Experience with
(resistive) Micromegas for sampling calorimetry

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Outline

- Introduction
  - Particle Flow calorimetry
  - Micromegas as sensitive medium
- Non-resistive Micromegas
  - Possible mechanical designs
  - Readout options for EM showers
  - Readout options for Hadron showers
  - Some performance of large-area prototypes
  - Magnetic field & spiralling delta-electrons
- Resistive Micromegas
  - A simple model including time constants
  - R-electrodes shapes and resistivity
  - Sparks VS linearity, test protocols & results

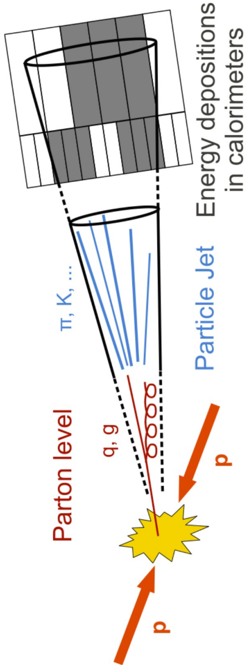
Particle Flow calorimetry

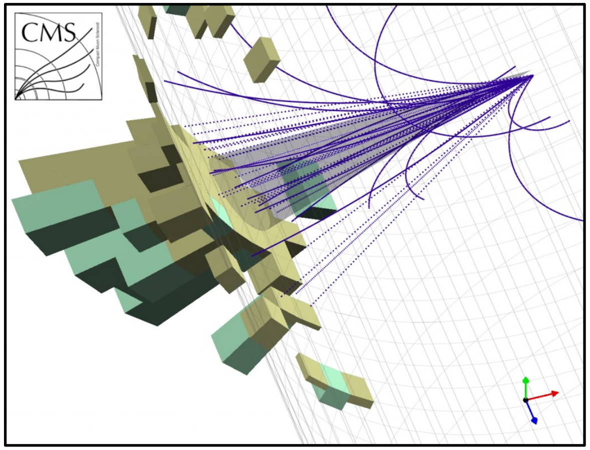
Particle Flow (imaging) calorimetry for future LC (or at LHC & HL-LHC)

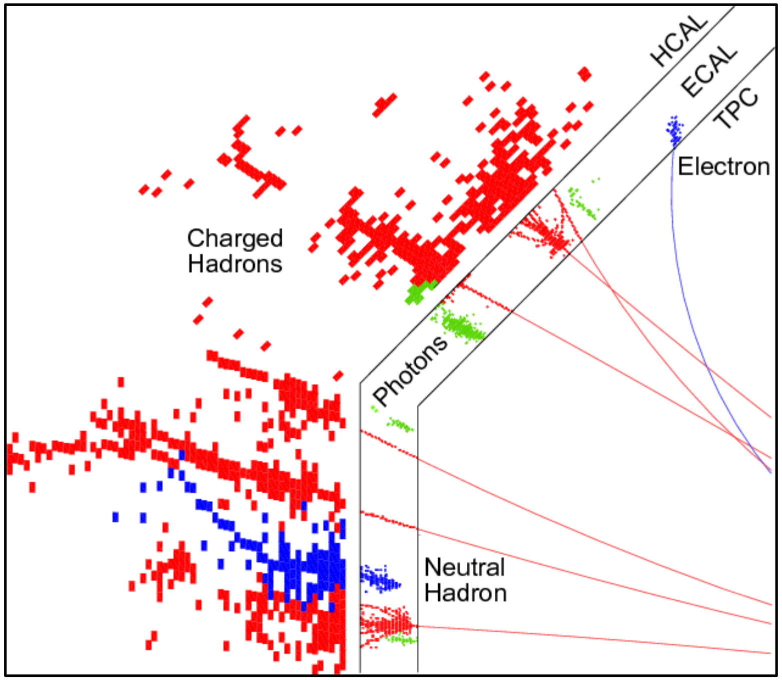
Introduced to improve the energy resolution on jets (calorimeters inside the coil):
Granularity + software→ match tracks & showers → use calorimeters only for neutrals
Works till jet cone too narrow → minimise confusion with small cells & compact showers

General requirements on sensitive medium (e.g. Si, Sc, Gas)

Small Moliere radius, large-area & thin sensors, high sampling fraction
[LC: + other technical requirements (front-end electronics on PCB, power-pulsing, self-trigger)]
… gas detectors apparently not favoured







Sampling with MPDG/Micromegas

Still, (Micro Pattern) gas detectors present several advantages

Cheap (argon), proportional mode, large area, fine segmentation, no ageing, no rate dependence

Micromegas, 3 mm drift gap, 1x1 cm^2 pads

MIP ~ 0.3 keV (15 e- MPV), Moliere radius already high (4.5 cm) but fine for HCAL

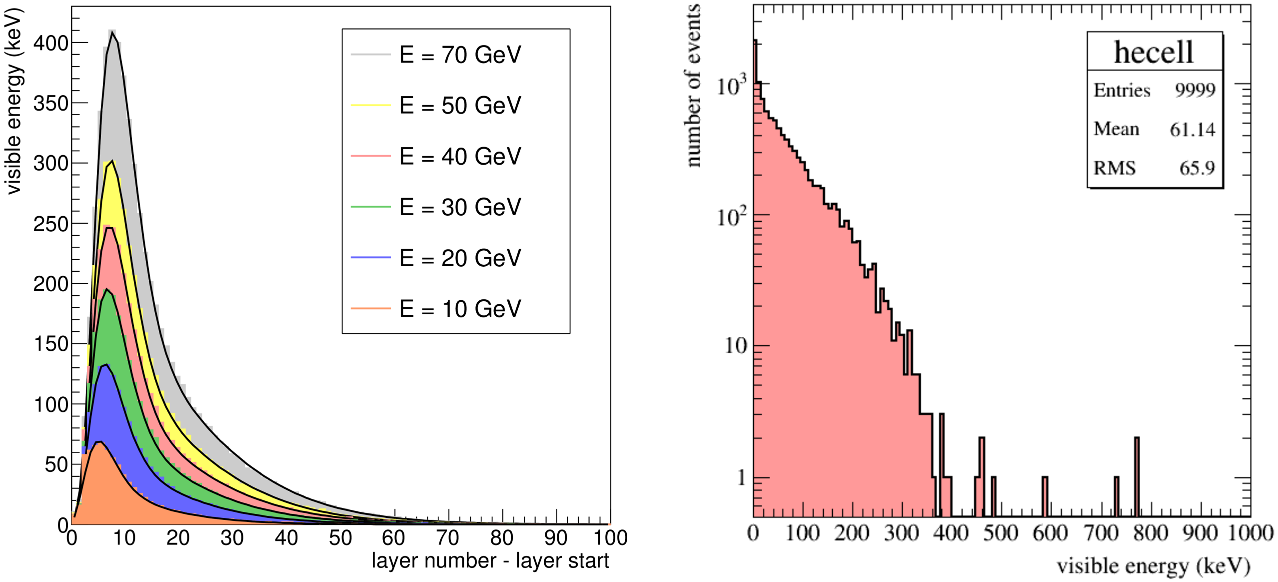
HCAL (1.5 cm Fe absorbers), 50 GeV pion shower (Geant4)

@ shower max.: 300 keV / layer, 60 keV in central pad with fluctuations up to 300 keV

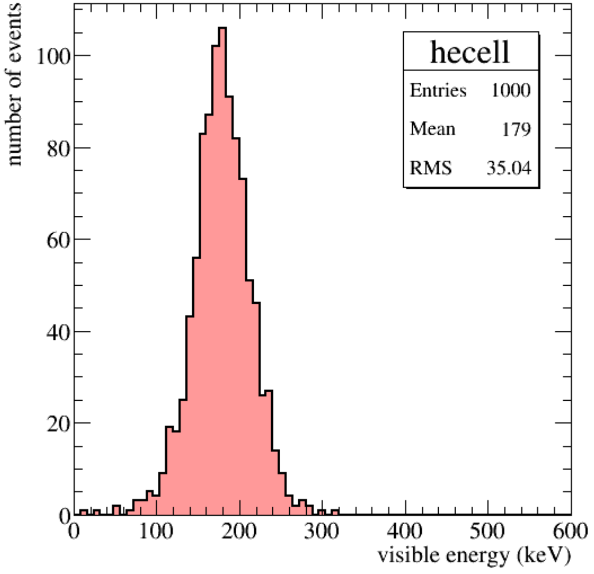
In usual Ar-CO2 mix.: all electrons arrive at the mesh in < 75 ns

