy-ion collisions




- Fundamental questions will remain open after LHC Run 4, demanding for a **next heavy-ion generation experiment**
- Letter of Intent submitted in March 2022 ALICE CERN-LHCC-2022-009
- **Scoping document submission this year**

# The ALICE 3 upgrade

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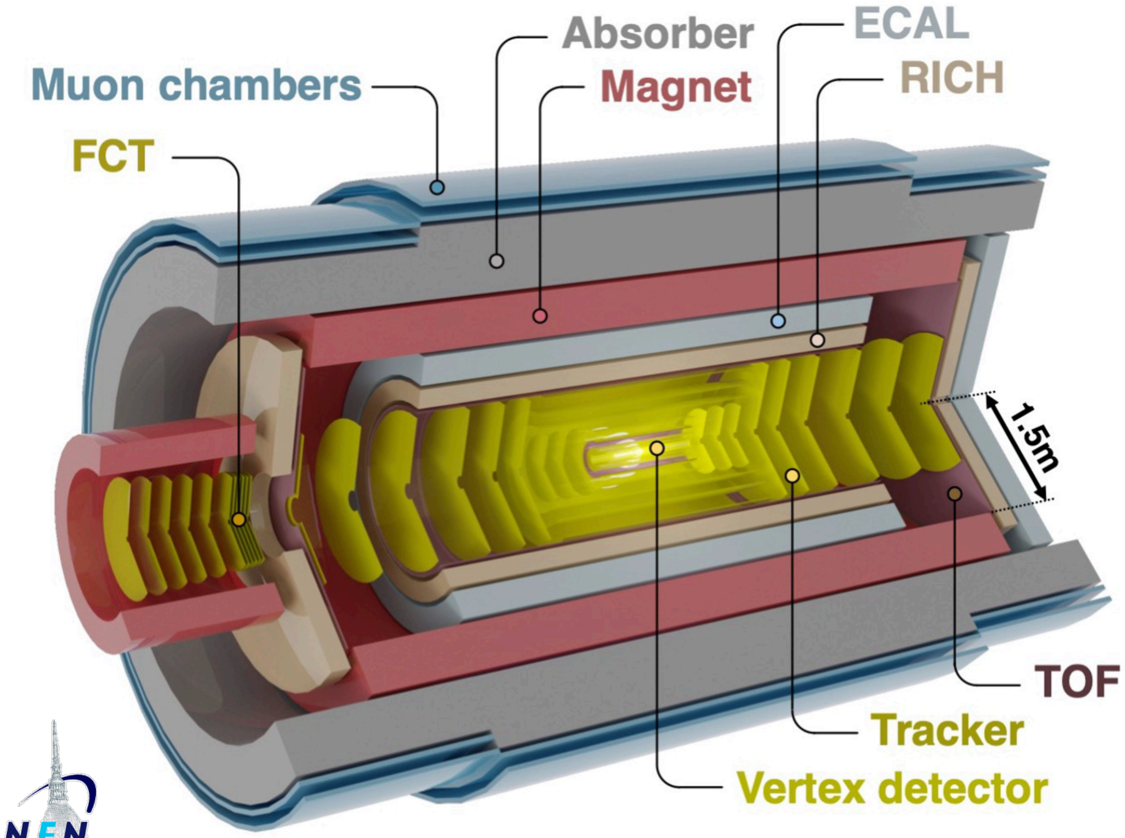


1. Plenary talk by F. Reidt on **June 6th**
2. Talk on Heavy Ion physics at the HL-LHC experiments by F.Jonas on **June 7th**

- Fundamental questions will remain open after LHC Run 4, demanding for a **next heavy-ion generation experiment**
- Letter of Intent submitted in March 2022 ALICE CERN-LHCC-2022-009
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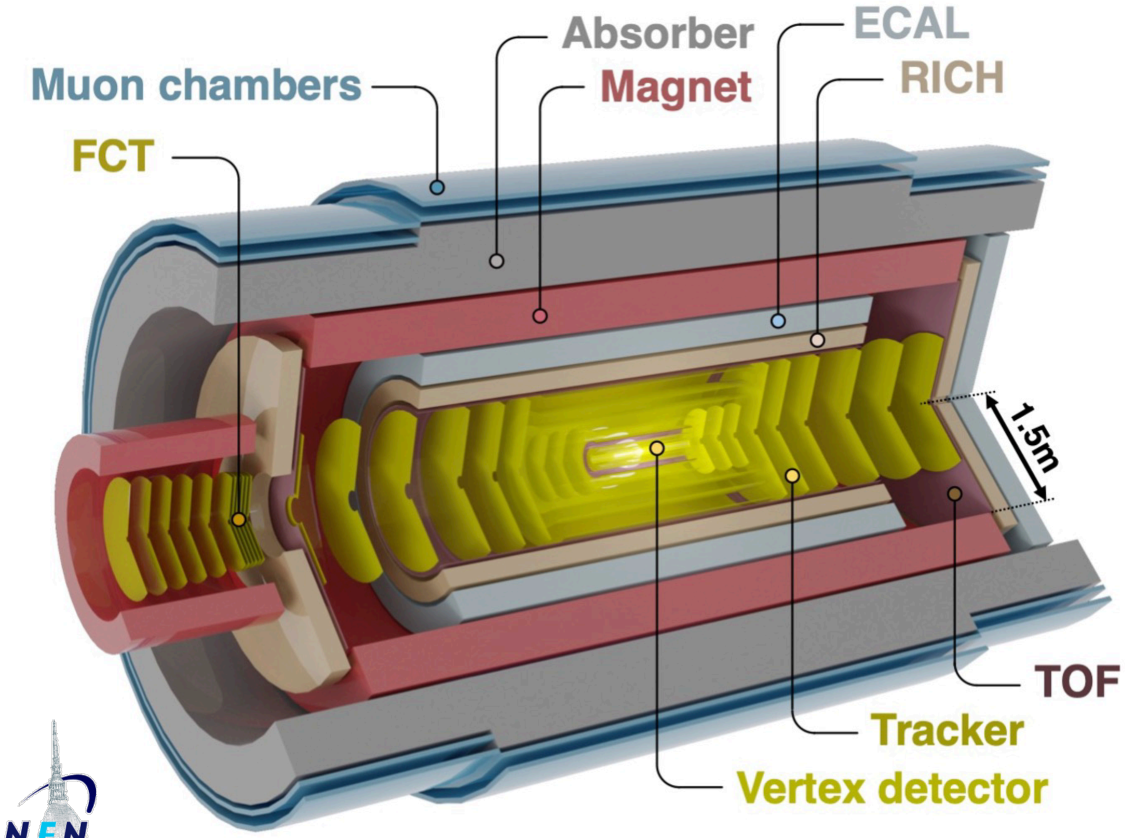
# The ALICE 3 detector

**ALICE main goal:** access the dynamics of the strongly interacting matter produced in heavy-ion collisions



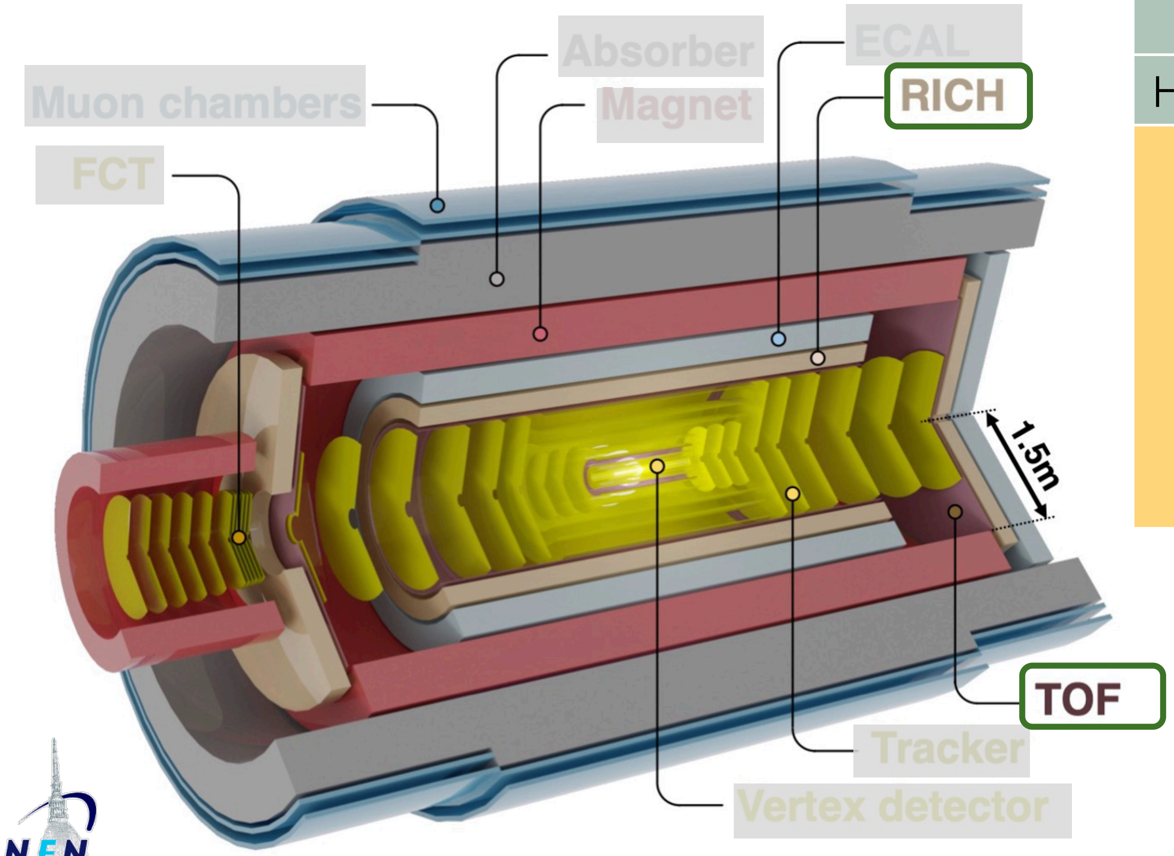

| Physics | Observable |
|---|---|
| Early stages | Dilepton and photon production and flow |
| HQ thermalization diffusion | Heavy flavours correlations and flow |
| Hadronization | Multi-charm baryons, quarkonia |
| **Detector requirements** | Pointing resolution:≈10 $\mu$m at 200 MeV/c |
| | Large pseudorapodity coverage: $\|\eta\|<4$ |
| | Extensive Particle IDentification |
| | Tracking relative $p_T$ resolution ≈1-2% |
| | Forward Conversion Tracker (FCT): photons with $1 < p_T < 50$ MeV at $\eta > 4$ |

## ALICE 3 charged PID system

- Time-Of-Flight
- Ring-Imaging Cherenkov
- EM Calorimeter
- Muon Identifier Detector

# The ALICE 3 detector

**ALICE main goal:** access the dynamics of the strongly interacting matter produced in heavy-ion collisions

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## ALICE 3 charged PID system

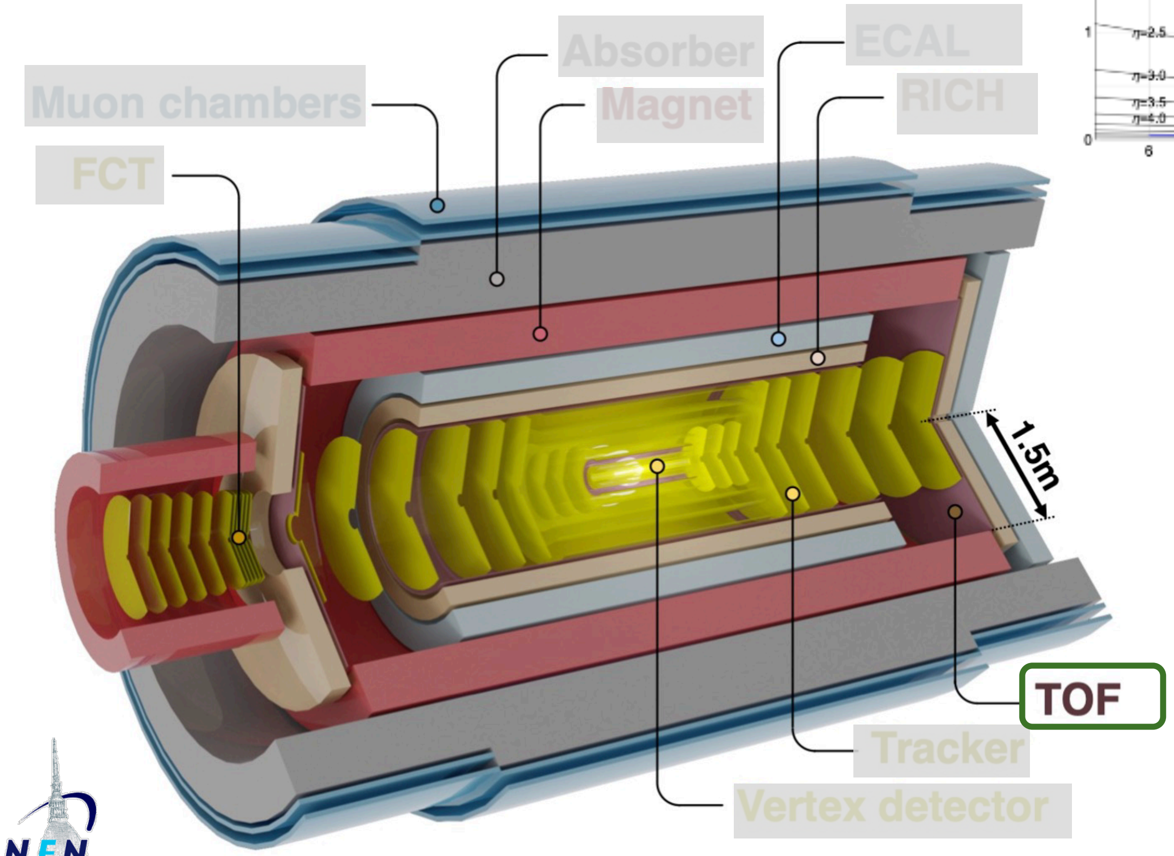
- **Time-Of-Flight**
- **Ring-Imaging Cherenkov**

