RD51

R&D on gaseous detectors for hadron calorimetry at future linear colliders

M. Chefdeville, LAPP, Annecy

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Laboratoire d'Annecy-le-Vieux de Physique des Particules

Argonne NATIONAL LABORATORY

Overview

- Gaseous calorimetry

  Why a gaseous media? Why a (semi)-digital readout?

- Resistive Plate Chamber and Micro Pattern Gas Detectors

  Operation? Pros & Cons? Performance?

- Prototype limitations and current R&D

  What can be improved and how?

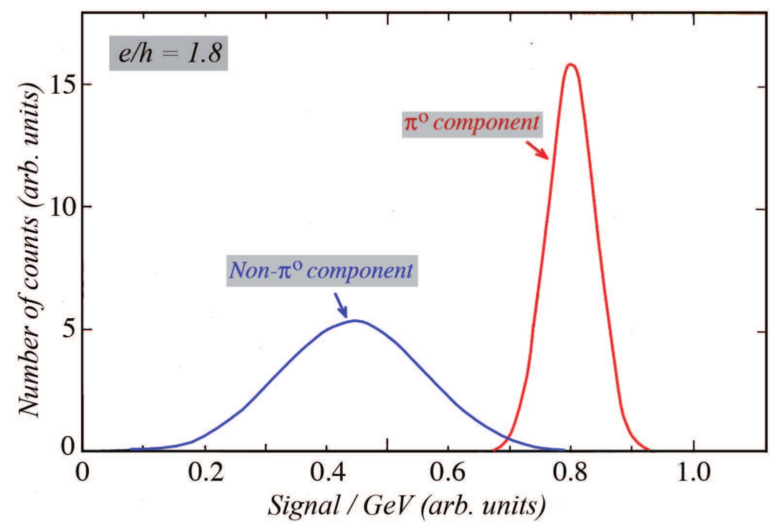
Energy resolution of hadron calorimeters

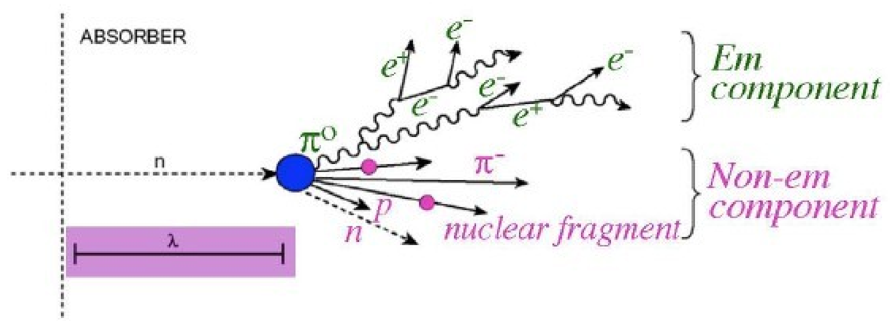
The HCAL performance are generally poor
(and dominate the jet energy resolution) for 2 reasons:

NON COMPENSATION ($e/h \neq 1$)
+ large fluctuations of EM fraction → poor resolution

+ the EM fraction is energy dependent → non linear response if $e/h \neq 1$

Response functions of EM & non-EM components of hadron showers in a non-compensating calorimeter



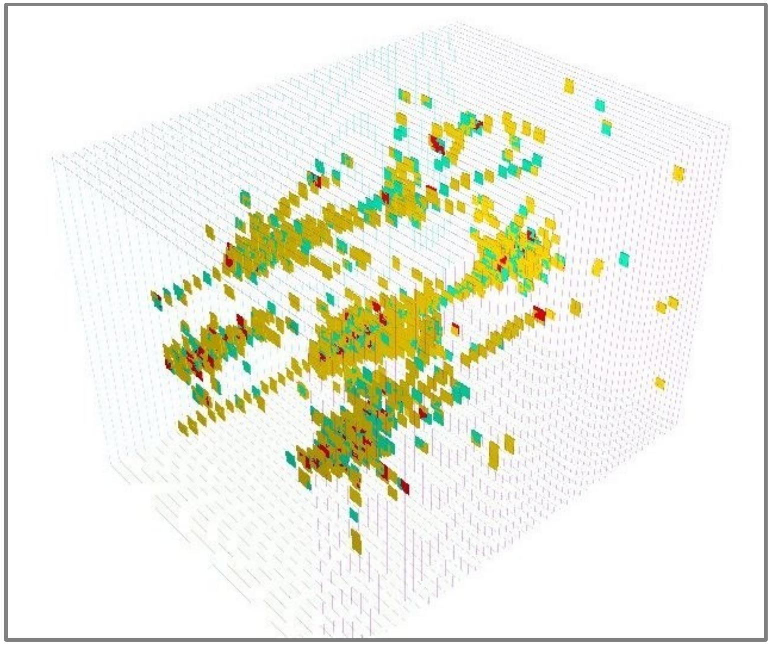


This motivated 2 approaches

Target the intrinsic limit (invisible energy)
→ measure EM and H parts of shower separately (**DREAM**)

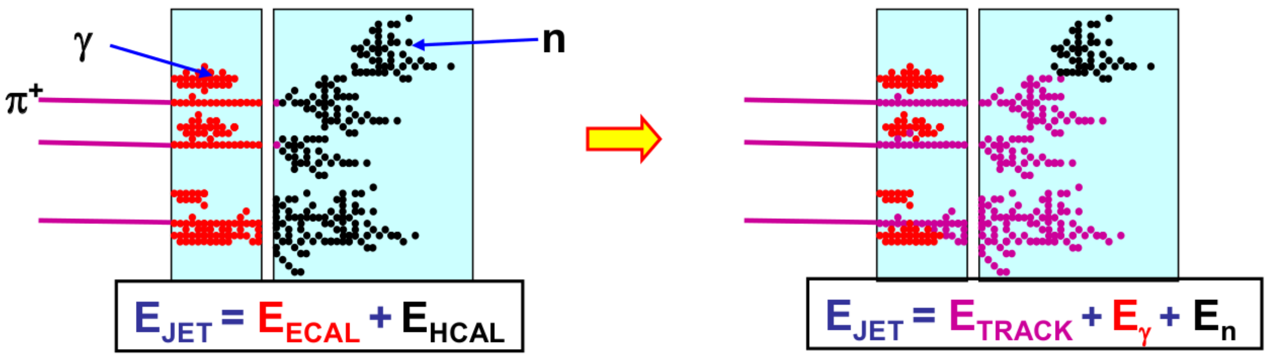
Live with fluctuations but use the HCAL
only when not possible otherwise (neutral hadrons)
→ ***Particle Flow*** **(CALICE)**

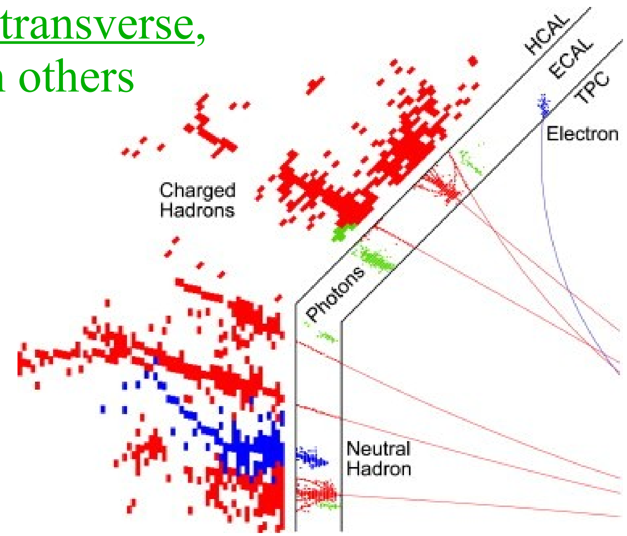
Pions simultaneously showering in the CALICE/SDHCAL



Particle Flow reconstruction

Fine segmentation of the calorimeters, both longitudinally and transverse, is necessary to disentangle neutral hadron energy deposits from others





Particle Flow calorimeters

ECAL Small x_0 and R_M, high λ_{int}/x_0 ratio → W absorber (0.32, 0.8 cm, 31 respectively) and Si wafers

HCAL Good mechanical properties & small λ_{int} → Fe (16.7 cm) or W (9.9 cm) absorbers for ILC and CLIC

Resolution VS segmentation?

→ Scintillating tiles 3x3 cm^2 (better energy resolution thanks to higher sampling fraction)

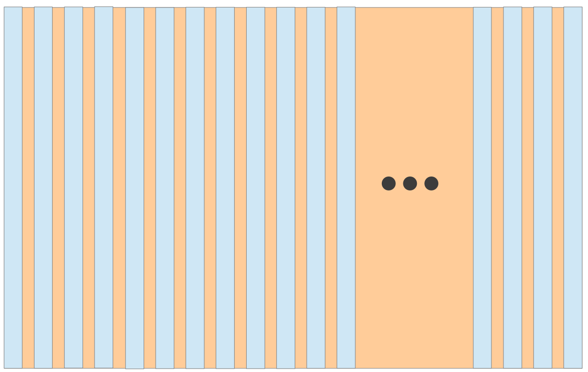
→ Gaseous detectors 1x1 cm^2 (allow for increased segmentation)

Gaseous hadron calorimeter ("AHCAL")

A Monte Carlo simulation shows that
a gaseous sampling Fe HCAL as proposed by CALICE

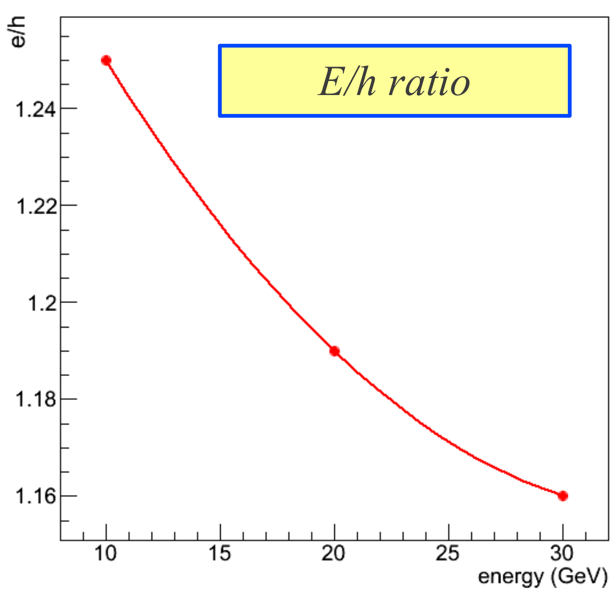
Is not compensated (e/h > 1) and therefore non-linear.

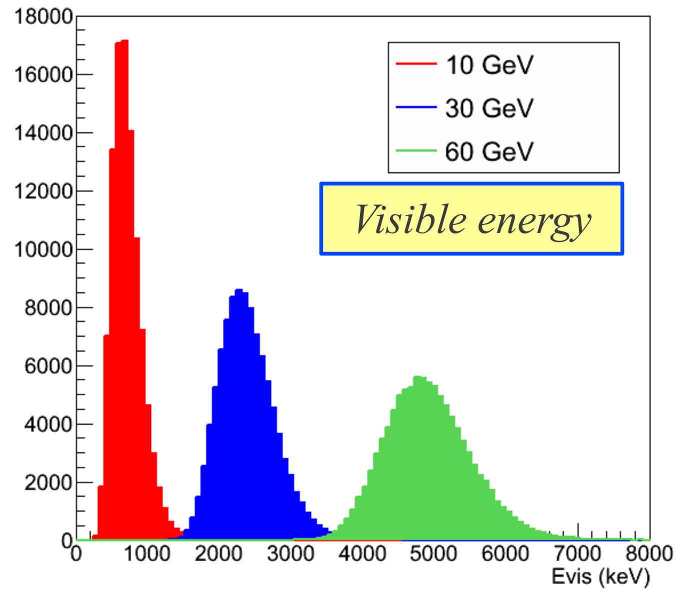
Should have a poor energy resolution due to the
Landau fluctuations arising from a small sampling fraction.

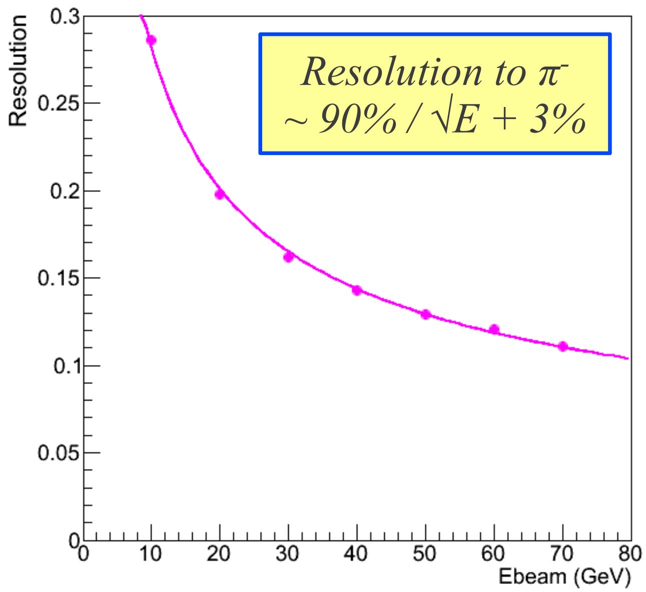


MC sim. Proto.: 2 m deep (~ 10 λ_{int}), 100 layers of 1x1 m^2 with 1x1 cm^2 pads – Assume proportionality: Evis = Edep

Performance of a gaseous HCAL with analogue readout







Gaseous hadron calorimeter (DHCAL)

Is it worse with a digital readout?

