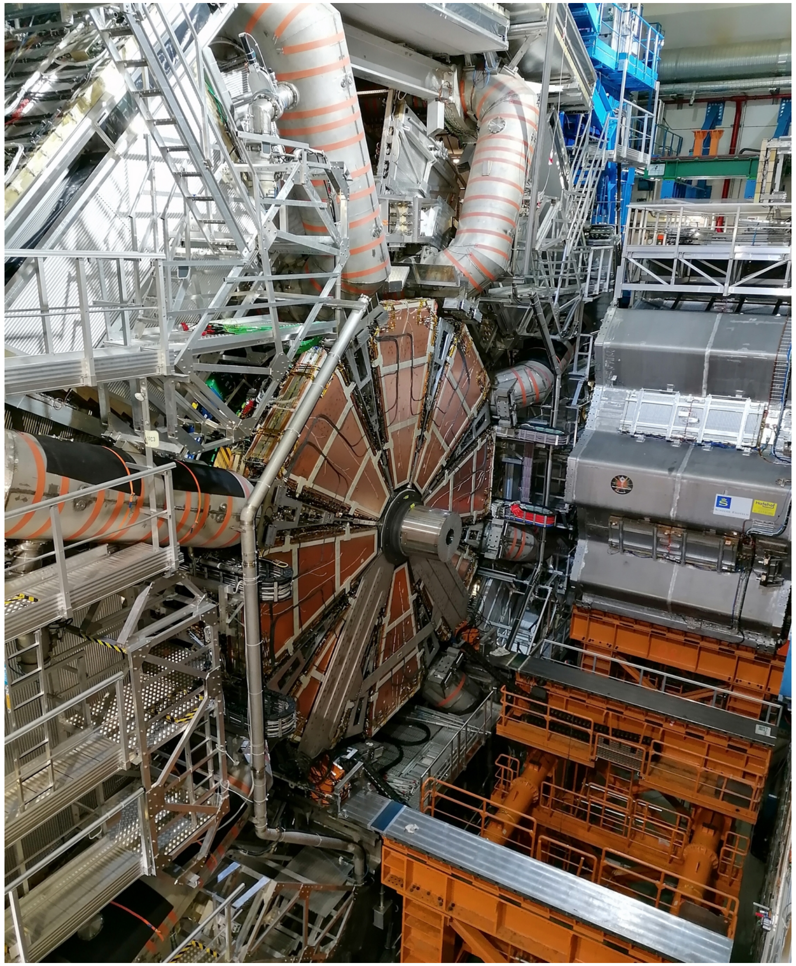
Large-Area Micropattern Gaseous Detectors Used for Precision Muon Tracking at HL-LHC: $\sqrt{s}$ = 14 TeV and L=7.5 10^{34} /cm^2 sec

ATLAS New Small Wheel



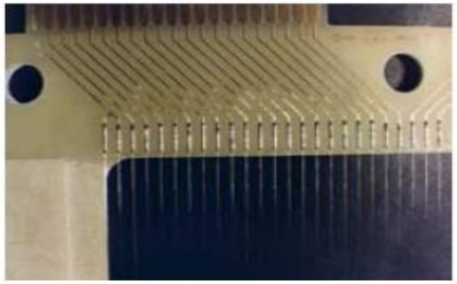
CEPC 2025, Barcelona, 16. June 2025

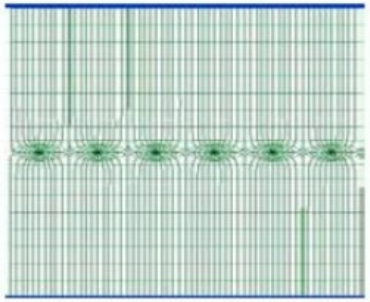
Ralf Hertenberger, LMU München

MPGD: Micropattern Gaseous Detectors

First MPGD → Micro Strip Gas Chamber (MSGC)

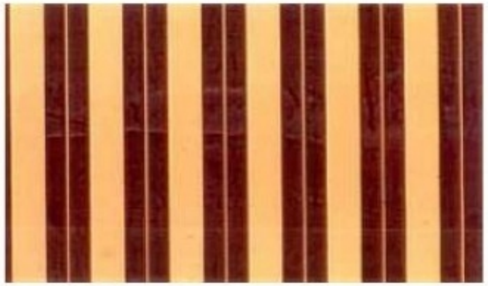
MWPC

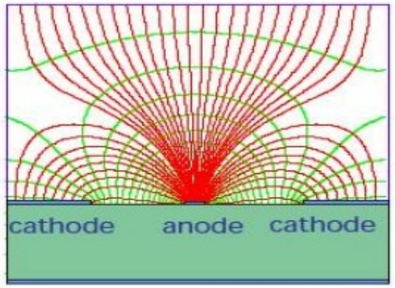




Pitch limited to 1 to 2mm due to mechanical and electrostatic forces.

MSGC





Glass substrate with anode strips of 10 um with a pitch of 200 μm.
More simple than a wire Chamber.
Short ion drift path!

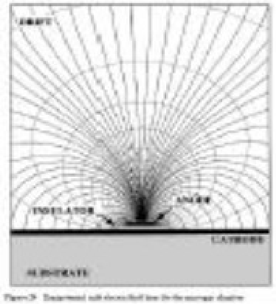
A. Oed
Nucl. Instr. and Meth. A263 (1988) 351.

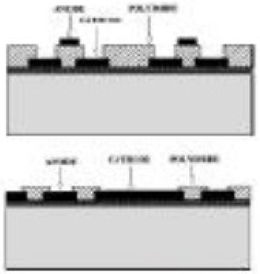
RESULT:

Spatial resolution ~50μm
Rate capability ~10^6 Hz/mm2

***Lithography* on PCBs (printed circuit board)**

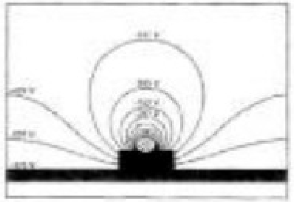
Micro Gap Chambers





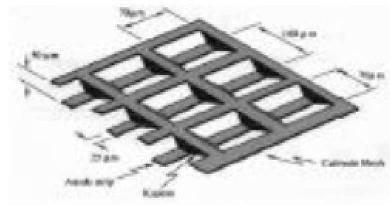
Angelini F, et al. Nucl. Instrum. Methods A335:69 (19

Micro Gap Wire Chamber



E. Christophel et al, Nucl. Instr. and Meth, vol 398 (1997) 195

Micro Wire Chamber



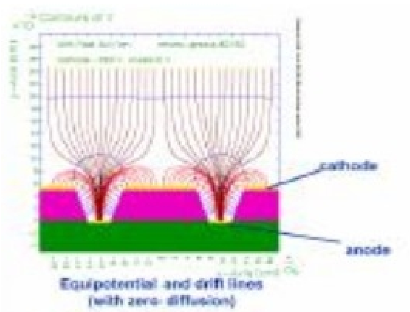
B. Adeva et al., Nucl. Instr. And Meth. A435 (1999) 402

MicroDot

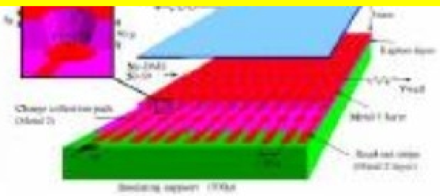
all types are NOT long term stable !
danger: heavily ionizing events create discharges (Raether: 10^8 e^-/ avalanche)
microstructures are destroyed if stored energy on cathode-anode is too high

Biagi SF, Jones TJ. Nucl. Instrum. Methods A361:72 (1995)

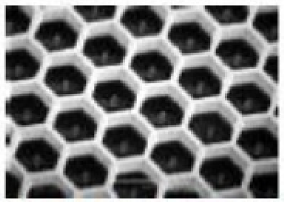
MicroGroove



R. Bellazzini et al
Nucl. Instr. and Meth. A424(1999)444

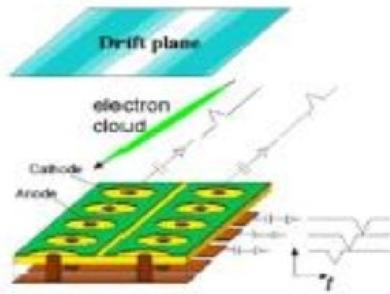


R. Bellazziniet al
Nucl. Instr. and Meth. A423(1999)125



P. Rehak et al., IEEE Nucl. Sci. Symposium seattle 1999

μPIC



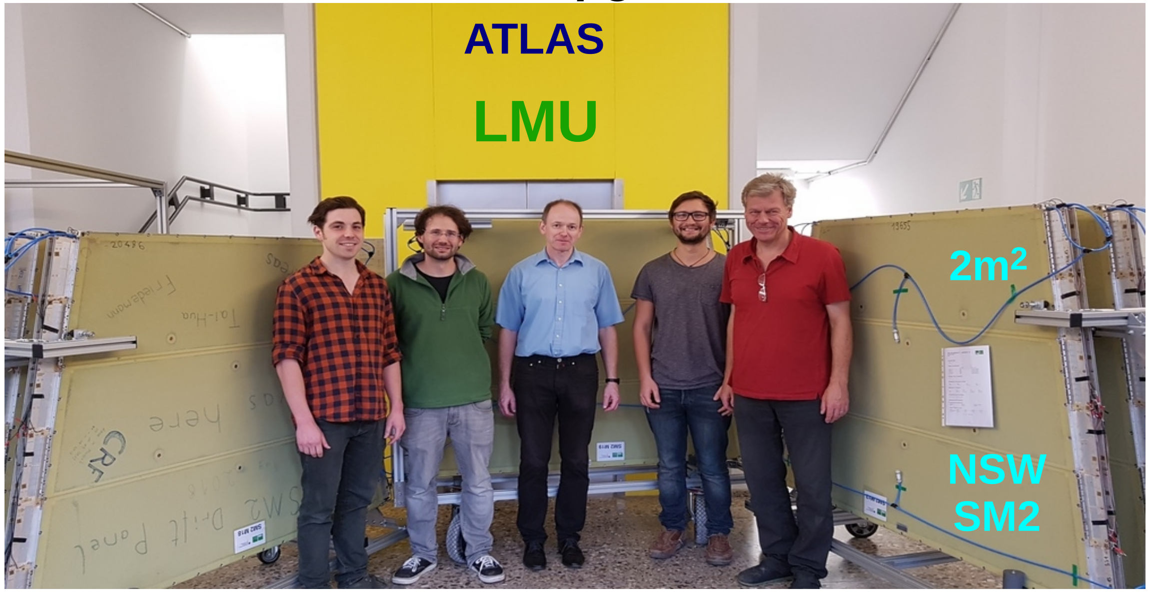
Ochi et al NIMA471(2001)264

AND MANY OTHERS ....

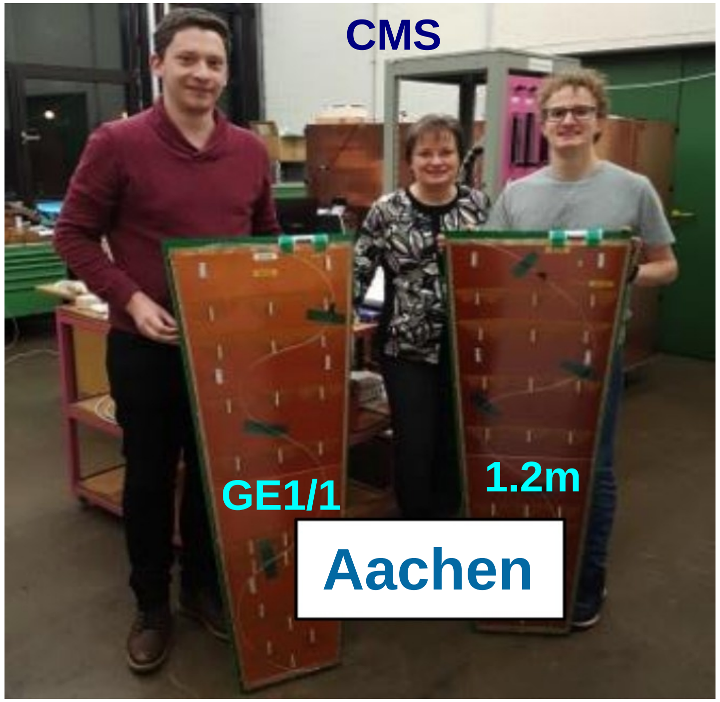
but 2 technologies made it for LHC:

Micromegas and Triple-GEM Detectors

Upgrade of Muon Forward Spectrometers



5 **Miromegas** quadruplets of 32 SM2
BMBF: Freiburg, Mainz, Munich, Würzburg



2 **GEM** detectors of 144

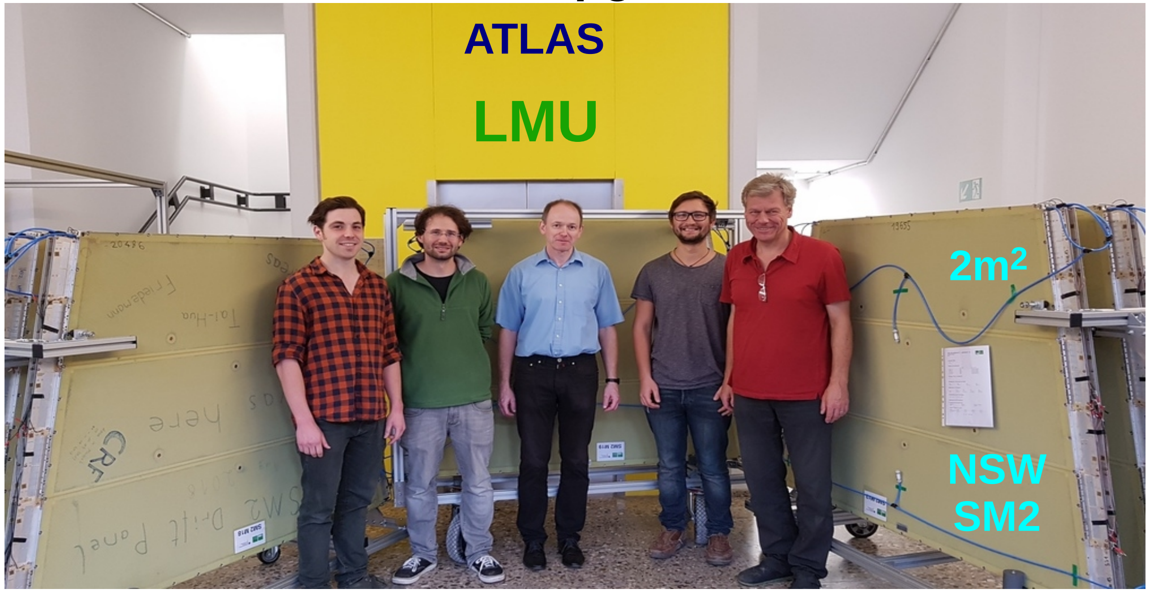
ALICE TPC - 700 GEM

GEM detectors for the **ALICE** TPC
TUM development
not covered in this talk

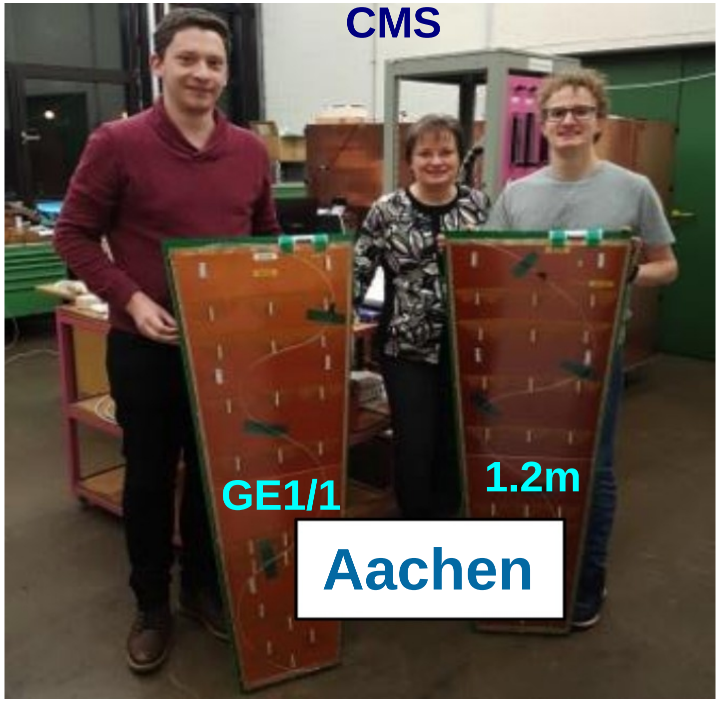
but 2 technologies made it for LHC:

Micromegas and **Triple-GEM** Detectors

Upgrade of Muon Forward Spectrometers



5 **Miromegas** quadruplets of 32 SM2
BMBF: Freiburg, Mainz, Munich, Würzburg



2 **GEM** detectors of 144

ALICE TPC - 700 GEM

GEM detectors for the **ALICE** TPC
TUM development
not covered in this talk

3. technology:

µRWELL: Micro Resistive WELL detectors
1.5 m
simple construction cheaper
Jefferson Lab Clas12 1 MHz/cm^2
ILC

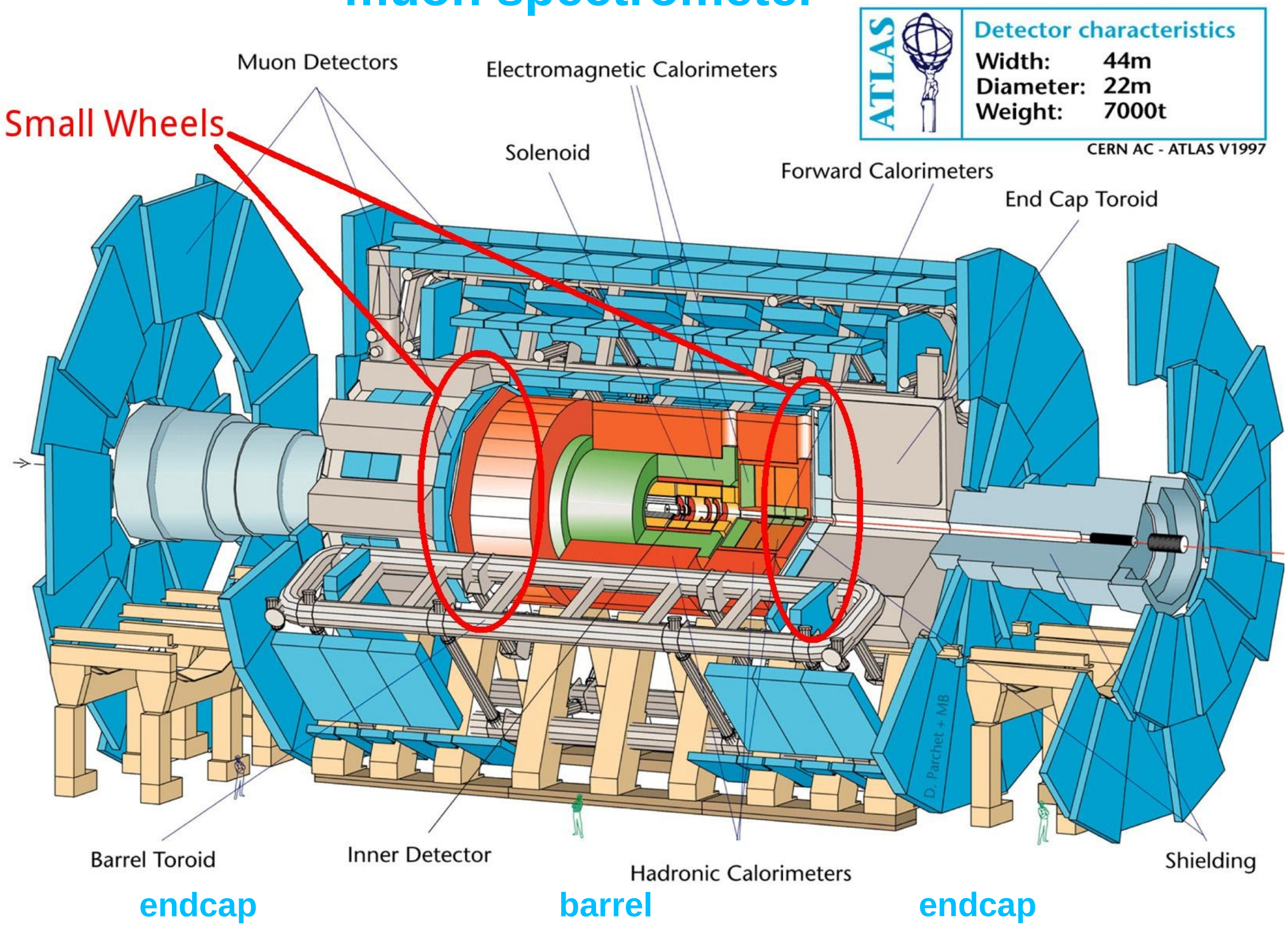
Micromegas for the ATLAS NSW

I. Giomataris & G. Charpak et al., NIM A376 (1996) 29

Voltaire 1752

ATLAS: A Toroidal Lhc ApperatuS

muon spectrometer

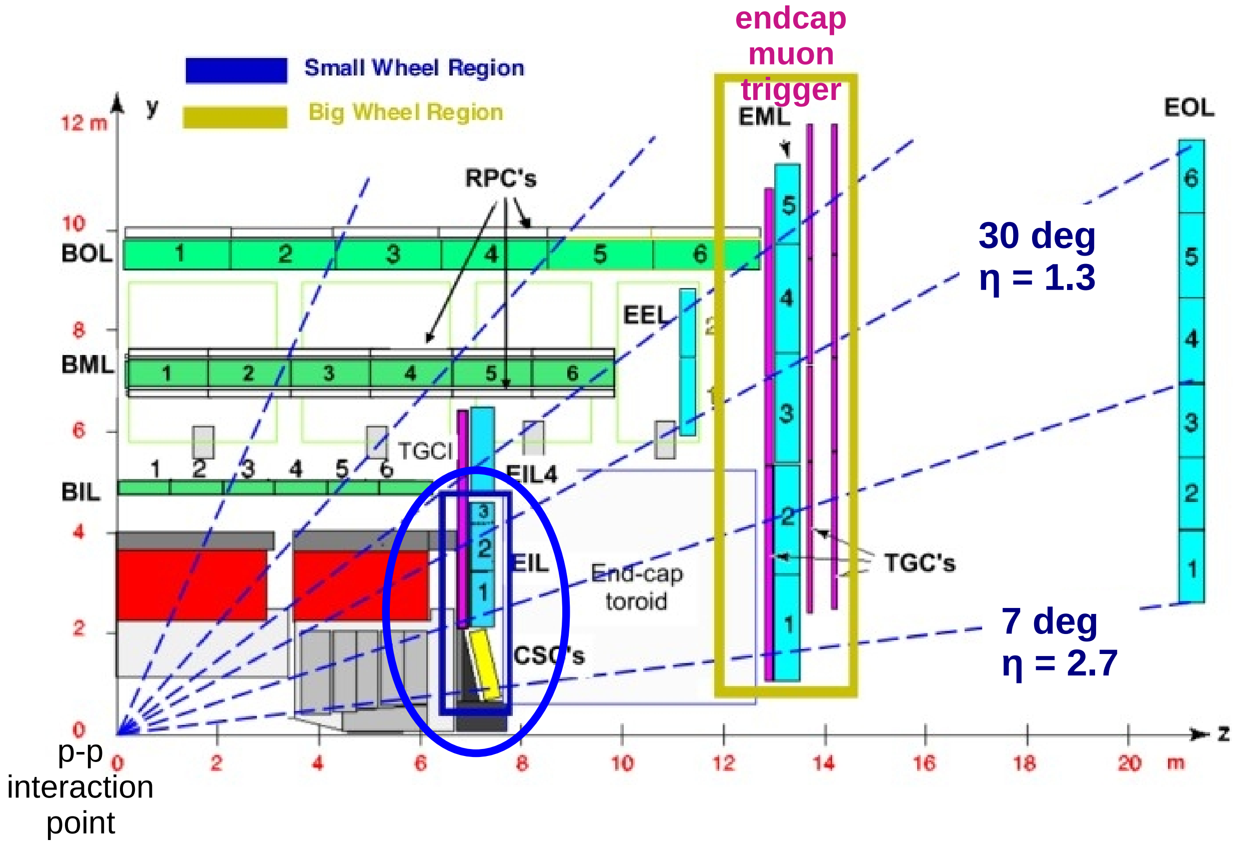


toroidal magentic field => endcap: η (radial direction) is precision direction

ATLAS: Micromegas and sTGCs replace the old Small Wheel

Scheme: ¼ ATLAS

radial precision direction (η)



2 Old Small Wheels:
- drift tube chambers
(rate limited)
- cathode strip chambers
(lifetime limited)
- no trigger information

=>

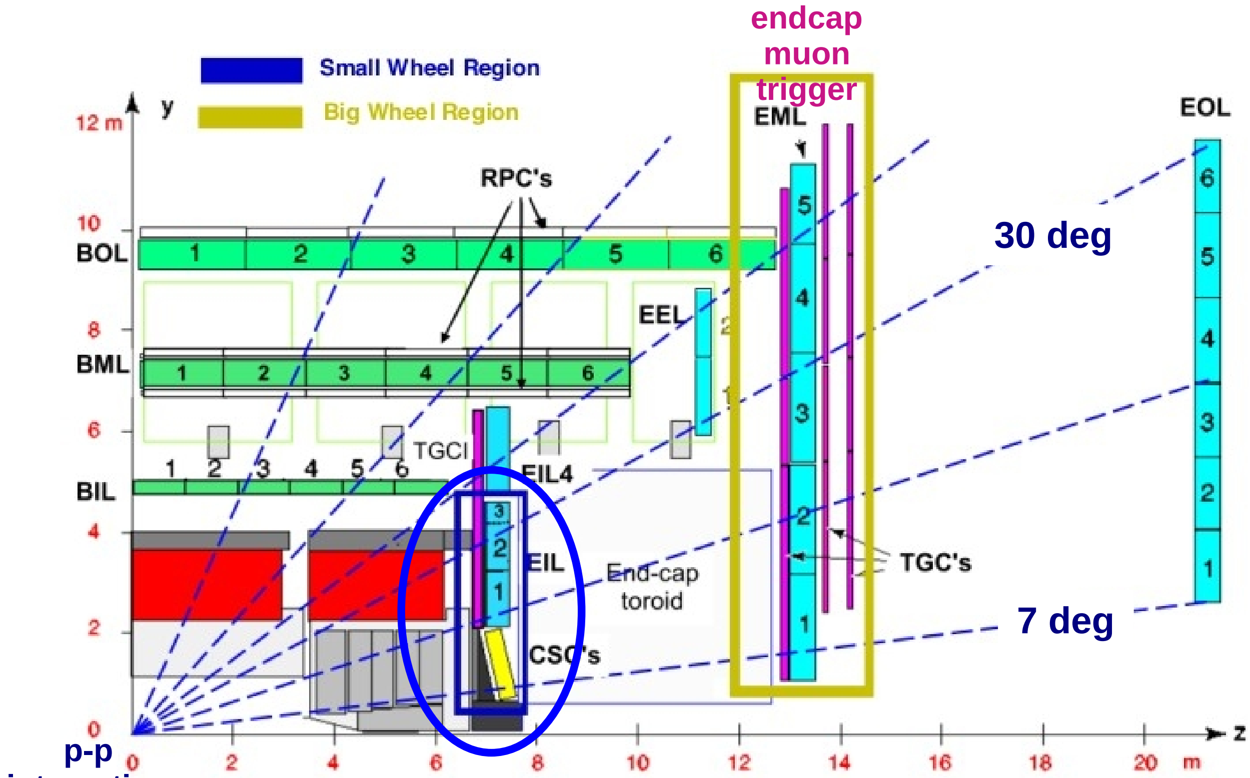
for HL-LHC 2 NSW are needed

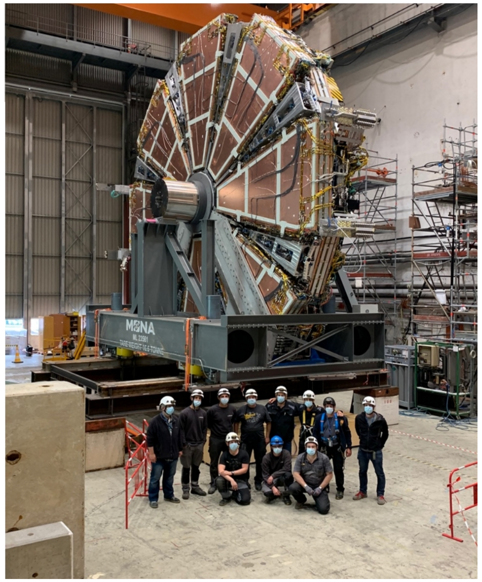
New Small Wheel (NSW) :
Micromegas detectors — MICROMEsh GAseous Structure
sTGC: fast wire detector — small strip Thin Gap Chamber

ATLAS: Micromegas and sTGCs replace the old Small Wheel

Scheme: ¼ ATLAS

radial precision direction (η)