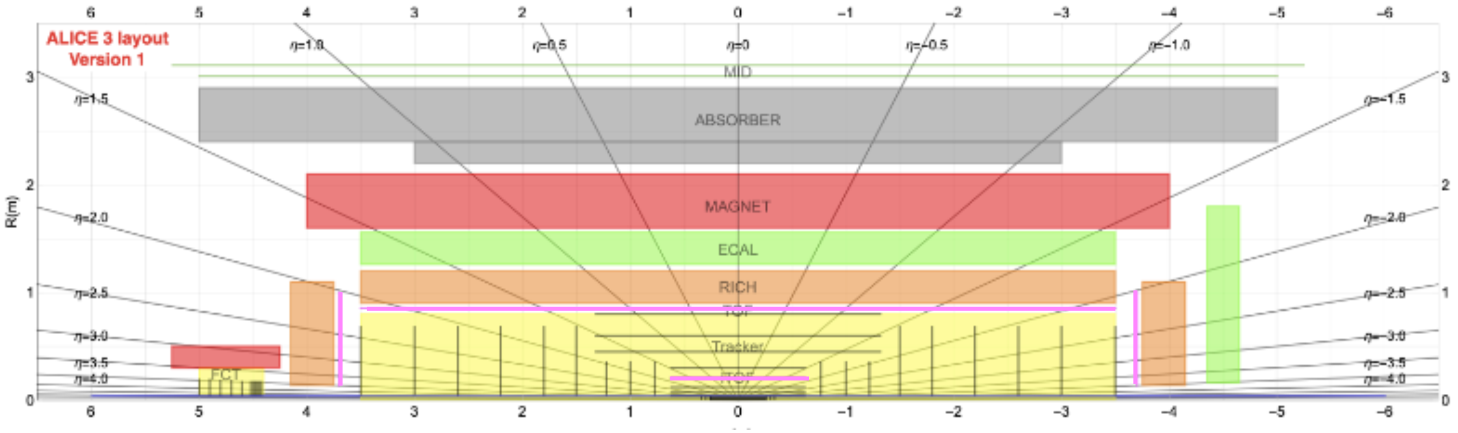
} **THIS TALK**

- EM Calorimeter
- Muon Identifier Detector

# ALICE 3 TOF implementation

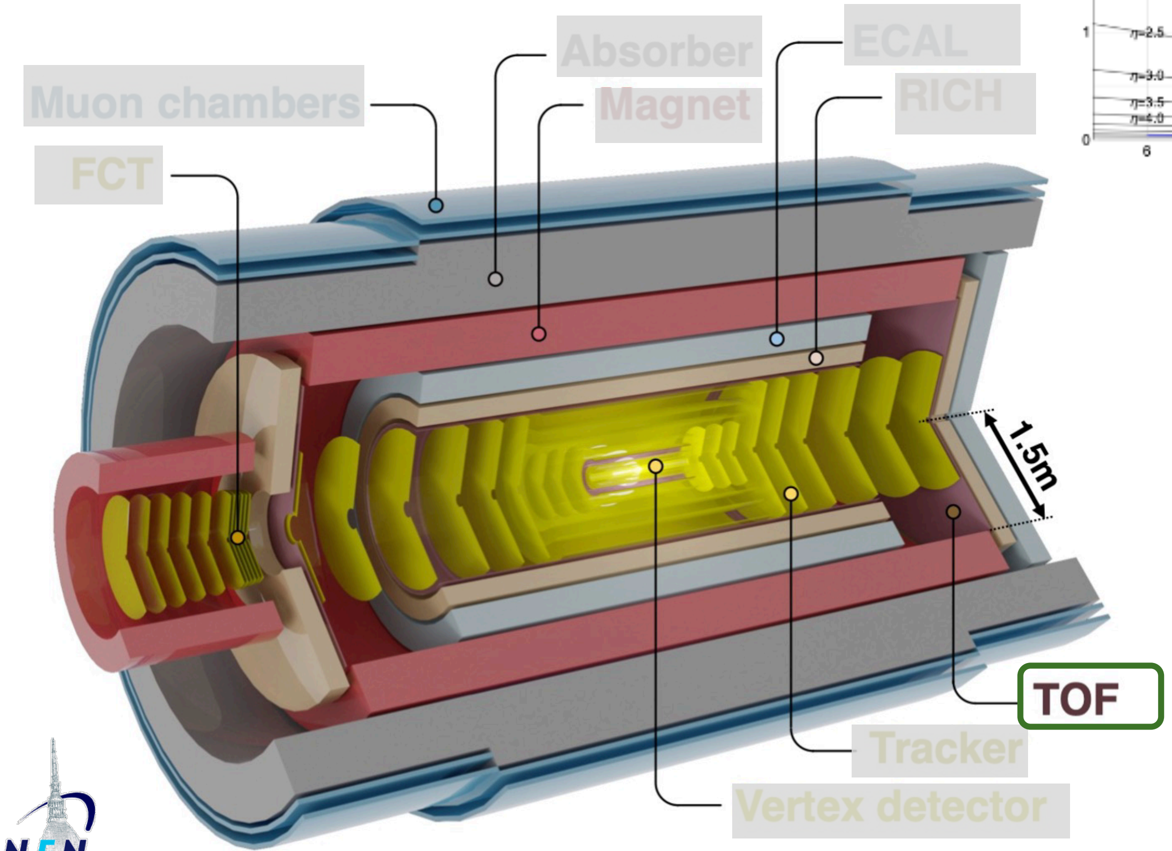
- iTOF & oTOF (barrel)+ 2 forward disks
- Inner TOF at $R \approx 0.19$ m, $|z| < 0.62$ m
- Outer TOF at $R \approx 0.85$ m, $|z| < 3.50$ m
- Forward TOF at $z \pm 3.70$ m, $|R| < 1.0$ m

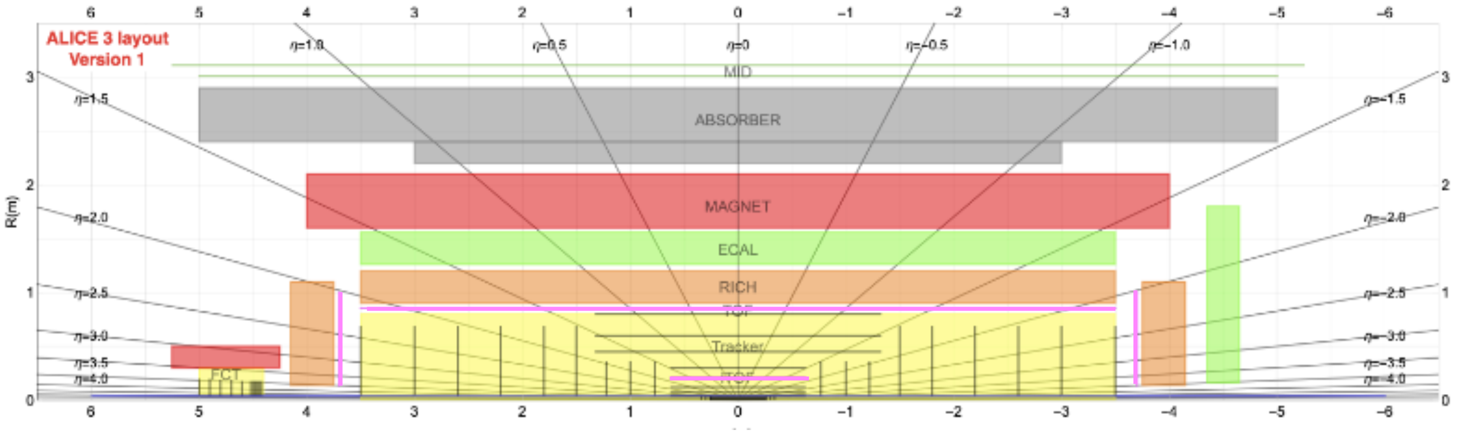


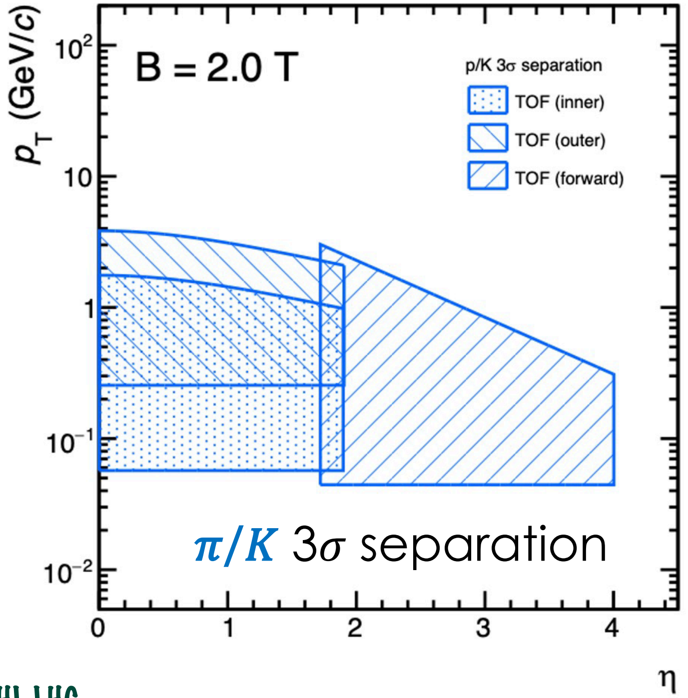



# ALICE 3 TOF PID

- $e/\pi$ separation up to ≈ 500 MeV/$c$
- $\pi/K$ separation up to ≈ 2 GeV/$c$
- $K/p$ separation up to ≈ 4 GeV/$c$
- separation power $\propto L/\sigma_{TOF}$, → $\sigma_{TOF}$ ≈ **20 ps**

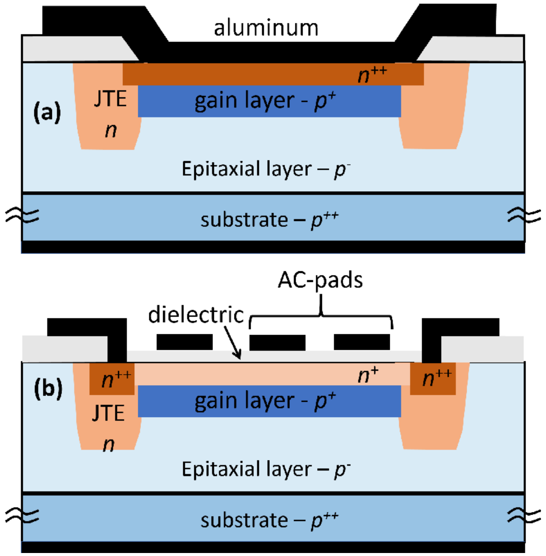


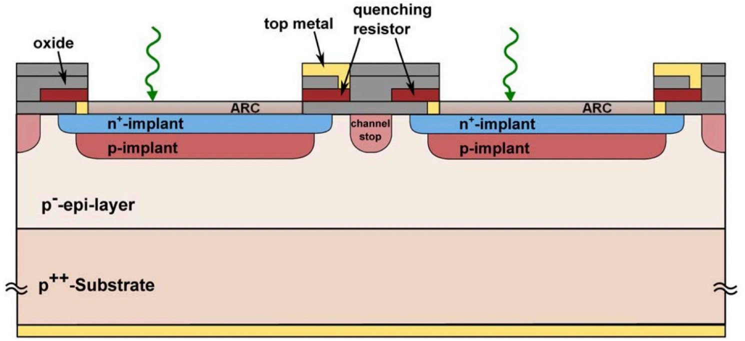
# ALICE 3 TOF R&D

## LGAD



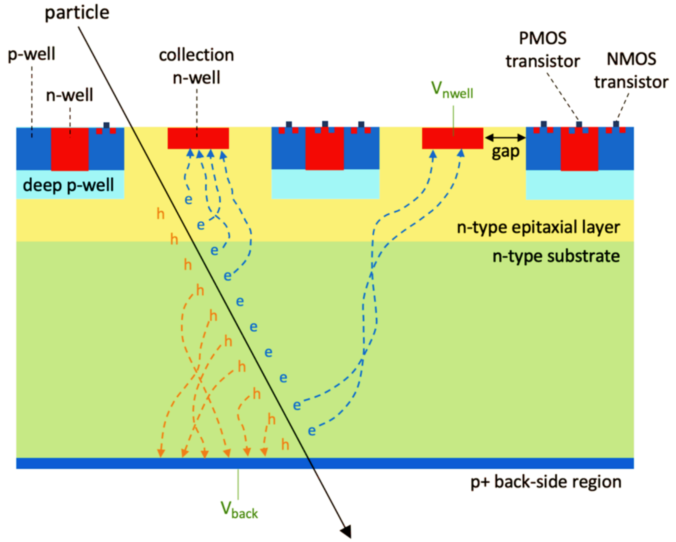

- Timing resolution of ~ 30 ps demonstrated with 50 µm up to (1-2)$10^{15}$ 1-MeV-neq/cm$^2$
- thinner LGADs produced by different manufacturers

## SiPM




- Timing resolution of 40 ps for single photons detection so far
- Very promising results on MIP detection

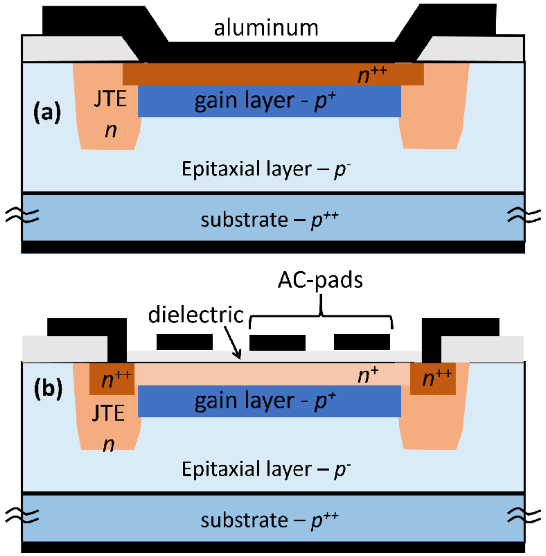
## CMOS MAPS




- Low material budget
- High SNR
- Low power
- Investigation on innovative design to proof timing performance

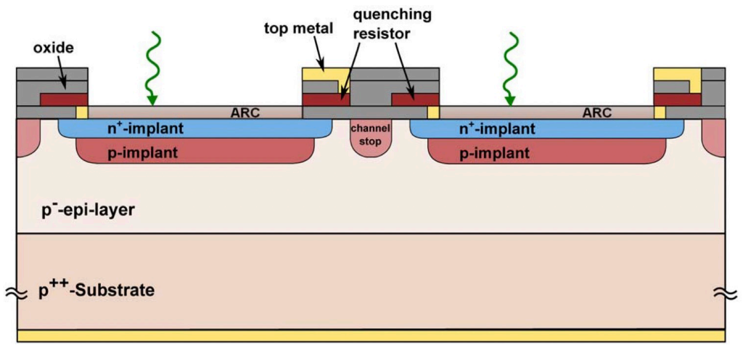
# ALICE 3 TOF R&D

## LGAD




**simulations show that with 25 µm thickness an intrinsic time resolution of 20 ps is feasible**
**→ first results from test beam**

