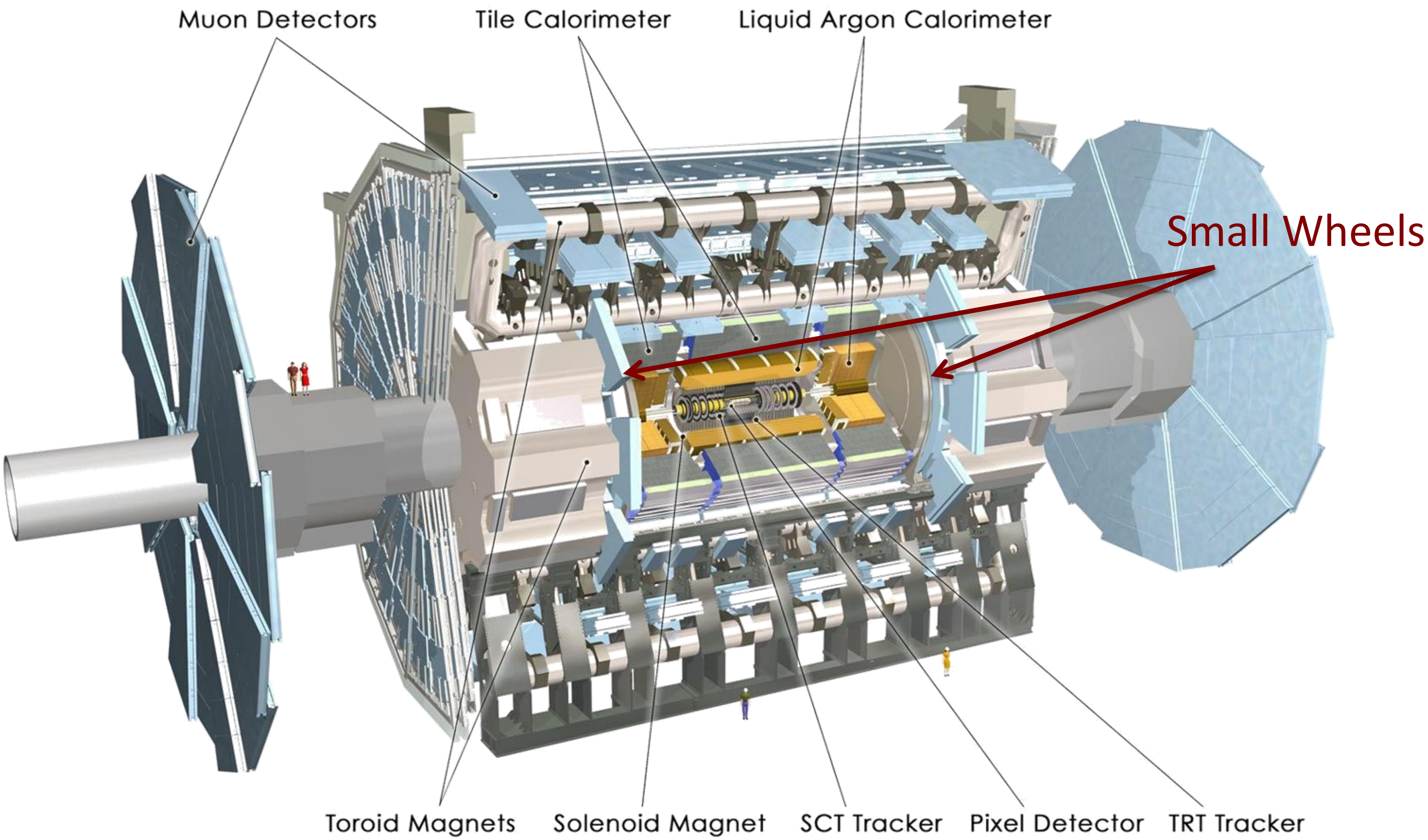
What we have learned in the MAMMA* R&D activity

*) Muon Atlas MicroMegas Activity

The beginning …

- 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 my 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.

The ATLAS Detector



ATLAS Small Wheel upgrade project

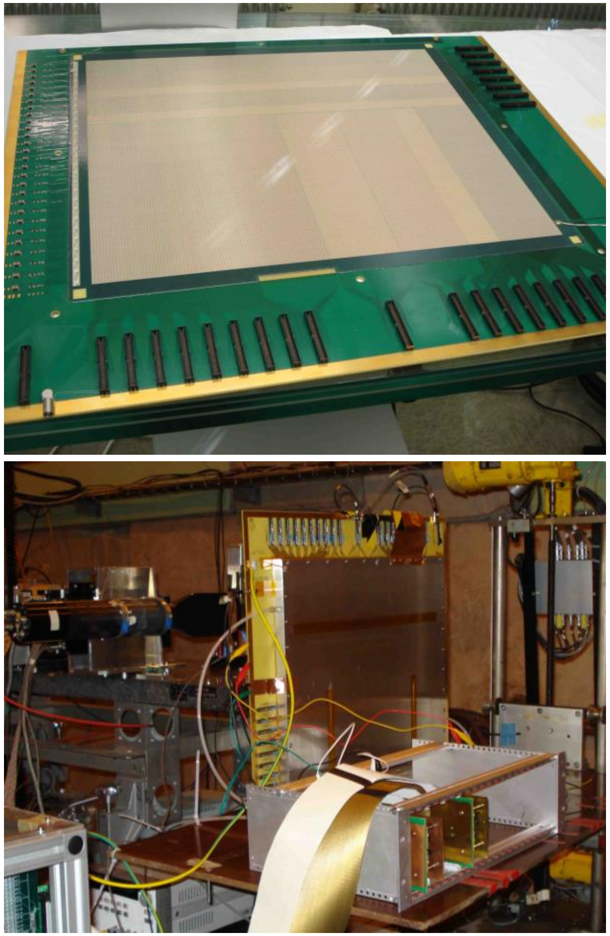
- The LHC upgrade foresees a step-wise luminosity increase of factor 5–10 a starting in 2019
- Replace the existing Small Wheels equipped with MDTs (drift tubes) and Cathode Strip Chambers (CSC) in the inner (high-rate) region. These detectors were designed to work up to the LHC design luminosity of L≈ $1x10^{34}$ $cm^{-2}s^{-1}$
- New Small Wheels (NSW) should be able to cope with this rate increase and add trigger capacity
- They are to be installed in ATLAS in the LS2 (2018/19)

Detector requirements for the NSW

- 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

Early performance studies (2007-2009)

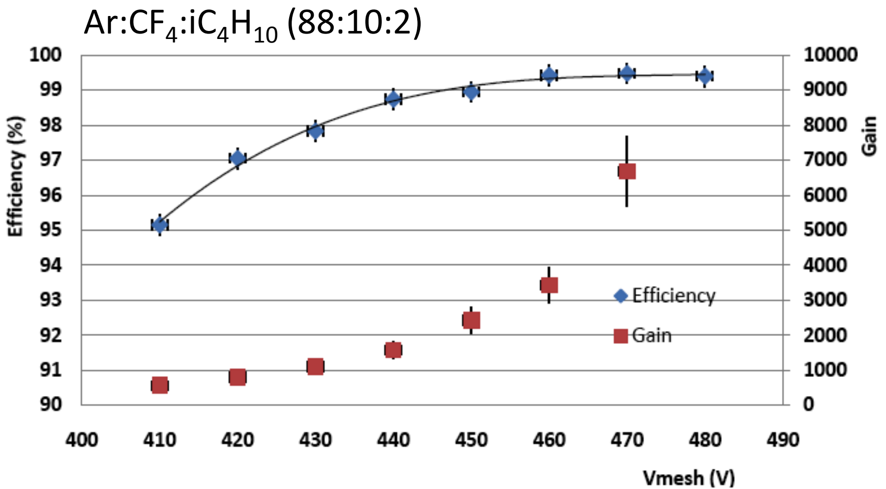
- All initial performance studies were done with ‘standard’ micromegas chambers
- P1 was a standard bulk MM (40 x 50 cm^2) with several strip patterns (250 µm to 2 mm pitch) and strip lengths of 250 and 400 mm
- It was tested extensively with hadrons in the H6 test beam at CERN but also with gammas using an ^{55}Fe source
- We used different gas mixtures, initially $Ar:CF_4:iC_4H_{10}$ (88:10:2, 95:3:2), moved later to $Ar:CO_2$ (80:20, 85:15, 93:7)



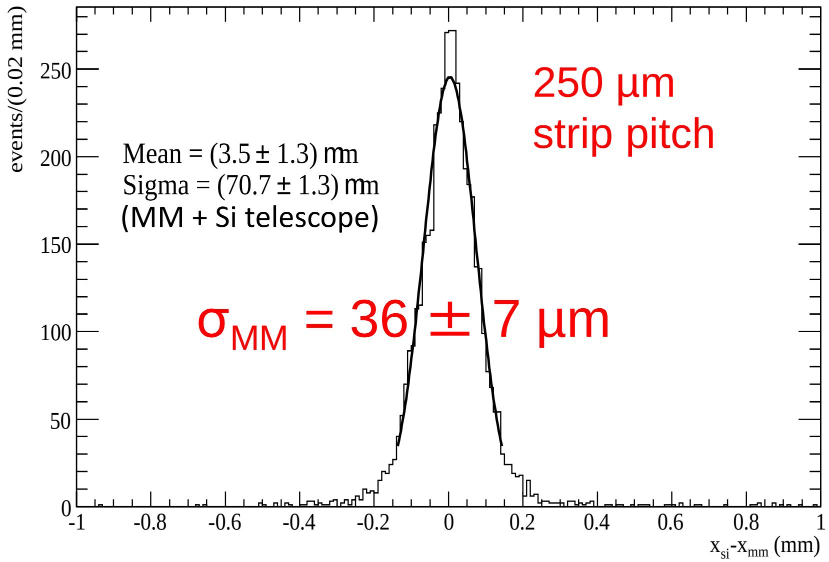
P1 (40 X 50 cm^2), H6 Nov 2007

2008: Demonstrated performance

- Standard micromegas (P1)
- Safe operating point with efficiency ≥99%
- Gas gain: 3–5 x 10^3
- Very good spatial resolution



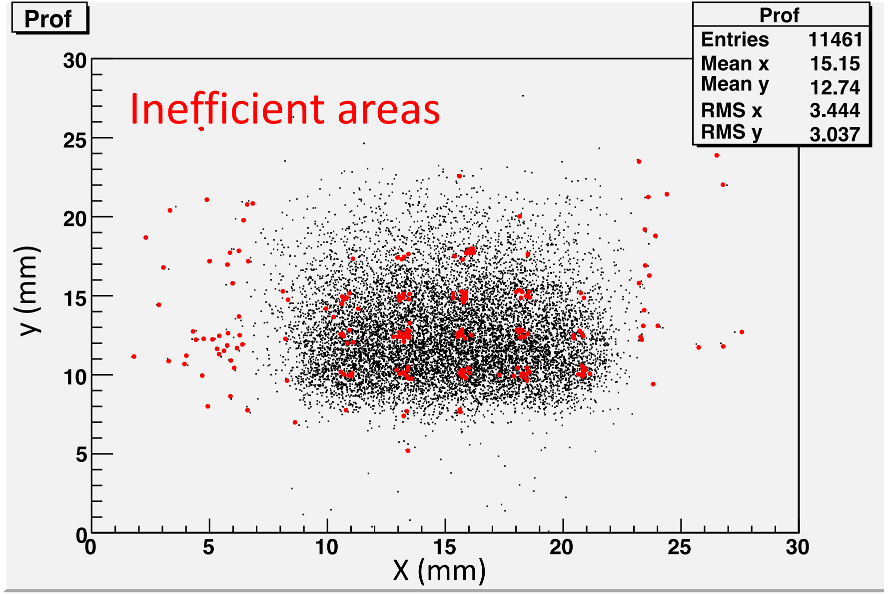
Ar:CF_4:iC_4H_{10} (88:10:2)



