DEVELOPMENT OF LARGE MICROMEGAS DETECTORS FOR THE UPGRADE OF THE ATLAS MUON SPECTROMETER

9 October 2009

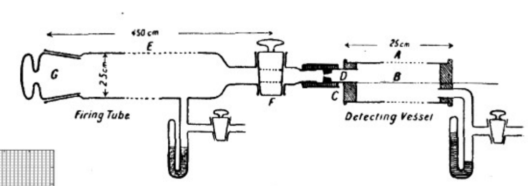
Paolo Iengo - LAPP

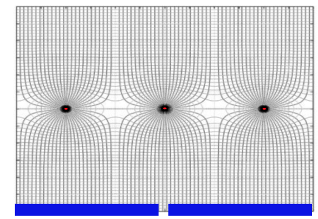
Outline

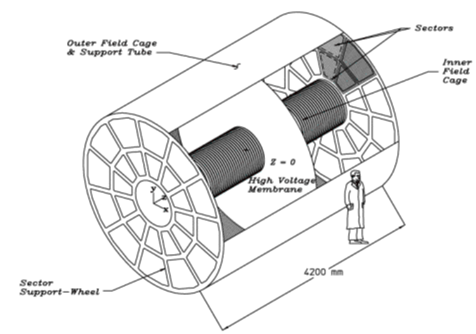
- Introduction on gaseous detectors
- Limits on rate capability
- Micro Pattern Gaseous Detector & Micromegas
- LHC upgrade and limitations of present ATLAS muon detectors
- Micromegas for the upgrade of ATLAS
- Recent trends in Micromegas detectors

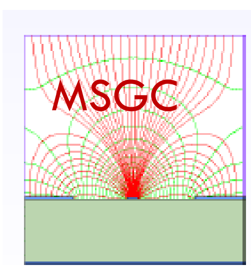
A century of gaseous detectors

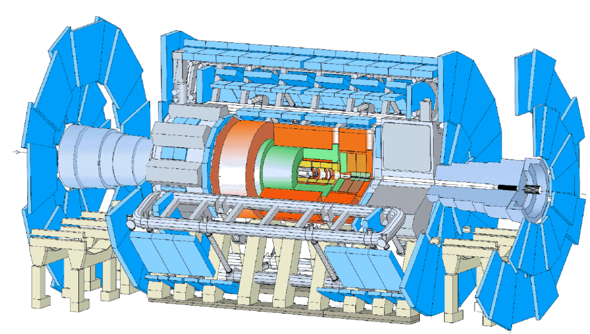
- 1908: Rutherford used the first wire counter (Geiger) for studying natural radioactivity
- 1968: Charpak invented the Multi Wire Proportional Chamber
- 1978: Time Projection Chamber (D. Nygren)
- '90: Micro Pattern Gaseous Detector
- 2009: LHC experiments largely based on 'traditional' gaseous detectors







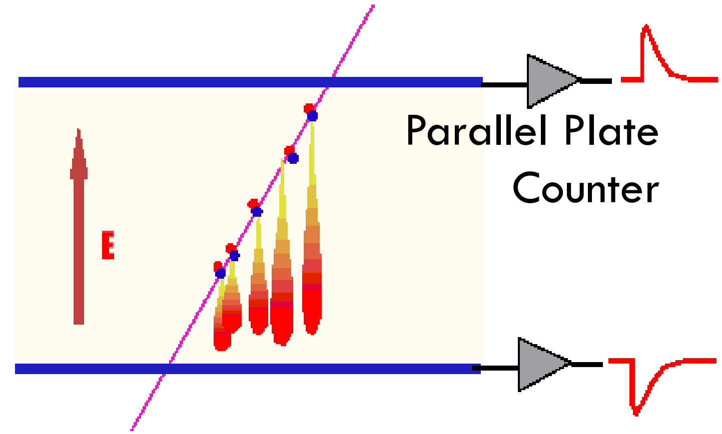




Gaseous detectors

Particle detectors are based on the EM interaction of charged particles with the detector material

Gaseous' detector ingredients:
- Filling gas
- Electrodes with HV (electric field)
- Read Out electronics



Ionization → secondary ionization → electron avalanche.

$$N(x) = N_0 e^{\int_0^x \left(\alpha(E(\xi))-\eta(E(\xi))\right)d\xi}$$

α= Townsend coefficient
η= attachment

Gas amplification

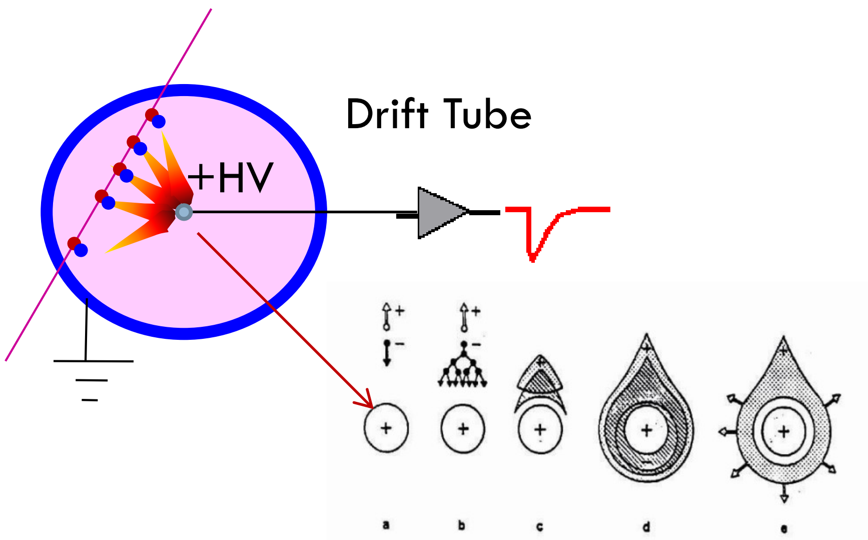
$$G = \frac{N(L)}{N_0}$$

E ↓ Working region	Avalanche size (ion pairs)
Proportional	10^3-10^4
Semi-proportional	10^4-10^5
Saturation (avalanche)	10^6
Streamer	10^7- 10^8
Geiger	10^9

Signals are due to induction on the read-out electrodes (wires, pads, strips…) by moving charges : electrons AND ions

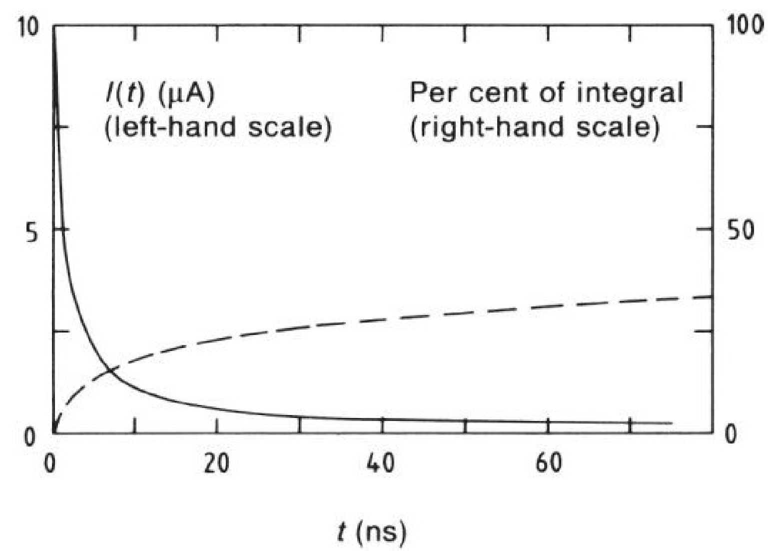
Drift chamber

Electrons drift to the anode wire
Multiplication takes place close to the wire



Measuring the electron drift time the particle trajectory can be reconstructed
$\sigma \approx 50\ \mu m$ at rate<1MHz/cm^2

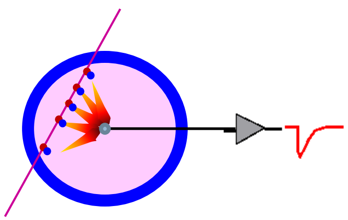
electrons → $V_D \sim 5$ cm/μs
ions → $V_D \sim 10$ m/s (ion tail)
Ion tail can be reduced with proper electronics (filtering)



Ions drift
→ Space charge density
→ Reduction of the effective electric field
→ Limits on rate capability

Wire chambers: rate limit

- Gain drop due to space charge effect
- Expressed as equivalent voltage drop to reduce the gain of the same amount

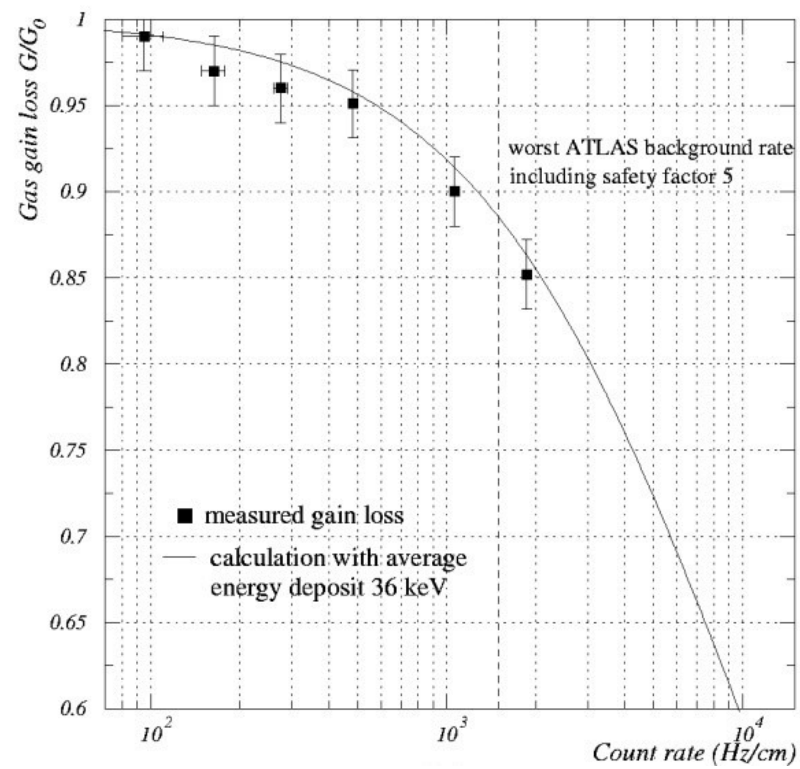


$$\Delta V = \frac{R^3 q \ln \frac{R}{r}}{4\pi\varepsilon_0 \mu V_0} \times \Phi$$

Φ = Particle flow (Hz/cm^2)
r = wire radius
μ= ion mobility
V_0=applied wire voltage
q=average total avalanche charge per track

Classical wire chambers (with reasonable geometry) have an 'intrinsic' rate limit

ATLAS MDT:
1 kHz/cm^2 → 10% gain loss.



More on rate capability

- Space charge effect while being the ultimate limitation for wire chambers is not the only factor affecting the rate capability of gaseous detectors:
  - Ion tail
  - Pulse width
  - Occupancy
  - Pad response function
  - Breakdown
  - Dead time

Example:

Rate: 1MHz/cm^2

Pad r/o 1x1cm^2

Pulse width (~ampl. peaking time) 100 ns

Occupancy = 1MHz·100ns = 0.1 = 10% ineff.

⇓

If not acceptable improvements are needed:

Smaller r/o electrodes (number of channels)

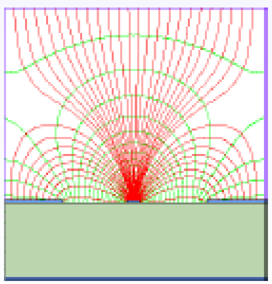
Faster electronics

- Which detector technology is suitable to be employed in harsh conditions (fixed target experiments with intense beam; next generation colliders sLHC, ILC, CLIC …)?
  - Si detectors can stand with higher rate, but
    - Radiation length
    - Not usable to equip thousands square meters (muon systems)

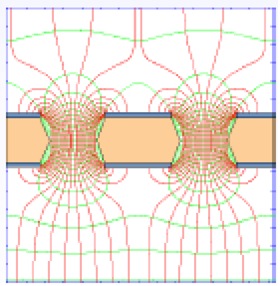
MPGD: increasing the rate limit

- Many efforts have been put in R&D for new gas detectors, leading to Micro Pattern Gas Detectors using photolithographic technology

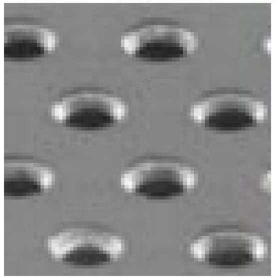
MSGC



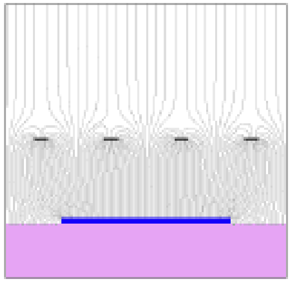
GEM



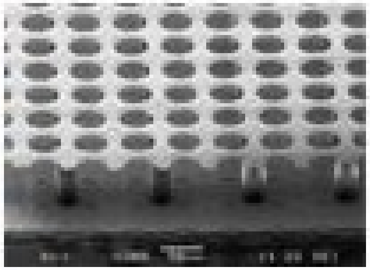
TGEM



Micromegas



InGrid



- Separation between ionization (drift) and amplification regions
- Short (~100 µm) ions drift path
- Fast ions collection
- Higher rate capability (~200 MHz/cm^2)

Still limited to rather small area

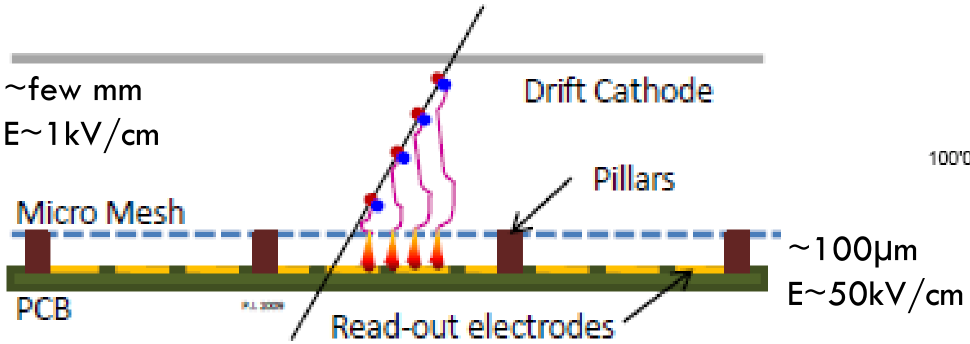
Micromegas

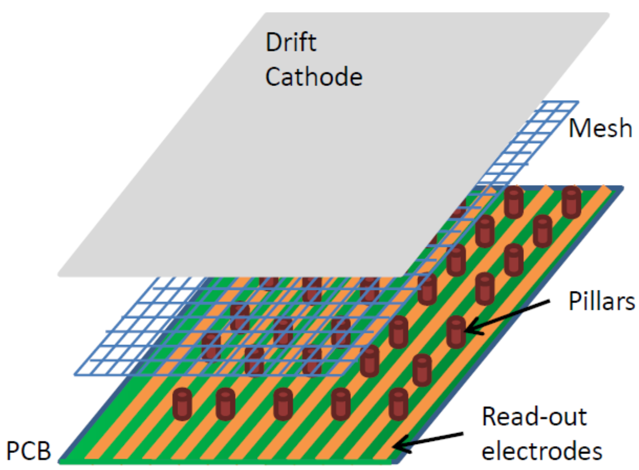
- MICRO MEsh GAseous Structure
- Developed in 1994 (Y. Giomataris, G. Charpak)

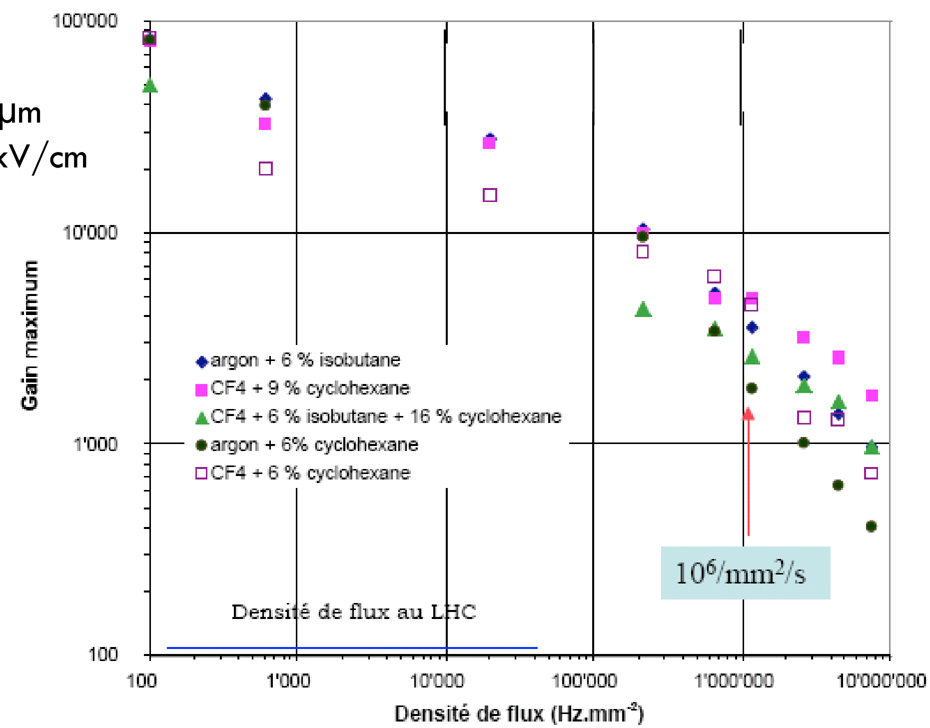
No space charge effect

Reduced ballistic deficit (only for fast electronics <20 ns)