ECAL (2.5 mm W absorbers), 50 GeV electron shower (Geant4): 180 keV in central pad

HCAL - Energy Profile and energy in central pad @ shower maximum



ECAL - Central pad energy



Possible mechanical designs

Target area for LC/SiD HCAL is 3000 m^2, layer of 3x1 m^2 to fit in 1.2 cm absorber gaps

→ Bulk (better suited than InGrid), implies lamination of photo-films+mesh on PCB

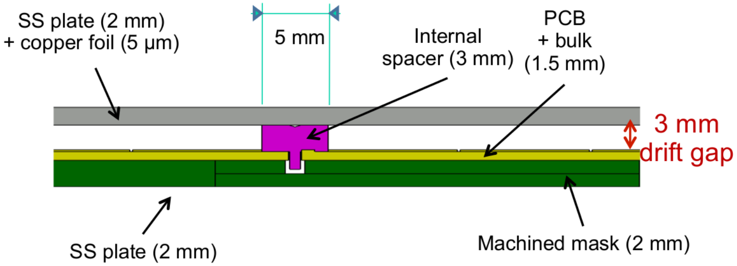
Size limitations from PCB manufacturer, Cabling of ASICs, Rui's workshop

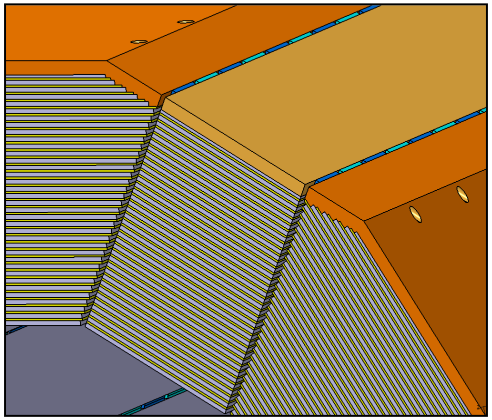
*Back In 2011, we choose 1x1 m^2 ~ (32x48 cm^2) * 6*

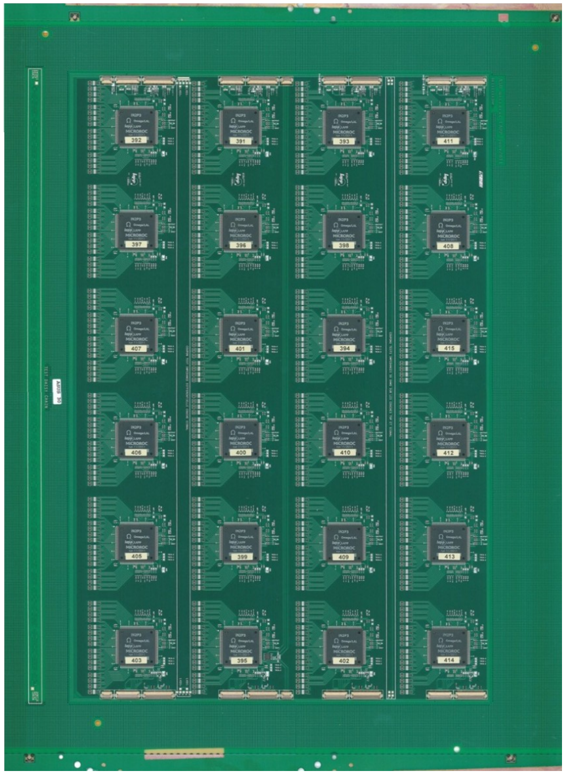
→ spacers between PCBs (dead zones ~ 2%), we are currently working on 48x48 cm^2 units.

Design strongly constrains by thickness requirements of ~ 1 cm

→ No screws, everything is glued (sealed, “no way back”)







Readout options for EM showers

No space available for active cooling inside LC calorimeters

→ power-pulsing + low-power electronics (save on analogue part)

ECAL should measure showers and MIP tracks

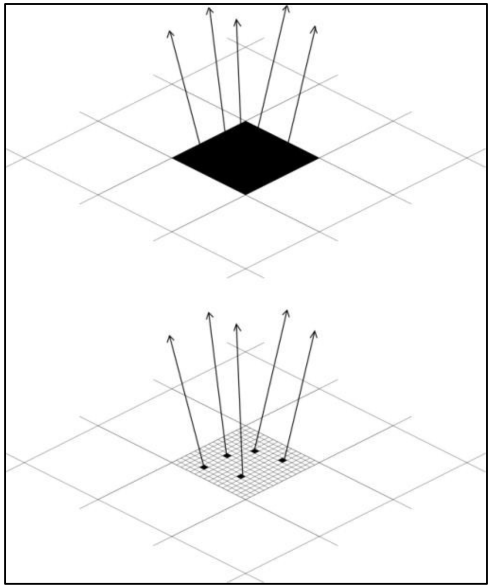
→ large dynamic range (0.1-1000 MIPs) & high ADC resolution (e.g. 16-bits)

Digital option (16-bit → 1-bit) works if Nparticle / cell < 1

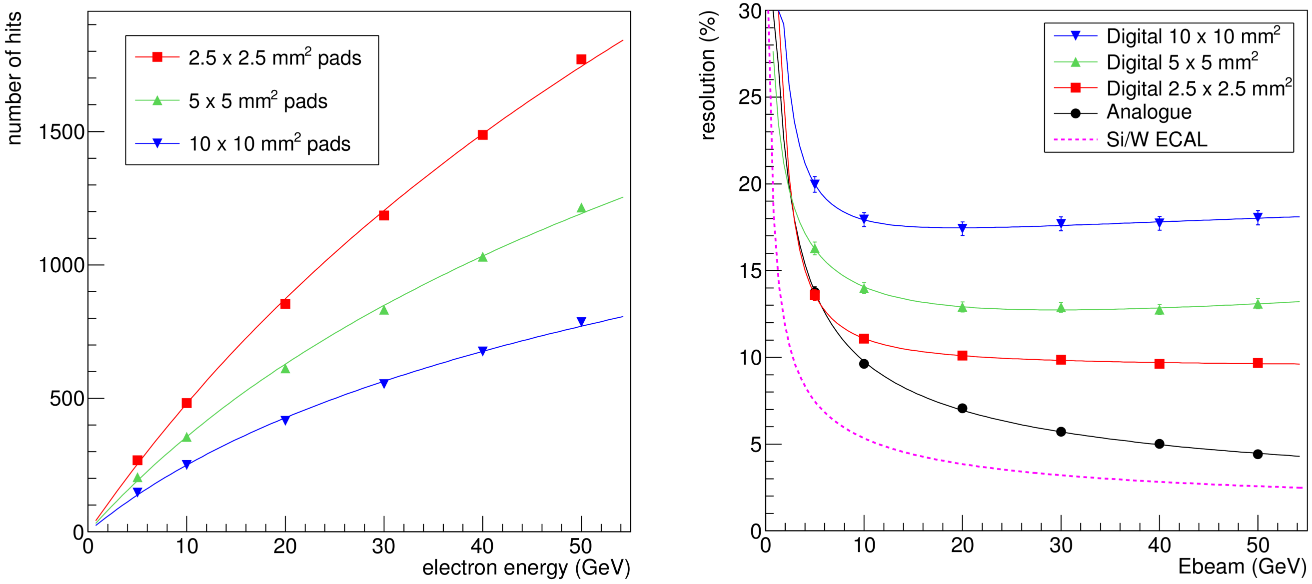
This depends on relative size of shower cone & cell

For ECAL = use pixels or stick to analogue readout (in which case, intrinsic detector linearity is a must)

For HCAL, might be good enough...



ECAL W-Ar: Digital response (1x1 cm^2 pads) – Energy resolution



Readout options for H showers

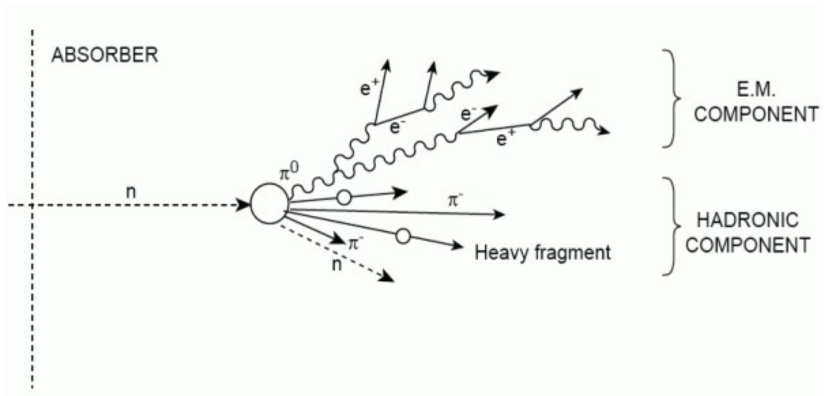
Digital option: shower transverse size VS cell size

H shower = EM part (from pi0, eta) + H part (n, pi, p...)