Mean = (3.5 ± 1.3) mm
Sigma = (70.7 ± 1.3) mm
(MM + Si telescope)

250 µm
strip pitch

σ_{MM} = 36 ± 7 µm



Inefficient areas

Conclusions by end of 2009

- Micromegas (standard) perform very nicely
  - Clean signals
  - Stable operation for detector gains of 3–5 x 10^3 with pure Ar:CO_2 gas mixtures
  - Efficiency of 99%, limited by the dead area from pillars
  - Required spatial resolution of 100 µm can easily be achieved with strip pitches between 0.5 and 1 mm
  - Timing performance could not be measured with the ALTRO electronics used at that time
- 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

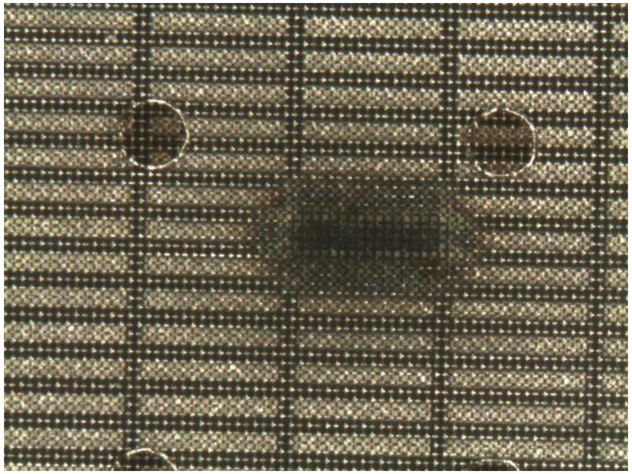
2010: Making MMs spark resistant

- 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

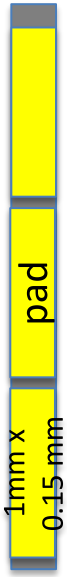
Local damage of resistive layer

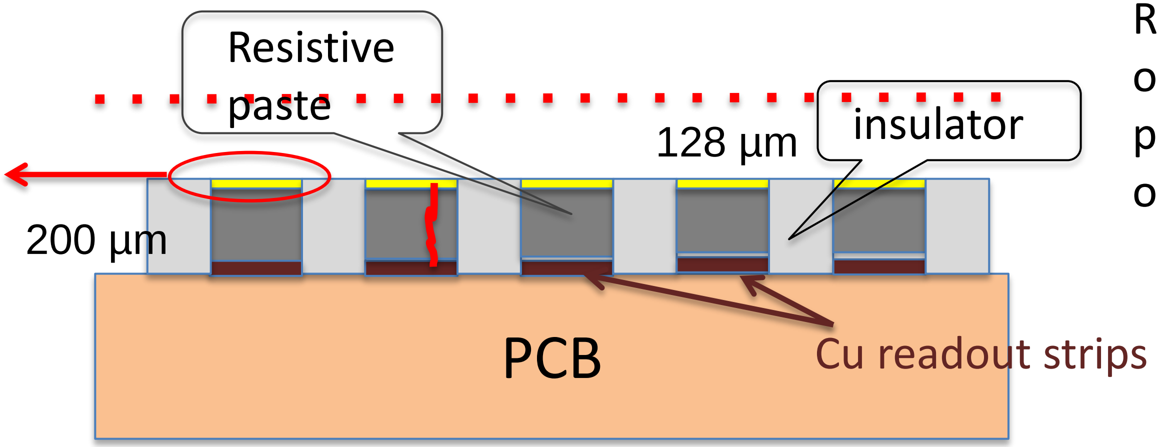
- Resistive layer is locally damaged, induced by some large charge

  (Resistive paste not very homogeneous, manually applied)
- Regions with lower resistance (or some defects) are affected first.
- Once the resistive layer is locally damaged, sparks with higher currents develop at the affected pad

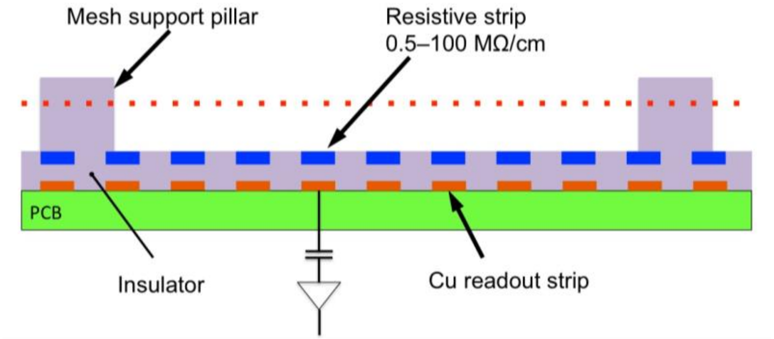


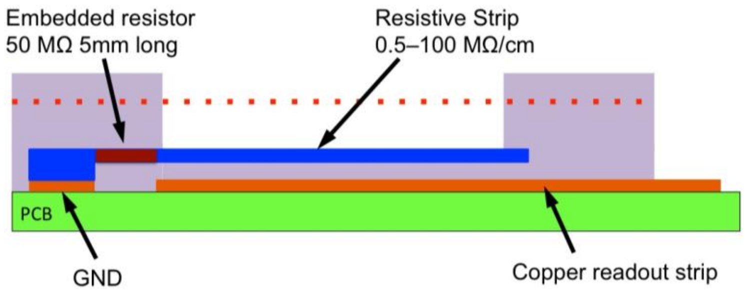
R3 with resistive paste on top of readout strips and metal plating to protect the surface of the resistive paste



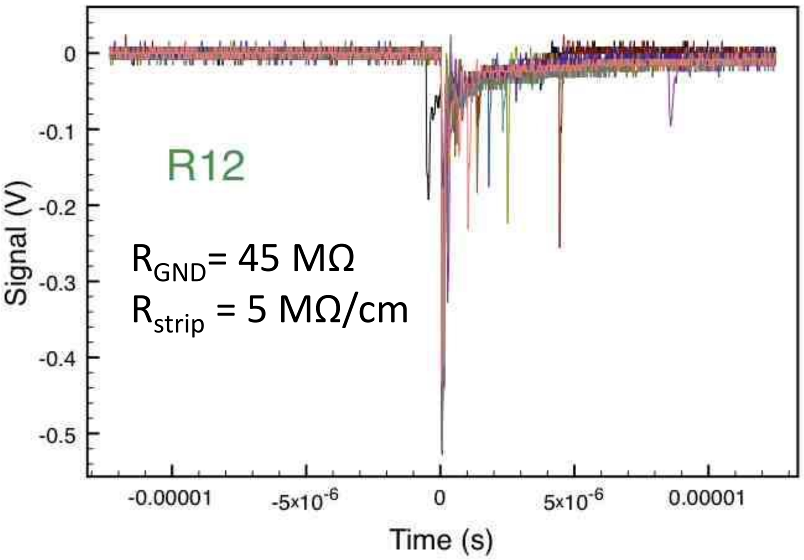


Resistive-strip protection concept



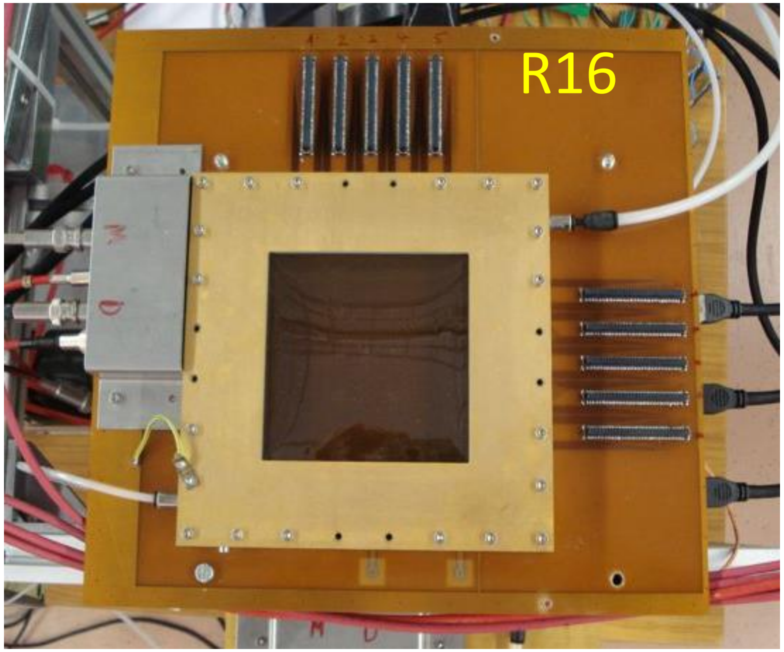


- A layer of resistive strips, separated by an insulating layer, above the readout strips (NIM A 640 (2011) 110–118) makes sparks largely inoffensive
- With a strip resistivity of 10–20 MOhm/cm spark currents are reduced by about three orders of magnitude
- Sparks are quickly quenched
- The strip pattern constrains sparks to regions of typically one or two strips



Large number of resistive-strip detectors tested

- Small chambers with 9 x 9 cm^2 active area
- Large range of resistance values
- Number of different designs
- Gas mixtures
  - Ar:CO$_2$ (85:15 and 93:7)
- Gas gains
  - 2–3 x 10^4
  - 10^4 for stable operation



