TPC trackers for SAND
The TPCs of T2K Near Detector

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outlook

- The current T2K ND280 TPCs
  using the “historical” standard bulk-micromegas readout
- The new High-angle TPCs for the ND280 upgrade
  using the **E**ncapsulated **R**esistive **A**node **M**icromegas (ERAM) readout
- Using TPCs in KLOE for SAND

DUNE collaboration meeting, january 28th 2020 / DUNE ND bi-weekly meeting, february 19th 2020

IRFU (CEA)

- **French CEA laboratory** (**I**nstitute of **R**esearch into the **F**undamental Laws of the **U**niverse) composed of 7 Divisions with ~450 permanent physicits, engineers and technicians
  - Particle Physics, Nuclear Physics, Astrophysics,
  - Electronics-Detectors-computing, Systems Engineering
  - Accelarators-Cryogenics-magnetism, **G**rand **A**cclérateur **N**ational d'**I**ons **L**ourds (GANIL)

- Large and sophisticated facilities for **development and production of detectors and electronics: IRFU invented the MicroMegas technology** (1996 patent : Y. Giomataris, G. Charpak, Ph. Rebourgeard, J-P Robert)

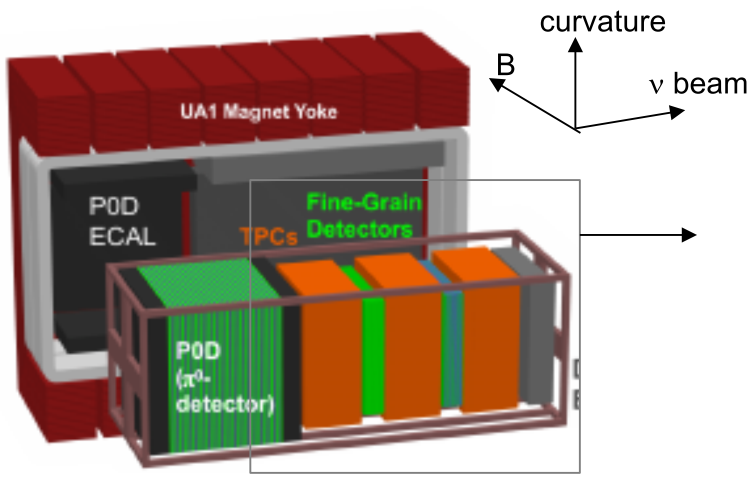
- Involved in **T2K since the beginning** of the experiment:

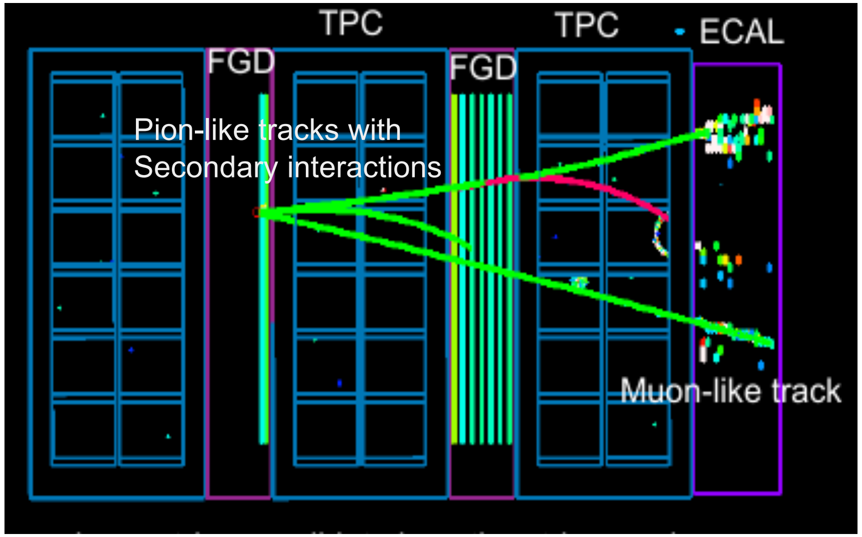
  development, building and maintenance of the **Near Detector (ND280) TPCs**
  deep expertise in ND physics

- **DUNE**:

heavily involved in the **Double Phase technology (WA105)**: charge readout system (LEM)
Interest in participating to **PIP2**

The role of TPCs in ND280





- **Momentum reconstruction:**

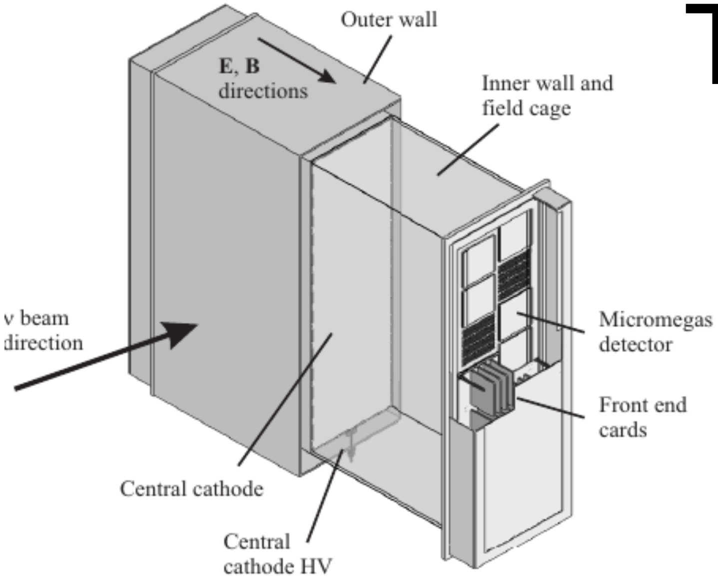
  Spatial Resolution for dp/p ~10% (→ @0.2T space point resolution ~0.7mm: pads of 7x10 mm2)
  beyond 10%, limited by Fermi momentum smearing → better resolution achievable with resistive MicroMegas / pad size, depending on the improved understanding of νN cross-section model

  Momentum scale ~2% → direct impact on mean flux energy → Δm^2_{32}

- **Particle identification through dE/dx:**

  Energy resolution ~10% (~45% more ionization for electrons than muon/pions)

The ν-TPC design (2009)



Dedicated gas: Ar+2%iC_4H_{10}+3%CF_4
Non-flammable, low transverse diffusion, very large v_{drift} (7.5 cm/μs), minimize effect of impurities (30m attenuation length)

Dirft E field 200 V/cm

Field cage: electric distorsion <0.2mm & minimal amount of material (G10/rohacell)

Cathode in the middle and 12 **micromegas** at each endplate (9m^2)

2 incapsulated boxes (CO_2) → 3.3% rad length

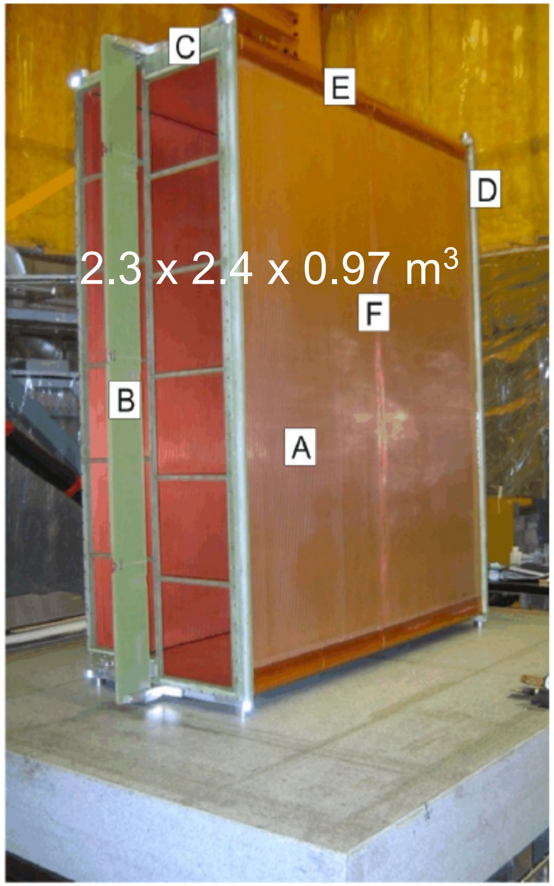
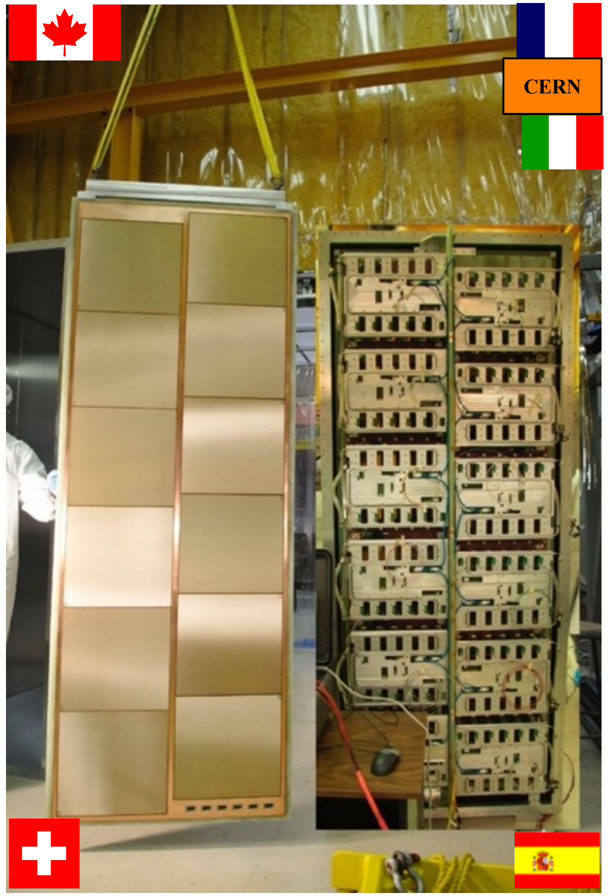


Figure 2: Inner box on the granite table in the TRIUMF clean room. A: one of inner box walls; B: module frame stiffening plate; C: module frame; D: inner box endplate; E: field-reducing corners; F: central cathode location.

