R&D of MPGD-based HCAL for a Muon Collider Experiment

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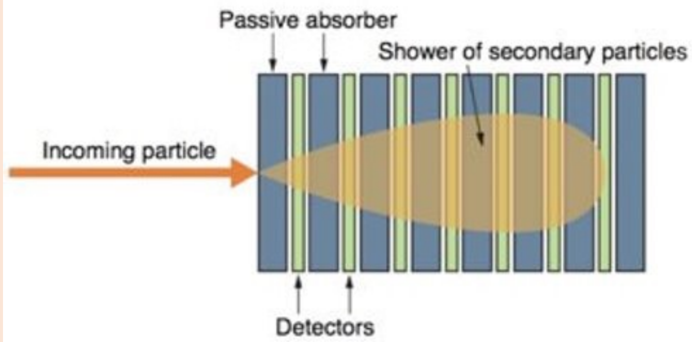
Why MPGD based HCal?

Proposal of a sampling calorimeter with **Micro-Pattern Gas Detector** as active layer

Advantages

- Radiation hardness
- High rate capability (MHz/cm^2)
- Suitable for fine granularity
- Good space ($> 50\mu m$) and time resolution ($5 - 10\ ns$)
- Good response uniformity (~10%)
- Relatively cheap for large area instrumentation



μRWell and resistive **Micromegas** best MPGD options for reducing discharge effects

MPGD-based HCAL development: the strategy

From simulation to prototype

Simulation in G4 to study the response to hadronic showers
- MuCol setup
- Prototype setup

Implementation of the proposed design in the **muon collider full simulation** and study the impact on the reconstruction

Develop a **HCAL cell prototype** to measure the performance with test beam

Additional founding:

- **Obtained in 2021: R&D51 Common project** (15ke/y, 2y) *"Development or resistive MPGD calorimeter with timing measurement"*, P. Verwilligen, INFN (Ba, LNF), RM3
- **Submitted in 2022, PRIN:** «*An Innovative and Radiation Hard Calorimeter Proposal for a future Muon Collider Experiment*», 110k (UniBa) + 140ke INFN

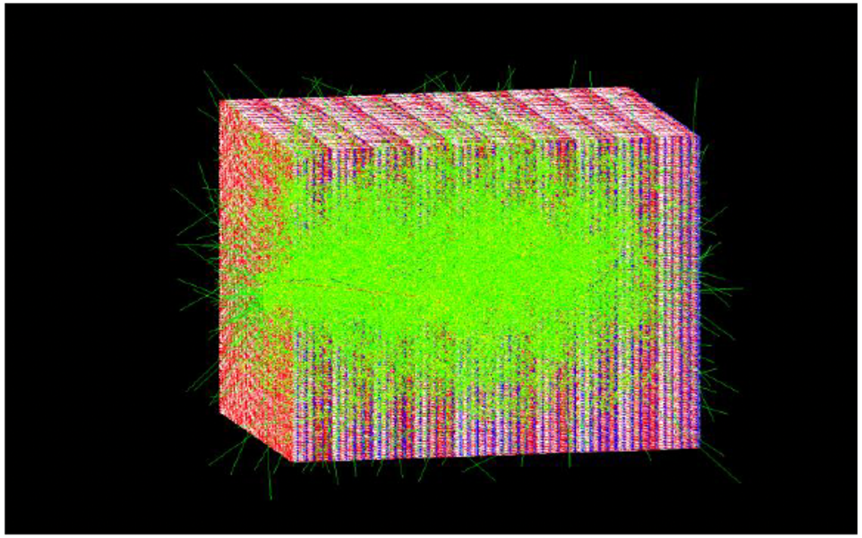
Overview

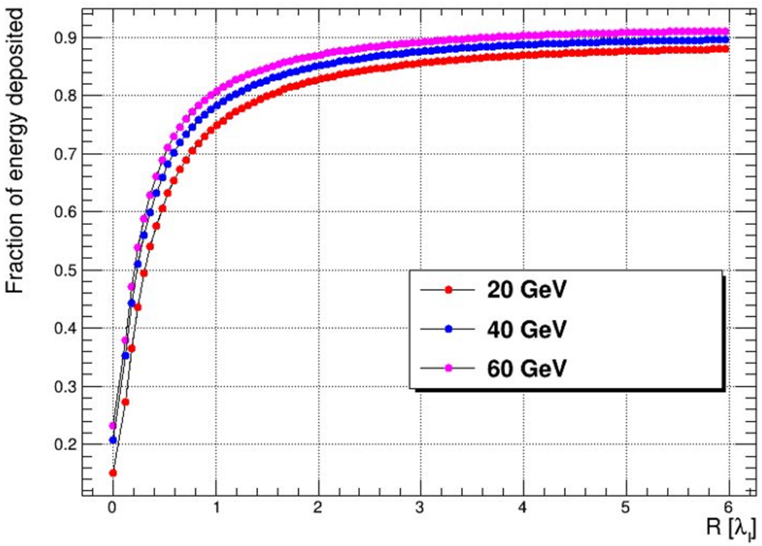
1. MPGD based HCAL for Muon Collider in Geant 4
2. MPGD based HCAL for Muon Collider in Muon Collider Framework
3. MPGD based HCAL Prototype in Geant 4
4. MPGD based HCAL cell Prototype characterization

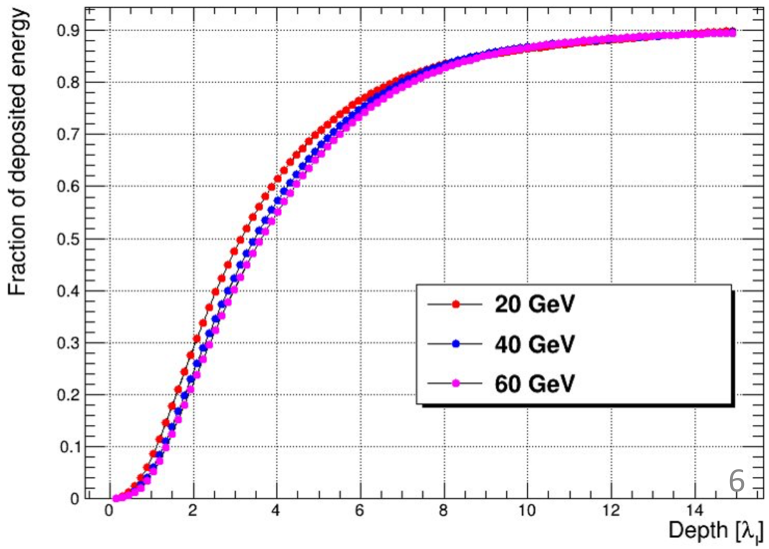
MuCol MPGD-based HCAL in Geant4

G4 simulations: shower containment

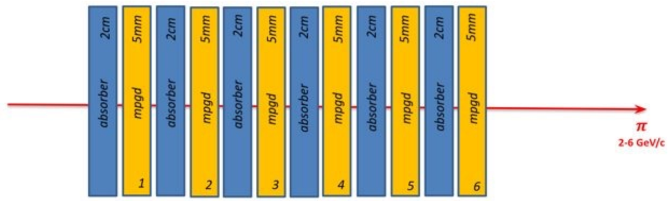
- Implementation of geometry with a sampling
  - 2 cm of Fe (**absorber**)
  - 5 mm of Ar (**active gap**)
- Granularity given by cell of 1x1 cm^2
- Geometry optimization for shower containment
  - 3 $\boldsymbol{\lambda}_I$ for 90% transverse containment
  - 14 $\boldsymbol{\lambda}_I$ for 90% longitudinal containment



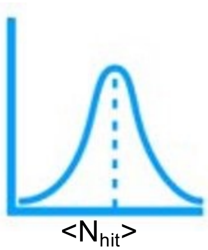




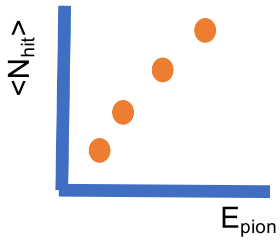
Energy resolution workflow



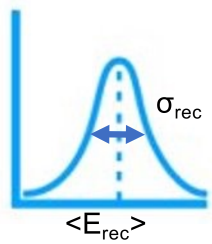
1st step: Get the N_{hit} distribution for each energy value E_{pion} and extract the mean value $\langle N_{hit} \rangle$



2nd step: Plot $\langle N_{hit} \rangle$ as a function of E_{pion} to find the calorimeter response function $N = f(E)$



3rd step: Reconstruct the energy distribution through the inverse response function $E = f^{-1}(N)$ and extract $\langle E_{rec} \rangle$ and σ_{rec}



