MPGD-based HCAL for a future experiment at Muon Collider

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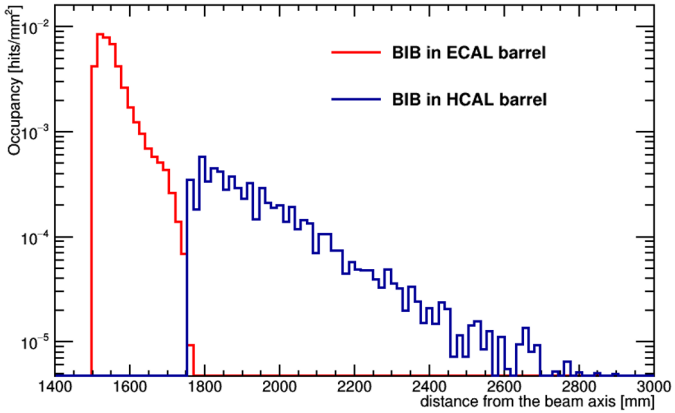
Requirements for calorimetry at Muon Collider

BIB IN CALORIMETERS (study at sqrt s= 1.5 TeV)

- Come mainly from photons (96%) and neutrons (4%).
- Occupancy for E>0.2 MeV
  - ECAL: 0.9 hits/cm^2
  - HCAL: 0.06 hits/cm^2

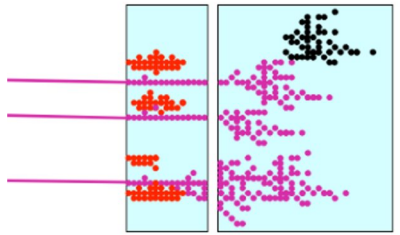


https://arxiv.org/abs/2303.08533

REQUIREMENTS:

- High granularity: O(<1cm^2) cell in ECAL, O(<3cm^2) cell in HCAL
- Longitudinal segmentation
- Good timing (σ_t = 100 ps-few ns)
- Energy resolution to work in Particle Flow approach
  - ECAL: 10/%√E
  - HCAL: 30/%√E
  - Goal: provide 3-4% jet energy resolution for hadronic Z decays

5D calorimeters



$E_{JET} = E_{TRACK} + E_\gamma + E_n$

MPGD for Hadronic calorimeter

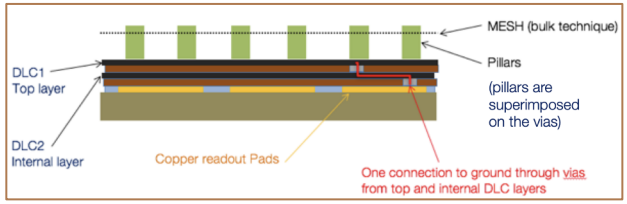
- Paradigm for calorimetry at muon collider: work in particle flow approach
  - High granularity
  - High time resolution
- Proposal: sampling calorimeter with MPGD active layers
- CALICE already proposed gaseous detectors for sampling calorimeter (RPC).
  - MPGD also explored but also less mature

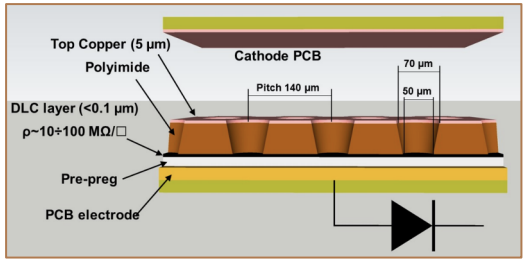
Why MPGD-based HCAL?

- Radiation hardness,
- fine granularity,
- rate capability O(MHz/cm2)
- good space (<100 um) resolution,
- response uniformity,
- cheap for large area instrumentation.

Technologies

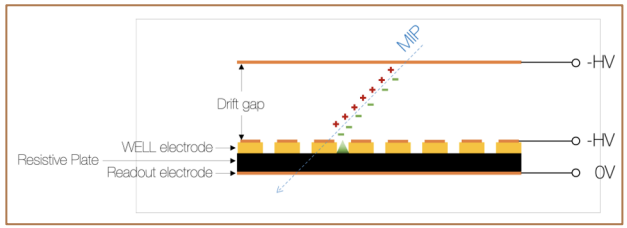
Micromegas (MM)