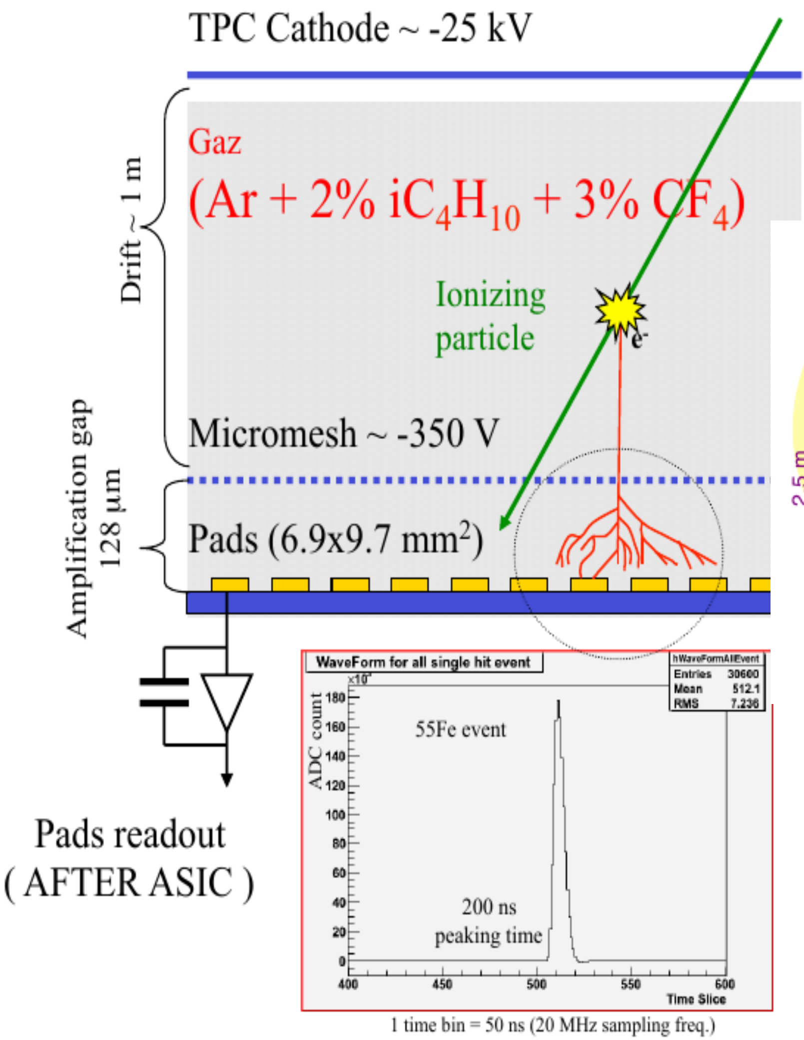


Micromegas endplate
Inner & outer sides

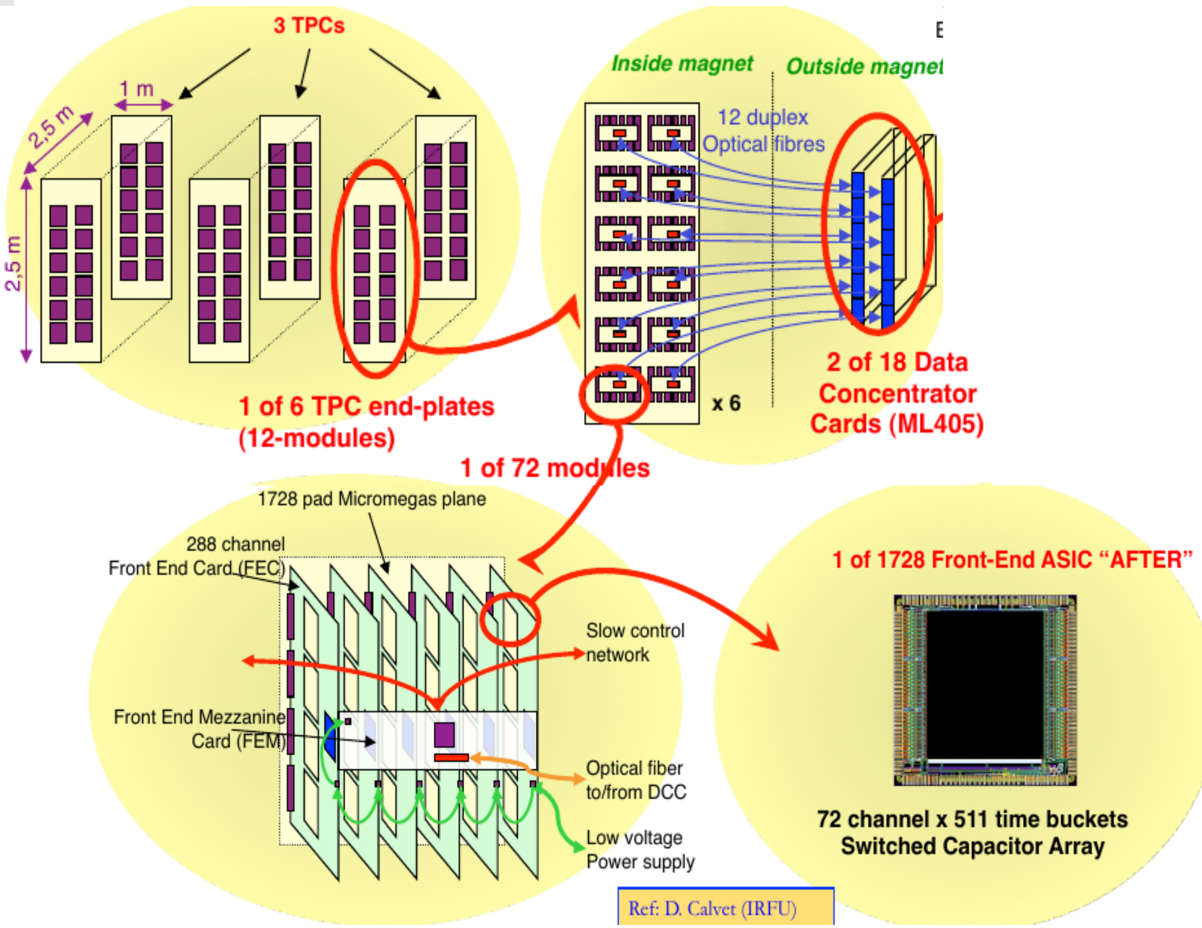
Calibration systems: - gas monitoring chambers (O_2<10ppm, H_2O<100ppm, CO_2<100ppm)

- photo-electron calibration with laser

Micromegas & electronics readout



Dedicated electronics developed for TPC purpose
(adapted for Micromegas or wire chambers):
chips AFTER + 6xFEC + 1xFEM

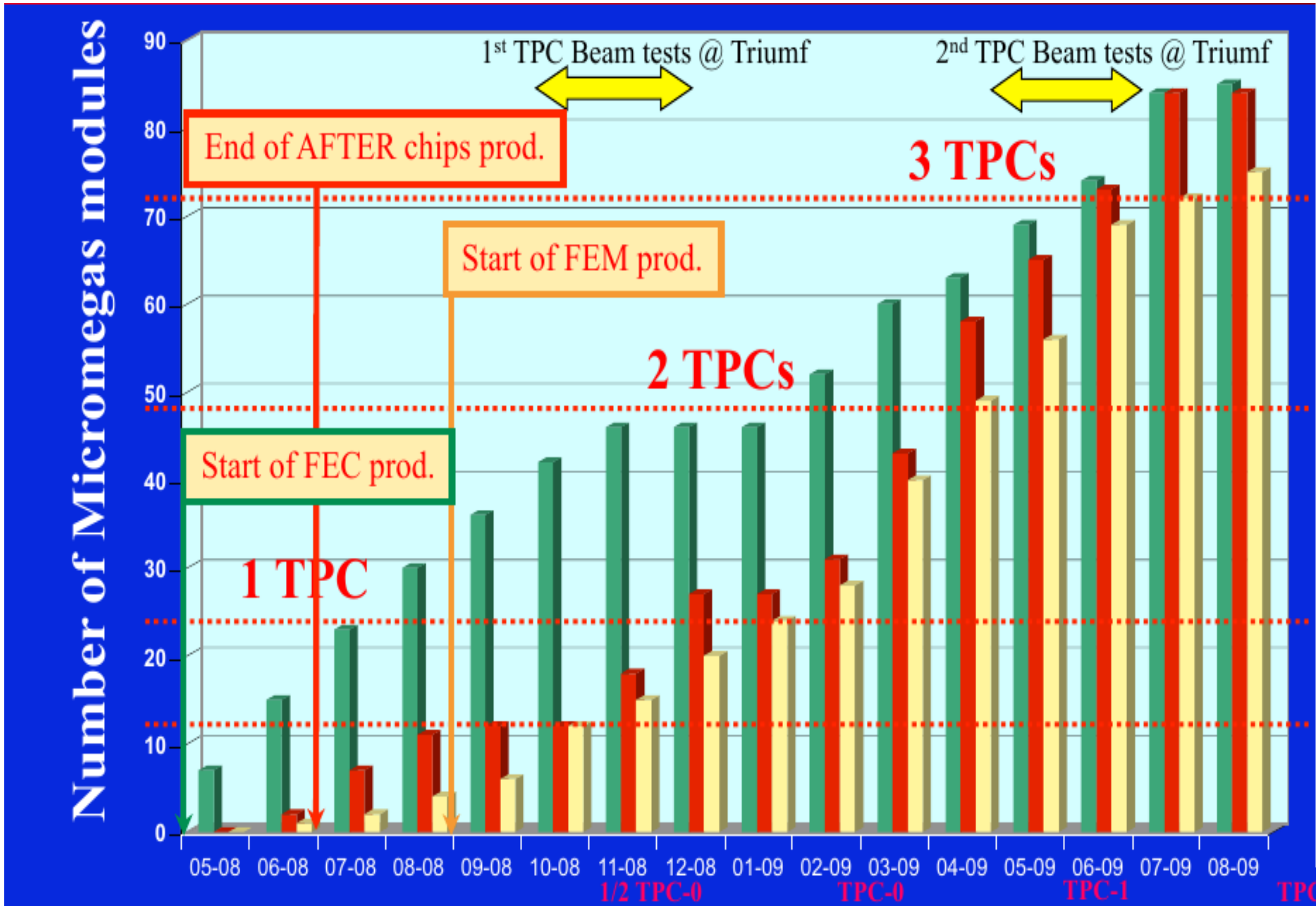


IRFU TPC readout electronics family

Parameter	AFTER T2K ν-TPC + upgrade (HA-TPC)	AGET 2013-2018 upgrade - STAGE chip	DREAM CLAS12 trackers (Jlab)
Polarity of detector signal	Negative or Positive	Negative or Positive	Negative or Positive
Number of channels	72	64	64
External Preamplifier	No	Yes; access to the filter or SCA inputs	Yes; access to the filter or SCA inputs
Charge measurement			
Input dynamic range/gain	120 fC; 240 fC; 360 fC; 600 fC	120 fC; 240 fC; 1 pC; 10 pC /channel	50 fC; 100 fC; 200 fC; 600 fC /channel
Gain v.s Cdet (200pF)			
200 fC; tp = 230 ns	- 13%	- 13%	-0,9%
Sampling			
Peaking time value	100 ns to 2 μs (16 values)	50 ns to 1 μs (16 values)	50 ns to 900 ns (16 values)
Number of SCA Time bins	511	512	512
Sampling Frequency (WCk)	1 MHz to 100 MHz	1 MHz to 100 MHz	1 MHz to 50 MHz
Triggering			
Discriminator solution	No	Leading edge	Leading edge
HIT signal		OR of the 64 discri. outputs in LVDS level	OR of the 64 discri. outputs in LVDS level; 8 multiplicity levels
Threshold Range		5% or 17.5% of the dynamic range	5% or 17.5% of the dynamic range
Threshold value		(3-bit + polarity bit) common DAC + 4-bit DAC / channel	(7-bit + polarity bit) DAC common to all channels
Readout			
Readout frequency	20 MHz	25 MHz	Up to 20 MHz
Channel Readout mode	all channels	All, hit or selected	all channels
SCA cell Readout mode	all	1 to 512	Triggered columns only
Trigger rate			Up to 20kHz (4 samples read/trigger).
Counting rate	< 0.3 Hz / channel	< 1 kHz / channel	< 50 kHz / channel
Power consumption	< 10 mW / channel	< 10 mW / channel	< 10 mW / channel
Status	Production	Production	Production
Noise 120 fC; 200 ns peaking time	370 e- + 14.6 e- / pF (measured)	580 e- + 9 e- / pF (measured)	
Noise 200 fC; 200 ns peaking time	700 e- + 8.5 e- / pF (measured)		610 e- + 9 e- / pF (measured)
Electronics	T2K (AFTER + FEC + FEM) AFTER + FEC + evaluation kit AFTER + FEC + STUC AFTERSED	GET AGET + AsAd + rCoBo FEMINOS	DREAM + FEU + SSP DREAM + FEU + TCM

Ref: P. Baron (IRFU)

A success story



	05-08	06-08	07-08	08-08	09-08	10-08	11-08	12-08	01-09	02-09	03-09	04-09	05-09	06-09	07-09	08-09
Bulk MMs	7	15	23	30	36	42	46	46	46	52	60	63	69	74	84	85
MM Modules	0	2	7	11	12	12	18	27	27	31	43	58	65	73	84	84
Validated MM Modules	0	1	2	4	6	12	15	20	24	28	40	49	56	69	72	75

Final percentage of good modules/produced:
Micromegas (82/89) 92%
FEC (499/514) 97%
FEM (84/93) 90%

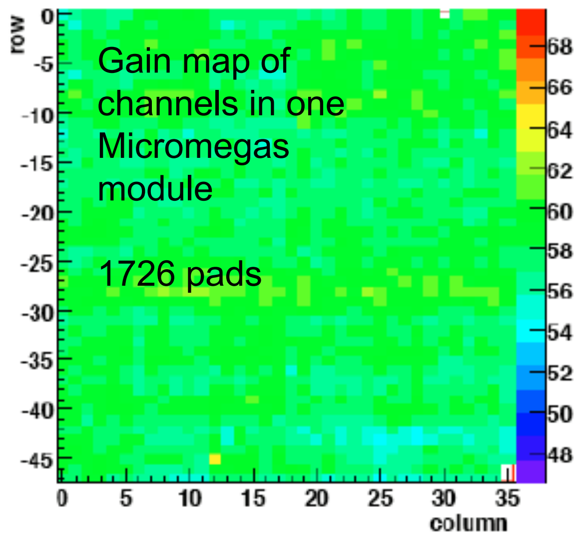
12 **dead MM channels** over 124272 channels (0.01%)

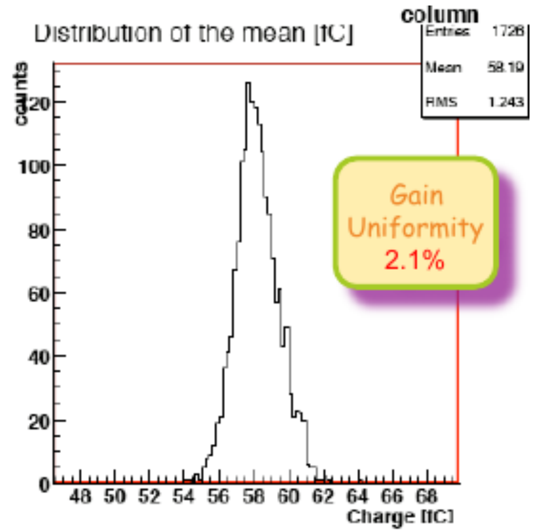
10 years of operation with only 1 FEM failure and 2 MM HV filters to repair

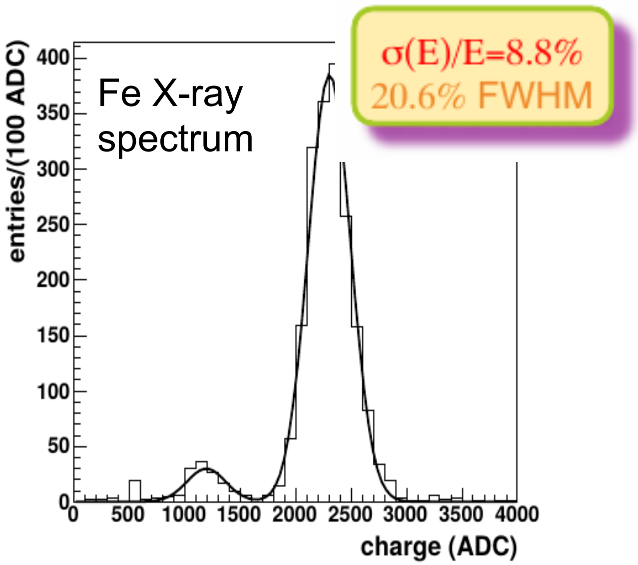
The bulk-micromegas performances

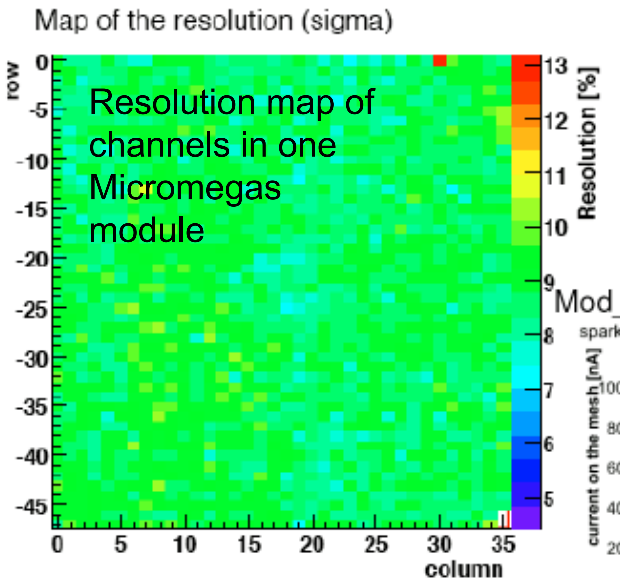
- Micromegas gain~1500 with spark rate <0.1/h and 2% uniformity