4th step: Get the energy resolution

parameters fitting $\frac{\sigma}{E[GeV]} = \frac{S}{\sqrt{E[GeV]}} \oplus C$

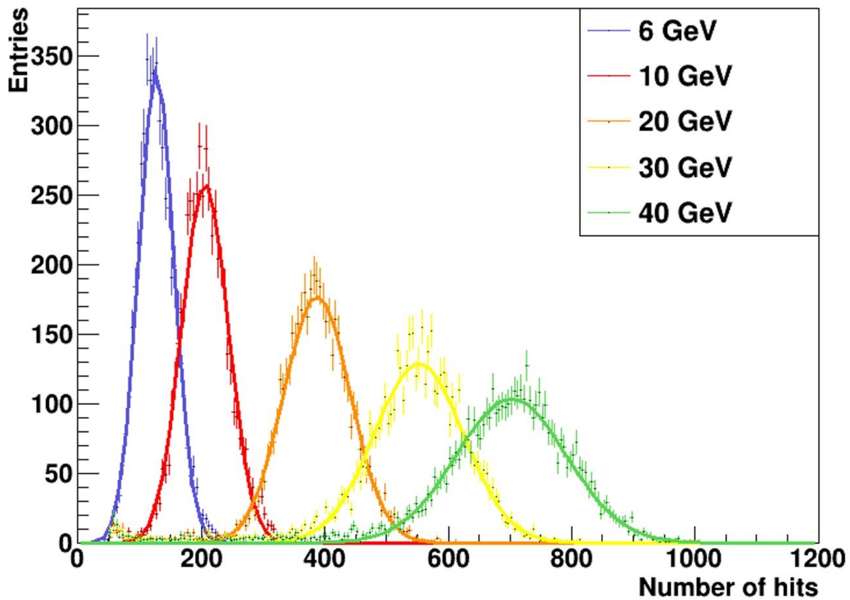
to the data

G4 simulations: energy resolution

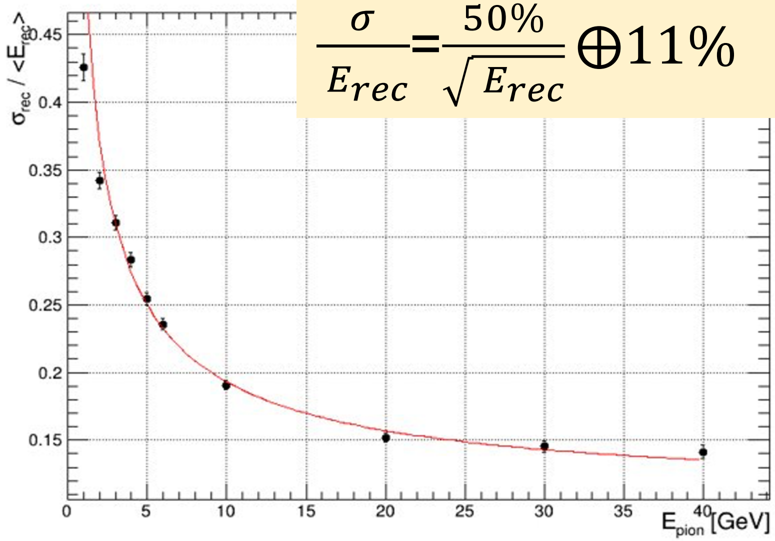
Results presented at PM22:
"*Design and simulation of a MPGD-based hadronic calorimeter for Muon Collider", A. Stamerra*

- Pion guns with energy in 1-60 GeV
- Detector Geometry:
  - 50 layers, 1x1 m²
  - 1x1 cm² cell vs 3x3 cm² cell
- **Digital RO** (single threshold) 1 hit = 1 cell with deposited energy higher than 30 eV
- Response function

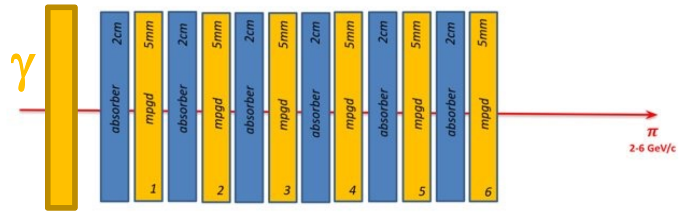
$$N_{hit} = f(E_{pion}) \rightarrow E_{rec} = f^{-1}(N_{hit})$$



$$\frac{\sigma}{E_{rec}} = \frac{50\%}{\sqrt{E_{rec}}} \oplus 11\%$$



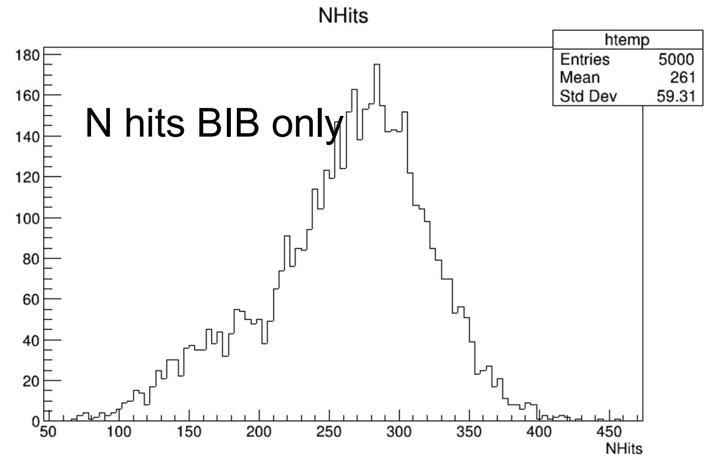
Calorimeter response function – BIB modeling

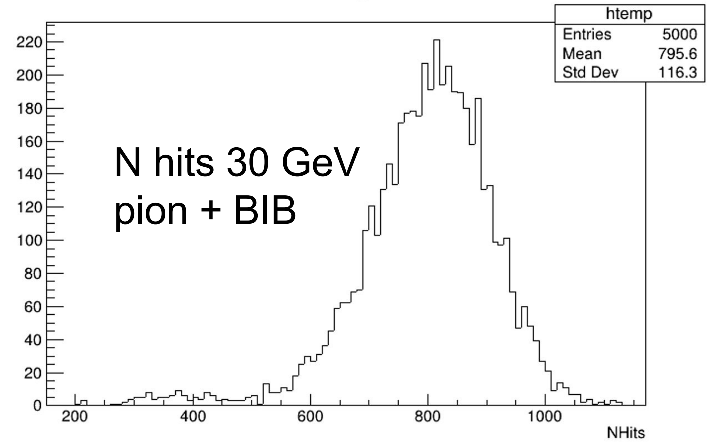


In order to reproduce the Muon Collider conditions of BIB, besides the pion guns a first attempt of BIB model is implemented → Just BIB photons considered for now

- Pion gun, 1 GeV to 40 GeV
- Plane source of photons
    - **3gamma/cm²** per event, Eγ =**1.7 MeV**

- The presence of the photon background complicates the energy reconstruction (shifted peak, increased width, tails)





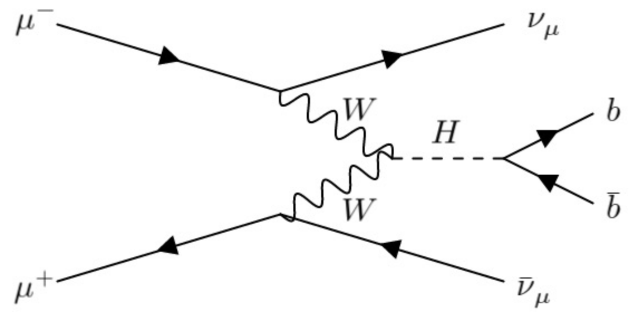
Ongoing:
- study a fit model to perform background subtraction to extract mean number of hits when BIB is included, in order to build the energy response function
- Add neutron bkg
- Implementation of analogic (RO**)**

MuCol MPGD-based HCAL in Muon Collider full simulation

MPGD-based HCal for the Muon Collider

Jet reconstruction performance evaluation

- 10k events produced with Pythia
- 100 BIB events
- Signal events simulated within the detector system with the BIB overlayed
- Full event reconstruction performed
- x2 geometries



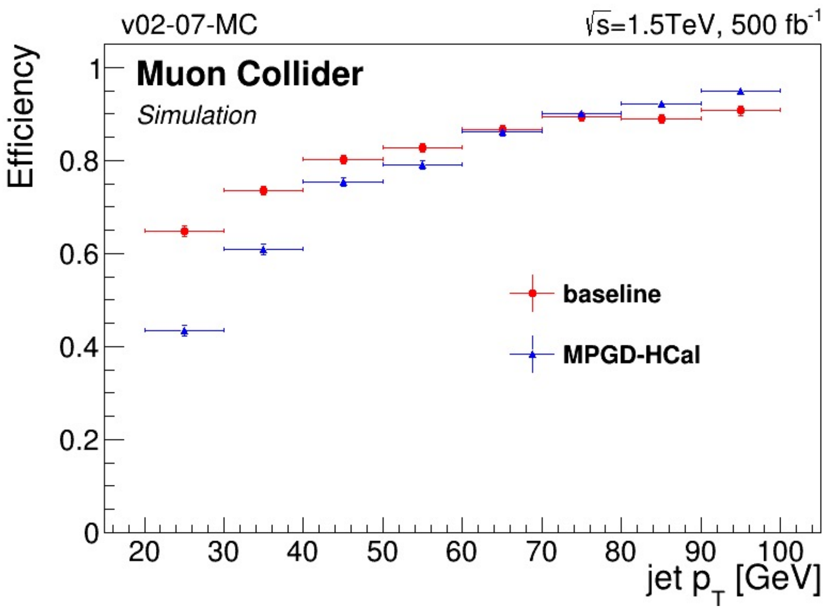
Benchmark process: $\mu^+\mu^- \rightarrow H\nu_\mu\overline{\nu_\mu} \rightarrow b\bar{b}\nu_\mu\overline{\nu_\mu}$