Saturated response described by e.g. *N(E) = a/b * log (1 + b*E)*.

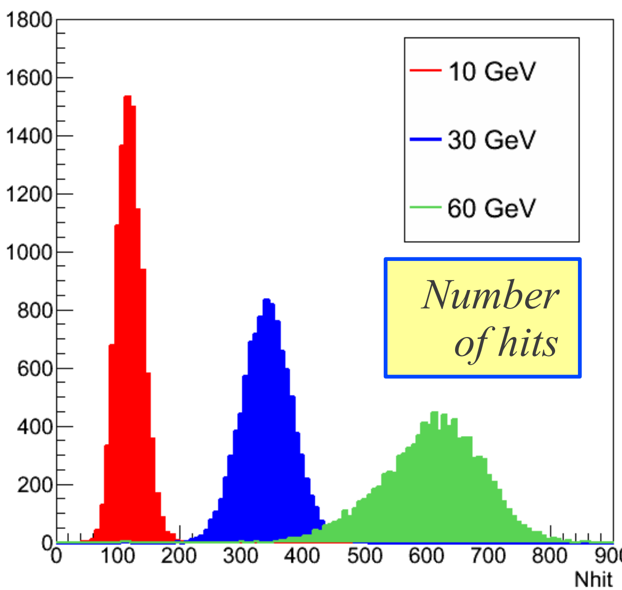
(In the meantime: e/h is now < 1 for E > 10 GeV)

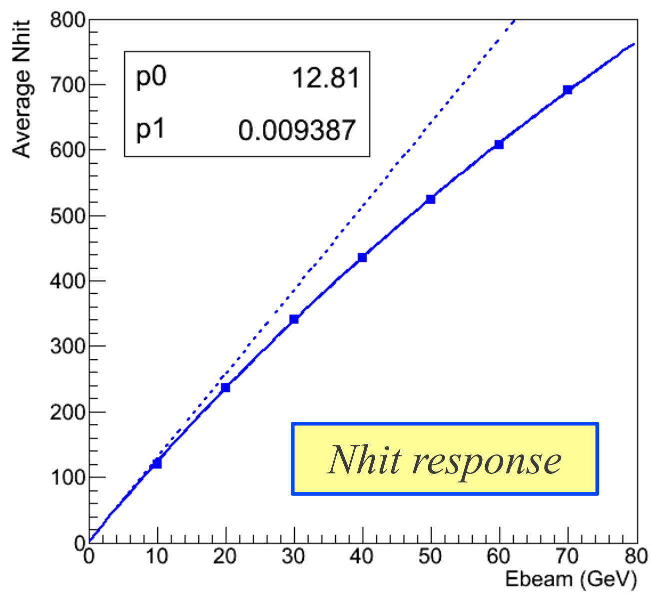
After reconstructing the energy in the simplest way: *N(E) → E(N)*

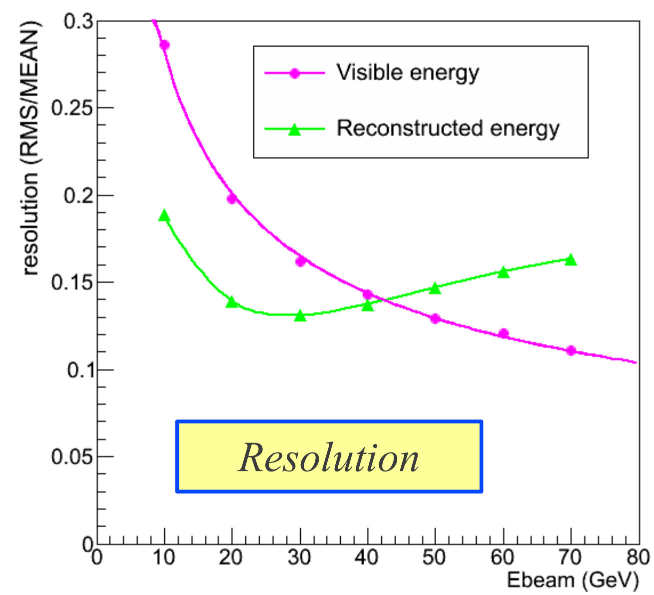
The resolution is better than the one obtained with an analogue readout up to 40 GeV.

Beyond ~ 30 GeV, saturation degrades the energy resolution.

Software compensation is a possible way to restore linearity and resolution (not used here)







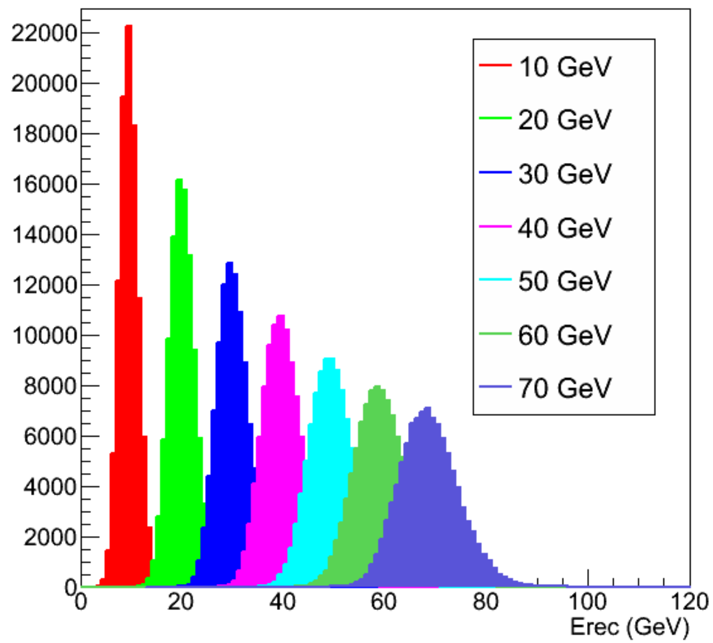
Gaseous hadron calorimeter (SDHCAL)

Improve the resolution above 30 GeV with additional readout thresholds (2 bit / cell)

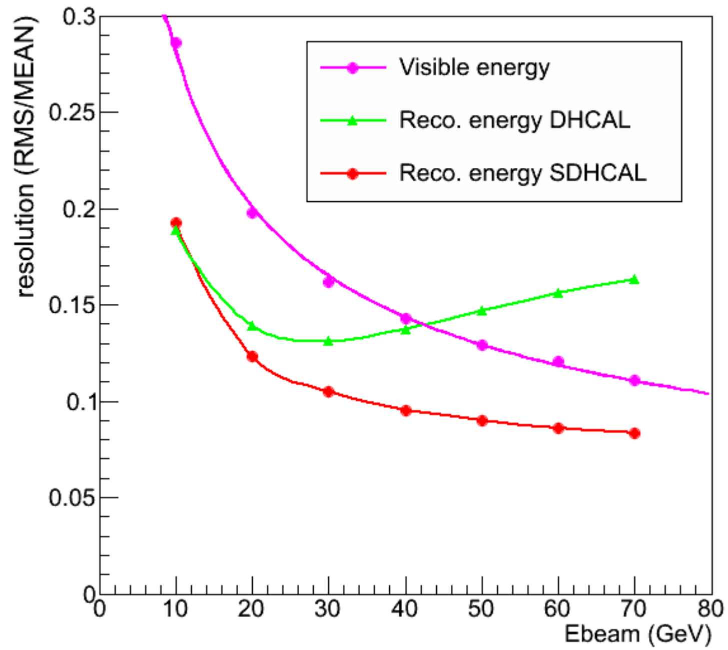
Combine the information in some way (weighting, likelihood...).
With a particular set of thresholds, simulation promises quite some improvement w.r.t. the pure digital case.

Better energy resolution over simulated energy range

Reconstructed energy



Energy resolution



This conclusion is independent of the type of detector used (3 mm of argon).

Nevertheless, it *assumes proportionality: cell signal are proportional to the deposited energy*.

Gaseous hadron calorimeters
A summary

Analogue readout
→ not worth it

Digital readout
→ suited for "low energy" (below saturation)

Semi-digital readout
→ improve at "high energy" (beyond saturation)

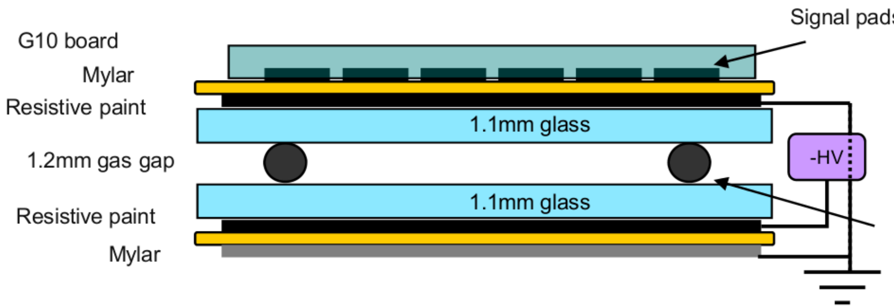
Proposed technologies

Resistive Plate Chambers
Micro Pattern Gas Detectors

PS: these statements are supported by simulation studies. They are being confronted to measurements in test beams of the CALICE DHCAL and SDHCAL prototypes.

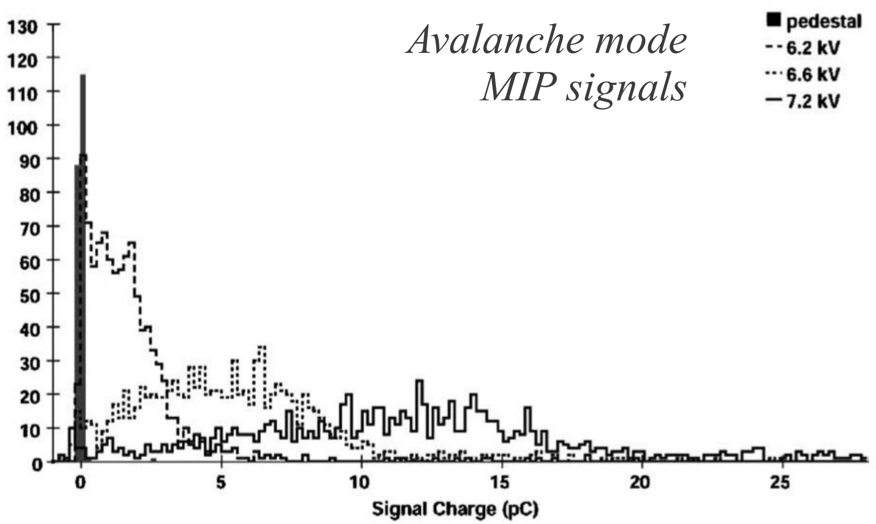
RPC operation principle

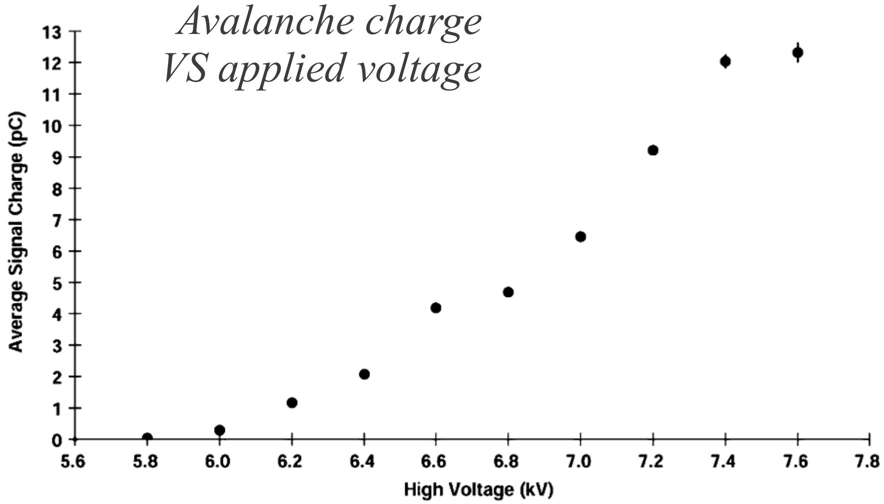
Avalanche or streamer mode (depending on HV)
Fast (< 1 ns) and large MIP signals (1-10 pC)



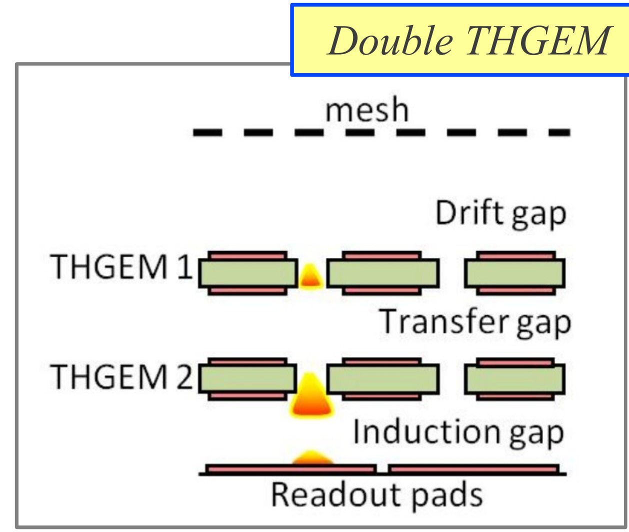
Spark-proof but rate limited (100 MIP/cm^2/s with typical resistivities)

The multiplication stops by itself when the space charge field becomes too high.
The applied field settles back after a certain recovery time given by the resistivity of the glass.





