Micromegas Detectors for the Muon Spectrometer Upgrade of the ATLAS Experiment

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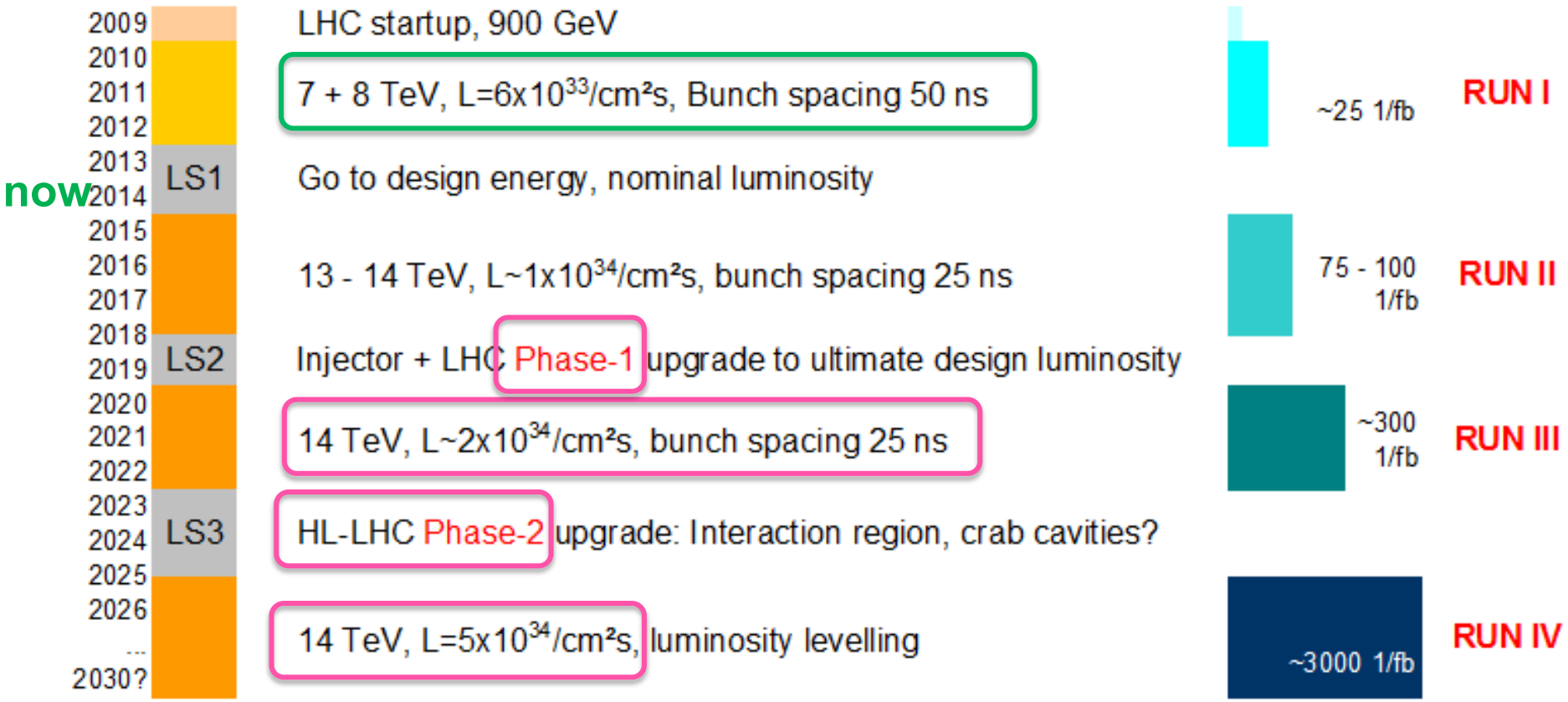
OUTLINE

- LHC and ATLAS Upgrade program
- Detectors in the present Small Wheel and Motivations for the New Small Wheel
- NSW chamber technology and challenges

- Micromegas
  - History and detector breakthroughs
  - ATLAS Micromegas Design
  - Construction
  - Prototypes, tests
  - Test-beam and Performance Studies

- Conclusions

LHC and ATLAS Upgrade Program



ATLAS:

- Phase-0 Upgrade: Consolidation + Insertable B-Layer (IBL) in LS1
- Phase-1 Upgrade: New Small Wheels, LAR Calo + TDAQ upgrade, Fast Track Trig.
- Phase-2 Upgrade: New Inner Tracker

The ATLAS Detector

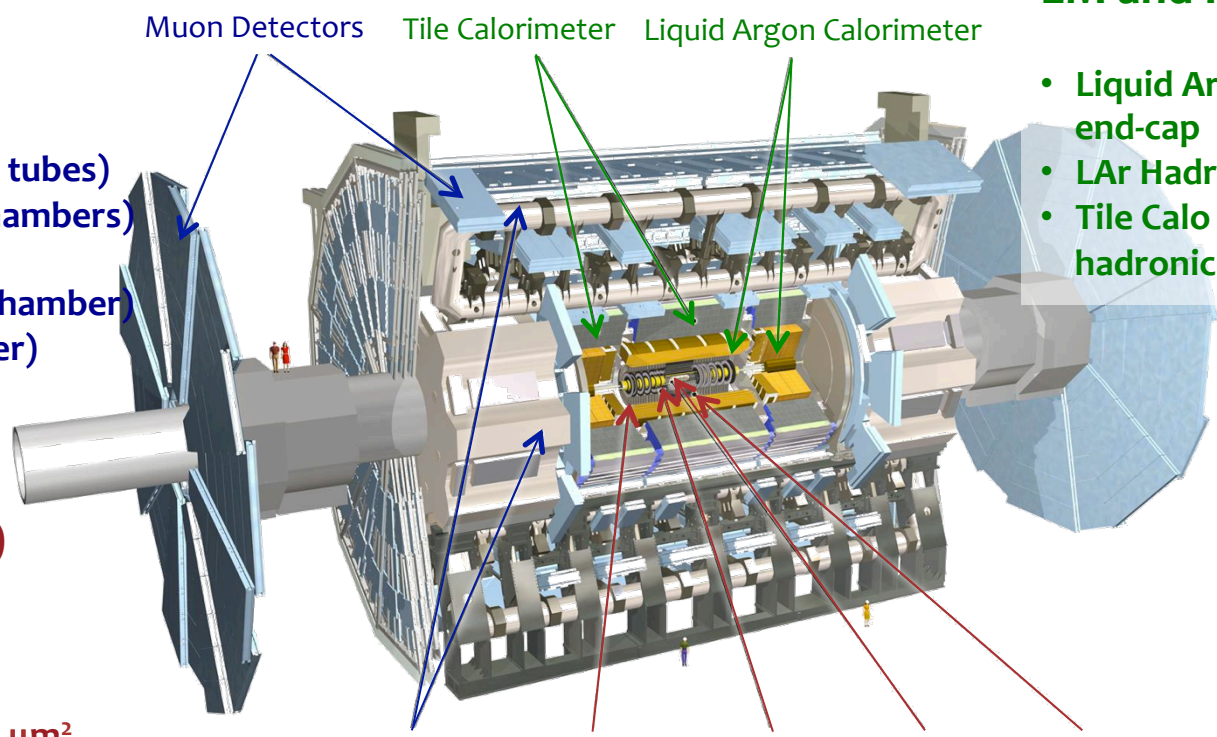
Muon spectrometer
μ Tracking
Toroid Magnet

Precision Tracking:
- MDT (Monitored drift tubes)
- CSC (Cathode Strip Chambers)

Trigger:
- RPC (Resistive Plate Chamber)
- TGC (Thin Gas Chamber)

Calorimeter system
EM and Hadronic energy

- Liquid Ar (LAr) EM barrel and end-cap
- LAr Hadronic end-cap
- Tile Calo (Fe–scintillator) hadronic barrel



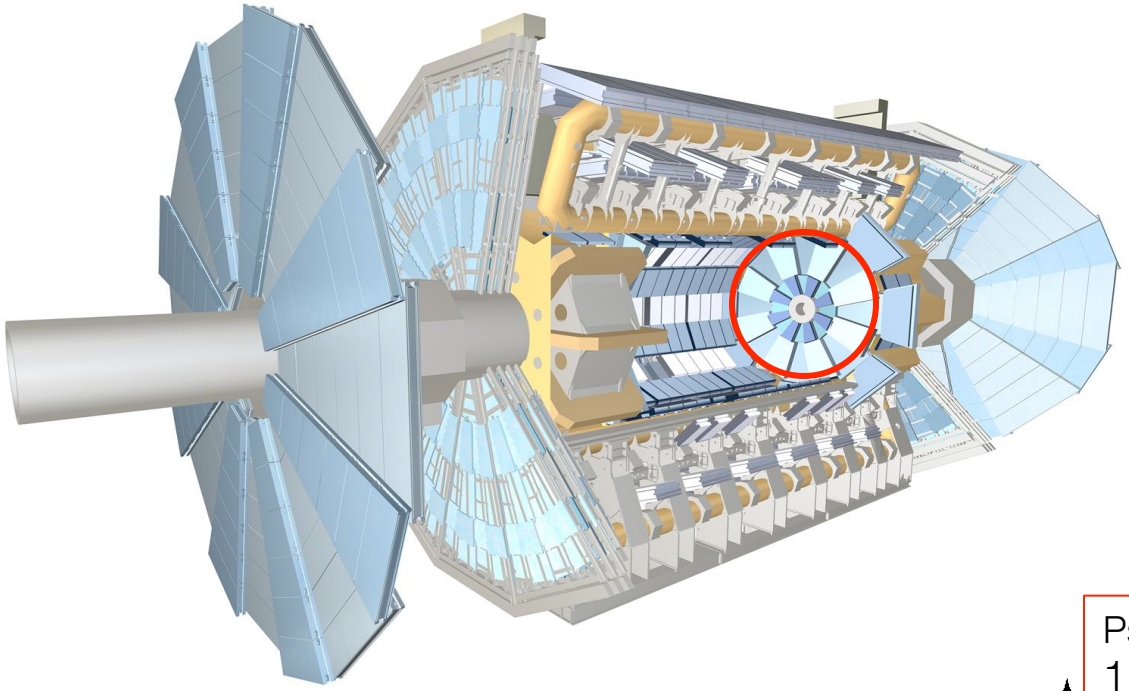
Inner Detector (ID)
Tracking
2T Solenoid Magnet

- Silicon Pixels 50 x 400 μm²
- Silicon Strips (SCT) 80 μm stereo
- Transition Radiation Tracker (TRT) up to 36 points/track

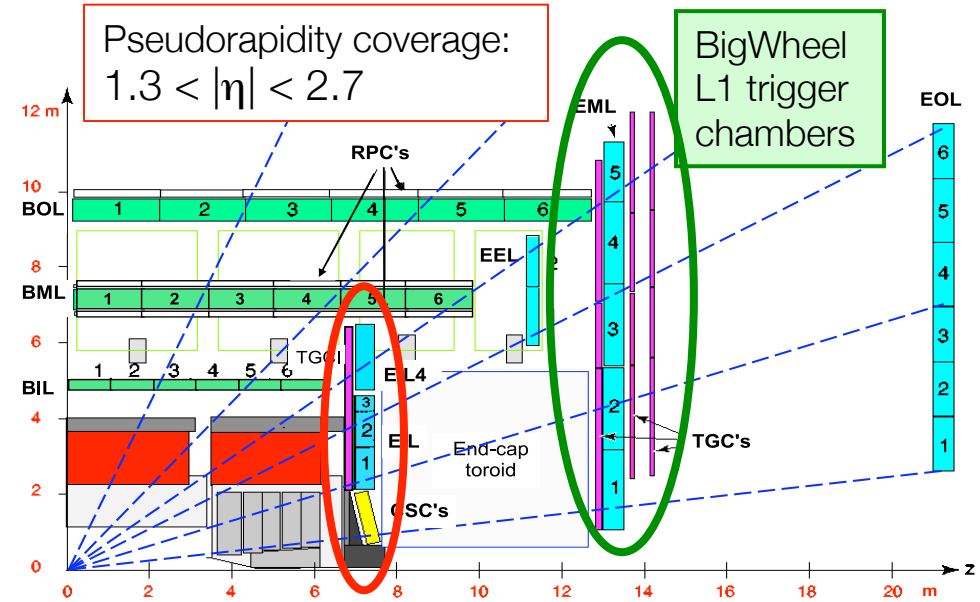
3 Level Trigger system

- L1 – hardware – 100 kHz 2.5 μs latency
- L2 – software – 3-4 kHz 10 ms latency
- EF – software – 100 Hz 1-2 s latency

The ATLAS Muon Spectrometer – the (New) Small Wheel



- The Small Wheel (Innermost Endcap Muon Station) is the region with highest background rates in the present ATLAS Muon Spectrometer
- The present system is based on Cathode Strip Chambers (CSCs), Monitored Drift Tubes (MDTs) and TGC for particle tracking
- Located between endcap calorimeter and endcap toroid

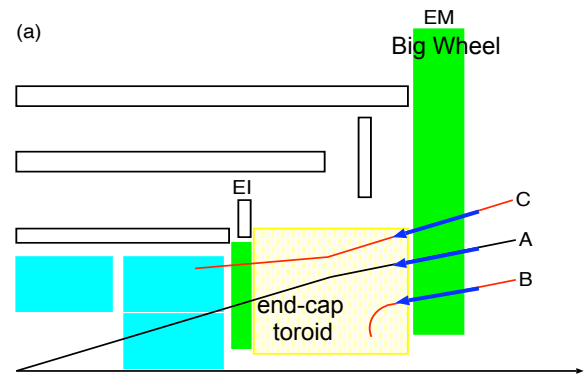


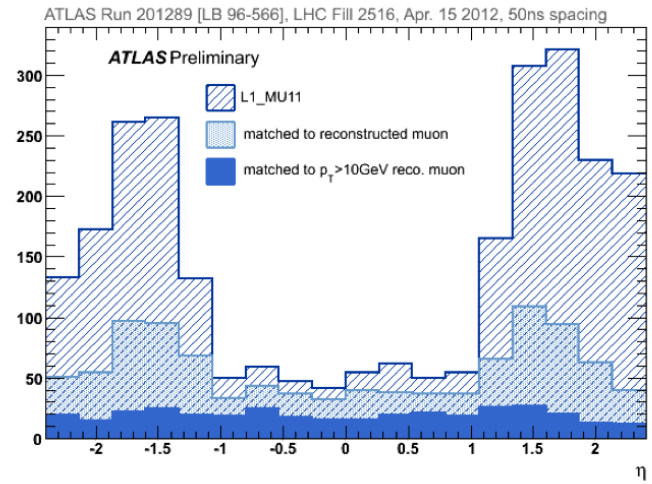
New Small Wheel – Motivations: TRIGGER

Consequences of luminosity rising beyond design values for forward muon wheels

- Present Muon L1 trigger in the EndCap relies on the Big Wheel station only: Calculating a track angle/vector and extrapolating to IP
- The Level1 Trigger rate in the EC is dominated by fake triggers
- At a 3 x 10^{34} $cm^{-2}s^{-1}$ L1MU20 (p_T>20 GeV) rate is estimated ~60 kHz, exceeding the available bandwidth (~15kHz for muons)

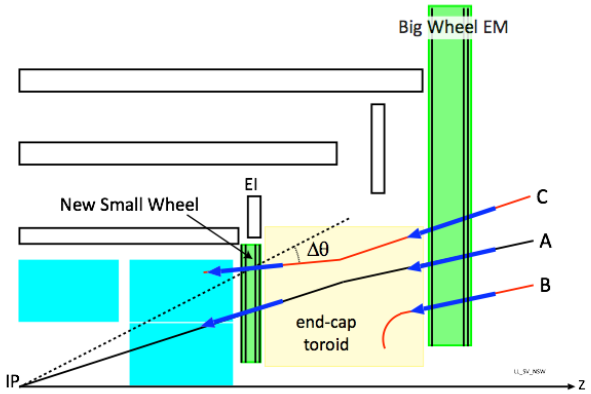
Present Level1 muon trigger





Cannot distinguish cases A (real high-pt track), B (low-pt particle created in the toroid area) and C (multiple scattering)

Upgrade L1 with NSW



Replace the Muon Small Wheels with the New Small Wheels

- Can filter out fake tracks by being able to reconstruct track vector/ direction also in the endcap inner (EI) station

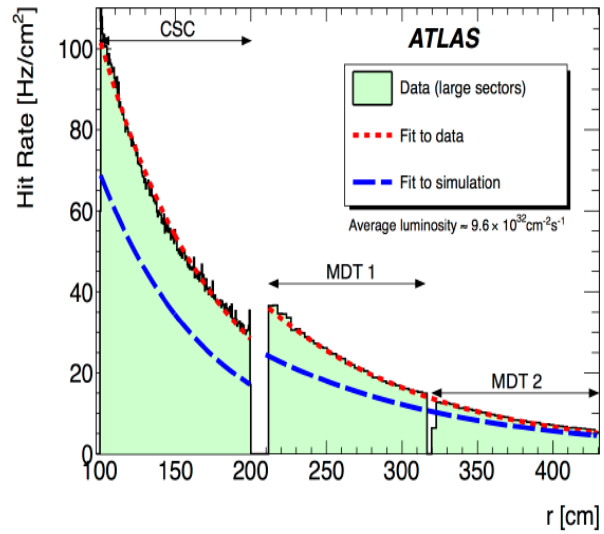
→ Extend L1 trigger coverage to η = 2.6 with angular resolution of 1 mrad

NEW SMALL WHEEL – MOTIVATIONS: TRACKING

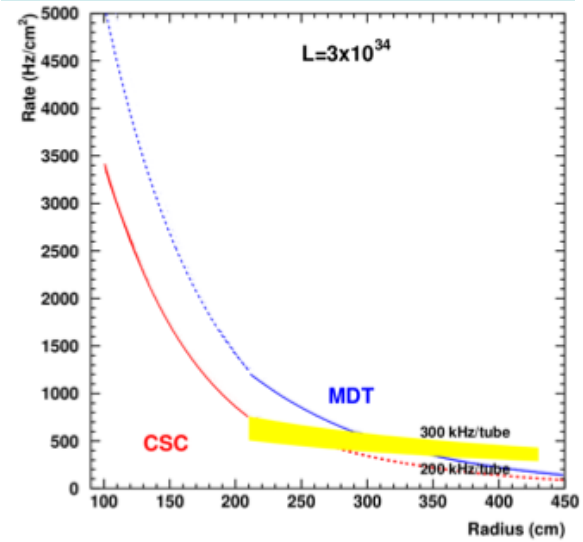
Cavern Background

- Measured hit rates in the Endcap Inner (Small Wheel) and extrapolated to $3x10^{34}$ cm^{-2} s^{-1}
- At $5x10^{34}$ cm^{-2} s^{-1} (luminosity of HL-LHC) the maximum expected rate in the NSW is about 15 kHz/cm^2 (>5 MHz/MDT_tube) (incl. Safety factor of 1.5)

Measured hit rates @ 10^{33} cm^{-2} s^{-1}

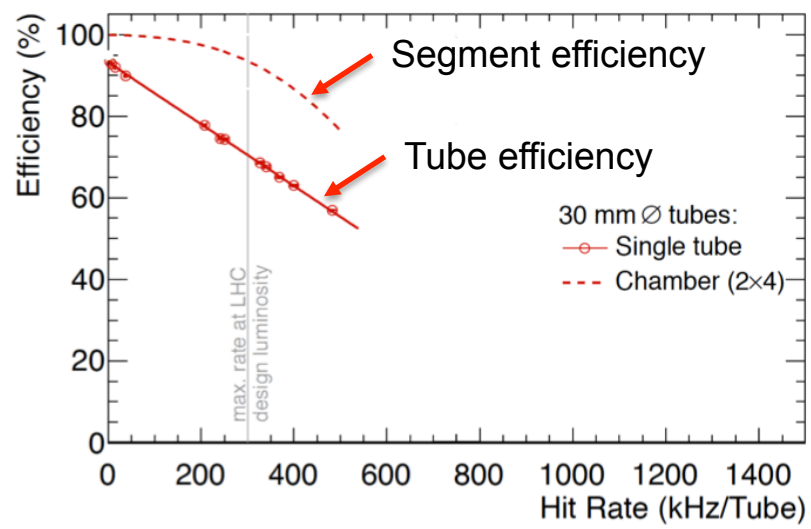


Expected rates @ $3x10^{34}$ cm^{-2} s^{-1}



Efficiencies and resolutions

- Above 300 kHz/tube the MDT efficiency drops significantly due to dead time from background hits
- Limit for CSCs is reached even earlier, due to only 4 detection layers (instead of 6 for MDT)
- MDT Resolution degradation due to gain loss caused by space charge