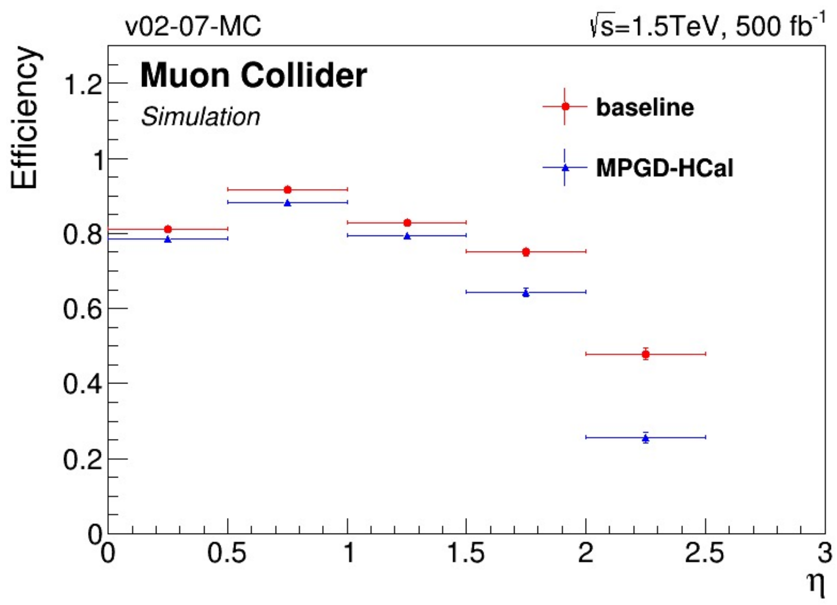
1.5 TeV center-of-mass energy

- HCal geometry in the Muon Collider software
  - Cell granularity: 3x3 cm^2
  - Active layer depth: 3 mm
  - Absorber depth: 20 mm
- Digital readout in both options
- **Baseline HCAL**: scintillators (Polystyrene) + Steel
- **MPGD-Hcal:** Argon + Iron
- Hit digitization: different hit energy smearings due to the different physical process involved in signal formation and different thresholds applied in the two HCal implementations

Jet Reconstruction Efficiency

PRELIMINARY

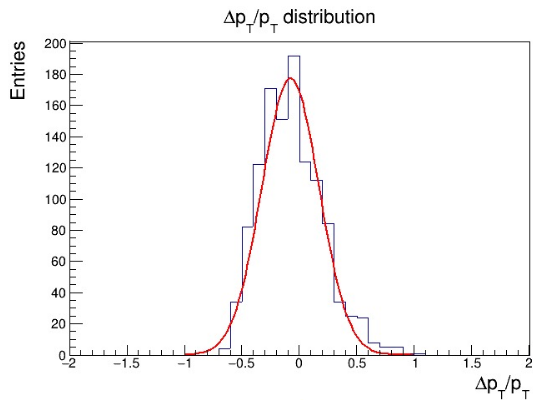




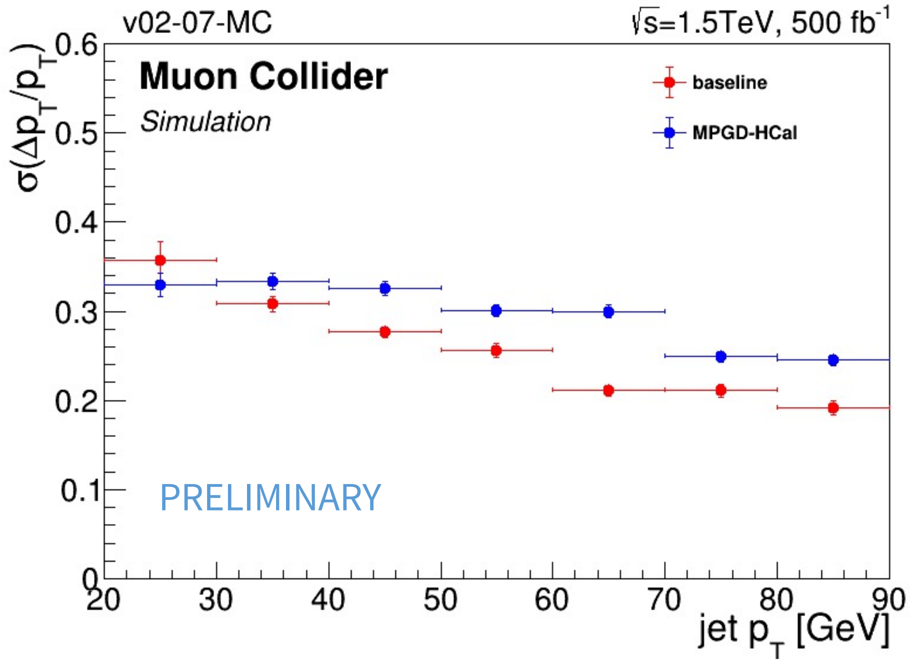
Jet reconstruction efficiency estimated with the MPGD-HCal is comparable to the baseline one.

To be understood:
Drop at low pT, high eta with MPGD based geometry

Jet p_T Resolution



Jet momentum resolution extracted with a gaussian fit on $\Delta p_T / p_T$ ($\Delta p_T = p_T$ gen - p_T reco). Small sample statistics → suboptimal fit quality



The jet p_T resolution evaluated with the new MPGD-HCal is comparable with the baseline.

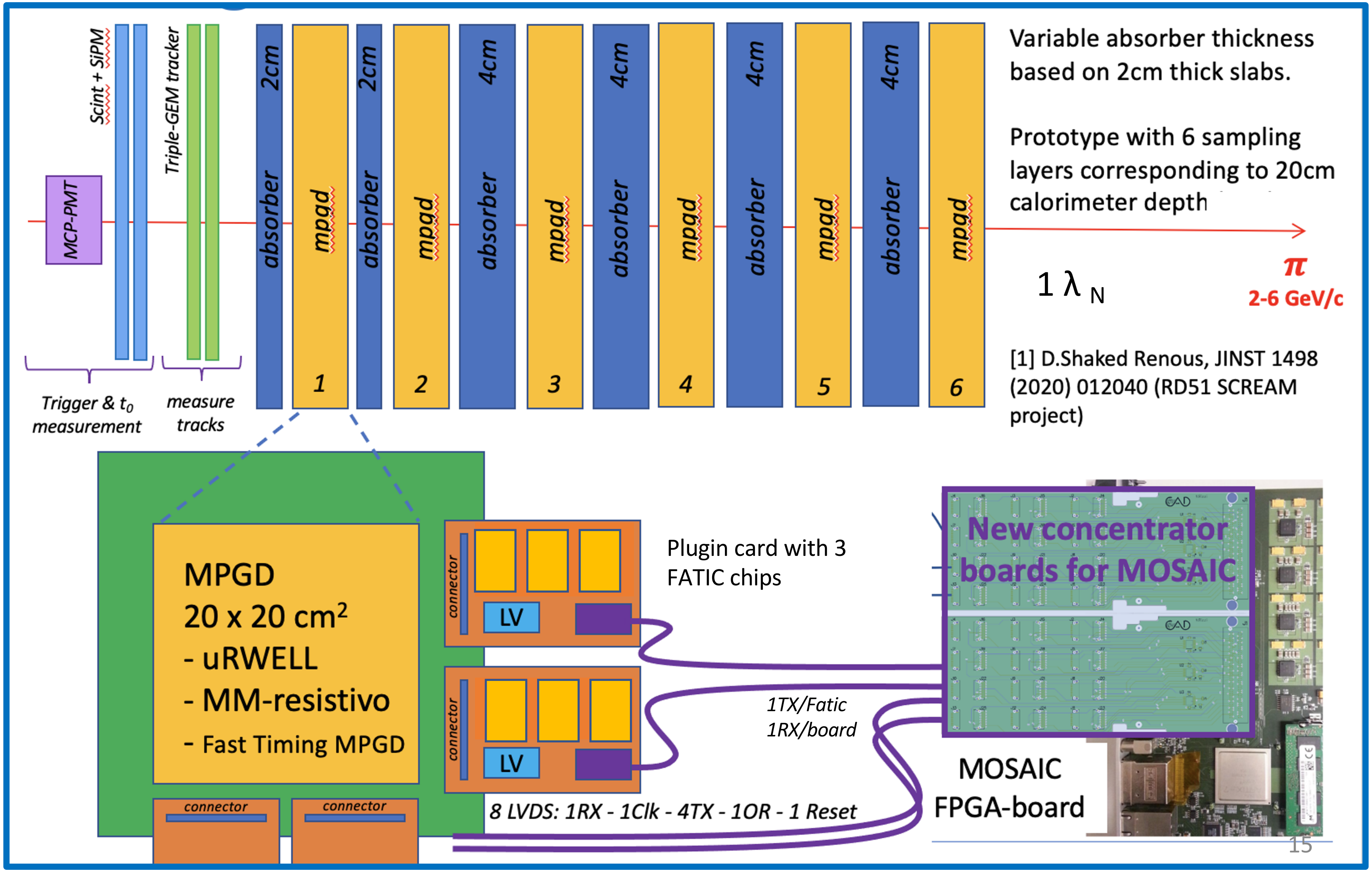
Plans:

- Implementation of analogic readout
- Study the reconstrunction performance as a function of cell granularity
- Study response to single pions
- Simulate the process and the BIB at higher center-of-mass energies

