Resistive MPGDs for a hadronic calorimeter

M. Alviggi[5], M. Bianco[6], M. Biglietti[4], M. Buonsante[1,2], M. Borysova[3], A. Colaleo[1,2], M. T. Camerlingo[1], M. Della Pietra[5], R. Di Nardo[4], L. Generoso[1,2], P. Iengo[5], M. Iodice[4], L. Longo[1], M. Maggi[1], L. Moleri[3], **A. Pellecchia**[1], R. Radogna[1,2], G. Sekhniaidze[5], F. M. Simone[1,2], A. Stamerra[1,2], R. Venditti[1,2], P. Verwilligen[1], D. Zavazieva[3], A. Zaza[1,2]

[1] INFN Bari

[2] University of Bari

[3] Weizmann institute of science

[4] INFN Roma 3

[5] INFN Napoli

[6] CERN

3rd DRD1 Collaboration meeting

December 10th, 2024

HCAL readout with MPGD

Proposal: micro-pattern gaseous detectors as readout layers for a sampling hadronic calorimeter

Why using MPGDs?

- **cost-effectiveness** for large area instrumentation
- radiation hardness up to several **C/cm^2**
- **discharge rate** not impeding operations
- rate capability O (**MHz/cm^2**)
- high granularity
- time resolution of **few ns**

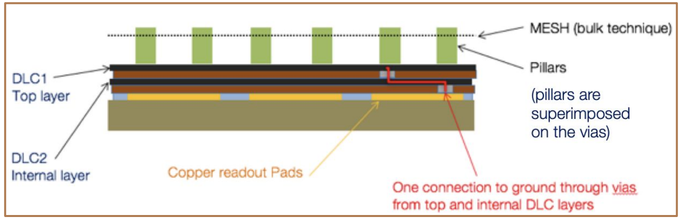
Resistive MPGDs

Past work:

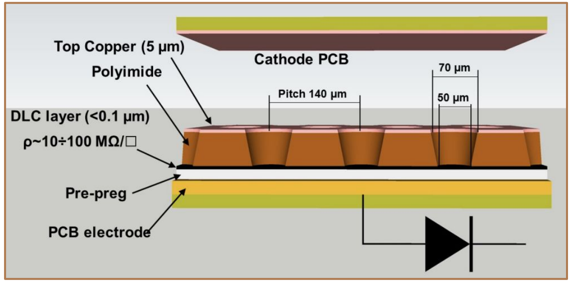
- CALICE collaboration: a sampling calorimeter using **gaseous detectors** (RPC) but also tested MicroMegas
- SCREAM collaboration: a sampling calorimeter combining RPWELL and resistive MicroMegas

Our plan → systematically **compare** three MPGD technologies for hadronic calorimetry: resistive MicroMegas, μRWELL and RPWELL, while also investigating **timing**

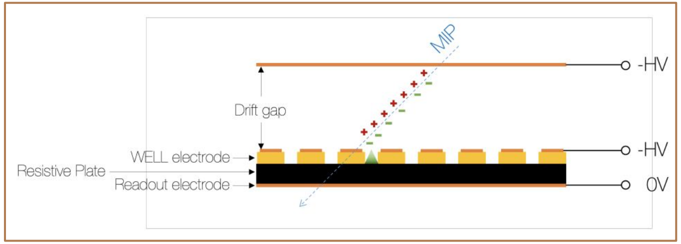
Micromegas (MM)



μRWELL



RPWELL



Target case: muon collider

A $\mu^+\mu^-$ collider for precision SM measurements and BSM searches

Large rate of asynchronous **beam-induced background** in experiments

- At $\sqrt{s}$ = 3 TeV, 10^{12} - 10^{13} cm^{-2} / year 1-MeV n equivalent
- TID 100 Gy / year

Goal for HCAL: 3-4 % jet energy resolution for hadronic Z decays obtainable through particle flow algorithm → 60%/$\sqrt{E}$ resolution for HCAL

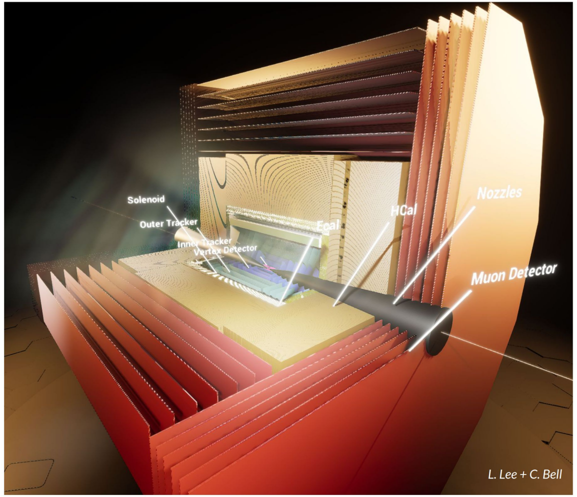
BIB in barrel hadron calorimeter

- Mostly **neutrons** (photon component absorbed by ECAL)
- Large **asynchronous** component
- Occupancy: 0.06 hits / cm^2

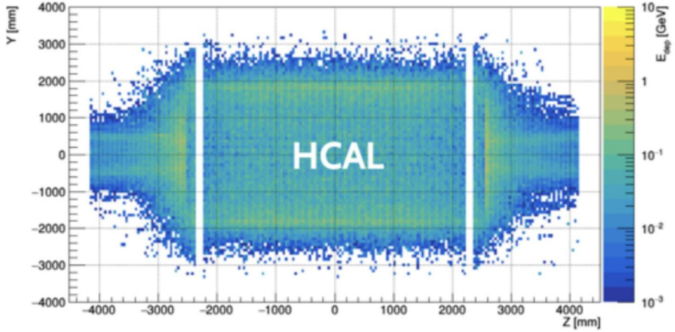
Detector requirements

- Longitudinal **segmentation** for BIB rejection
- High **granularity** (1x1 - 3x3 cm^2)
- Single layer **timing** of few ns

Not limited to muon collider (technology suitable for FCC-ee as well)



Muon collider detector design at $\sqrt{s}$ =10 TeV



Energy deposited by BIB in HCAL for a single bunch crossing

Muon collider HCAL performance

Preliminary

Simulation: 60 layers of Iron (19mm) + Ar (3mm)

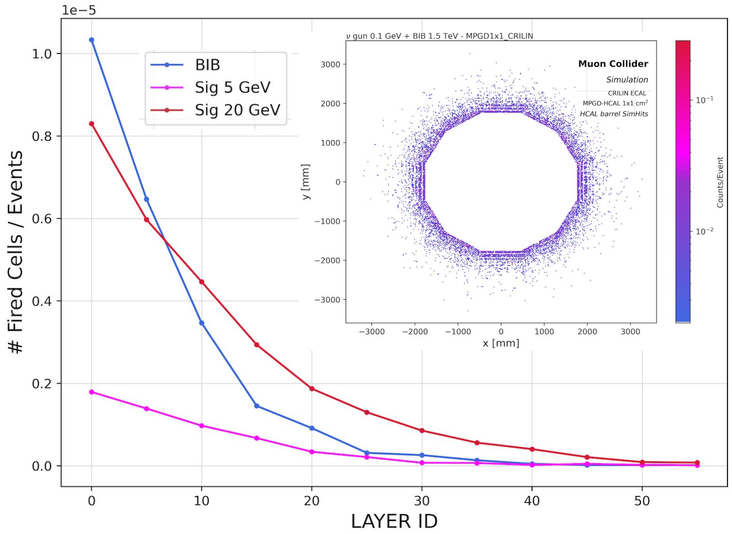
Hit Occupancy:

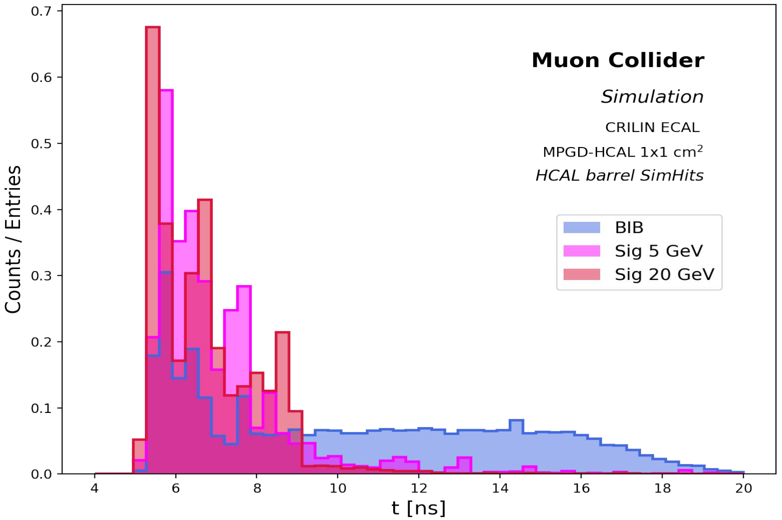
- **BIB** containment within the **first 20 layers** of HCAL
- Probability of a cell to be fired in the first layer :
  - **BIB** : ~ 1 x 10^{-5}
  - **$\pi^{\pm}$ 5 GeV** : ~ 0.2 x 10^{-5}
  - **$\pi^{\pm}$ 20 GeV** : ~ 0.8 x 10^{-5}
- Challenge for low energy pion reconstruction

Arrival time:

- **BIB** arrival time distribution uniform in the **range 7-20 ns**;
- **signal** arrival time peaks at **~ 6ns**;
- discrimination possible for ***t>9/10 ns*** → **achievable with MPGD**

