UNI FREIBURG

The ATLAS New Small Wheel Upgrade Project

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ATLAS Collaboration

- Introduction: LHC and ATLAS Upgrade Program
- The Present Small Wheel Detectors
- Limitations at High Rate and Impact on Physics – Why a New Small Wheel ?
- New Small Wheel Chambers and Detector Technologies. Chamber Construction Challenges
- Alignment System, Mechanical Challenges
- Conclusion

Many thanks to all my colleagues who provided material !

ATLAS EXPERIMENT

ATLAS Upgrade Roadmap

The present ATLAS detector was designed for a nominal luminosity of 10^{34} s^{-1} cm^{-2} and a expected lifetime/period of operation of 10 years.

Discover of the Higgs particle in 2012:
LHC planned to run until at least 2028 – 2030, with a substantial luminosity upgrade: The High Luminosity LHC (HL-LHC)

European Strategy Update

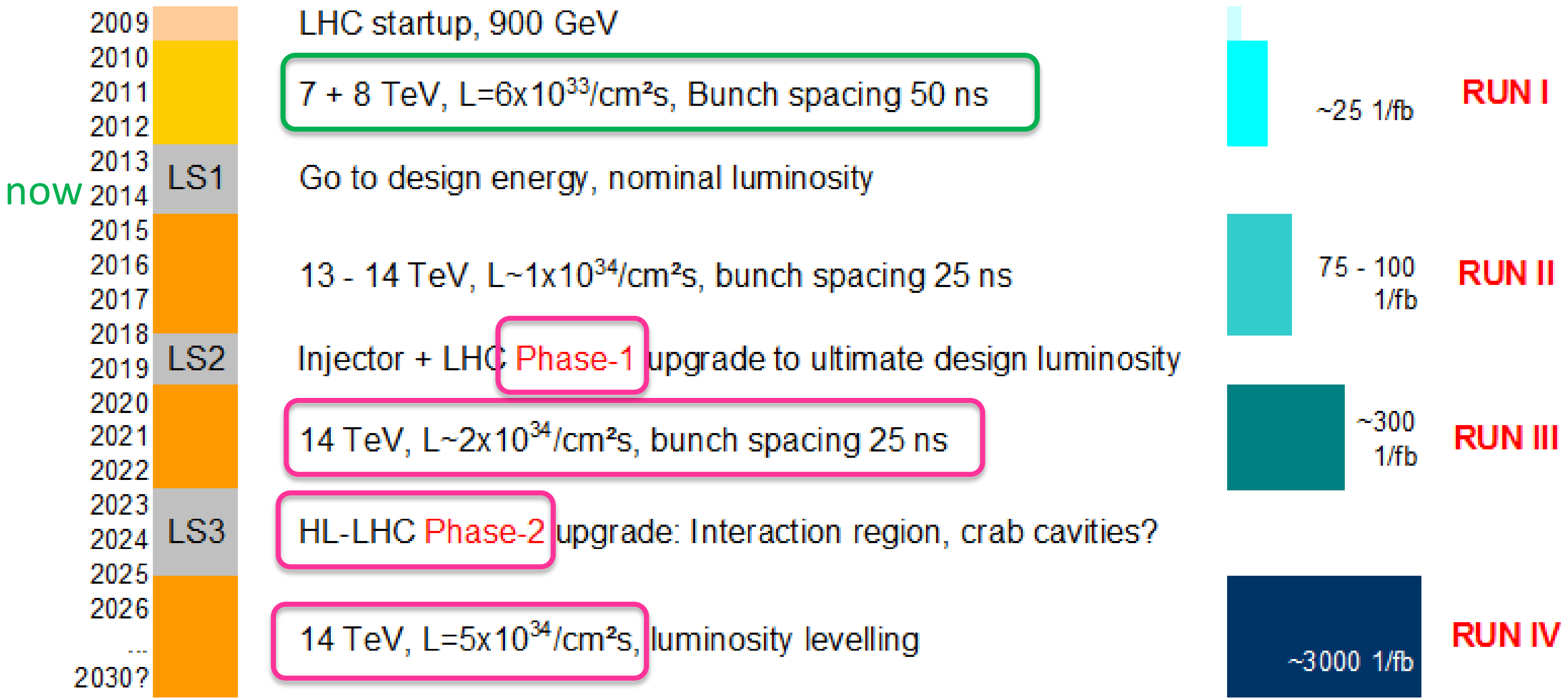
European Strategy for Particle Physics (autumn 2012)

"The discovery of the Higgs boson is the start of a major program of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this program."

High statistics

High accuracy

LHC and ATLAS Upgrade Roadmap

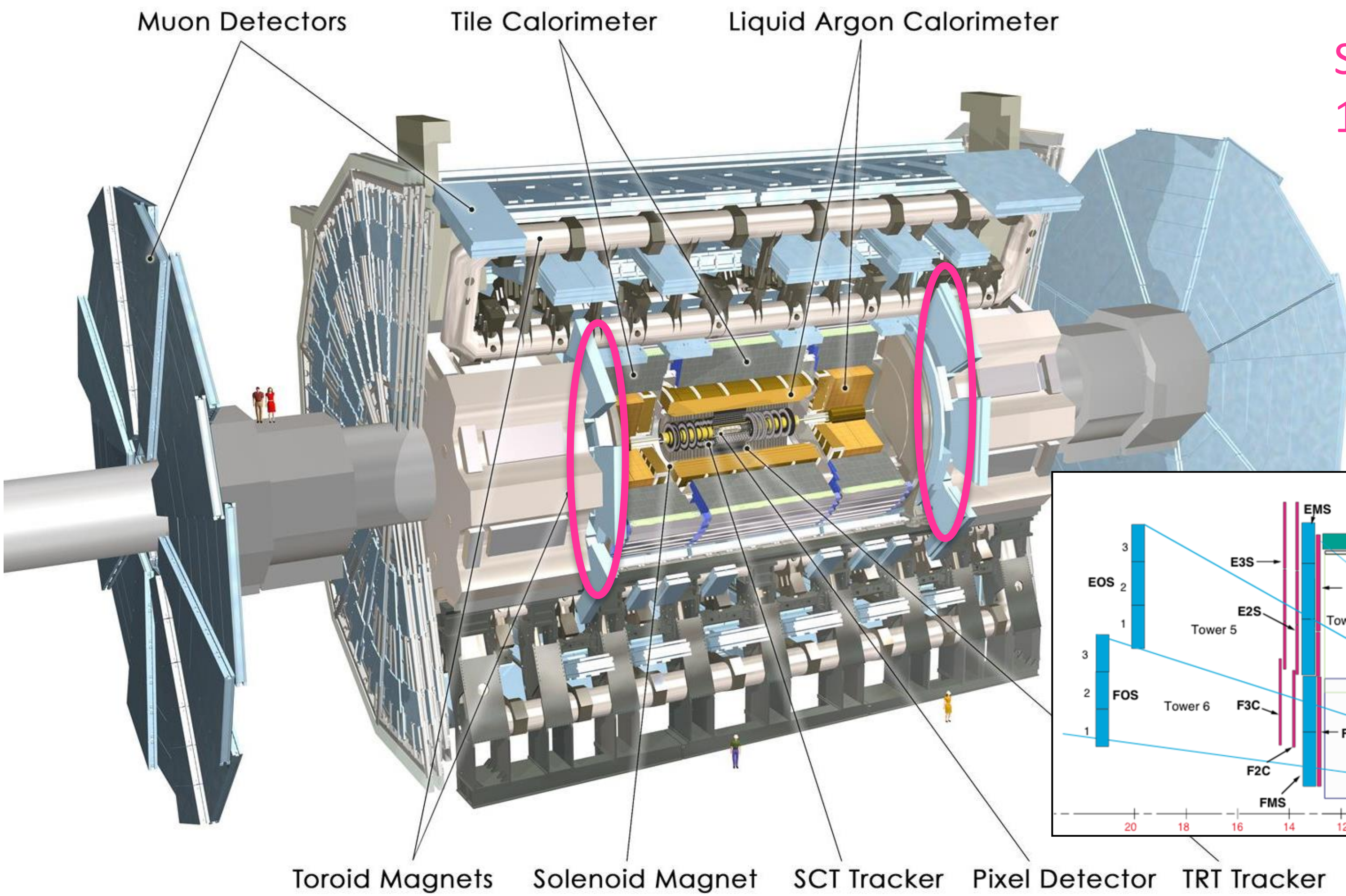


ATLAS:

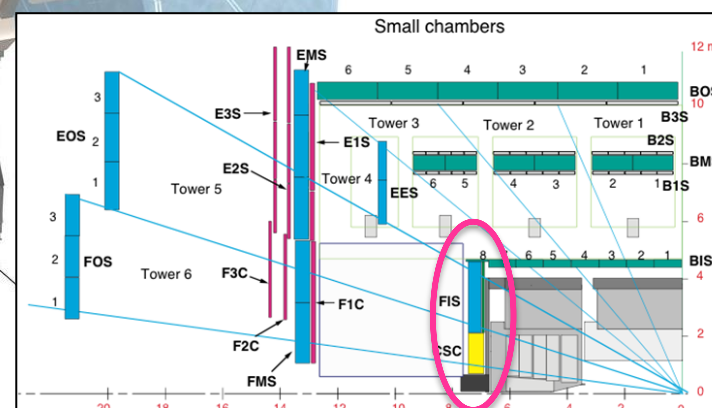
- Phase-0 Upgrade: Consolidation + Insertable B-Layer (IBL) in LS1
- Phase-1 Upgrade: New Small Wheels, LAR Calo + TDAQ upgrade, Fast Track Trig.
- Phase-2 Upgrade: New Inner Tracker

The ATLAS Detector – (New) Small Wheels

New Small Wheels will replace the present Innermost endcap station of the Muon Spectrometer



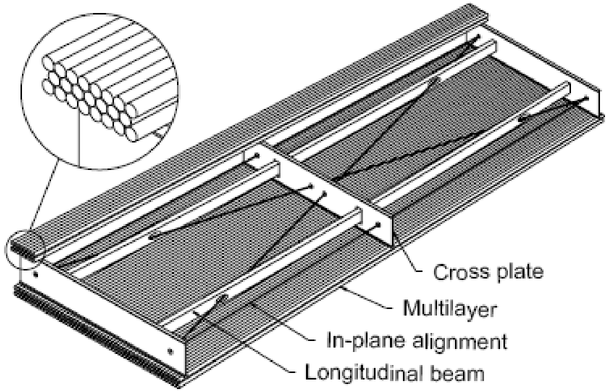
Small Wheels
10m ∅



Present Muon Detectors (Small Wheel)

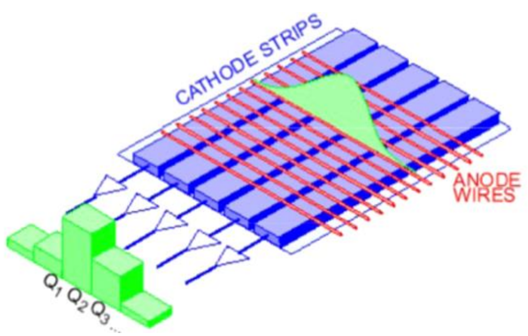
Present Muon Detectors (Small Wheel)

Present Muon Spectrometer Technologies: CSC, MDT (Tracking) RPC, TGC (Triggering)



Monitored Drift Tubes:

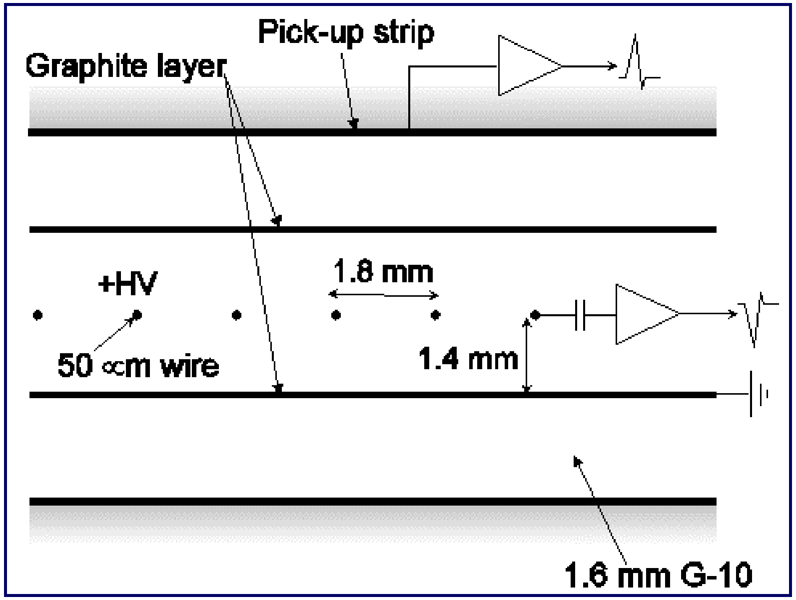
- gas filled with Ar:CO_2 @ 3bar abs
- 3 cm diameter
- tube resolution <= 80 µm, track resolution/station <= 50 µm
- Rate capability limited by 1 dimensional readout
- Optical rays for monitoring deformation and displacement



Cathode Strip Chambers:

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

Present Muon Detectors (Small Wheel)



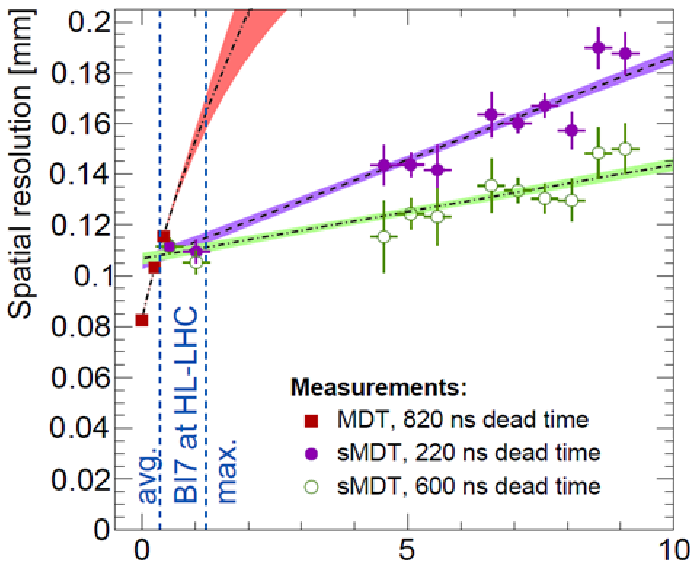
Thin Gap Chambers:

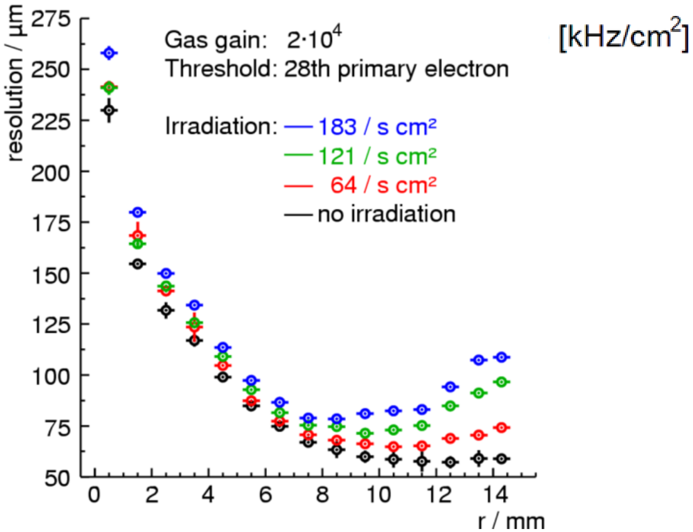
- Multi-Wire proportional chambers with very small gap size
- Cathode – wire distance smaller than distance between wires
- Operating gas: n-pentane + CO_2
- Operated in quasi saturated mode
- Fast readout, small intrinsic time jitter (<~ 1.5ns), high efficiency
- Provide also 2nd coordinate measurements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

