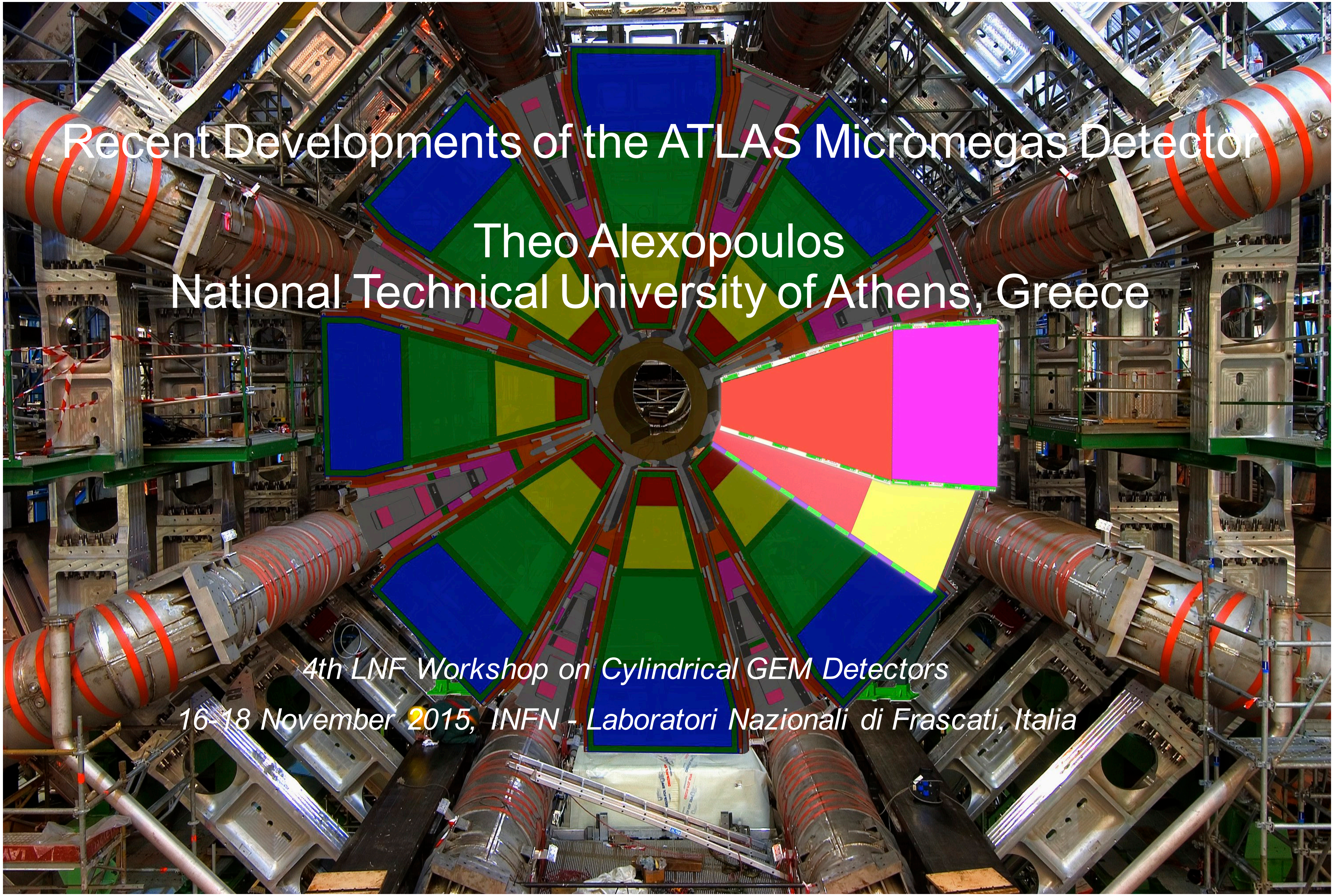


Recent Developments of the ATLAS Micromegas Detector

Theo Alexopoulos
National Technical University of Athens, Greece

4th LNF Workshop on Cylindrical GEM Detectors

16-18 November 2015, INFN - Laboratori Nazionali di Frascati, Italia

Outline - Menu

✓ LHC and ATLAS Upgrade

✓ Motivation for the New Small Wheel (NSW) Upgrade

✓ Micromegas Technology

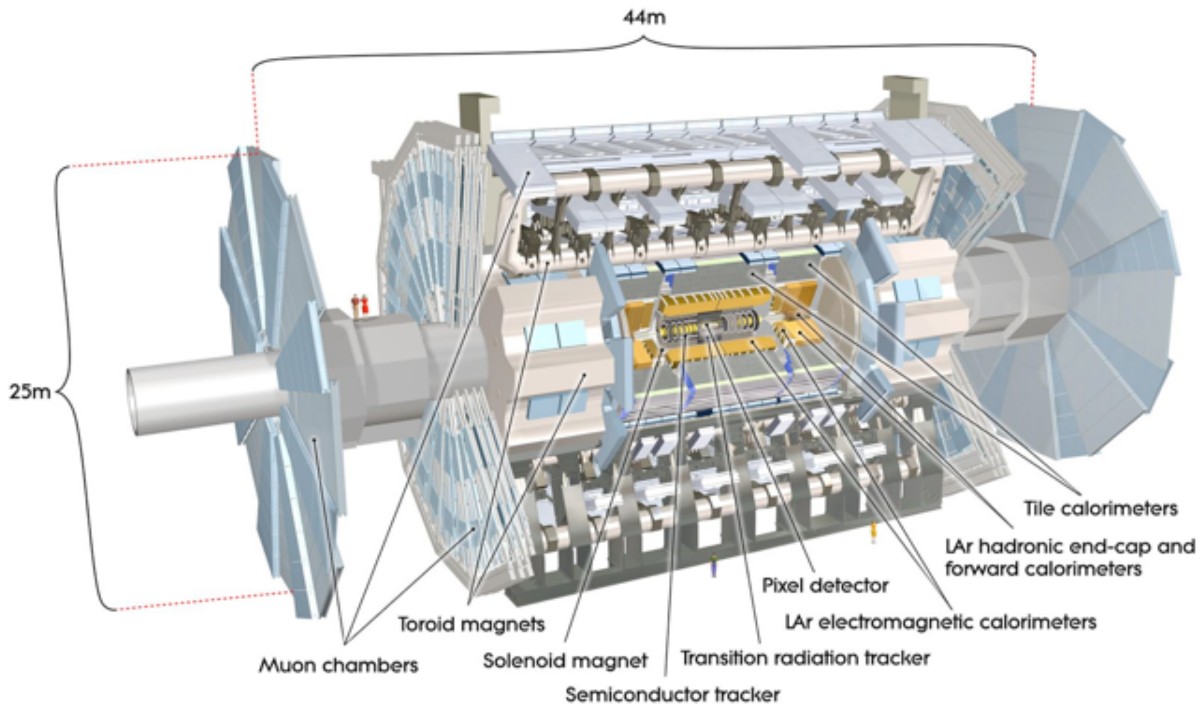
✓ Performance of Micromegas detectors:

- Hit & Track reconstruction techniques
- Spatial resolution for perpendicular tracks - The Centroid method
- Optimizing the μTPC method
- Efficiency studies
- Studying the effect of the pillars
- Performance inside a magnetic field
- MM Timing Information
- Test of large surface MM
- Test of MM quadruplet prototype with stereo strips
- Test of MM prototype with multiplexed readout strips

✓ Summary

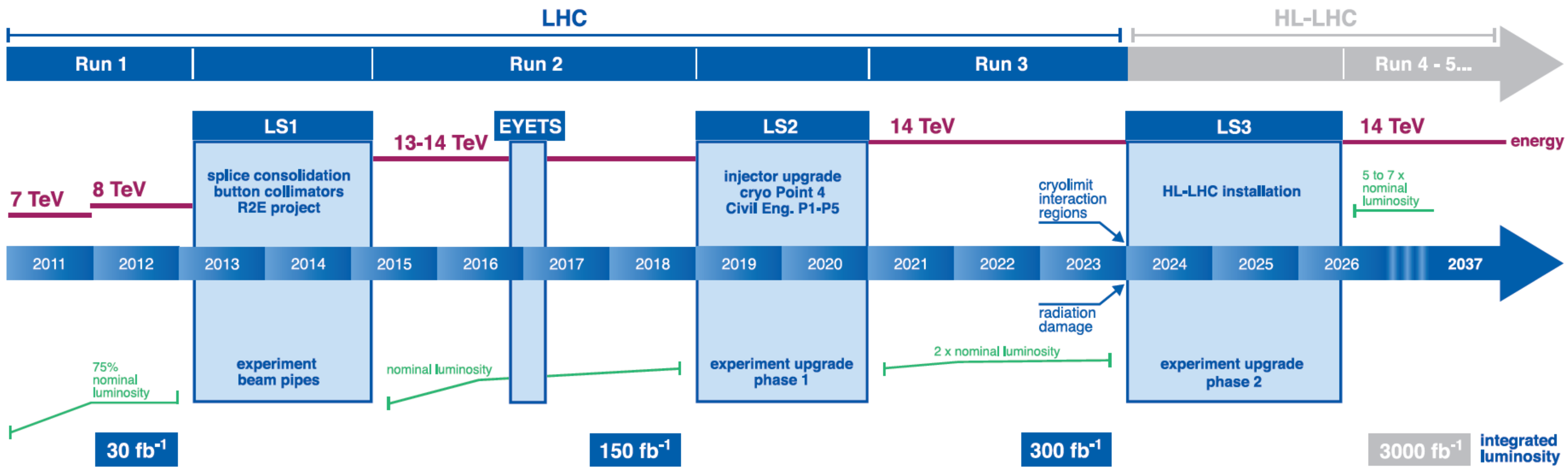
ATLAS Detector

- General purpose detector at the LHC
  - Tracking
    - Silicon (Pixel+SemiConductor Tracker) and Transition Radiation Tracker
    - 2 T solenoidal field
- Muon identification:
  - Dedicated tracking & triggering chambers: MDT, CSC, RPC, TGC
  - 0.5-2T toroidal field



- LAr & Tile Calorimeters

LHC / HL-LHC Plan

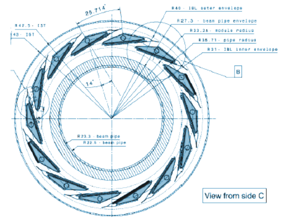


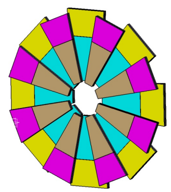
LS_2 ~2019, LS_3 ~2024
LS_4 ~2030, LS_5 ~2034

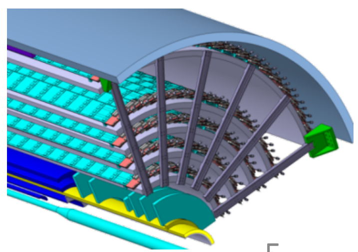
ATLAS Future Upgrades

LHC Upgrade Schedule

- **Phase 0 (installed):**
  - **new Pixel Inner B-Layer**
- **Phase I (approved):**
  - **Fast Track Trigger (electronics)**
  - **LAr (trigger electronics)**
  - **TDAQ**
  - **NSW (New Small Wheel)**
- **Phase II (planning): Replace complete inner detector, …**

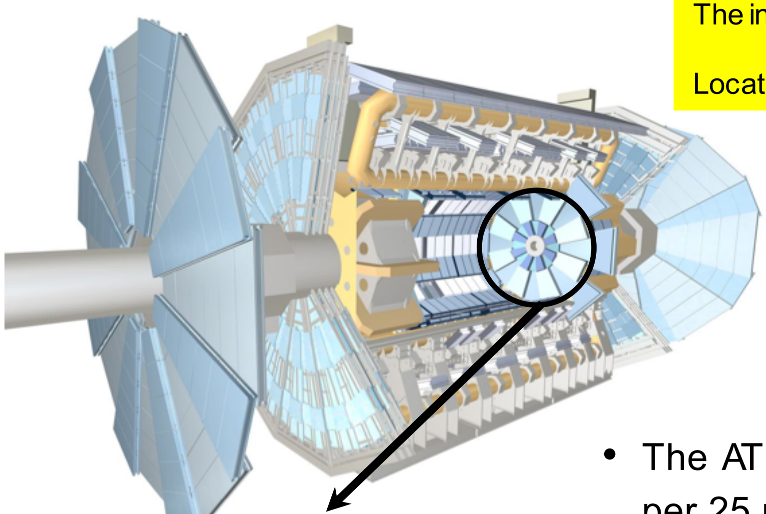






LHC: Large Hadron Collider

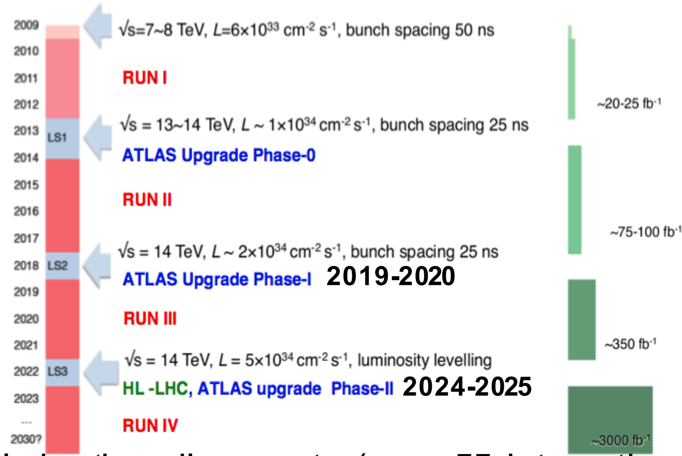
Motivation ATLAS Small Wheel Upgrade 2019-20 (Phase I)

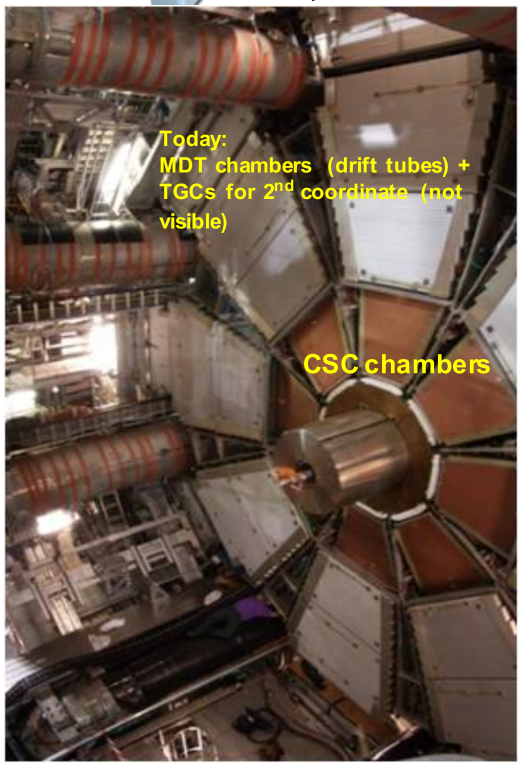


The innermost station of the muon endcap

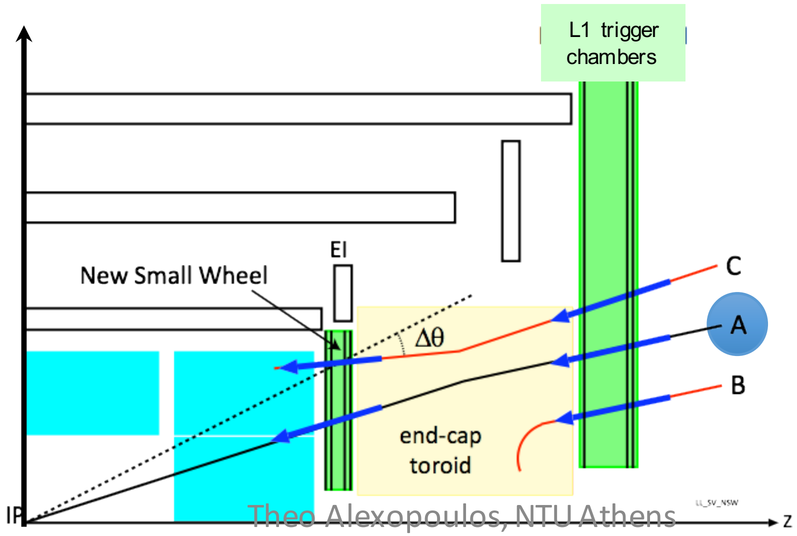
Located between endcap calo and toroid

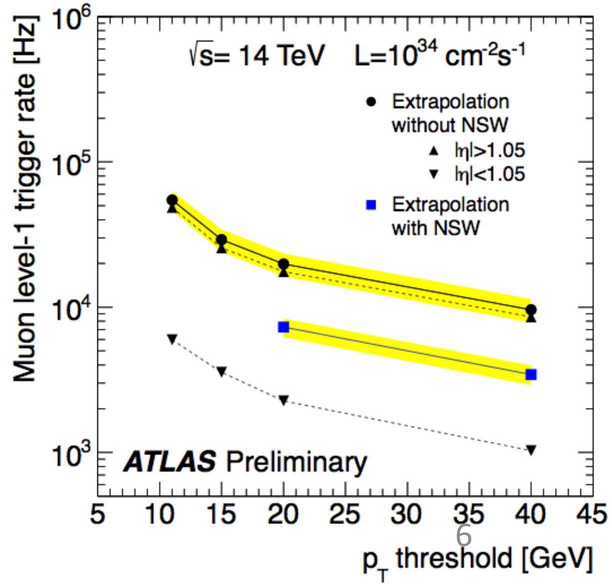
Pseudorapidity coverage:
$1.3 < |\eta| < 2.7$





- The ATLAS upgrade is motivated primarily by the pile-up rate ($<n>$=55 interactions per 25 ns bunch crossing) that are expected at $L=2\times10^{34}$ cm^{-2}s^{-1}. This will lead to an increased particle flux (rate) which the present detectors (MDT + CSC) cannot handle efficiently. Also, added trigger capability.
- Replacing the Small Wheels with a detector that can provide precise tracking and trigger segments will eliminate fake triggers without loss on physics acceptance.