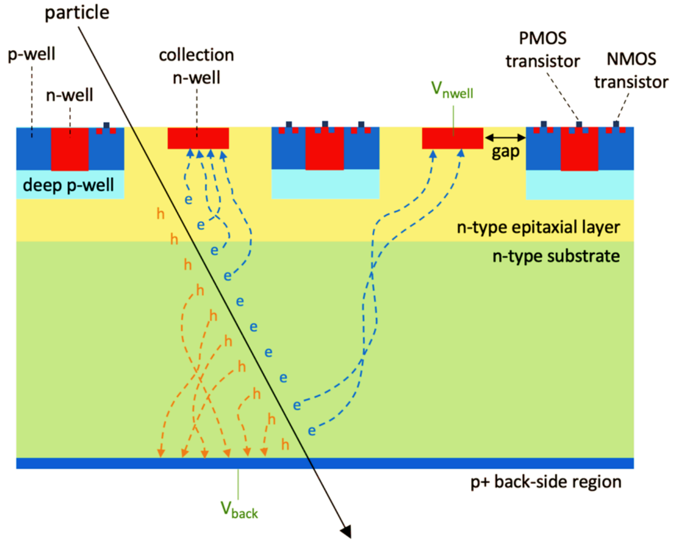
## SiPM




- Timing resolution of 40 ps
demonstrated with charged particles

**characterisation of SPADs/SiPMs**
**→ first results from test beam**

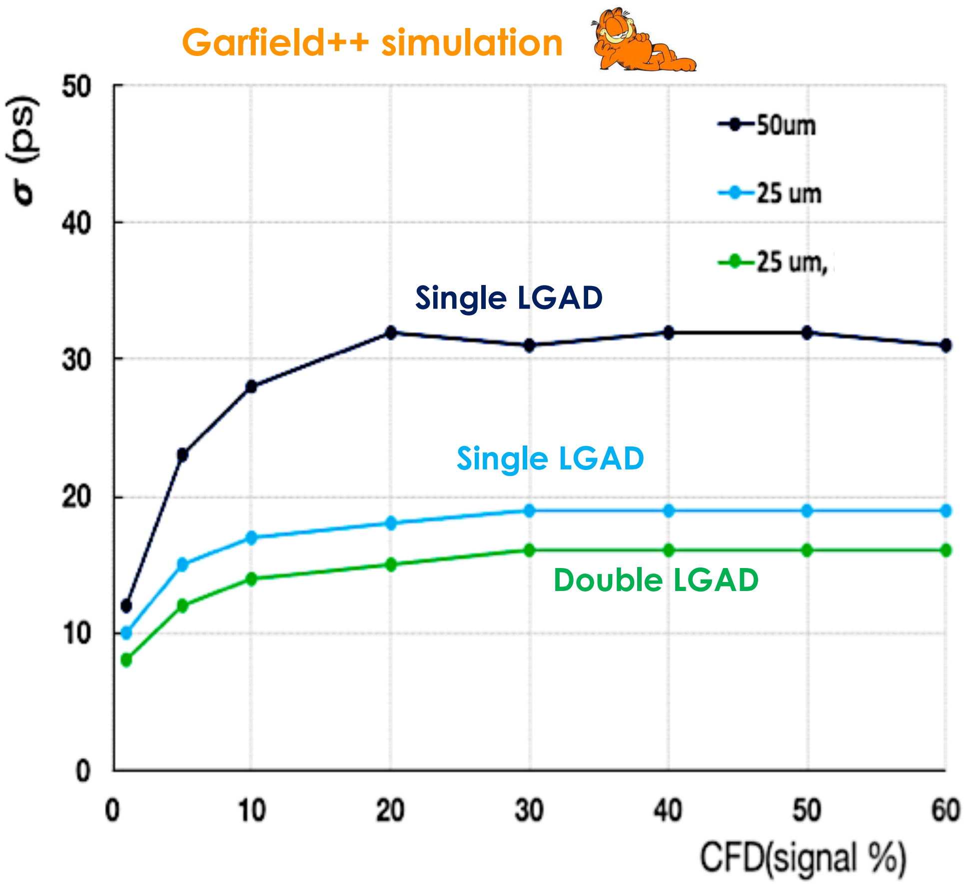
## CMOS MAPS




- Low material budget

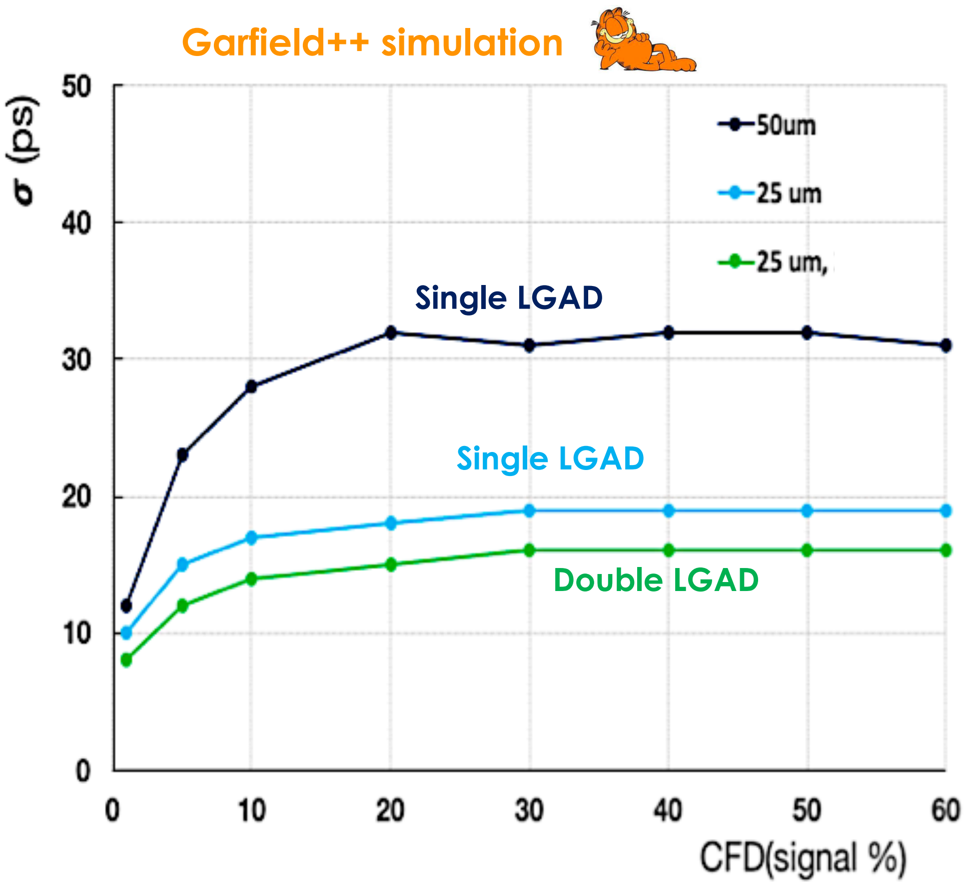
**R&D for the addition of a gain layer**
**→ extensive activities of sensor simulation and design**

# ALICE 3 TOF R&D: LGADs




→ Improved performance for thinner LGADs

# ALICE 3 TOF R&D: LGADs

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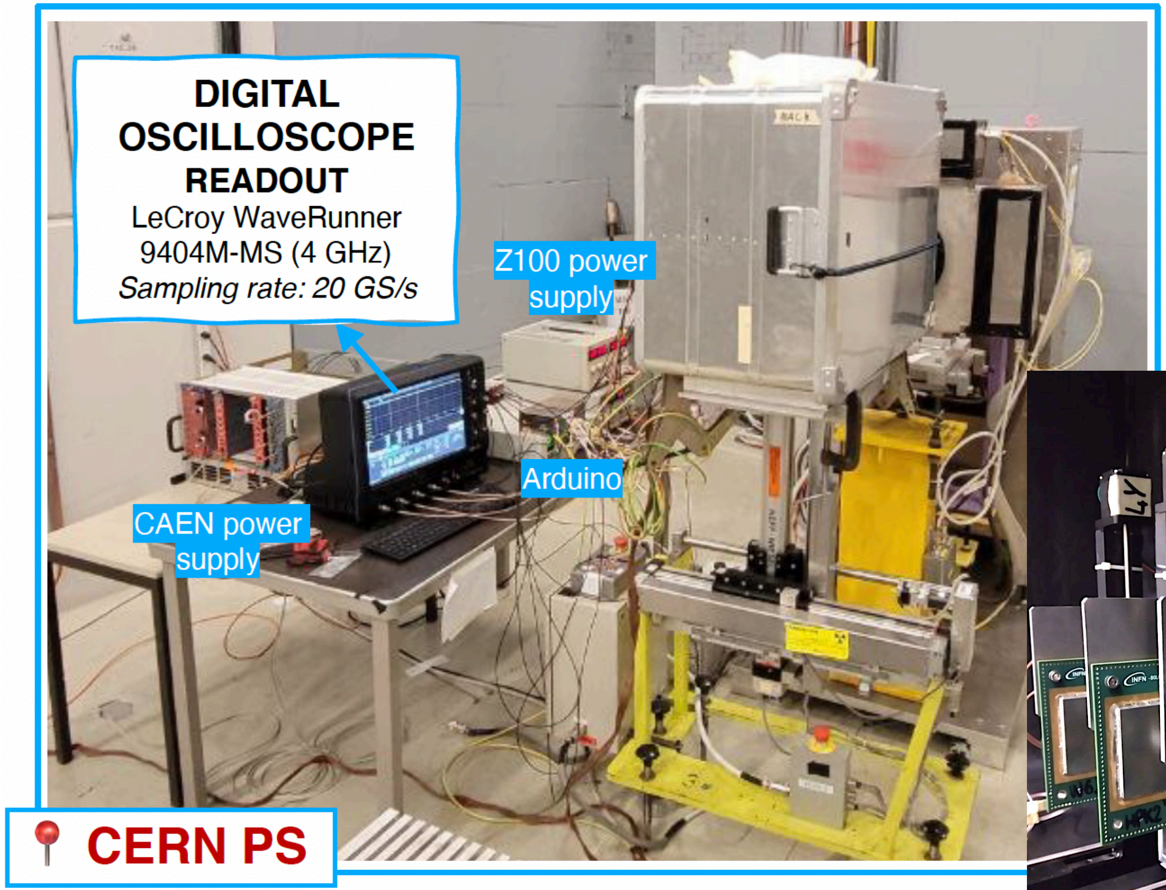
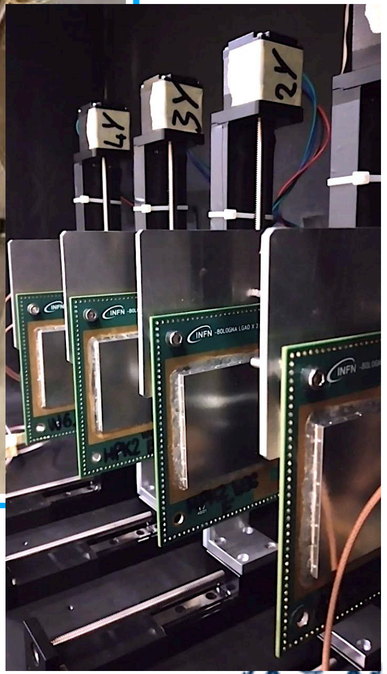