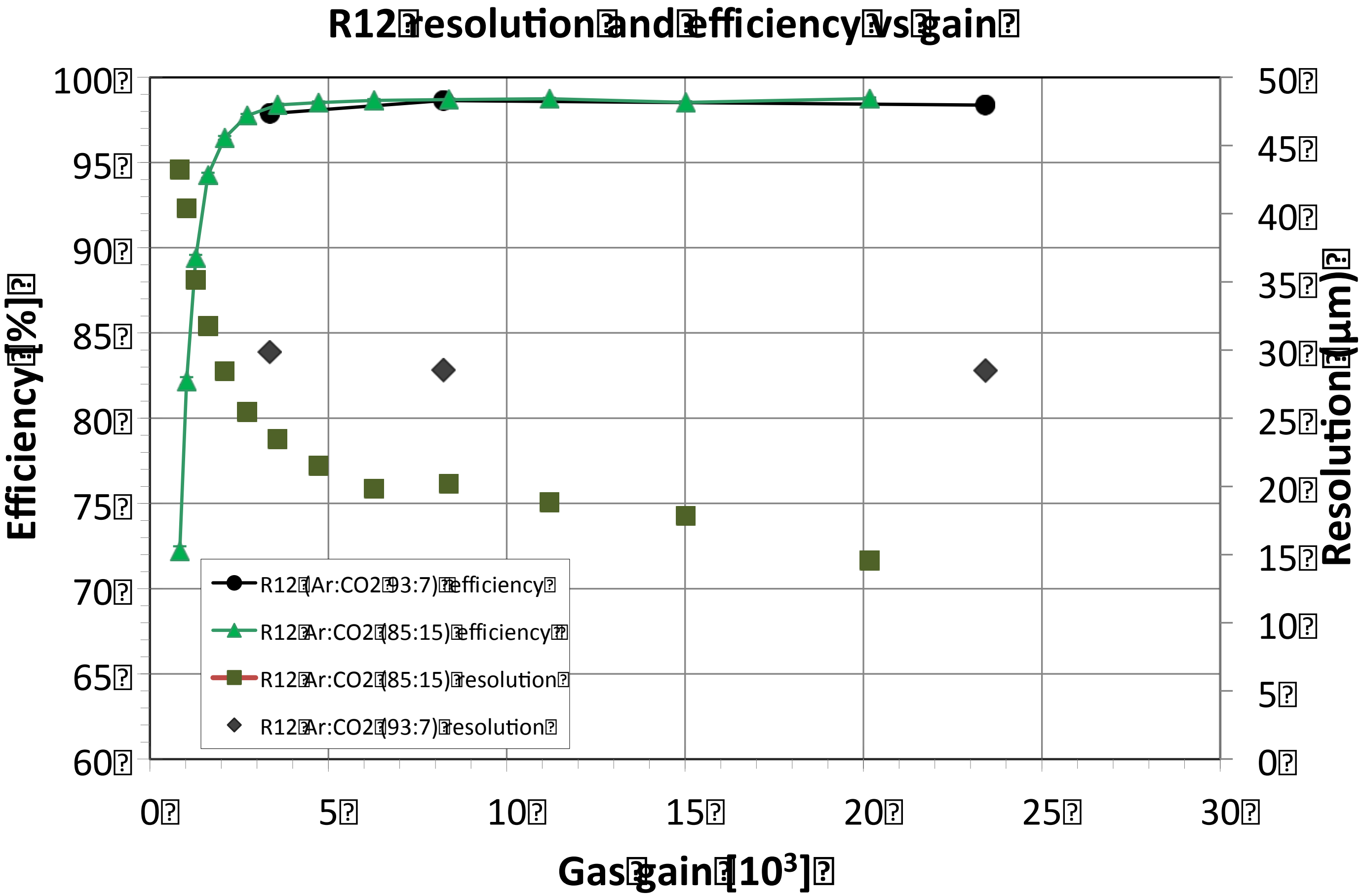
R16, first chamber with 2D readout

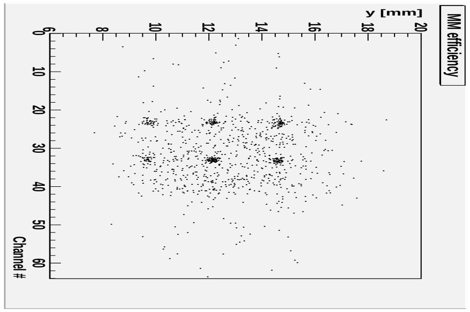
Small resistive-strip detectors

Chamber	R_{GND} (MΩ)	R_{strip} (MΩ/cm)	Readout coord. (N_R:N_{ro})	Strip pitch (µm)	
R11	15	2	x (1:1)	250	
R12	45	5	x (1:1)	250	
R13	20	0.5	x (1:1)	250	
R14	100	10	x (1:1,2,3,4,72)	250	
R15	250	50	x (1:1,2,3,4,72)	250	
R16	55	35	x-y	250	
R17a,b	100	45	x-y	250	Used for ageing tests
R18	200	100	x-y	250	
R19	50	50	xuv	350/900/900	Mesh & GEM
R20	80	25	x	250	+HV on strips
R21	250	150	x-y	500/1000	+HV on strips
MBT0	100	100	x-u (x-v)	500/1500	2 gaps/+HV on strips

Spatial resolution & efficiency for R12 (250 µm strips)

Analysis of data taken in July 2010



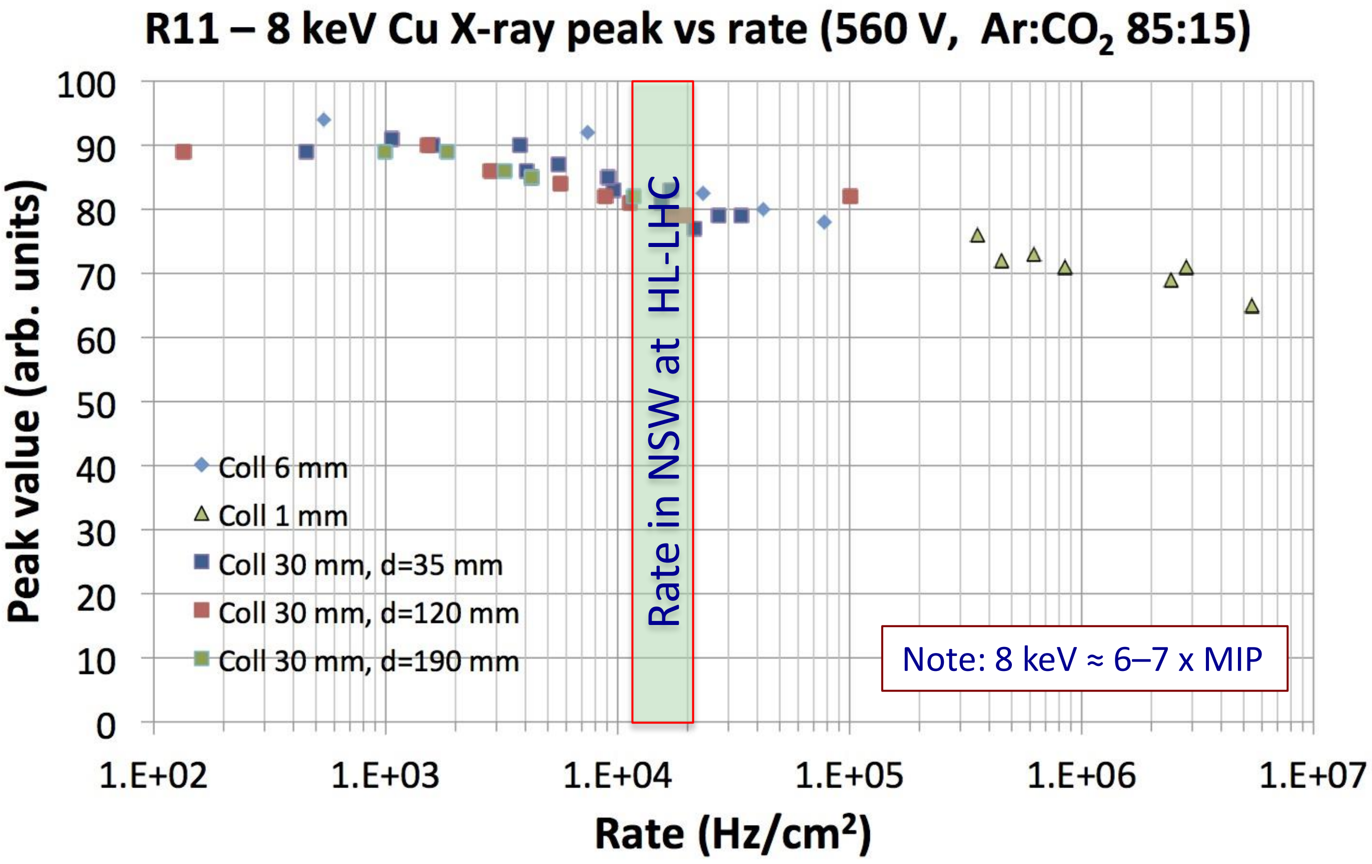


Inefficiency compatible with area of mesh support pillars (d=2.5 mm)

Resistive strip chambers are fully efficient (≈98%) over a wide range of gains

Spatial resolution with 250 µm strip: ≈30 µm with Ar:CO_2 (93:7), even better with 85:15

Rate capability of resistive-strip MMs


R11 – 8 keV Cu X-ray peak vs rate (560 V, Ar:CO_2 85:15)

Rate in NSW at HL-LHC

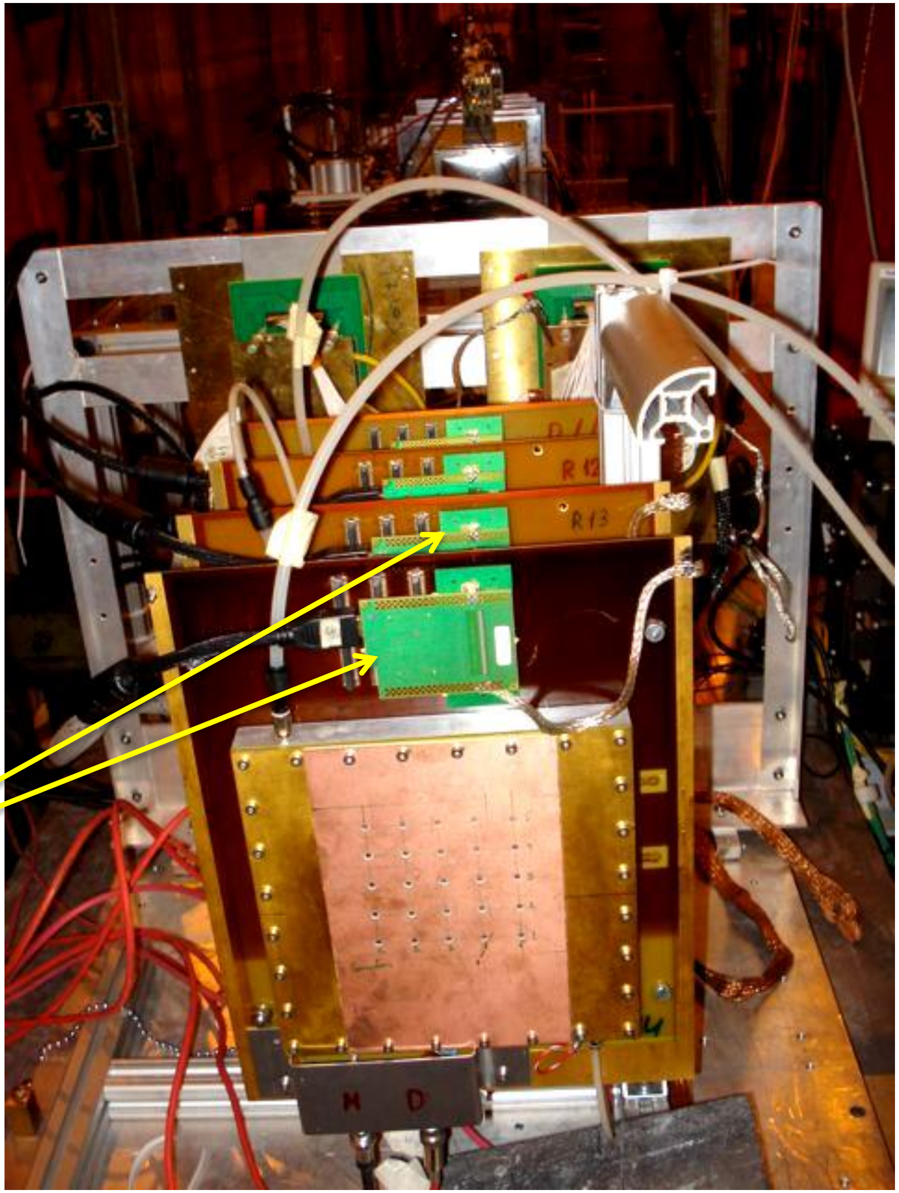
Note: 8 keV ≈ 6–7 x MIP

- Rate capability has been extensively studied using Cu X-ray beams up to MHz/cm^2
- Small double-gap MM with resistive strips has been successfully operated during one year in front of the e/m calorimeter of ATLAS with rates up to 150 kHz/cm^2