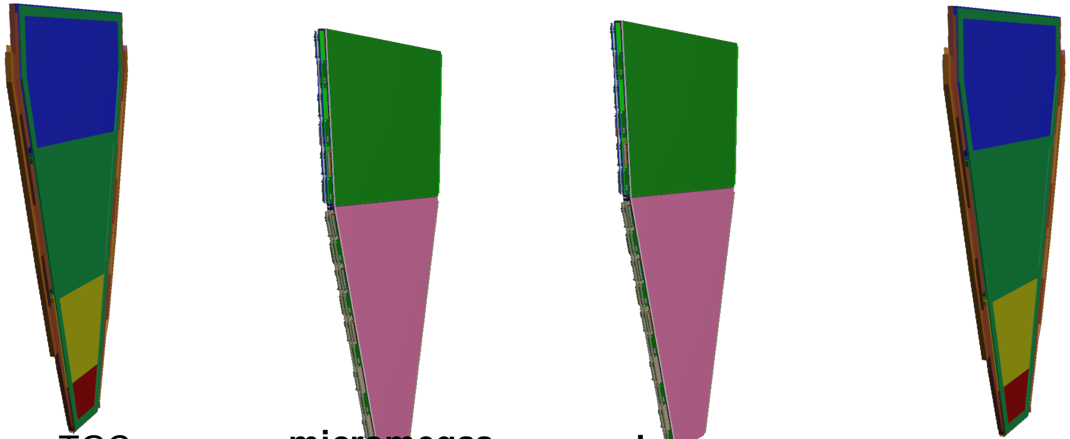
Detector Requirements for the New Small Wheel

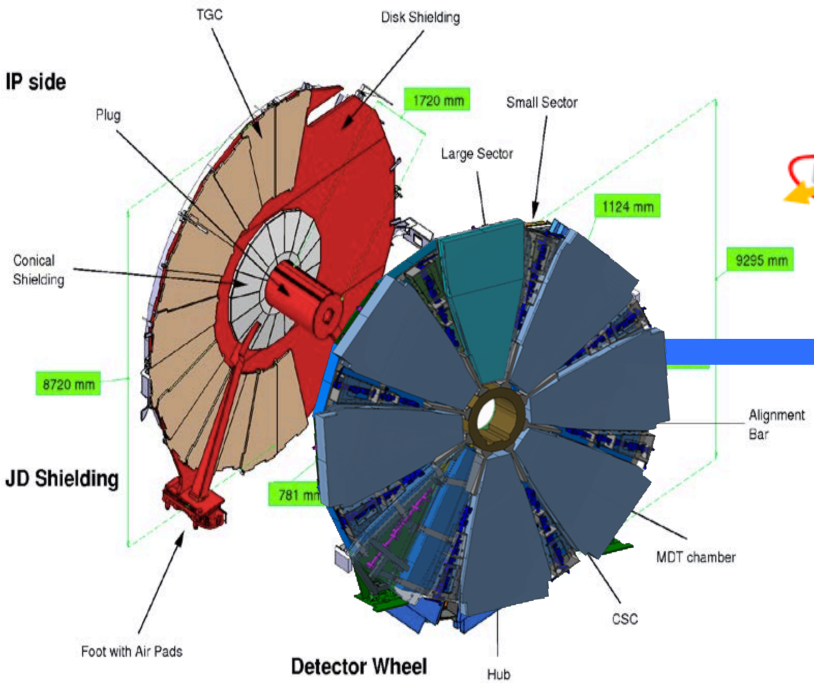
- High rate capability: 10–15 kHz/cm^2 (n, γ, p, μ) at small radii
- Spatial resolution: ≤100 μm independent of track angle
- Efficiency: ≥95% per plane
- Trigger capability (25 ns bunch identification)
- Radiation tolerance: (100 kRad/year) for ≥10 years
- Affordable costs

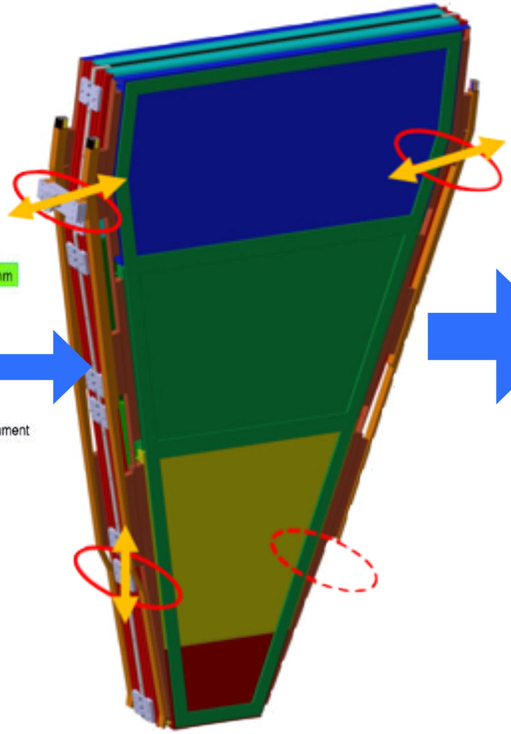
New Small Wheel (NSW) Layout

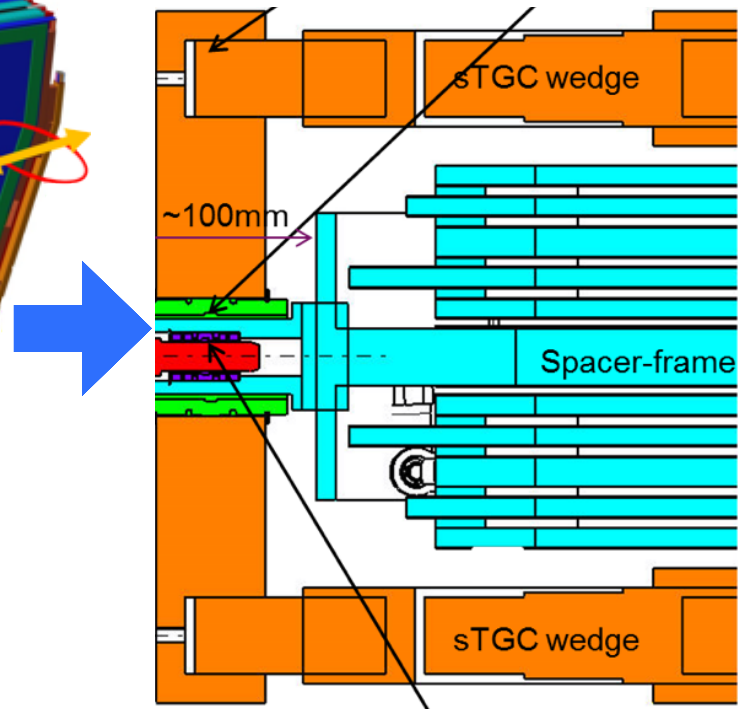
8 MM + 8 sTGC layers per NSW sector

- Two technologies: Both Micromegas & sTGC detectors will provide tracking and trigger data
- 16 Sectors per Wheel (8 large, 8 small)
- 2 Multilayers per Sector for Micromegas & 3 Multilayers per Sector for sTGC
- 8 Micromegas Layers & 8 sTGC Layers per Multilayer





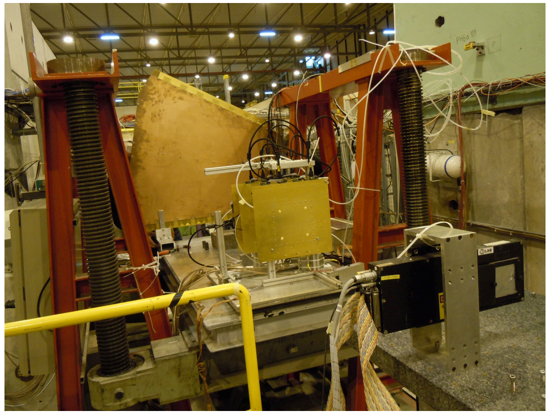




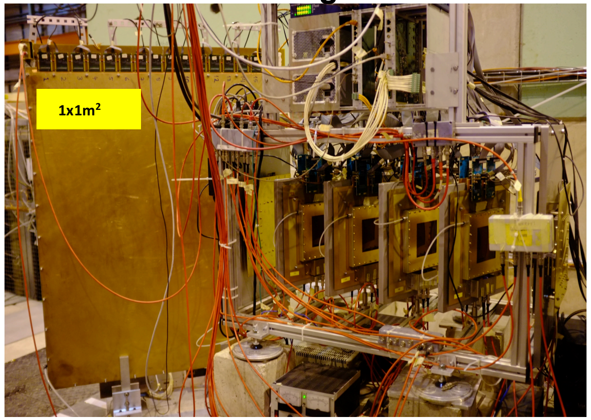
sTGC (mainly for triggering) & Micromegas (mainly for tracking) detectors, both providing tracking and triggering information, combined into a fully redundant NSW system!

Full Development Time-Plan

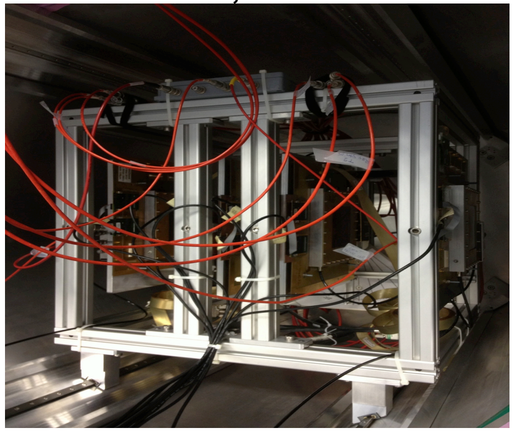
non-resistive MM, SPS/CERN, Demokritos-GR



resistive MM, SPS/CERN, Demokritos-GR, Garching-GE

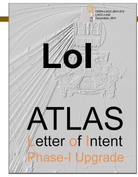


resistive MM, DESY II/DESY, LNF-IT, CEA-FR

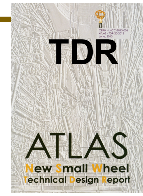


2008 2009 2010 2011 2012 2013

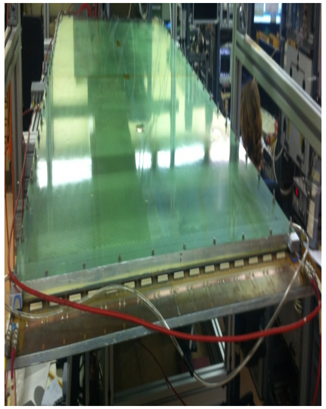
developed new MM technology



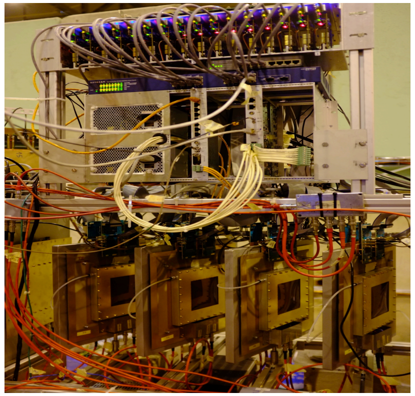
approved by ATLAS



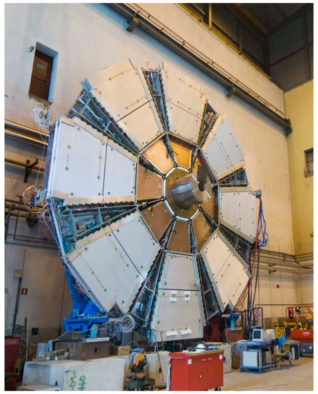
module-0 production & qualification



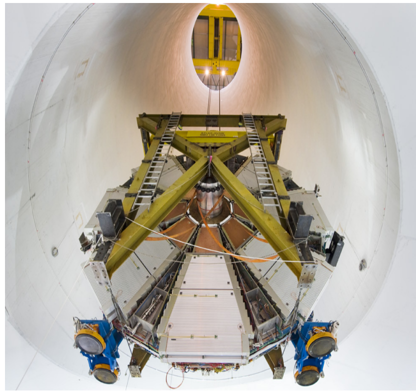
Full-production of chambers and electronics



Full commissioning on surface



Full installation in cavern



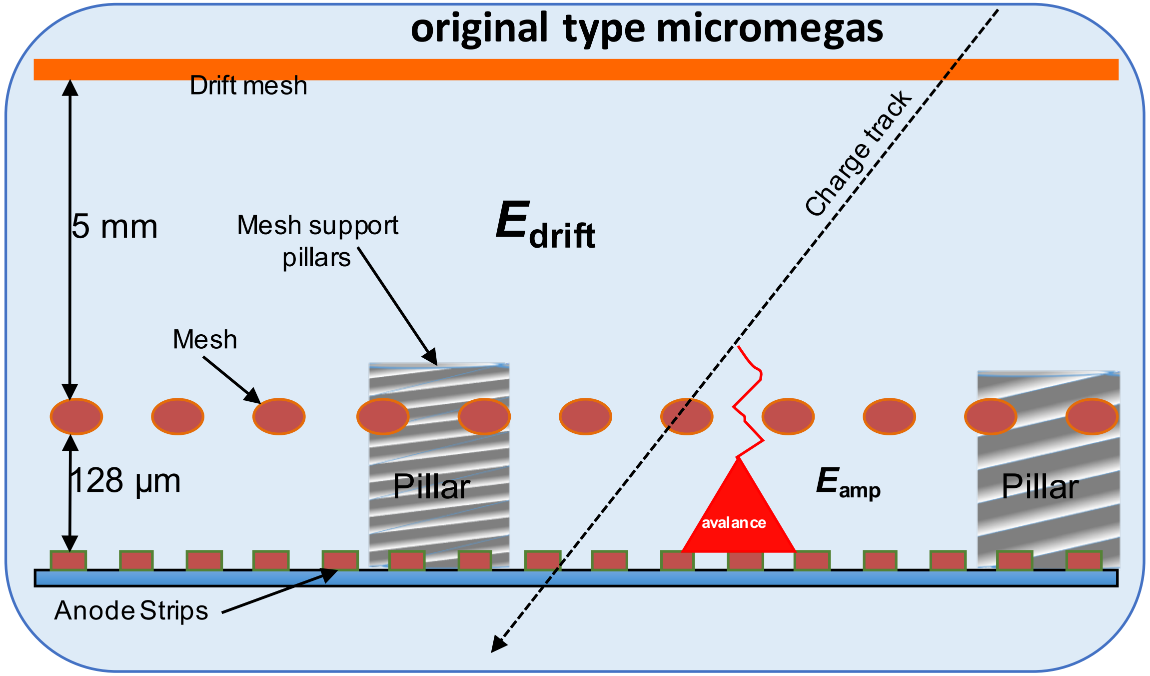
Running...

2014 2015 2016 2017 2018 2019 2020

Micromegas Detector Technology (MM) – original type

Planar structure with two asymmetric E-field regions, separated by a metallic micromesh.

