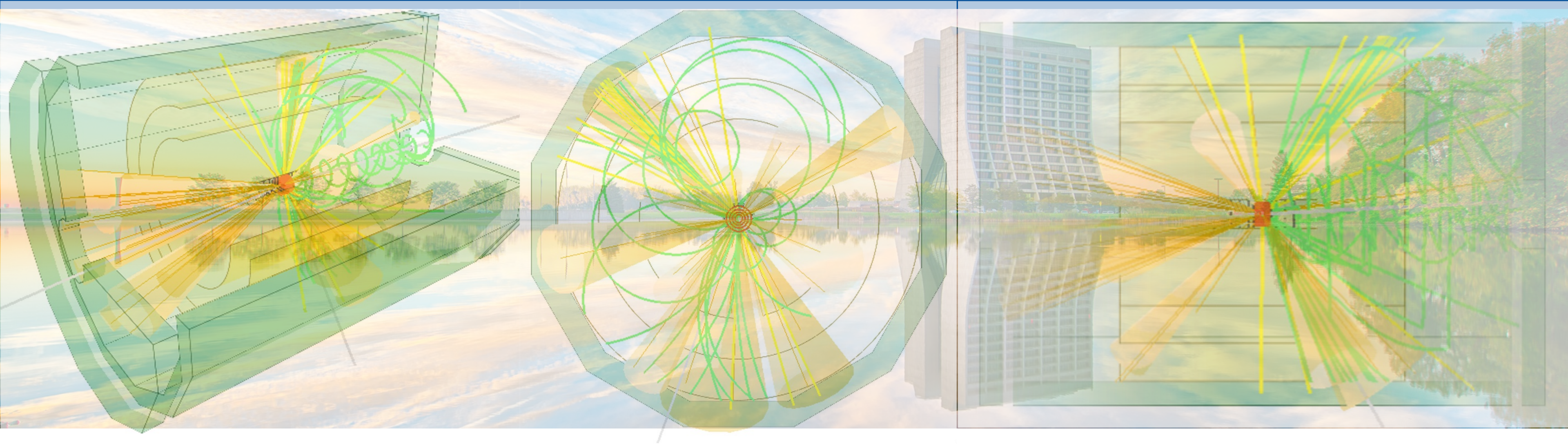


# Muon Collider: Detector R&D summary

Sergo Jindariani (Fermilab)

IMCC Annual Meeting

June 21th , 2023

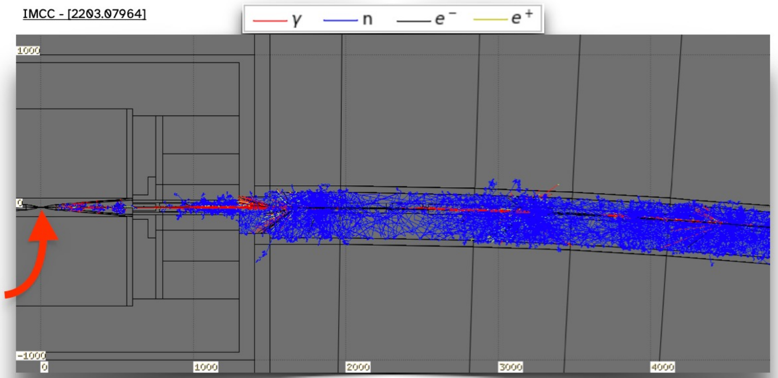
With big thank you to everybody who helped with material!

D.Acosta, A.Apresyan, N.Bachetta, D.Calzolari, N.Cartiglia, G.Cummings, M.Garcia Sciveres, Z.Gecse, N.Tran, I. Vai, I.Sarra, L.Sestini, R.Venditti and others

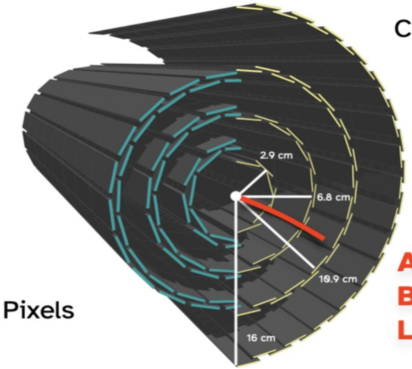
# Why special detectors?

Unique feature/challenge of Muon Collider detectors – beam induced background (BIB)

10 TeV detectors for lepton colliders is an uncharted territory



nteraction Point



CMS Run 2 Pixels

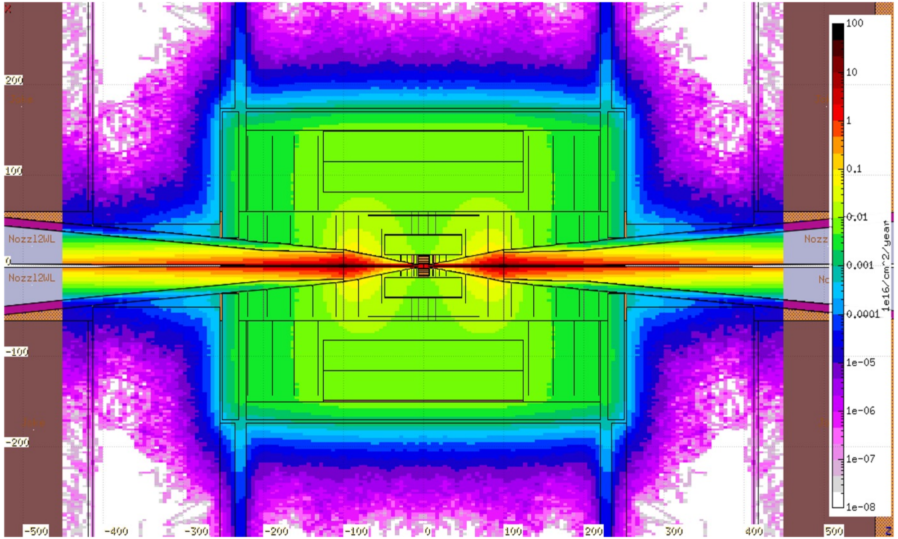
CMS Run 1 Pixels

Average 1 TeV B-Hadron Decay Length

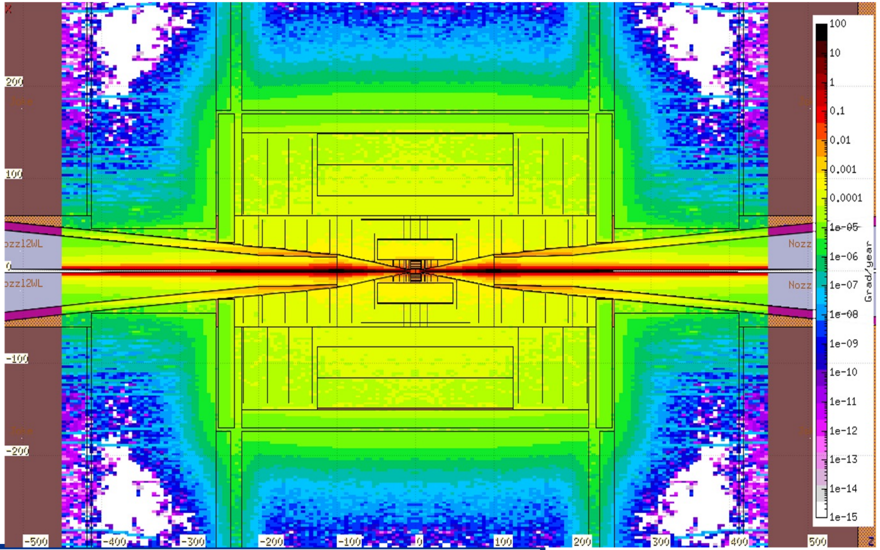
Sketch: L. Lee

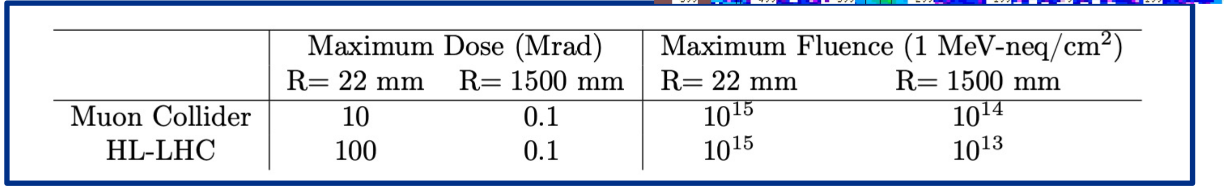
# Radiation Levels

1-MeV-neq fluence for one year of operation (200 days)



Total Ionizing Dose for one year of operation (200 days)



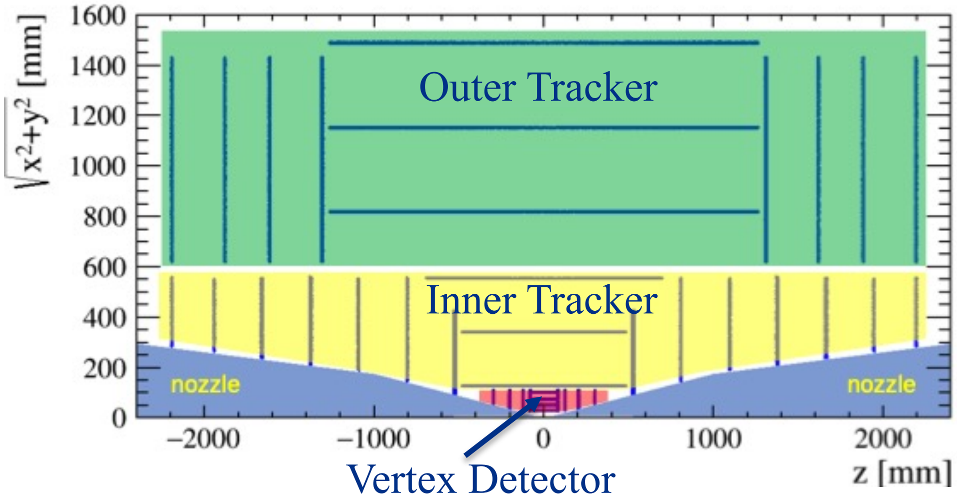


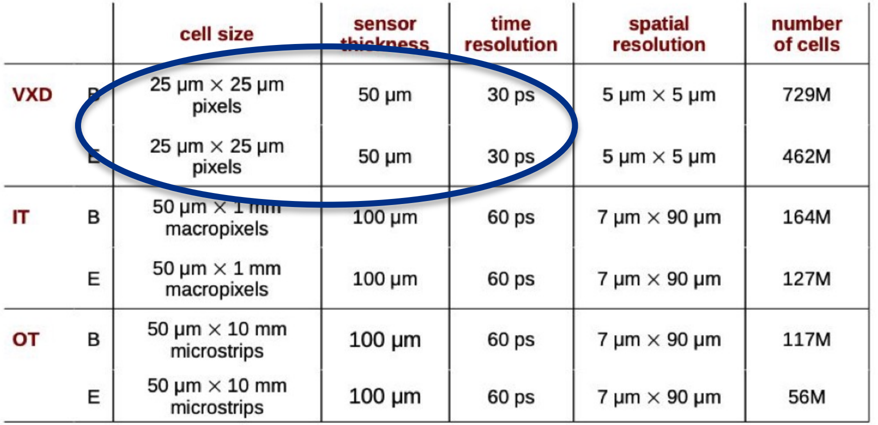
| | Maximum Dose (Mrad) | | Maximum Fluence (1 MeV-neq/cm$^2$) | |
|---|---|---|---|---|
| | R= 22 mm | R= 1500 mm | R= 22 mm | R= 1500 mm |
| Muon Collider | 10 | 0.1 | $10^{15}$ | $10^{14}$ |
| HL-LHC | 100 | 0.1 | $10^{15}$ | $10^{13}$ |

Muon Collider 10 TeV tbc O(0.1) tbc O($10^{14}$)

# Tracker Requirements

- ~100 m$^2$ of silicon sensors
- Low mass/power, radiation tolerance, low noise
- Pixel size optimized to bring occupancy to <1%
- Total number of channels ~ 2B





| | | cell size | sensor thickness | time resolution | spatial resolution | number of cells |
|---|---|---|---|---|---|---|
| **VXD** | B | 25 µm × 25 µm pixels | 50 µm | 30 ps | 5 µm × 5 µm | 729M |
| | E | 25 µm × 25 µm pixels | 50 µm | 30 ps | 5 µm × 5 µm | 462M |
| **IT** | B | 50 µm × 1 mm macropixels | 100 µm | 60 ps | 7 µm × 90 µm | 164M |
| | E | 50 µm × 1 mm macropixels | 100 µm | 60 ps | 7 µm × 90 µm | 127M |
| **OT** | B | 50 µm × 10 mm microstrips | 100 µm | 60 ps | 7 µm × 90 µm | 117M |
| | E | 50 µm × 10 mm microstrips | 100 µm | 60 ps | 7 µm × 90 µm | 56M |

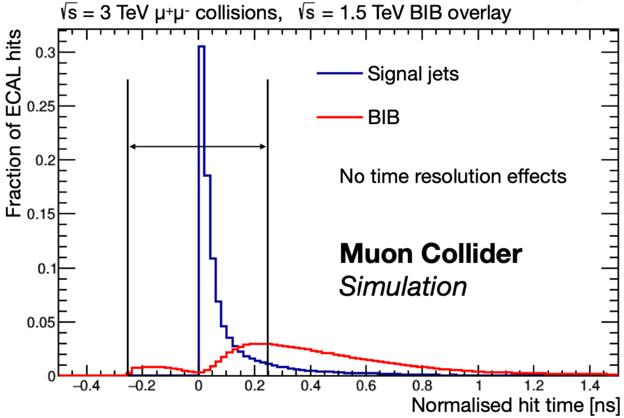
# Calorimeter Requirements

Average Energy density per unit area 40 GeV- similar to HL-LHC

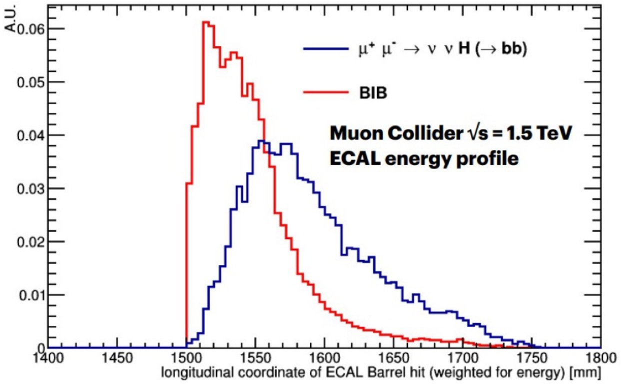
General Features:

- High granularity and shorter integration windows
- Hit time measurement O(100ps)
- Longitudinal segmentation

ECAL hit time



ECAL hit longitudinal coordinate

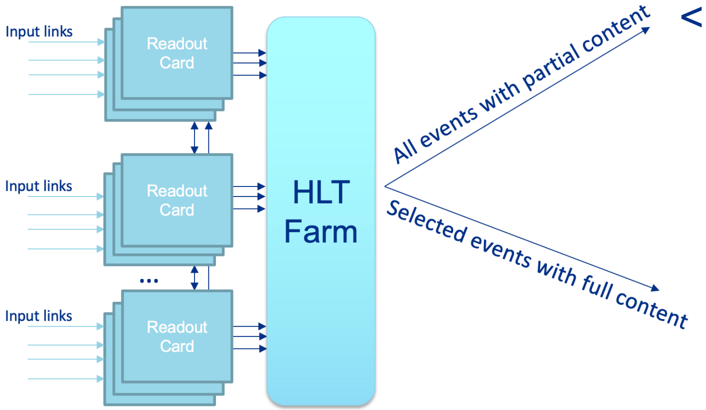


# Data Volumes

- Vertex detector inner layers can generate up to 70 Gbps/module. Reducible with timing and cluster shape selection

| | Upper timing cut (ns) | Module size (cm$^2$) | Maximum hits/cm$^2$ | Reduction using cluster shapes | Data payload per module (Gbps) | Transmission power per module (W) | Total Transmission Power (W) |
|---|---|---|---|---|---|---|---|
| VXD barrel L1/L2 | 15 | 10 | 4600 | x2 | 70 | 0.7 | 38 |
| VXD barrel L1/L2 | 1 | 10 | 1600 | x2 | 25 | 0.25 | 14 |
| | | | | | | | |
| VXD barrel L3-8 | 15 | 10 | 1600 | - | 50 | 0.5 | 96 |
| VXD barrel L3-8 | 15 | 10 | 1600 | | | | |
| VXD barrel L3-8 | 1 | 10 | 300 | | | | |

50 MB/ev * 100 kHz



<< 1 MB/ev * 100 kHz

and

50 MB/ev * <1 kHz

# AC-coupled LGADs

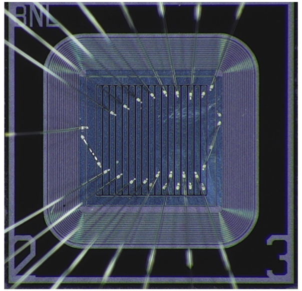
JINST 17 (2022) P05001
NIM A 1003 (2021) 165319

- **Improve 4D-trackers to achieve 100% fill factor**

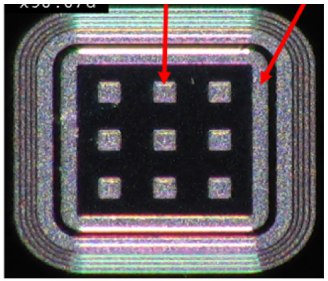
  Active R&D at different manufacturers (FBK, BNL, HPK, etc)

  100% fill factor, and fast timing information at a per-pixel level

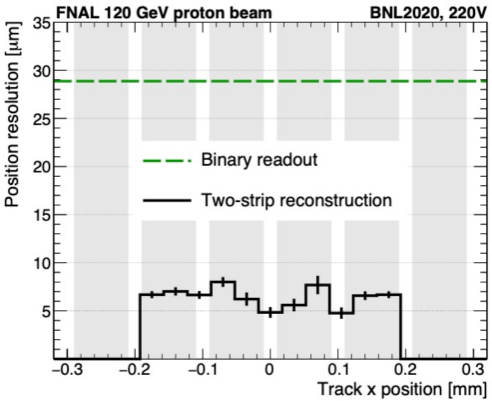
  Can optimize position resolution, timing resolution, fill-factor, …
- **Excellent performance from several rounds of production**
- **First demonstration of simultaneous ~5 µm, ~30 ps resolutions in a test beam: technology for 4D-trackers!**

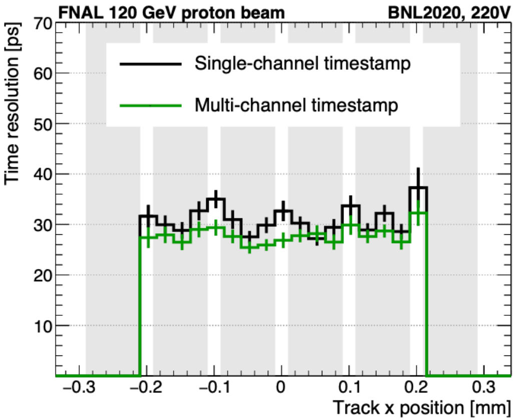


**BNL strip AC-LGAD**



**FBK pad AC-LGAD**





# Towards Better Time Resolution

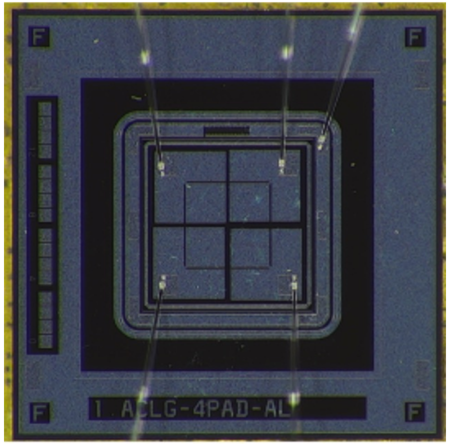
C. Madrid in TREDI 2023

- How do you get better time resolution?

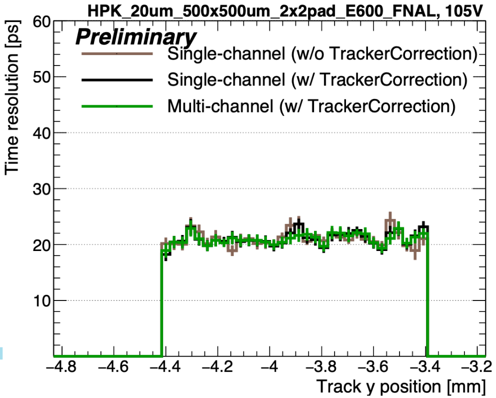
  Thinner sensors to decrease Landau contribution

- Uniform time resolution across full sensor area

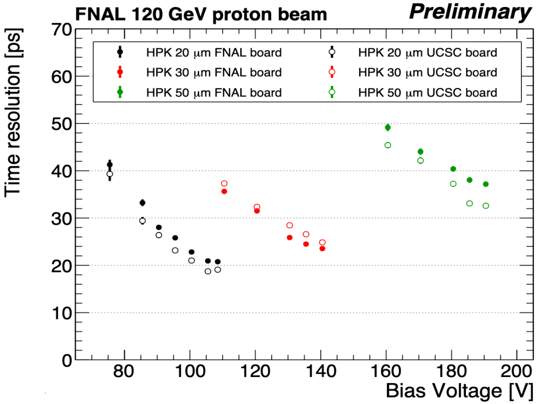
  25 ps for 30 µm thick sensor, 20 ps for 20 µm thick sensor



HPK 2x2, 500x500 µm$^2$ pixel size



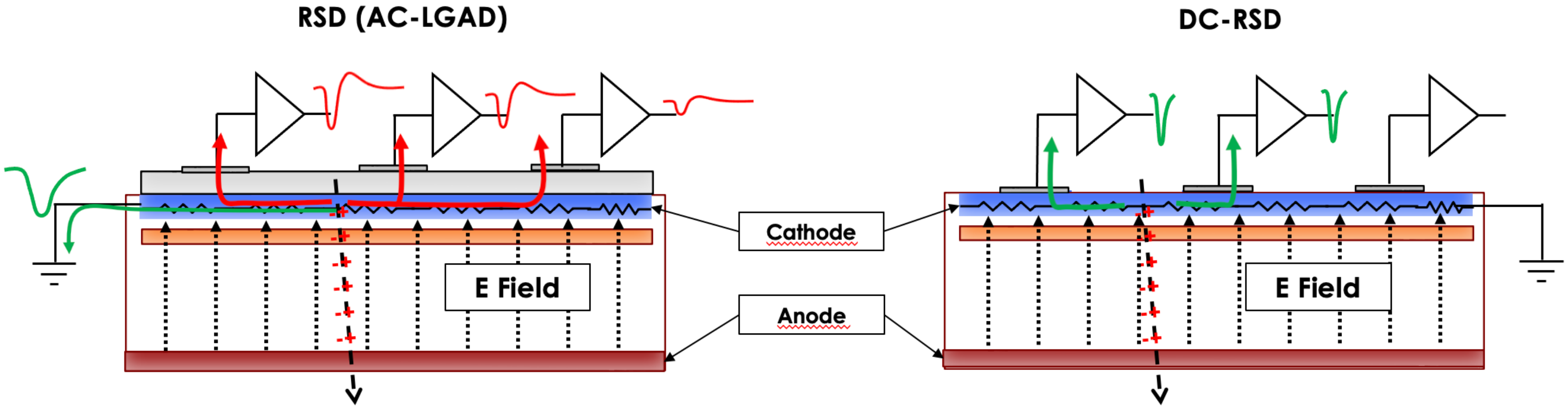
20 ps across full sensor surface



Time resolution for **20**, **30** and **50** µm-thick sensors

# DC-RSD Devices

- Development of DC-coupled resistive silicon detectors, **DC-RSD at INFN-Torino**
- DC-RSD has certain advantages with respect to AC-coupled RSD (AC-LGAD) as it limits signal sharing to a few electrodes and removes possible baseline fluctuations.

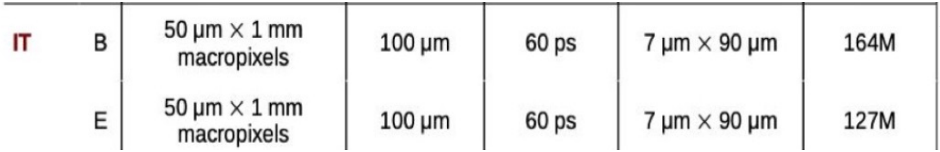


This design has been manufactured in several productions by FBK, BNL, and HPK

This design is presently under development by FBK

The main advantage of the DC-RSD design is the ability to control the signal spread

# Matching RSD to Muon Collider needs

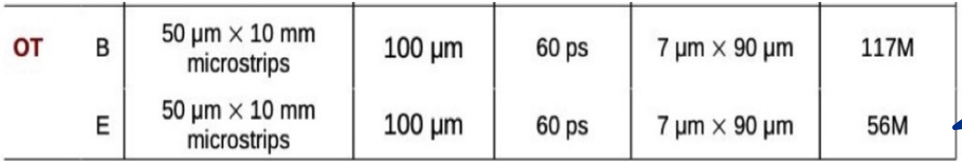


| | | | | | | |
|---|---|---|---|---|---|---|
| IT | B | 50 µm × 1 mm macropixels | 100 µm | 60 ps | 7 µm × 90 µm | 164M |
| | E | 50 µm × 1 mm macropixels | 100 µm | 60 ps | 7 µm × 90 µm | 127M |

Low occupancy and radiation levels. Ideal for macro-pixels.

Pixel size, spatial, and temporal resolutions are a perfect fit for present AC-LGAD technology

DC-RSD can strongly reduce the number of pixels



| | | | | | | |
|---|---|---|---|---|---|---|
| OT | B | 50 µm × 10 mm microstrips | 100 µm | 60 ps | 7 µm × 90 µm | 117M |
| | E | 50 µm × 10 mm microstrips | 100 µm | 60 ps | 7 µm × 90 µm | 56M |

Very Low-occupancy and radiation levels. Long strips do not provide accurate temporal resolution.

Better performances can be obtained with DC-RSD macro pads

# Monolithic Active Pixel Sensors

- Monolithic sensors with embedded readout

  Take advantage of electronics on top layer, good signal-to-noise

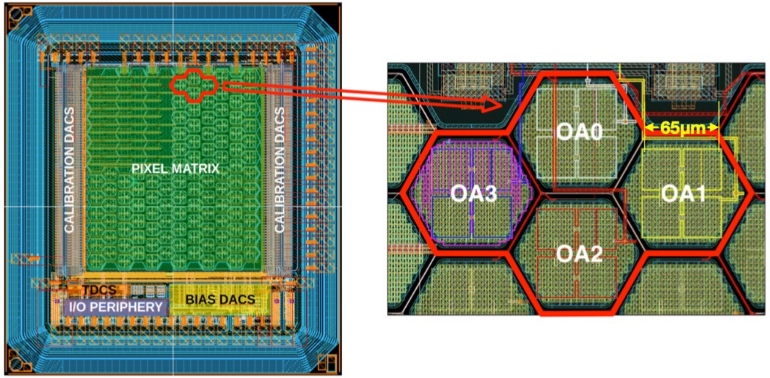
- Promise to be paradigm-shifting for next-gen detectors

  Allows for: very high granularity, few $\mu$m resolution , large area sensors (up to wafer size with stitching), low power density (air cooling possible), large production volumes at low cost, low mass (0.05% X0)

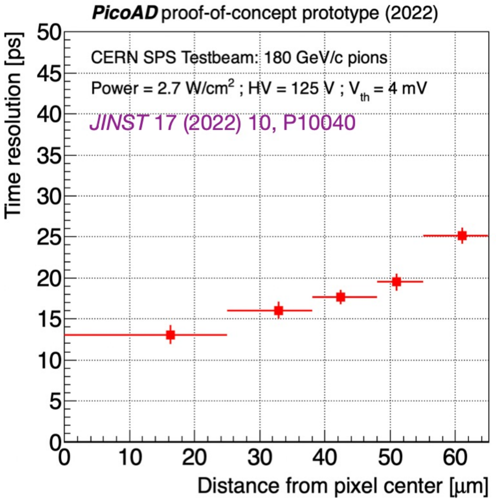
  Now exploring new developments to include: improve spatial resolution, timing, rate and radiation hardness

  Challenges consists mainly in achieving all the goal performances (low mass, resolution, timing, rate, data density and radiation hardness) in a single device at a reasonable power consumption.