Detectors Choice for the New Small Wheels

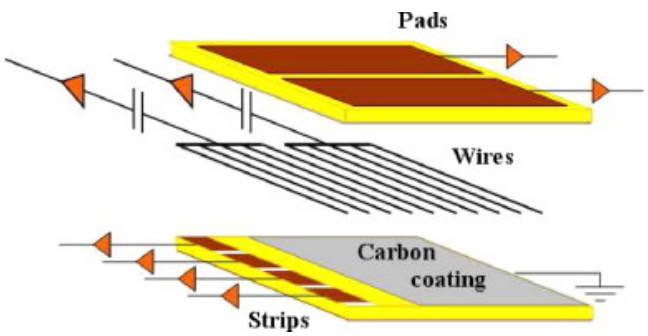
Combination of sTGC and MicroMegas (MM) multiplets: 4+4+4+4 detector planes

***sTGC** (small strip TGC) primary trigger detector*

- Bunch iD with good timing resolution
- Good online space resolution for NSW track vector with <1 mrad angle resolution

***MicroMegas (MM)** primary precision tracker*

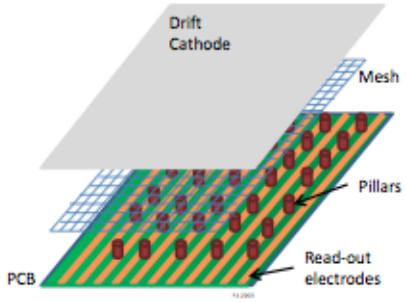
- Good Space resolution ~100 μm, independent of angle
- Good track separation (0.4 mm readout granularity)
- Provide also online segments for trigger

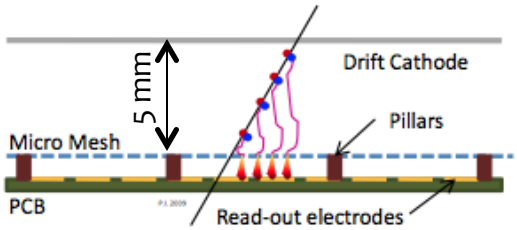


(a) a

***sTGC** (strip pitch 3.2 mm)*

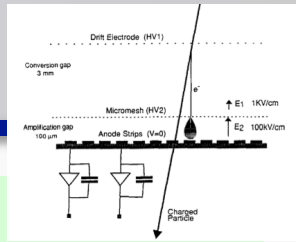
MM (strip pitch ~ 0.4 mm)

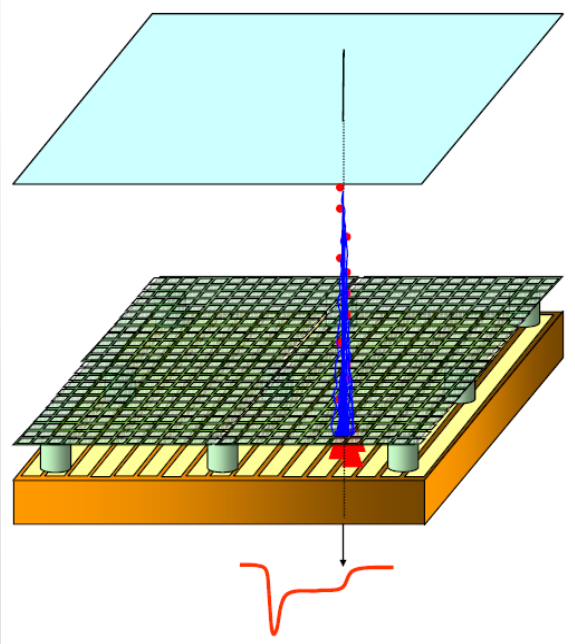




- Common front-end ASIC: VMM under development at BNL. First prototype tested on detector at beam test in 2012; new version soon available for tests
- Work together to make a robust detector for the high rate region of very limited access
- **The NSW will operate from <u>2019 until 2032</u> → ROBUSTNESS and REDUNDANCY**

MICROMEGAS: THE HISTORY – BIRTH



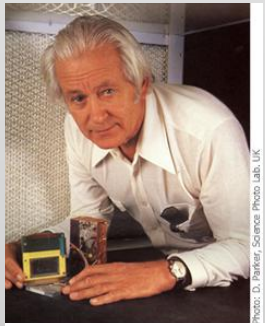


Micromegas (MICRO-MEsh GASeous Structure)

Belongs to the family of Micro-Pattern Gas Detector (MPGD), the gaseous detector family born in the 1988 with the Micro-Strip Gas Chamber (A. Oed).

MM are parallel-plate chambers where the amplification (up to 10^5) takes place in a thin gap, separated from the conversion region by a fine metallic micro-mesh, supported by ~100 μm high insulating pillars.

Charge is collected on the anode readout board, generally realized with suitable segmented standard PCB.

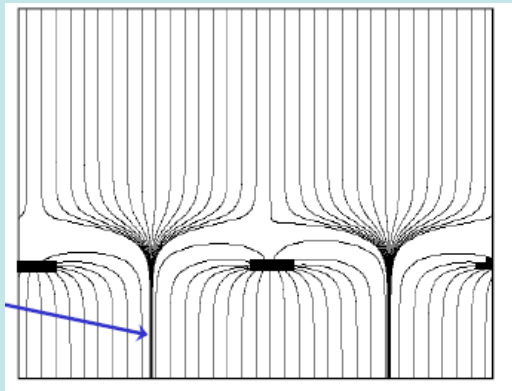


Y.Giomataris,
Ph.Rebourgeard,
JP Robert
and G. Charpak,
NIM A 376 **(1996)** 29-35

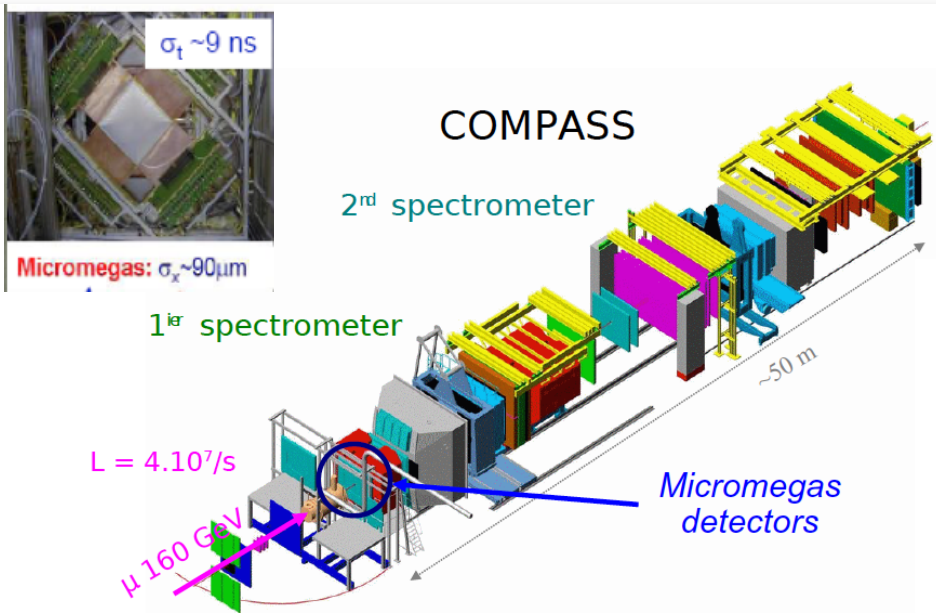
"….our detector combines most of the qualities required for a high-rate position-sensitive particle detector: excellent resolution can be obtained with fine strips printed on a thin G10 substrate or a thin kapton foil."

Funnel field lines → electron transparency very close to 1

Small gap → fast evacuation of the positive ions (~100 ns)



MICROMEGAS: THE HISTORY – FIRST USE IN HEP

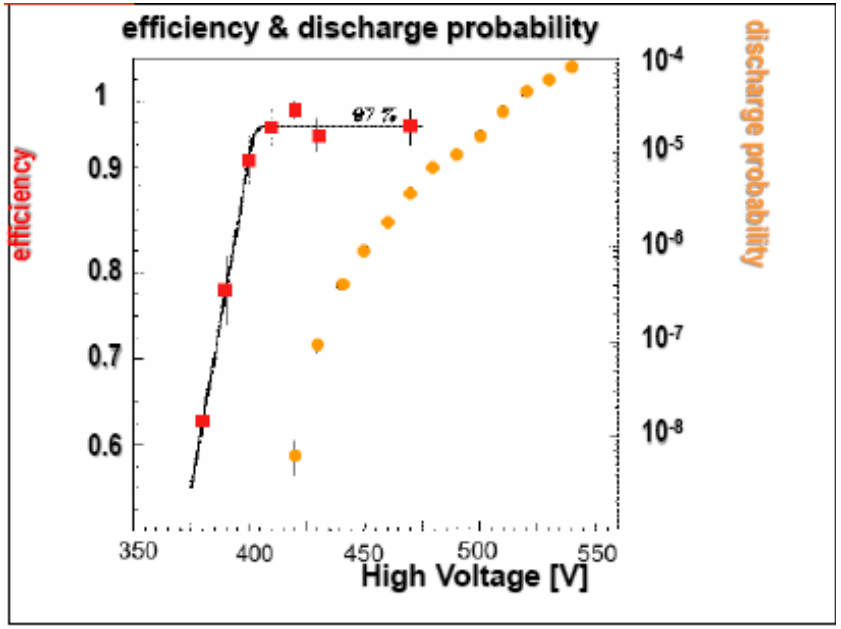


The first use of MMs in a large scale HEP experiment was in COMPASS in 2001:

twelve 40x40 cm^2 MMs, developed by the CEA-Saclay group were installed in the tracking system of COMPASS

- The greatest "enemy" of MMs was the discharges with high flux of high ionizing particles (hadrons) → sparks between mesh and strips → inefficiency + aging

→ The main limitation for very large diffusion of Micromegas



MICROMEGAS: THE HISTORY – BULK MICROMEGAS

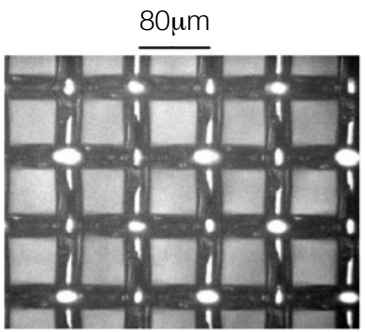
Mesh at very small distance from the cathode (~100 μm)

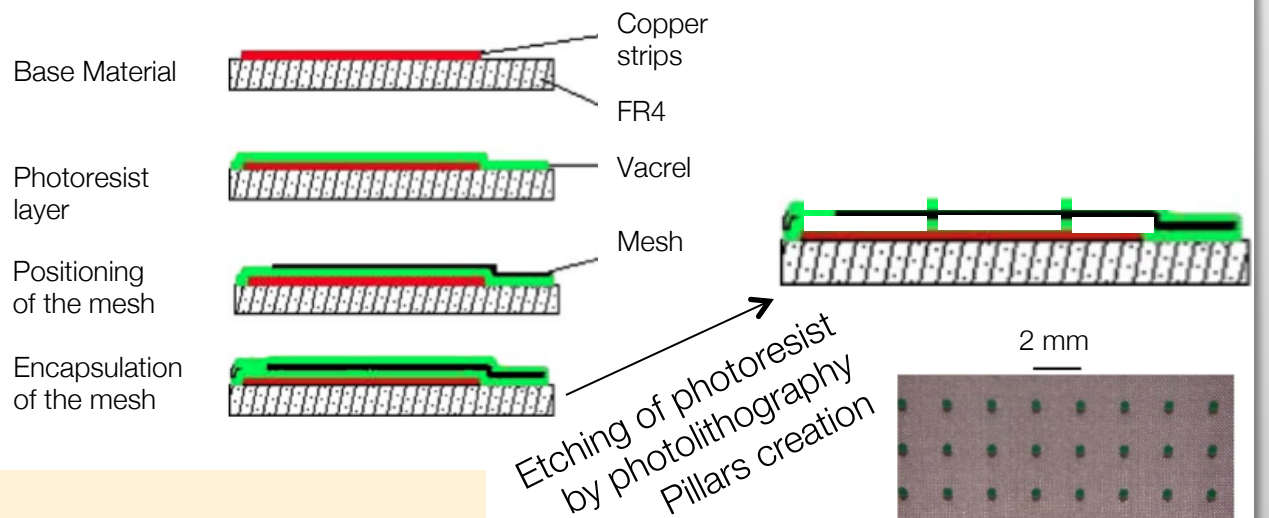
- Issue of very small variation in distance → Gain uniformity
- Very stringent mechanical requirements

→ BULK Micromegas (I.Giomataris, et a. NIMA 560(2006)405) :

- A simple process based on the Printed Circuit Board (PCB) technology.
- could be extended to "large" area detectors made by the industry.
- The low cost fabrication and robustness

woven wire mesh, instead of the usual electroformed micromesh





Limitation of bulk MM:

PCB Industries → limited to 60 cm wide manufacturing

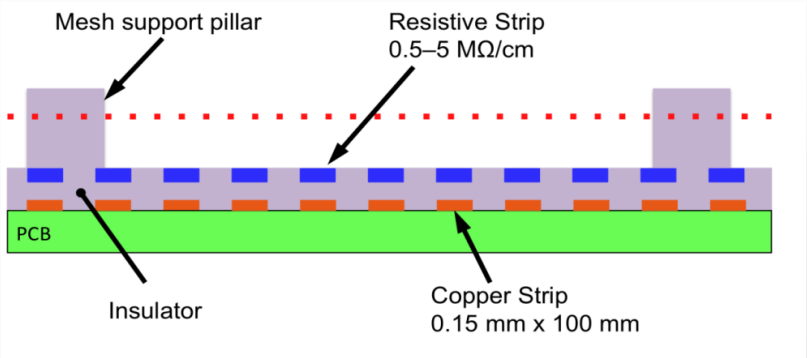
MICROMEGAS: REQUIREMENTS FOR ATLAS

ATLAS Needs	Requirements for the Micromegas. NEEDS for IMPROVEMENTS
Size: several m^2	– New construction/assembly concept starting from the 40x40 cm^2 size to 2-3 m^2 – Overcome the limit of 60cm wide PCB manufacturing (abandon bulk MM)
Environment: particle fluence dominated by n, γ, hadrons (few real muon tracks)	Ageing
Rates: up to 15 kHz/cm^2 in the hottest region in HL-LHC	High Rate capability
Precision Tracking independent from the angle of the track	Position resolution < 100 μm (and mechanical precision – see slide 19)
Trigger capability	Angular resolution (~1 mrad in a multilayer system)

→ *Several years of developments and tests at CERN in the context of the ATLAS Upgrade*

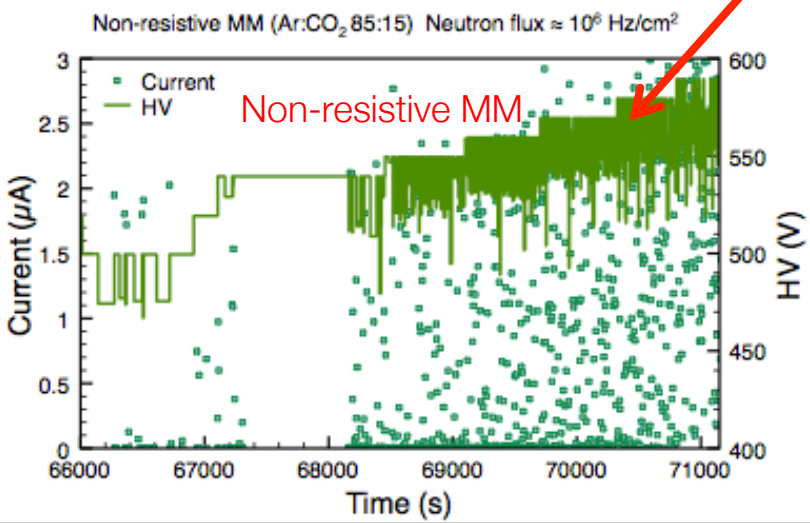
Technology Breakthrough: The Resistive Micromegas

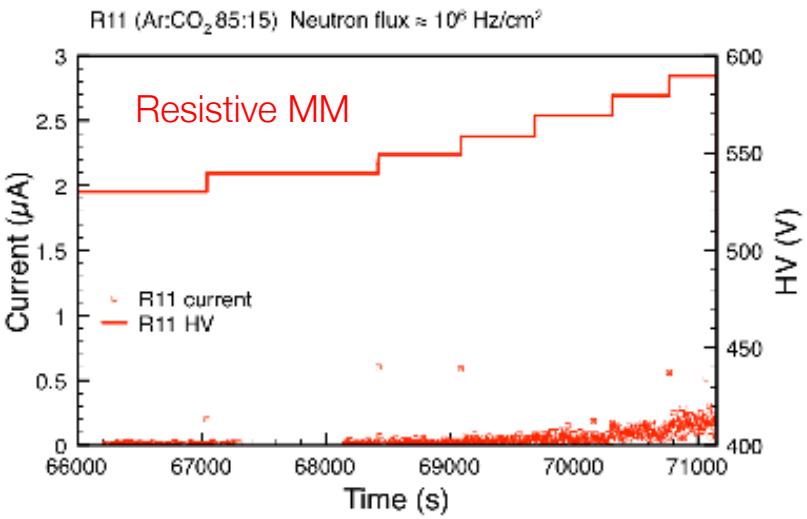
- The discharge problem has been overcome with the implementation of a layer of resistive strips facing the amplification gap.
- In case of spark, the electric field locally drops down damping the discharge



In MMs the resistive layer is realized as resistive strips capacitively coupled with the copper readout strips.

voltage drop due to sparking



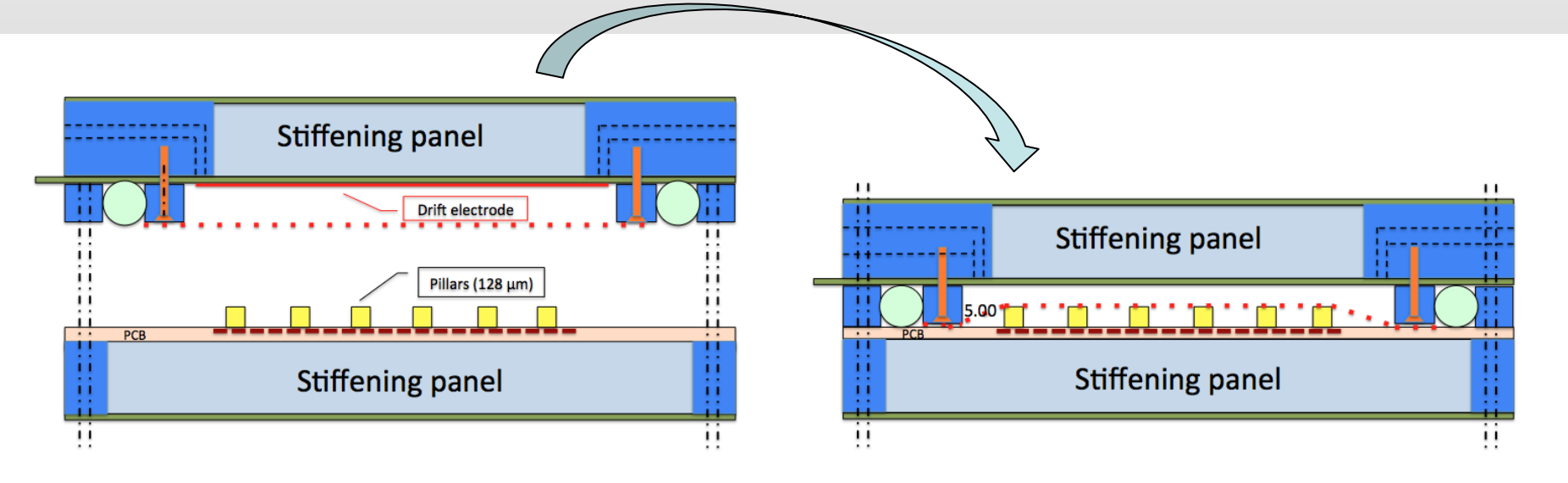


T.Alexopoulos et al. "A spark-resistant bulk-micromegas chamber for high-rate applications" NIM A 640 (2011) 110

ATLAS Micromegas Design

Decoupling of the mesh from the readout plane (no bulk micromegas)
→ essential for reliable construction for large-dimension detectors

- In the ATLAS MMs the mesh is integrated in the Drift electrode, while pillars are realized on the anode readout PCB.
- Closing the detector the mesh is "pushed" on the pillars that guarantee its distance (128 μm high) from the anode, thus defining the amplification gap.
- The conversion/drift gap is 5 mm wide. The gas tightness is ensured by an O-ring.