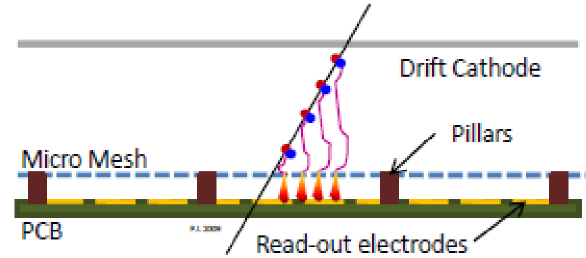
Intrinsic rate limit ~200 MHz/cm^2





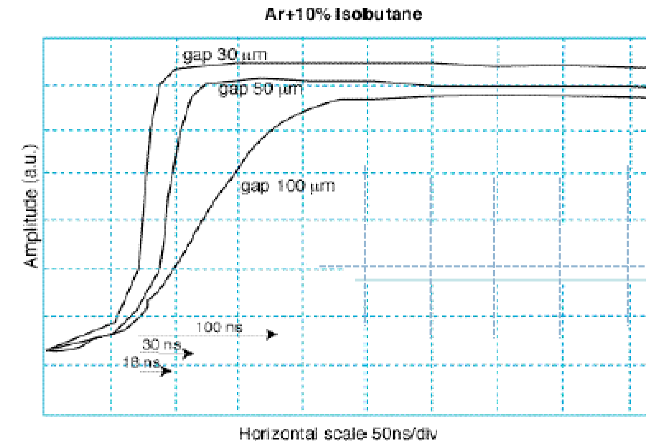


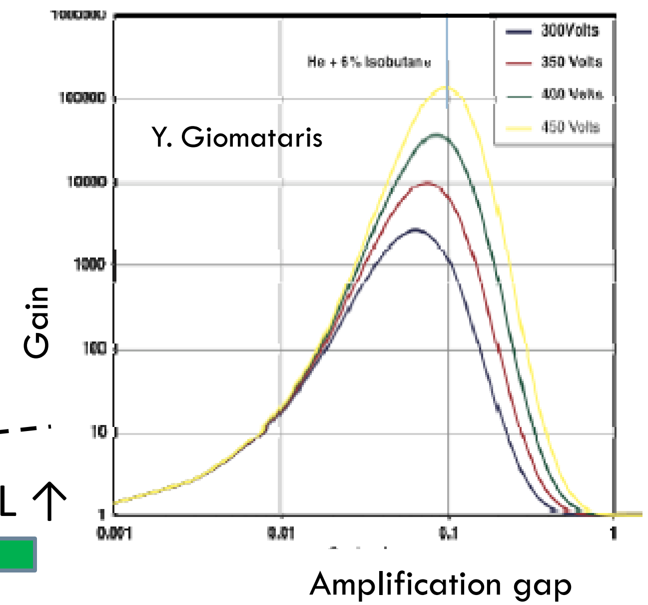
Micromegas

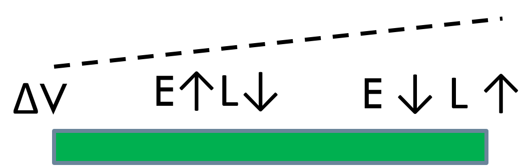


- Main characteristics:
  - Single electron pulse <1ns
  - Electron signal collected in 30-100 ns
  - Time resolution limited by statistic fluctuation of primary ionization in the drift gap <10 ns
  - Spatial resolution depending on read-out electrodes shape (pad response function, charge interpolation etc.) for perpendicular tracks σ<<100 μm possible
  - Stable gain for optimized amplification gap size
  - In first approximation immunity to local flatness defects of the mesh thanks to two competing effects:
    - i.e. if the mesh distance is smaller
      - Higher electric field
      - Smaller amplification path

      ⇨ Stable gain
  - Potential for going to large areas with industrial process: bulk-Micromegas







Bulk-Micromegas

Y. Giomataris & R. De Olivera (2006)

Lamination of a woven grid (mesh) on an anode with a photo-imageable film

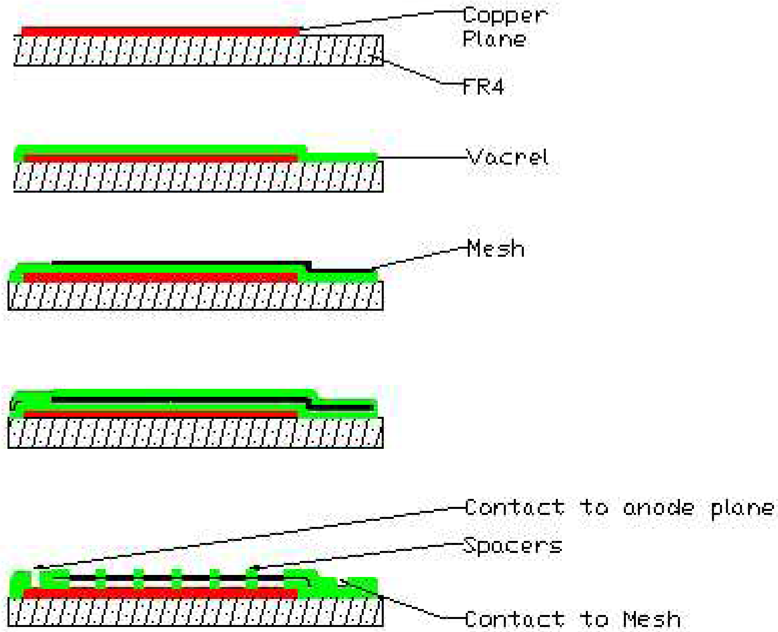
Base material (PCB)

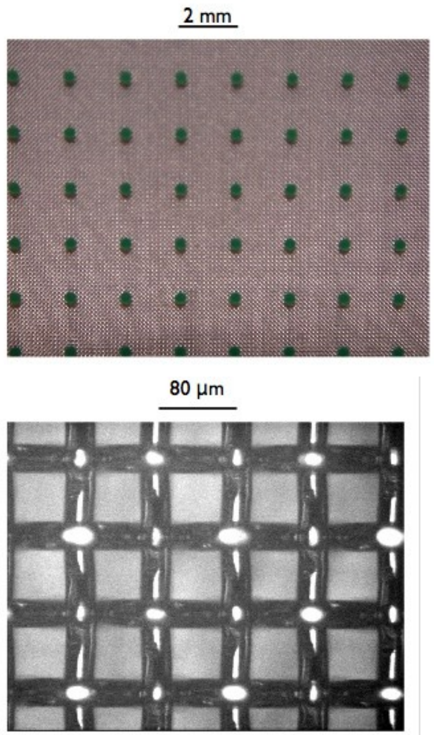
Lamination of photo-imageable film

Mesh positioning

Encapsulation of mesh

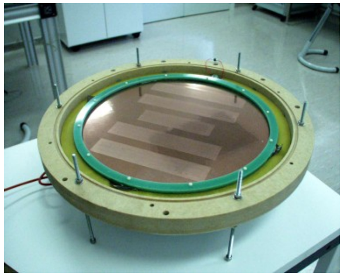
Development of contacts and spacers



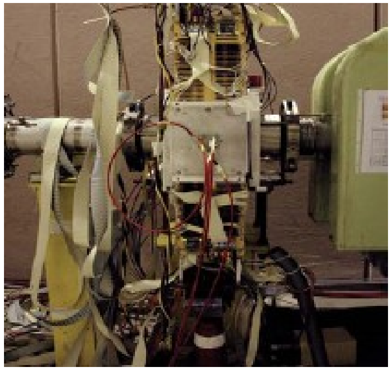


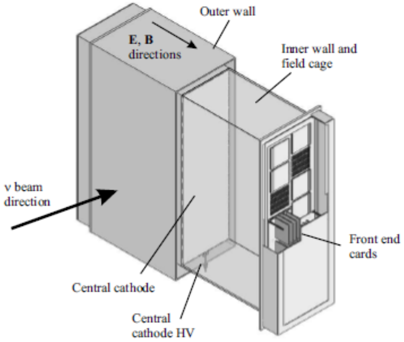
- Reliable technology for industrial process

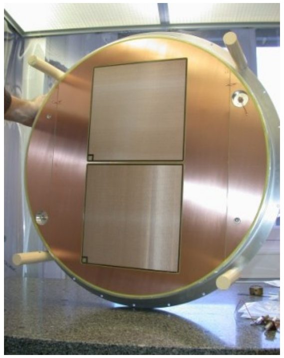
Micromegas: applications

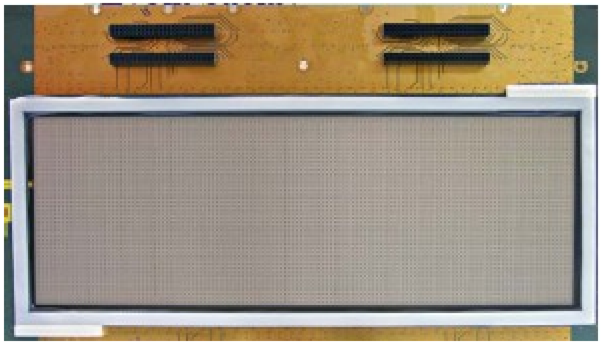


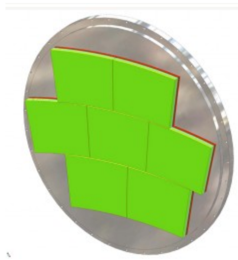
- Compass
  - 40x40 cm^2; σ=70μm, r>100 KHz/ cm^2
- NA48
- TPC @ T2K
  - 72 mod. 36x34 cm^2 ~ 10 m^2
- HCAL for ILC
- TPC for ILC
- TPC for Panda @ FAIR
- Upgrade of ATLAS Muon System
- …and many others
  - Nuclear, medicine, astroparticle…





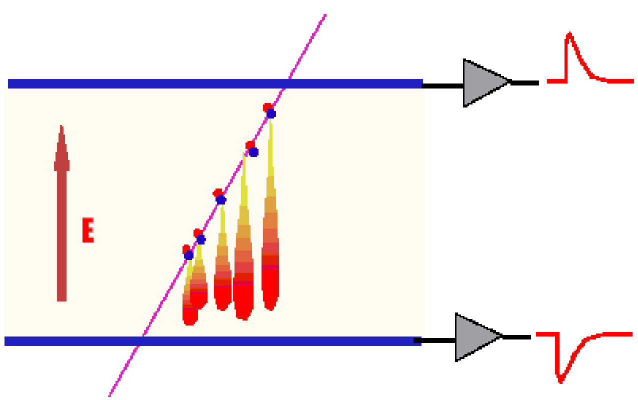


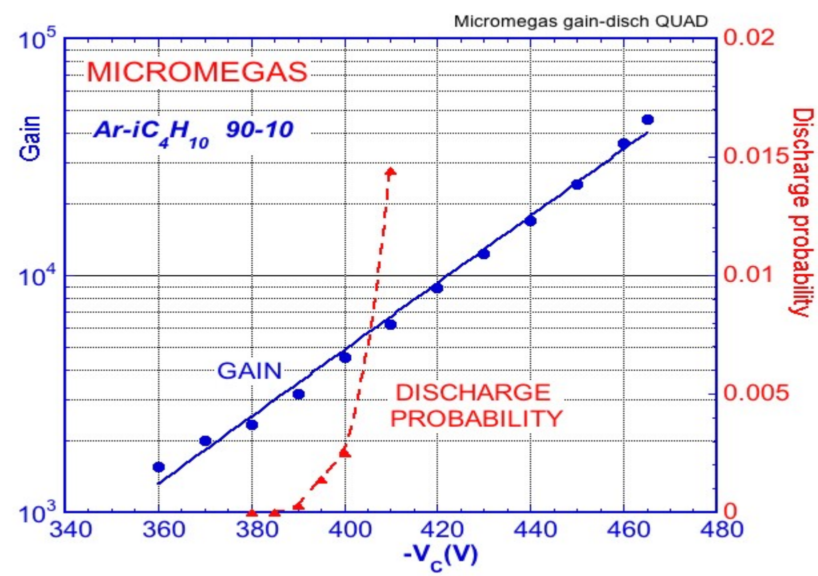




Micromegas: weakness

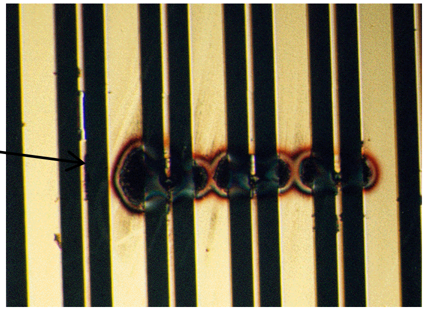
- In any parallel plate device small defects or impurities on the detector surfaces usually trigger discharges (breakdowns)
- Even in device of good quality, when the avalanche reaches a critical value of 10^6-10^7 e^- (Raether limit) a breakdown appear in the gas, often referred as 'spark'
- In PPC a walk-around has been found with the use of resistive materials (glass, silicon, bakelite…) for the electrodes (RPC)
- MPGD and Micromegas are not immune from this problem

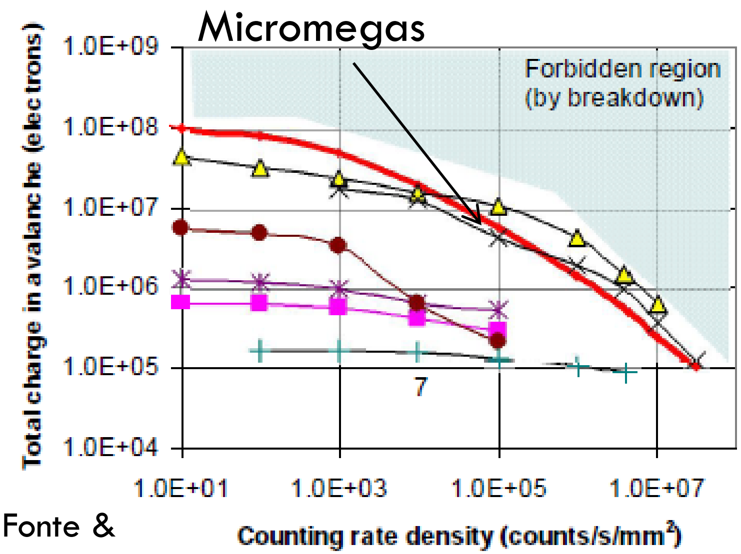




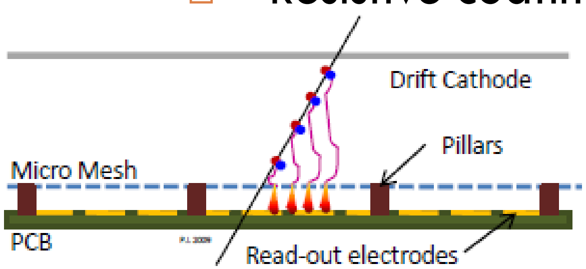
Breakdown

- Problems induced by sparks:
  - Damage of r/o electrodes
    - True for MSGC, not for GEM & Micromegas
  - Damage of front-end electronics
    - Protection circuitry must be foreseen
  - HV electrodes are discharged leaving the detector unready to detect a second particle until the potential is re-established
    - Dead time $\tau = R \cdot C$
    - Mesh segmentation (reduce C, reduce spark energy)
    - Resistive coating (RPC principle)



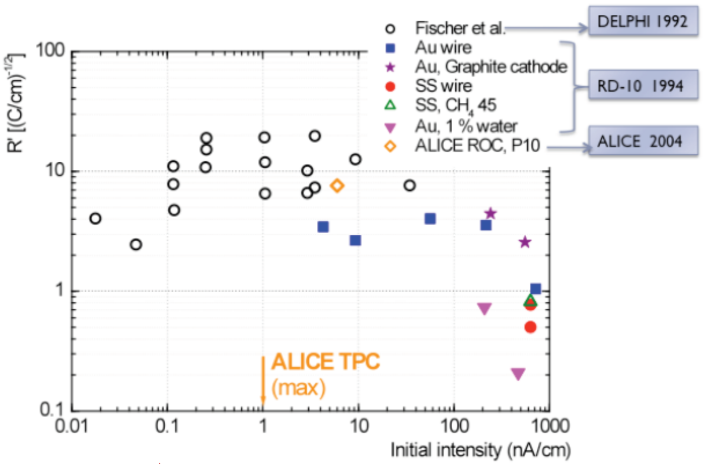


P. Fonte & V. Peskov



Ageing: the Pandora's box

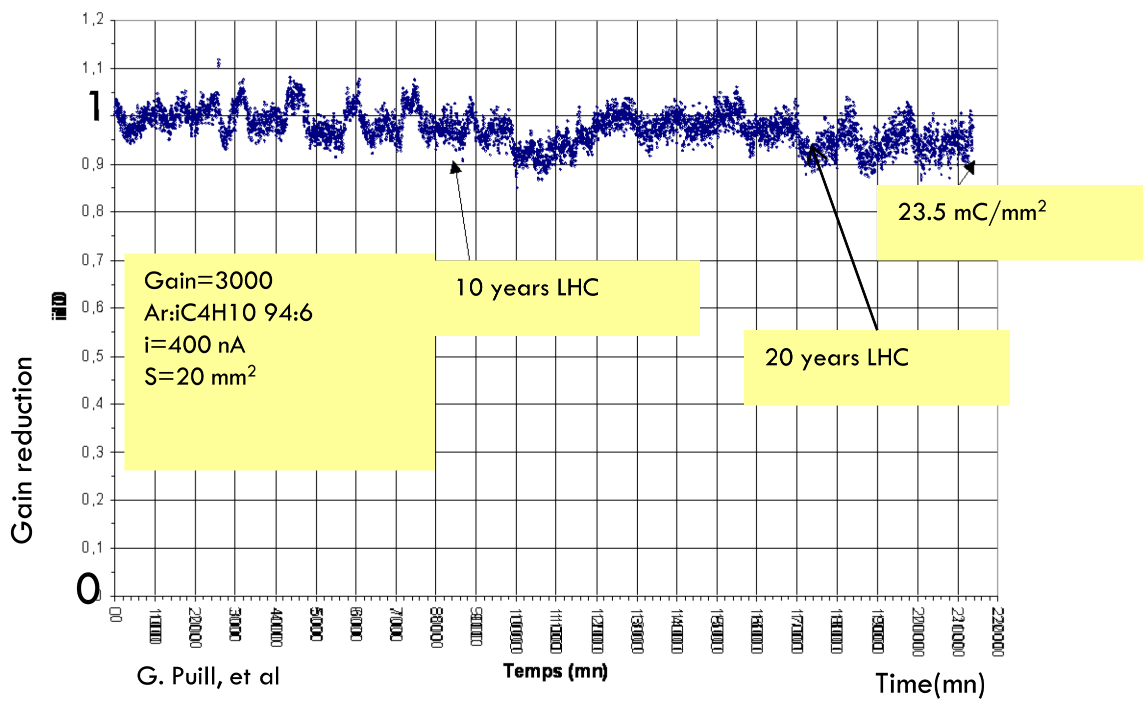
- The ageing process of any detector technology must be carefully studied in order to establish the limits of application
- Ageing phenomena is usually observed in any detector, but it's not always fully understood (it's a very subtle process)
- Many different causes can contribute to gaseous detector ageing:
  - Gas: Polymerizing mixtures, pollution, reactive avalanche products, interaction with detector materials etc.
  - Material: Outgassing, structural changes due to radiation etc.
- Ageing is usually described in terms of integrated charge
- Ageing tests are normally run at accelerated rates, often on small prototypes, but ageing may depends on:
  - Gas mixture and flow
  - Irradiation type and irradiated area
  - Detector geometry
  - Ionization current density
- The 'perfect' test would be the final experiment!