Limitations at High Rate

Limitations at High Luminosity

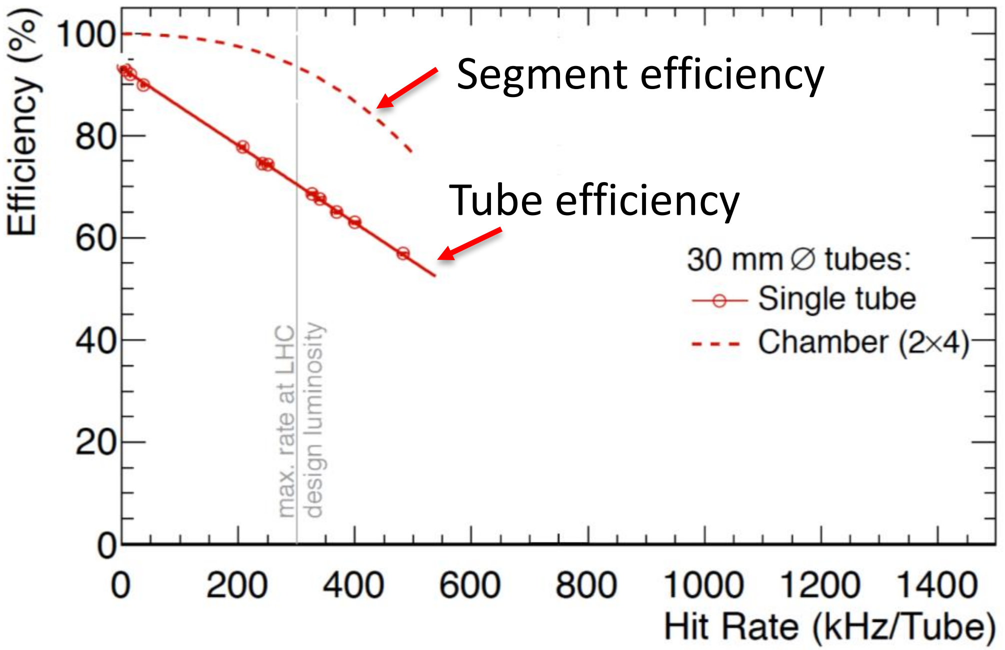
Resolution and efficiency degradation



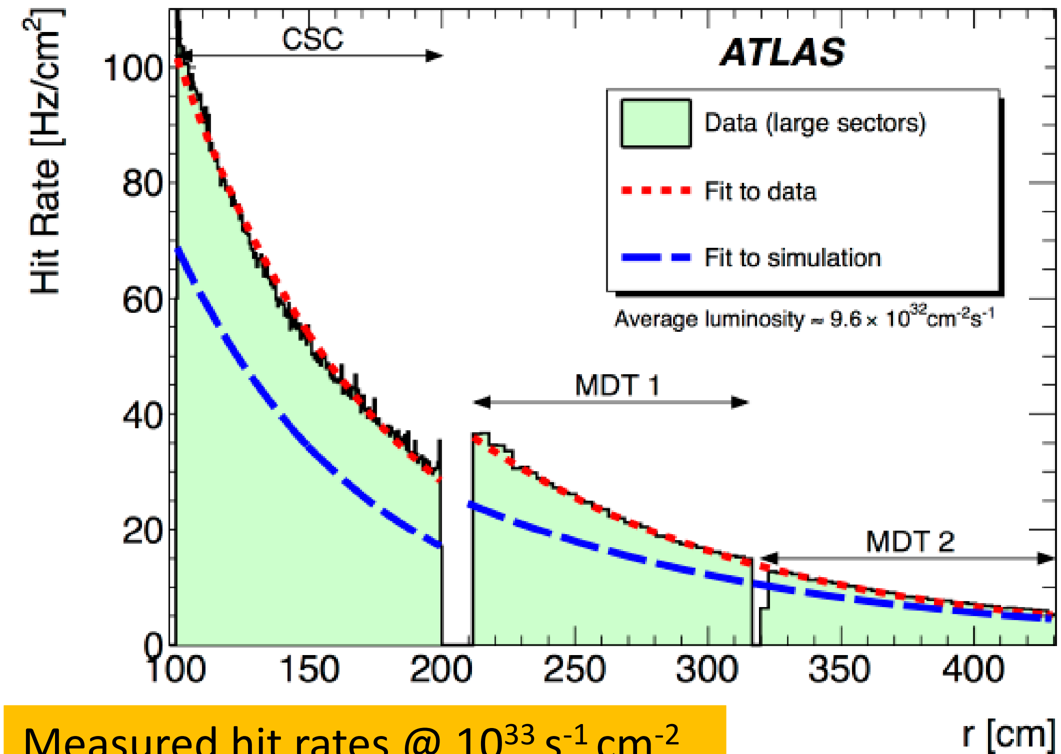


Rate limit of 3cm MDTs reached at ~300 kHz/tube

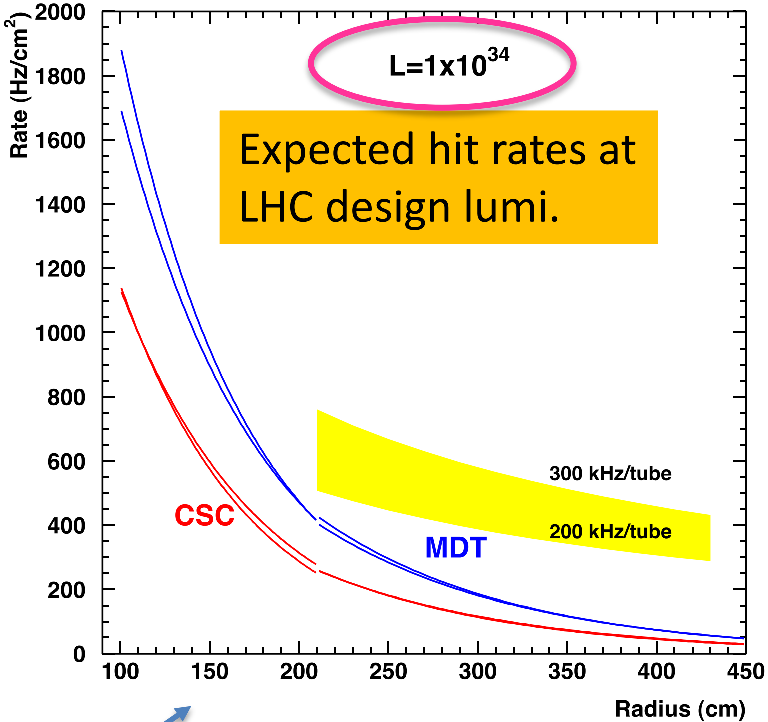
- Degradation of tube and segment efficiency, due to dead time from background hits
- Resolution degradation
  - Due to gain loss caused by space charge
  - Due to space charge fluctuations



Expected Rates at High Luminosity



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

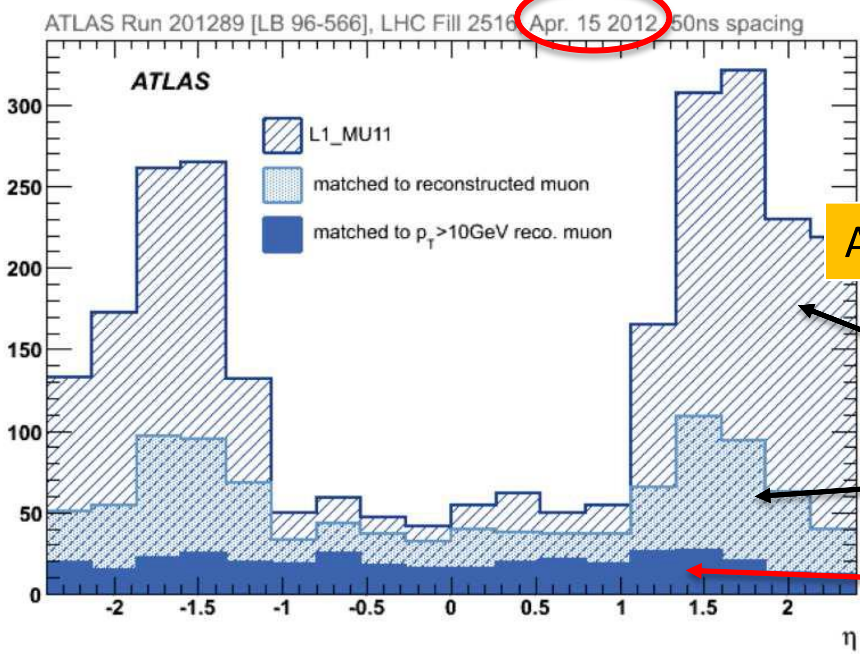


Expected hit rates at LHC design lumi.

- At luminosities exceeding ~ $2*10^{34}$ s^{-1} cm^{-2} and even more at HL-LHC rates ($5*10^{34}$ s^{-1} cm^{-2}) MDT rate limit is exceeded for a large part of the present Small Wheel
- Limit for CSCs is reached even earlier, due to only 4 detection layers (instead of 6 for MDT)

Limitations at High Luminosity

Fake single muon L1 trigger rate



Run-1 trigger status:

- Single muon L1 trigger rate dominated by fake events

Analyzing recorded hits offline

All L1_MU11 (p_t > 11 GeV) L1 triggers

Reconstructed tracks with p_t > 3 GeV

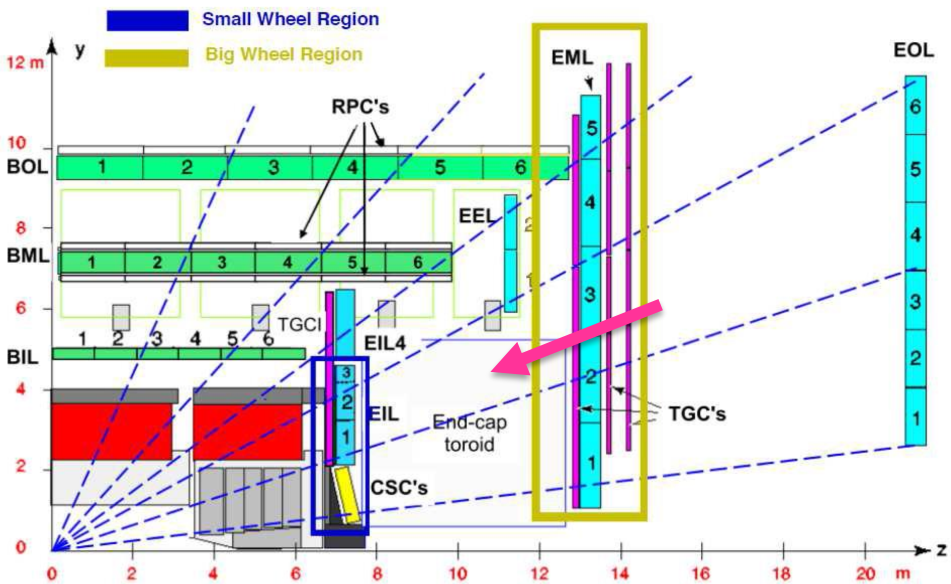
Reconstructed tracks with p_t > 10 GeV

L1 muon rates extrapolated to $3*10^{34}\ s^{-1}\ cm^{-2}$

LV1 single Muon threshold (GeV)	LV1 rate (kHz)
pT > 20 GeV	60 +- 11
pT > 40 GeV	29 +- 5

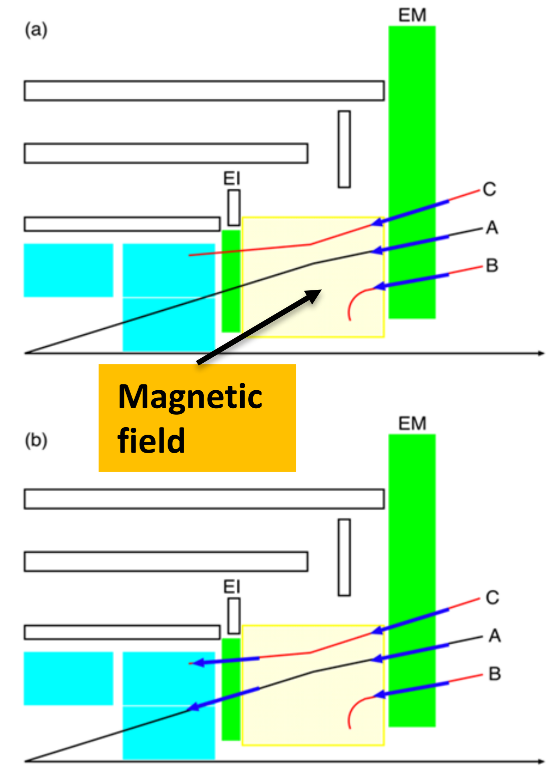
Fake track rate is ~9 times higher than true high-pt single muon tracks, well exceeding the available L1 rate budget of 20 kHz for single muon trigger !!

Cause of the fake L1_MU tracks



Present Muon L1 trigger in the endcap relies on the Big Wheel station (Endcap Middle, EM) only

- Calculating a track angle/vector and extrapolating to IP

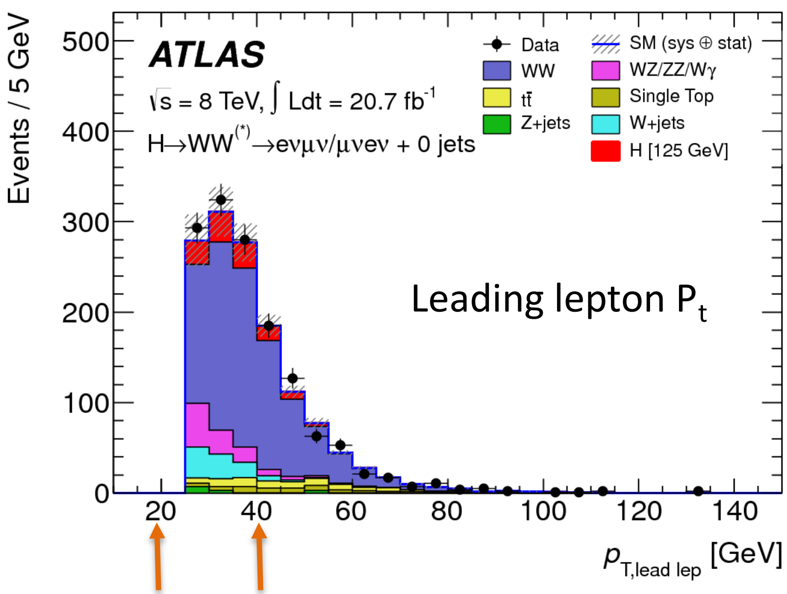


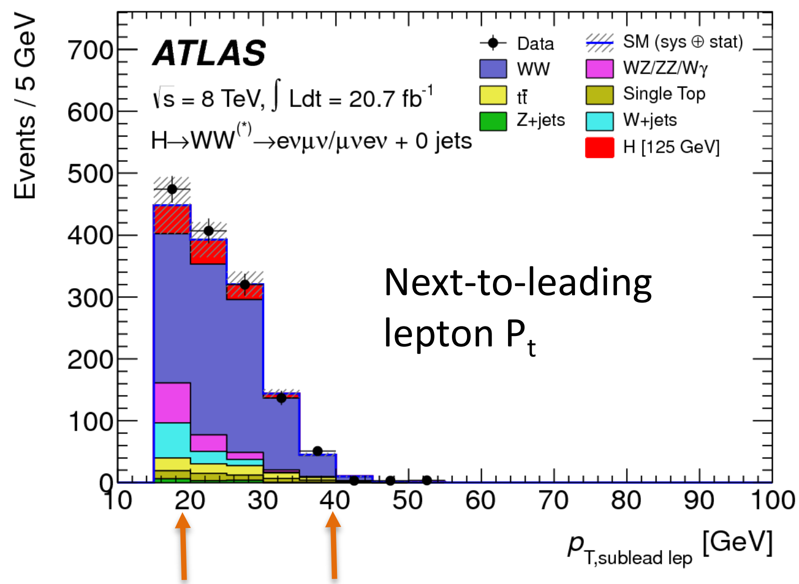
- Can not distinguish cases A (real high-pt track), B (low-pt particle created in the toroid area) and C (multiple scattering) in figure a)

- Can filter out fake tracks by being able to reconstruct track vector/direction also in the EI endcap inner station → New Small Wheel, extend L1 trigger coverage to η = 2.6 with angular resolution of 1 mrad

Importance of L1_MU rate and consequence of high fake rate

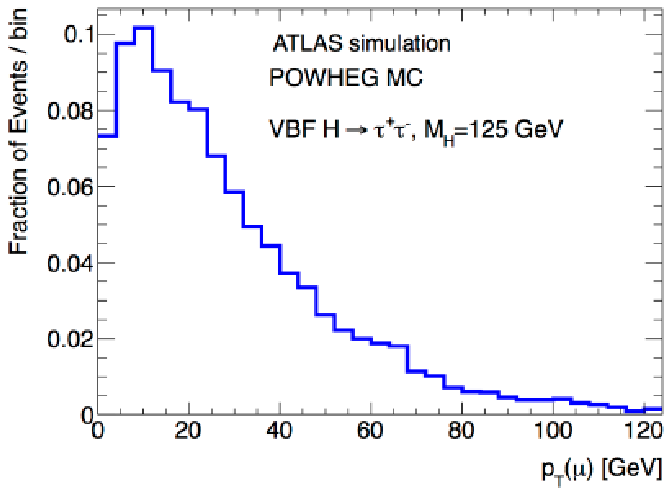
Losing low p_t single lepton trigger: Example Higgs production + leptonic decay

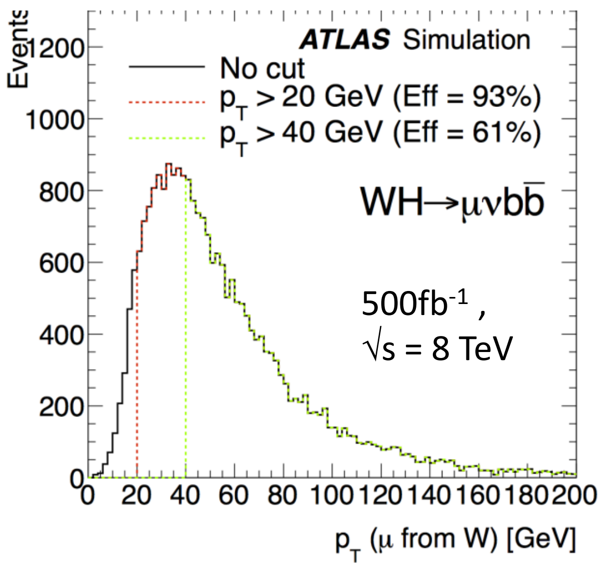




- Higgs production in pp collisions mainly from gg fusion → p_t of the Higgs relatively low
- Raising the pt threshold for single lepton from 20 to >= 40 GeV would lead to loss of most of the signal

Importance of L1_MU rate and consequence of high fake rate





- Few 100 fb^{-1} integrated luminosity: Sufficient statistics for VBF produced Higgs events despite low cross section.