Test beam
Nov 2010

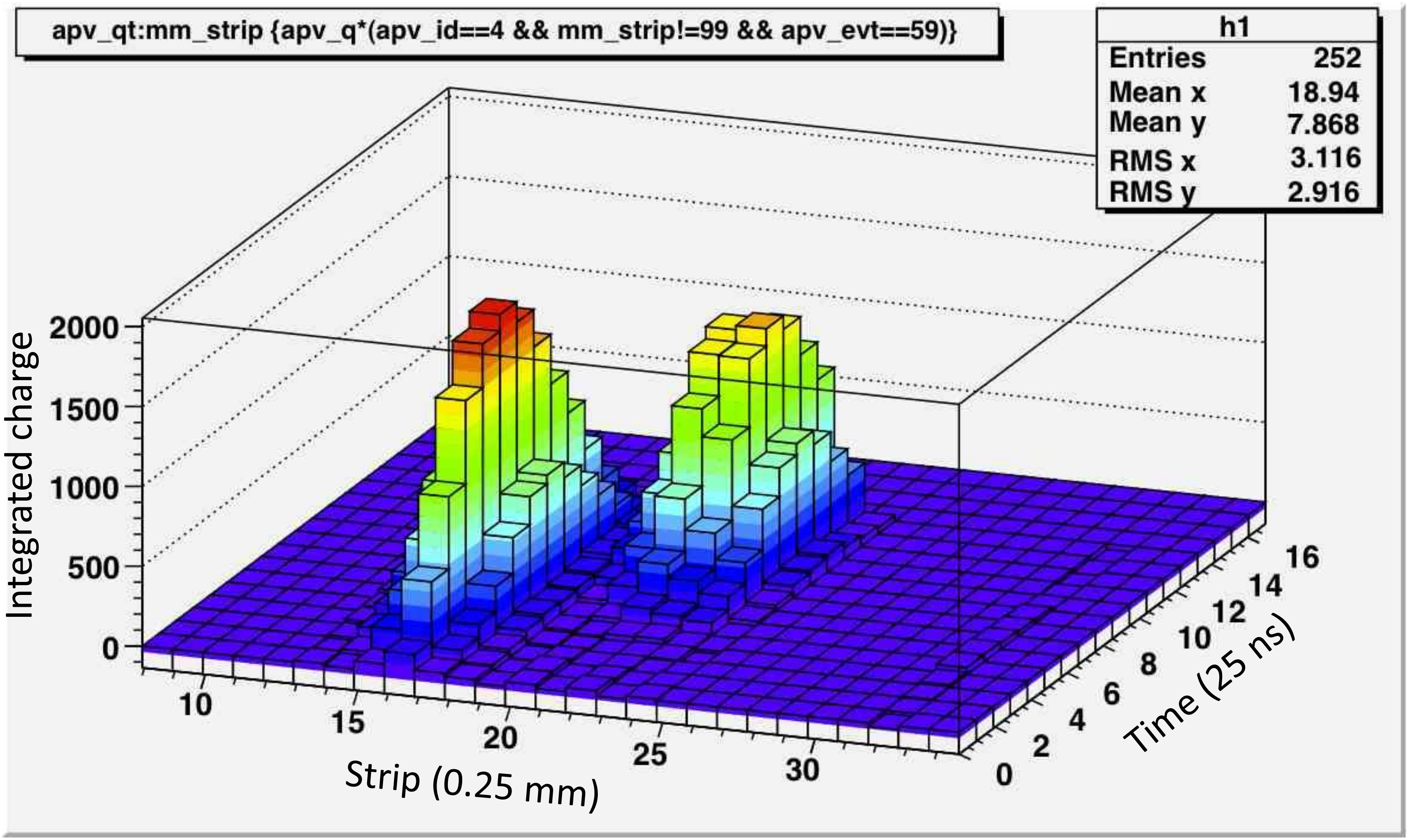
Four chambers with resistive strips aligned along the beam

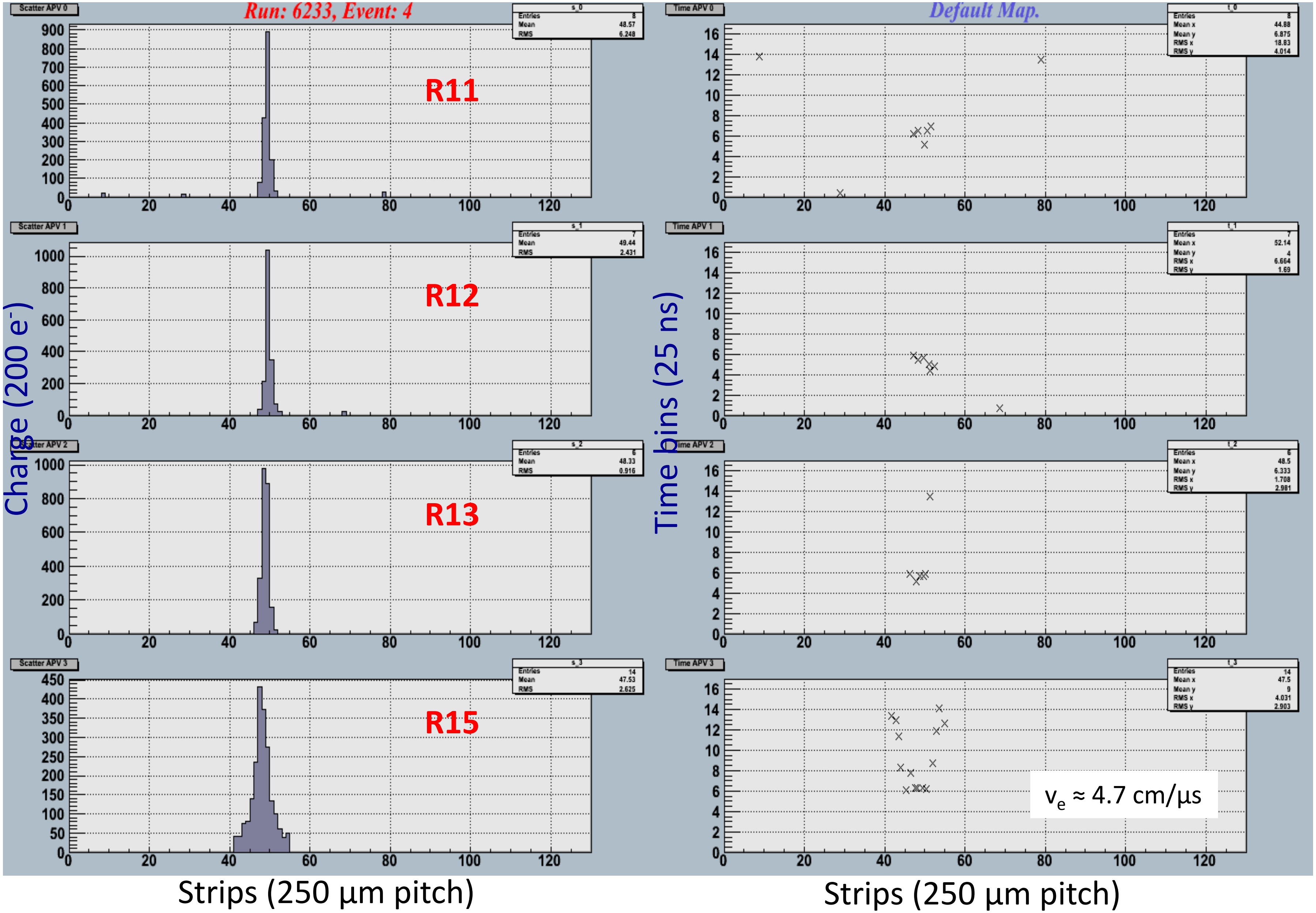
NEW: Scaleable Readout System (SRS) – RD51 (H. Muller at al.), a major step forward



