ARISTOTLE UNIVERSITY
OF THESSALONIKI

The New Small Wheel Upgrade Project of the ATLAS Experiment and the Greek Contribution

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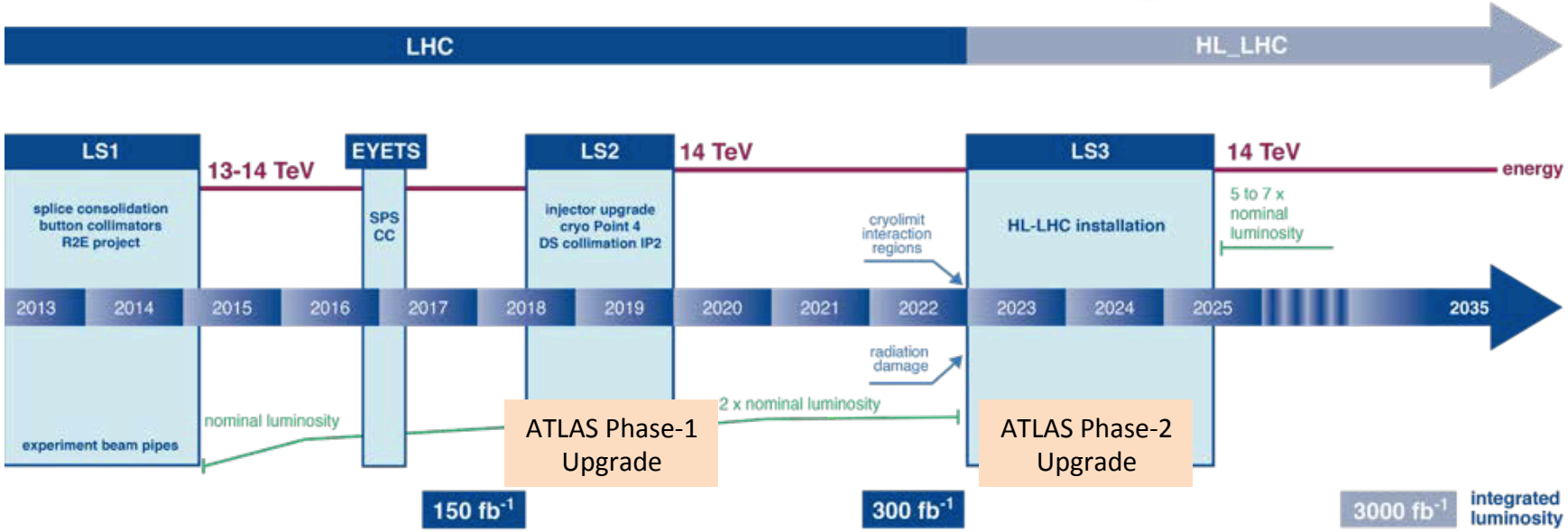
for the ATLAS Greek group

HEP 2018, Recent Developments in High Energy Physics and Cosmology
Athens, 29th March 2018

Outline

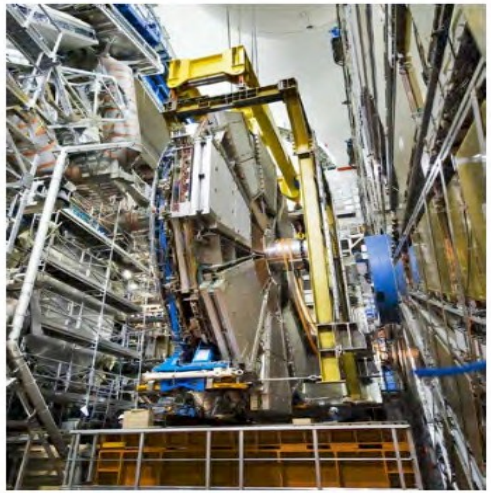
- Introduction: LHC and ATLAS Upgrade Program
- Limitations at High Rate - Why a New Small Wheel ?
- New Small Wheel Chambers and Detector Technologies.
- Greek contribution to the NSW project

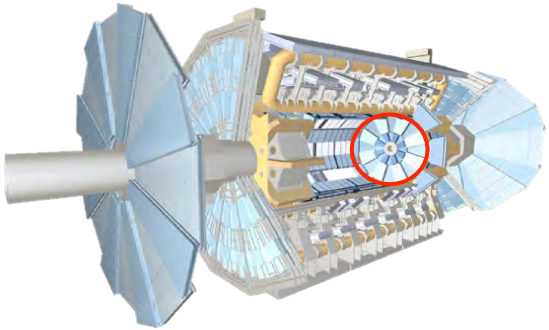
LHC / HL-LHC Plan



- Phase-1
  - Luminosity: $L = 2 * 10^{34}\ cm^{-2}s^{-1}$
  - Requirements for the trigger rate:
    - Level-0 @ 1 MHz
    - Level-1 @ 100 KHz
- Phase-2
  - Luminosity: $L = 5-7 * 10^{34}\ cm^{-2}s^{-1}$
  - Requirements for the trigger rate:
    - Level-0 @ 1 MHz
    - Level-1 from 200 KHz → 400 KHz → 1 MHz

The Small Wheel





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

- The Small Wheel is the region with highest background rates in the present ATLAS Muon Spectrometer
- Present system: Cathode Strip Chambers (CSCs), Monitored Drift Tubes (MDTs) and TGCs
- Expected rates at HL-LHC: up to 15 kHz/cm2 → present detectors performance severely affected
  - Spatial resolution is deteriorated
  - Efficiency decreases
  - Trigger bandwidth limit exceeded due to fake triggers

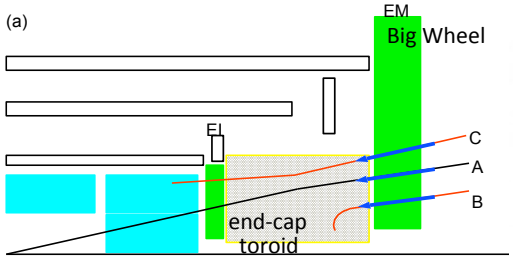
  Replace with novel high-rate capable detectors (New Small Wheel)

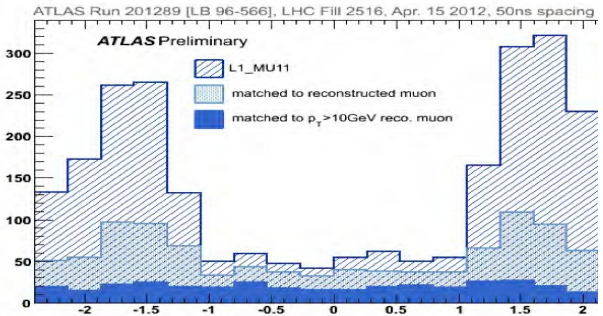
NEW SMALL WHEEL – MOTIVATIONS: TRIGGER

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)

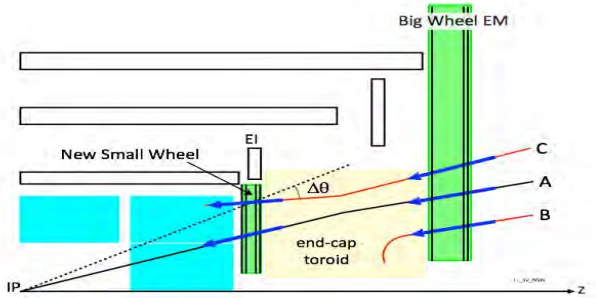
Present Level1 muon trigger





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

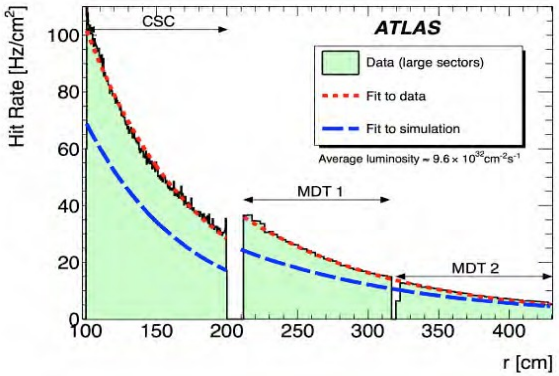
→ Extend L1 trig coverage to η = 2.6 with angular resolution of 1 mrad

NEW SMALL WHEEL – MOTIVATIONS: TRACKING

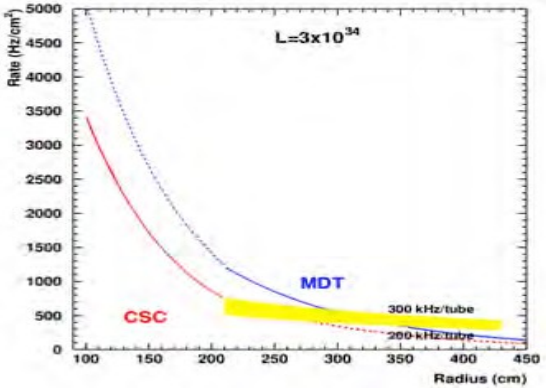
Cavern Background

- 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}

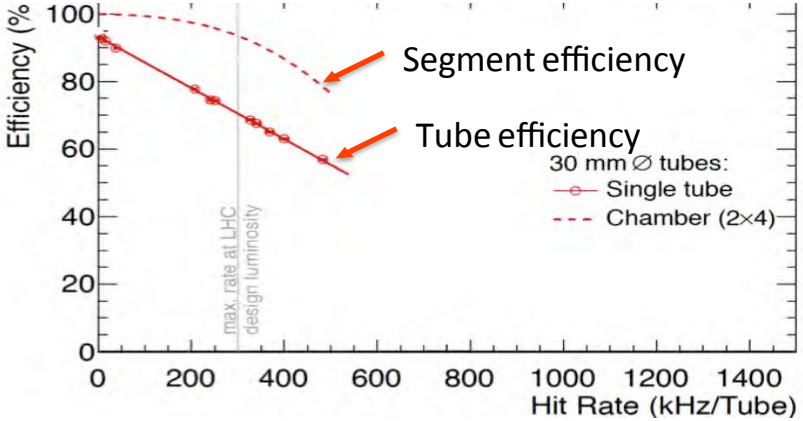


Expected rates @ $3x10^{34}$ $cm^{-2}s^{-1}$



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



Specifications and Requirements of the NSW

Compatibility with the existing tracking detectors and endcap alignment system

- precision coordinate of all chambers parallel to drift tubes of EM and EO stations to within 2 mrad
- coverage: $|\eta| > 1.3$ (minimum size of chambers)
- same segmentation into 16 pie-shaped sectors as the present Small Wheel

Layout

• Momentum resolution:	better than 15 % up to pt = 1 TeV
• Single plane resolution:	100μm, independent from track angle
• Track segment reconstruction:	50 μm
• Track segment efficiency:	>= 97% @ pt > 10 GeV
• Online angular resolution (trig):	<= 1 mrad
• Spatial resolution 2nd coordinate:	~cm, from stereo strips or wires
• Hit rate capability:	15 kHz/cm2 (meeting perform. requ.)
• Accumulated charge without ageing:	1 C/cm2 (3000 fb-1 w/o degradation)

Performance

Redundancy of tracking and triggering → provision against failure in a detector plane or element, limited accessibility