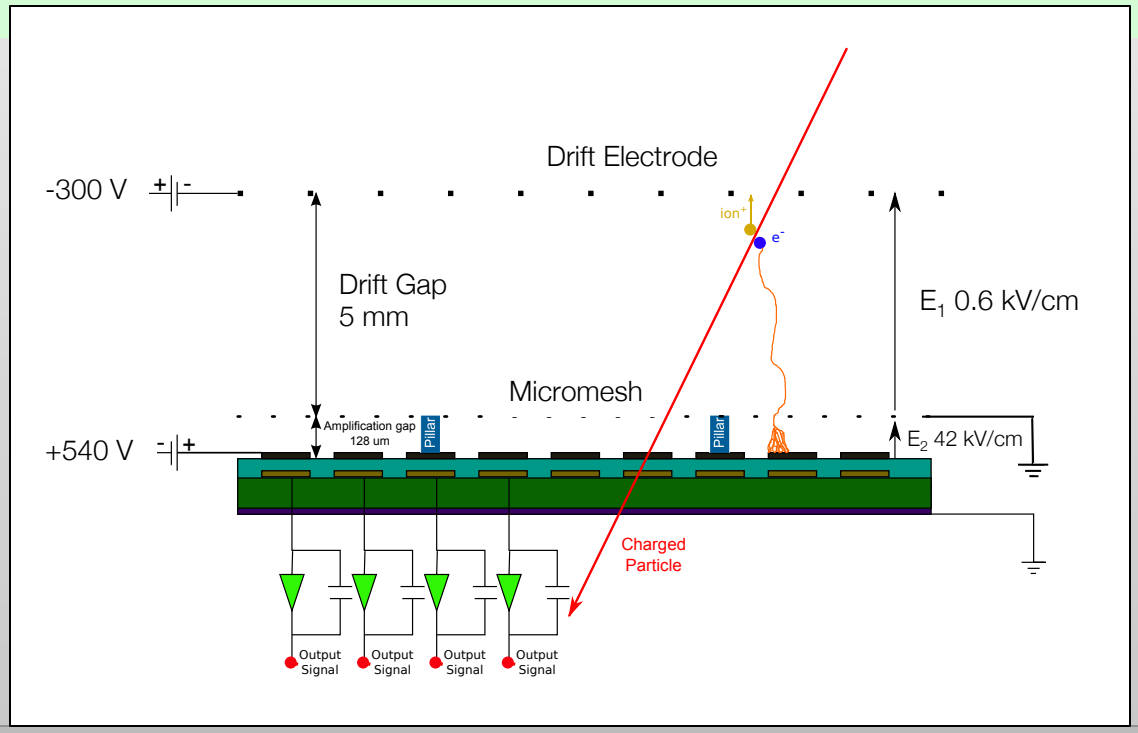
ATLAS Micromegas Configuration

High Voltage Configuration:

First resistive MM had the cathode at ~ -800 V, mesh at ~ -500 V, Strips at ground

MESH AT GROUND ("Inverted HV scheme")

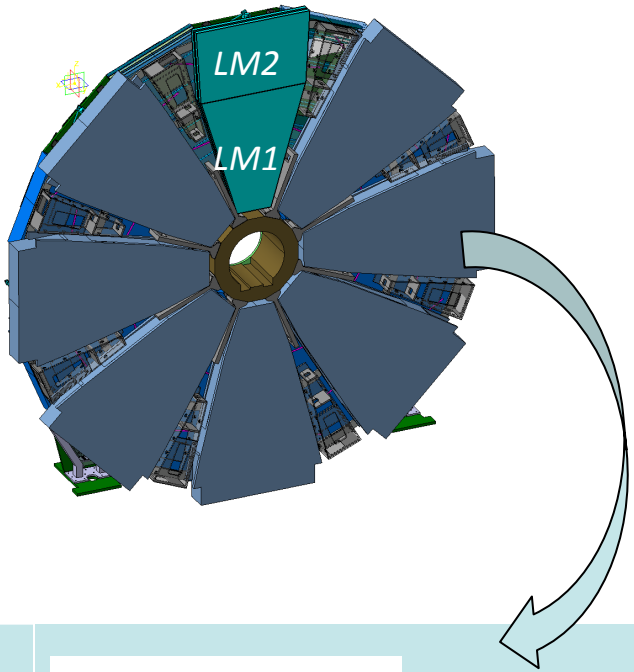
- Allows the segmentation of the HV on the anode plane
- Easier from construction point of view (no insulation needed between the mesh and the supporting metallic frames)
- More stable operation of the detector (good ground, better electrostatic configuration between mesh and resistive strips)



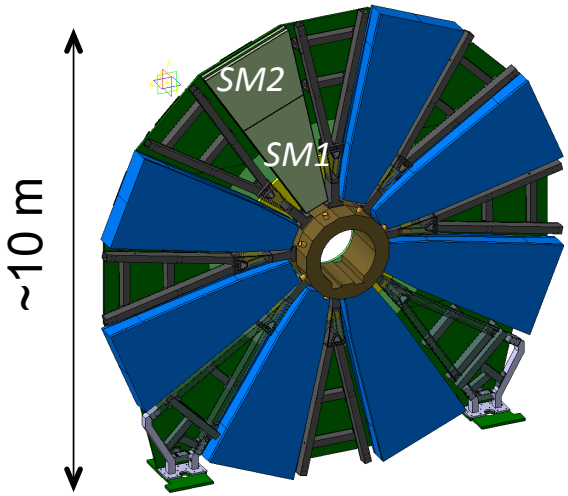
The Layout of the New Small Wheel

16 Sectors:
8 Small
8 Large

MM Large Sector



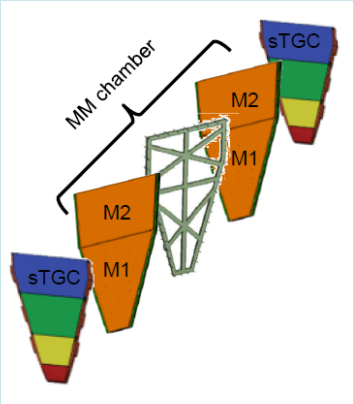
MM Small Sector

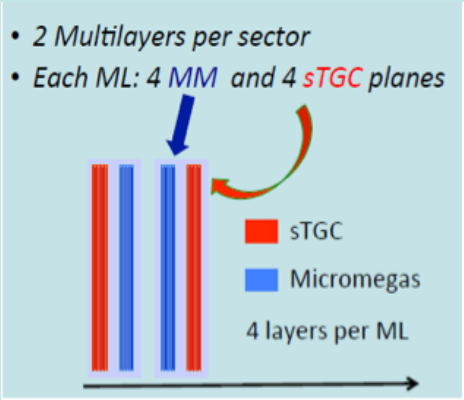


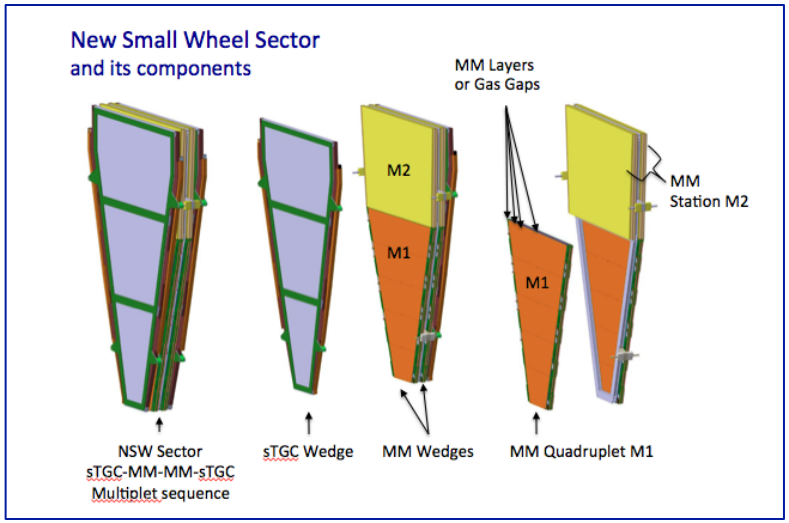
Non-IP side: Large sectors, covering area from r = 92 cm to 465 cm

IP side: Small sectors, covering area from r = 90 cm to 445 cm

Sectors: Package of sTGC and MicroMegas "wedges" + central spacer frame

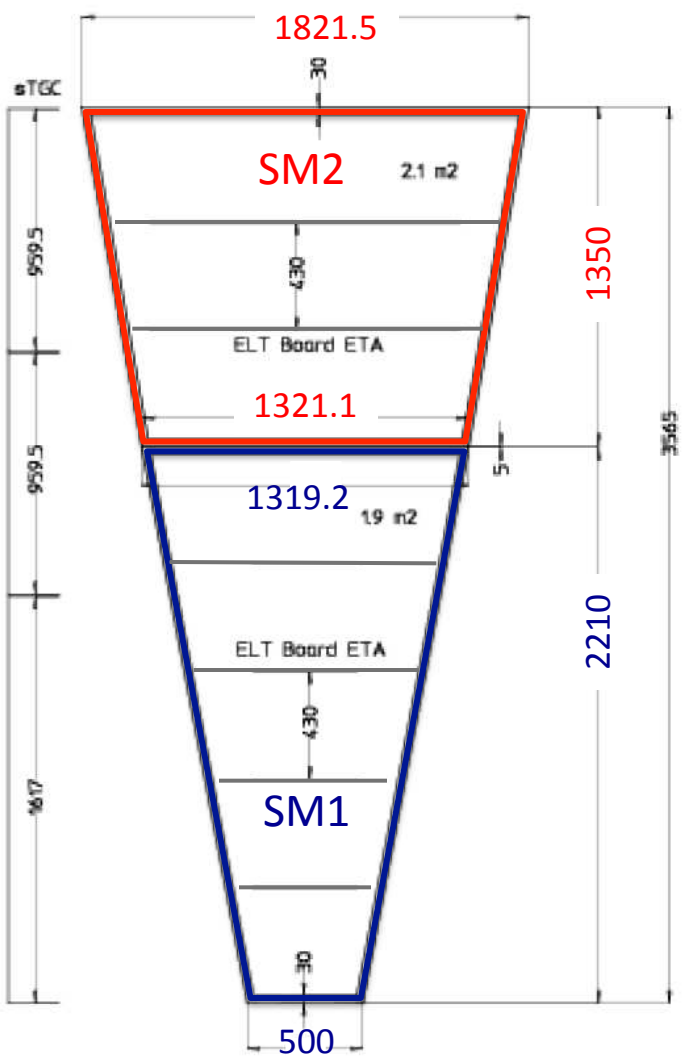




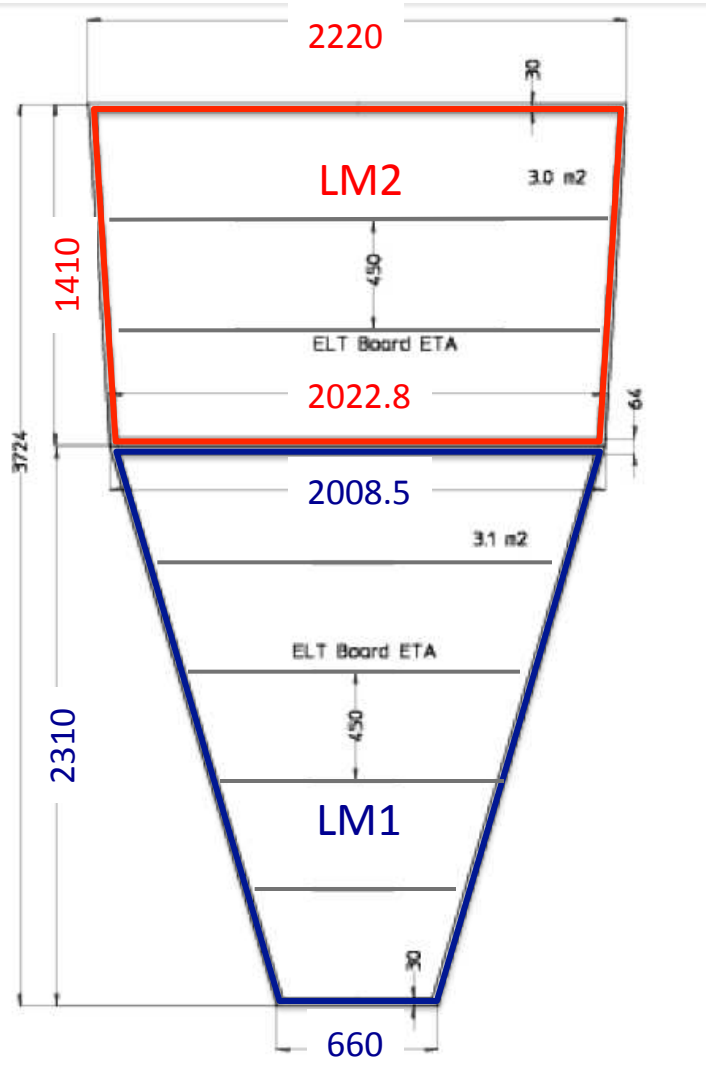


Micromegas Wedge Segmentation

Small sector modules



Large sector modules



Radial segmentation in 2 chambers per wedge

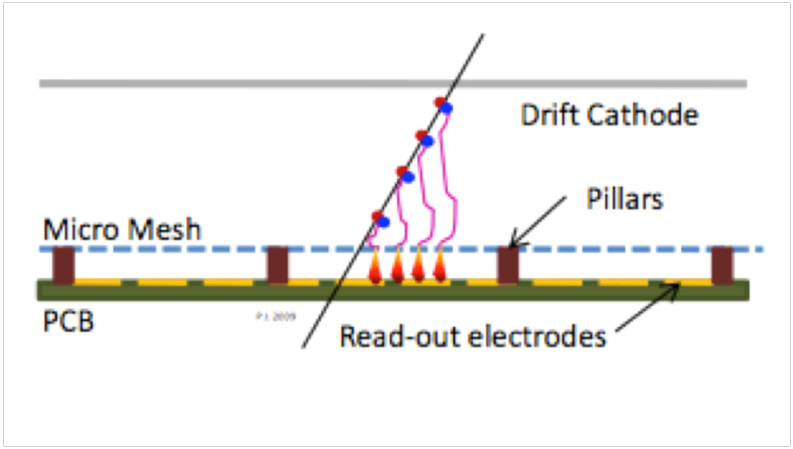
Construction Sites:

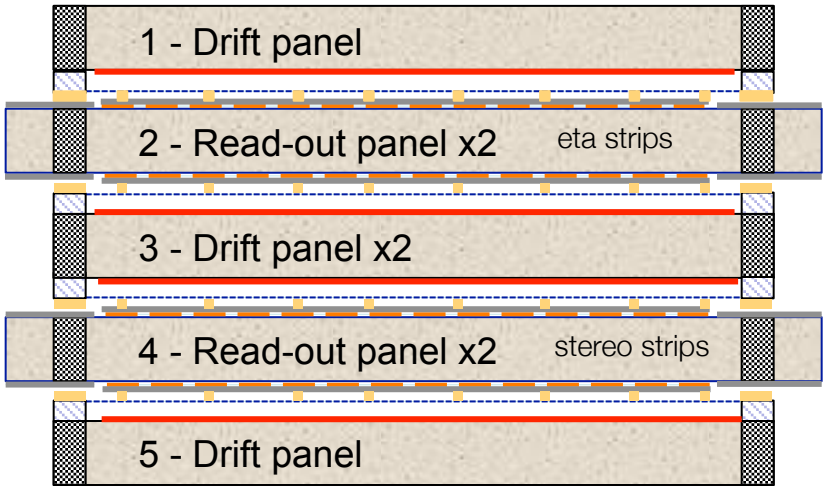
- SM1: Italy/INFN (Pavia, Rome1, Rome3, Frascati, Lecce, Cosenza, Napoli)
- SM2: Germany – Munich, Freiburg, Wurzburg, Mainz
- LM1: Saclay
- LM2: Thessaloniki + Dubna (+ CERN)

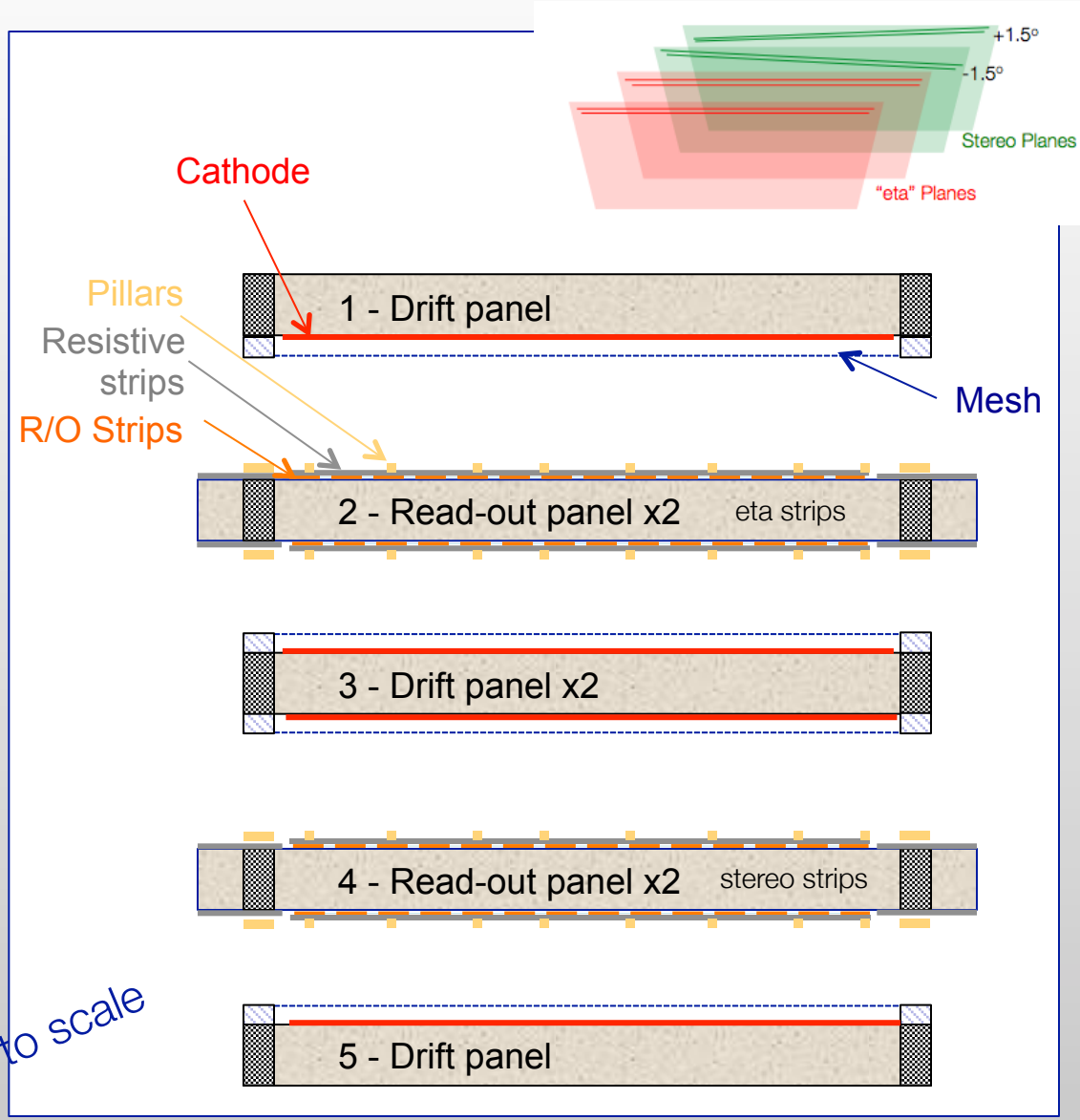
Radial segmentation of R/O PCB per plane

- SM1 and LM1: 5 PCBs
- SM2 and LM2: 3 PCBs

MM Quadruplet Configuration – a simplified sketch







Micromegas Construction – Mechanical Precision

Requirements for the precision in the construction of any NSW chamber in order to reach a momentum resolution of 15% at 1 TeV in ATLAS:

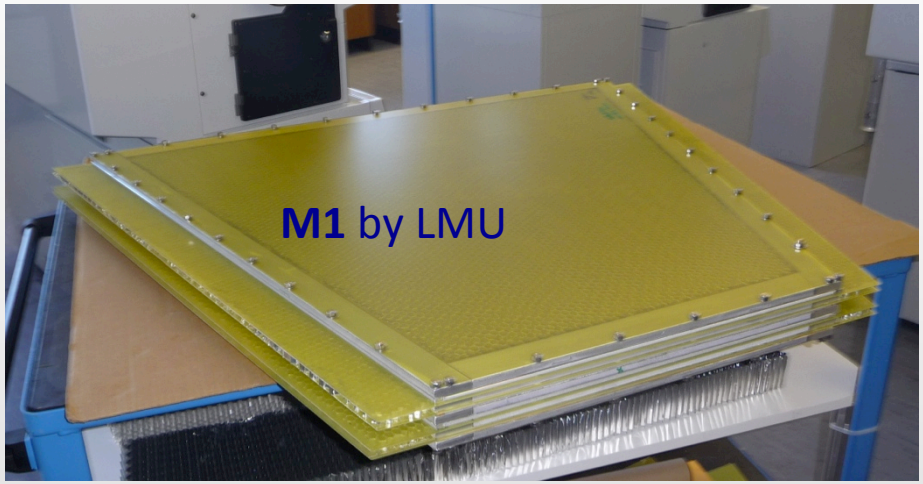
- "For every detector plane, the position along the precision coordinate should be known with an RMS error of less than 30 μm".
- "The position of any chamber element on the coordinate perpendicular to the above precision coordinate should be known with an RMS error of less than 80 μm"

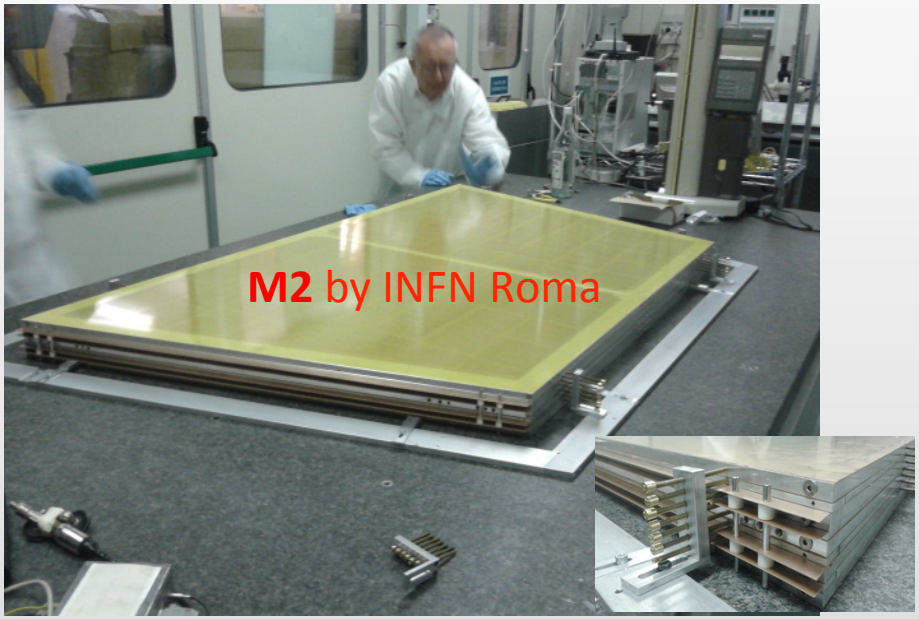
…THE MECHANICAL PRECISION IS A VERY BIG CHALLENGE !

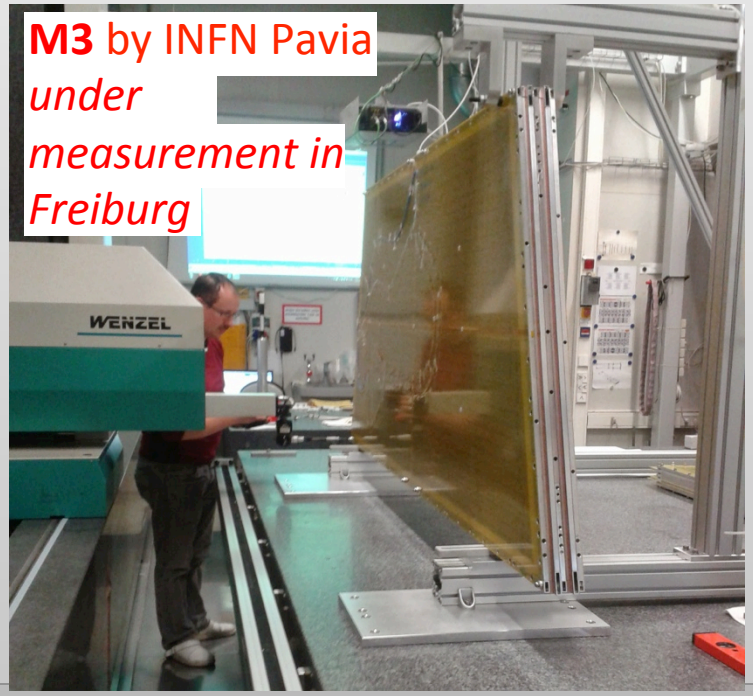
→ Chamber Construction: Prototypes, Experience, Status

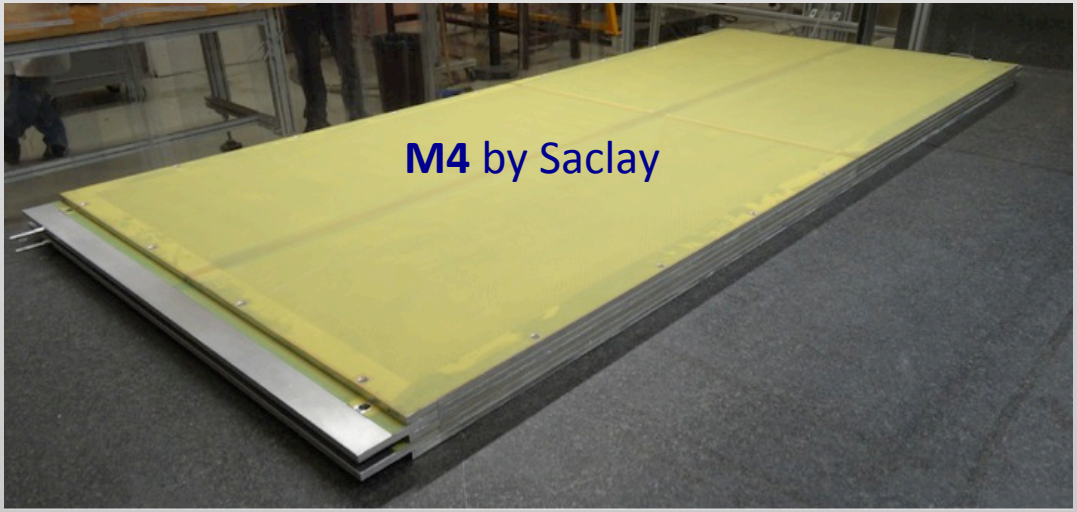
- Mechanical Prototypes
- Operational Prototypes
- First Micromegas Quadruplet with ATLAS Configuration

Micromegas Construction – Mechanical Prototypes





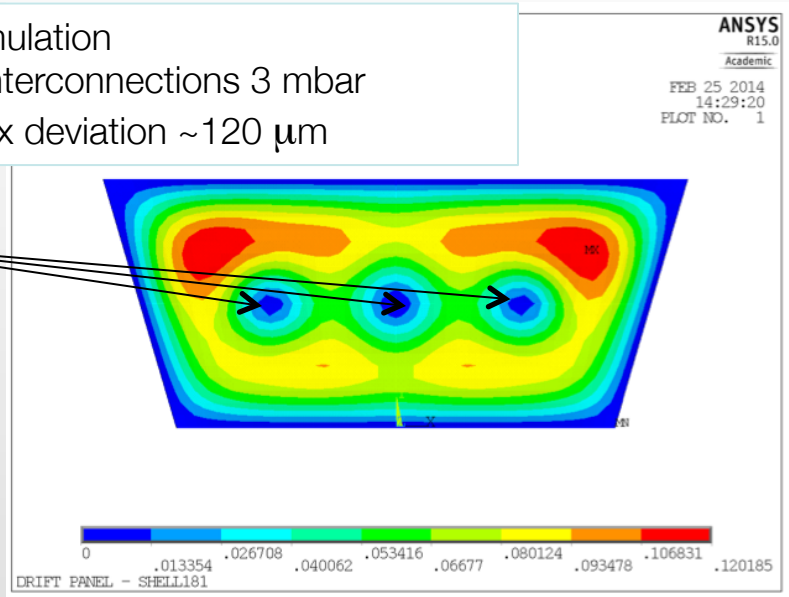


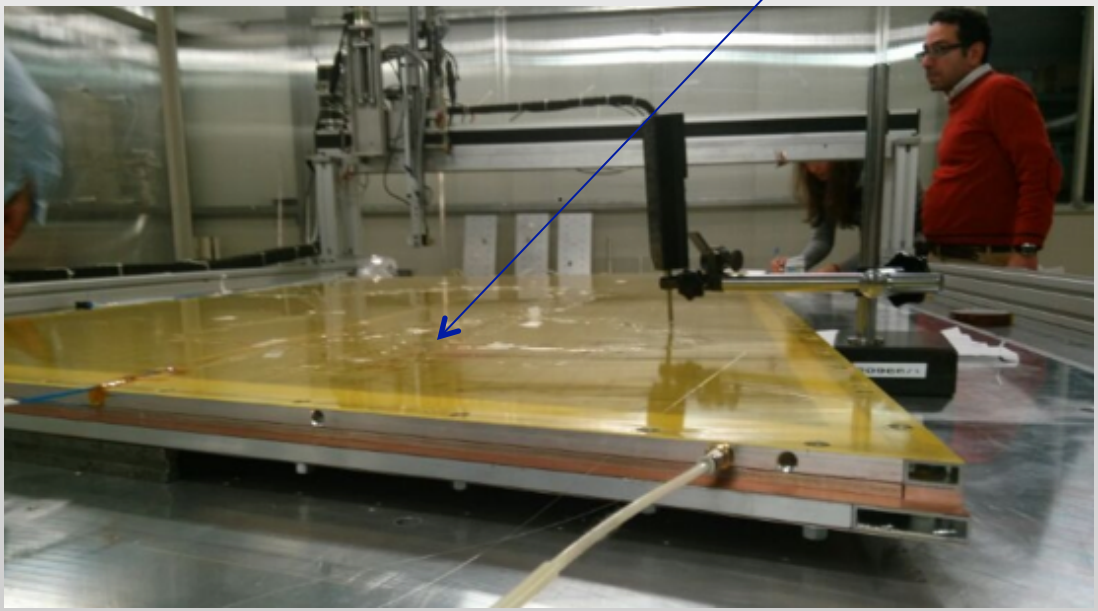


Gas Overpressure Induced Deformations

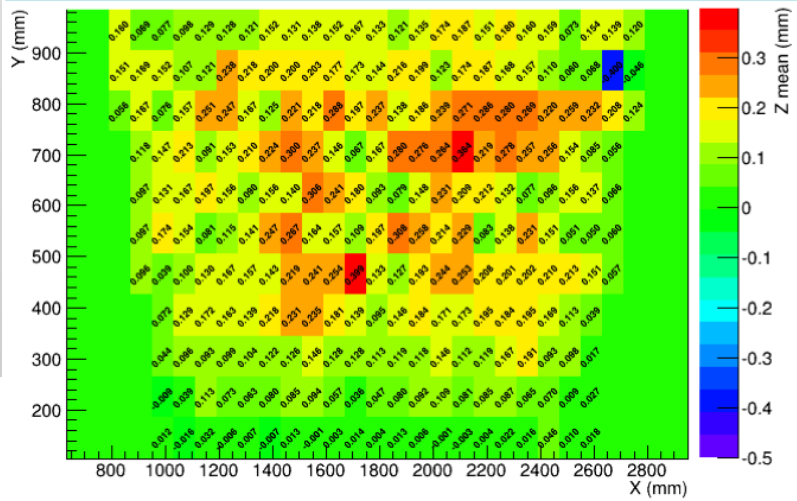
- The effect of Gas over pressure has been tested using a Single Gap with Mesh.
- Deformation mitigation with INTERCONNECTION SCREWS (3 screws used)
- Mechanical deformations due to Gas over pressure (3 mbar) have been studied using, Laser and Optical Fibers (Fiber Bragg Grating)

Simulation
3 interconnections 3 mbar
Max deviation ~120 μm





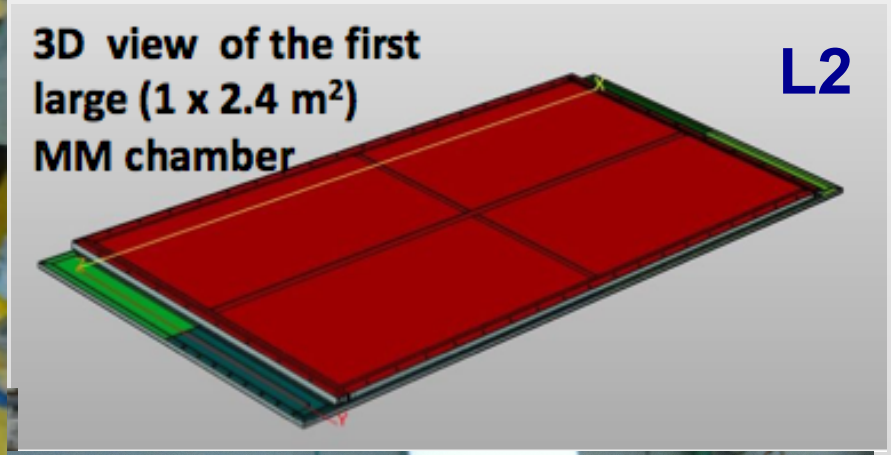
Deformation map (3mbar – 0 mbar)

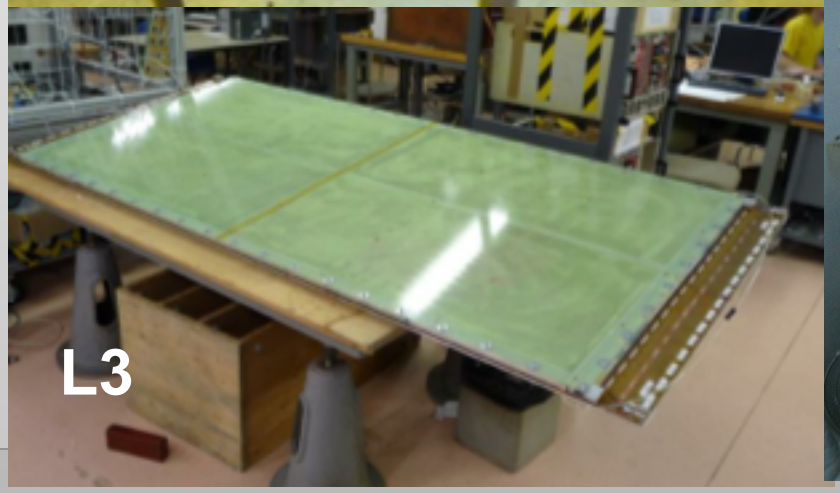


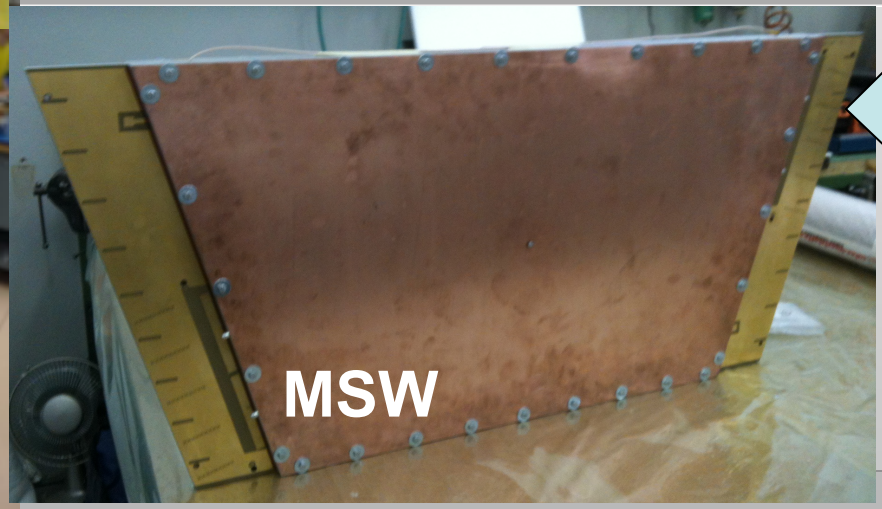
Observed deformations due to Gas overpressure
AverageDeformation = 140 μm ; MaxDef <300 μm

Large Area Micromegas Chambers

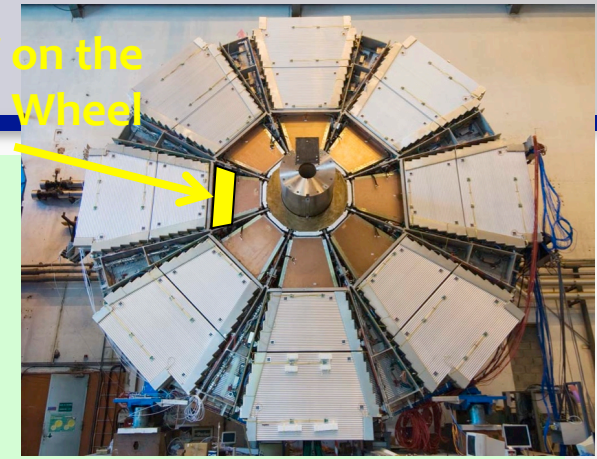
- Several large area single gap chambers built at CERN in the past year: L1, L2, L3
- New multi-gap operational prototypes are currently being built at ~all construction Labs
- New multi-gap prototypes with ATLAS MM Configuration recently built at CERN. Considered as a Module -1 of ATLAS MM







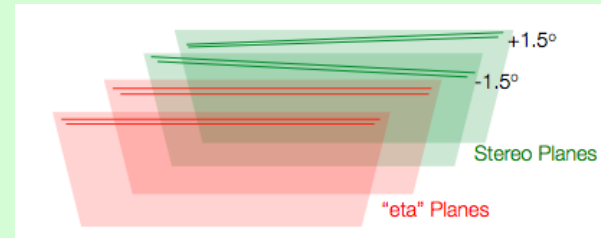
MICROMEGAS FOR THE SMALL WHEEL

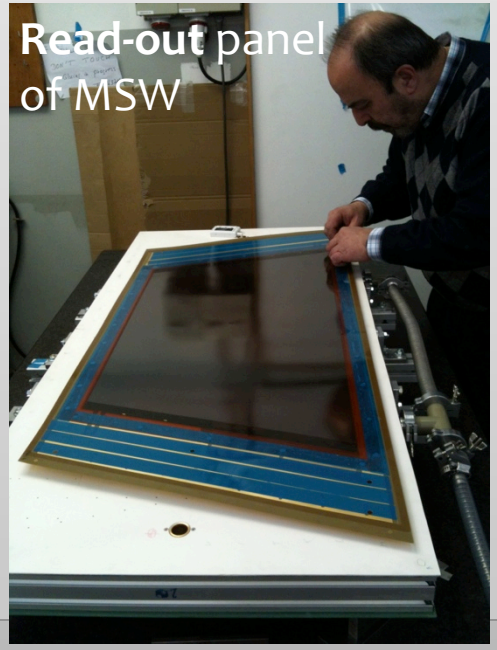


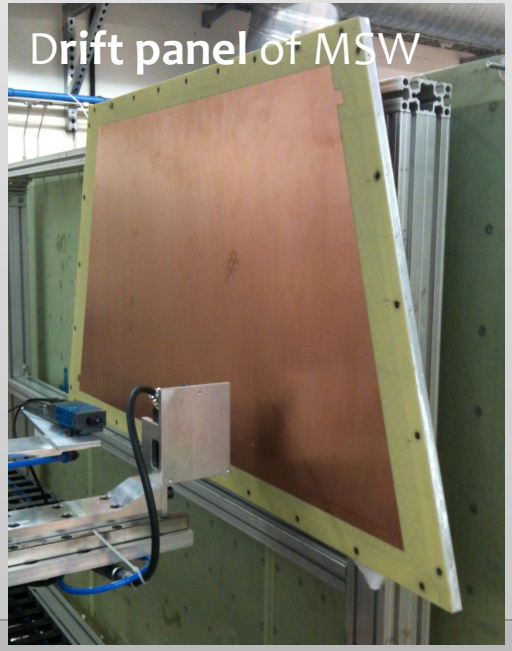
The Micromegas Small Wheel Project (MSW)