Ageing rate vs ionization current for different wire chambers

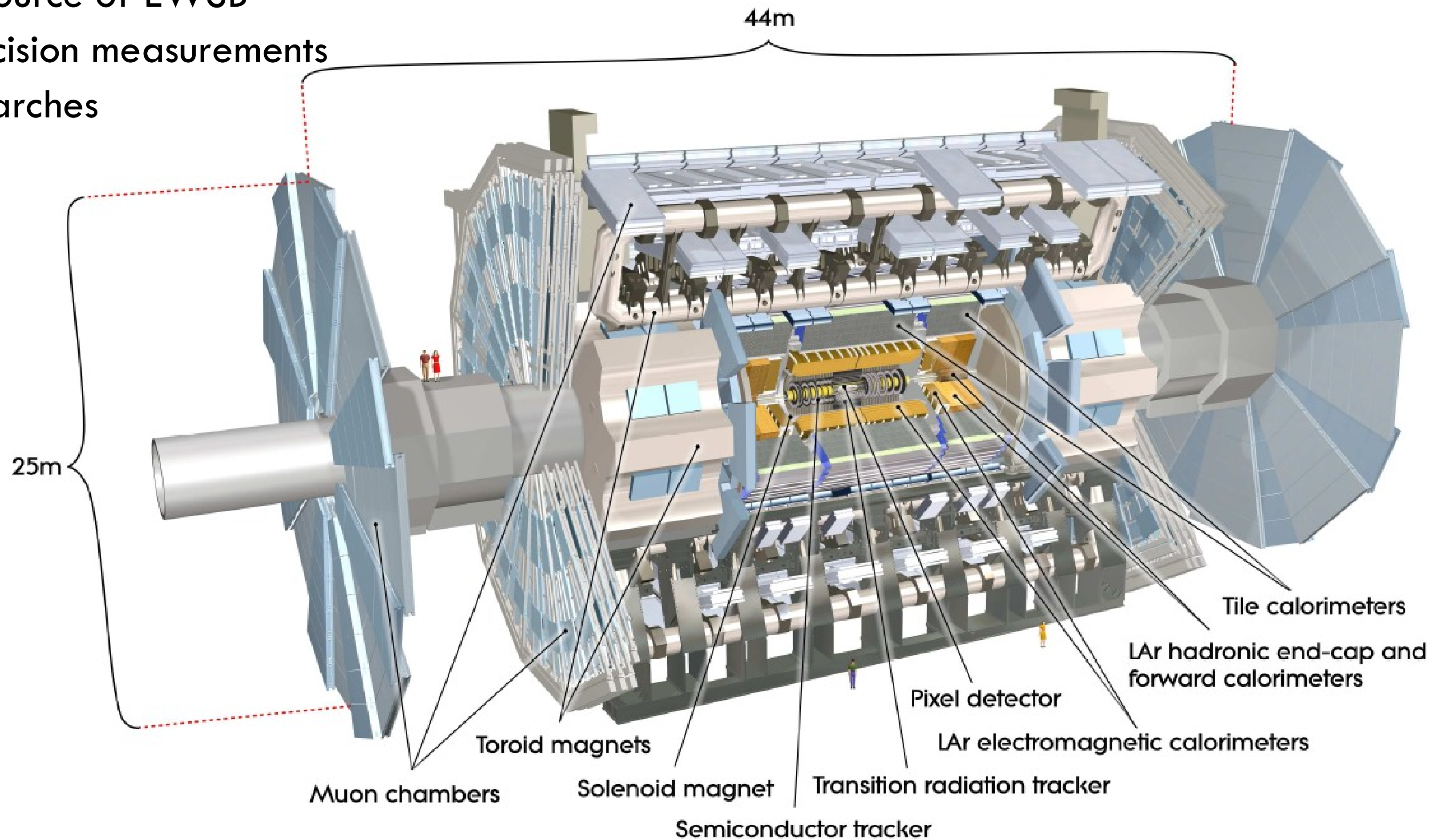
Ageing of Micromegas

- Micromegas has shown good ageing properties
- Extrapolation to different chambers never trivial
- Ageing test must be foreseen for any specific application

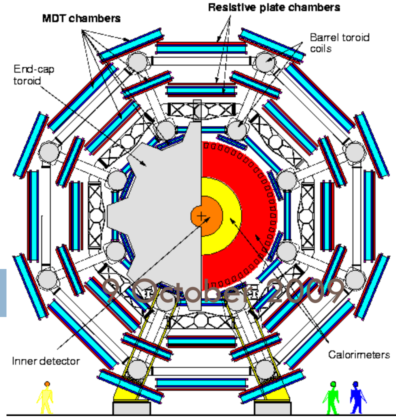


ATLAS: A Toroidal LHC ApparatuS

- General purpose experiment
  - pp collision E_{cm}=14TeV $L=10^{34}cm^{-2}s^{-1}$
  - Probe source of EWSB
  - SM precision measurements
  - BSM searches

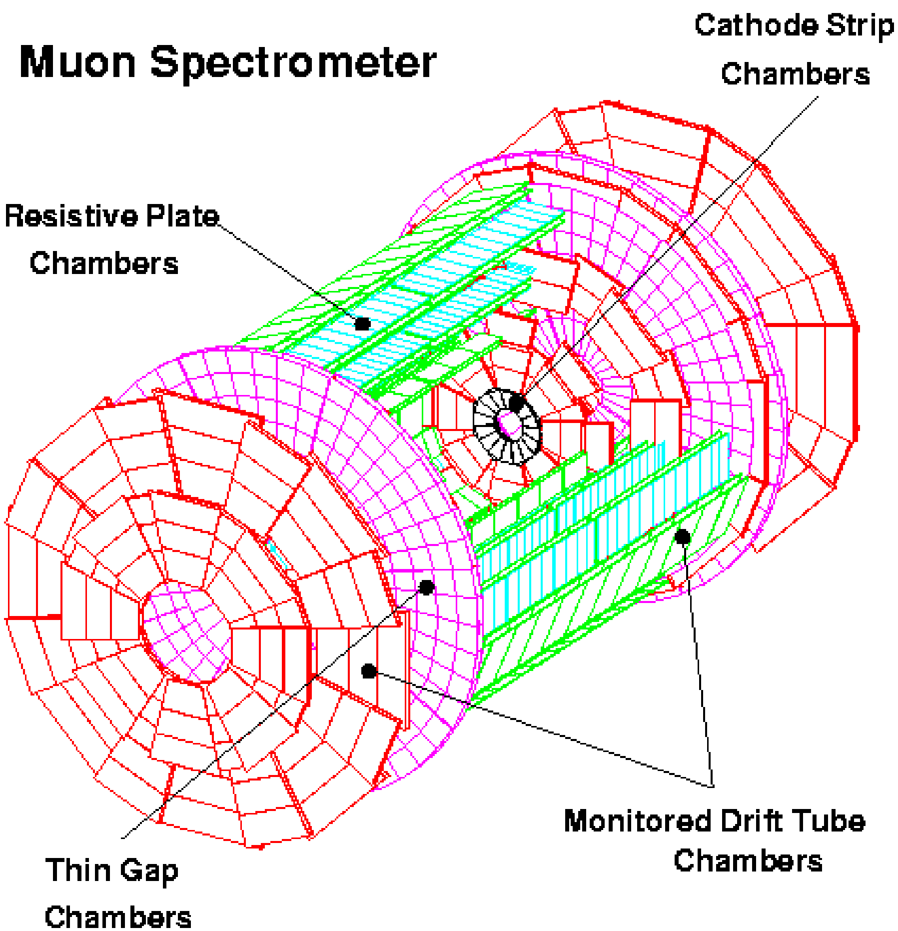


The ATLAS Muon Spectrometer

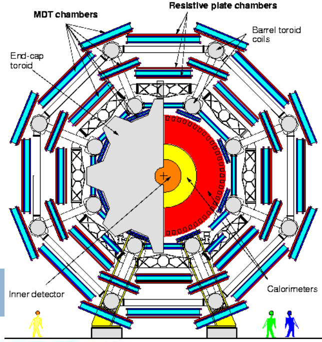


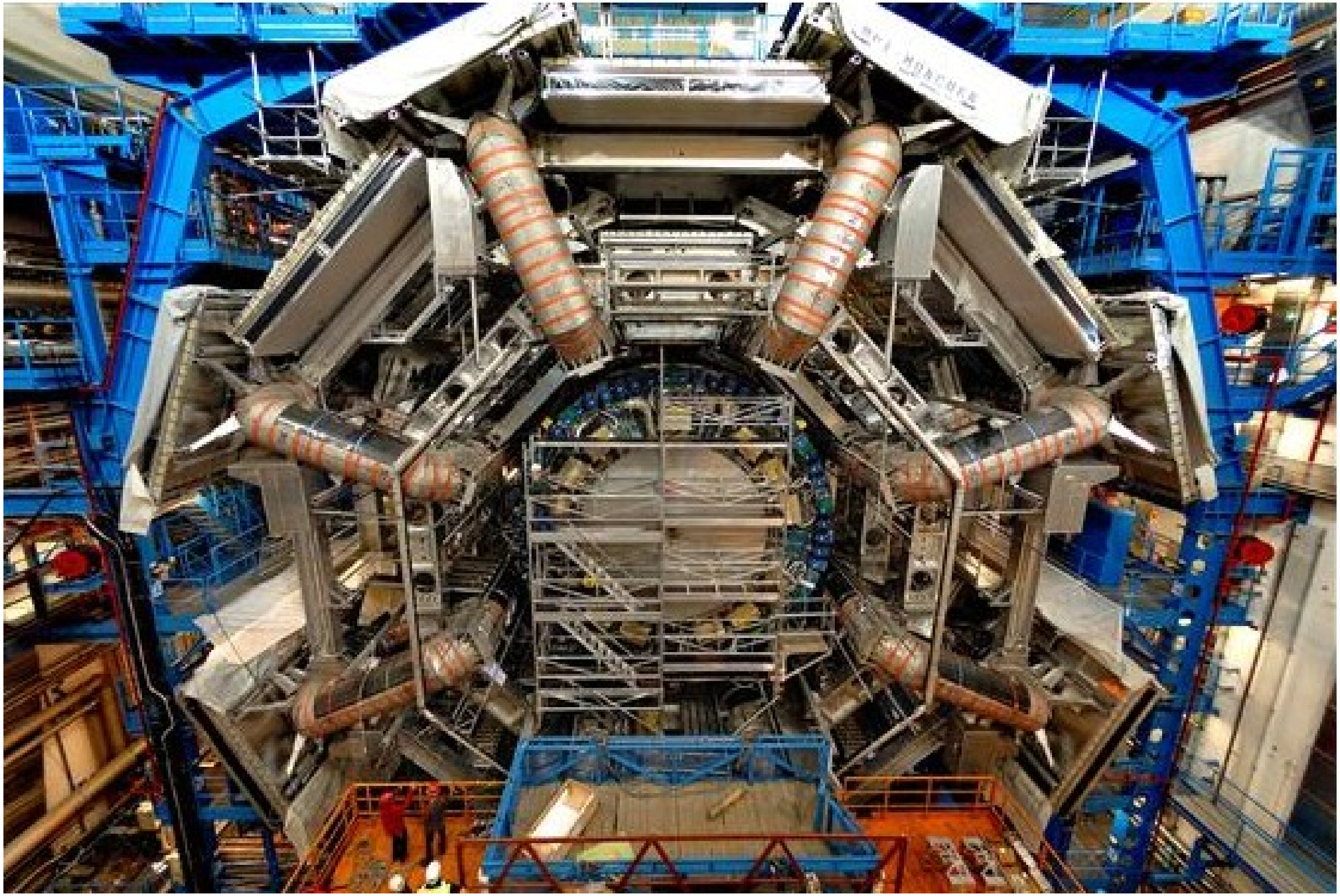
- Precision chambers:
  - MDT (barrel & endcap)
    - σ_{tube} = 80 μm
    - 370000 ch
    - 5500 m^2
  - CSC(endcap |n|>2)
    - σ = 60 μm
    - 67000
    - 27 m^2
- Trigger chambers:
  - RPC (barrel)
    - σ_t = 3 ns
    - 355000 ch
    - 3650 m^2
  - TGC(endcap |n|>2)
    - σ_t = 1 ns
    - 440000
    - 2900 m^2

A mosaic of gaseous detector

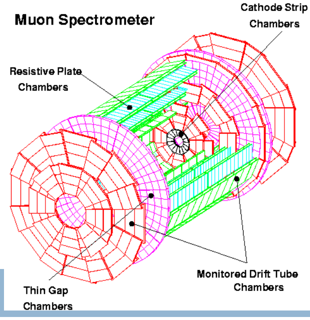


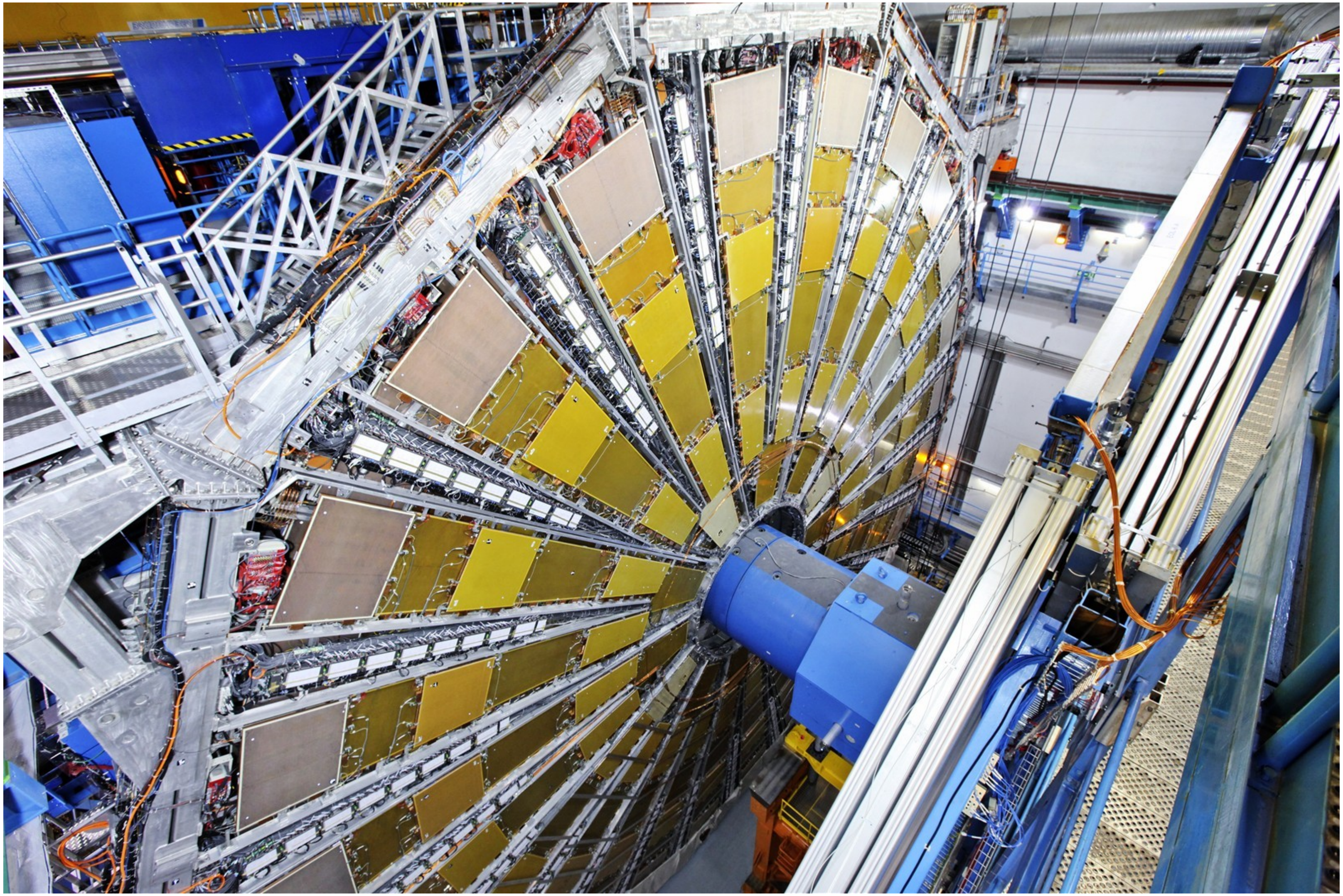
ATLAS in reality





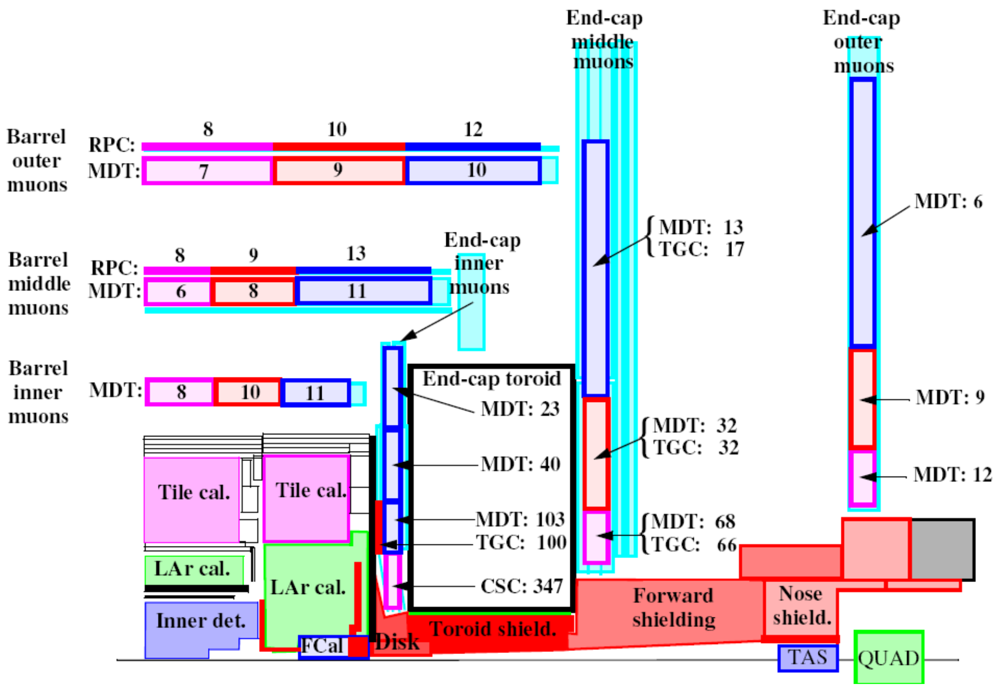
ATLAS in reality





Counting rates

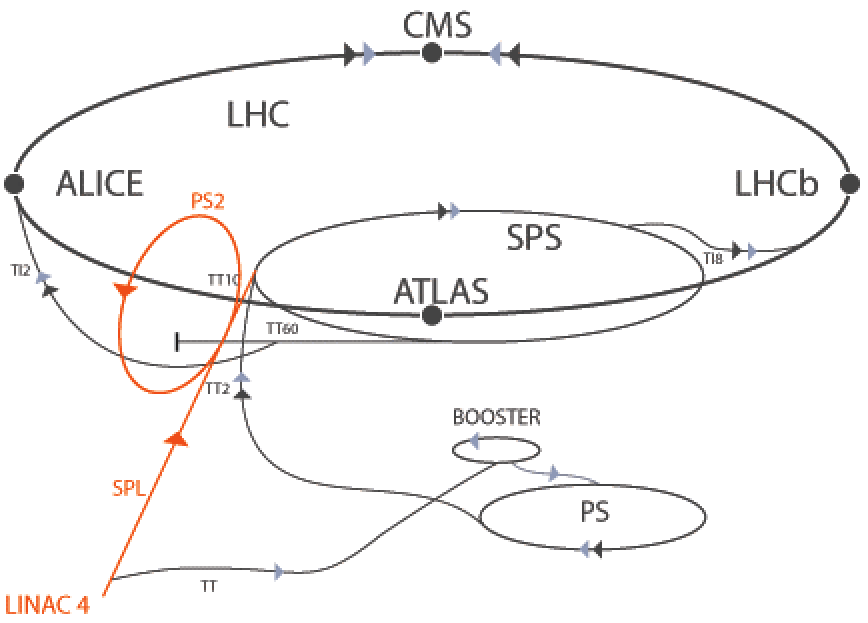
- Expected counting rates in the inner wheel:
  - MDT: 100 Hz/cm^2
    - Rate limit: 500 Hz/cm^2
    - Mainly due to space charge effect
  - TGC: 100 Hz/cm^2
    - Rate limit: 1kHz/cm^2
    - Due to occupancy and resistivity limit
  - CSC: 350 Hz/cm^2
    - Rate limit: 2 kHz/cm^2
    - Due to occupancy
  - Measure of the real counting rate possible only after the first LHC collisions (2010)