New Small Wheel detector technologies

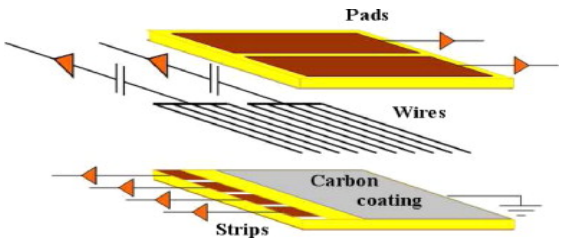
Combination of sTGC and MicroMegas detector planes

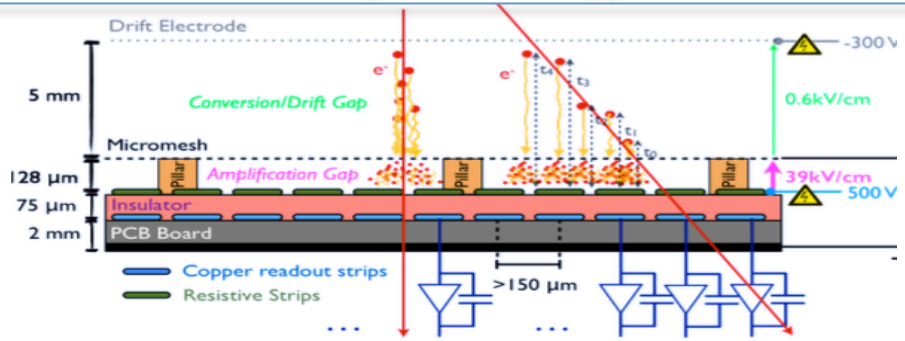
Small Strips TGC (sTGC)
primary trigger detector

- Bunch ID with good timing resolution
- Online track vector
  with <1 mrad angle resolution
- pads: region of interest
- strips: track info (strip pitch 3.2 mm)
- wire groups: coarse azimuthal coordinate

MicroMegas (MM)
primary precision tracker

- Good Spatial resolution < 100 μm
- Good track separation (0.4 mm readout granularity)
- Resistive anode strips → suppress discharge influence on efficiency
- Provide also online segments for trigger

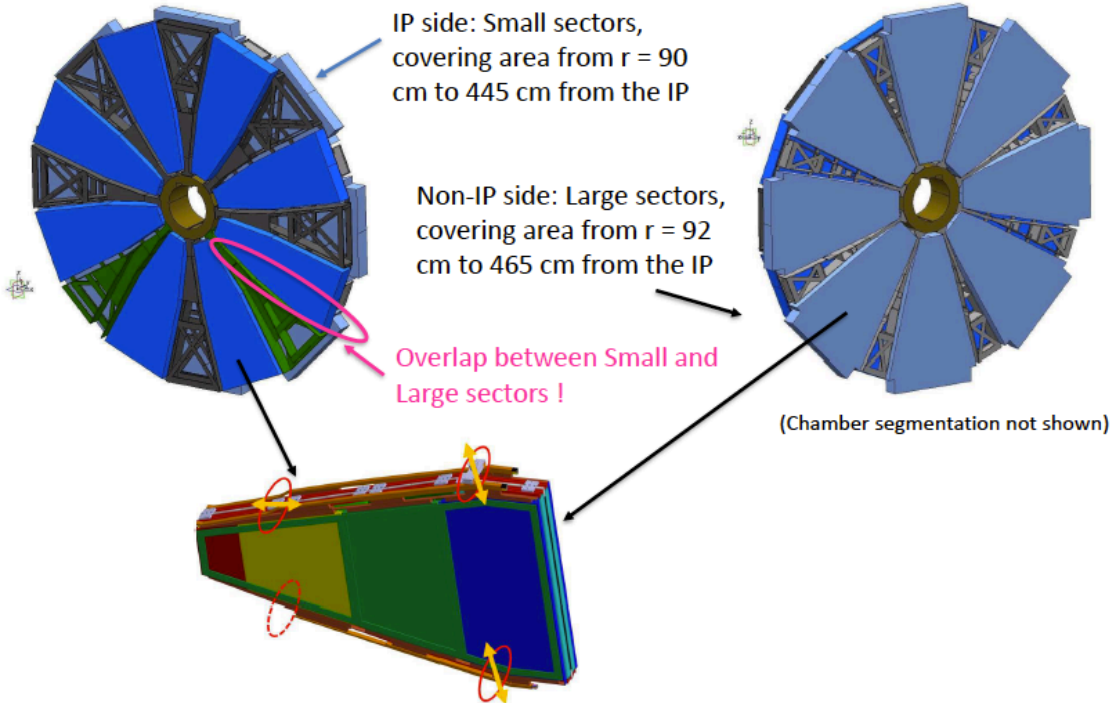


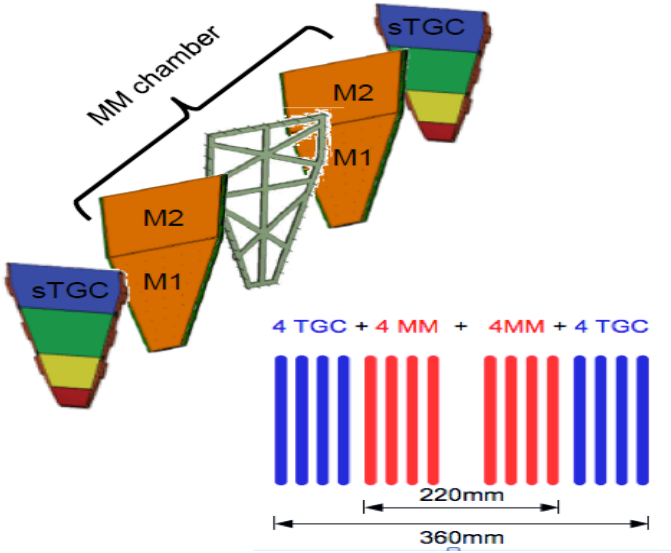


- Common front-end ASIC: VMM

New Small Wheel - Layout

Each NSW has 16 sectors: 8 Large + 8 Small

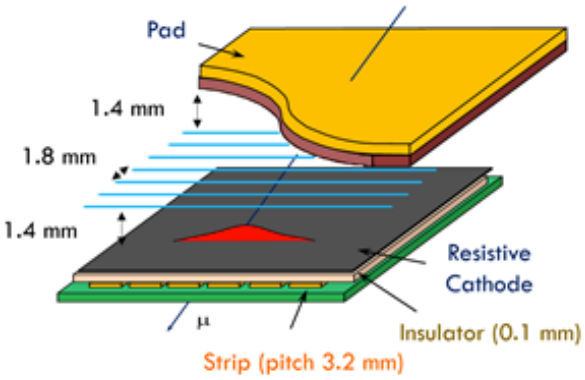


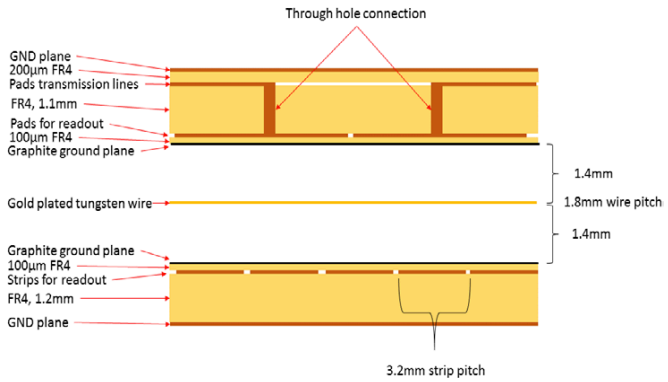


Each Sector is a package of sTGC and MM quadruplets

sTGC structure

- Au plated W wires between two resistive cathode planes (2.8 mm apart)!
  → measurement of transverse (phi) coordinate !
- Precision cathode plane: 3.2 mm pitch strips for Level-1 trigger and precision coordinate measurement!
- Cathode pads for Level-0 trigger → define which strips to read for trigger

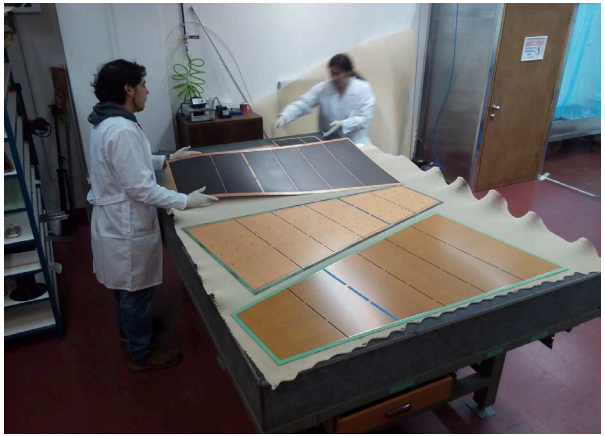


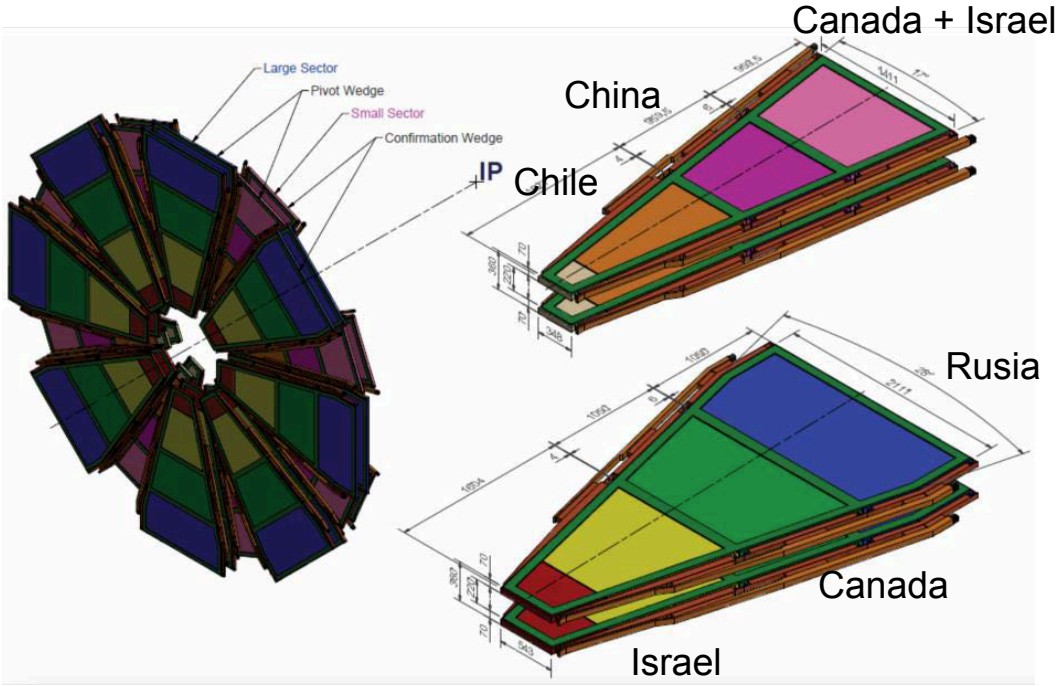


Gas: n-pentane:CO2 45:55
Operating HV=2.9 kV!
Graphite cathode resistivity
~ 100/200 kΩ/□

sTGC Layout

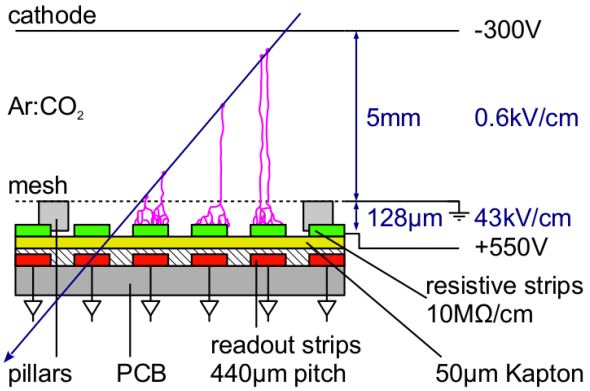
Trapezoidal shape quads, up to 2 m^2 surface!
6 quad types; 32 detectors per type!
Institutes from 5 Countries