MPGD-based HCAL Prototype in Geant4

Prototype development: MPGD-based HCAL cell

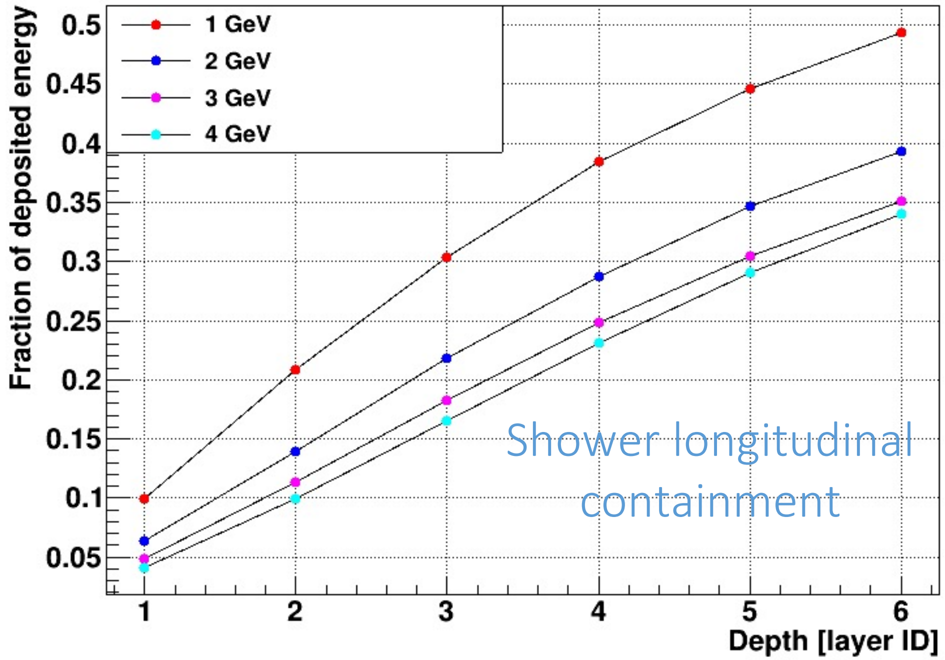
Common project
Cofounded by RD-51

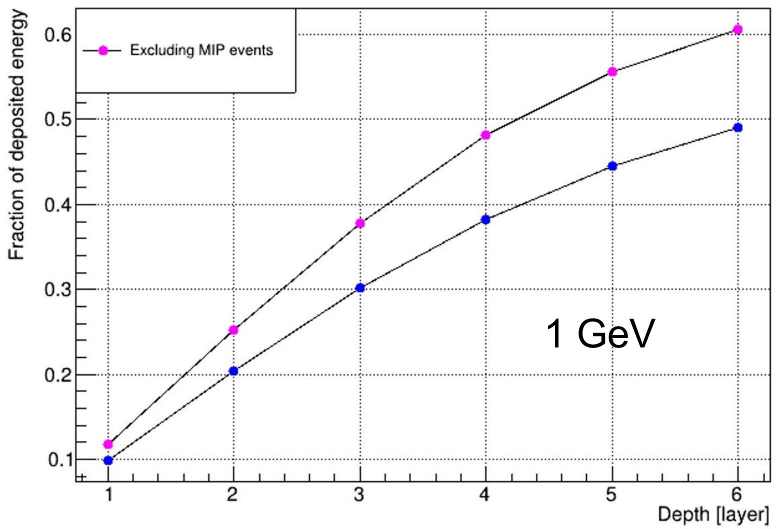


Hadronic shower containment

Implemented geometry
6 layers of 20x20cm^2
- 4 cm of Steel (absorber)
- 1 mm of copper (for the cathode)
- 5 mm of Ar/CO2 (active gap)
- 1 mm of Fr4 (for the PCB RO board)
- Granularity given by cell of 1x1 cm²

Pions with energy in 1,6 GeV

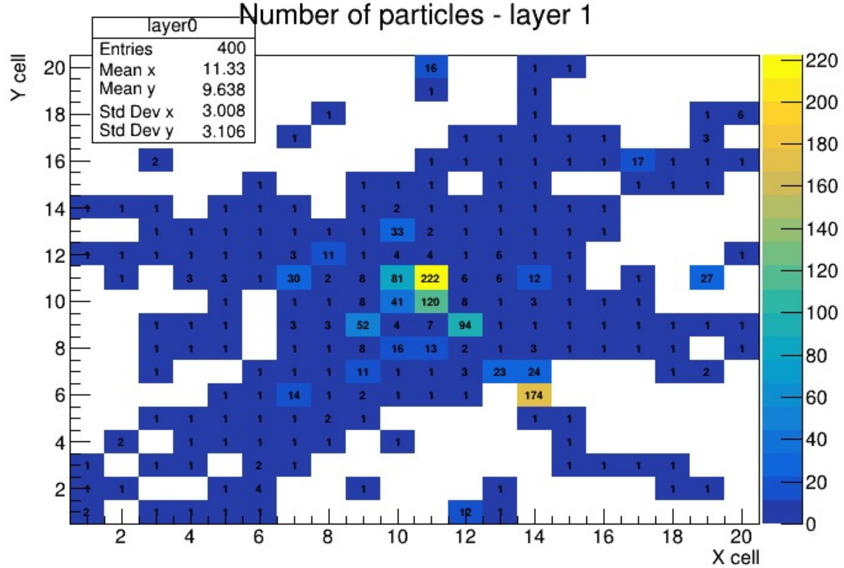




To be understood:
Full shower containment is not reached, even with
- increased prototype size
- MIP exclusion in fraction of deposited energy computation

G4 study of analogic Readout

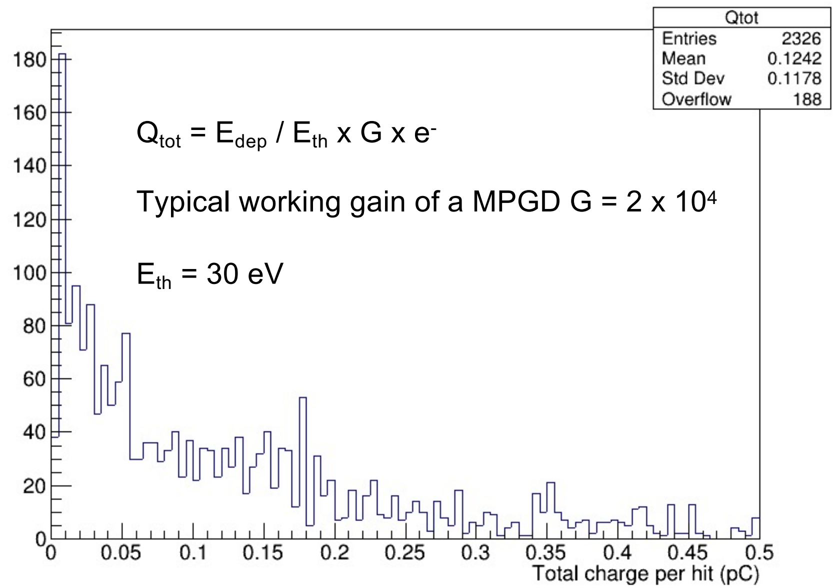
- Semidigital/analogic RO (FATIC) would allow to improve the energy resolution
- First study carried out in order to understand the configuration of the FATIC chip to be used on the prototype in test beam environment → 1 GeV pion
- Compute electric charge released by the particles in the hadronic shower in a 1x1cm^2 cell in each layer



Extract the energy deposit for the single hit E_{dep}

Conversion from E_{dep} into charge arriving to Front End electronics

Hits Charge distribution



MPGD-based HCAL Prototype

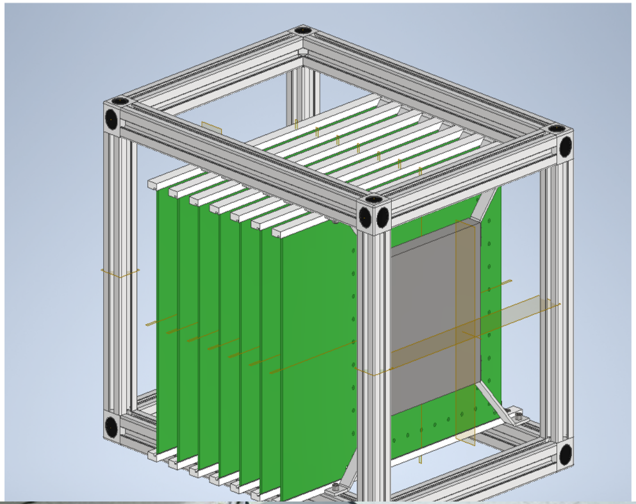
Prototype status

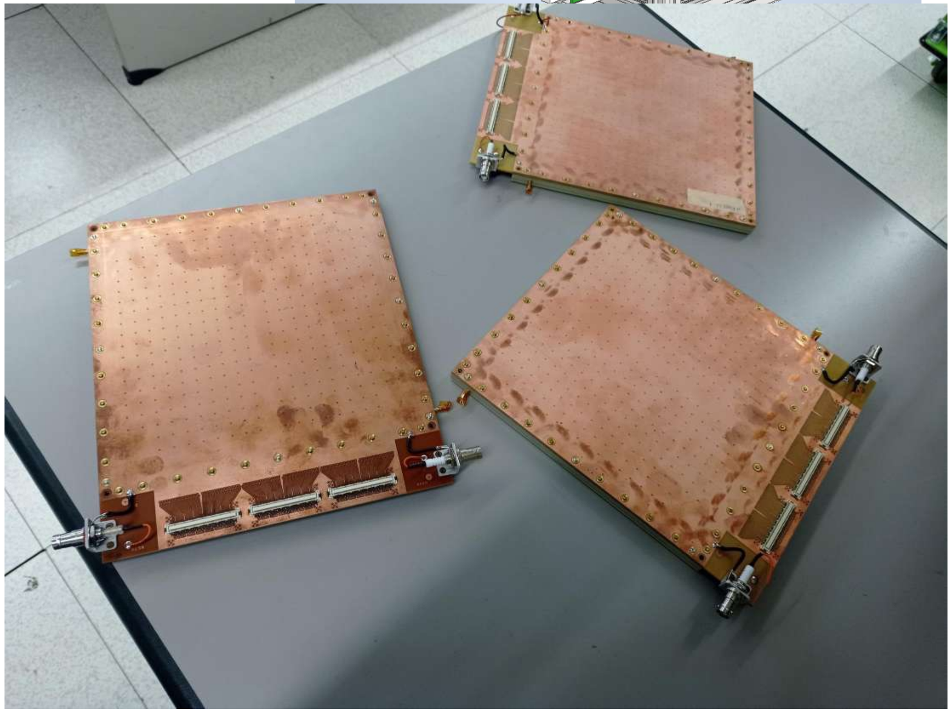
HCAL cell Protoype design:

- 6 MPGD based active layers + 6 steel absorber layers ($1\lambda_N$)
- RO by FATIC + MOSAIC

Detectors and ROB design and construction by CERN MPT Workshop & INFN:

- 20x20 cm^2 detectors
- $1cm^2$ pixels→ 384 pixels
- Common Readout board (uRWELL, uMEgas)





Detectors now ready and delivered on sites last week:

8 uRWELL, 4 microMegas

→3 detectors shipped to Bari, 2 CERN, 3 Roma3, 4 LNF

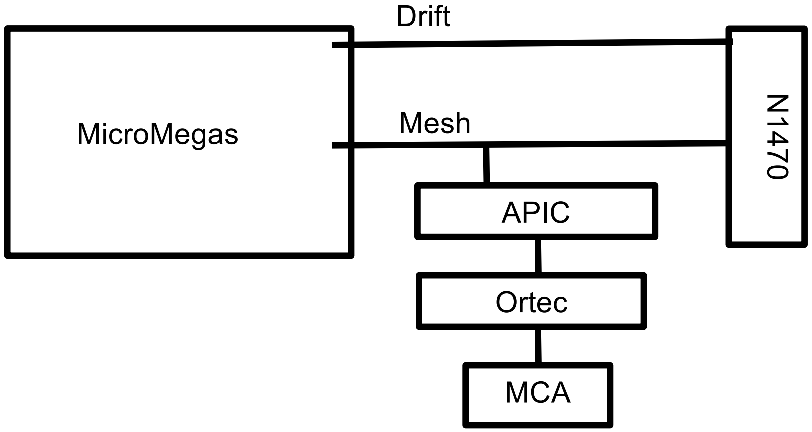
- Preliminary test done at CERN after Rui delivery (next slides)
- Study the two MPGD technologies with the goal to maximize the Hcal cell performance

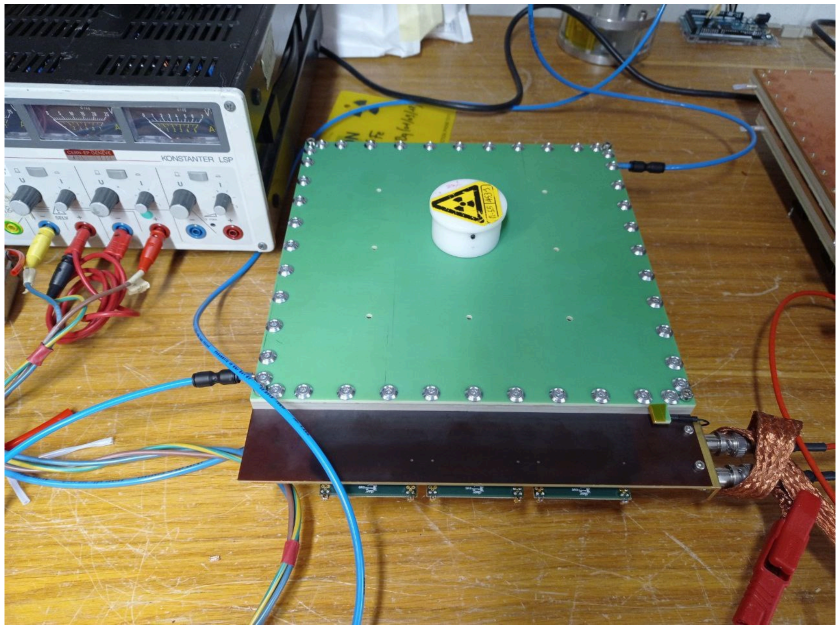
Very preliminary results: µMegas

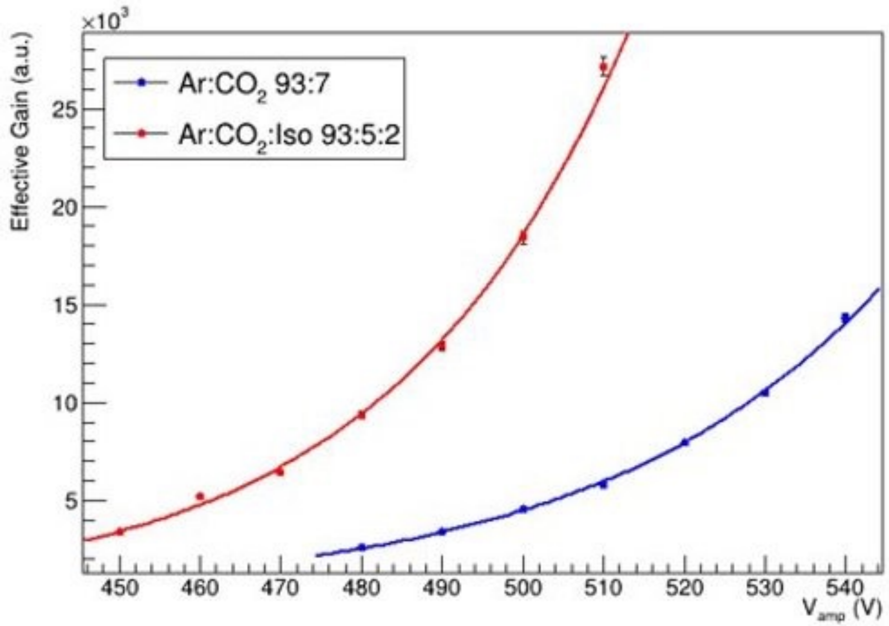
Gas gain measured with Fe55 X ray source for two different mixtures

- Ar/CO_2 93/7
- $Ar/CO_2/Iso$ 93/5/2

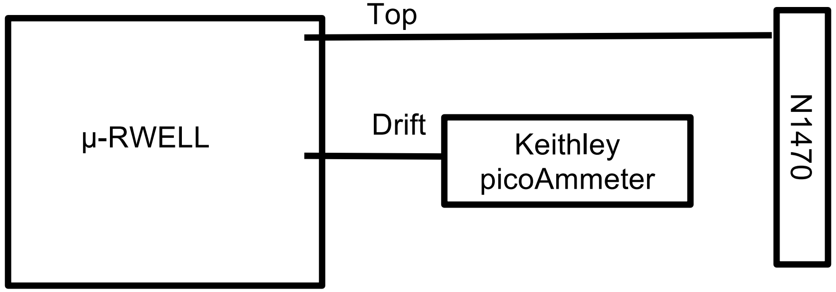
The amplified currents on the mesh is compared with the Xrays interaction rate