Average single plane counting rates (Hz/cm^2) at the nominal LHC luminosity

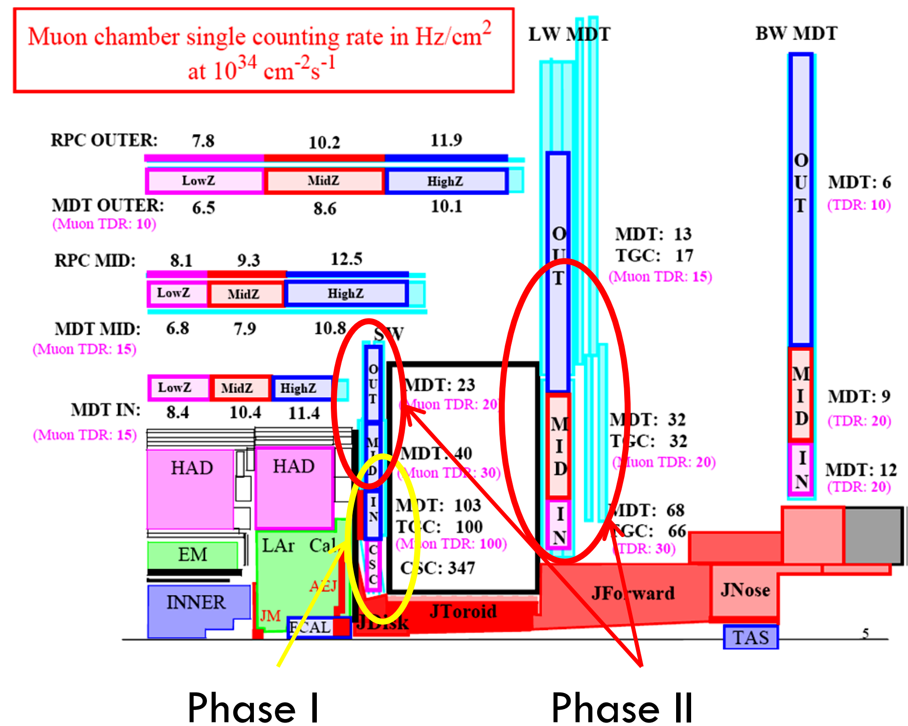
The Upgrade of LHC

- LHC will (re)start operations next month
- Luminosity will be increased up to $2x10^{32}$ in 2010 and to nominal (10^{34}) afterwards (2012)
- Super-LHC:
  - Extend lifetime of the accelerator
  - Complete LHC research program
  - Bridge LHC with future activities (ILC, CLIC)
  - Physics studies:
    - Higgs rare decays, couplings and Higgs potential
    - Scattering of W and Z (no Higgs)
- Machine upgrade foreseen in two phases
  - Phase I: L → $3*10^{34}$
    - Injector (Linac 4), LHC IR (beam focusing)
    - ≥2014
  - Phase II: L →10^{35}
    - SPS upgrade
    - ≥2018
  - Bunc-Crossing: 25 ns (possibly 50 ns in Phase II)



The Upgrade of ATLAS

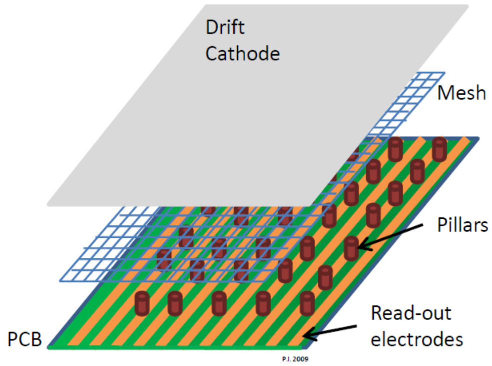
- The ATLAS detectors will likely need major changes
- Critical regions in Muon System ~200 m^2
- Phase I:
  - Complement the present CSC
  - 32 thin chambers of 1 m^2
- Phase II:
  - Replace all small wheel chambers (MDT & TGC)
  - Replace big wheel chambers (MDT & TGC) with $\eta>2$
  - 400 chambers of 1-2 m^2
- Several proposals exist (small MDT, new TGC…)



Micromegas for the upgrade of the ATLAS Muon Spectrometer

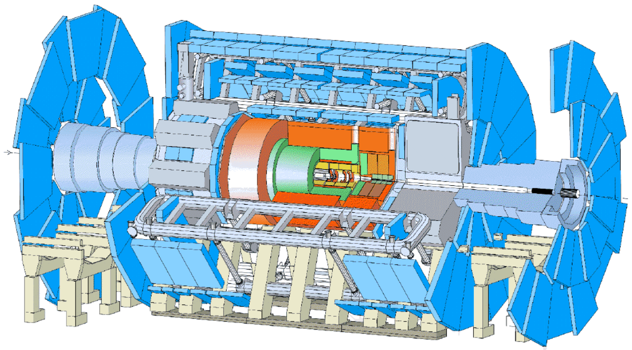
Required performances

- Combine triggering and tracking functions
- Required performances:
  - Spatial resolution ~ 100 μm (Θ_{track}<45°)
  - Good double track resolution
  - Time resolution ~ 5 ns
  - Efficiency > 98%
  - Rate capability > 10 kHz/cm^2



- Potential for going to large areas ~ 1mx2m
- Affordable costs (engineering, mass production)
- Can Micromags satisfy all the requirements?
  - R&D program has been launched in 2007 to prove/disprove

MAMMA program

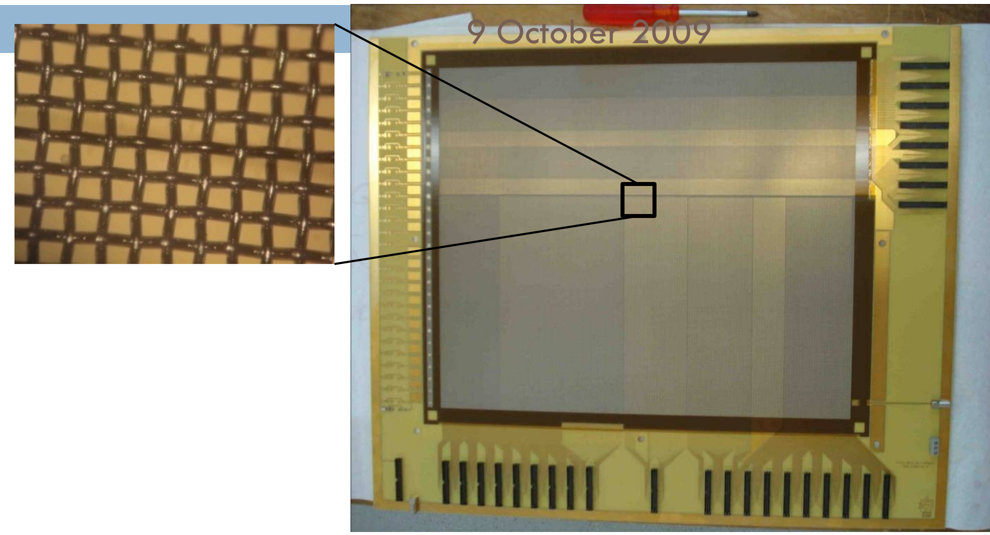


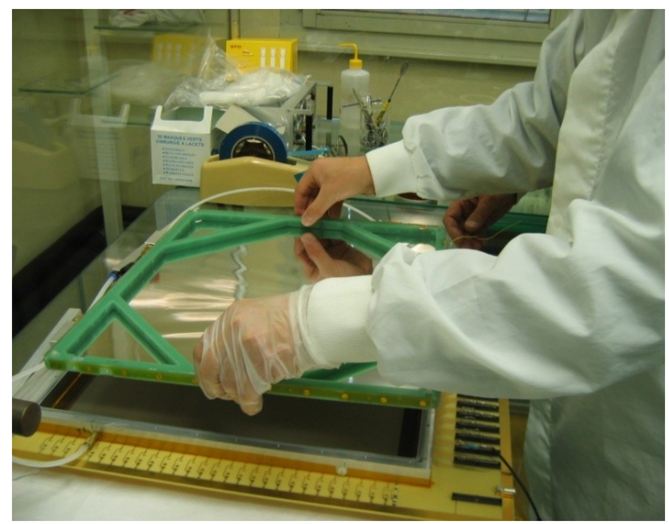
- Muon Atlas MicroMegas Activity
- Construction of medium-size prototypes
- Beam tests and laboratory tests
  - Gas studies
  - Resolutions
  - Optimization of geometrical parameters (drift distance, mesh pitch/diameter…)
- Front-end electronics
  - Analog vs digital read-out (strip pitch, number of channels…)
  - Different approach for trigger and tracking?
- Production and assembling of large-size prototype
- Trigger logic
- Ageing studies
- Industrial production
- Integration in ATLAS

18 Institutes involved/interested
Part of CERN RD51 Collaboration

The first prototype

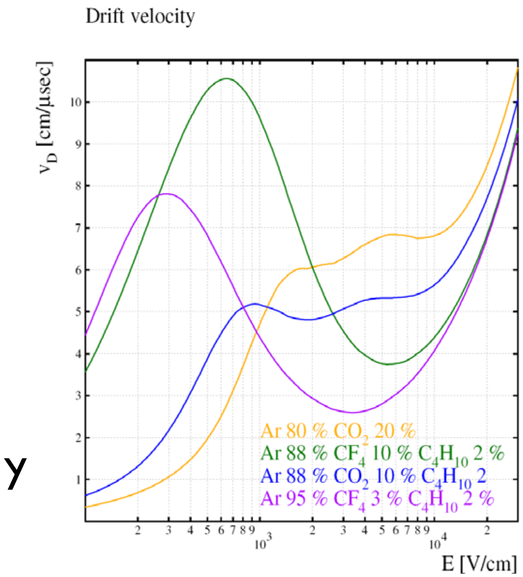
- Standard bulk micromegas fabricated at CERN in 2007
- Homogeneous stainless steel mesh
- 325 line/inch = 78 μm pitch
- Wire diameter ~25 μm
- Amplification gap = 128 μm
- 450mm x 350mm active area
- Different strip patterns (250, 500, 1000, 2000 μm pitch; 450 mm and 225 mm long)
- Drift gap: 2-7 mm
- One of the largest Micromegas built at the time

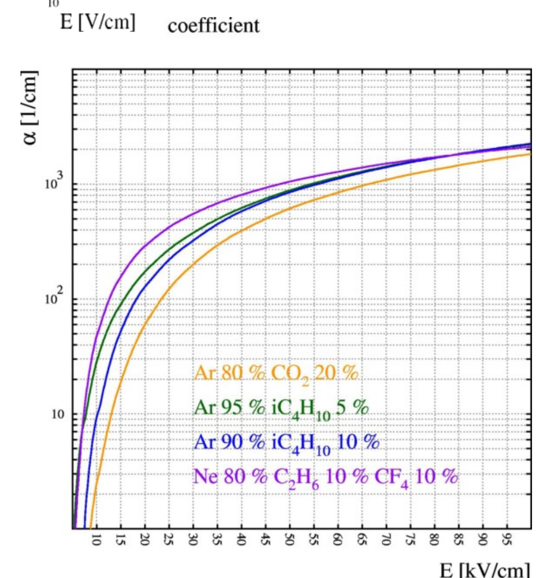




Gas mixture

- $Ar:CO_2$ baseline
  - Safe, not flammable
  - Minor ageing concerns
- Adding CF_4
  - Higher drift velocity
  - F^- ions →HF very corrosive (assembly materials, components)
- Adding iC_4H_{10}
  - Higher gain (Townsend coeff.)
  - Flammable (limit of few %)
  - Ageing (hydrocarbon polymerization → surface deposit)

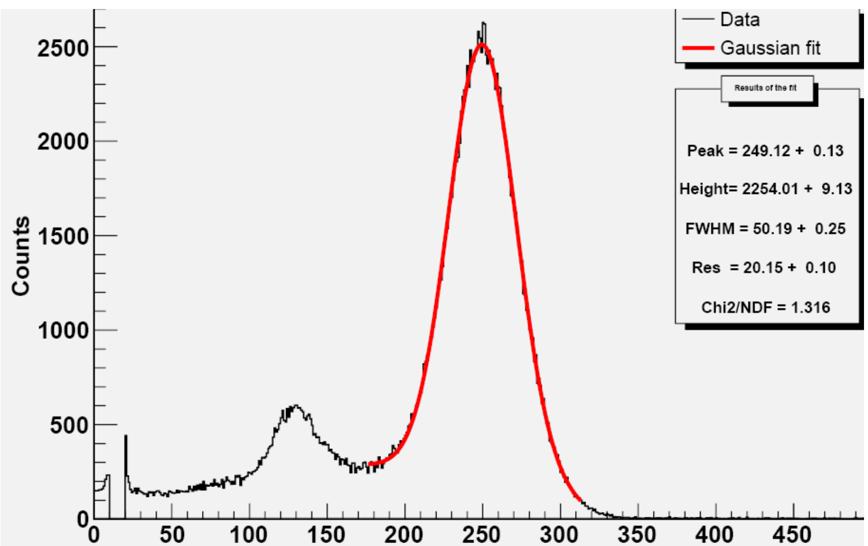




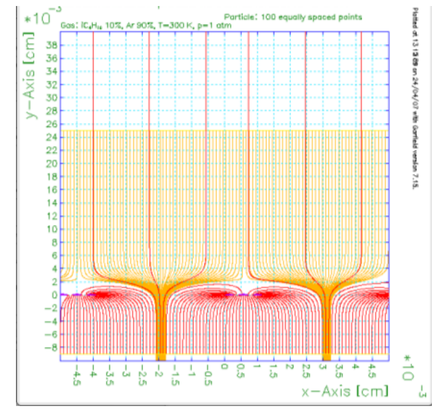
Laboratory test

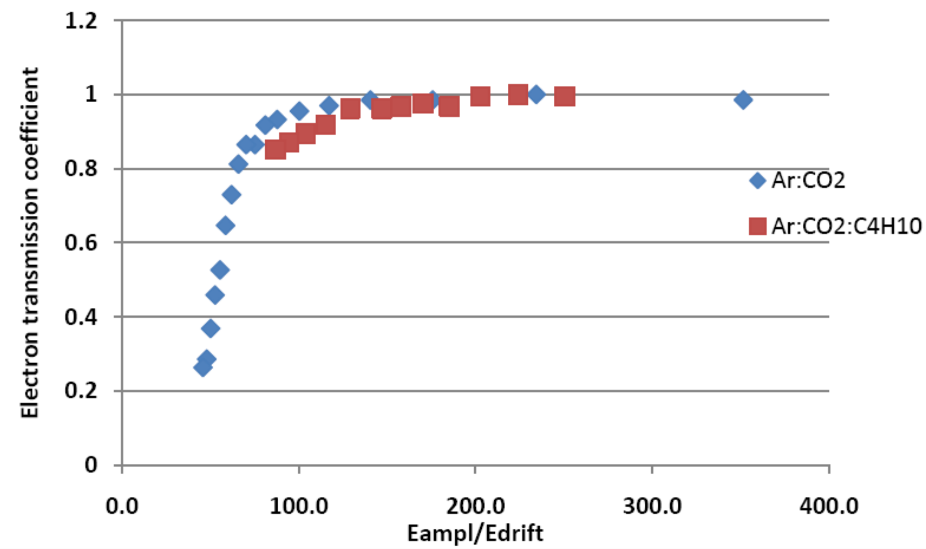
Test with ^{55}Fe source

Energy resolution $\sigma \approx 22\%$
Not crucial for our application



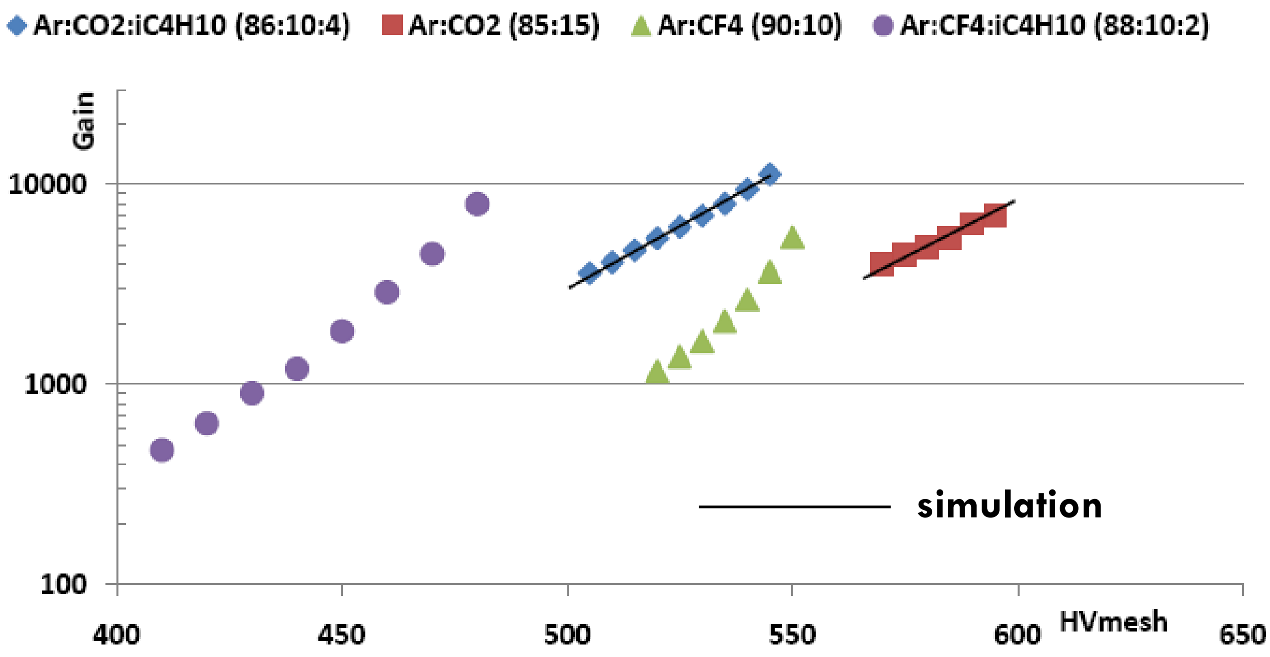
Electron transmission coefficient > 90% for $E_{amp}/E_{drift} > 120$