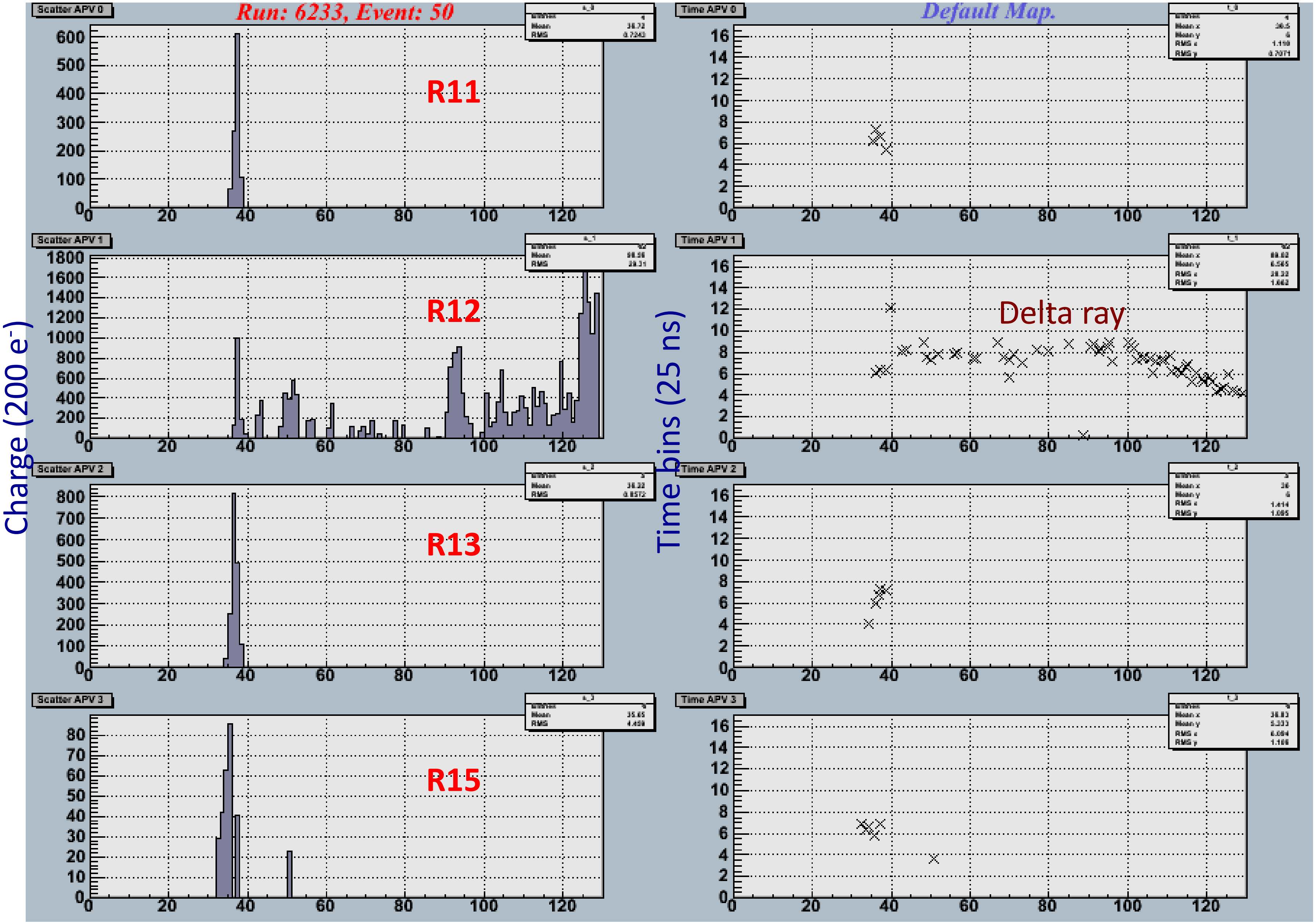
APV25 hybrid cards

APV25 data – two track example

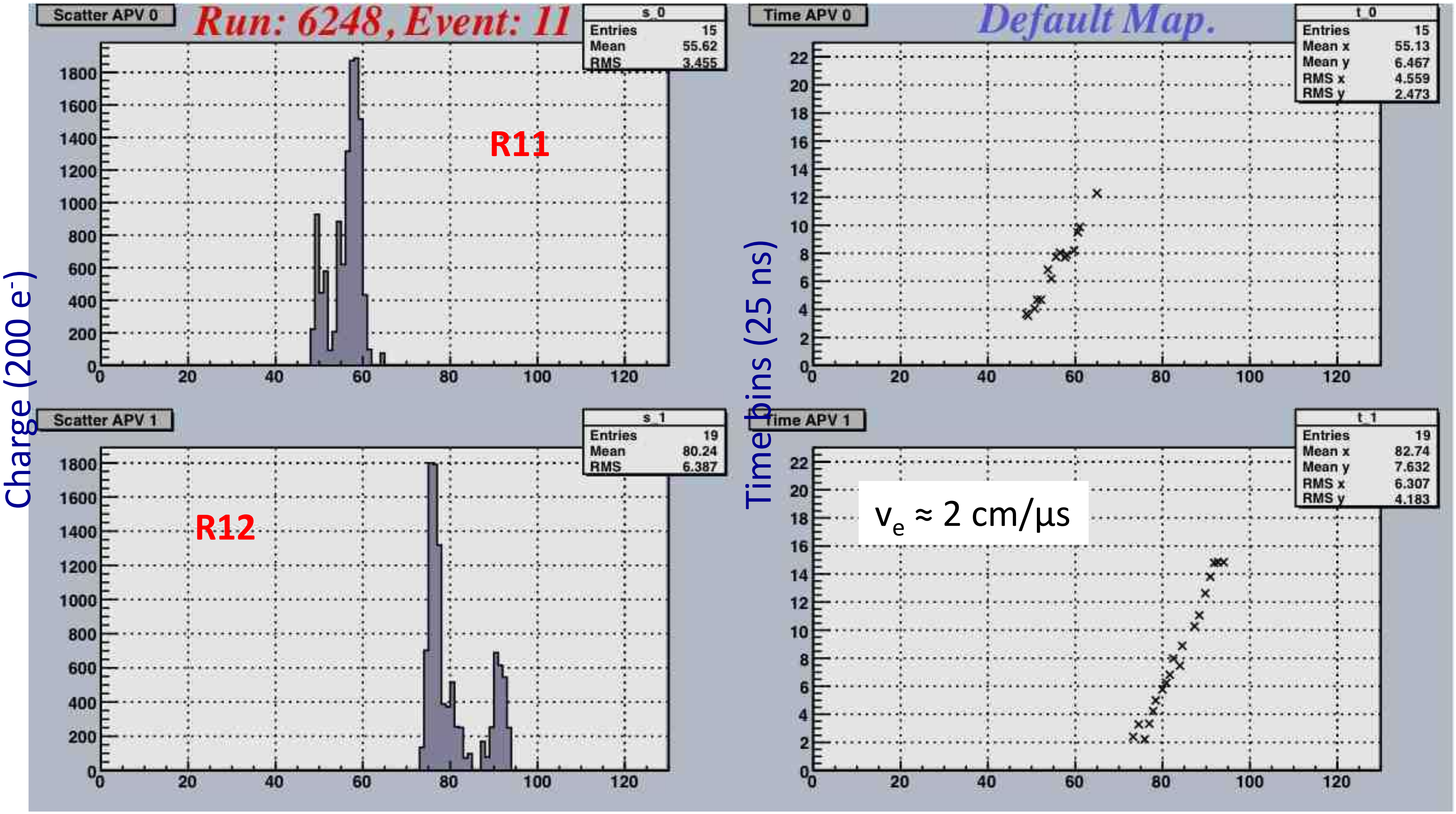




$v_e \approx 4.7$ cm/µs


Run: 6233, Event: 50
Default Map.
Scatter APV 0
Time APV 0
R11
Scatter APV 1
Time APV 1
R12
Delta ray
Scatter APV 2
Time APV 2
R13
Scatter APV 3
Time APV 3
R15
Charge (200 e⁻)
Time bins (25 ns)
0
20
40
60
80
100
120

Inclined tracks (40°) – µTPC

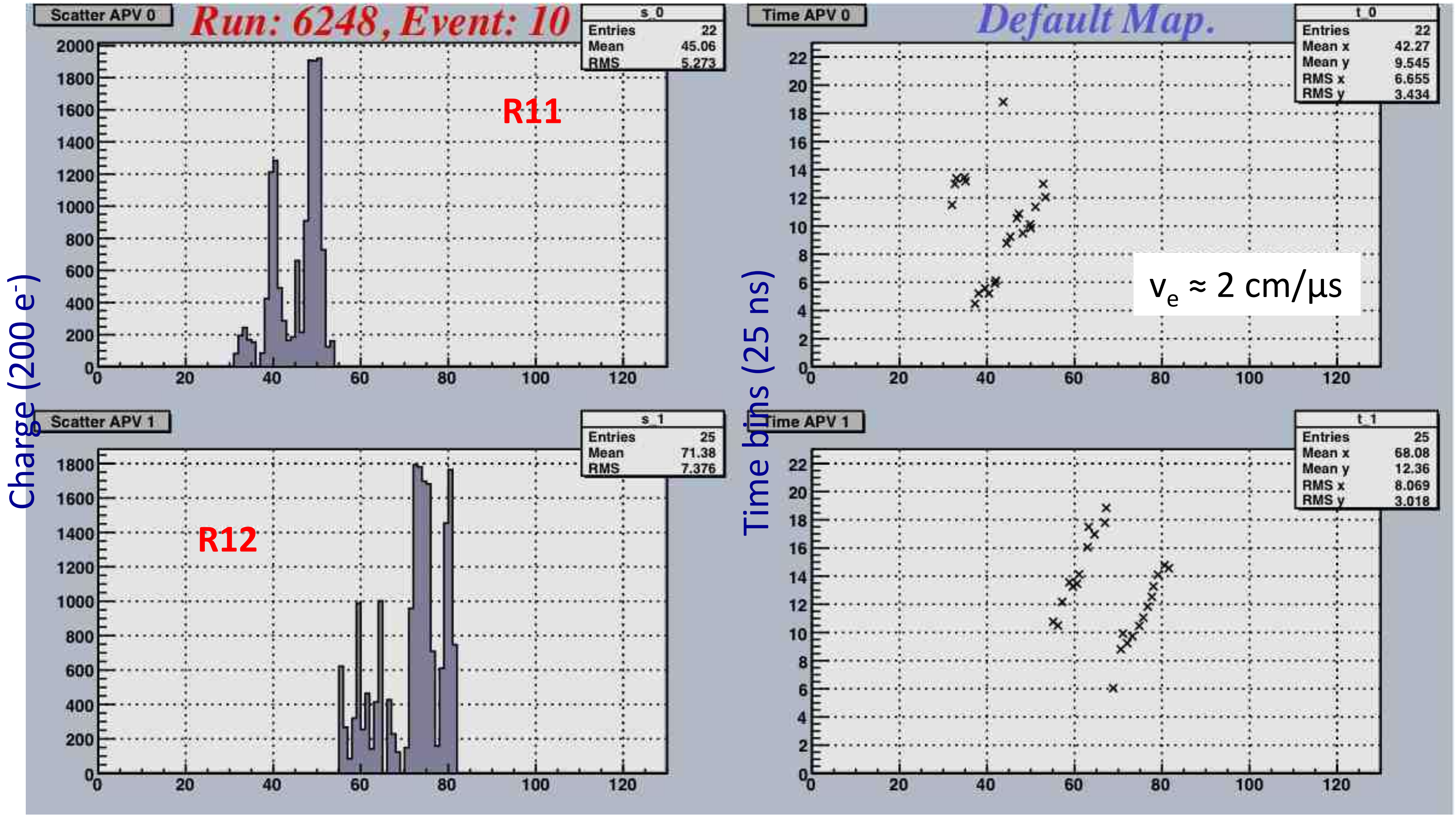


R11

R12

$v_e \approx 2$ cm/µs

… and a two-track event



R11

R12

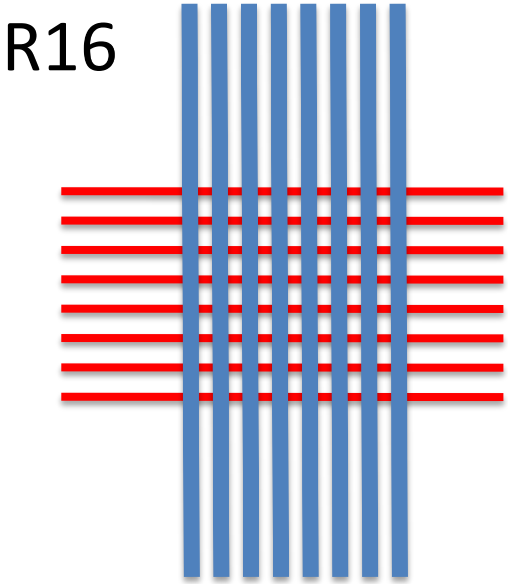
$v_e \approx 2$ cm/μs

Charge (200 e^-)

Time bins (25 ns)

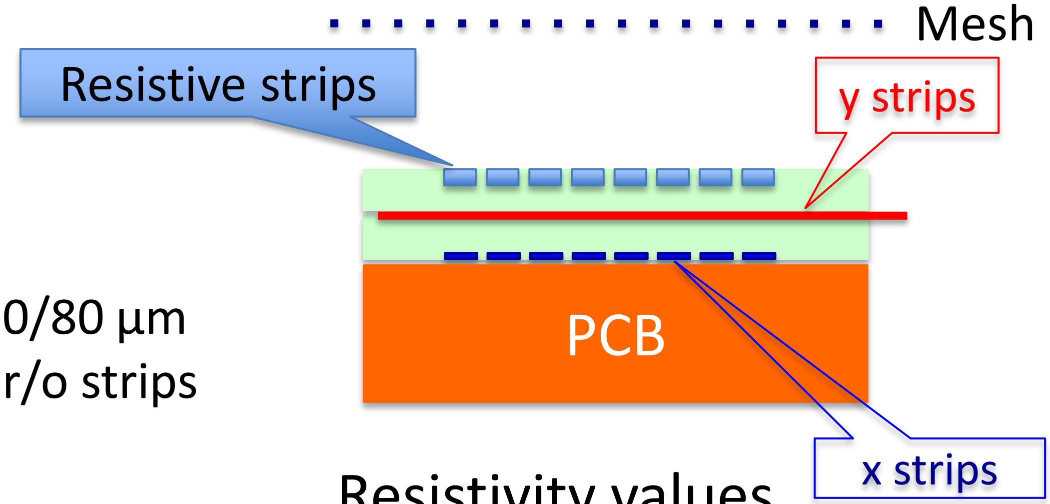
2D readout (R16 & R19)

- Readout structure that gives two readout coordinates from the same gas gap; crossed strips (R16) or xuv with three strip layers (R19)
- Several chambers successfully tested