four aligned LGAD-boards

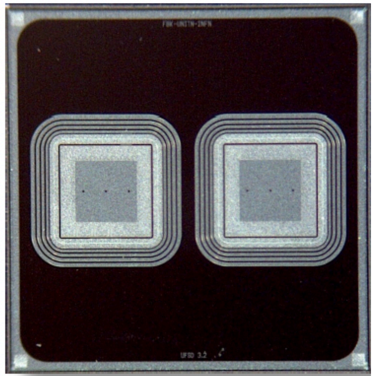
# ALICE 3 TOF R&D: LGADs

## TESTED LGADs & ELECTRONICS

First very thin LGAD prototypes produced by FBK

**25 μm** and **35 μm** -thick FBK single channel

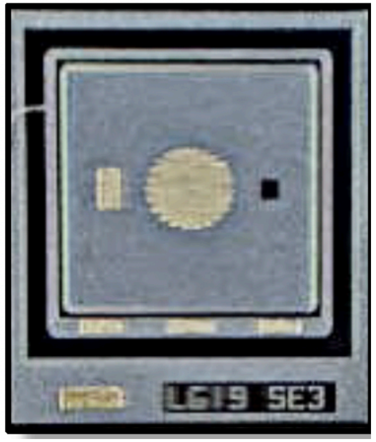
Area = **1x1 mm²**

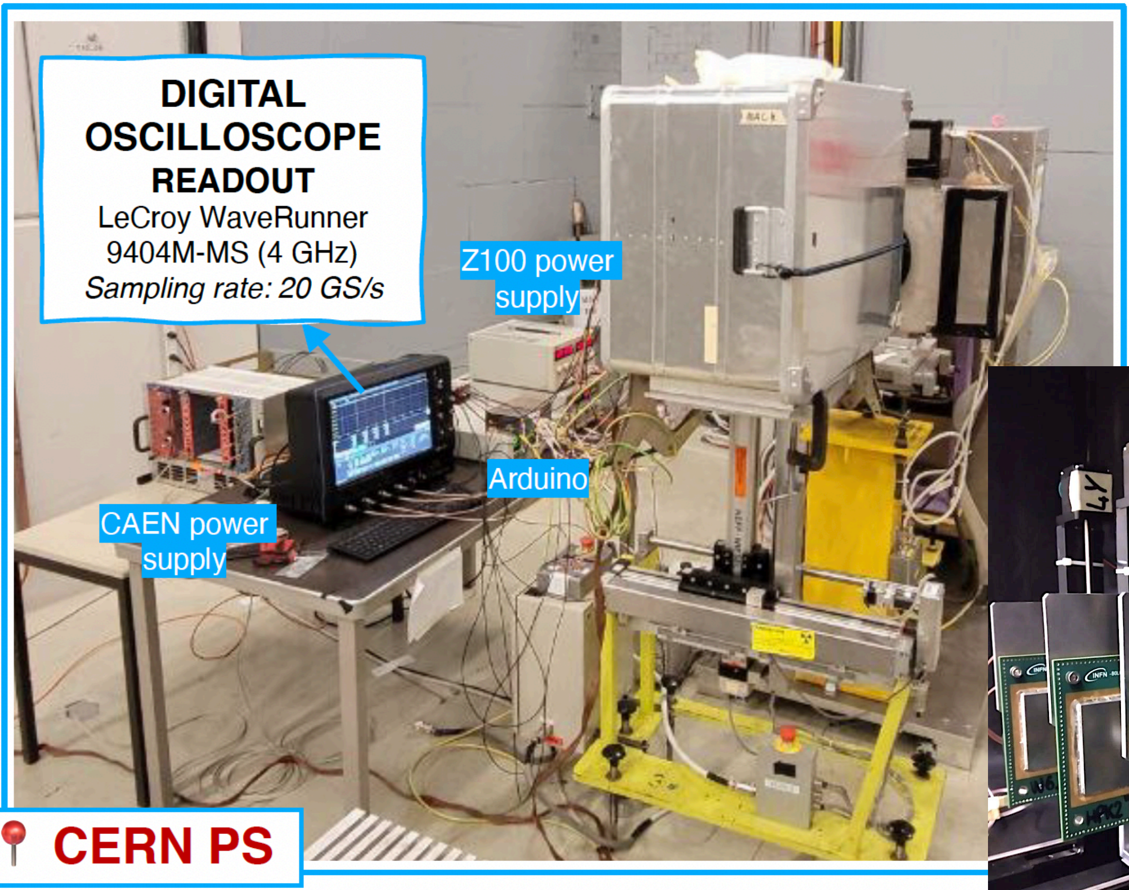


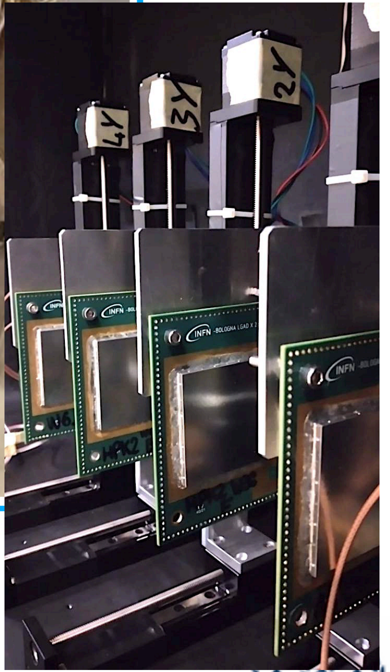
Standard sensors produced by HPK

**50 μm** -thick HPK single channel
(W42 & W36 with different doping concentrations)

Area = **1.3x1.3 mm²**



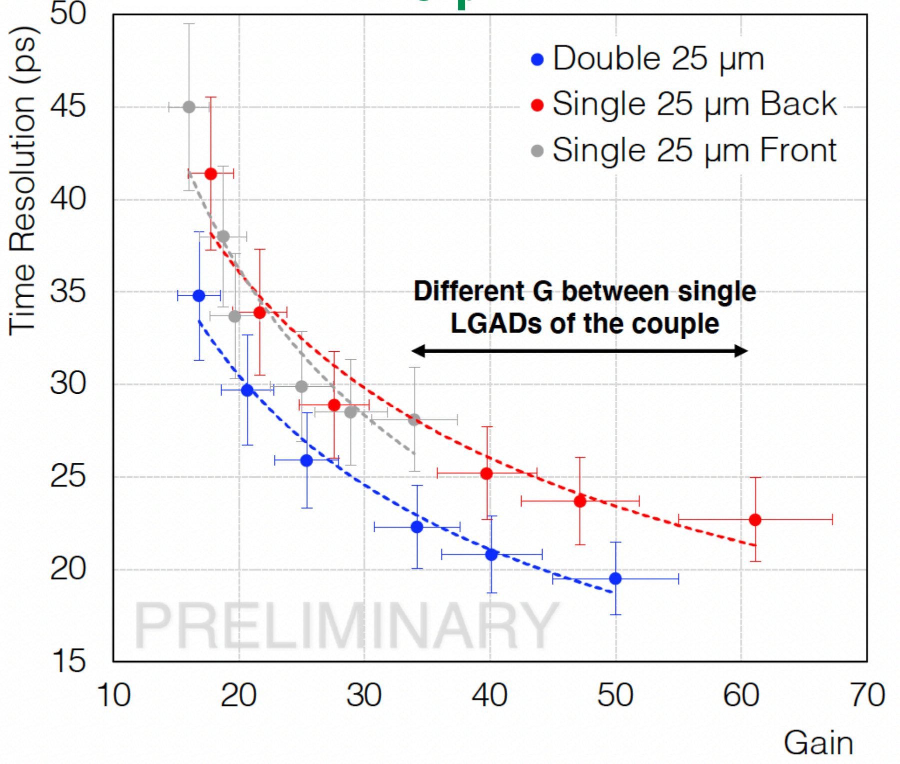



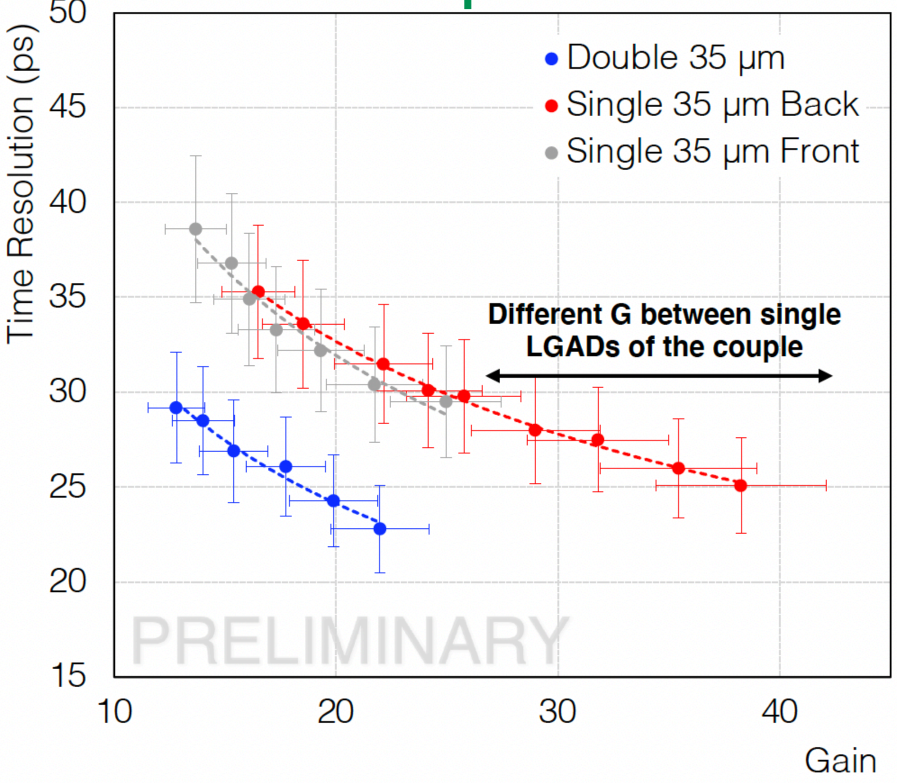

Four aligned LGAD-boards

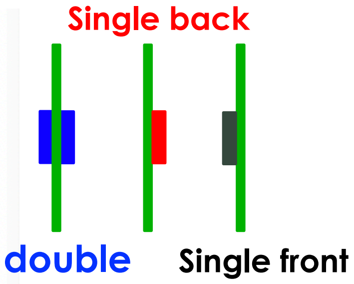
# Single and double LGADs

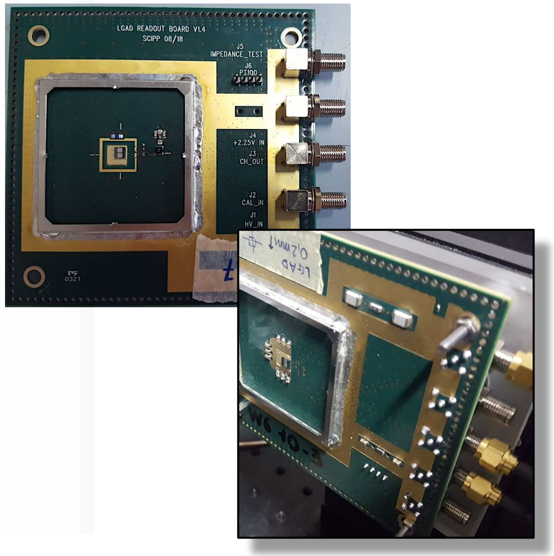
## 25 µm




## 35 µm



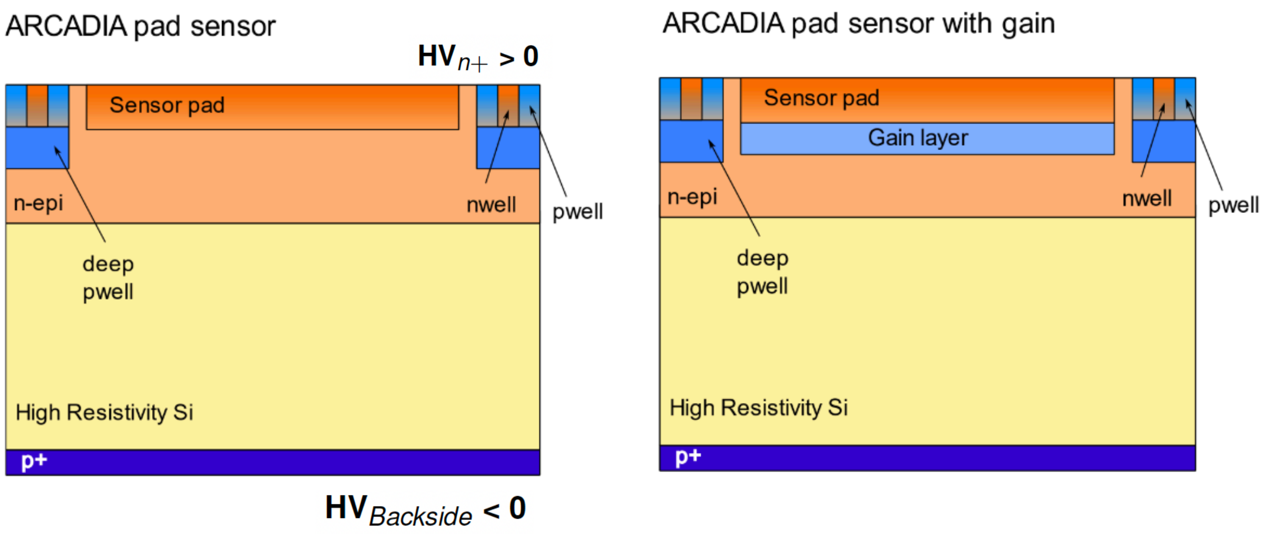




Single LGADs: **comparable** time resolution **for a similar gain**

**Better time resolution for a double-LGAD** in respect to single ones

(~15% for 25 µm & 24% for 35 µm)

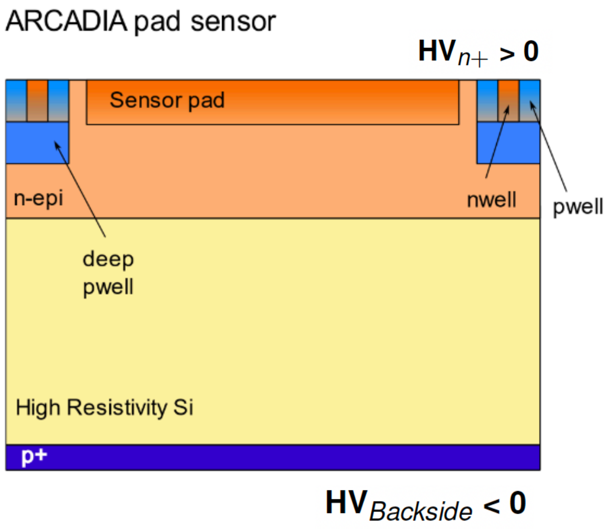
# ALICE 3 TOF R&D: CMOS- LGAD

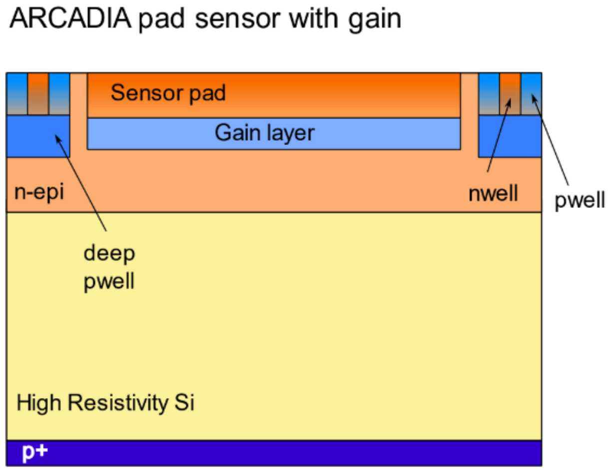



- One extra mask to implant the gain layer
- CMOS electronics in the pixel area
- Trade-off between electronics in pixel and timing
- AC coupling between sensor and electronics

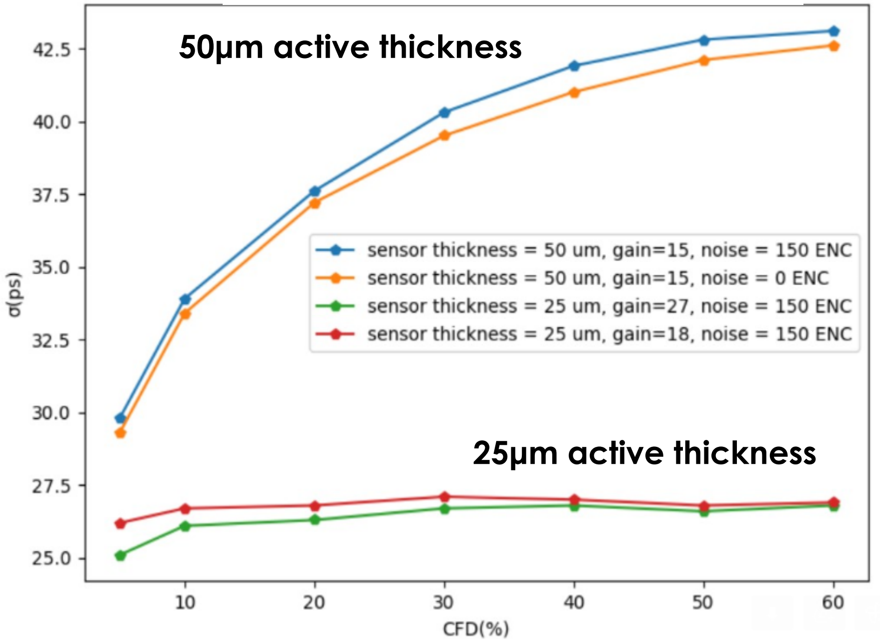
**Process:** modified LFoundry CMOS 110nm with 3 different active thicknesses
50µm, 100µm and 200 µm
**Process add-on:** gain layer implantation with moderate gain

# ALICE 3 TOF R&D: CMOS- LGAD




Garfield++ simulation



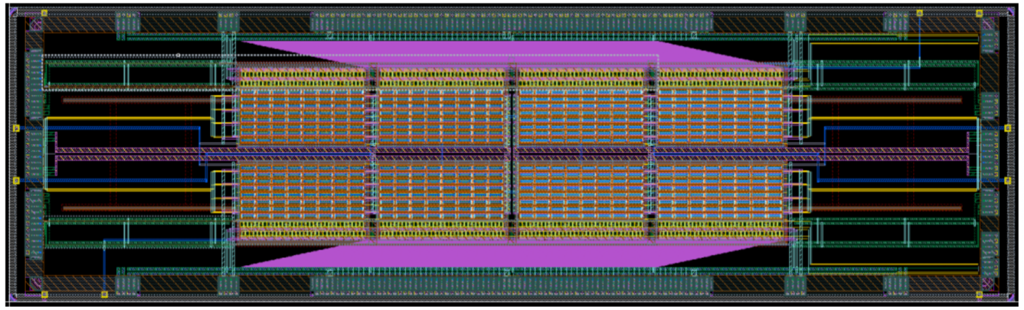

Intrinsic timing resolution
$\sigma_{Distortion}$ and $\sigma_{Landau\ noise}$

- For improved timing resolution, the active thickness can be easily changed with **customized substrates**
- No need to change masks for the first run just– "fast track" option

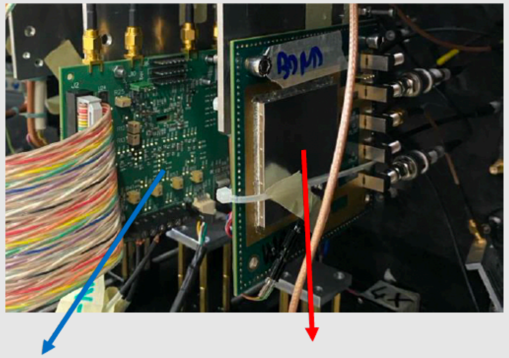
**Transfer function: integrated amplifier**
designed by micro-electronics expert

# ALICE 3 TOF R&D: CMOS- LGAD

First **prototype with integrated electronics** and gain layer produced by LFoundry in 110 nm commercial CMOS Process

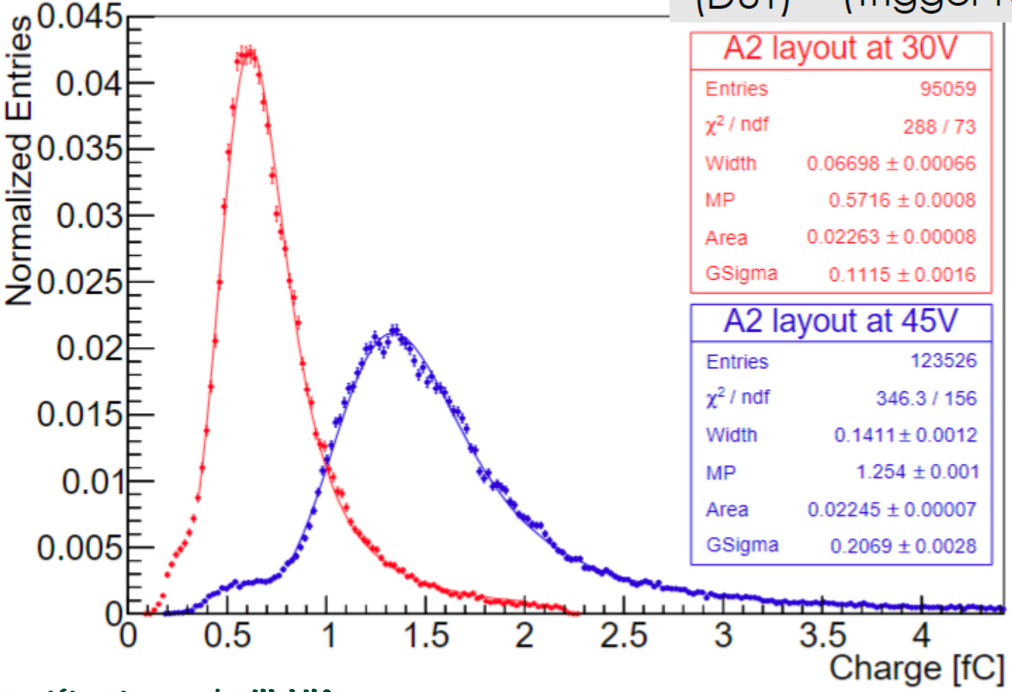


**In beam measurement @ CERN PS**




**Active thickness: 48 µm**

- Presence of deep-p-wells hosting the front-end electronics
- Backside HV allows full depletion -25 V to -40 V
- Topside HV manages the gain 30 V to 50 V



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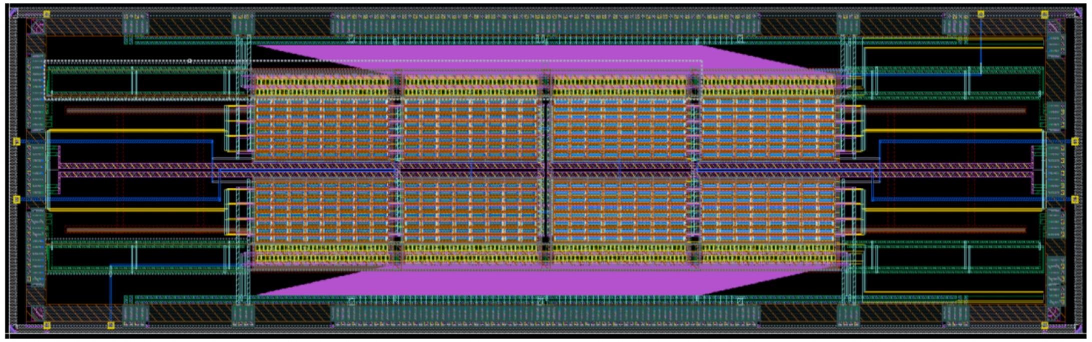

