Muon Spectrometer Phase-I Upgrade for the ATLAS Experiment

The New Small Wheels Project

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Conference on the Intersections of Particle and Nuclear Physics
Palm Springs (USA)
May 29 – June 3, 2018

McGill

ATLAS EXPERIMENT

The Large Hadron Collider (LHC)

The road towards high luminosity

- A series of LHC upgrades are planned during Long Shutdown (LS) periods.
- Instantaneous luminosity expected to increase up to 5 to 7 times higher than nominal following LS3 in 2026.
- Expect to collect approximately 3000 fb^{-1} of data by the end of LHC operations in 2037.

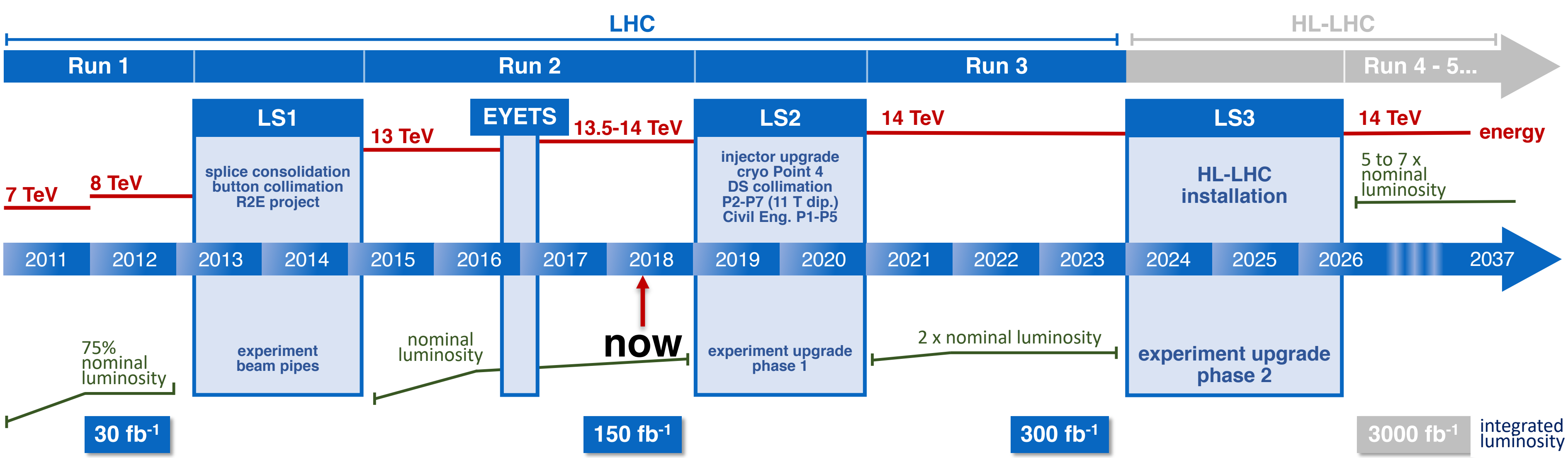
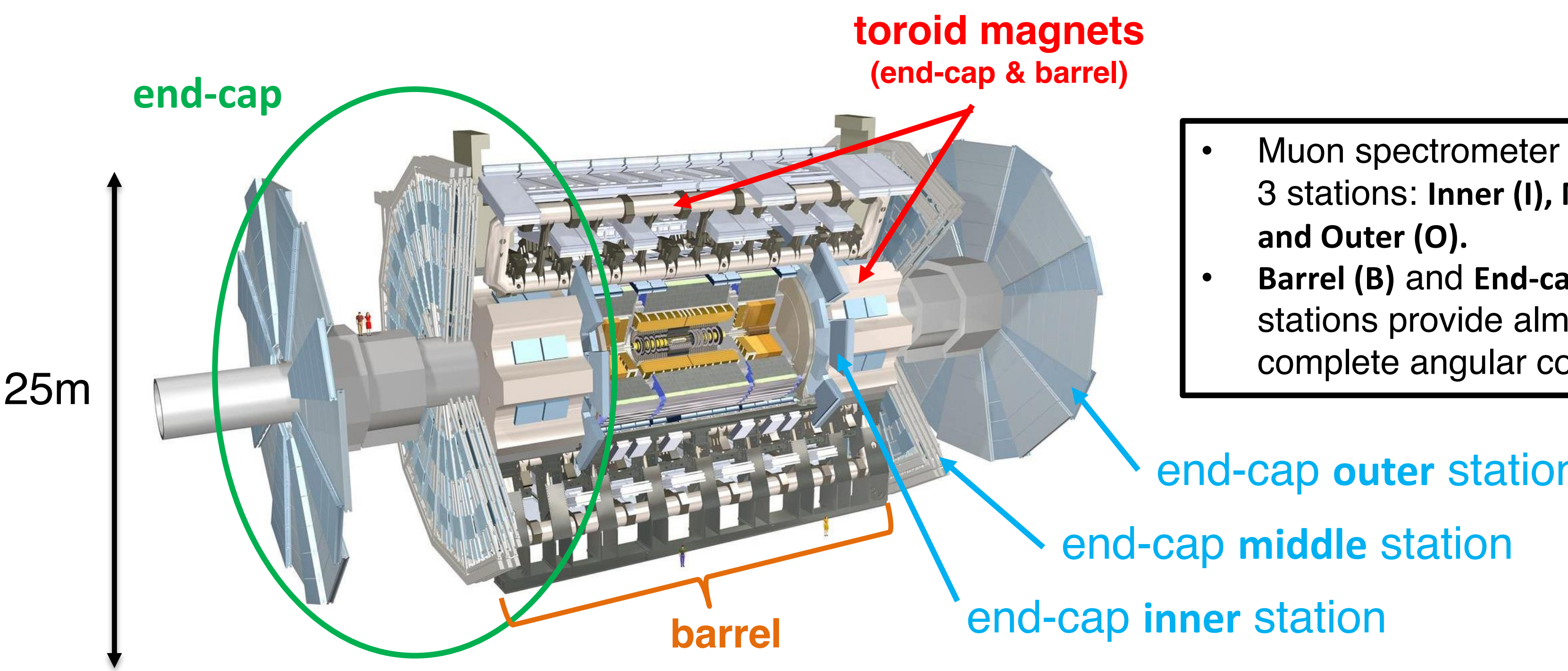