**PicoAD Proof-Of-Concept Prototype (2021)**



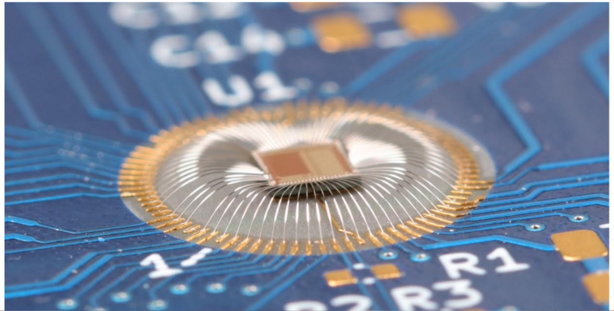
**Time resolution**

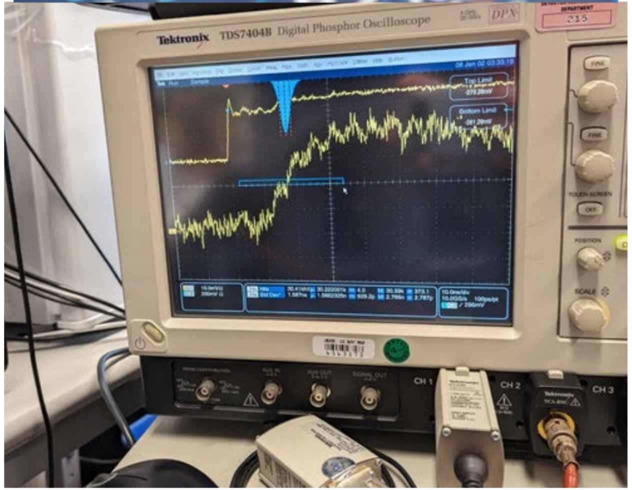


**(13.2 ± 0.8) ps** at the pixel center

# 28nm CMOS for 4-D tracker readout chip

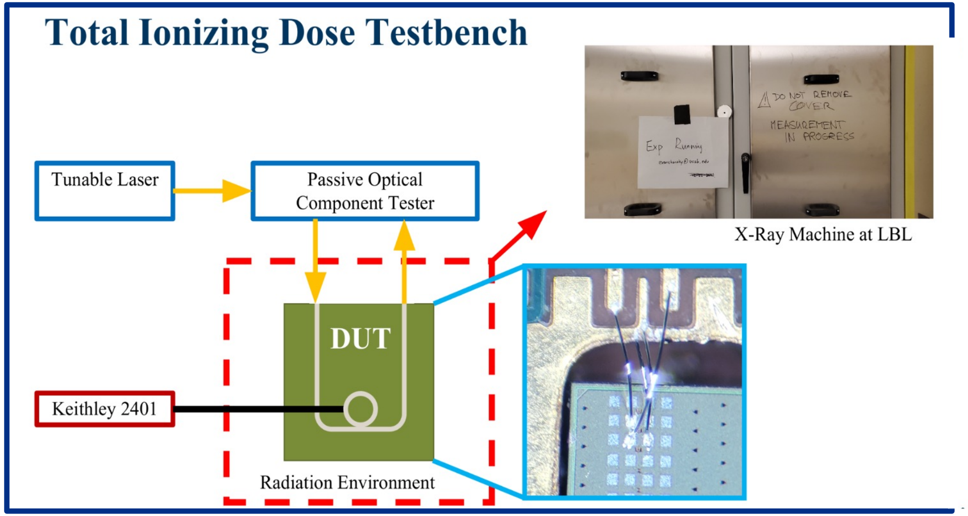
- Need powerful yet power-efficient ASICs
- Low power, fast, pixel front end prototype chip (“Pebbles”) under test
- Low power, in-pixel, <50ps high dynamic range in-pixel TDC test chip under design
- Currently supported under LDRD- ends this September, Work will continue under KA25 in FY24
- Interest in RD53 collaboration in pivoting to 28nm under new ECFA framework, after CMS chip is submitted later this year
(ATLAS RD53 Production chip was just submitted!)





# Radiation Hard Silicon Photonic Link Development

- R&D was started under SBIR with Freedom Photonics
- Work continuing in collaboration between LBNL+UCSB, with SCGSR E. Chansky now at LBL designing, testing and irradiating ring resonator modulators.



**Total Ionizing Dose Testbench**

Tunable Laser

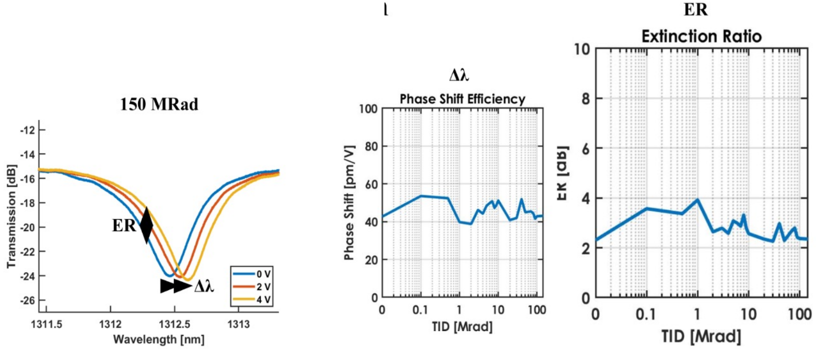
Passive Optical Component Tester

Keithley 2401

DUT

Radiation Environment

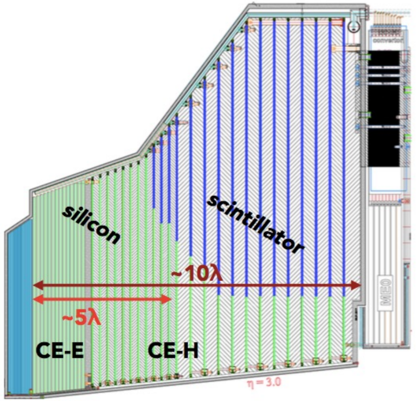
X-Ray Machine at LBL

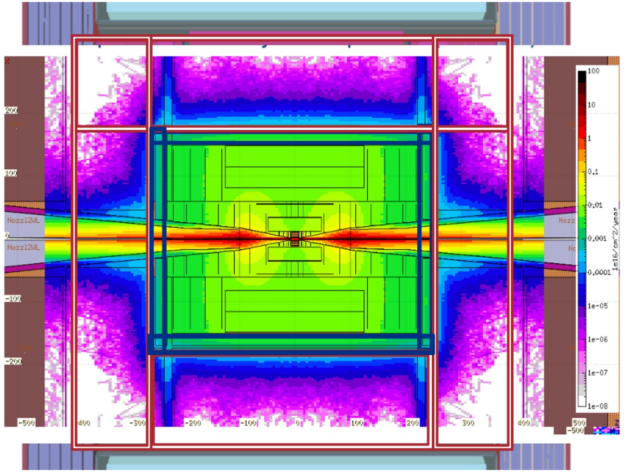


# SiW+ Steel/Scintillator Calorimeter

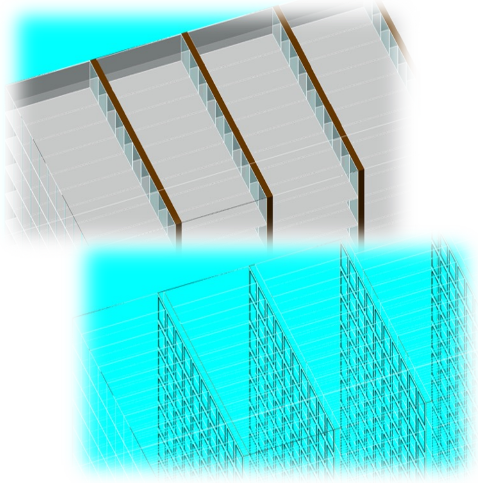
- Many lessons to be learned from CMS HGCal
- ECAL largest fluence ~ $10^{14}$/y , 10^15 in 10 years
- For this 200um thick sensors of CMS HGCAL would work, they are rated to $2.5*10^{15}$
- HGCAL cell size is $1.3cm^2$ to calibrate, do we really need much smaller cells?

- Front of HCAL is is $5*10^{12}$/year, total $5*10^{13}$ in 10 years.
- The scintillator HCAL would just survive!





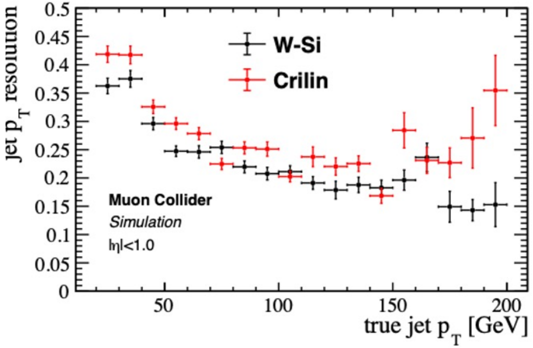
# Crilin Concept

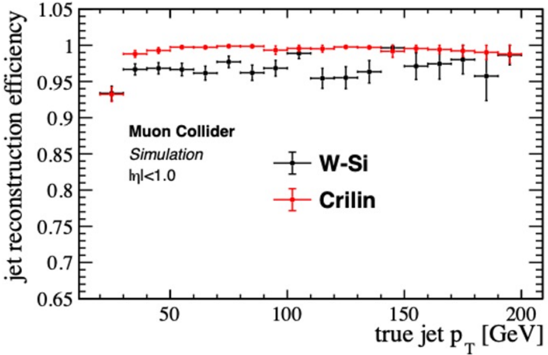


## Cristal Calorimeter with Longitudinal Information:

- Alternative solution for Muon Collider ECAL barrel
- High granularity, longitudinal segmentation, excellent timing
- Improved radiation resistance
- Modular and flexible architecture with stackable sub-modules allows for design optimization in many Physics scenarios

- 1x1x4 $cm^3$ PbF2 Cherenkov crystals + dual, UV-extended 10μm SiPM readout
- optimal rejection of beam-induced background
- Supports particle flow algorithms





# Crilin R&D Status

**Prototype versions**

- Proto-0 (2 crystals + 4 channels)
- Proto-1 (3x3 crystals + 36 channels) x2 layers

**Front-end electronics**

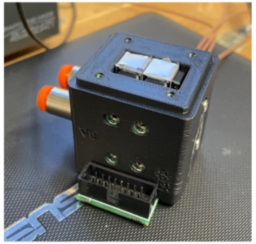
- Design completed
- Production and QC completed

**Radiation hardness campaign**

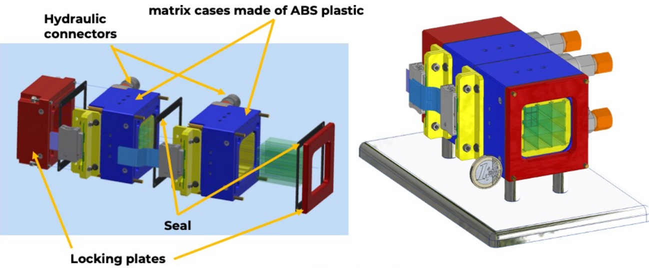
- 10 and 15 um px-size SiPM tests up to $10^{14}$ n-1MeV-eq/cm$^2$ (ENEA-FNG)
- TID tests on PbF2 and PWO-UF crystals w/ various wrapping configuration up to **100 Mrad** w/ Co-60 photons (ENEA-Calliope)

**Test beam campaigns**

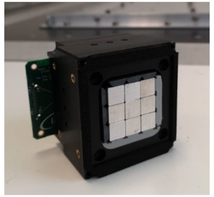
- Proto-0 at CERN H2 2022



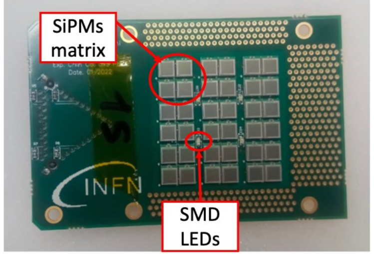
Proto-0

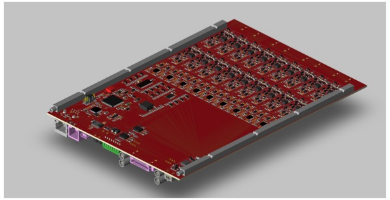


Proto-1



Copper exchanger

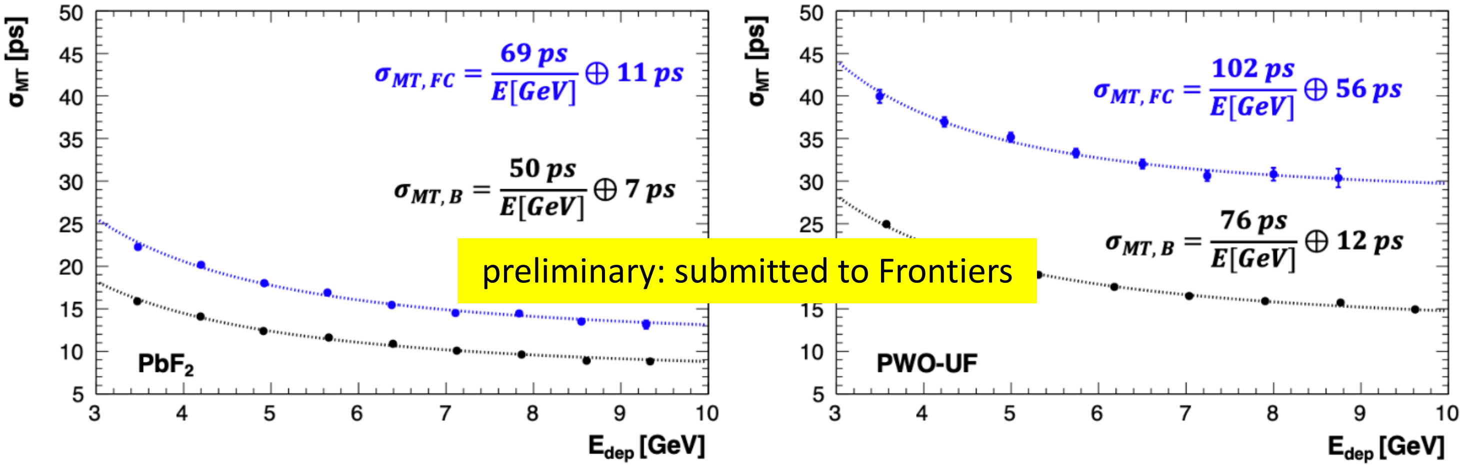




# Crilin Timing Performances

**SINGLE CELL PERFORMANCE**

PbF2 → sigmaT < 25 ps worst-case for Edep > 3 GeV
PWO-UF → sigmaT < 45 ps worst-case for Edep > 3 GeV



preliminary: submitted to Frontiers

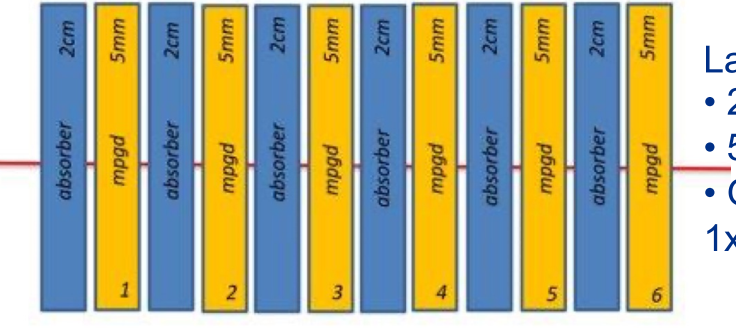
- PbF2 outperforms PWO-UF (purely Cherenkov solutions → better timing)
- Timing well within requirements in both cases

- Beam tests at LNF-INFN w/ 500 MeV e- (July 2023) and at CERN SPS and PS w/ 10-100 GeV (summer 2023)
- Next step: developing a 5x5 x4(layers) Crilin prototype.