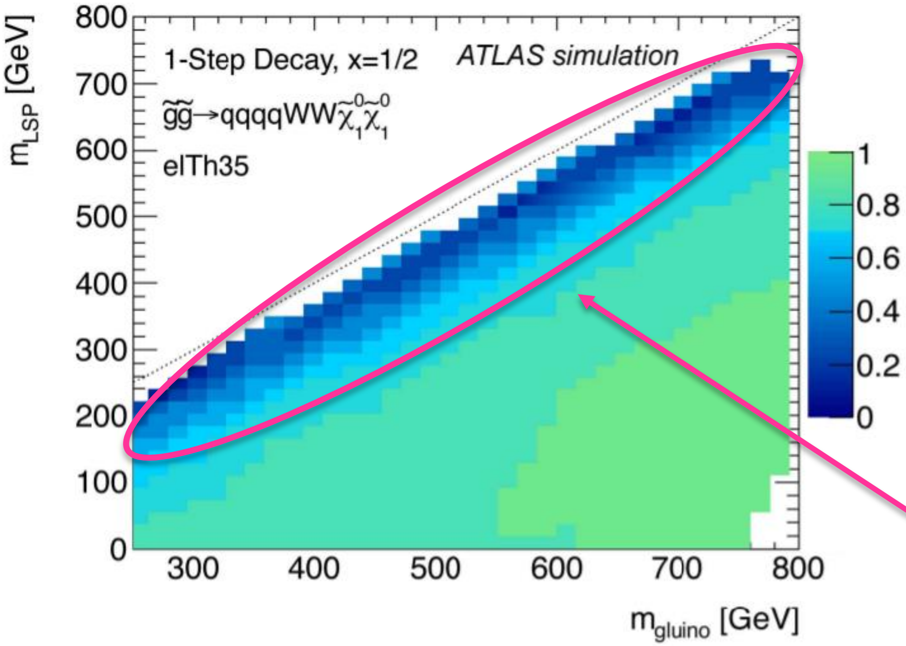
  Example H(VBF) → ττ (√s = 14 TeV): 60% of leading muons have pt > 25 GeV, whereas only 28% have >40 GeV

- Few 100 fb^{-1} integrated luminosity: Precise determination of Higgs couplings (to W,Z, fermions) using the production channels like Higgs-Strahlung from W: pp → WH
  - Use leptons from W decay as trigger
  - Spectrum, for WH → μνbb, harder than for inclusive H→ WW*, fraction of low-pt leptons nevertheless significant

Importance of L1_MU rate and consequence of high fake rate

- SUSY searches: Leptons in many cases produced through cascade decays, with kinematic distribution of the final particles depending on the mass relation of the particles in the decay and the couplings

→ Raising the p_t threshold for single leptons (as well as for jets, $E_{T,miss}$) results in a reduction in sensitivity and accessible parameter space of SUSY/BDSM models …



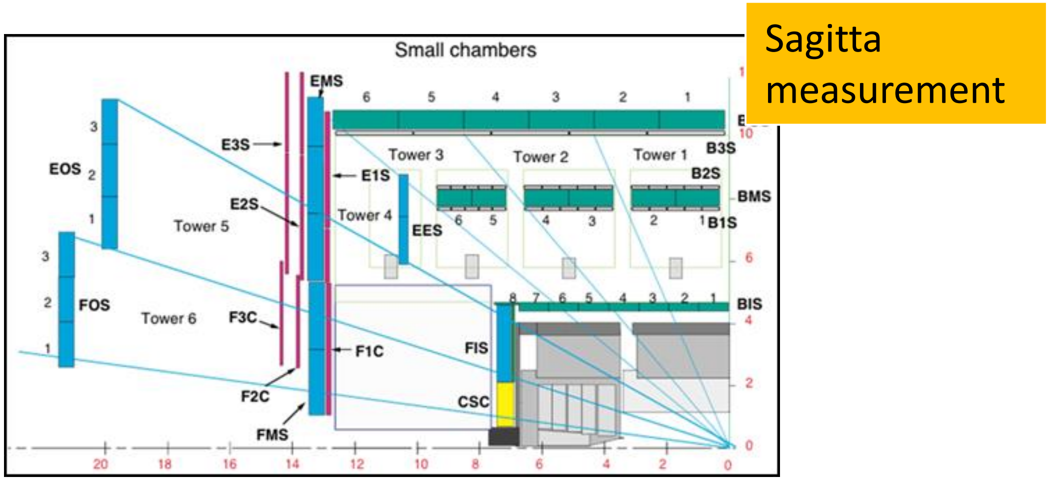
Sensitivity ration between 35 and 25 GeV lepton pt- threshold for a example SUSY decay chain

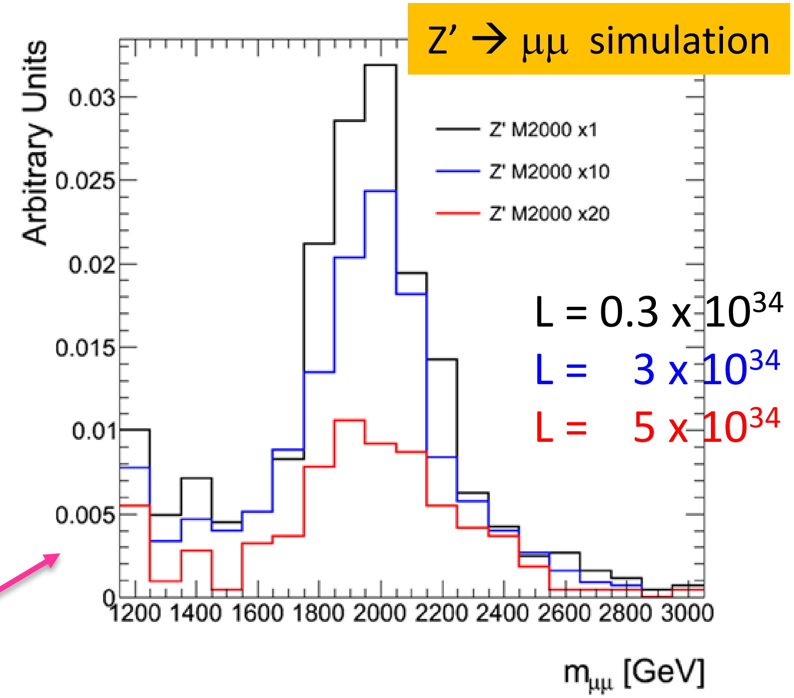
Sensitivity mostly lost for 35 GeV instead of 25 GeV threshold …

Importance of high-quality tracking

Degradation in tracking efficiency and resolution is most relevant for high p_t muons (> 100 GeV):

- Momentum resolution in this range primarily determined by the Muon Spectrometer
- Precise measurement of the muon momentum requires track segments to be present in all 3 Muon stations to allow a sagitta measurements
- Impact of reduced efficiency in particular for searches for high mass Z', W', also for the pseudo-scalar Higgs in super-symmetric models, decaying into muons





Simulated events in the Small Wheel using the over-lay technique to extrapolate from measured data: Loss in Z' reconstruction efficiency clearly visible !

Specifications and Requirements of the New Small Wheels

- 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

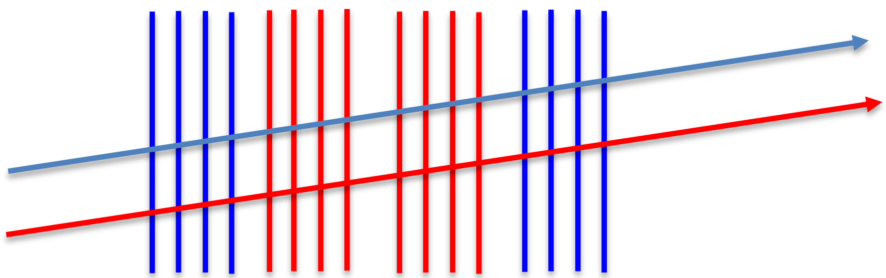
Momentum resolution:	better than 15 % up to p_t = 1 TeV
Single plane resolution:	100µm, independent from track angle
Track segment reconstruction:	50 µm
Track segment efficiency:	>= 97% @ p_t > 10 GeV
Online angular resolution (trig):	<= 1 mrad
Spatial resolution 2nd coordinate:	~cm, from stereo strips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

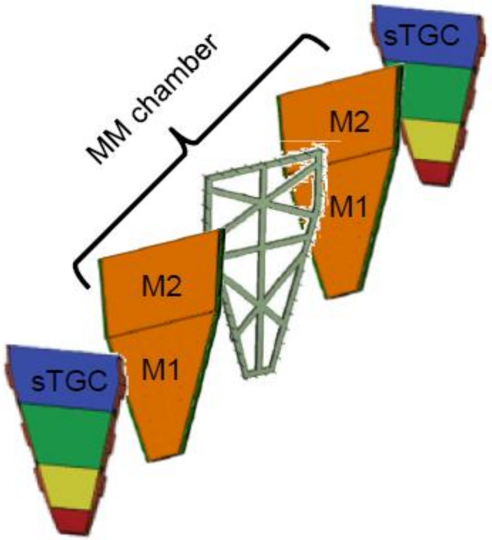
Performance

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

New Small Wheels: Detectors

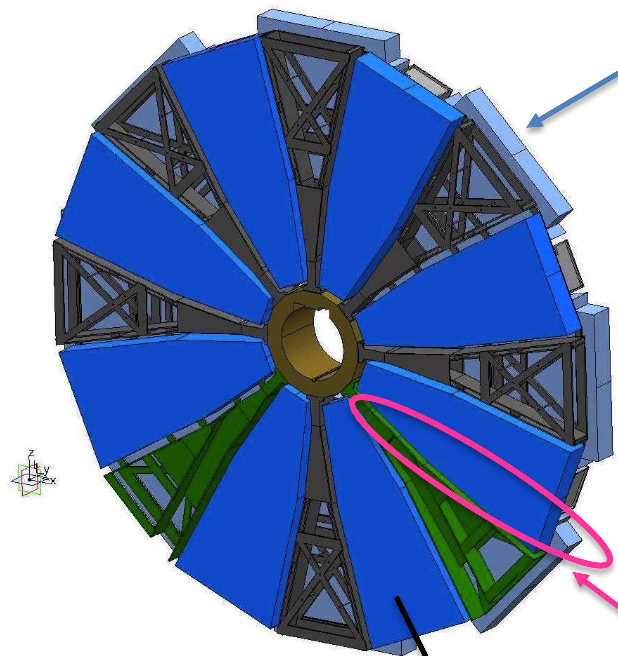
- 2 detector technologies for NSW chambers: small strip Thin Gap Chambers (sTGC) and MicroMegas (MM)
- 4 + 4 + 4 + 4 detection planes





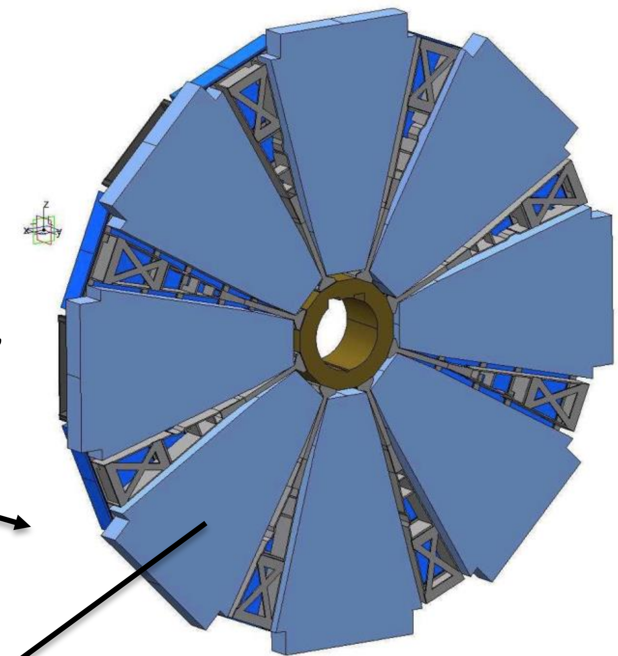
- sTGC – Primary trigger detector
  - Outside → longer lever arm
  - Track vector with angular resolution < 1 mrad
  - Good space resolution --- contribute to resolution offline track reconstruction, redundant tracking
- MM – Primary tracking detector
  - 500 µm strip pitch – very good position resolution of 100 µm independent of track angle, excellent track separation capabilities
  - Provide independent track vector – redundant triggering

New Small Wheels: Layout



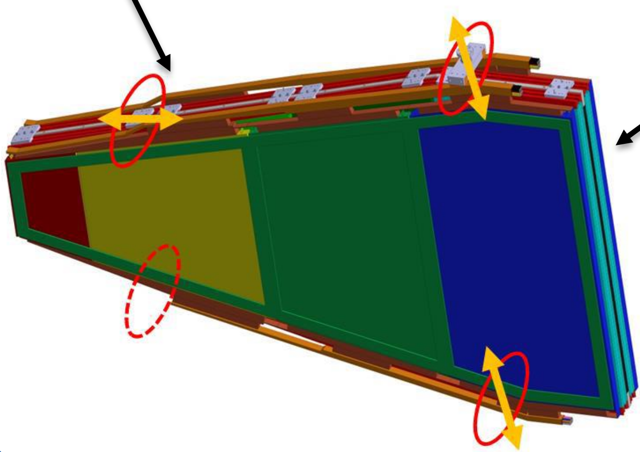
IP side: Small sectors, covering area from r = 90 cm to 445 cm from the IP

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



(Chamber segmentation not shown)

Overlap between Small and Large sectors !