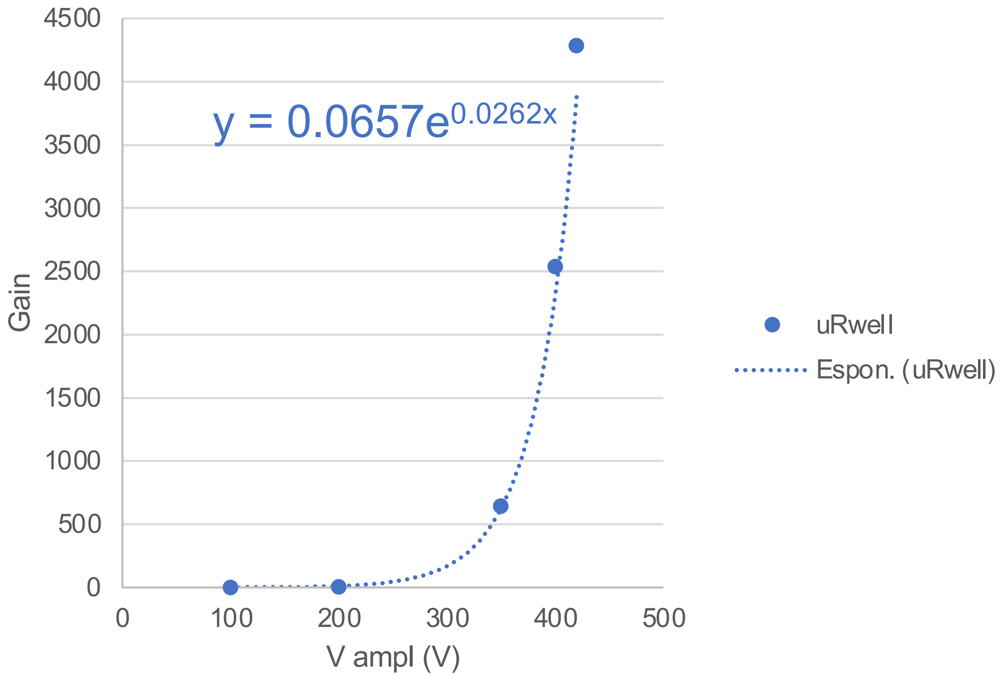


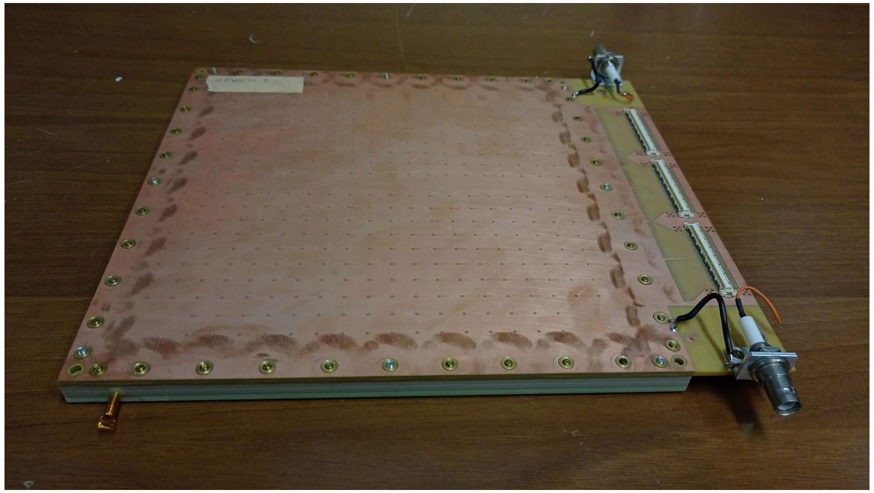


Very preliminary results: µRwell



- Tests with MiniX ray gun with Silver target
- The gain is measured by comparing the amplified currents on the top with the primary current on the cathode





Summary and Plans

Summary 2022

Milestone	Description	Expected	Achieved
MS1	Design of 20x20 readout board	Feb '22	*June '22*
MS2	Production uRWELL & MM dets	Jun '22	*All components in Bari in October '22 ?*
MS3:	Lab tests of produced detectors (gas tightness, IV curve, gain, uniformity)	December 22	ongoing
MS1-Sim:	GEANT simulation of MPGD-HCAL	July 22 Containment and Energy resolution without BIB, with digital RO.	**December 22 *?*** Containment and Energy resolution with BIB and analogic and semidigital readout
MS2-Sim:	Impact on charged hadrons/jet reconstruction in Muon Collider full simulation	July 22 Preliminary results with BIB (small stat) with modified geometry	**December 22 *?*** Update the digitization and reconstruction.

Obiettivi il 2023

Milestone	Description	Expected
MS4	Test dei layer attivi su fascio a SPS con MIPs	March 2023
MS5	Assemblaggio del prototipo (1λ_N) di cella calorimetrica	June 2023
MS6	Test su fascio del prototipo (1λ_N) di cella calorimetrica	Oct 23
MS7	Realizzazione prototipo con 2 λ_N	Dec 23
MS1-Sim:	GEANT simulation of MPGD-HCAL	Dec 23: Study the response to multiple MIPs, introduce timing.
MS2-Sim:	Impact on charged hadrons/jet reconstruction in Muon Collider full simulation	Dec 23: Define optimal time and spatial resolution in a particle flow approach

Backup

Misure su fascio

MS4: MPGD active layers test with 130 GeV/c charged hadrons/muons

- **Goal: Measure efficiency, cluster size, spatial resolution, time resolution of micromegas and micro-rwell**
- Task-1: DAQ software preparation
- Task-2: mechanical infrastructure preparation
- Task-3: data analysis

MS6: HCAL prototype test with 1-6 GeV/c charged hadrons

- Goal: **Measurement of energy resolution, shower containment**
- Task-1: mechanical infrastructure preparation
- Task-2: data analysis

Toward 2 λ_N prototype

- $5\lambda_N$ needed for full shower containment (assuming infinite transverse size)
- In order to improve shower containment and make more reliable energy resolution measurement, we ask to extend the prototype at least to 2 λ_N
- What we need
  - 2 detectors (1 founded by RD51-CP)
    - we are limited by available electronics (we have material to read 2 further detectors)
  - $1\lambda_N$ steel absorber (we can find material for $0.25\lambda_N$)

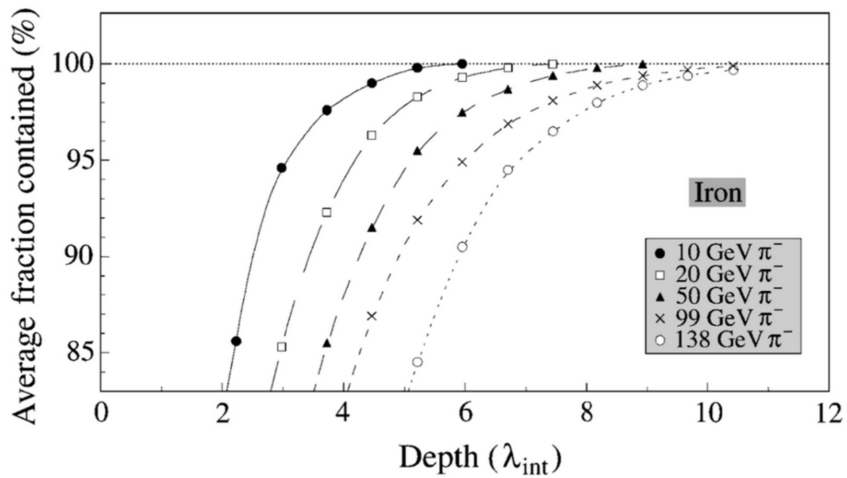
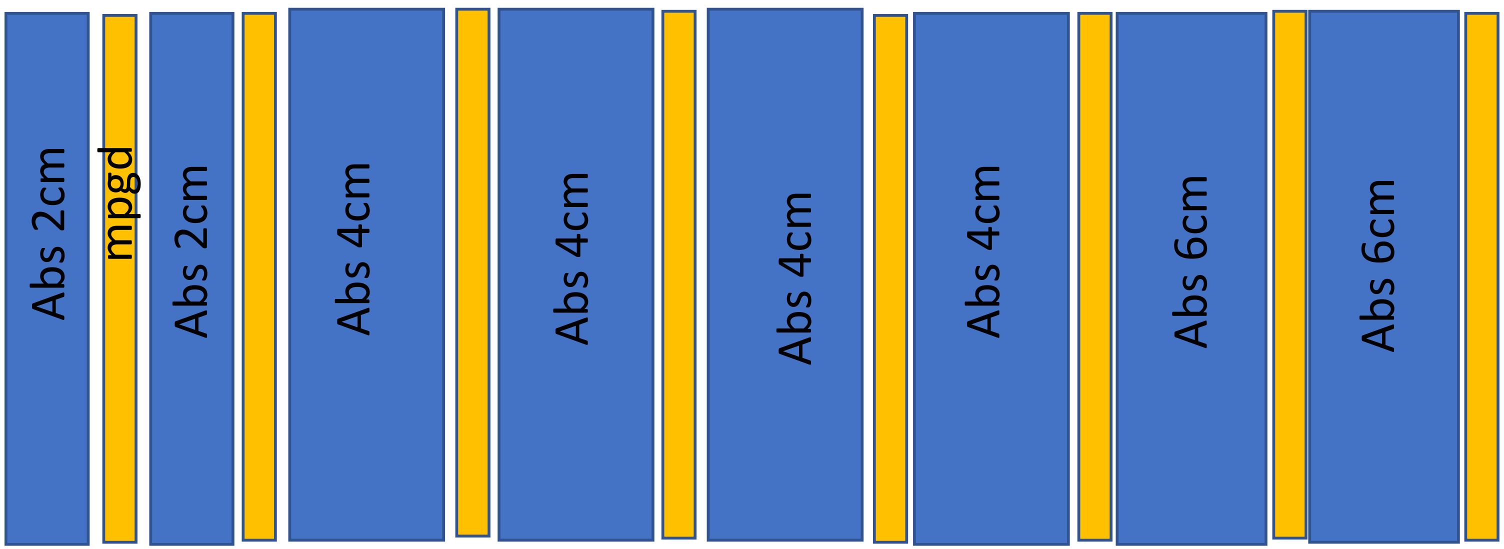
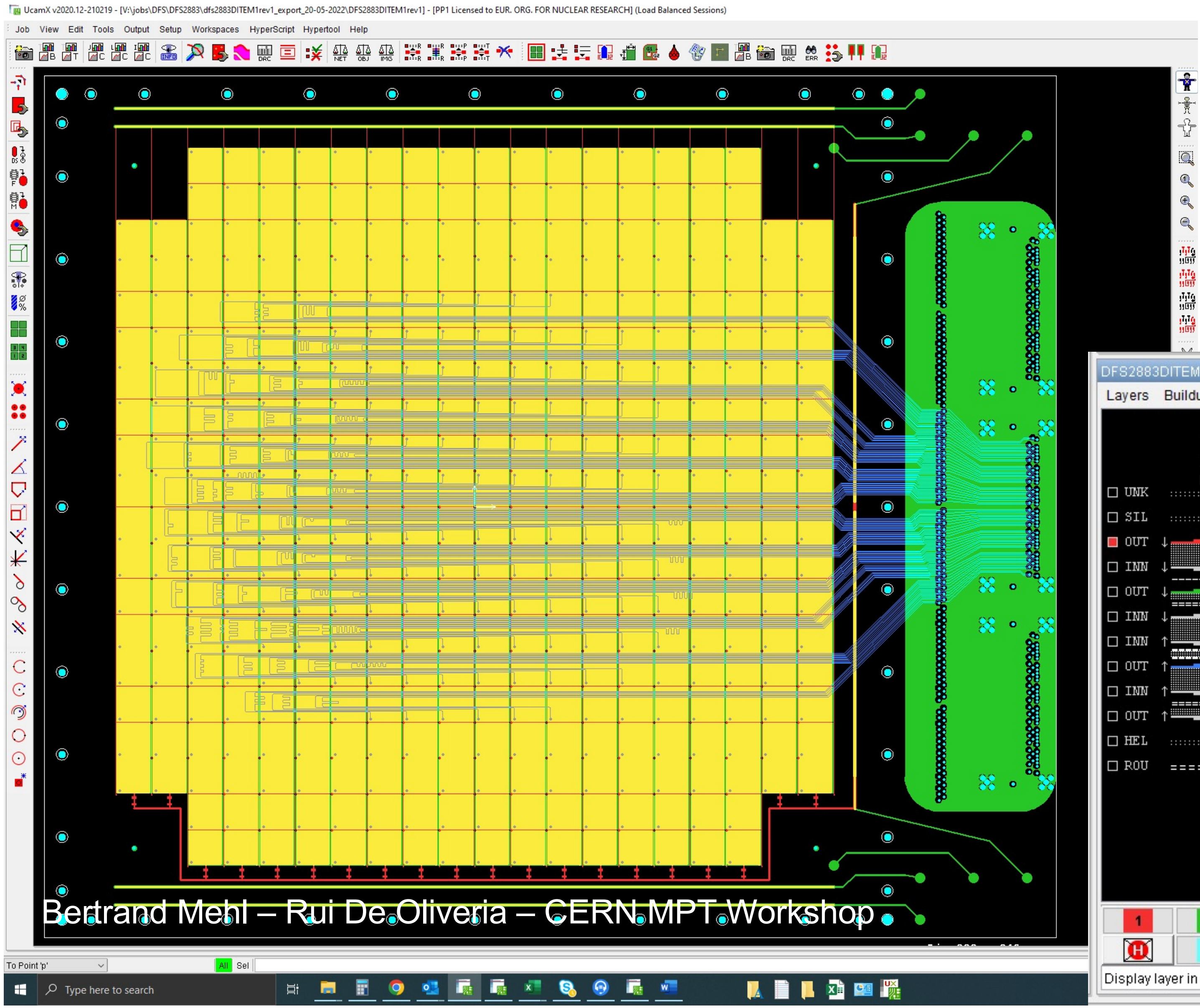