2 m^2 / 3 m^2 large detector components 2021

Requirements for the New Small Wheel

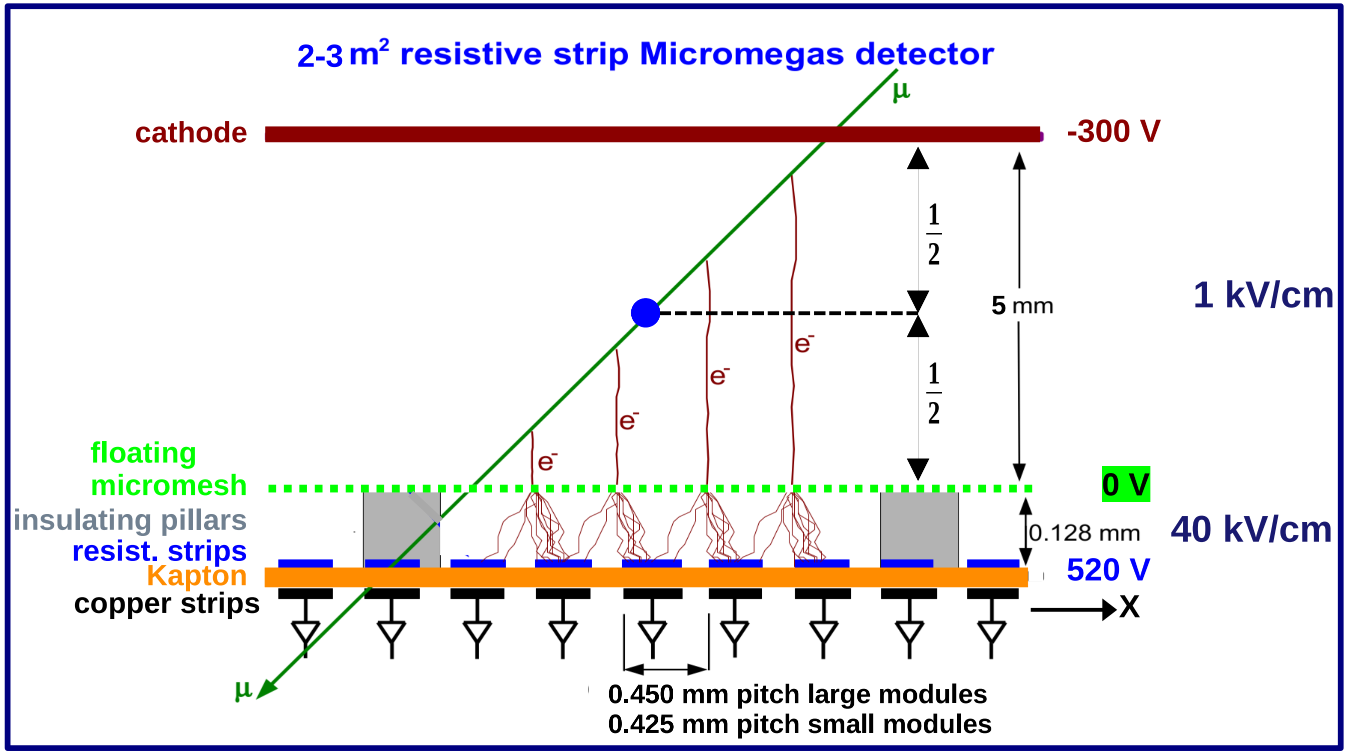
HL-LHC: $L=7.5*10^{34}$ $cm^{-2}s^{-1}$
background rates: 20 kHz/cm^2

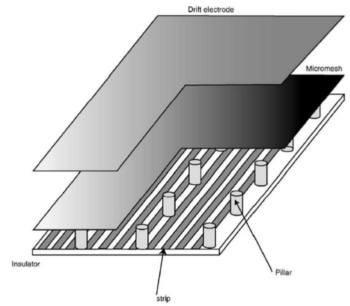
online trigger information:
- constant trigger rate over η
- online track segment reconstruction

muon precision tracking:
- 150 µm spatial resolution
- $\Delta p_T/p_T < 15$ % for µ @ $p_T > 1$ TeV
- $\varepsilon > 97\%$ for µ @ $p_T > 10$ GeV

precision construction
high accuracy during execution
quality assurance and
calibration

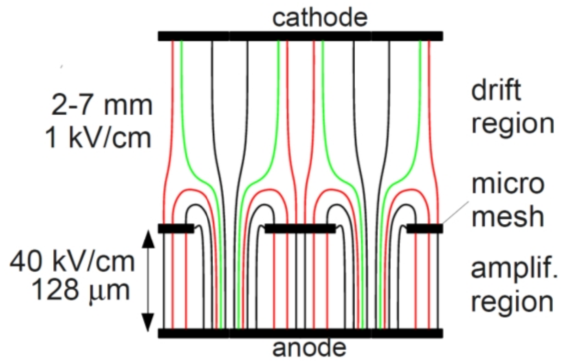
Micromegas Detectors: MICROMesh Gaseous Structures





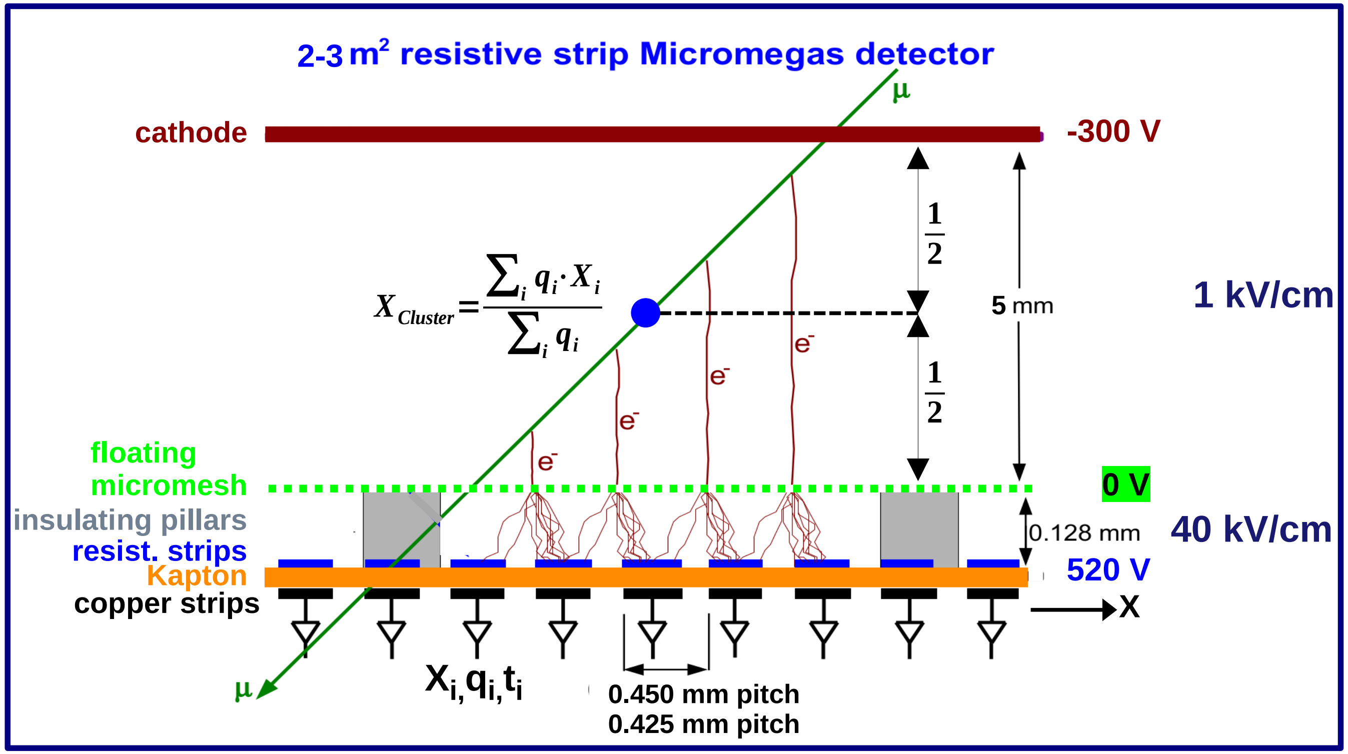
3 planar structures:

- cathode plane	3 pieces
- micromesh plane	1 piece
- anode / readout plane	3 pieces



resistive microstrips   sheet resistance: ≈ MΩ / sq.
+ copper readoutstrips

Micromegas Quadrupet Detectors: MICROMesh Gaseous Structures



gases:

Ar:CO2:isobutane 93:5:2 Vol% — U_{anode}= 520 V

Ar:CO2 93:7 Vol% — U_{anode}= 570 V

2% isobutane: increased HV stability and better performance

! large area capability

resistive microstrips   sheet resistance: ≈ MΩ / sq.
+ copper readoutstrips

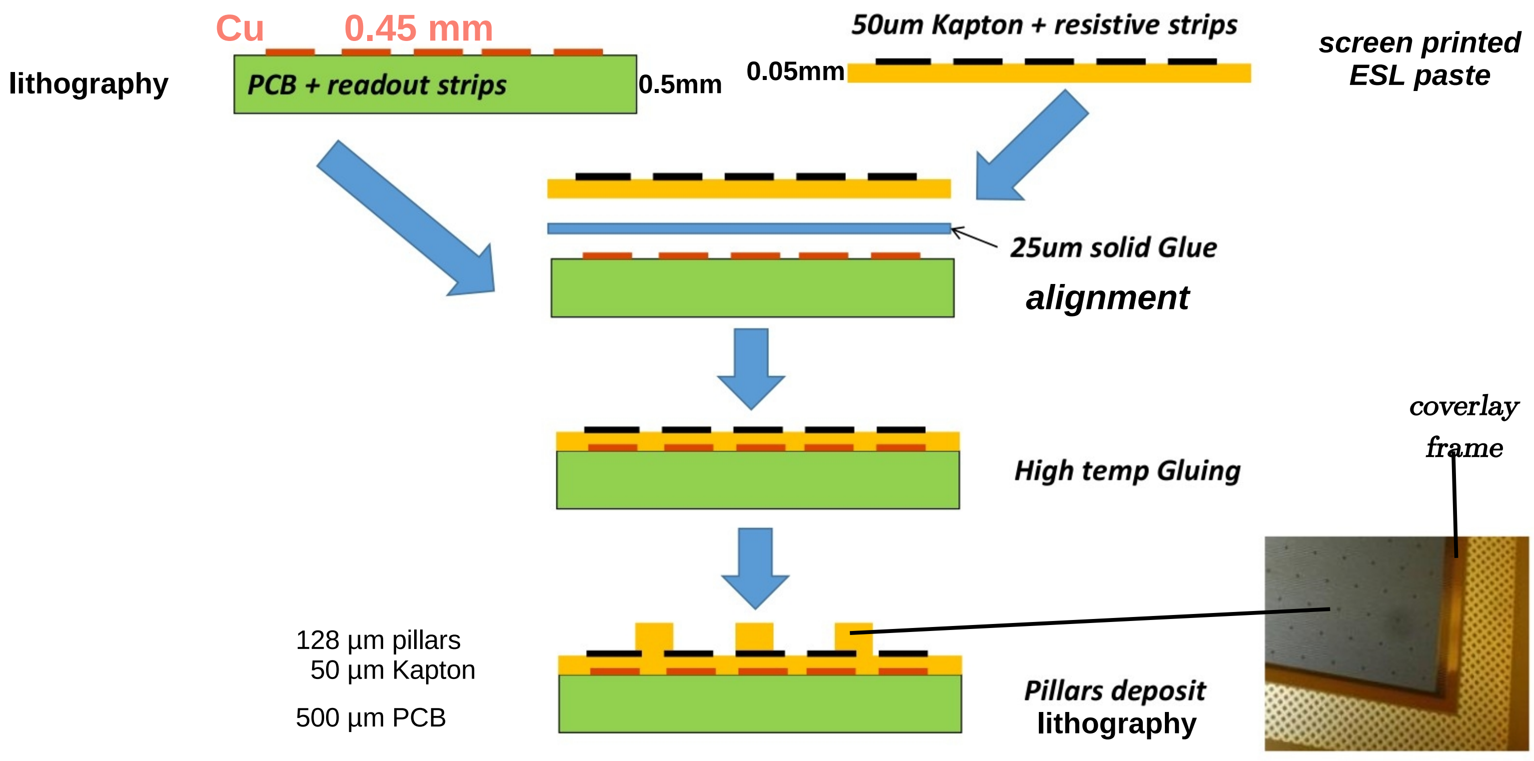
X_i, q_i, t_i information per strip (strip nr., charge on the strip, arrival time of the signal)

a cluster is a sequence of responding strips

MM Resistive Strip Anode

(PCB: printed circuit board)

(breakthrough for large area capability)



coverlay frame
=>
pre-resistor !

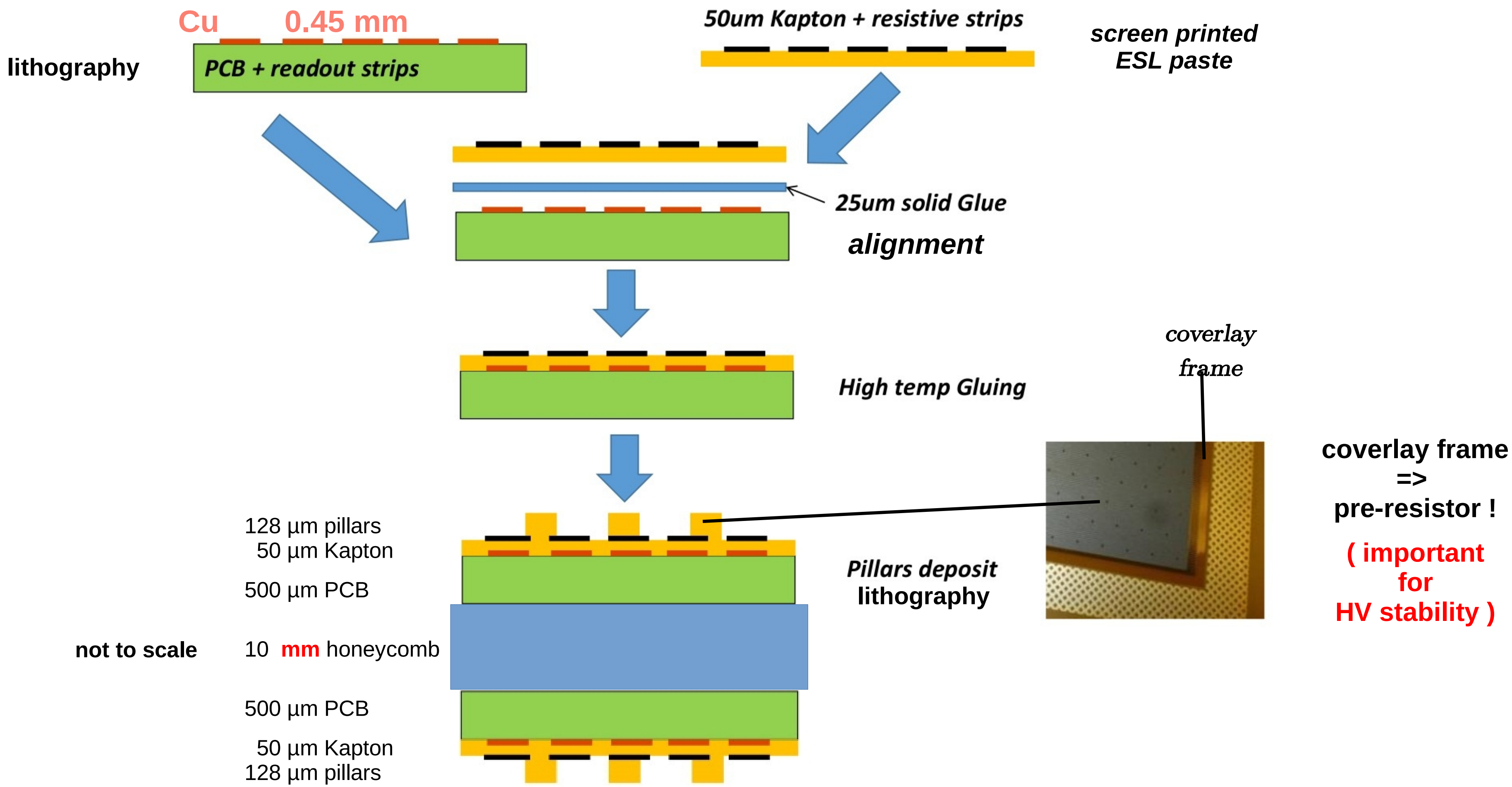
(important for HV stability)

development: CERN detector lab
resistive strip layers: Univ. Kobe (Jp)
production: Elvia (F), Eltos (I)

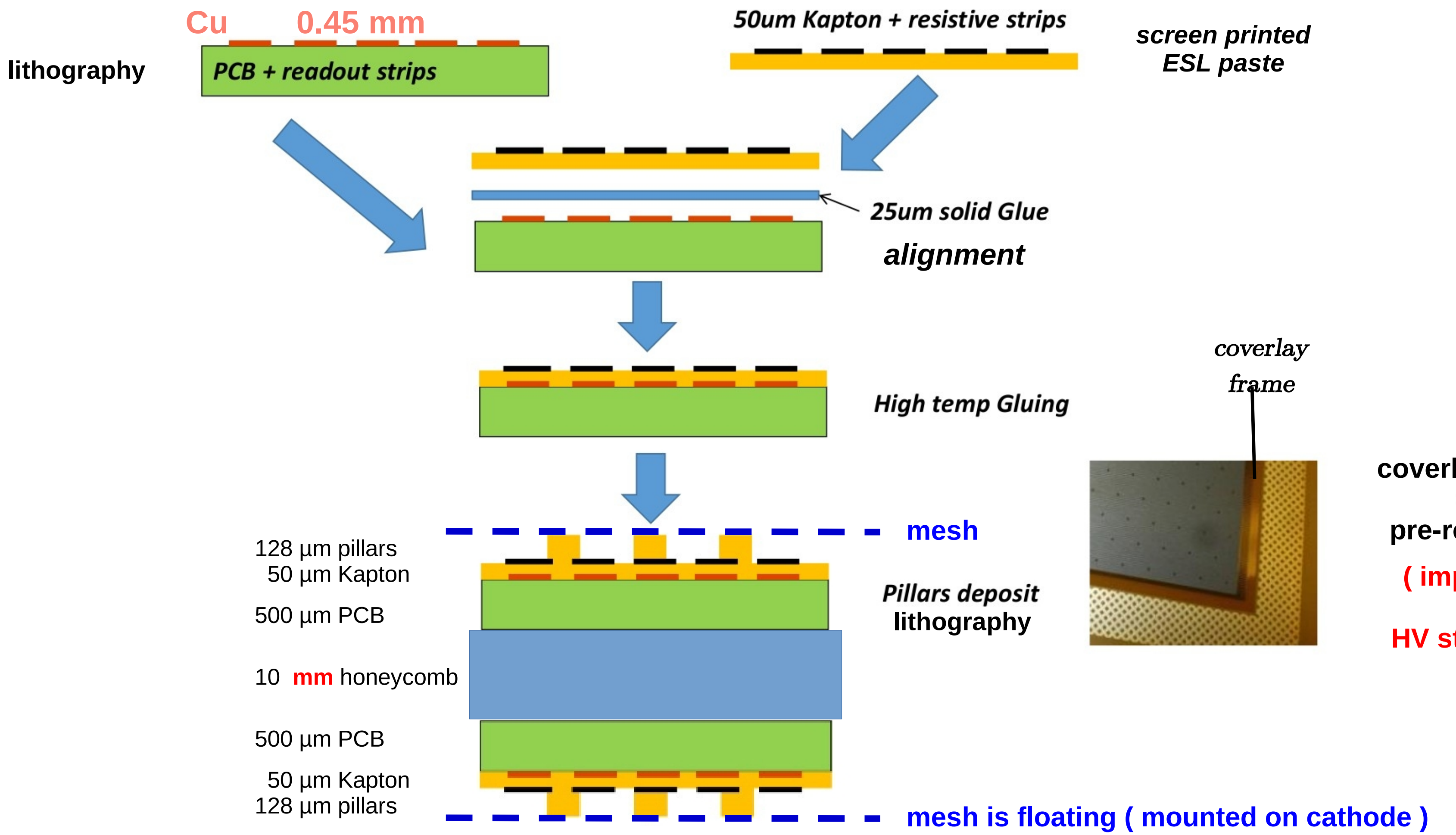
Double MM Resistive Strip Anode

(PCB: printed circuit board)

(breakthrough for large area capability)



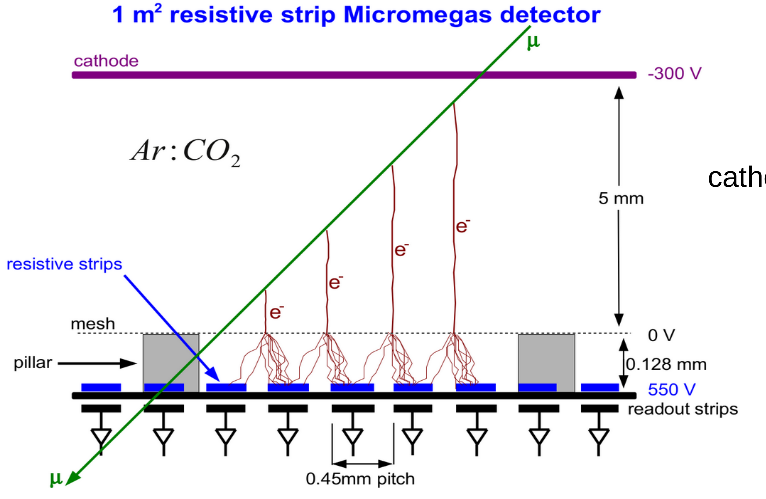
Double MM Resistive Strip Anode
(PCB: printed circuit board)
(breakthrough for large area capability)



coverlay frame => pre-resistor !

(important for HV stability)

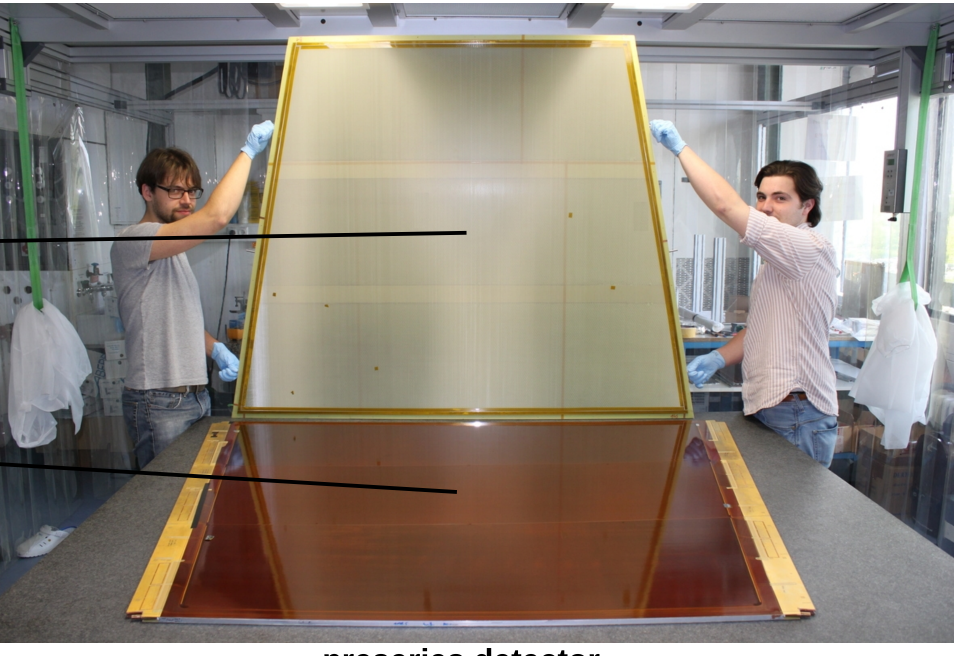
Micromegas Quadrupet Detectors



floating mesh mounted on the cathode

cathode + mesh

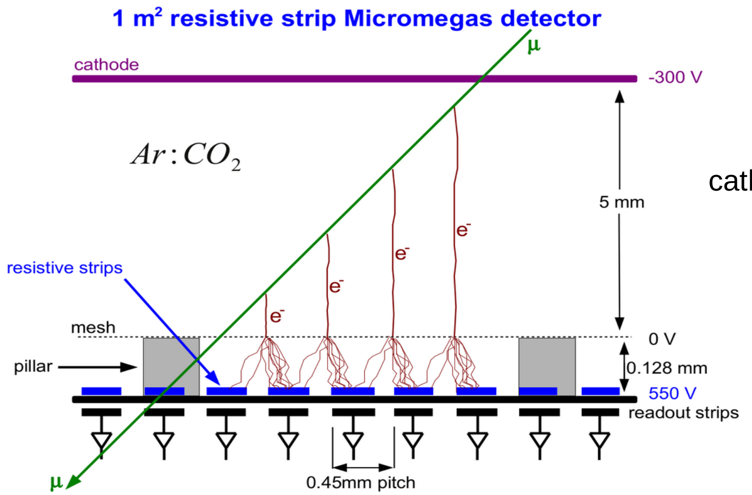
double
anode
+
pillars



preseries detector

mechanically floating meshes:
attracted by electrostatic force onto the pillars

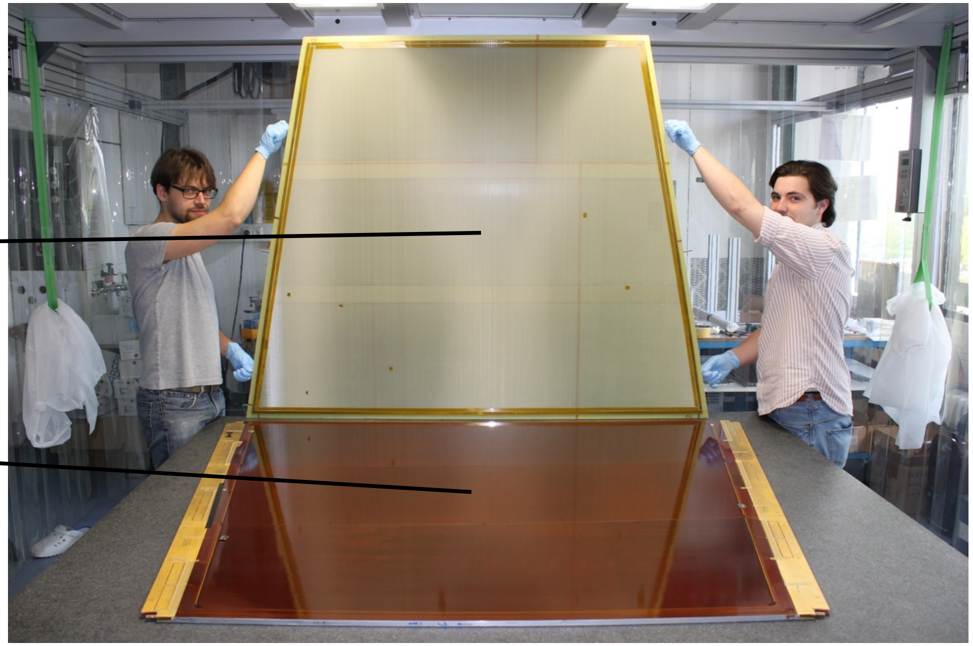
Micromegas Quadrupet Detectors



floating mesh mounted on the cathode

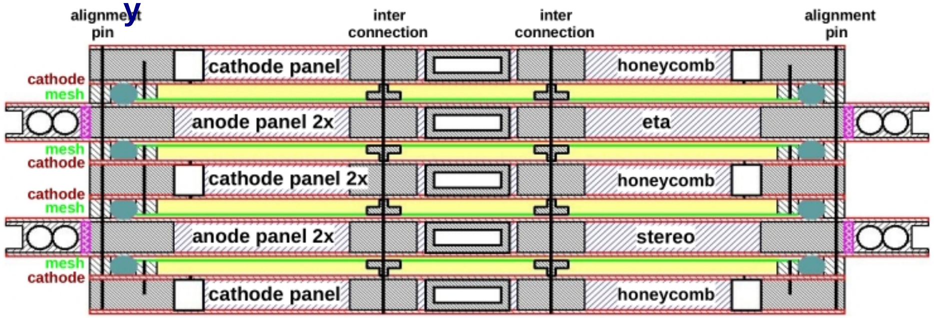
cathode + mesh

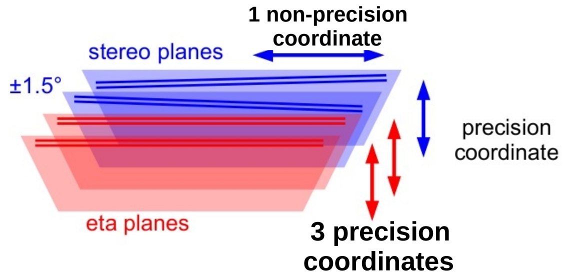
double
anode
+
pillars



preseries detector

mechanically



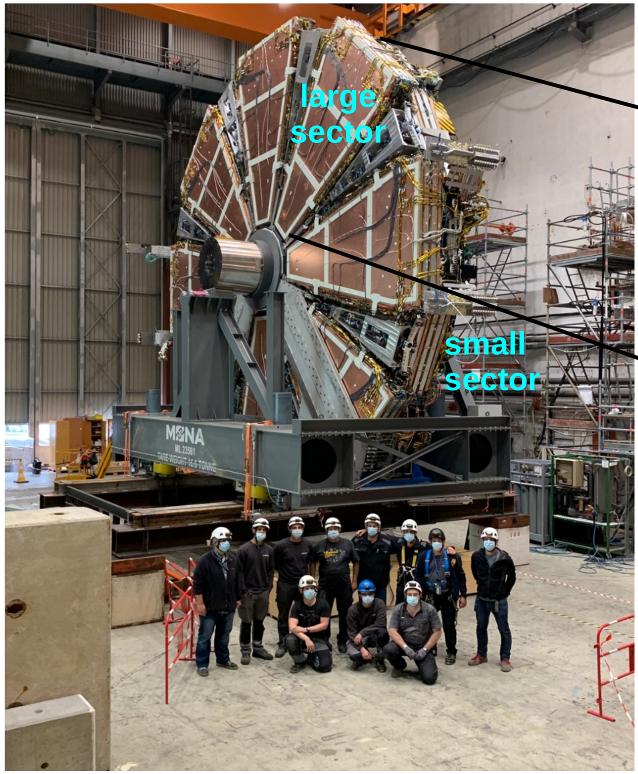


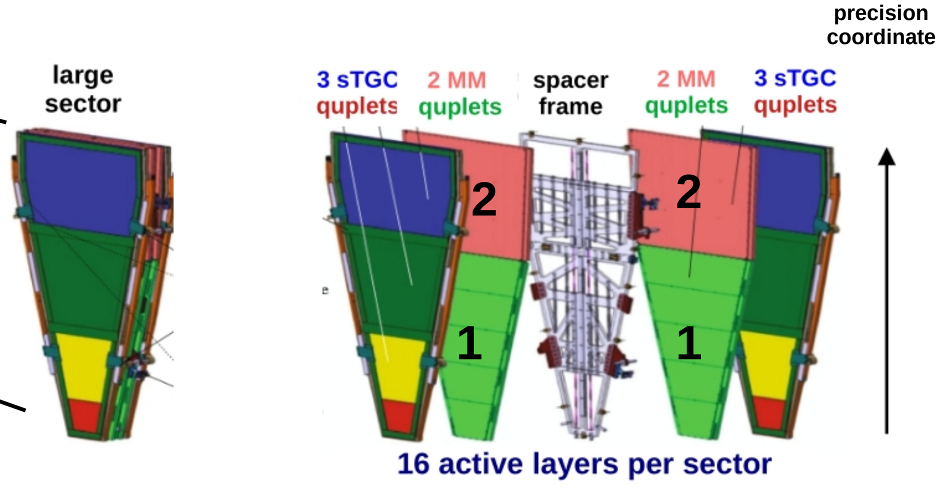
quadruplet: (4 active MM layers)