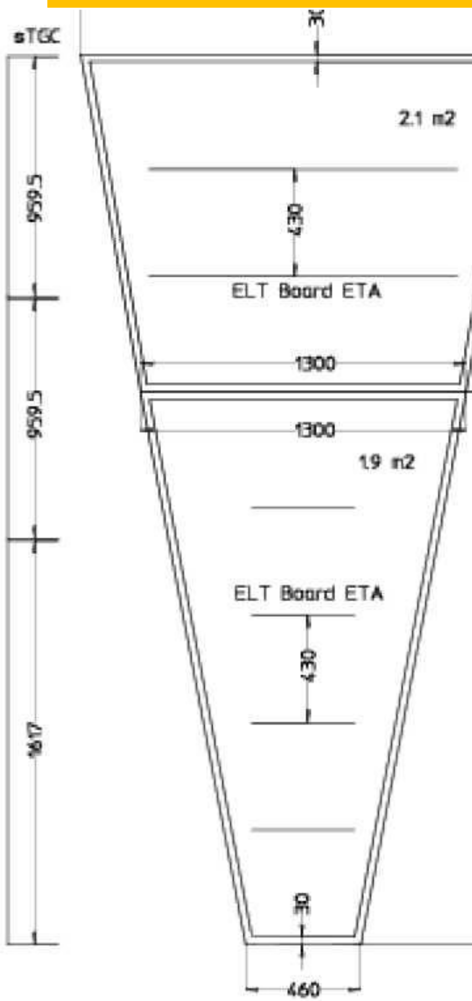


Sectors: Package of sTGC and MicroMegas “wedges” + central spacer frame

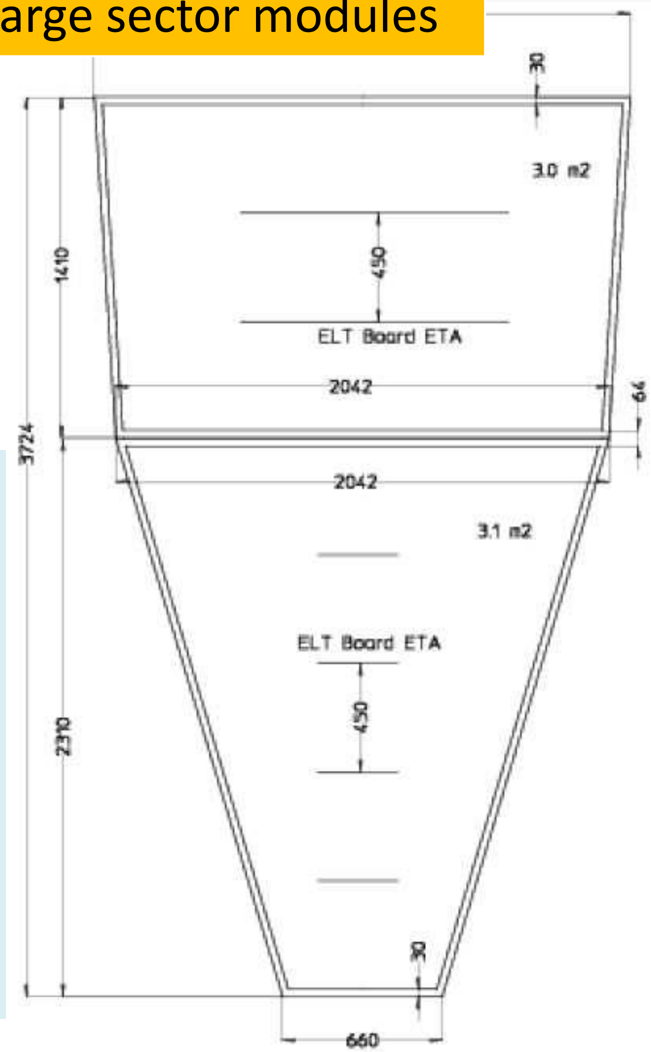
New Small Wheels: Layout

Wedge Segmentation – MicroMegas:

Small sector modules



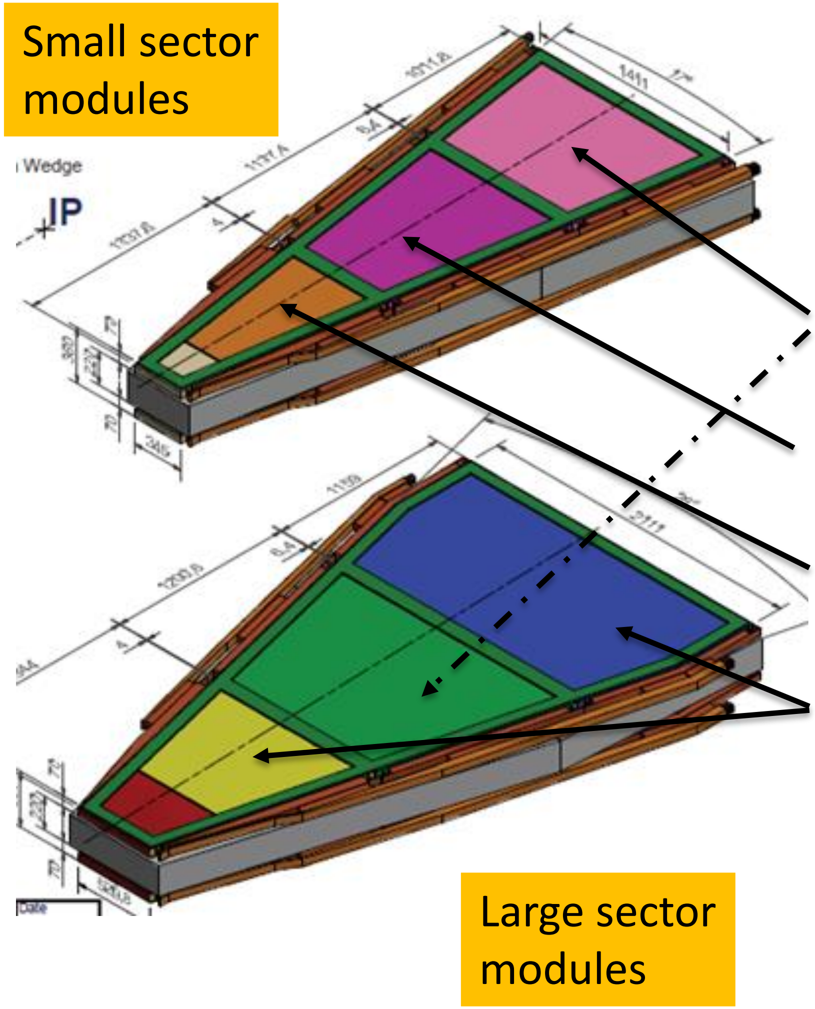
Large sector modules



- Radial segmentation in 2 chambers per wedge – decided based on handability
- SM1: Italy/INFN
- SM2: Germany – Munich, Freiburg, Wurzburg, Mainz
- LM1: Saclay
- LM2: Thessaloniki + Dubna

New Small Wheels: Layout

Wedge Segmentation – sTGC:



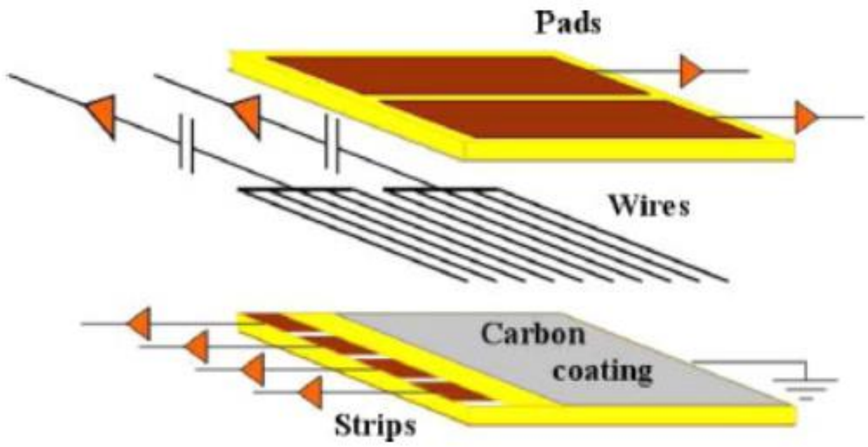
Radial segmentation in 3 modules per wedge

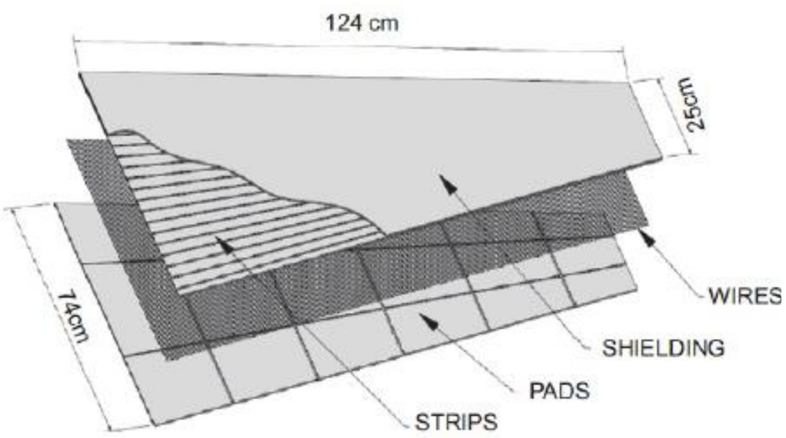
Construction sites:

- Canada (TRIUMF, Carleton, McGill clusters)
- China (Shandong)
- Chile (PUC Santiago, Valparaiso)
- Israel (Weizmann, Tel Aviv, Technion)

NSW Detector Chambers

sTGC: Principle of Operation





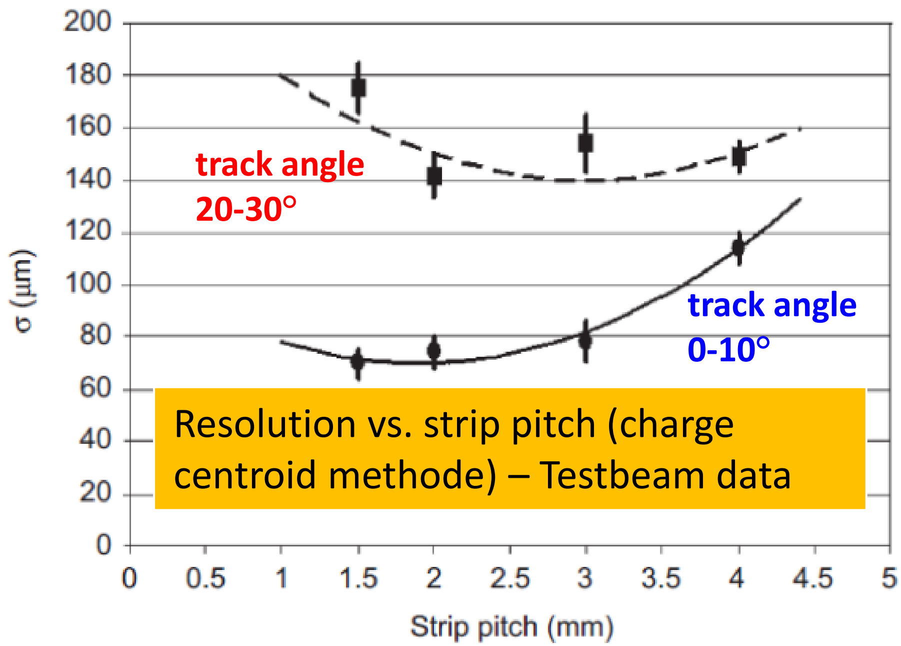
- 50µm gold-plates tungsten wires, spaced 1.8mm apart,
- Wires sandwiched between 2 cathode planes 1.4 mm from the wires
- Cathode surface resistivity 100 kΩ/m^2 reached by graphite coating
- Strip or pad layer, strip pitch: 3.2 mm (much smaller than previous TGCs → sTGC)

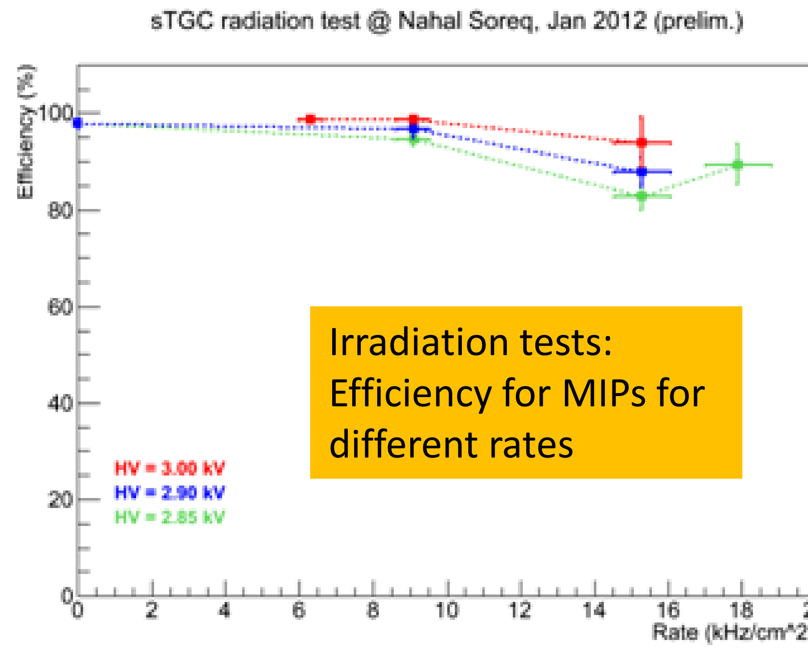
- Trigger: Coincidence of pad signals define Region of Interests (RoI), selected strip information sent to trigger processor for precision position calculation

- Track position reconstruction from strip charge centroid, 2nd coordinate from wire readout

sTGC: Performance

- Space charge itself is not a limiting factor for TGC chambers due to the small gap size and the quasi saturated operation mode;
- Limitations stem from the resistive coating of the cathode for large area detectors for locations far away from the GND contact: reduction of the effective operating voltage → lower resistivity was a main focus of the sTGC R&D

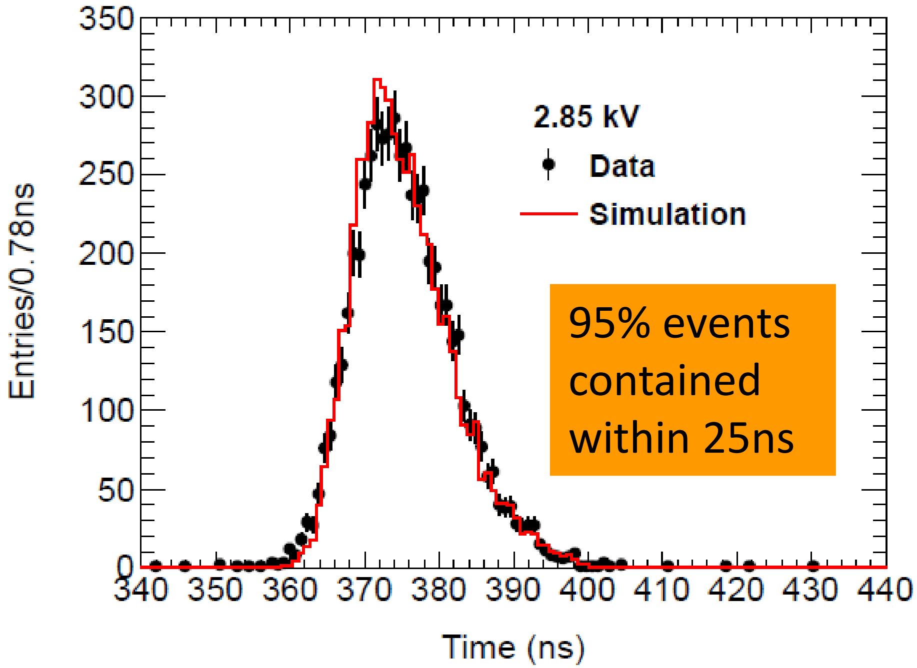




Resolution of 60µm for perpendicular, ~140µm for tracks inclined by 30° achieved with 3.2 mm strip pitch. Single plane eff. essentially unaffected until 17kHz/cm^2

sTGC: Performance

Cluster signal arrival time



95% events contained within 25ns

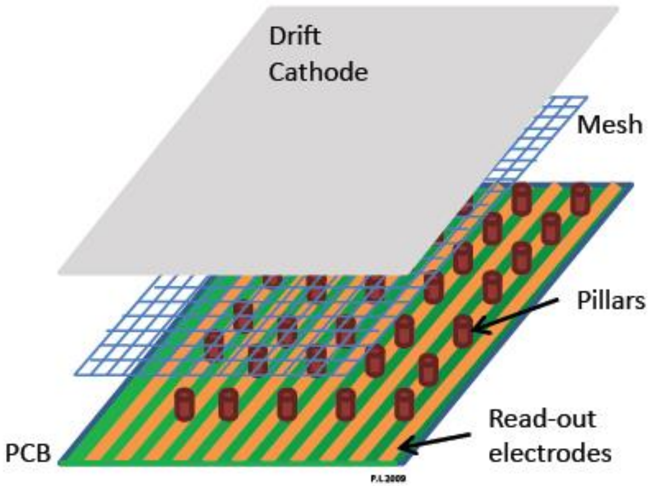
Small sTGC gas gap and strong electric drift field ensure good timing properties:

- Drift time for most electrons < 25ns
- High gas amplification ensures high efficiency even for single clusters

Ok for BCID identification (Pad coincidence logic)