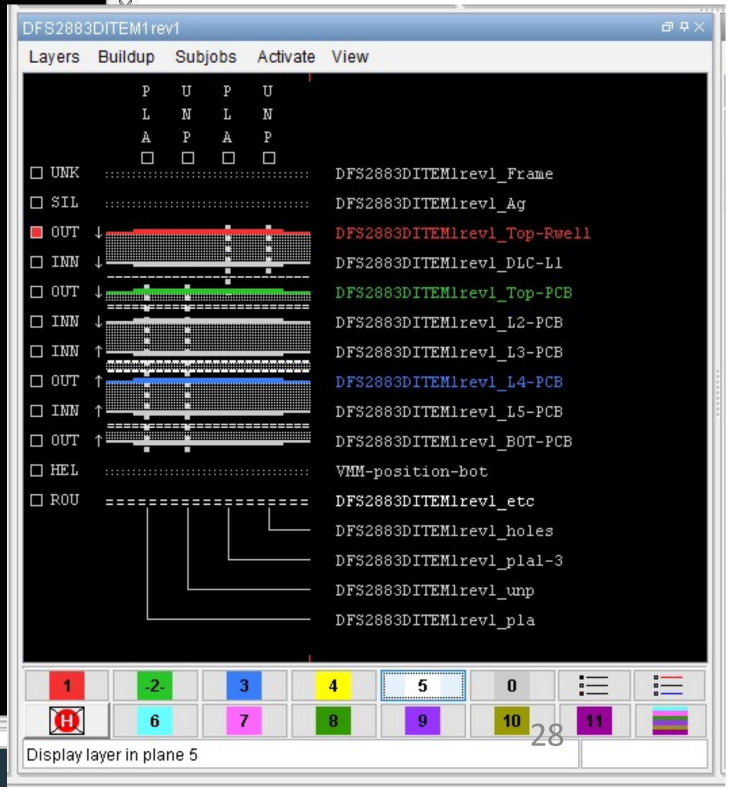
FIG. 2.43. Average energy fraction contained in a block of matter with infinite transverse dimensions, as a function of the thickness of this absorber, expressed in nuclear interaction lengths. Shown are results for showers induced by pions of various energies in iron absorber. Experimental data from [Abr 81].



Design 20x20 Readout Board

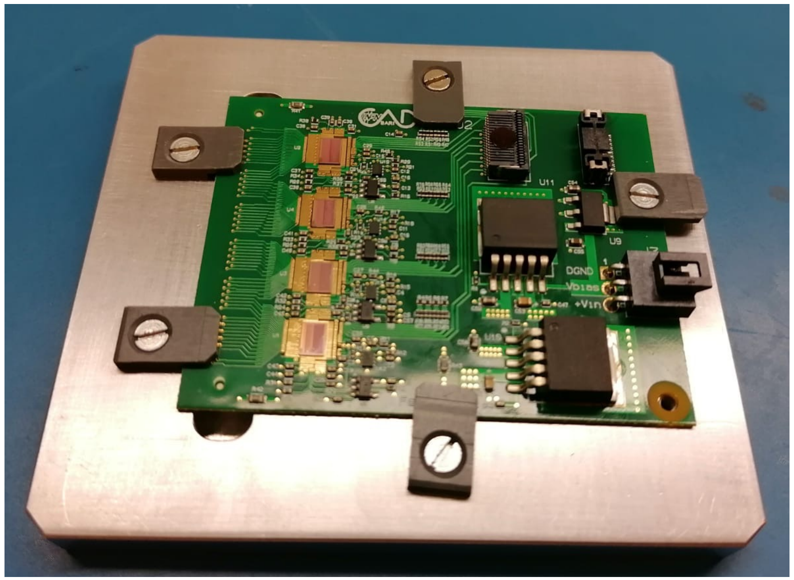


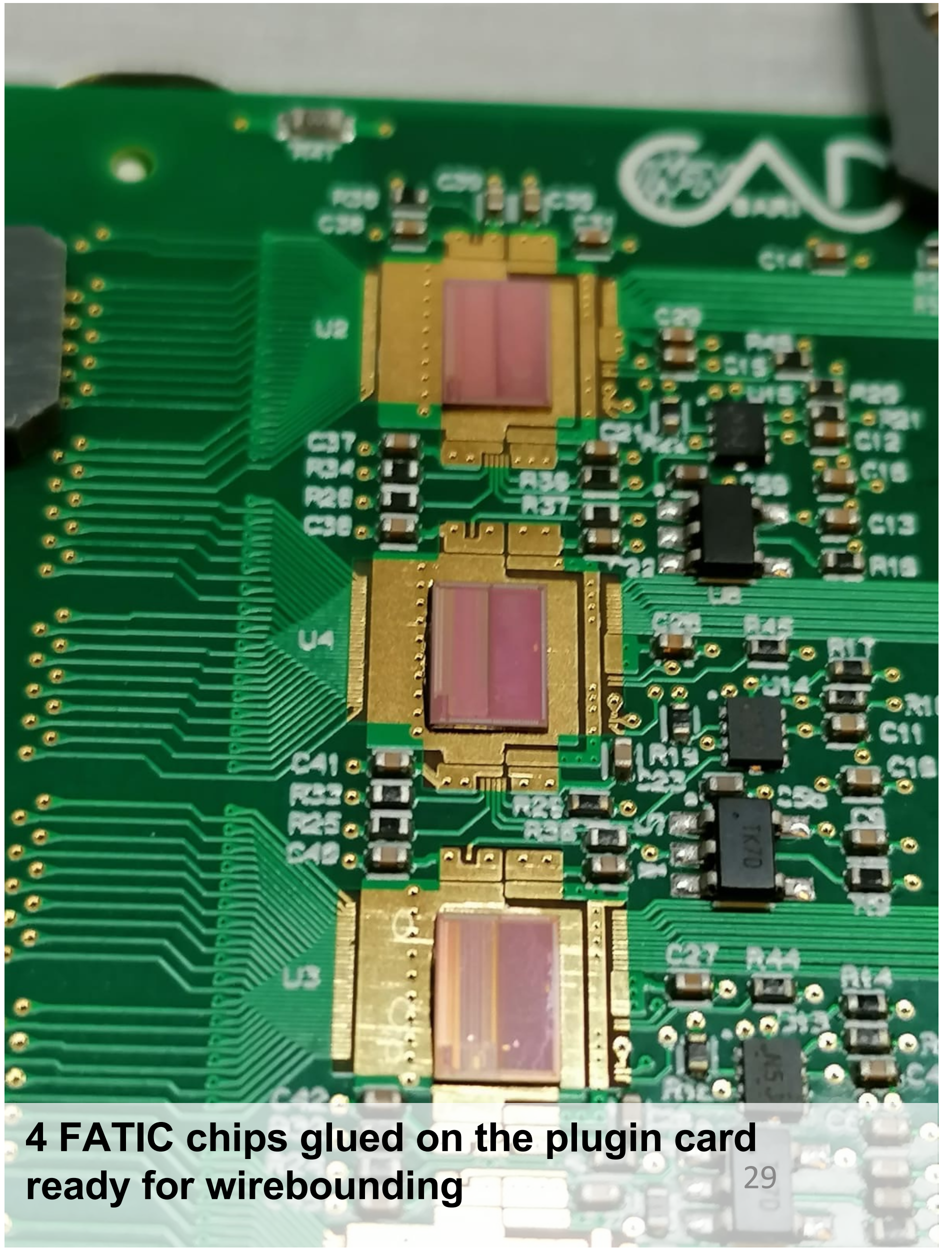
- Common RO board is 6-layer PCB
- 386 pixels – 3 HRS connectors
- Equalized Tracelength