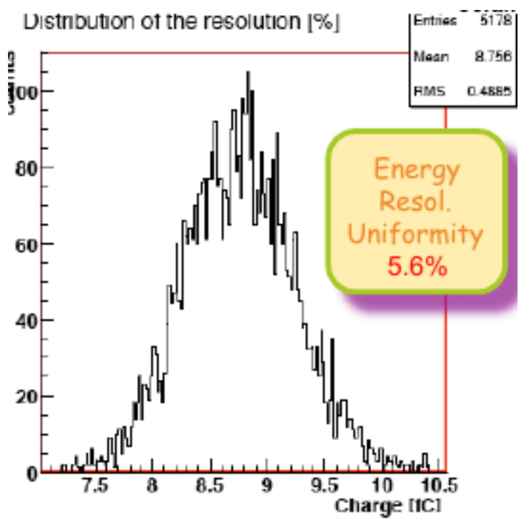
- Energy resolution 8-9% with uniformity better than 8% (3% between detectors)



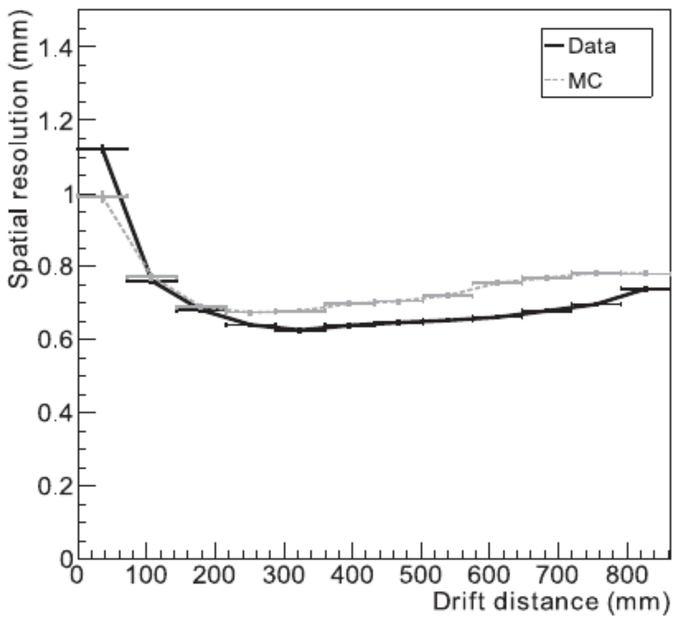


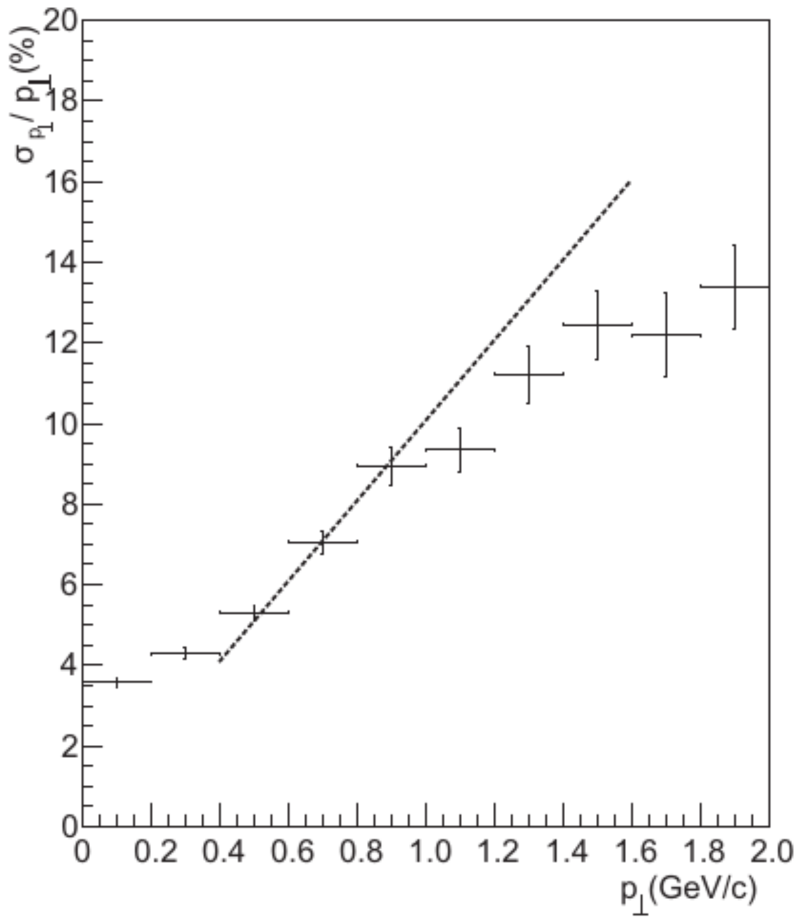


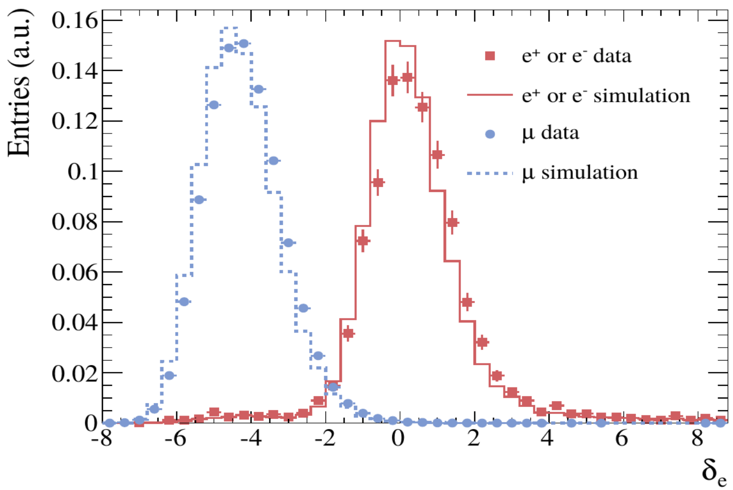


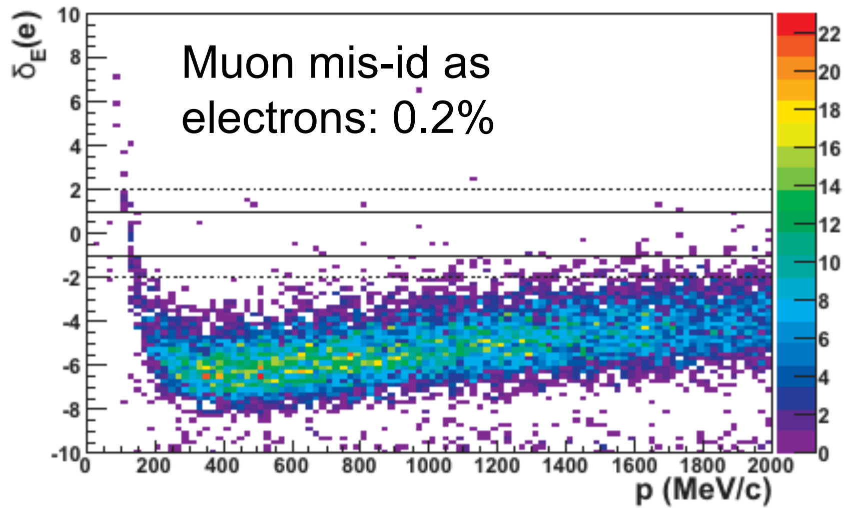


The v-TPC performances

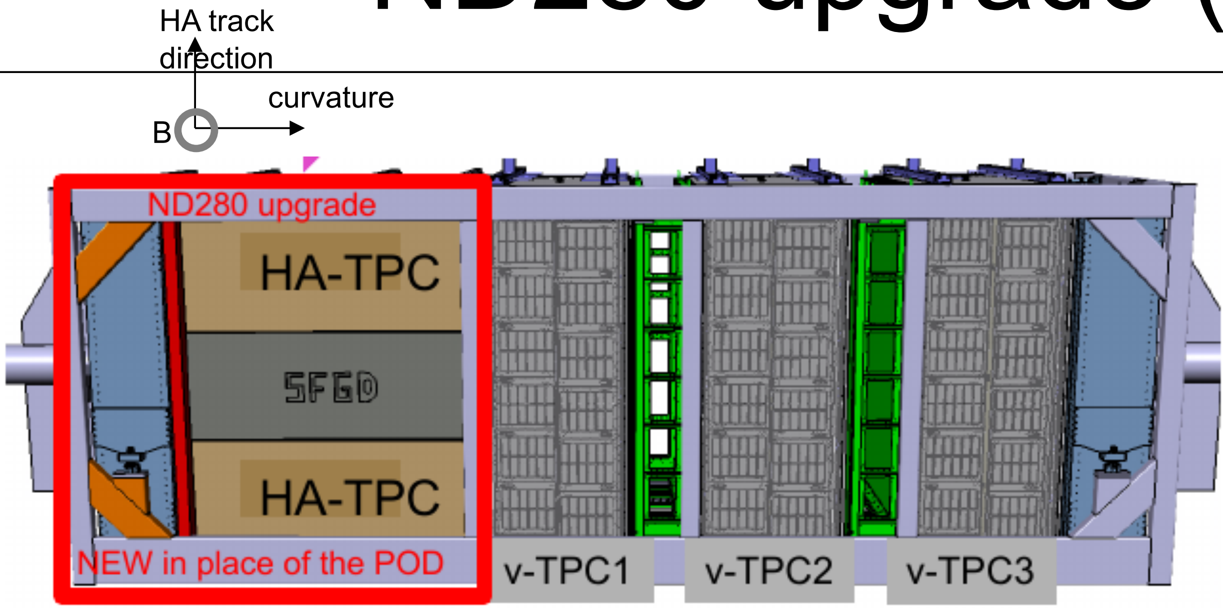






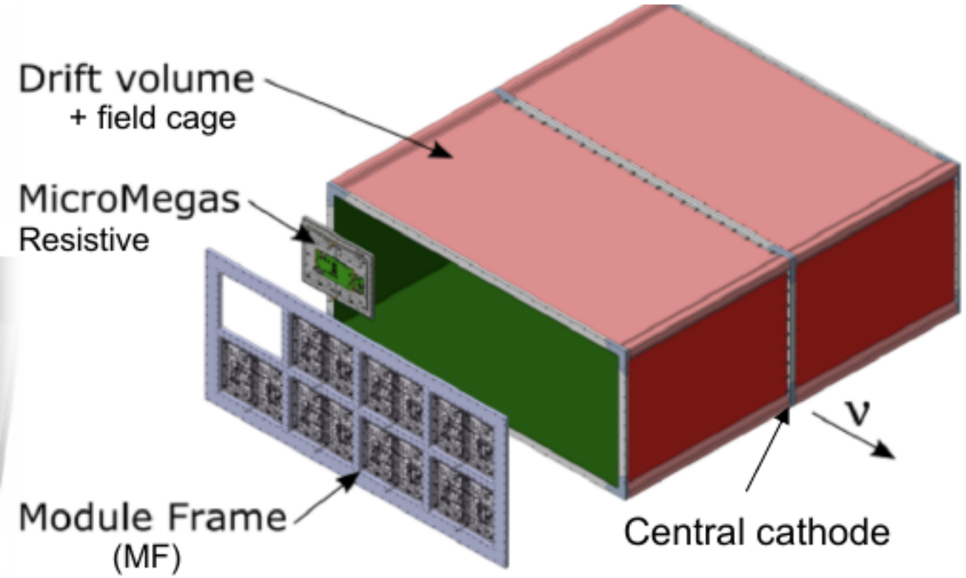


ND280 upgrade (2022-)



High Angle TPCs to recover same acceptance as at SK

+ 6 TOF planes surrounding the new tracker



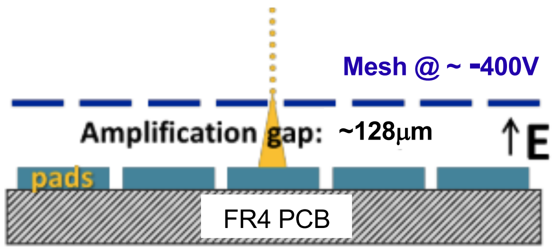
Parameter	HA-TPC Value	V-TPC
Overall x × y × z (m)	2.0 × 0.8 × 1.8	0.85 x 2.2 x 1.8
Drift distance (cm)	90	
Magnetic Field (T)	0.2	
Electric field (V/cm)	275	
Gas Ar-CF_4-iC_4H_{10} (%)	95 - 3 - 2	
Drift Velocity $cm/\mu s$	7.8	
Transverse diffusion ($\mu m/\sqrt{cm}$)	265	
Micromegas gain	1000	
Micromegas dim. z×y (mm)	340x420	340x360
Pad z × y (mm)	10 × 11	7x10
N pads	36864	124272
el. noise (ENC)	800	
S/N	100	
Sampling frequency (MHz)	25	
N time samples	511	

Encapsulated Resistive Anode Micromegas

Spread the charge from the avalanche over multiple pads → compute the charge 'barycenter'
→ get good resolution with larger pads (less number of channels). Heavily based on ILD R&D
→ provides spark protection for the Front-End ASICs (→ more compact FEE)