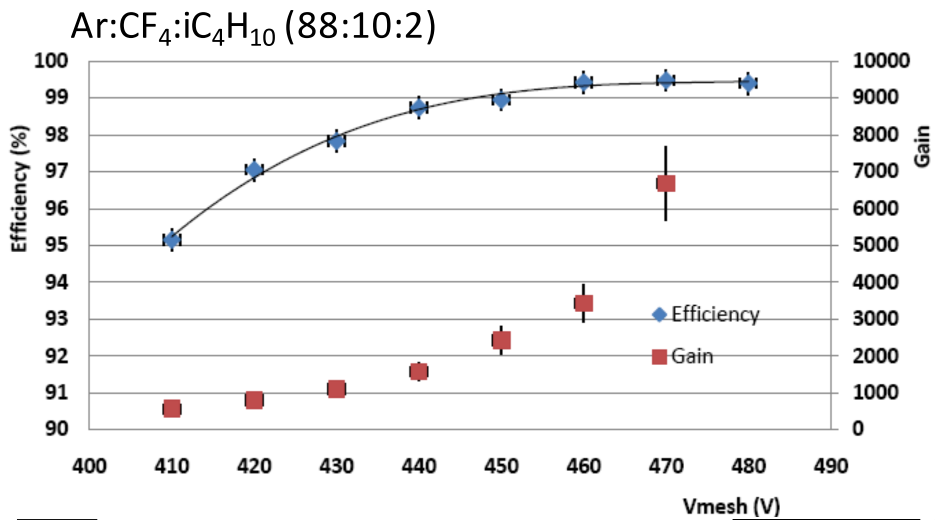
- Drift Gap (5mm), $E_{drift} \simeq 0.6$kV/cm
- Amplification Gap (128μm), $E_{amp} \simeq 39$ kV/cm
- Gas mixture Ar+7% CO_2, gain ~ 10^4

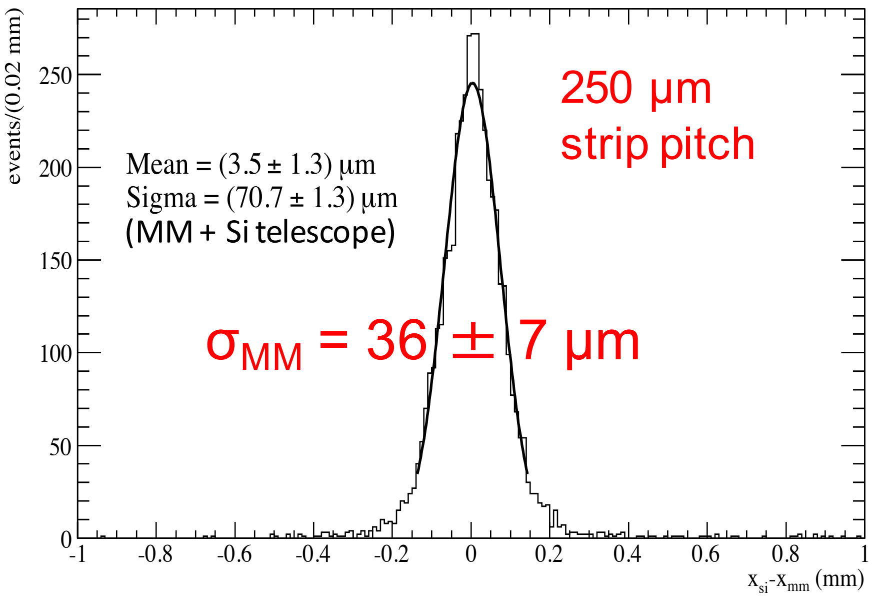


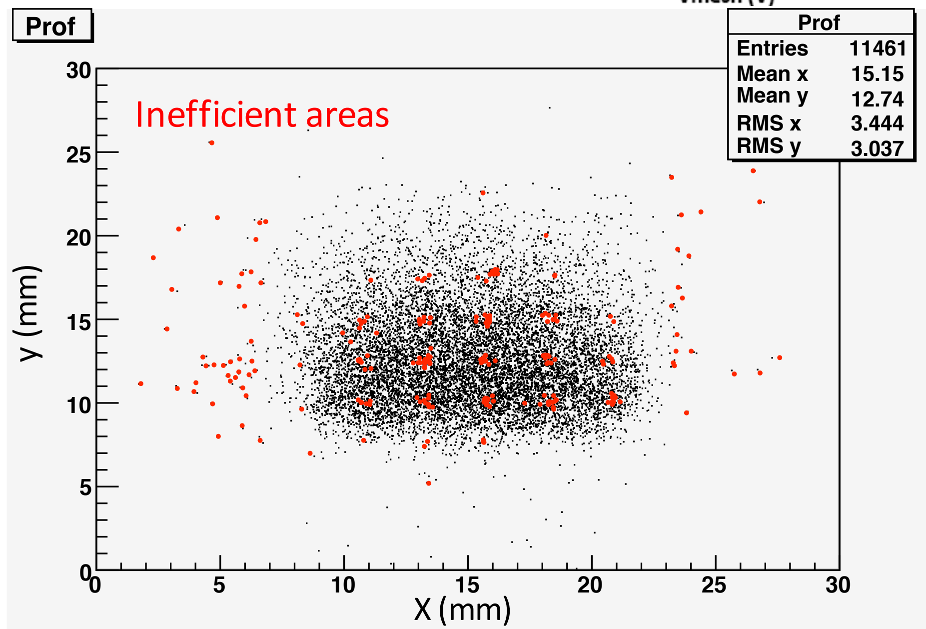
e^- drift towards the mesh (95% transparent) in ~100ns.
Avalanche formation in the amplification region (1ns) with fast ion evacuation (~200ns).

2008: Demonstrated Performance

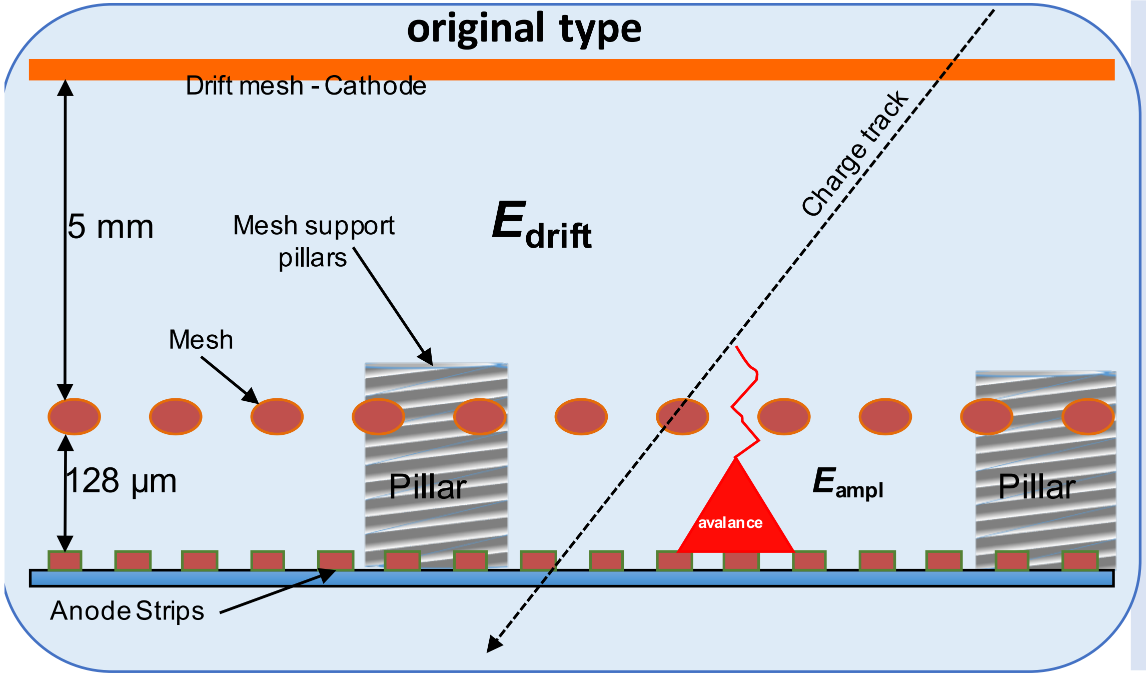
- Standard micromegas (P1)
- Safe operating point with efficiency ≥99%
- Gas gain: 3–5 x 10^3
- Very good spatial resolution
- Sparks are a problem for the operation at the LHC
  - Sparks lead to a partial discharge of the amplification mesh => HV drop & inefficiency during HV ramping up
  - The good news: no damage, despite many sparks

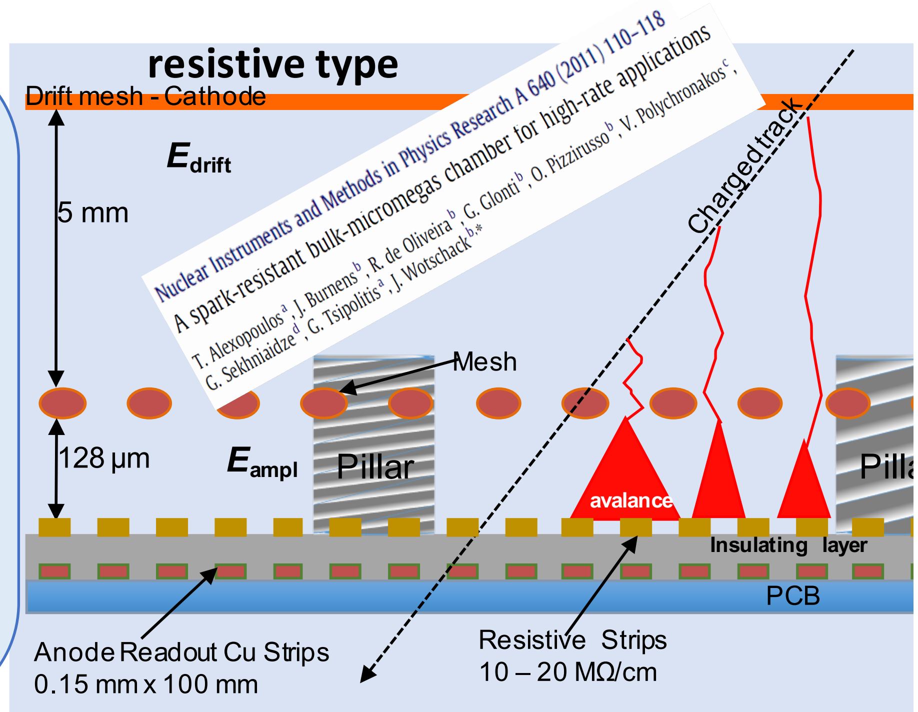






2010: Making Micromegas Spark Resistant





Tested several protection/suppression schemes

- A large variety of resistive coatings of anode strips
  - Did not manage to find a safe solution; damage after few hours or days (sometimes minutes) of operation
  - Problems cured by adding an insulating layer: R11 ++
- Double/triple amplification stages to disperse charge, as used in GEMs (MM+MM, GEM+MM)

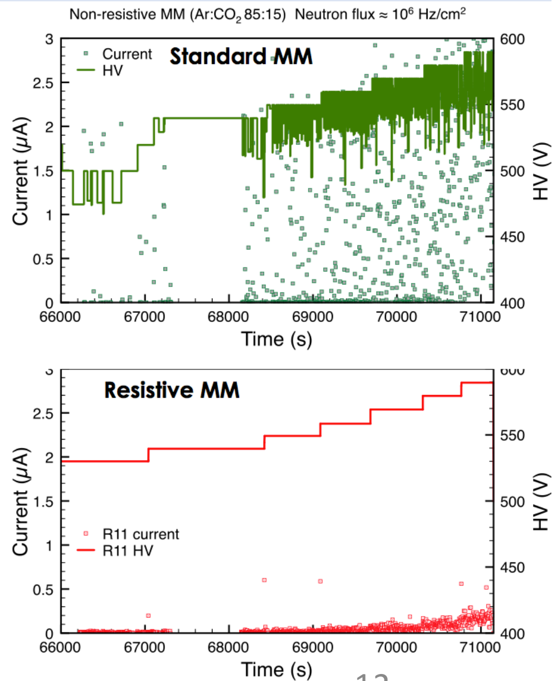
Settled finally on a protection scheme with resistive strips

Tested the concept successfully in the lab (^{55}Fe source, Cu X-ray gun, cosmics), H6 pion & muon beam, and with 2.3 MeV and 5.5 MeV neutrons

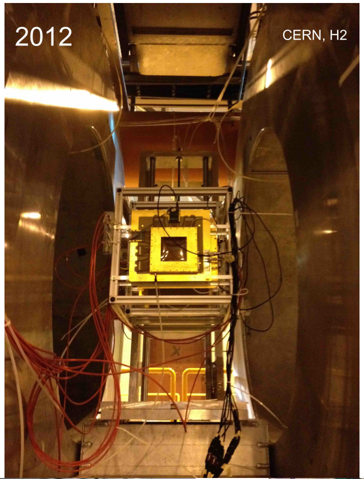
Test in neutron beam (10^6 Hz/cm^2)