See Lisa's talk at SIF 2024



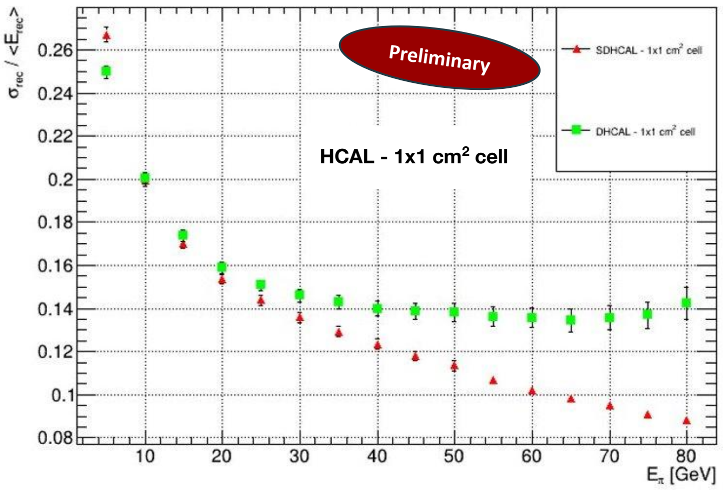


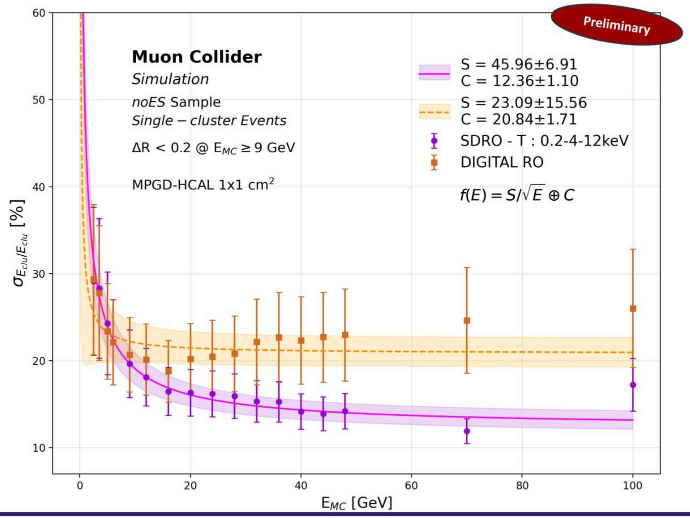
Simulation: digital and semi-digital HCAL

HCAL energy resolution simulated with **standalone Geant4** and with **full muon collider software**

- SDHCAL shows better resolution for $E_\pi > 40$ GeV
  - At E_π= 80 GeV, **DHcal ~ 14%, SDHcal ~ 8%**
  - DHCAL suffers from **saturation effect** for $E_\pi > 40$ GeV
- Comparable results for granularity of 1x1cm^2 (~9% at 80 GeV) and 3x3 cm^2 (~11% at 80 GeV)

Ongoing work: implementing **particle flow algorithm** to measure the final jet energy resolution





MPGD prototypes

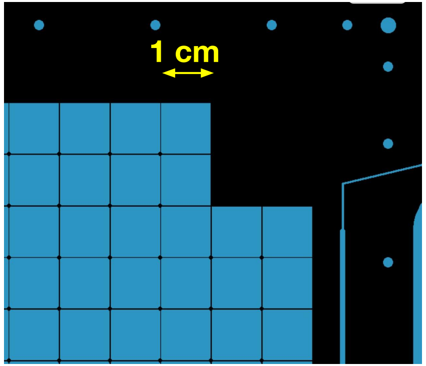
Prototypes produced and tested within **RD51 common project**:

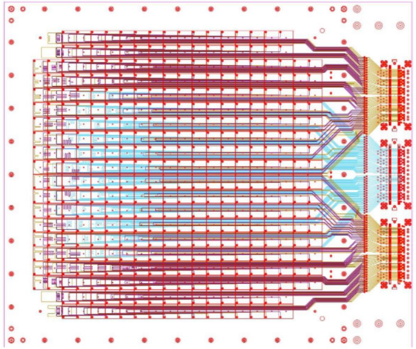
- 7 μ-RWELL
- 4 MicroMegas
- 1 RPWELL

Detector design:

- Active area 20×20 cm^2, pad size 1×1 cm^2
- **Common readout** board

Prototype characterization performed in all the laboratories



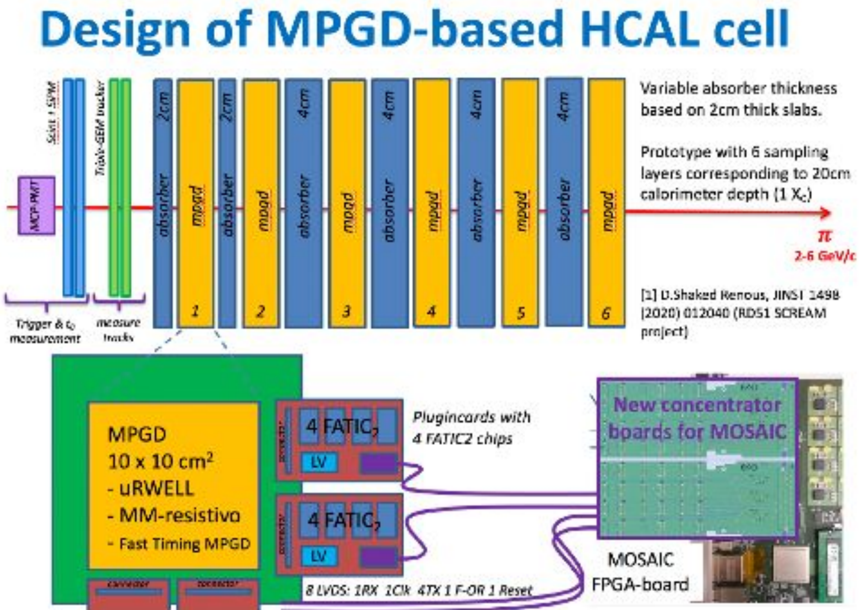


Request for Project Funding from the RD51 Common Fund

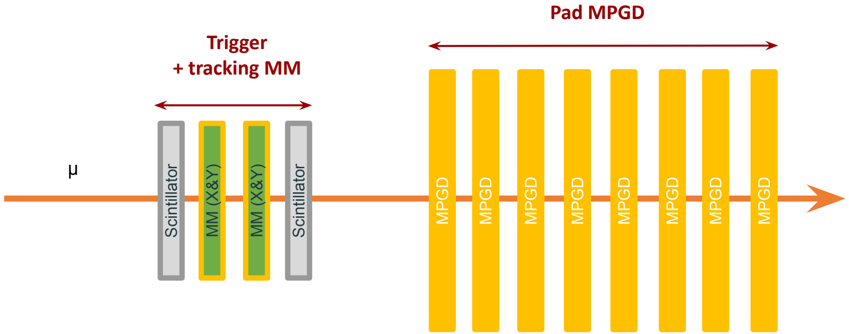
- Date: *31.07.21*-

Title of project:	*Development of Resistive MPGD Calorimeter with timing measurement*
RD51 Institutes:	**1.** *INFN sez. Bari, contact person: piet.verwilligen@ba.infn.it*
	2. *INFN sez. Roma III, contact person: mauro.iodice@roma3.infn.it*
	3. *INFN LNF Frascati, contact person: giovanni.bencivenni@lnf.infn.it*
	4. *INFN sez. Napoli, contact person: massimo.dellapietra@na.infn.it*

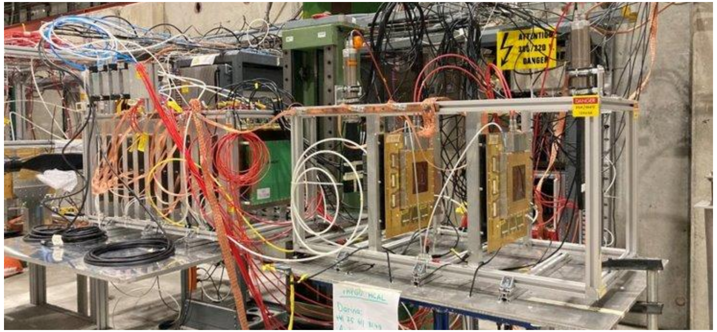
+ ***Weizmann Institute of Science, contact person: luca.moleri@weizmann.ac.il***



MPGD performance at SPS test beam



Test beam setup at SPS



Readout layers operated in two **test beams at SPS** *(July 2023, June 2024)*

- Tracking: 2 MicroMegas (256 μm-strip) + 1 triple GEM
- Tested: 12 MPGD prototypes

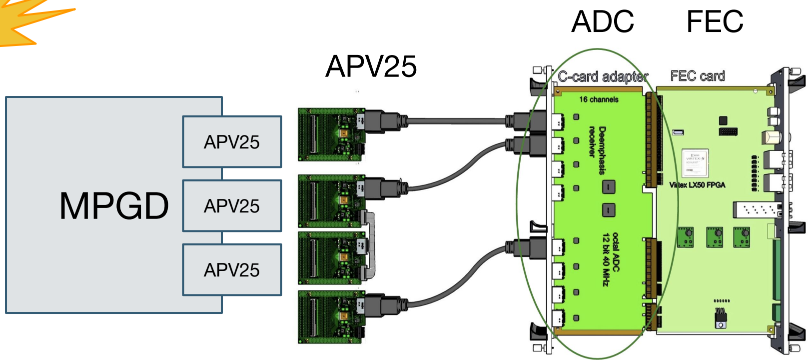
  Gas: **$Ar:CO_2:C_4H_{10}$** (MicroMegas & RPWELL),

  $Ar:CO_2:CF_4$ (μ-RWELL)
- Particle: O(100) GeV/c **muons**

No absorbers

Readout **electronics**:

- **APV25** front-end chip (analog readout + time information)
- **SRS** back-end



Readout electronics based on the APV25 SRS

Goal: **validating** the readout detectors **with MIPs** and **compare** the three **technologies**