Front-End Electronics: Plugin-Card

- Plugin card with HRS connector processes signals from 128 channels
- 4 FATIC2 asics (32 channels each)
- Plugin-card board designed in 2021
- Order in Febr’22 – PCB produced and components mounted Jun’22
- Currently: chip glueing and wirebounding on 1 card (demonstrator)
- In total 18 cards were produced



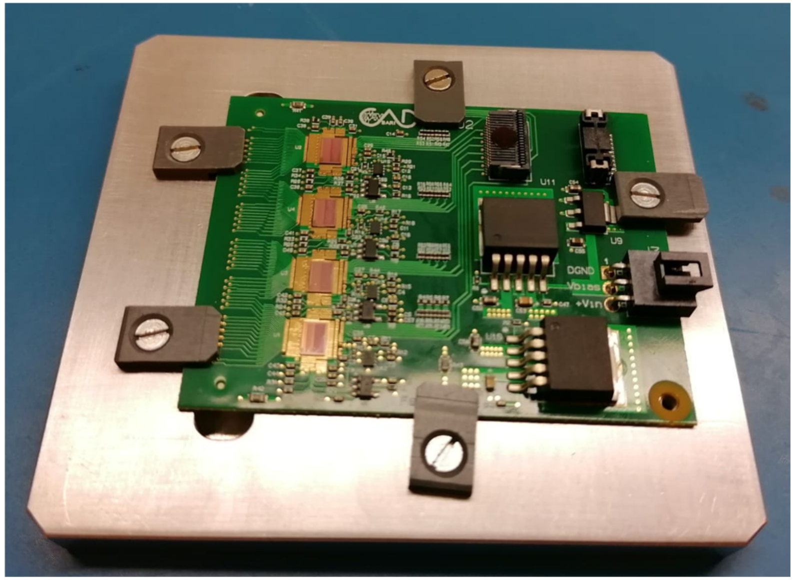


4 FATIC chips glued on the plugin card ready for wirebounding

Front-End Electronics

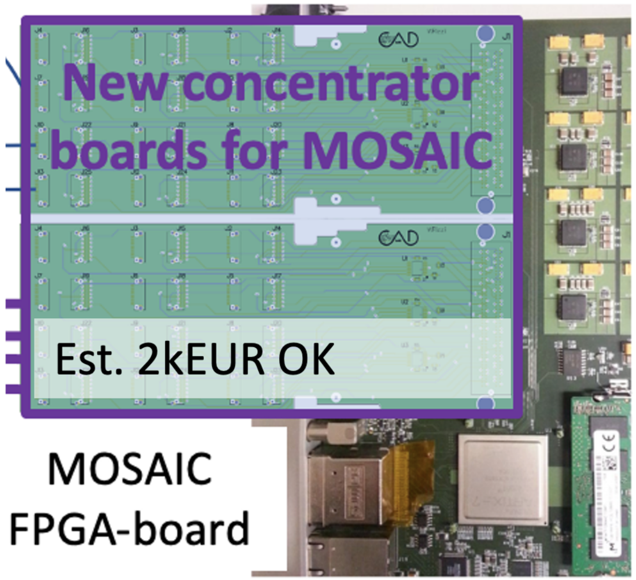
18 Plugin card produced

- HRS connector processes signals from 128 channels
- Will host 3 FATIC2 asics32 channels each
- Currently: chip glueing and wirebounding on 1 card (demonstrator) in Bari

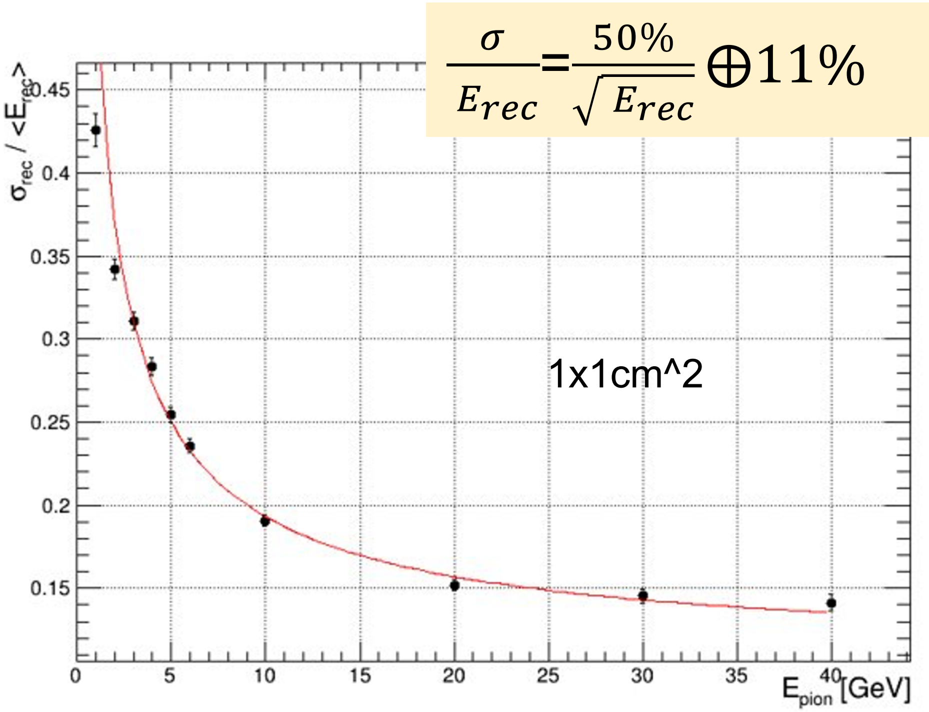


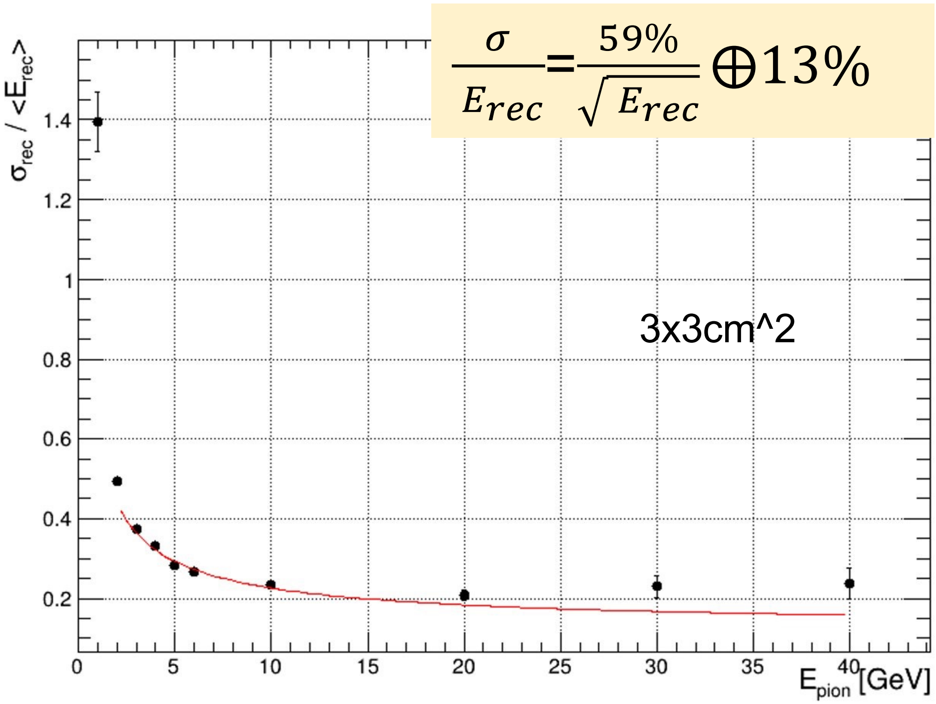
Backend: Concentrator board + MOSAIC

- Each Concentrator board receives signals from 4 plugin-cards (12 asics)
  - 4 boards ordered in Feb’22 – PCB produced and components mounted Jun’22
- Each Mosaic can mount 2 Concentrator boards (32 asics)
  - 2 MOSAIC boards available



Energy resolution vs cell granularity





- Energy resolution is computed for single pion impinging the detector
- Slightly worse energy resolution performance with increased cell size
- To be assessed in Muon Collider full simulation with charged hadrons and jet