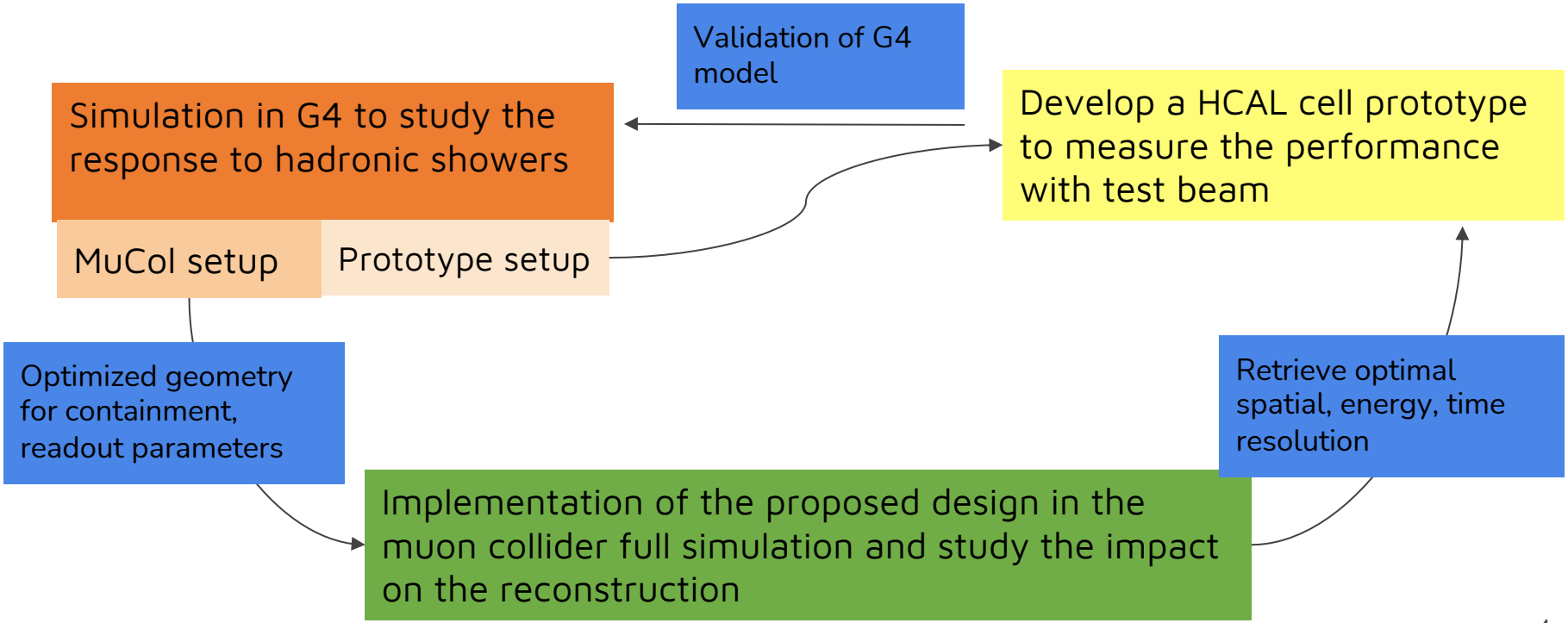


µRWELL

RPWELL



General Roadmap for MPGD HCAL R&D



G4 Containment studies

Geometry implemented

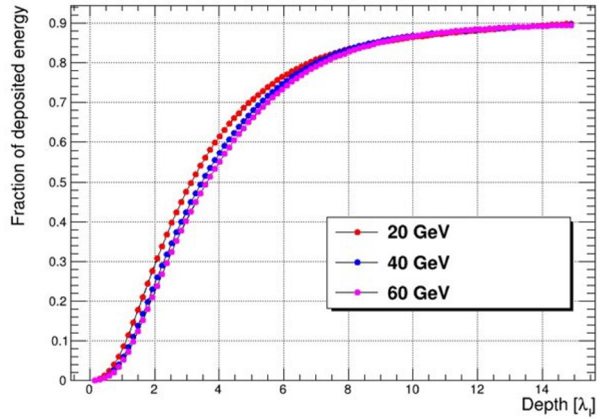
- Sampling calorimeter made of
  - 2 cm of Iron (**absorber**)
  - 5 mm of Ar/CO2 (**active gap**)
  - Cell granularity: 1x1 cm2

Source: π gun from 1 to 80 GeV

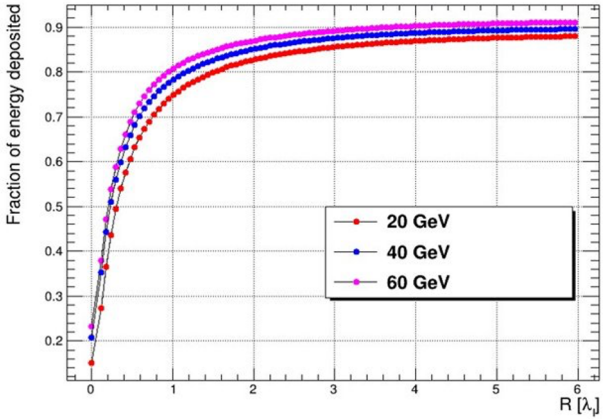
Energy contained at 90%

- 14 $\boldsymbol{\lambda}_N$ in the direction of the incoming π (2.4 m)
- 3 $\boldsymbol{\lambda}_N$ in the orthogonal direction (0.5 m)

Longitudinal direction



Transverse direction

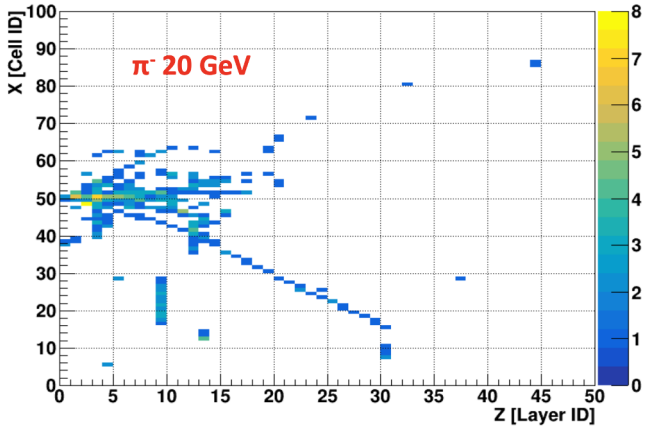


G4 simulation - Digital and Semi-digital HCAL

Preliminary

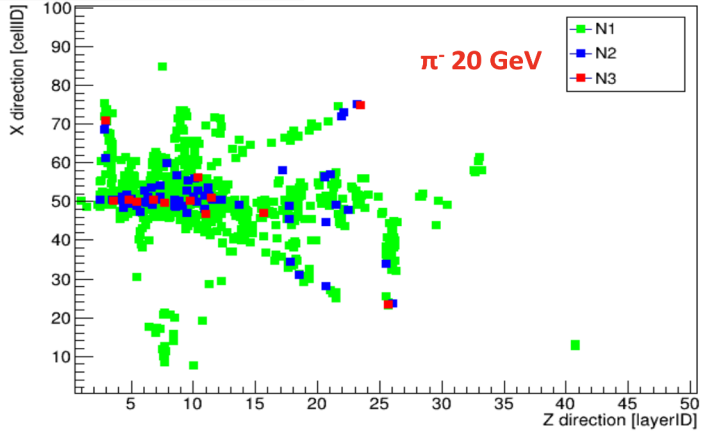
- Digitization: 1 hit=1cell with energy deposit higher than the applied threshold
- Calorimeter response function: $<N_{hit}> = f(E_\pi)$
- Reconstructed energy: $E_\pi = f^{-1}(<N_{hit}>)$