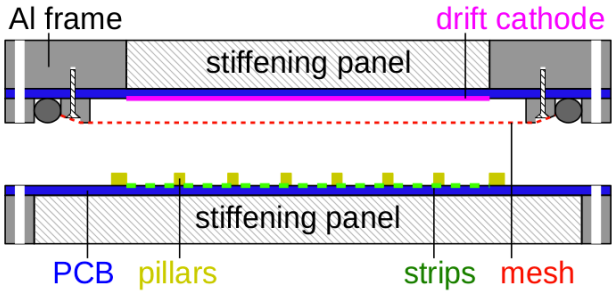


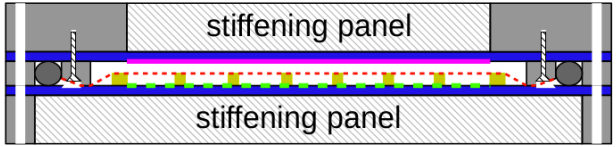
Resistive Strip Micromegas

- resistive anode strips
  → suppress discharge influence on efficiency
- floating mesh, attached to cathode
  → facilitate cleaning & simplify commissioning
- large active areas: 2.5 x 1.5 m.
- detectors based on stiff but light-weight panels
  → cathode on drift panel
  → mesh attached to drift panel
  → readout structure on readout panel



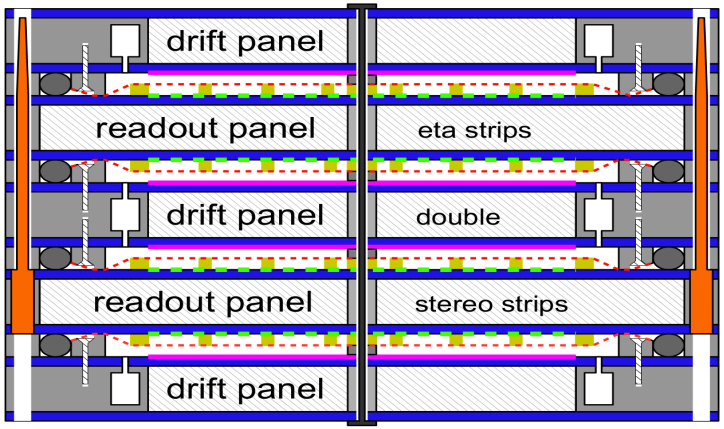
- Gas: Ar:CO2 97:3!
- Operating HV = 560V ampl; 300V drift!
- Resistivity of resistive patter ~ 1 MΩ/□





Resistive Strip Micromegas

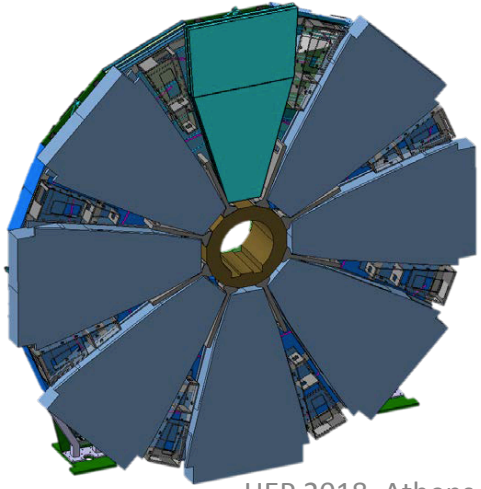
Quadruplet module:
2 readout layers with parallel strips (eta)
2 readout layers with ±1.5° stereo strips
→ 32 different types of readout boards
→ 2176 boards to be produced

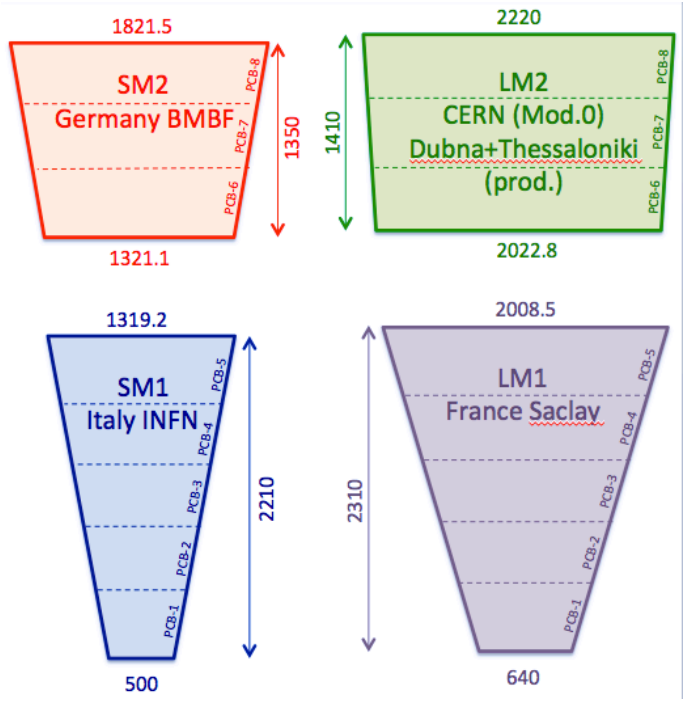


- Resistive micromegas: 128 μm amplification gap, 5 mm drift gap
- 415/450 μm strip pitch for precise position measurement
- Two layers with stereo strips (±1.5°) for coarse tracking in the transverse coordinate

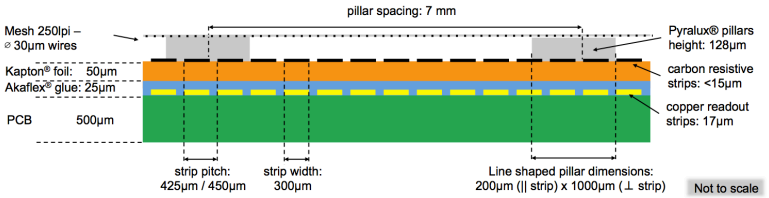
Micromegas Layout

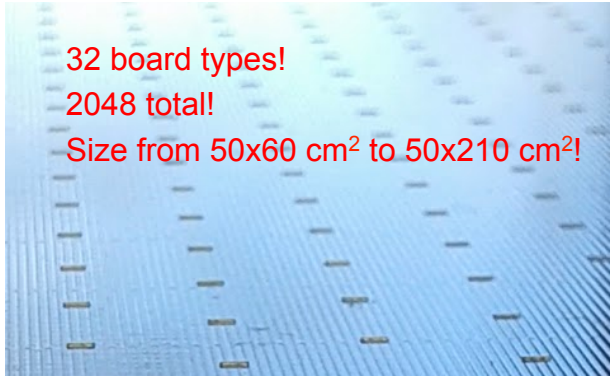
- Trapezoidal shape quadruplets, up to 3 m^2 surface!
- 4 quad types; 32 detectors per type!
- Each quad has 2 anode and 3 cathode panels!
- Institutes from 5 Countries + CERN!





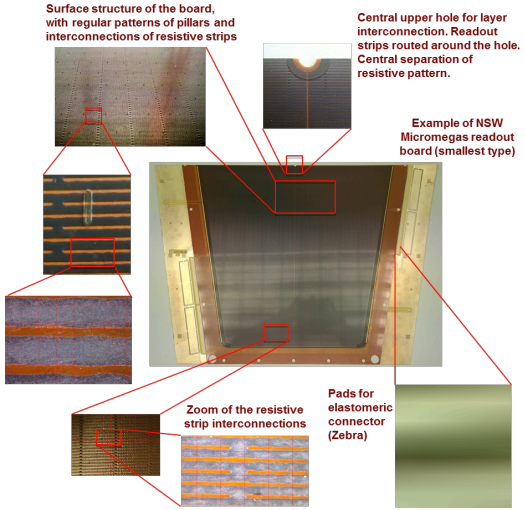
Micromegas anode boards





- Stringent technical requirements on production
- Non-standard operations, cleanliness, etc.
- Resistive kapton foils produced by screen printing in industry (JP)
- Long technology transfer process from CERN to industries
- Many quality issues during prototyping, now solved
- Production ongoing in industries (started end of 2016, IT, FR)
- >25% boards completed; good quality, production rate OK

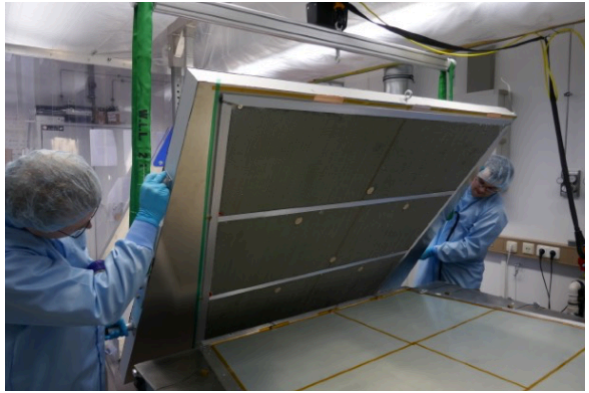
- Constant follow-up at companies
- All boards undergo detailed QAQC at CERN

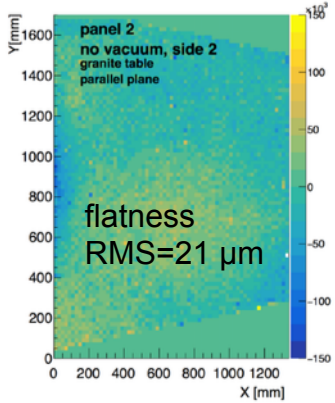


MM construction

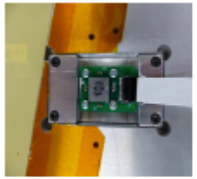
Construction steps

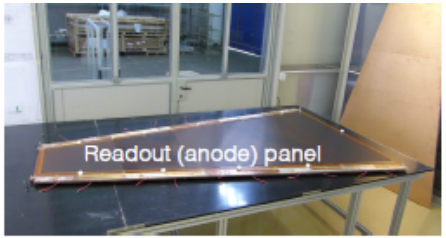
- Boards production
- Gluing of boards into panels
  - Vacuum
  - Al-honeycomb and Al frames
- Mesh stretching and gluing on cathode panels!
- Detector assembly, closing

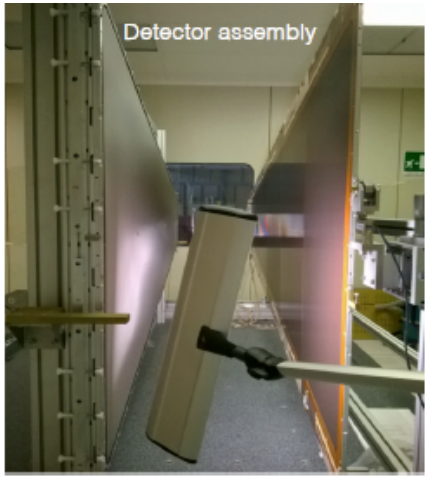




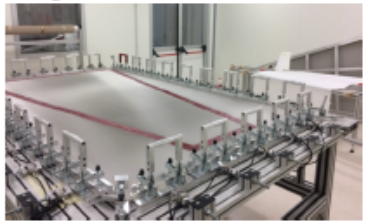
PCB alignment with contact-CCD cameras
Precision <10 μm