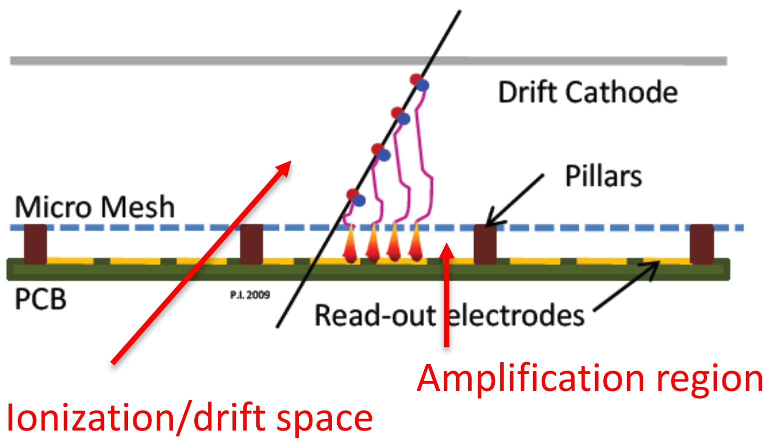
Note: Also require fast strip charge centroid information for online precision position determination
→ Conventional ADCs to slow, resolved by the custom VMM frontend ADC which implements a Flash ADC for transmitting of the pulse charge to the the centroid finder (trigger processor)

MM: Principle of Operation



Micro-Mesh Gaseous Detectors:

- Planar geometry
- Simple components: cathode, readout PCBs, mesh
- Large area can be achieved fairly simply and with rel. cheap cost
- Industrialization (PCB fabrication)
- Excellent high rate capability



- Small amplification gap (100 – 150 µm) → space charge effects very limited
- Segmentation of readout strips → limit “dead” time

NSW MicroMegas

Weak point of classical MicroMegas: vulnerability to sparking when number of electrons in the avalanche reaches few 10^7 electrons

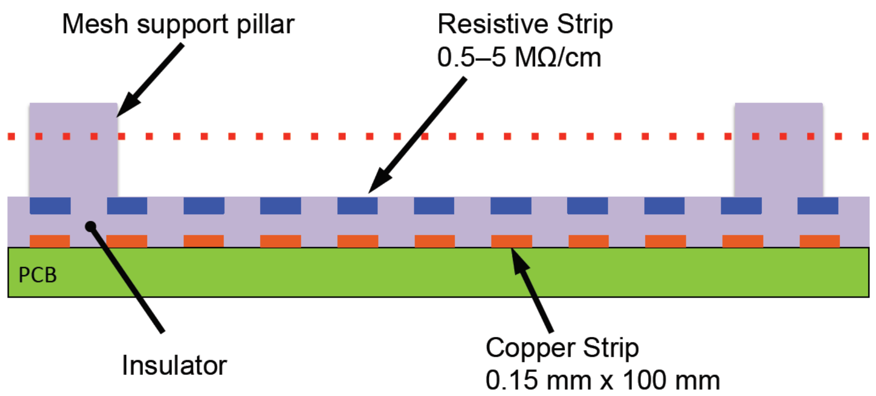
→ Large deadtime (HV break down)

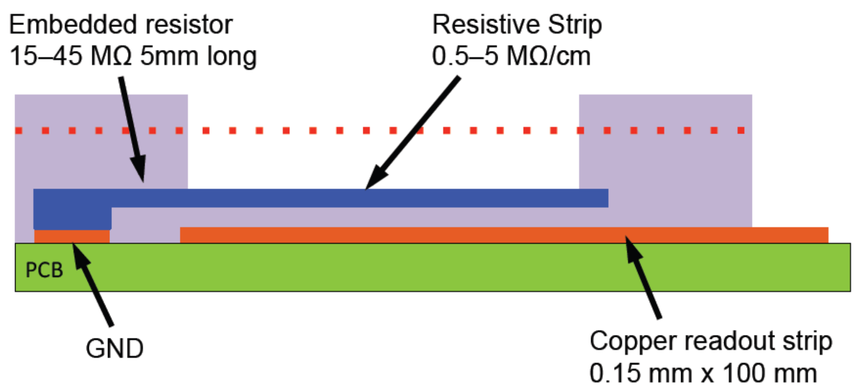
→ Potential risk of damage to the detector and/or readout electronics

NSW MicroMegas: Resistive strip layer added on top of readout strips, separated by a thin insulation layer

- Signals capacitively coupled to readout strips
- Small fraction of the signal height lost
- Can operate chamber at higher gain since readout electrodes are protected

→ Reduction in spark intensity by 3 orders of magnitude !

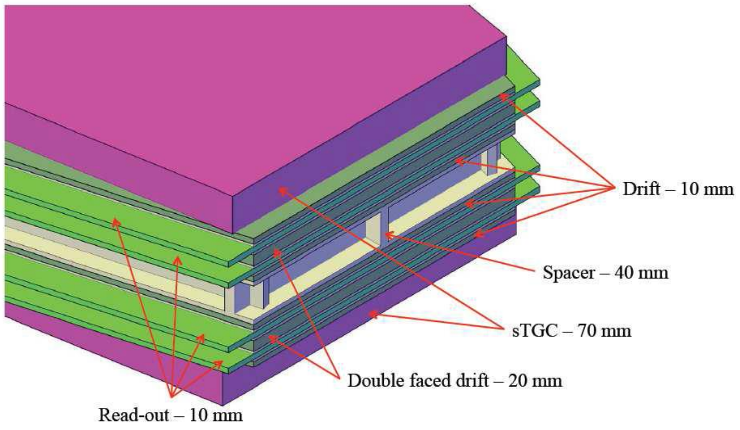




NSW MicroMegas

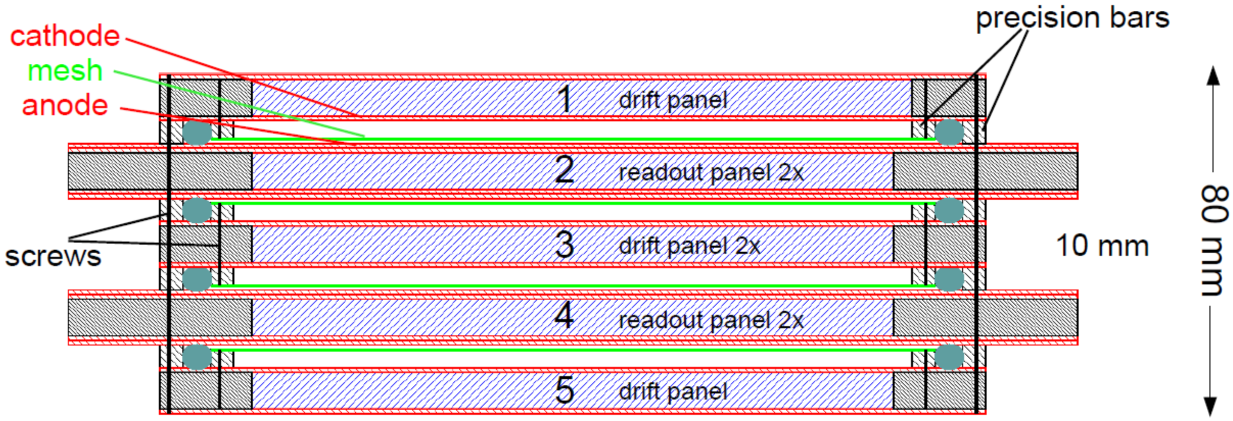
Characteristics & operating parameters:

- Operating gas: Ar:CO_2
- Drift gap: 5 mm
- HV (resistive strips): 550 V (GND on mesh)
- Drift field: 600 V/cm



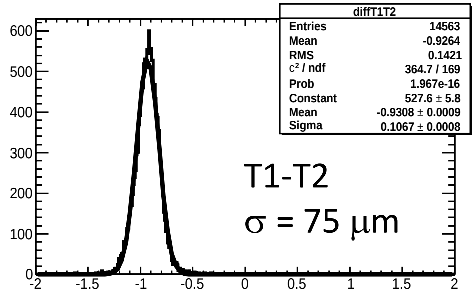
Per quadruplet:

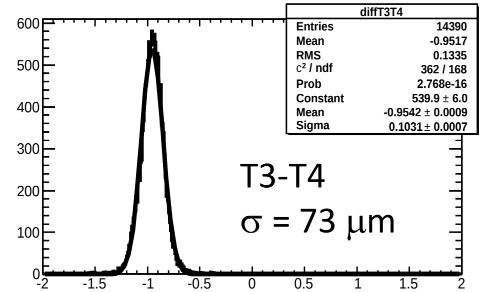
- 4 drift gaps, symmetric configuration to compensate forces from mesh tension
- 2 layers eta strips
- 2 layers stereo strips (rotated by 1.5°)
- Required mechanical precision: 40µm

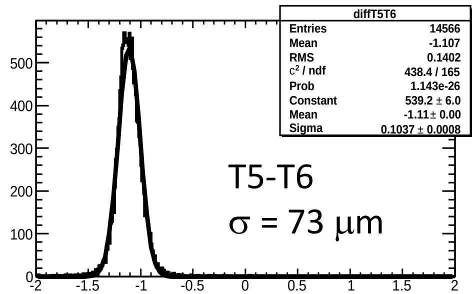


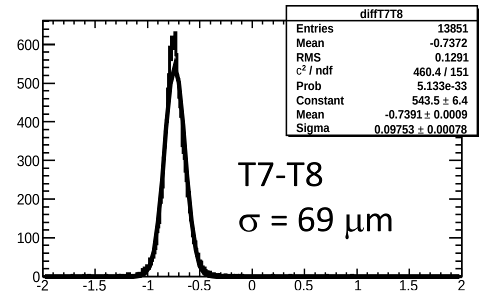
MicroMegas: Performance

Intensive test beam program in the last years resulted in well understood performance



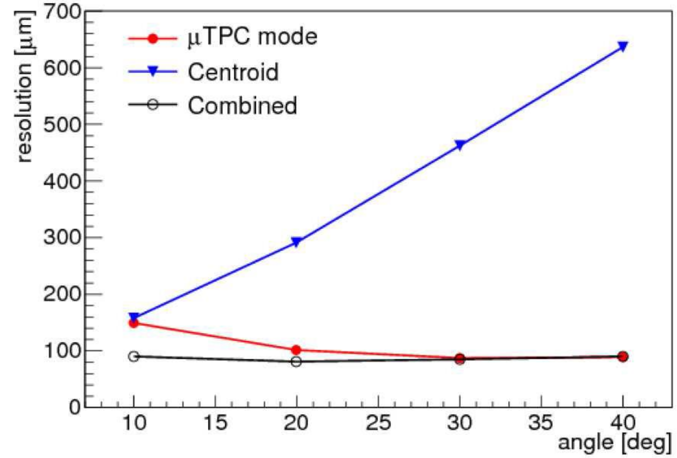


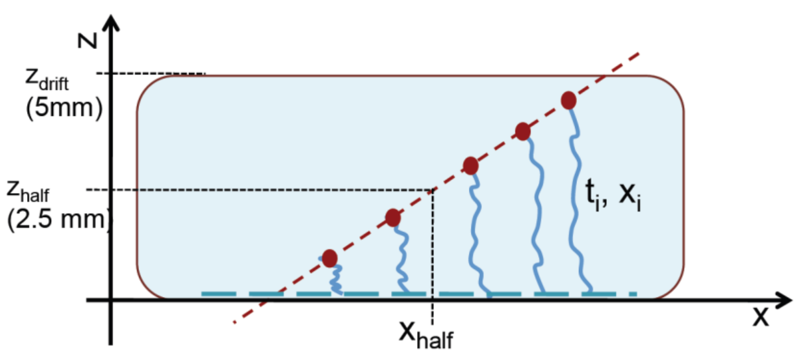




M. Iodice, Zaragosa 2013

- Perpendicular tracks: resolution < 100 µm from charge centroid
- Global efficiency 98-99%, consistent with dead area from pillars supporting the mesh





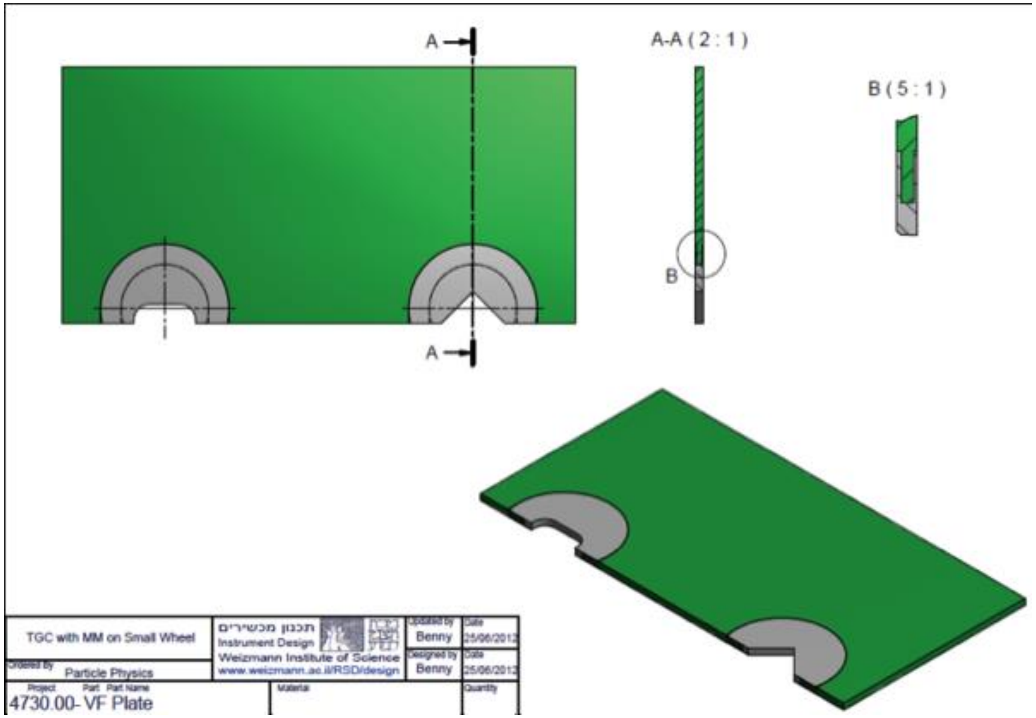
µTPC mode for inclined tracks with α >~ 10°: use time information from hit arrival, reconstruct z coordinate for each x

→ Combined resolution meets < 100µm requ.