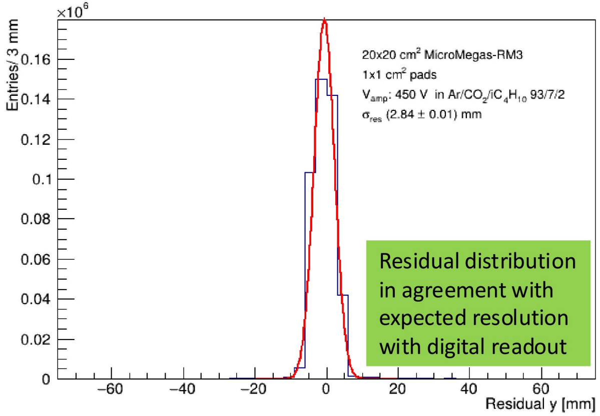
Detector performance with MIPs

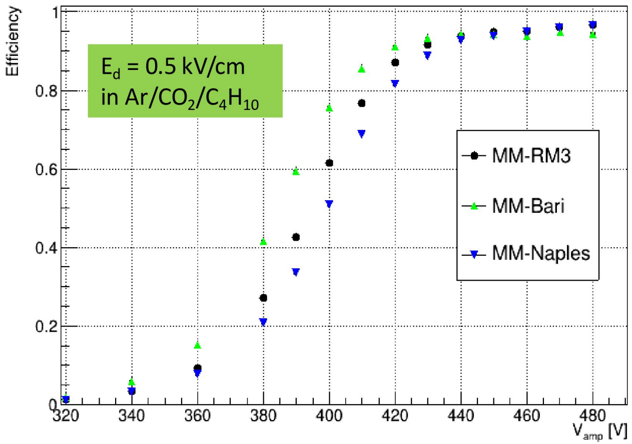
Reconstruction:

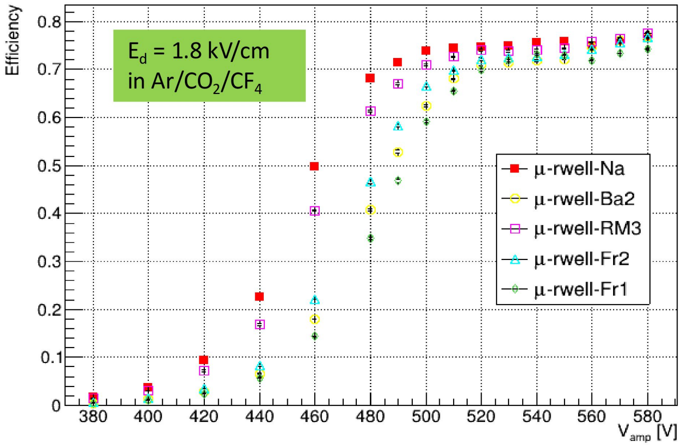
- Observed high probability of **cross-talk** between pads
  Due to routing of readout vias from pads to front-end
- Patched **offline** by clustering pads based on charge sharing fraction
- Tracks built with 2 tracking MicroMegas (256 μm pitch)

Plateau efficiency: about **90% for MicroMegas, 75% for μ-RWELL**

Response uniformity: 10% MicroMegas, 16% μ-RWELL, 22% RPWELL







Detector	Uniformity (%)
MM-RM3	(12.3 ± 0.8)%
MM-Na	(11.6 ± 0.8)%
MM-Ba	(8.0 ± 0.5)%
RPWELL	(22.6 ± 4.7)%
μrw-Na	(11.3 ± 1.0) %
μrw-Fr2	(16.2 ± 1.7)%
μrw-Fr1	(16.3 ± 1.1)%

Investigations on inefficiencies

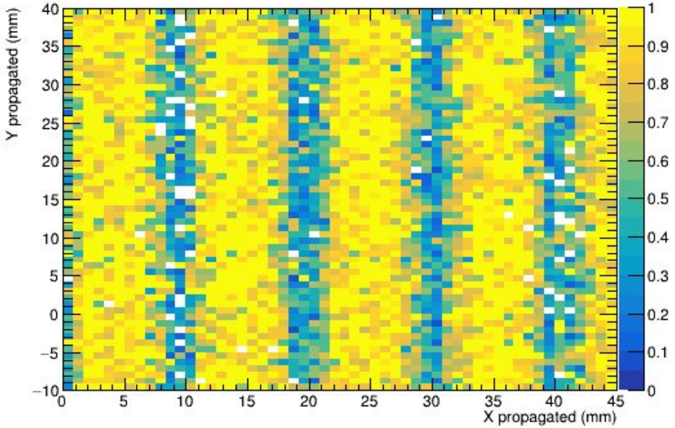
Preliminary

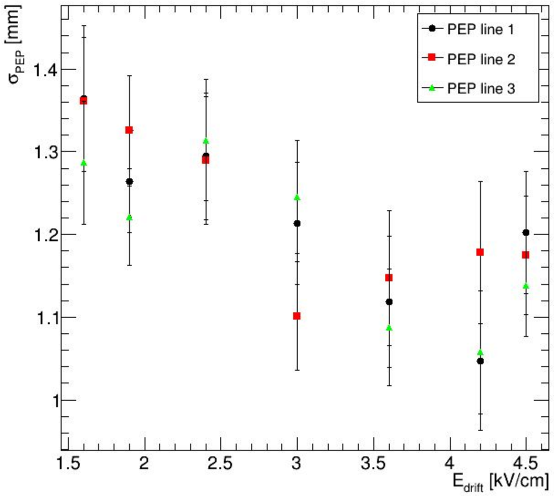
Inefficiency of **μ-RWELL** due to **PEP lines** introducing dead areas

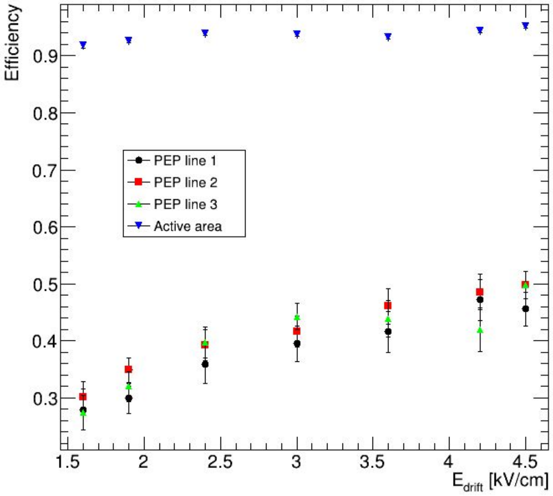
- **Locally very high** efficiency
- PEP lines introduce a **region of ~ 1 mm with ~50% efficiency drop**
- At **increasing drift** field, efficiency drop region **gets thinner and smaller**

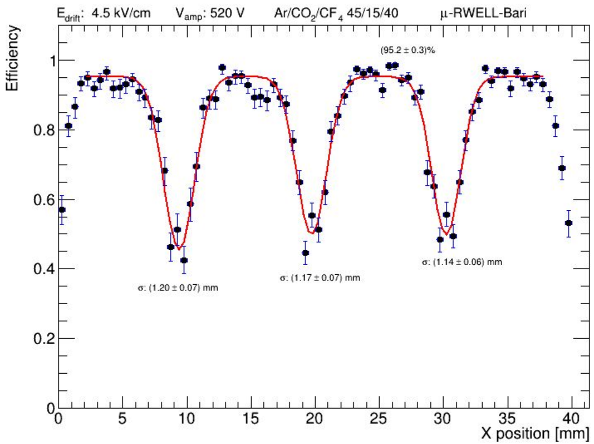
Excluding PEP areas, the efficiency is up to 95%

→ **Optimization of drift field** to be repeated with cosmics









Integration with VMM electronics

Thanks to Lucian, Karl and Eraldo for all the support!

µ-RWELL prototype tested with VMM (cosmics and TB)

See also Darina's talk at MPGD24

- **Rate** *(1 night data taking with APV → two spills with VMM)*
- Lower **thresholds** reachable (down to 0.8 fC)
- Potentially better **timing**, to be checked

Scans vs fields give further understanding of **charge collection and inefficiencies**:

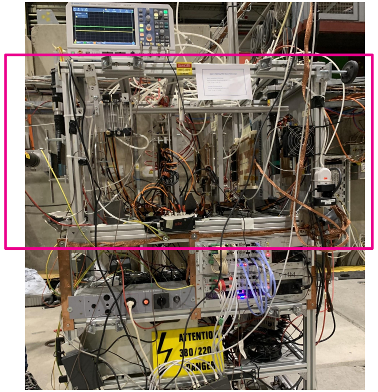
- For any amplification field, **charge MPV has a peak** at drift field ~ 3 kV/cm
- For high enough gain, the **efficiency keeps increasing with drift** field
- **Plateau efficiency increases with drift** field

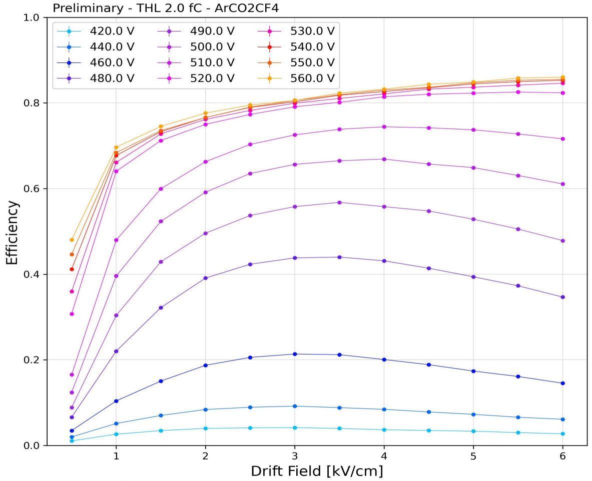
Interpretation:

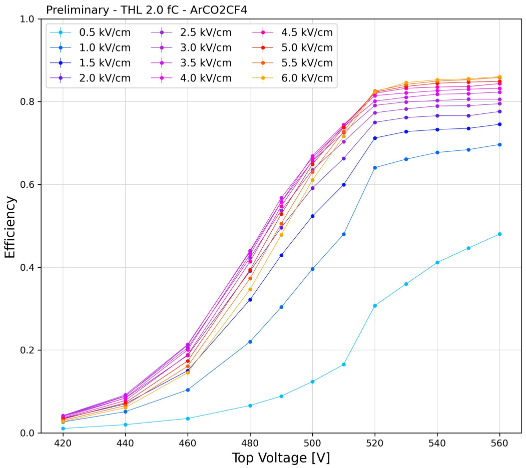
- The **drift field increases the charge collection** in the PEP lines, increasing the average efficiency, but only if the **amplification field is high** enough