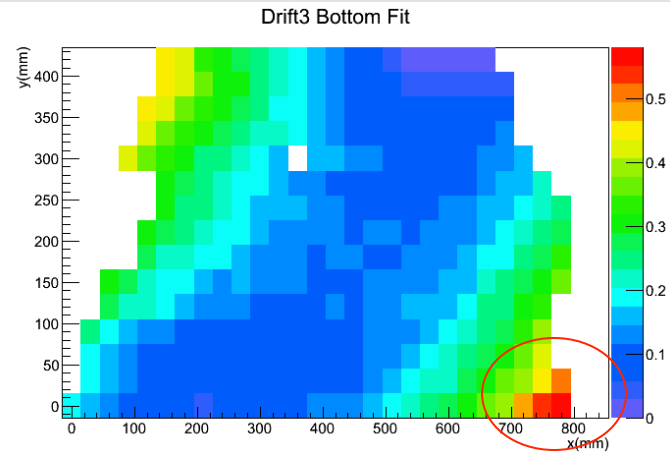
Two identical detectors are being built

- One for the 2014 test beam campaign
- One will be installed in ATLAS, (initially in the outer wheel) at a later stage moved on the Small Wheel, to operate during Run2 in real conditions
  - Dimensions 1.2 x 0.5 m^2 (to fit upper half of CSC)
  - Configuration very close to final module
  - Four layers (quadruplet) 2 eta 2 stereo (x and u,v planes) →
  - strip pitch 0.425 mm, 1024 strips/layer
  - PCB Production as close as possible to final production



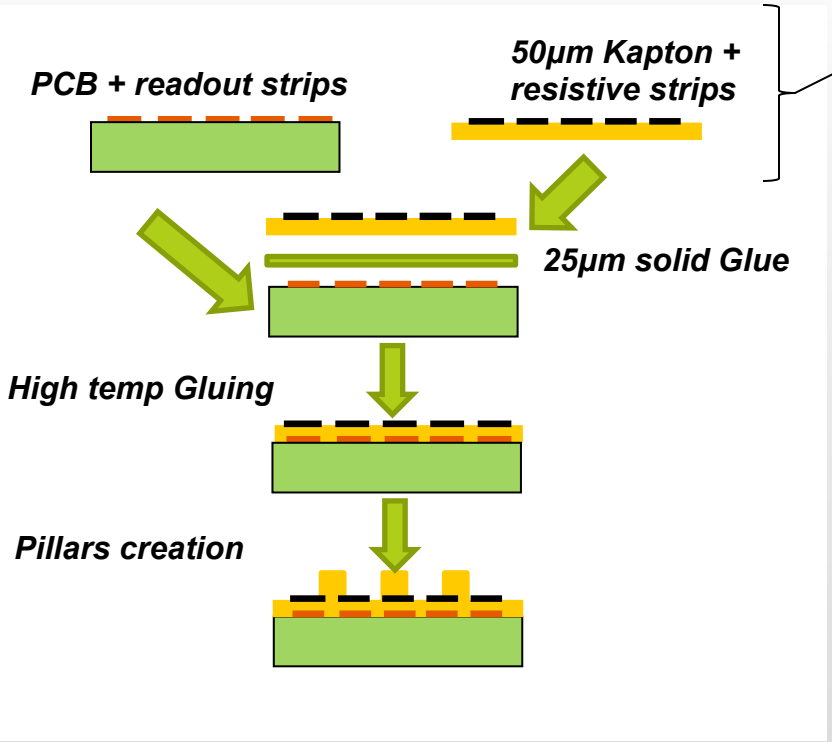




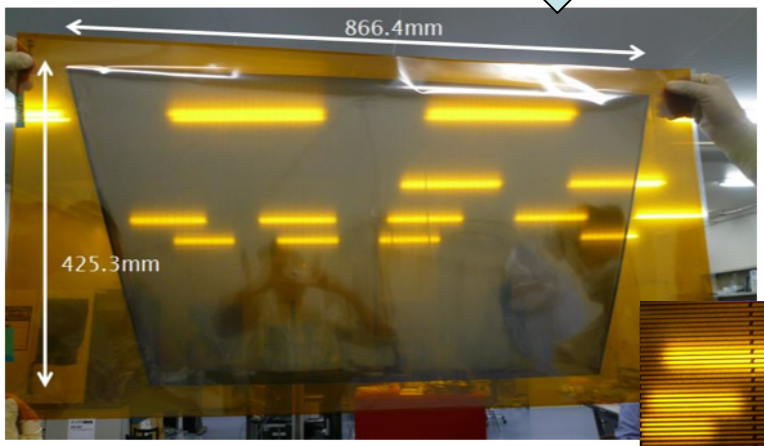


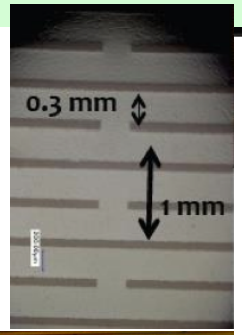
Small deformation of a drift panel visible
Overall flatness of the single panel σ <100 μm
Flatness improves after detector assembly

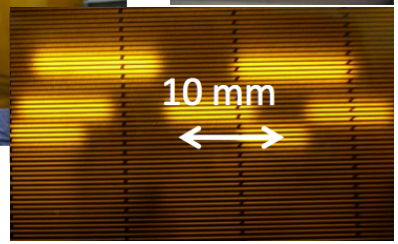
Readout PCB Construction Process



- Resistive strips on 50 μm kapton foil are glued on the PCB with readout strip pattern
- Two technique for resistive strips currently being evaluated:
  - Sputtering
  - Screen Printing

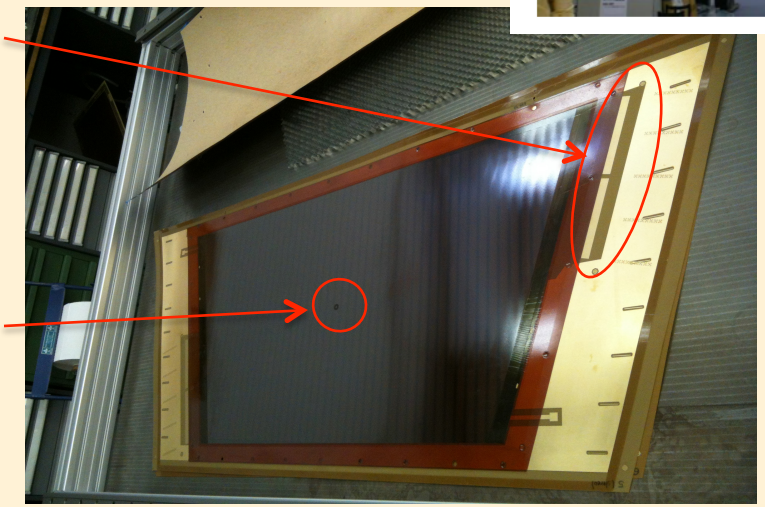






Readout strips (512 channels per side) for Zebra interconnection (no connector mounted on the boards)

Central hole for panels interconnection



Typical resistivity:

~ 10-20 MΩ/cm (~300-600 kΩ/□)

Resistive strips interconnection

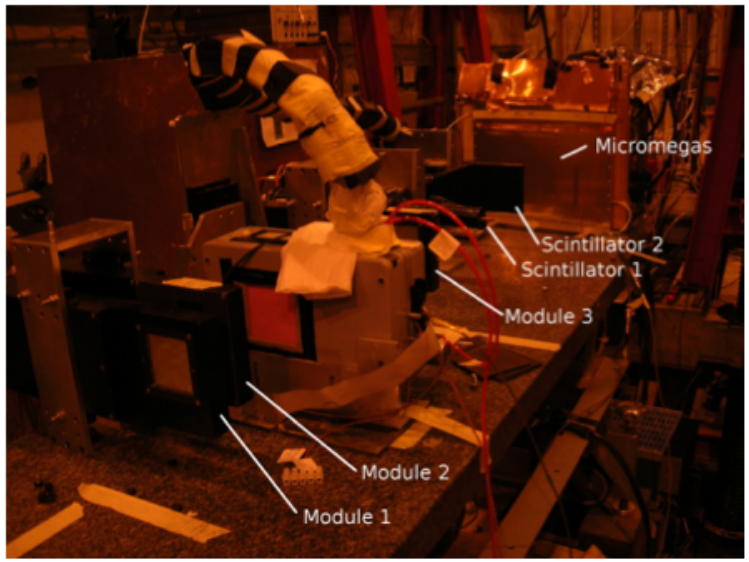
- Homogeneous resistivity (independent from distance)
- Insensitivity to broken lines

TEST-BEAM AND PERFORMANCE STUDIES

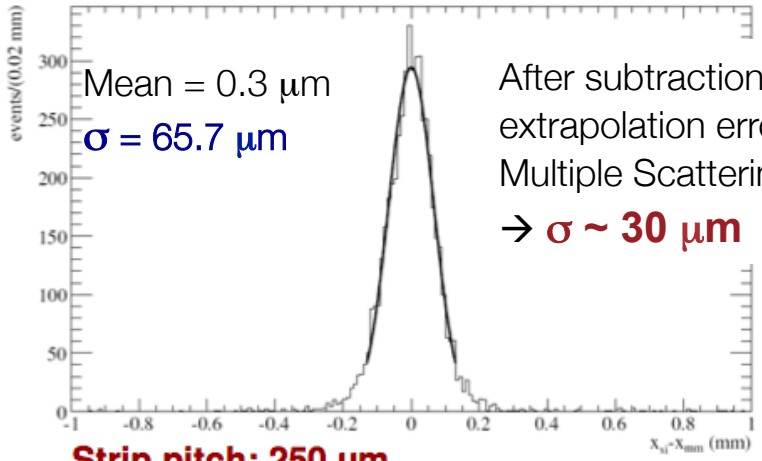
- Initiate a process of MM Performance Review, implying test-beam re-analysis, simulation, software development, algorithms improvements

Early Experience and Choices for ATLAS MM

Test Beam Summer 2008
CERN SPS 120 GeV Pions



Gas: $Ar:CF_4:iC_4H_{10}$ (88:10:2)
V_{mesh} = 470 V (36.7 kV/cm)
Drift field = 220 V/cm
Perpendicular tracks



VERY GOOD RESOLUTION (perpendicular tracks) can be reached with:

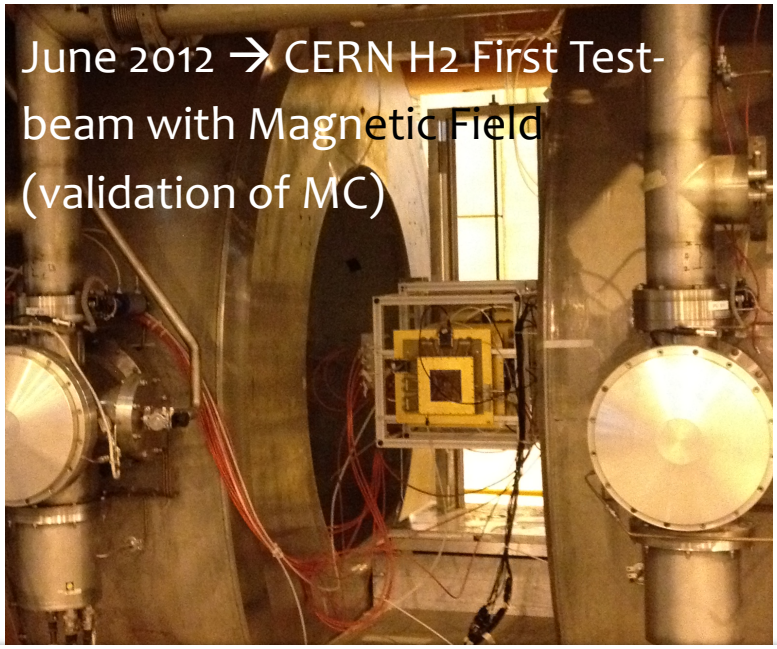
- Small size strip pitch → Issue with number of channels in ATLAS
- Ar-iso-butane-Freon gas mixtures → Ageing issues for operation in ATLAS

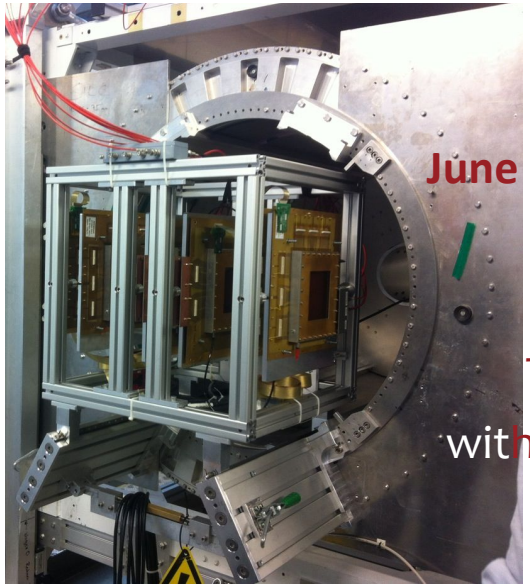
The CHOICE FOR ATLAS Micromegas:

- Pitch size ~ 0.4 mm → ~2M total number of channels
- Gas mixture $Ar-CO_2$ (93/7 subject to further optimization)

→ Fulfills ATLAS requirements

TEST-BEAM SETUP 2012-2013



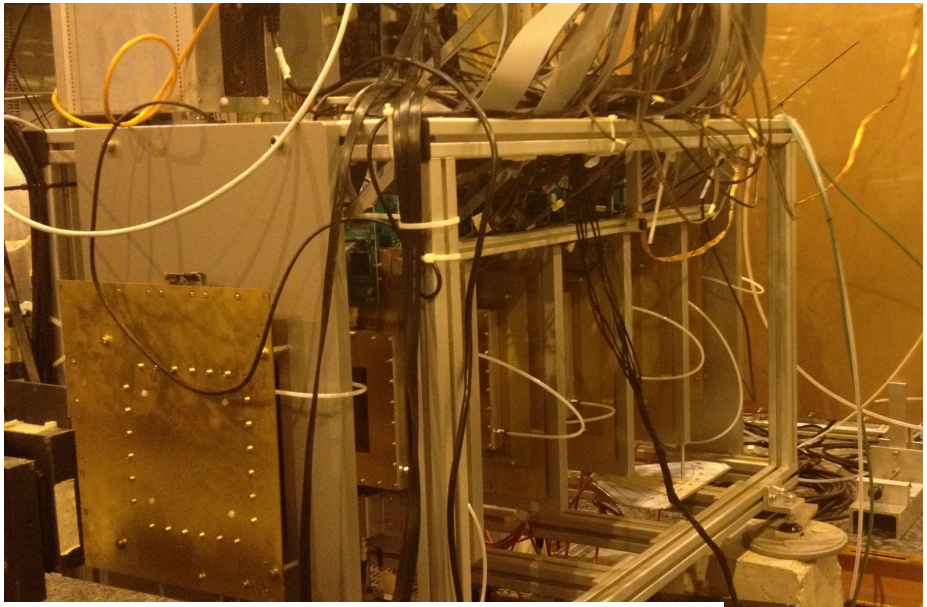


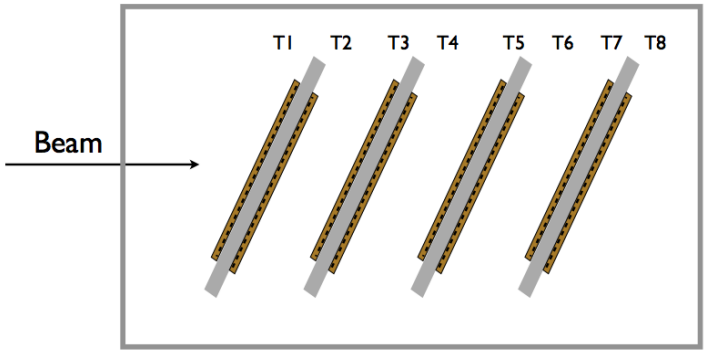
June 2013 DESY (5 GeV electrons)

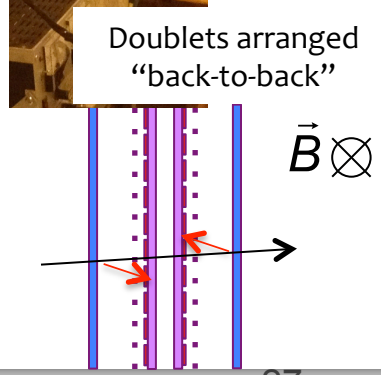
Test-Beam with Magnetic Field

July-September 2012 → CERN H6 (120 GeV pions)

- Tests and validation of μTPC mode with APV25
- First test of VMM1 chip.
- First tests on large size MM 1x1m^2



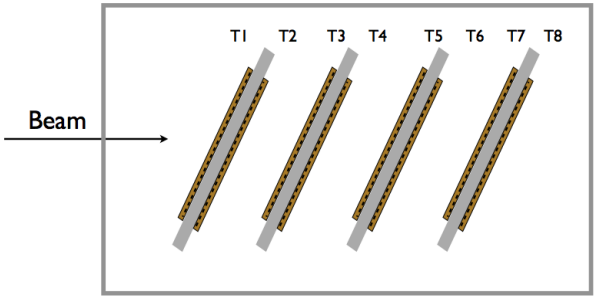




Test-Beam Setup 2012-2013 – Typical Setup

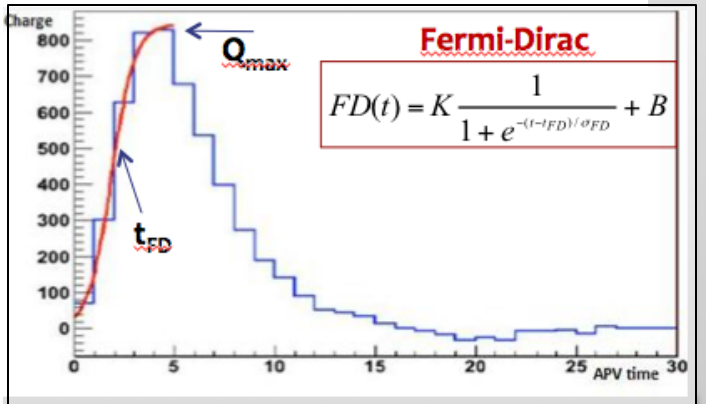
Typical setup

- Up to 8 MM Test chambers aligned along the beam line (plus reference chambers)
- Test Chambers: Resistive strips, Active area of 10x10 cm^2,
- Oriented in back-to-back configuration forming doublets
- Strip pitch of 0.4 mm, drift gap of 5 mm, Amplif. Gap 128 mm
- operated with $Ar:CO_2$ gas mixture (93:7).
- Our "nominal" HV configuration (mesh at ground) :
  - E_{drift} = 600 V/cm; vdrift = 47μm/ns
  - Amplification Voltage 450 -- 550 V (Gain ~10^4)



FE and DAQ

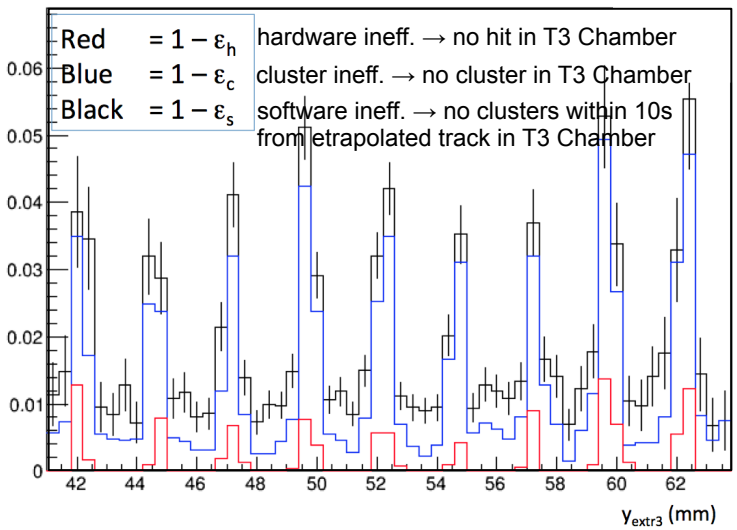
- APV25 operated at 40 MHz – 27 samples – tot time window of 675 ns
- SRS (RD51-CERN) Read-Out system adopted
- Preliminary tests of new FE chip, first version of VMM



Strip read-out with APV25 chip
Sampling rate 40 MHz

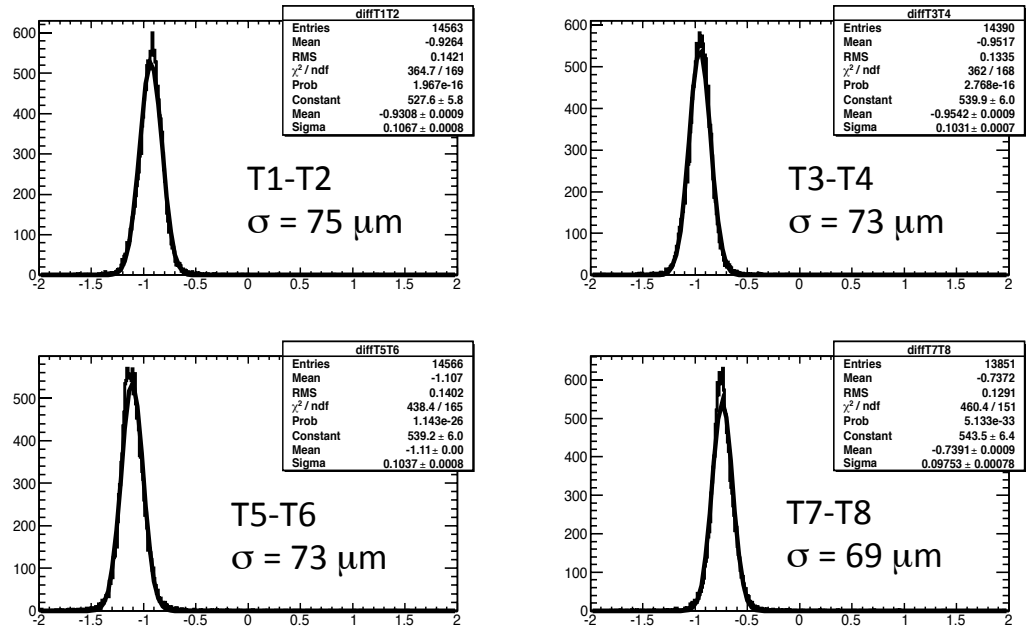
Efficiency and Position Resolution for Perpendicular Tracks

Distribution of local inefficiencies as measured from the missing hits on one chamber corresponding to a reconstructed track from the other chambers



Cluster inefficiencies in the range 1 to 2% consistent with the partially dead area due to the presence of 300μm diameter pillars separated by 2.5 mm.