y: 250/80 µm
only r/o strips

x strips: 250/150 µm
r/o and resistive strips

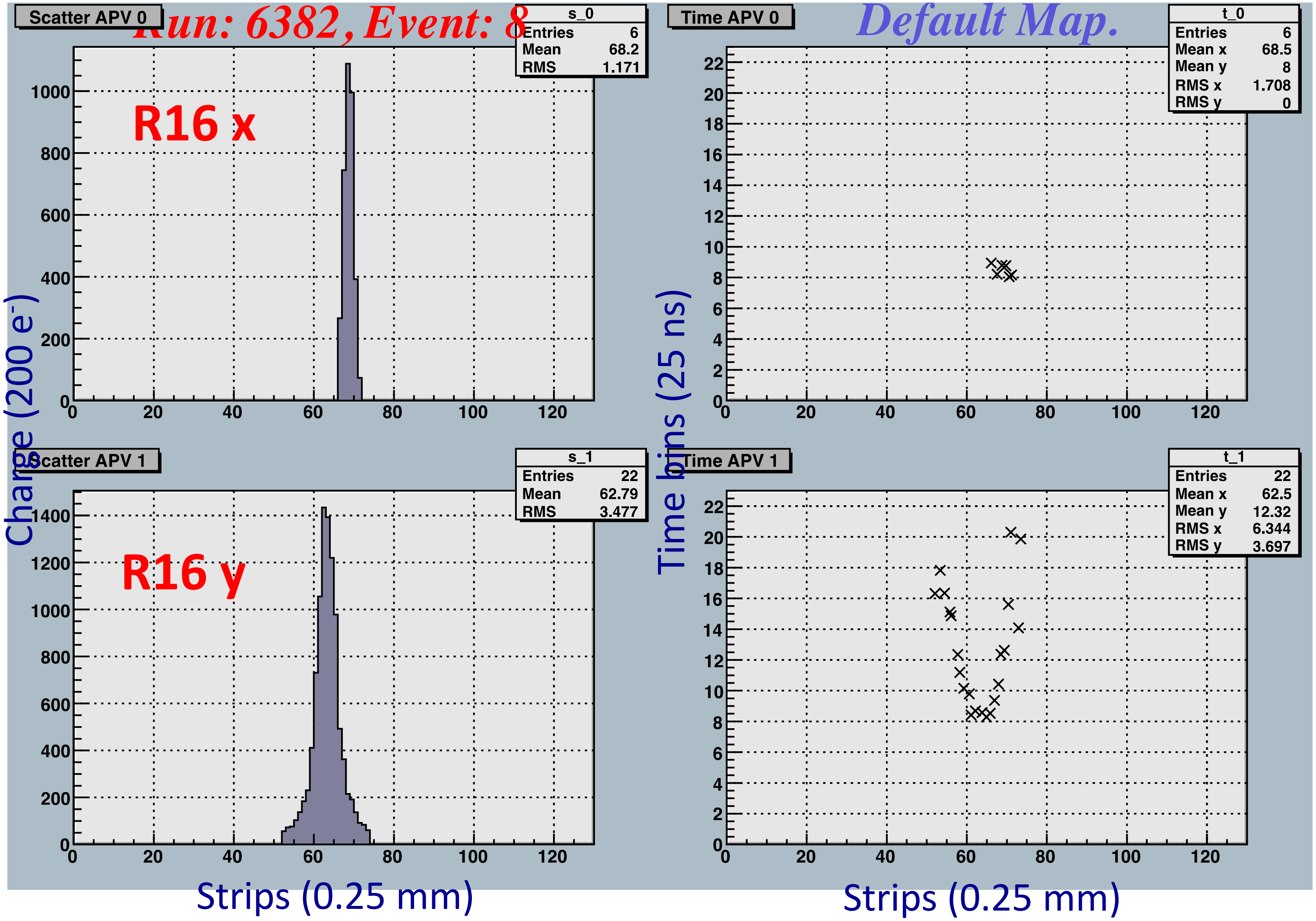


Resistivity values

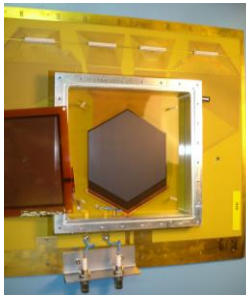
$R_G \approx 55\ \mathrm{M\Omega}$

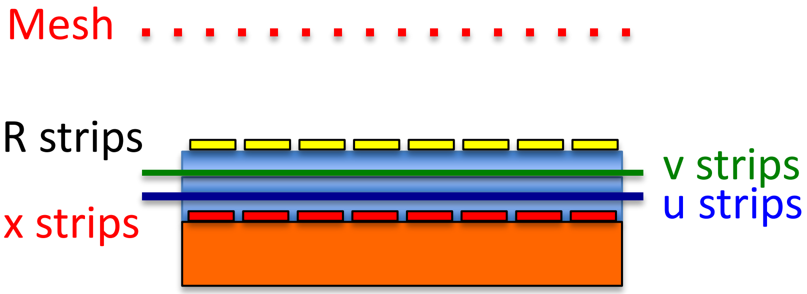
$R_{strip} \approx 35\ \mathrm{M\Omega/cm}$

R16 x-y event display (^{55}Fe γ)

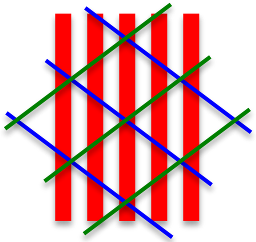


R19 with xuv readout strips



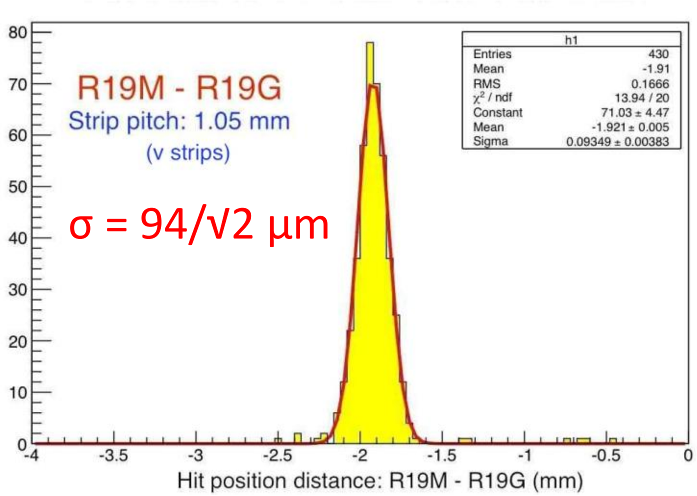


- x strips parallel to R strips
- u,v strips ±60 degree



R19	R	v	u	x
Depth (µm)	0	-50	-100	-150
Strip width (mm)	0.25	0.1	0.1	0.25
Strip pitch (mm)	0.35	0.9	0.9	0.35
Q collected (rel.)		0.84	0.3	1

- Tested two chambers with same readout structure (R19M and R19G) in a pion beam (H6) in July
- Clean signals from all three readout coordinates, no cross-talk
- Strips of v and x layers well matched, u strips low signal, too narrow
- Excellent spatial resolution, even with v and u strips



R19M - R19G
Strip pitch: 1.05 mm
(v strips)

σ = 94/√2 µm

Ageing

Radiation	Energy	Integrated charge	Result
Cu X-rays	8 keV	5 years HL-LHC equivalent	No evidence for ageing
Reactor neutrons	5–10 meV	10 years HL-LHC equivalent	No evidence for ageing
Gamma (^{60}Co)	1.17 & 1.33 MeV	10 years HL-LHC equivalent	No evidence for ageing
Alpha particles in gas	5.64 MeV	5 x 10^8 sparks equivalent	No evidence for ageing

- Extensive tests at CEA Saclay with two almost identical 10 x 10 cm^2 resistive MMs (R17a,b; one irradiated, one used as reference)
- No significant difference between irradiated and non-irradiated detector observed
- Plans: large-area exposure in GIF++

Conclusion on resistive MMs by 2012

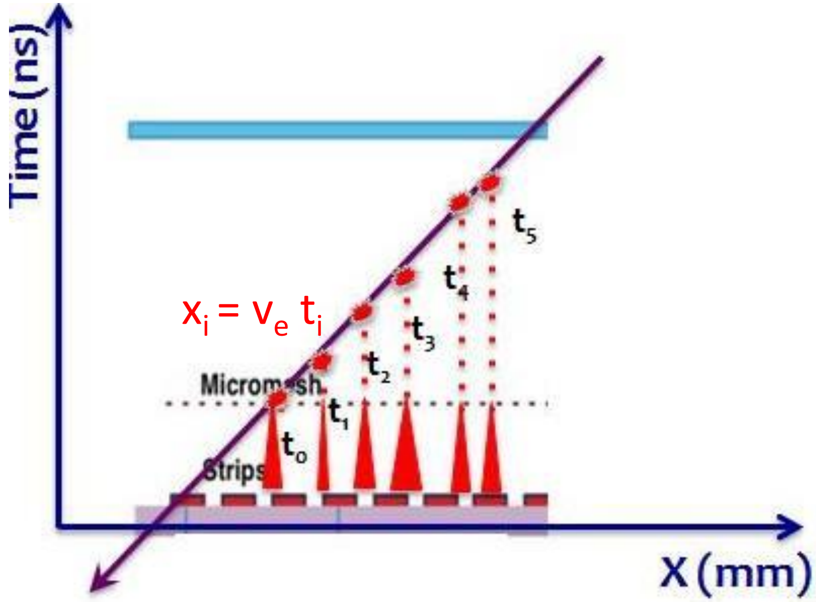
- The addition of the spark protection layer solves the spark problem
- Resistive-strip MMs show the same excellent performance as standard MMs
- No signs of ageing have been observed for exposures equivalent to 10 years of HL-LHC operation
- A small double-gap MM operated stably in ATLAS at 150 kHz/cm^2 for a full year

Detector & performance optimization

2^{nd} coordinate

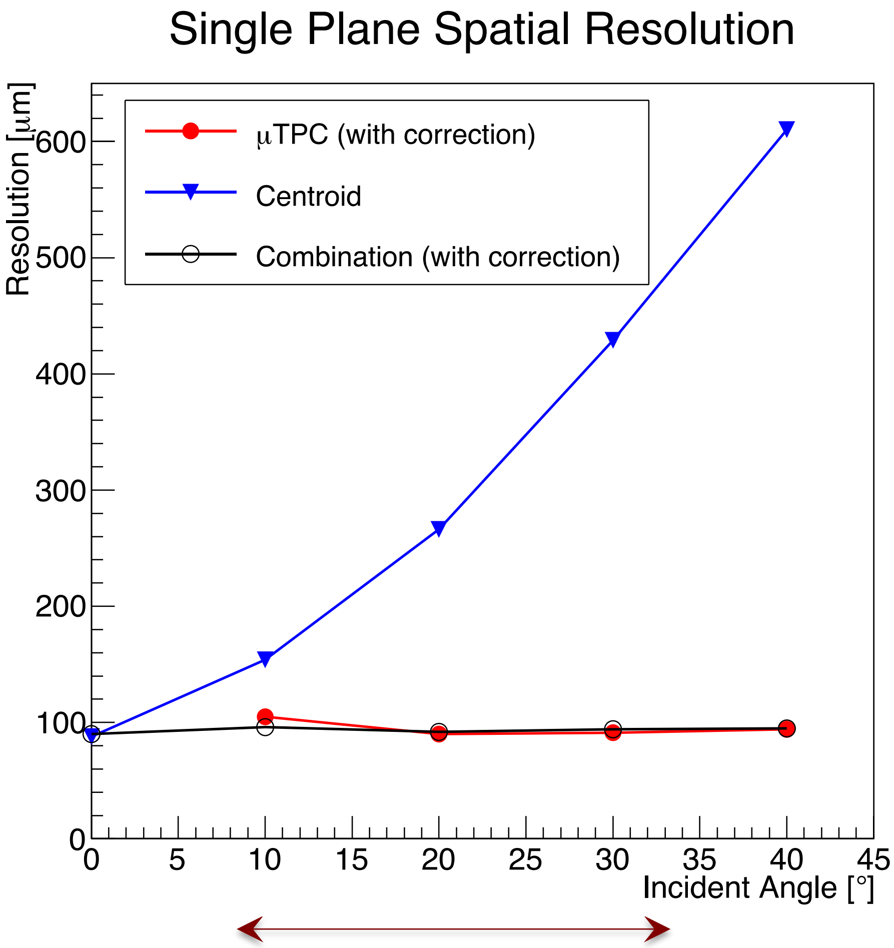
- Although 2D readout with resistive-strip MMs had been shown to work very well (this type of MMs is now a standard item of the CERN PCB workshop) we chose not to follow this road for the ATLAS NSW MM. We will use stereo strips instead.
  - Difficult geometry for x,y-strip connection routing without creating dead areas
  - Smaller strip (= electronics channel) count with stereo strips; symmetric small-angle stereo strips contribute also to the precision coordinate, with the same precision as eta strips
  - Larger signals (no charge sharing)
  - Smaller number of ghost hits (limited narrow bands)
- First implementation in MMSW chamber with ±1.5° stereo angle
  - Test beam results show a 2^{nd} coordinate spatial resolution of 2.2 mm (see talk in WG1).