MPGD operation principle



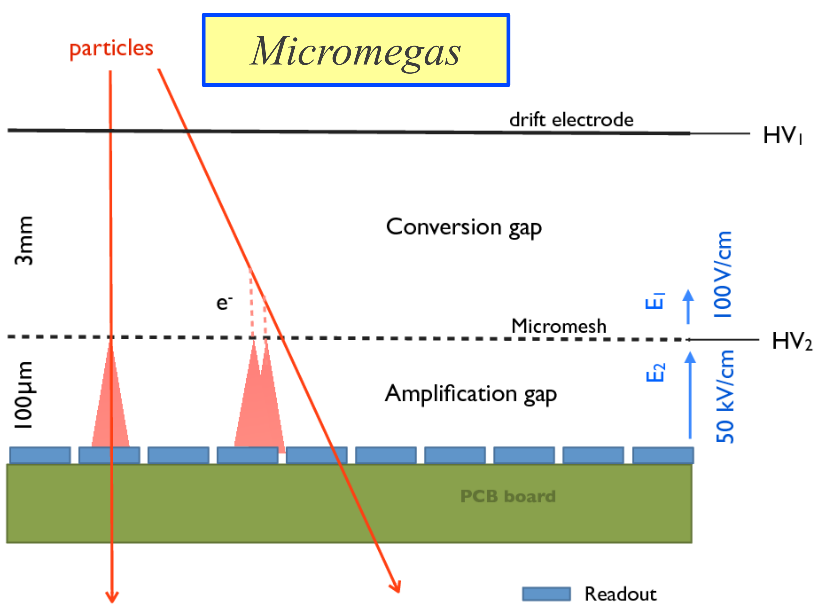
Avalanche ions quickly collected thanks to closely spaced electrodes (50-100 um)

→ Micromegas, GEM and variants (e.g. THGEM, WellGEM)

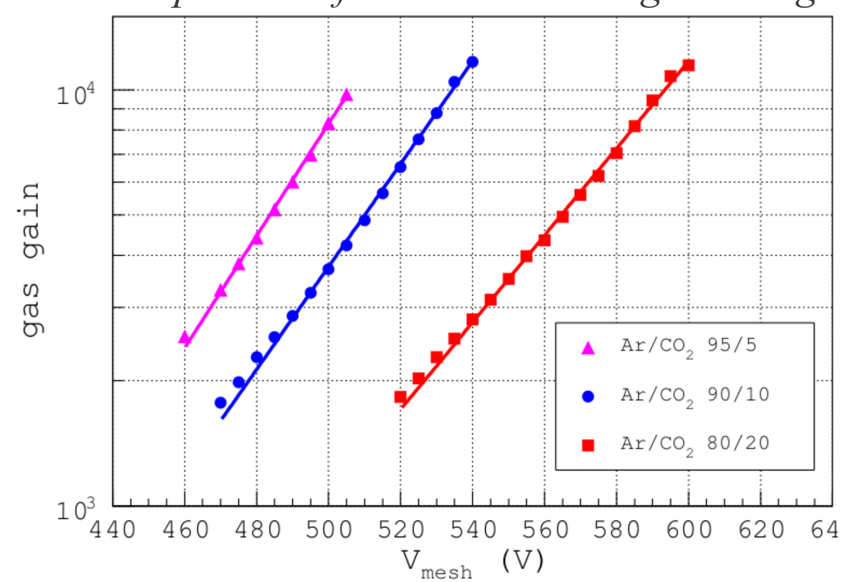
Fast (~ 5 ns) and small MIP signals (10-100 fC)

Rate capable (~ 10^6 MIP/mm^2/s) but **occasional sparks** (no self-quenching process)

The readout electronics needs protection against sparks.



Multiplication factor VS Micromgas voltage



Application for hadron calorimetry

PROS / CONS

MPGD

PROS	CONS
Low operating voltage, "Safe" gases (Ar/CO_2) Available in large area, small pads	Expensive technology w.r.t. RPC Industrialisation just starting
Proportional response High MIP efficiency, low hit multiplicity Can be operated at low discharge rates (negligible dead time for HCAL rates)	Need sensitive electronics with protections against sparks

RPC

PROS	CONS
Long efficiency plateau & No sparks	Rate limited (huge gas gains) but should be OK for ILC
Available in large area Quite thin (< 4 mm with gas + 1-glass + PCB) Well-known & cost-effective technology	→ behaviour in dense shower? SD readout? High operating voltage, complex gas mix.

The Micromegas project

Bulk manufacturing process

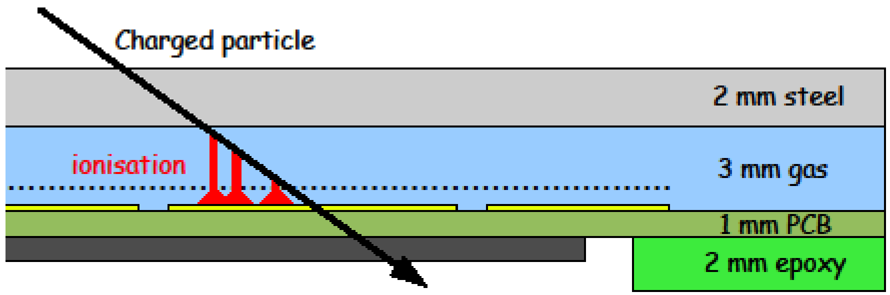
Lamination of photosensitive films and steel mesh

→ Compact design (~ 9 mm)

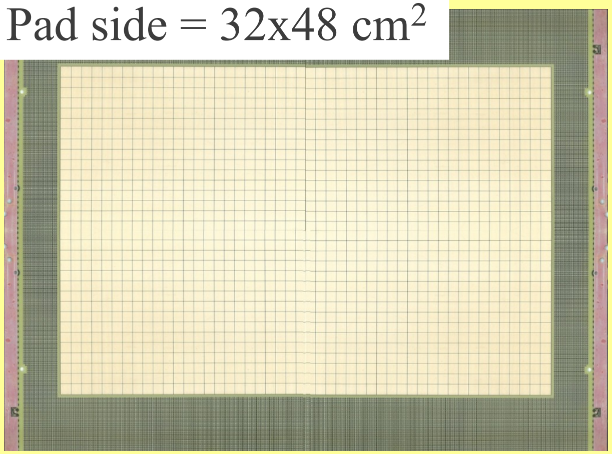
The mesh, the PCB with pads and the ASIC (MICROROC) form one element called Active Sensor Unit (ASU) of 32x48 cm^2

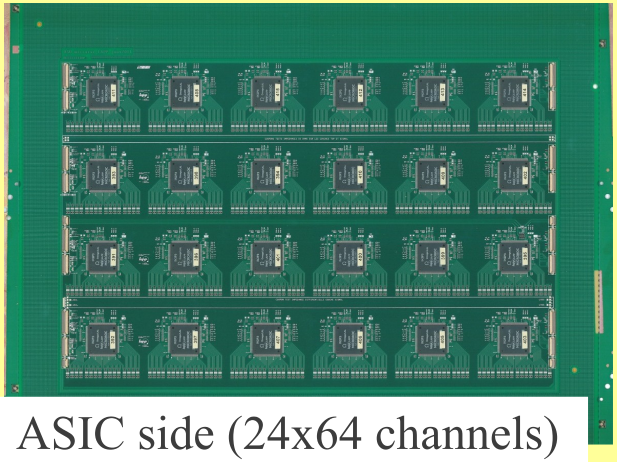
→ Design well suited for large area (several m^2 / chamber)

ASU can be chained thanks to flexible inter-connections
Scalability to large area



Pad side = 32x48 cm^2

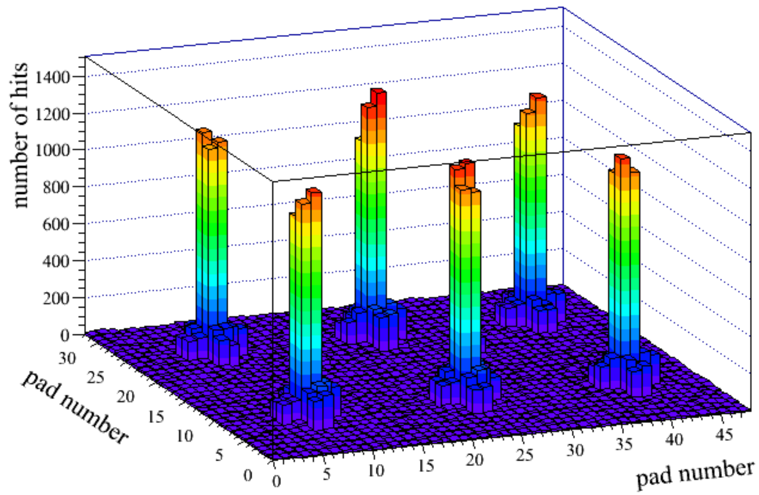


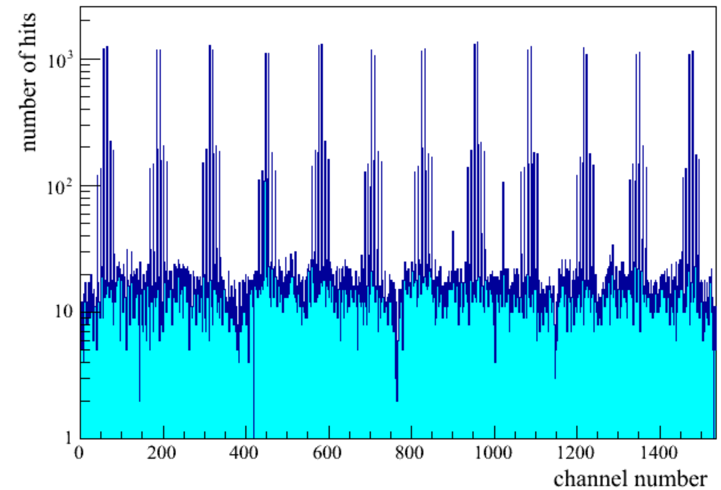


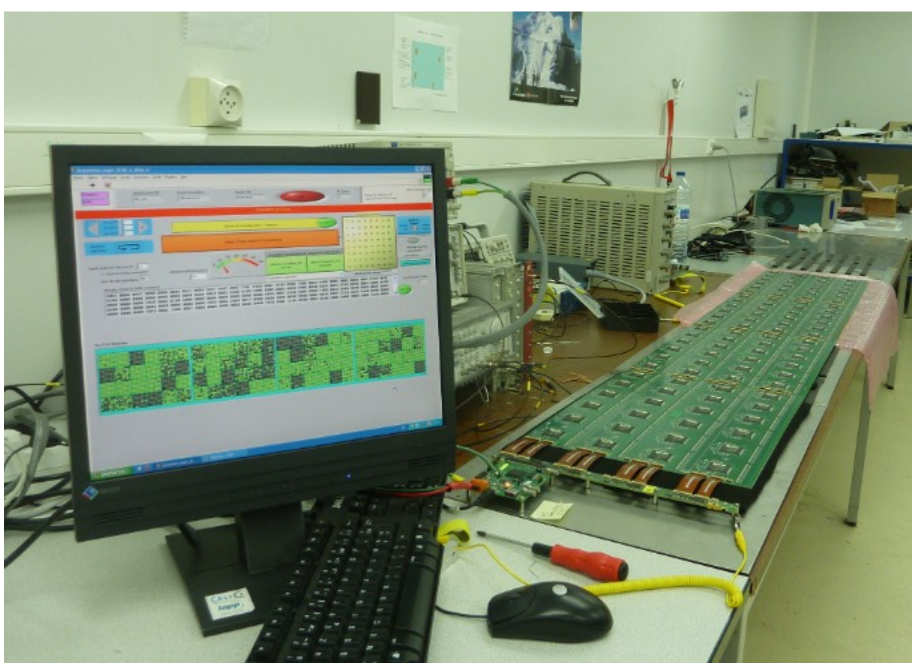
ASIC side (24x64 channels)

Average number of primary electrons of ~ 30 e-, Gas gain up to a few 10^4, MIP charge of 5-20 fC in 150 ns

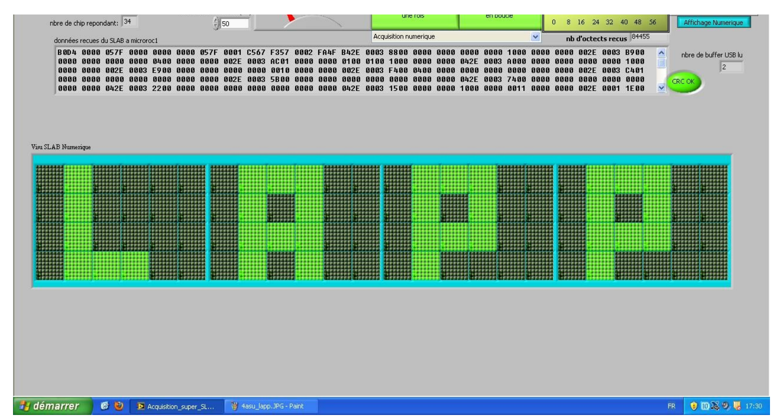
ASU perform very well (1-2 fC threshold)
^{55}Fe quanta peaks above flat (cosmic) background: no noise!







Chaining works: successfully tested with a chain of 4 ASU of ~ 2 m long! Can be extended to 3 m.