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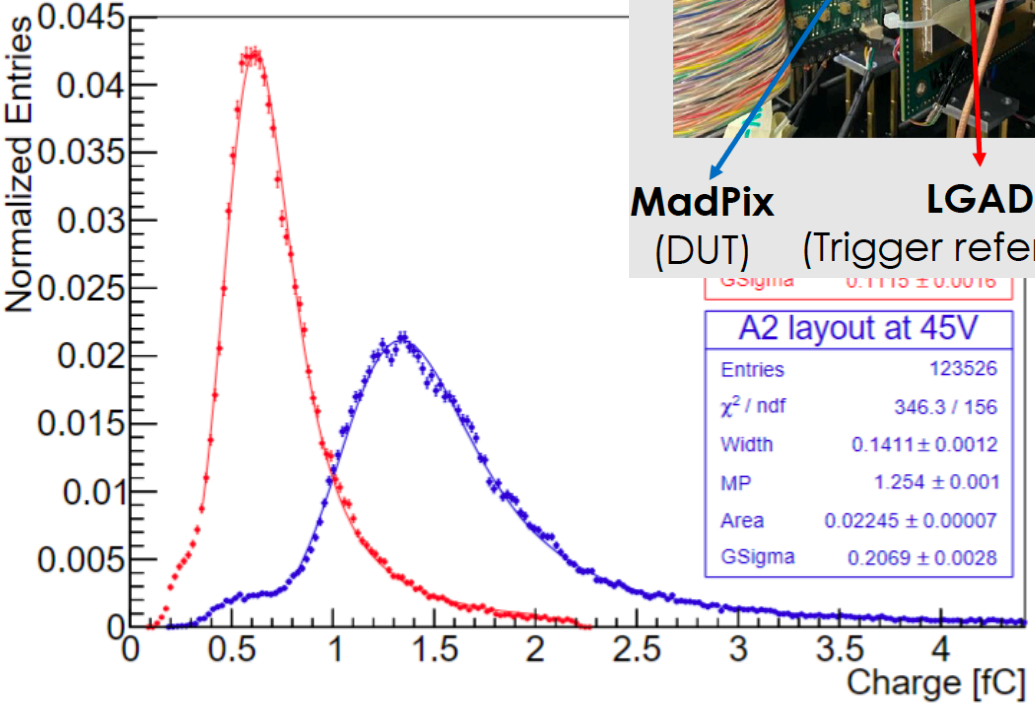
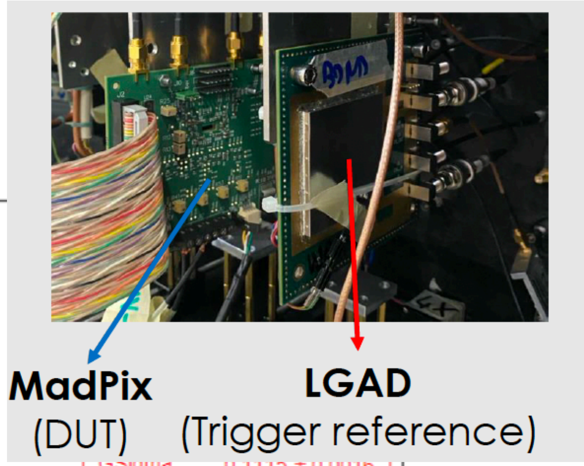


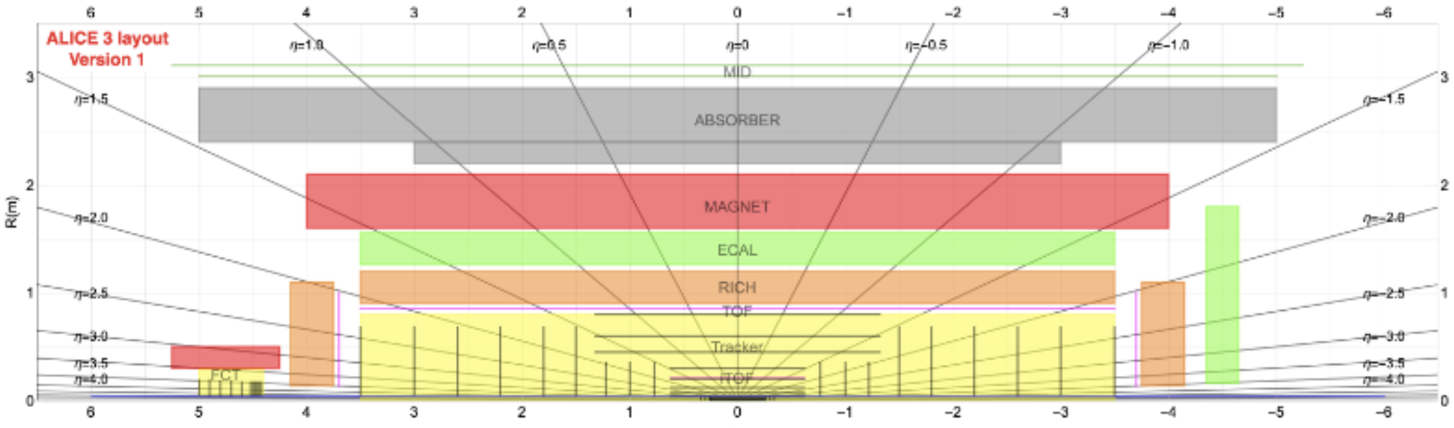



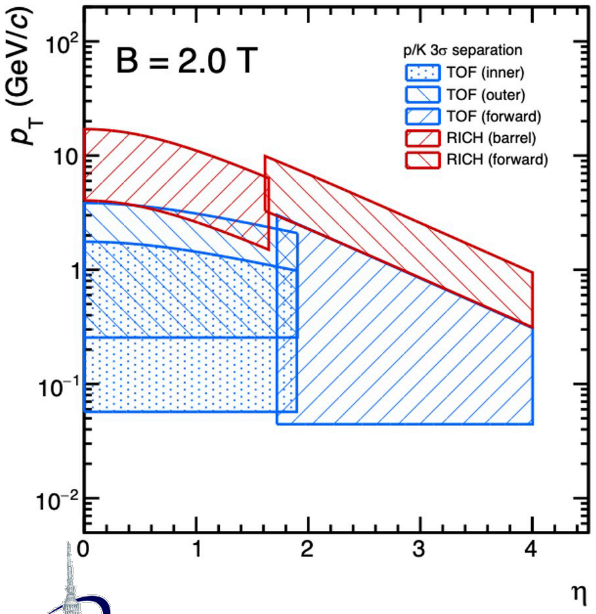

Measured gain lower than expected
New monolithic devices with higher gain to be tested this year

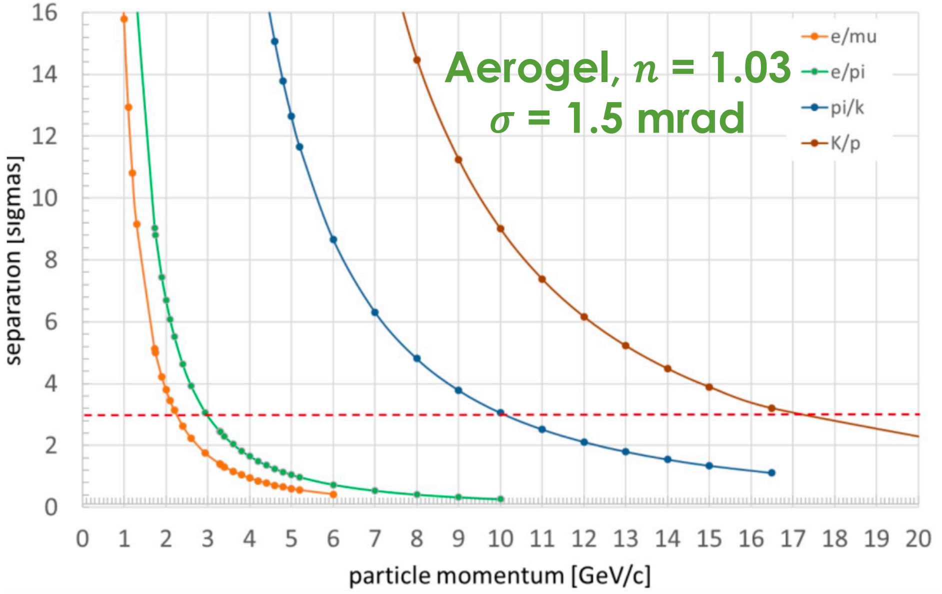
# ALICE 3 RICH implementation

**Extend charged PID beyond TOF limits**

- $e/\pi$ up to ≈ 2 GeV/$c$
- $\pi/K$ up to ≈ 10 GeV/$c$
- $K/p$ up to ≈ 16 GeV/$c$




1(barrel)+ 2 disks

- **Barrel** RICH at $R \approx 0.90$ m, $|z| < 3.50$ m
- **Forward** RICH at 3.75<|z|<4.15 m, $|R| < 1.15$ m
- Silicon Photomultipliers (**SiPMs**)

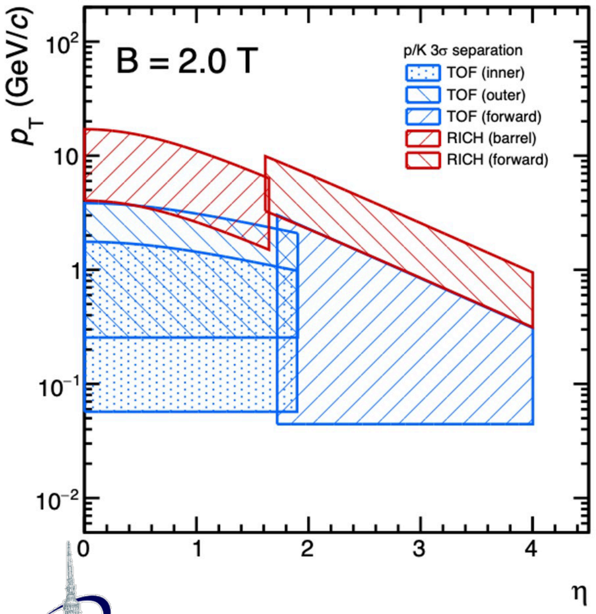
# ALICE 3 RICH R&D

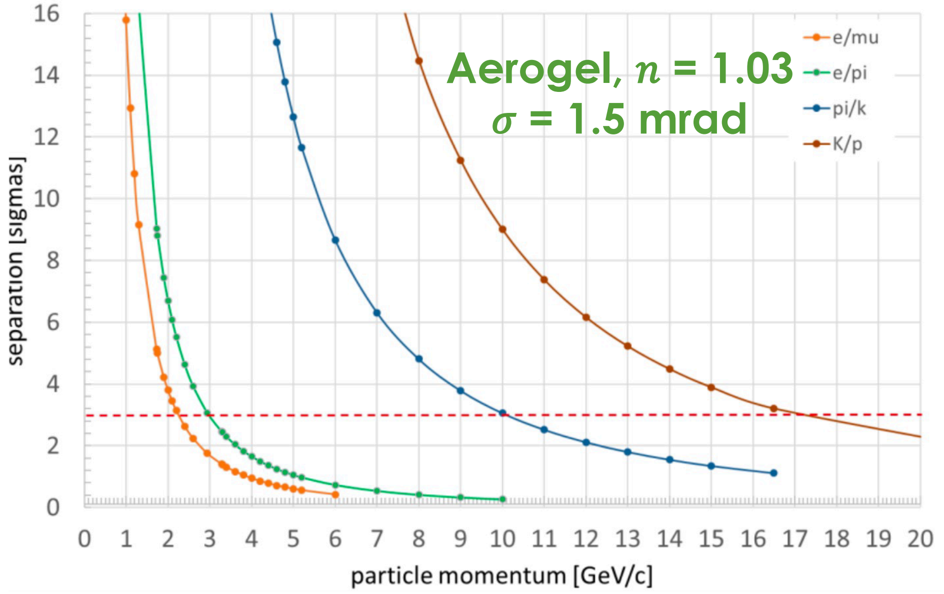
**Extend charged PID beyond TOF limits**

- $e/\pi$ up to ≈ 2 GeV/$c$
- $\pi/K$ up to ≈ 10 GeV/$c$
- $K/p$ up to ≈ 16 GeV/$c$

**R&D challenges**

- Projective bRICH to improve coverage at large $|\eta|$ while saving on overall photosensitive area
- **Merged oTOF+bRICH system using a common SiPM layer** coupled to a thin radiator window

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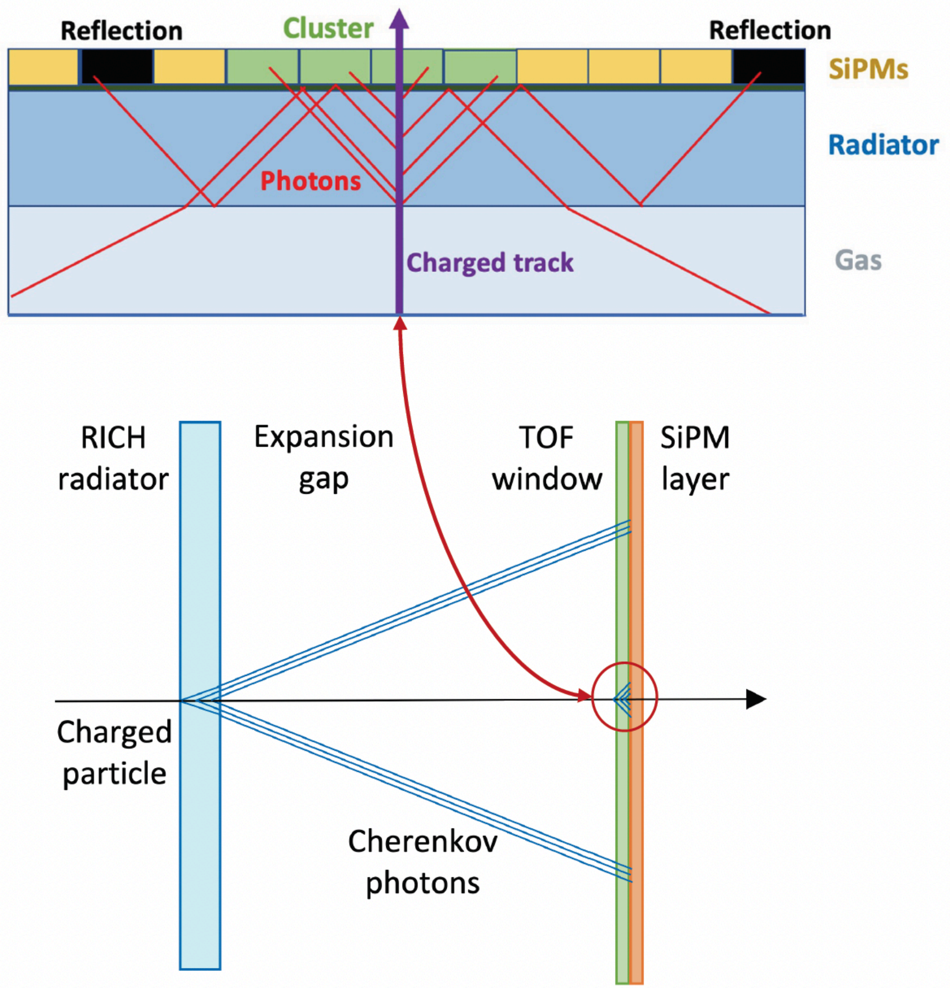
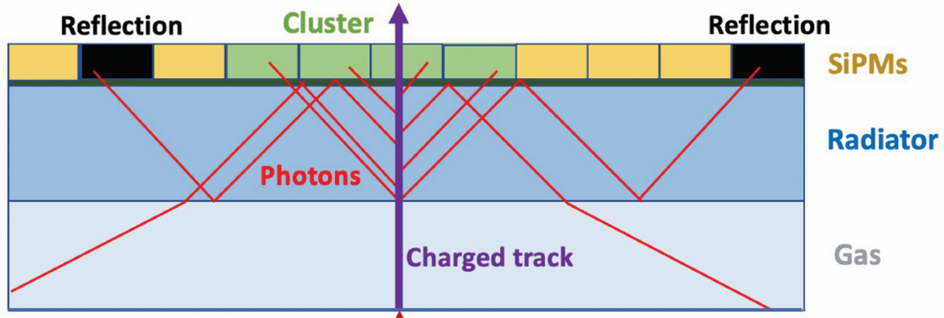
# MIP timing using bRICH SiPMs