EM fraction increases with H energy

→ Digital might work at “low” energy

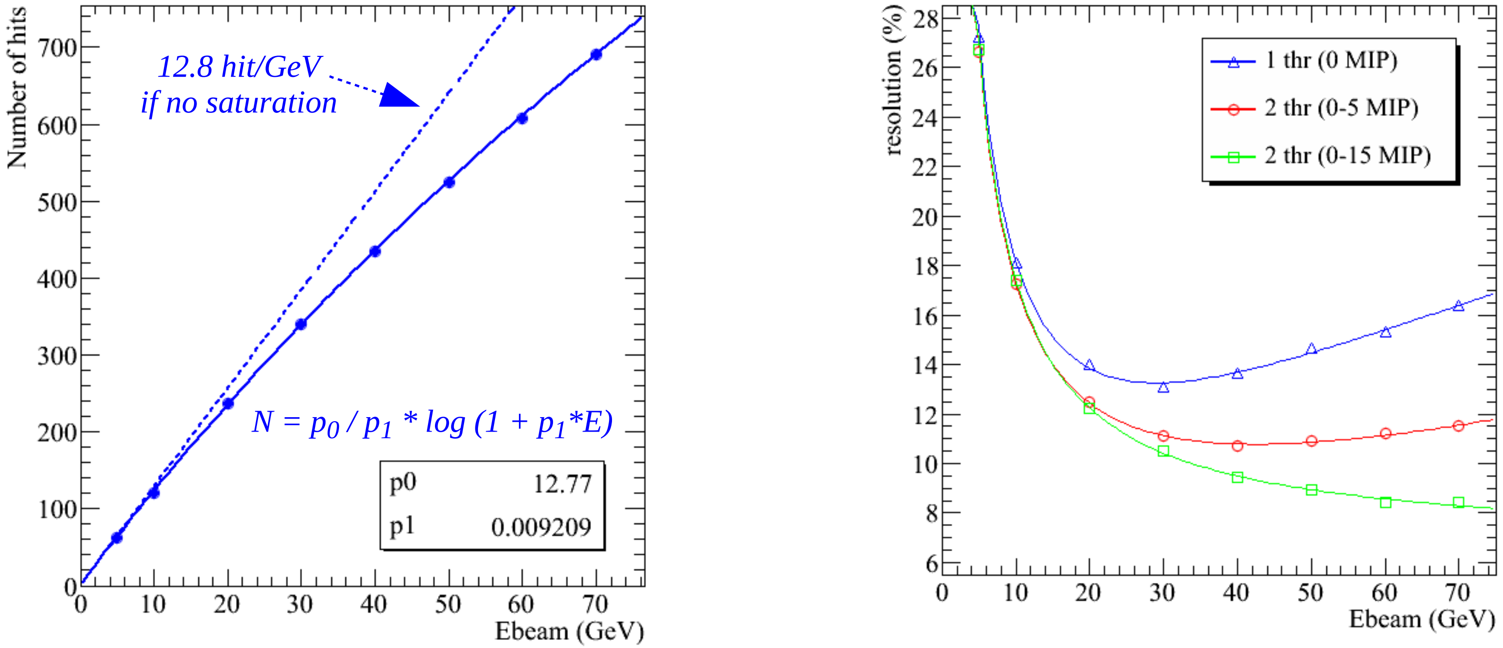
Absorber choice is important (R_M(W)<R_M(Fe))



Semi-digital option (1-bit → 2-bit) to compensate geometrical saturation

Relies on intrinsic detector linearity, favours MPGD VS saturated devices (e.g. RPCs)

Response and resolution to single pions of a 11 λ_{int} deep ***Fe/Ar DHCAL*** *with 1x1 cm^2 cells*



1x1 m^2 prototype performance

Already reported in RD51, *this is just a reminder of important results*

Combined test with RPC (CALICE SDHCAL SPS/H2)

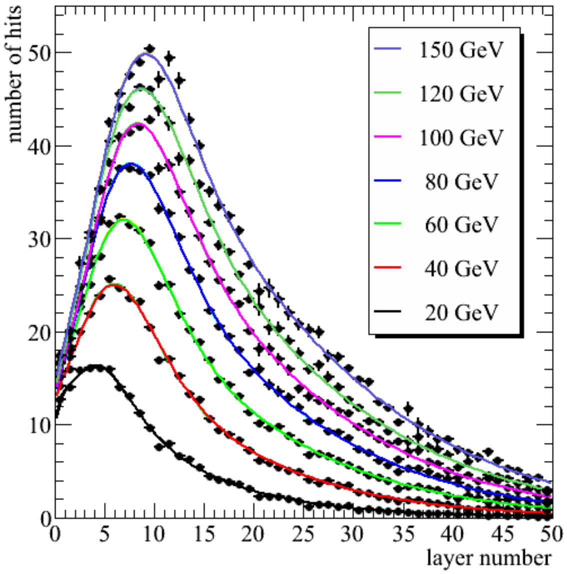
The expected geometrical saturation is observed (deduced from longitudinal profiles)

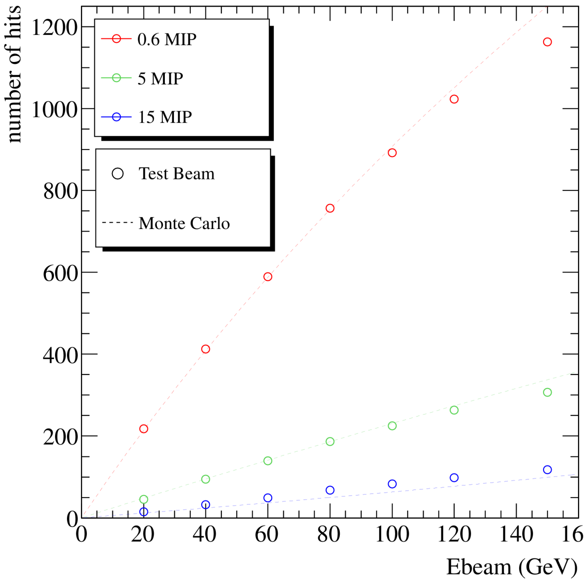
Standalone test (SPS/H4), findings should hold for any MPGD

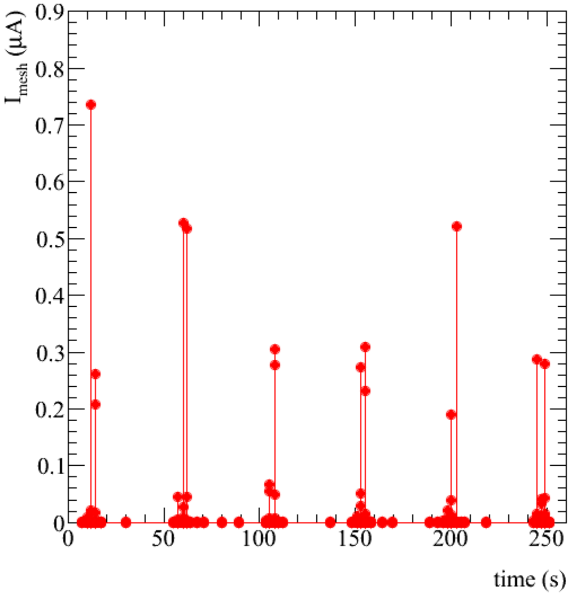
Excellent uniformity (eff. 95%, abs. variation of 1% RMS)

No effect of rate on response (verified up to 30 kHz pion showers, beam of 1x1 cm^2)

Except during occasional sparks (10^-5 / shower, EM core fluctuations, nuclear recoils)





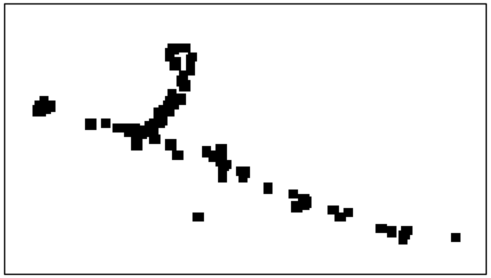


Magnetic field & spiralling electrons

Colliding beam experiment with Barrel, 2 Endcaps [Calorimeters inside solenoid]