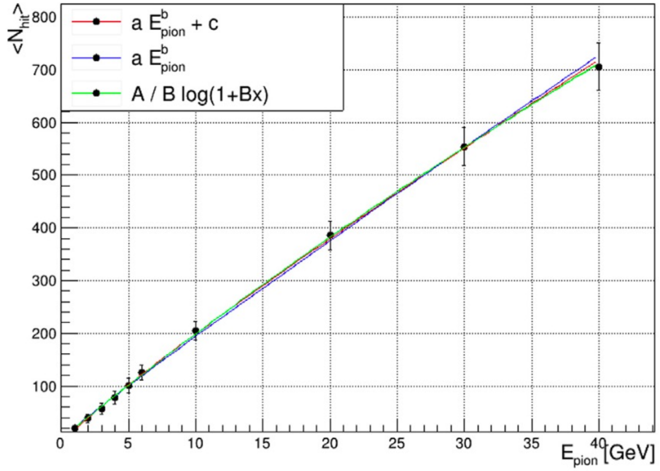
# Micropattern Gas Detectors for HCAL

- MPGDs in particular feature high-rate capability (MHz⁄cm2), flexible spatial, up to 100 μm and modest time resolution (few ns) and good response uniformity (30%).
- Studying micromegas and $\mu$RWELL technologies

Sketch of the implemented calorimeter



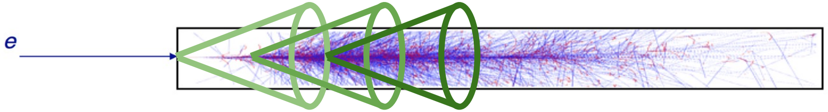
Layers made of
- 2 cm of Fe (**absorber**)
- 5 mm of Ar (**active gap**)
- Granularity given by cell of 1x1 cm2



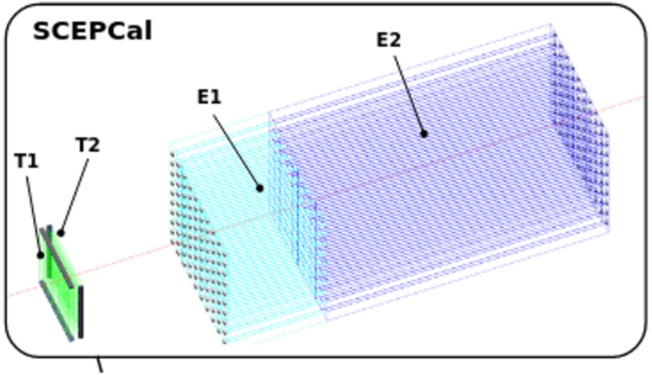
- Next steps: Optimize in simulation and build a prototype
- Crilin and MPGD-HCAL: Submitted and won a joint PRIN proposal for a 210 kEUR grant for the project CALORHINO: an innovative radiation-hard calorimeter proposal for a future Muon Collider Experiment.

# CalVision: Dual-Readout Crystal Calorimetry

image credit, PWO w/ electron
https://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors2/sma_ElectromagneticCalorimeters.pdf



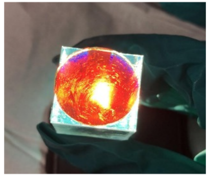
- Hadronic energy resolution suffers from large EM component fluctuations
- Ratio of EM/had can be inferred from the ratio of the Cerenkov to scintillation light
  - Event-by-event correction achievable with Dual Readout (DR) technique
- DR in a precision crystal ECAL preserves HCAL performance
  - CalVision idea
- High light yield crystal scintillators provide excellent EM energy resolution



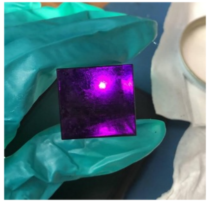
Initially targeting SCEPCal design:
Timing layer + moderate segmentation for particle ID

# CalVision: Dual-Readout Crystal Calorimetry

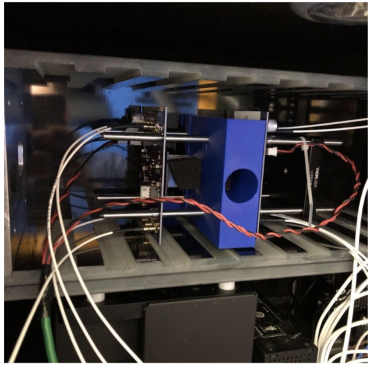
- Three test beams with single-crystal test setup
    - 150 mm crystals - targeting Cerenkov and scintillation light separation
    - Precision timing capabilities
    - Beam types
        - 8 MeV electron beams (Notre Dame Radiation Laboratory)
        - 120 GeV Proton beams (Fermilab)
        - Data-analysis ongoing, all within last 2 months!
- Future
    - Crystal-matrix tests (next year)
    - Full EM shower containment
    - integration with DR fiber HCAL



660 nm long-pass on PWO



U330 notch-filter on BGO

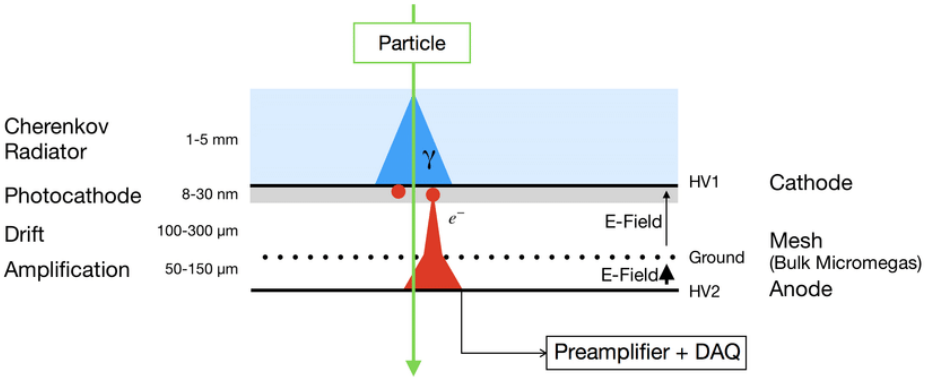


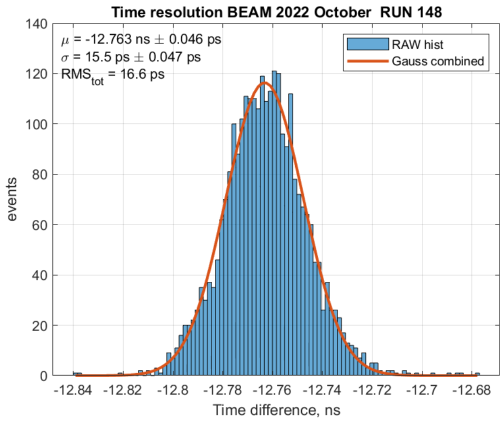
Test beam at Fermilab, April 24-26

Test beam at Fermilab, May 31st - June 7th

# Picosec Micromegas Detector

PICOSEC
Micromegas



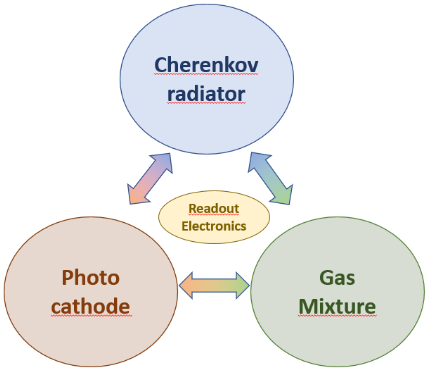


## Working principle

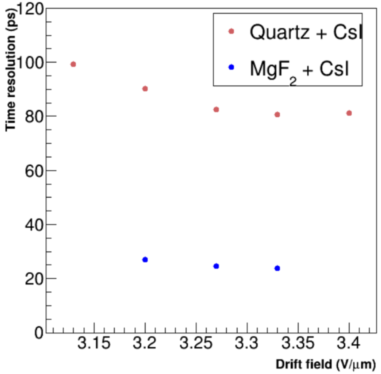
- Highly energy particles cross the Cherenkov radiator and produce **Cherenkov photons**
- Photons are converted by the **photocatode**
- **Electrons** enter the micromegas and are amplified

A. Utrobicic, A large area 100 channel PICOSEC Micromegas detector with sub 20 ps time resolution, MPGD2022

# R&D in the Muon Collider context

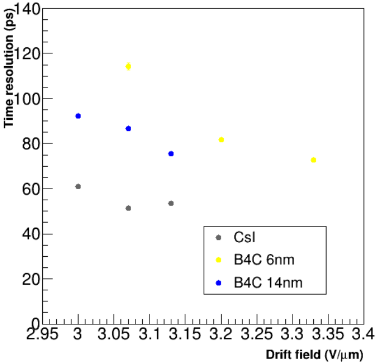


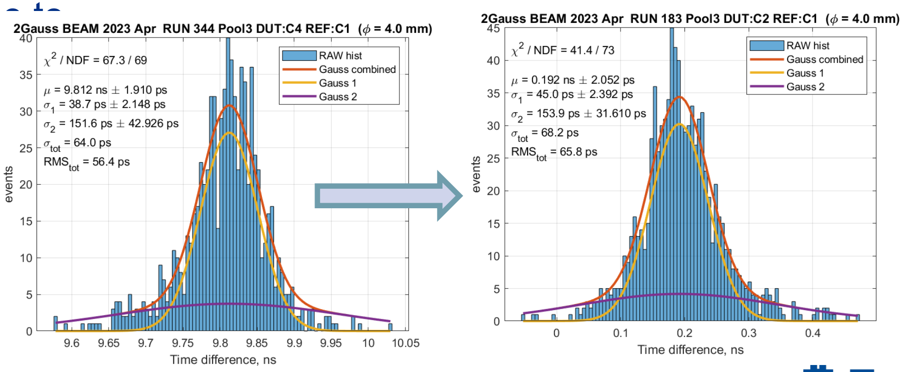
**Cherenkov radiator**: **baseline** is MgF2, but it's fragile and costly; **alternatives**: quartz, sapphire → worst time resolution due to lower PE/MIP, more investigation needed



**Gas mixture**: **baseline** is Ne/C2H6/CF4, but it's costly with high GWP; **alternatives**: several Ar-based or Ne-based mixtures → interesting results with **Ne/iC$_4$H$_{10}$**

**Photocathode**: **baseline** is CsI, but it's hygroscopic and not resistant to ion bombardment; **alternatives**: metallic, carbon-based → worst time resolution due to lower PE/MIP, more investigation needed

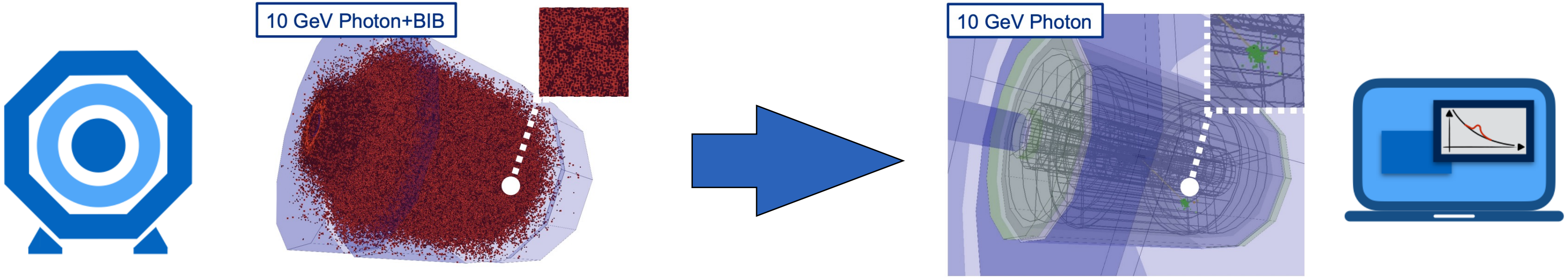




D. Fiorina, Picosec Micromegas detector for precise muon timing in the Muon Collider detector, FAST2023

I. Vai, Fast timing detectors for the muon system of a muon collider experiment, ANIMMA2023

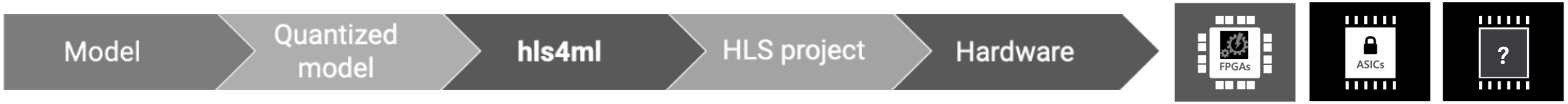
# Intelligent on- and near-detector readout



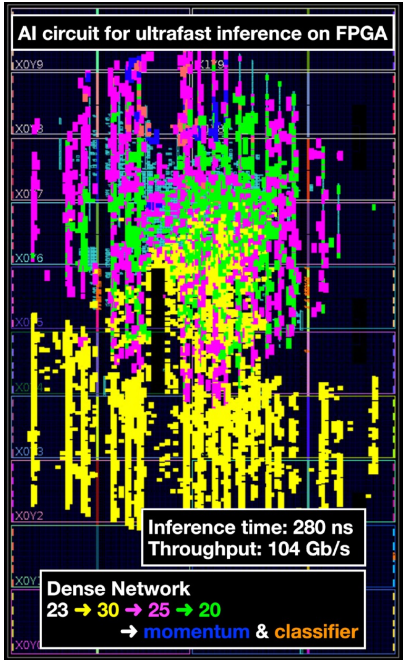
- Beam backgrounds create a very busy collision environment
  - Beyond that of HL-LHC (tracker, calorimeter occupancy), but with lower collision rate
- On- and near-detector intelligence can:
  - Reduce computational complexity offline
  - Reduce offline data volumes
  - Enable real-time analysis, autonomous feedback
- Readout architectures and technologies to be designed based on requirements

Think about DAQ when
designing the detector!