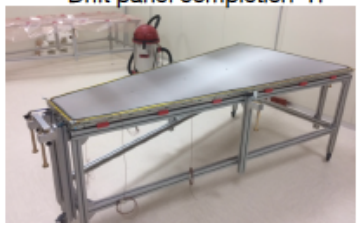




Mesh stretching - IT

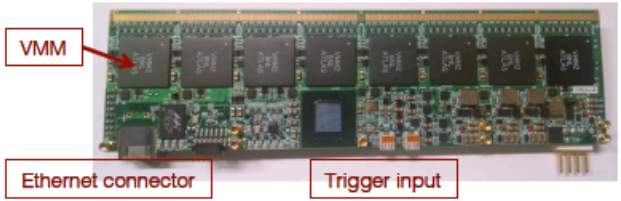


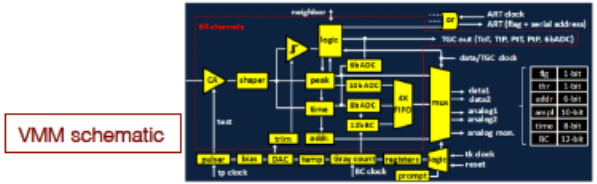
Drift panel completion- IT



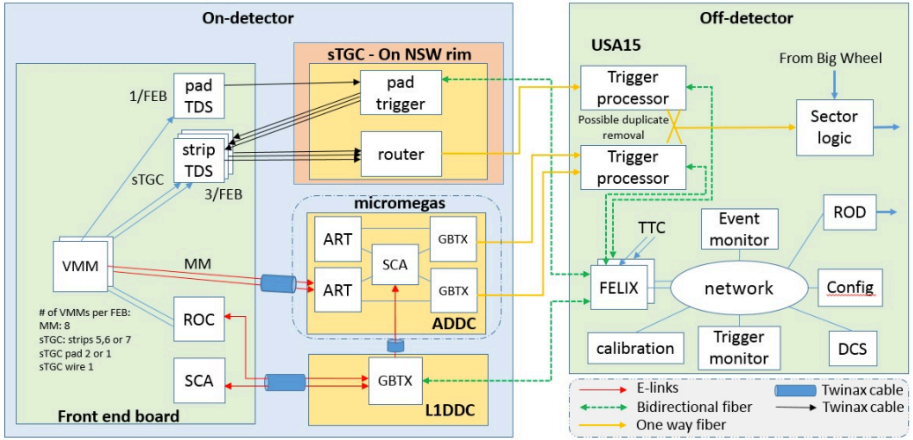
NSW - Electronics

- 2.4 M readout and trigger channels!
- 4096 FE boards for MM (MMFE8)
- 1536 FE boards for sTGC (sFE & pFE)
- Custom FE ASICs (VMM)
- drives trigger and tracking primitives with high speed serializers
- drives trigger candidates to the backend trigger processor system
- Same for sTGC and MM
- Total power consumption ~75 kW





NSW trigger and Data acquisition architecture



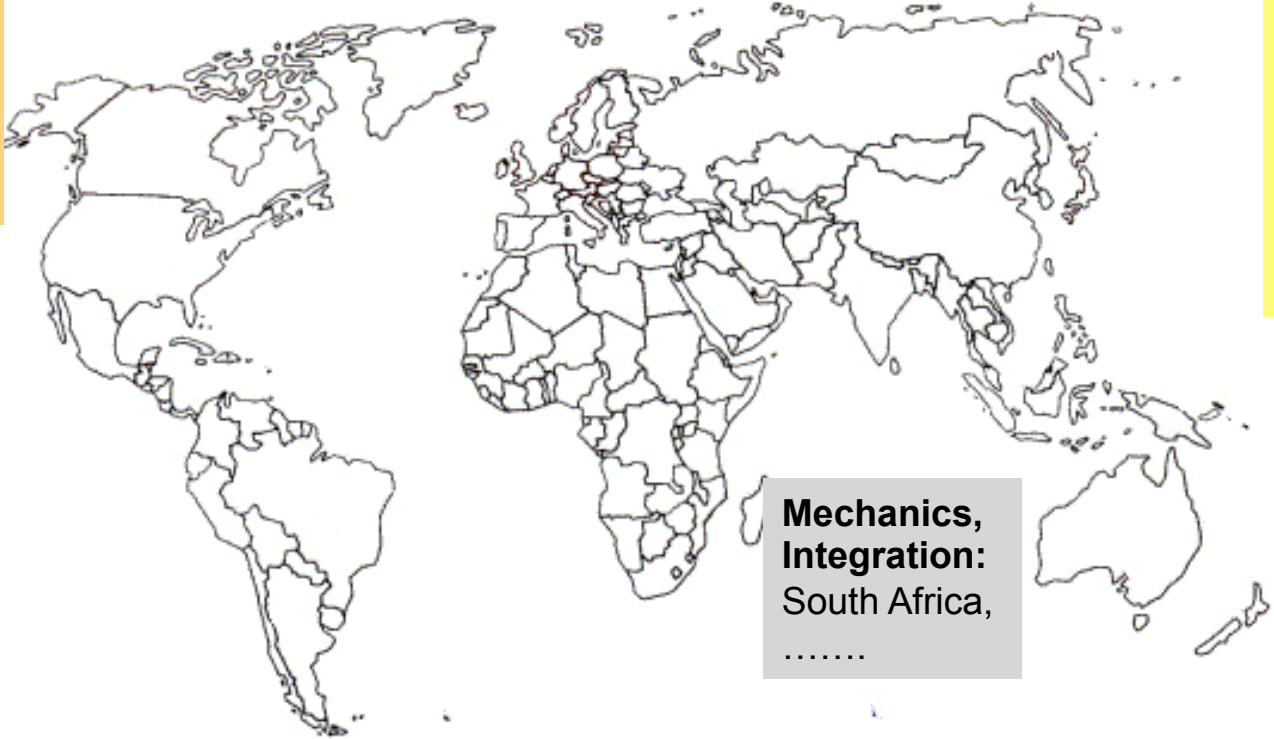
- Radiation tolerant ASIC
- 130 um Global Foundries 8RF-DM process
- 64 channels low noise charge amplifier
- Shaper w/ baseline stabilizer
- Discriminator with trimmer
- Peak and time detector
- ToT and TtP measurements
- Low power ADCs (6-. 10-. 8-bit)

see Th.Alexopoulos talk

NSW Collaboration

sTGC chambers:
Canada
Chile
China
Israel
Russia

MM chambers:
CERN
Germany
Greece
INFN Italy
Saclay France
Dubna
Japan



Electronics:
China
Greece
Hongkong
INFN Italy
Israel
Netherlands
Rumania
Taiwan
US

Mechanics, Integration:
South Africa,
…….

Alignment:
Germany
Saclay
US

New Small Wheel Upgrade project is team effort from groups from almost all continents !

The Greek Contribution to the NSW

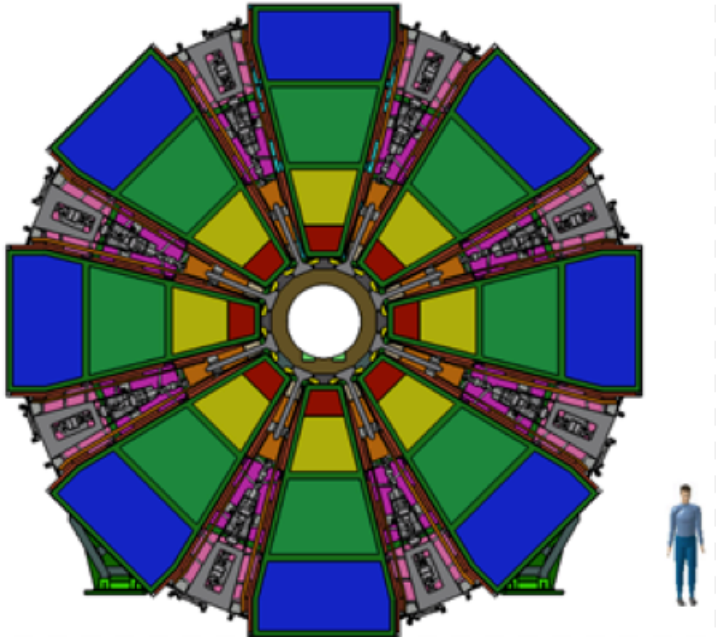
Development of Large-Size Micromegas Detector for the Upgrade of the ATLAS Muon System, MAMMA project (2007- 2013).
Test beam activities with Micromegas prototypes and Large size (~2 m^2)

MM Chamber Construction

AUTH (LM2)

Detector Integration

AUTH, NTUA, Aegean



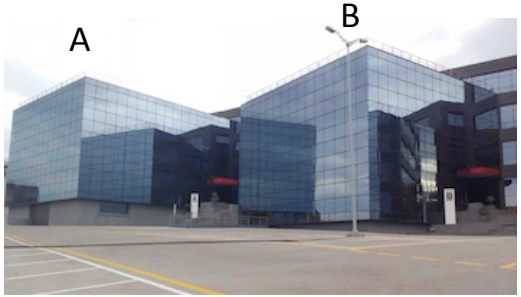
Electronics

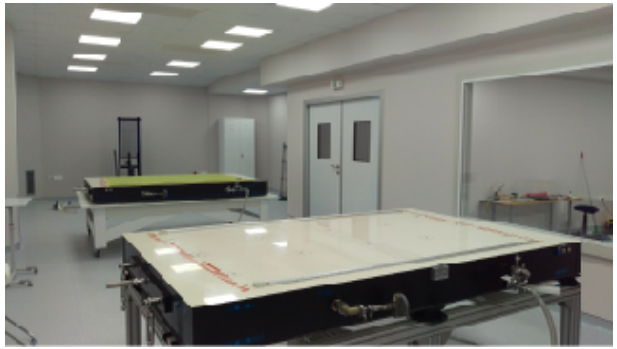
NTUA, NKUA, Aegean, UWA, DEMOKRITOS

LM2 Drift panels production @ AUTH

Aim: The production and test of 96+6 Drift panels equipped with mesh sent to Dubna for the chamber assembly (quadruplet)

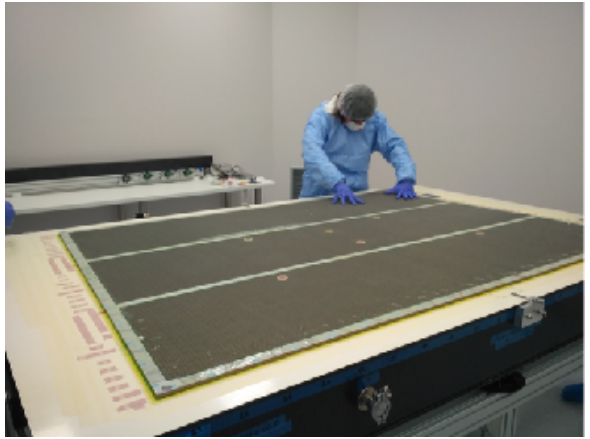
- New Laboratory for detector construction established (360 m^2)
- Based in the Center of Interdisciplinary Research and Innovation of AUTH
- New Clean Room (145 m^2), 2 preparation rooms, a small workshop
- Site was reviewed (May 2107)
- Production Readiness Review (June 2017)