Gas amplification

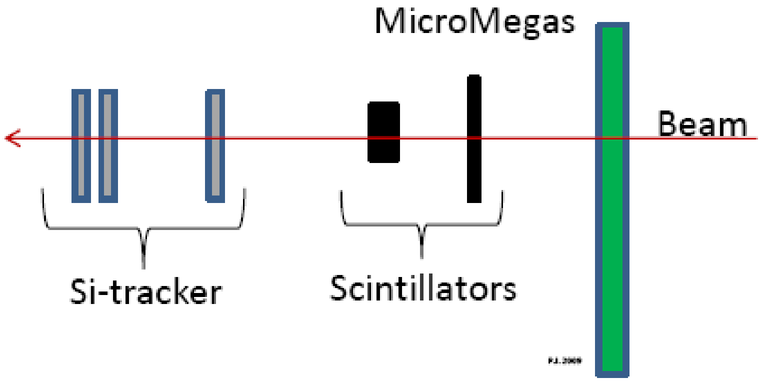
Test with ^{55}Fe source



Maximum gas amplification 10^4
Good agreement with simulation (w/o CF4)

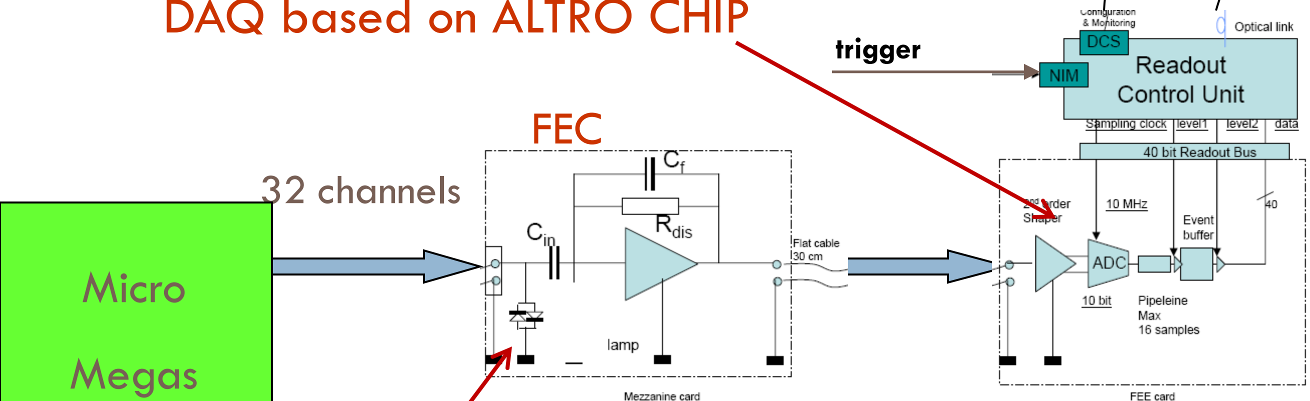
Test beam set up

- Detector tested @ CERN H6 beam line in 2008
- 120 GeV pion beam
- Scintillator trigger
- External tracking with three Si detector modules (Bonn Univ.); independent DAQ
- Three non-flammable gas mixtures with small isobutane percentage:
  - Ar:CO_2:iC_4H_{10} (88:10:2)
  - Ar:CF_4:iC_4H_{10} (88:10:2)
  - Ar:CF_4:iC_4H_{10} (95:3:2)
- Data acquired for 4 different strip patterns and 5 impact angles (90° to 40°)



Readout

DAQ based on ALTRO CHIP



DAQ PC (ALICE DATE)

Two inverted diodes for spark protection

Zero channels died

32 channels

200 ns integration time

65 charge samples/ch

100 ns/sample

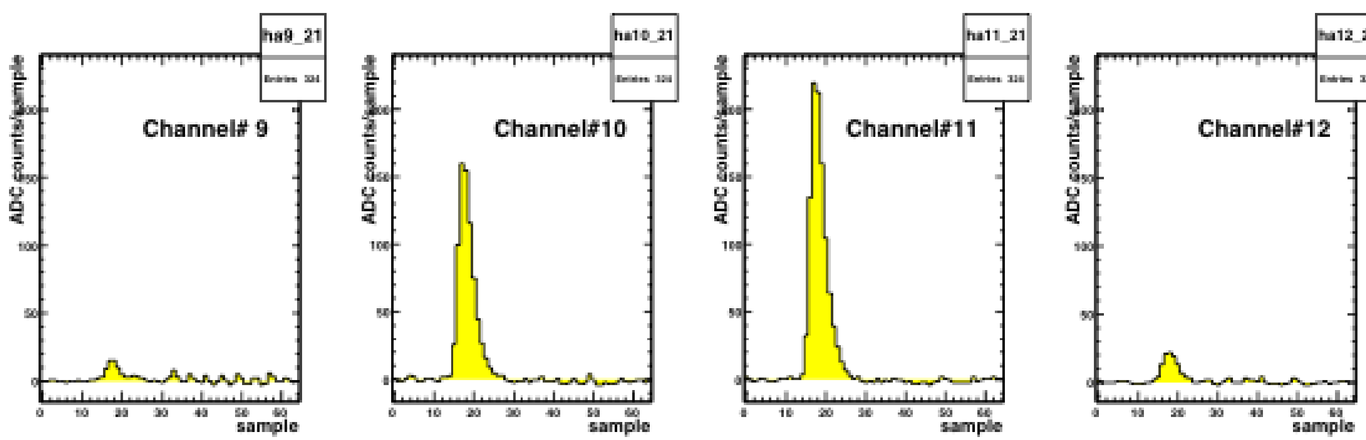
15 pre-samples

1 ADC count ~ 1000 e^-

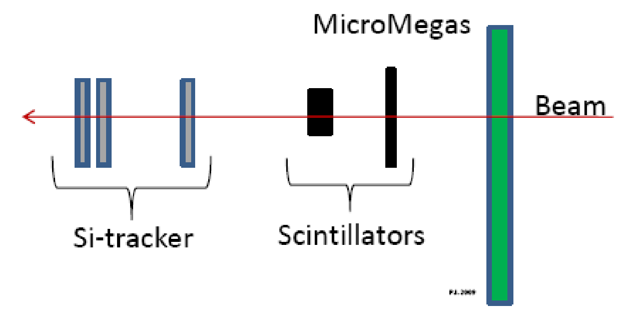
No trigger time info recorded

Typical ADC spectra

- Noise subtraction
- Custer position from center of gravity

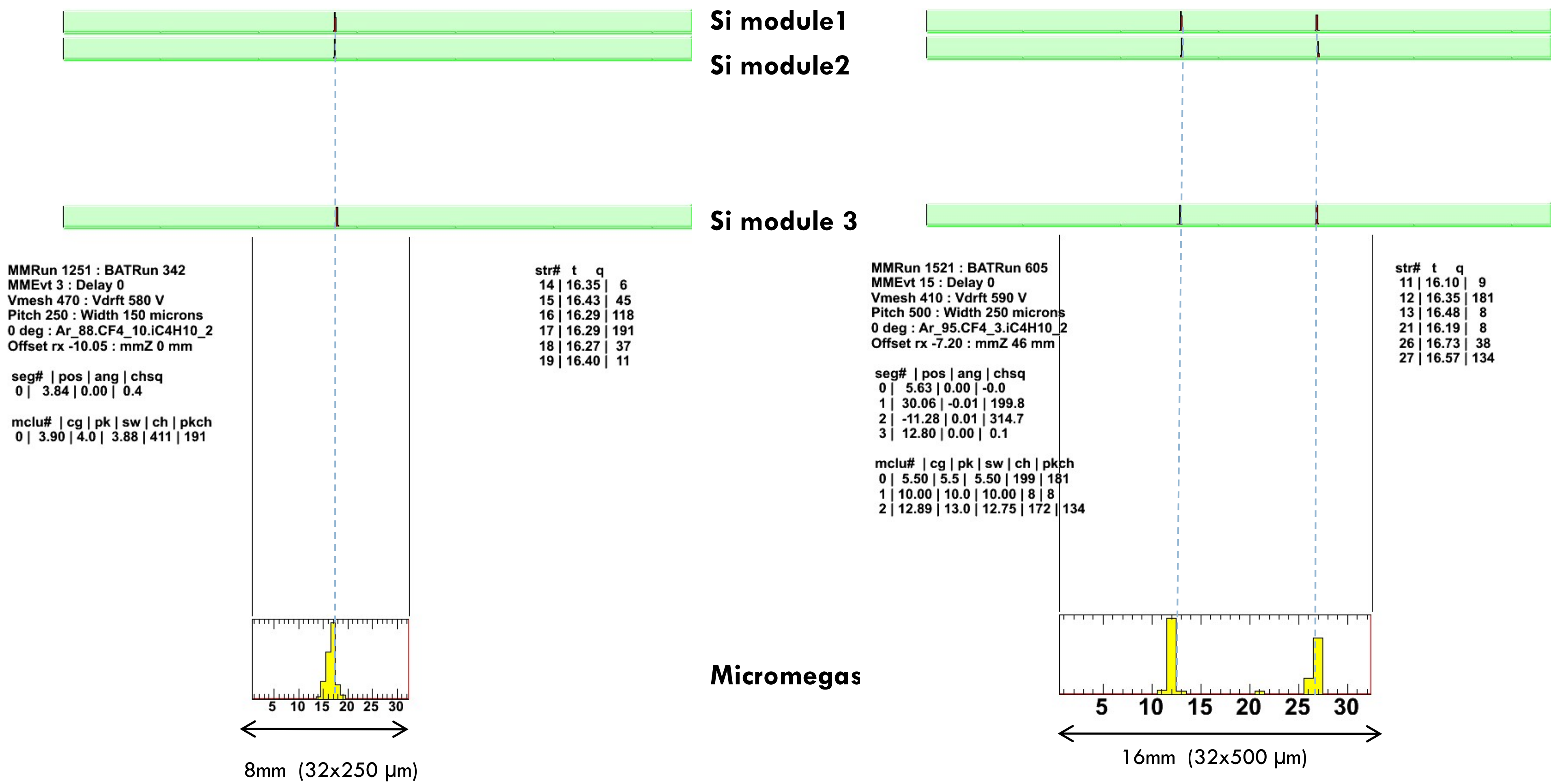


Simple event display



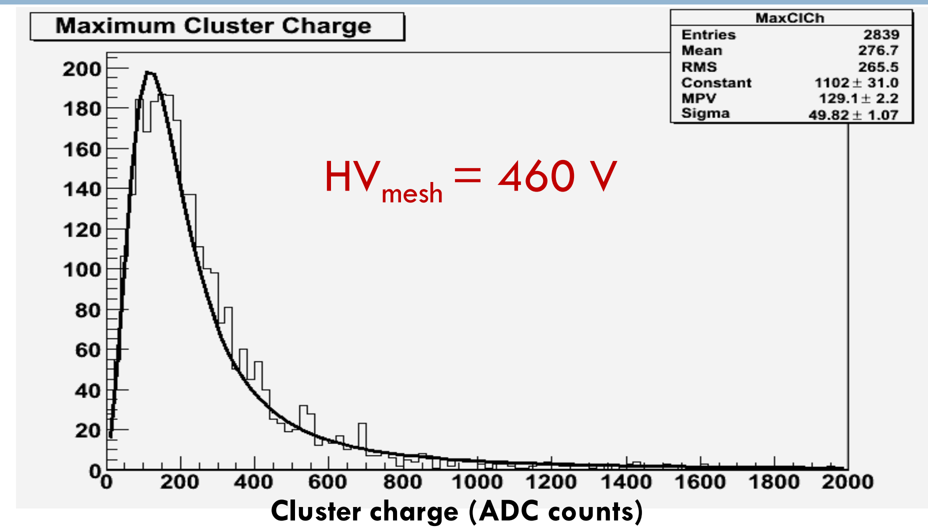
Single track event

Double track event

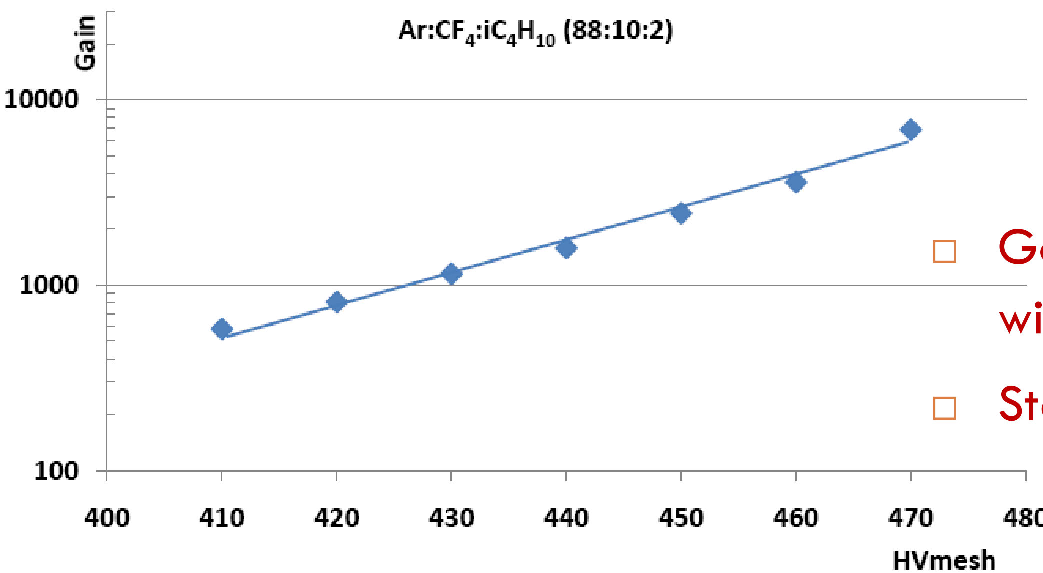


Cluster charge & gain

- Gas mixture: $Ar:CF_4:iC_4H_{10}$ (88:10:2)
- Drift gap 5 mm; drift field = 200 V/cm
- Strip pitch = 250 µm
- 1 ADC count = 1000 electrons



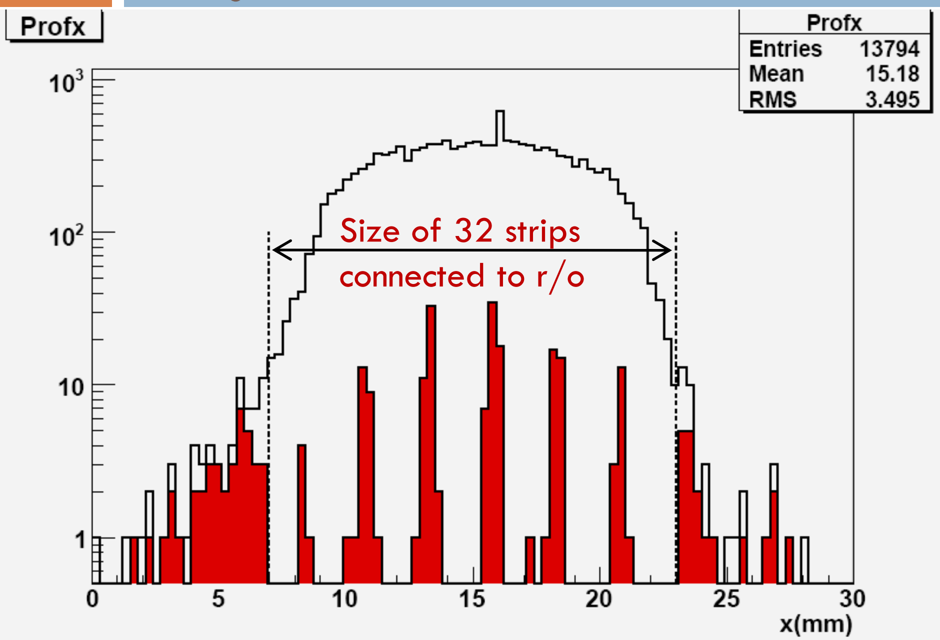
Distribution of cluster charge induced on the read-out strips