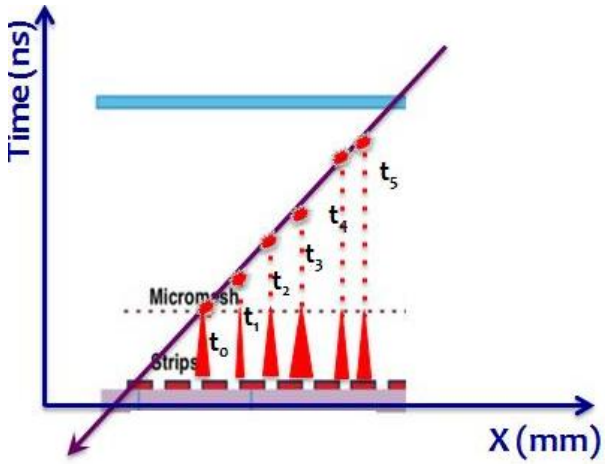
Position resolution for perpendicular tracks estimated by difference of cluster charge centroid measurements of pairs of MM chambers

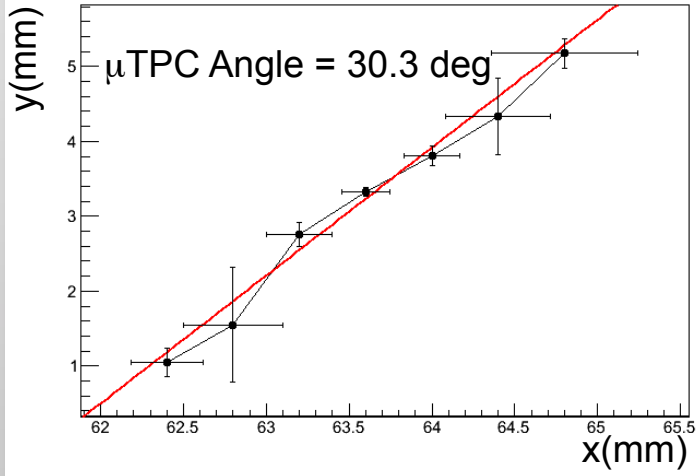


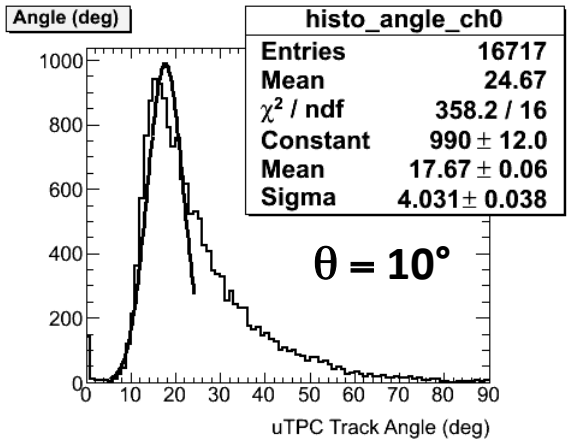
About **73 μm** with an average cluster size of 3.2
Similar results obtained with a full track reconstruction method.

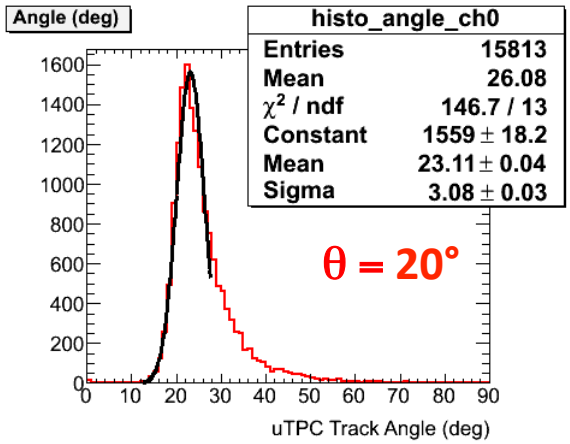
THE MICRO-TPC METHOD FOR INCLINED TRACKS

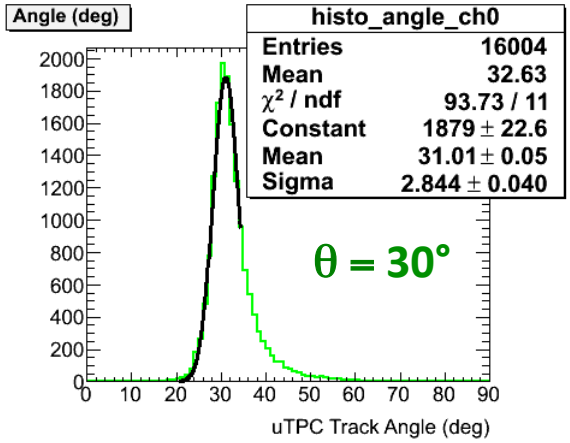
- Sub 100 μm spatial resolution easy to achieve for perpendicular tracks.
- For inclined tracks need to exploit time information to operate in "micro-TPC" mode

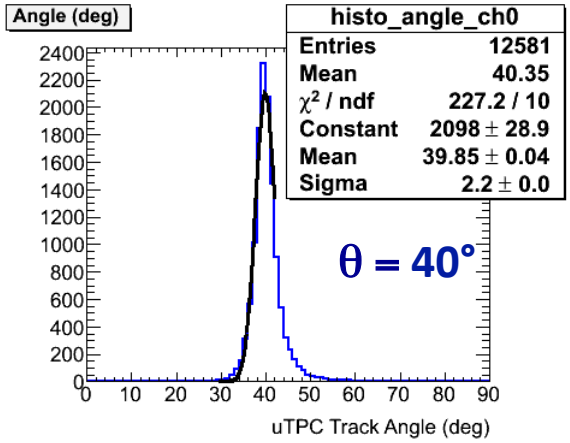






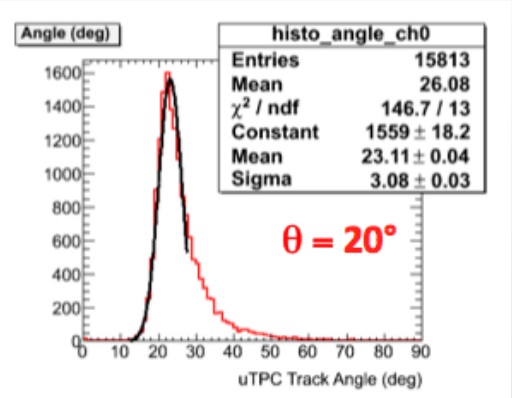


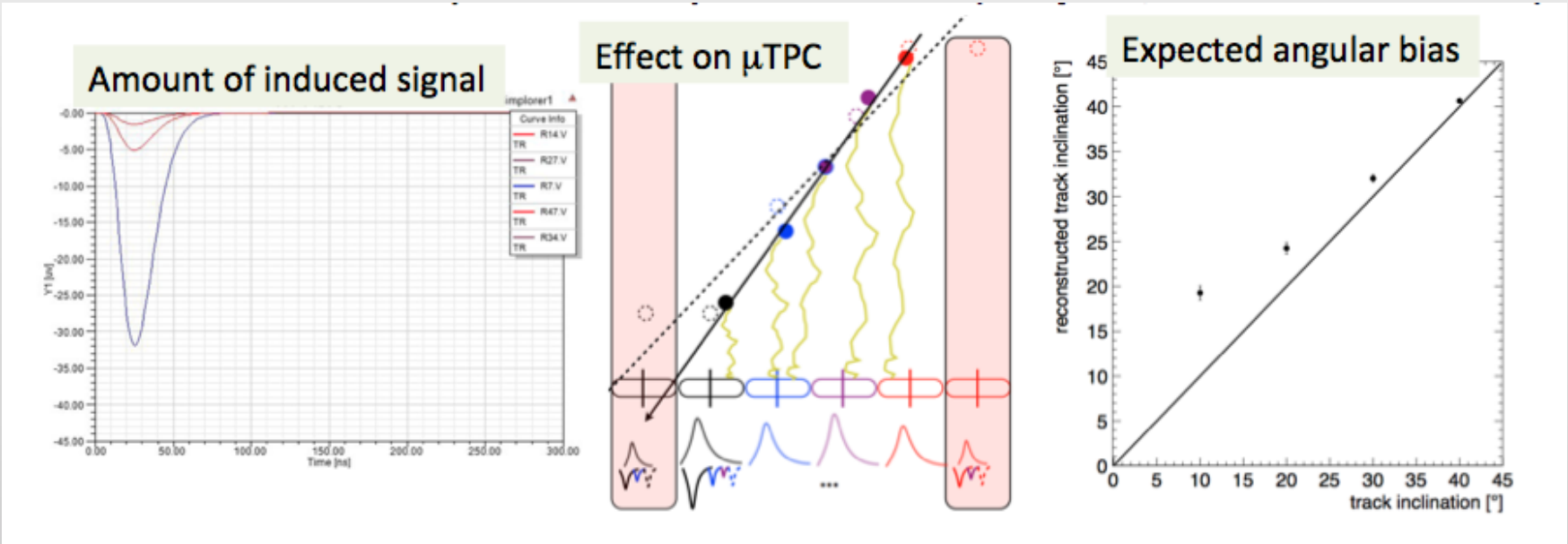




OPTIMIZATION OF THE MICRO-TPC METHOD

- The μTPC method has been successfully applied in many test-beam data
- However a sizeable angular bias is observed due to capacitive induction of the signal on neighbouring strips.
- The effect is well reproduced by simulations (LTSpice, ANSOFT Maxwell).



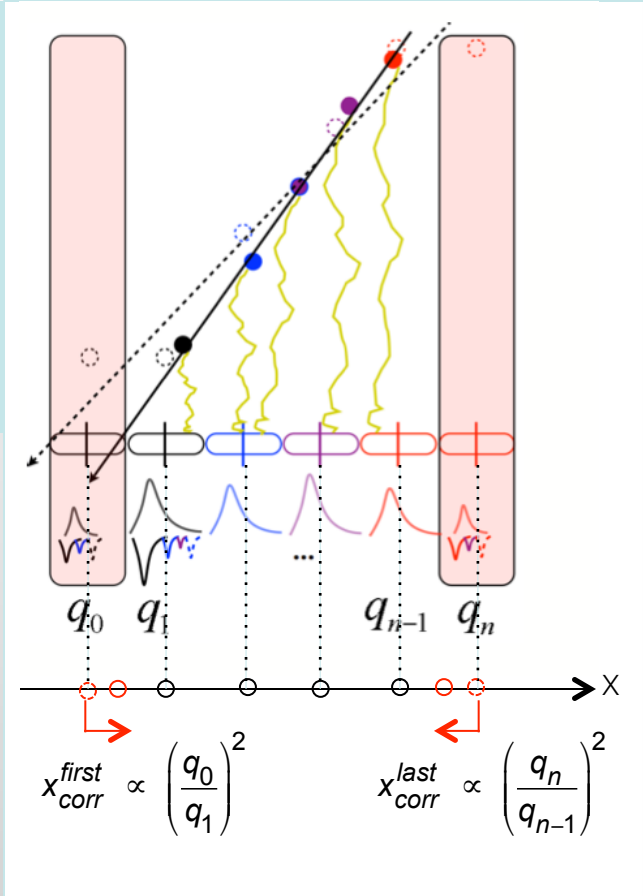


→ a new procedure was developed to take into account this effect to reduce the angular bias and to improve the spatial resolution

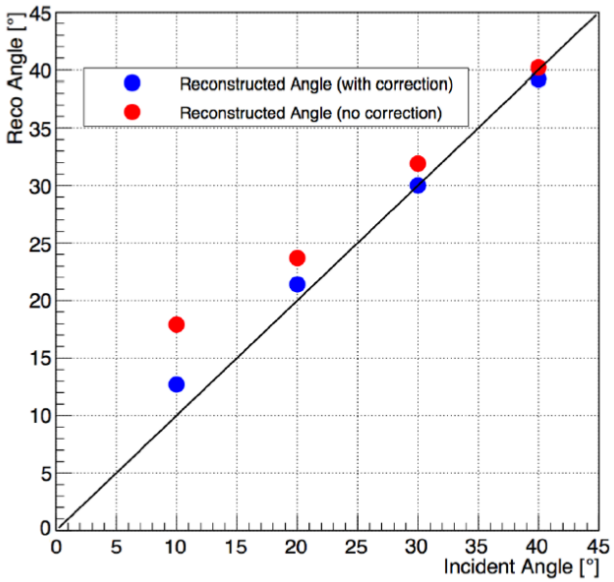
Optimization of the micro-TPC method

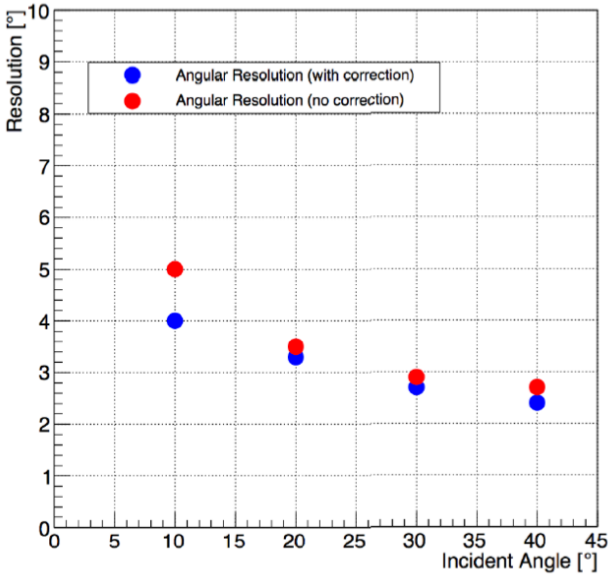
The optimized correction only applied to the first and last strips:

- Do not use first/last strip if its charge is more than 6 times smaller than its neighbour.
- Otherwise correct the charge position for the edge strips of the cluster in proportion to the ratio of charges with their neighbours



After correction, a significant reduction of the angle bias and an improvement in the μTPC angle resolution is obtained

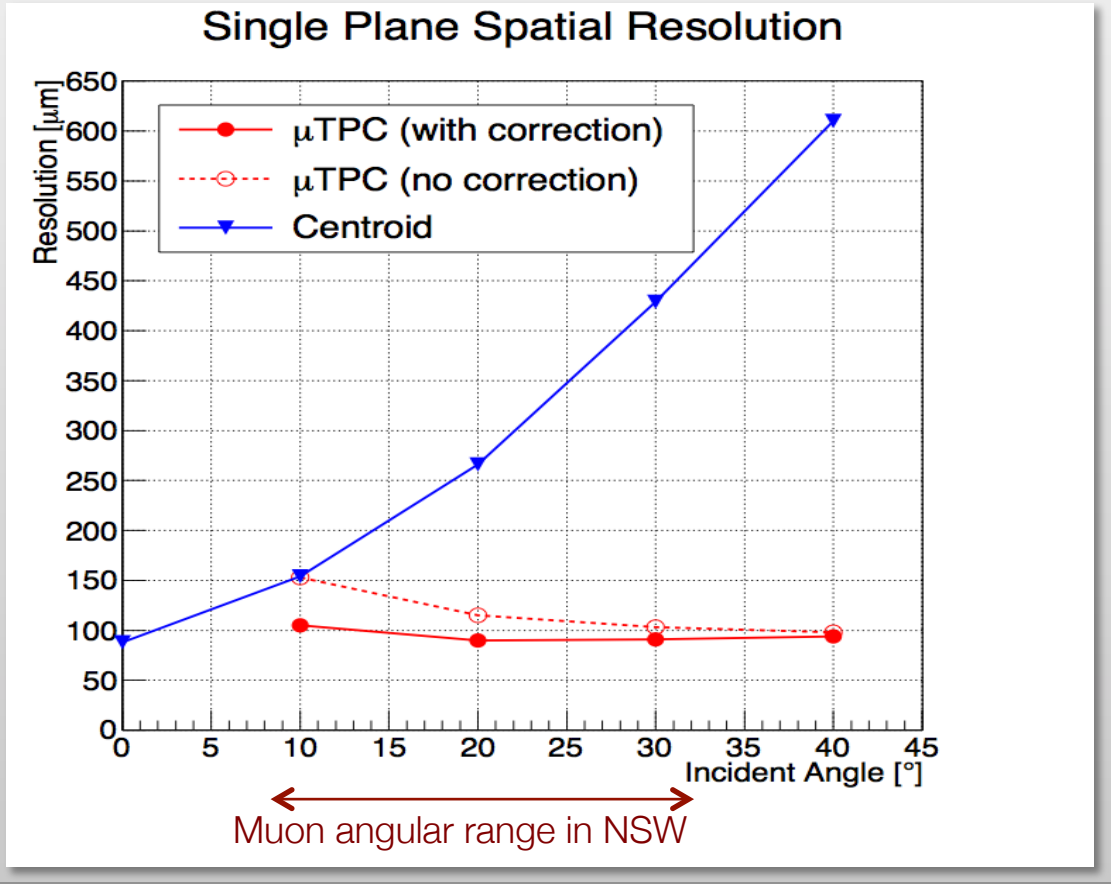


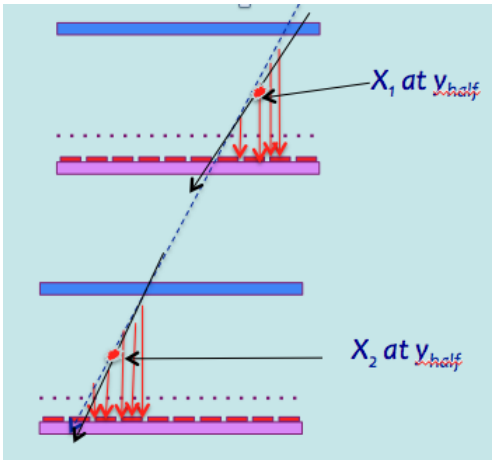


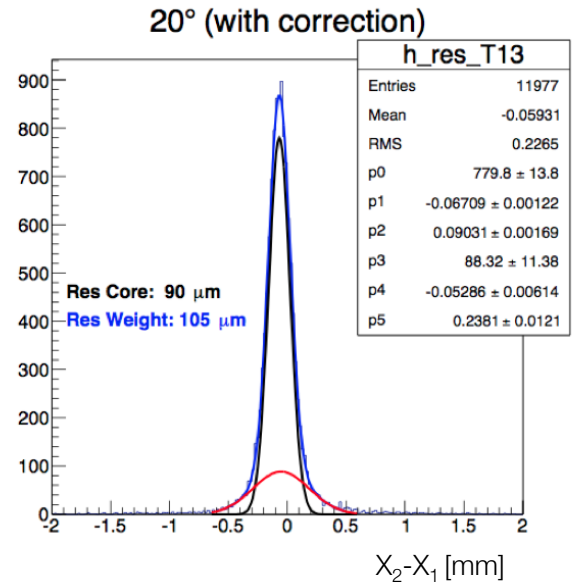
Position Resolution

Spatial resolution is measured from the difference of the reconstructed position in two chambers