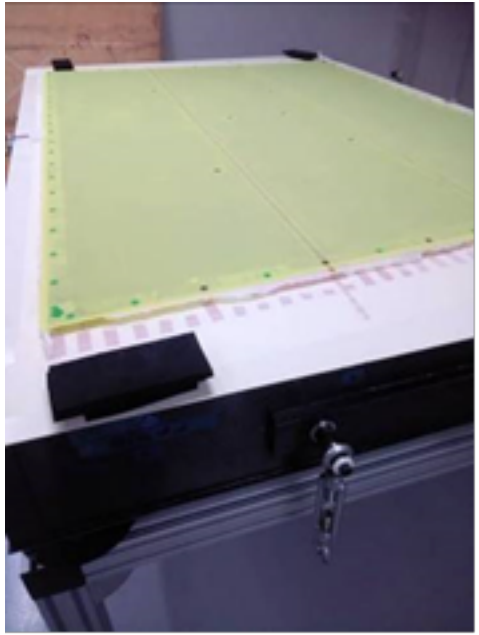




LM2 Drift panels production @ AUTH

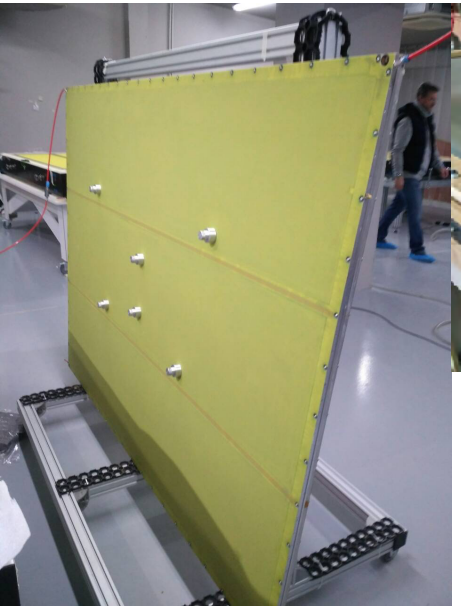
- Production started July 2017
- After September 17, production rump up
- 30% of the production achived





LM2 Drift panels production @ AUTH

Gas tightness test



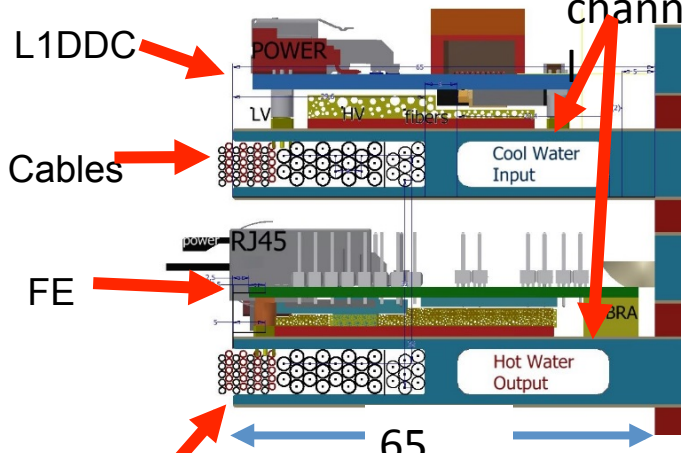
Mesh stretching

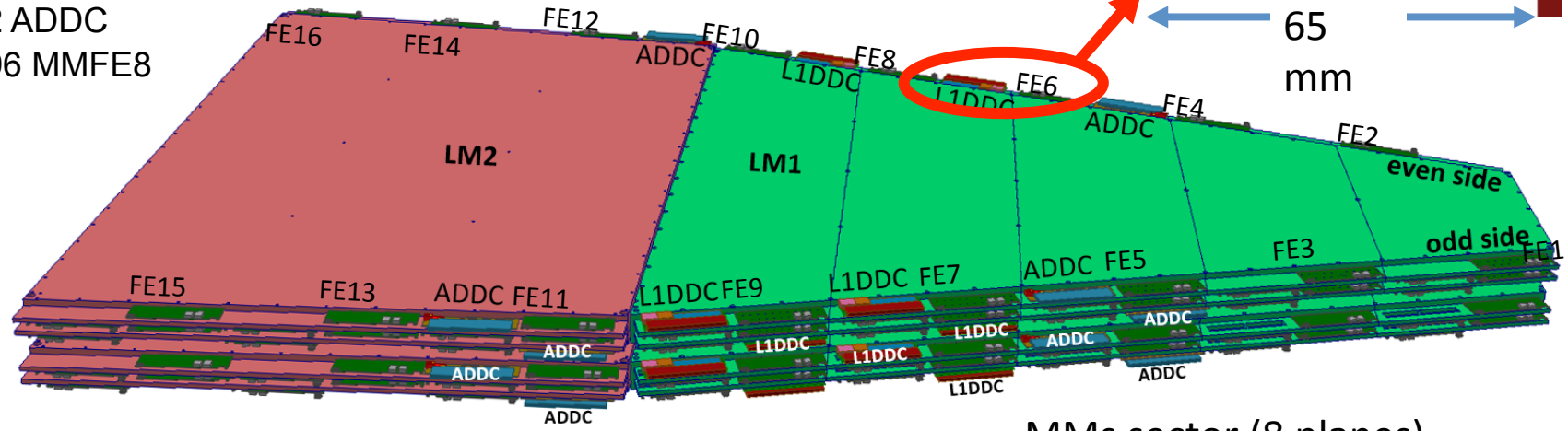
Panel & Mesh washing

Drift panels ready for shipment to Dubna

Electronic board placement on MM detectors

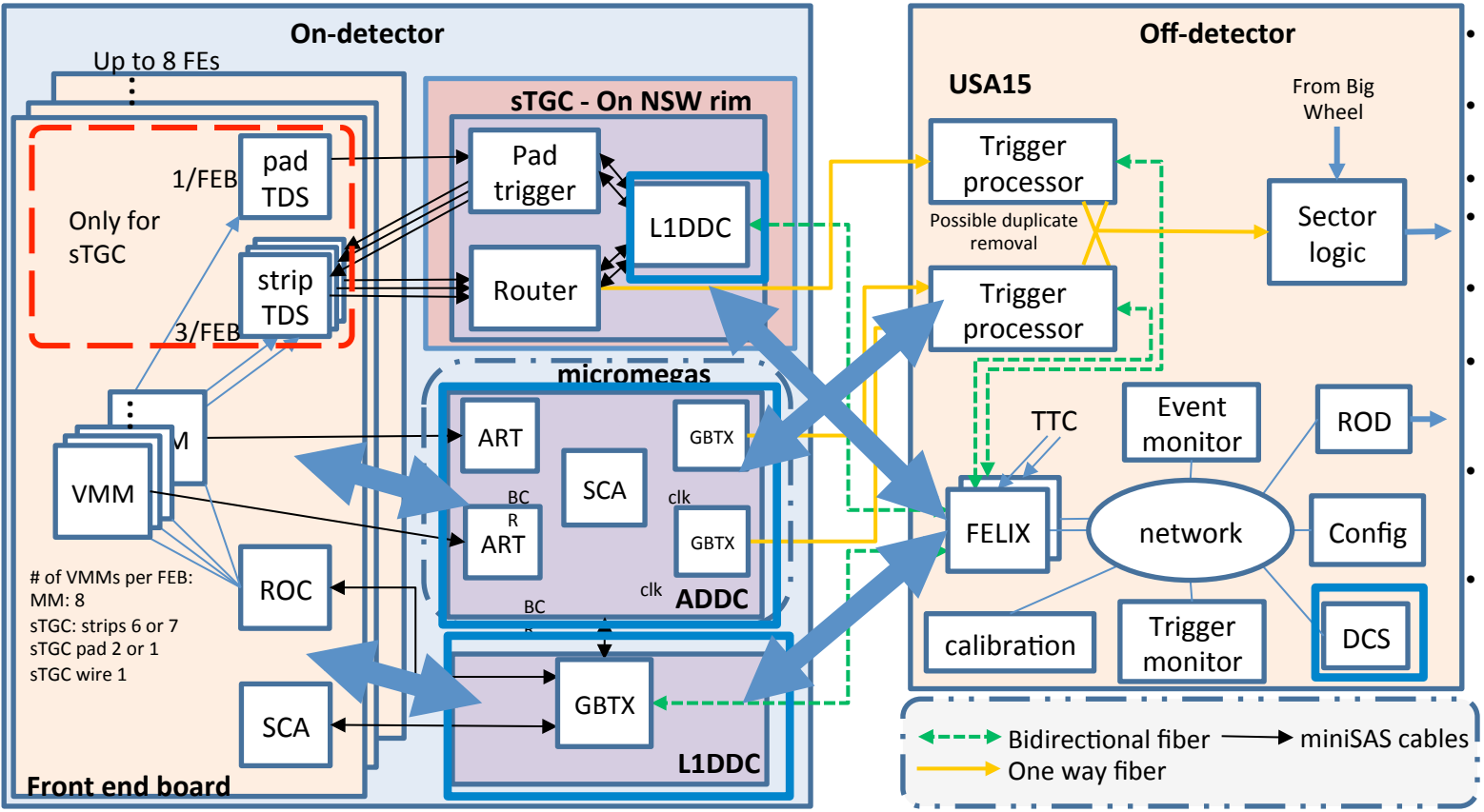
- FEs will be placed radially on both sides of each plane
- L1DDC and ADDC boards will be placed only on the 1st and 4th plane of each wedge (4 planes)
- 1 L1DDC & 1 ADDC will serve the 8 FE located on each side of a plane and will be placed on the center to minimize the cable length
- 512 L1DDC
- 512 ADDC
- 4096 MMFE8





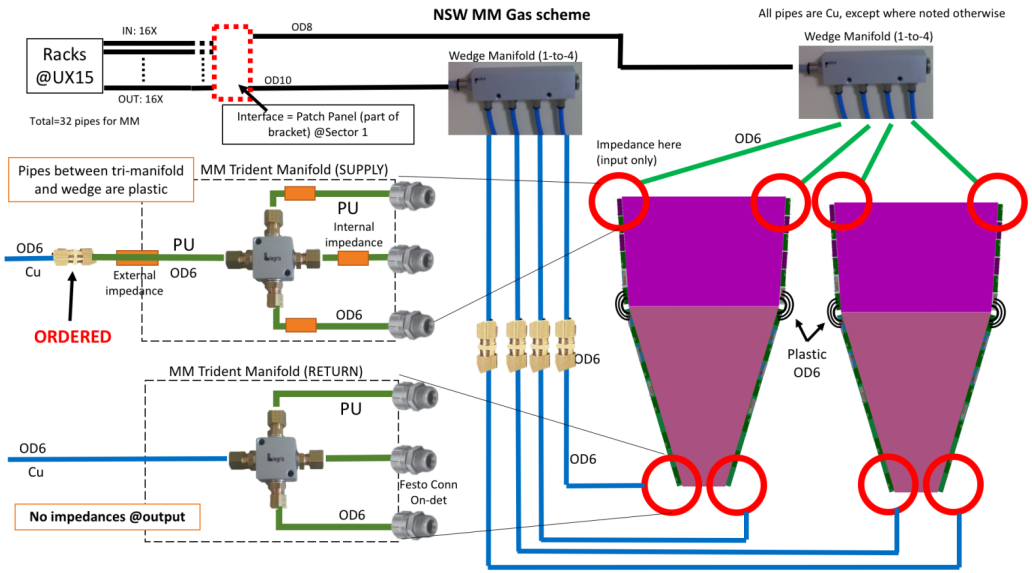
MMs sector (8 planes)