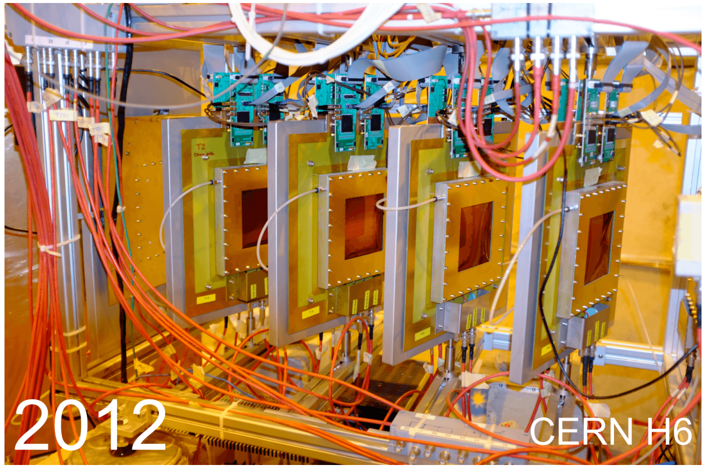
original type MM

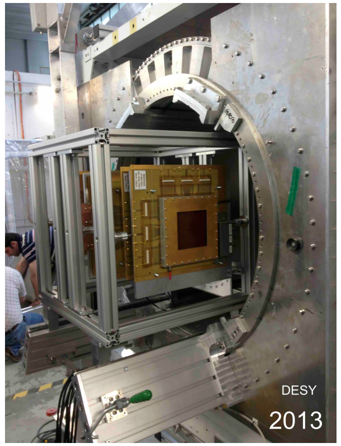
resistive type MM

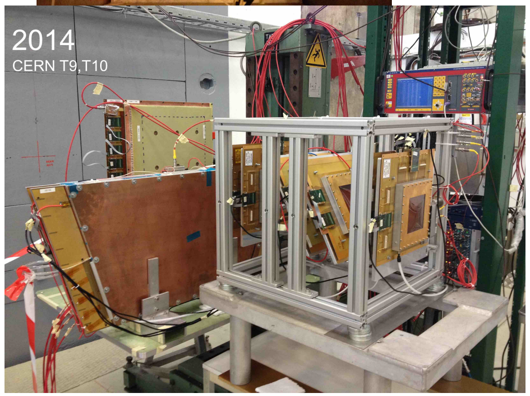


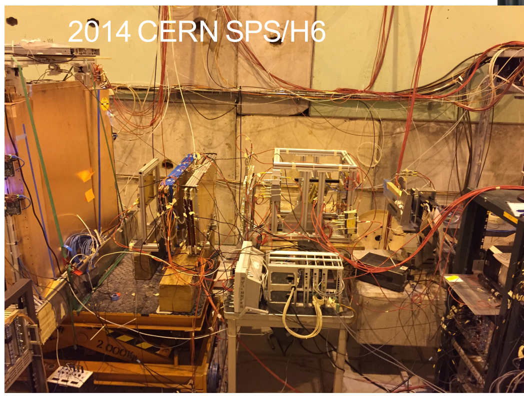
Performance Studies in Testbeams



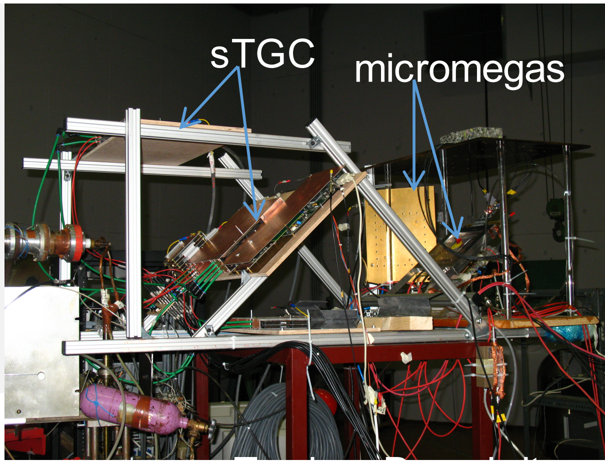


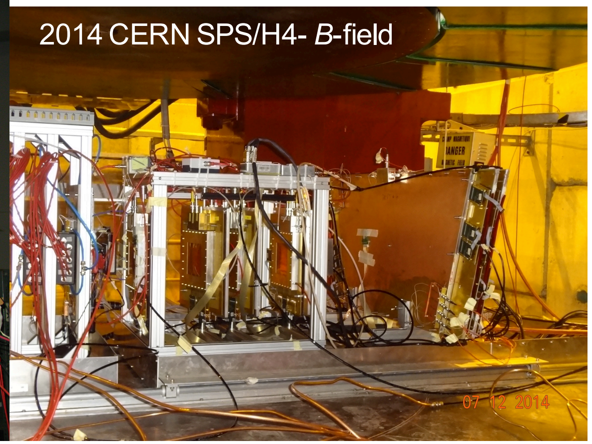






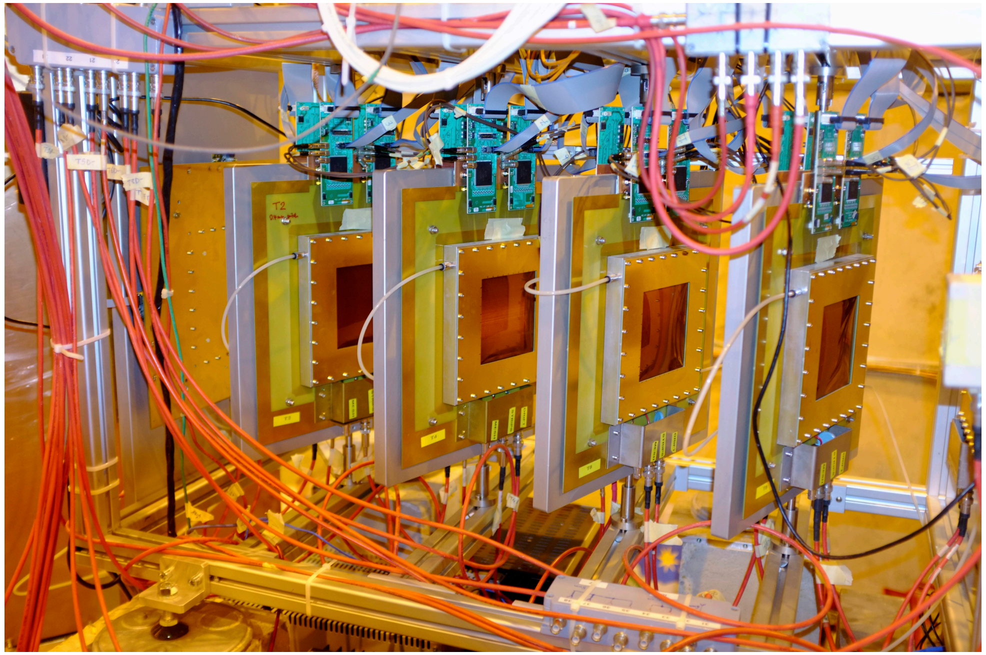
Several test beam periods (since 2008) studying different Micromegas prototypes ((non)resistive, small, large, multi-readout, multi-layer etc.) in various beam and magnetic field conditions

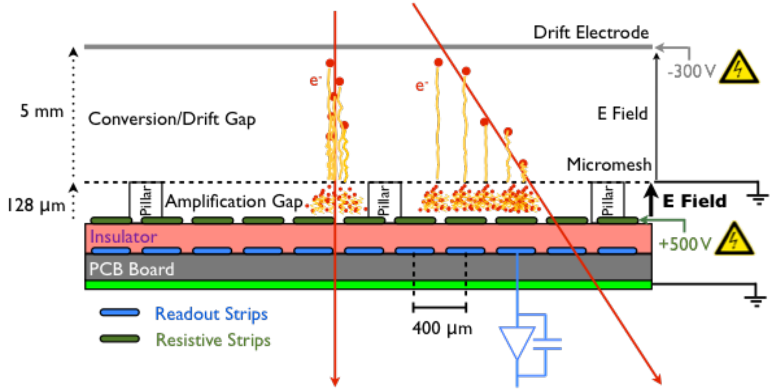


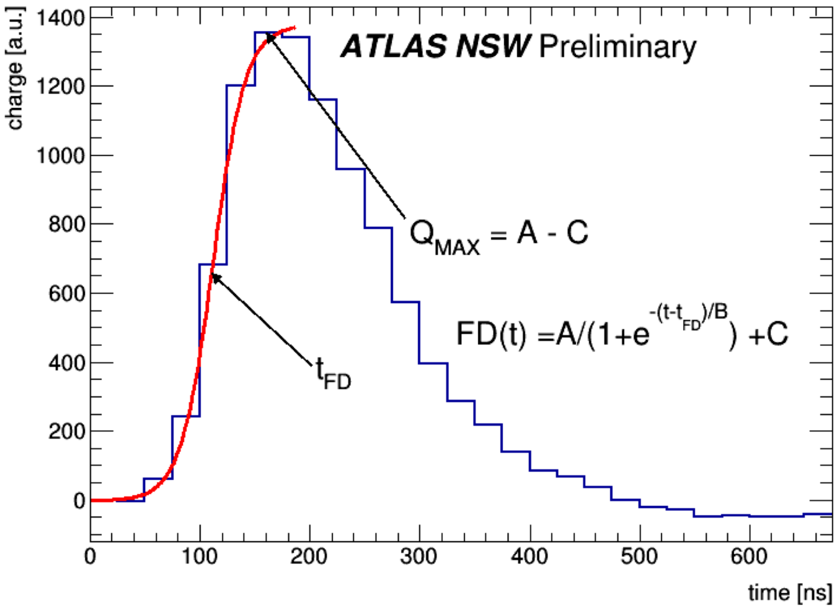


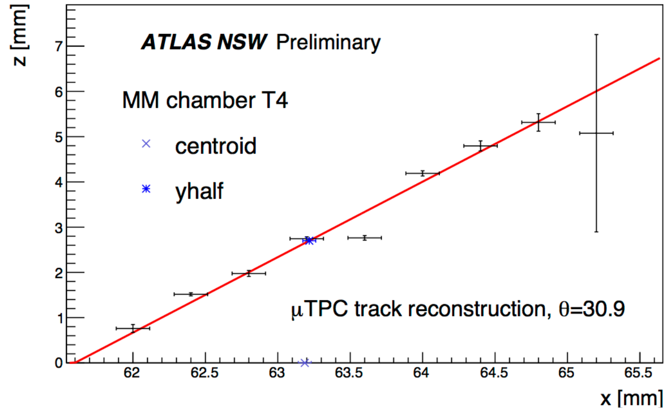
Extracting hit Information

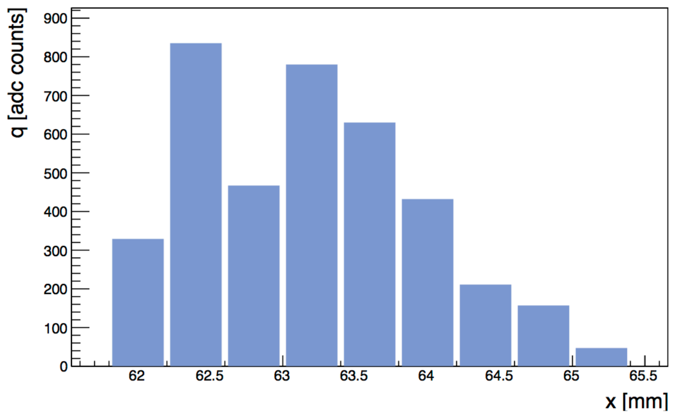
- Use APV25 and Scalable Readout System (SRS)





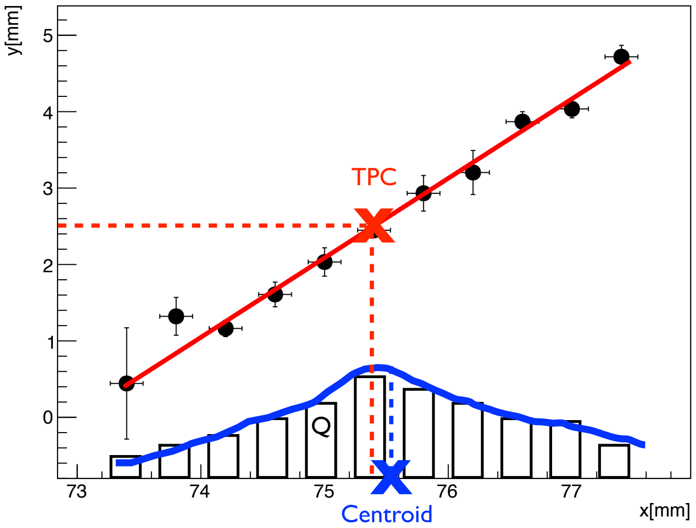






Performance Studies of the Micromegas Prototypes

- **Micromegas will be the main precision tracker of the NSW (required spatial resolution 100m).**

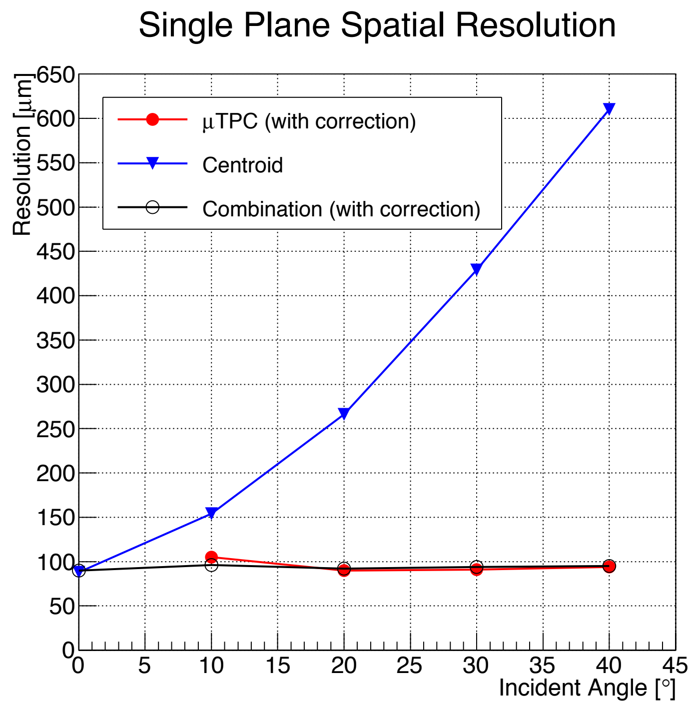


Hit & Track reconstruction
- Using charge amplitude (Centroid hit)

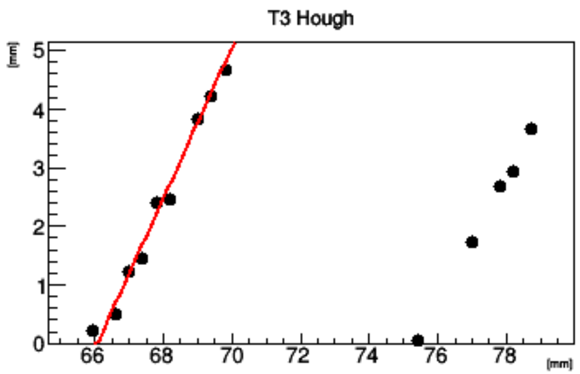
Accuracy rapidly decreasing for larger track angles.
- Using time information (TPC segment).

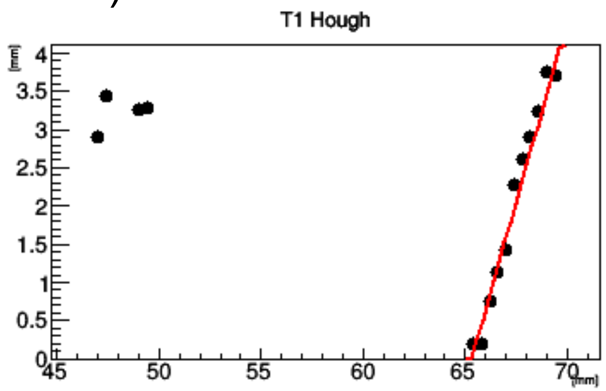
Performance improving with increasing cluster size.

Tracks expected @ NSW 8◦ to 30◦. So we are relying mostly on TPC.



Refinement of TPC recipe (Significant improvement)
- Correct for capacitive coupling between strips.
- Fine tuning of the primary e^- position assignment along the strip width.
- Implement pattern recognition techniques for track identification (Hough transform)



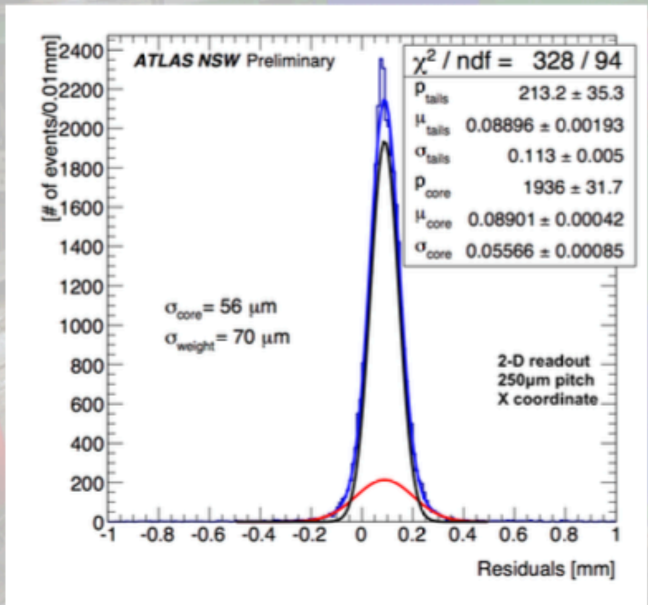


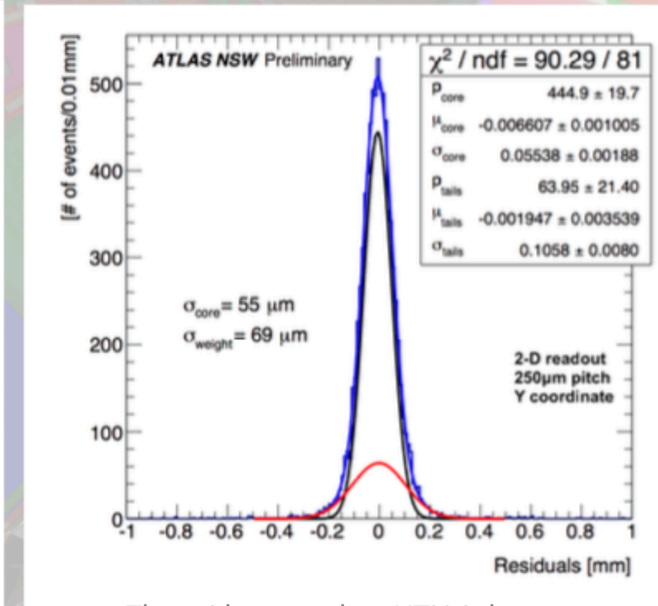
Combination of centroid & TPC provides spatial resolution < 100m independently of track incident angle!