In case of the micro-TPC between tracklets extrapolated to half gap of the chambers ("y-half")

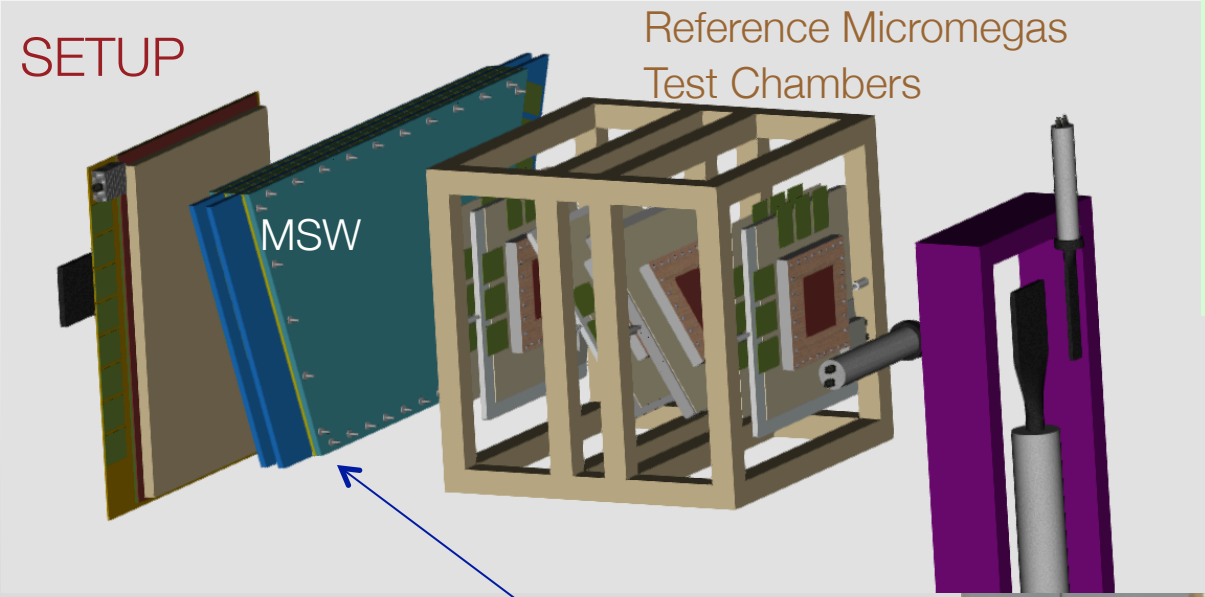






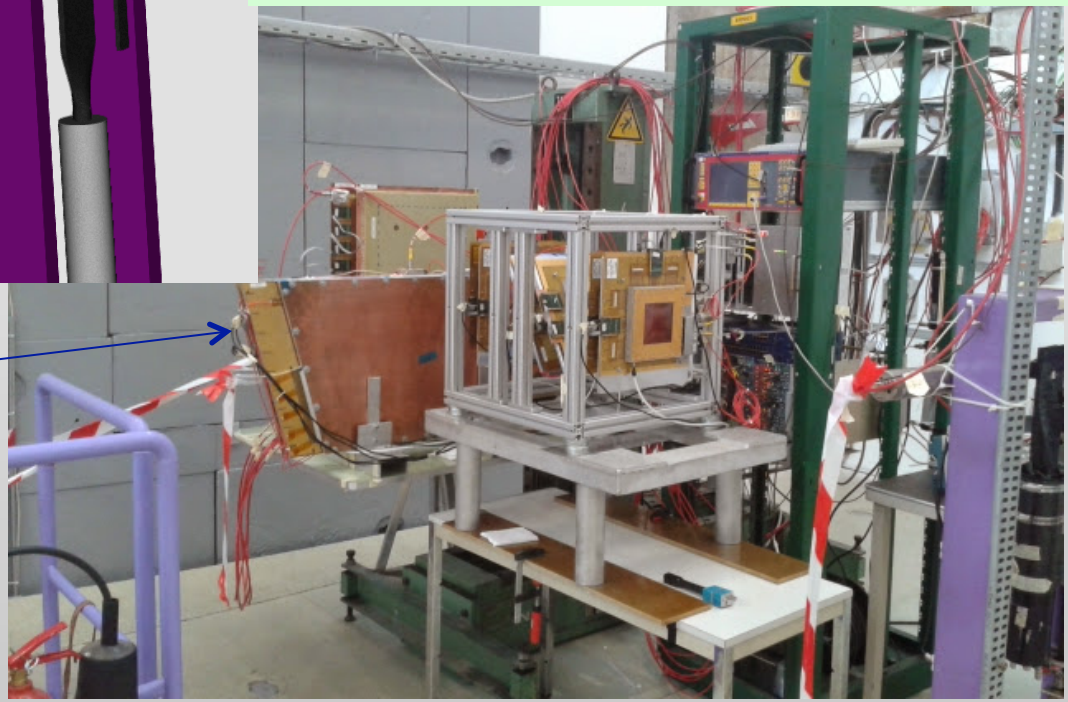
TEST-BEAM AUGUST 2014

August 7-14 (and August 15-27 parasitically) at PS/T9 – beam: 10 GeV/c π^+/p



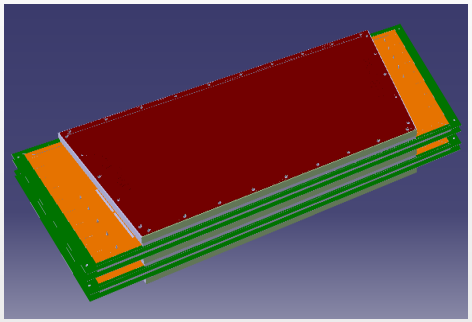
MSW Operation Conditions

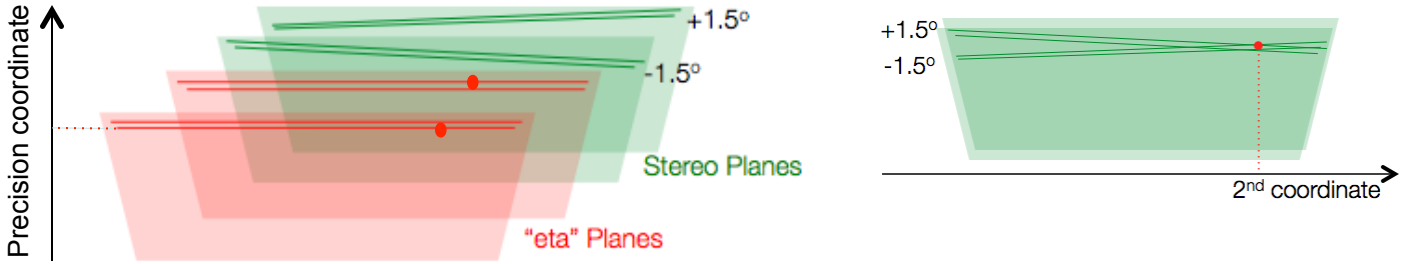
- $Ar:CO_2$ gas mixture (93:7)
- HV configuration (mesh at ground):
  - E_{drift} = 600 V/cm; v_{drift} = 47μm/ns
  - Amplification Voltage ~550 V (Gain ~10^4)
- Strip pitch ~0.4 mm



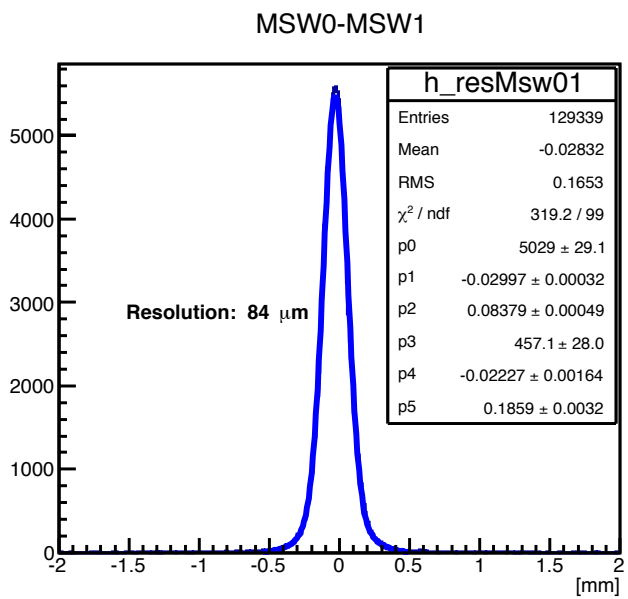
Test of the MSW prototype
First test of an assembled quadruplet with the same configuration as the ATLAS quadruplets

Test-Beam Setup 2014 MSW preliminary results

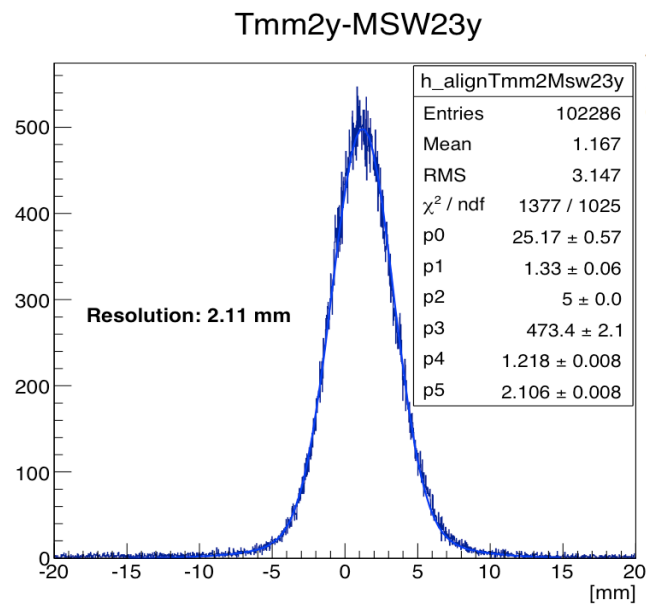




Preliminary result of Spatial Resolution on the precision coordinate
(corrections for beam angular spread not included)



Preliminary result of Spatial Resolution on the second coordinate.
In very good agreement with expectations

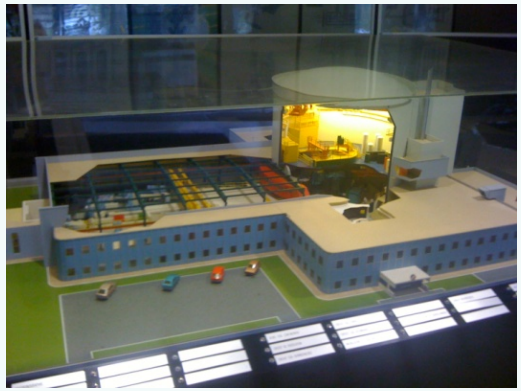


2nd coordinate from the stereo planes, compared with reference chamber Tmm2

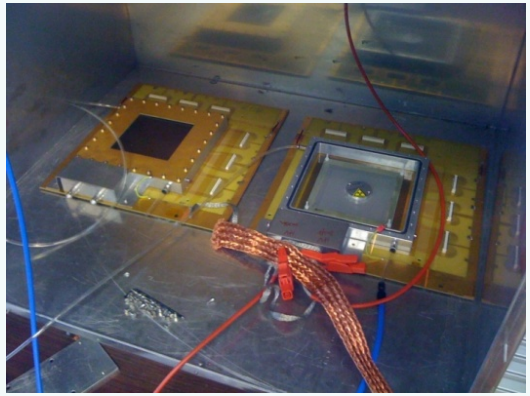
Overview of Micromegas Ageing Tests

X-ray beam

Cold neutron beam

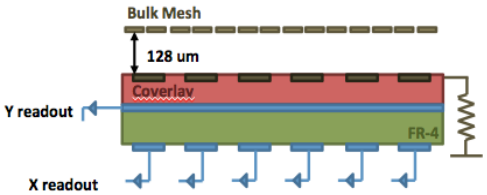


Alpha source



Gamma source

Extensive Program of irradiations done in 2012 at Saclay



R17a detector is exposed to different radiation sources

R17b detector is kept unexposed as reference

Gain control measurements are performed before and after each exposure.

After the ageing both detectors are taken to the H6 CERN-SPS pion beam line.

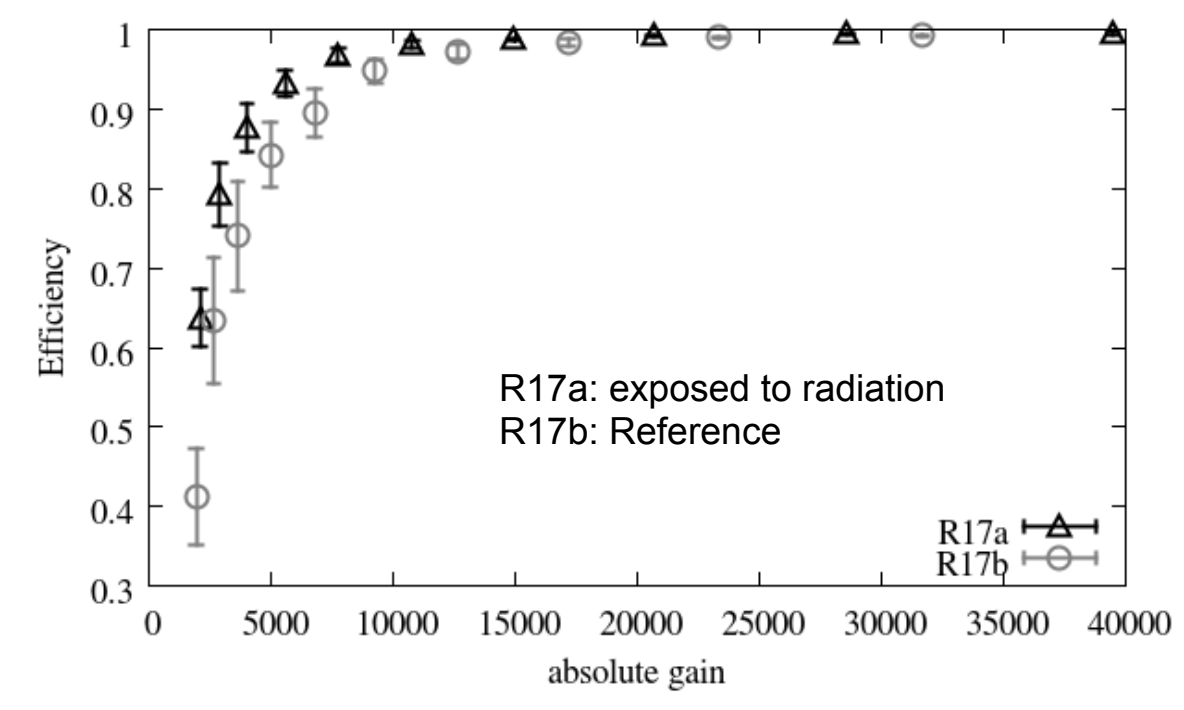
The goal was to accumulate an integrated operation charge equivalent to the one would be obtained at the HL-LHC for 10 years for each type of radiation.

Overview of Micromegas Ageing Tests - Exposure

Irradiation with	Charge Deposit (mC/cm^2)	HL-LHC Equivalent
X-Ray	225	5 HL–LHC yrs equivalent
Neutron	0.5	10 HL–LHC yrs equivalent
Gamma	14.84	10 HL–LHC yrs equivalent
Alpha	2.4	5×10^8 sparks equivalent

The two R17 prototypes were taken to the H6 SPS CERN pion beam to perform a **comparative study between both prototypes**, **irradiated** and **non-irradiated** one.

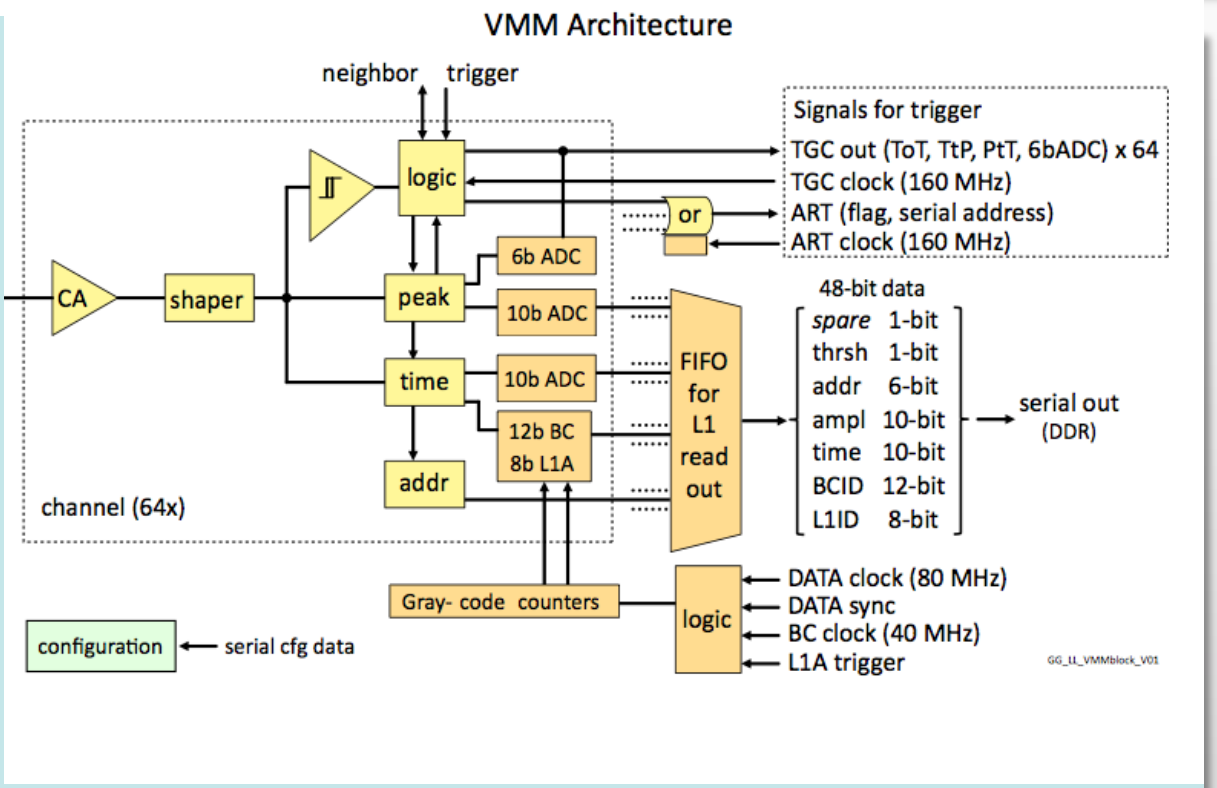
Both detectors reach efficiencies of about 99.5%, proving that **there is no visible degradation effect in these measurements**



New Electronics for ATLAS: the VMM chip

VMM ASIC Main Features

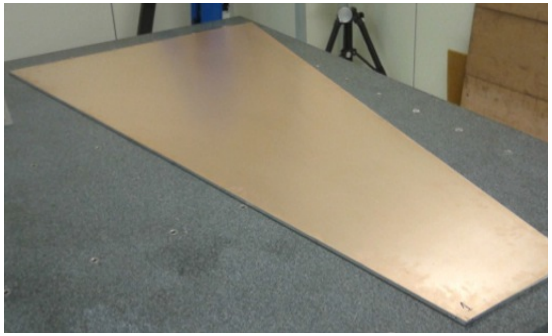
- Highly programmable ASIC provides both precision measurement and trigger primitives
- low noise charge amplification, shaping with baseline stabilization
- 64 channels digital output
- Digital zero-suppressed readout of the address, amplitude, and time