NTUA/BNL Involvement on Electronics



- **Design & commissioning of:**
- Micromegas L1DDC boards
- sTGC L1DDC boards
- Rim L1DDC
- **Readout of ADDC**
- **Readout of Frontend boards**
- **Development of readout path to FELIX**
- **NSW DCS**

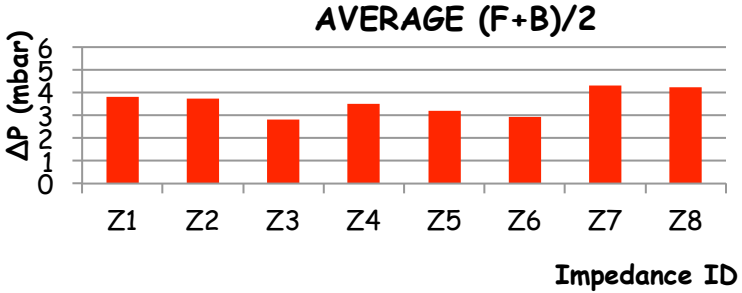
Gas Distribution System for the NSW MM Quadruplets



Theoretical model used for the design

$$(\Delta p)_{S_1S_2} = b\left\{\frac{8\rho}{\pi^2 D^4}\left[a k_{LC} + k_{LE}\right]Q^2 + \frac{128 L\eta}{\pi D^4}Q\right\}$$

$a = 1$ (geom. factor), $b = 1.25$ (calibr. factor)



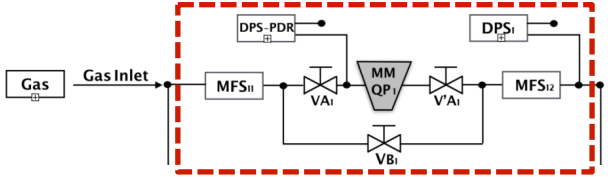
Design & commissioning

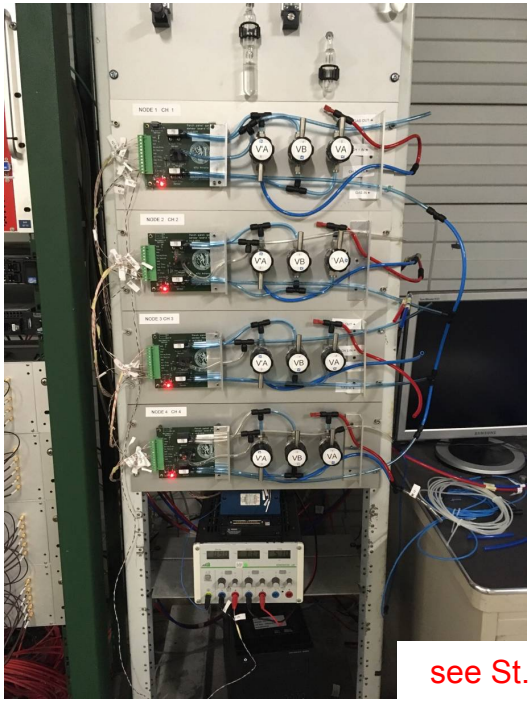
- Gas distribution configuration
- Individual manifold design for providing gas mixture
- "Trident Manifold" design based on "internal" impedances
- Homemade "External" Impedances for uniform gas distribution

Production of external impedances

- Inline interpolation inside the plastic pipes
- Laboratory evaluation technique
- 571 pieces should be produced
- High accuracy in channel diameter (±2 μm)

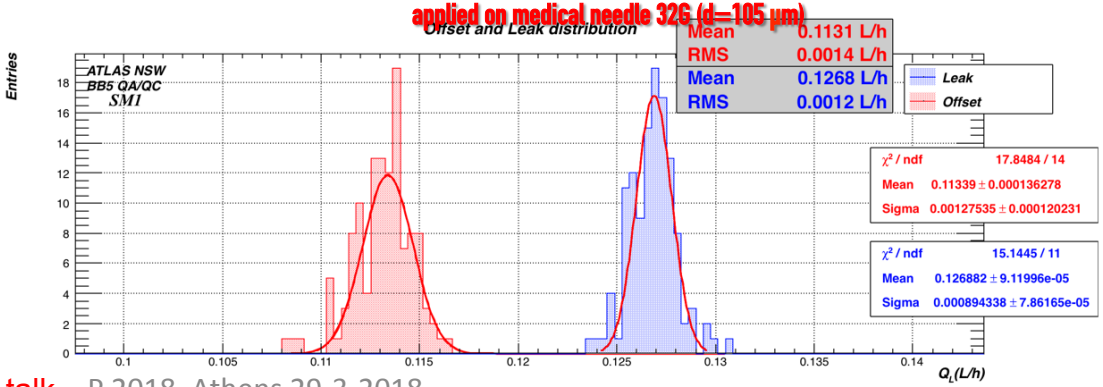
Gas Tightness Station for QA/QC of MM QP at BB5 - CERN





- Implementation on the novel method "Flow Rate Loss" for testing 4 MM QPs at simultaneously. The PDR method can be implemented too
- Monitoring of the mass flow sensors
- Alarm handling and warnings for the leak rate and pressure
- Access of data history of MM QPs (type or batch id)
- NSW Oracle DB (Freiburg GUI)
- Settings (calibration factors, offsets, gas type etc.)
- Automatic advanced analysis using ROOT

Statistical advanced analysis using ROOT of the obtained leak rate applied on medical needle 326 (d=105 μm)

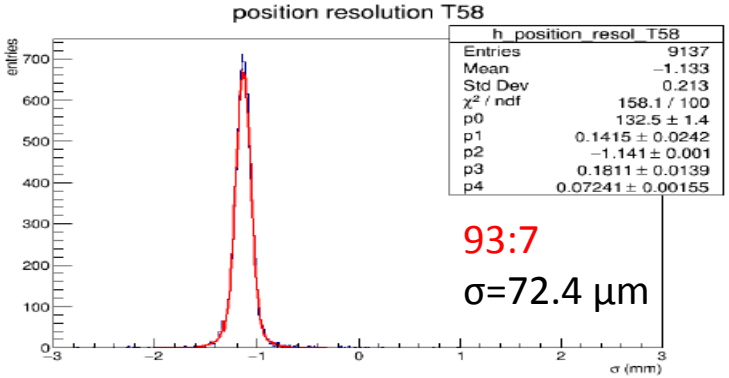


see St. Maltezos talk

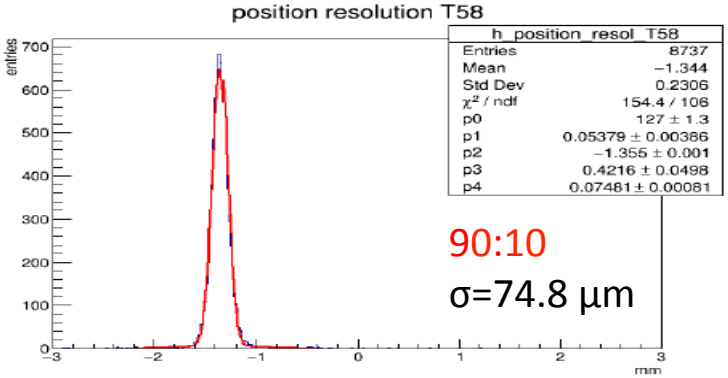
Test beam data analysis (NKUA)

M. Boura (MSc thesis), D. Fassouliotis, I.Gkialas, C. Kourkoumelis

Comparison of Ar&CO_2 93:7 and 90:10 gas mixtures in terms of efficiency and spatial resolution

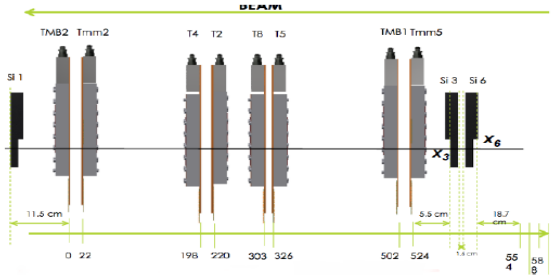


Vertical incidence



Position resolution – Incidence 30°

Chambers Pair (run #)	Core Resolution (μm)	
T5-T2 (11960)	124 ± 2	93:7
T8-T4 (11960)	116 ± 2	
T5-T2 (12194)	114 ± 3	90:10
T8-T4 (12194)	118 ± 2	



Despite difference in drift velocity, no performance differences were observed

Test beam data analysis (NKUA)

P. Bellos (MSc thesis), D. Fassouliotis, I.Gkialas, C. Kourkoumelis

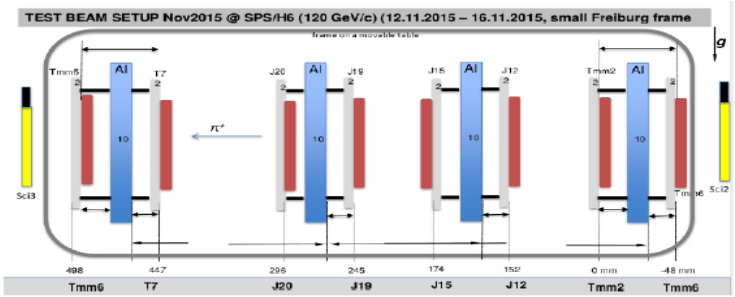
Comparison of amplification gaps for floating mesh micromegas construction in terms of spatial, angle and time resolution

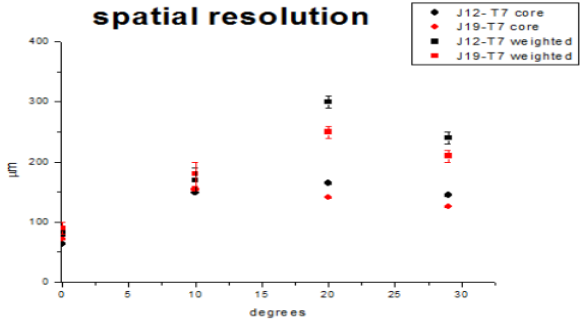
Amplification gaps

J12: 128 μm (black points)

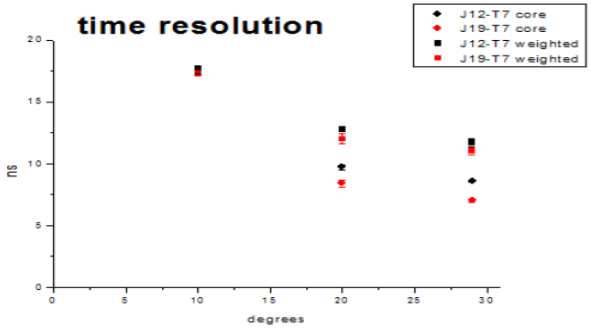
J19: 100 μm (red points)

Resolution of 100 μm of floating mesh similar to 128μm bulk mesh micromegas and better compared to 128 μm floating mesh