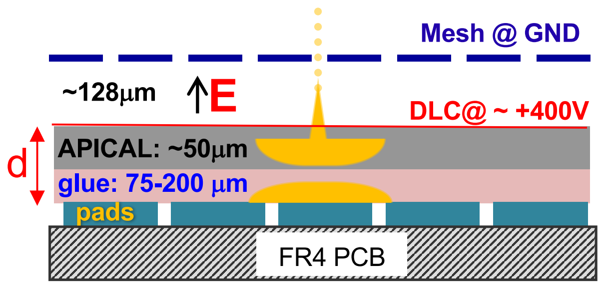
T2K/ND280 v-TPC

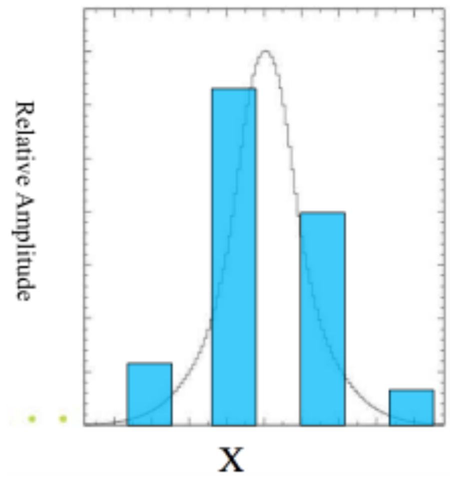
Standard bulk-micromegas



T2K/ND280 HA-TPC
ERAM

Resistive foil micromegas





2-D RC network

$$\rho(r,t) = \frac{RC}{2t}\exp\left[-\frac{-r^2RC}{4t}\right]$$

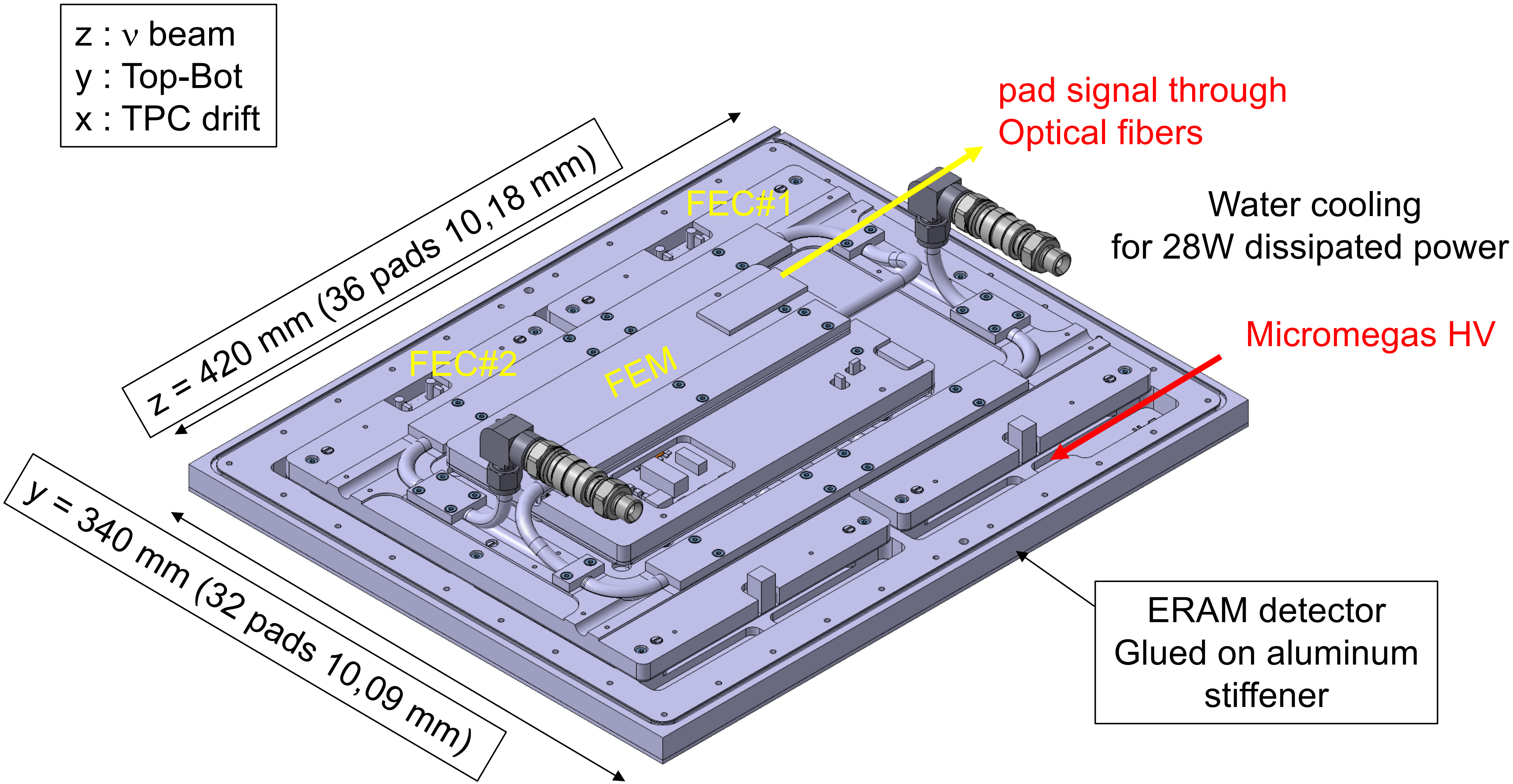
R- surface resistivity
C- capacitance/unit area

Gaussian spreading as a function of time with

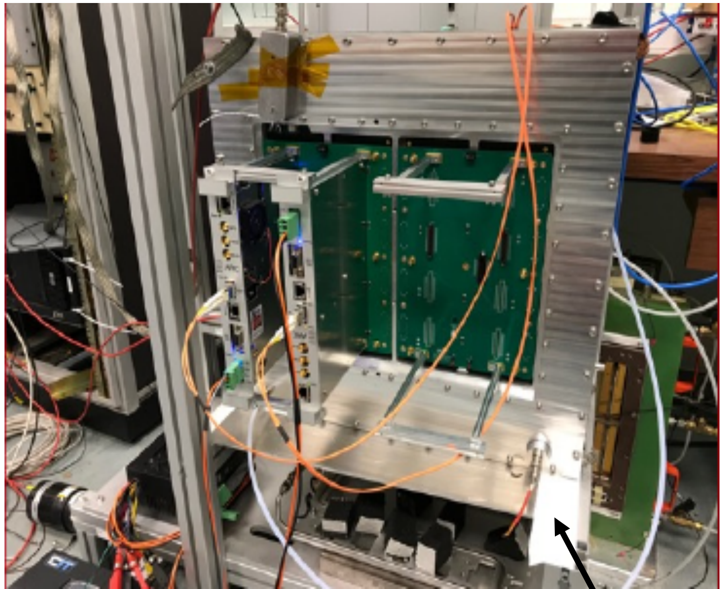
$$\sigma_r = \sqrt{\frac{2t}{RC}} \quad \begin{cases} t \approx shaping\ time\ (few\ 100\ ns) \\ RC_{[ns/mm^2]} = \dfrac{180\ R_{[M\Omega/\blacksquare]}}{d_{[\mu m]}/175} \end{cases}$$

The HA-TPC ERAM module

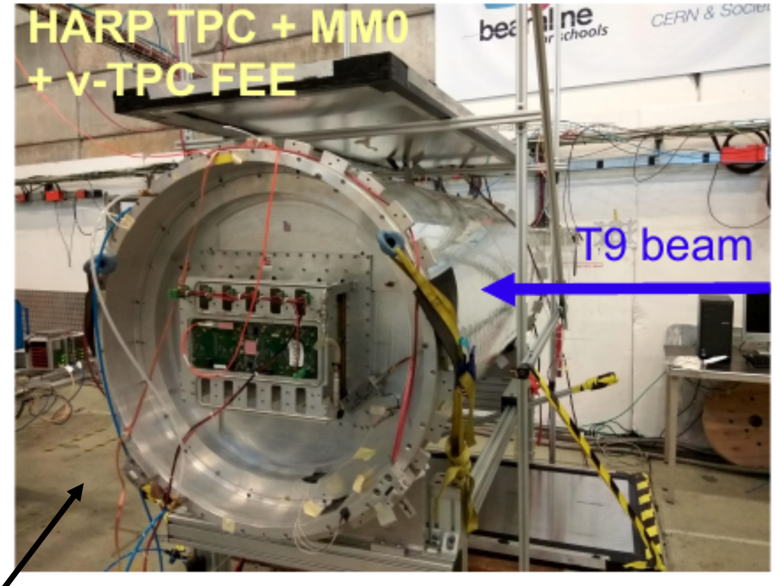
1152 pads readout by 2 Front-End cards equipped with 8x72 ch. AFTER asics



Extensive tests with cosmics & beams



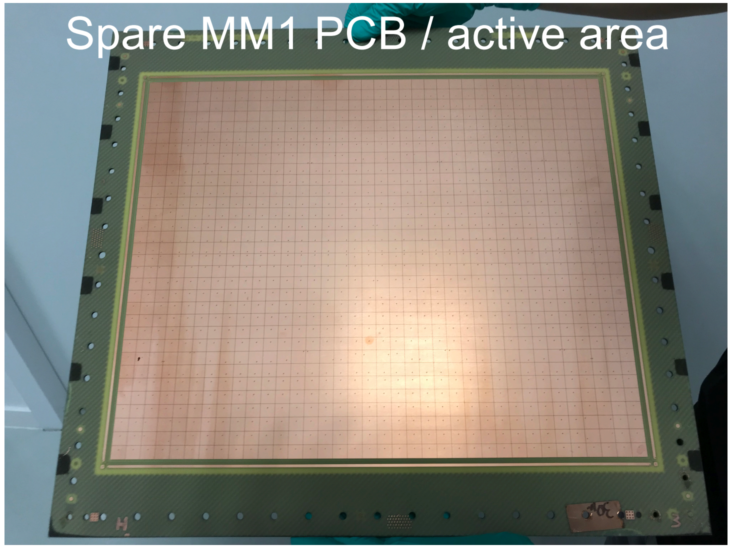
arXiv:1907.07060 / Nucl.Instrum.Meth. A957 (2020)

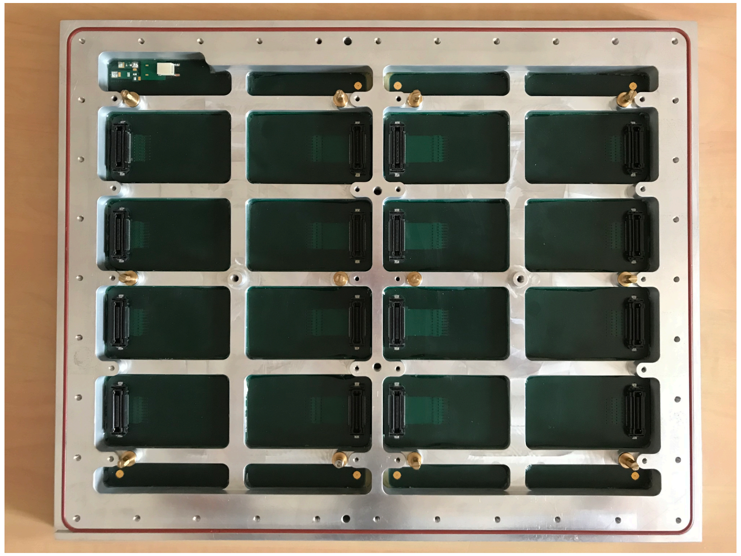


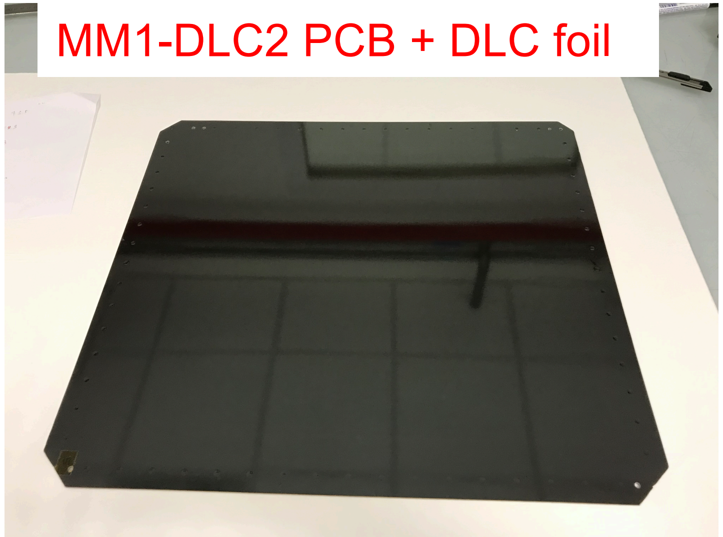
2019 DESY test beam

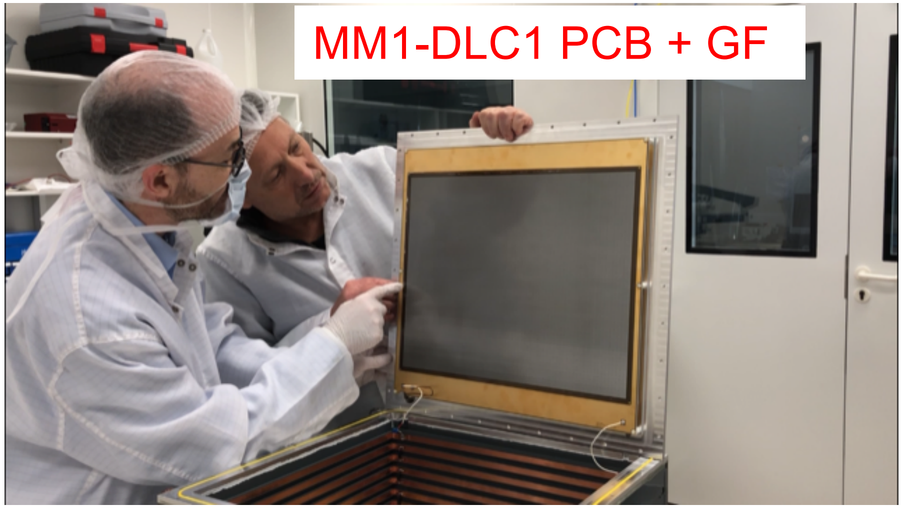
- Cosmic test bench (Saclay mini TPC with 15 cm drift)
- Test beam at CERN **in 2018** (on HARP TPC)
- Test beam at DESY, with Saclay mini TPC & magnetic field, **in june 2019**
- Test beam at DESY with field cage prototype planned **in oct 2020**
- Installation at ND280 in summer 2021