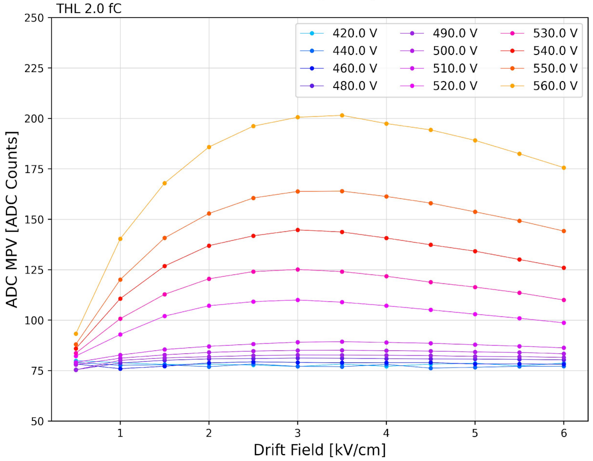
  Otherwise, you lose acceptance by lower collection efficiency in the holes

To be confirmed with track-based efficiency (ongoing)

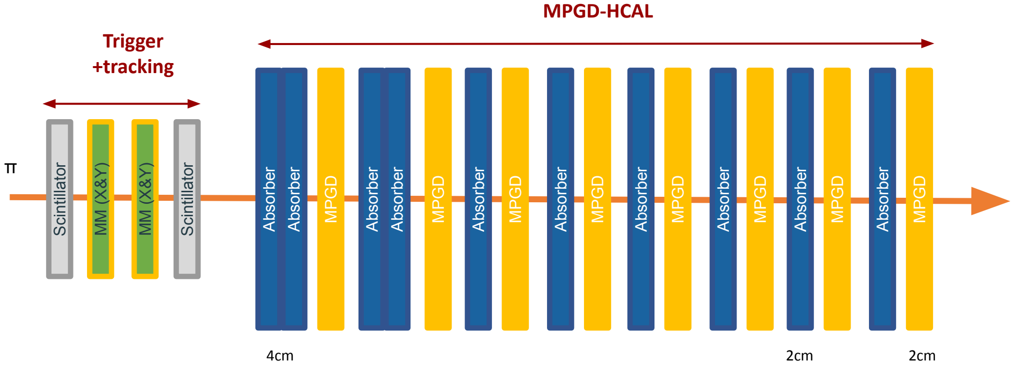


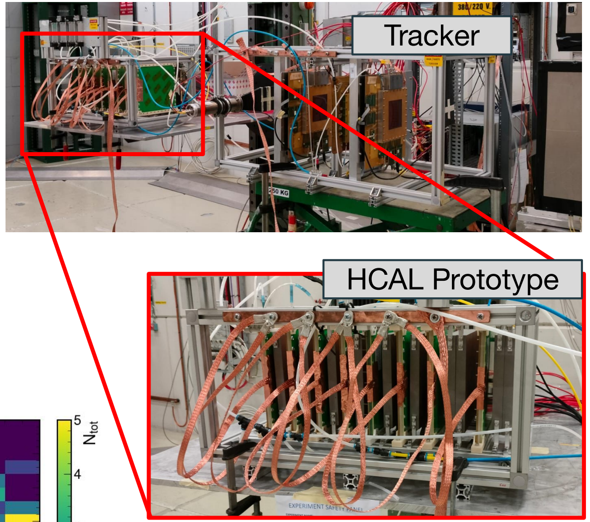






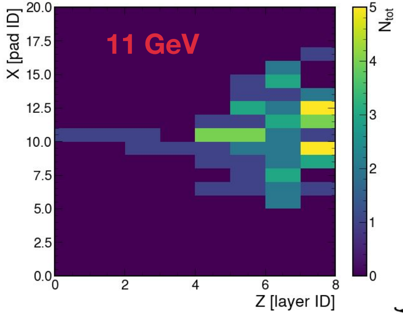
Calorimeter prototype at PS test beam

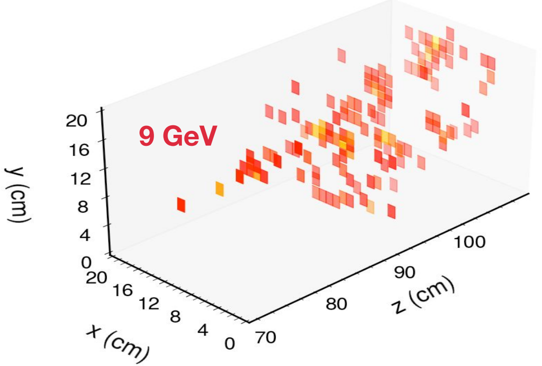




Two test beams at PS with calorimeter prototype
(September 2023, July 2024)

- Goal: **measuring** the energy resolution of a 1 λ calorimeter prototype with 1-10 GeV pions beam
- Developed **G4 simulation** for the **small prototype**, including a **digitization algorithm** to account for charge-sharing among adjacent pads and detector efficiency
- **Issue for 2023:** problematic electronics for the first 2 MPGD layers → taken into account for data/MC comparison





Pion shower studies

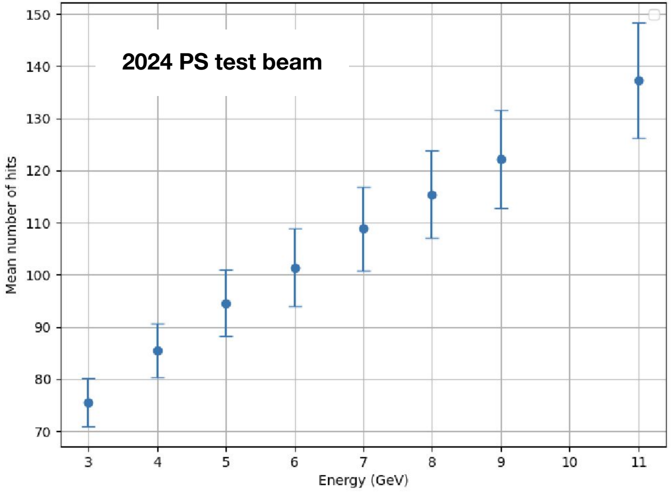
Preliminary

Preliminary results for digital readout (hit charge not used)

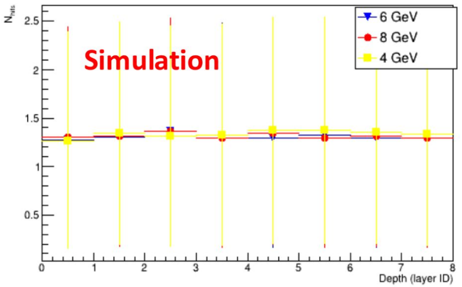
- MIP events identified as having at most one hit per layer
- Good **data/MC comparison** in number of hits per shower
- Good **linearity** in number of hits with energy

  Saturation at high energy due to shower containment

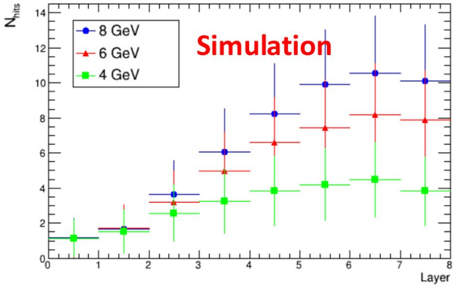
Studies to fully exploit all the data are ongoing