Design of the 1x1 m^2 chamber

The 1 m^2 chamber consists of 3 slabs with independent readout (DIF + interDIF + ASU + ASU)

This design introduces very little dead zone (~ 2%) and is scalable to larger sizes

The drift gap is defined by small spacers and a frame

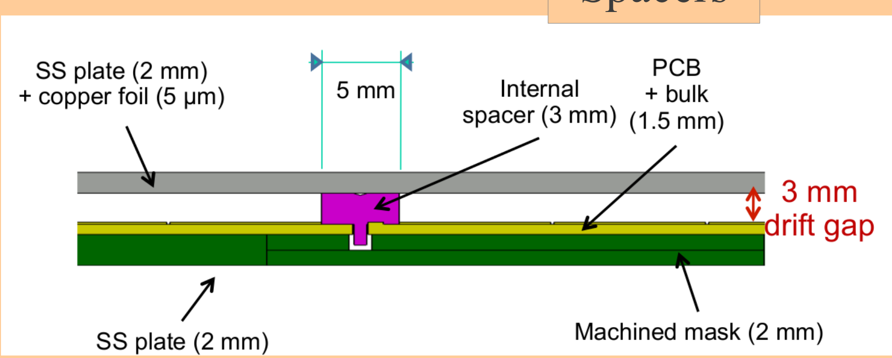
The final chamber thickness is 9 mm

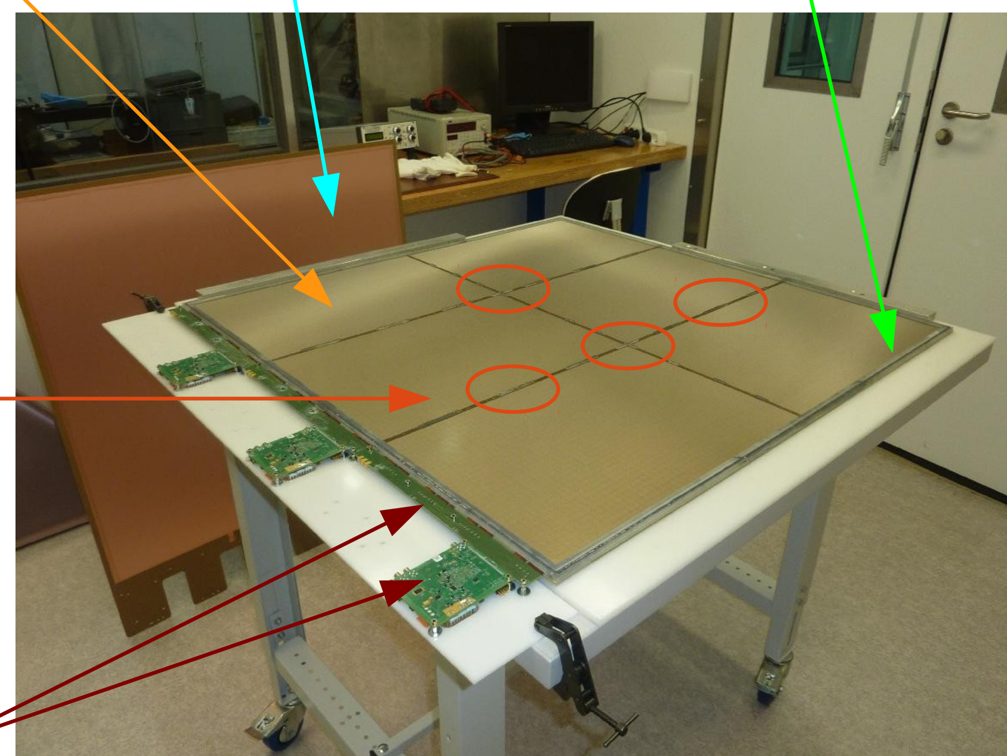
ASU (mesh)

Drift cover

Frame with 2 gas pipes

Spacers





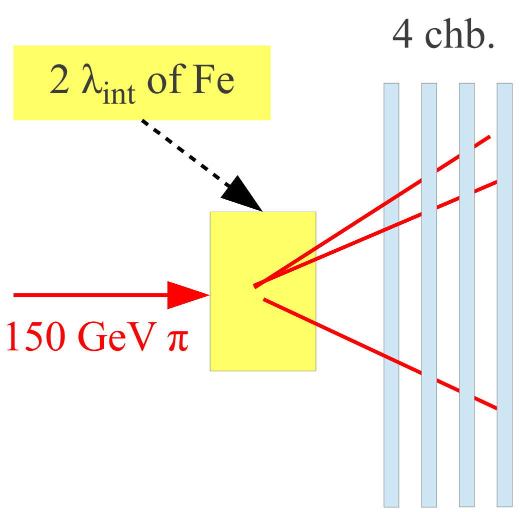
Readout boards (DIF+interDIF)
Also provide ASIC LV & mesh HV

Performance to MIPs and in hadron showers

Since 2011, 4 chambers were constructed and tested.
Efficiency to MIPs is larger than 95 %, hit multiplicity of about 1.1 for 90° tracks (at 370 V).
Full chamber irradiation shows no noise and uniform response.

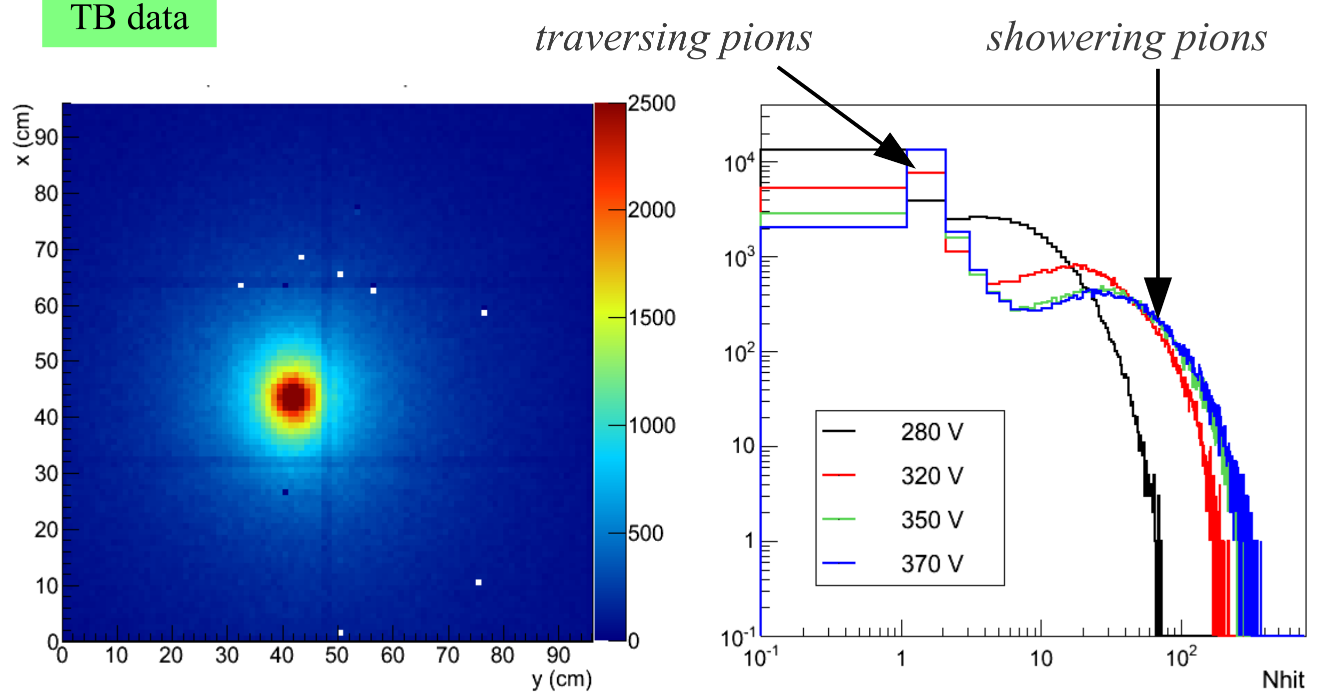
Operates at a gas gain of 2000 only (370 V): image most of the shower and no sparking.

Exp. setup



XY occupancy & number of hits

TB data

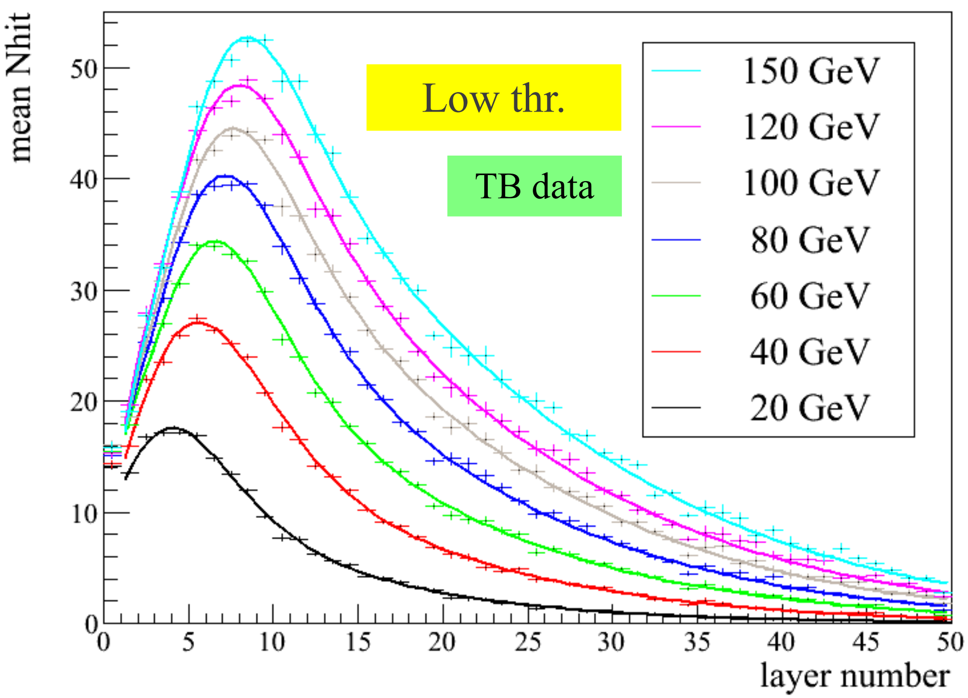


Response to pions of a Micromegas SDHCAL

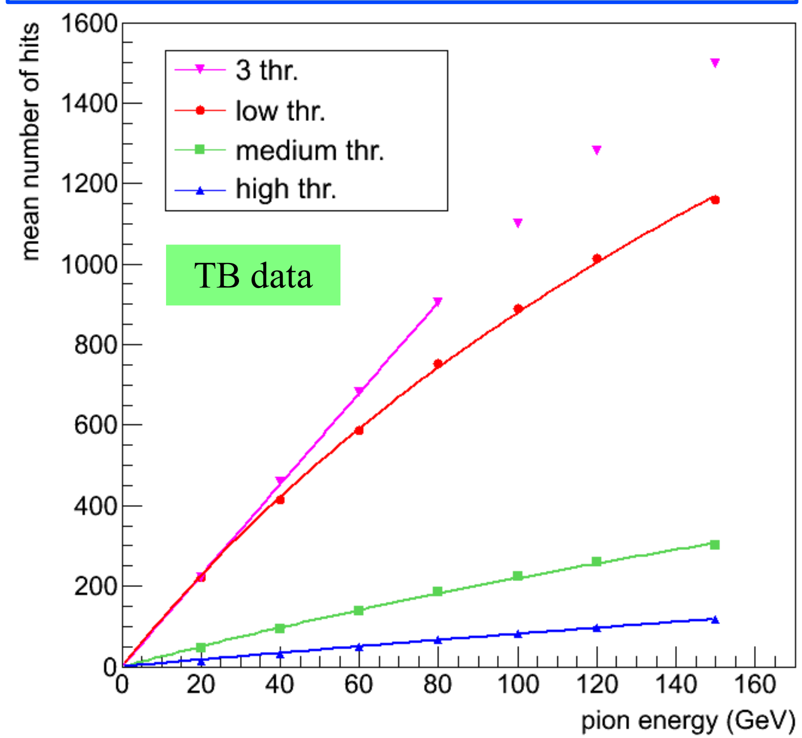
EU RPCs and Micromegas use the same DAQ → common test inside SDHCAL (46 RPCs + 4 Micromegas)

The response to pions can be extracted from the longitudinal shower profiles for the 3 thresholds. Expected saturation is observed.

Pion shower profile measured with 4 Micromegas chb.