Inclined tracks (µTPC mode)



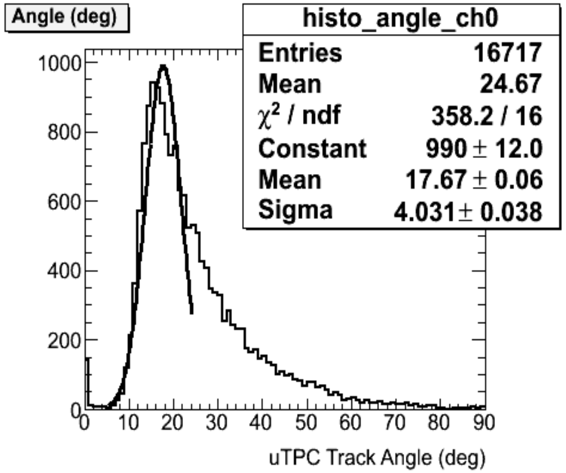
- Spatial resolution rapidly decreases for inclined tracks if the cluster centroid or charge weighting is used
- Measuring the arrival time of the signals opens a new dimension and the MM functions like a TPC

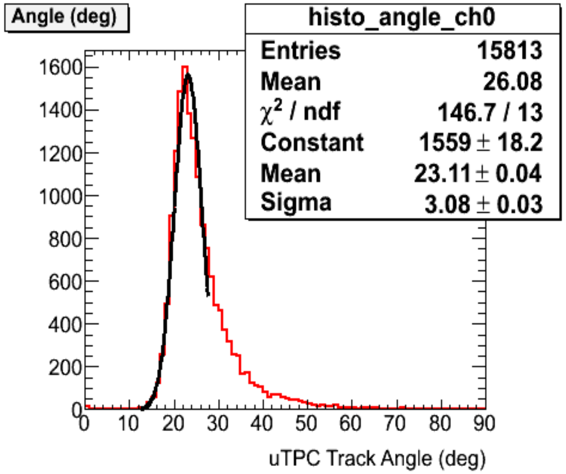
=> Track vectors for inclined tracks

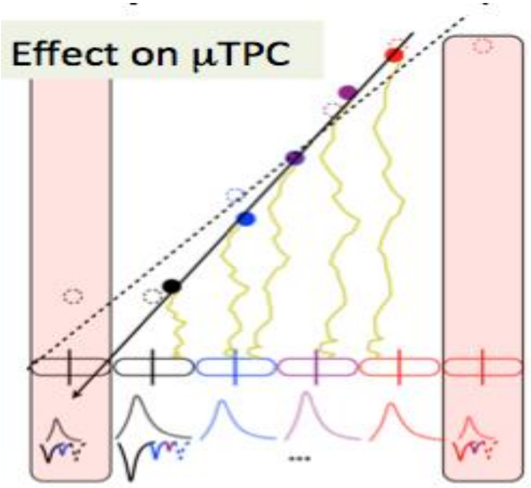


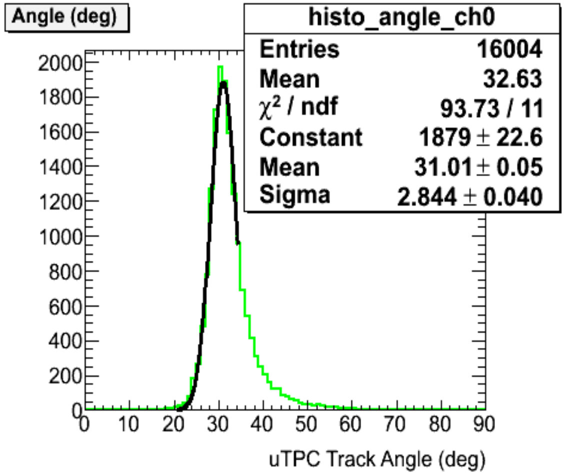
Range of track angles in NSW

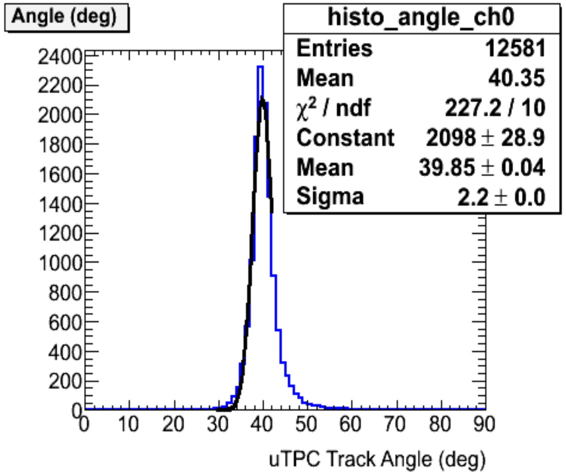
µTPC mode

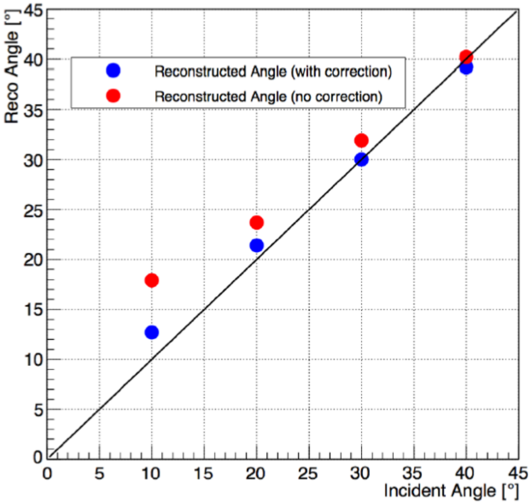

Angle (deg)
histo_angle_ch0
Entries 16717
Mean 24.67
χ^2 / ndf 358.2 / 16
Constant 990 ± 12.0
Mean 17.67 ± 0.06
Sigma 4.031 ± 0.038
0
200
400
600
800
1000
0 10 20 30 40 50 60 70 80 90
uTPC Track Angle (deg)


Angle (deg)
histo_angle_ch0
Entries 15813
Mean 26.08
χ^2 / ndf 146.7 / 13
Constant 1559 ± 18.2
Mean 23.11 ± 0.04
Sigma 3.08 ± 0.03
0
200
400
600
800
1000
1200
1400
1600
0 10 20 30 40 50 60 70 80 90
uTPC Track Angle (deg)


Effect on µTPC
...

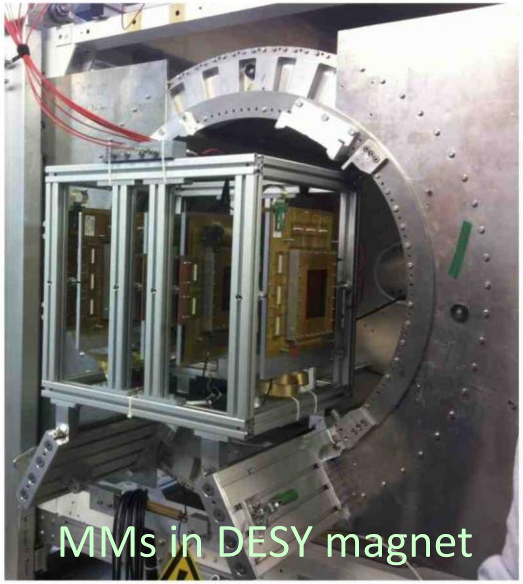

Angle (deg)
histo_angle_ch0
Entries 16004
Mean 32.63
χ^2 / ndf 93.73 / 11
Constant 1879 ± 22.6
Mean 31.01 ± 0.05
Sigma 2.844 ± 0.040
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0 10 20 30 40 50 60 70 80 90
uTPC Track Angle (deg)


Angle (deg)
histo_angle_ch0
Entries 12581
Mean 40.35
χ^2 / ndf 227.2 / 10
Constant 2098 ± 28.9
Mean 39.85 ± 0.04
Sigma 2.2 ± 0.0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
0 10 20 30 40 50 60 70 80 90
uTPC Track Angle (deg)


Reco Angle [°]
● Reconstructed Angle (with correction)
● Reconstructed Angle (no correction)
0
5
10
15
20
25
30
35
40
45
0 5 10 15 20 25 30 35 40 45
Incident Angle [°]

MMs in magnetic field

MMs in H2 magnet

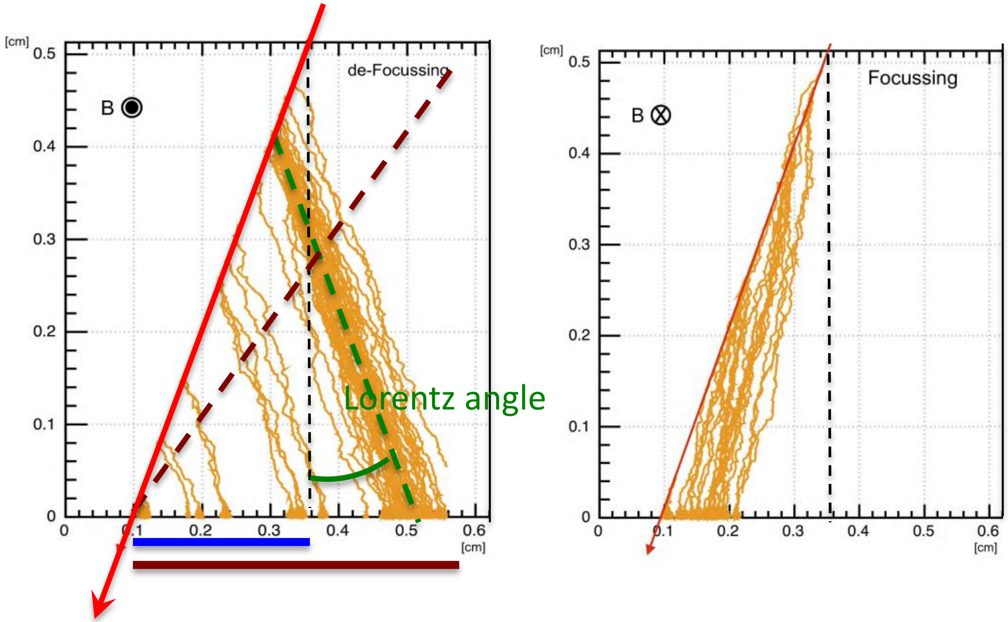


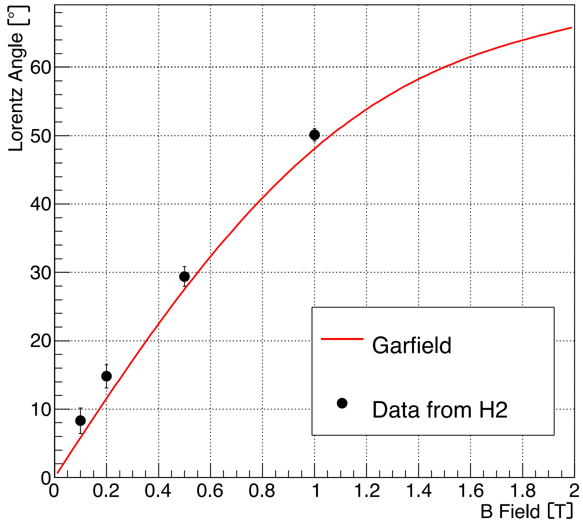
MMs in DESY magnet

Two test beam campaigns in magnetic field so far

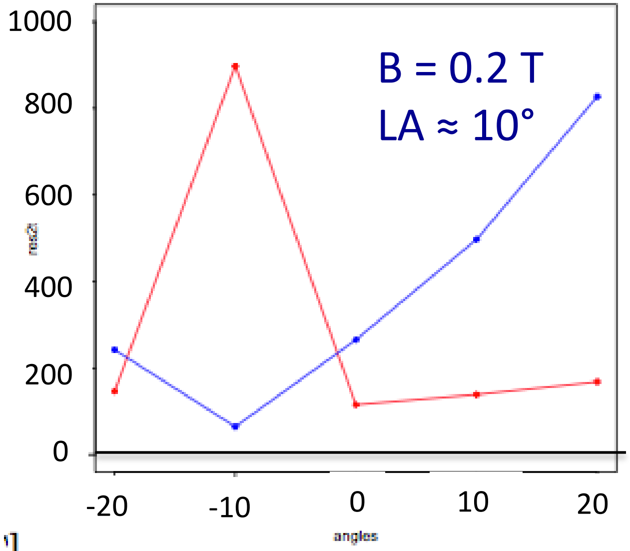
- 2012 in the H2 beam at CERN (120 GeV pions) showed
  - our MMs work well in magnetic field; measured up to 1 TeV
  - Our gas/operating point may not be optimal for magnetic field because of the large Lorentz angle
- 2013 at DESY (5 GeV electrons) consolidated the H2 results
- Nov/Dec 2014 next run in H4 in the Goliath magnet in the RD51 area