5 precise honeycomb panels: 3 cathodes 2 anodes
4 active volumes (Ar:CO2:isobutane)
4 micromeshes connected to cathodes
precise mesh frames + precise gas-gap frames
o-ring sealing + screws

ATLAS New Small Wheel: Layout

NSW-A 2021





each sector consists of 16 active layers:
- 8 layers small-strip Thin Gap Chamber
- 8 layers Micromegas (4 eta, 4 stereo)

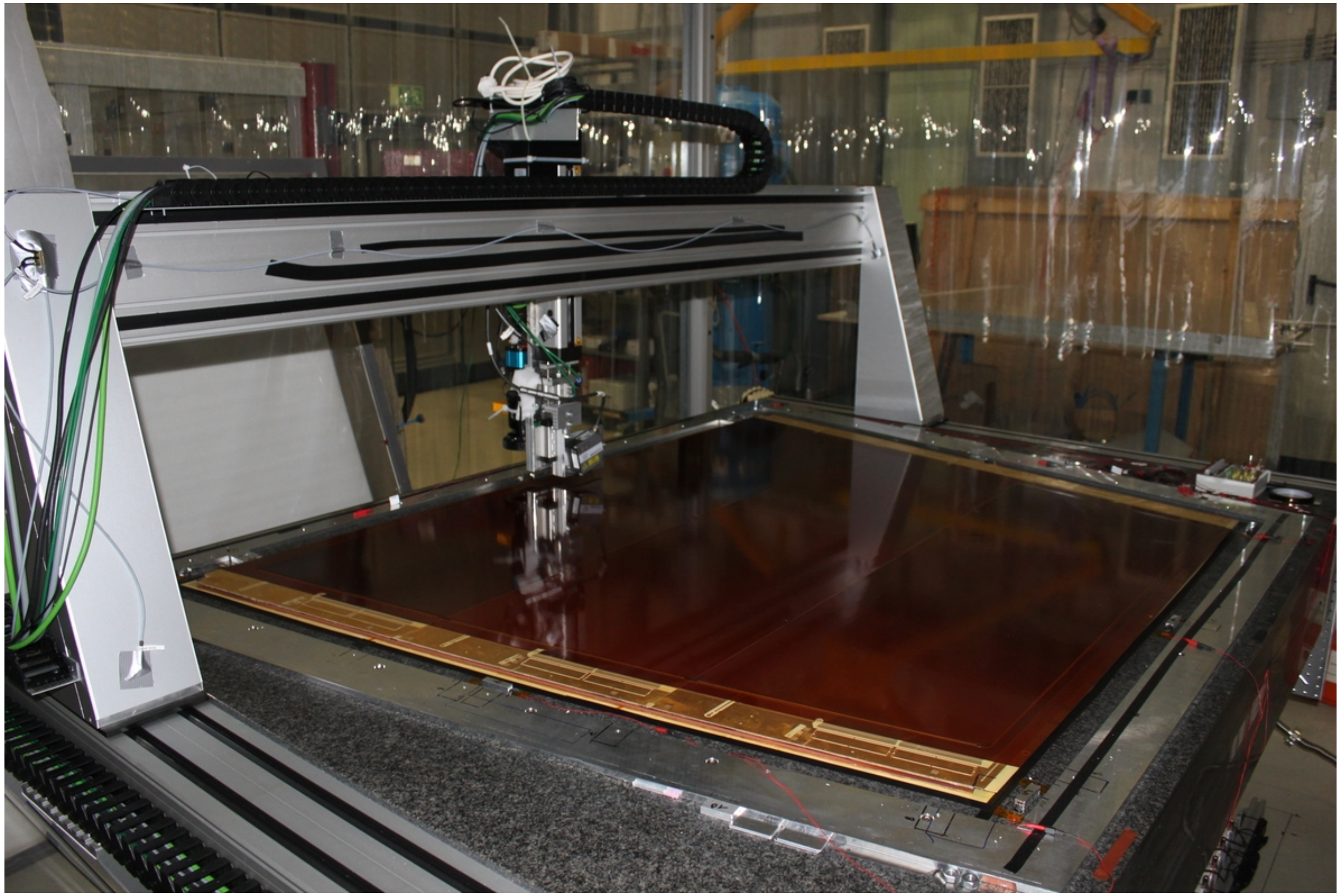
- 2.5 million readout channels
=> VMM frontend electronics

NSW-A / NSW-C:
16 sectors in total with 16 active layers each
8 large sectors
8 small sectors

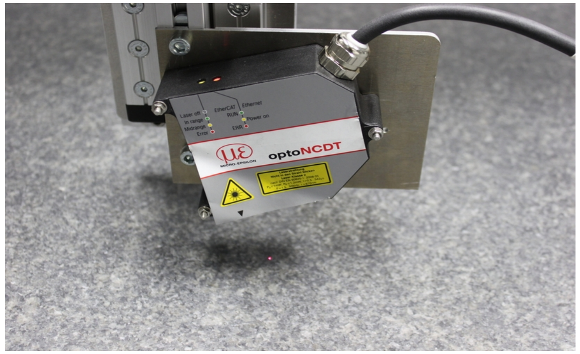
LM1 Saclay (F)
LM2 Cern, Dubna, Thessaloniki
SM1 INFN (I)
SM2 BMBF (D)

Precision Calibration
and
Quality Assurance

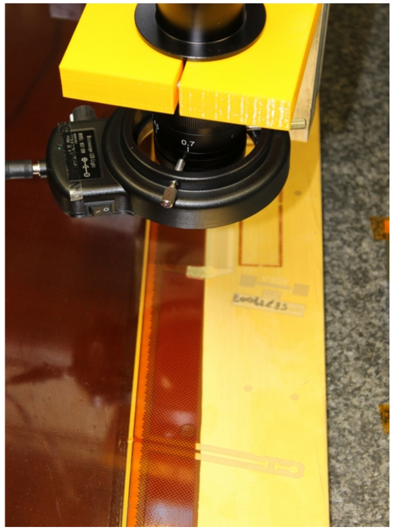
Planarity Scan of the Surface Using a CMM 2-Axis H Machine



planarity measurement of a SM2 readout panel (M0)



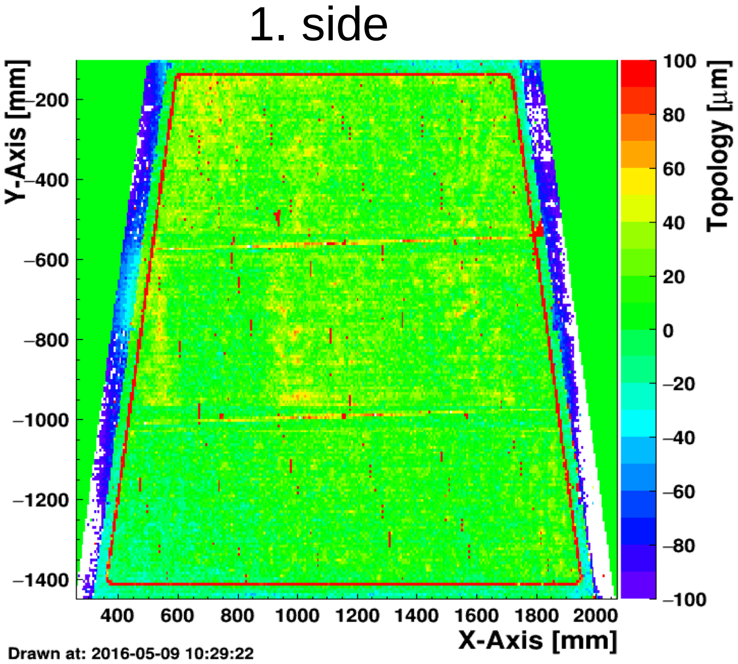
a laser head allows
for a fast scan
t = 1.5 h @ 7000 dp
t = 0.75h @ 3500 dp
dp: data points

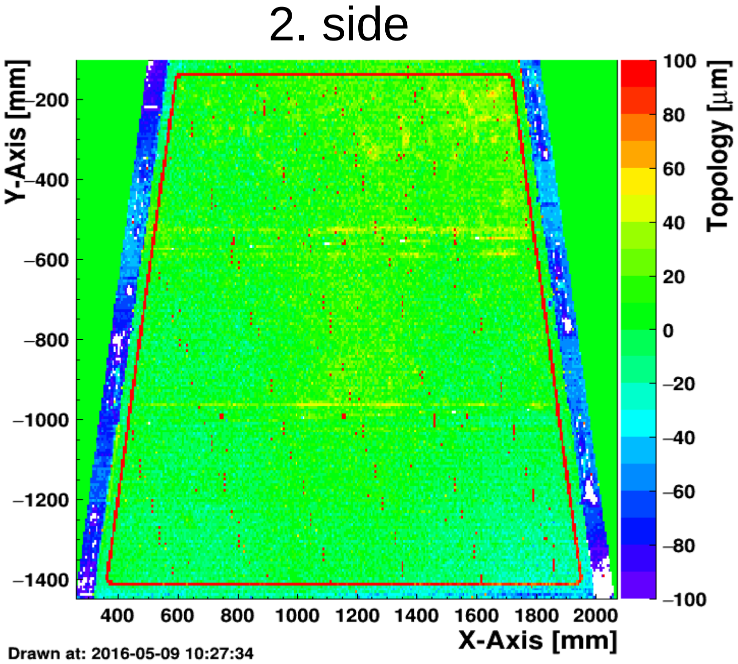


for p.50

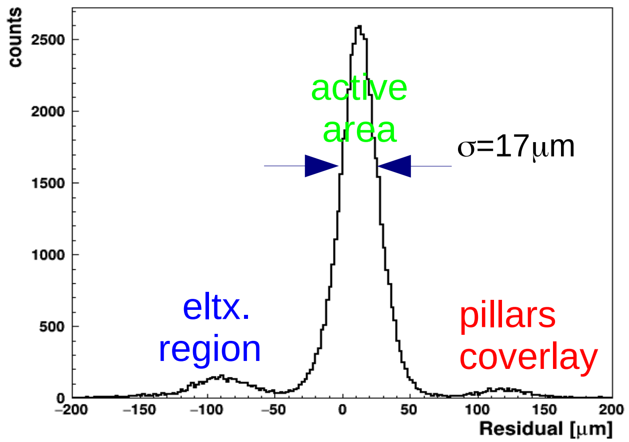
Planarity of Panel RO1 (Stereo)

surface scan 40000 points (reference: average value)

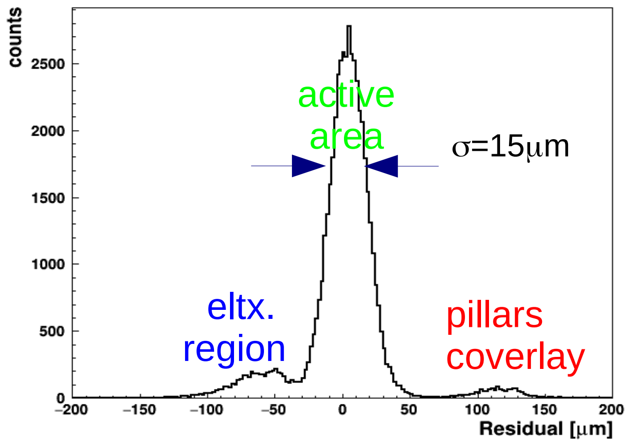




thickness @ assembly holes: 11.559±0.032 mm (11.564 design)

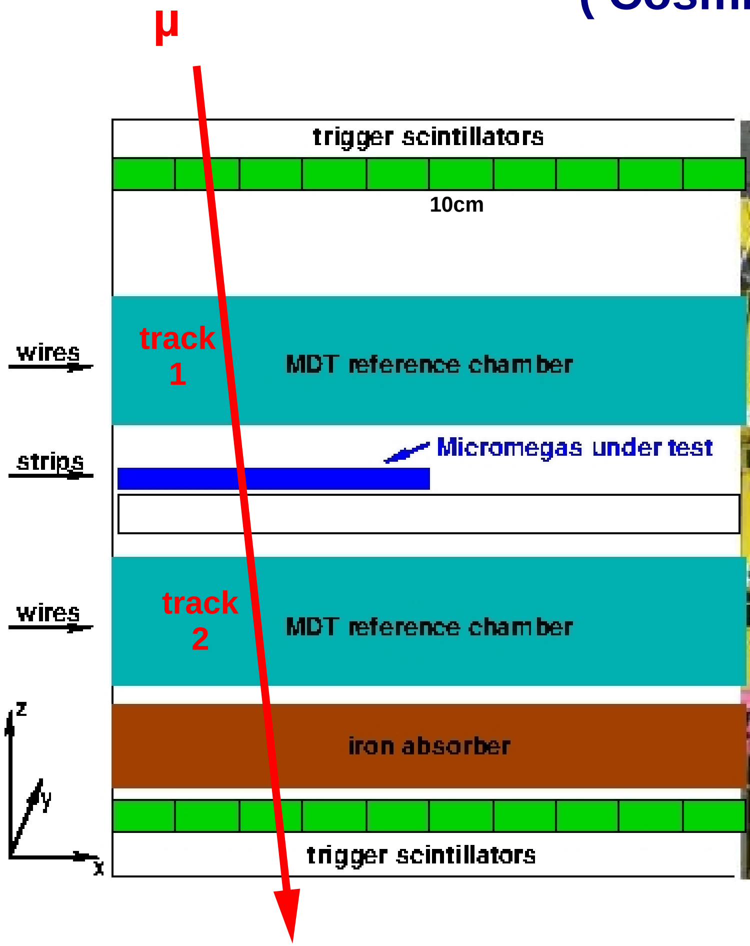


<< 37 µm



measurement is exactely as it should be: flat and parallel surfaces! ✔

Precision Calibration Using Cosmic Rays
(Cosmic Ray Facility Garching)



precision direction Y

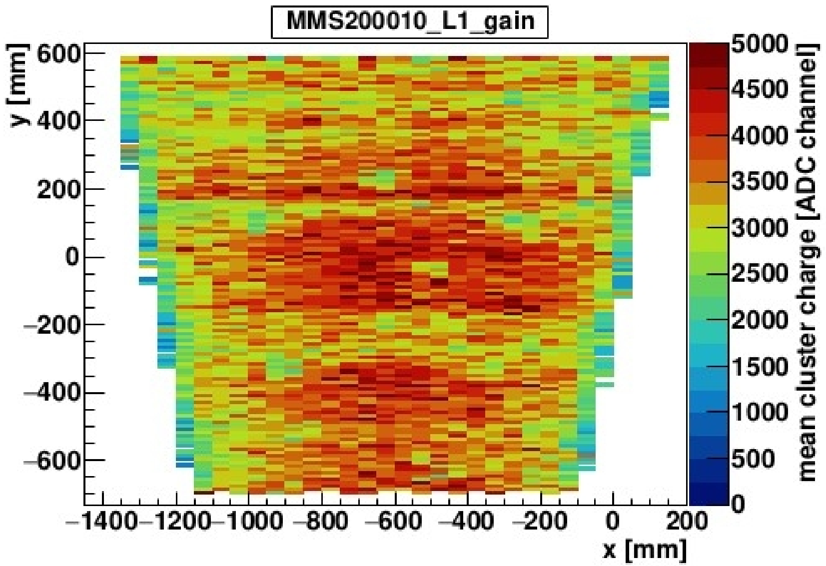
Results:

- **2D pulse height distributions**
- **residuum = Y_{ref} - Y_{meas} :**
  - **efficiencies**
  - **precision calibration of strips**
  - **precision calibration of pitch**

Cosmic Pulse Height and Efficiency Distributions

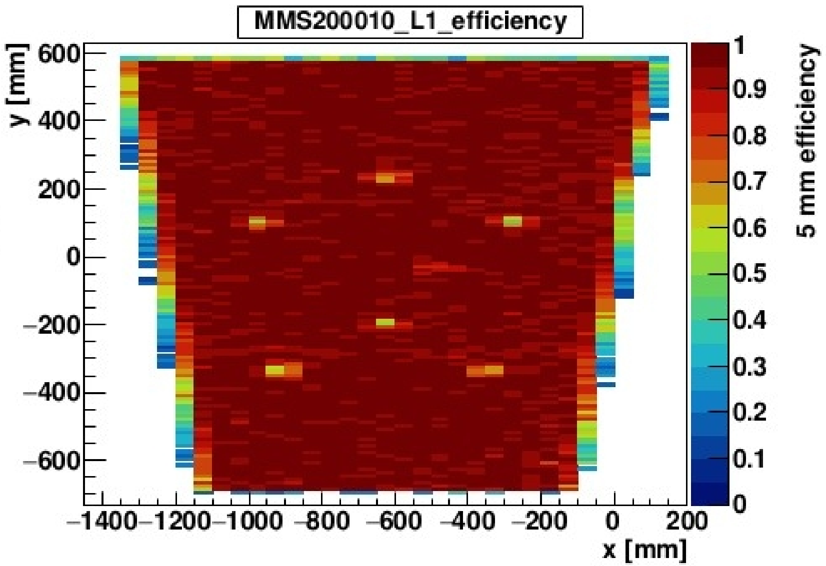
Ar:CO2 93:7 Vol%   580 V

pulse height



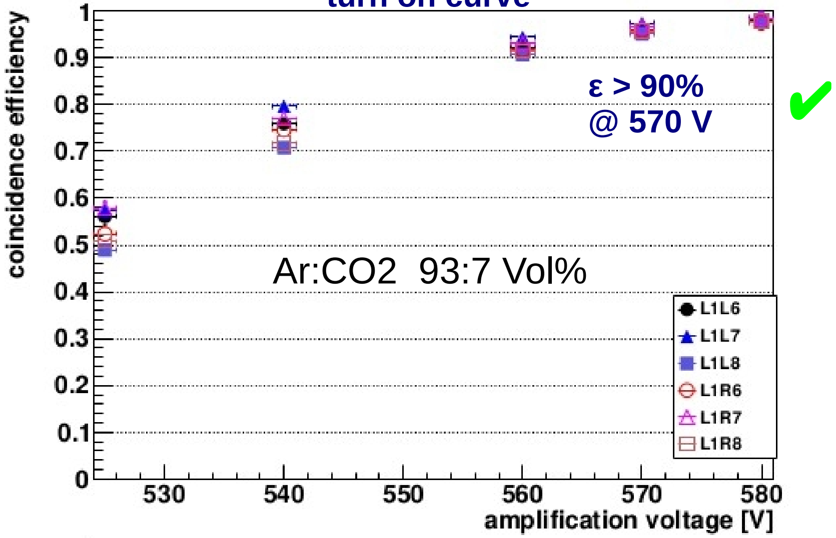
homogeneous pulse height distribution

5mm efficiency

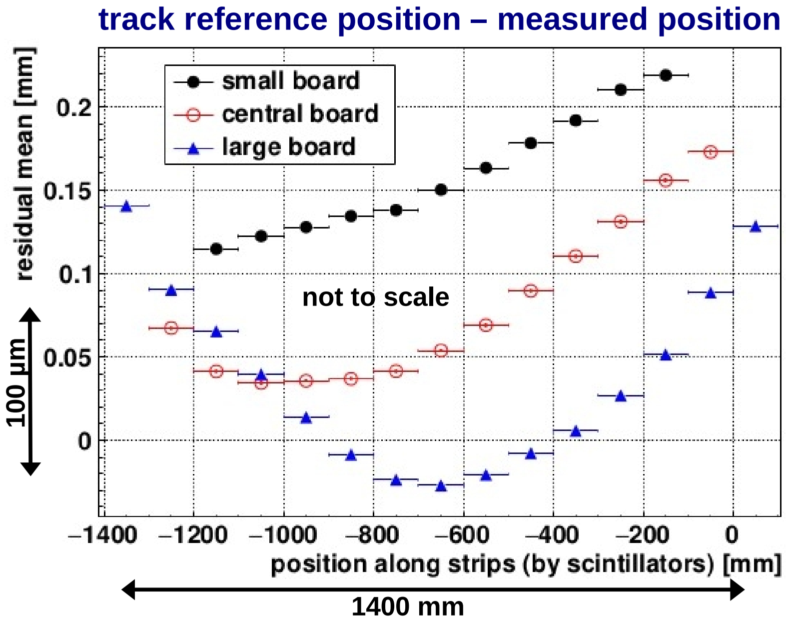


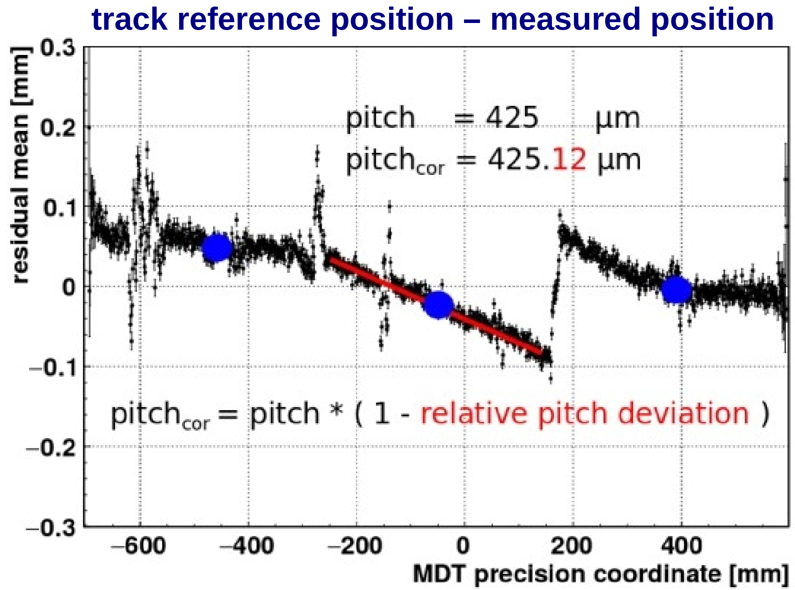
homogeneous efficiencies > 90%
for cosmic muon tracking

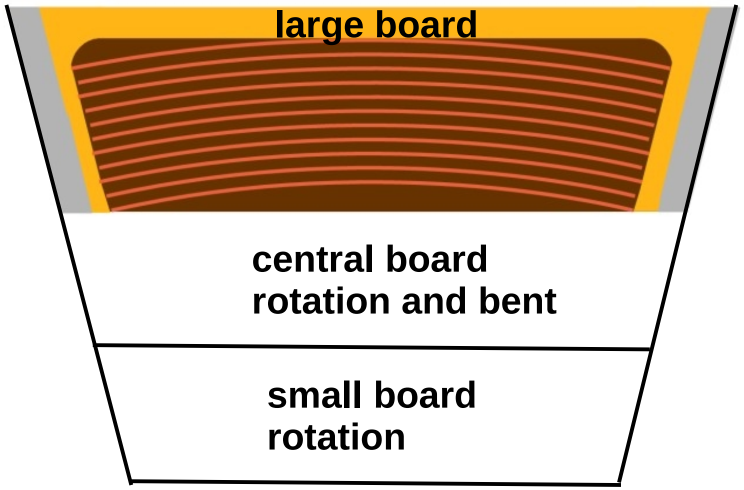
“turn on curve”



Cosmic Ray Facility: Calibration Results -> Database



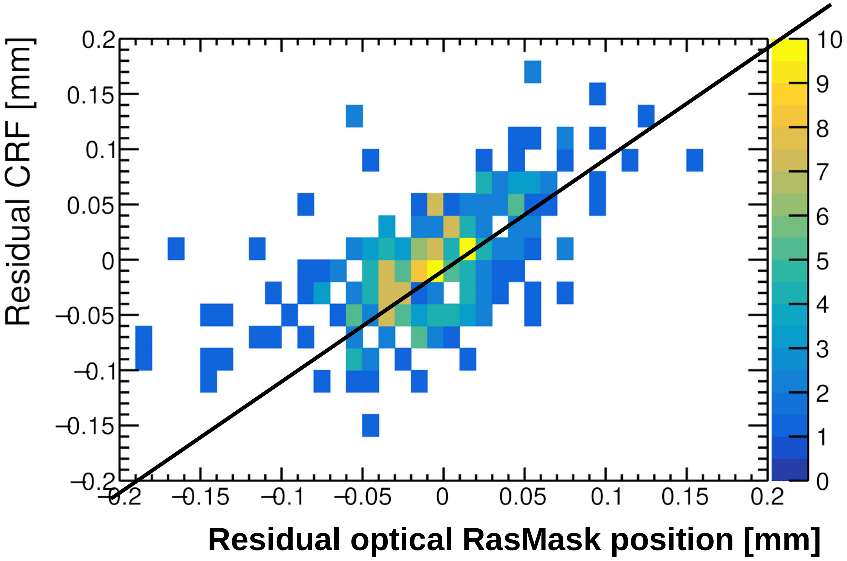


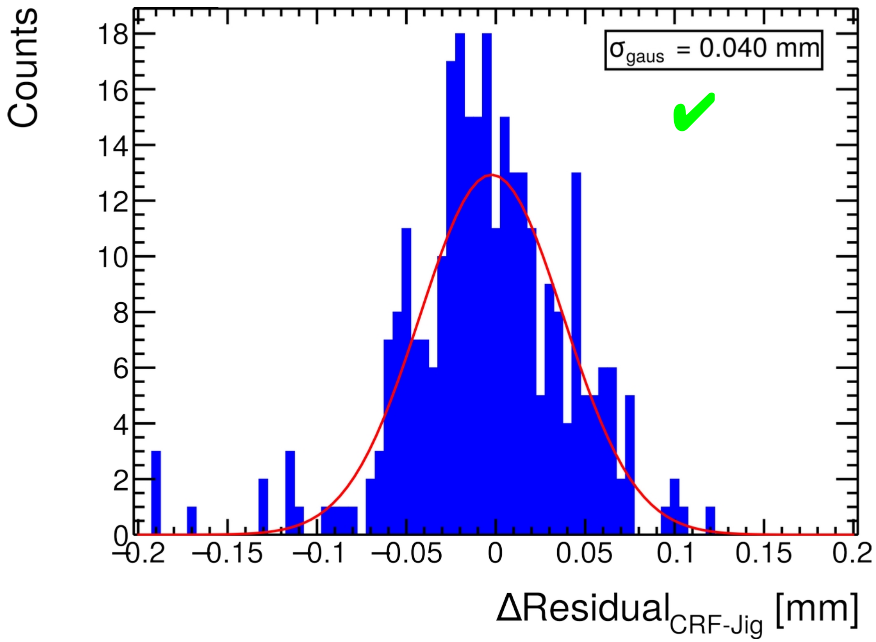


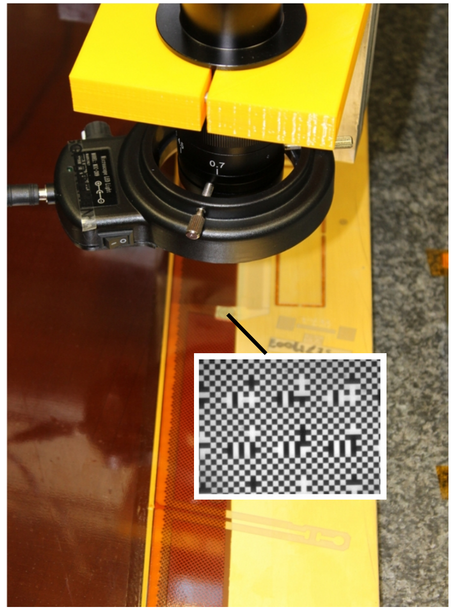
results are considered in the database (as built parameters) ✔

Comparison: Cosmic Deformations with Position Coded RasMasks

(from: Red Alignment System NIKhef (RasNik))