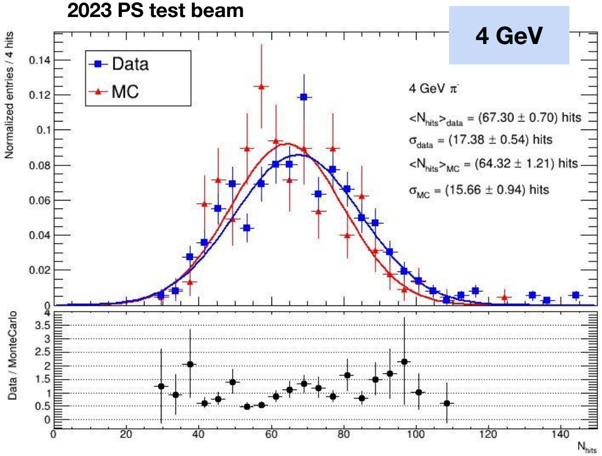


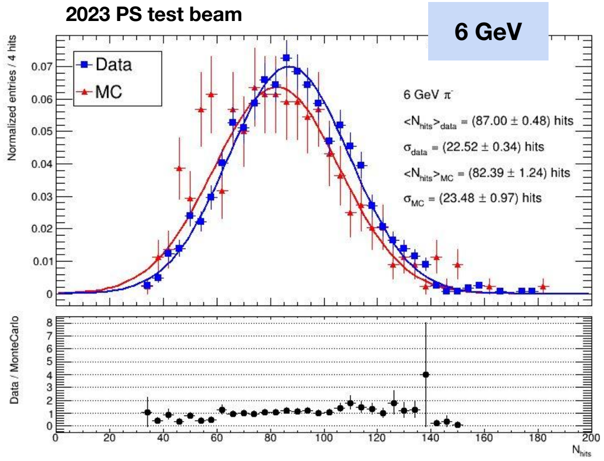
MIP-like events



Shower events







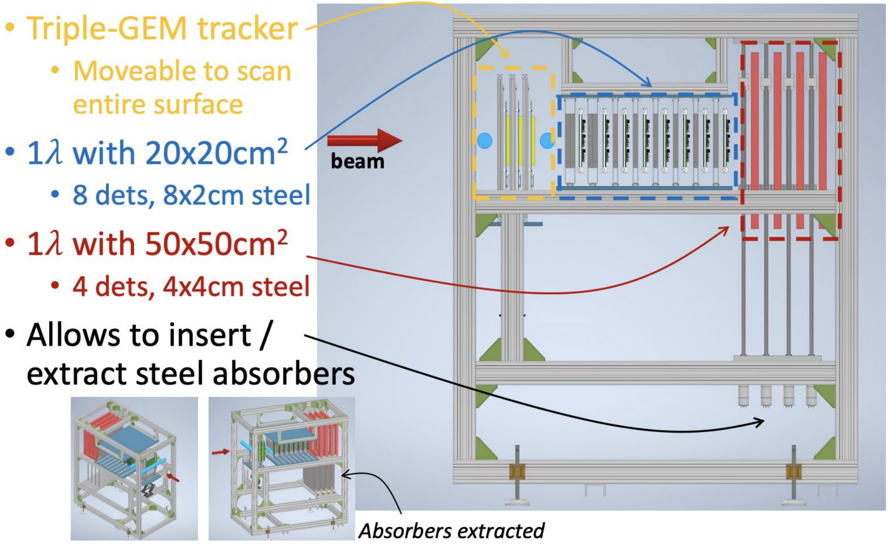
Plans for 2025

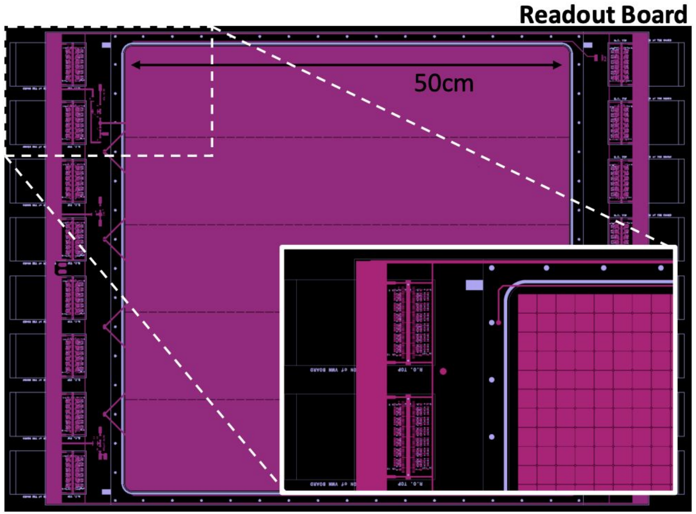
1. Development of a new cell **prototype of ~ 2 λ**:
   - New 50×50 cm^2 detectors to be produced in beginning of 2025:
     121 mm^2 pads, read out by 16 APV/VMM cards
   - 8 old 20 x 20 cm^2 chambers + 4 **new 50 x 50 cm^2** chambers
   - To be operated in **common test beam with CRILIN** (Muon collider ECAL)
2. Continuing integration with **VMM** and testing **FATIC3**

The majority of data still has to be analyzed:

- Energy resolution using **semi-digital** approach
- Tracking data with **VMM**
- **Timing, timing, timing**

Thanks to Rui and the MPT workshop for all the support and discussions!





Conclusion

Development of MPGD-HCAL ongoing in **simulations** and **hardware**

- Tested 12 MPGDs and small cell calorimeter within RD51 **common project**
- In 2024 we consolidated previous 2023 results with present prototypes in two test beams:
    - SPS: efficiency and acceptance, response uniformity, field optimizations
    - PS: test of a fully equipped 8 MPGD layers prototype

  Analysis focusing on timing and energy resolution now
- First integration with VMM performed, with good results

2025 plans:

- 4 **large detectors** (50×50 cm^2) to be built in 2025:
    - Design **optimization** to exclude cross-talk and simplify manufacturing
    - Ongoing work on designing a mechanical structure hosting 8 MPGD layers 20×20cm^2 + 4 new 50×50cm^2 MPGD layers
- **Electronics**: further testing with **VMM** + integration with **FATIC3** (but looking for synergies as well)

Further on:

- Understanding most **suitable technology** between MicroMegas, μ-RWELL, RPWELL
- Producing **50×100 cm^2 detectors**
- Producing detectors with **integrated electronics and cooling**

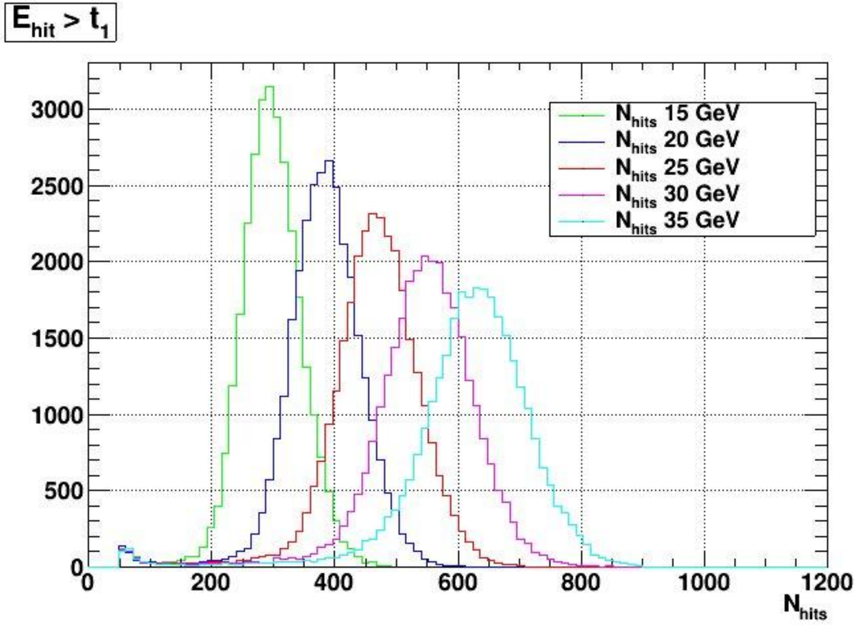
Backup

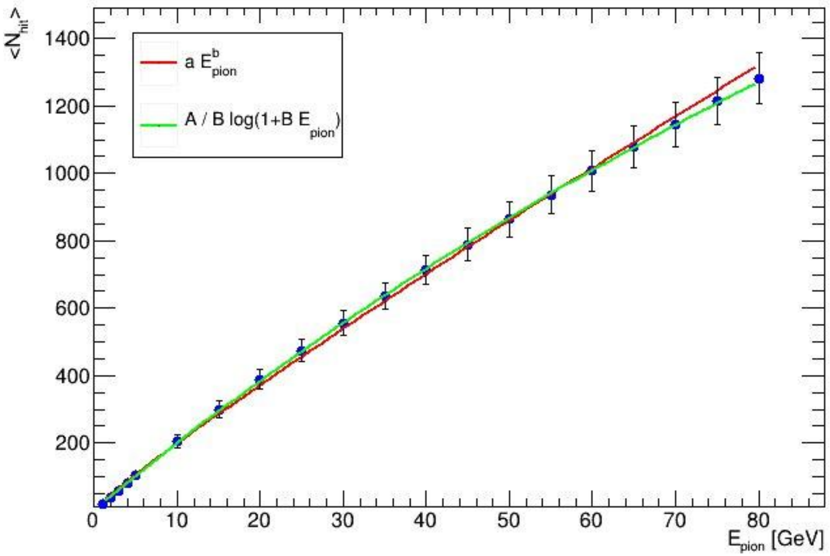
Simulation: Digital readout

Preliminary

- **Digitization:** 1 hit --> 1 cell with energy deposit higher than the applied threshold

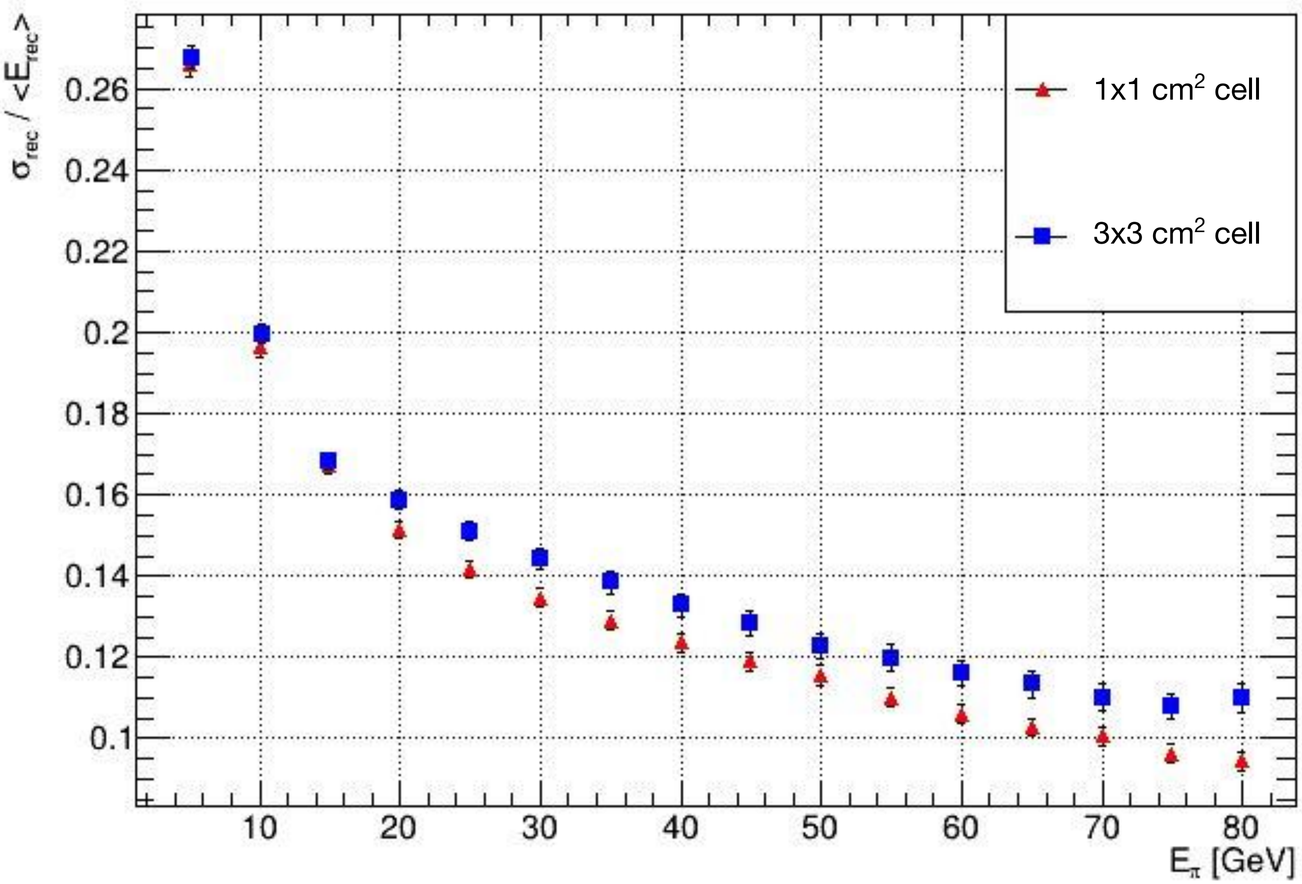
- **Calorimeter response function:** $<N_{hit}>=f(E_\pi)$
- **Reconstructed energy:** $E_\pi=f^{-1}(<N_{hit}>)$