Response to pions of a virtual 50 layer Micromegas SDHCAL



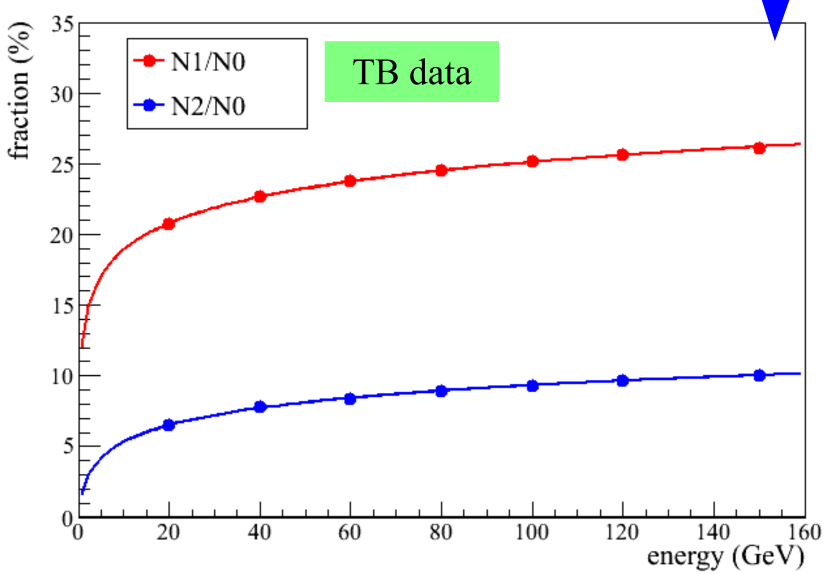
Preliminary conclusions

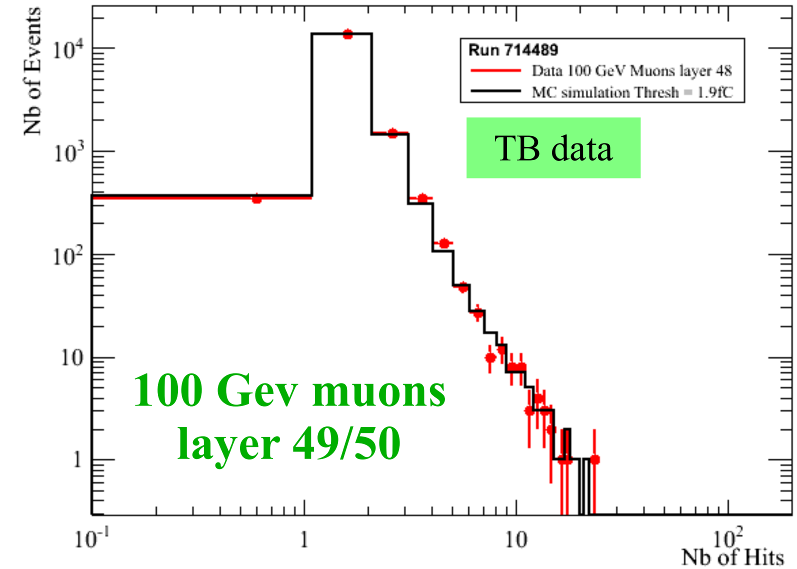
Micromegas work very well!

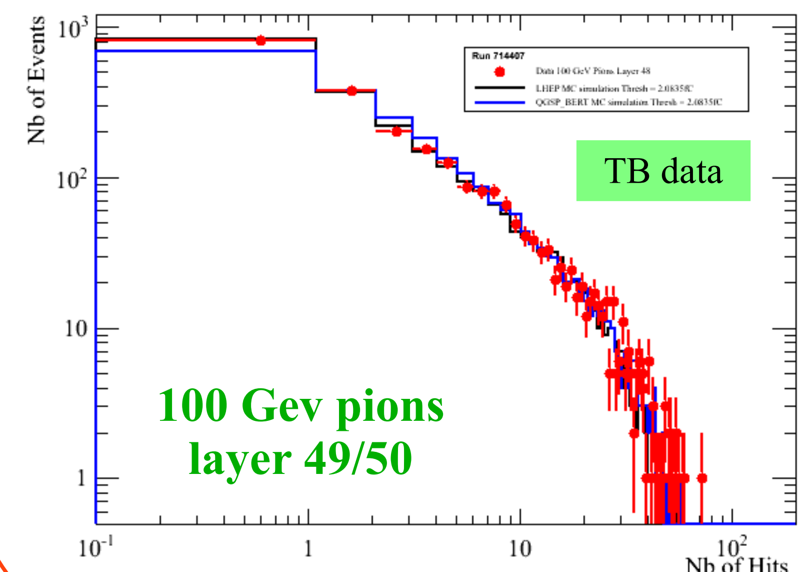
Good understanding of the detector (Data / MC)

Proportionality is seen as energy increasing probabilities to cross medium and high thresholds

Proba. to cross medium and high thresholds VS energy





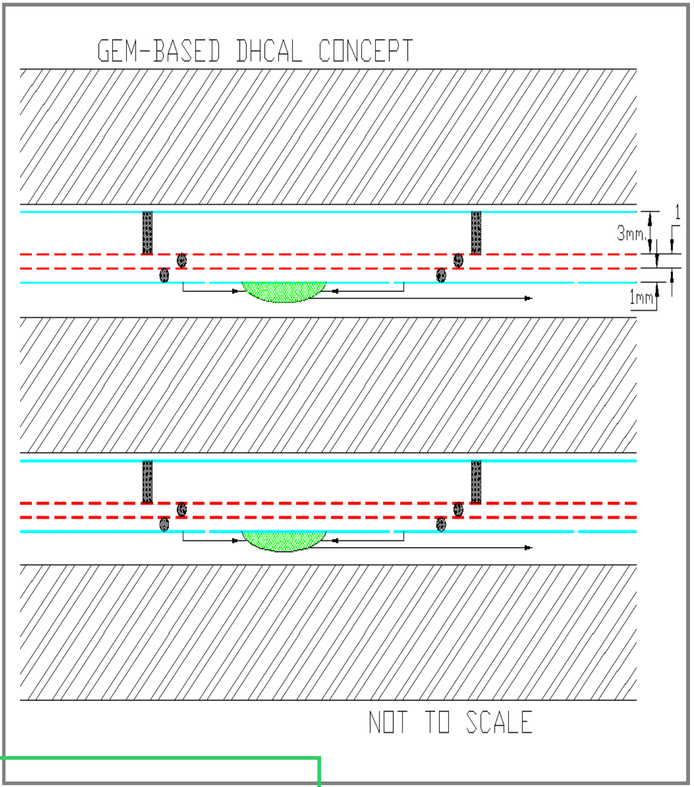


What about other MPGDs?

The GEM project

Double GEM configuration offers gas gains up to a few 10^4
While keeping gas thickness below 5 mm

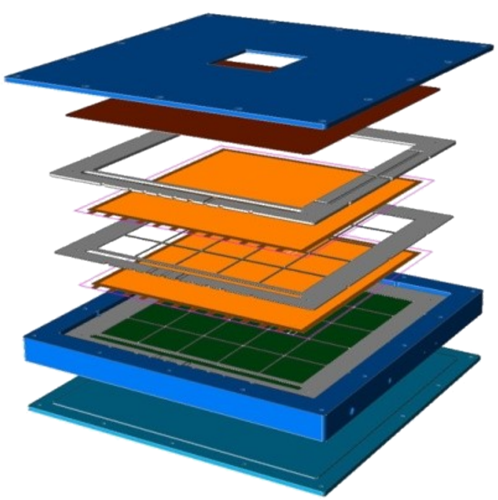
Current prototype size uses 30x30 cm^2 GEM foils.
The 1x1 m^2 chamber design uses 33x100 cm^2 foils.

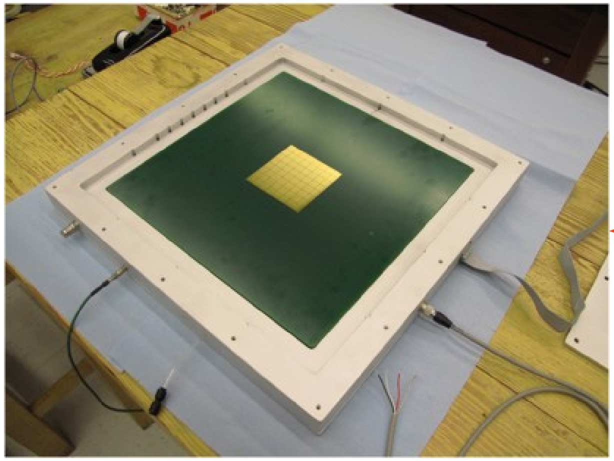


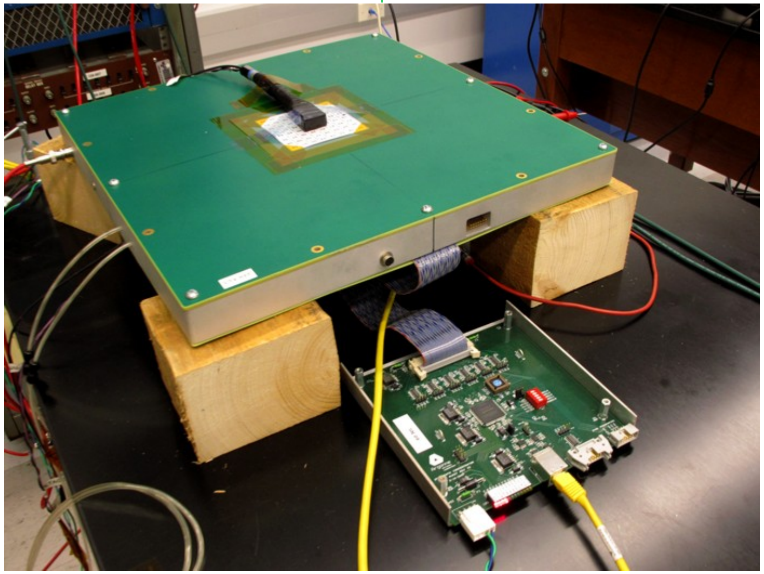
Two readout electronics used

→ Analogue with KPIX (8x8 cm^2)
Also applied to the US Si/W ECAL

→ Digital with DCAL (16x16 cm^2)
Used by the RPC US DHCAL → future test in DHCAL







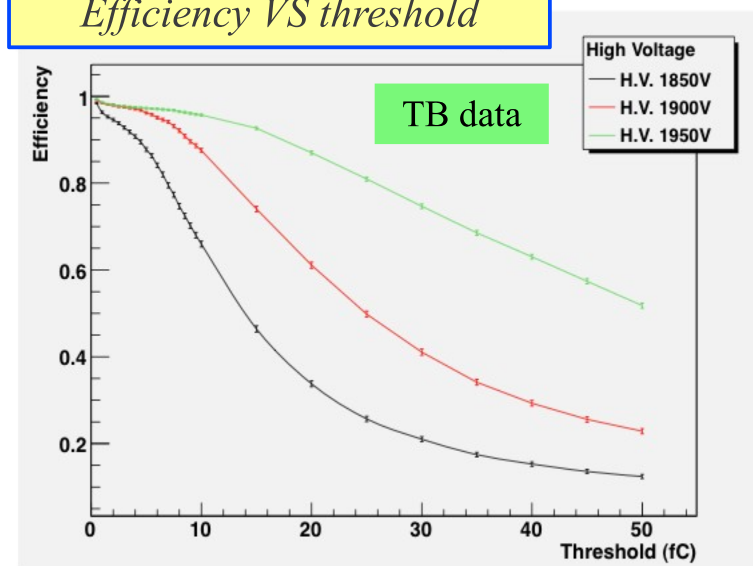
GEM performance (1/2)

Detailed characterisation with KPIX

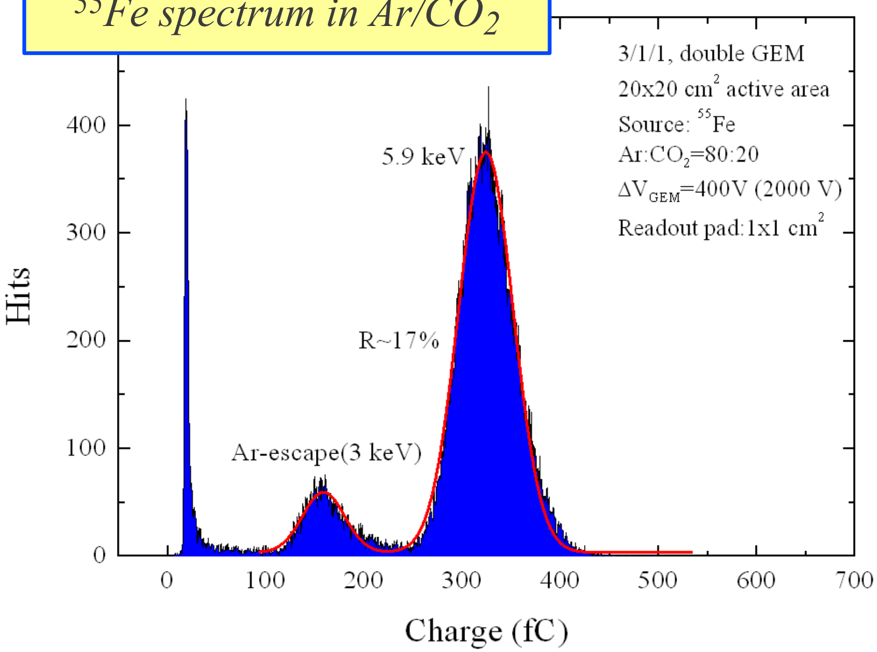
Radioactive sources
→ MIP values
→ Gain curves
→ P/T dependence