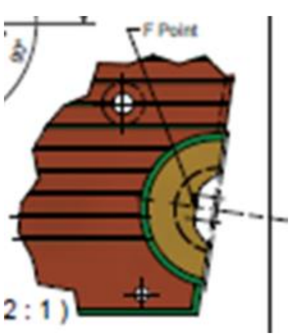
Chamber Construction
Prototypes, Experience, Status

40µm accuracy on knowing position of every active detector element is not a difficulty for strips or pads within a PCB ….
…. But it is a very big challenge for chamber construction + assembly !!

sTGC Construction



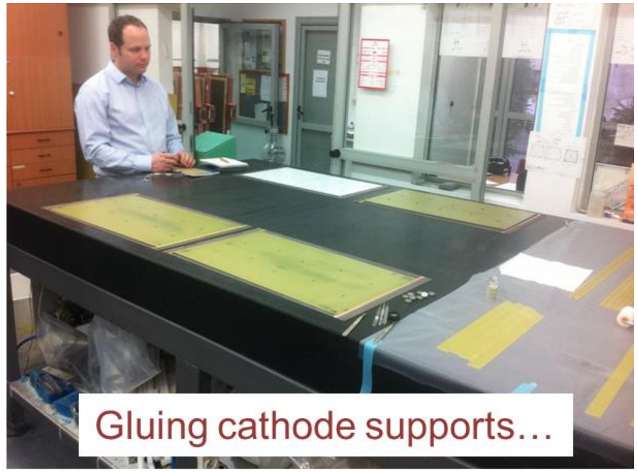
Wire winding on rotating table (China)



- Strip panels sucked flat by vacuum on a granite table, honeycomb sheet and frame glued to it → rigidity
- Positioning of strip panels using brass insert set into the strip PCBs and machined in the same production step as the strips in (PCB) industry
- Reference insert pushed against stainless steel reference tool mounted on the granite table → precise stacking

sTGC Construction

After wire-winding…



Gluing cathode supports…

Preparing to glue a gap…

Applying glue…

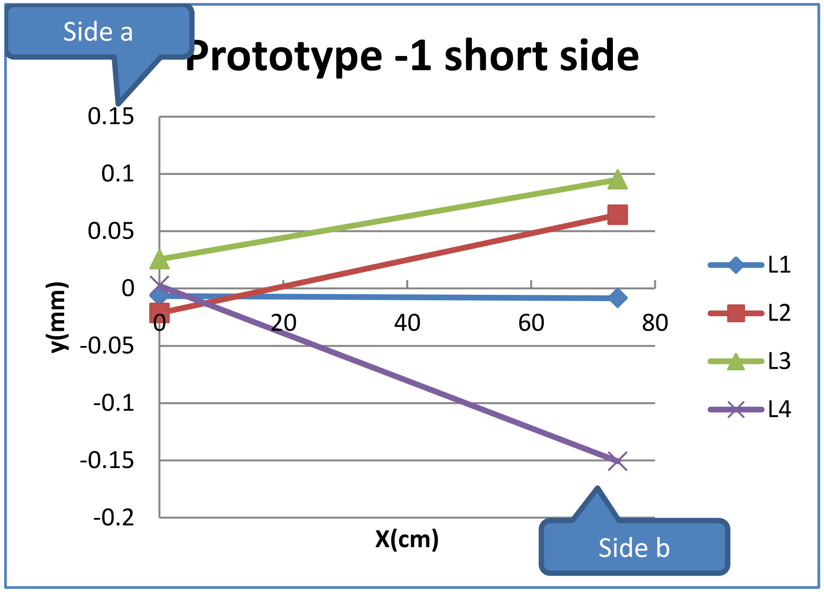
Resistance measurement…

Joined exercise of Israeli and Canadian teams building 60x40 cm protype in spring

sTGC construction follows the same method as successfully used for the ~3500 TGC of the present Muon system …

sTGC Construction

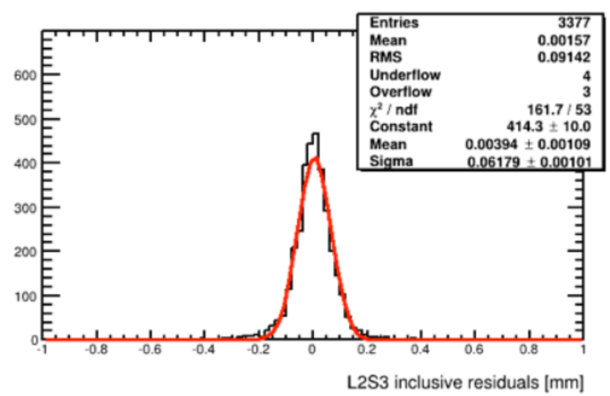
Surprises and results …. (module -1 prototype, 1.3 x 1.1m):



- Mechanical tolerances within layers met
- deviation in alignment between layers: Brass reference inserts not machined in one go together with strips by mistake

- Problems with cleaning of boards --- non dry machining of pads in industry lead to many shorts and high resistivity connection to GND

Module -1 tested @ FNAL test beam in May

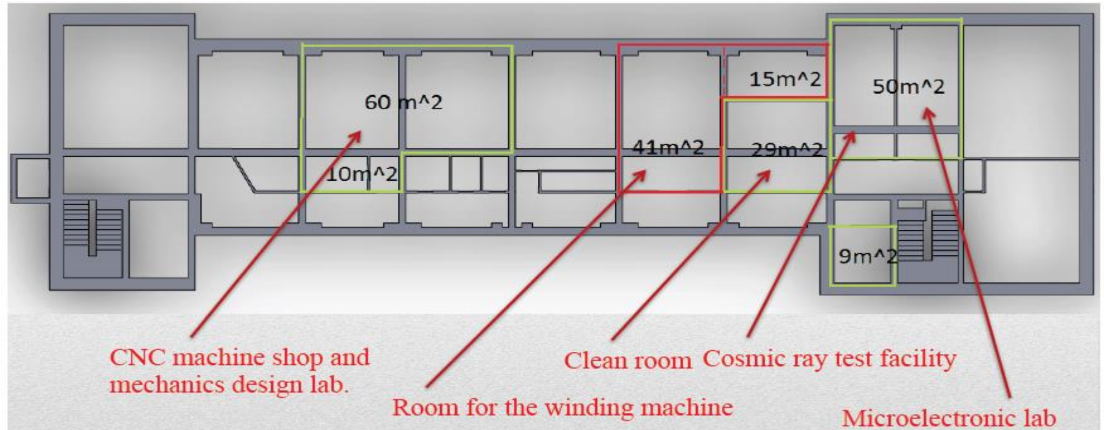


Data currently being analysed, preliminary resolution per plane 70 – 100 µm, meeting speci-fication

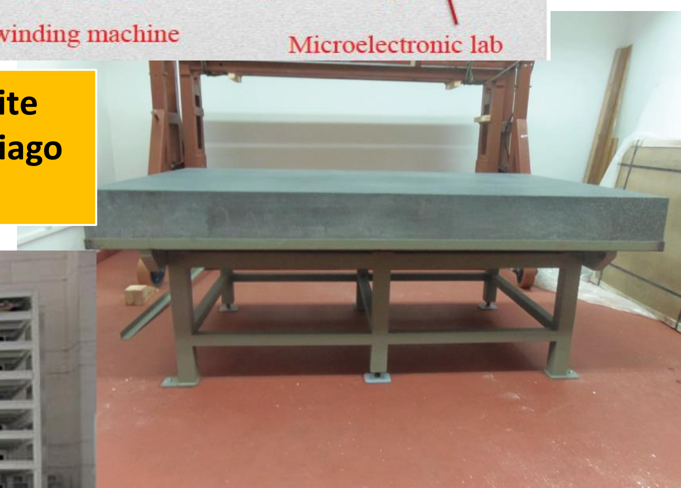
sTGC Production Site Preparations

Infrastructure on production tooling set up well advanced in all 4 sites:

Clean room @ Carleton (Canada)



Cathode spraying @ Weizmann



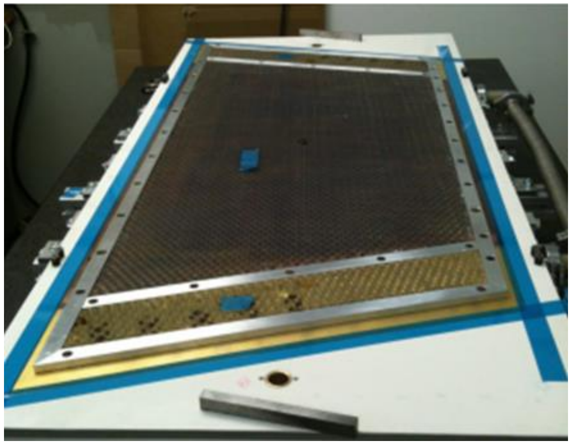
Lab and first granite table at PUC Santiago (Chile)

Cosmic ray test facility at Shandong Univ. (China)

Ready to start module-0 in autumn !

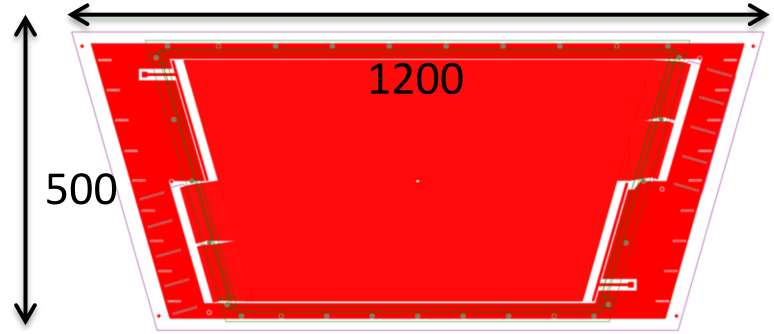
MicroMegas Construction

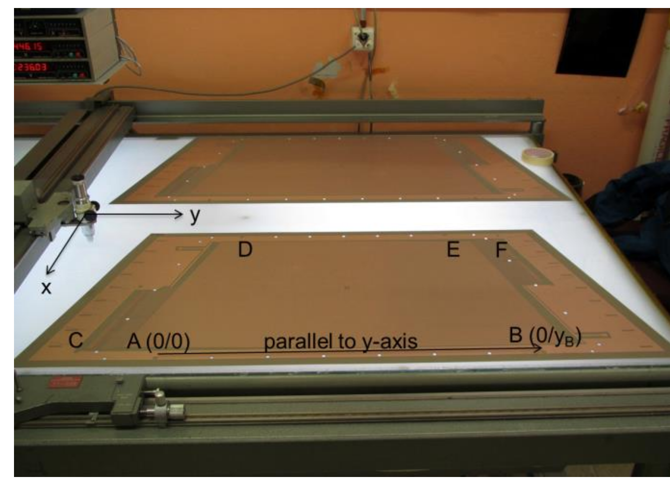
MSW prototype (1.2x0.5m) completed @ CERN, chamber will be installed in ATLAS before data taking in 2015



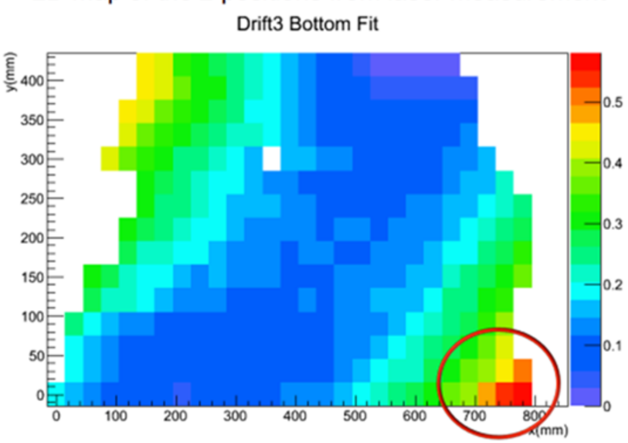
Positioning of Al frames and honeycomb

Panel Flatness/Planarity measurements (Laser based)





2D map of the z-positions from laser measurement

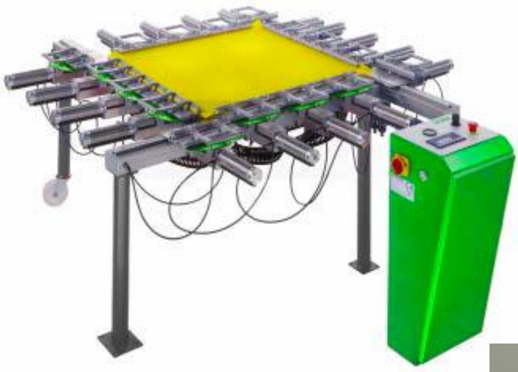


Lessons learned

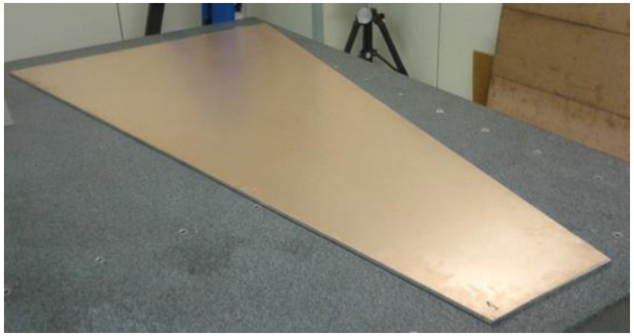
- Deformation of the drift panel visible – rms <~ 100 µm, deformation will improve after module assembly due to interconnections
- Local deviation → due to imperfection of the used stiff back tool

MicroMegas Production Site Prep.

Mesh stretching tests in Frascati

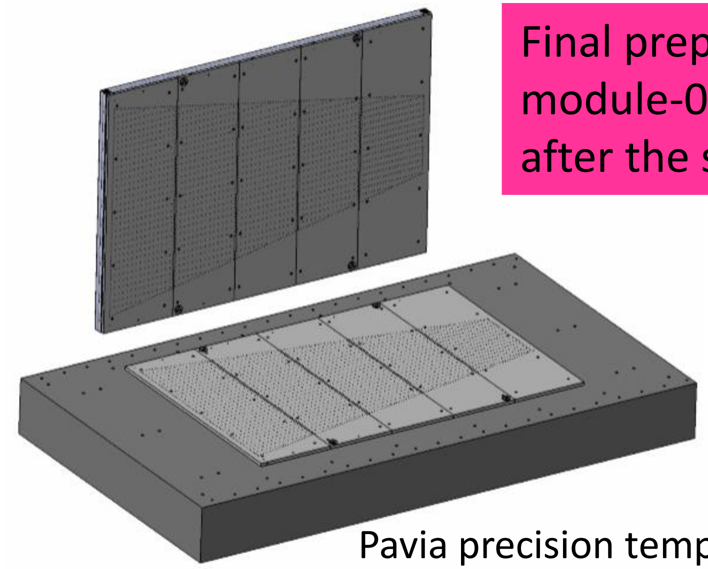


Industrial solutions



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

INFN



Pavia precision templates for RO board alignment

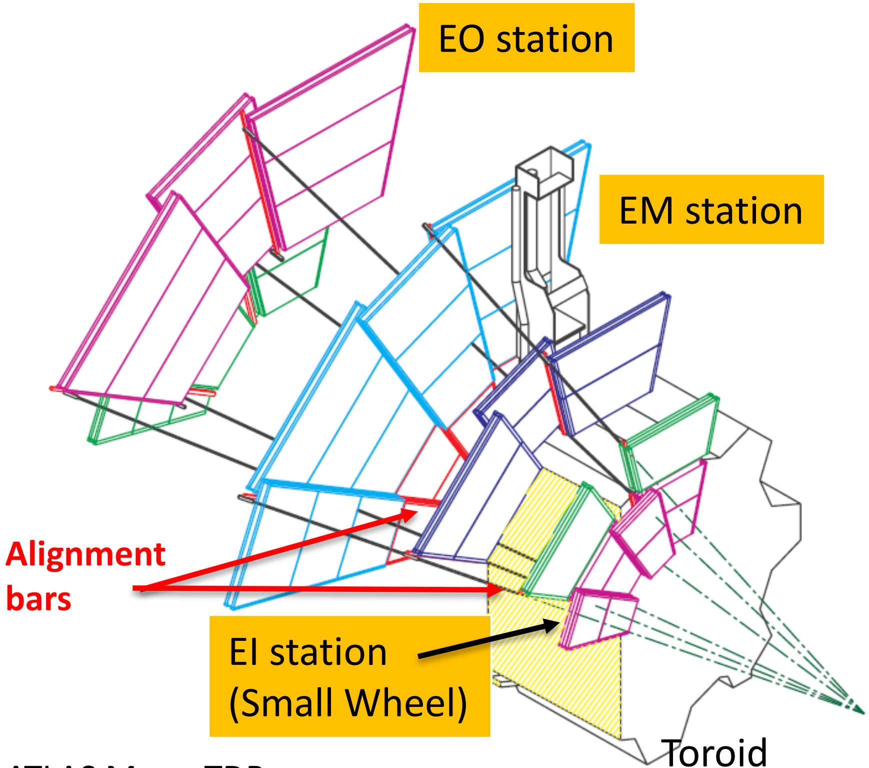
Alignment System and NSW Mechanics

Alignment System

Requirement of knowing the position of active elements (strips, …) to within 40µm does not hold only for module construction

→ Need to consider module position in (absolute) space for sagitta measurement and displacements from nominal coordinate

→ Need to consider module deformations

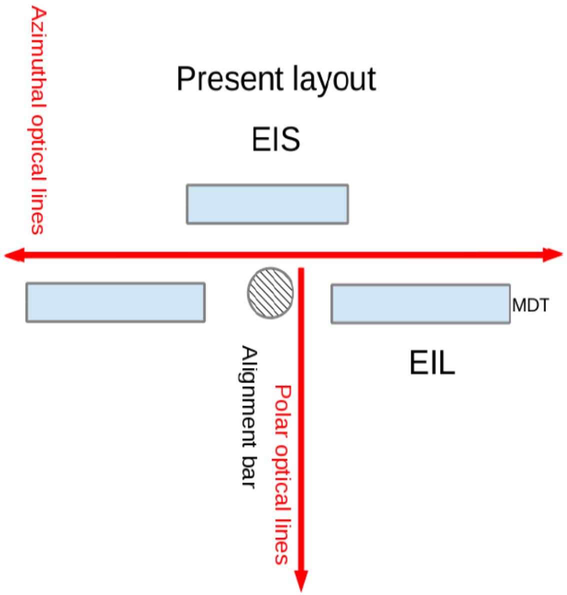


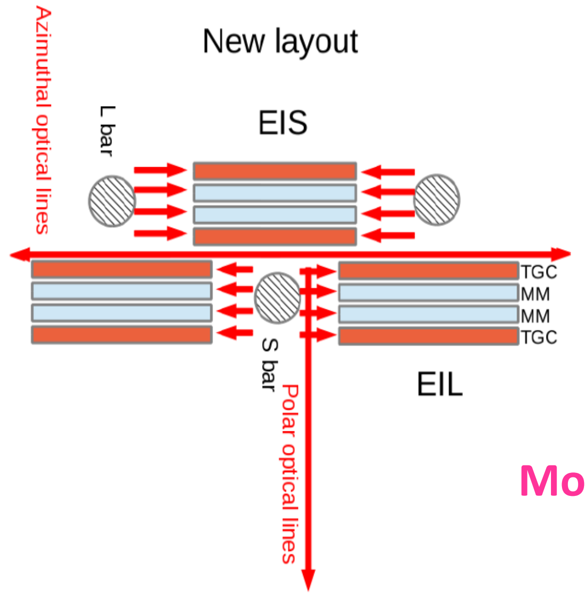
ATLAS Muon TDR

New Small Wheel chamber alignment uses the same technology of the present Muon Spectrometer alignment