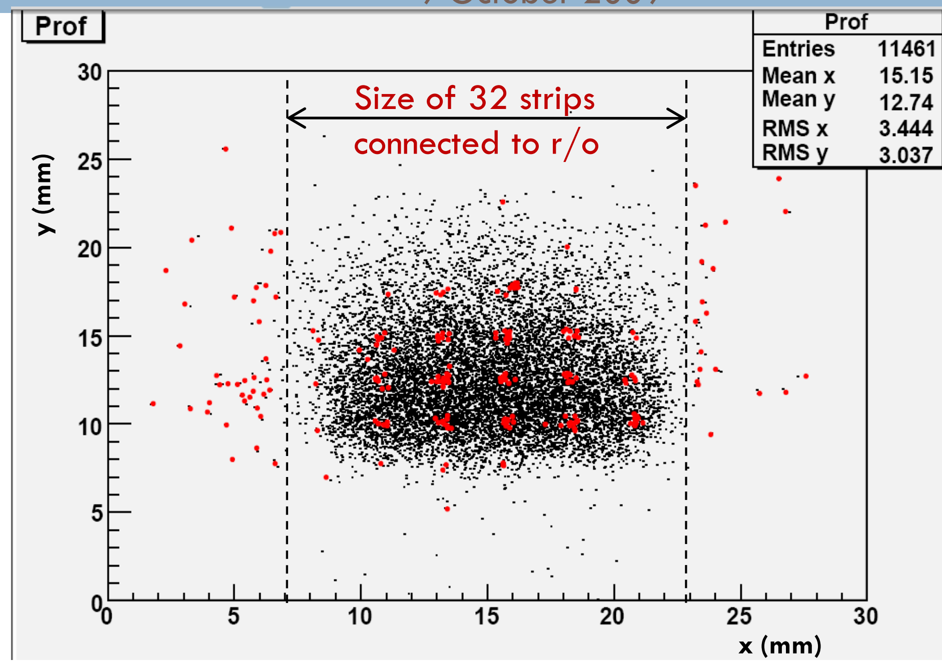


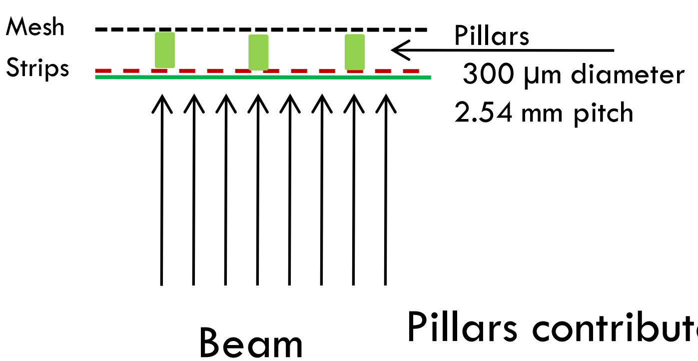
- Good agreement with measurement with ^{55}Fe source
- Stable working point @ gain ~ $5 \cdot 10^3$

Efficiency

- Gas: $Ar:CF_4:iC_4H_{10}$ (88:10:2)
- Strips: 500 µm pitch 400 µm width
- V_{mesh} = 450 V
- Drift field = 200 V/cm





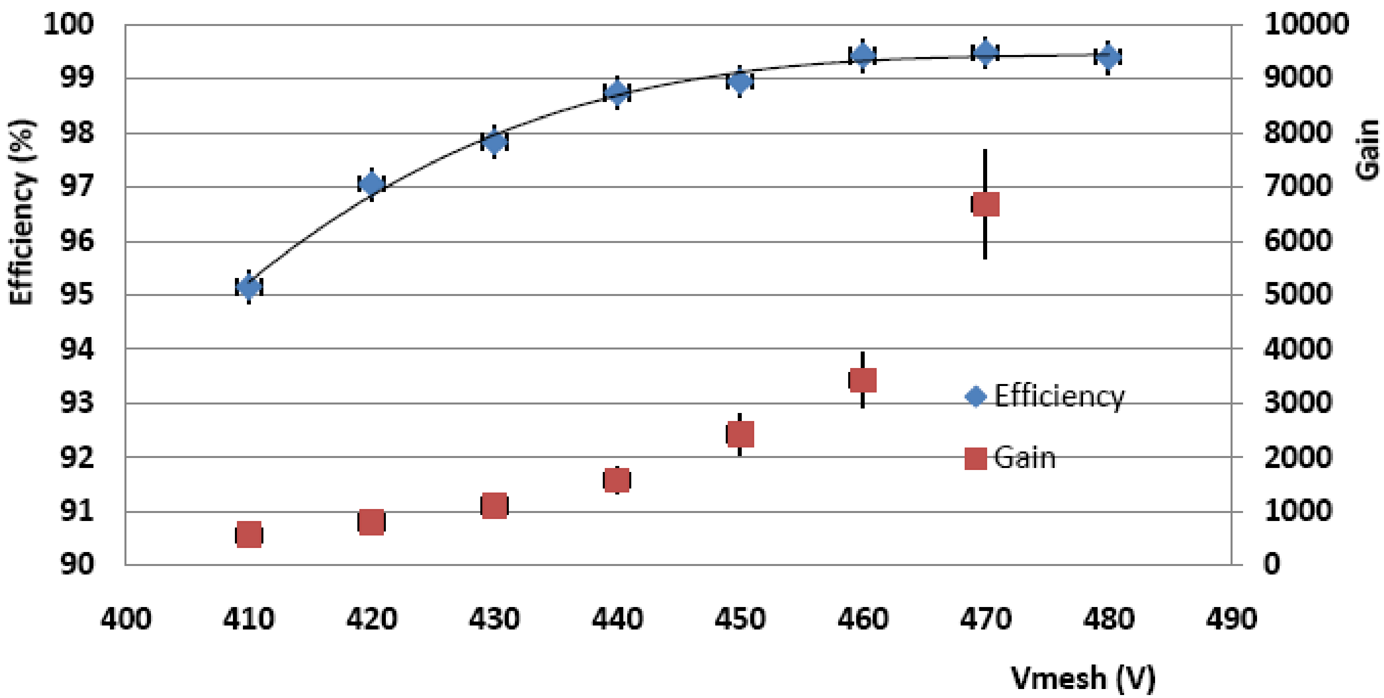


- Black: beam profile
- Red: track w/o Micromegas hits

Pillars contribute to geometrical inefficiency at ~1% level

Efficiency vs V_{mesh}

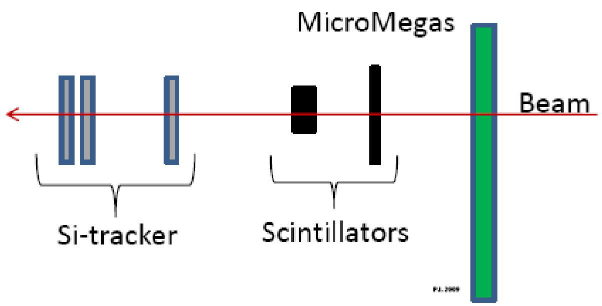
- Gas: $Ar:CF_4:iC_4H_{10}$ (88:10:2)
- Strips: 500 μm pitch 400 μm width
- V_{mesh} = 450 V
- Drift field = 200 V/cm



- Eff > 98% @ V_{mesh} > 430 V (Gas Ampl. > 10^3)
- Working point: V_{mesh} = 440-450 V

Spatial resolution

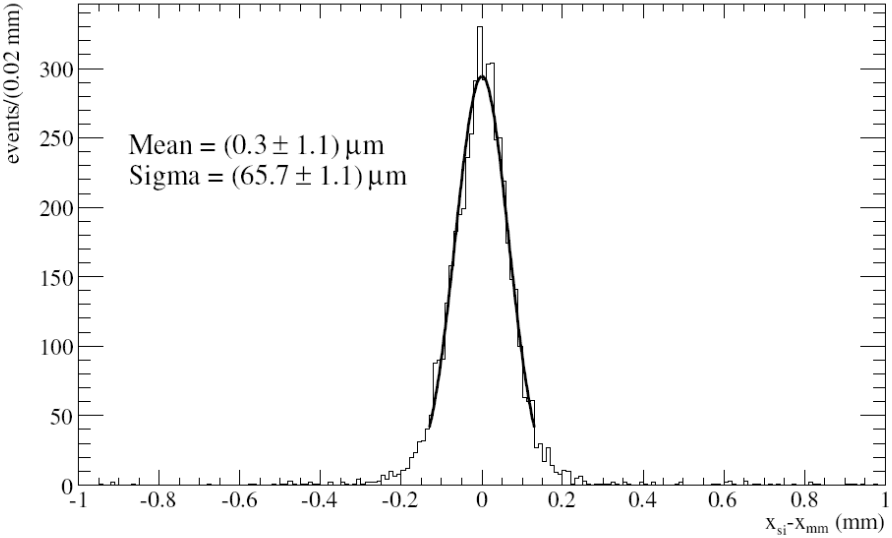
Gas: $Ar:CF_4:iC_4H_{10}$ (88:10:2)
V_{mesh} = 470 V
Drift field = 220 V/cm
Perpendicular tracks



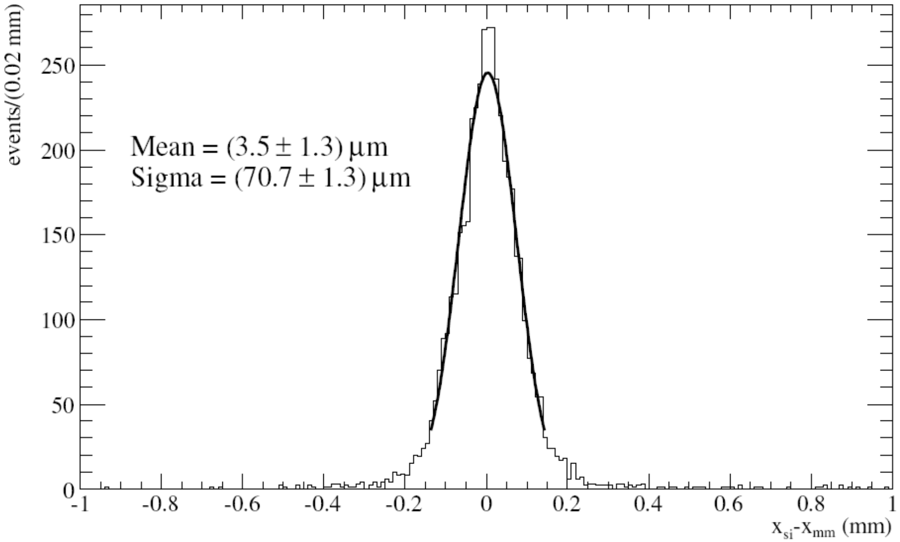
- Residuals of MM cluster position and extrapolated track from Si
- Convolution of:
  - Intrinsic MM resolution
  - Tracker resolution (extrapolation)
  - Multiple scattering

  } ~61 μm

Strip pitch: 250 μm
Strip width: 150 μm
σ_{MM} = (24±7) μm

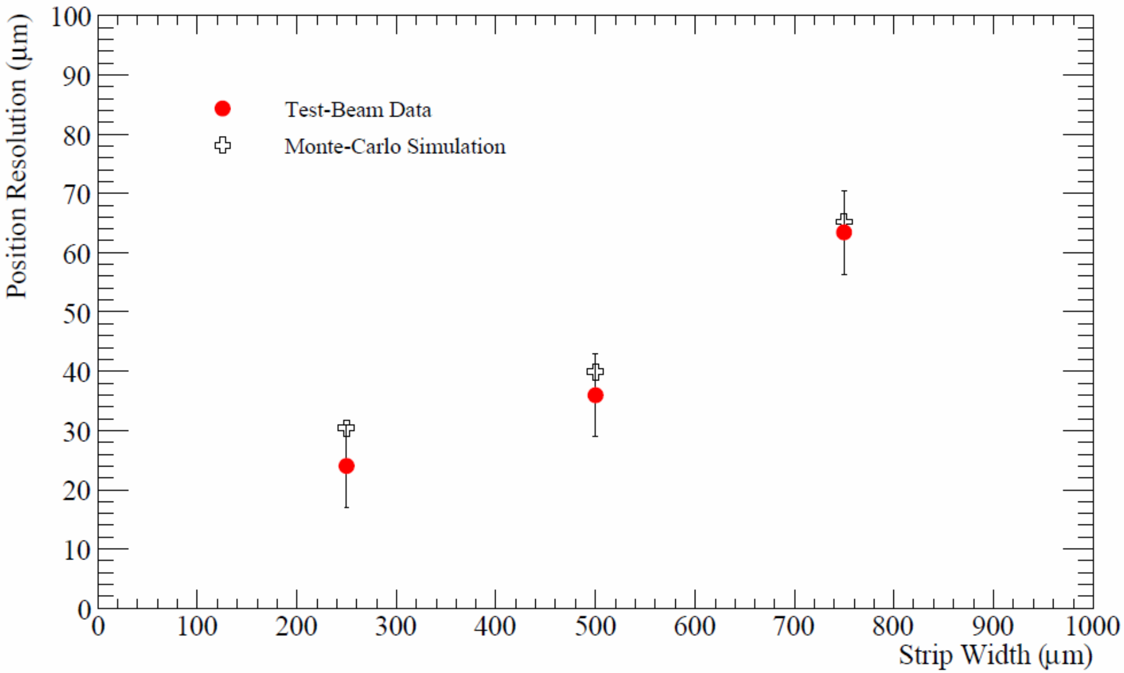


Strip pitch: 500 μm
Strip width: 400 μm
σ_{MM} = (36±5) μm

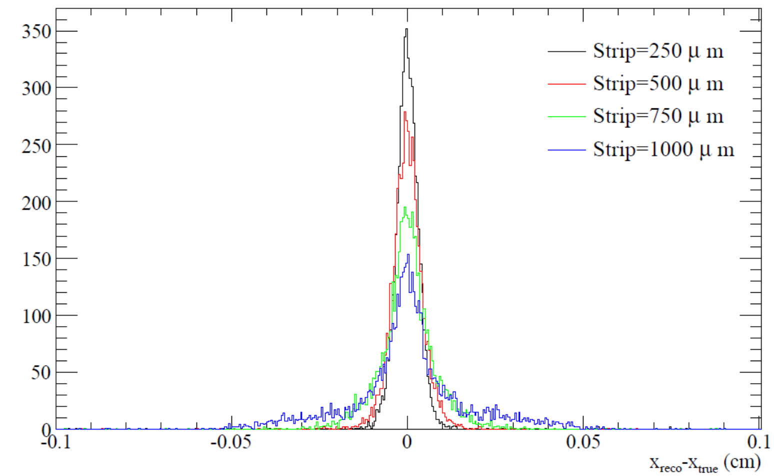


Spatial resolution

- Simulation of the induced signal:
  - Electron production and drift (Garfield, Heed, Magboltz)
  - Semi-analytical approximation of the ions induced charge
  - Include shaper simulation, electronic noise etc.



Simulated spatial resolution for different strip pitches

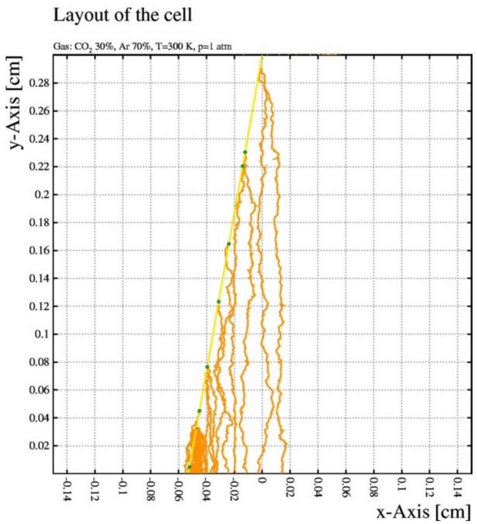


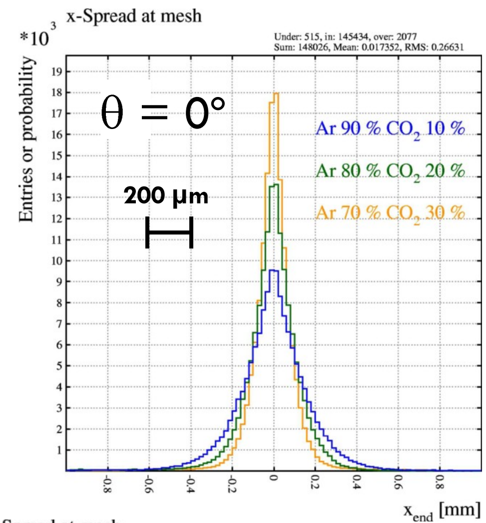
Good agreement between data and simulation

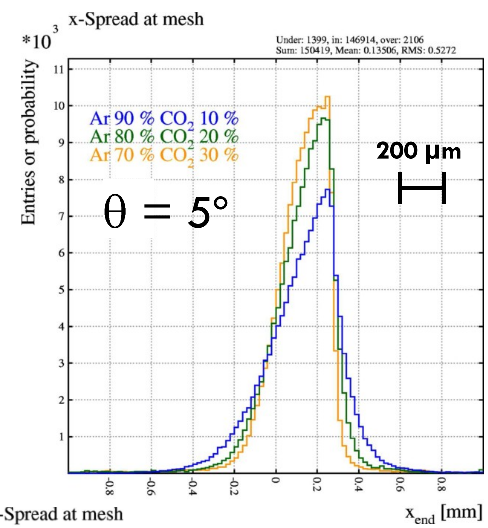
What about inclined tracks?