ERAM module pictures
MM1 prototype









ERAM prototype tests at DESY (1)

ERAM module prototype

- Final size of 34x42 cm^2
- Final segmentation : 32 (10,09 mm) x 36 (11,18 mm) = 1152 pads
- DLC resistive foil of ~0,4 MΩ/square original resistivity (0,2 to 0,27 MΩ/square final R)
- 75 μm glue thickness for an expected 84 ns/mm^2 < RC <113 ns/mm^2 which correponds to an expected charge spreading σ ~ 2,7 to 3,1 mm
- 4 x AFTER based Front-End cards
- Saclay mini TPC, 15 cm drift
- T2K gas (95%Ar+2%iso+3%CF4)

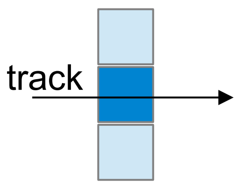
Test beam conditions

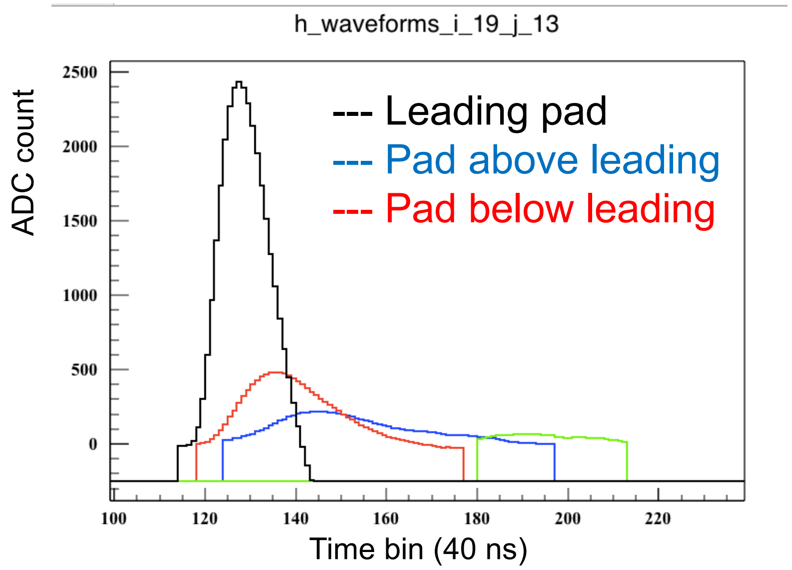
- electron beam : 1-5 GeV, most of the data with 4 GeV
- Gain scan with ERAM voltages 330 - 400 V (380V default setting)
- Y and Z position scan (in the detector plane and along drift distance)
- 0, 20, 30, 45, 60, 80 degree ERAM plane rotation

ERAM prototype tests at DESY (2)

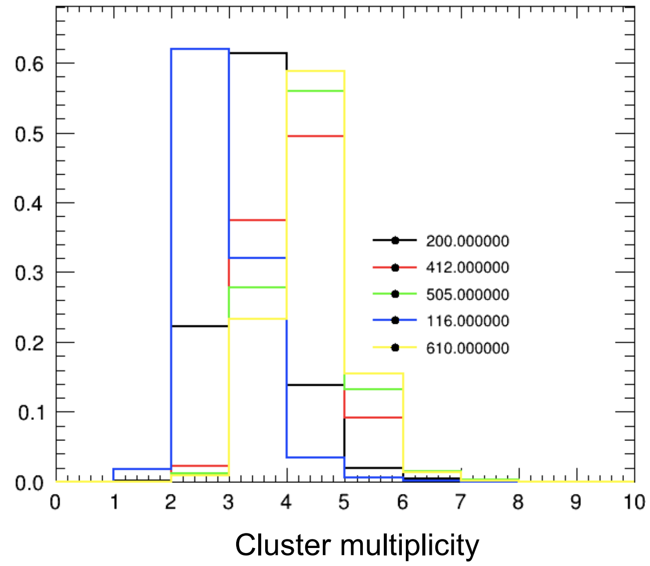
Signal waveform : on-going modelization

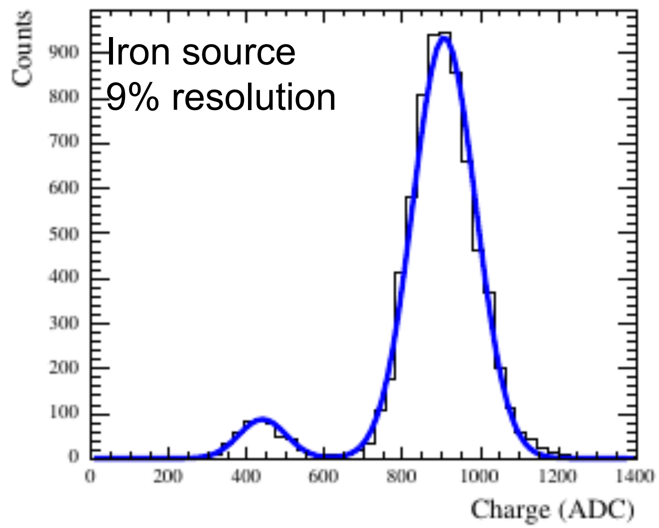
Pads with charge spreading





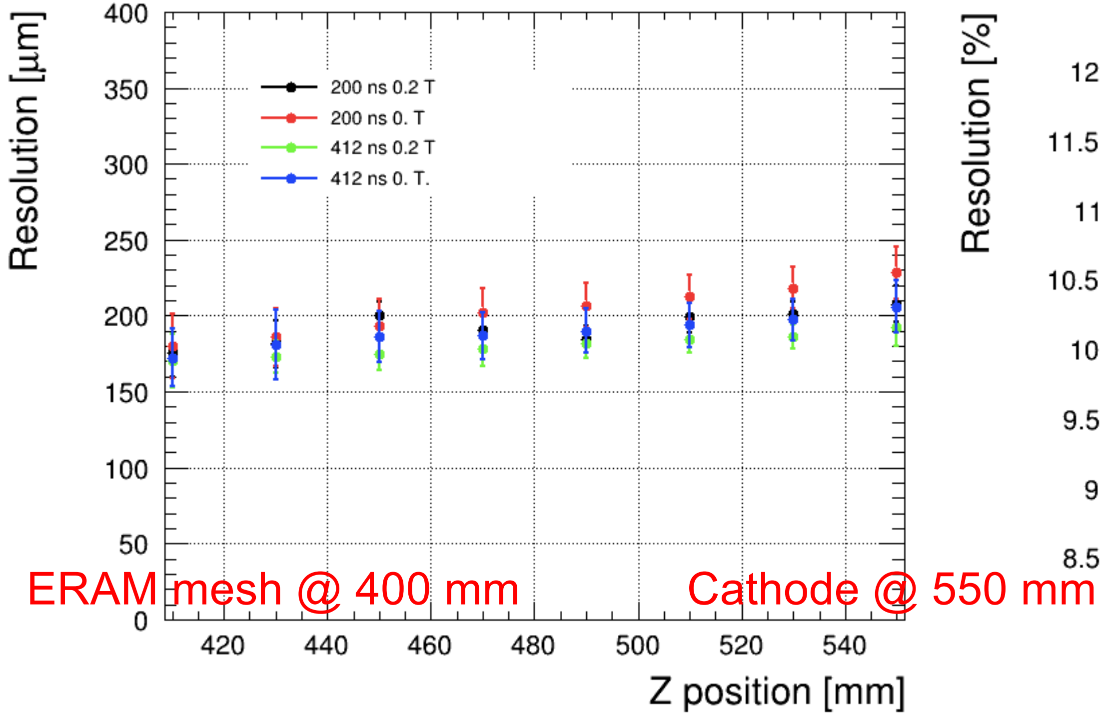
Pad multiplicity Vs peaking time @ 380V



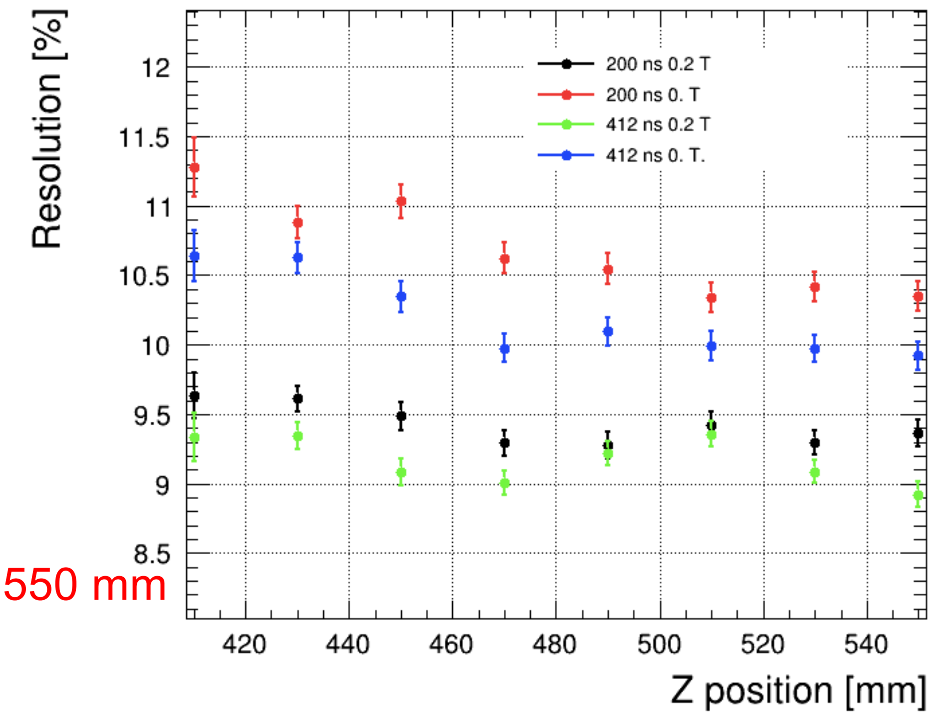


ERAM prototype tests at DESY (3) (preliminary)

Spatial resolution



de/dx with truncated mean

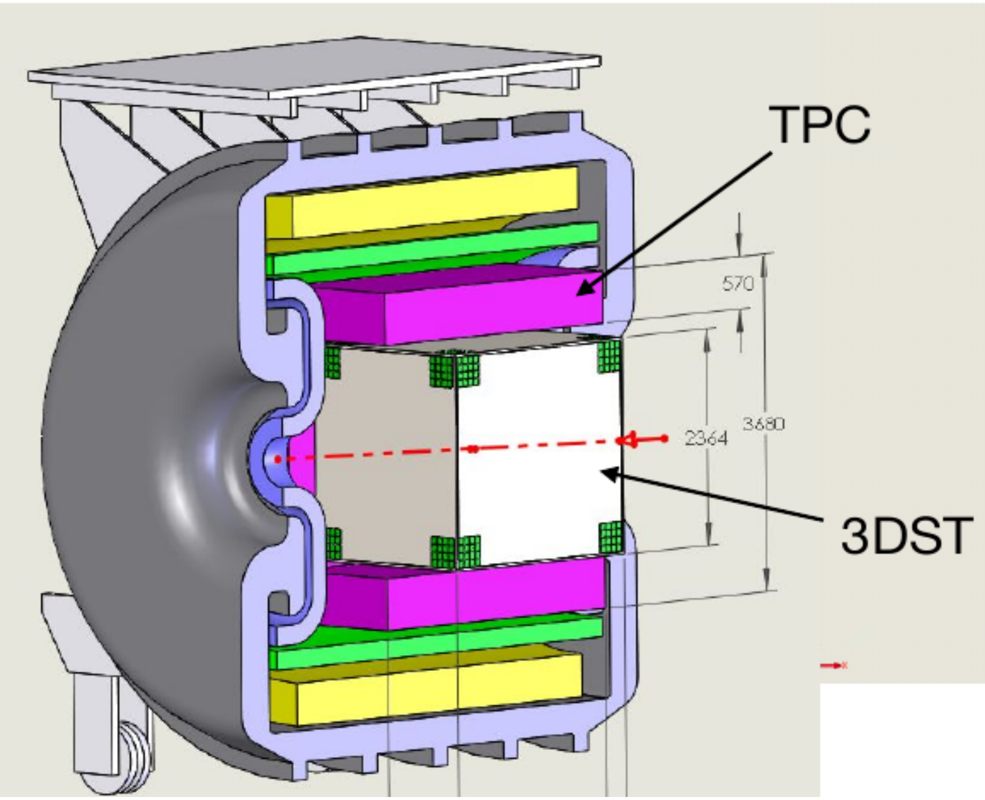


Excellent performances compared to v-TPC with ~40% larger pads (~200 μm Vs ~600 μm)

But space point resolution dependance with track position within a pad (middle / edge)

Cosmic tests of a new ERAM module with 200 μm glue thickness for a larger expected charge spreading of σ ~ 4,4 to 5,1 mm

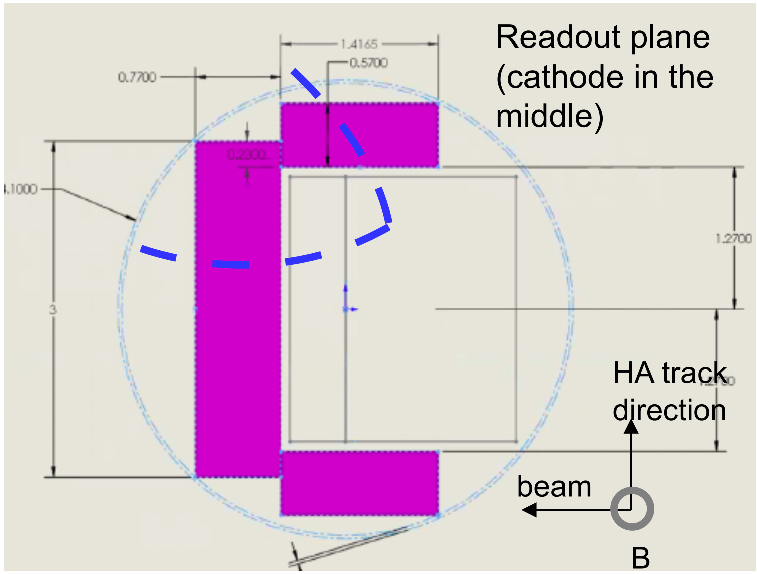
SAND TPCs



Resistivity and pad size can be adjusted to match the SAND needs, given the E_{ν}, magnetic field and space available