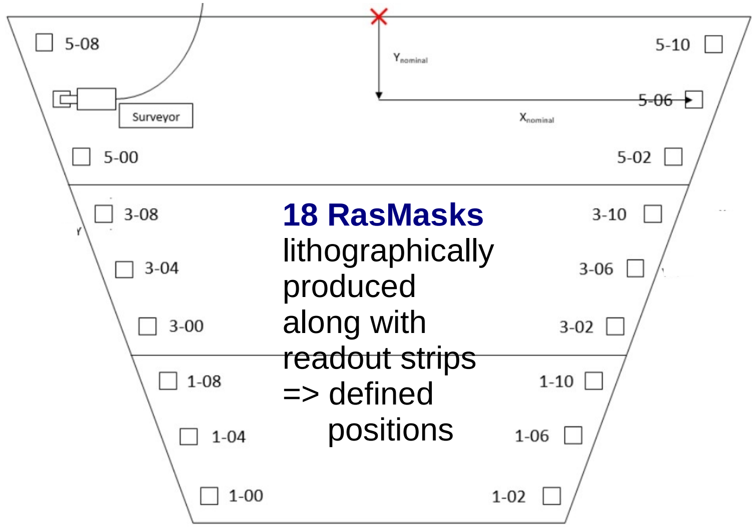






CCD photo of a RasMask (chessboard with position coding)

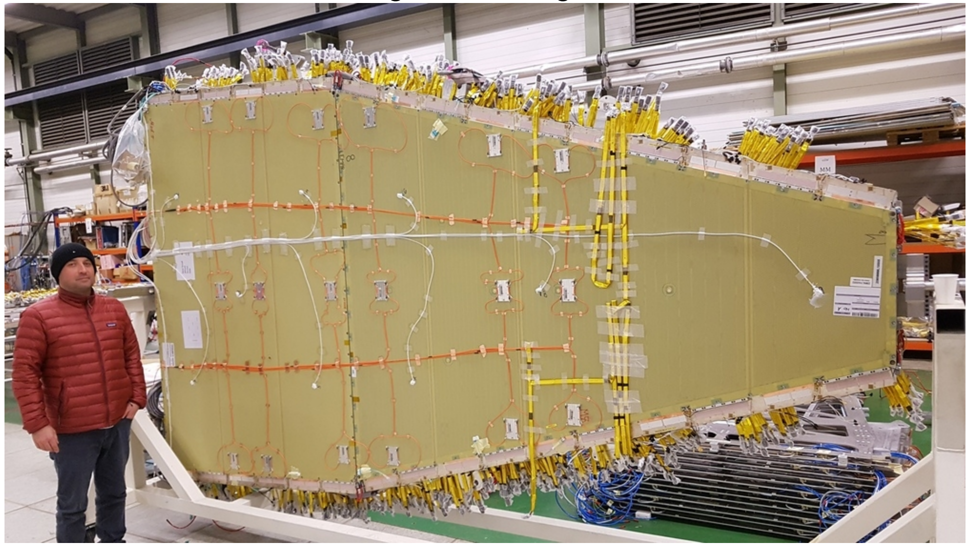
SM2 anode panel with 18 RasMasks

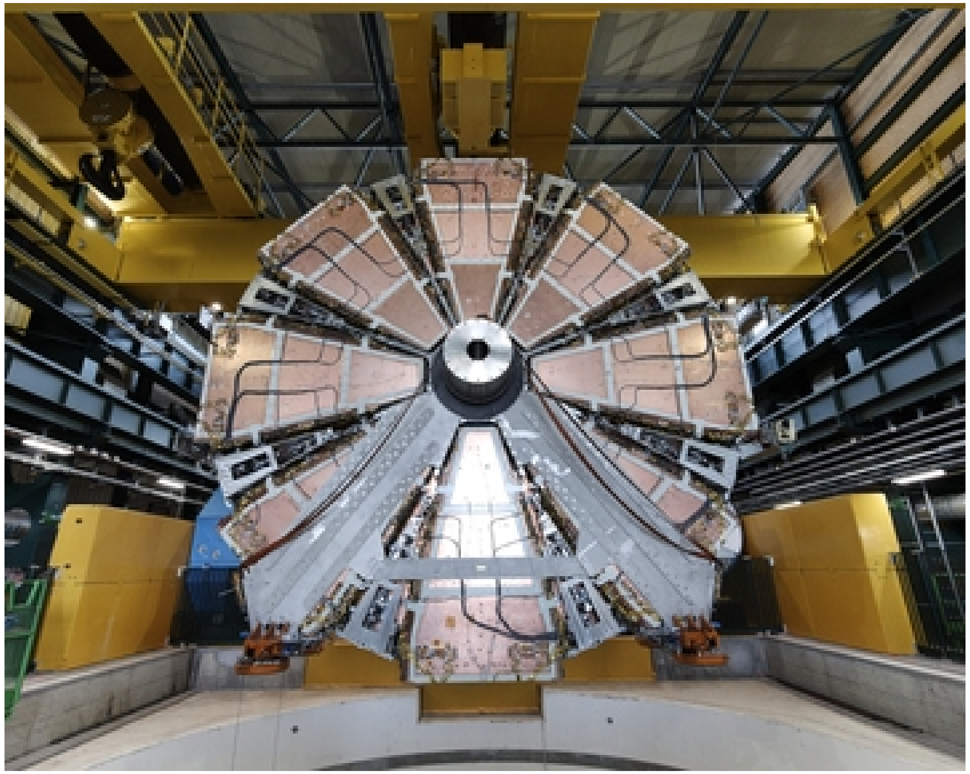


good agreement between cosmic measurtement and RasMask anlysis, even after months => stable panels ✔

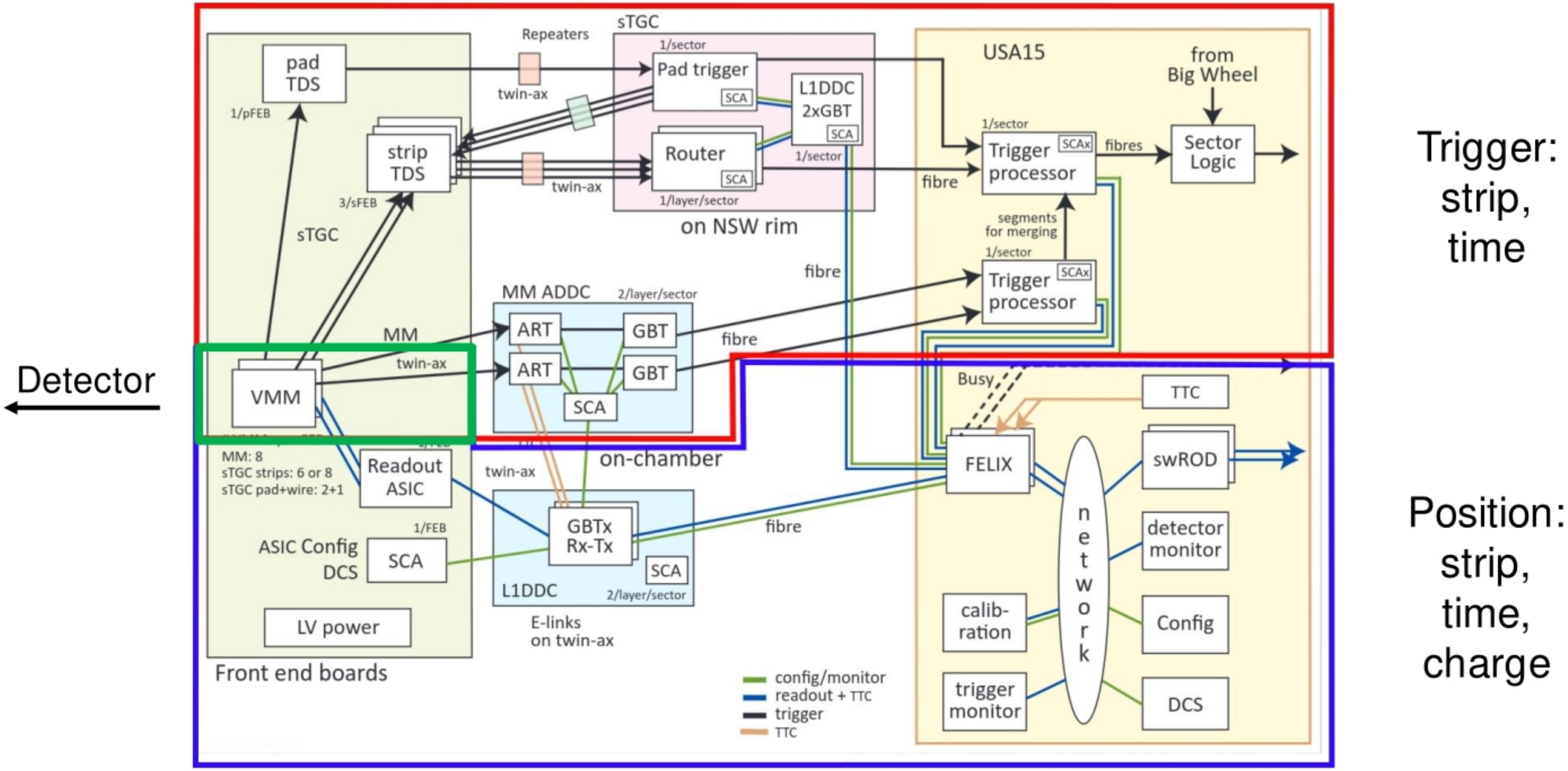
ATLAS 2021: Installing the New Small Wheels

a large Micromegas sector





VMM: ATLAS New Small Wheel Frontend Electronics:

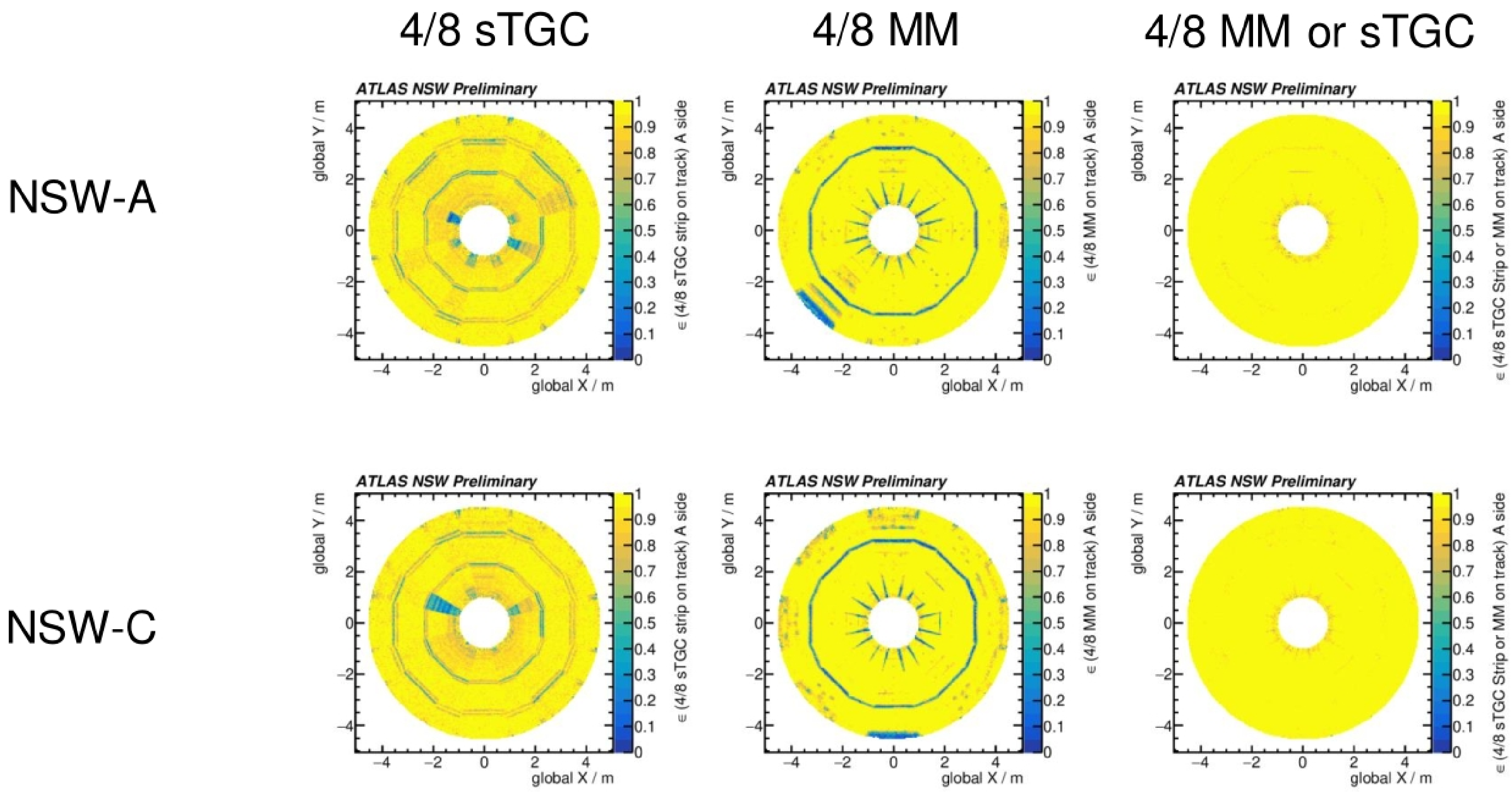


G. Iakovidis et al 2023 *JINST* **18** P05012, adapted

2 purposes:

- improve ATLAS muon endcap trigger
- provide precision muon tracking:
$\Delta p_T/p_T < 15$ % for $p_T > 1$ TeV
spatial resolution 150 µm

On Track Efficiency: 4 layers of 8 layers in 2024

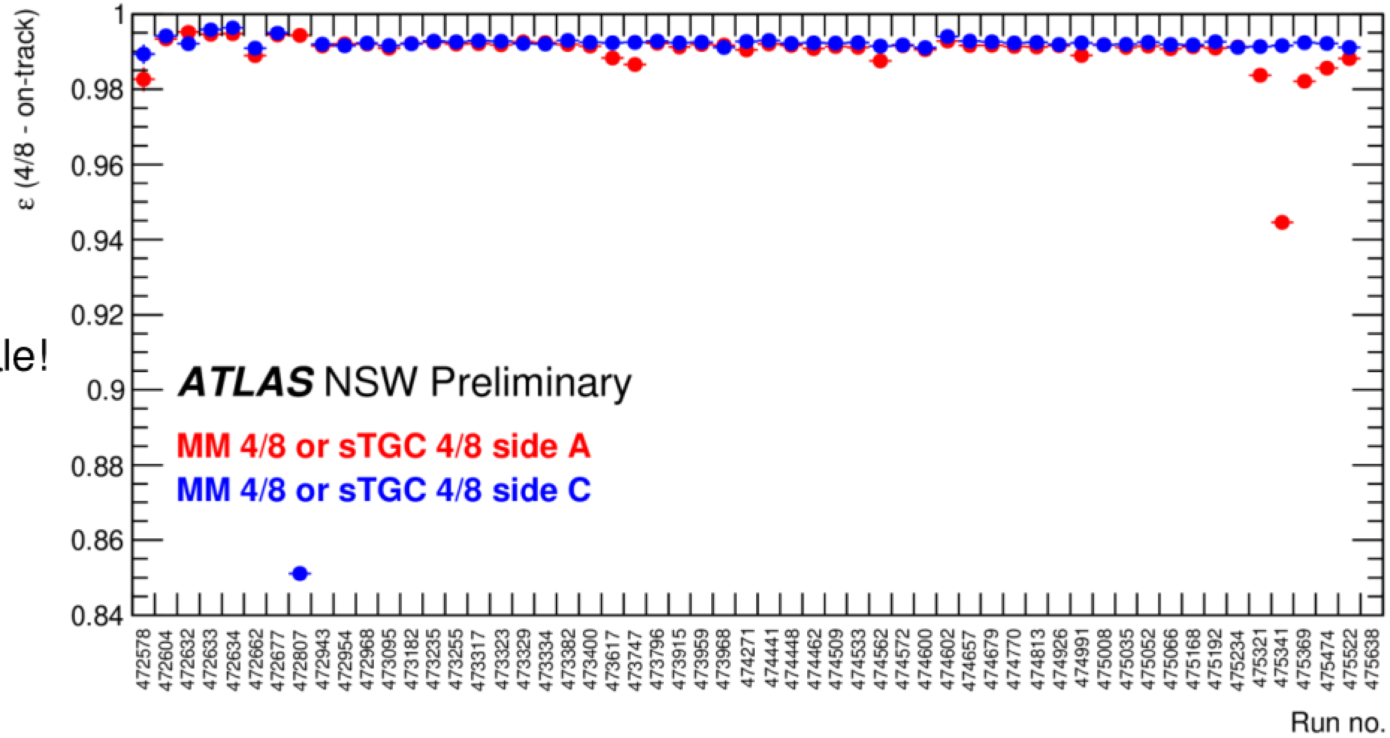


ε > 95% over both NSW surfaces ✓

ATL-COM-MUON-2024-011

On Track Efficiency: 4 layers of 8 layers in 2024

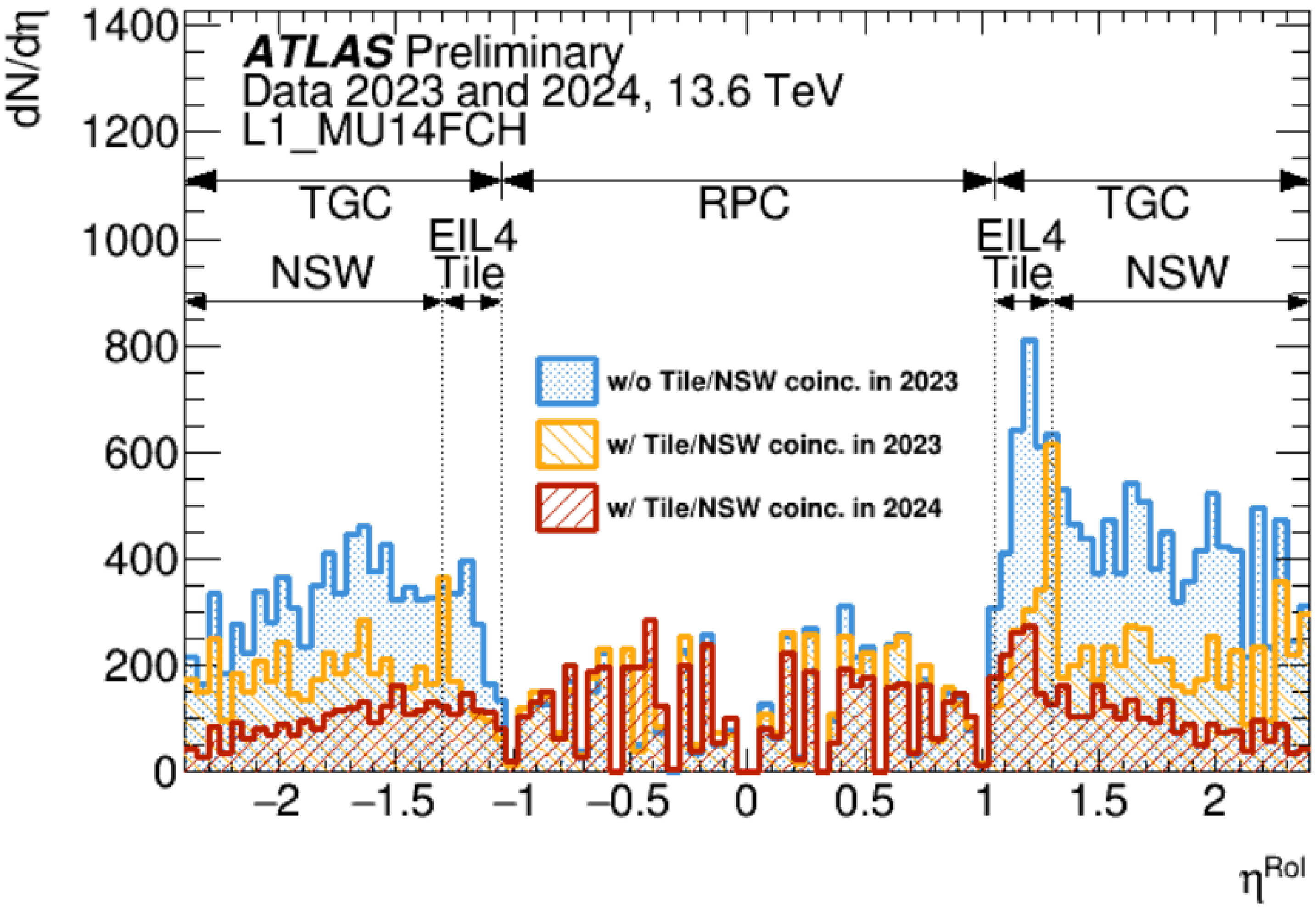
expanded scale!



consistently > 98% efficiency ✓

ATL-COM-MUON-2024-011

Online Trigger Efficiency: 4 layers of 8 layers in 2024



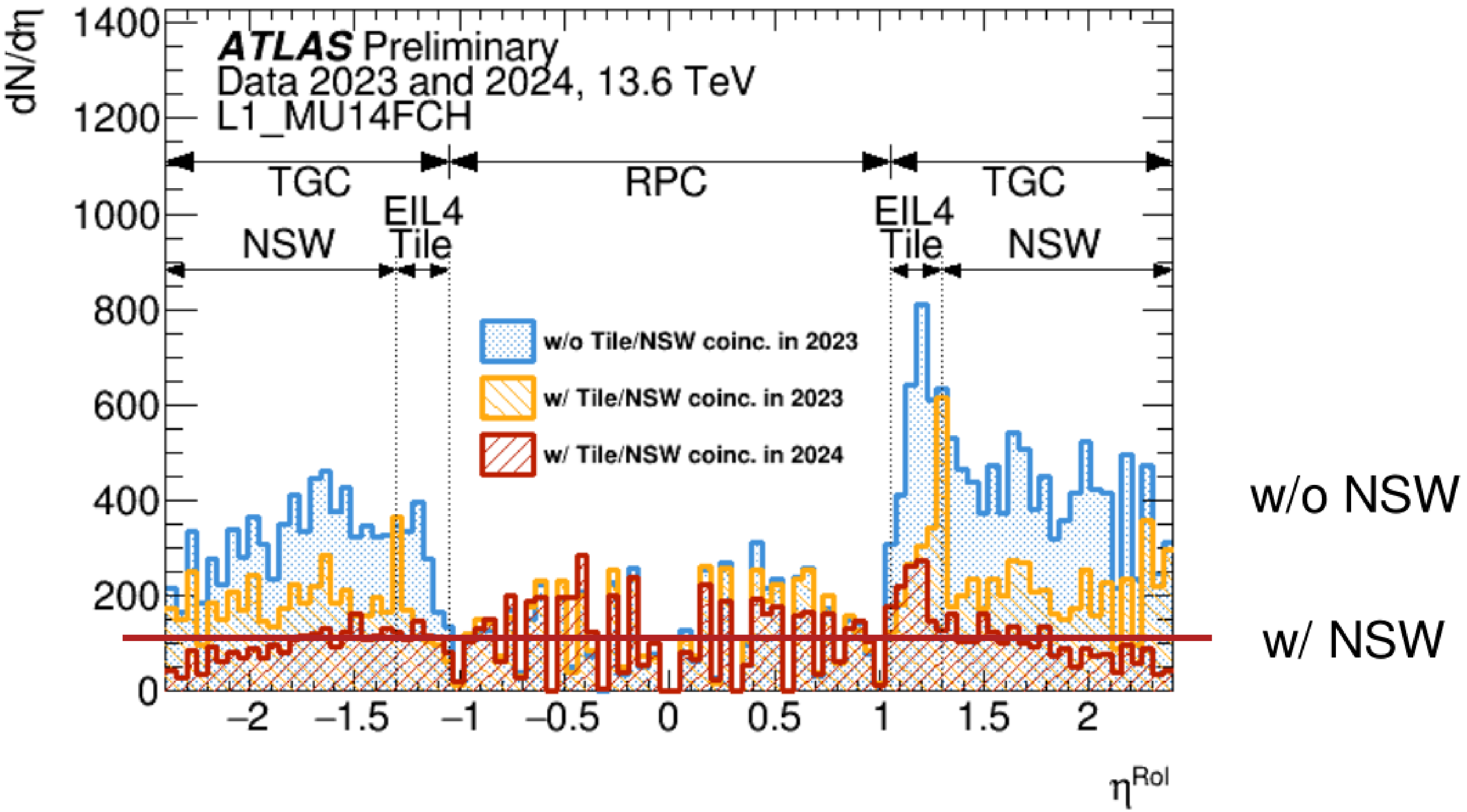
w/o NSW

w/ NSW

Homogeneous trigger rate along η achieved! ✓

ATL-COM-DAQ-2024-065

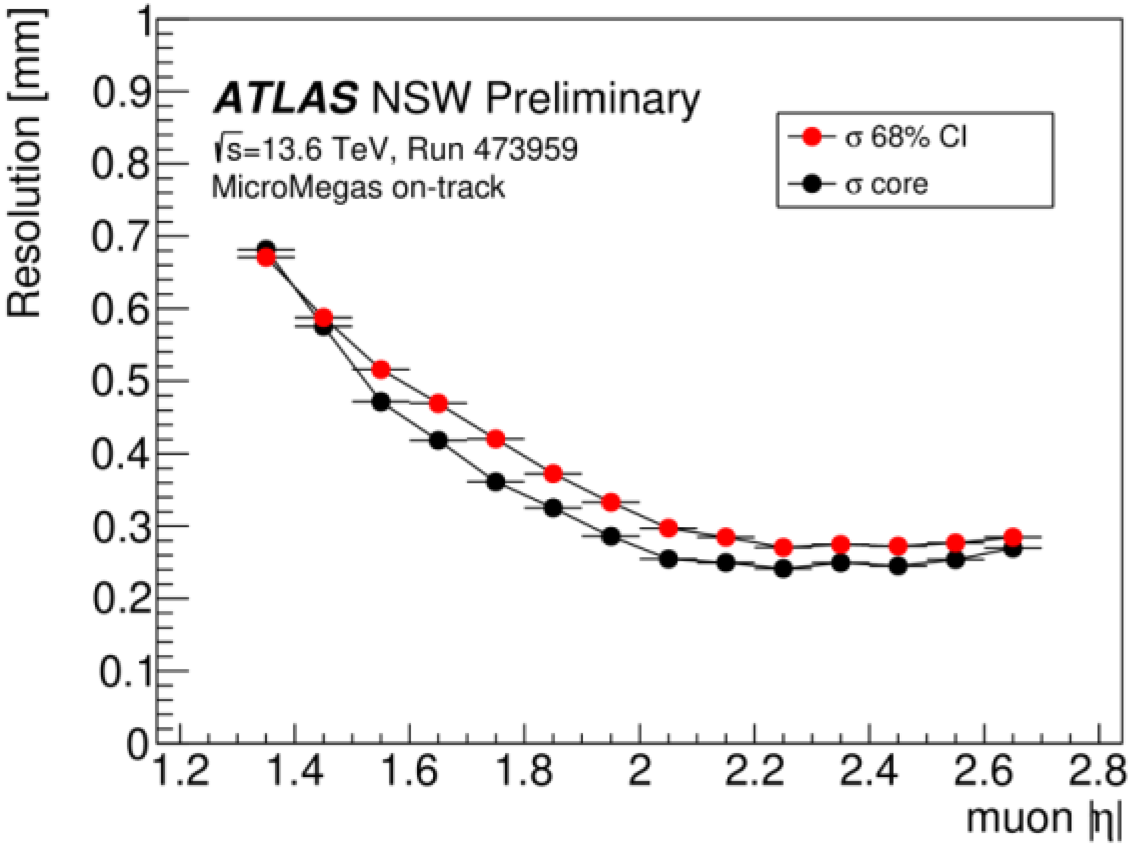
Online Trigger Efficiency: 4 layers of 8 layers in 2024