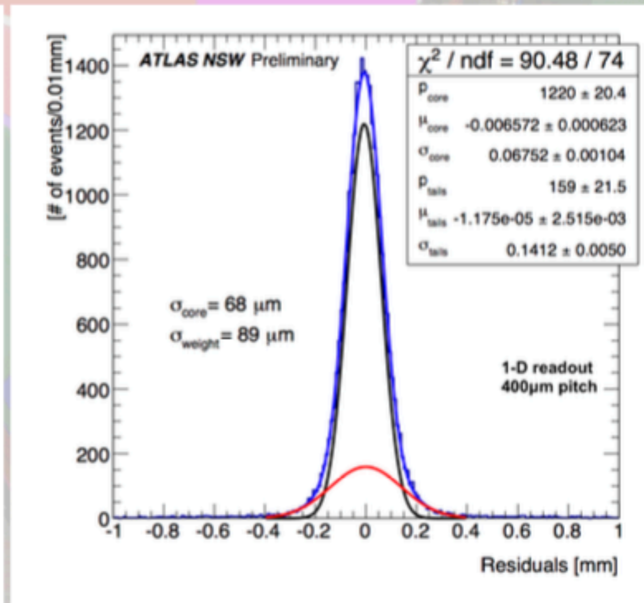
Spatial resolution for perpendicular tracks - The Centroid method

- For perpendicular tracks the, charge is most likely spread among 3 resistive strips of one cluster, assuming 400 μm strip pitch (4 strips for 250 μm pitch)
- This accounts for very precise charge interpolation for the hit reconstruction
- The average of the strip addresses, in one cluster, weighted by their charge provides the Centroid reconstructed hit position
- The spatial resolution of the Centroid hit is only limited by the granularity of the readout elements (strip pitch)

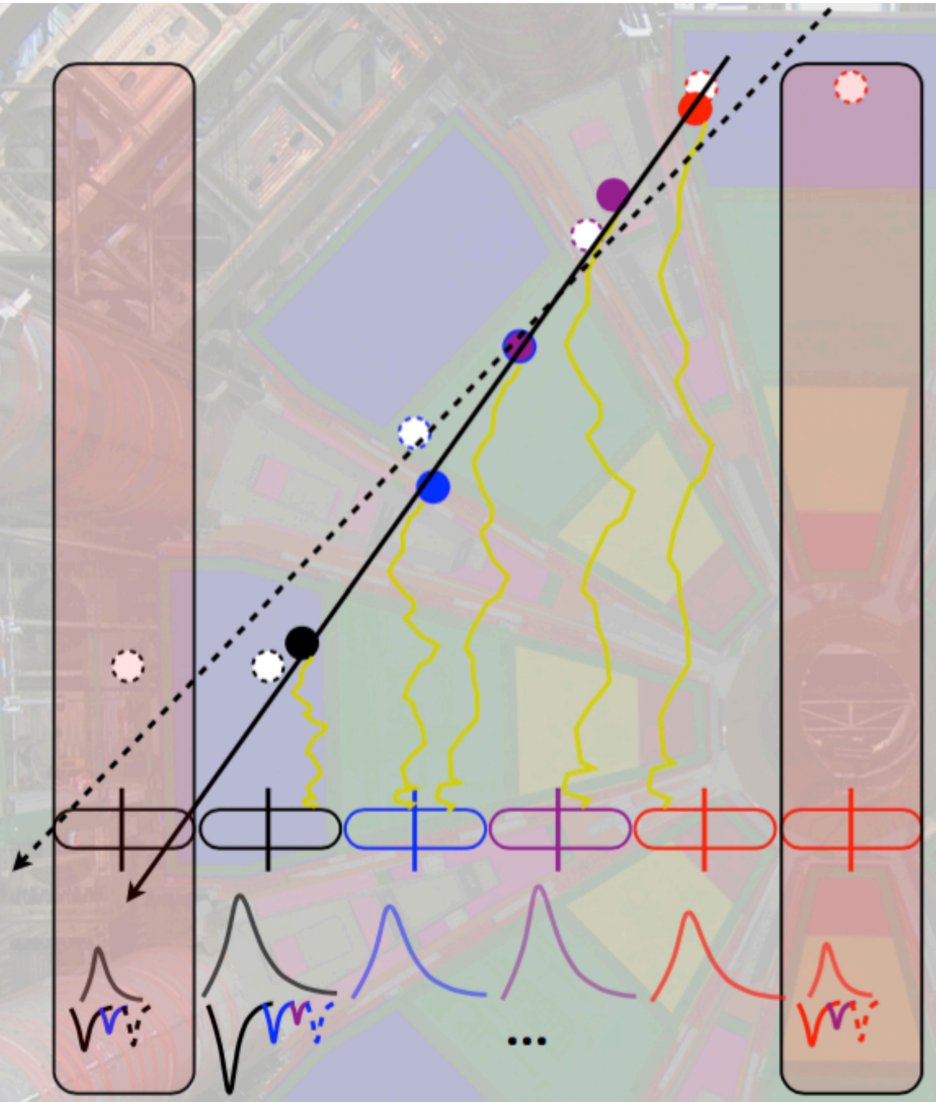
- In the case of 2-D readout chambers the y-strips direction is perpendicular to the resistive strips
- The charge, owing to its propagation along the resistive strips, is spread along several Y readout strips
- No difference in the resolution between X and Y readout strips has been observed

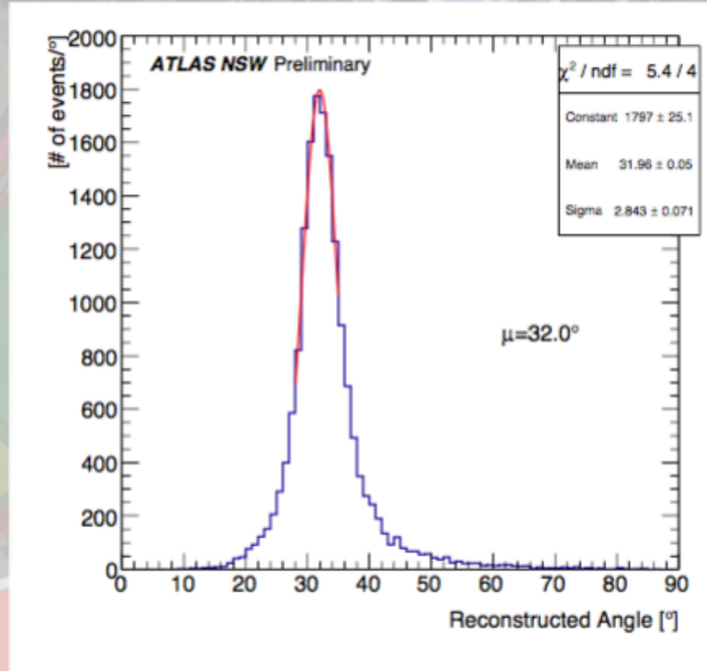


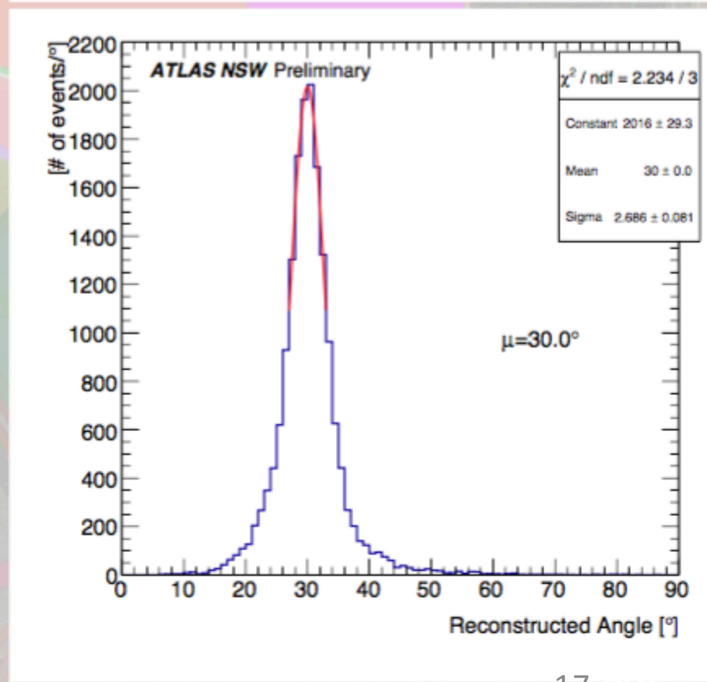




Optimizing the μTPC method







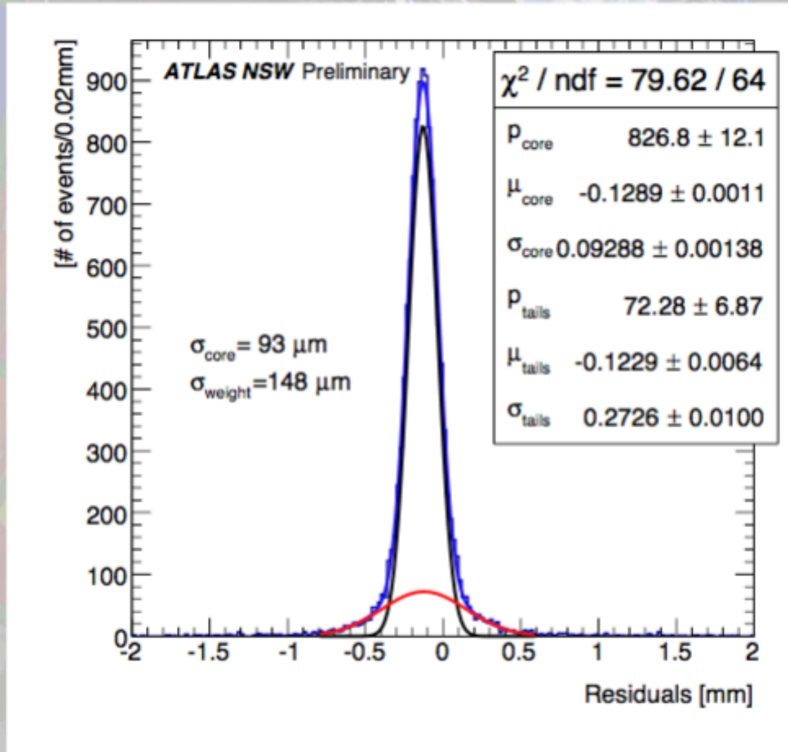
Significant Improvement of the μTPC reconstruction method:

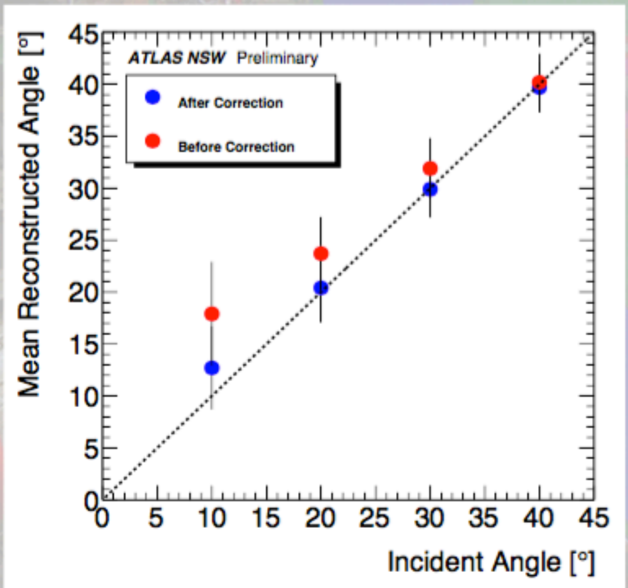
- Correct for capacitive coupling between strips.
- Fine tuning of the primary e^- position assignment along the strip width.

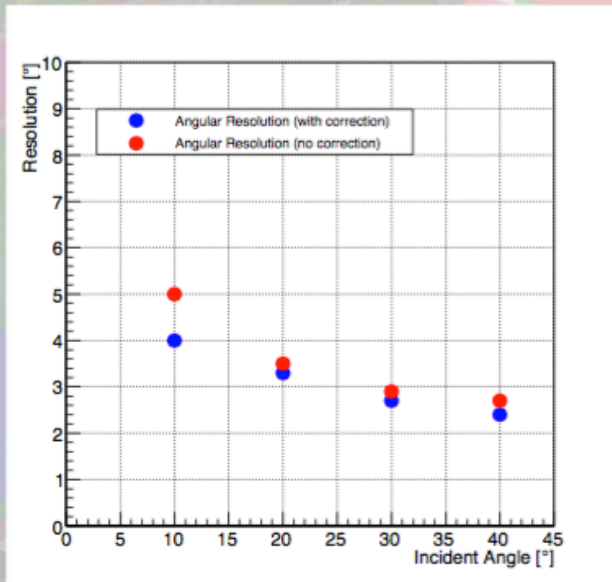
Optimizing the μTPC method

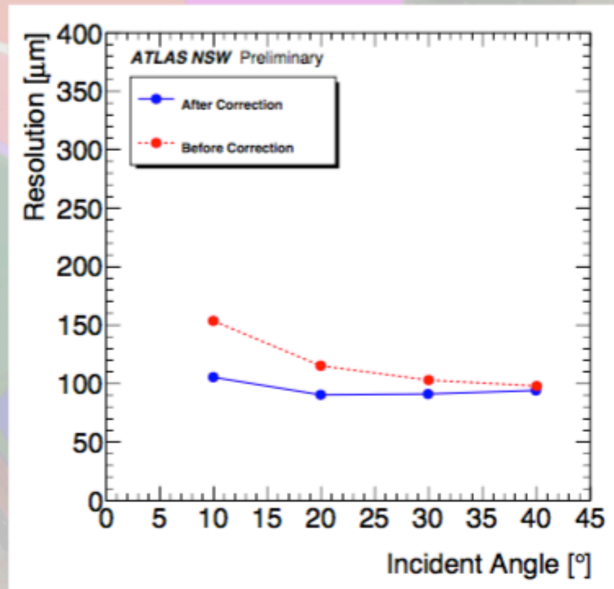
Improvement is larger at smaller track incident angles where the cluster size is smaller.

- Significant reduction the mean reconstructed angle bias due to the capacitive coupling between strips
- Improved spatial resolution per plane measurement
- Reduced uncertainty in track angle reconstruction in a single detector plane