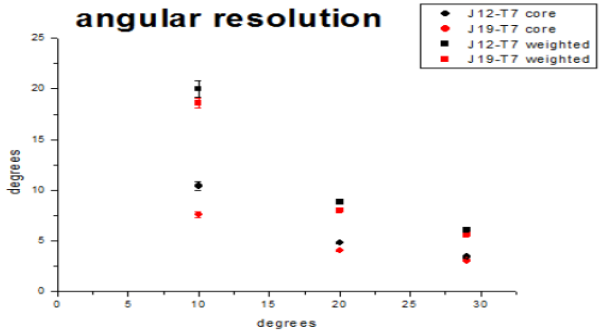




(b) Spatial resolution as a function of angle



(b) Time resolution as a function of angle



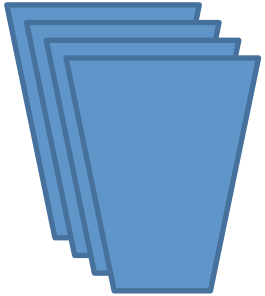
(c) Angular resolution as a function of angle

BB5 HV tests on completed Chambers (I. Gkialas)

MONITORING AND CONTROL SOFTWARE

HV TEST TASK

One Chamber (Module)
(4 Layers - Quadruplet)



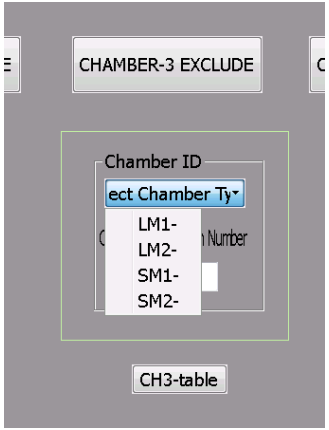
Maximum of 11 X 4 = 44 channels

Aiming at testing of 4 modules simultaneously
(160+16 HV channels)

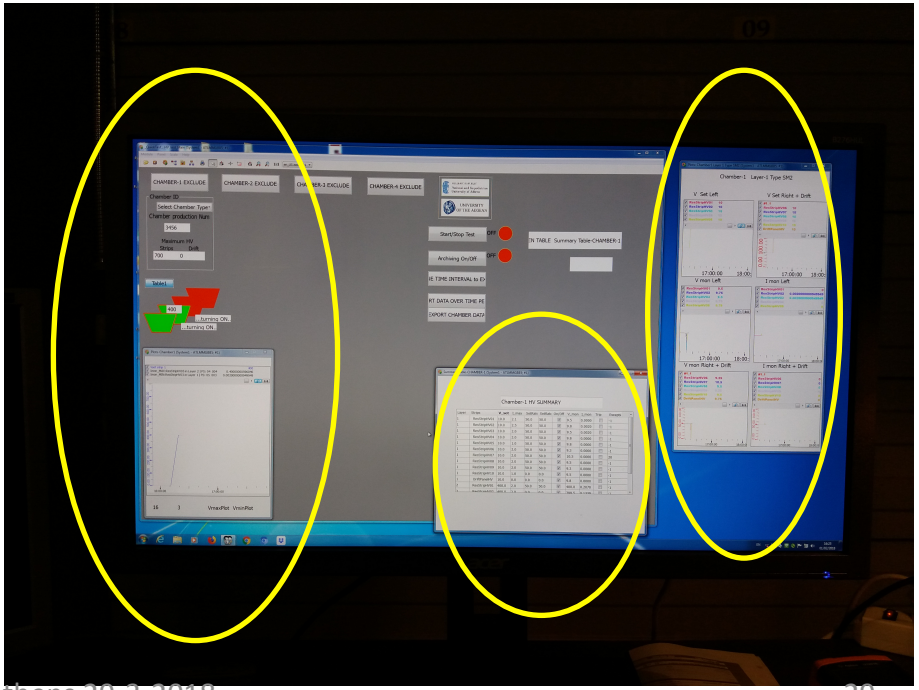
A few months ago: Anticipating to match the delivery rate of modules (1 per 2 weeks per construction site => 2 per week)

Record Chamber data based on

- Chamber Production ID andType
- Production Site
- Set Maximum Voltage

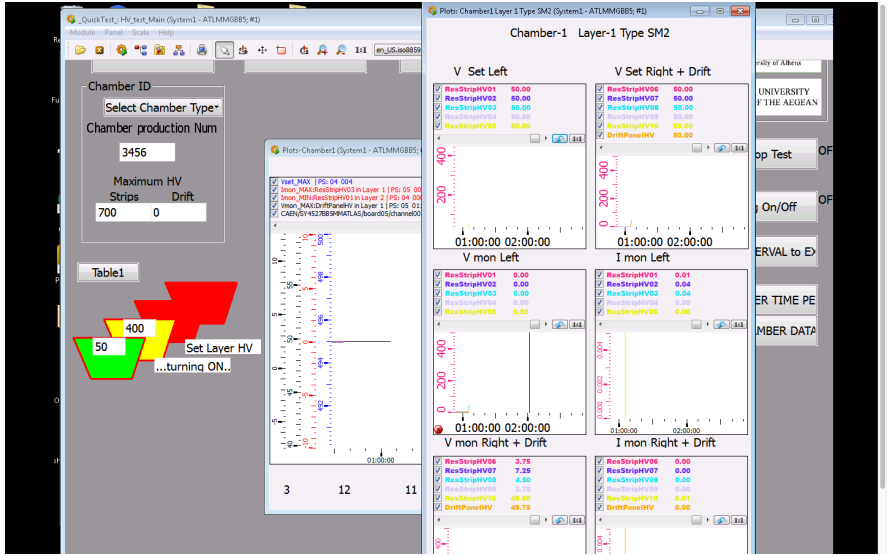


Activated independently for each chamber



BB5 HV tests on completed Chambers (I. Gkialas)

General view of the Console



Experimental Station in BB5

PRESENT STATUS:

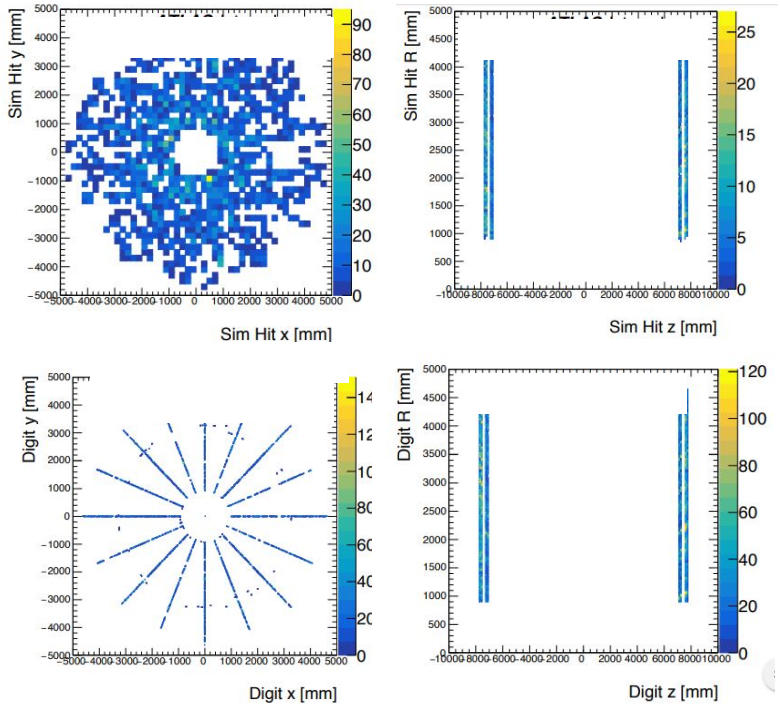
- Control Program for the HV tests is in good shape
- All cabling has been prepared
- The first communication between the PS, the control program and a real Chamber (SM2-Mod0) has been achieved in both ways.

To be done!

- Addition of Alerts
- Refinement and debuging of the control software
- Migrate project to the Linux Machine (half-way there)
- Test the software on the linux machine with the existing PS's
- Complete the new CAEN 7038 PS OTP server
- Merge HV and gas software into one project (or at least on the same machine)

MICROMEGAS SOFTWARE VALIDATION

K. Papageorgiou , P. Pappas (University of the Aegean)



- MicroMegas Software/Digitization Validation

University of West Attica

University of West Attica team (former PUAS) is associated to NKUA team

Staff: Prof. Stathis Kyriakis-Bitzaros, Prof. Katerina Zachariadou

Students: Nondas Politis, Ioannis Mesologgitis.

Close collaboration with:

-NKUA (Kourkoumelis Christine, Fassouliotis Dimitris).

-NTUA (Αλεξόπουλος Θεόδωρος, Γκουντούμης Πάνος).

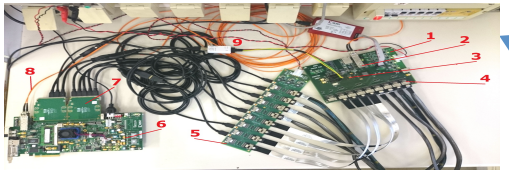
Tasks completed:

- Development of firmware for L1DDC configuration and testing using ML605
- (prototype 0 and L1DDC for STGCs and MMs ver. 1 and ver. 2)
- Test of e-links at different data rates (80 and 320 Mbps)
- Loopback tests of both directions (uplink and downlink)
- Long term (~24 hours) continuous operation and error logging

Results

- Correct operation verified
- Minor design problems revealed
- Problematic signals detected

Detected error in data stream

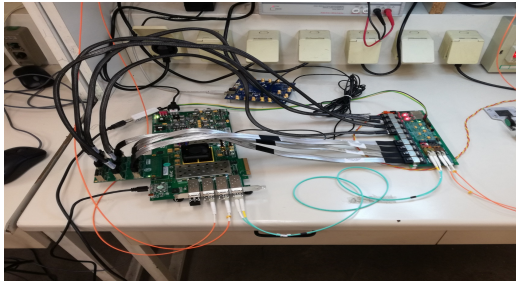


Prototype 0 testing setup

University of West Attica

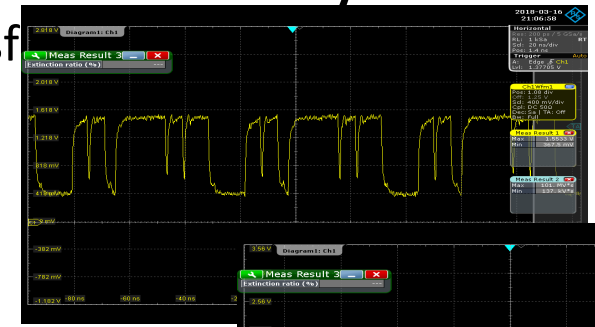
New equipment acquired for final test station setup

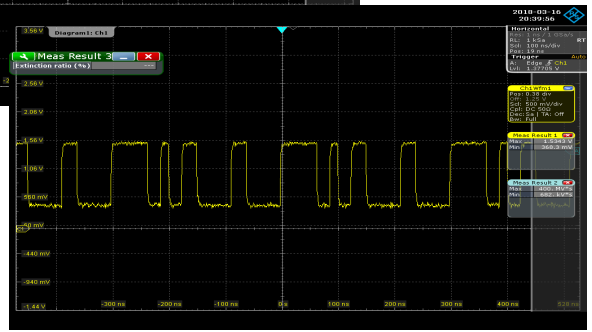
- VC709 development board
- Supermicro server



Firmware migration from Virtex6 to Virtex7 is under way.