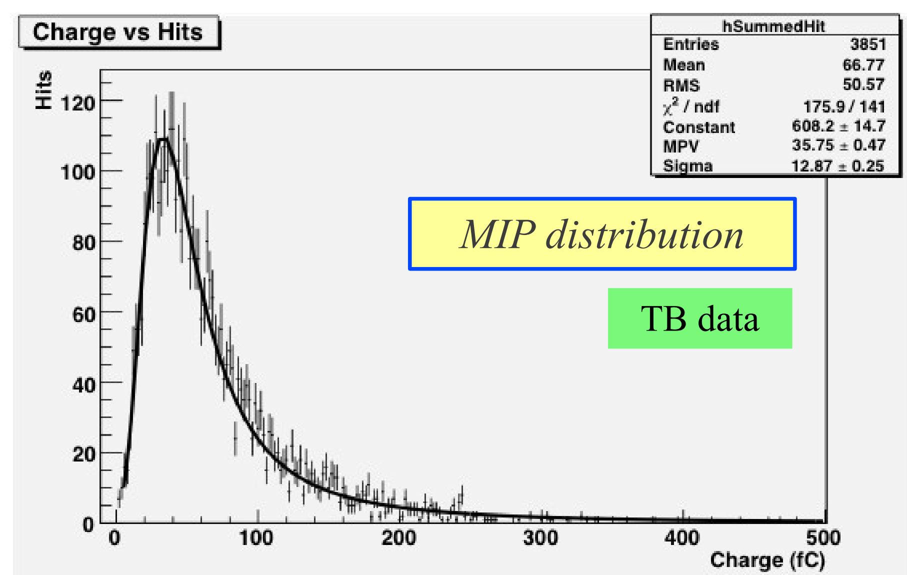
Particle beams
→ efficiency & multiplicity
→ threshold effects
→ uniformity

Efficiency VS threshold



^{55}Fe spectrum in Ar/CO_2

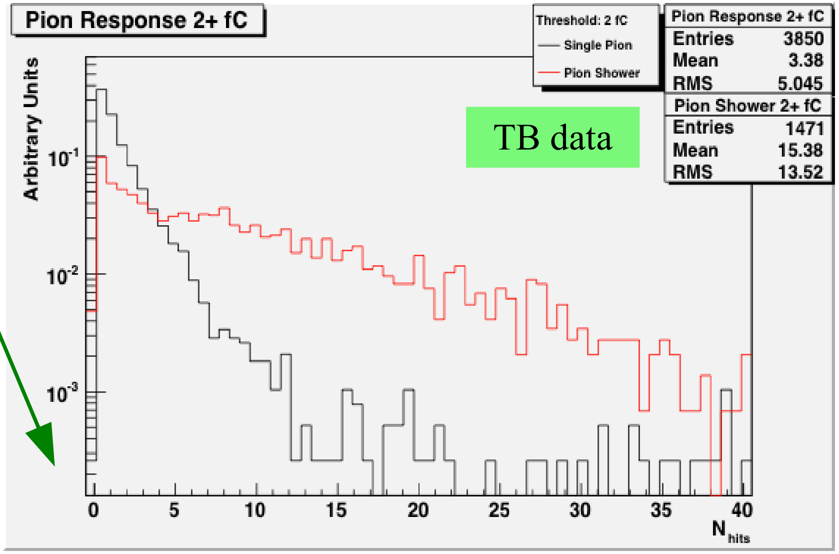




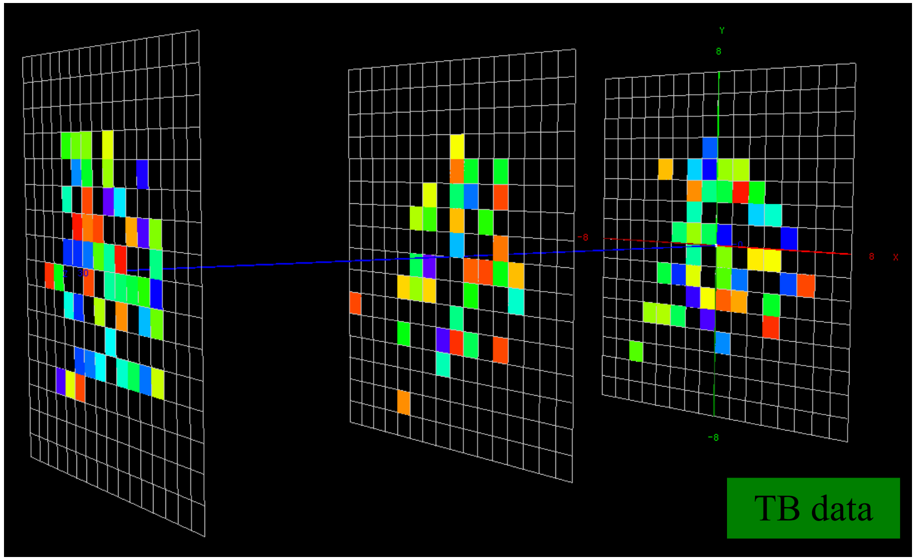
GEM performance (2/2)

Number of hits distribution in KPiX chamber
(offline threshold)

DCAL chambers could be used to detect MIP tracks.



Testbeam setup at FTBF: 1 KPiX + 3 DCAL



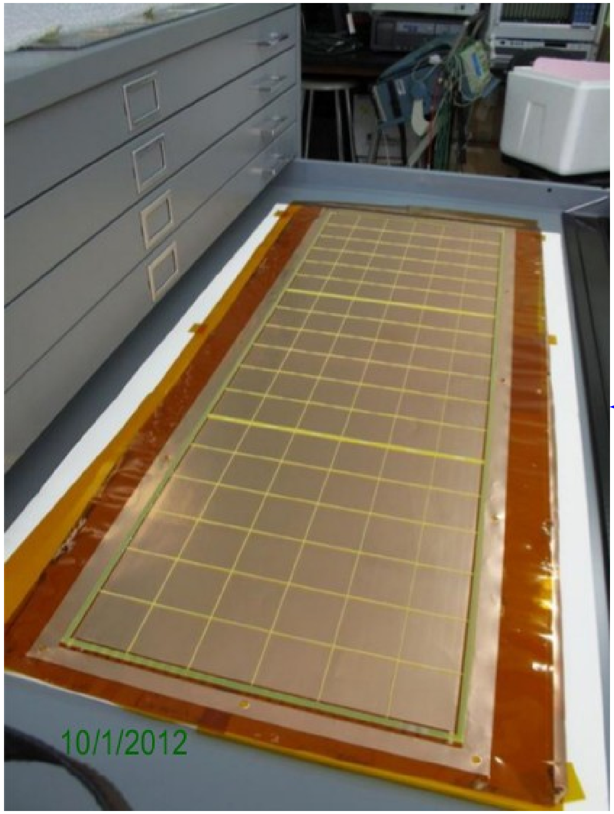
The 1x1 m^2 GEM DHCAL layer

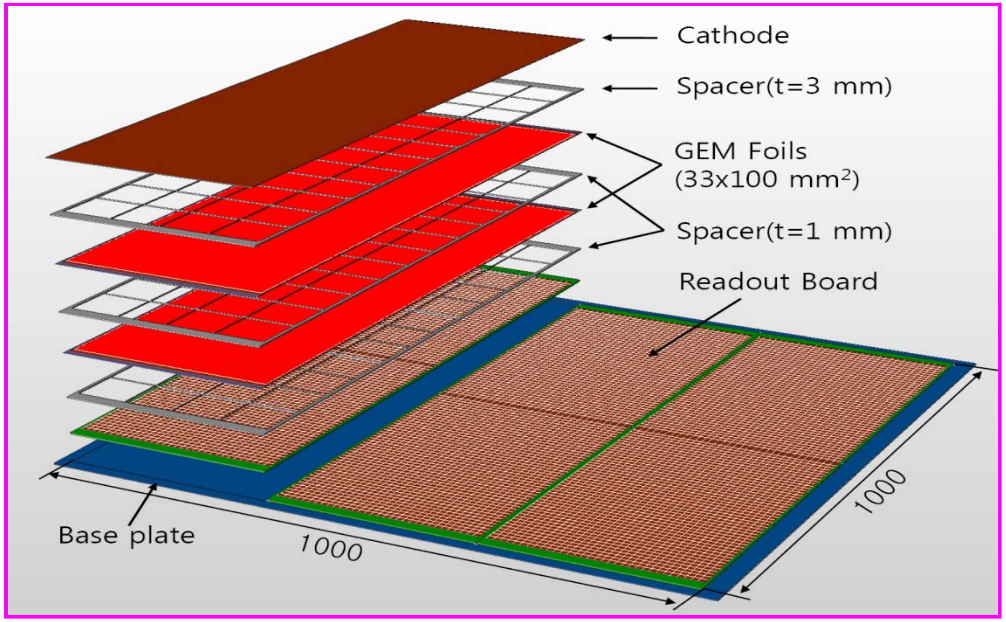
A GEM HCAL layer would consist of 3 unit chambers equipped with two 33x100 cm^2 GEM foils

Spacers define the different gaps between cathode / GEMs / anode.

Several large foils received, **construction of unit chambers has started**!

1x1 m^2 layers will eventually be tested in CALICE DHCAL.





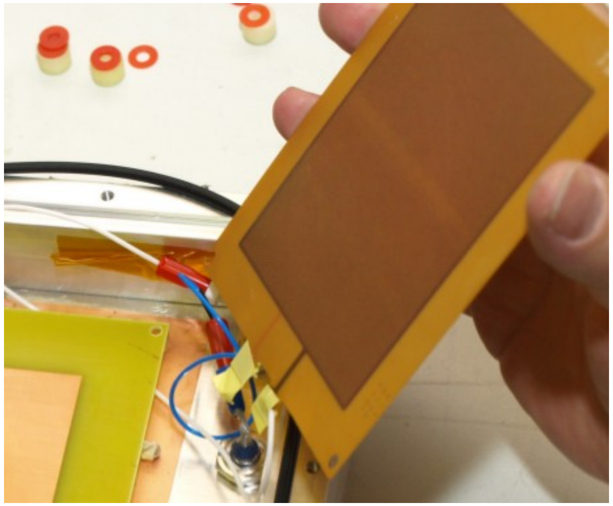
The THGEM project

Motivation: use one gas gain foil instead of two

→ so-called THick GEM (10 fold expanded GEM)

Robust, cost-effective and gas gains > 10^4

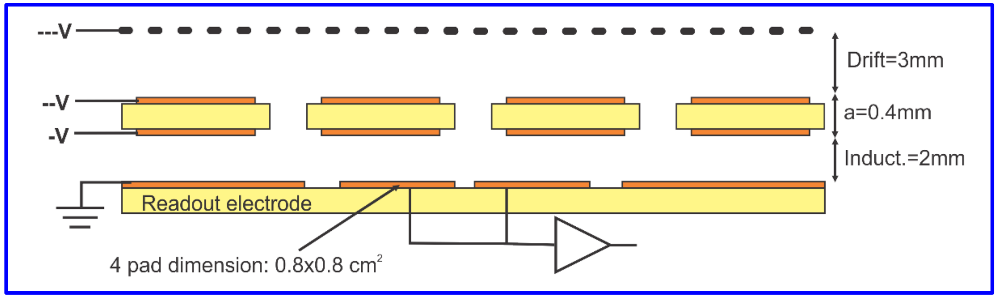
Multi/single stage configurations perate best in Ne mixtures



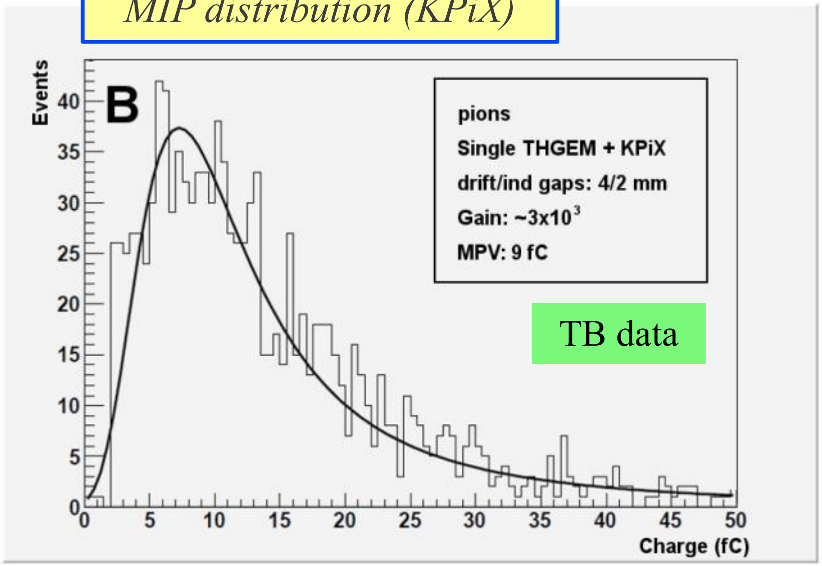
Successfully tested with RD51 Scalable RO system (SRS), KPiX and MICROROC chips

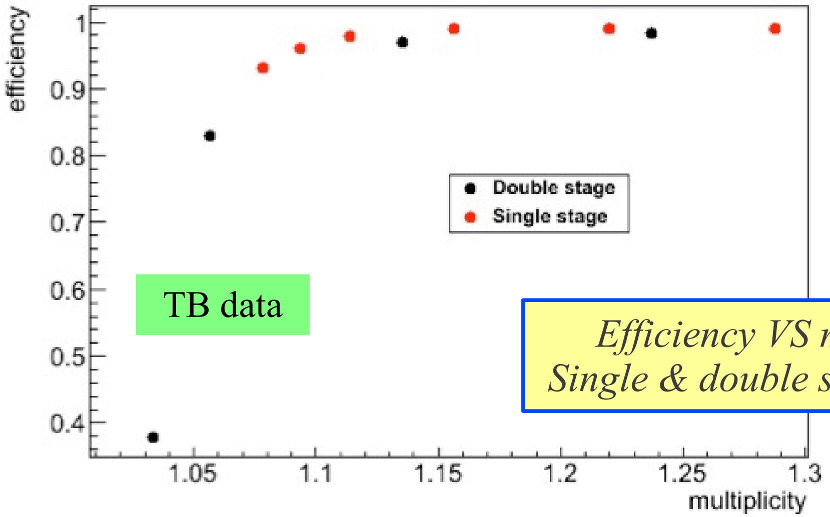
→ high efficiency (> 98%), low hit multiplicity (< 1.2)