Endcap: No ExB effects, drift velocity unchanged

Transverse diff. reduces with omega.tau, Rather limit possibly closer



Barrel: more problematic, high-energy delta-electrons

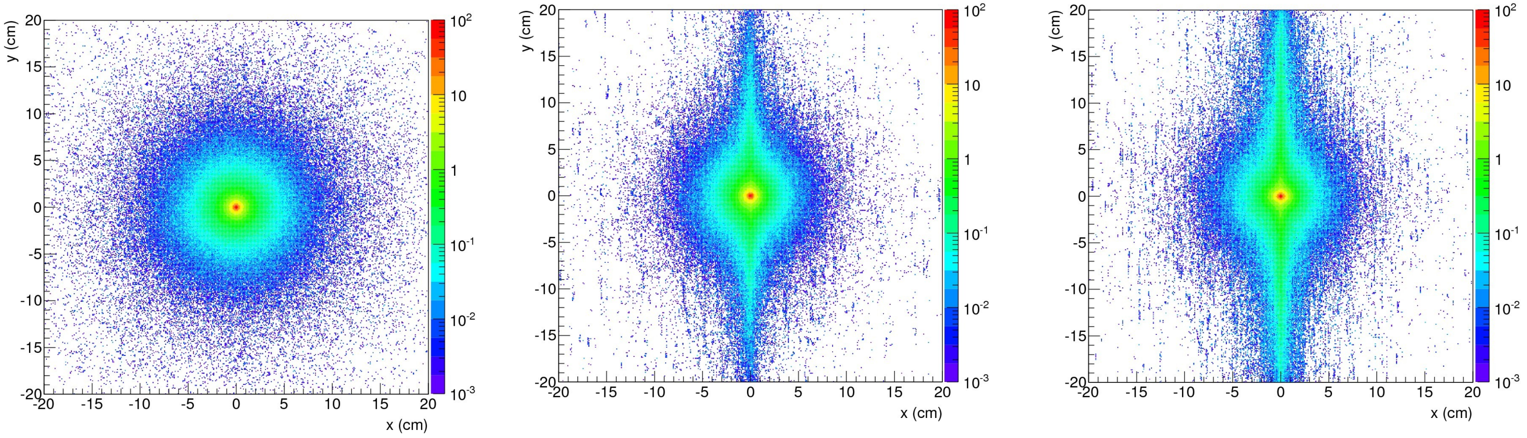
Lorentz force + initial momentum → travel over a few cm!

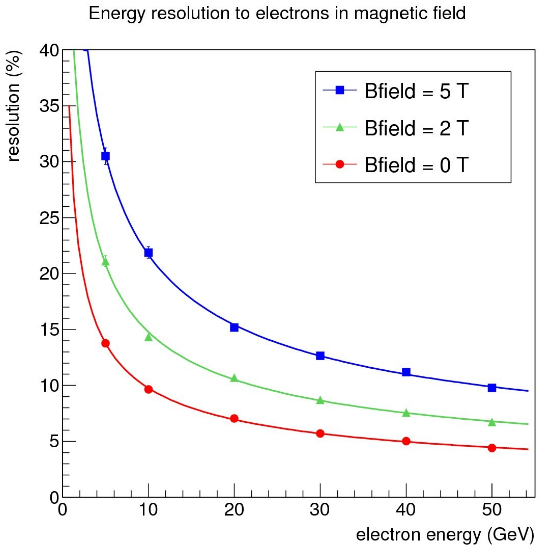
Was simulated for an ECAL geometry (2.5mm W + 2.5 mm Ar)

Small effect on EM shower shape (log-scale below!) but large on measured energy & resolution

For hadron shower, impact should be less (high track density in EM core only), to be simulated (can be identified and removed?)

ECAL W-Ar: 50 GeV electron showers with no B field and in 2 T and 5 T field





Sampling with Resistive Micromegas

Guarantee stability in showers by suppressing sparks

The RC network implies that the charge stays on the R-electrode for a while, changing locally the voltage: above some charge the field reduces significantly, avoiding sparks.

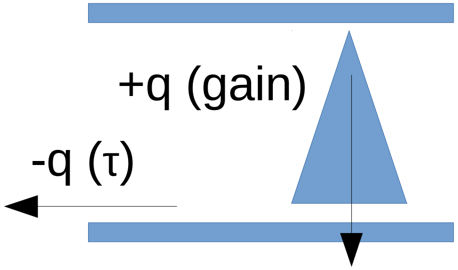
But might comprise the intrinsic linearity of MPGD, depending on the scenario

Time-dependent charge-up effects, the simplest model: all electrons arrive at the same time

* Effective capacitance (transverse size of the avalanche), relates dQ to dV, 1 pF for R =2.sigma (sigma of 325 um)

* RC constant (geometrical capacitance)
* Gain (G0, voltage dependence)

* Beam (flux, number of primary e- Np)
* Gas (transverse diffusion Dt)