Homogeneous trigger rate along η achieved! ✓

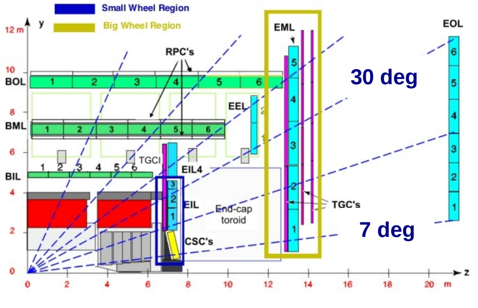
ATL-COM-DAQ-2024-065

Spatial Resolution of NSW Micromegas

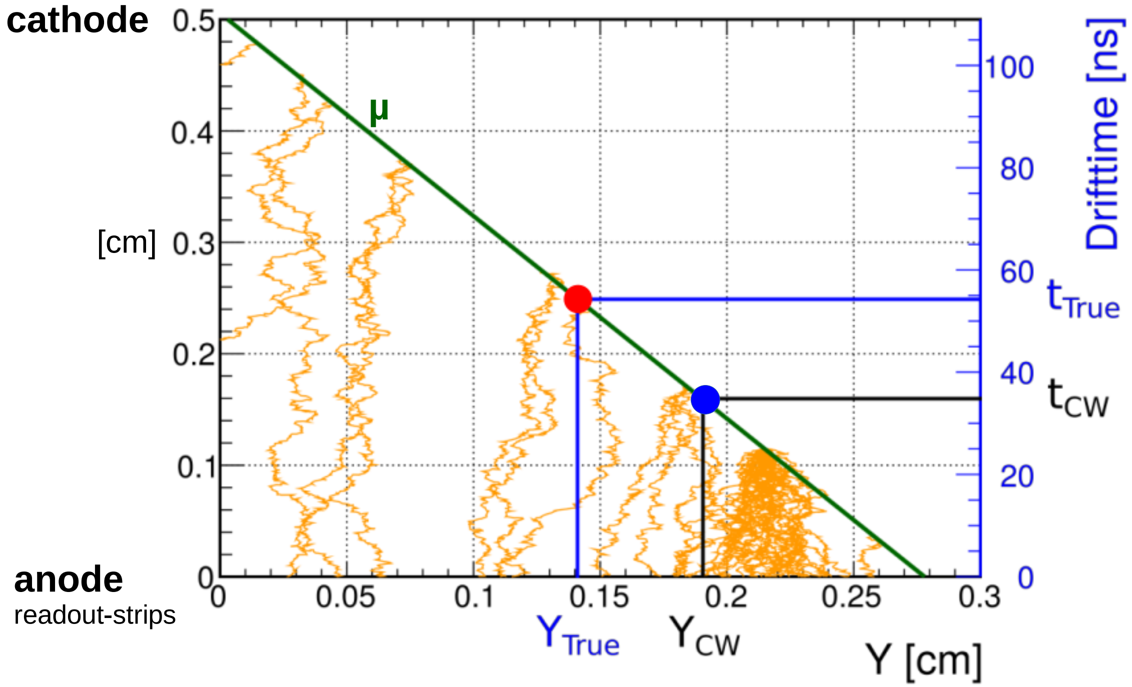


$\eta = -\ln\tan(\theta/2)$

30° 15° 7° θ: μ angle of incidence



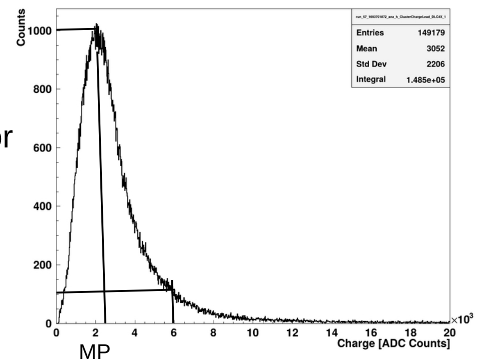
Spatial Resolution μ-Detection: using charge weighted mean over responding strips



Charge weighted position $$Y_{CW} = \frac{\sum_i q_i \times y_i}{\sum_i q_i}$$

- real μ position
- measured μ position is distorted by local large energy loss

thin detector



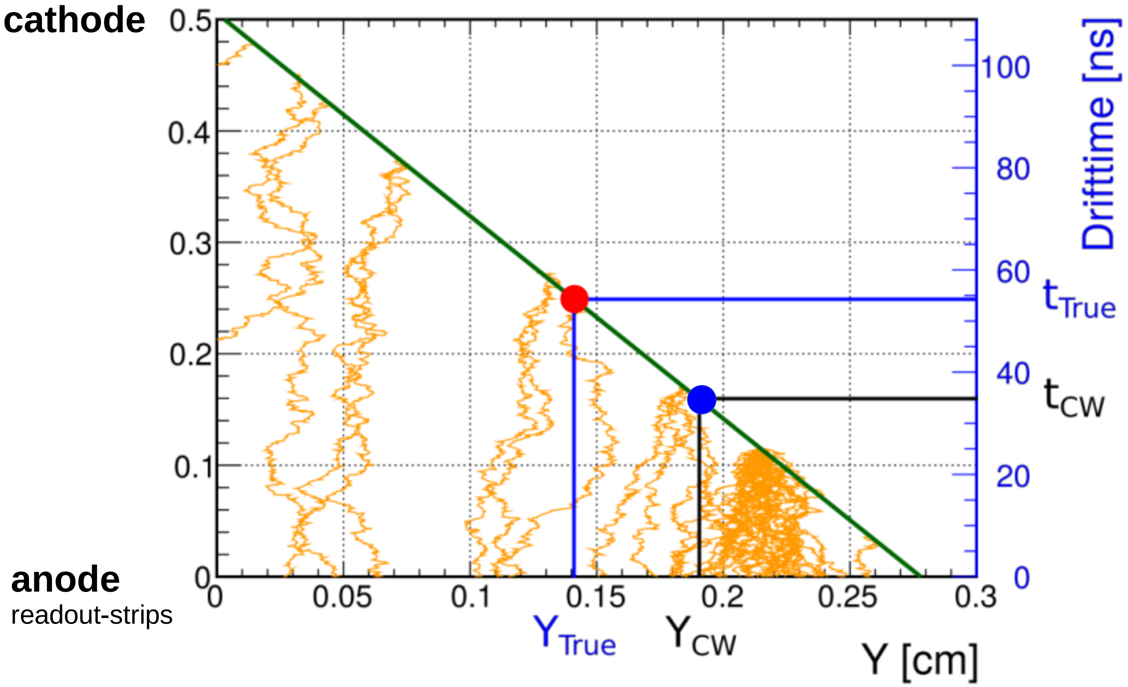
MP
V

electronic energy loss of muons in 5mm Ar:CO2

many ionisations:
ΔE ≈ 3 * MPV

figure from PHD F. Vogel (LMU)

Spatial Resolution:
using charge weighted mean over responding strips

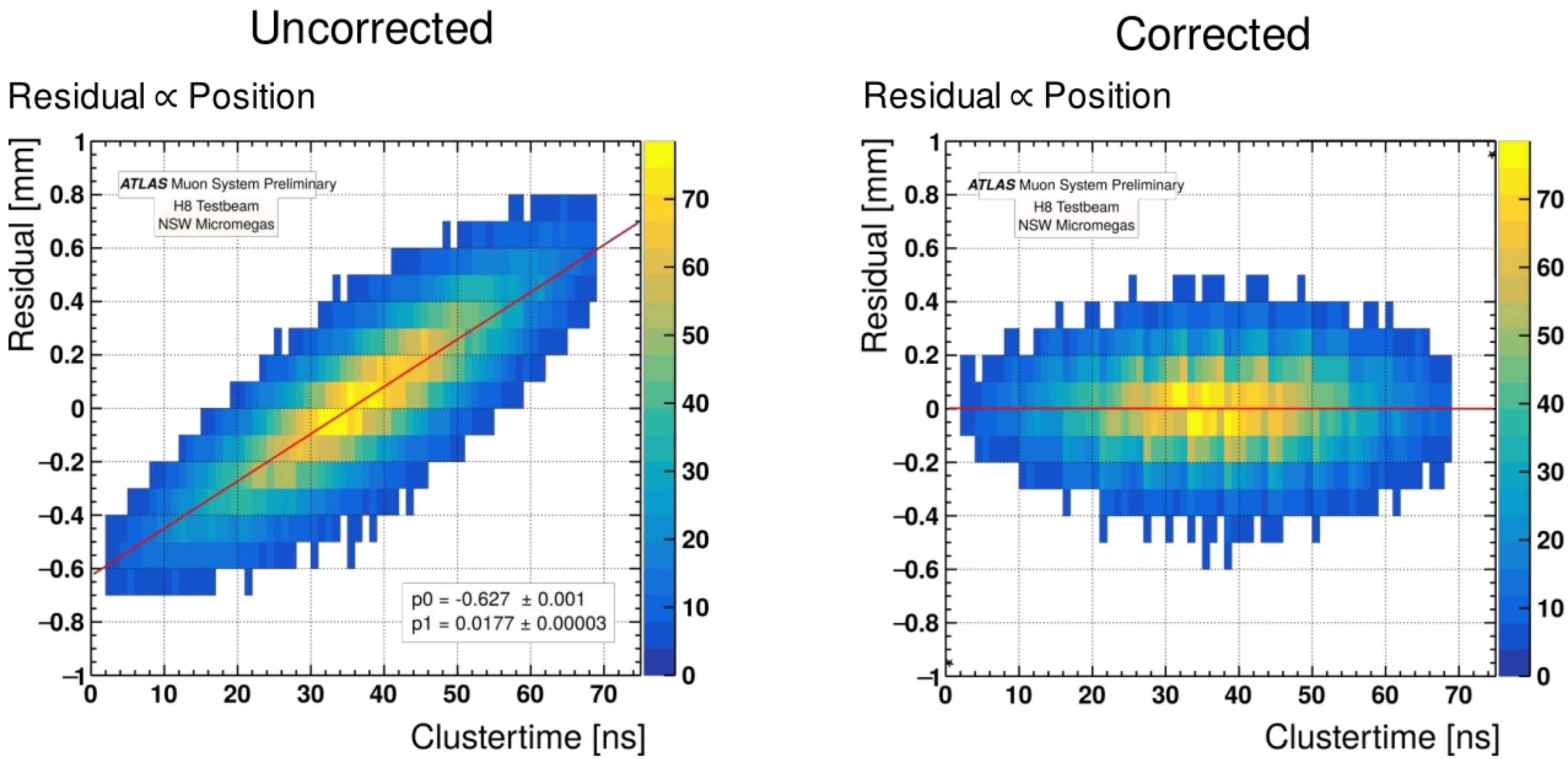


Charge weighted position $Y_{CW} = \frac{\sum_i q_i \times y_i}{\sum_i q_i}$

Charge weighted timing $t_{CW} = \frac{\sum_i q_i \times t_i}{\sum_i q_i}$

it's physics
it must be correlated !!!

Correlation: Measured Position <-> Measured Timing



Correlation parameter p_1 is depending on η (incident angle)

→ Precise correction over the whole NSW η range

ATL-COM-MUON-2024-078

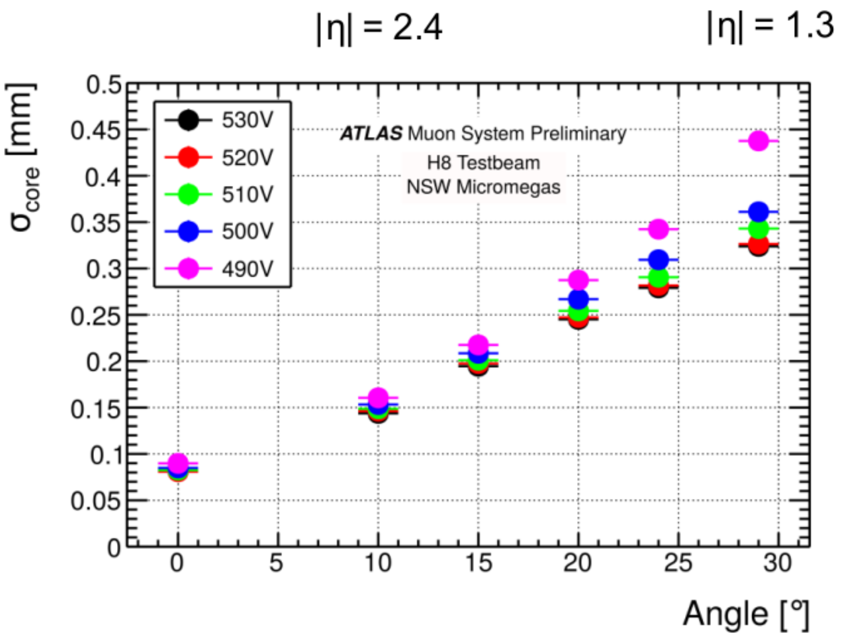
method developed in **PHD B. Flierl LMU**

Cern SPS Testbeam Results: Spatial Resolution

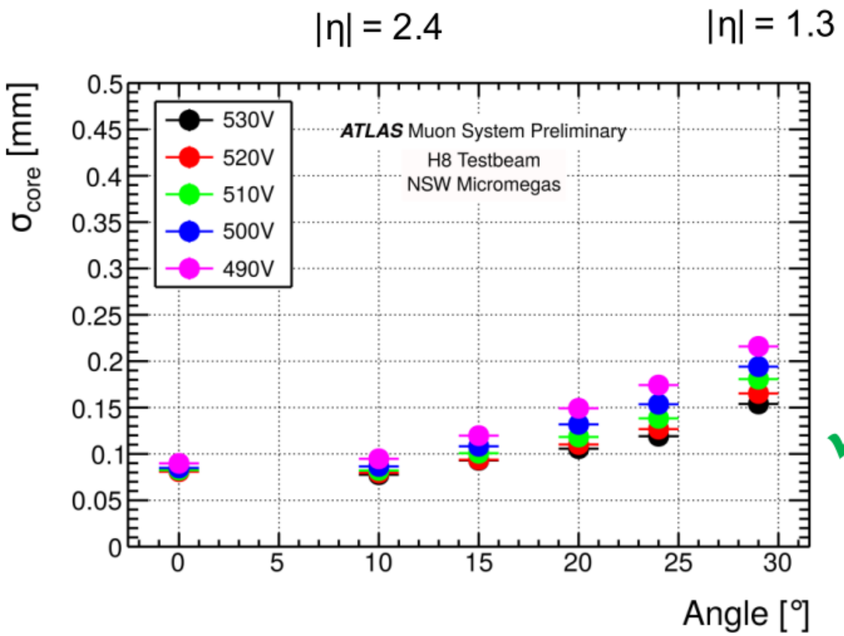
$2m^2$ Micromegas from Series Production
120 GeV μ

4 reference tracker

uncorrected
Charge Weighted Position



time-corrected
Charge Weighted Position



✓

Strongly improved spatial resolution
→ Now under implementation in ATLAS

ATL-COM-MUON-2024-078

Summary:

- 2 - 3 m^2 Micromegas work reliably in ATLAS
20 kHz/cm^2 background-rate tolerated
- spat. resolution of **150 µm** observed
of series modules in test beams from 0-30 deg. µ incidence angle
- precision calibration and manufactoring successful O(**40µm**)

ATLAS requirements already fulfilled:
- muon tracking efficiency 4/8 **close to 1**
- online trigger successful: ✔
homogeneous distribution over η (pseudorapidity)
≈ **20 kHz** trigger rate ✔

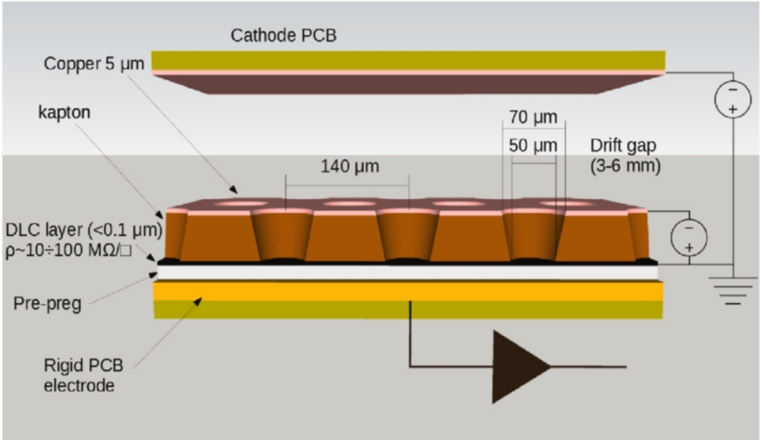
- spatial resolution will be improved using
cluster-time – cluster-position correlation
better detector alignment ✔
better clustering in analysis
timing calibration

- extensive ageing tests => no ageing expected for HL-LHC ✔

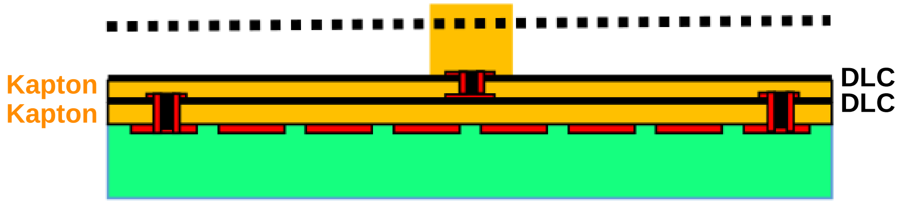
Outlook:

(Rui de Oliveira)

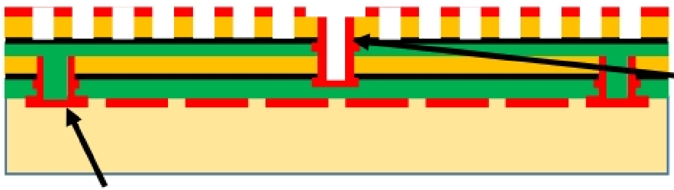
µRWELL



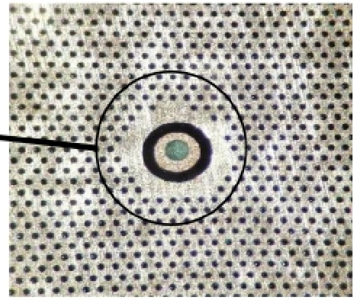
Micromegas



- 2 DLC layers without patterns



- 2 DLC layers connected by plated holes

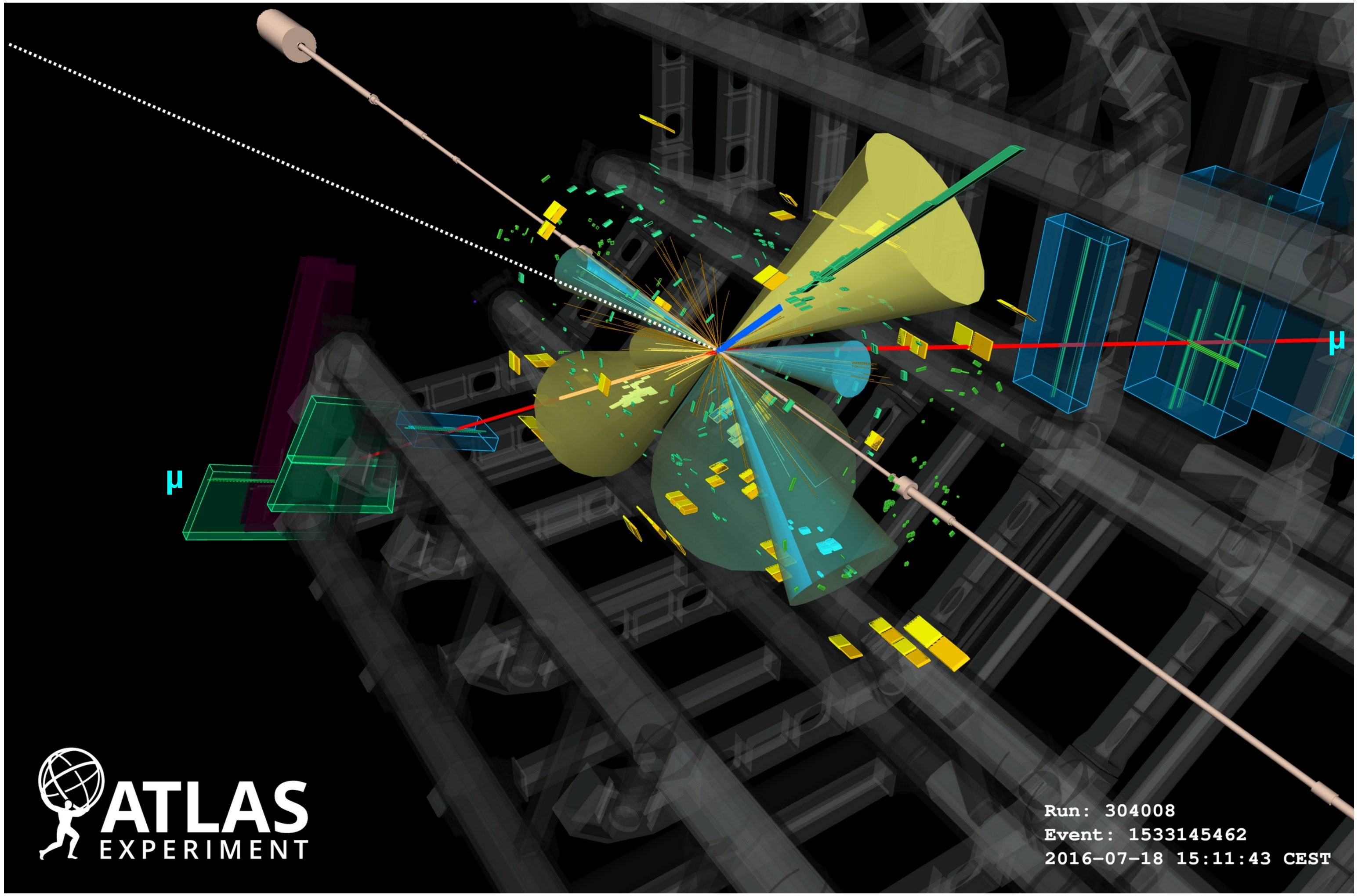


Backup Slides

LHC: pp induced simultaneous 4 top production (700 GeV)

observation: decay into 2-4 muons

(Moriond 2023)



1 e^- blue
2 μ red

μ detection is relatively easy, being almost free of background in contradiction to the jet reconstruction (cones)

1. anode panel production

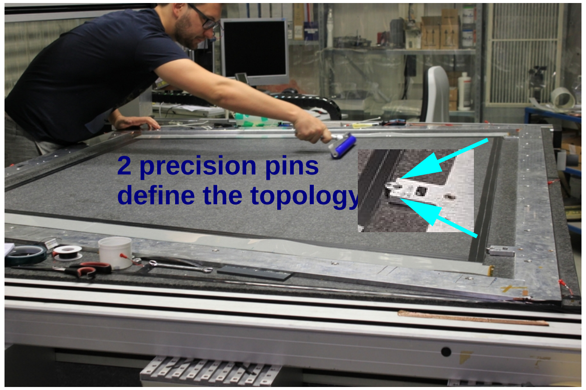
2. cathode panel production and mesh stretching

3. cleaning procedure

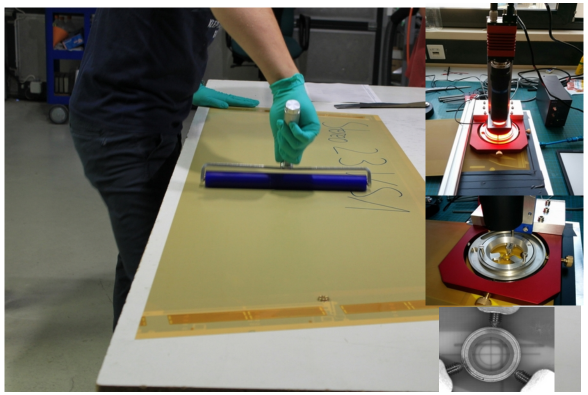
4. vertical assembly

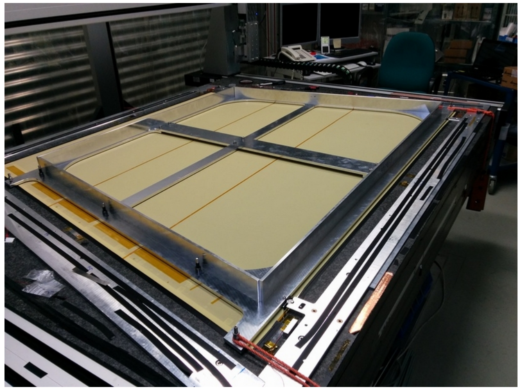
5. calibration and quality assurance

How to Glue a Flat and Parallel Anode Honeycomb-Panel

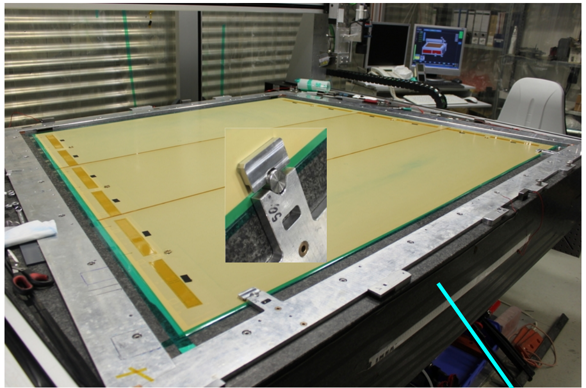


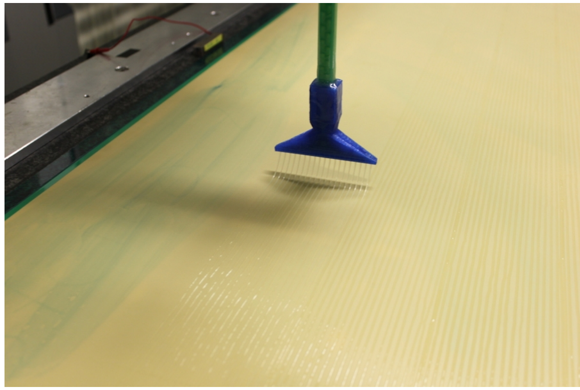
preparational cleaning

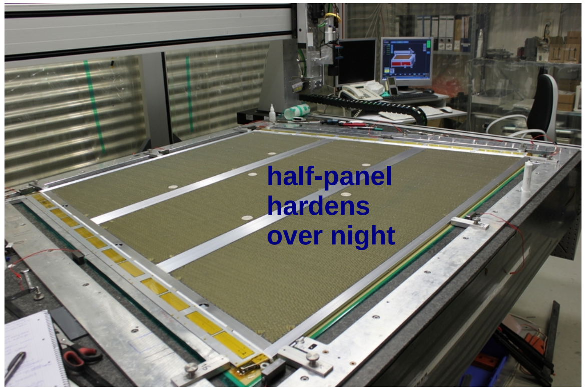

precision rings glued onto markers


alignment of 3 PCBs using a prec. frame

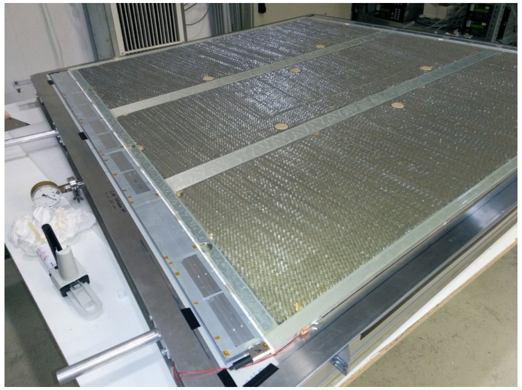
glueing of **anode** and **cathode** panels is very similar


vacuum preserves the PCB position


automatic glue dispenser



frames and honeycomb are placed into the glue


the half-panel is sucked against a stiff and very flat holding structure P=-900 mbar

the half-panel on the stiff holding structure is aligned against the 2 pins on the table
8 prec. shims => correct thickness of panel


weights press the alignment washers against the 2 pins on the table

final check


10 LEDs must burn !
10 * contact

Glueing the Micromesh (30/71) onto the Cathode Panel (Wzbg)

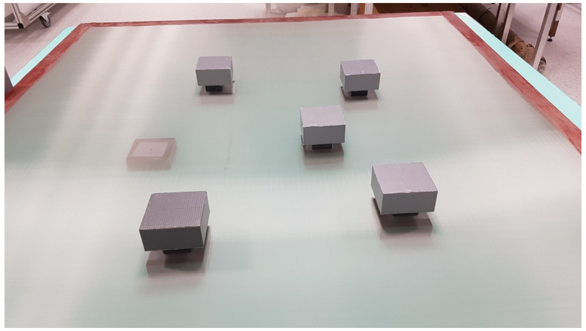
floating mesh technique, mesh is mounted on the cathode panel

mesh stretching using commercial clamps

glue the mesh to a transfer frame

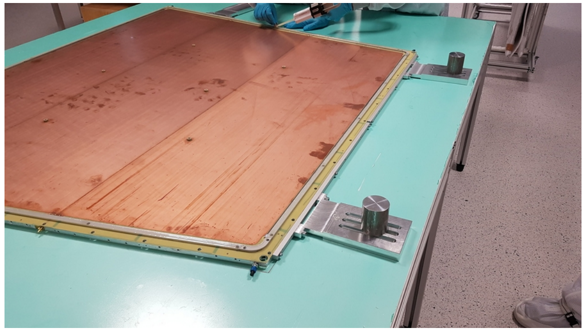
cleaning of the mesh step 1

cleaning of the mesh step 2
deionized high pressure water

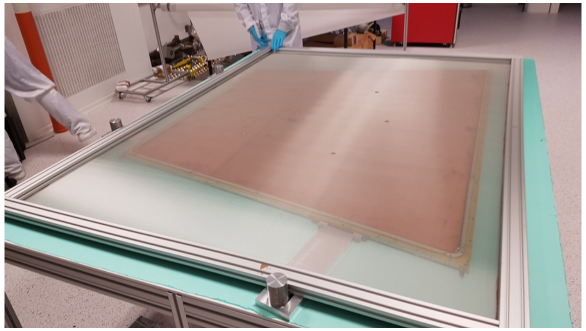


glueing Araldite 2011 reinforcements
at the positions of the interconnections

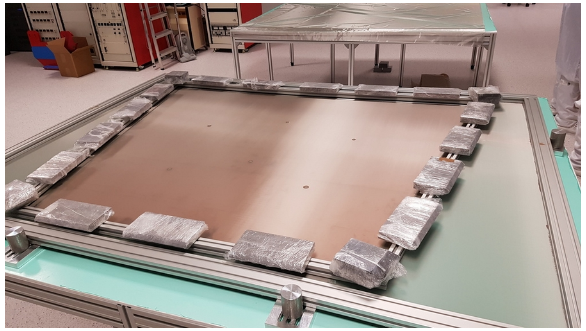
punch holes for the inteconnections



distribute Araldite 2011 on the mesh-frames



place mesh+transf. frame on top of the cathode panel



place the pressing frame and let blocks

overnight curing of the glue, then cut the mesh along the outside of the mesh frame

Cleaning Before Assembly (cleaning, cleaning, cleaning ...)