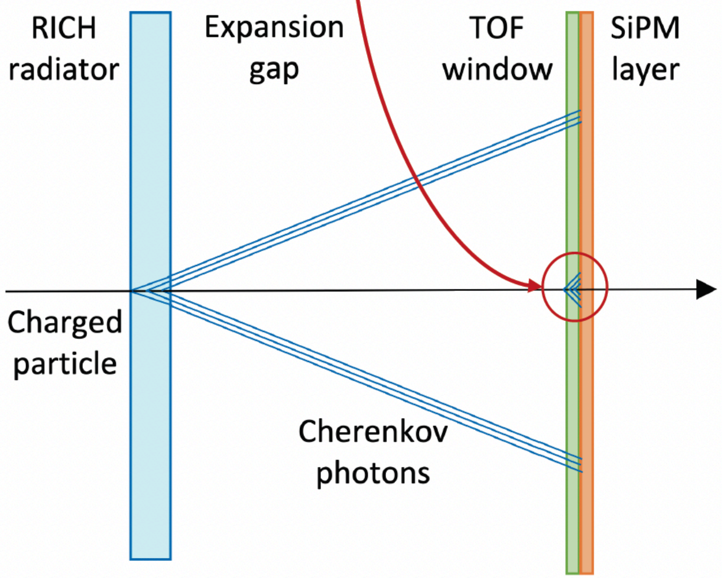



**Principle of operation**

- Introduction of Cherenkov radiator coupled to SiPM layer
- Use SiPM clusters due to radiator photons for MIP timing

# MIP timing using bRICH SiPMs




## Principle of operation

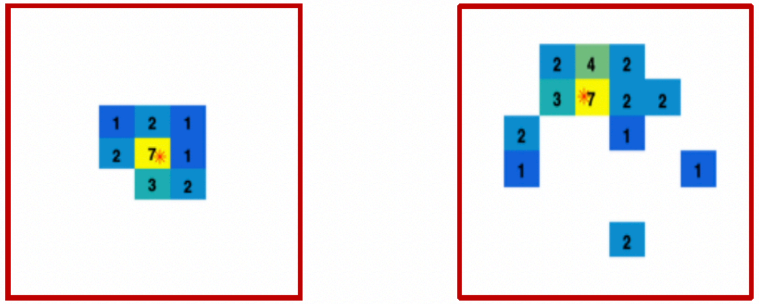
- Introduction of Cherenkov radiator coupled to SiPM layer
- Use SiPM clusters due to radiator photons for MIP timing

## Radiator choice

Use high refractive index material to minimize Cherenkov thresholds and to enhance both photon yield and spread

**1 mm $SiO_2$ (n=1.47) + 0.45 mm epoxy resin (n=1.55), 1x1 $mm^2$ SiPMs**

*MIP at 0° incidence



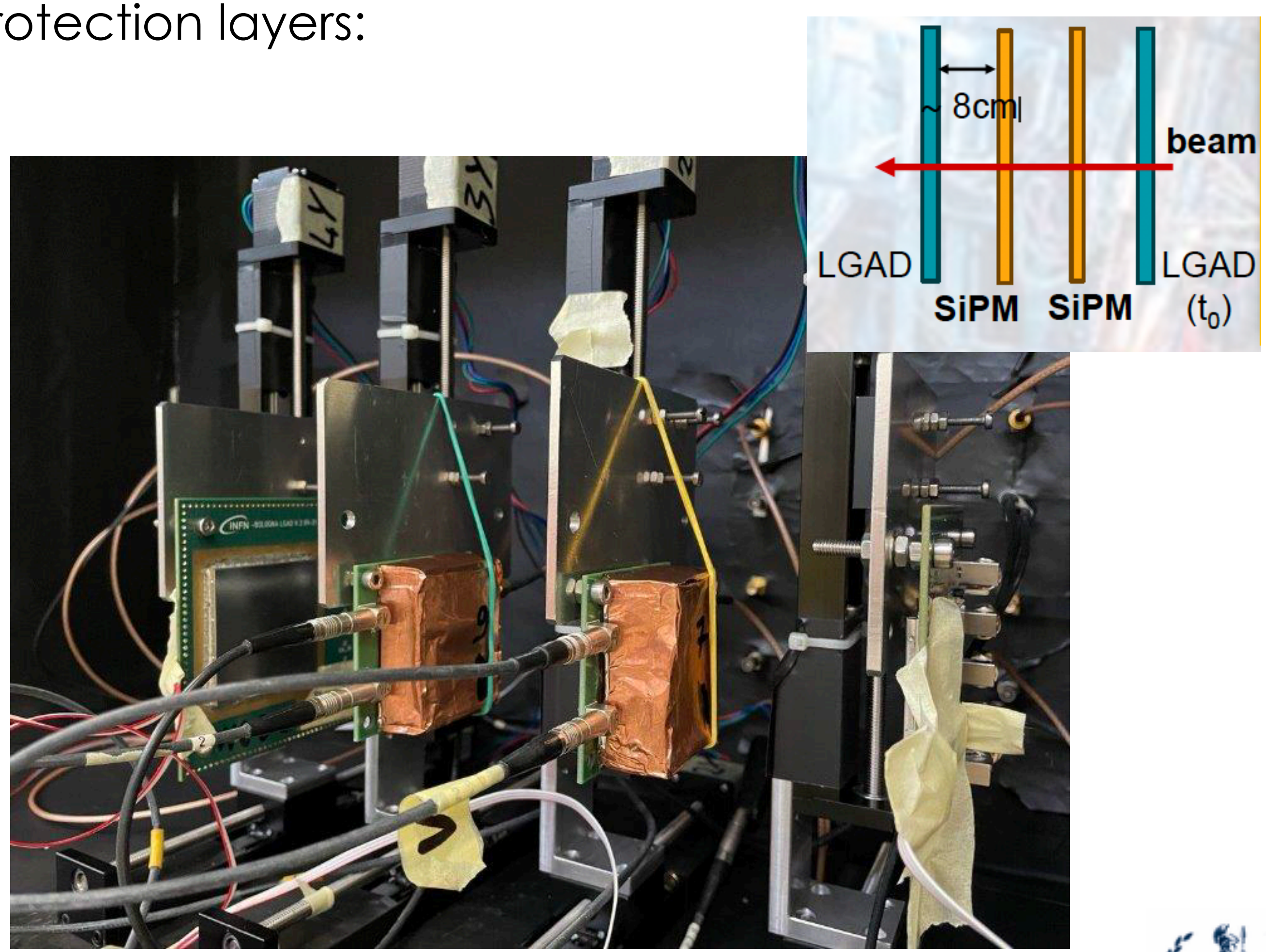
*MIP at 50° incidence

**Assuming PDE of S13360-**50CS SiPMs at recommended overvoltage**

# Beam test
# MIP timing using bRICH SiPMs

Available FBK NUV-HD-RH SiPM with different protection layers:

- Silicone Resin 1 mm (SR1) (n=1.5)
- Silicone Resin 1.5 mm (SR15)
- Epoxy Resin 1 mm (ER1) (n=1.53)
- Without resin (WR)
- Customized FE with 40 dB amplification



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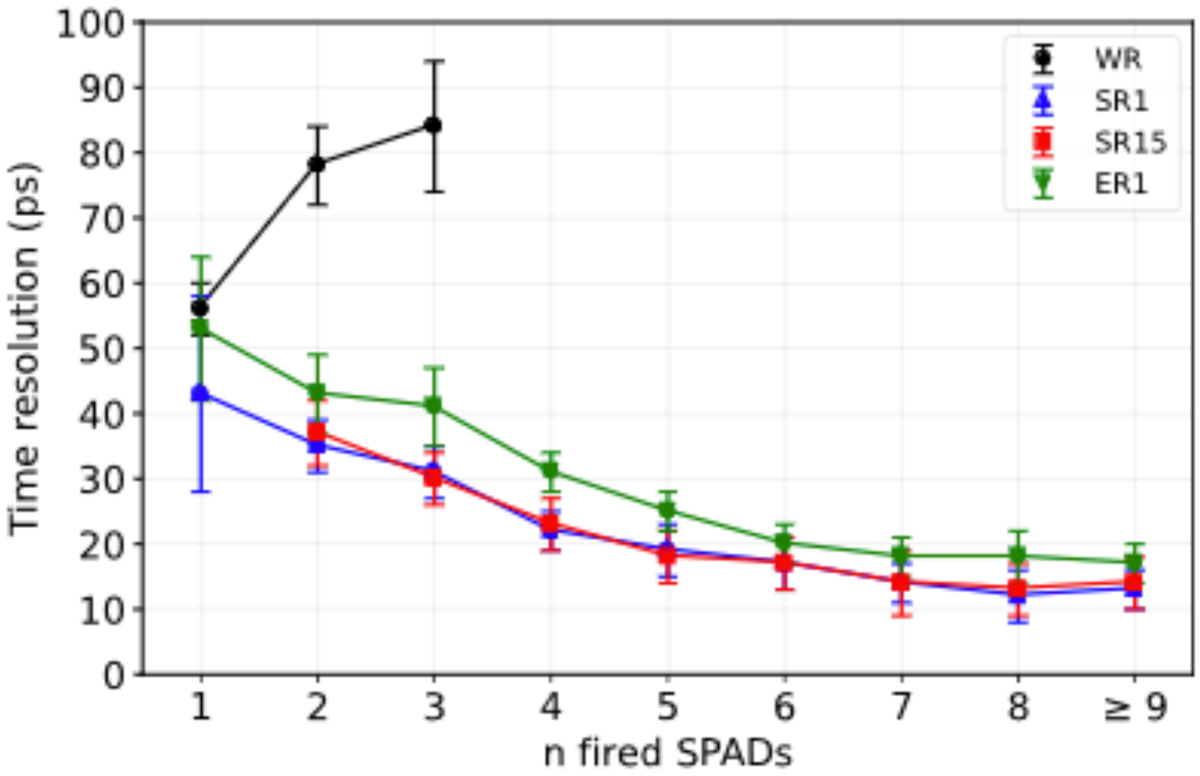
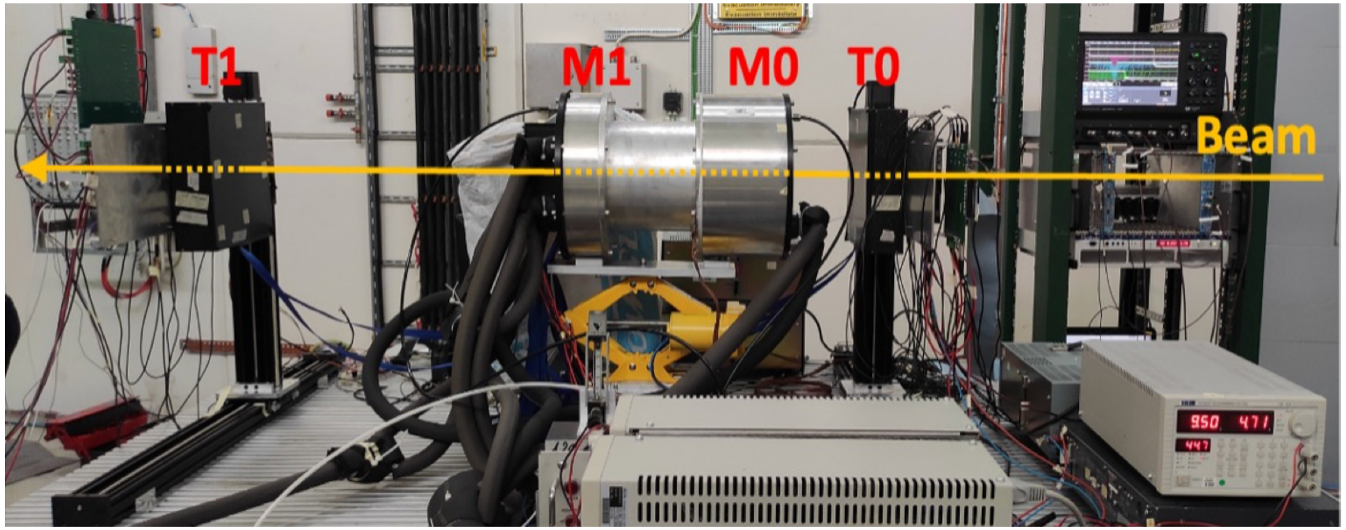
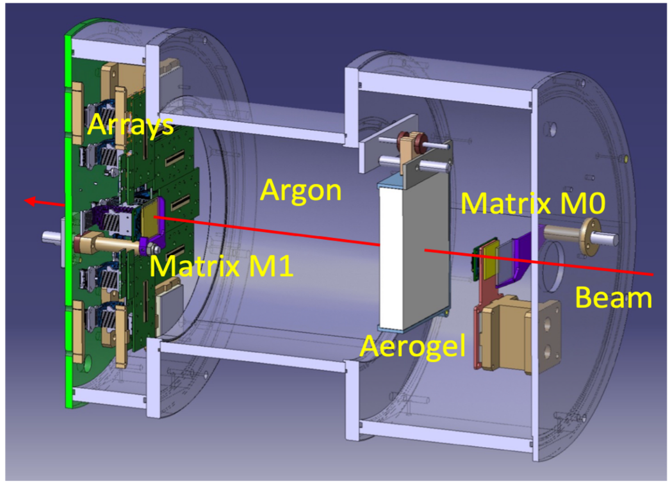
Exploiting Cherenkov radiation in the protection layer
the time resolution improves as a function of the number of fired SPADs, reaching **20 ps for six or more SPADs**




**Eur. Phys. J. Plus 138, 788 (2023)**

# RICH: SiPM with radiator window

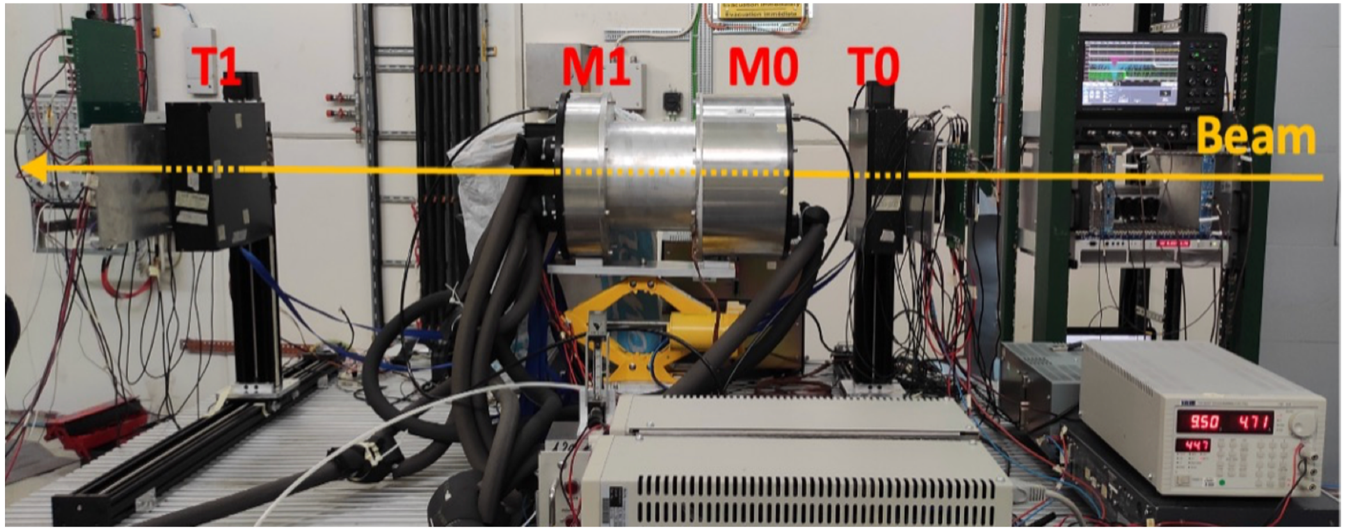


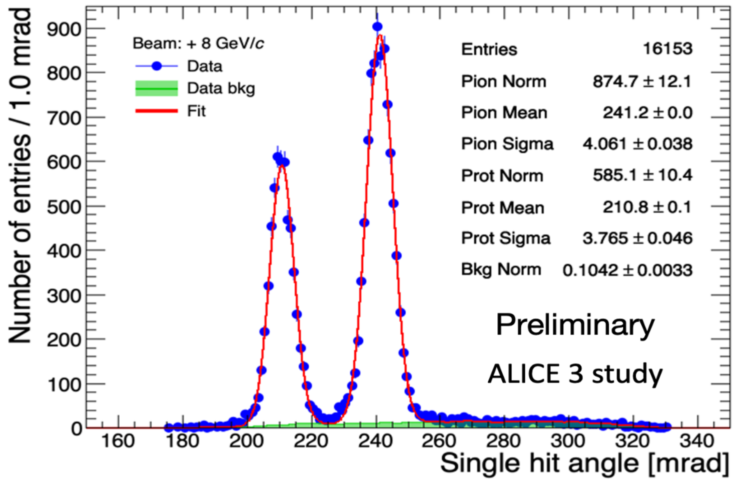

## Test beam in  Oct 2023 at CERN PS

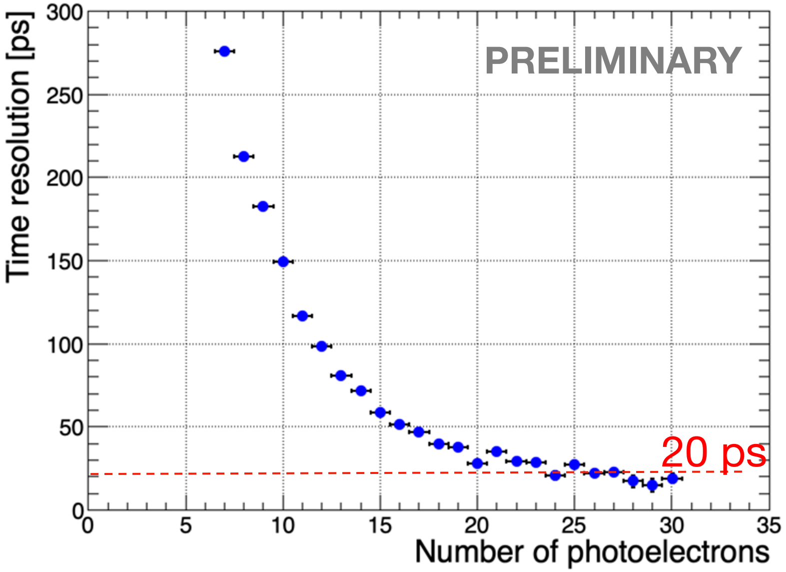
- Aerogel radiator by Aerogel Factory LTD (Japan)
- 8x8 SiPM matrices from HPK and FBK, various pixel sizes
- Different radiator windows coupled to SiPM to test TOF+RICH integrated concept