- Important to have small B non-uniformities and small $B_{r\phi}$ component, (in general less harsh requirements for TPC equipped with MPGD than drift chambers)
- Geometry:

  3 rectangular TPCs with readout planes:
  2 x 2 x (57 x 141)cm^2 ; 2 x(300 x 77)cm^2 ~ 8m^2

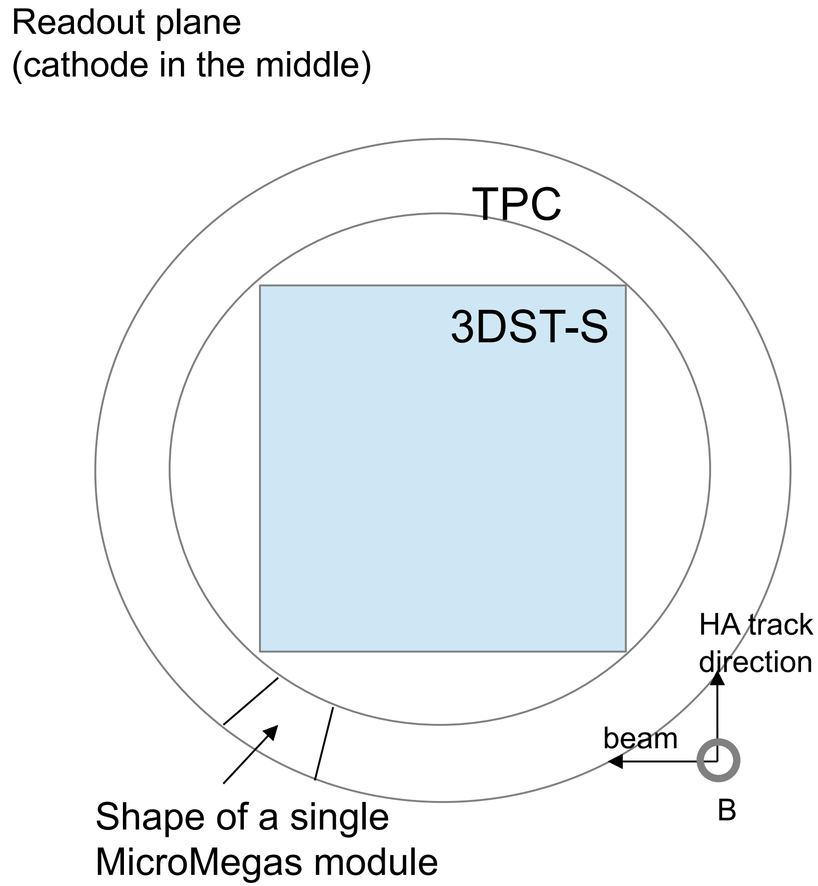


- Using ~1*1.1 cm^2 pads and RC as ND280 upgrade (200 μm space point resolution) :

71K channels→ few % resolution @ 3 GeV

Pad size and RC can be optimized to improve resolution vs # electronics channel for fwd/HA TPCs:
eg for 10% resolution ~20-30k channels should be enough

Cylindrical geometry ?



Keeping the same geometry/mass for 3DST-S
Keeping the same overall envelope
→ cylindrical TPC

- field cage: easier to have uniform electric field
- ~40 cm thick (readout planes ~ $8m^2$): resolution~8% at 3 GeV
  with 1x1.1cm2 pads and same RC (~200um resolution)
- Full angular coverage: backward tracks with lower momentum and lower occupancy: can use larger pads → less channels

Empty spaces between TPCs and 3DST-S: can be filled with additional cubes or other materials
→ gain in target mass

Simulation studies to optimize the design and tests of dedicated MM modules with different pads sizes and different values of RC

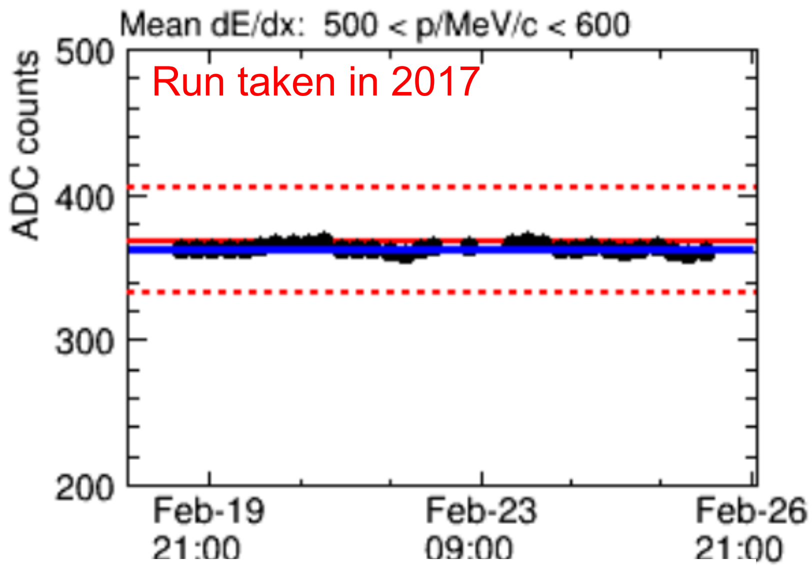
Conclusions

- TPCs are a robust detector with good performances which have proven to be a **crucial ingredient in T2K physics**
  - **Great experience** on building/installing/maintining it at IRFU (and in ND280 community in general)
  - **Very smooth production and 10 years of running** have shown the astonishing stability and reliability of such detector
  - On-shelf **TPC dedicated electronics** already developed
- The Resistive Anode micromegas allows to tune the resolution vs number of channels by playing on RC and pad size to adapt the design to DUNE/SAND needs
- A cylindrical geometry may be more adapted to KLOE magnet: more easy to build/operate, larger acceptance, may allow to increase the 3DST-S mass

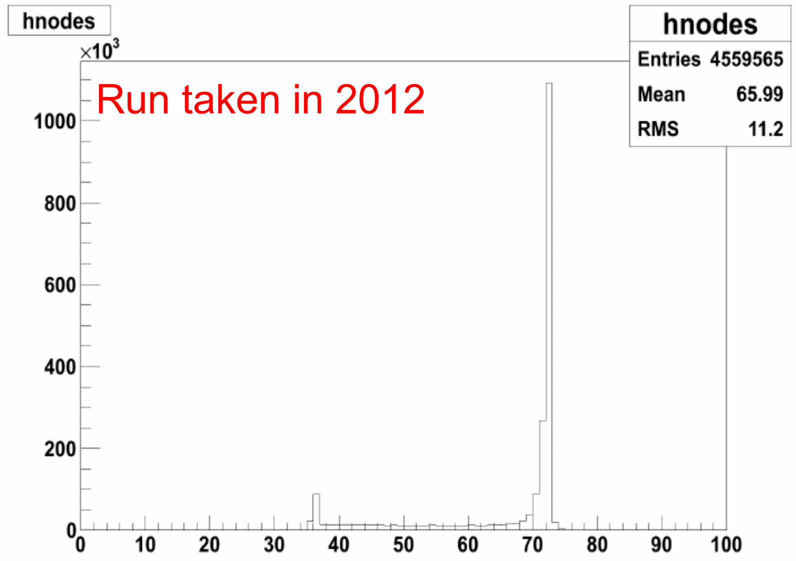
Back-up

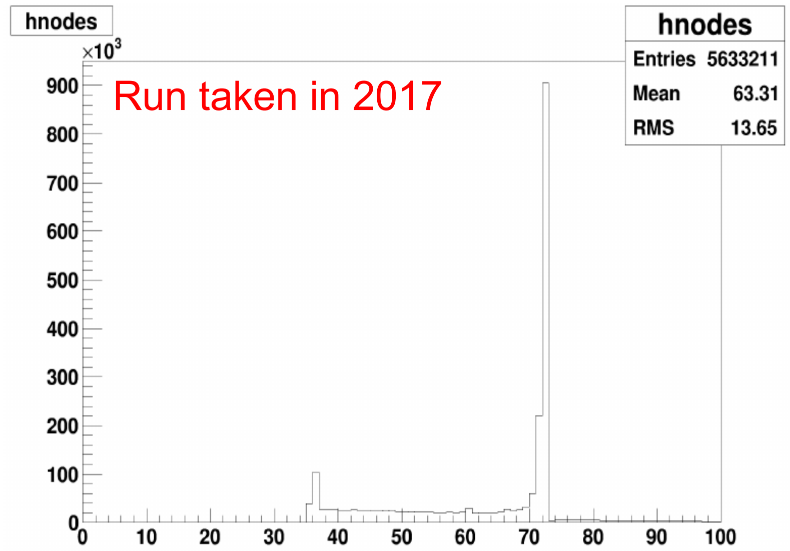
Astonishing stability/reliability in 10 years