Digital Readout

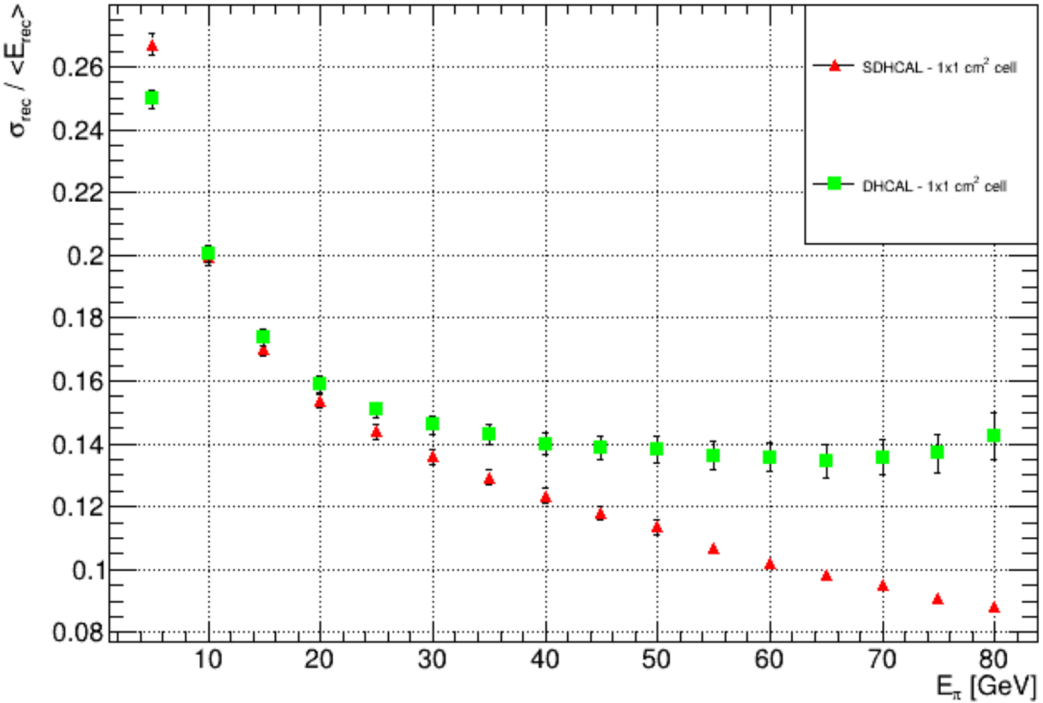


- Digitization: defined multiple thresholds
- Reconstructed energy: $E_\pi = \alpha N_1 + \beta N_2 + \gamma N_3$ with:
  - $N_{i=1,2,3}$ number of hits above *i*-threshold
  - α, β, γ parameters obtained by χ^2 minimization procedure

Semi-digital Readout



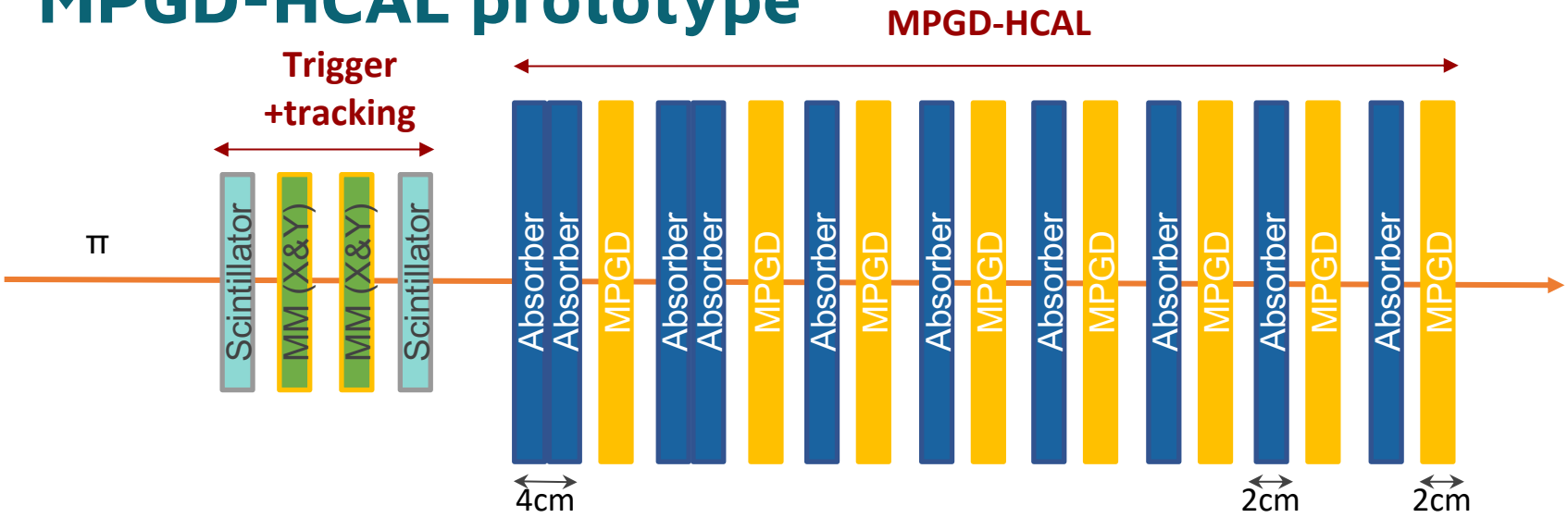
G4 simulation - Digital and Semi-digital HCAL



- **Digital HCAL (DHCAL)** is affected by the **saturation** of the number of hits at energies above 40 GeV

- **Semi-digital HCAL (SDHCAL)** shows an energy resolution of ~8% for a pion of 80 GeV