# RICH: SiPM with radiator window




Cherenkov angle of pions and protons

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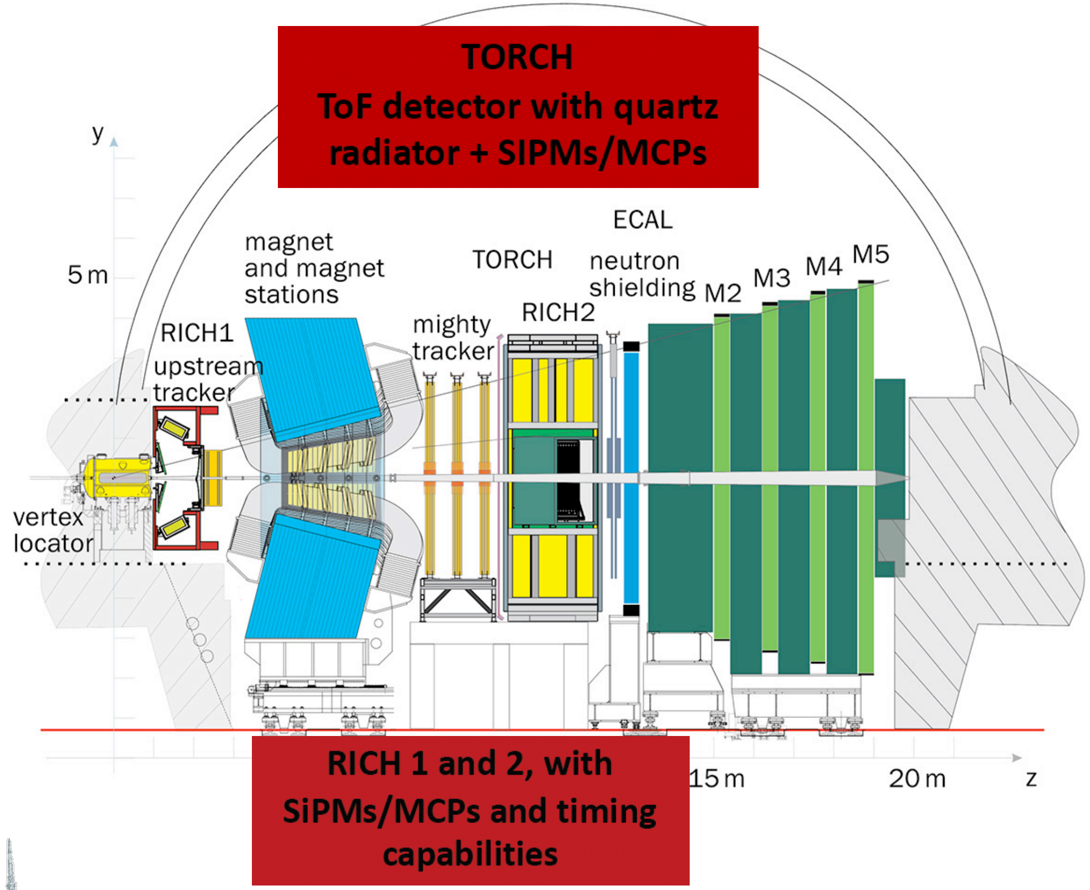
# LHCb Phase II Upgrades

*The ultimate flavour physics experiment at the HL-LHC*





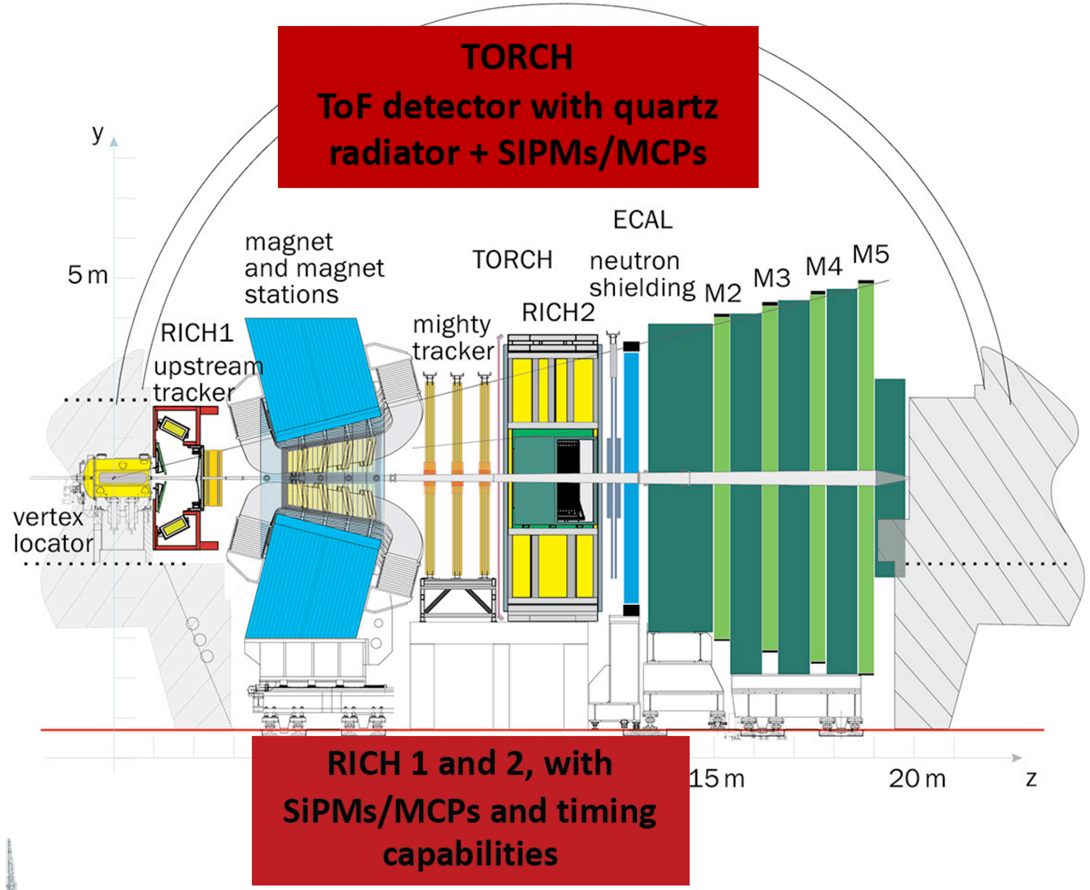
LHCC-2018-027


LHCC-2021-012

- Installation of a new **time of flight detector (TORCH)**
- No more hadron calorimeter
- Addition of timing information to cope with increased detector occupancy
- Physics programme relies on **good PID**: need to add timing to the Cherenkov photons (**RICH Upgrade**)

# LHCb Phase II Upgrades: PID detectors

*The ultimate flavour physics experiment at the HL-LHC*




## TORCH

- large area time of flight detector to provide PID in the GeV/c momentum range
- Exploit prompt production of Cherenkov light in a quartz radiator plate to provide a fast timing signal.
- Aim for a resolution of 10-15 ps per track

## RICH Detectors

- Current detectors would have 100% occupancy
- Three-fold plan:
  - Adjust optics
  - Finer segmentation
  - Shift sensitivity towards green
- Possible time resolution of ~ 100 ps

# LHCb Phase II Upgrades: PID detectors

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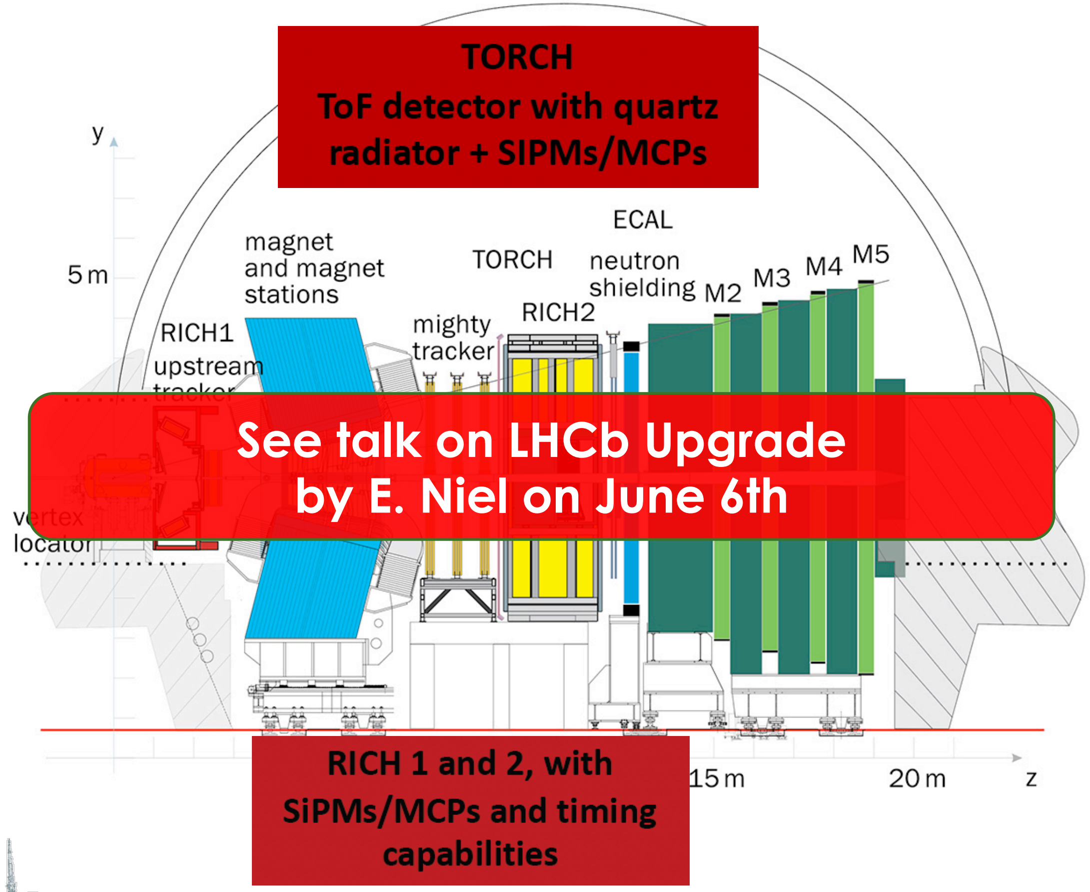


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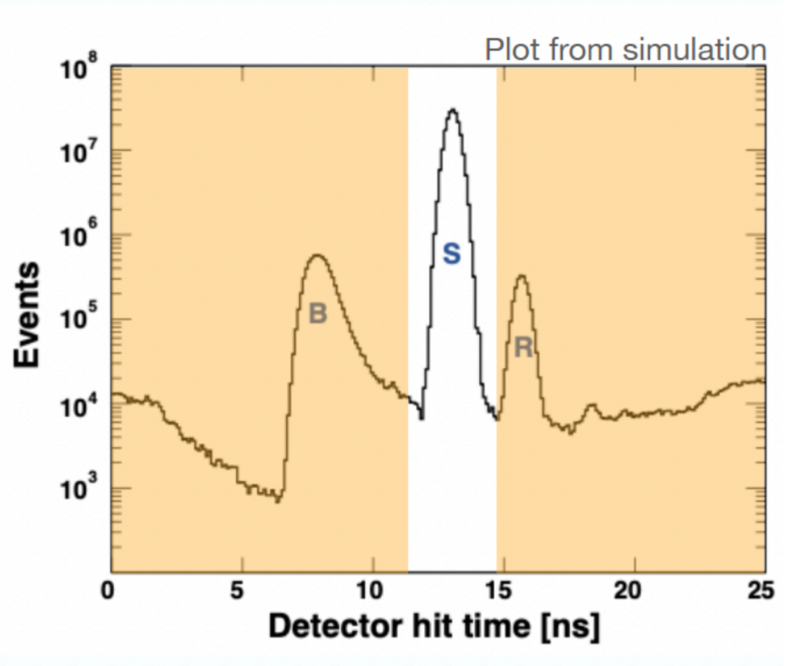
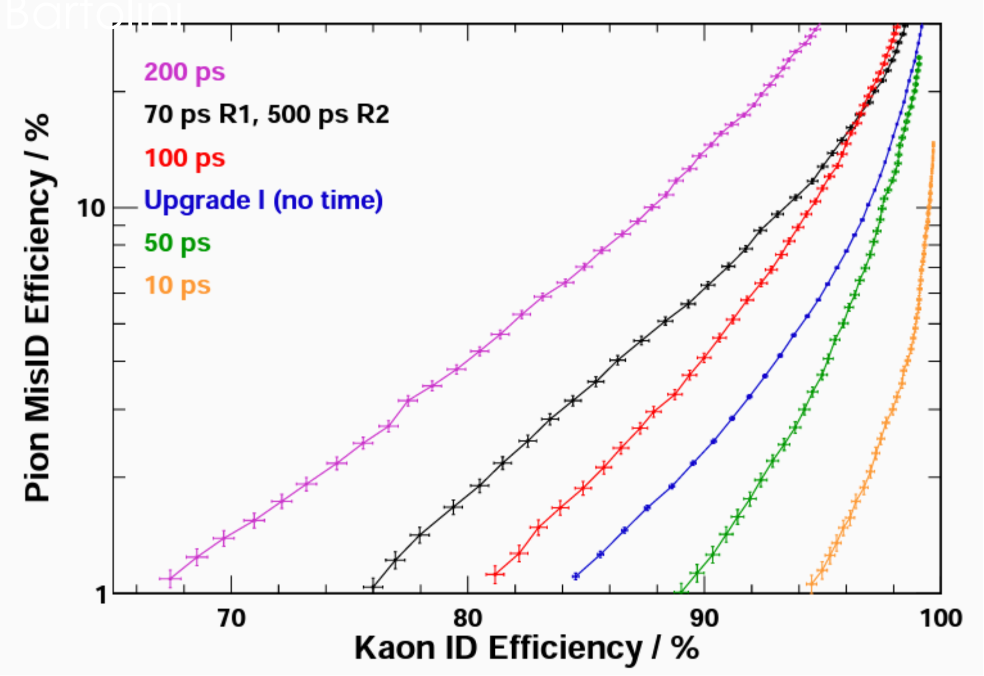
# The LHCb RICH: timing information