# Intelligent near-detector readout



- Incredible evolution of tools for intelligent FPGA and ASIC designs
- hls4ml developed for efficiently designing optimized NNs in hardware
  - [fastmachinelearning.org/hls4ml](https://fastmachinelearning.org/hls4ml)
- In L1 trigger FPGAs — actively being used for LHC Run 3 physics for improving performance and enabling new searches
  - e.g. include displaced muon identification and anomaly detection algorithms


AI circuit for ultrafast inference on FPGA

Inference time: 280 ns
Throughput: 104 Gb/s

Dense Network
23 → 30 → 25 → 20
→ momentum & classifier

# Intelligent on-detector readout

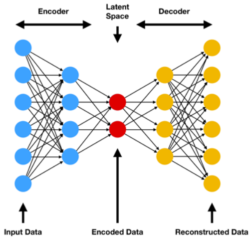
https://arxiv.org/abs/2105.01683
CPAD talk, paper coming soon

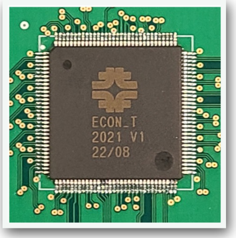
## Case 1: calorimeter data compression

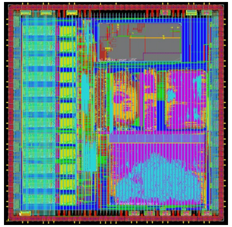
- Autoencoder architecture used for lossy data compression of CMS HGCal information: ECON-T
- Fixed architecture w/reconfigurable weights, rad-hard auto encoder
- Continued algorithm development, e.g. arxiv:2306.04712

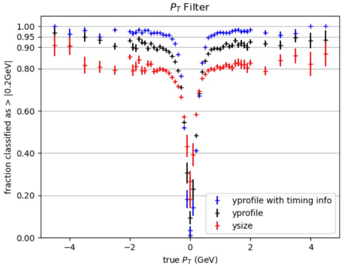
## Case 2: pixel data filtering/features

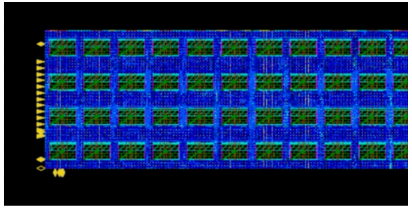
- NN integrated into fine-pitch pixel readout on-sensor
  - Filtering: remove hits from low pT tracks
  - Featurization: translate raw clusters into features (position, angle, time)
- First design and implementation nearly done; platform for studying emerging technologies (e.g. memristor)









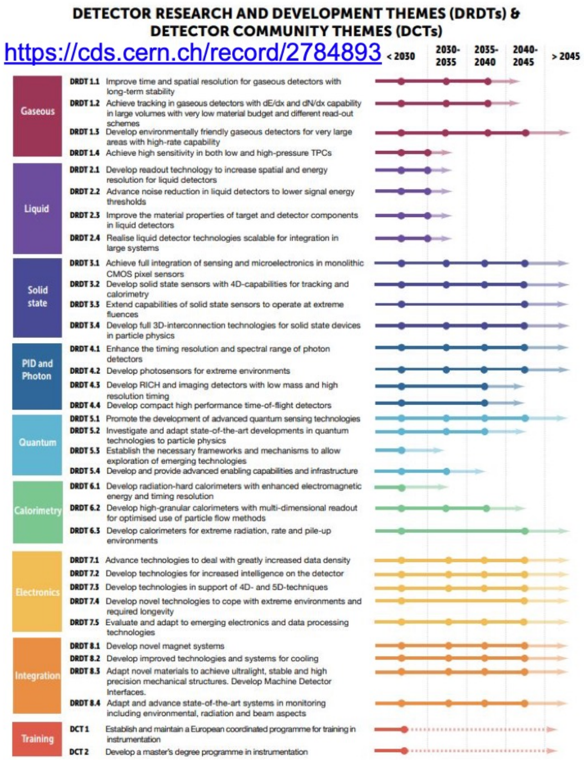


# Moving Forward

Details in Nadia's talk on Monday

- Detector R&D coordination and planning in both US and Europe
- Europe: ECFA Detector R&D Roadmap
- US: BRN Report + Snowmass Instrumentation Frontier
  - Expecting more information from CPAD soon
- We need to stay engaged in both processes
- And maintain strong connection between two regions

ECFA detector R&D groups

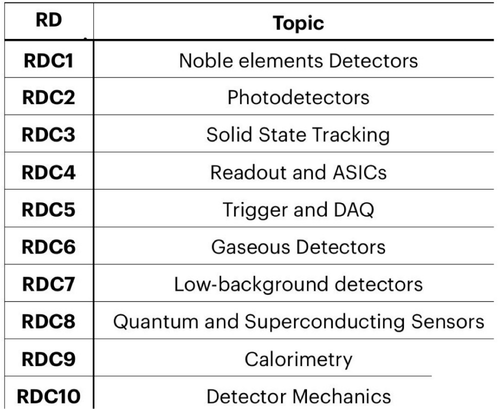


DETECTOR RESEARCH AND DEVELOPMENT THEMES (DRDTs) & DETECTOR COMMUNITY THEMES (DCTs)

https://cds.cern.ch/record/2784893

| | | |
|---|---|---|
| Gaseous | DRDT 1.1 | Improve time and spatial resolution for gaseous detectors with long-term stability |
| | DRDT 1.2 | Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes |
| | DRDT 1.3 | Develop environmentally friendly gaseous detectors for very large areas with high-rate capability |
| | DRDT 1.4 | Achieve high sensitivity in both low and high-pressure TPCs |
| Liquid | DRDT 2.1 | Develop readout technology to increase spatial and energy resolution for liquid detectors |
| | DRDT 2.2 | Advance noise reduction in liquid detectors to lower signal energy thresholds |
| | DRDT 2.3 | Improve the material properties of target and detector components in liquid detectors |
| | DRDT 2.4 | Realise liquid detector technologies scalable for integration in large systems |
| Solid state | DRDT 3.1 | Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors |
| | DRDT 3.2 | Develop solid state sensors with 4D-capabilities for tracking and calorimetry |
| | DRDT 3.3 | Extend capabilities of solid state sensors to operate at extreme fluences |
| | DRDT 3.4 | Develop full 3D-interconnection technologies for solid state devices in particle physics |
| PID and Photon | DRDT 4.1 | Enhance the timing resolution and spectral range of photon detectors |
| | DRDT 4.2 | Develop photosensors for extreme environments |
| | DRDT 4.3 | Develop RICH and imaging detectors with low mass and high resolution timing |
| | DRDT 4.4 | Develop compact high performance time-of-flight detectors |
| Quantum | DRDT 5.1 | Promote the development of advanced quantum sensing technologies |
| | DRDT 5.2 | Investigate and adapt state-of-the-art developments in quantum technologies to particle physics |
| | DRDT 5.3 | Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies |
| | DRDT 5.4 | Develop and provide advanced enabling capabilities and infrastructure |
| Calorimetry | DRDT 6.1 | Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution |
| | DRDT 6.2 | Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods |
| | DRDT 6.3 | Develop calorimeters for extreme radiation, rate and pile-up environments |
| Electronics | DRDT 7.1 | Advance technologies to deal with greatly increased data density |
| | DRDT 7.2 | Develop technologies for increased intelligence on the detector |
| | DRDT 7.3 | Develop technologies in support of 4D- and 5D-techniques |
| | DRDT 7.4 | Develop novel technologies to cope with extreme environments and required longevity |
| | DRDT 7.5 | Evaluate and adapt to emerging electronics and data processing technologies |
| Integration | DRDT 8.1 | Develop novel magnet systems |
| | DRDT 8.2 | Develop improved technologies and systems for cooling |
| | DRDT 8.3 | Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces. |
| | DRDT 8.4 | Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects |
| Training | DCT 1 | Establish and maintain a European coordinated programme for training in instrumentation |
| | DCT 2 | Develop a master's degree programme in instrumentation |

CPAD detector research consortia



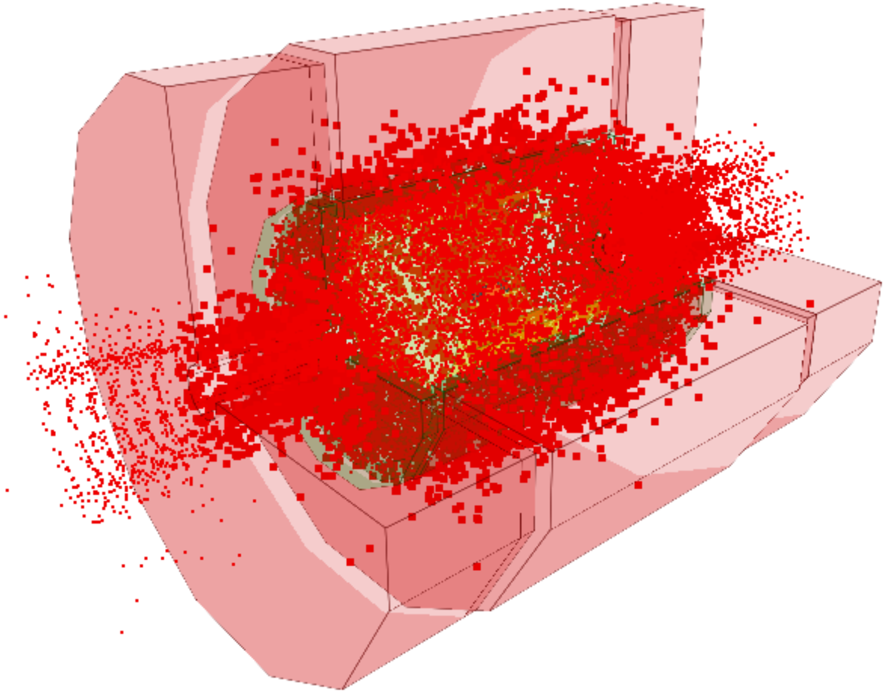
| RD | Topic |
|---|---|
| RDC1 | Noble elements Detectors |
| RDC2 | Photodetectors |
| RDC3 | Solid State Tracking |
| RDC4 | Readout and ASICs |
| RDC5 | Trigger and DAQ |
| RDC6 | Gaseous Detectors |
| RDC7 | Low-background detectors |
| RDC8 | Quantum and Superconducting Sensors |
| RDC9 | Calorimetry |
| RDC10 | Detector Mechanics |

# Summary

- Muon Collider detectors are not easy, combination of stringent requirements on granularity, timing, resolution and radiation hardness
- Many promising R&D paths exist, the progress is encouraging
- Will be at the leading edge of collider detector development in the next couple of decades – synergies exist with EIC, e+e-, pp

- Recall we are discussing detectors for 20 years from now – need a broad R&D program and avoid locking into a particular technology
- Significant R&D resources are necessary, and work on detector technology should proceed in close collaboration with detector design
- Close collaboration and coordination between Europe and US, building on strengths of both sides, is a must!

# Backup



# The 3 TeV Detector

hadronic calorimeter

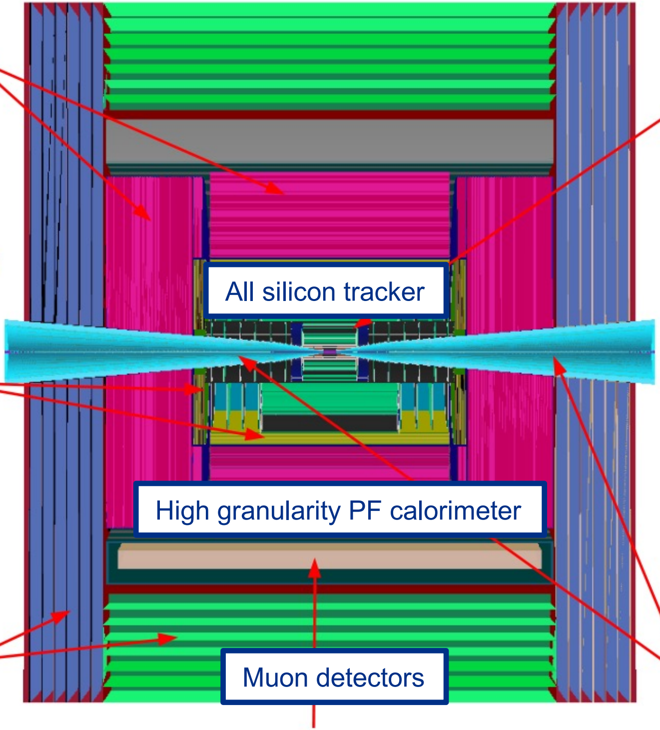
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 $mm^2$ cell size;
- 7.5 $\lambda_I$.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 $mm^2$ cell granularity;
- 22 $X_0$ + 1 $\lambda_I$.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 $mm^2$ cell size.



superconducting solenoid (3.57T)

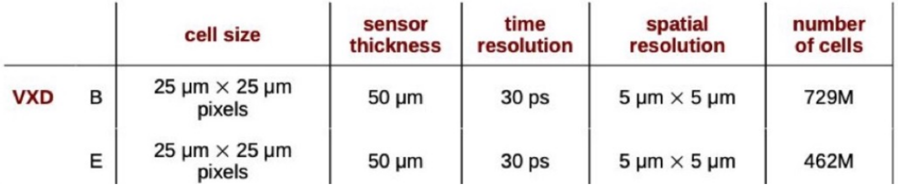
tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 $\mu m^2$ pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

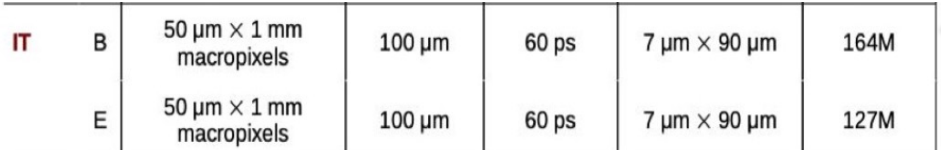
shielding nozzles

- Tungsten cones + borated polyethylene cladding.