inspection

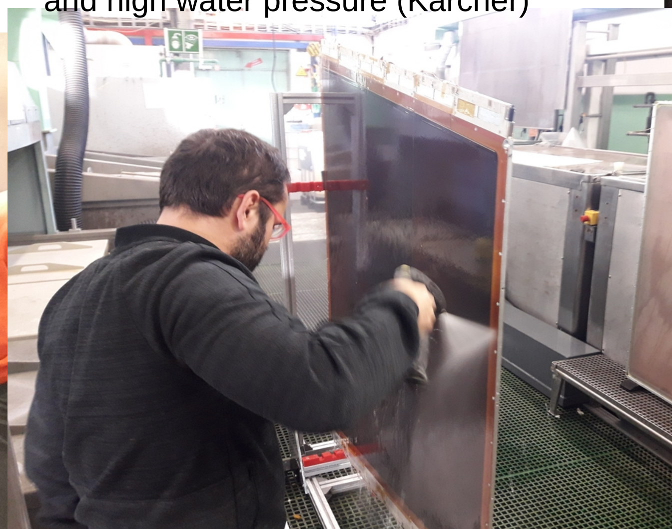
micro crystal cleaner
1st side anode panel

NGL cleaning
cathode panel

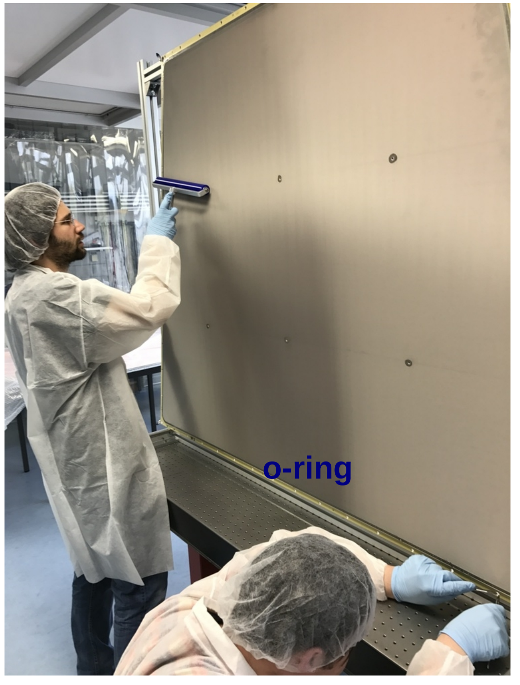
micro crystal cleaner
2nd side ro panel

rinsing with warm tap water + brush

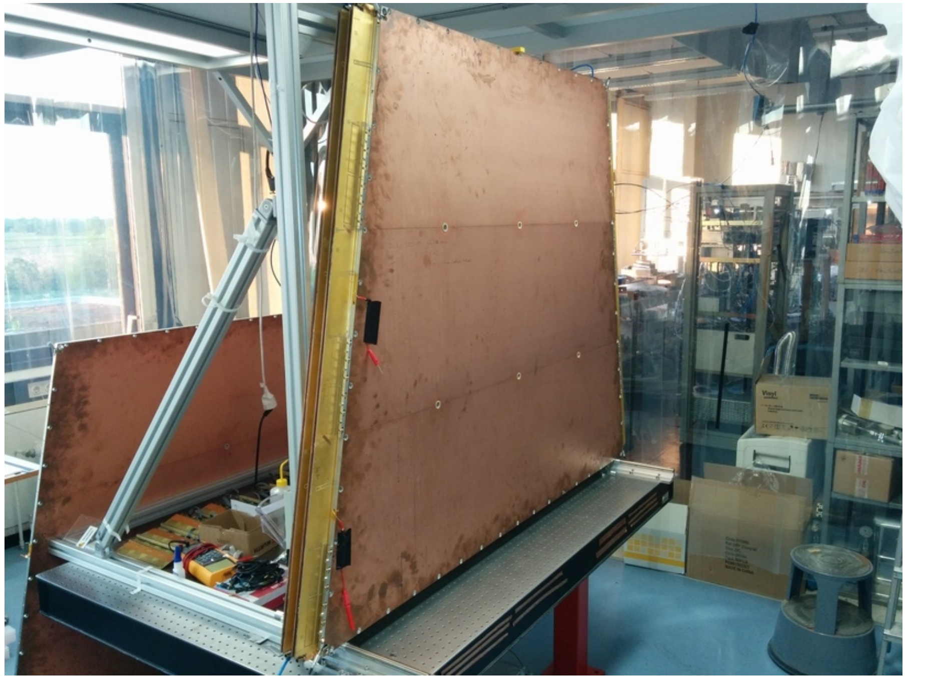
cleaning with deionized water
and high water pressure (Kärcher)



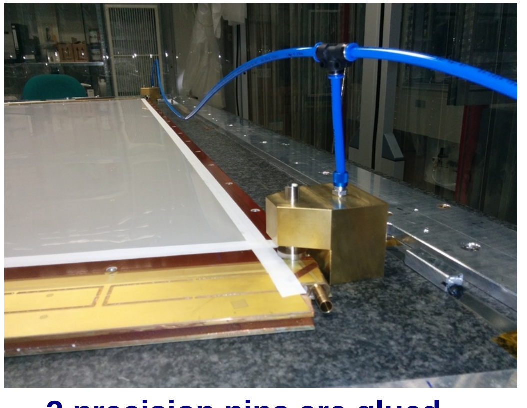
Vertical Assembly of SM2 Module0 (cleanliness)



1st cathode panel is placed on the vertical assembly station



full assembly of
cathode - stereo - double cathode - eta - cathode



2 precision pins are glued perpendicularly into the stereo anode panel

assembly in a class 5 laminar flow tent (clean room)

- cleaning by vacuum and static roller is mandatory on each surface
- 2 precision pins provide the long term alignment of the 2 anode panels
- the V and the flat shaped fitting pieces are sitting on 2 precision rails

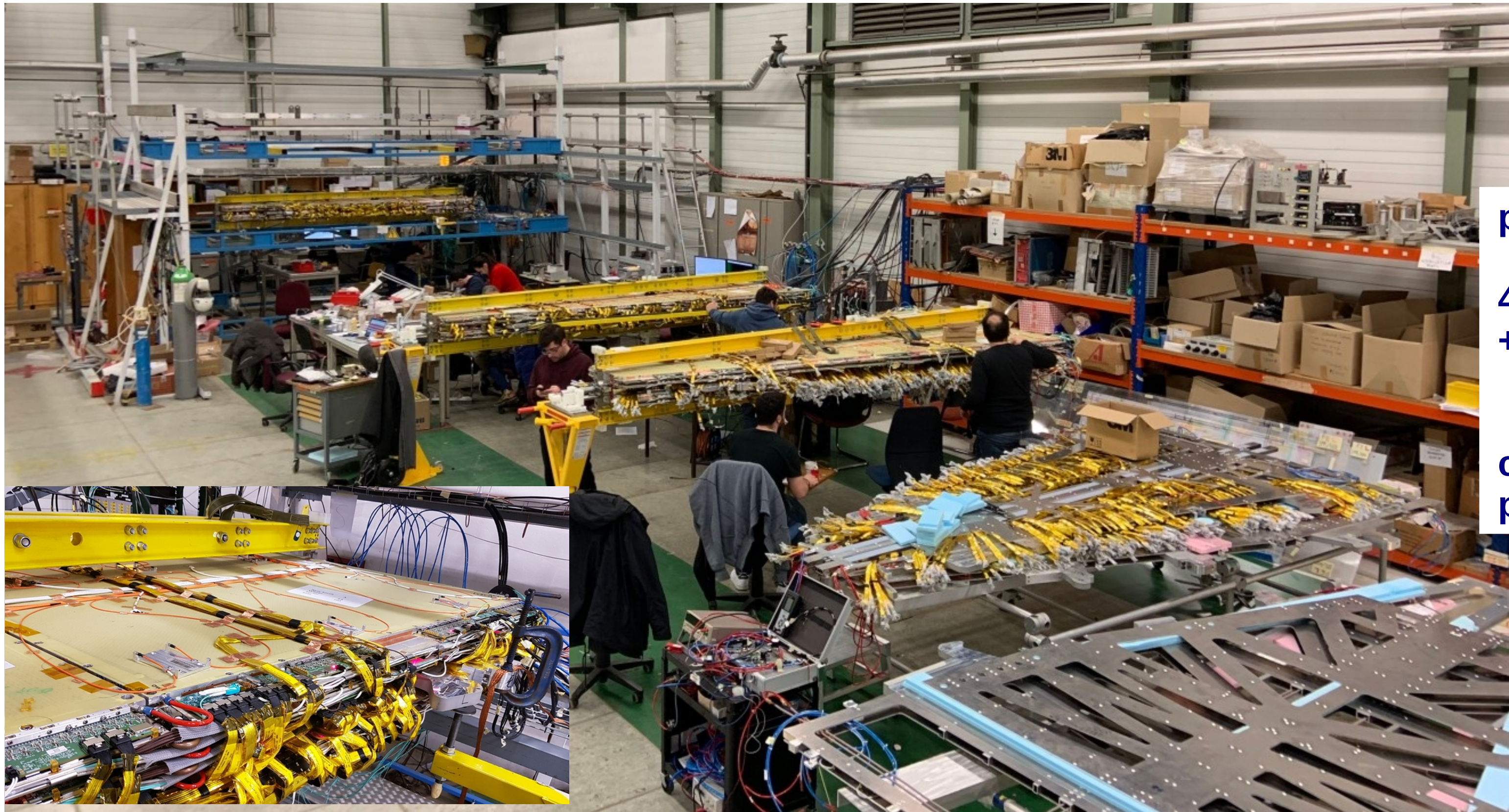
1. anode panel production
2. cathode panel production and mesh stretching
3. cleaning procedure
4. vertical assembly
5. calibration and quality assurance

10cm x 10cm -> 165cm x 125cm

a lot of infrastructure
a lot of learning / brain
a lot of effort
a lot of time
a lot of people, nothing can be done alone

Assembly of all 4 MM types
SM1, SM2, LM1, LM2
32 Modules Each
in BB5 at Cern

CERN: Sector Assembly at Bldg. BB5

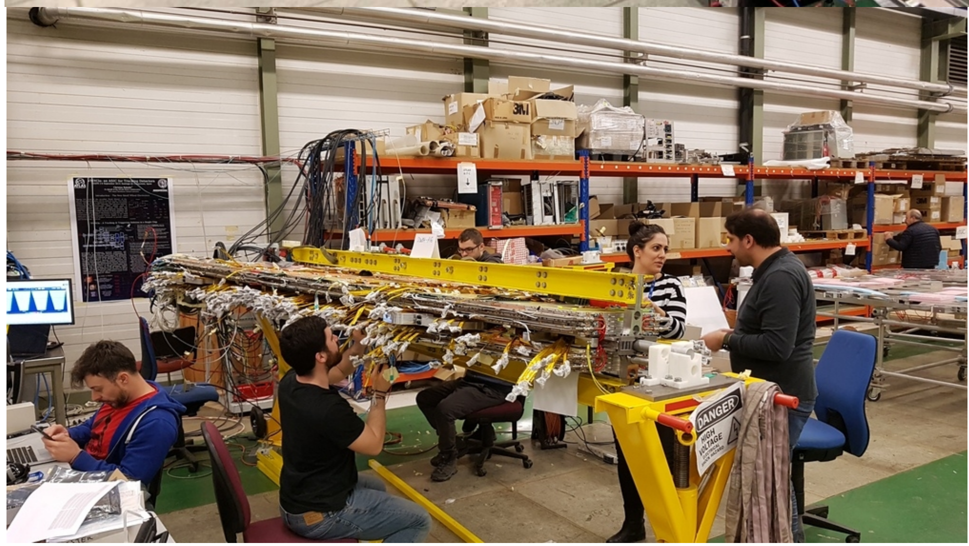


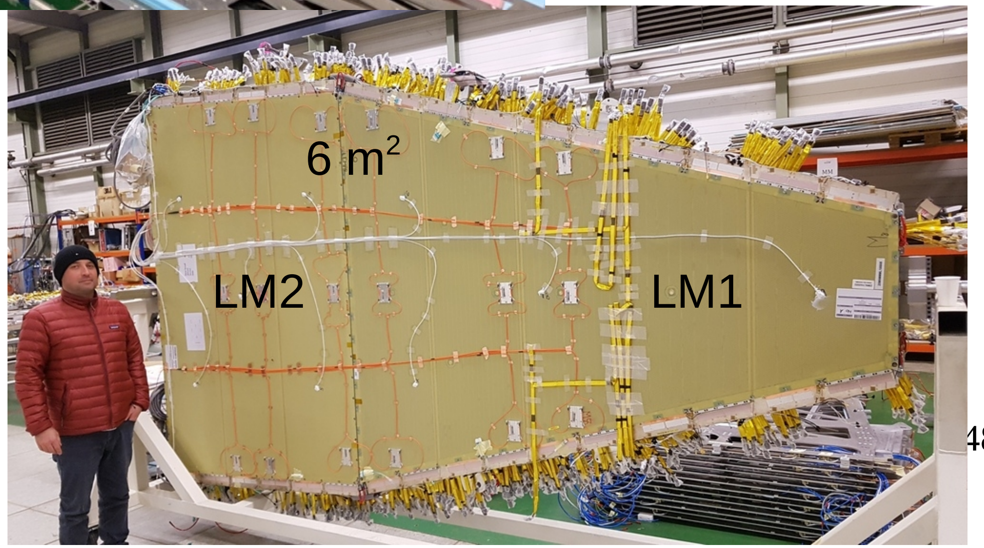
production street at CERN BB5

4 assembly stands in parallel
+ cosmic muon measurement of a full MM sector

considerable amount of personal power

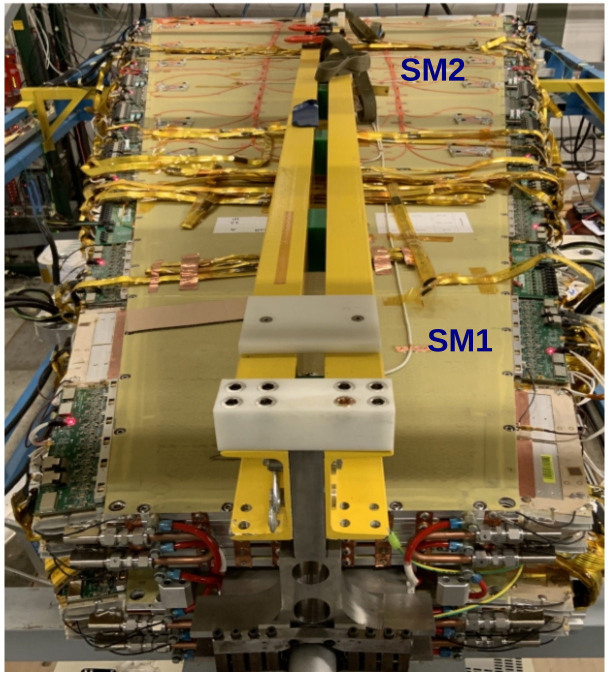
a large sector incl. services without electronics

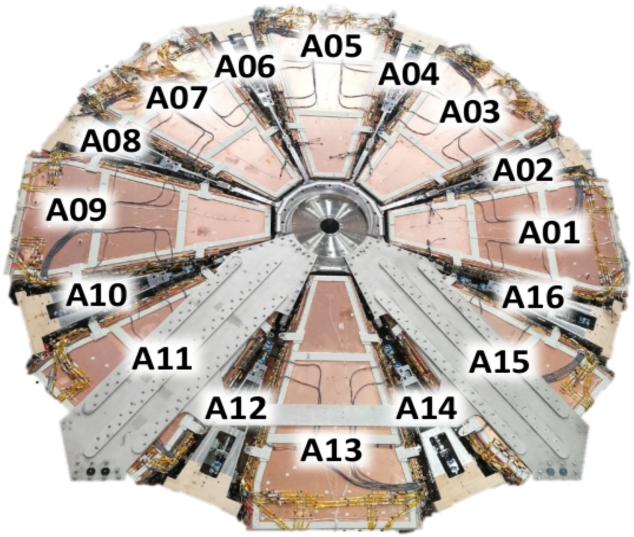




CERN: Wheel Assembly sTGC+MM in Bldg. 191 at CERN

MM sector small

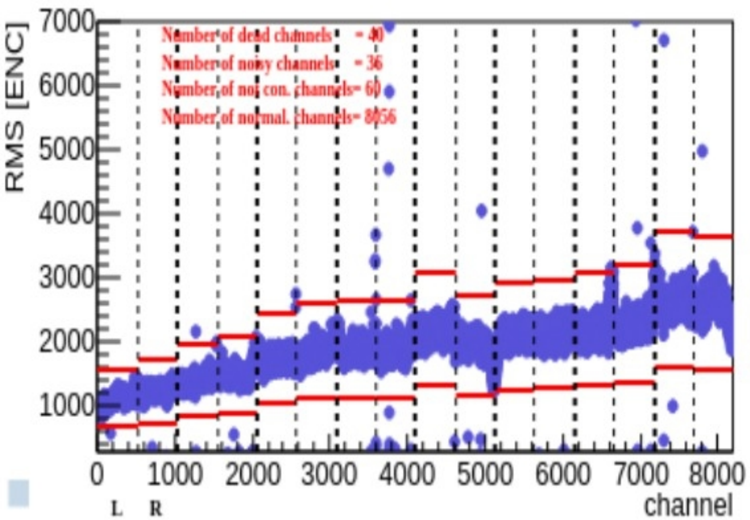


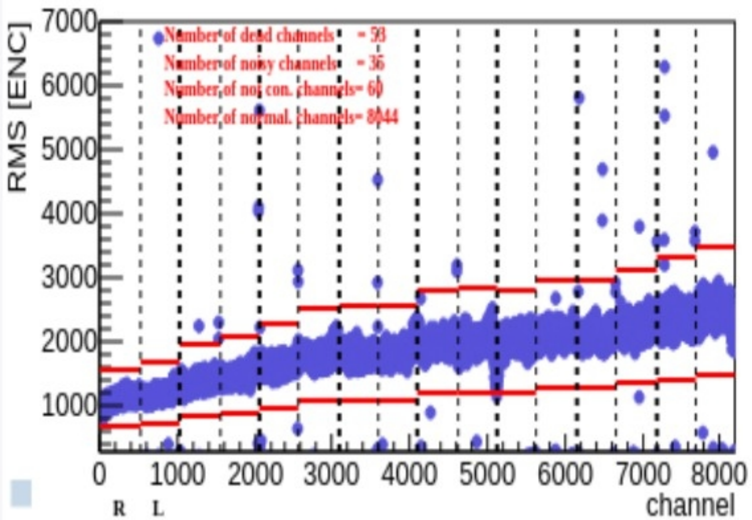


the assembly of a sector was a huge amount of work

dito the assembly of the wheels

even much more work due to all the unforeseen





huge efforts were made to bring the noise level to the degree close to theoretical expectation, as shown

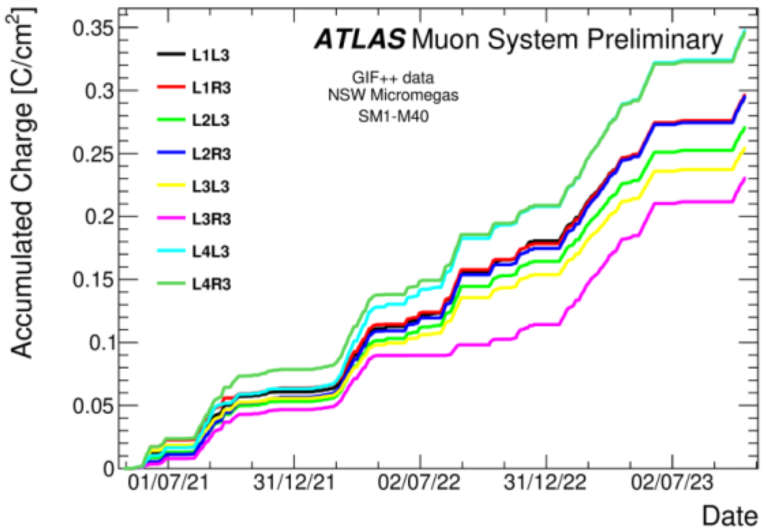
the noise increases as expected from 0 – 8000 ch due to the increasing readout strip length

Long Term Ageing Tests $Ar:CO_2:iC_4H_{10}$

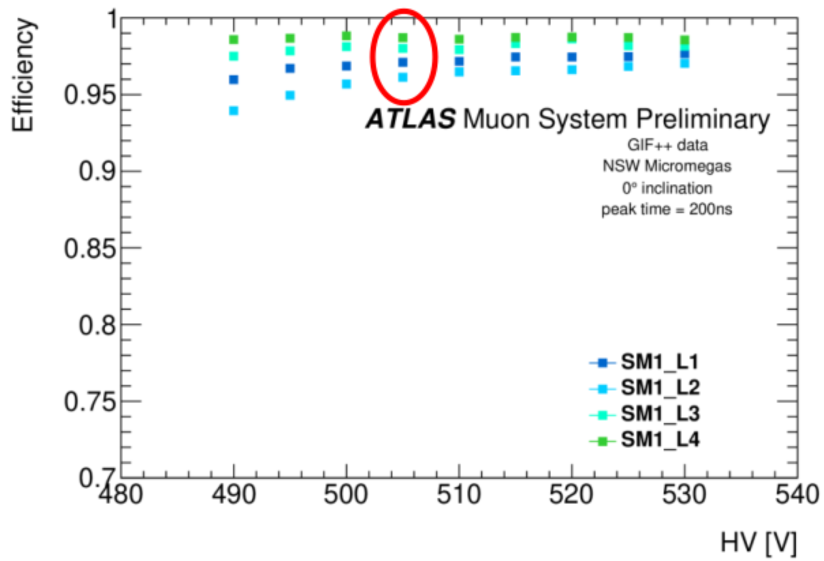
Spare modules irradiated under the ternary gas mixture $Ar:CO_2:iC_4H_{10}$

- 14 TBq ^{137}Cs at GIF++ (~10y HL-LHC; no safety factor; ongoing)
- 10 GBq Am-Be neutron source at LMU (2y of irradiation at 3x HL-LHC equivalent neutron fluxes)

GIF++ irradiation



after irradiation

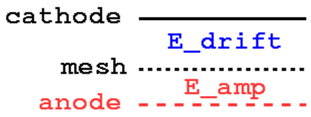


Excellent detection efficiency after 10y HL-LHC irradiation equivalent → no aging ✓

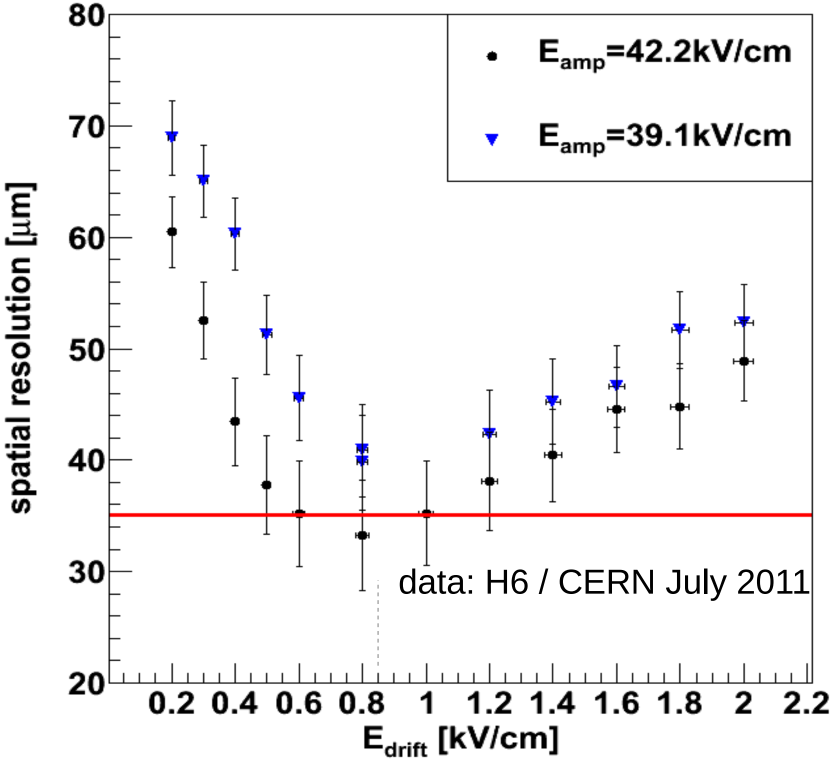
ATL-COM-MUON-2023-044

4 standard micromegas: copper strips, 250 μm pitch

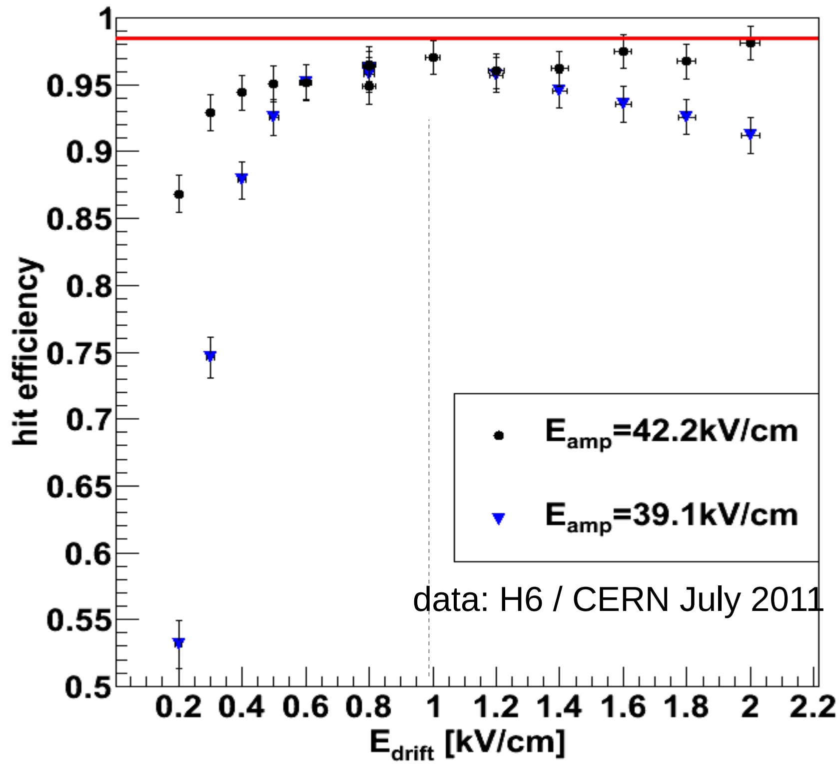
9 x 10 cm² Gassiplex readout (J.Bortfeldt)



spatial resolution



hit efficiency

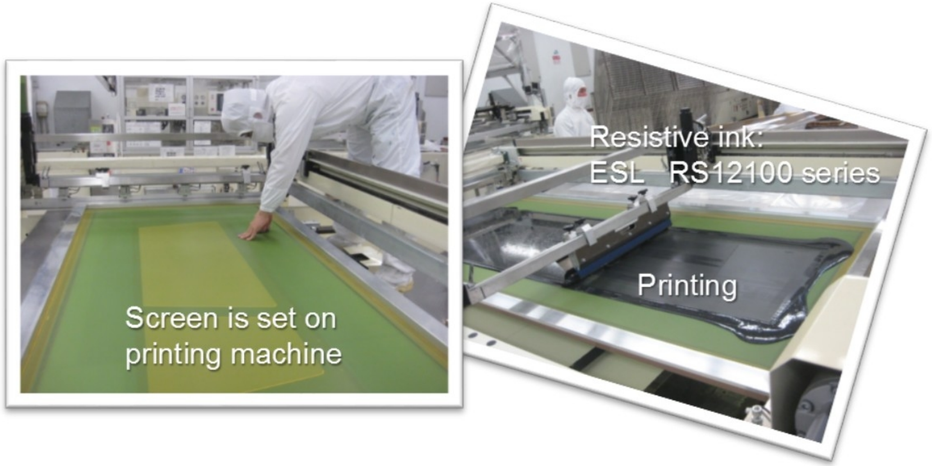


pillars
98.5%
1.5 %
insens.
area

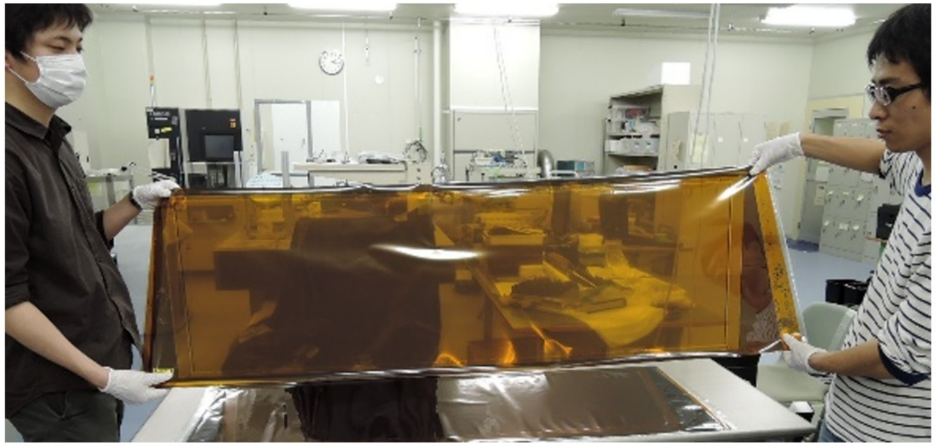
spatial resolution 35 μm @ 160 GeV π, orthogonal beam
tracking resolution < 20 μm to study large structures using 4 micromegas
efficiency > 98 % @ orthogonal beam, Ar:CO2 85:15 1 bar