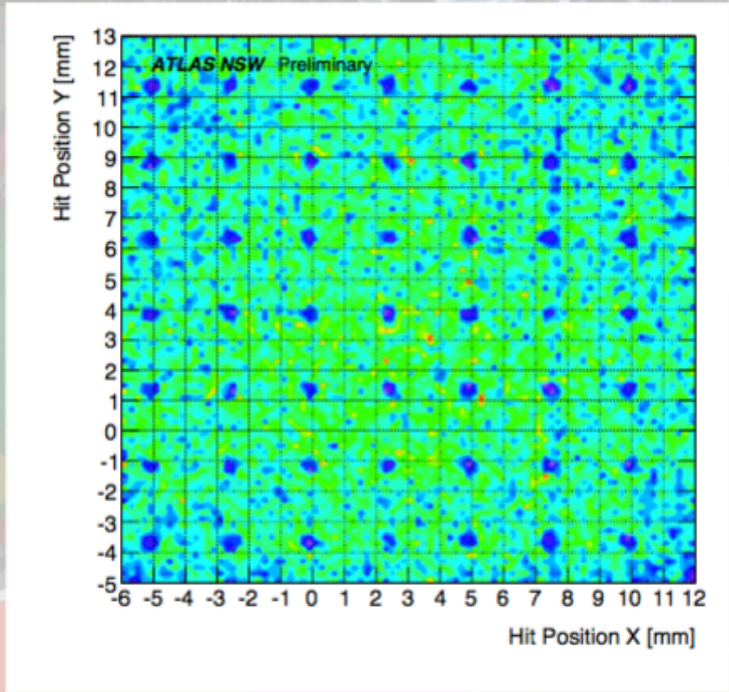


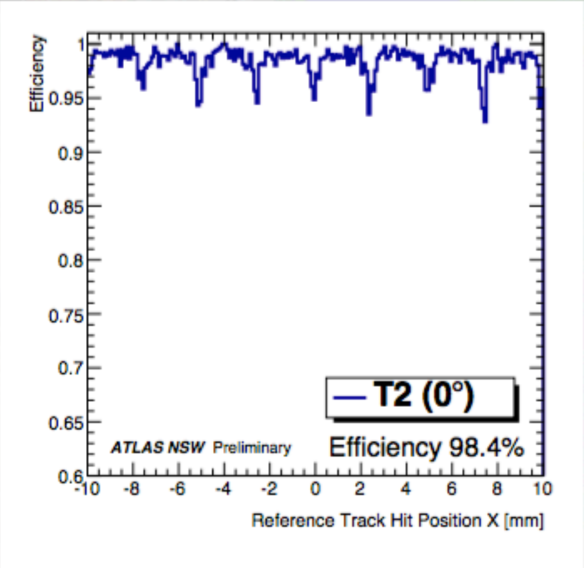


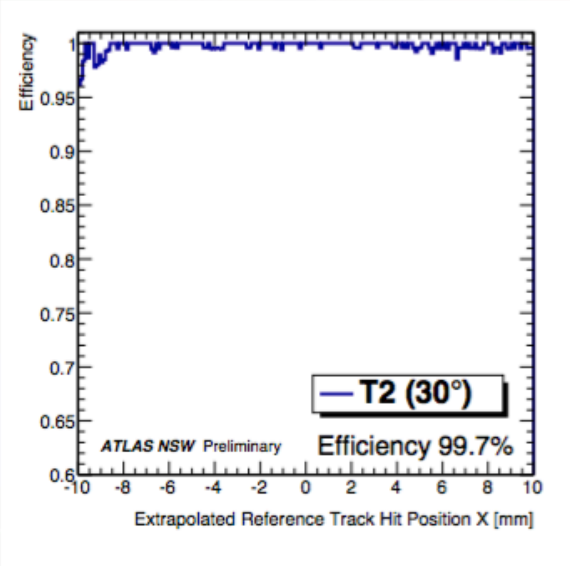


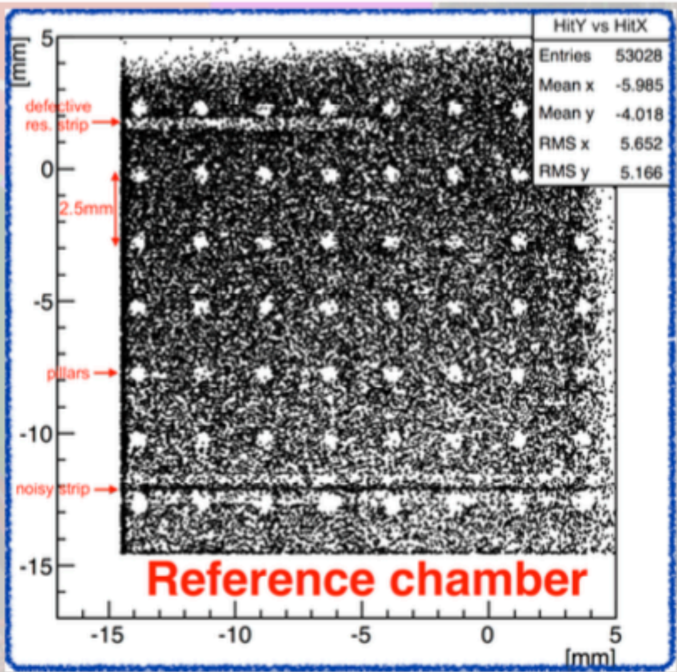
Efficiency Studies

- Measurement of the efficiency as a function of the extrapolated reference track hit position
- The efficiency dips ($\sim 5\%$) appearing every 2.5 mm, in the case of the perpendicular tracks, correspond to the pillar structure supporting the mesh
- When the chambers are inclined the particles traverse the chambers under an angle inducing signal in a larger number of strips compared to the 0° case. In this case we expect efficiency to be unaffected by the pillars
- Bonus : Owing to the excellent spatial resolution other defects or inefficient areas can be spotted!



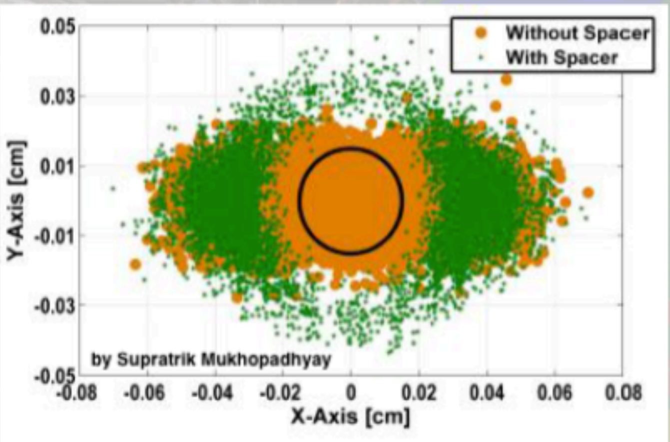


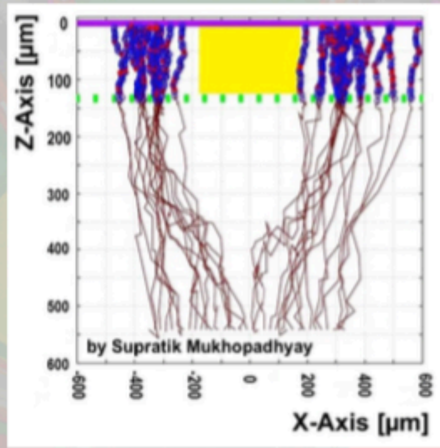


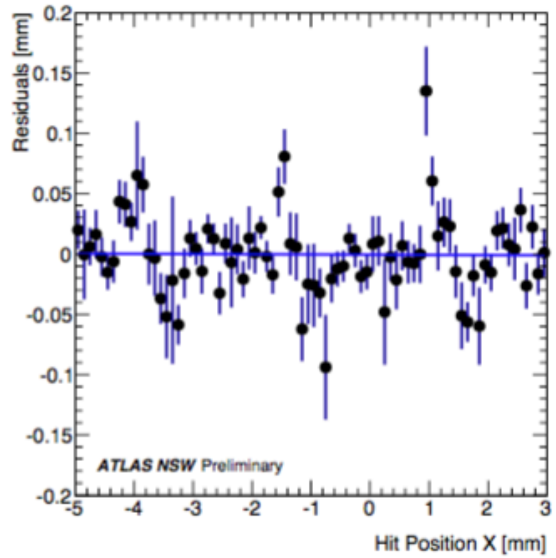


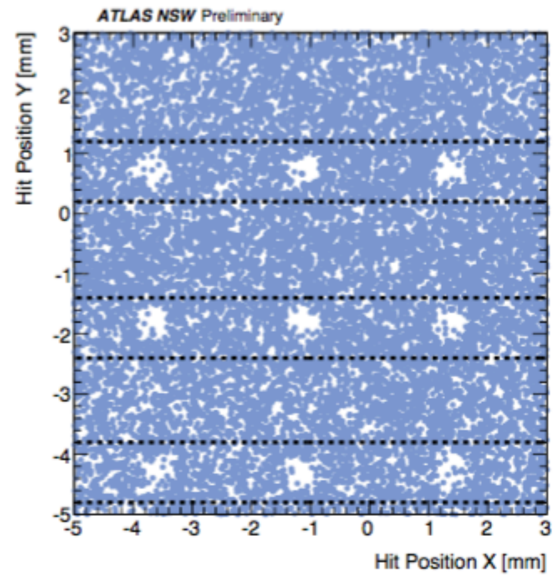
Study of the pillar effects – Pillars are not so innocent!

- The presence of pillars locally distorts the electric field lines
- Apart from the efficiency the pillar structure affects also the hit reconstruction introducing a bias in the hits reconstructed in their region.

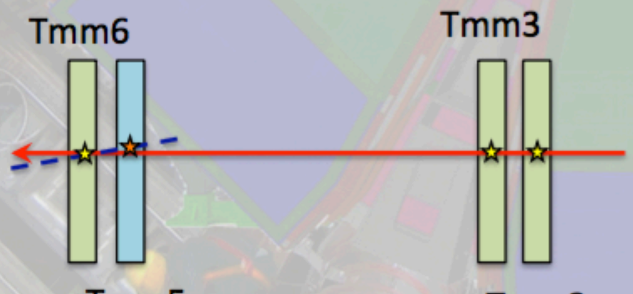






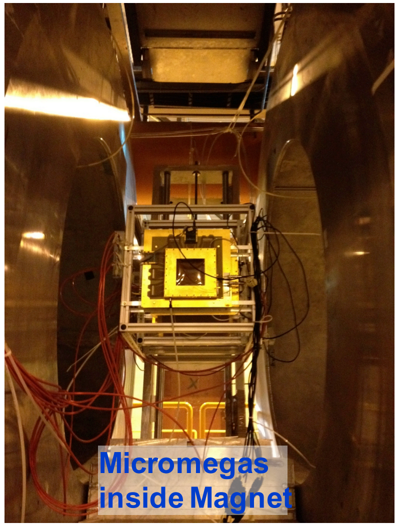


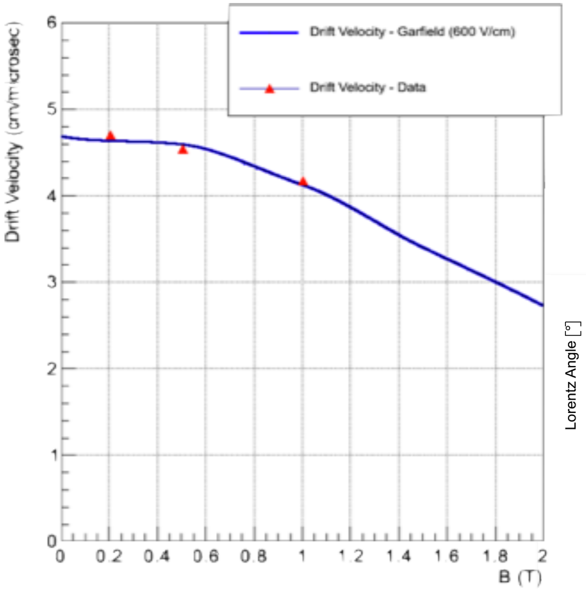
- This effect (bias) is studied calculating the residuals between a reference track and the reconstructef hit in a Tmm chamber
- Bias in each each pillar region with a maximum deviation of $\sim 150\mu m$.



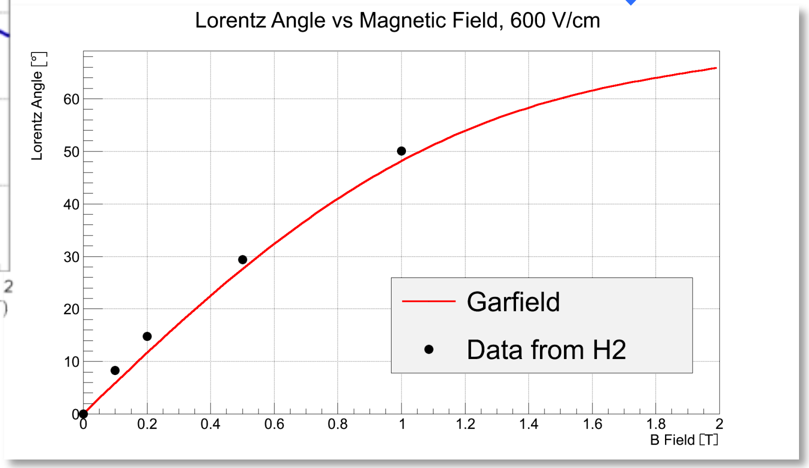
Micromegas Performance in *B*-field

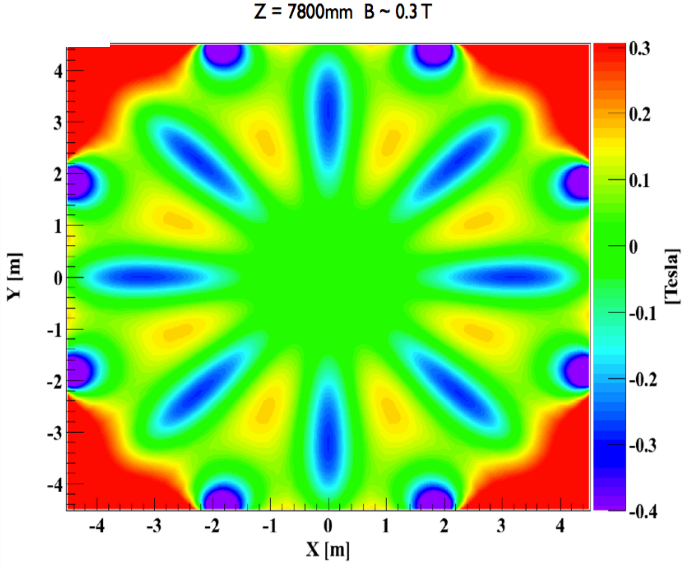
- ATLAS New Small Wheels will be operated in a mixed directional ***B*** field up to 0.4 T.
- Micromegas chambers tested successfully in a magnetic field up to 1 T showing no performance degradation.
- Lorentz angle & drift velocity measurements are in agreement with simulation.





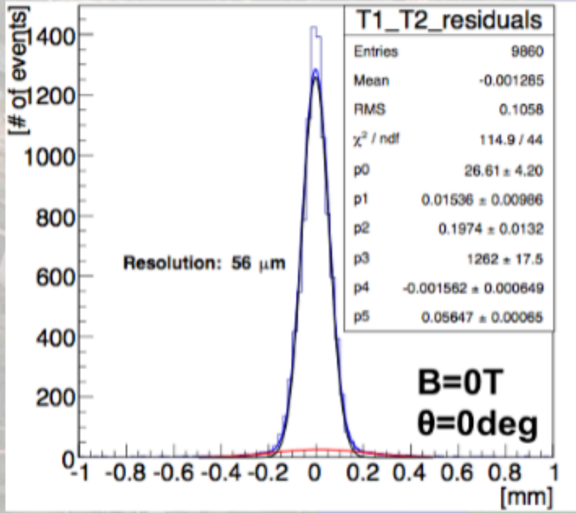
Lorentz angle from perpendicular tracks; E_{drift} = 600V/cm

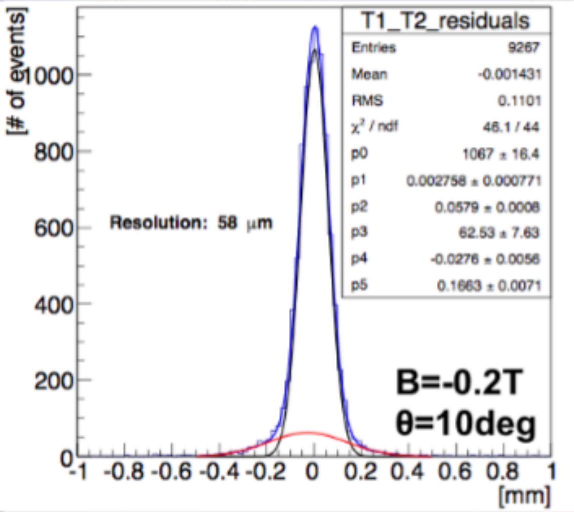


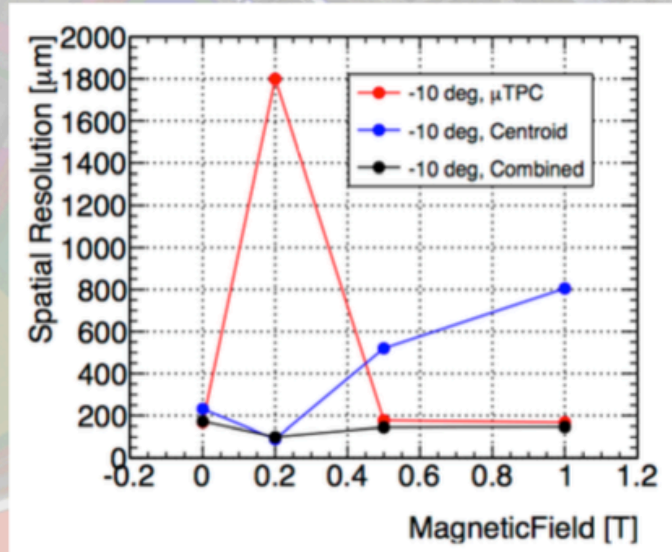


ATLAS End-Cap Toroid field

Micromegas Performance in *B*-field: Spatial Resolution

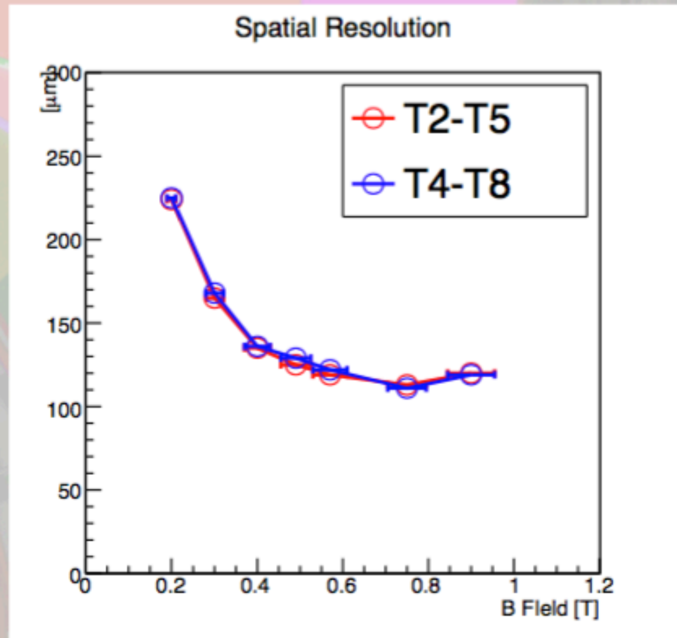






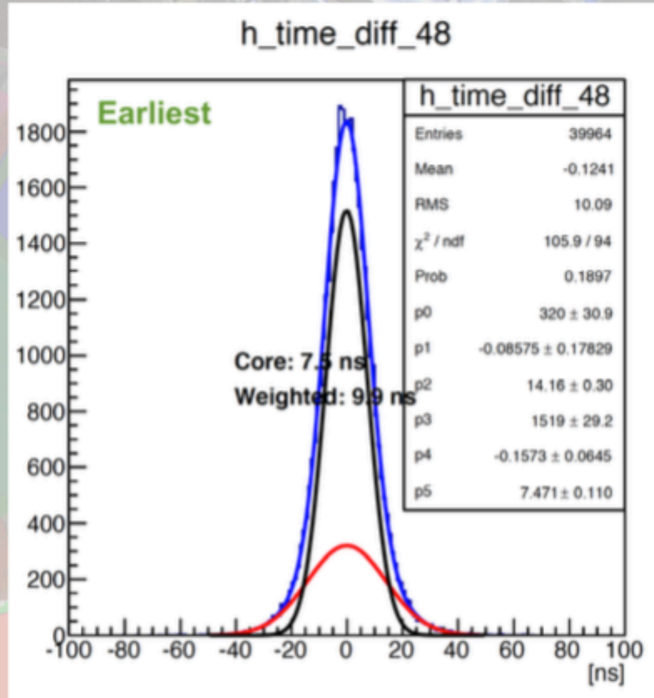
Spatial resolution has been measured as a function of the magnetic field intensity to be compatible with expectations