General view of test setup area

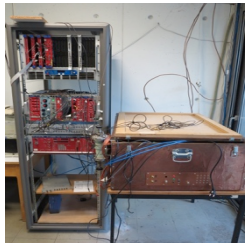


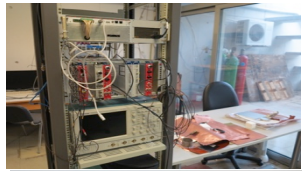


E-link signal integrity tests for different IO standards

NCSR Demokritos: new member in ATLAS

CB October 2017: NCSR Demokritos **full member** of **ATLAS**
Team members: **T. Geralis (representative), G. Fanourakis, G. Stavropoulos**





NCSR/INPP Laboratory INFRASTRUCTURE

- THREE FULLY EQUIPPED TEST BENCHES FOR STUDYING MPGDs
  - Electronics Rack, Gas distribution, Workstation, Osciloscope
- GAS MIXER and distribution of premixed gases
- ELECTRONICS AND DAQ SYSTEMS
  - VME Data Acquisition (CAEN controller, optical fiber connection CRAMS, sequencer, ADC unit, Gate generator, etc)
  - SRS - Scalable Readout System (APV FE, 2000 channels readout)
  - FEMINOS readout for TPC mode
  - Electronics: Racks (1 VME and 4 NIM crates), NIM units (Multifunction NIM modules, Amplifiers, Discrim., HV PS, LV PS, Pulse generators, NIM/TTL/NIM conv, etc), MCAs (2), Preamps
  - Faraday cage
- DESIGN PACKAGES
  - Electronics design (Europractice packages)
  - Finite Element Analysis (ANSYS, etc)
  - DAQ software (Labview version, C++ version)
  - FPGA (Altera, Xilinx) design workstations
  - FPGA Design platforms
- CLEAN ROOM (12 m^2 – two rooms Class 10,000 and Class 100,000)
  - Microscope

ATLAS Demokritos group projects

VMM ASIC irradiation studies (2013 – 2017)

Collaboration
INPP: A. Kourkoumeli (PhD), G. Fanourakis, T. Geralis
NTUA: T. Alexopoulos, M. Kokkoris, G. Tsipolitis
Aegean Univ.: K. Papageorgiou, I. Gialas

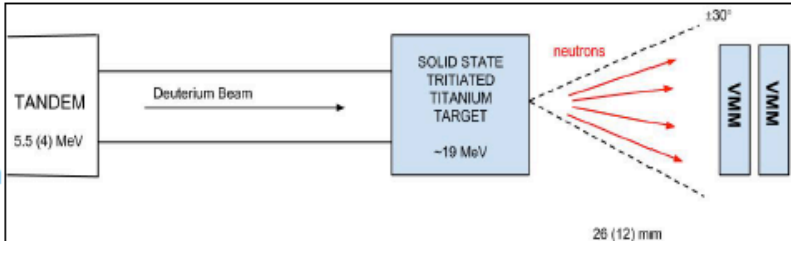
VMM will be used at the s-LHC➔ Should test radiation tolerance and SEU ASIC specifications:
130 nm Technology, 64 channels, BNL design
VMM will be used by ATLAS muon Micromegas group and also as the SRS FE chip
Irradiation took place at the Tandem Accelerator

Credits: T.Alexopoulos

Nuclear Reaction	Energy Range (MeV)	Range (MeV)
$^{7}Li(p,n)^{7}Be$	1.9 to 8.4	0.1 to 6.7*
$^{2}H(d,n)^{3}He$	0.8 to 8.4	3.9 to 11.5**
$^{3}H(d,n)^{4}He$	0.8 to 8.4	16.4 to 25.7***

[0.1,0.5] MeV & quasimonoenergetic up to ~2.5 MeV
** Quasimonoenergetic neutrons up to ~7.5 MeV
*** Monoenergetic neutrons [16.4,22] MeV

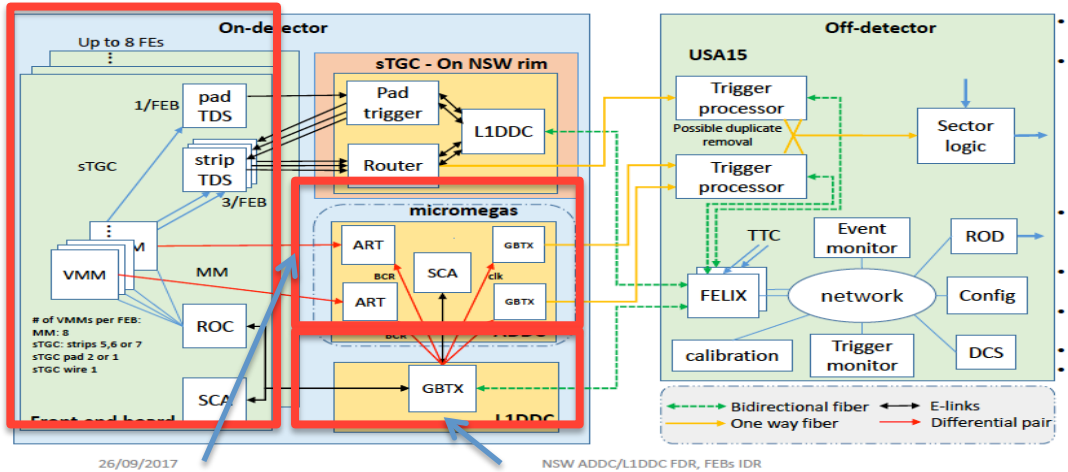
Tritium target (10 ci):
~10^6 neutrons/cm^{2}s of 18-22 MeV
Testing:
2 days @ E_d = 5.5 MeV, VMMs @ 26,36 mm
3 days @ E_d = 4 MeV, VMMs @ 12,21 mm



Micromegas Detector

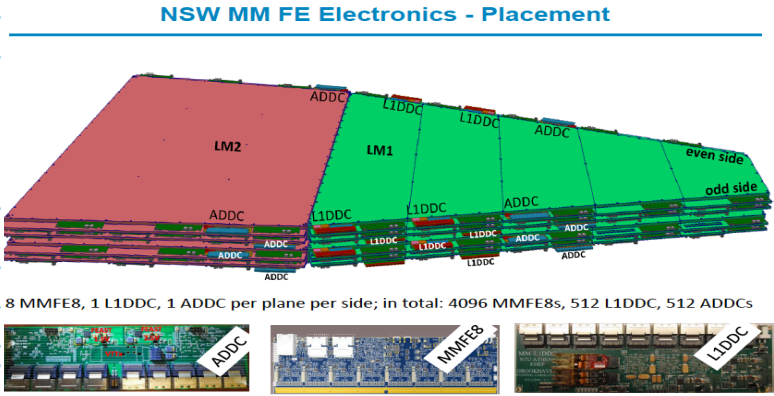
FE card

Overall readout and trigger Scheme



Trigger stream

Data stream



Demokritos commitments in Electronics testing

A) Qualification

1) QA/QC of 300 L1DDC cards
2) QA/QC of 150 ADDC cards

B) Commissioning

Presence at CERN for commissioning and integration of the NSW

C) Involvement in DAQ + Detector develop.

D) Involvement in Physics (at a later stage)

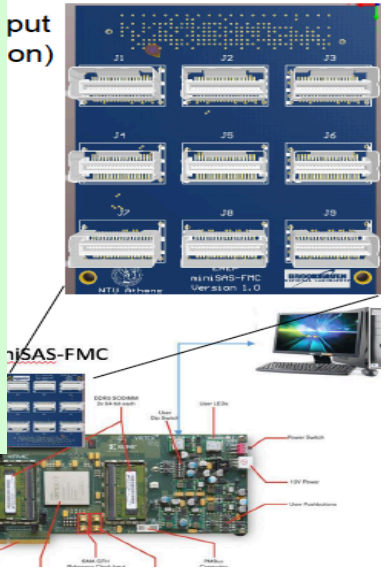
Infrastructure (minimal for qualification to start with)

Mobility (2018 – 2019):

3 FTE months at cern/year

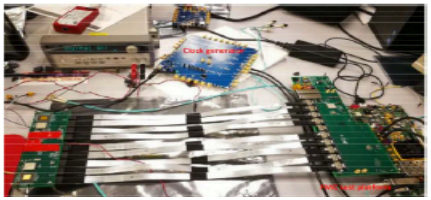
L1DDC Testing

1) Send data through 9 miniSAS connectors and receive Output via fiber
2) Test bench consists of
   i) VC709 evaluation boards
   ii) FMC card with 9 miniSAS
   iii) Fibers and miniSAS cables
   iv) PC workstation

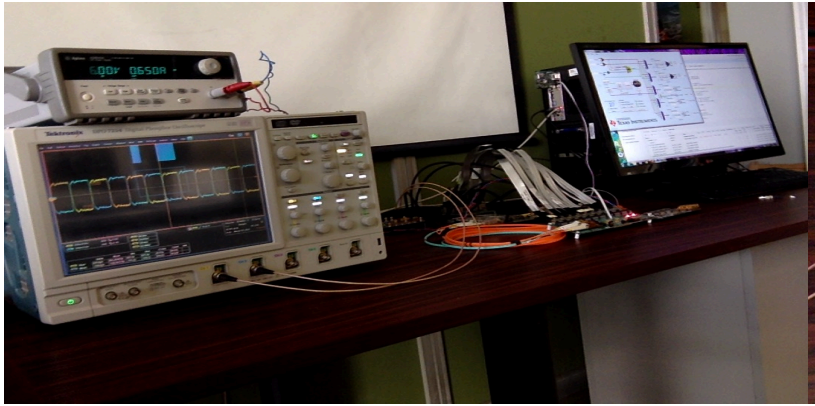


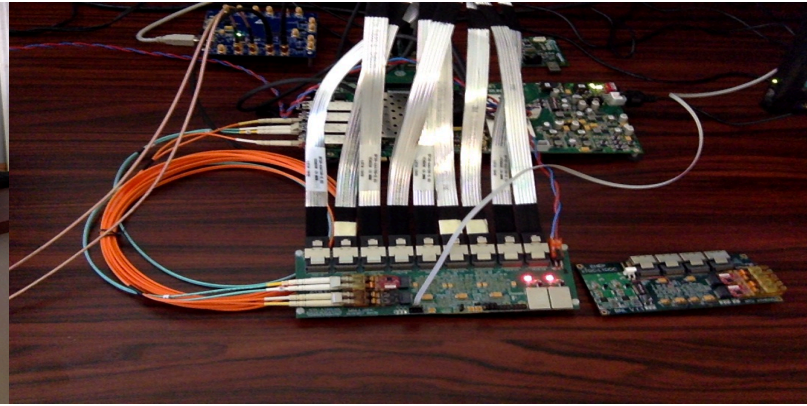
ADDC Testing

1) Closed loop with mezzanine and VC707
2) Test bench consists of
   i) VC707 board
   ii) FMC card
   ii[illegible] les
   iv[illegible]



L1DDC setup at Demokritos





Summary

The New Small Wheel is the largest ATLAS upgrade project for LHC Long Shutdown 2

- Challenging project:
  - Unprecedented use of Micromegas detector
  - sTGC pushed to the frontier
  - Custom FE ASIC and trigger/DAQ chain
  - Complex mechanics
  - Tight schedule, delays accumulated

The Greek ATLAS groups have a key role to the project

ATLAS fully committed to bring it to success !