MPGD-HCAL prototype



8 layers

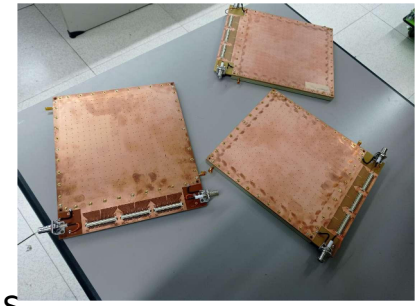
- MPGD: MM, µRWell, RPWELL
- Iron absorber ~ $1\lambda_N$

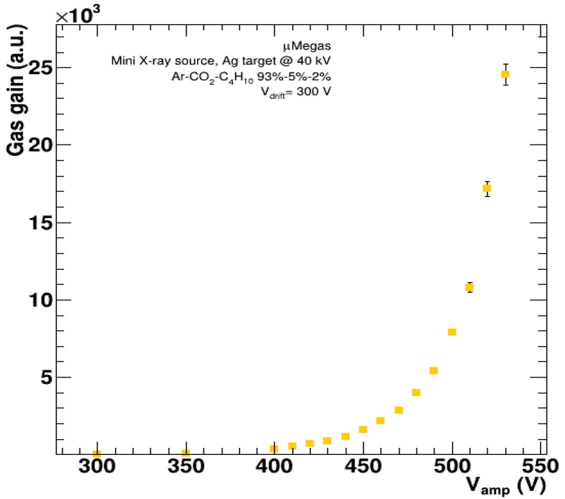
Two test beam campaigns in 2023 to measure:

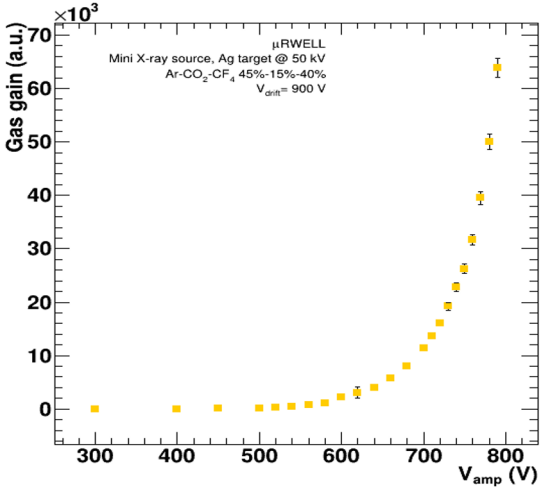
- **single MPGD performance (5-19 July)**
- **HCAL cell performance (30 August - 6 September)**

MPGD-HCAL prototype - Detector

- MPGD total production batch:
  - 7 uRWELL
  - 4 MicroMegas
  - 1 RPWELL
- detector size: 20x20 cm^2
- pad size: 1cm^2 pad→ 384 pads
- Common readout board







First characterizations (HV stability & effective gain) performed in all the labs involved in the project

MPGD-HCAL prototype - MPGD test beam

Summer 2023: MPGD test beam campaign at

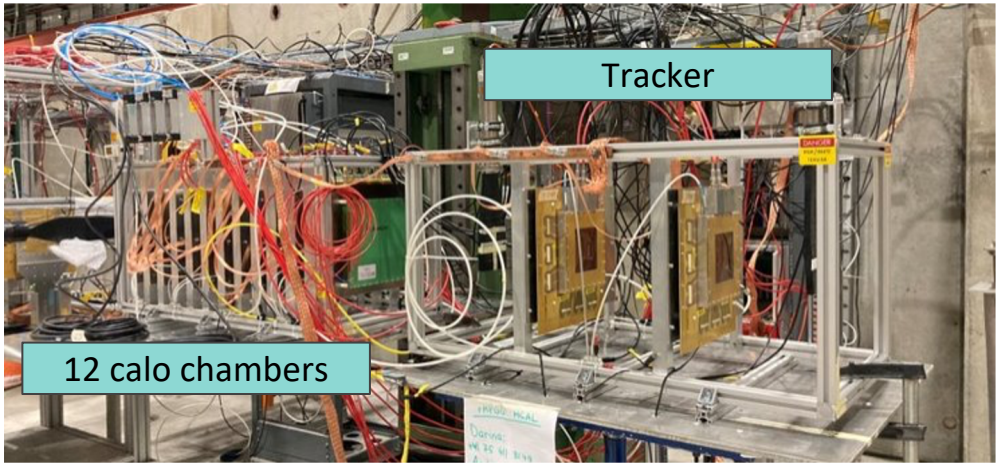
- SPS with O(100 GeV) muon beam
- PS with 1-10 GeV pion beam

with the goal to measure

- response uniformity
- efficiency
- spatial resolution

Data taking:

- 12 chambers to be tested in total, read 6 chambers at a time
- HV, XY position scan
- During last days instrumented only central pads to read all the calo-chambers at once

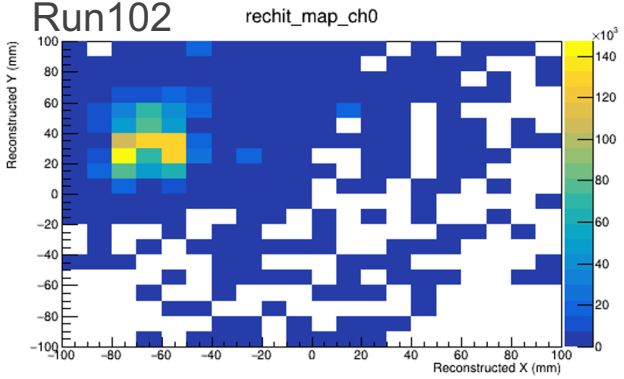


Track reconstruction:

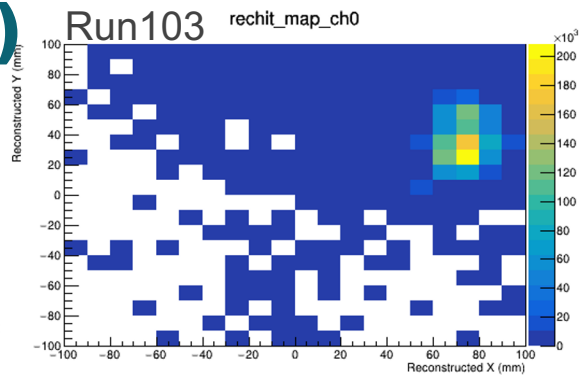
- TMM temporarily excluded
- reconstruct the track using hits from 5 calo detectors, the 6 chamber is the one under test

Beam profile (PS)

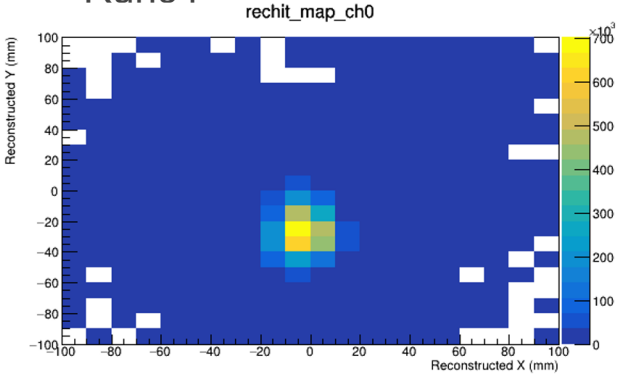
Run102



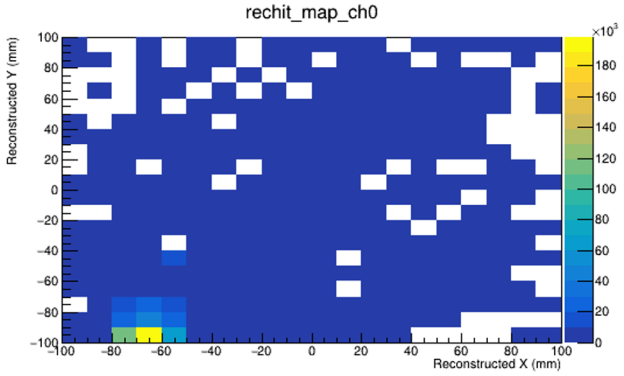
Run103



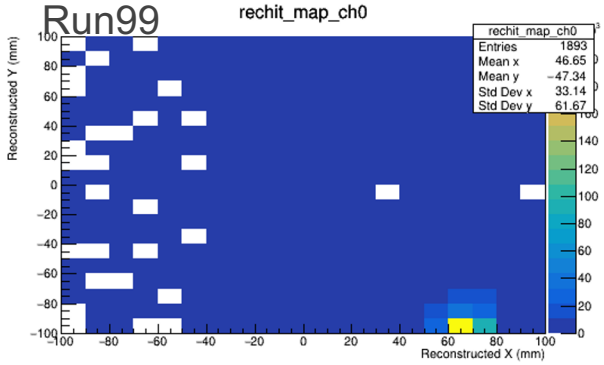
Run91



Run104



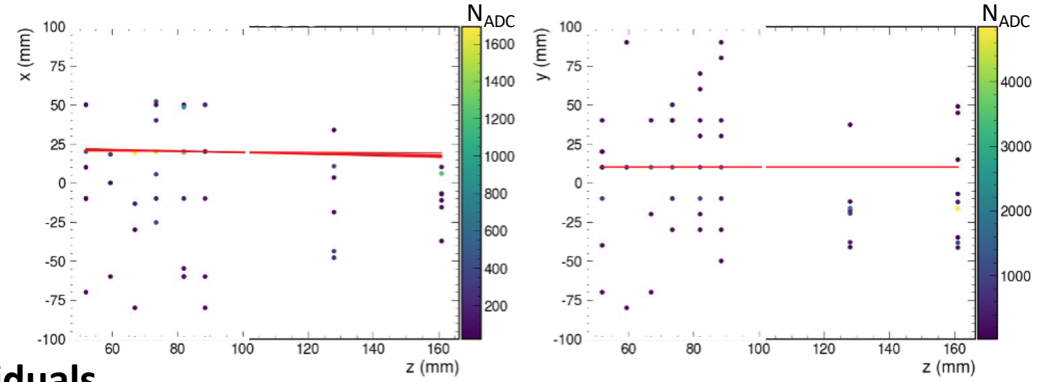
Run99



MPGD-HCAL prototype - July test beam

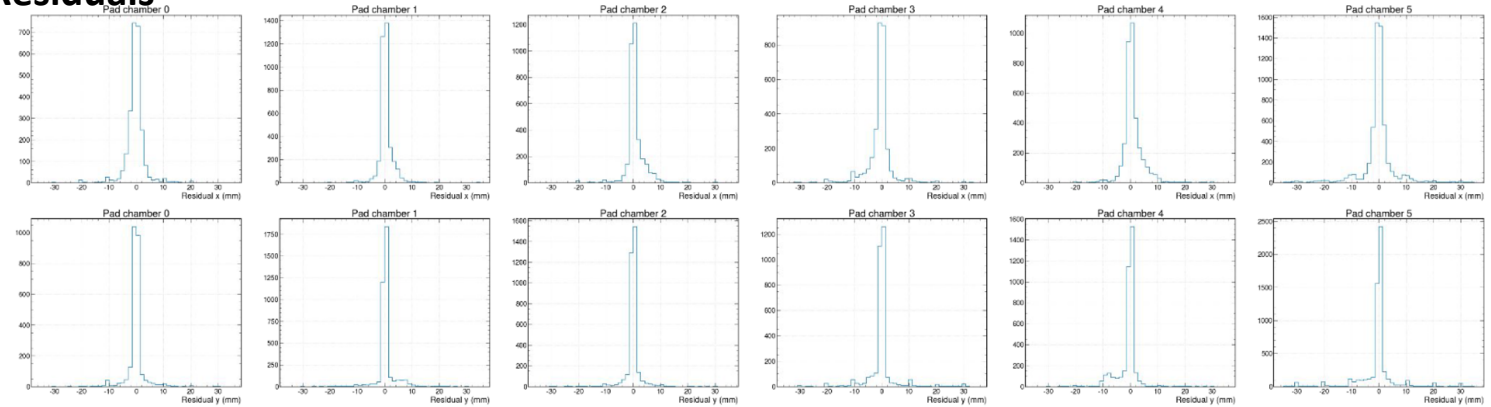
Preliminary

Reconstructed track in X-Z and Y-Z plane



Narrow residuals, in agreement with detector granularity

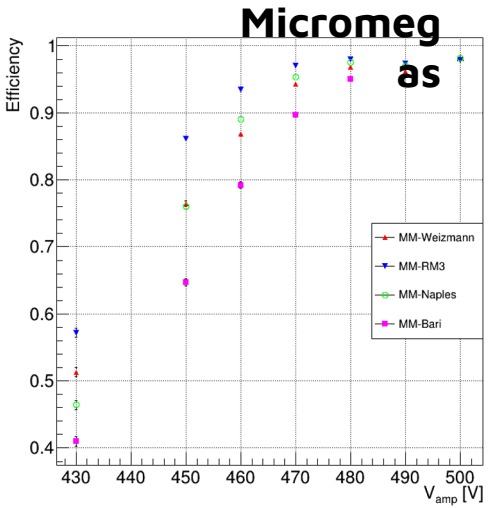
Residuals

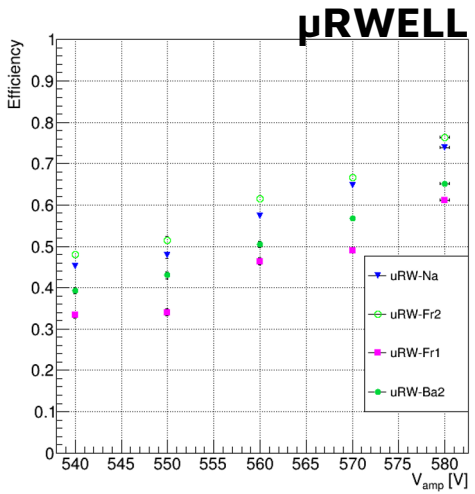


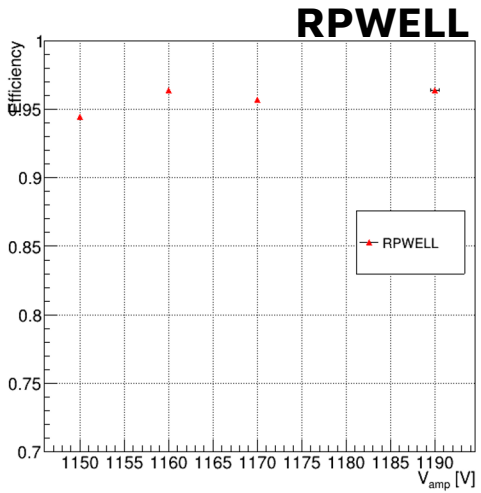
MPGD-HCAL prototype - July test beam

Preliminary

HV scan







- Micromegas and RPWELL show efficiency of above 95%
- μRWELL not in plateau for the scanned values → foreseen a new HV scan

Results coming soon

MPGD-HCAL prototype - Aug test beam

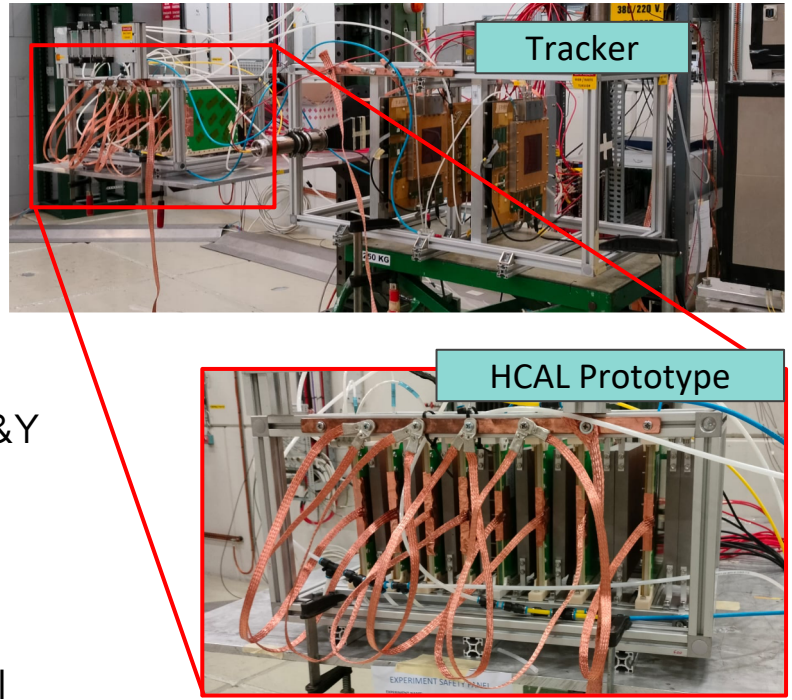
Full prototype test beam campaign at PS

- pure negative pion beams
- beam size of ~1cm^2
- monochromatic E=2, 4, 6,7,9,10 GeV

First operation of the full system!

Scientific program

- without absorbers: response to an X&Y scan
- with absorbers: energy and energy resolution measurement with monochromatic beam
- Define the thresholds for semi-digital readout using the per-pad charge distribution obtained with the analog readout



Plans

Full simulation studies

- Finalize geometry
- Digital and semidigital readout
- Optimize pandora for charged and neutral hadron reconstruction
- Define optimal segmentation in transverse and longitudinal direction (e.g. looking at track-cluster matching efficiency) and time resolution (bib rejection)
- Repeat for 10 TeV scenario

Prototype development

- 20x20 test beam data analysis:
  MIP and hadronic shower charge profile, spatial shower development, energy calibration and resolution, response unformity
- Design 50x50 prototype → test beam in late 2025 with CRILIN

MPGD HCAL in DRD1 and DRD6

- The roadmap **of gaseous detectors for calorimetry at future HEP experiments** is framed in **DRD1-WP5**. We are active part of the proposal.
- Main points for MPGD-HCAL R&D:
  - T6: study of the detector time resolution, crucial to reduce the BIB.
  - M1: construction of medium size gaseous detector.
  - M2: uniformity study including efficiency and cluster size with medium size detectors.
- The roadmap of **calorimetry at future HEP experiments**, framed in **DRD6-WP1** (sandwich calorimeters with embedded electronics) target the development of proof-of-principle HCAL cell of increasing size.