Time distribution of photon hits within 25 ns shows clear Cherenkov peak signal



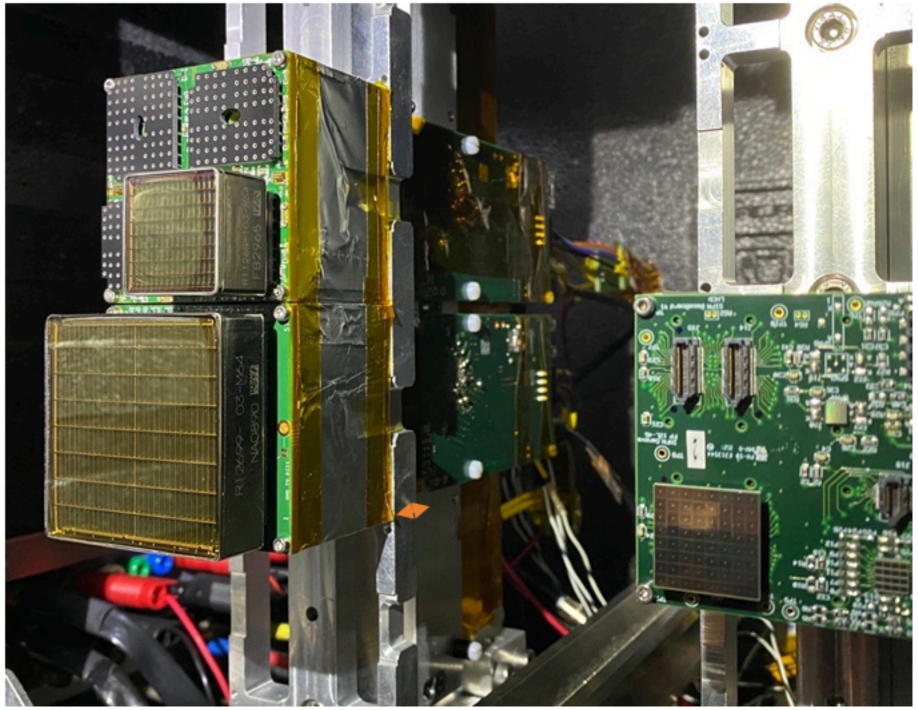

Framework TDR - LHCC-2021-012

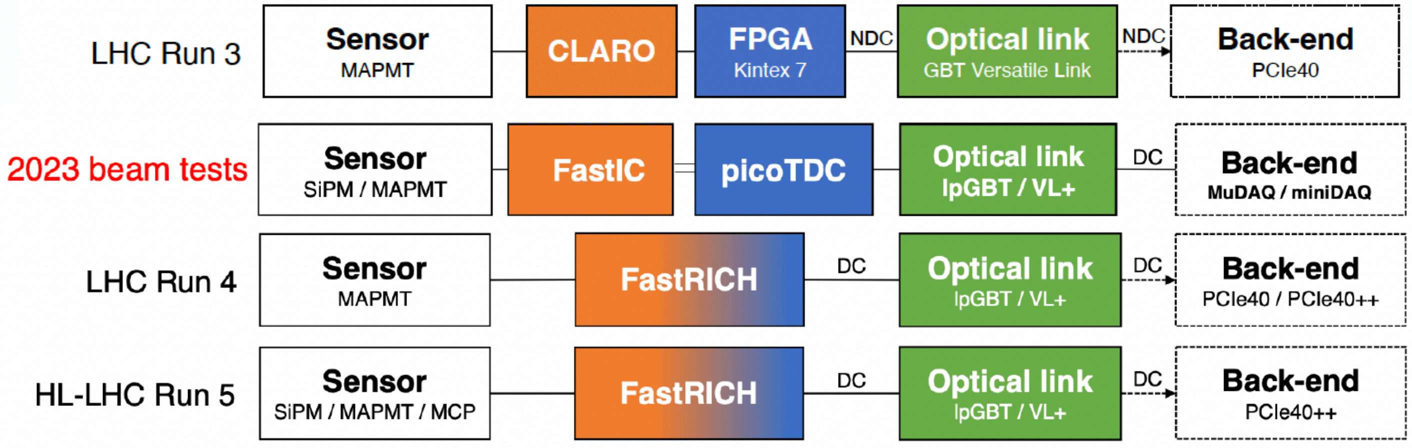
Current PID performance will be maintained if **$\sigma_t$ < 100 ps**
Assumes **precise knowledge of PV time** for reconstruction
→ Info provided by the VELO



# The LHCb RICH: test beam results

Need photodetectors with smaller
pixel size ~ 1mm$^2$
Need time resolution better than 100 ps

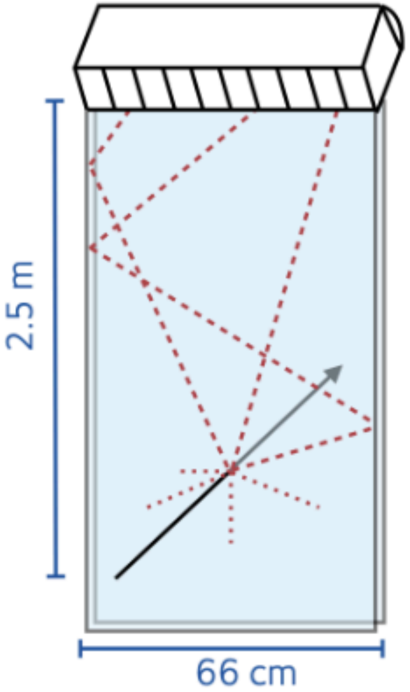


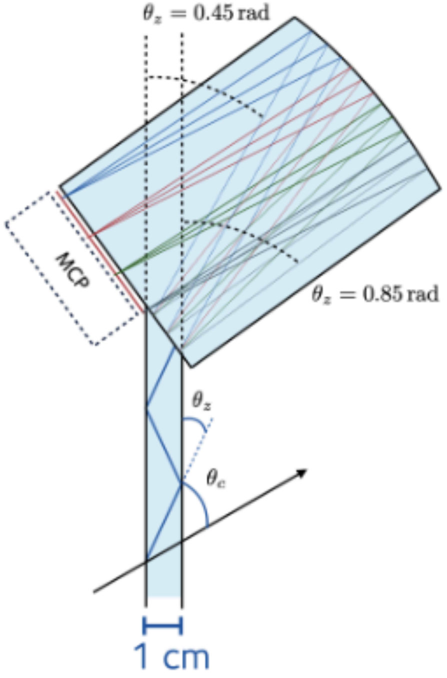



The test beam campaign focuses on the development and testing of prototype readout chains with fast- timing information.

# The LHCb TORCH

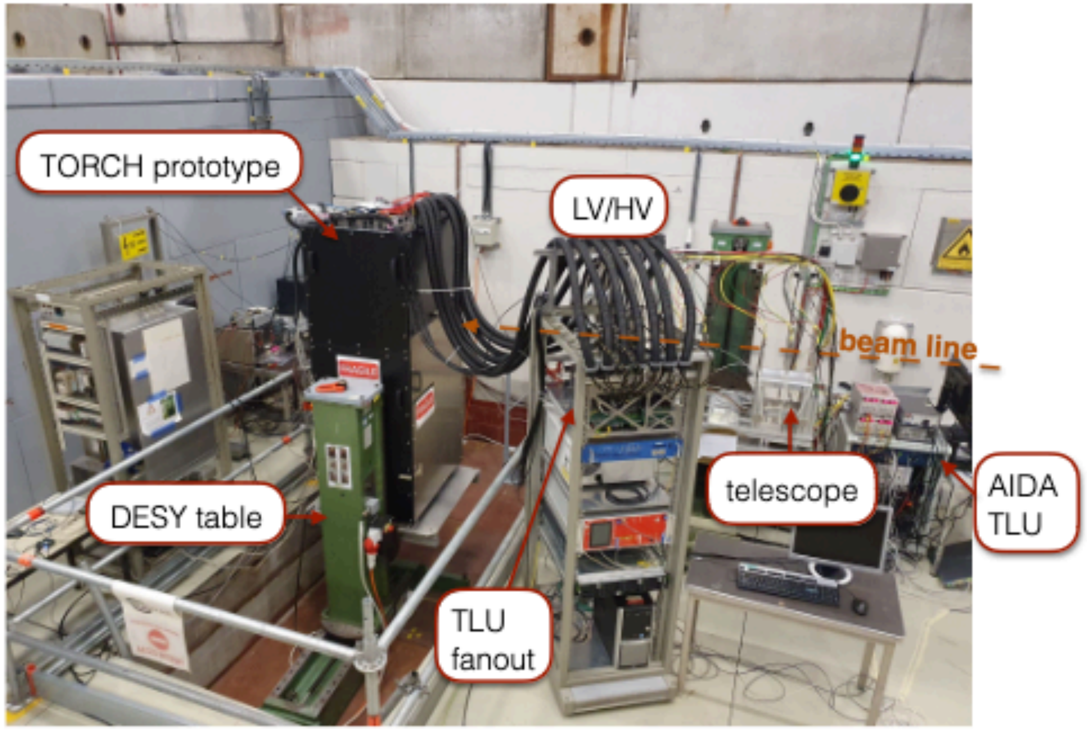
- Exploits prompt production of Cherenkov light in quartz bars
- Cherenkov photons travel to detector plane via total internal reflection
- MCP used as photodetector
- Provide PID below 15 GeV/c

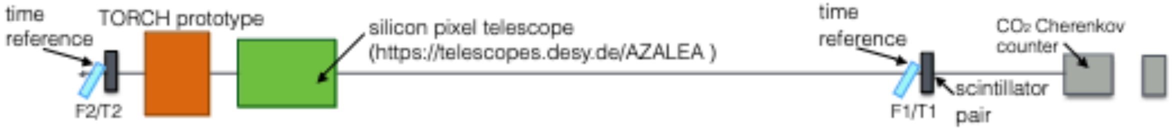



## Test beam at CERN PS

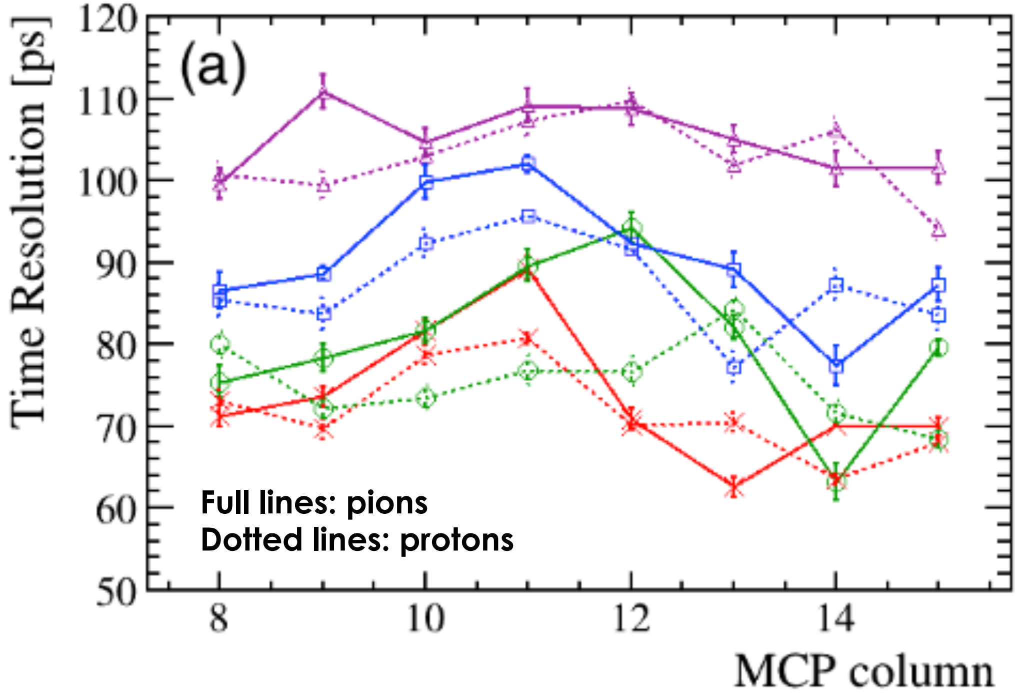
half-scale (660 x1250 x10 mm$^3$) TORCH demonstrator module



# The LHCb TORCH

**Timing resolution is approaching**
**70 ps/photon** for beam entry position close to the MCP-PMT (red line)

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arXiv:2111.04627

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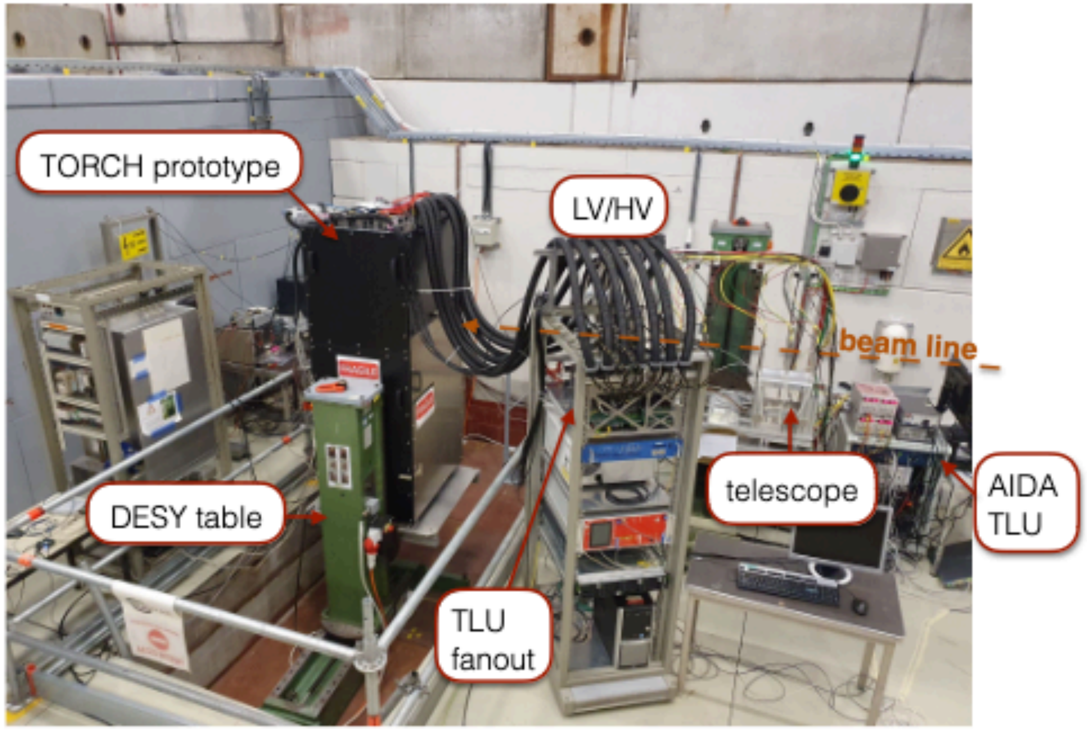


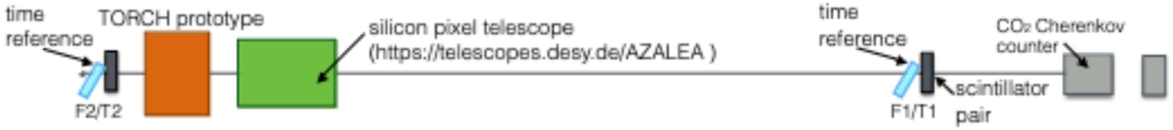

# Summary

- High luminosity running presents many challenges for experiments
- Exciting physics cases under study and PID detectors are cucial
- Use of timing also for PID is a key strategy to overcome challenges

- **ALICE 3**
  - robuts R&D for TOF measurement with 20 ps resolution
  - breakthrough concept of TOF measurements using bRICH

- **LHCb**
  - RICH and TORCH: R&Ds are ongoing for detector designs and next-generation technologies
  - the picosecond time information will add a new dimension to the experiment


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# THANK YOU