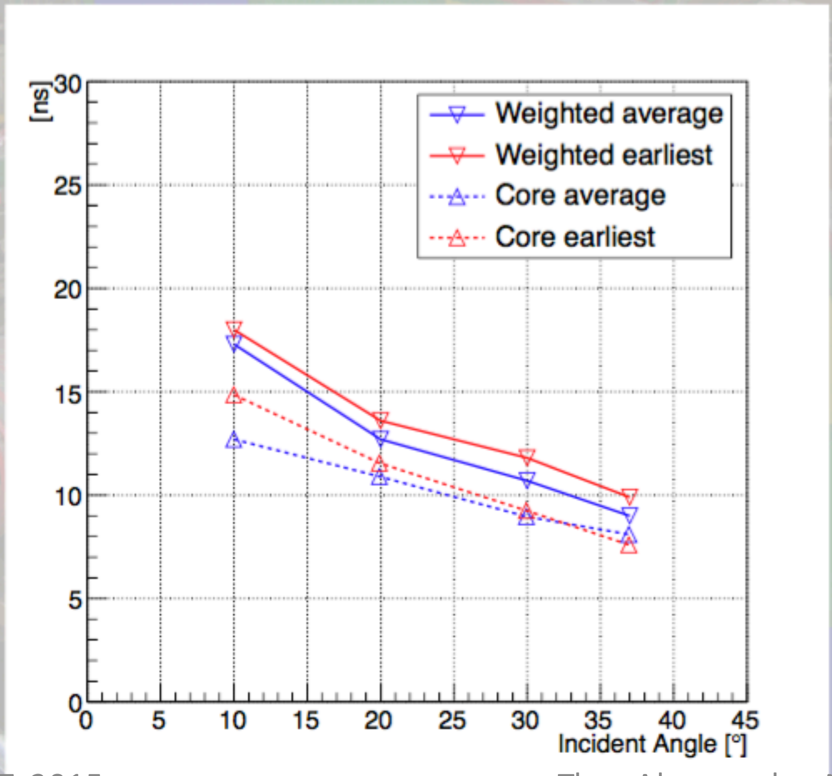
- The values obtained with the different reconstruction techniques follow similar trends to the no magnetic field case (Lorentz angle $\simeq$ μTPC inclination angle)
- Slight degradation due to the larger drift paths of the ionization charges
- When the Lorentz angle cancels out completely the track inclination angle the performance measured is exactly the same as in the no magnetic field case with perpendicular tracks.

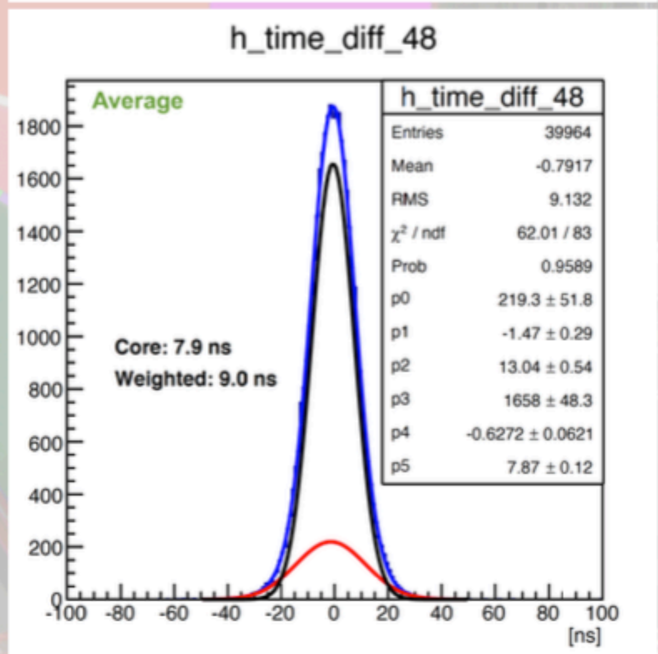


Micromegas timing studies

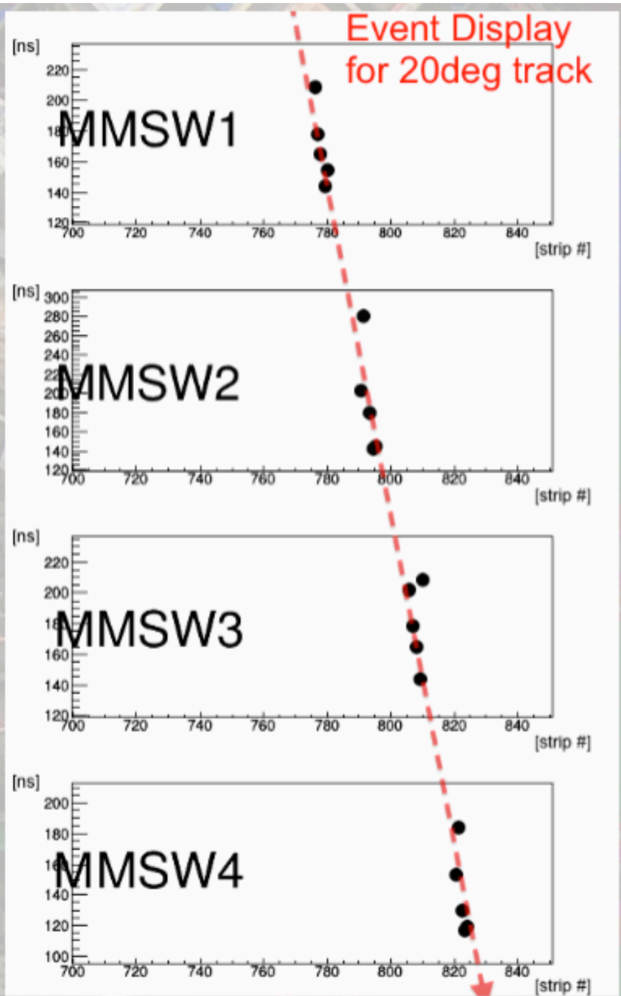
- Using the time difference between two MM chambers the single plane timing resolution is measured to be better than 10 ns for large chamber inclination angle
  - The earliest arrival time in each chamber per event
  - The average of all the arrival times in each chamber per event
- The measured timing resolution is a convolution of the MM detector response, the timing uncertainty of the front-end electronics and the uncertainty introduced by the timing extraction procedure (analysis dependent)

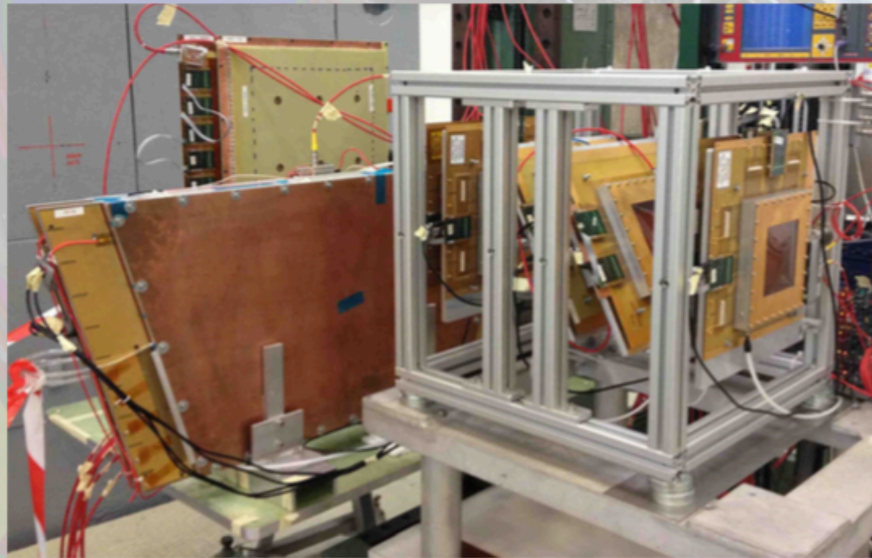




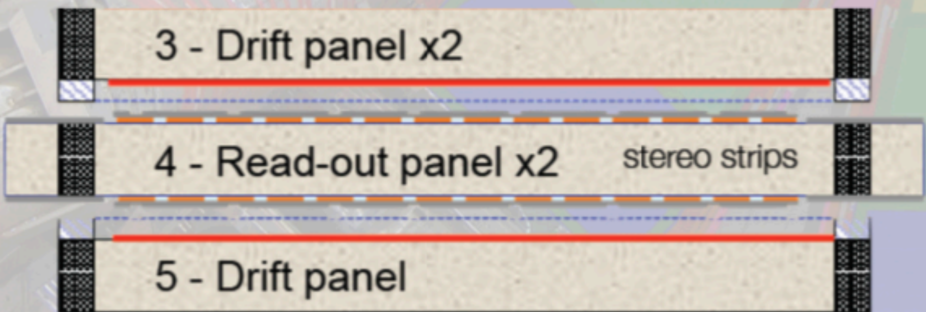


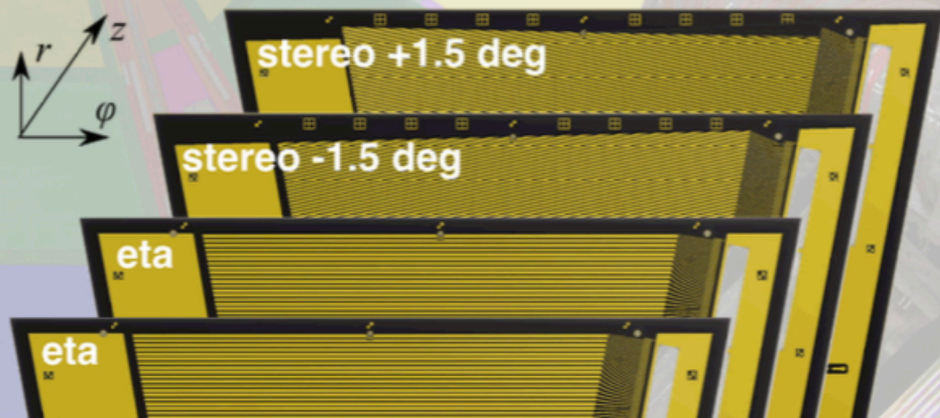
MMSW Performance Studies in Testbeams – Large scale MM (1/2)



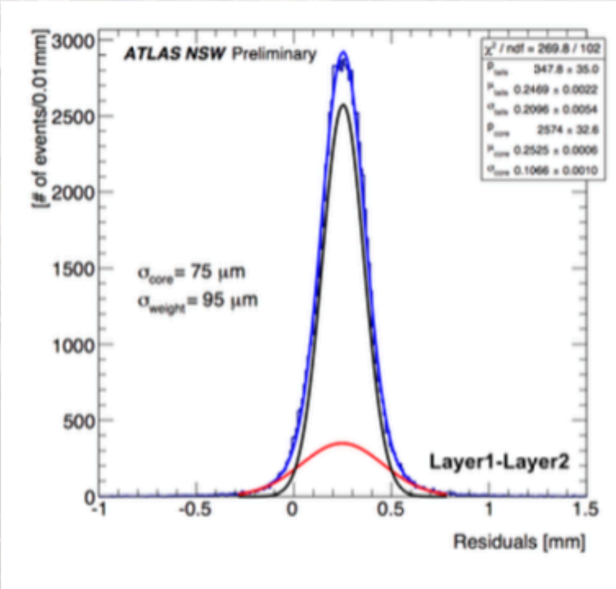


- Test of the MMSW 4-plet in p, π^+ beam ($6-9\,\mathrm{GeV/c}$) using a micromegas reference telescope (CERN, PS T9-10, August-October 2014).
- First 4-plet prototype following the NSW specifications with stereo readout strips ($415\,\mu\mathrm{m}$ pitch)

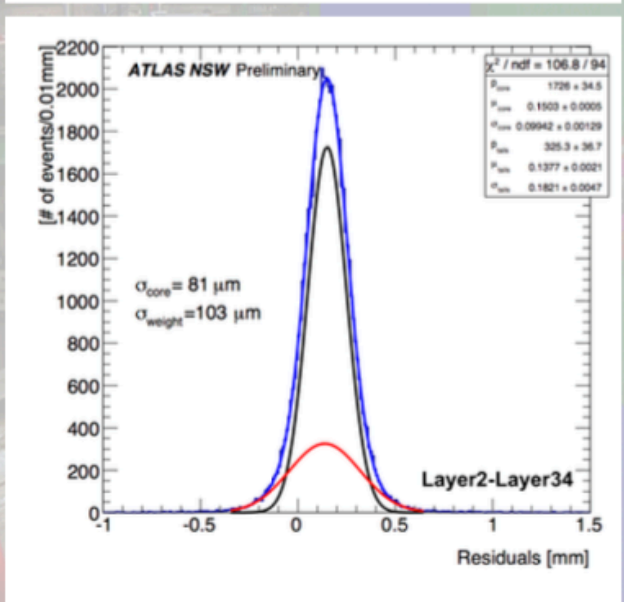


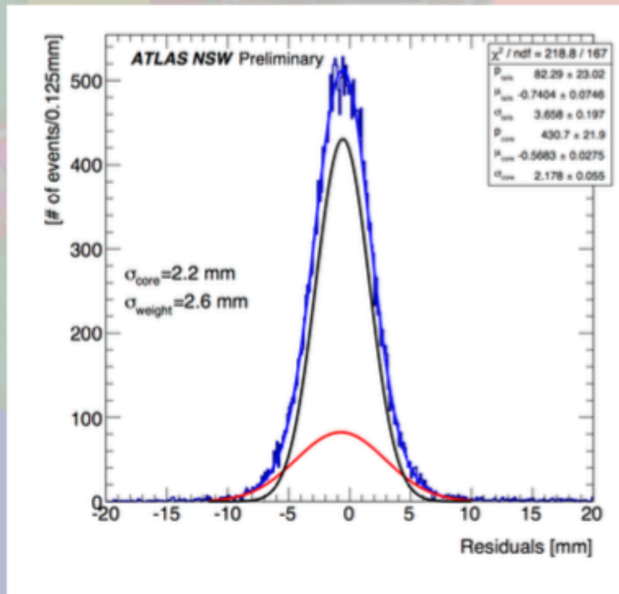


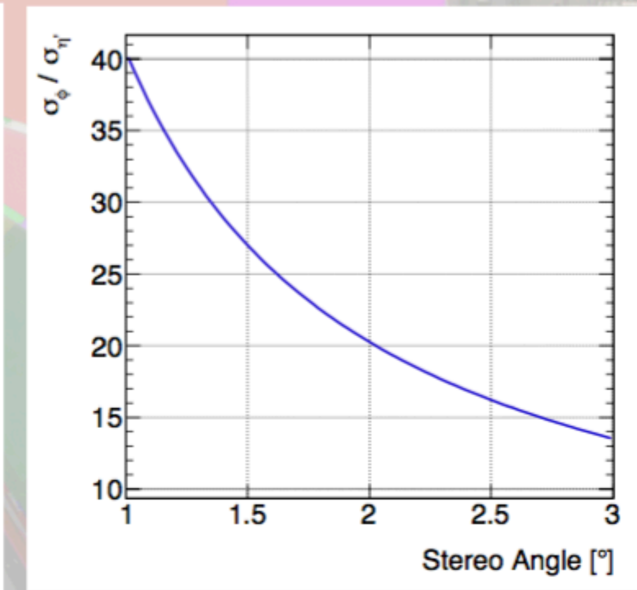
MMSW Performance Studies in Testbeams – Large scale MM (2/2)