MPGD-HCAL	Hadronic		MPGD (Micromegas, μRWELL)/Steel	$\mu^+\mu^-$ collider central detector	Small prototype for proof-of-principle, Lateral and longitudinal extension envisaged
MPGD-HCAL	M1.11		Specifications for 50x50 cm^2 prototype		2025
	M1.12		Design of 50x100 , cm^2 layers		2026
		D1.14	Completion of 6 layers 20x20 cm^2 prototype		2024
		D1.15	10 layers prototype (6L:20x20cm^2, 4L:50x50 cm^2)		2026
		D1.16	3x100x100 cm^2 layers		>2026

From DRD6 Proposal document

Project and cost overview

2024-2026: 10 layer prototype (6 20x20 + 4 50x50) proof of concept

- Finalize results from 20x20 TB → technology choice
- Design, produce, characterize 4 layers of 50x50 modules [DRD1] 40k
- Produce and characterize 10 layers proto [DRD6] 10k
- Readout electronics and backend procurement [DRD6] 50-100k

100-150k

Total FTE: 3

>2026: 3 layers of 100x100 ready for CALICE test beam

- Pre-production and test of 2 MPGD 50x100 [DRD1] 30k
- Production of 4 MPGD 50x100 [DRD1] 50k
- Absorber + integration in HCAL cell for 3 layers of 100x100cm^2 [DRD6] 15k
- Readout electronics and backend procurement [DRD6] 100-200k
- 100x100 CALICE test beam

195-295k

Total DRD1: 120k

Total DRD6: 175-325k

PRIN 2022 and INFN Contribution for 2024

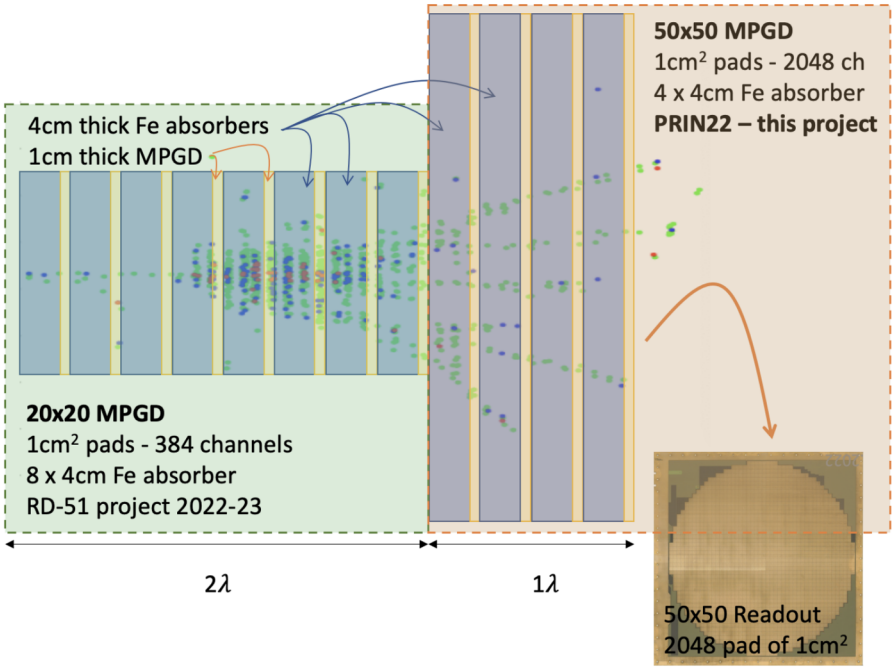


Fig. 2.4: Layout of the HCAL prototype with 3λ depth. The first 2λ is made of the 20x20cm² prototype developed in the RD-51 project in 2022, while the last λ necessary to contain longitudinally (95%) protons and pions of 1-6 GeV is made of 50x50cm² detectors developed in this project.

PRIN 2022 found 90k for 2023-2025
-25k for 1 y AdR
-65k for 10 layer proto R&D
- 30k for MPGD
- 35 for Readout

→ most part of the budget allocated for RO
- Up to now we used APV + SRS
- Keep this strategy is not feasible (APV are analogue chip out of production)
- Investigation ongoing (options considered: FATIC, GEMROC, VMM)

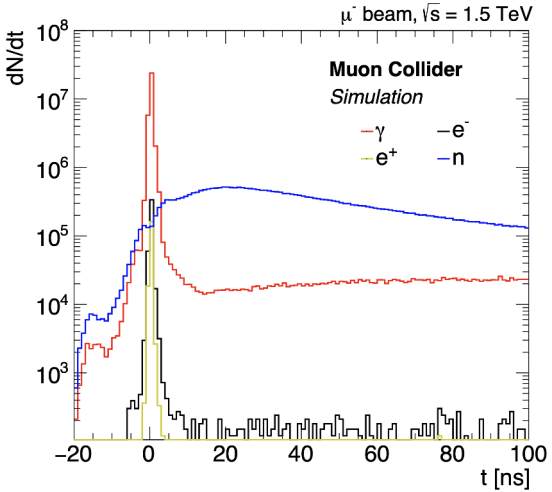
Backup

BIB in the detectors

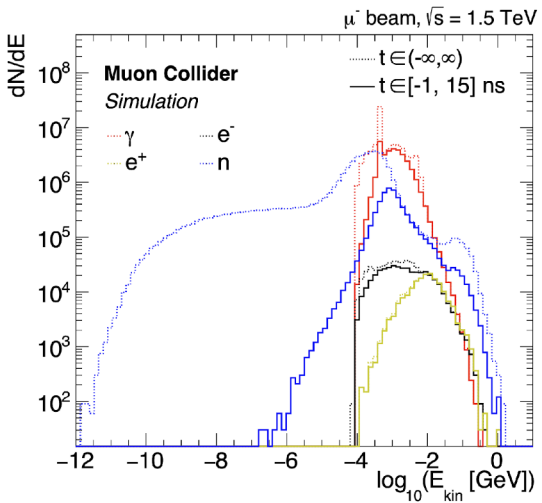
•Main BIB components entering the detector per bunch crossing: photons (~10^8), neutrons (~10^8), electrons/positrons (~10^6).