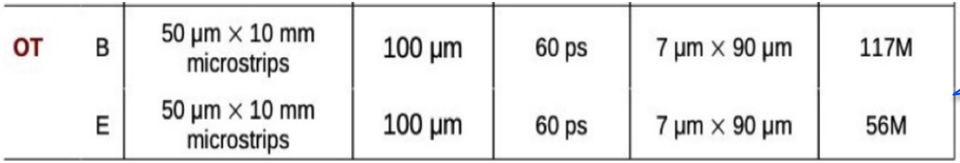
# Matching DC-RSD to MuC needs



| | | cell size | sensor thickness | time resolution | spatial resolution | number of cells |
|---|---|---|---|---|---|---|
| **VXD** | B | 25 µm × 25 µm pixels | 50 µm | 30 ps | 5 µm × 5 µm | 729M |
| | E | 25 µm × 25 µm pixels | 50 µm | 30 ps | 5 µm × 5 µm | 462M |



| | | | | | | |
|---|---|---|---|---|---|---|
| **IT** | B | 50 µm × 1 mm macropixels | 100 µm | 60 ps | 7 µm × 90 µm | 164M |
| | E | 50 µm × 1 mm macropixels | 100 µm | 60 ps | 7 µm × 90 µm | 127M |



| | | | | | | |
|---|---|---|---|---|---|---|
| **OT** | B | 50 µm × 10 mm microstrips | 100 µm | 60 ps | 7 µm × 90 µm | 117M |
| | E | 50 µm × 10 mm microstrips | 100 µm | 60 ps | 7 µm × 90 µm | 56M |

**Low occupancy and radiation levels. Ideal for macro-pixels.**

**Pixel size, spatial, and temporal resolutions are a perfect fit for present RSD technology DC-RSD will strongly reduce the number of pixels**

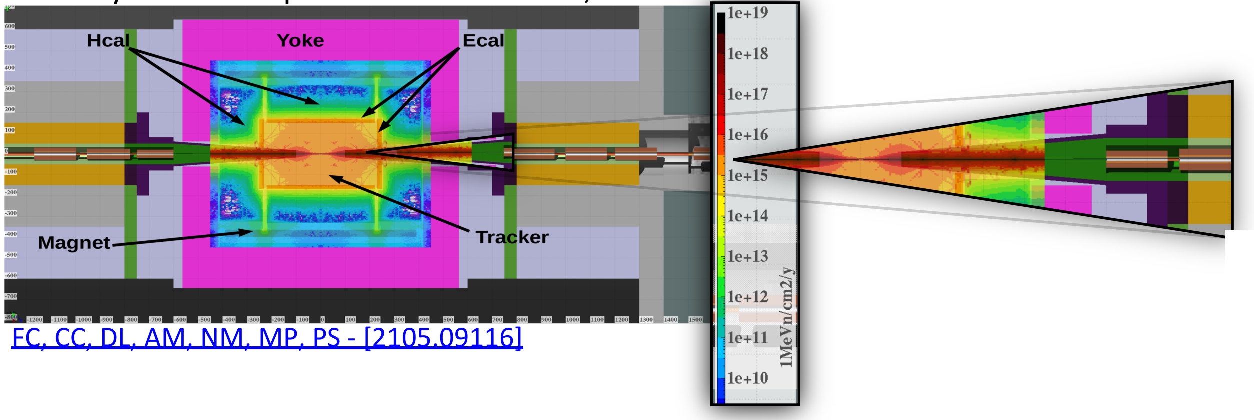
**Very Low-occupancy and radiation levels. Long strips do not provide accurate temporal resolution.**

**Better performances can be obtained with DC-RSD macro pads**

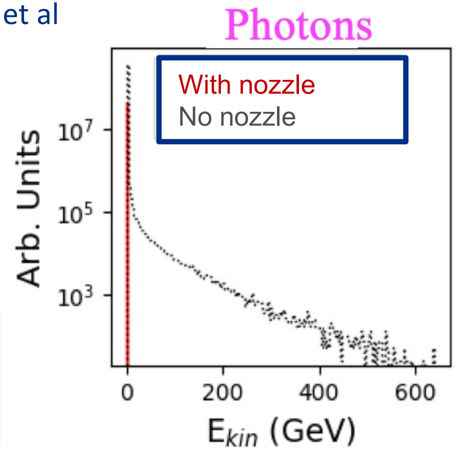
# Machine-Detector Interface (MDI)

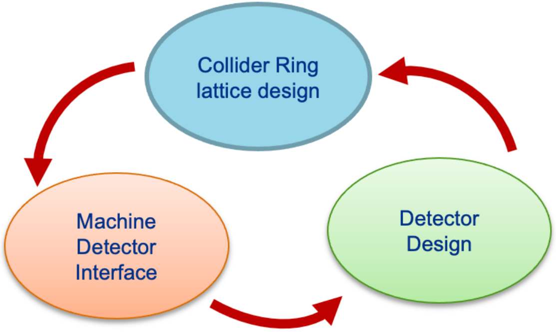
Initial design by N.Mokhov et al

200-day 1-MeV-neq Fluence - √s=1.5 TeV, MARS15+FLUKA



FC, CC, DL, AM, NM, MP, PS - [2105.09116]



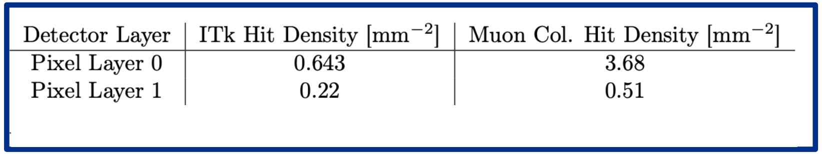


Forward region covered by coated tungsten nozzles:

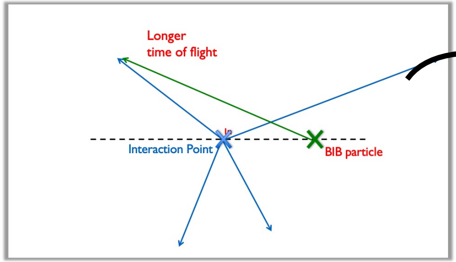
- Reduces BIB in detector by orders of magnitude
- Turns highly localized incident energy into diffuse detector energy

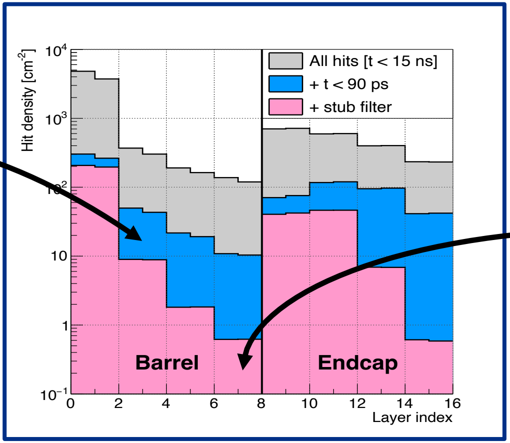
# Tracker

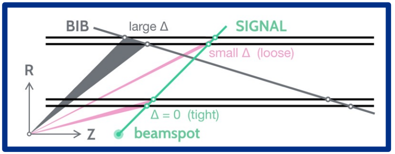
- The BIB is mostly low energy, out of time and not pointing to the Interaction Point
- Some similarities with LHC pileup - **can build on that experience!**



| Detector Layer | ITk Hit Density [$\mathrm{mm}^{-2}$] | Muon Col. Hit Density [$\mathrm{mm}^{-2}$] |
|---|---|---|
| Pixel Layer 0 | 0.643 | 3.68 |
| Pixel Layer 1 | 0.22 | 0.51 |

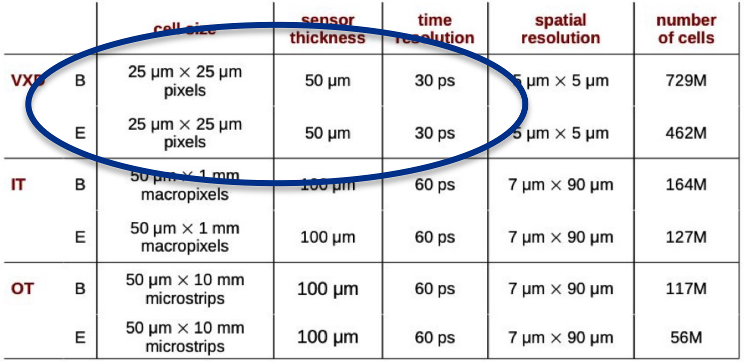






# Tracker

- ~100 m$^2$ of silicon sensors
- Low mass/power, radiation tolerance, low noise
- Pixel size optimized to bring occupancy to <1%
- Total number of channels ~ 2B



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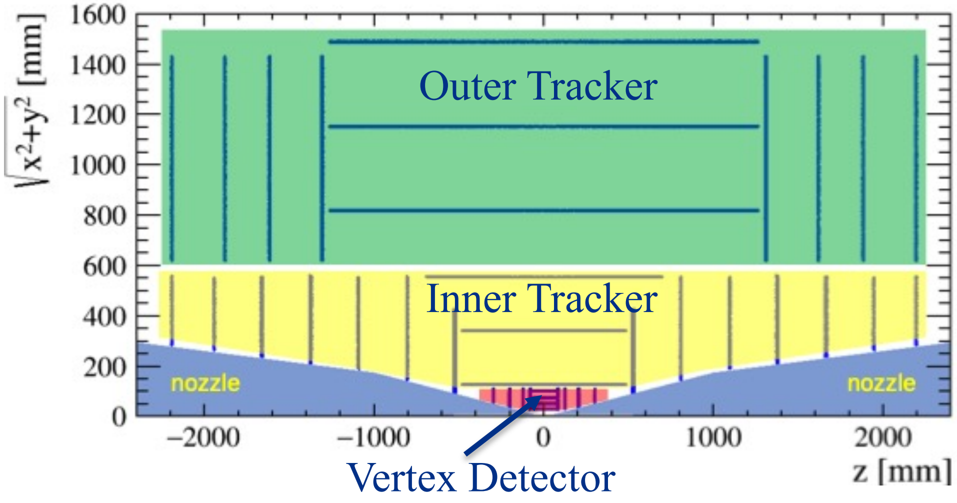
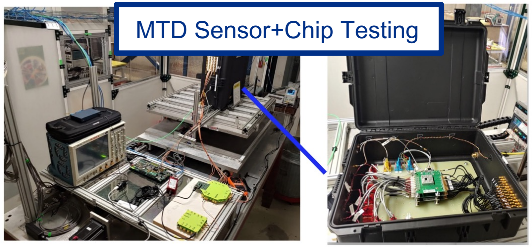




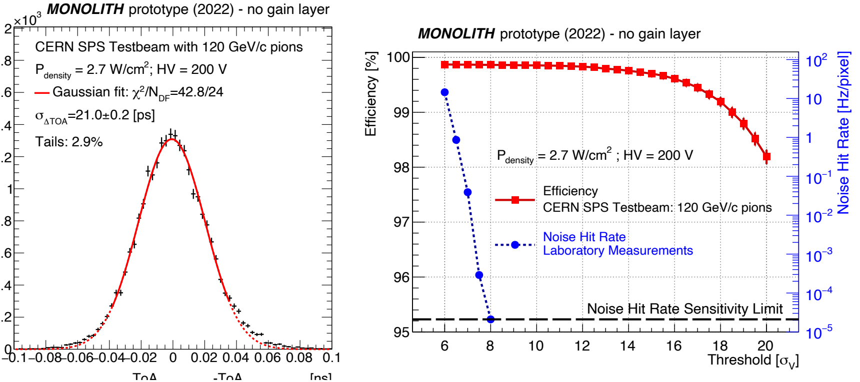
MTD Sensor+Chip Testing

Outer Tracker Module

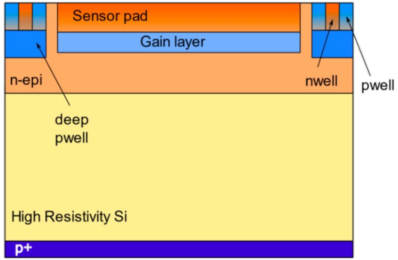
For Phase-2, CMS is building a timing detector with ~30 ps timing resolution and a new Outer Tracker with on-detector filtering using hit pairs

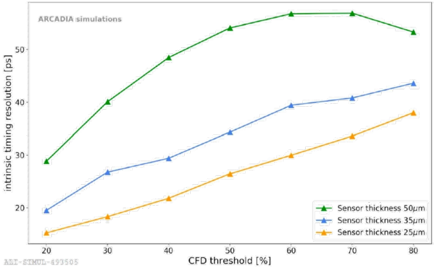
# MAPS

- Improved timing (examples):
  - The MONOLITH project demonstrated 20ps time resolution in a monolithic silicon pixel detector (130nm SiGe BiCMOS technology) without internal gain layer
  - ARCADIA: adding a gain layer to standard CMOS MAPS (110nm CMOS L-Foundry) 10-20 ps resolution is possible

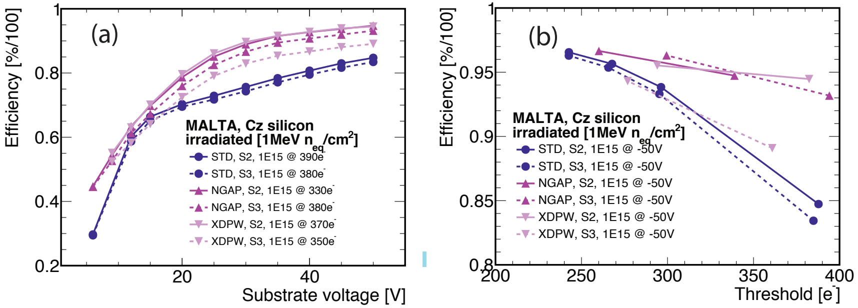


S. Zambito et al 2023 JINST 18 P03047



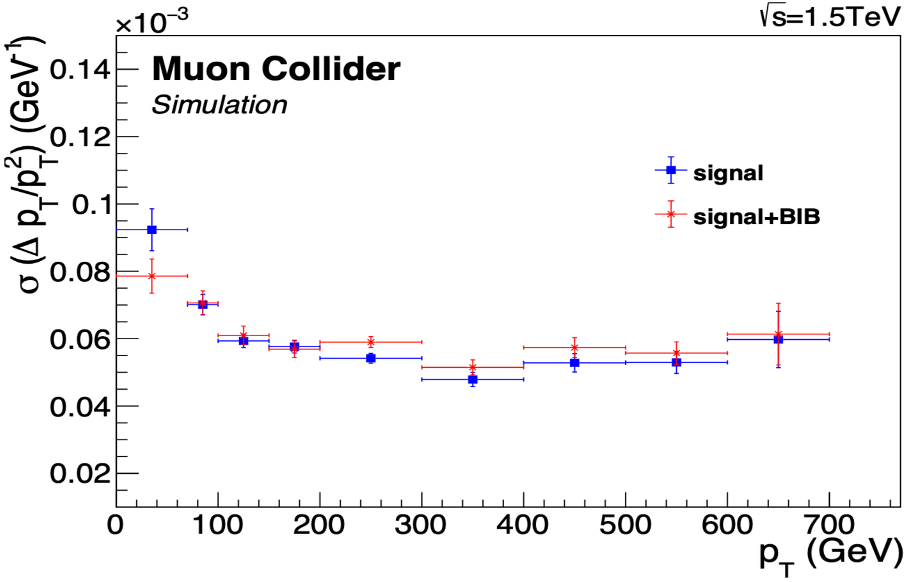


- Radiation hardness (example):
  - MALTA: Tower Semiconductor 180 nm CMOS imaging process demonstrated full efficiency up to $10^{15}$ 1MeV neq
- More developments starting with 65 nm CMOS imaging process
- Challenges consists mainly in achieving all the goal performances (low mass, resolution, timing, rate, data density and radiation hardness) in a single device at a reasonable power consumption.