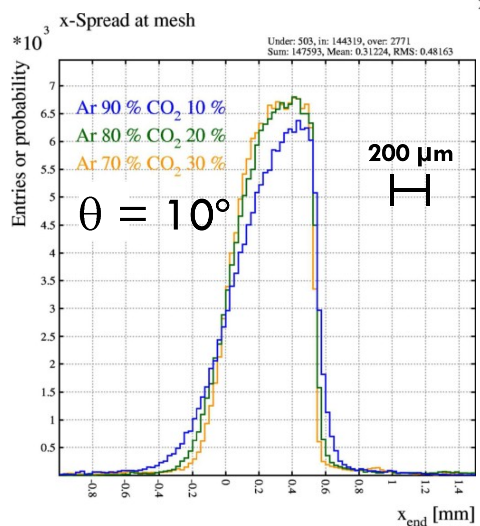
Micromegas is not a drift chamber: impact angle affects the resolution

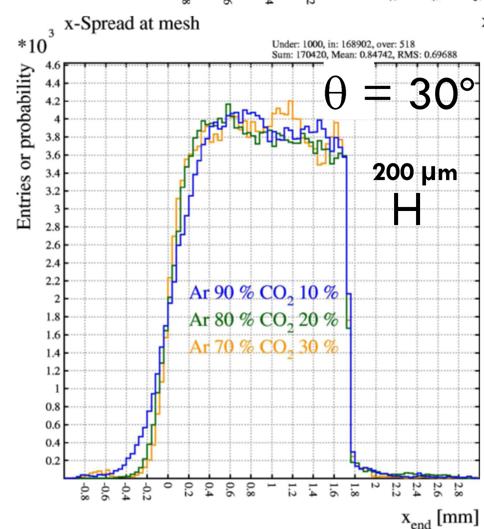
Fluctuation of charge deposition along the track







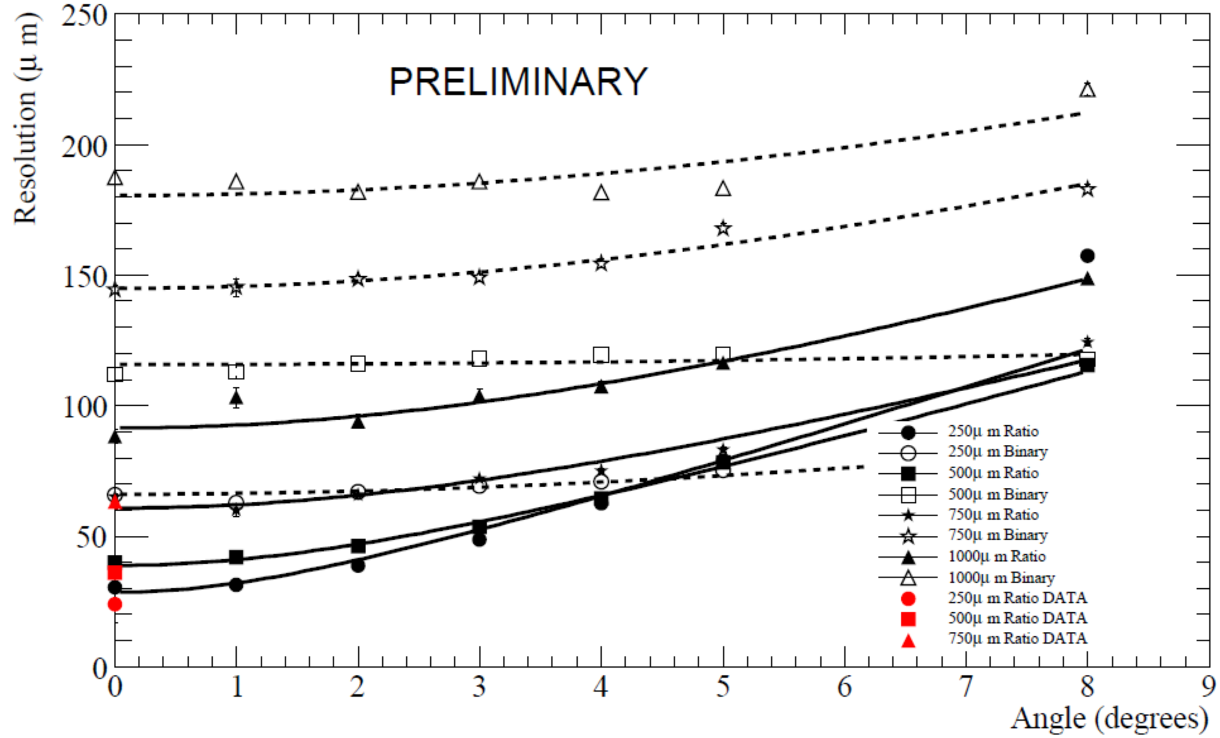




Charge spread at the mesh in 3 mm wide ionization gap for various impact angles

Resolution vs Incident Angle

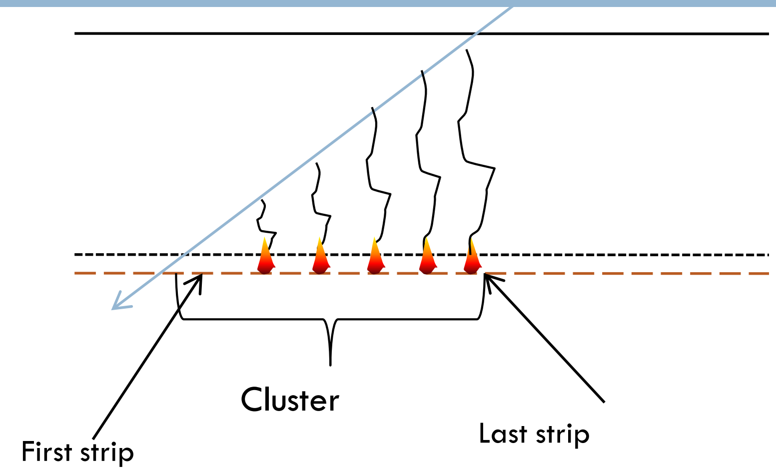
- Spatial resolution for charge interpolation (black) and binary read-out (dashed) for different strip pitches as a function of the track impact angle - from simulation -



- Good resolution for inclined track is crucial in detector for large muon systems

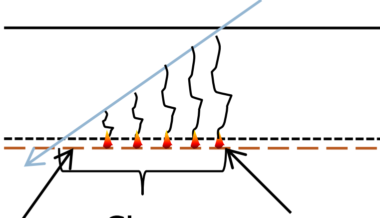
Micromegas as μ-TPC

- Measure arrival time of signals on strips and reconstruct space points in the drift gap ($y = V_D \cdot t$)
- Time resolution 10 ns results in a space point resolution of 50-100 μm along the drift direction:
  - σ_y = 50-100 μm
  - $\sigma_x = w/\sqrt{12}$ = 70 μm (w=250 μm)
- Requirements for μ-TPC mode:
  - Optimize drift gap
  - Optimize gas mixture (small diffusion, high V_D not needed)
  - Short peaking time O(few ns)
  - Moderate charge measurement (TOT or 8-10 bits ADC)



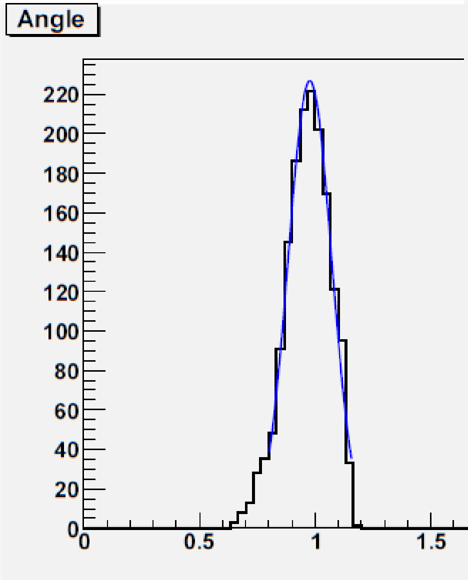
- Potentially solves the problem of degradation of spatial resolution for inclined tracks
- Local track direction advantageous for pattern recognition and track reconstruction
- Powerful tool for background rejection (tracks not coming from IP)
- Could be used in the L1 trigger (an on-chip local track reconstruction is needed)

Micromegas as μ-TPC



Feasibility checked with test-beam data

- Set-up not optimal
  - Long peaking time (200 ns)
  - Trigger time not available
    - Strip times referred to the time of the first fired strip
  - Chamber geometry (drift gap) & gas not optimized
  - Drift velocity from simulation (Magboltz), no calibration

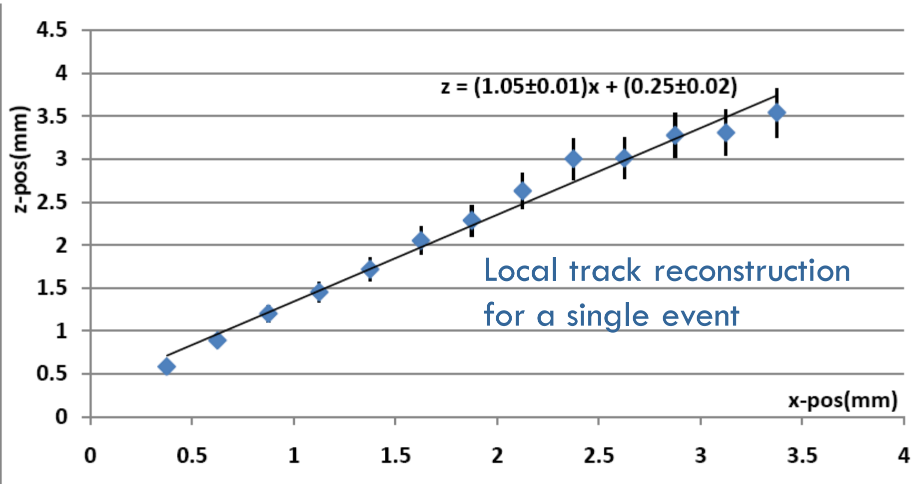


Reconstructed angle distribution

Resolution ~ 10%

θ_{meas} = (56.0±0.2)°

θ_{real} = (55±5)°



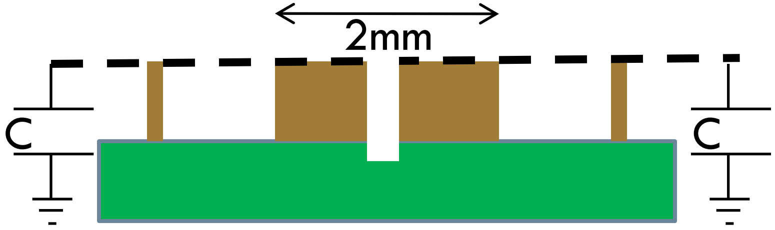
Local track reconstruction for a single event

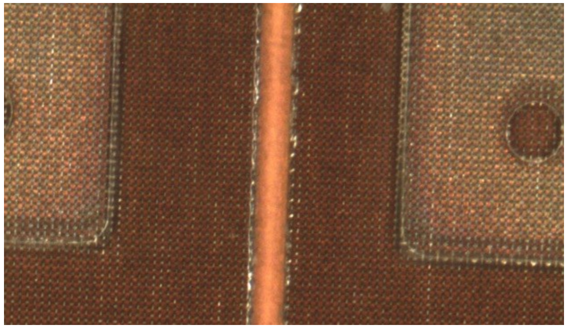
- Promising but challenging
- Application to other fields (e.g.: T2DM2 collaboration: Temporal Densitometry Tomography Measurement by Muons)

Going to large size

- Building a large detector from a small-size prototype is not a simple scaling exercise
  - Stable and reliable operation is needed for big experiments
  - Discharge energy must be minimized
    - Segmented mesh
    - Hybrid mesh
  - Breakdown probability must be kept at minimum
    - Double amplification stage
    - Resistive coverlay

Segmented mesh

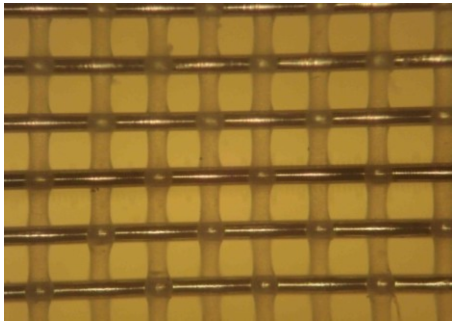




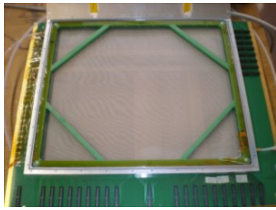
2 mm dead area (~1% if done any 20 cm)
Decoupled HV channels
Reduced capacitance
Reduced stored energy
Faster recovery time

Going to large size

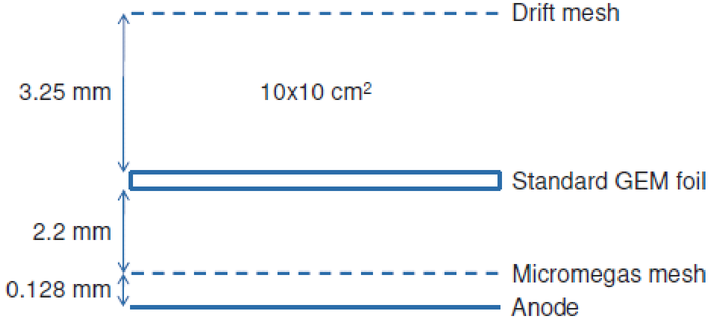
- Hybrid mesh
  - Attractive features:
    - Mesh segmentation w/o dead area
    - Read-out the mesh (group of wires)
    - Second coordinate measurement
    - Dedicate trigger read-out
  - Drawbacks:
    - Plastic wires inside the detector area
    - Charging-up
    - Ageing
- Double amplification stage
  - Split the amplification in two stages
  - Micromegas + GEM
  - Indication of lower spark probability wrt single Micromegas with same gain and gas (M. Villa)
  - Study very preliminary, better characterization needed



Unidirectional mesh: steel wires in one direction plastic in the other

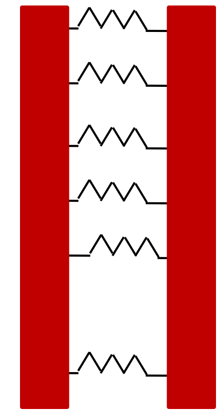


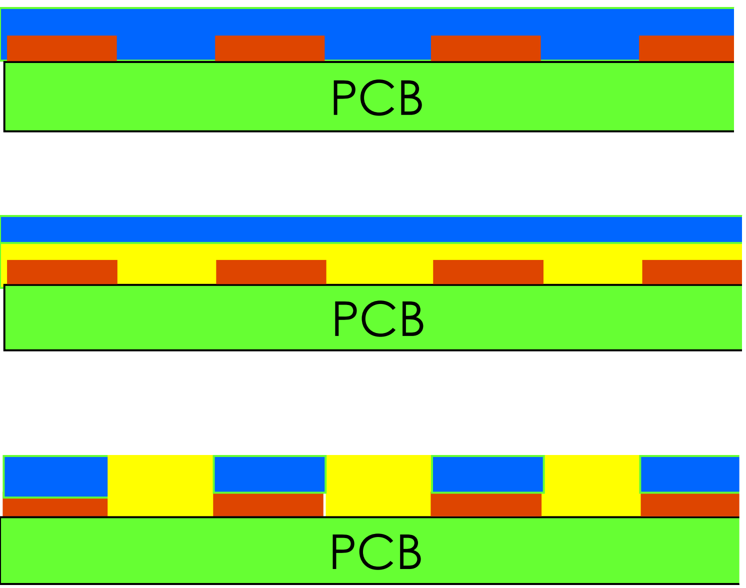
Discouraging results on the first prototype: charging up observed, low operating gain, detector design not optimal (wire diameter ~ amplification gap)
Put aside for the moment, could be re-considered in future (thinner mesh, new materials, resistive wires…)



Resistive layer

- The RPC reloaded: drastic reduction of spark probability

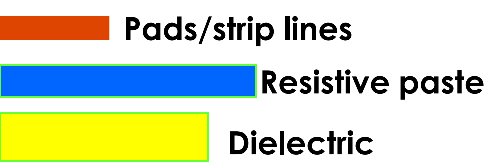




Not adequate for long strips: with $\rho = 1 M\Omega/cm^2$ two strips 50 cm long and 100 μm apart will be electrically coupled with a resistance of ~200Ω

Intermediate isolating layer (~$10^{11}\ \Omega/cm^2$)
Signal formation similar to TGC
Charge spread on a larger footprint
not optimal in μ-TPC mode

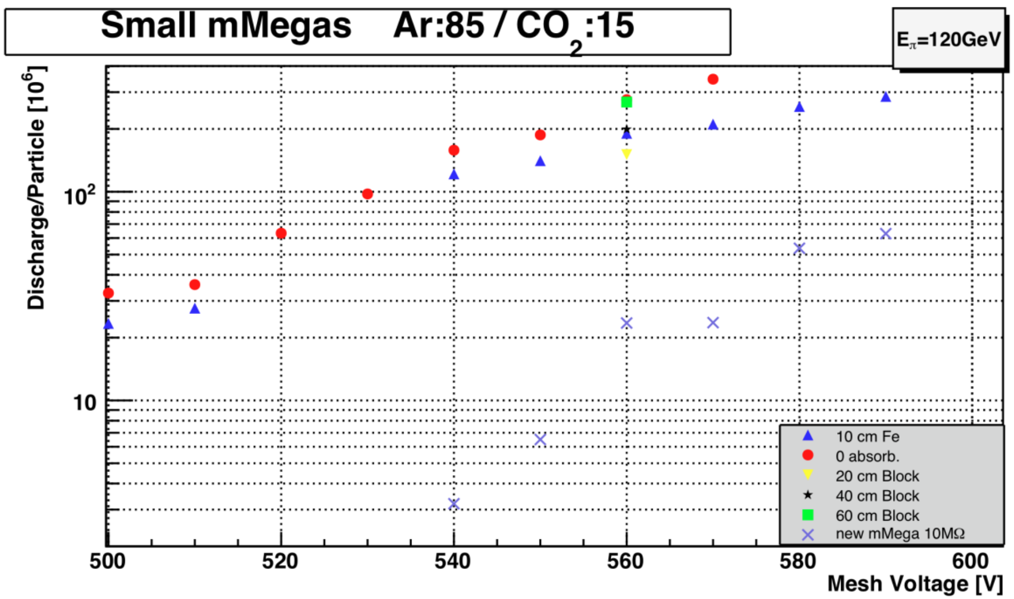
New technique currently under test

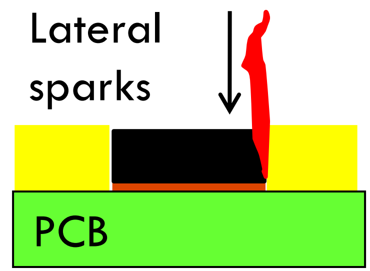


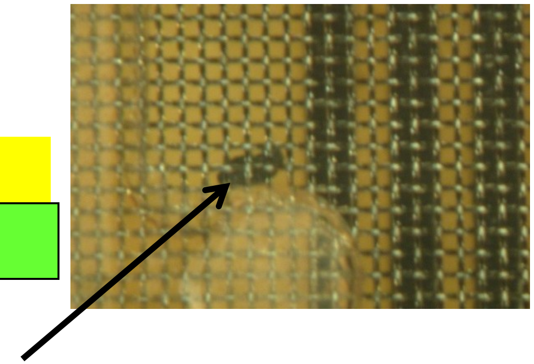
- Different materials & deposition techniques:
  - Resistive epoxy based polymers : any decade up to 1MΩ/□
  - Resistive polyimide based polymer : only a few values
  - Amorphous silicon
  - Deposition by: screen printing, painting, lamination

Resistive layers

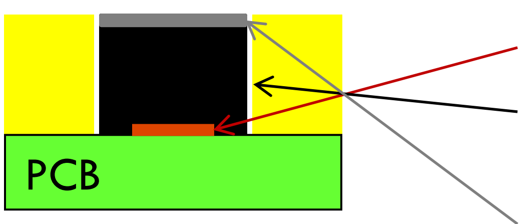
- Preliminary tests on small prototypes seems encouraging, but problems encountered (R. De Oliveira)