τ>>1/Rate, fluctuations around mean value reached after τ = RC

τ ~ 1/Rate, continuous charge-up with positive fluctuations above 0 V

τ<<1/Rate, charge-up during event if total charge high enough

→ linearity degradation at low rate

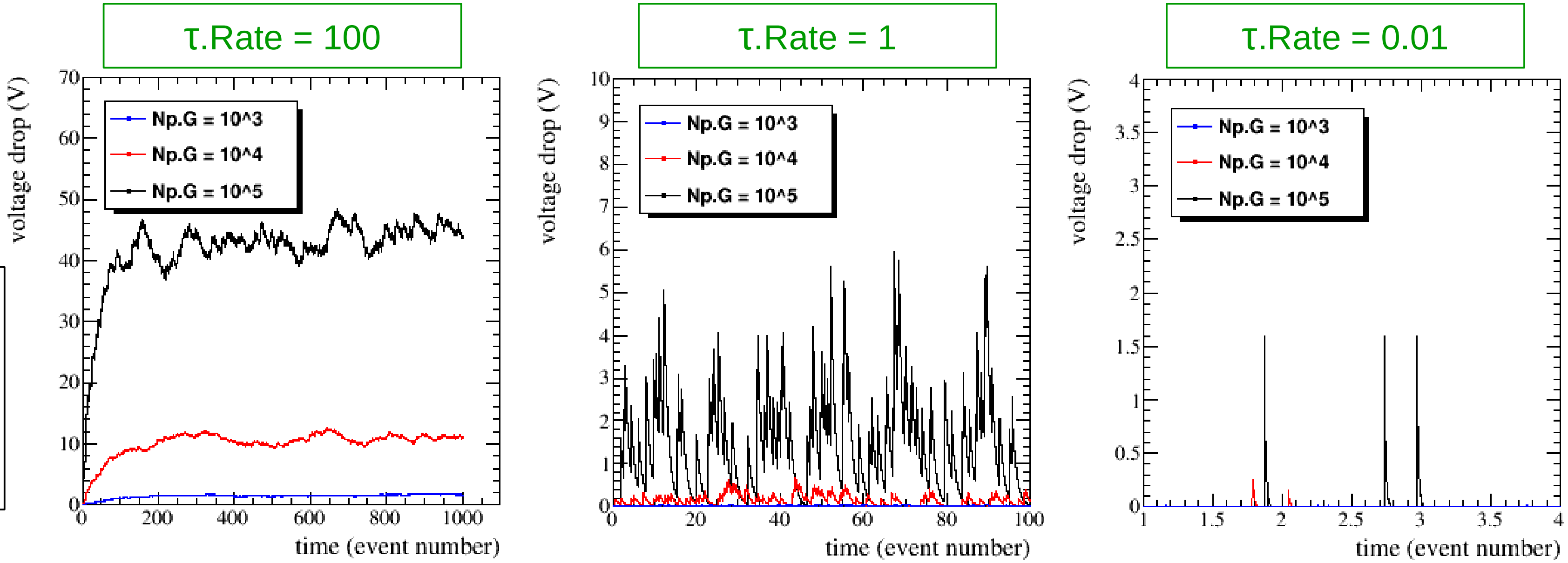
τ.Rate=100

Gain drop

70%

25%

5%



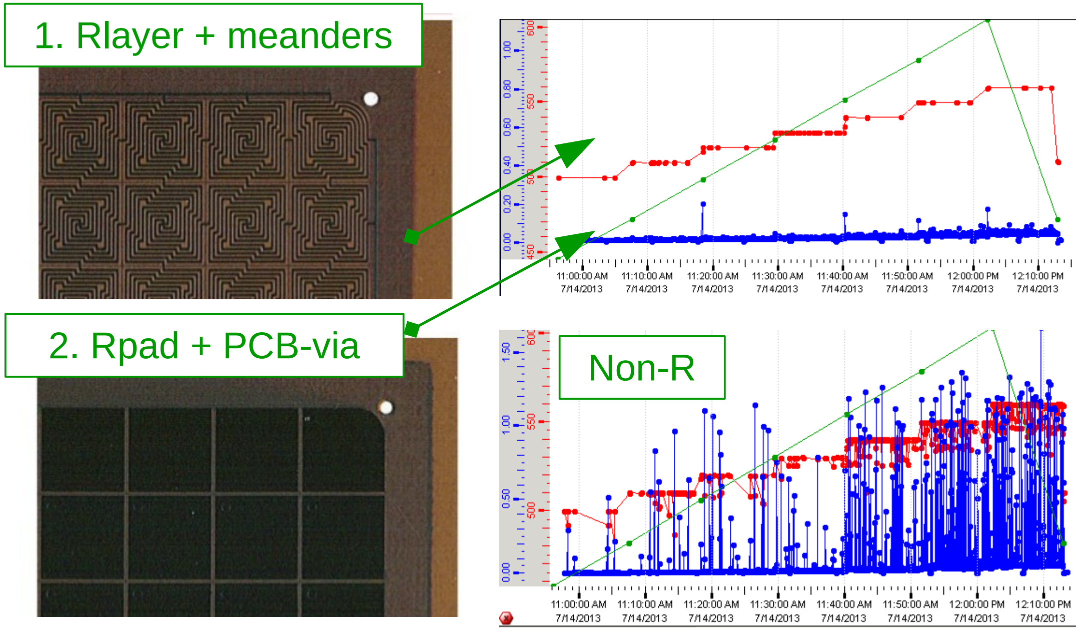
Resistive electrode shapes

Different ways to introduce RC

2012-2014 (ANR-funded project: Spark Protected Large Area Micromegas)
→ Spark suppression demonstrated (DESY) @ the cost of rate capability loss

Small prototypes (with embedded digital front-end electronics)

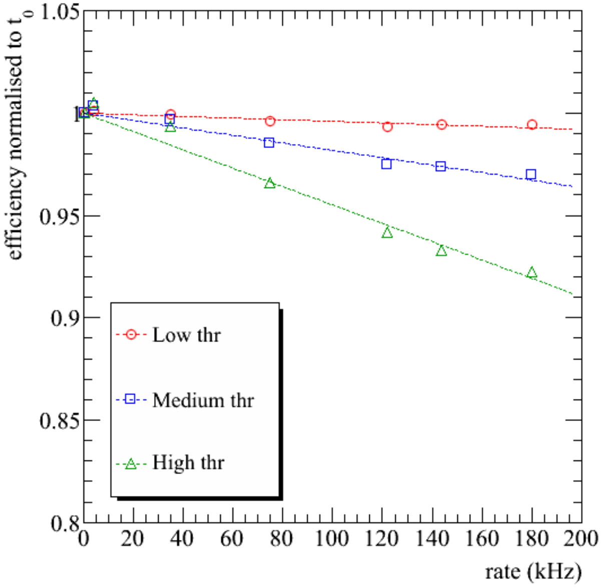
0. Continuous horizontal R grounded on the side forbidden (would increase pad-to-pad cross-talk)
1. Horizontal R layer (grounded on PCB side) with meanders to reduce X-talk
2. Horizontal pad-segmented R to avoid X-talk with through-PCB via for grounding
3. Vertical R, so-called embedded resistance contacting R and readout pads
(did not work because of fabrication errors, much progress since then...)


1. Rlayer + meanders

2. Rpad + PCB-via

Non-R

Efficiency loss VS ebeam rate



Electrode resistivity

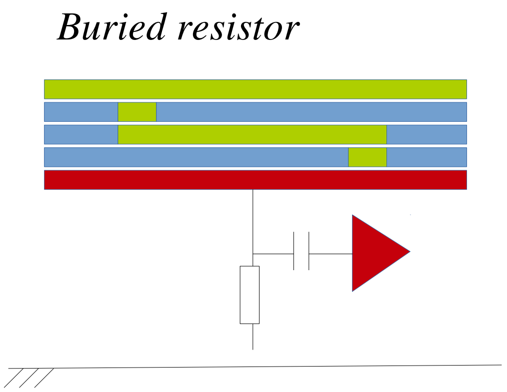
Resistive electrode shape

Horizontal R not suited for large-area (R linearly adds up), through-PCB via not cost effective
Vertical R fully scalable → stick to embedded R and minimise rate effects, i.e. minimise RC

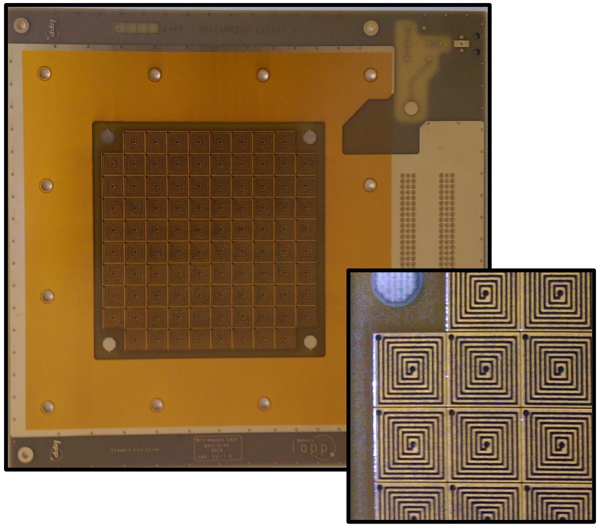
What is the minimal resistivity needed to suppress sparking?

Empirical approach:
Prototypes with resistivity varying over several orders of magnitude
SCREAM (Sampling Calorimetry with Resistive Anode Micromegas
→ Demokritos (T. Geralis), CEA/Irfu (M. Titov), IN2P3/LAPP

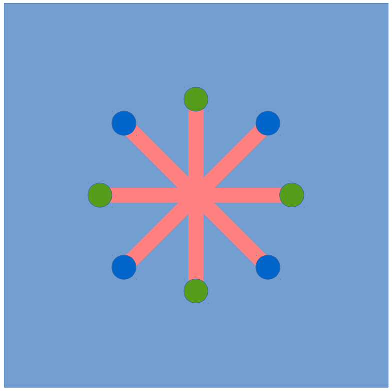
What is the effect of RC on signal magnitude?


Buried resistor

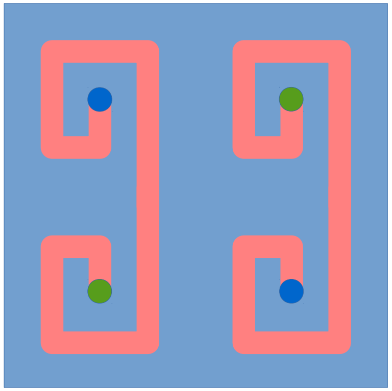
Board for Gassiplex RO



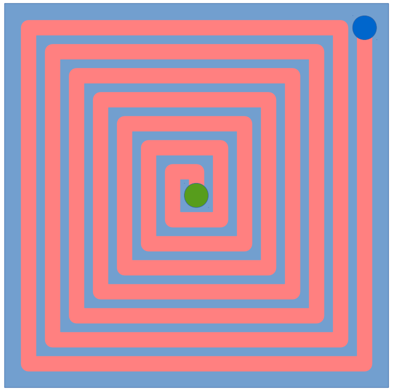
Star, 400 kΩ, τ = 40 μs



Mirror, 4 MΩ, τ = 0.4 ms



Snake, 40 MΩ, τ = 4 ms



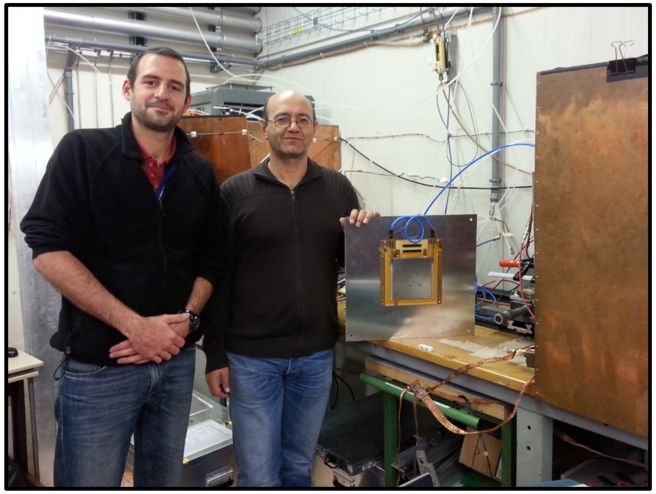
Green dot = R-pad contact, blue dot = RO-pad contact