MMs in magnetic field II



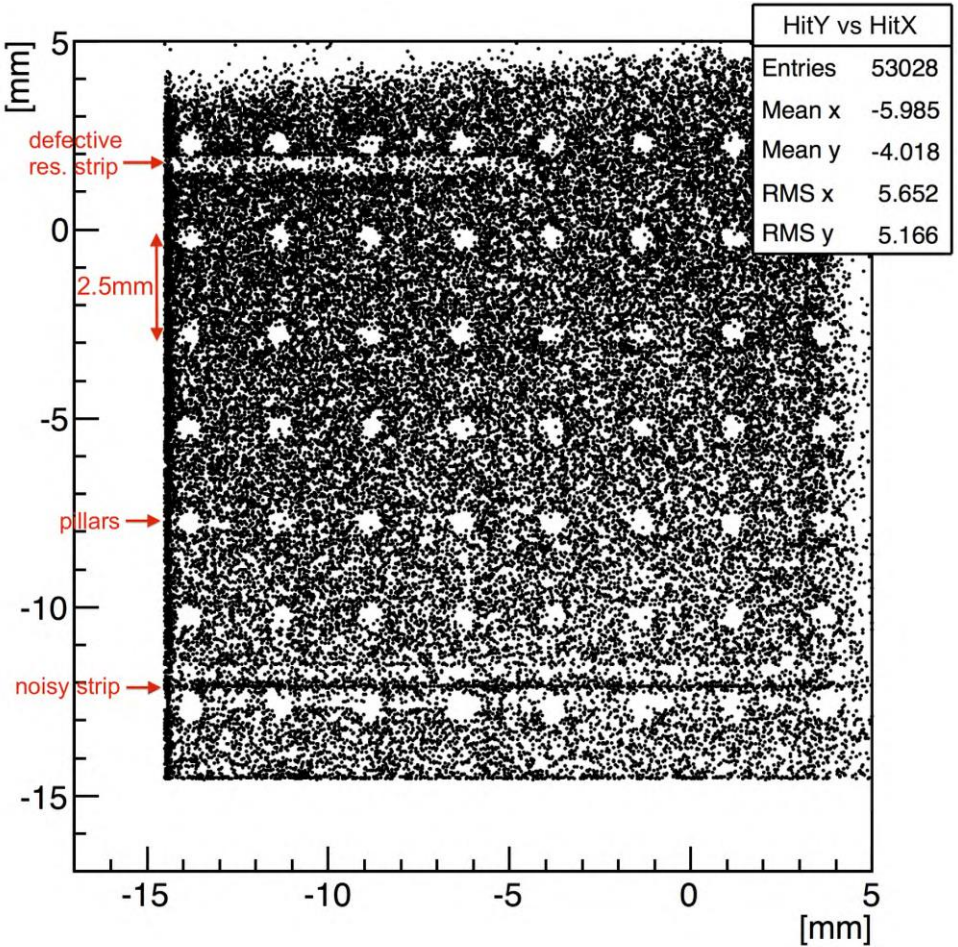


- Data and simulation agree well
- Lorentz angle (LA) is close to 30° for Ar:CO_2 (93:7) and B=0.5 T
- LA leads to bias in cluster position and width
- Position bias recovered by arranging MMs in back-to-back configuration
- Bias in cluster size creates singularities in µTPC reconstruction algorithm; recovered by combination of charge weighting and µTPC method

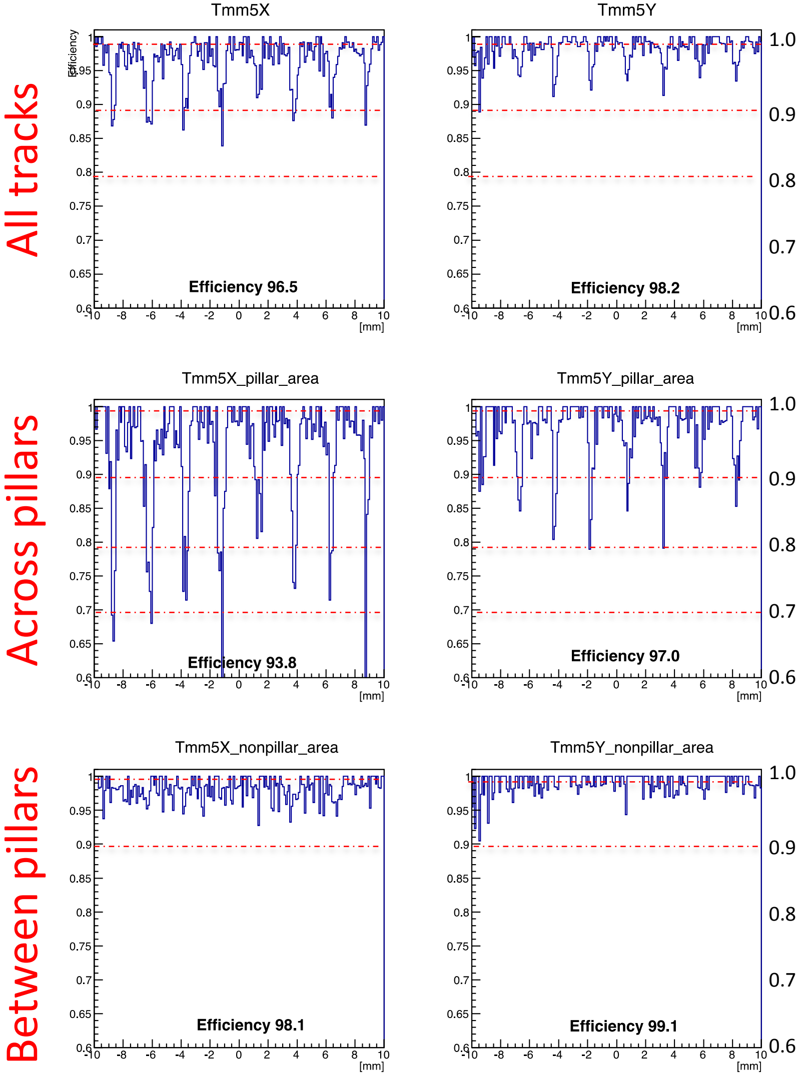


Some recent results from the analysis of high statistics test beam runs

Efficiency of Tmm5 in x and y

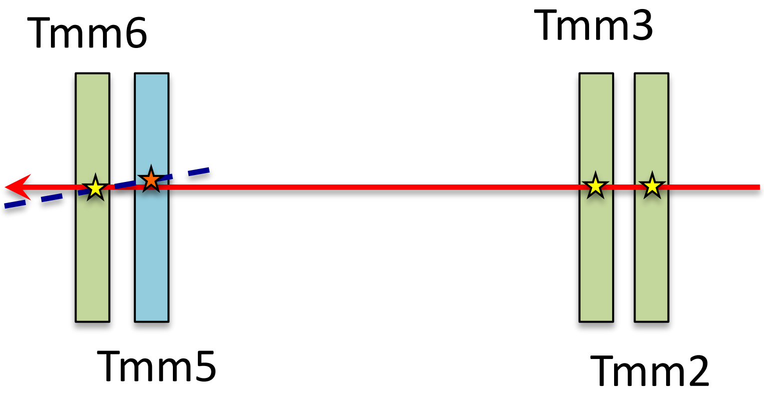


Radiography of (part of) a small 2D MM in the T10 beam

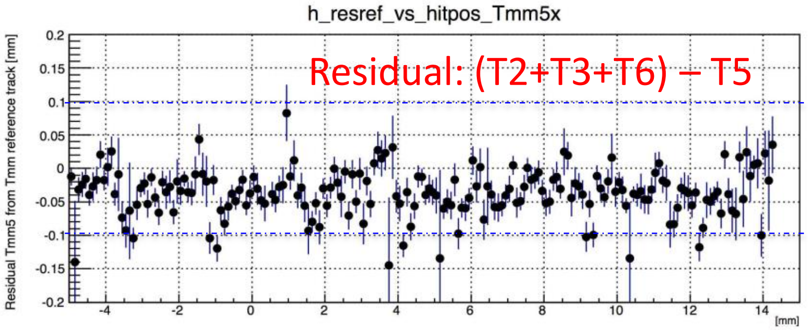


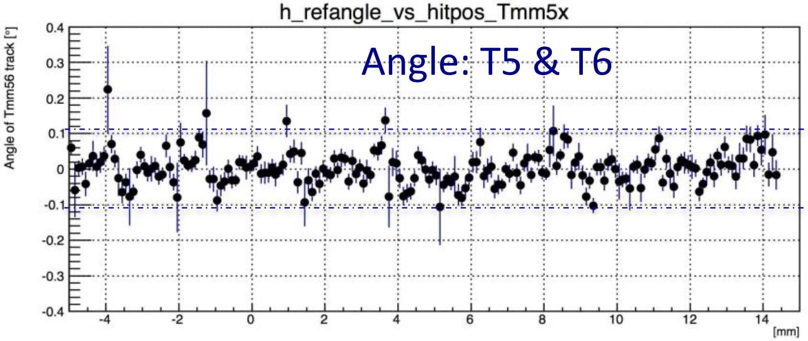
See simulation results in talk by Supratik M. in WG4

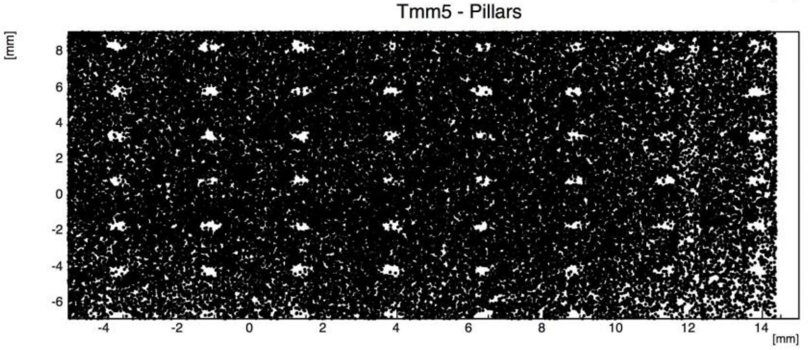
Effect of pillars on track reconstruction



- Results from T9 test beam (August 2014)
- High statistics data with 10 x 10 cm^2 MMs with 2D readout with 250 µm strip pitch (courtesy of E. Oliveira). Pillar distance: 2.5 mm
- Select single tracks events in band of pillars and look at cluster position residuals in one MM with respect to the track reconstructed in the other three MMs
- Look at reconstructed track angle using two close-by MMs







Conclusion

- Over the last seven years we learned
  - that MMs are very nice and robust detectors, no ageing observed
  - how to work with them
- We learned that MM need protection against sparks if operated in a high-rate LHC like environment and we found a solution
- We learned how to make large MMs of several m^2
  - We still have to learn how to assemble MM detectors in such a way that we do not need to open detectors too often
- We learned how to achieve the required track reconstruction precision using the µTPC mode
- What still needs to be done (apart from building the detectors) is to optimize the operating conditions for best performance in magnetic field, finding a compromise between stable operation, good gain, good mesh transparency, and small Lorentz angle.