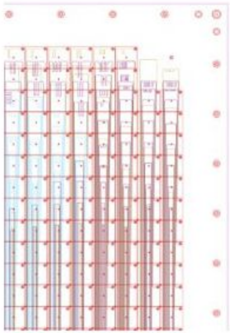
Simulation: Semi-Digital readout

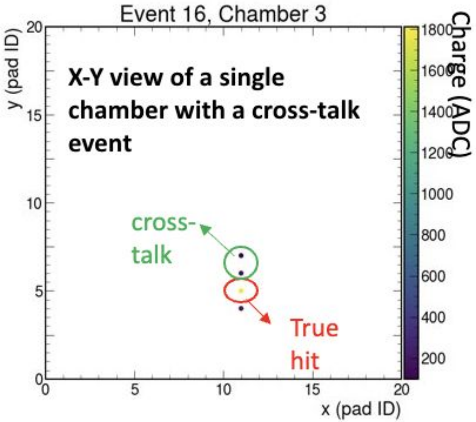
Preliminary



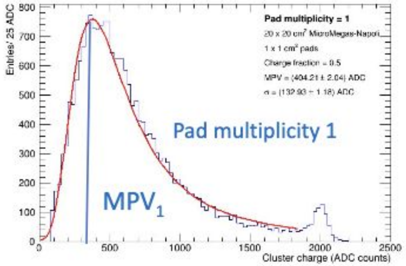
Cluster reconstruction

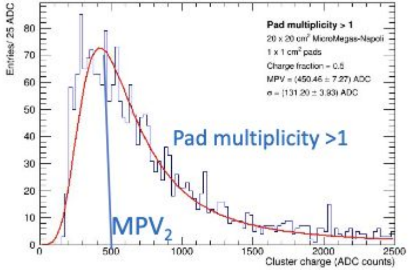
Preliminary

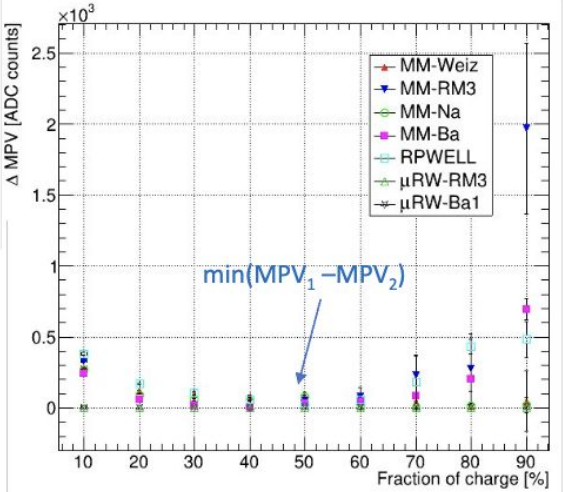




High probability of **cross-talk** effect observed among adjacent pads due to routing of the vias connecting pads to the connectors







Developed ad-hoc **clustering algorithm** based on charge sharing criterium

- Selected pad with **highest charge** Q_{max}
- Add a second pad if $Q = 50\% \ Q_{max}$

Detector uniformity and inefficiency

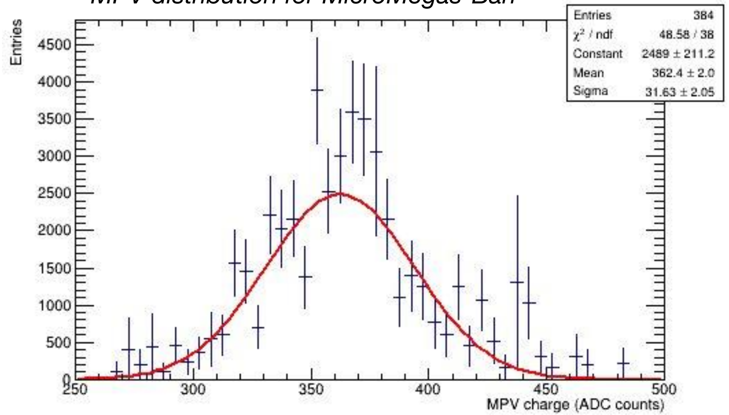
Preliminary

Response uniformity measured using clusters matching muon tracks

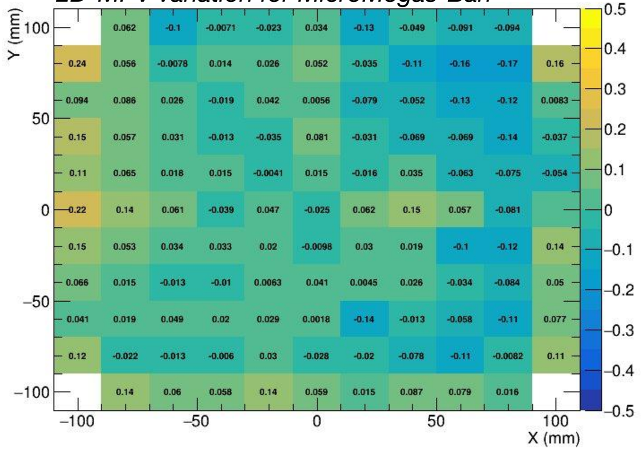
- Good uniformity for **MicroMegas** (~10%)
- Regions of non-uniformity observed on some **µ-RWELLs** → under investigation in lab
- Slightly worse uniformity for **RPWELL**

Detector	Uniformity (%)
MM-RM3	$(12.3 \pm 0.8)\%$
MM-Na	$(11.6 \pm 0.8)\%$
MM-Ba	$(8.0 \pm 0.5)\%$
RPWELL	$(22.6 \pm 4.7)\%$
μrw-Na	$(11.3 \pm 1.0)\ \%$
μrw-Fr2	$(16.2 \pm 1.7)\%$
μrw-Fr1	$(16.3 \pm 1.1)\%$

MPV distribution for MicroMegas-Bari

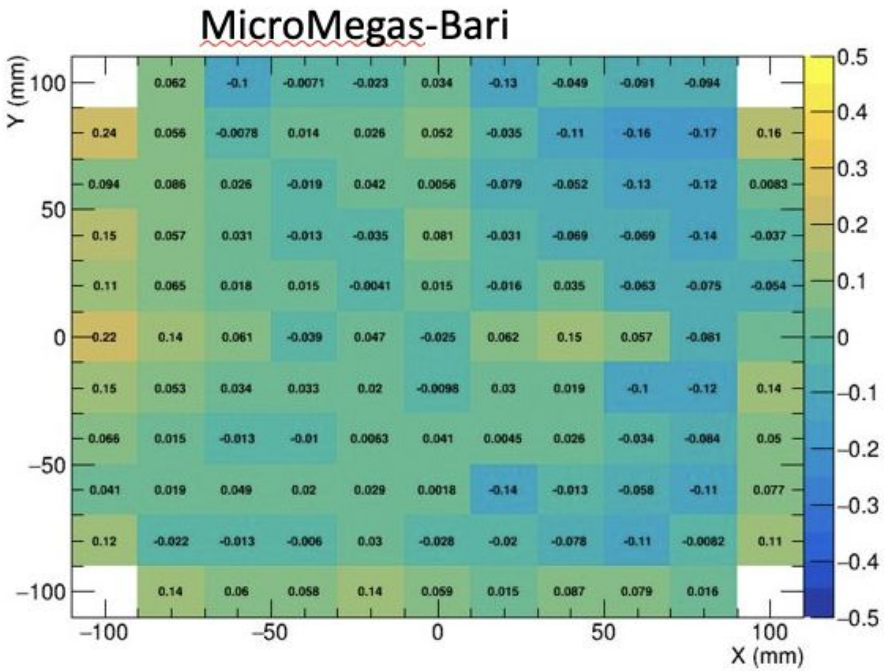


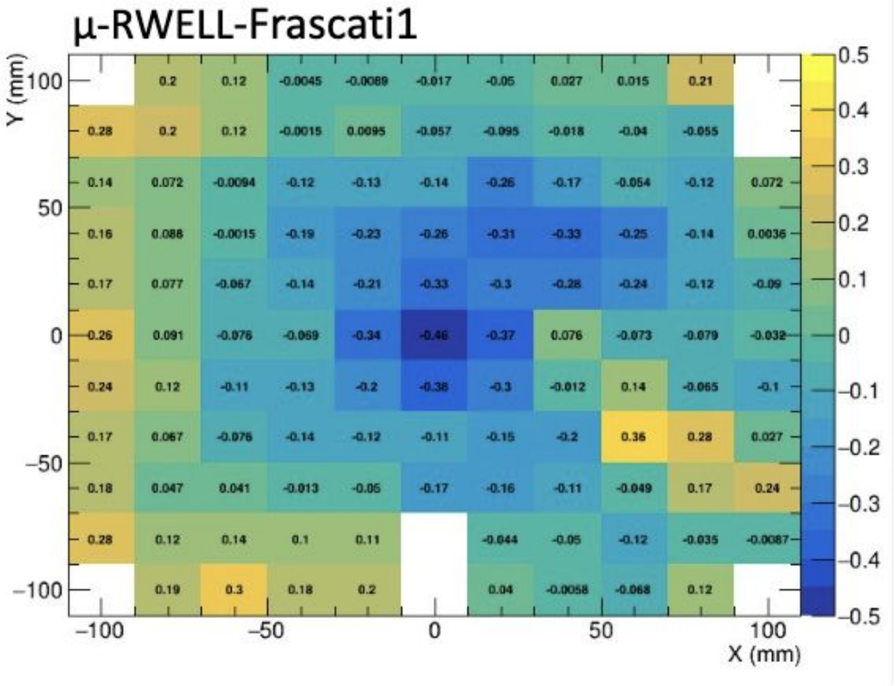
2D-MPV variation for MicroMegas-Bari



Response uniformity

Preliminary





Detector performance (2023)