- Optical lines with sensors and CCDs, position/displacement reconstruction from optical images of sensor masks
- Projective lines (to IP) are blocked by the endcap toroid → additional precision alignment reference bars to "transfer" optical measurement

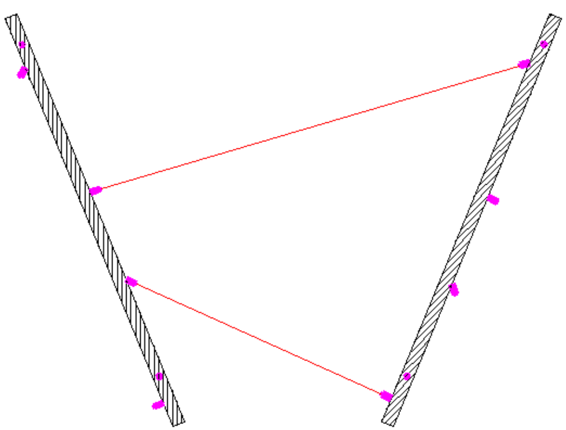
New Small Wheel Alignment

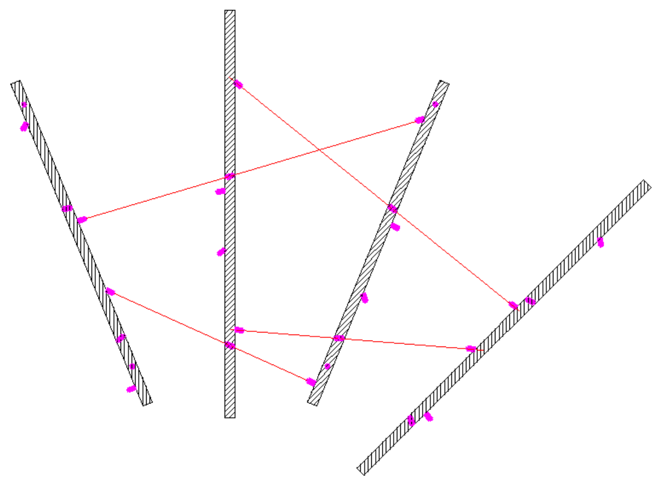




- Precision alignment information needed for sTGC and MicroMegas
- 2 sTGC + 2 MM wedges as independent object

More complex alignment system !!

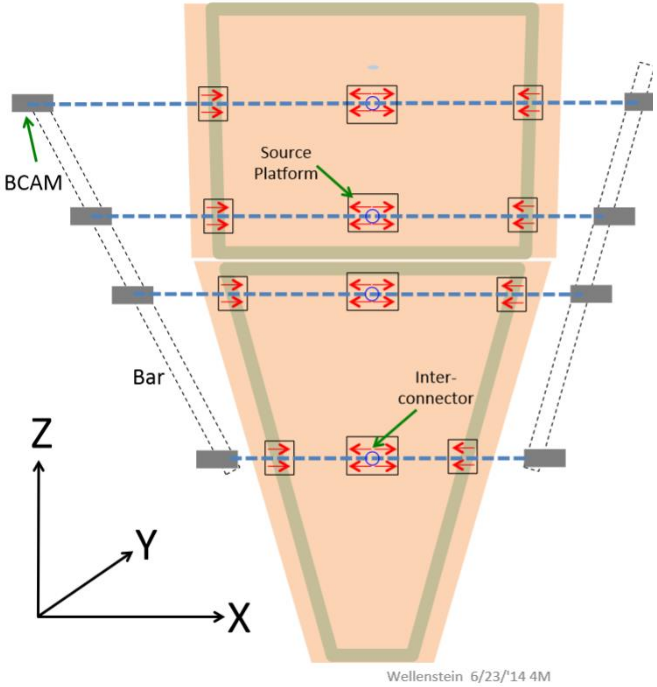




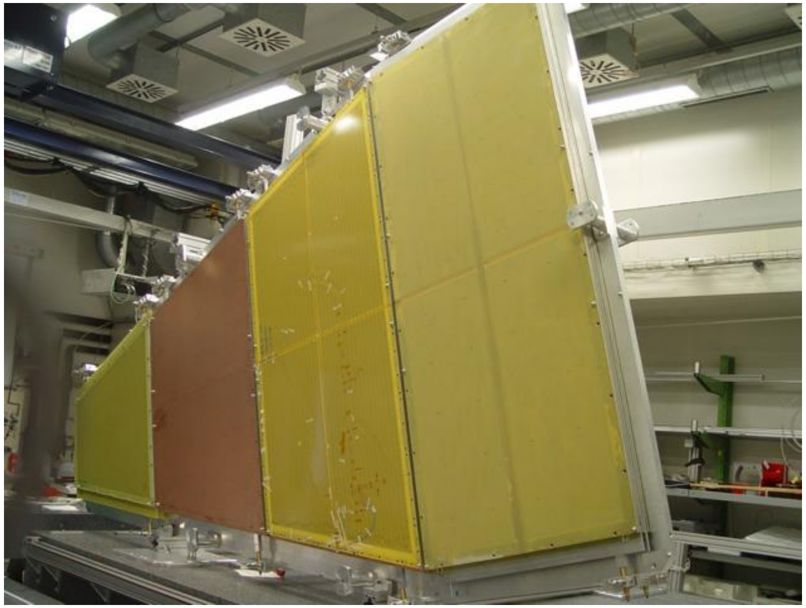
- NSW contains 16 instead of 8 alignment bars per wheel !

New Small Wheel Alignment

Alignment system components and principle remains the same:



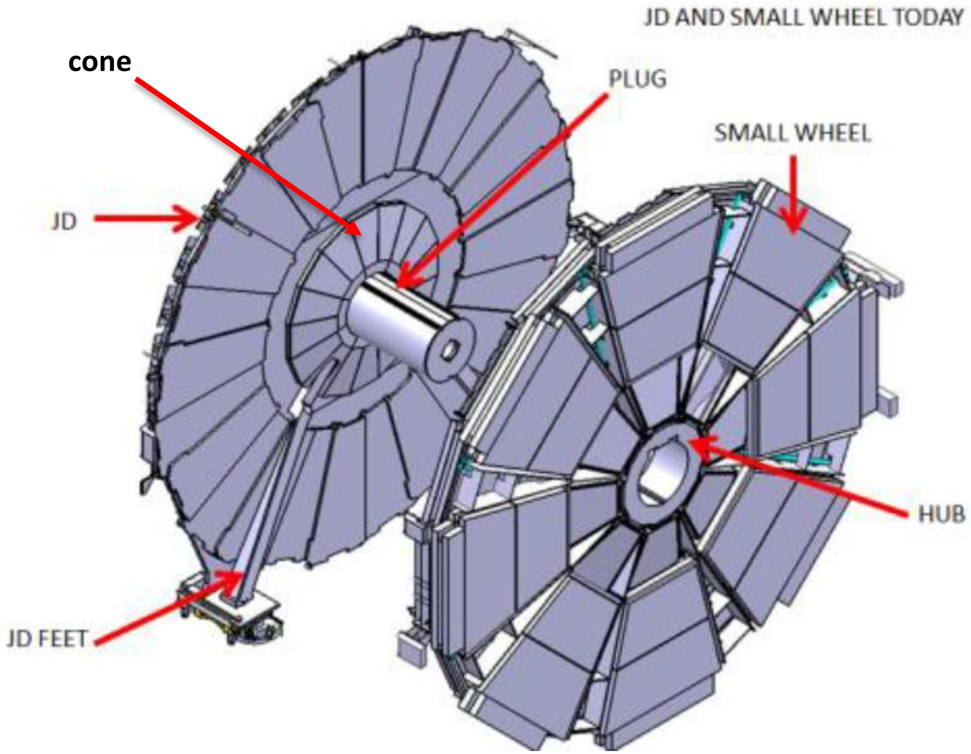
- CCD based alignment "sensors" on the alignment bars "look" at light sources and masks mounted on the chambers/quadruplet
- Reconstruction of chamber displacement from image distortion and magnification



Number of lines needed for monitoring chamber distortions depend on deformation modes → dedicated "sector test" ongoing at Freiburg with prototype chambers assembled into a dummy sector and put under load/temperature gradients, CMM measurement to validate FEM model

Support Structure and JD Disk

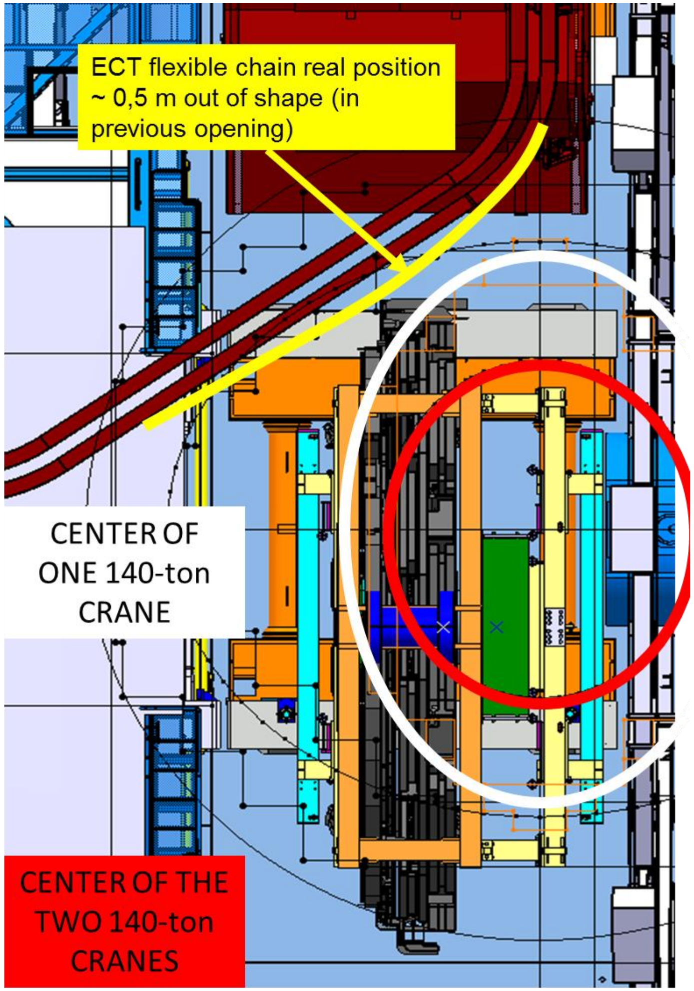
Present forward endcap

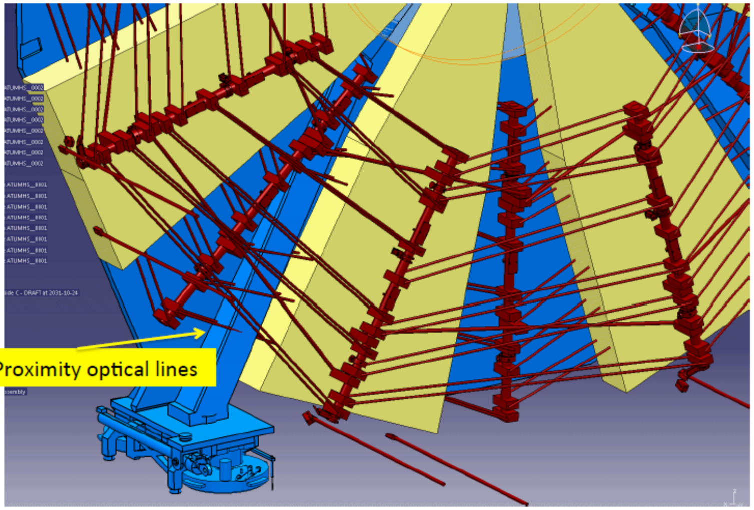


- Support structure of the New Small Wheels is an integral part of the project
- Combines support structure for the chambers, radiation shielding (plug + cone), magnetic flux return for ATLAS solenoid and barrel toroid
- Full Small Wheel (140 tons) rests on the “JD feet”

Challenges for NSW Structure

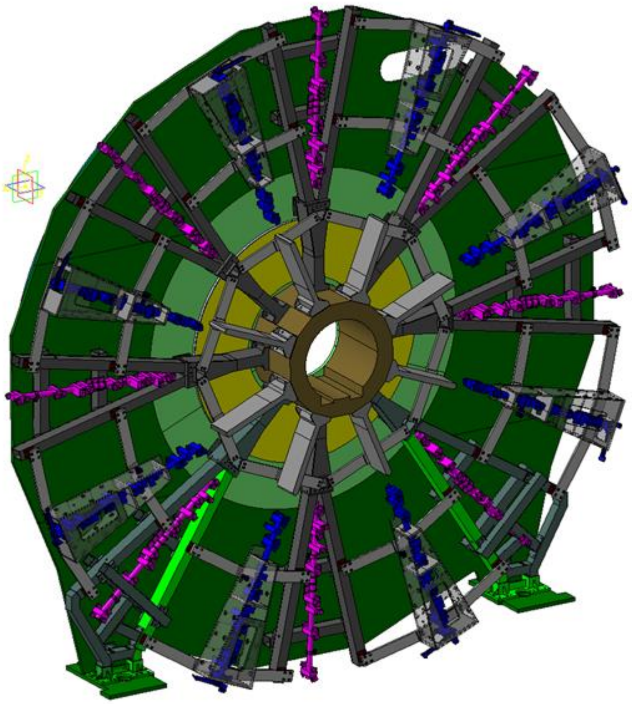
- Total weight → constraint by the max. load of the crane, and range limitation for using single crane in UX15: < 140 tons
  - present SW: ~110t → 120t, plus lifting tool
- Delicate centre of gravity
- Need for increase in stiffness (heavier weight)
- Instability of the sTGC wedge positioning
- Lack of space for independent kinematic mounts of sTGC and MM sectors
- Interference of alignment lines with SW + JD feet





Can be solved by a new JD disk with integrated support structure ….