Experimental protocols

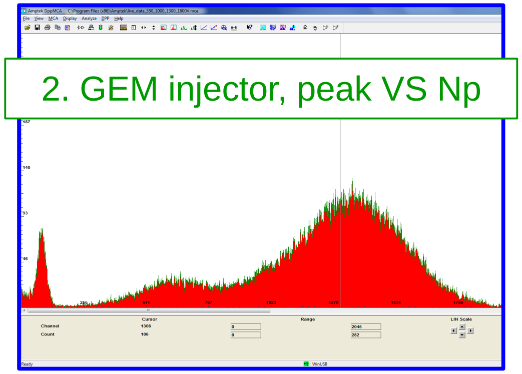
What is the effect of RC on signal magnitude?
→ Measure influence of detector current (rate & dE/dx) on gas gain

1. High rate (τ>>1/Rate) Rate scan @ constant dE/dx: X-gun
2. Low rate (τ<<1/Rate) dE/dx scan @ constant rate: GEM-injector
3. Medium Rate (τ~1/Rate) Rate scan @ variable dE/dx: pion beam (showers)

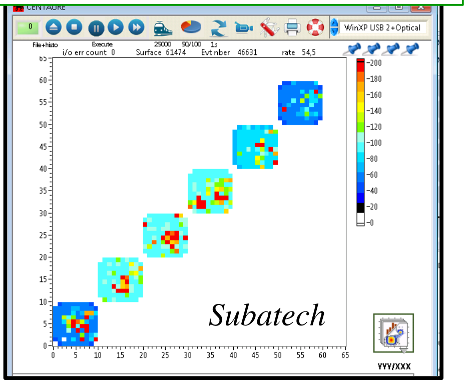
1. X-gun, Imesh VS rate

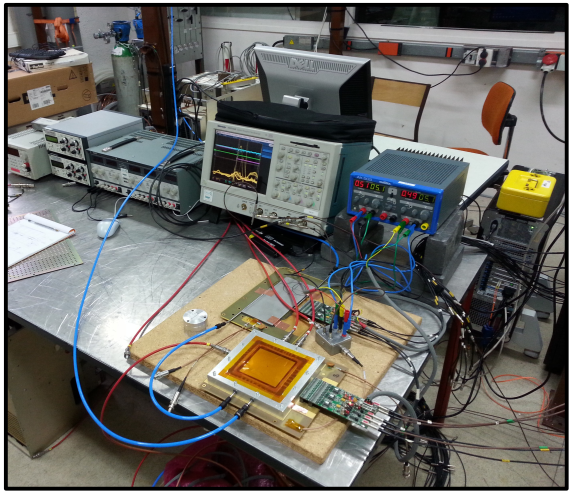


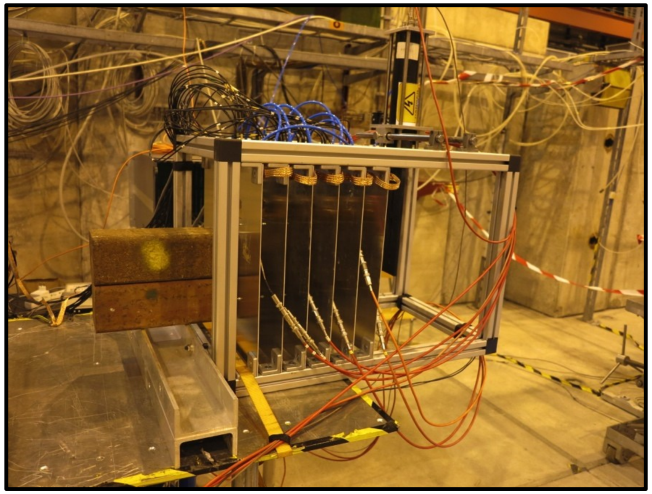
2. GEM injector, peak VS Np



3. Beam, ADC sum VS Rate







High rates

Detector time constant >> event rate

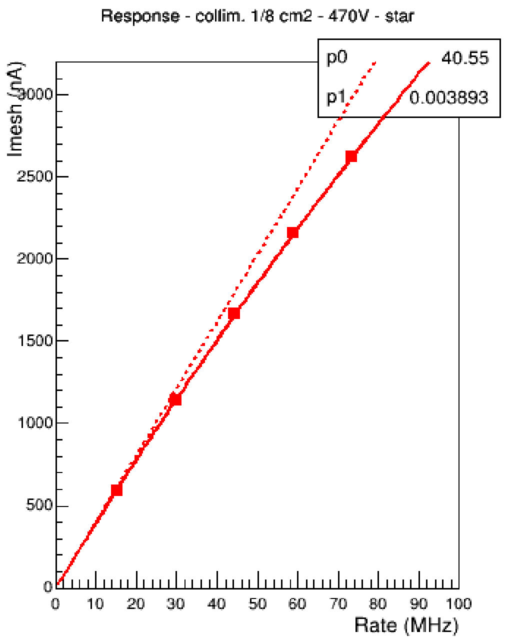
Influence of one event on next one? Yes, of course.

Setup 1: 8 keV X-rays, Rate [10,100] MHz → measurable current on HV-supply, gas gain up to 10^3

At given rate, gain drops and quickly stabilises (evacuated Q ~ incoming Q on R pad)
Departure from linear response calculated from log-fit.

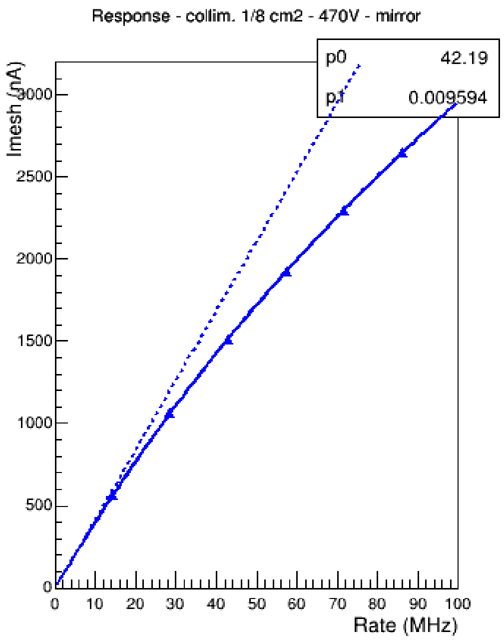
Extrapolation @ 1 MHz yields deviations of ~0.5%, 1%, 10% (Star, Mirror, Snake).

Star, 400 kΩ, τ = 40 µs



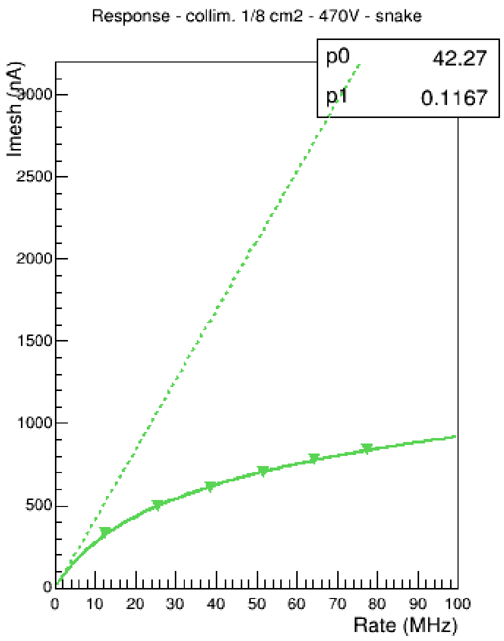
Response - collim. 1/8 cm2 - 470V - star