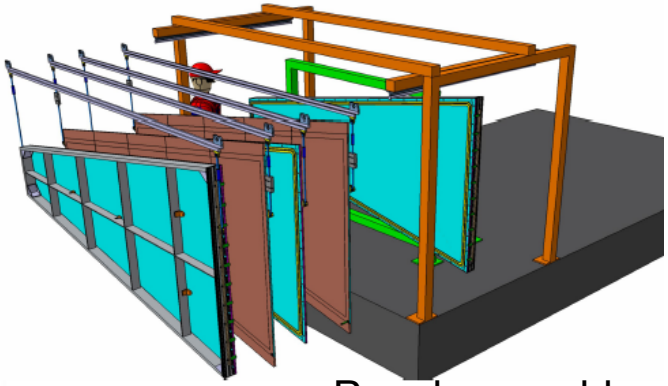


- Peak detector provides signal amplitude
- Peak Timing with negligible time walk and ~2ns resolution
- Neighbor enable logic allows processing below threshold signals
- The address of the channel with the earliest time with respect to the trigger, the Address in Real Time (ART) → used for triggering with the micromegas

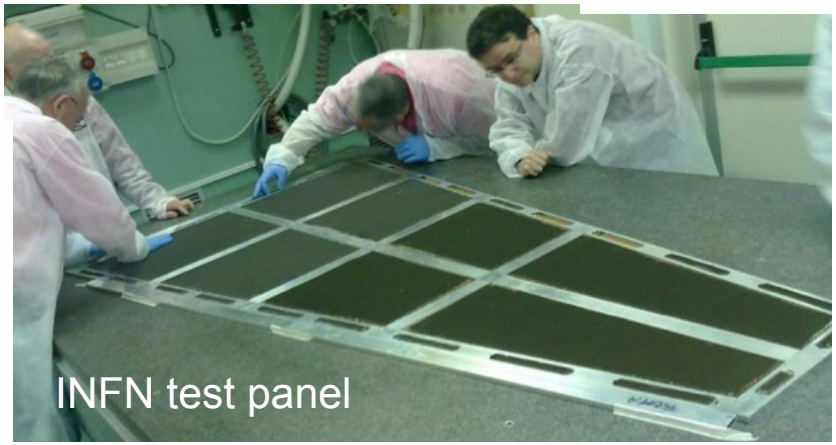
Moving to Production: Construction Sites Preparation

Mesh stretching tests in INFN Roma Tre

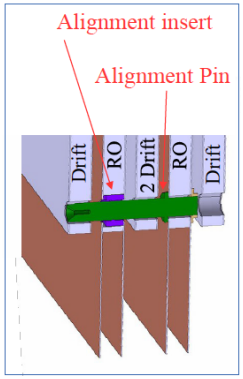


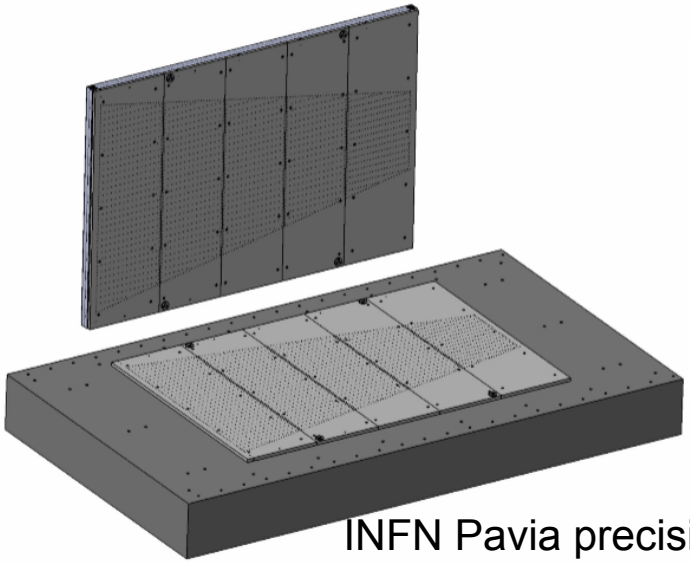


Panel assembly



INFN test panel





INFN Pavia precision templates for RO board alignment

Final preparations to start module-0 construction after the summer …

CONCLUSIONS

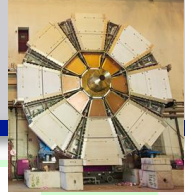
- The ATLAS NSW Upgrade will enable the Muon Spectrometer to retain its excellent performance also beyond design luminosity and for the HL-LHC phase
- Deployment of a new detector technology, Micromegas, for the first time for a very large scale detector and with large area chambers
- Test-Beam and performance studies show that the Micromegas fulfil the ATLAS requirements

And …there is much more not covered in this presentation: Electronics, Alignment, …

- Detector construction is not the only challenge: Alignment, Mechanics, Electronics are equally crucial and highly complex areas needed for a success
- End of this year and 2015 will be crucial:
  - Module-0 production
  - Transition to series production
  - First prototypes for many of the electronics components

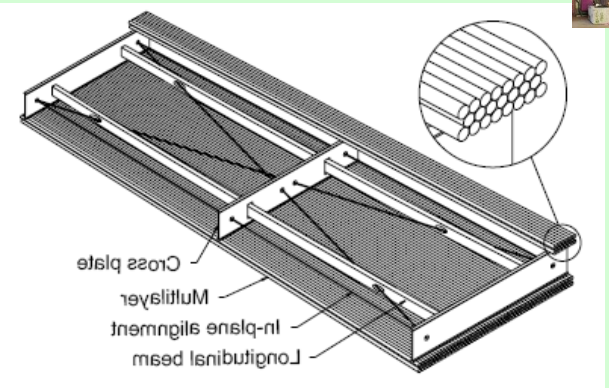
BACKUP SLIDES

The Detectors in the Present Small Wheels



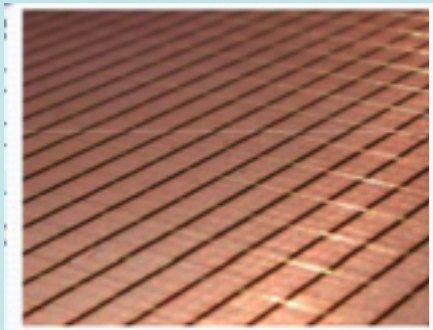
Monitored Drift Tubes:

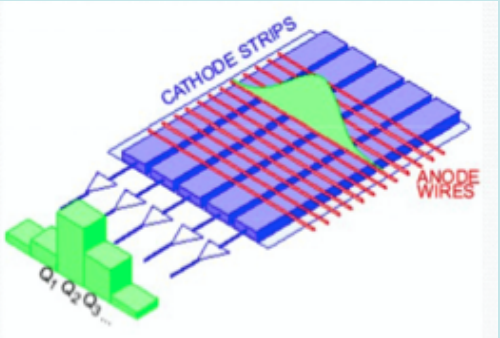
- 3 cm diameter tubes filled with Ar:CO_2 @ 3bar abs
- tube resolution <= 80 μm, track resolution/station <= 50 μm
- Rate capability limited by 1 dimensional readout
- Optical rays for monitoring deformation and displacement



Cathode Strip Chambers:

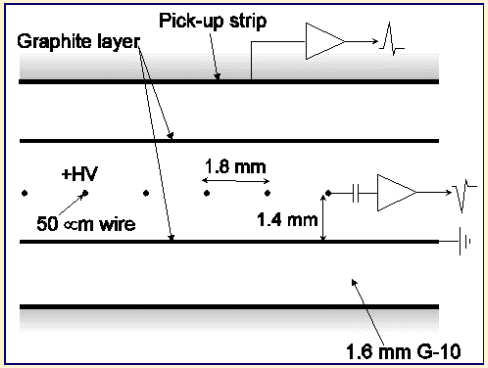
- Innermost part of the inner endcap station
- Multi-wire proportional chambers, operated at 1 bar (Ar:CO_2)
- segmented cathode, strips perpendicular to wires
- resolution/plane: 60μm from strip charge distribution



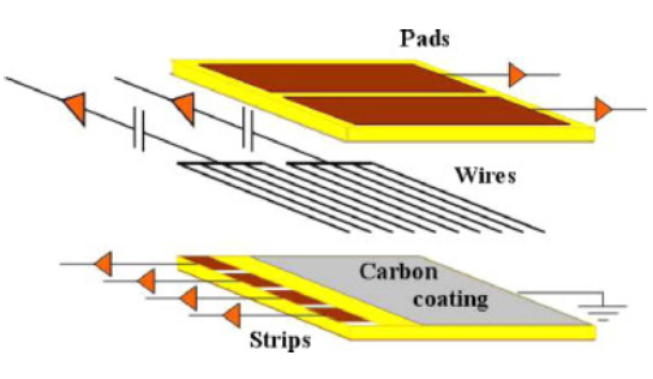


Thin Gap Chambers:

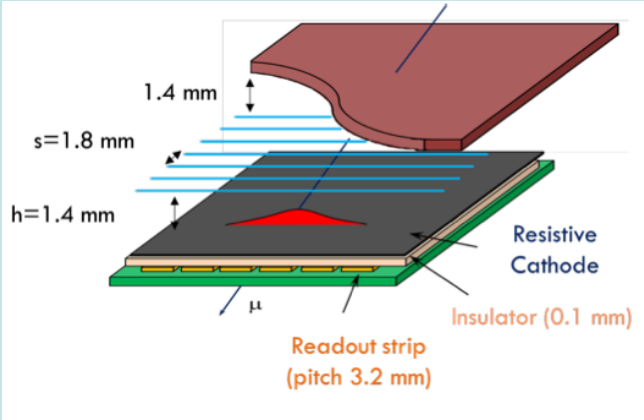
- Multi-Wire proportional chambers with very small gap size
- Cathode – wire distance smaller than distance between wires
- Operated in quasi saturated mode with n-pentane + CO_2
- Fast readout, small intrinsic time jitter (<~ 1.5ns), high efficiency
- Provide also 2nd coordinate measurements for MDTs, main purpose in the present Small Wheel !



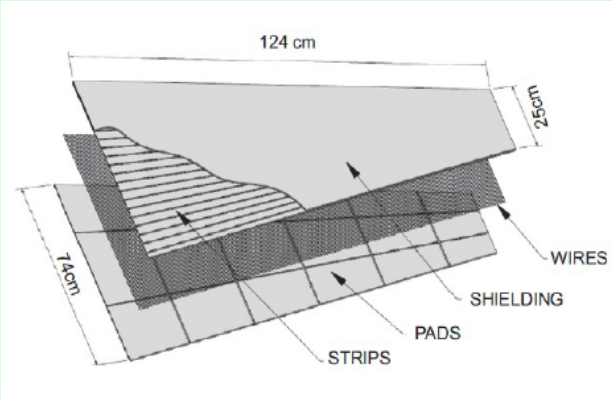
ATLAS Small Strips Thin Gap Chambers (sTGC)



- TGC already used in OPAL, DELPHI @ LEP and also present in the ATLAS Endcap Muon region
- From the ~2 cm strip pitch of the TGC already in ATLAS → to 3.2 mm strips (small-strips TGCs)



- 50μm gold-plates tungsten wires, spaced 1.8mm apart,
- Wires sandwiched between 2 cathode planes 1.4 mm from the wires
- Cathode surface resistivity 100 kΩ/m^2 reached by graphite coating



- Trigger: Coincidence of pad signals define Region of Interests (RoI), selected strip information sent to trigger processor for precision position calculation
- Track position reconstruction from strip charge centroid, 2nd coordinate from wire readout

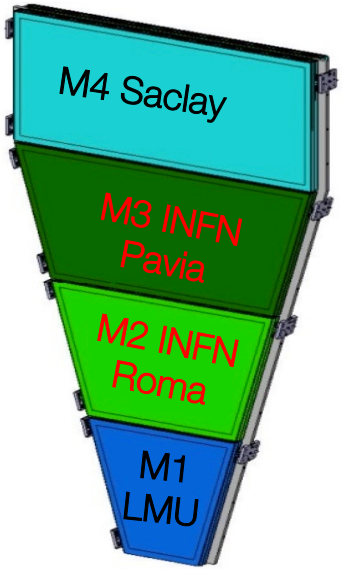
- Resistive cathodes (i.e. the graphite layer) set a limit to the rate capability
- To increase rate capability (> 10 kHz/cm^2) necessary to pass from present TGC cathode resistivity (1 MΩ/cm^2) to 100 kΩ/cm^2

Micromegas Construction – Mechanical Prototypes

- Construction of single wedge full size mechanical prototype CONCLUDED: CERN

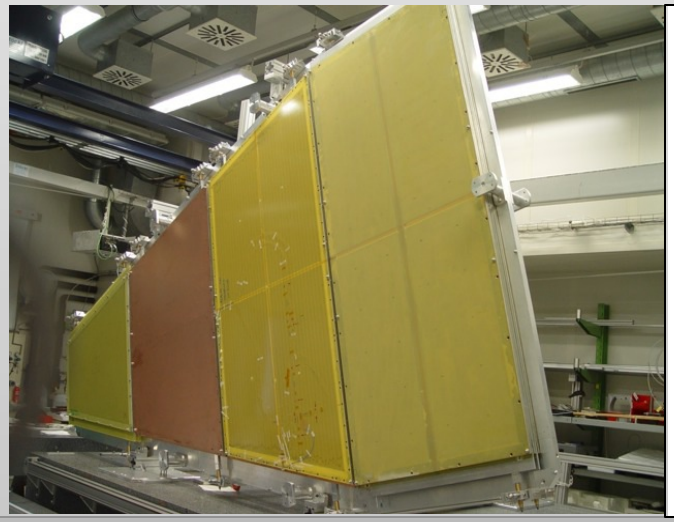
- Construction of 4 modules Mechanical Prototypes is CONCLUDED (according to old segmentation): INFN PV, RM (IT) , Saclay (FR), LMU (DE)

Mechanical prototypes
(based on old segmentation)

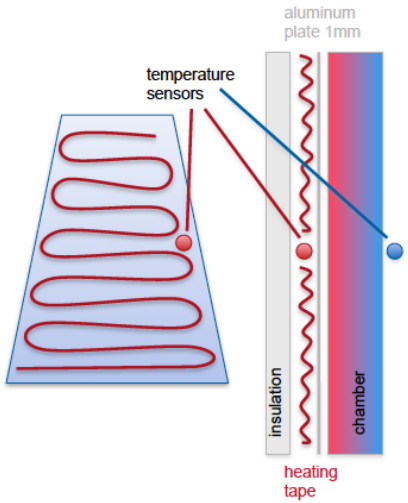


Ongoing measurements:

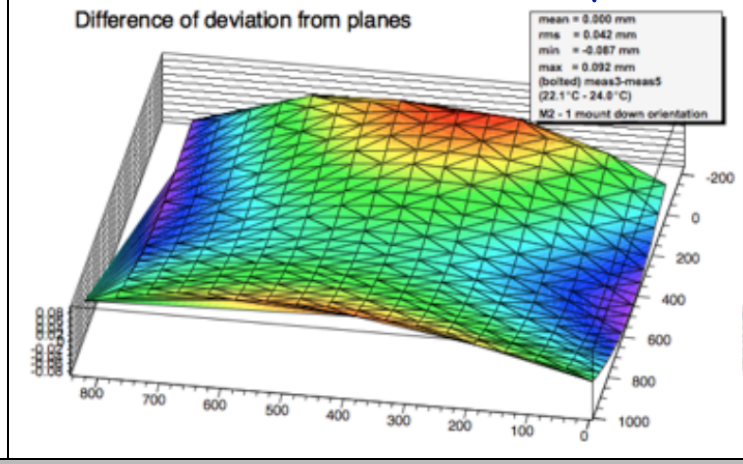
- Mesh tension and gas overpressure induced deformations
- Thermo-mechanical deformations – Validation of simulations
  - Crucial input for in-plane alignment needs
  - Assess and define method to attach modules to sector structure



heating of one side of the chamber via voltage regulated electric heating tapes

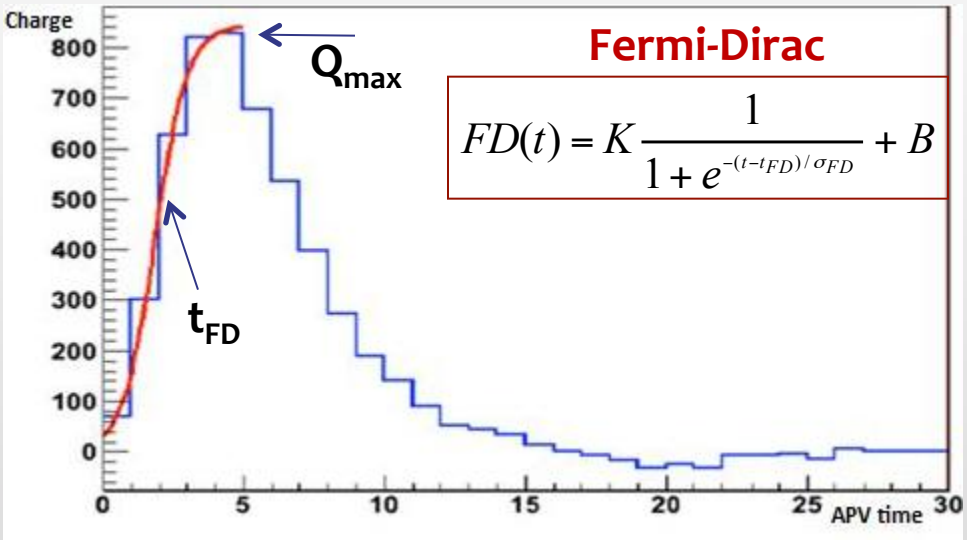


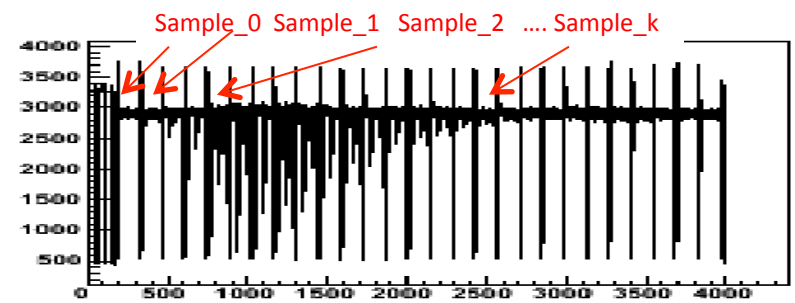
M2 ΔT=1.9° → Deformation ~ 42 μm RMS



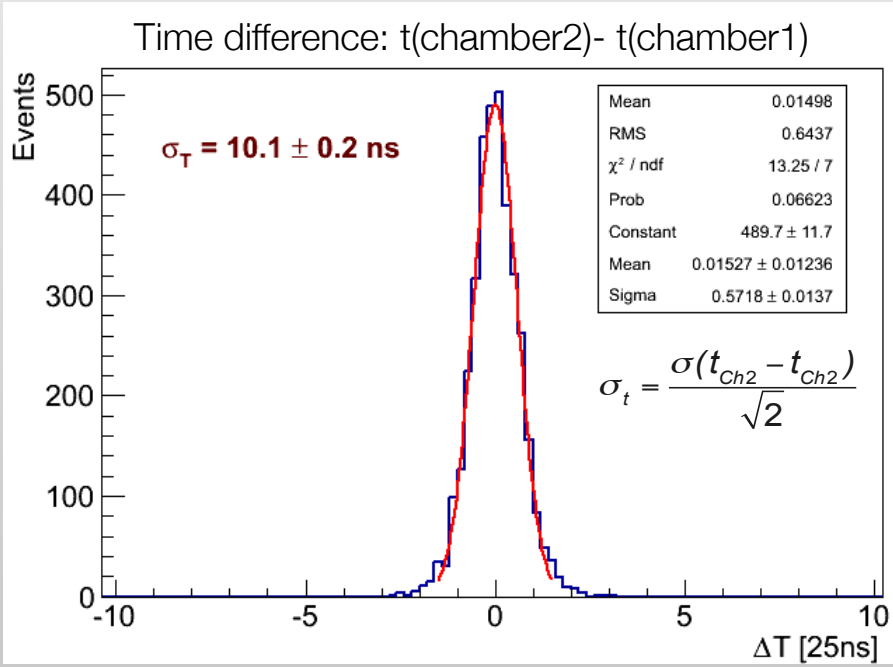
Performance studies with the APV25 Readout Chip

Timings and Amplitudes measured for each hit-strip applying a fit function to the sampled shaper output values





Strip waveform as a function of time (1 sample = 25 ns)



- Intrinsic Time Resolution ~ 5ns (primary ionization spread)
- Temporal resolution estimated from earliest strip differences between two MM back-to-back for inclined tracks (30°)
- Measured σ_T~10 ns. Dominated by APV25 response and precision of the fit