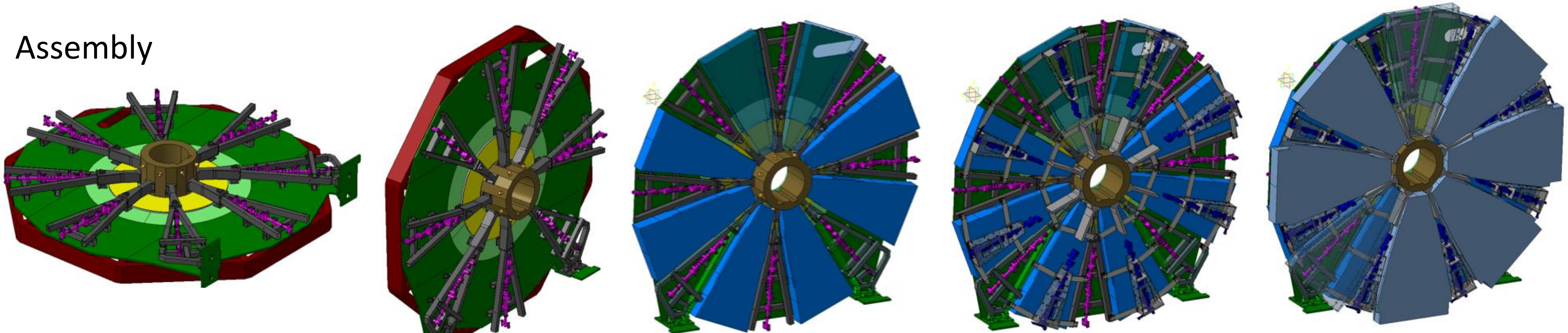
NSW new Mechanical Structure



New design, currently under review and approval:

- JD disk integrated with New Small Wheel support structure (bolted together) → increased stiffness
- Disk thickness reduced from 80 to 50 (40) mm
- Alignment bars integrated with "spokes" supports
- NSW assembly can start independent from retrieval of present endcap from the cavern at the start of LS2

Assembly

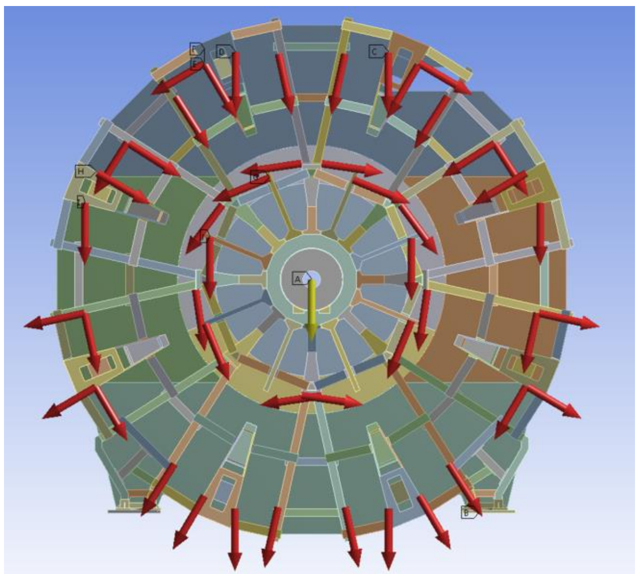


G.Spigo, M. Ciapetti

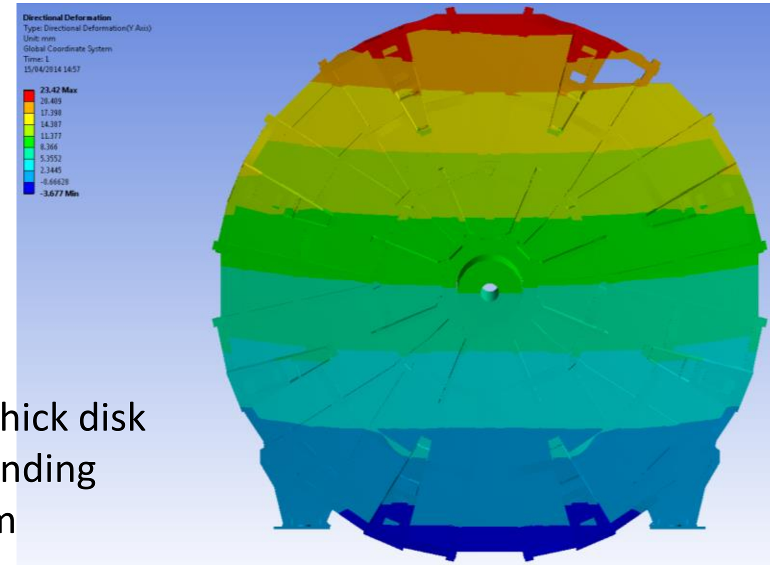
NSW new Mechanical Structure

Mechanical engineering challenge …

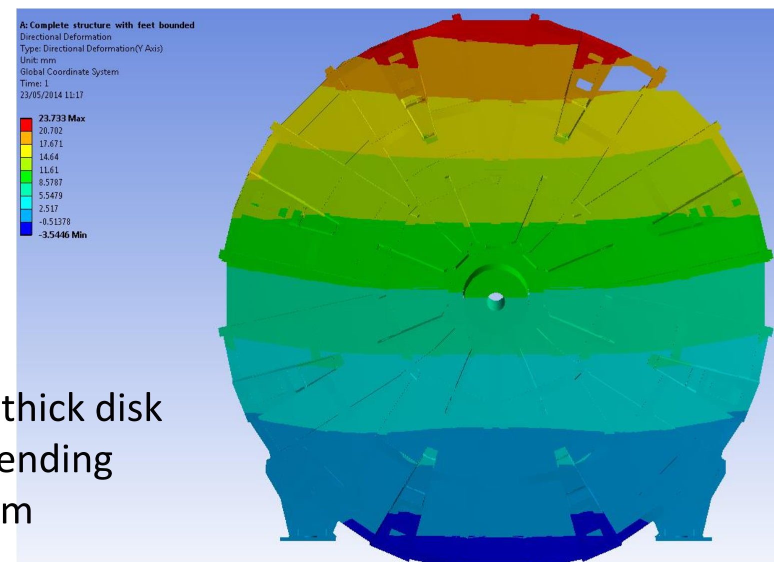
FEM calculation of deformation
when loaded with the detectors



Forces and force distribution



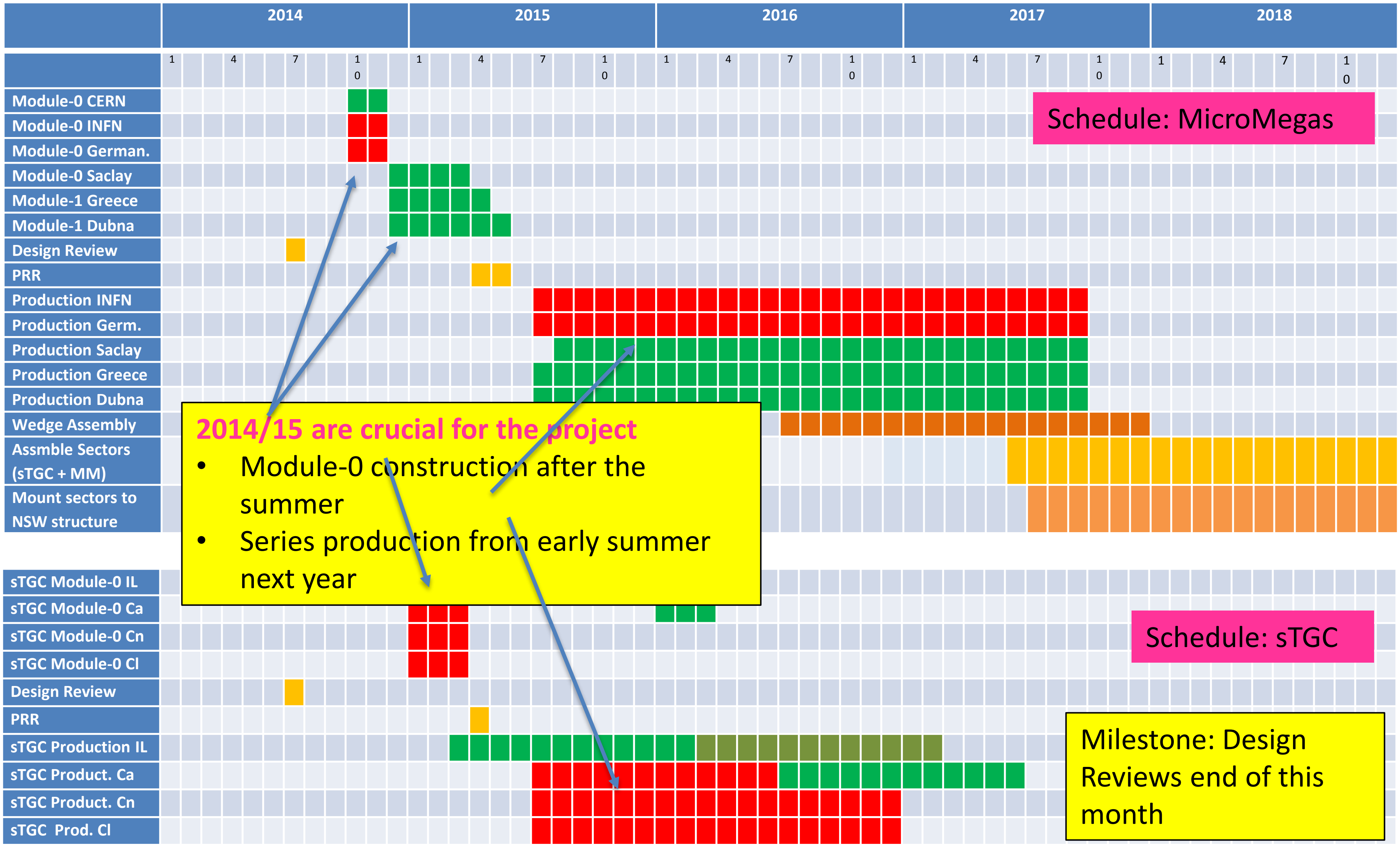
50mm thick disk
max. bending
23.4 mm



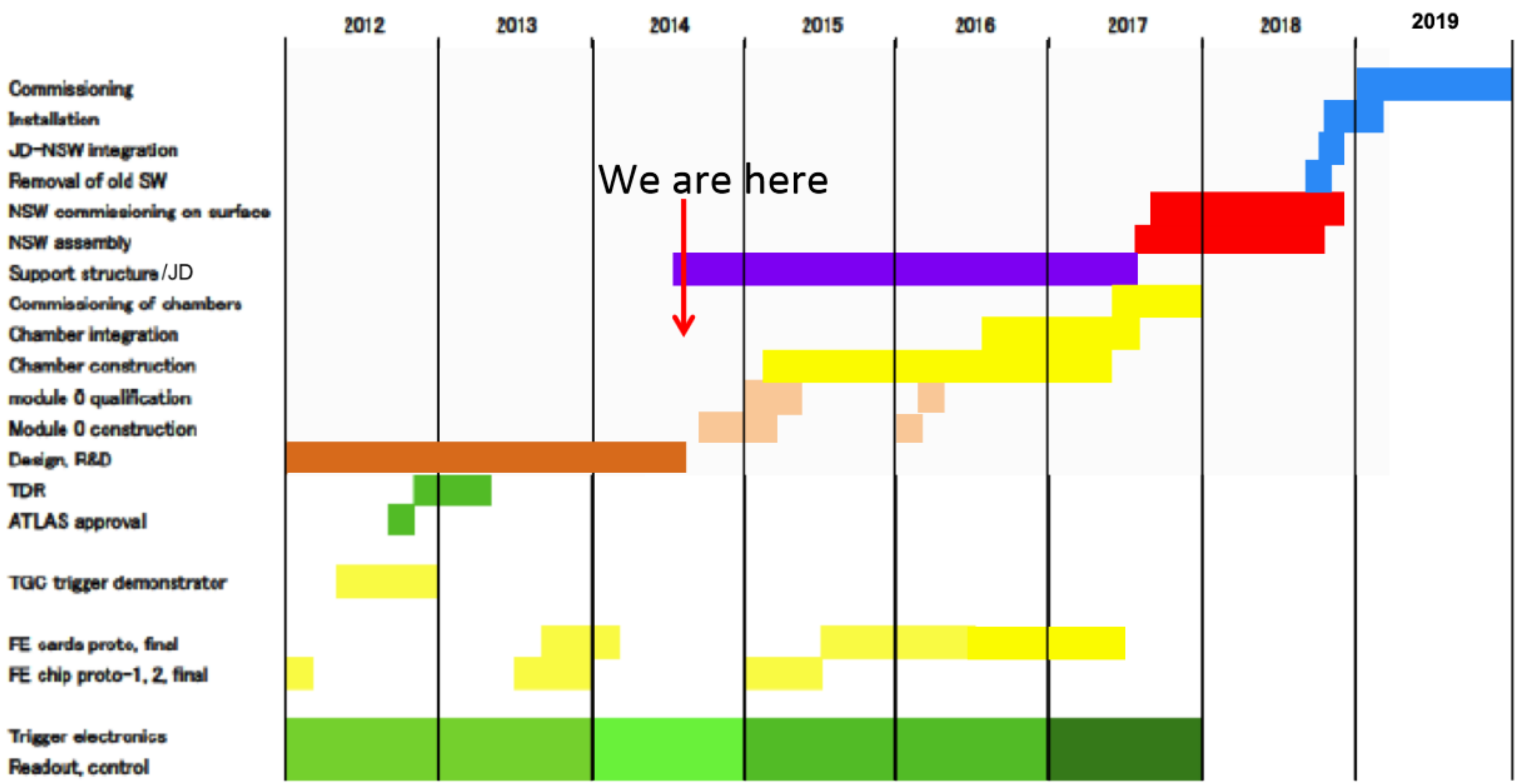
40mm thick disk
max. bending
23.7 mm

Outlook and Conclusions

Detector Activities schedule …



Overall Schedule



B. Stelzer, ICHEP

- Detectors: R&D phase completed, moving into series production
- Electronics: Protype modules and submission of first chip version for most components under way
- At about the 30% of the project, will stay challenging !

Conclusions

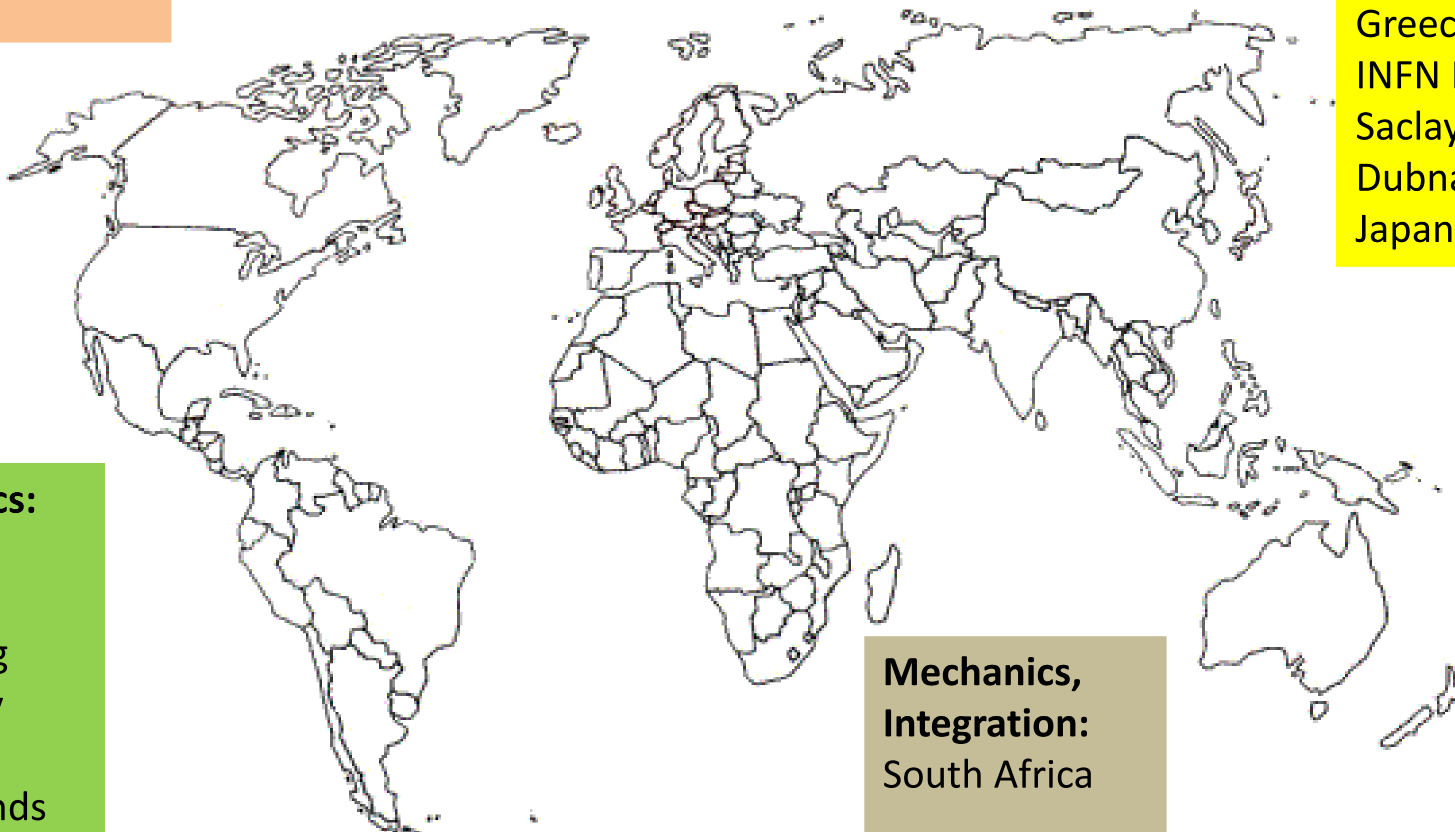
- The ATLAS NSW Upgrade will enable the Muon Spectrometer to retain its excellent performance also beyond design luminosity and for the HL-LHC phase
- Deployment of a new detector technology, MicroMegas, for the first time for a very large scale detector and with large area chambers
- Detector construction is not the only challenge: Alignment, Mechanics, Electronics are equally crucial and highly complex areas needed for a success
- 2nd half of this year and 2015 will be crucial:
  - Module-0 production
  - Transition to series production
  - First prototypes for many of the electronics components

NSW Collaboration

sTGC chambers:
Canada Chile
China Israel
Russia

Alignment:
Germany Saclay
US

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
….

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

Thank You !