Test beam **analysis workflow**:

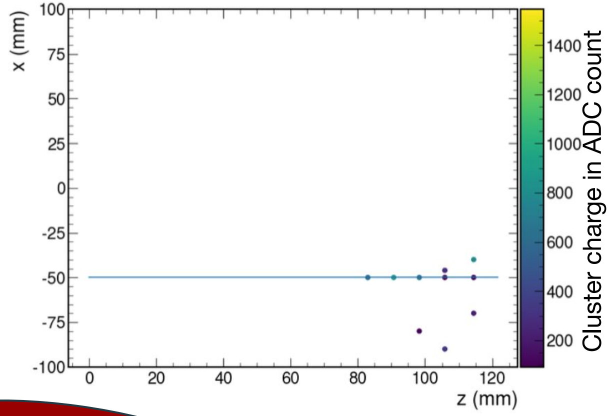
- **Tracking detectors unused** in reconstruction for the moment (high noise → possible to recover the tracker offline, currently ongoing). **Tracks built using MPGDs** under test (5 out of 6 at a time)

Track residuals:

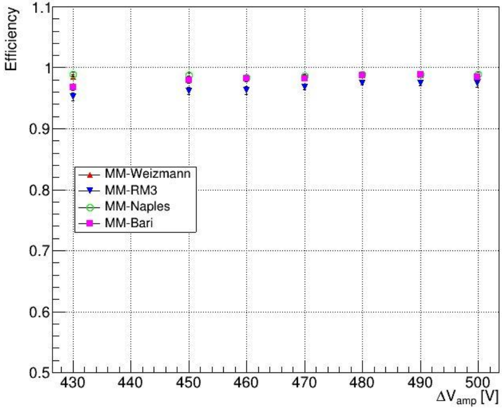
- Observed high probability of **cross-talk** between pads *due to routing of readout vias from pads to front-end*
- Patched **offline** by clustering pads based on charge sharing fraction

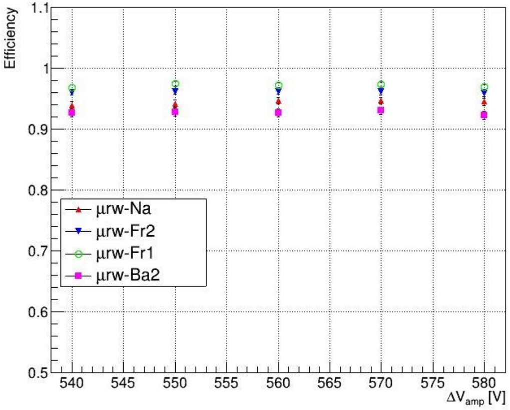
High average **efficiency** (detectors always operated at plateau)

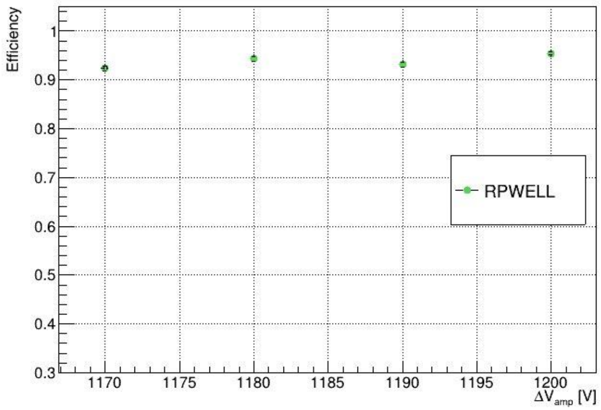
Track reconstructed using 4 detectors out of 5



Preliminary



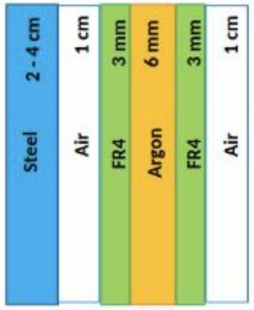




G4 simulation: small prototype

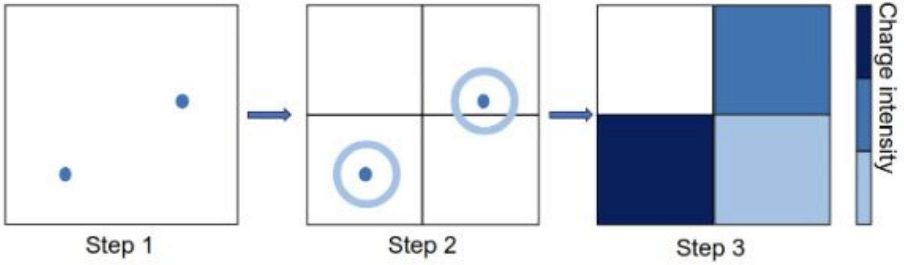
Preliminary

- Small detector geometry implemented
  - 8 layers of alternating of 2 cm stain-less steel absorbers and MPGD
    - First 2 layers with 4 cm absorbers to increase probability of shower development in the first layers
  - 20x20 cm^2 active surface
  - 1x1 cm^2 pad granularity
- Pion gun of energy range available at PS (4 – 8 GeV)

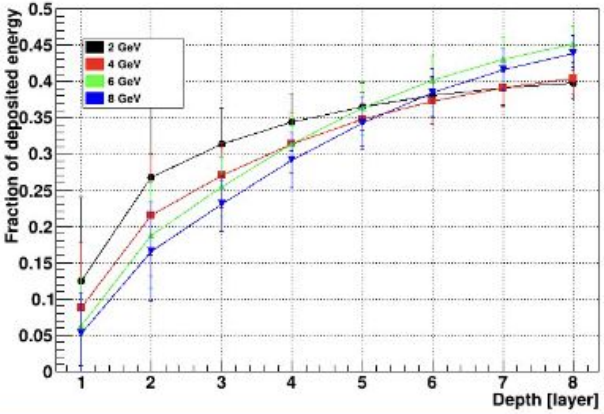


- **Digitization algorithm** implemented to account for charge-sharing among adjacent pads and detector efficiency

Digitization algorithm



Shower containment



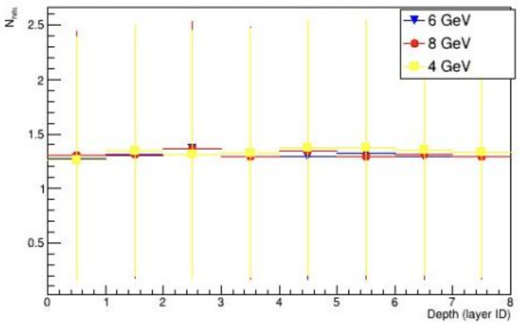
PS data / G4Sim prototype - event selection

Preliminary

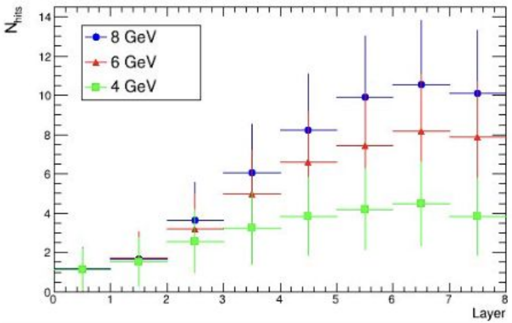
Event **selection criteria** supported by **simulation** using MC truth

- MIP-like events:
  - single hit in each layer
- Shower events:
  - more than 4 hits per layer starting from layer 3

MIP-like events - simulation

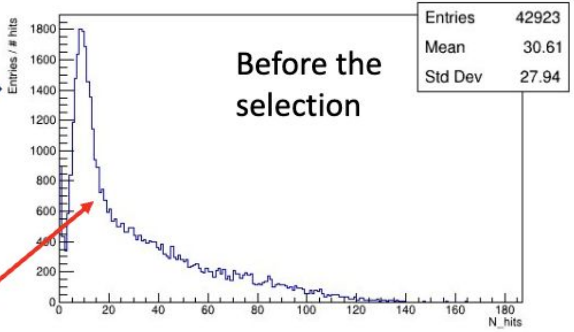


Shower events - simulation



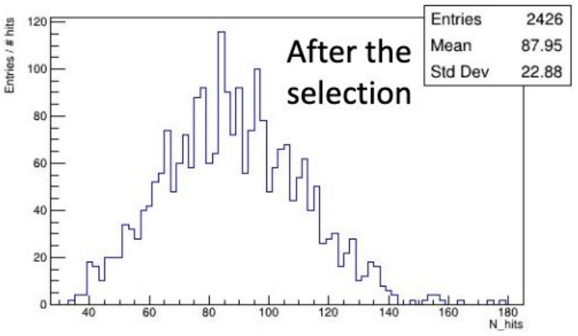
Distribution of the **number of hits** in all active layer from the **experimental data**