Resistive material pulled away



Proposed solution:

Strip embedded in the resistive paste

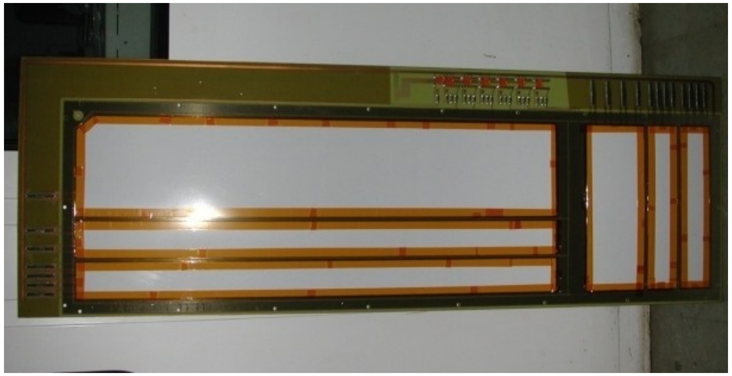
Doubling the thickness to prevent from material breakdown

Protection with metal hut

…start becoming very complex, to be studied

Toward the Full-scale chamber

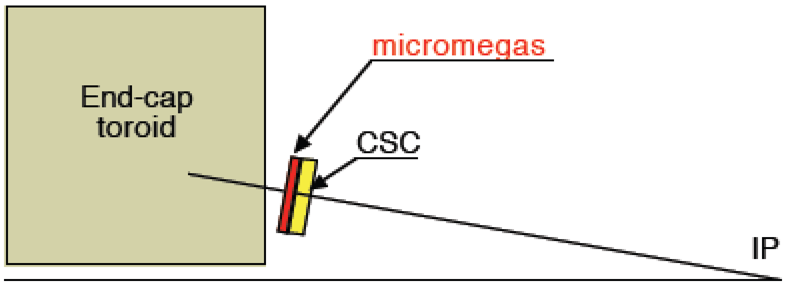
- Half-size prototype under construction at CERN (R. De Oliveira)
  - 400x1300 mm2 active area
  - Segmented mesh (6 regions)
  - Long strips ~100 cm
  - Short strips ~40 cm
  - Pitches: 250 µm -500 µm
  - Ready for next test-beam (mid. Nov.)
  - No resistive layer

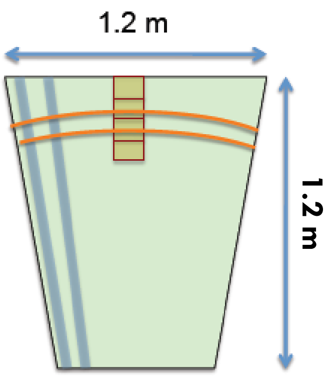


Implementation in ATLAS

- Phase I

Thin chambers to be added to CSC

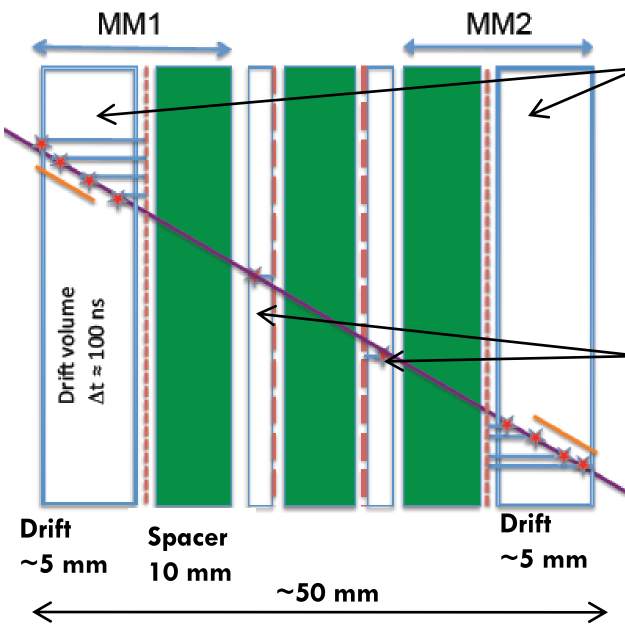




Strips for precision coordinate arranged circularly
Read-out for second coordinate shaped in strips or pads

Total number of chambers: 32
Total area ~100 m^2
Total n. of channels ~ 200 k

- Phase II



Two precision modules back-to-back to be used in u-TPC mode (out-of-time tracks not aligned)

Two modules for trigger and 2nd coordinate with thinner gap and large strips/pad

Total number of chambers ~280
Total area ~2000 m^2
Total n. of channels ~2 M

Summary

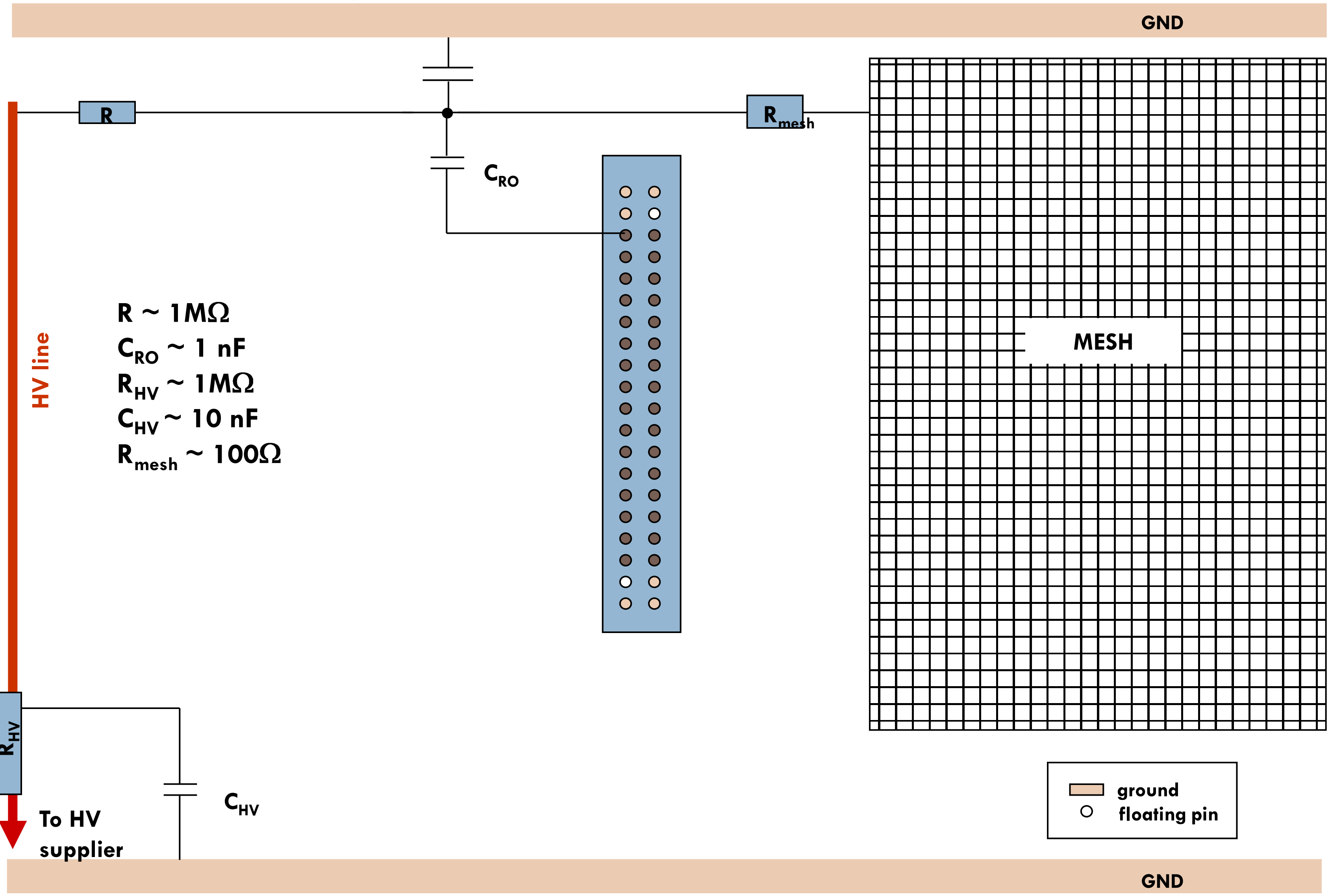
- LHC experiments employ a big variety of gas detector for covering many thousands of square meters
- Next generation (SLHC, ILC…) will extensively use Micro Pattern Gas Detectors to cope with the higher rates
- Micromegas have been proposed for the upgrade of the ATLAS muon Spectrometer
- A medium-size prototype has been built and tested with promising results and a half-size chamber (400x1300 mm^2) will be ready soon
- Still many things to do:
  - define chamber layout
  - high rate tests in neutron facility
  - ageing test
  - specify electronics and R/O system)

Conclusion

- Gaseous detectors have a glorious past, an prestigious present and a brilliant future
- Let's wait…
  - …1 month for the LHC re-start
  - …1 year for the performance of the ATLAS detector
  - …10 years for the upgrade of ATLAS
  - …1 century to see which progress the gaseous detector development will reserve to us!

Back-up slides

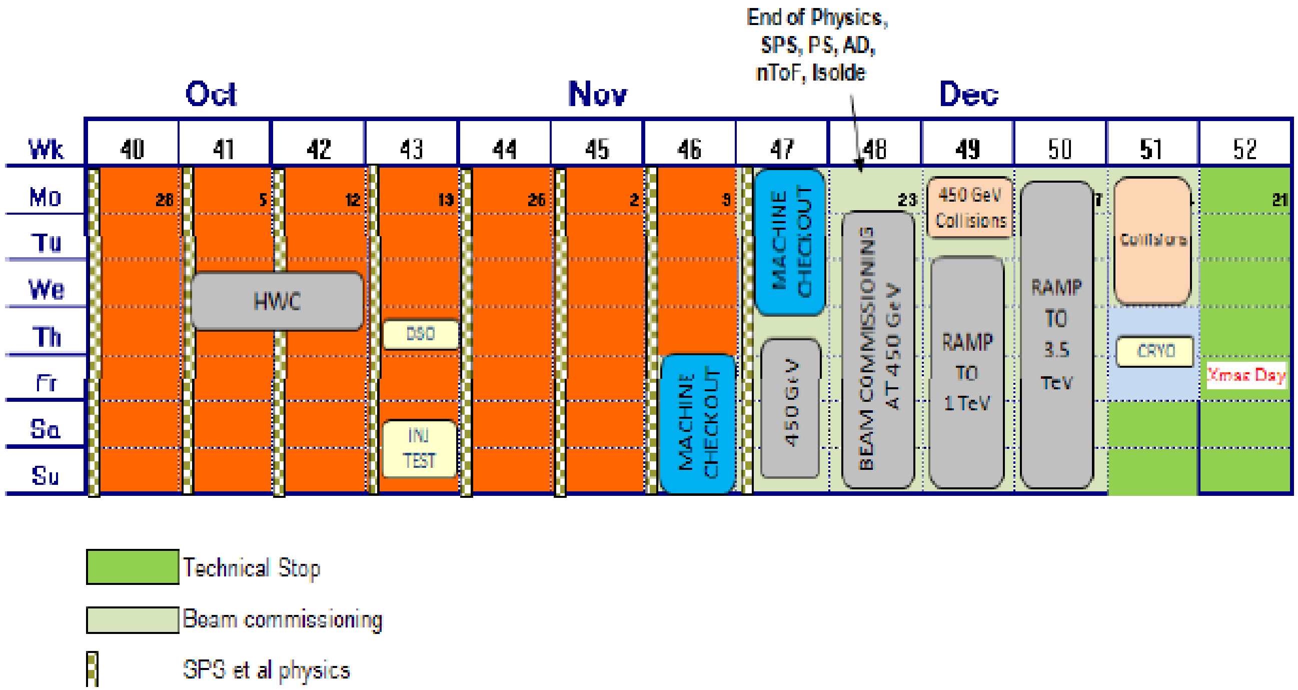
Homogeneous mesh read-out and HV distribution



$R \sim 1M\Omega$
$C_{RO} \sim 1$ nF
$R_{HV} \sim 1M\Omega$
$C_{HV} \sim 10$ nF
$R_{mesh} \sim 100\Omega$

LHC schedule - 2009

- S. Mayer 06.10.2009

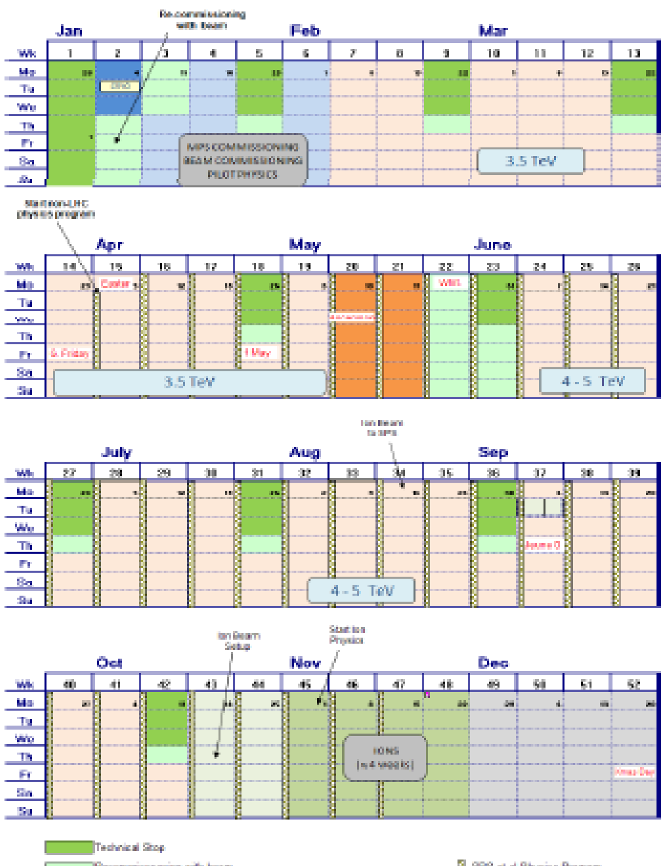


- All dates approximate…
- Reasonable machine availability assumed

LHC schedule – 2010-2012

- S. Mayer 06.10.2009

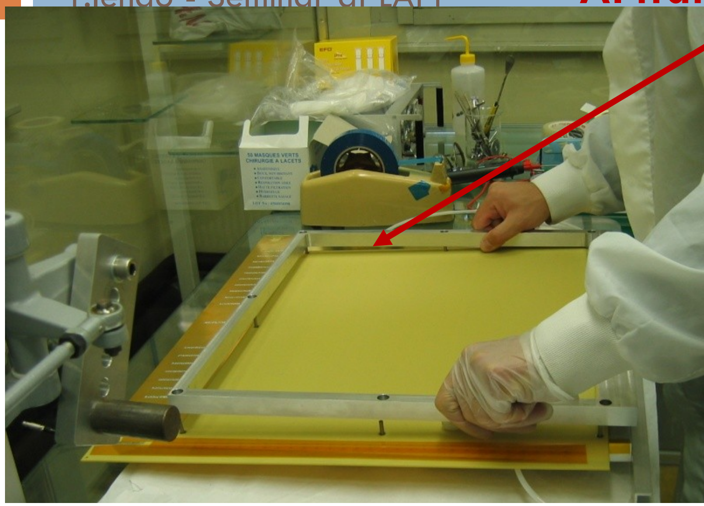
LHC 2010 – very draft

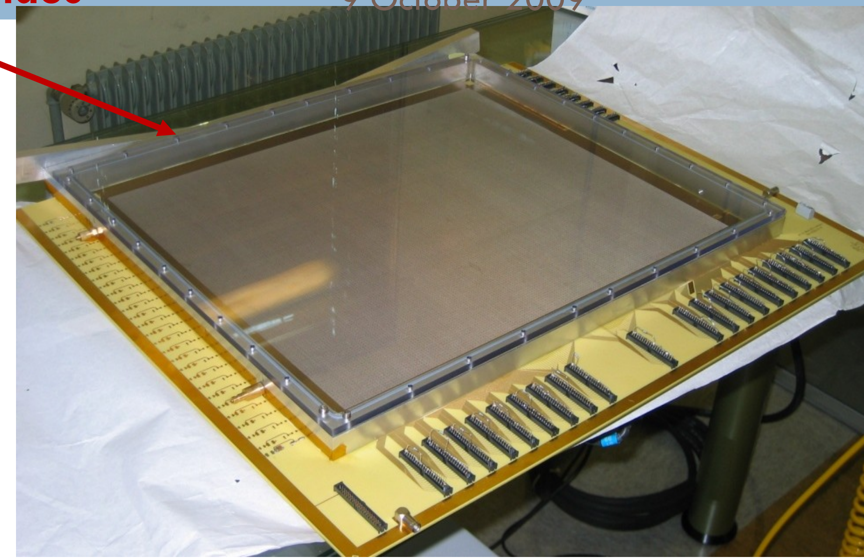


- 2009:
  - 1 month commissioning
- 2010:
  - 1 month pilot & commissioning
  - 3 month 3.5 TeV
  - 1 month step-up
  - 5 month 4 - 5 TeV
  - 1 month ions

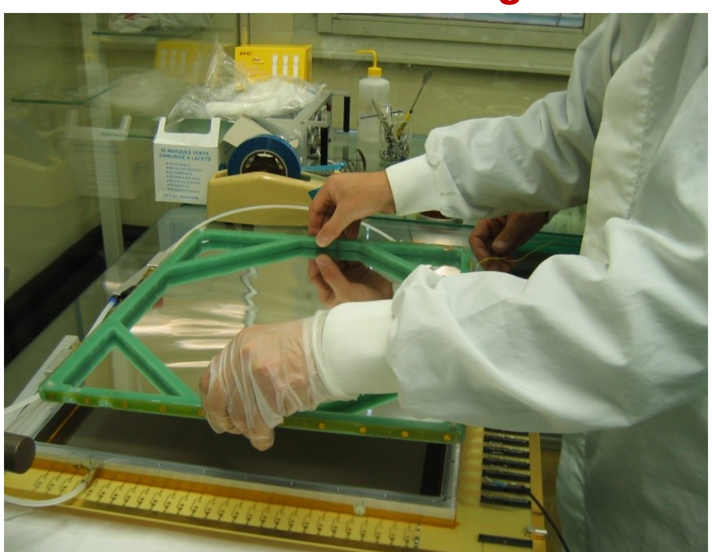
Prototype assembling

Al frame on both sides





Cathode mounting



Assembled chamber