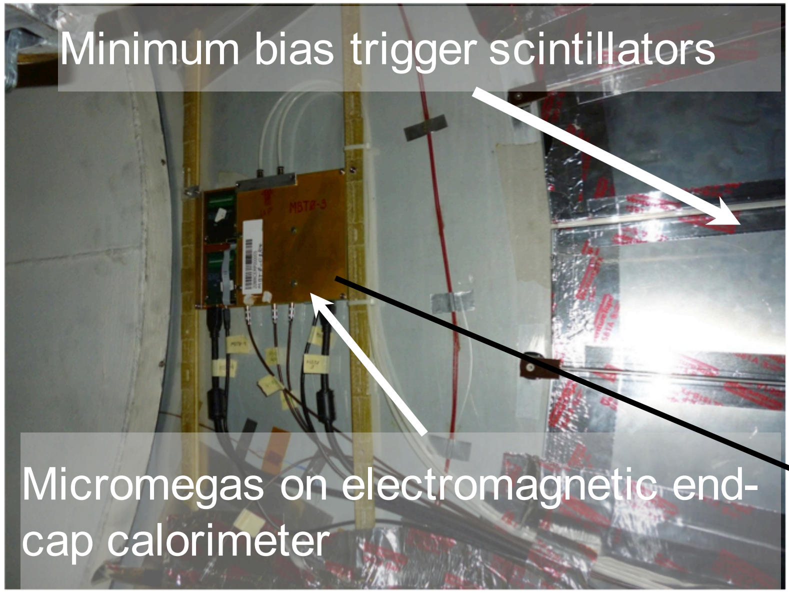
- 98% efficiency measured for all four layers
- Using the two first layers with parallel readout strips the spatial resolution for the precision coordinate was measured at 75 μm
- Combining the information of the two stereo layers the the precision and the perpendicular to it hit coordinates can be reconstructed
  - 80 μm resolution for the precision coordinate (larger distance between 2-34 layers compared to 1-2)
  - 2.2mm for the second coordinate (in accordance with theoretical expectations)

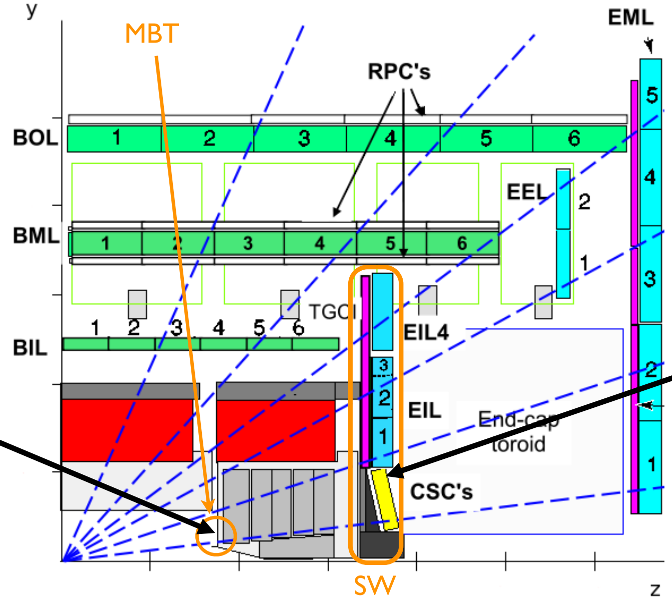


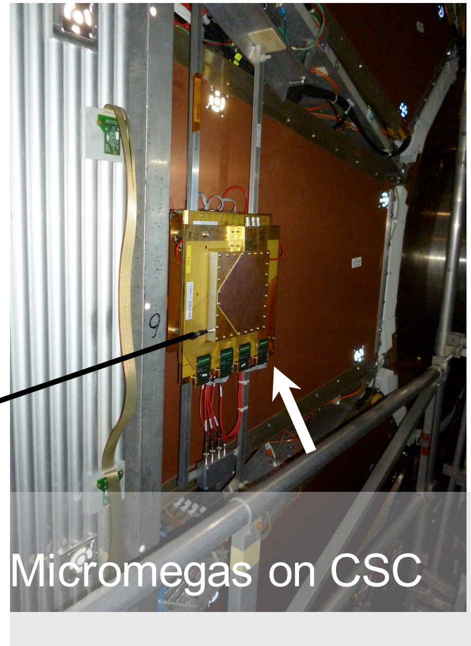


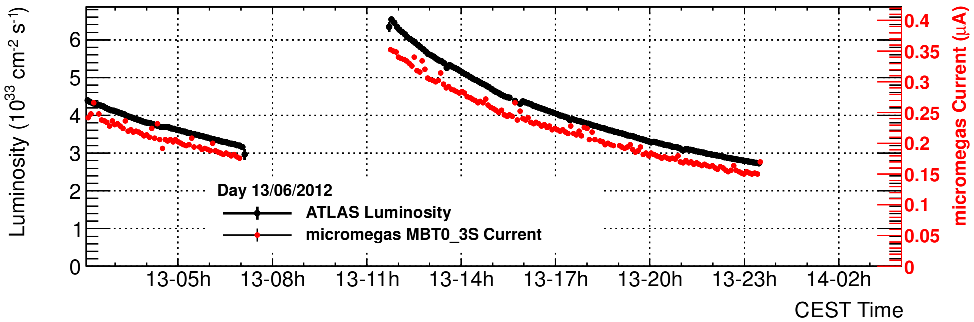


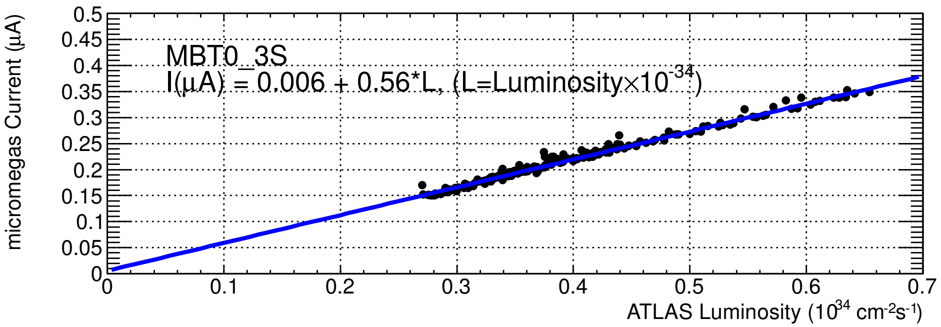
Micromegas Performance in ATLAS



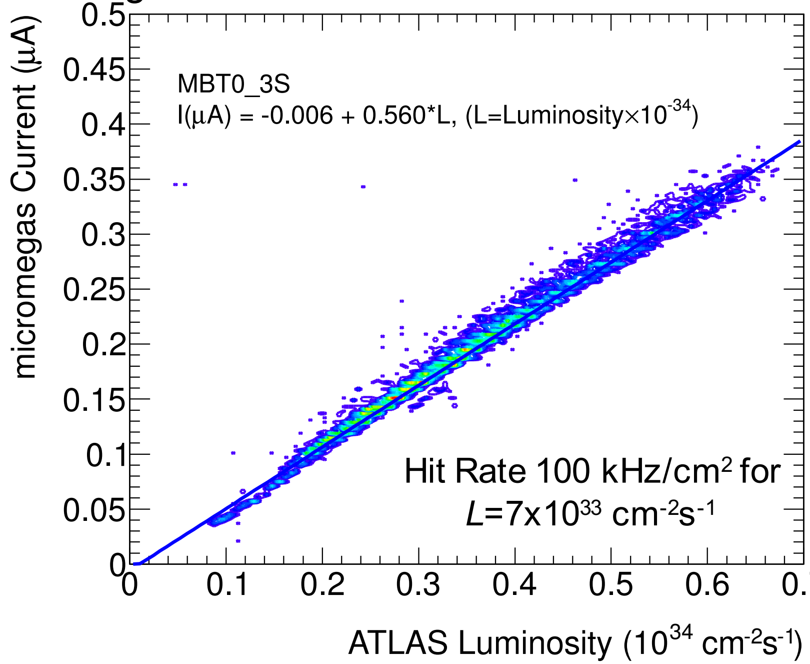




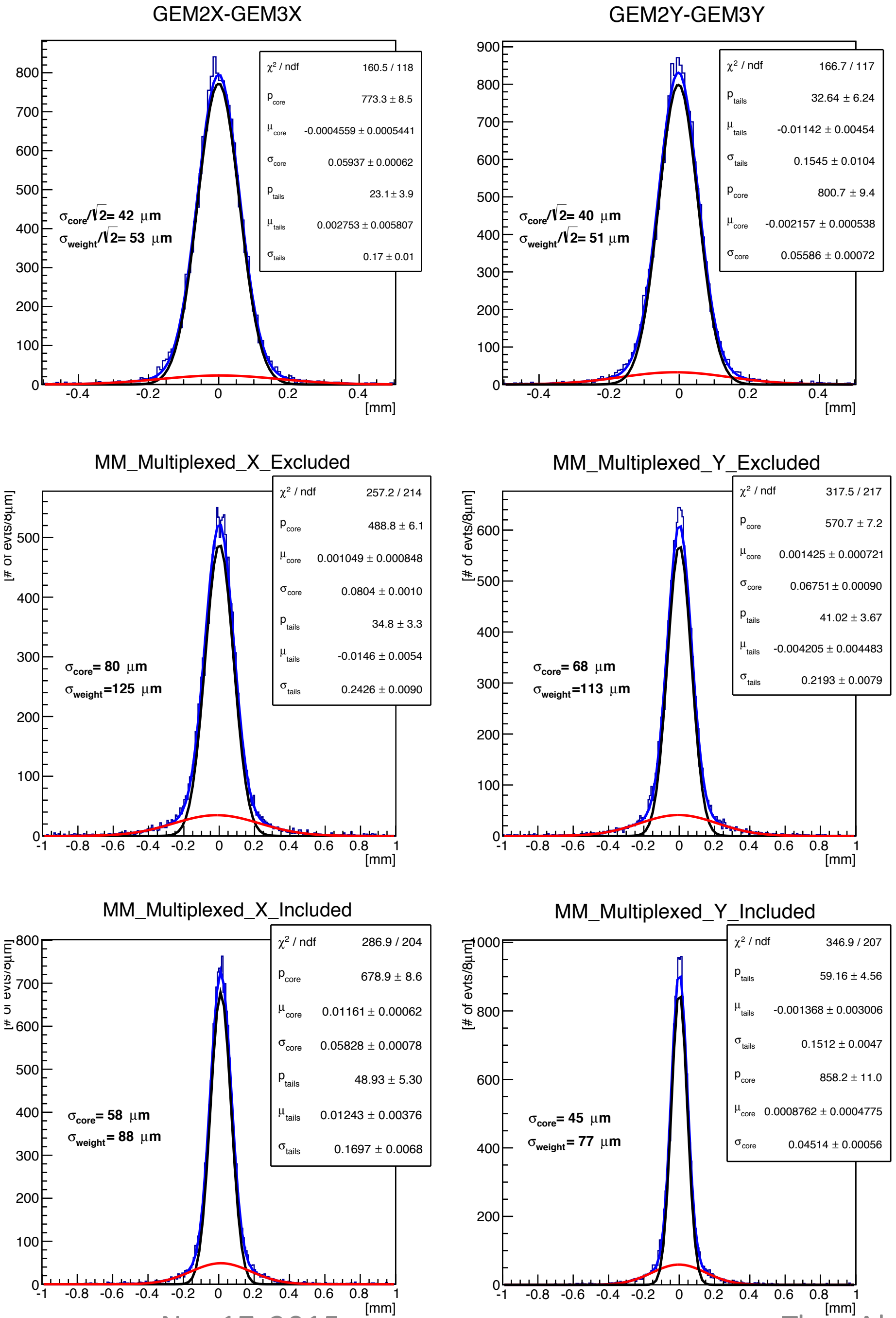


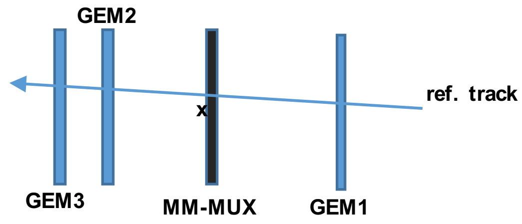


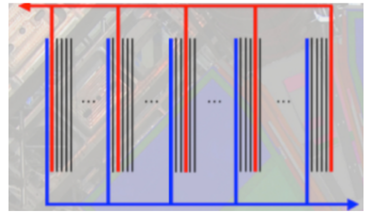
Micromegas Current Measured versus Luminosity



Test of MM prototype with multiplexed readout strips

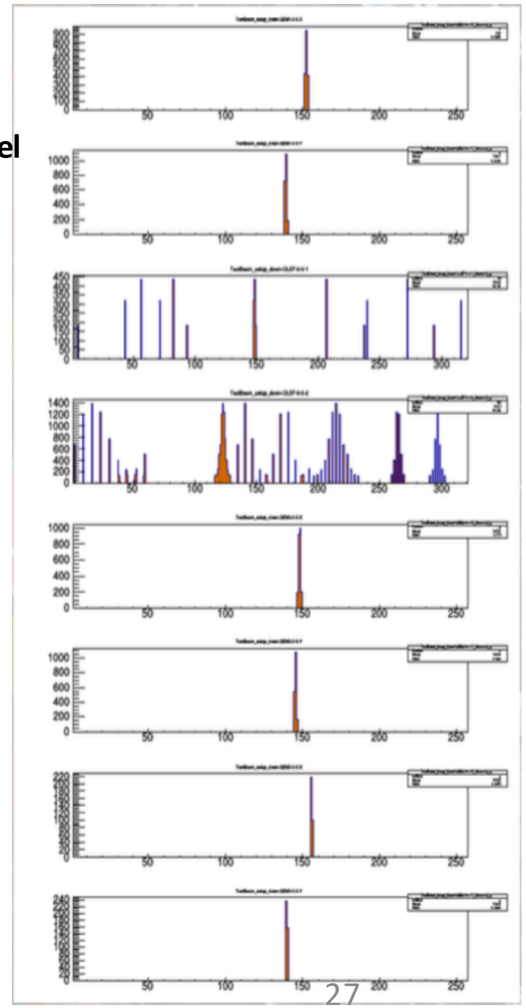






MM-MUX

- **Novel idea for reducing the number of elx channels in large scale experiments**
- **First test of 2-D MM-MUX by a factor 5**
- **Real cluster identification requiring consecutive strips shows very good efficiency**
- **Spatial reolution measured at the level of 63 µm**



Summary

- **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 Micropattern Gaseous Detector (MPGD) technology, Micromegas, for the first time in a very large scale experiment.
✓ Production of Micromegas planes to cover a total active area of 1200 m^2!

- **Extensive performance studies show that Micromegas fulfill the ATLAS requirements**

✓ Excellent spatial resolution (< 100μm) independent of the track incident angle.
✓ Studies inside magnetic field do not show any sign of degraded performance. Chambers perform flawlessly with magnetic field intensities up to 1T.

- **First test of the ATLAS-like prototype (MMSW 4plet) was very successful**

✓ Reconstruction of the precision coordinate with an uncertainty of ~75 μm.
✓ 2nd coordinate reconstruction using stereo readout strip configuration performs as expected, spatial resolution 2.2 mm.

Next years are expected to be even busier, series production, development of new electronics & testing, following the NSW project schedule…

Some History within ATLAS Experiment

- The ATLAS micromegas project started in 2007 after a brain-storming meeting organized at CERN by the ATLAS Muon System. In this meeting Ioannis Giomataris presented the micromegas concept as a potential detector technology for a future upgrade of the ATLAS muon system.
- It is fair to say: Not too many people believed in it at this time … and it took a lot of work to convince our colleagues in ATLAS of the contrary
  - “Too many sparks …”
  - “How to scale a detector of the size of a hand to several square meters?”
- However, a few of us saw a number of promising features of this technology, in addition to their excellent (not only high-rate) performance that had, by this time, already been proven, e.g., in COMPASS.
- As particularly strong points we saw:
  - Potential for industrial production
  - Relatively simple construction
  - Relatively low costs
- So we started the MAMMA R&D activity to develop micromegas detectors for the New Small Wheels of the ATLAS detector.