Number of hits for all events



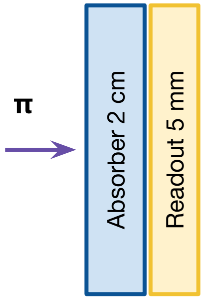
Peak at ~ 10 hits -> MIP-like events

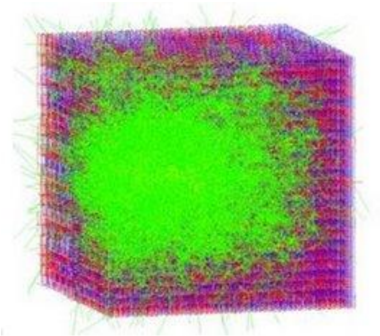
Number of hits for showers event



Simulation: shower containment studies

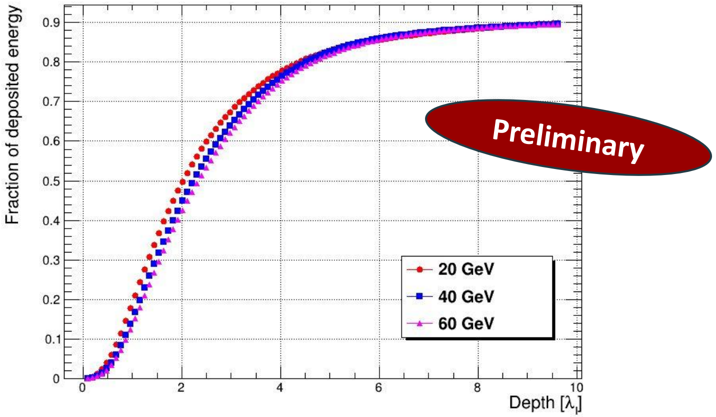
Geant4 simulation of a 100 layers calorimeter



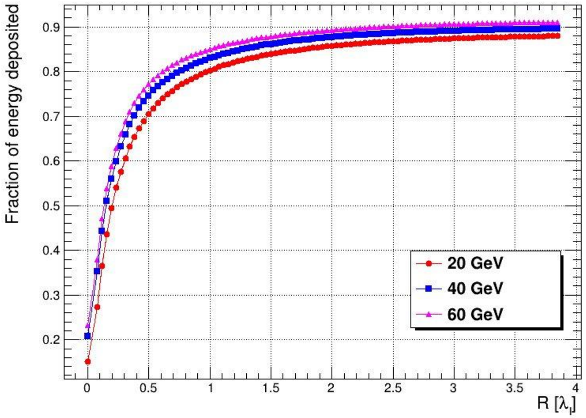


- Geometry: 2 cm iron, 5 mm gas (Ar/CO_2)
- Readout granularity → cell size of
  - 1×1 cm^2
  - 3×3 cm^2
- Pion guns of different energies
- **Result:** longitudinal containment in ~10 λ_I, transversal in ~2 λ_I

Longitudinal shower containment



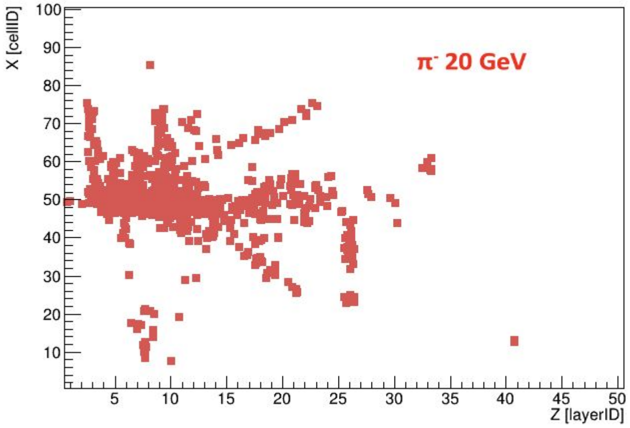
Transversal shower containment



Simulation: Digital and Semi-digital HCAL

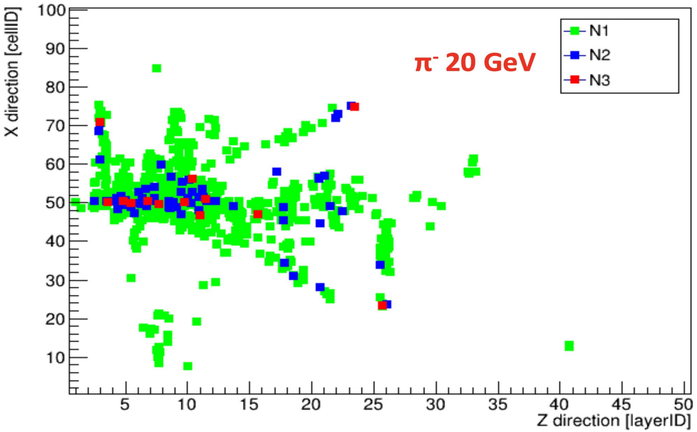
Digital Readout

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



Semi-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



The case for a muon collider

A high-energy lepton collider: combining cutting edge discovery potential with precision measurements

Motivations

- No synchrotron radiation: **higher energy** reachable than e^+e^-
- **Point-like** particles: comparable physics reach at lower centre-of-mass than pp
- Good **luminosity** to beam power ratio: high s-channel cross sections at high energy

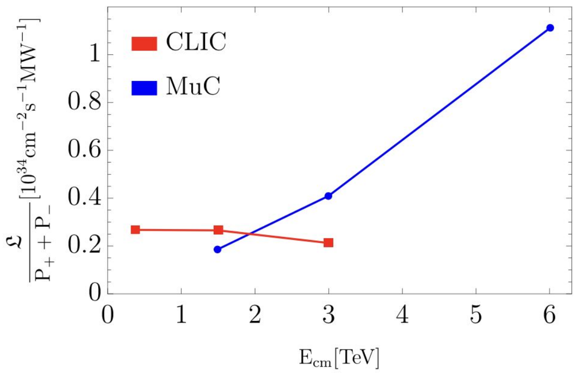
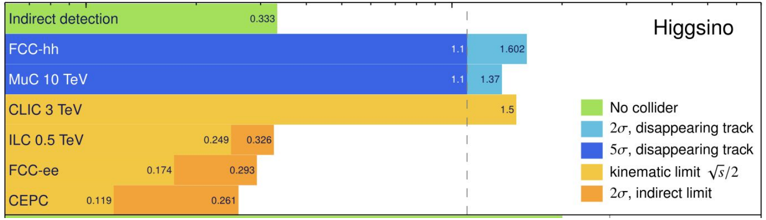


Fig. 10 MuC luminosity normalised to the muon beam power and compared to CLIC, for different beam energies

Towards a muon collider. *Eur. Phys. J. C* **83**, 864 (2023)

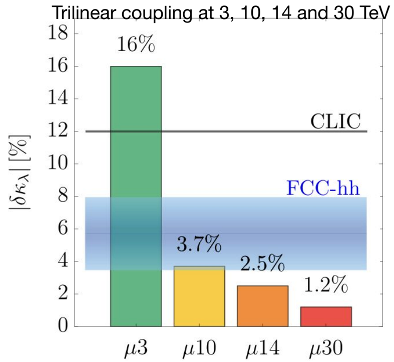
Physics reach

- Potential for new **discoveries**
- Precise **Higgs** studies
- Direct reach for physics coupled to **muons and neutrinos**



	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for the MuC



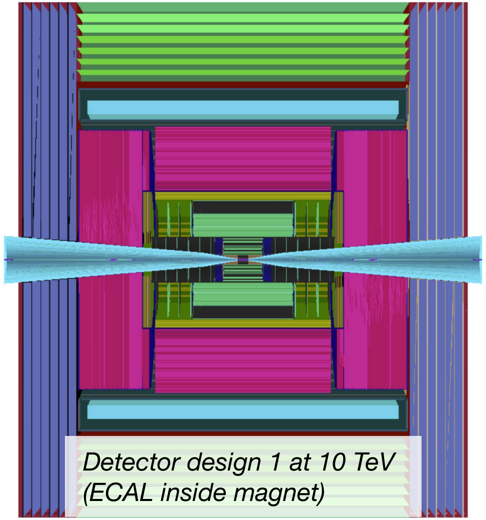
Detector design for 3 and 10 TeV

Design constrained by

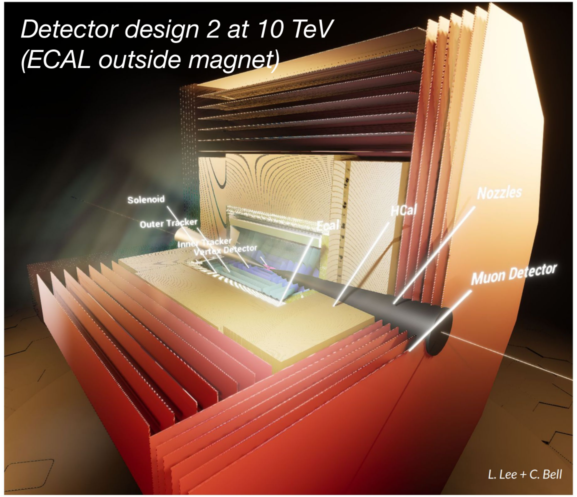
- **BIB** levels
- **Machine** design: focusing quadrupoles at **±6 m** from IP
- **Physics** requirements: detector has to be sensitive to
  - **Central** objects from massive particle decays
  - **Low-p_T** objects from standard model processes (e.g. Higgs decays)
  - **Non-standard** signatures (e.g. displaced vertices and jets)

Has effects on

- detector design
- detector technologies
- software (e.g. reconstruction)



Detector design 1 at 10 TeV (ECAL inside magnet)



Detector design 2 at 10 TeV (ECAL outside magnet)

Experiment requirements

- Need **shielding** (nozzles) in forward region
- For BIB rejection:
  - High-**granularity** to handle high occupancy
  - Excellent **time resolution** to reject asynchronous BIB component
  - Good **energy resolution** to reject soft BIB spectrum by thresholds

Can be reached with technology available at HL-LHC

Two experimental designs

- **Two interaction points** allowed by the machine
- Generic detector design adapted **from CLIC**

  Several improvements moving to 10 TeV, also valid for 3 TeV design
- Main change from 3 to 10 TeV design: moving **solenoid inside calorimeters** (higher B field)