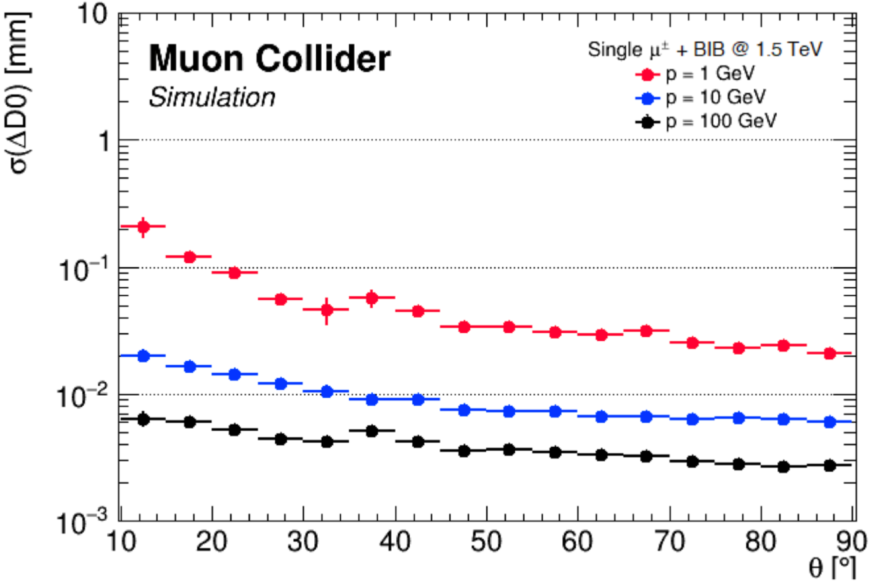


# Tracking Performance

Track relative momentum resolution
BIB effects are small

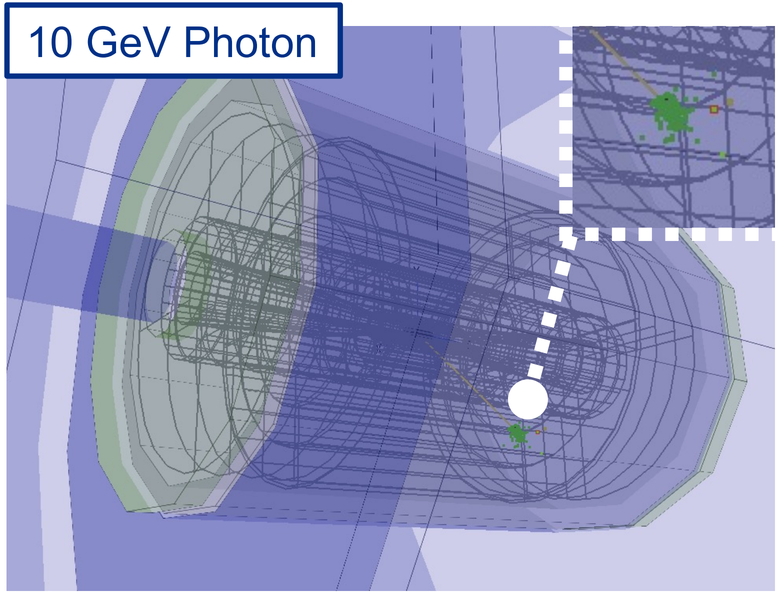


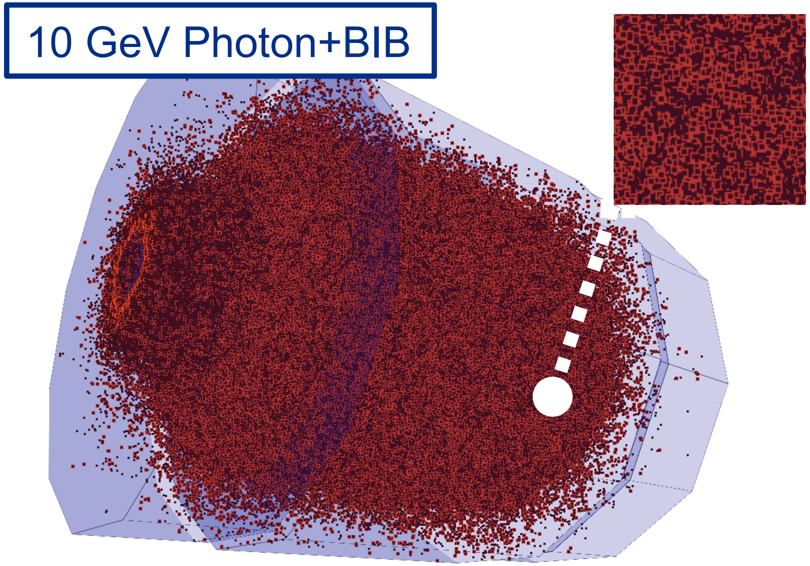
Track impact parameter resolution
approaching 10 microns



# Calorimeter

- BIB dominated by low energy neutrals: photons (96%) and neutrons (4%)
- A low energy noise cloud that needs to be subtracted





# Calorimeter

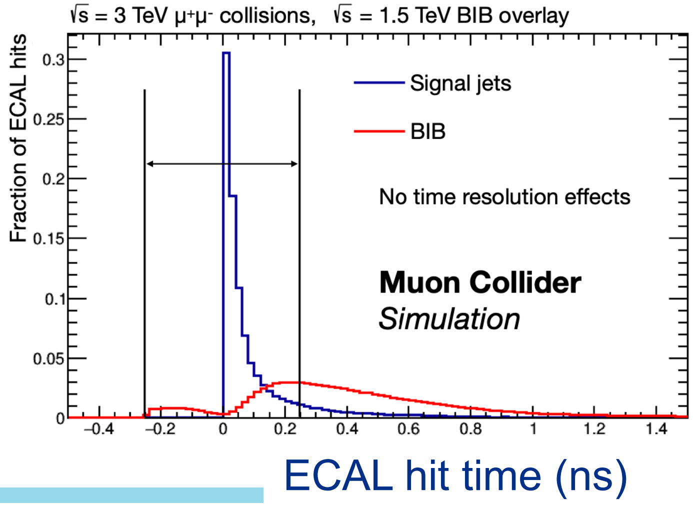
Average Energy density per unit area 40 GeV- similar to HL-LHC

SiW calorimeter is the current baseline

General Features:

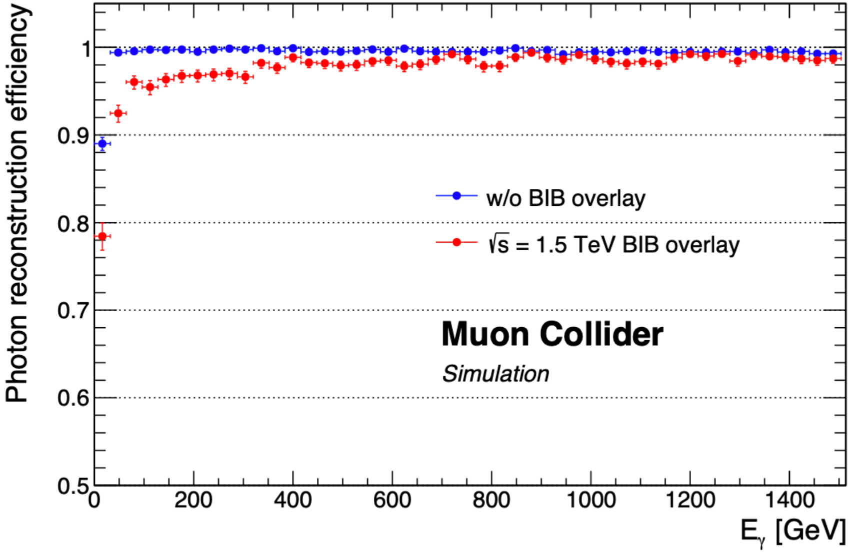
- High granularity and shorter integration windows
- Hit time measurement O(100ps)
- Longitudinal segmentation
- New ideas (e.g. Crilin, Calvision) can bring even better performance

Strong Synergies with CMS HGCal

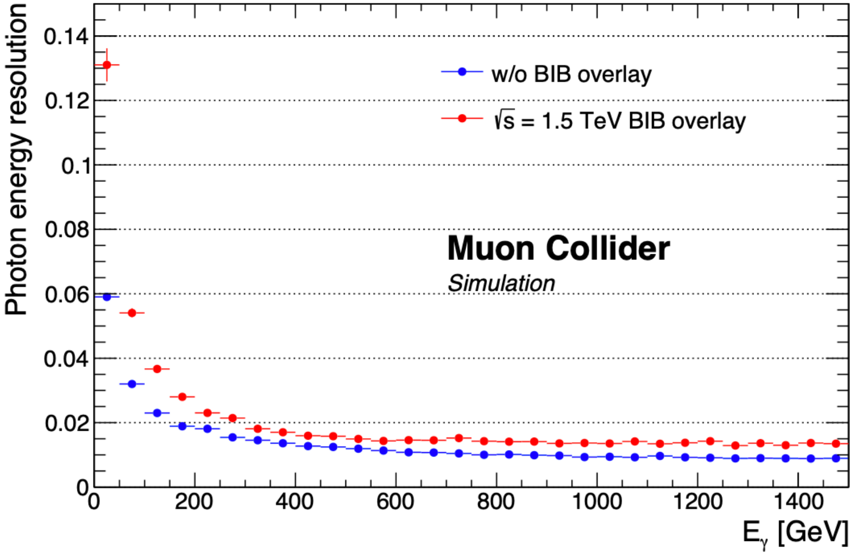


# Calorimeter Reconstruction

Photon Efficiency 90+%
BIB effects small



Few % Photon Energy Resolution
Improvements possible at low $E_T$



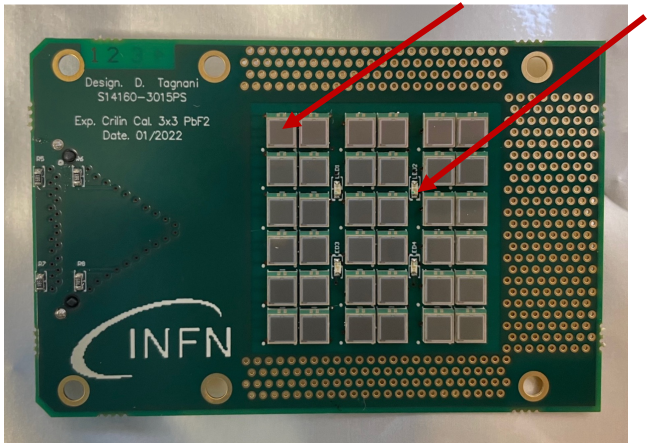
# Crilin Readout

**SiPM board**

- Custom SiPM array board
- 36x 10 $\mu$m Hamamatsu SMD SiPMs
- 4 SiPM/crystal (2x 2-series connection)
- 2 independent readout channels / cell
- Integrated SiPM matrix cooling system
- 4x SMD blue LEDs nested between the photosensor packages for SiPM diagnostics

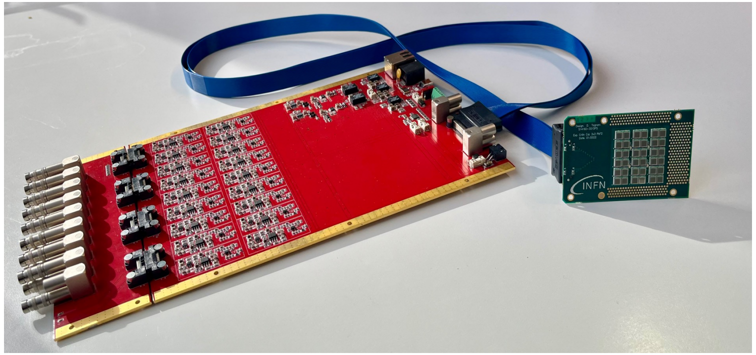
**FEE/controller board**

- 18x readout channels
- Amplification, shaping and individual bias regulation
- Slow control (temperature, bias and current monitors)



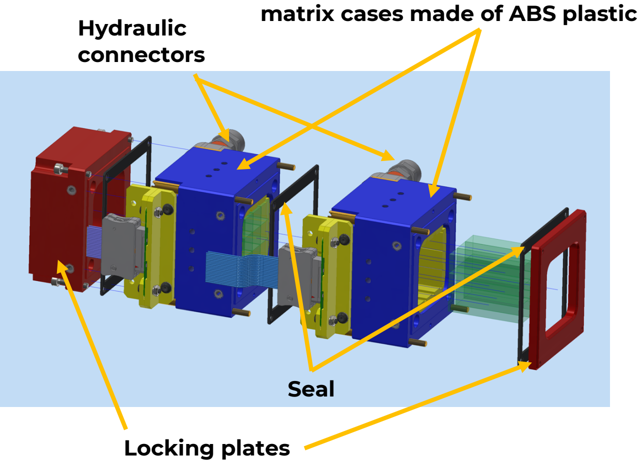
SiPM array (1 crystal)

SMD LEDs

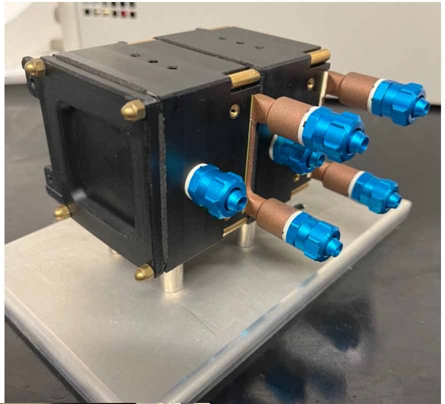


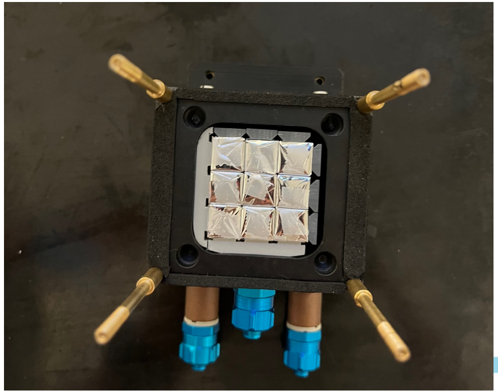
# Proto-1 → Mechanics

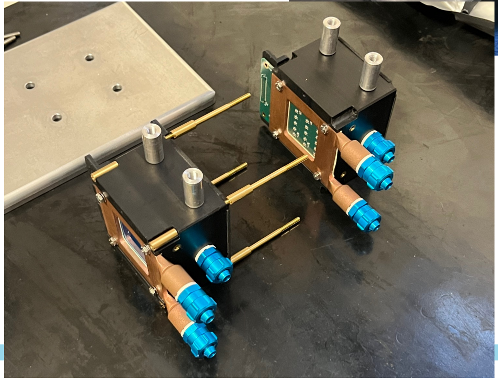
International MUON Collider Collaboration