Detector requirements:
-O(ns) time precision,
-excellent pointing capabilities,
-radiation hardness 10^{-3} Grad/y (tracking system) and ~ 10^{-4} Grad/y (electromagnetic calorimeter.)

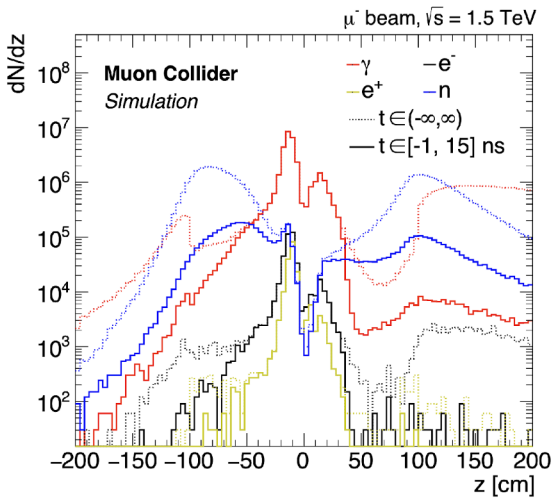
Asynchronous time of arrival wrt BX



Soft energy spectrum



Large displacement wrt to the impact point



Readout electronics cost estimation

Asic unit price GEMROC	detector	number of channels	Number of chips	Total ASIC GEMROC Cost	GEMROC + plugin card cost
270	20x20	384	3	810	1620
Plugin card	50x50	2048	32	8640	17280
270	6 20x20 + 4 50x50	10496	164	44280	88560
number of channel/asic	50x100	30000	468,75	126562,5	253125
64					
channl unit cost					
8,4375					

Asic unit price VFAT	detector	number of channels	Number of chips	Total ASIC fatic Cost	FATIC+Plugin card cost
70	20x20	384	12	840	1260
plugin	50x50	2048	64	4480	6720
35	6 20x20 + 4 50x50	10496	328	22960	34440
number of channel/asic	50x100	30000	937,5	65625	98437,5
32					
channl unit cost					
3,28125					

Summary: realistic timeline

28 September 2023: project start

March 2024 **M1**: Full implementation of Geant4 model and analysis for ECAL/HCAL

June 2024 **M2**: Full implementation of the proposed ECAL+HCAL geometry in Muon Collider simulation framework

(July 2024 **M4a**: 2 MPGD prototype construction and test beam)

Feb 2025 **M3**: ECAL prototype construction and BTF test beam

June 2025 **M4**: HCAL prototype construction

June 2025 **M5**: 2 (4) MPGD performance measurement with SPS test beam

August 2025 **M6**: Performance measurement for ECAL+HCAL

28 September 2025: closure

Fundings

Richiesto

nº		Total cost (euro)	Co-funding (item A.1) (euro)	MUR funding (other items) (euro)
1.	VENDITTI Rosamaria	127.050	20.031	107.019
2.	SARRA Ivano	192.424	49.640	142.784
	Total	**319.474**	**69.671**	**249.803**

Finanziato

17. 20229TBY8B			Cofinanziamento	Contributo MUR	
44	Rosamaria VENDITTI	Università degli Studi di BARI ALDO MORO	80002170720	19.827	89.895
45	Ivano SARRA	Istituto Nazionale di Fisica Nucleare	84001850589	38.697	119.939

Quello che possiamo spendere

Dettaglio capitoli di spesa

Budget rimodulato								
	A11	**A21**	**B**	**C**	**D**	**E**	**totale**	**contributo mur**
UniBa	19827	25000	26896	0	0	37999	109722	89895
INFN-LNF	38698	0	23219	0	0	96720	158636	119938

Breakdown for HCAL

Speravamo in un contributo INFN che (forse) arriverà solo nel 2025
Tabella da aggiornare con stime più realistiche

Detailed cost breakdown HCAL

ITEM	kEUR	QUANTITY	TOTAL	BUDGET POST
Resistive MPGDs (uRWELL/resMM) 50x50 with ~2000 pixels in circle (-20% of readout channels w.r.t. full instrumented square)	2	5	10	E (Consumables)
4 Wafers multi-project for in total 400 new FATIC3 asics	28	1	28	E (Consumables)
Plugin cards housing 4 FATIC3 asics with HRS130 and SAMTEC conn	0.2	70	14	E (Consumables)
SAMTEC Cables 8 twisted pair, screened	0.08	60	4.8	B (general expenses)
Concentrator boards sending output 4 plugin cards to MOSAIC	0.225	18	4.05	B (general expenses)
MOSAIC General Purpose DAQ board 1GB/s	2.4	7	16.8	B (general expenses)
Project Travel Costs for Meetings			3	E (Consumables)
2 year postdoc contract (DETECTOR construction + test + DAQ SW development + operation in testbeam)	25	1	25	A2.1 (contract for 12 months)
TOTAL			**105.65**	

5 MPGD foreseen
-2k/MPGD (under!!!)estimated →
9k from last quotations
40k final estimate for MPGD

Readout electronics 42k

DAQ: 26k

68k for readout → to be updated

Saranno utilizzati per coprire la percentuale da dare a DIF/UniBa

Attivata procedura per bandire su UniBa