Mean dE/dx from cosmics



Number of hits per track

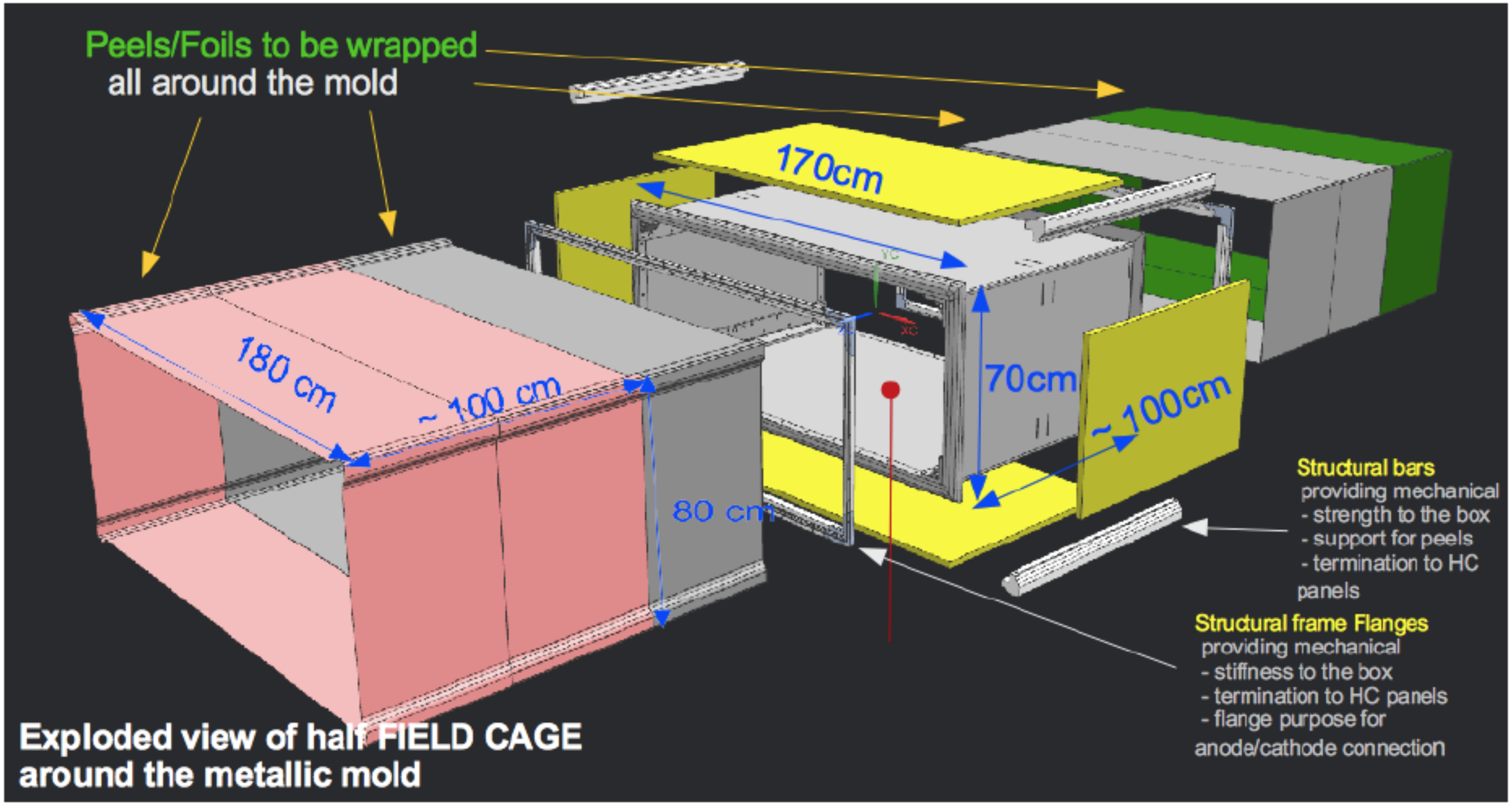




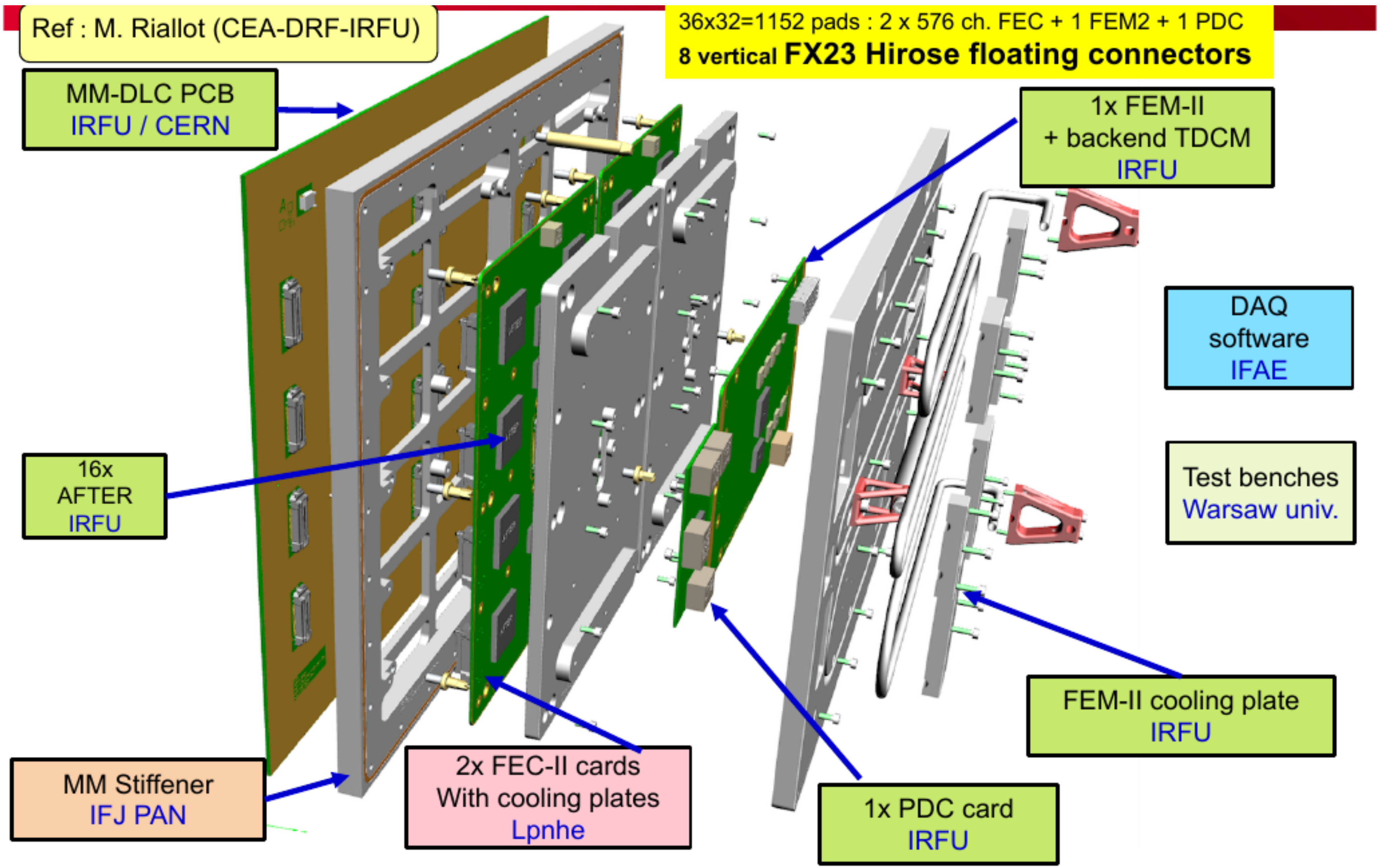
Field cage

INFN
Padova-Bari

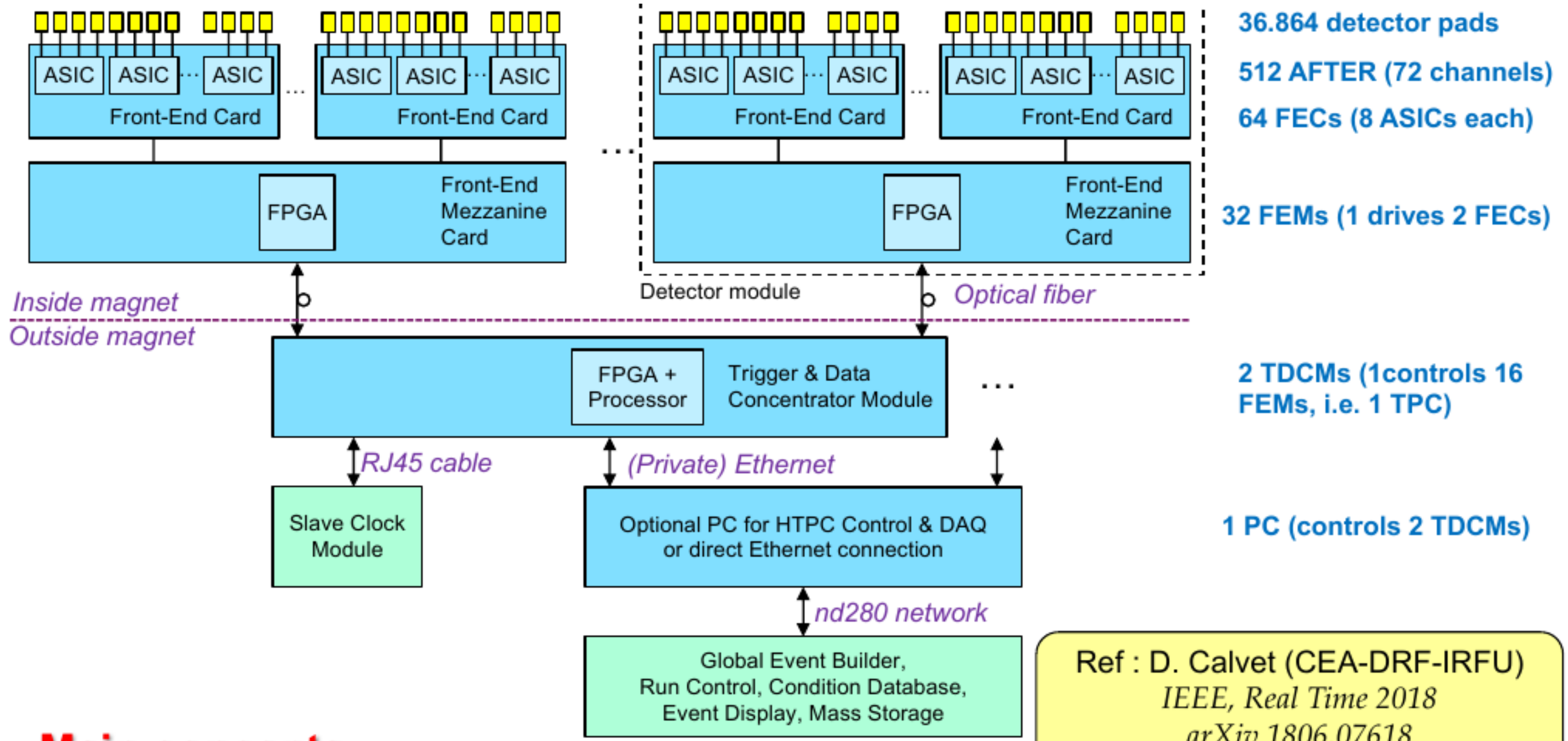
To keep $^{\Delta E}/_{E} \leq 10^{-4}$ confined at <1cm from FC walls, the TPC cage requirements are :
Cathode flatness better than 0.1mm, Micromegas plane flatness better than 0.2 mm,
Cathode/Anode planes parallel to within 0.2mm, Field Cage walls flatness better tham 0.3mm
Voltage divider resistors matched within rms ~ 0.1%



HA-TPC ERAM module v2.7



HA-TPC electronics readout

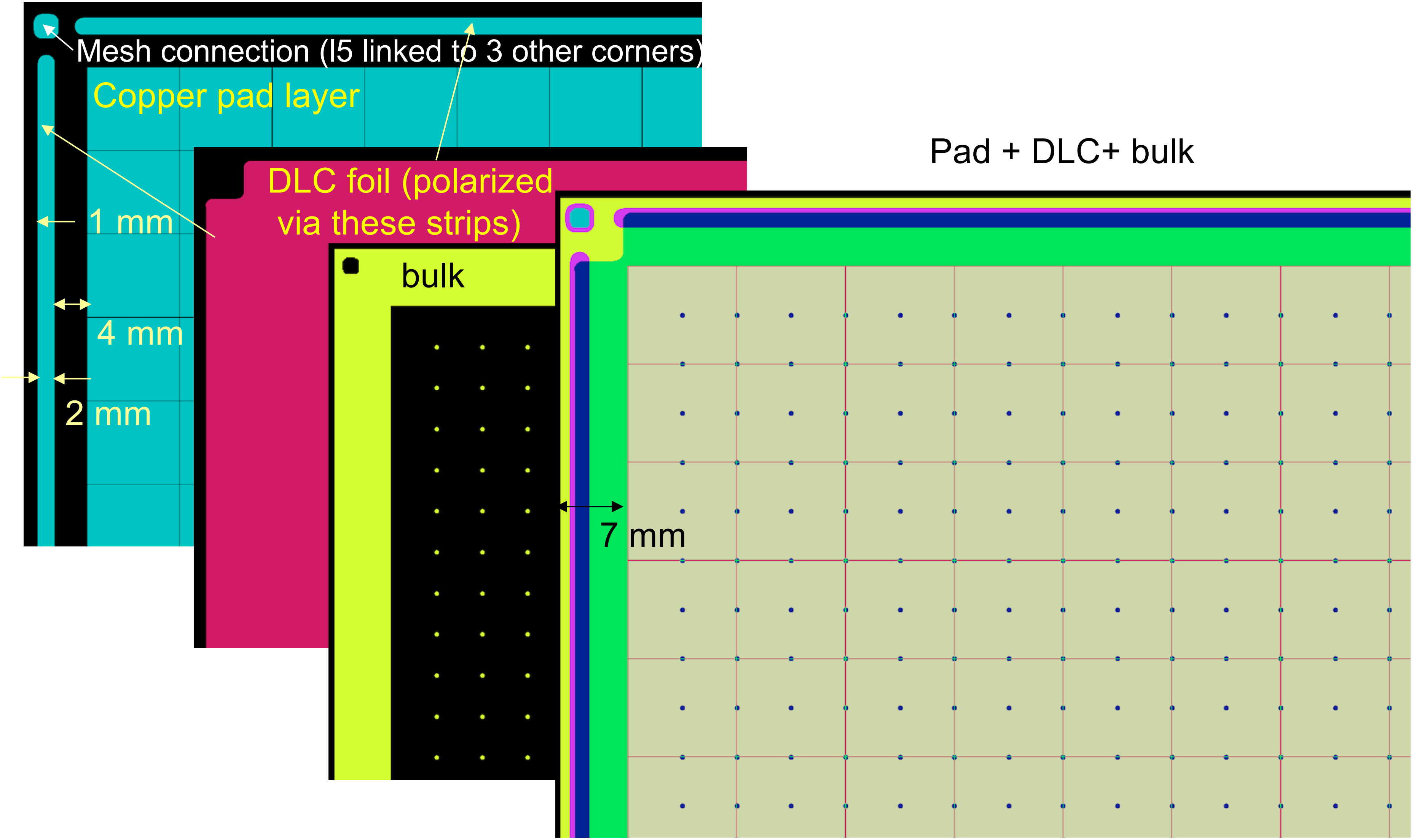


Ref : D. Calvet (CEA-DRF-IRFU)
IEEE, Real Time 2018
arXiv 1806.07618

Main concepts

- AFTER chip designed for T2K (511 bucket SCA sampling@25 MHz, 120fC-600 fC, 100ns-2μs peaking time)
- New FEC with 8 AFTER chips which digitizes pad signal with an 8 ch. ADC (minimum dead time of 3.3 ms)
- FEM provides control (&trigger), synchronization, data aggregation, data buffering & data zero suppression
- The TDCM is a generic clock and trigger distributor and data aggregator (FPGA+2 xilinx CPU+1 GB DDR3)

ERAM active area



DLC foil resistivity (ERAM #01)

Seen from pad side

4th Film	5	15	25	35	45	55	65	75	85	95
5	612	660	741	525	400	394	368	341	297	283
15	613	690	769	536	414	392	372	344	305	277
25	629	665	759	511	446	391	344	348	296	279
35	603	634	723	510	404	390	357	321	297	275
45	589	638	752	516	417	389	357	331	295	280
55	567	610	750	501	417	394	379	360	285	283

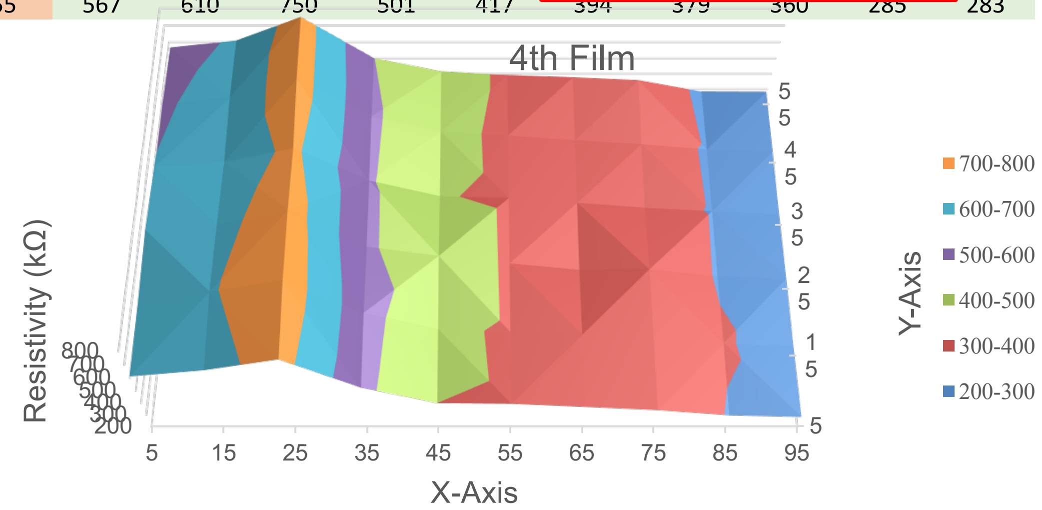
HV

Y (10.09 mm pad)

Z (11.18 mm pad)