Mirror, 4 MΩ, τ = 0.4 ms



Response - collim. 1/8 cm2 - 470V - mirror

Snake, 40 MΩ, τ = 4 ms



Response - collim. 1/8 cm2 - 470V - snake

Low rates

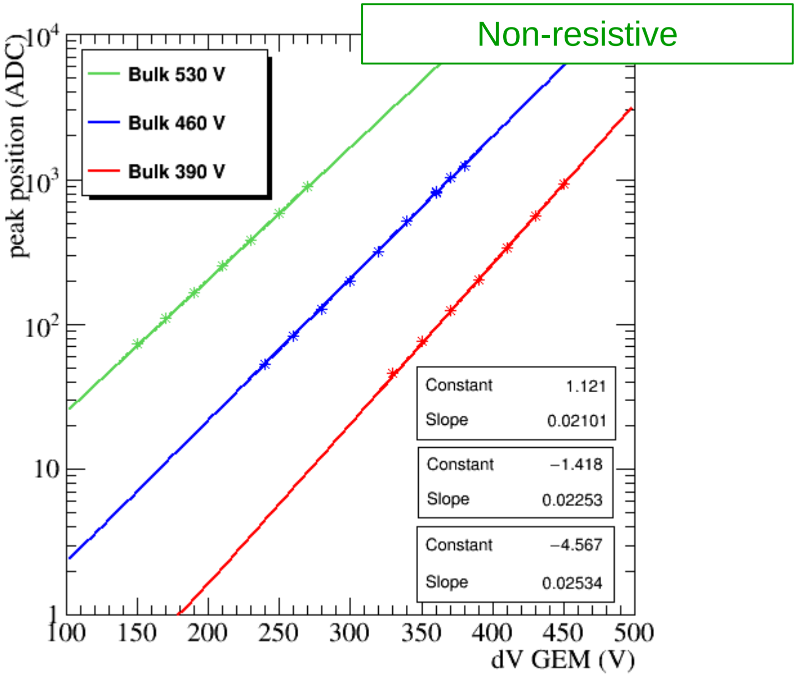
Detector time constant << event rate

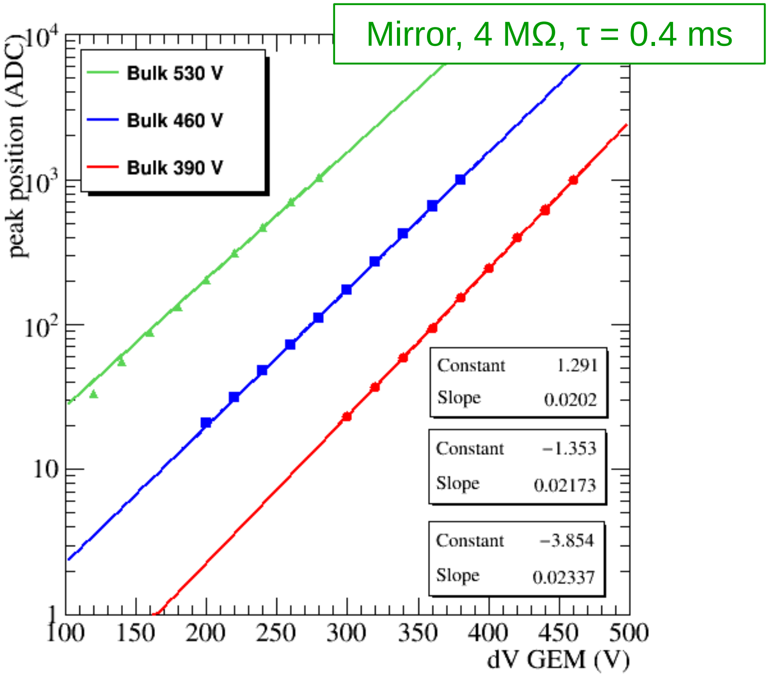
Influence of first primary electrons space charge on last primary e- multiplication? Not sure...

Setup 2: GEM injector (Geff up to 800) + low activity 55Fe source (100 Hz event rate) + Pocket MCA
After diffusion, primary electrons arrive at the mesh within +/- 65 ns, distributed with +/- 325 um
Bulk gain from 10^2 to 10^4

Ability of R pad to charge-up given by its capacitance only (RC does not matter here)
Ceff ~ S with S the spread of the Q distribution onto the pad (~ 1 pF)

Saturation of readout at overall gain (Bulk*GEM) of 10^5, pity, GEM & Bulk could go higher.
Comparing response curves (photopeak VS Vgem) in R and non-R prototypes:
Slopes slightly lower for R-prototypes, any effect? More test needed, probably at higher gains.


Non-resistive


Mirror, 4 MΩ, τ = 0.4 ms

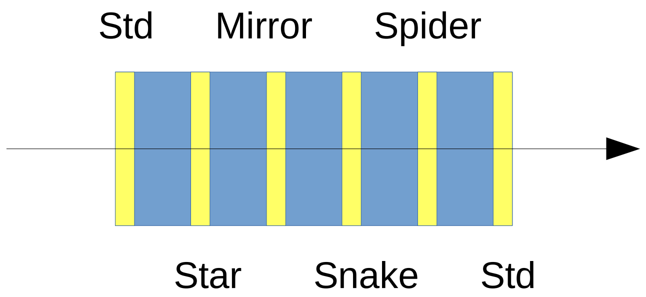
Intermediate rates

Intermediate rates: Detector time constant ~ event rate

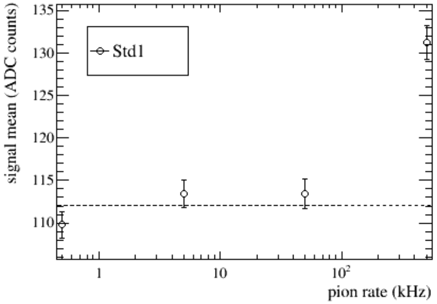
Events influence each other if dE/dx high enough

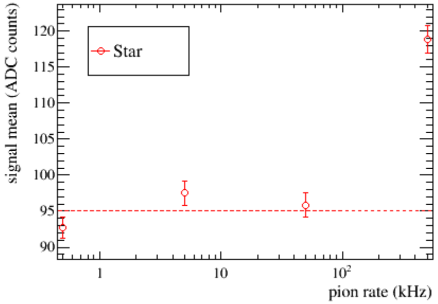
Setup 3: Rate scan in test-beam (pion with or w.o. absorber (2 int. length of iron)
Runs @ beam intensity of: 0.5, 5, 50, 500 kHz/cm^2
Shaping time of Gassiplex chips (1 us) → last point only useful for sparking study

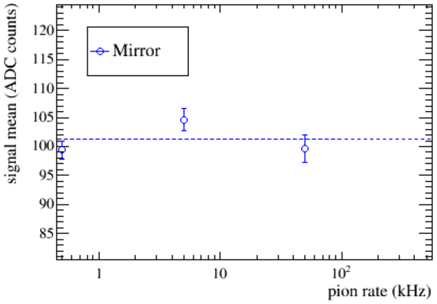
No absorber → MIPs yield small charge, average measured charge constant with rate
With absorber → Showers yield potentially much larger charge.
But annoying effect shows up...

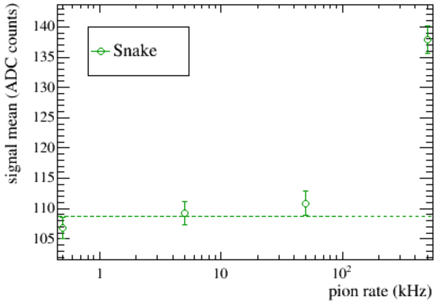

Std Mirror Spider

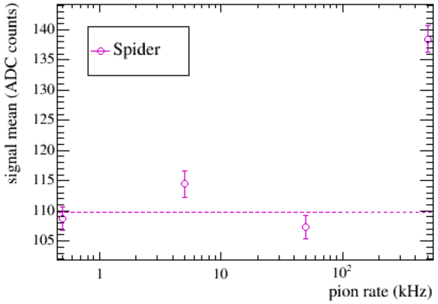
Star Snake Std

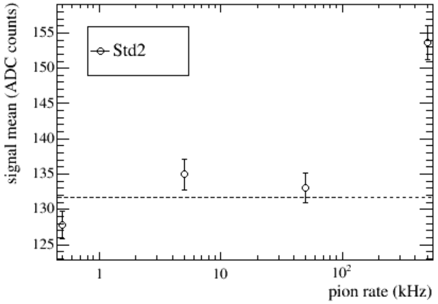












Operation in showers (1)