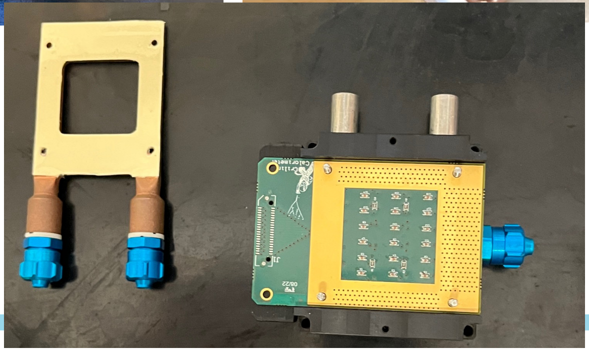


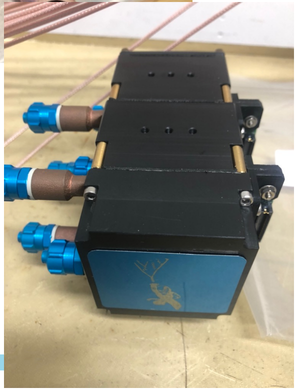
- **350 mW / crystal** thermal load
- Additively manufactured micro-channel heat exchanger for liquid coolant circulation











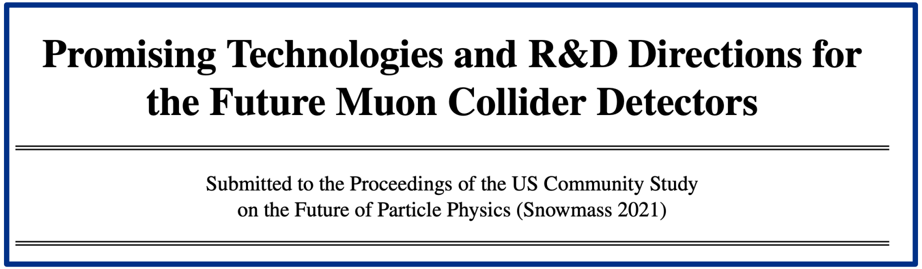
# Next steps

- Beam tests at LNF-INFN w/ 500 MeV e- (July 2023)
- Beam tests at CERN SPS and PS w/ 10-100 GeV (summer 2023)
- We submitted and won a PRIN proposal for a 210 kEUR grant for the project CALORHINO: an innovative radiation-hard calorimeter proposal for a future Muon Collider Experiment. 120 kEur has been assigned to develop a 5x5 x4(layers) Crilin prototype.
- The results presented in this talk were recently submitted to *Frontiers in Physics*

# These detectors don’t exist today – a lot of work to be done!

- 4D Trackers:
  - Design, Sensors, Data Transmission, Power, Mechanics
  - 3D Integration, ASIC, Intelligent Sensors/Modules
- Calorimeters:
  - Different technologies, design, reconstruction (with AI/ML)
  - Integration of precision timing
- Muons:
  - Qualification of new gases, fast timing,…
- TDAQ:
  - Architecture studies
  - Real-time reconstruction, novel readout technologies
- MDI+Forward:
  - MDI Design, Forward Muon Tagger
  - Luminosity Monitor
- Detector magnet

**arXiv: 2203.07224**



**Promising Technologies and R&D Directions for the Future Muon Collider Detectors**

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

***Very well aligned with Fermilab detector development interests and expertise!***

Significant synergies with HL-LHC and EIC, e+e-, and pp detectors

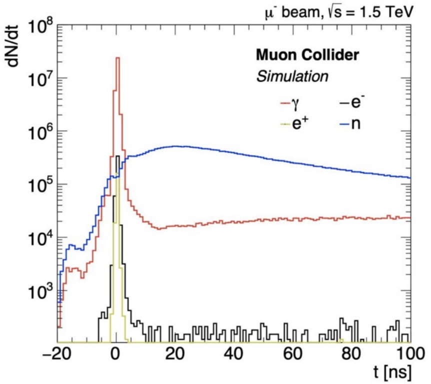
# Detector R&D: 3 TeV → 10 TeV Detector

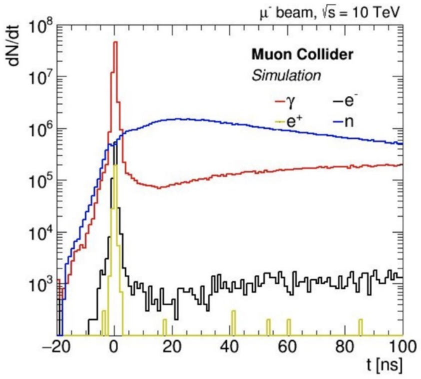
- Detector and MDI designs in early stages of development
- The backgrounds remain flat with energy

| Monte Carlo simulator | FLUKA | FLUKA | FLUKA |
|---|---|---|---|
| Beam energy [GeV] | 750 | 1500 | 5000 |
| $\mu$ decay length [m] | $46.7 \cdot 10^5$ | $93.5 \cdot 10^5$ | $311.7 \cdot 10^5$ |
| $\mu$ decay/m/bunch | $4.3 \cdot 10^5$ | $2.1 \cdot 10^5$ | $0.64 \cdot 10^5$ |
| Photons ($E_\gamma > 0.1$ MeV) | $51 \cdot 10^6$ | $70 \cdot 10^6$ | $107 \cdot 10^6$ |
| Neutrons ($E_n > 1$ MeV) | $110 \cdot 10^6$ | $91 \cdot 10^6$ | $101 \cdot 10^6$ |
| Electrons & positrons ($E_{e^\pm} > 0.1$ MeV) | $0.86 \cdot 10^6$ | $1.1 \cdot 10^6$ | $0.92 \cdot 10^6$ |
| Charged hadrons ($E_{h^\pm} > 0.1$ MeV) | $0.017 \cdot 10^6$ | $0.020 \cdot 10^6$ | $0.044 \cdot 10^6$ |
| Muons ($E_{\mu^\pm} > 0.1$ MeV) | $0.0031 \cdot 10^6$ | $0.0033 \cdot 10^6$ | $0.0048 \cdot 10^6$ |

[IMCC, Submitted to EPJC]

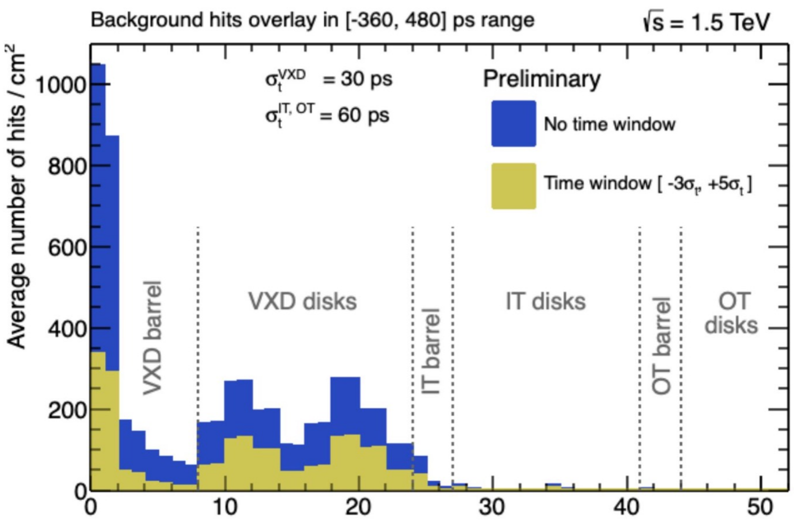
**No dramatic change!**

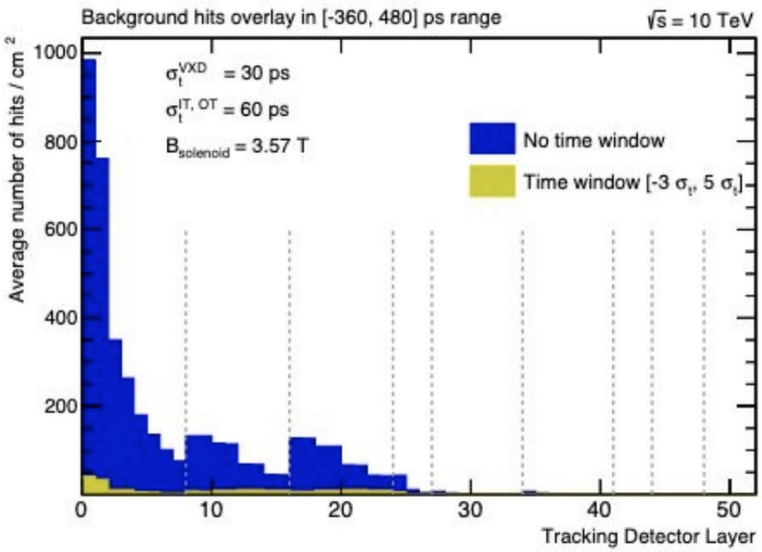




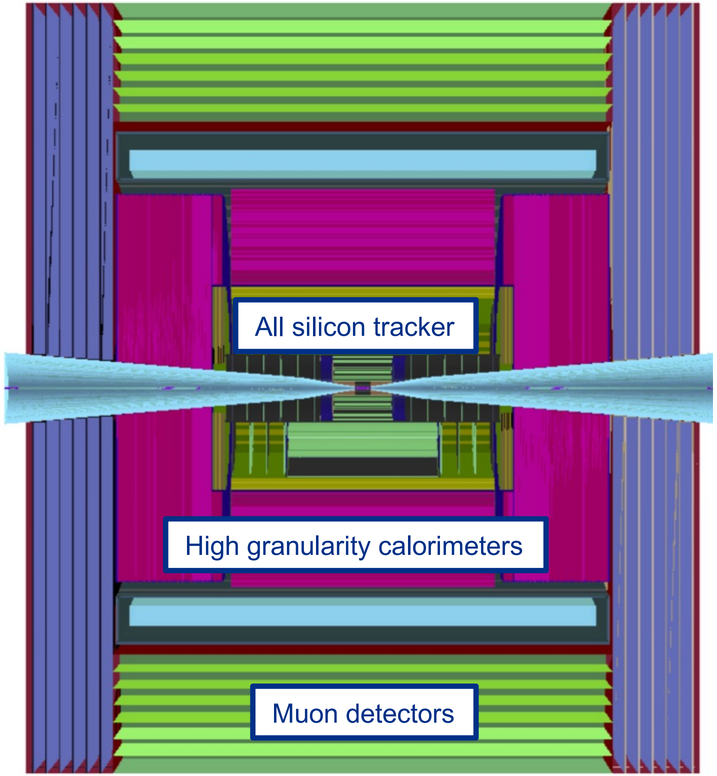
Without nozzle optimization
With optimization: 50% reduction

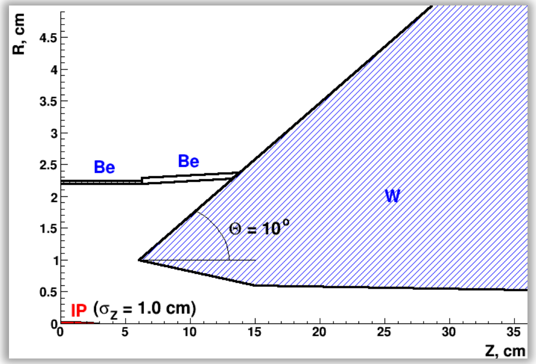
# Detector R&D: 3 TeV → 10 TeV Detector



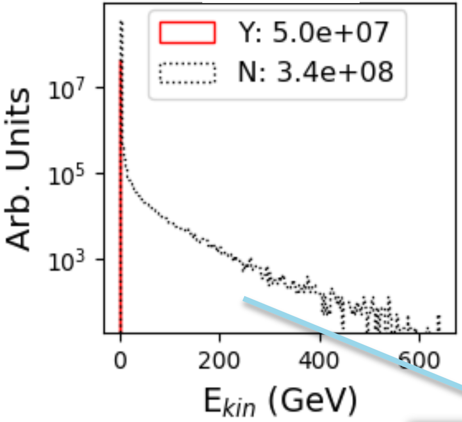


# Detector Design

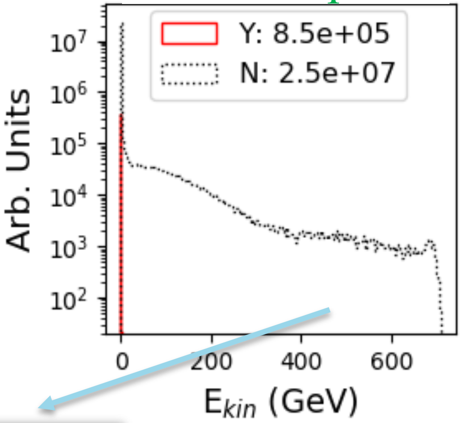




Photons



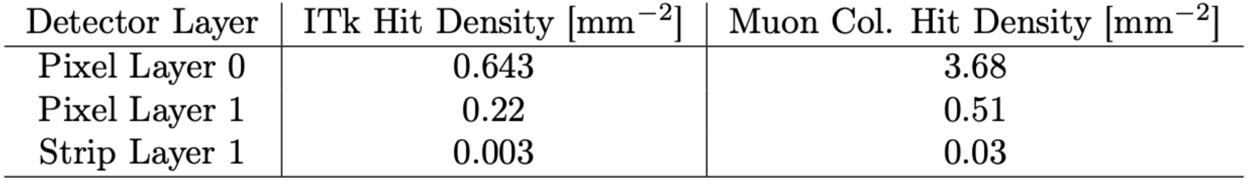
electrons/positrons



absorbed

# Occupancies

Tracker occupancy compared to ATLAS ITK (loose timing requirements applied)



| Detector Layer | ITk Hit Density [$\mathrm{mm}^{-2}$] | Muon Col. Hit Density [$\mathrm{mm}^{-2}$] |
|---|---|---|
| Pixel Layer 0 | 0.643 | 3.68 |
| Pixel Layer 1 | 0.22 | 0.51 |
| Strip Layer 1 | 0.003 | 0.03 |

Calorimeter Energy Density Measurements

- Muon Collider rho=45 GeV/(unit area)
- HL-LHC rho ~ 50 GeV/(unit area)