Latests results: 2012 JINST 7 C05011



MIP distribution (KPiX)



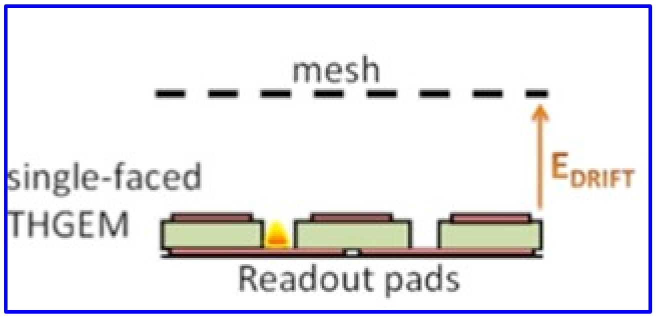


Efficiency VS multiplicity
Single & double stage THGEM

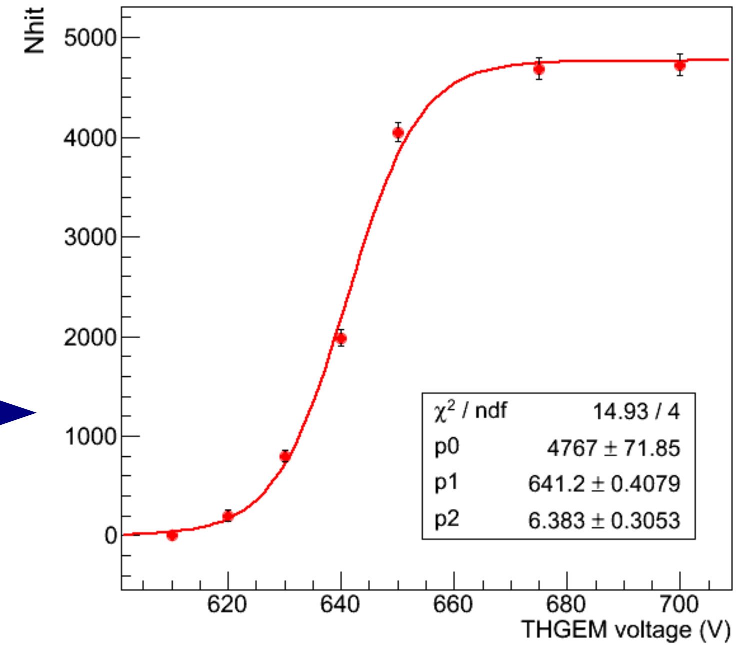
The THGEM project

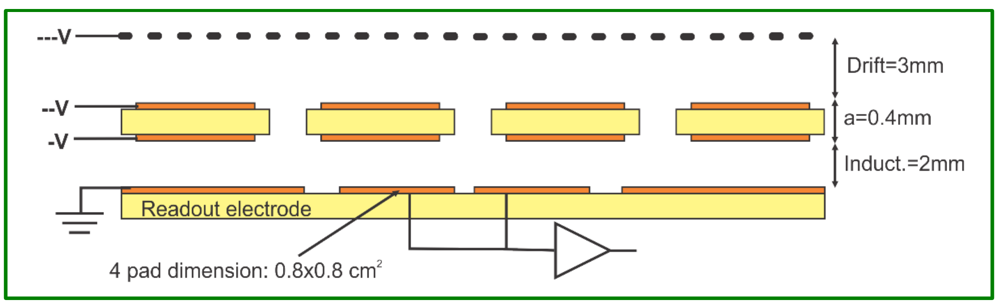
Results with MICROROC electronics

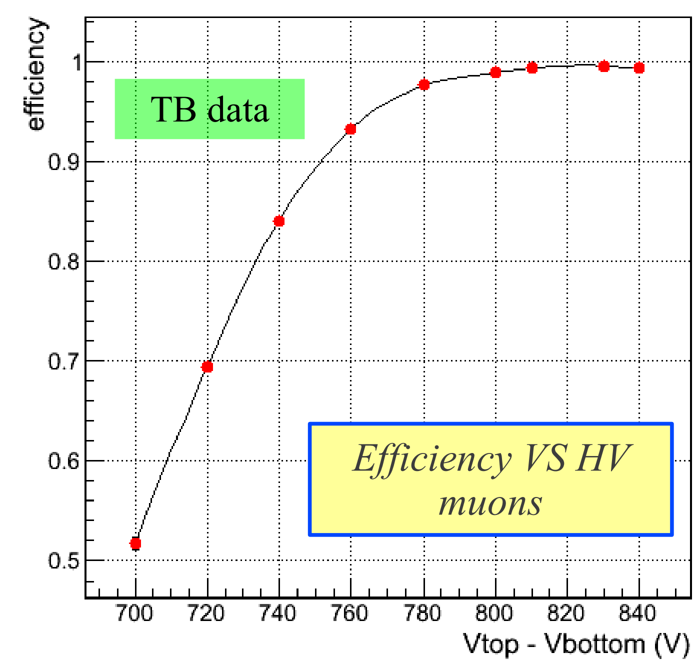
Successful preliminary tests of several THGEM-based detectors



Nhit from 55Fe VS HV







Towards the design of 1 m^2 prototype

→ R&D of 30x30 cm^2 electrodes with SRS readout
Study segmentation, and solve mechanical issues

→ Continue studying THGEM/MICROROC detectors.
Next: 32x48 cm^2 prototype

Sparking in MPGDs (1/2)

For an (S)DHCAL application, the problem of sparking is
more the potential damage to the electronics rather than the resulting dead time.

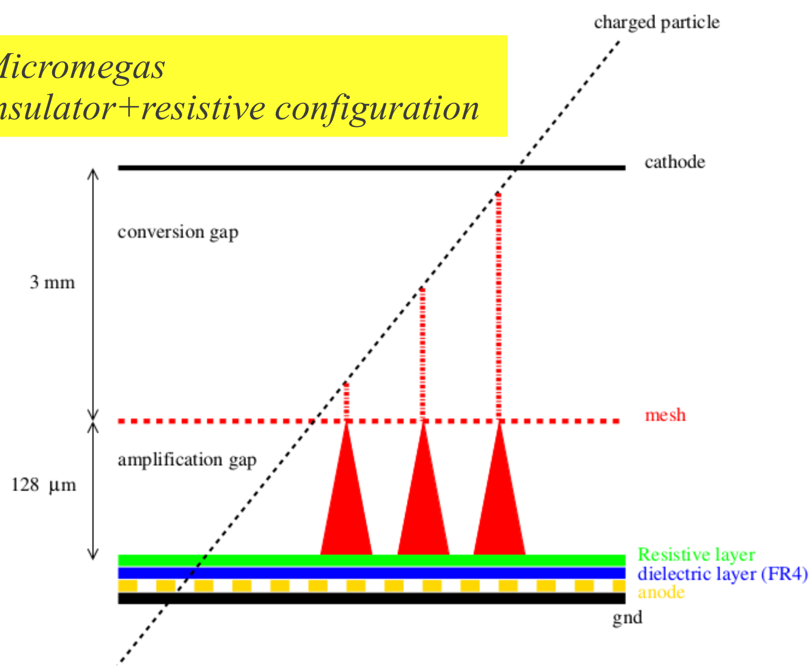
Diode networks (on PCB and/or chip)

Proved to work
Number of components / channels prohibitively high

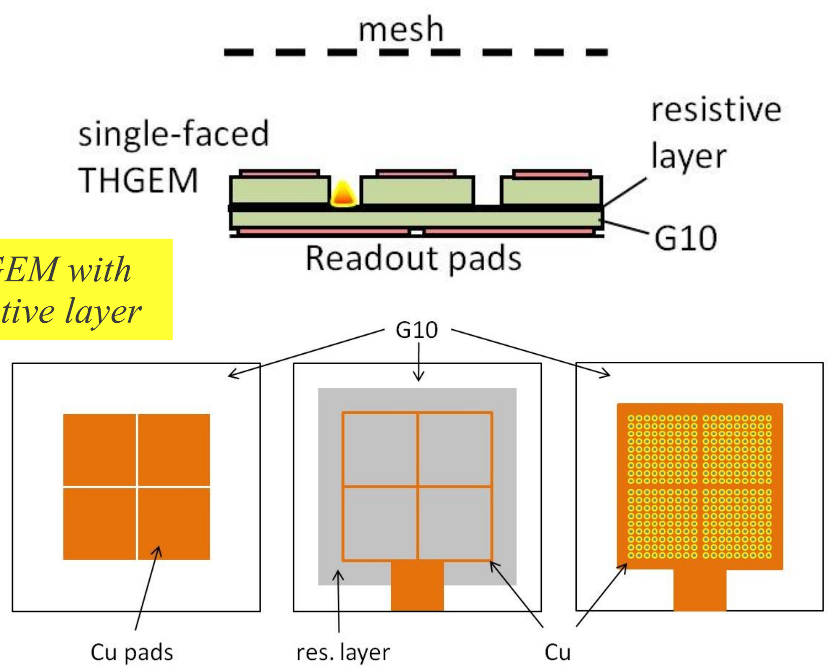
Next generation spark-proof MPGD developed in RD51 collaboration

Resistive coatings applied on the anode plane (very popular in tracking MPGD community, e.g. LC-TPC)
Benefit from RPC spark quenching without suffering drawbacks (rate limit, saturated response, Q spread)

Micromegas insulator+resistive configuration



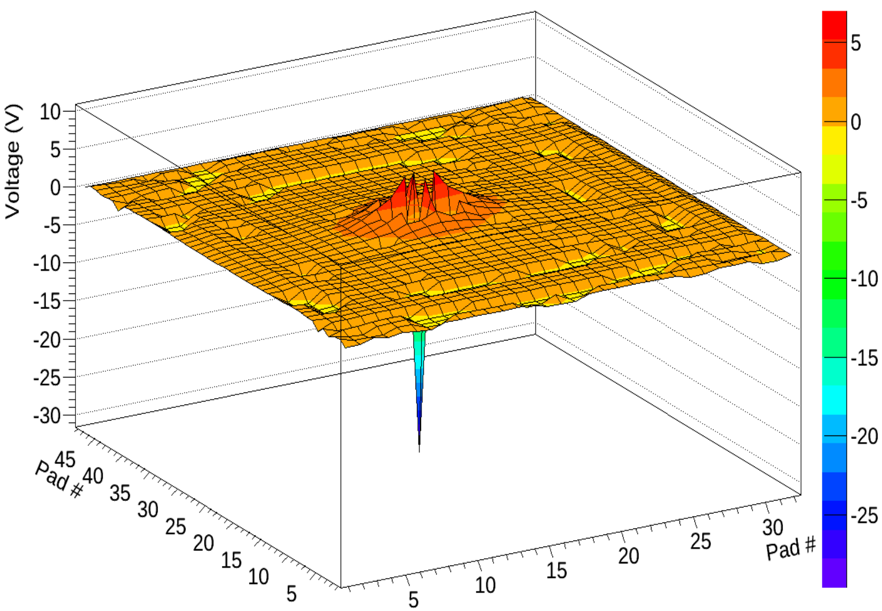
WellGEM with a resistive layer



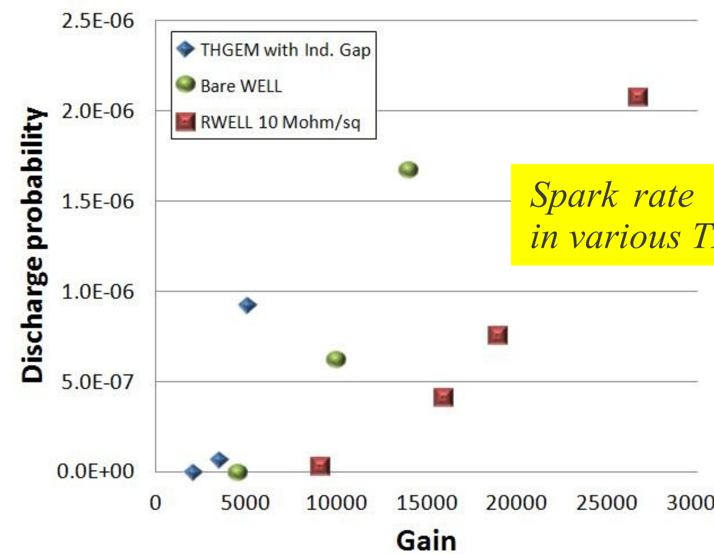
Sparking in MPGDs (2/2)

Resistive coatings applied on the anode plane (very popular in tracking MPGD community, e.g. LC-TPC)
Benefit from RPC spark quenching without suffering drawbacks (rate limit, saturated response, Q spread)

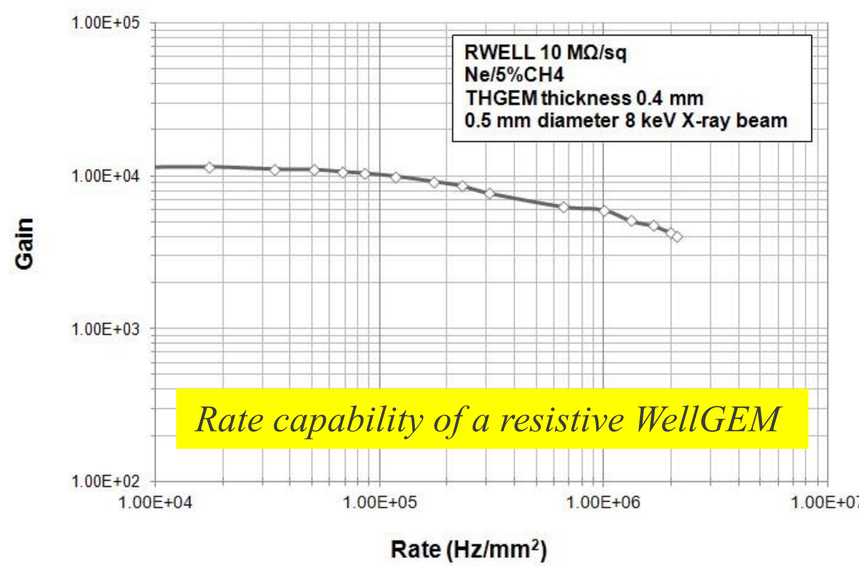
To minimize the spark rate and signal spread, several Micromegas & THGEM designs are being studied



Calculation of the maximum voltage drop across a resistive anode matrix of 32x48 pads (Micromegas)



Spark rate VS gain in various THGEMs



Rate capability of a resistive WellGEM

Space charge effects in RPCs (1/2)

Most undesired effect: decrease of field → loss of efficiency above some counting rate.