Under high deposited charge, we observed a pedestal shift

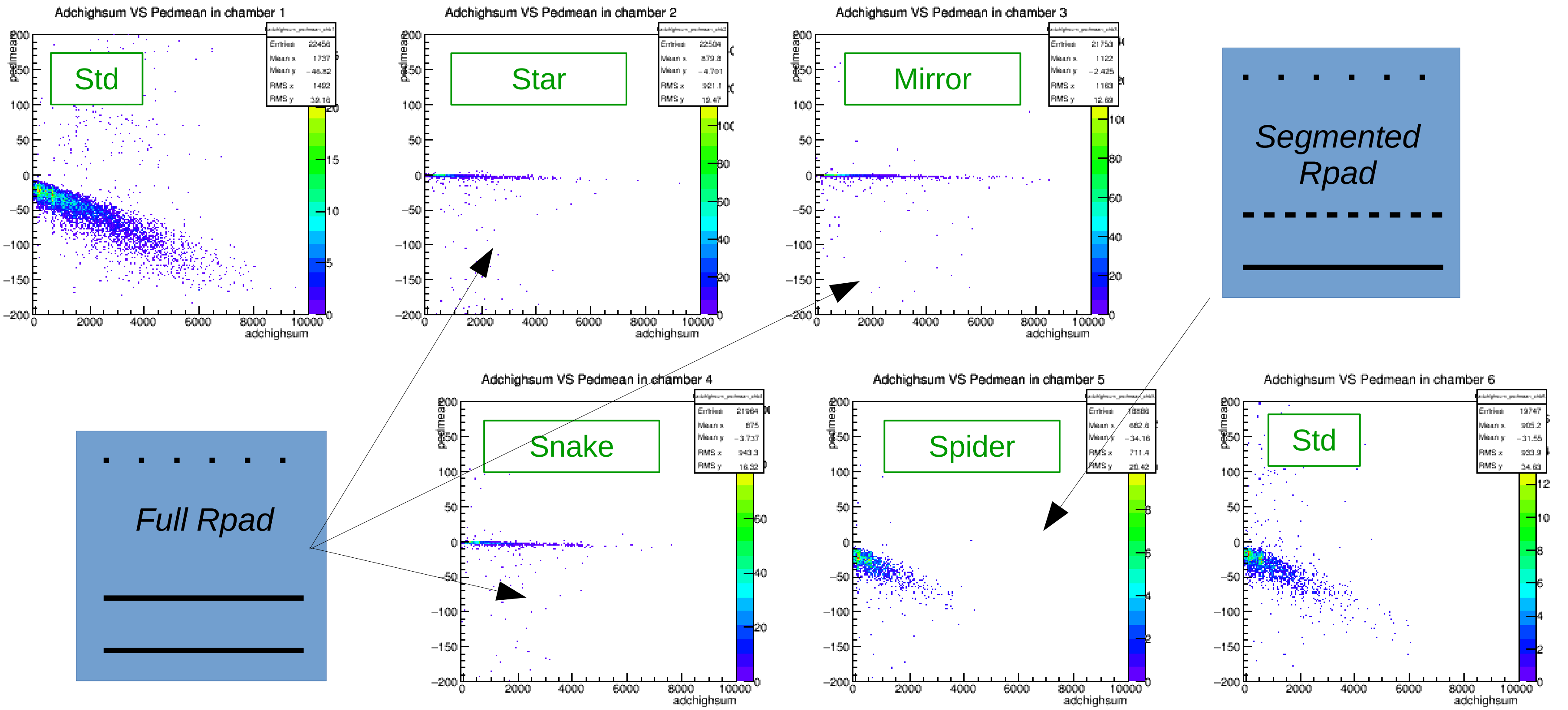
The shift seems to be proportional to the deposited charge

It shows up strongly in the non-R prototypes and 1 R with segmented R-pad

→ Implies corrections when measuring the energy

We think we see the small negative coupling between pads through the mesh

→ This coupling is strongly suppressed with full R-pads but not with segmented R-pads

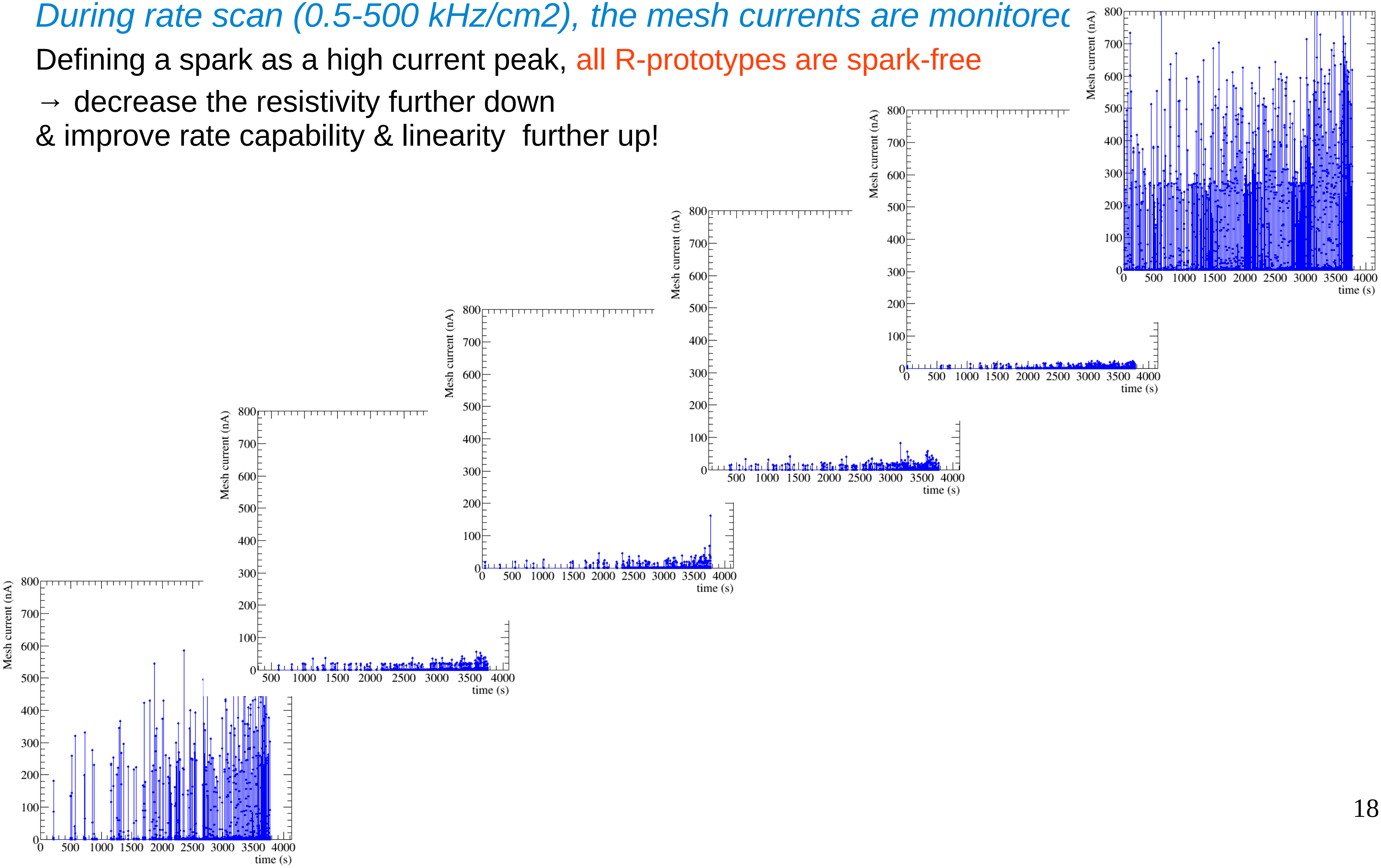


Operation in showers (2)

During rate scan (0.5-500 kHz/cm2), the mesh currents are monitore

Defining a spark as a high current peak, all R-prototypes are spark-free

→ decrease the resistivity further down
& improve rate capability & linearity further up!



Conclusions

- A Micromegas calorimeter should incorporate resistive elements to guarantee stability. For most applications, it seems that this can be done without spoiling the intrinsic linearity & high rate capability of the detector. More work is needed to quantify this:
  - Models & protocols
  - New prototypes with lower R
  - Test-beam (with electrons?)

- This talk mostly focused on resistive technology. Sorry for that as mechanical designs & production aspects are as important.