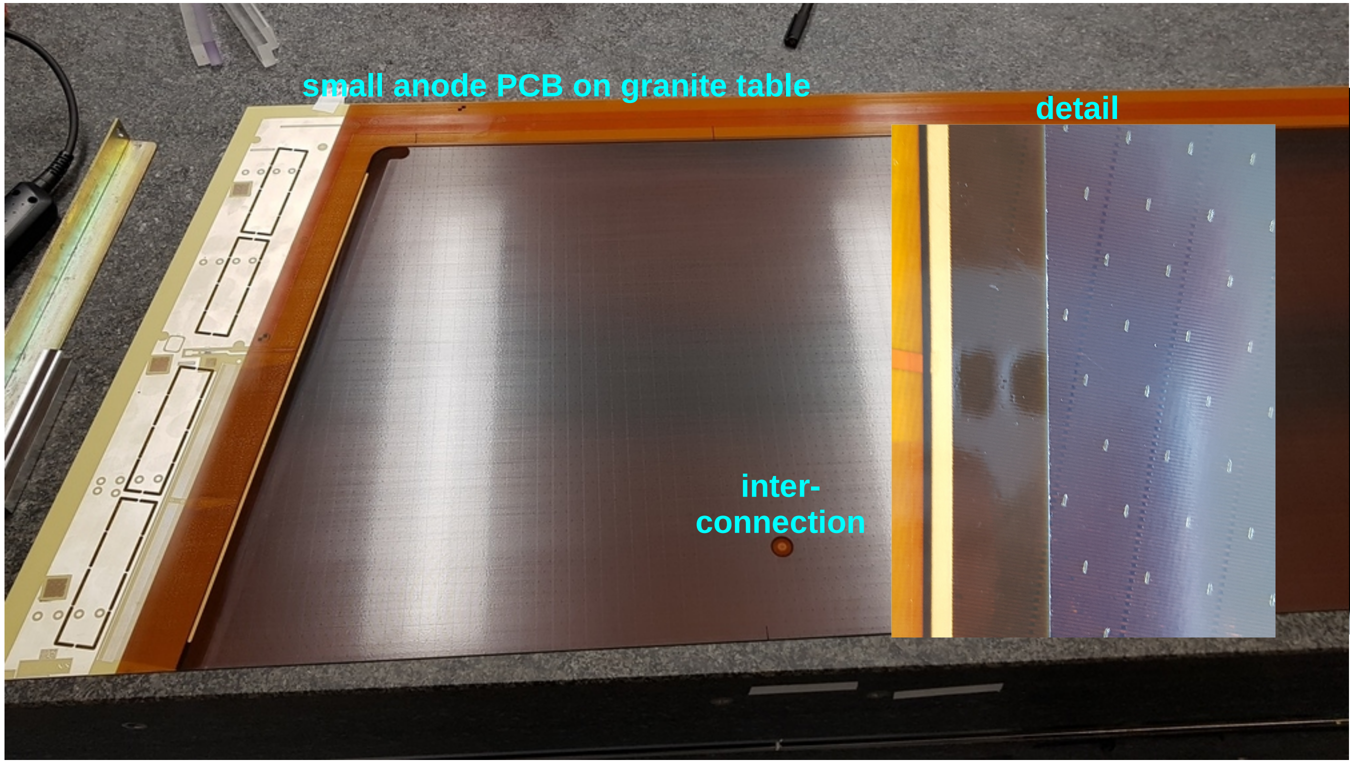
Screenprinting of a Resistive Foil (Univ. Kobe + Matsuda Co. Japan)

screen printing (industry standard)

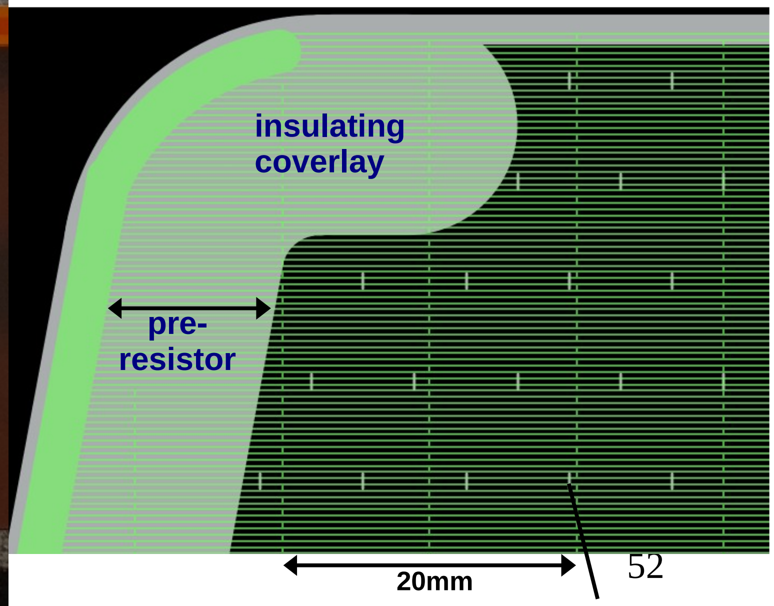


screen printed resistive strips on a 50μm thick Kapton foil



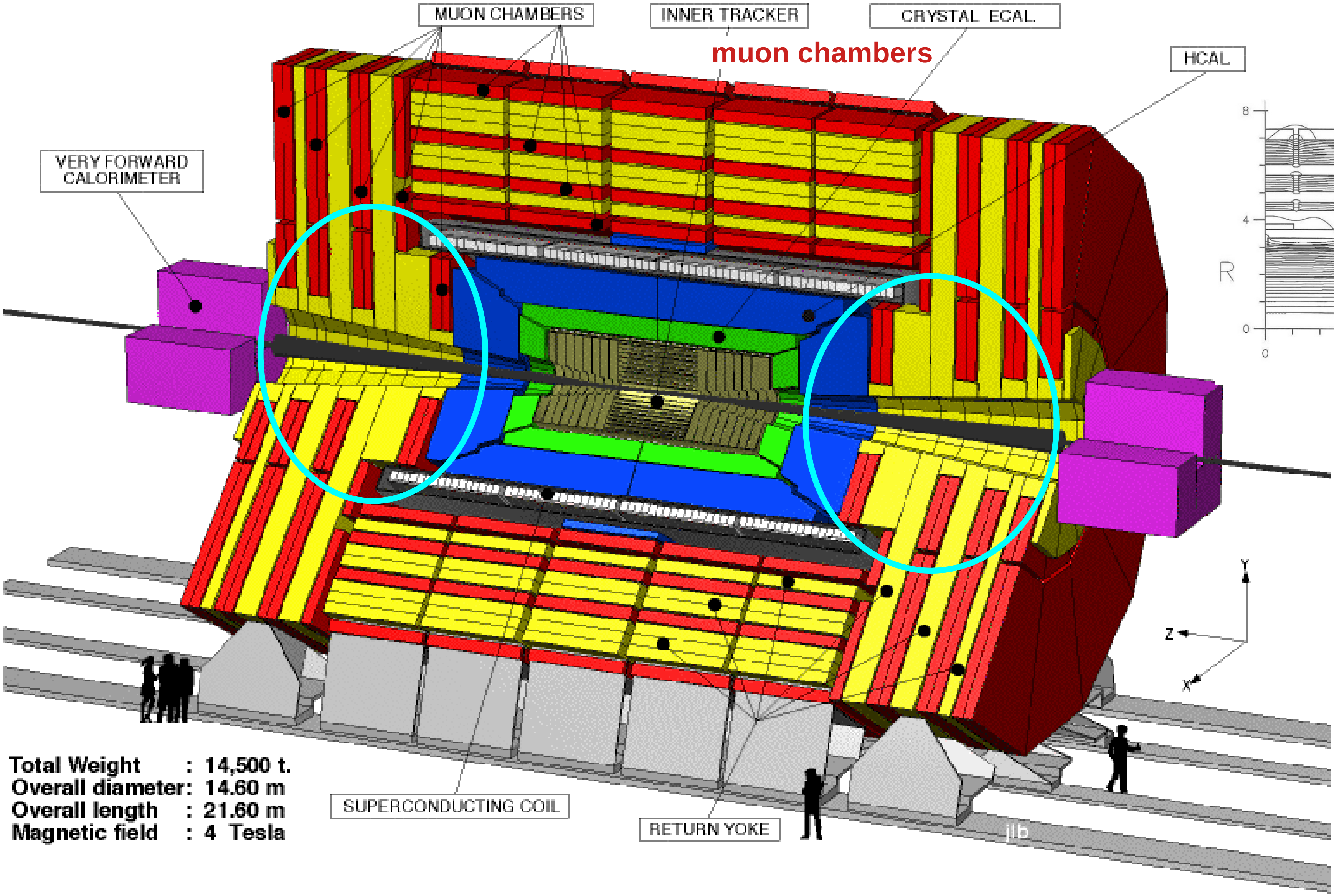


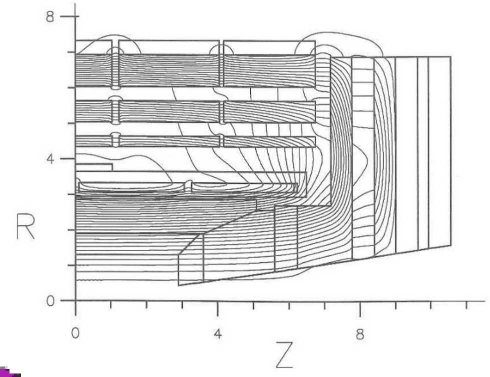
resistive strip layout



horiz. strips, bridges at 20mm

CMS: Compact Muon Solenoid



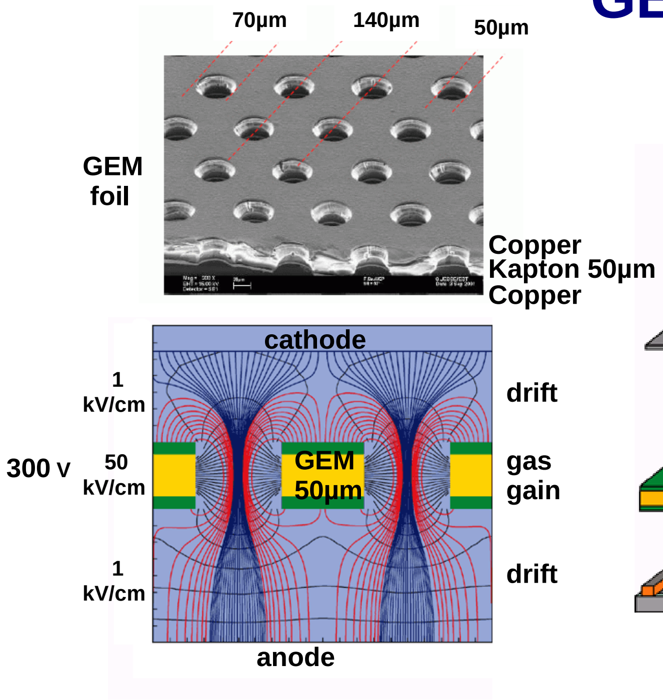


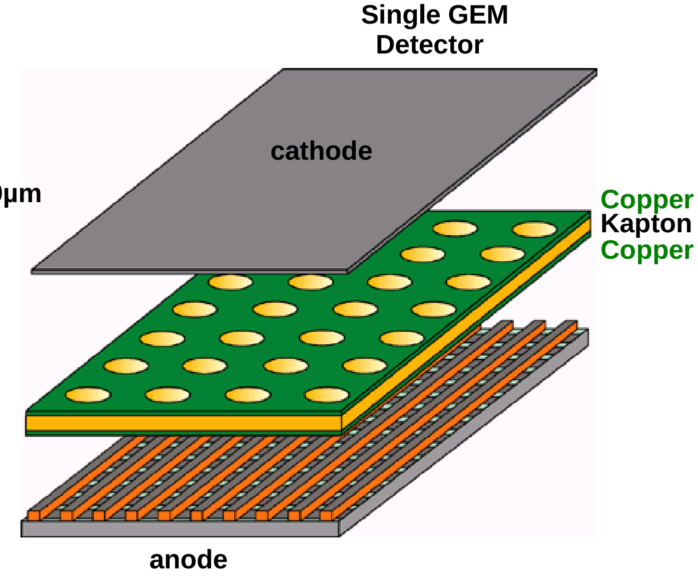
solenoidal magentic field, field return in iron
endcap: φ is precision direction

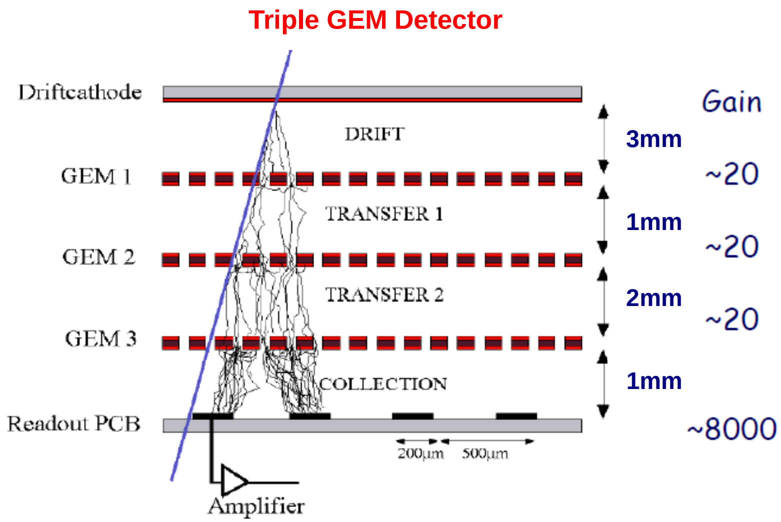
Triple GEMs for CMS

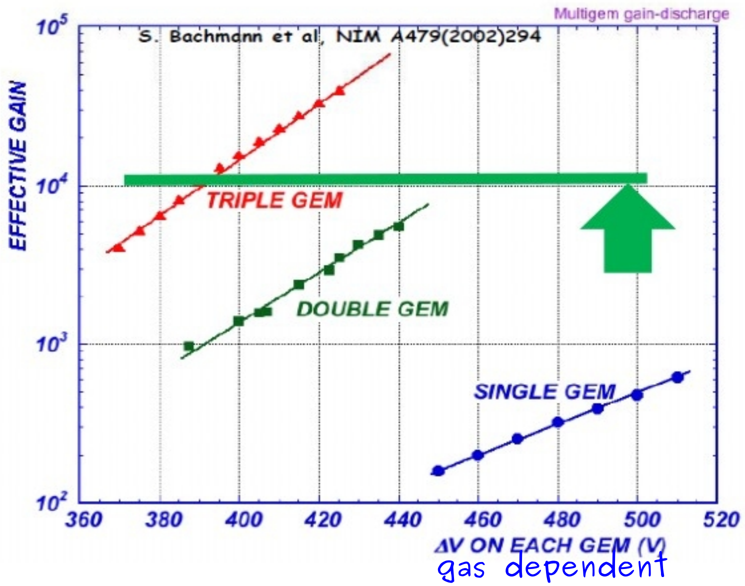
F. Sauli, NIM A386 (1997) 531

GEM Detector Basics (Gaseous Electron Multiplier)



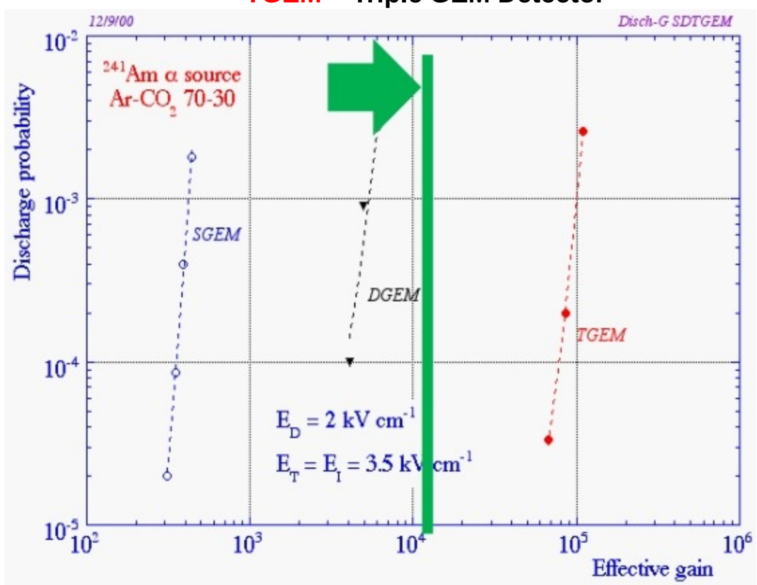






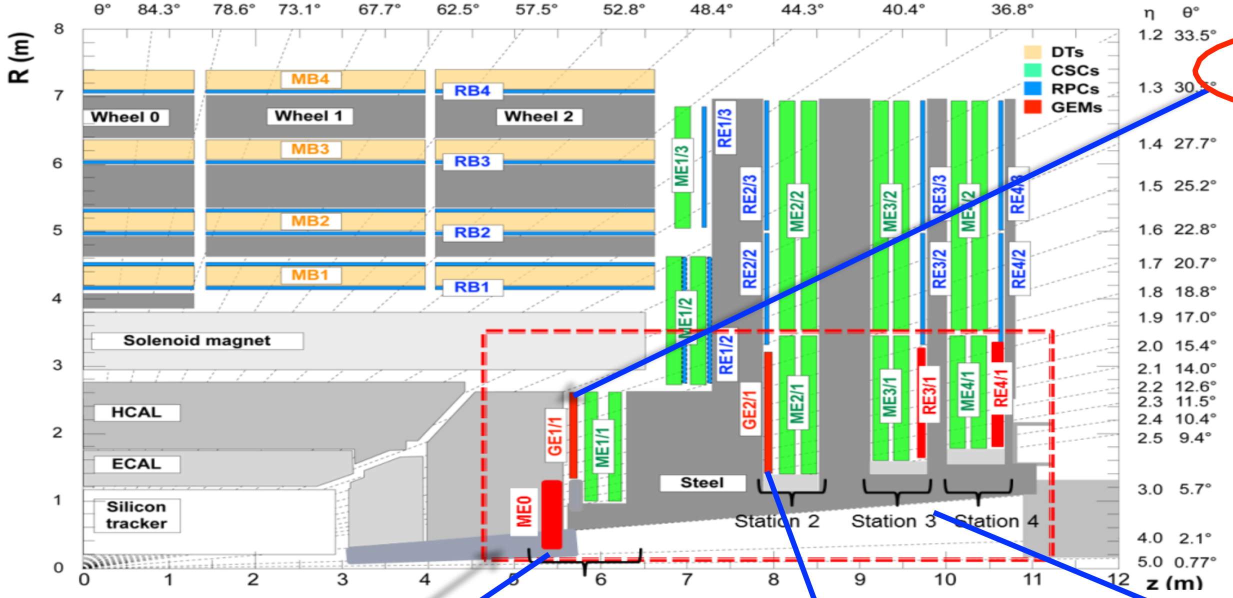
TGEM: gas gain 5000 – 10000 at moderate HV

TGEM = Triple GEM Detector



TGEM: @ HV setting for muons discharge probability for background hadrons is low

CMS Forward muon system upgrade



GE1/1:

Trigger and reconstruction

- $1.55 < |\eta| < 2.1$
- **baseline detector for GEM project**
- one super-chamber spans 10° and is made of 2 back-to-back triple-GEM det. each super-chamber spans 10°
- **72 triple-GEM** det. per endcap
- long: **120cm x 45/23cm** **0.41 m²**
- short: 106cm x 42/23cm 0.35m²
- **installed in CMS 2019 / 2020**

ME0:

- **Muon trigger and reconstruction** at highest η
- each chamber spans 20°
- 6 layers of GEM technology
- **150 kHz/cm2**
- **2025 / 2026**

GE2/1:

Trigger and reconstruction

- $1.55 < |\eta| < 2.5$
- **18 chambers** per endcap each chamber covers 20°
- 2 layers of GEM technology
- **183cm x 117/53cm 1.6 m²**
- **2024 / 2025**

RE 3/1 –RE4/1 :

Trigger and reconstruction

- $1.8 < |\eta| < 2.4$
- 18 chambers per endcap each chamber spans 20°
- 1 layer (per station) **RPC** technology

Challenges for Large Area GEM Foils

- exact alignment of the GEM holes on top and on bottom ✔

- proper stretching of the GEM foils ✔

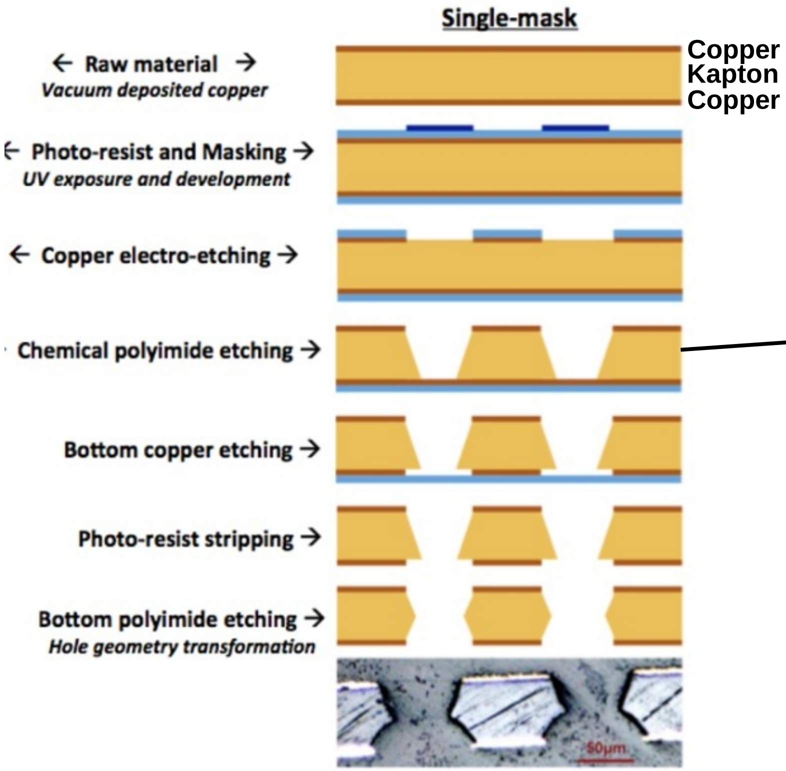
- keeping the active area in a range of 100 cm^2
  to minimize the stored energy in the GEM-foil capacitor
  to avoid damage after a discharge
  => segmentation of large foils ✔

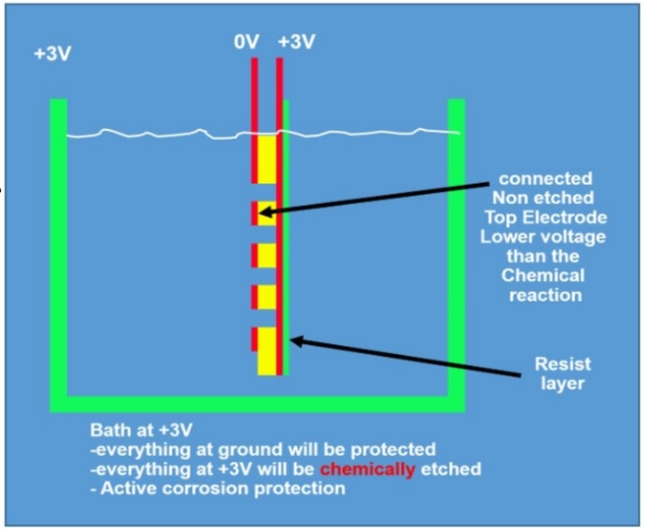
- simple construction, screwing, no glueing (takes too long) ✔

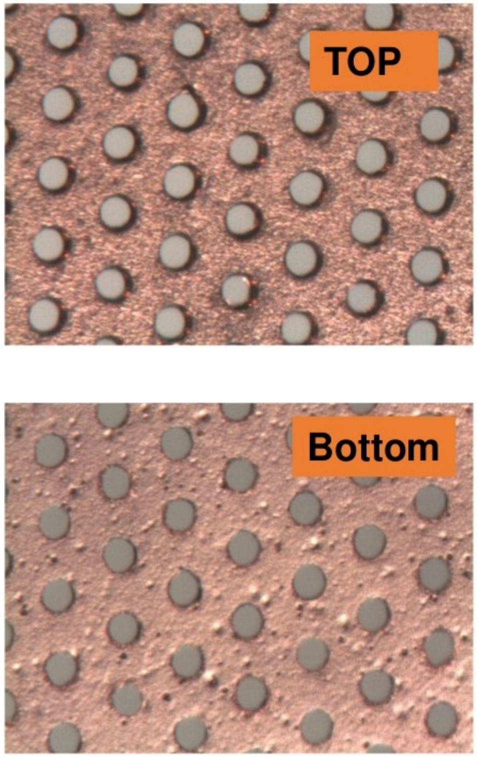
all 4 points are well solved !

1st Success: Production of Large GEM Foils

CERN detector lab + Mecaro (Korean company)



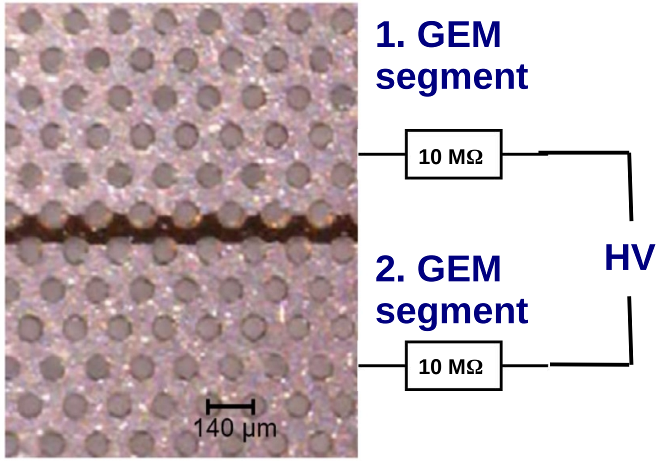




adapting the voltage on the electrodes provides sequential etching
=> perfectly aligned holes on both sides of large GEM foils
considerable reduction in cost ✔

2nd Success: “Random Hole” Segmentation of Large GEM Foils ✔

galvanic separation
part of the holes affected
(“random hole”)



10 MΩ resistors for contact of HV

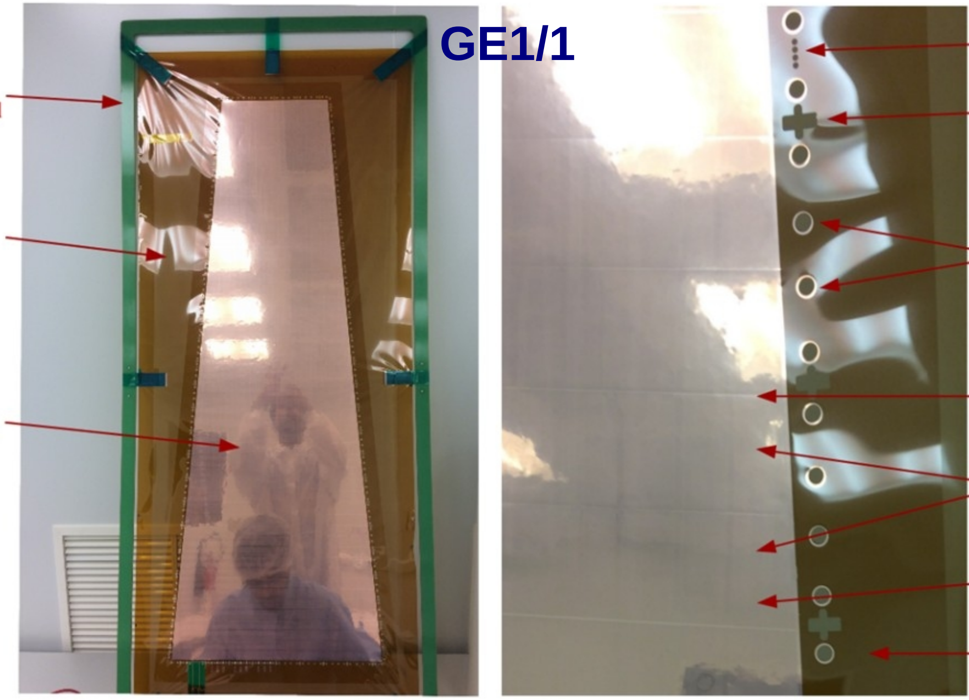
radially segmented GEM foil of ME0

GE1/1

Frame to hold the Foil

Dead Area

Active Area



GE1/1:
100 cm^2 segmentation areas
GEM1+2 segmentation double sided
GEM3 segmentation only on top