Rate capability generally achieved with MIPs ~ 100 Hz/cm^2 → will be lower in showers.

Second undesired effect (for SDHCAL): saturated response i.e. loss of proportionality.

Voltage across the RPC gap

Constant ∝ signal charge

High voltage applied on RPC

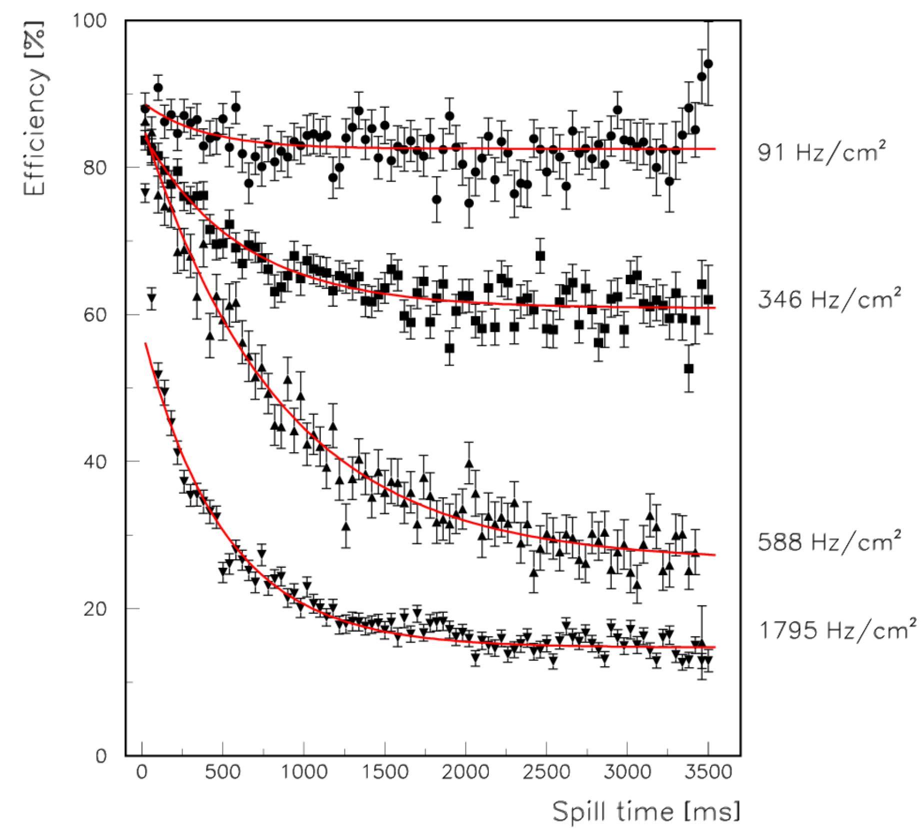
Threshold voltage for signal to appear

$$u_{1f} = \frac{u + 2cf\rho d_2 u_0}{1 + 2cf\rho d_2}$$

Particle flux rate

Thickness of resistive electrode

Bulk resistivity of electrode material



DHCAL RPC efficiency during beam

Ways to improve the rate capability

1. Lower electrode resistivity
2. Lower electrode thickness → mechanical limit (1-2 mm)
3. Reduce gas gain → depends on RO threshold

Space charge effects in RPCs (2/2)

New materials of lower resistivity (3 to 4 order of magnitude smaller) are investigated

Semi-conductive glass, Bakelite, ceramics...

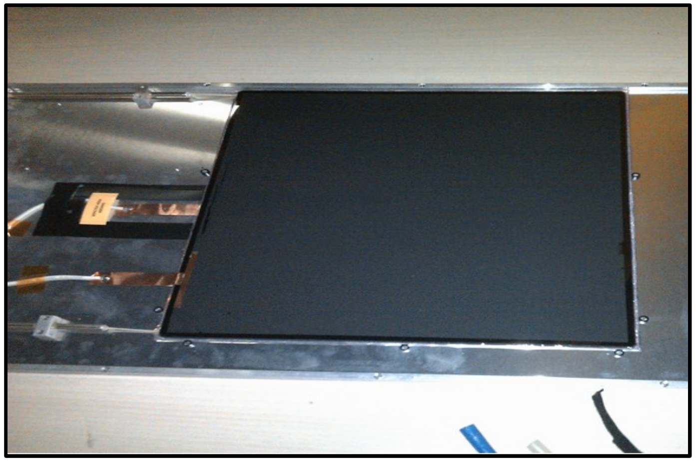
→ small prototypes test in particle beams

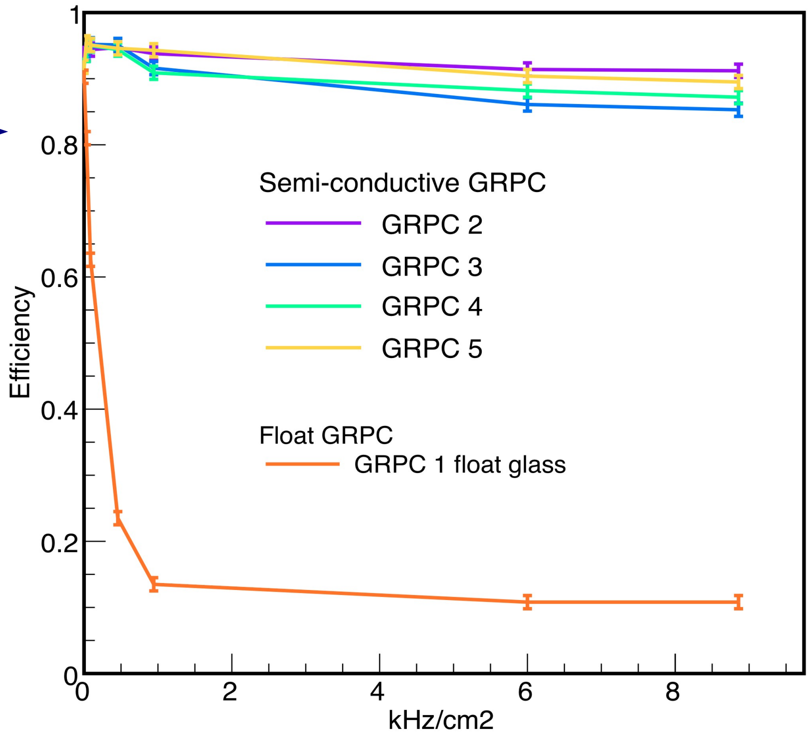
SDHCAL RPC test: efficiency VS rate

1 float glass + 4 SC glass RPCs (30x30 cm^2) in e- beam

Glass Specifications
(Tsinghua University)

Present max. size: 32×30 cm^2
Bulk resistivity ~ 10^{10} Ω.cm
Standard thick.: 0.5-2 mm
Thick. uniformity: ±0.02 mm
Dielectric constant: ≈ 9
Surface roughness: <10 nm





Impressive improvement of rate capability w.r.t. standard float glass RPC!

Important too: keep a useful pad response function (the hit multiplicity increases at low resistivity)!
→ single gap RPCs

Other R&D on RPCs

Thinner RPCs (DHCAL)
→ 1 gap configuration

Hit multiplicity close to 1

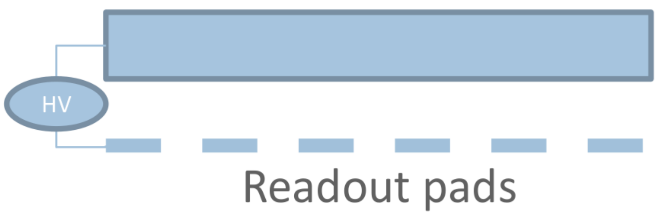
Cost saving for magnet

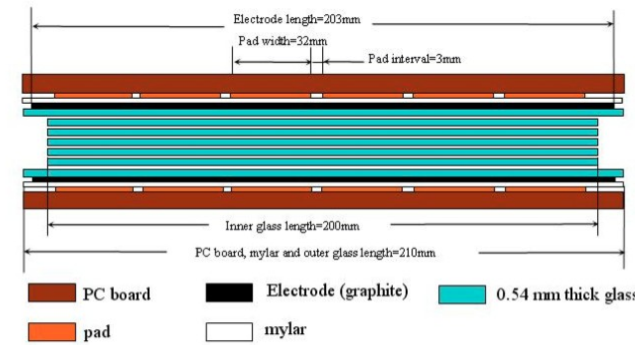
+ Avoid production difficulties

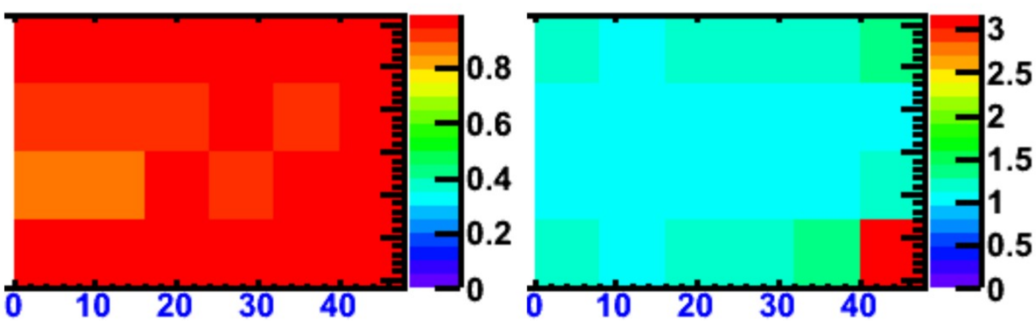
Faster RPCs (SDHCAL)
→ multi-gap configuration

Labs: IPNL, LLR, Ghent, Tsinghua

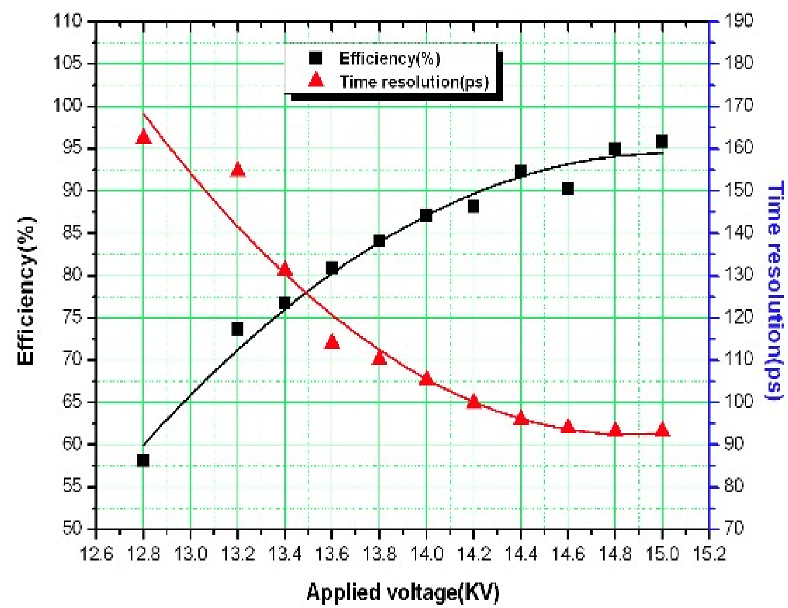
Improvement by a factor 10 of time resolution







Efficiency Hit multiplicity



2 large 32x48 cm^2 1-glass RPC prototypes (Argonne)

→ First test results look good

Conclusions

- Gas detectors allow high transverse segmentation and are therefore interesting for a *Partic*le Flow hadron calorimeter.

- In terms of hadron resolution, a digital readout seems superior than an analogue readout up to ~ 40 GeV, probably higher with a semi-digital approach.

- Today, 2 RPC HCAL prototypes have been constructed and are being studied.

  However, intense R&D efforts on MPGDs are deployed to catch up!
  - In a few years, resistive (spark proof) MPGDs will be a mature technology
  - In parallel, new materials are adequate to improve the rate capability of RPCs.

- At a CLIC experiment, considering the jet energies and background rates, rate capability and proportionality can be of significant value. MPGDs have both.