60 mm

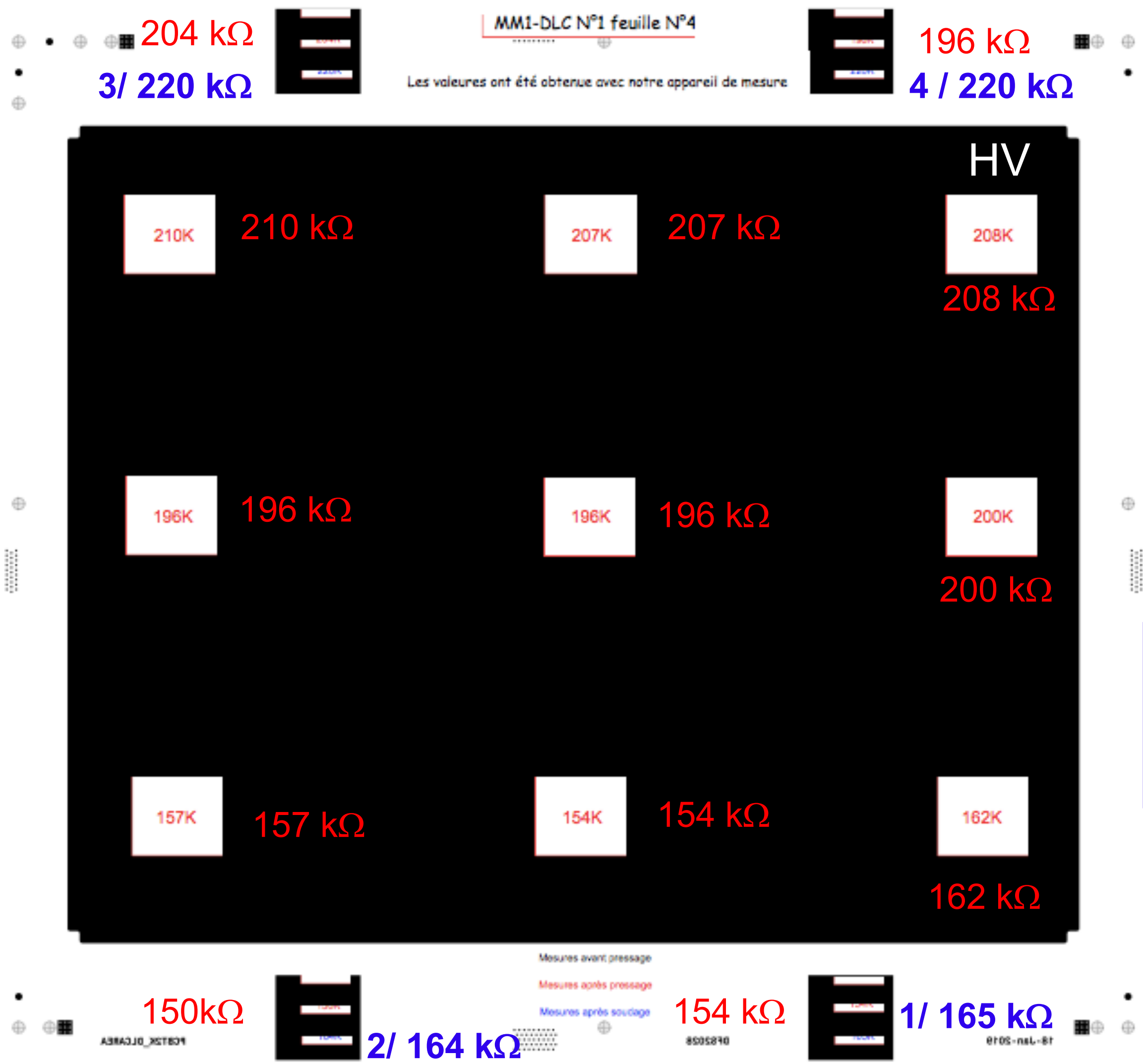
34 x 42 cm^2 ERAM
in
44 x 52 cm^2 raw PCB

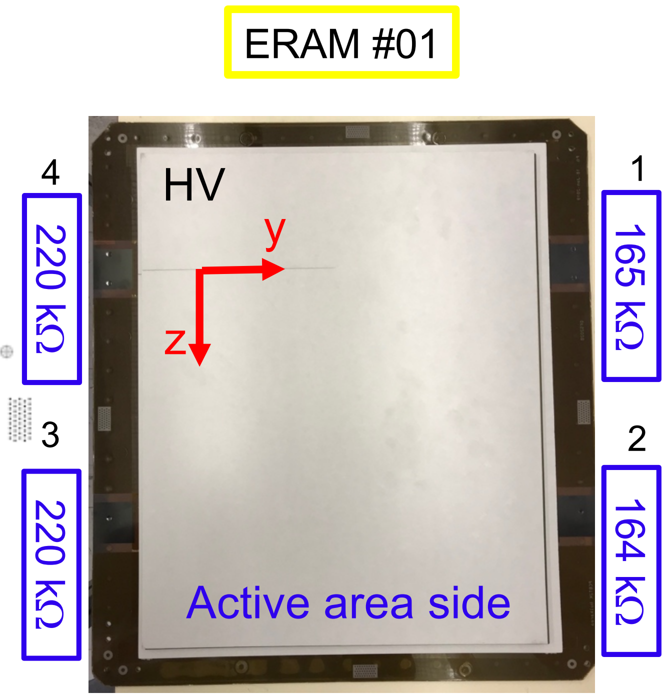


- Non-uniformity along Y due to sputtering process
- The very good uniformity is aligned with z (neutrino beam)

ERAM #01 final resistivity

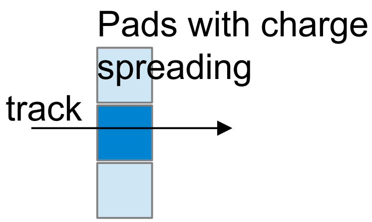
ERAM #01 resistivity – active area side

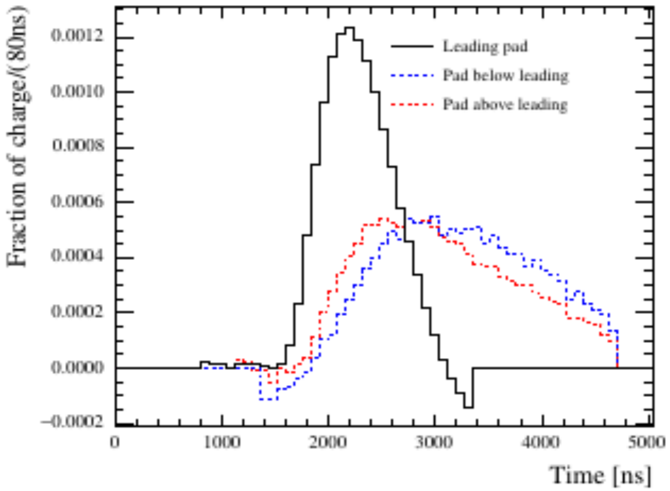


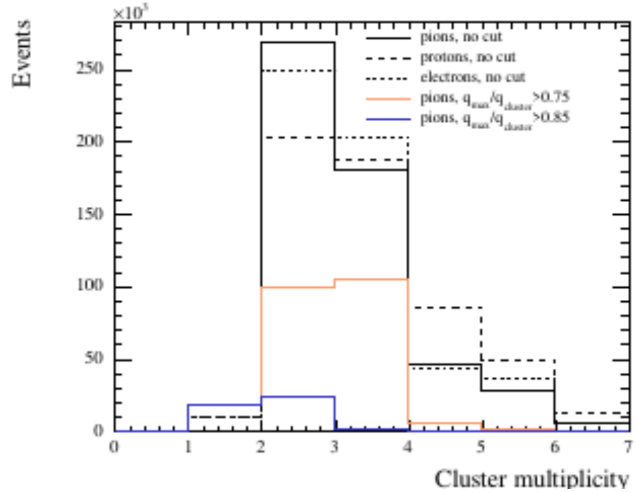


(arXiv:1907.07060)

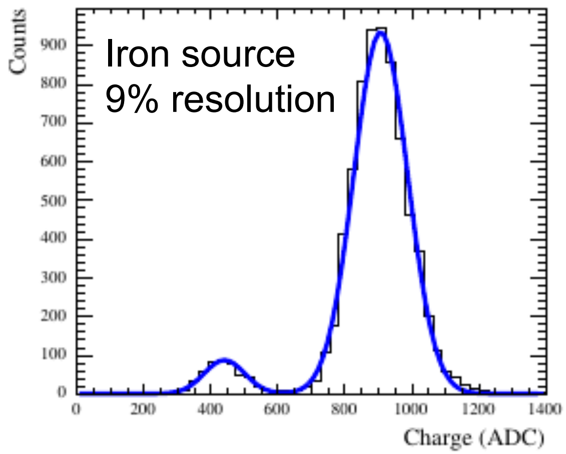
CERN prototype performances (1)

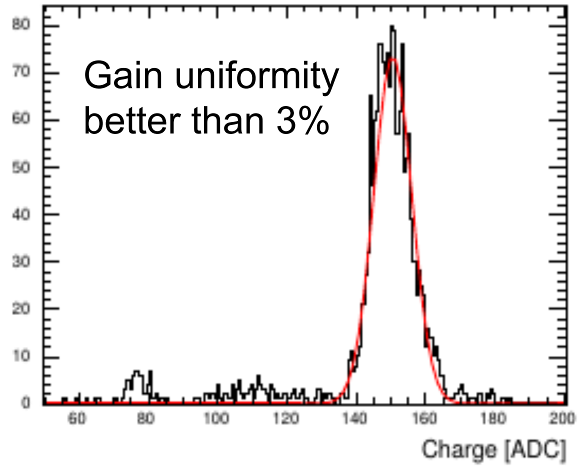






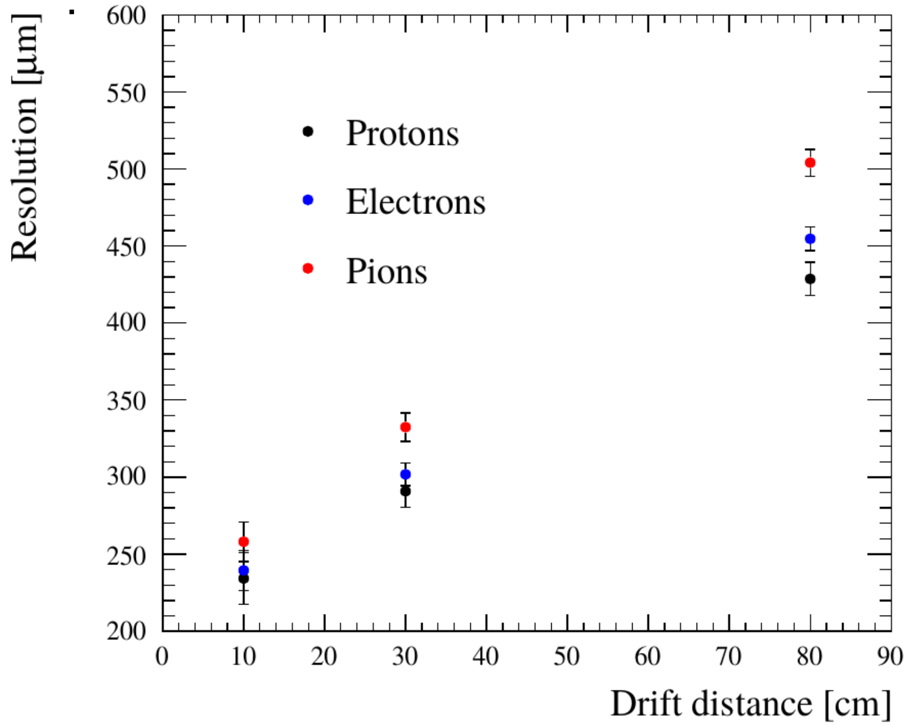
Results from preliminary prototype at CERN V-TPC micromegas (pad 9.8x7mm^2) with not optimal resistive foil 2.5 MΩ/square)

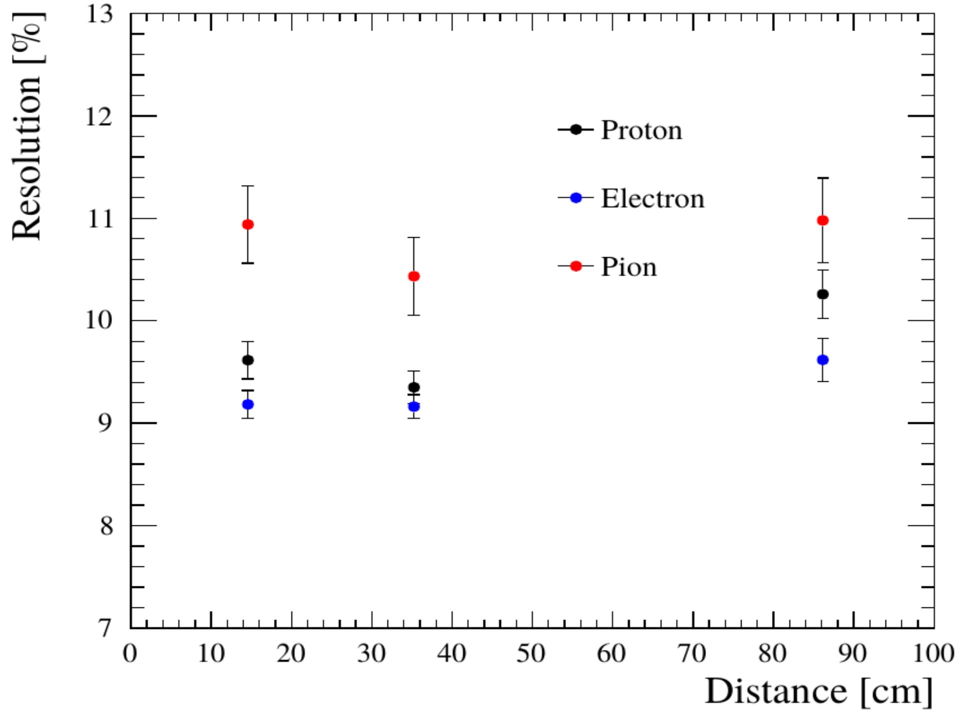




CERN prototype performances (2)

(arXiv:1907.07060)





Even better results at DESY with final pad design (10x11mm^2) and improved RC (500 kΩ/square)
(preliminary spatial resolution ~200um → factor 3-4 better than present TPCs)