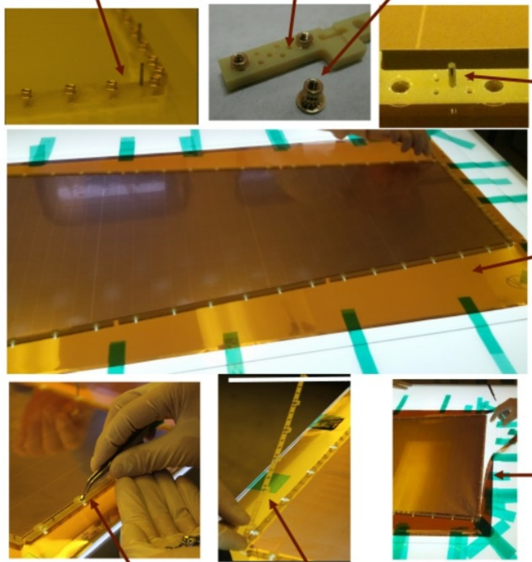
3rd Success: Simple and Reliable GEM Foil Stretching Mechanism (GE1/1)

prestretching + frames

3mm Frame showing Brass inserts and alignment pins

3mm frame fitted with Brass inserts

Brass Insert



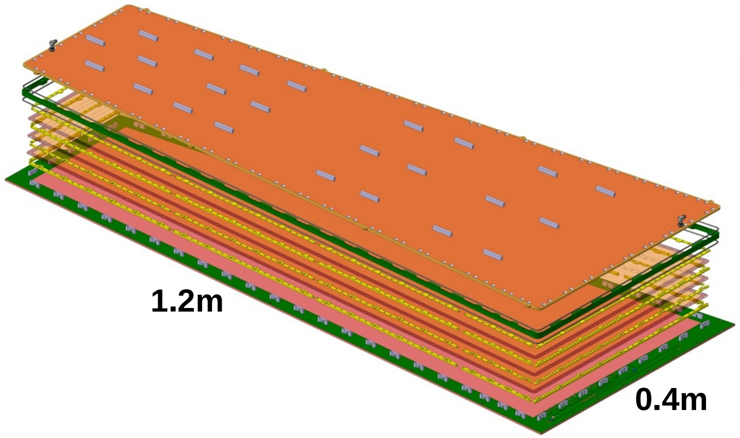
Alignment pin

Foil stretched to table with tape

Cutting of Extra dead polyamide area

Placement of nuts for foil stretching

Placement of piece of Internal frame



stretching mechanism

Piece of a frame

Screws to hold the GEM Stack

GEM Foil

Stretching Screw

Pull-Out

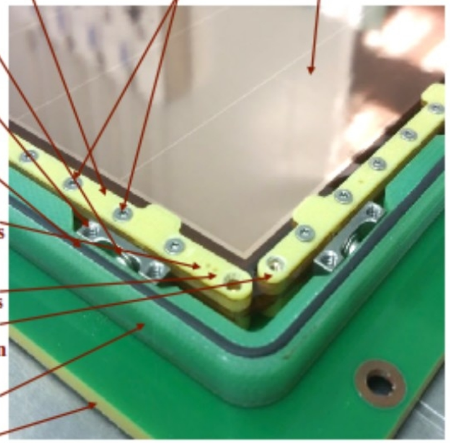
O-ring fixed in the gas frame

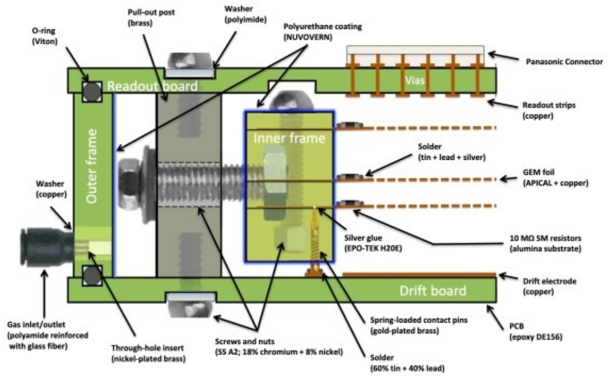
Holes for alignment pins

Holes left without screws for Demonstration

Gas Frame

Drift Board





✔

anode

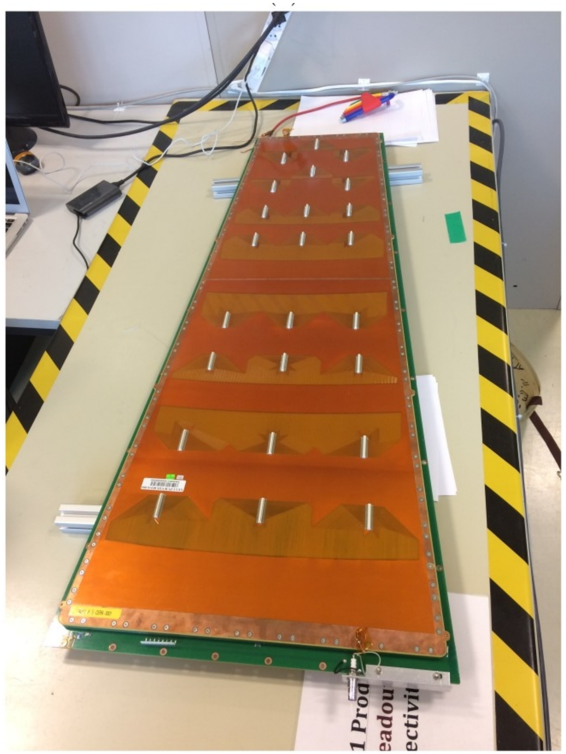
gas frame

3 mesh frames with meshes

gap frames 3mm,1mm,2mm,1mm

cathode

assembled GE1/1 module

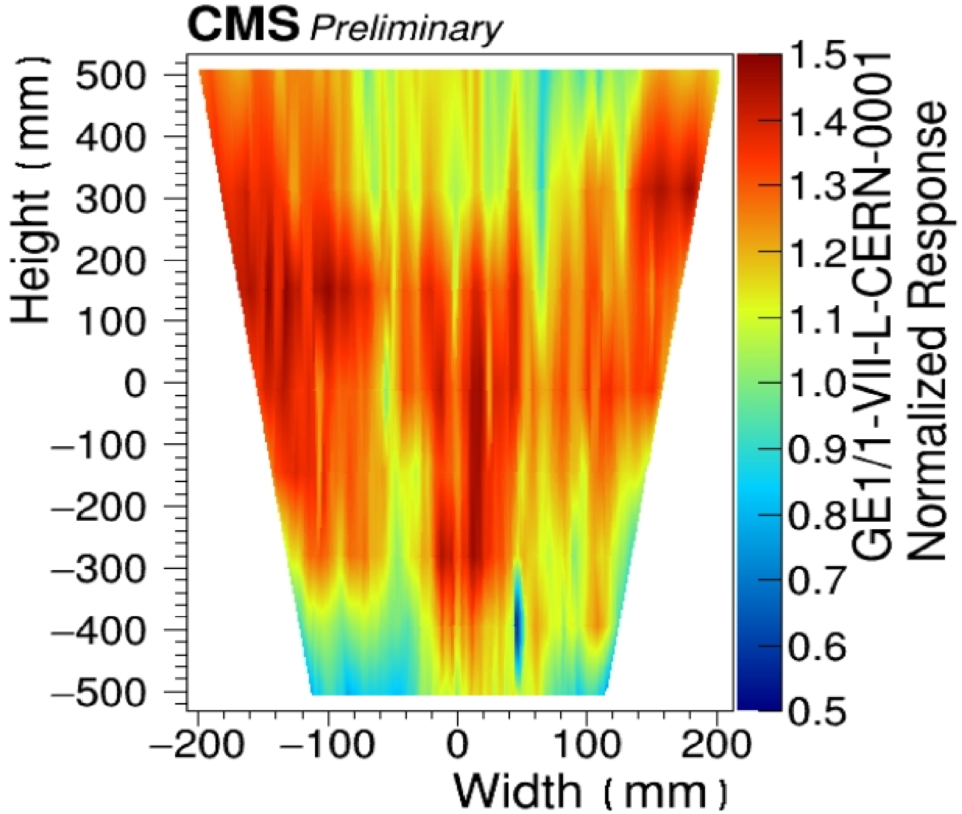


closed using screws

no supporting spacers !

Challenge for large areas: Response Uniformity

Response uniformity of first
CMS GE1/1
mber from serial production



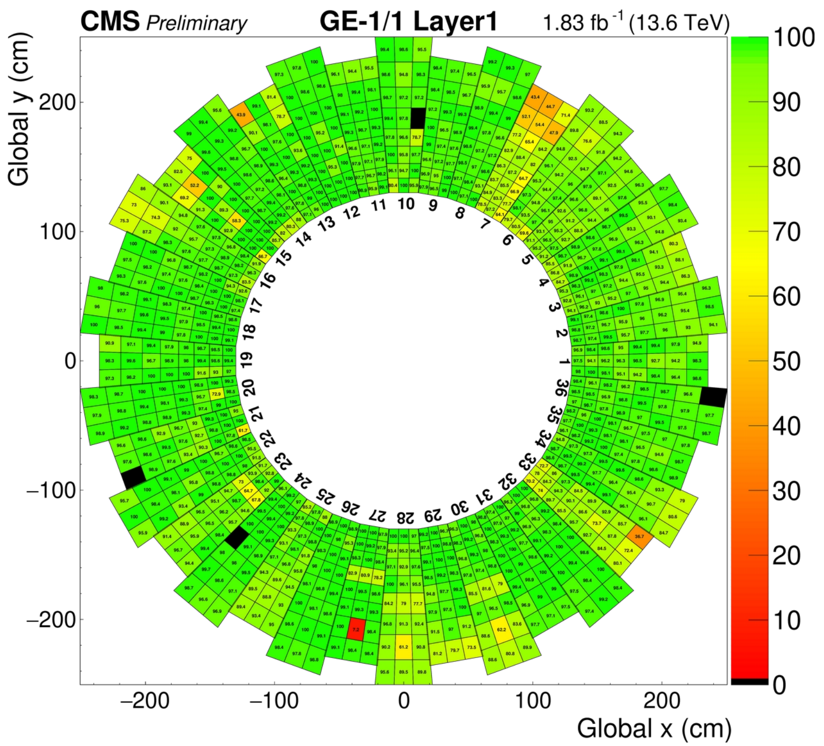
no dead space
novel method of foil
stretching (CMS GE1/1).

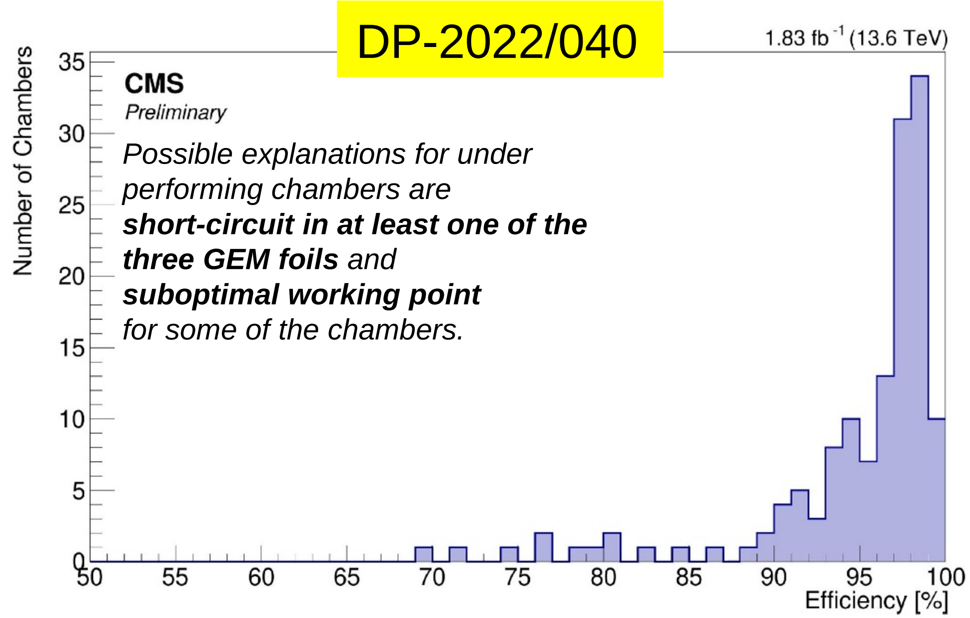
Response uniformity within 25%,
just within the specification.
Variations in uniformity at this level
do not negatively impact efficiency.

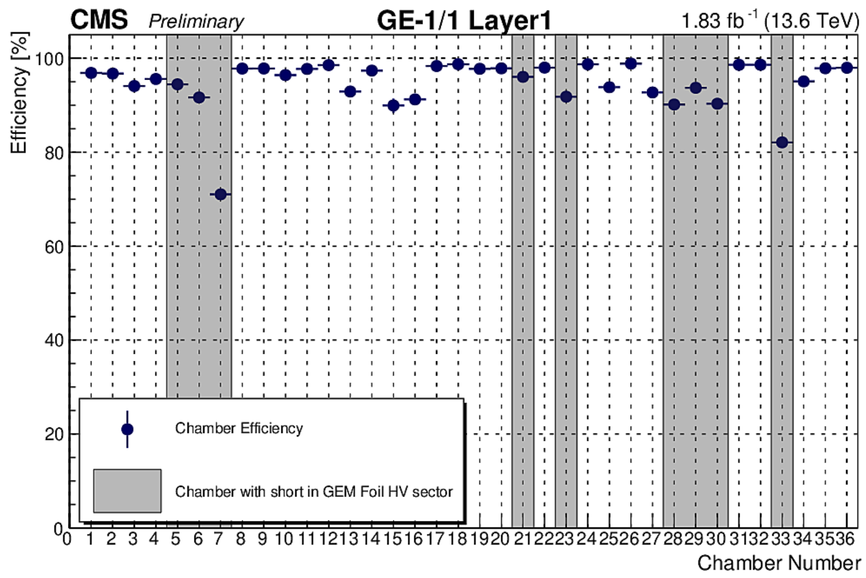
CMS GE1/1 Performance in CMS After the Installation 2019 / 2020

GEM chambers operated at 690 A equivalent divider current

The average efficiency is 96.6% ✔ excluding underperforming chambers.

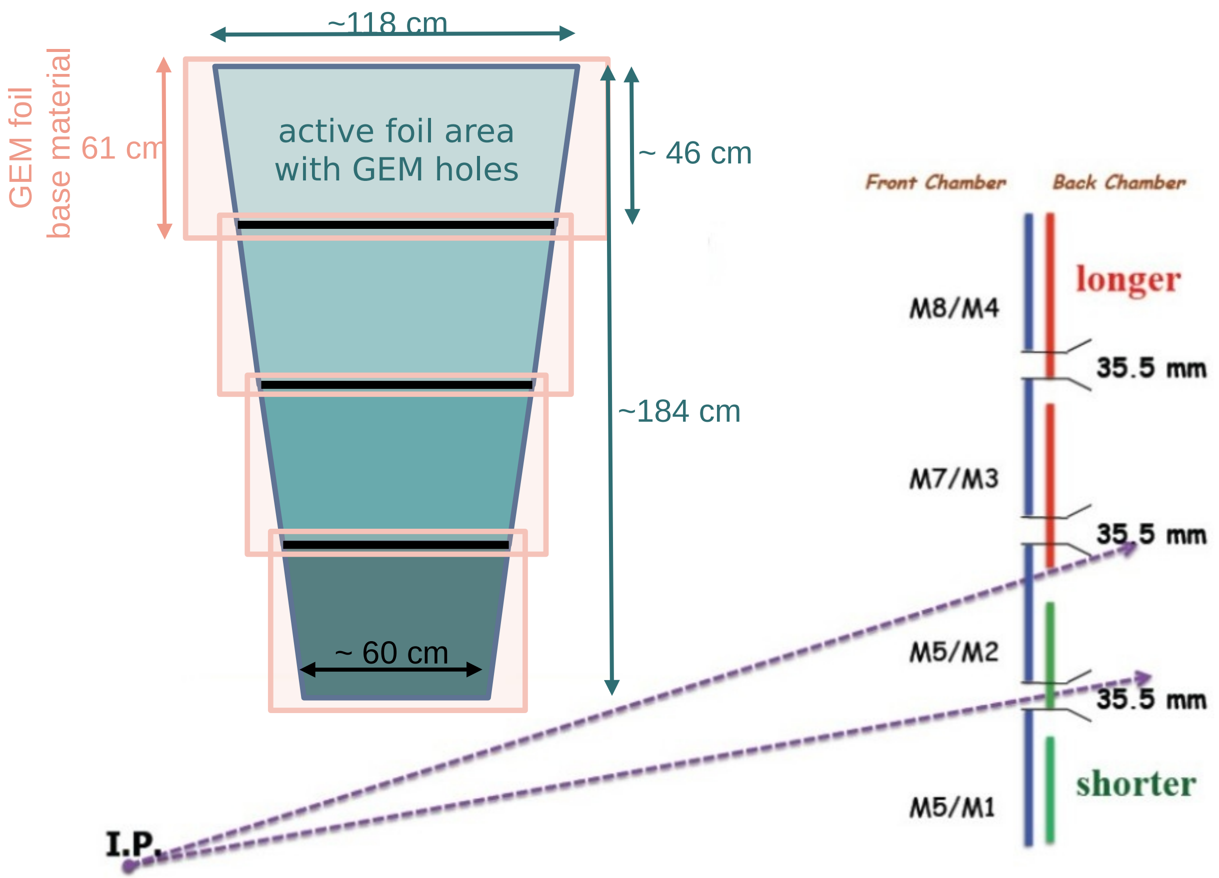


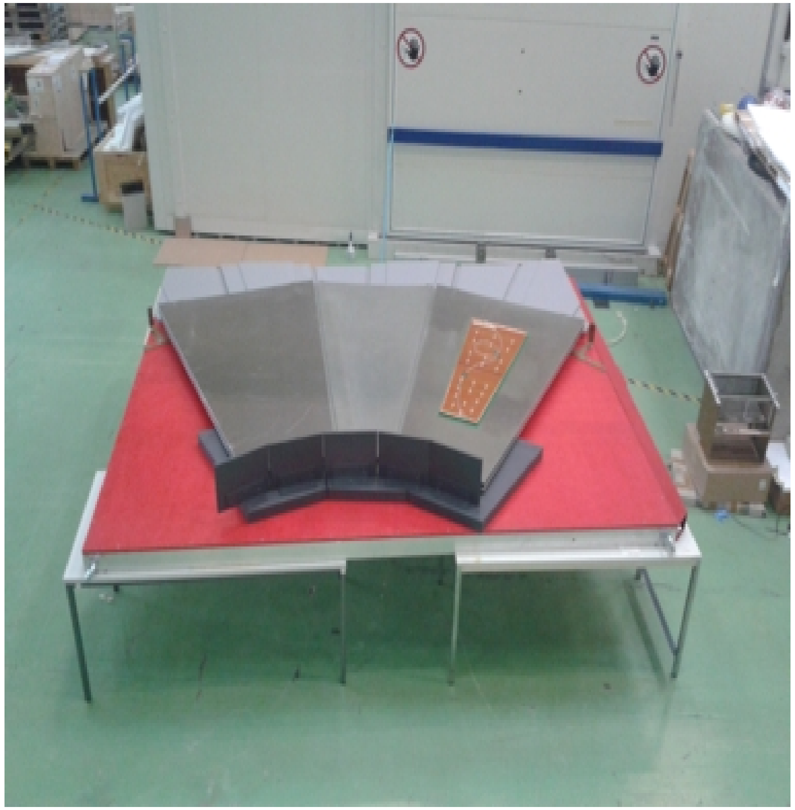




Large GE2/1 Triple GEM Chambers

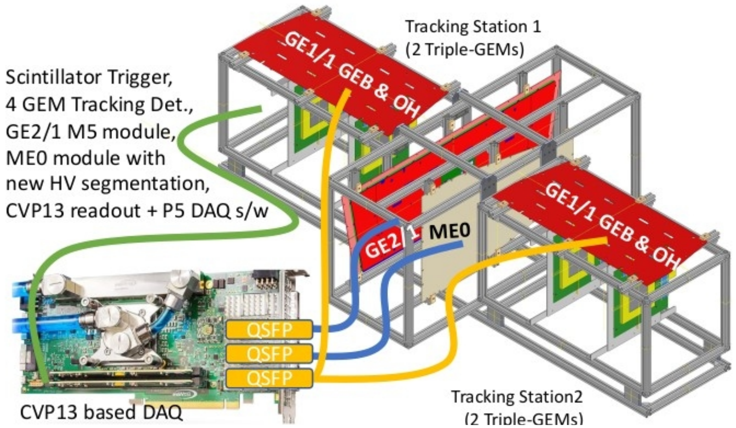
- dimension of ~2 m^2 for second CMS forward muon station
  2 layer per chamber
- smaller **GE1/1** foil stretching worked **without spacers**.
  for **GE2/1** could not avoid **internal spacers**

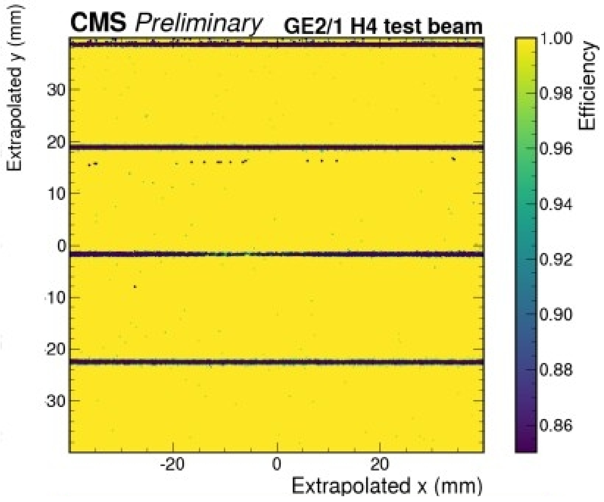




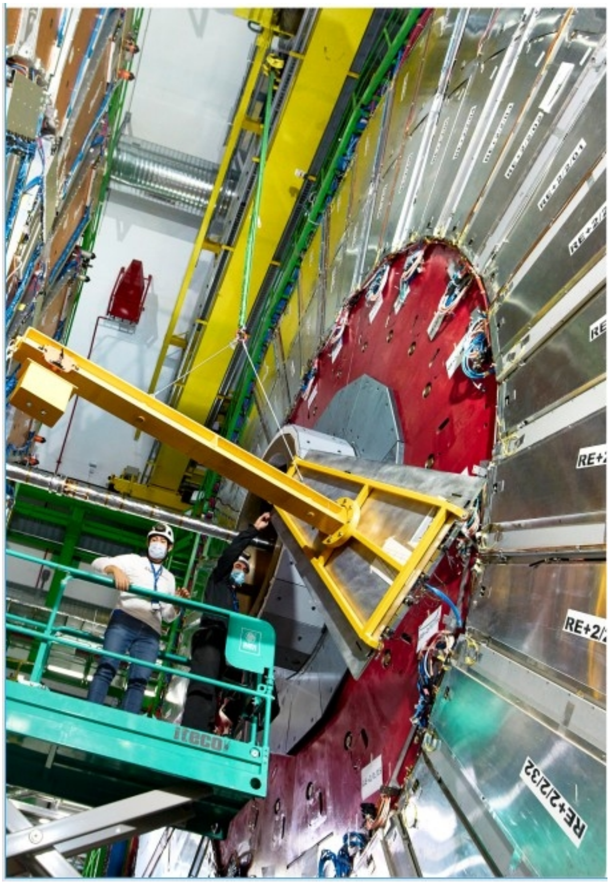
CMS GE2/1 H4 Testbeam + Demonstrator in Point5

H4 testbeam



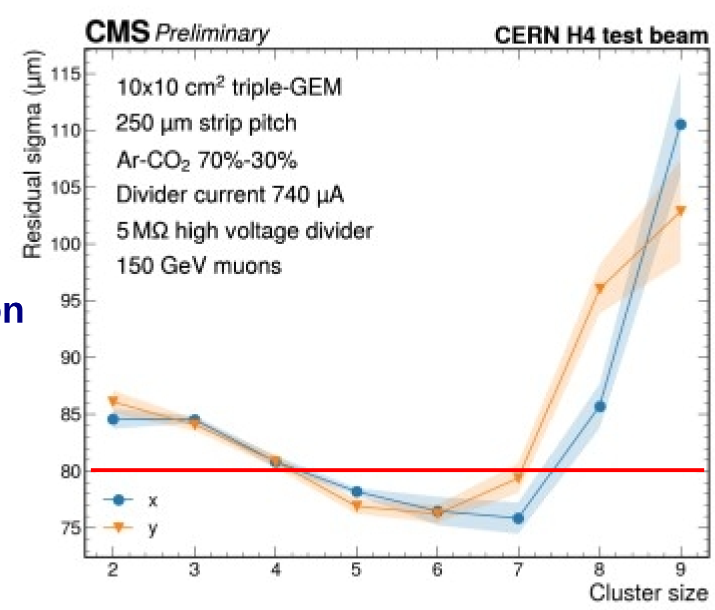


GE2/1 demonstrator 2022



data in 2023

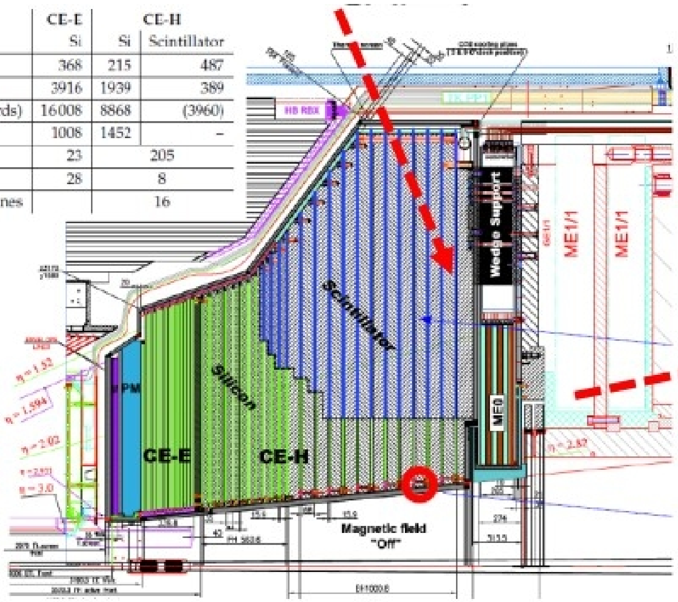
✔ **spatial resolution similar to 10 x 10 cm² chambers: σ = 80 μm**



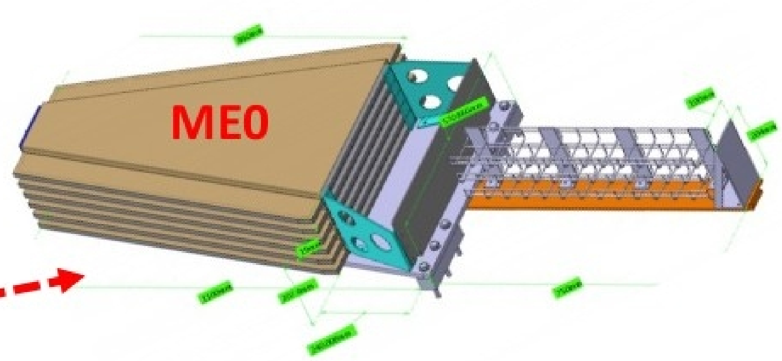
CMS ME0 Detector: Rate Capability 150 kHz/cm2

6 active layers, vertical segmentation of GEMs

	CE-E	CE-H	
	Si	Si	Scintillator
Area (m^2)	368	215	487
Channels (k)	3916	1939	389
Si modules (Tileboards)	16008	8868	(3960)
Partial modules	1008	1452	–
Weight (t)	23	205	
Si-only planes	28	8	
Mixed (Si+Scint) planes		16	

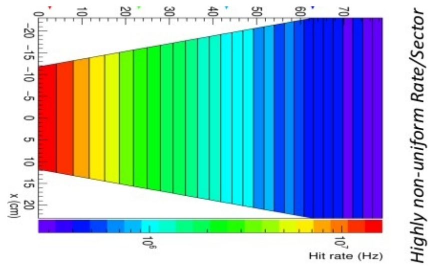


New High-Granular Calorimeter (HGCAL) CMS

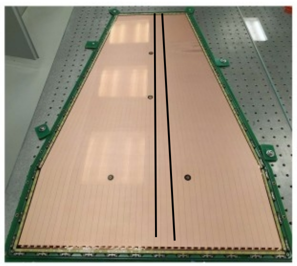


- 6-Layer stack of Triple-GEM
  - Install behind HGCAL (complex environment)
  - 18 stacks (20°) for each endcap
  - Coverage: $2.0 < \eta < 2.8$

simulated hit-rate in CMS

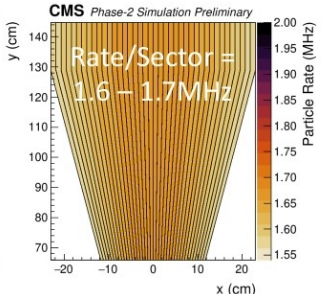


=> vertical segmentation

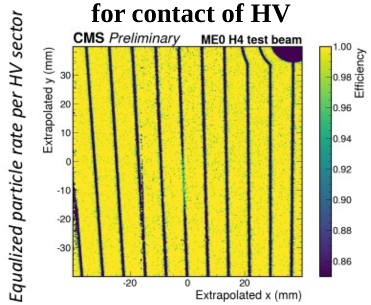


4 spacers to prevent blow-up

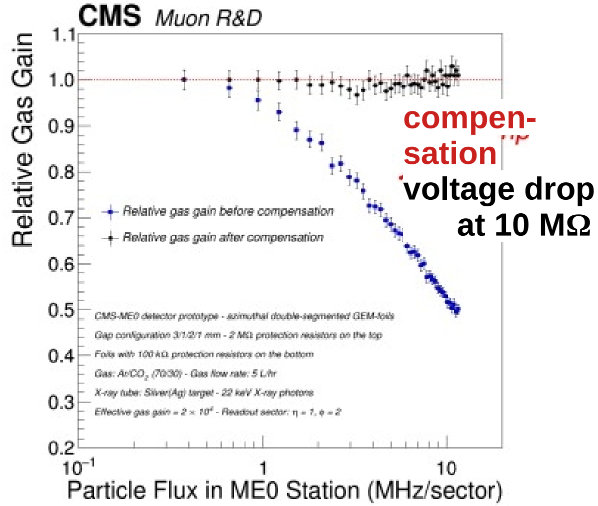
10 MΩ resistors for contact of HV



10 MΩ resistors for contact of HV



22



the design seems to be able to cope with the rate ✔

Summary GEMs for CMS

GE1/1 performs well
large GEM demonstrator is successful

GE2/1 shows high and homogeneous efficiency
and very good spatial resolution
the spacers proove successful

ME0 seems to be able to cope with the
very high backgroundrate of 150 kHz/cm^2

✔