Figure: 10.23731/CYRM-2017-004

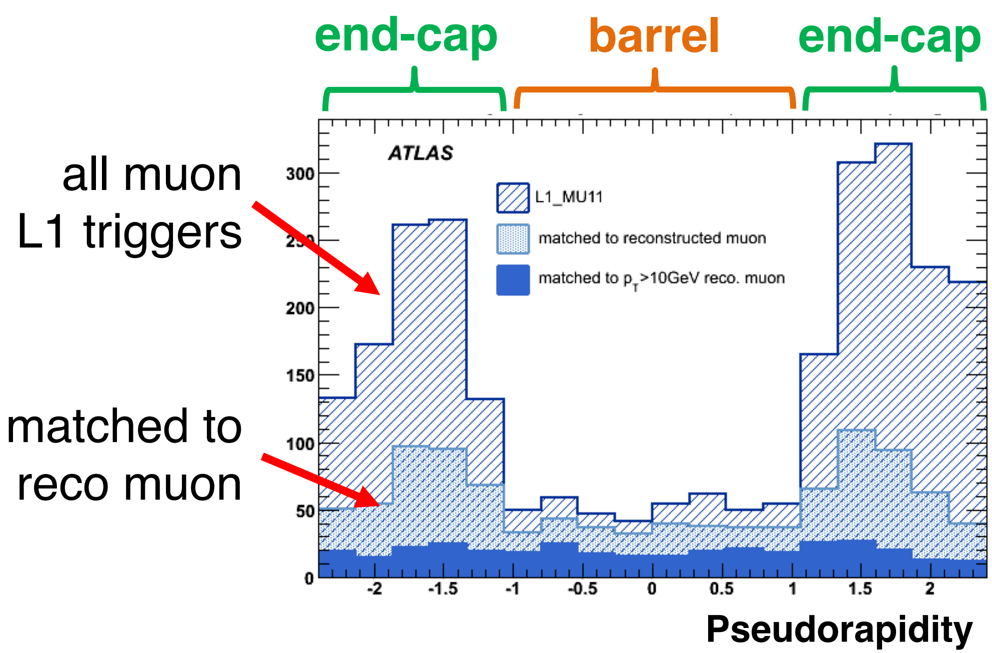
The ATLAS Muon Spectrometer

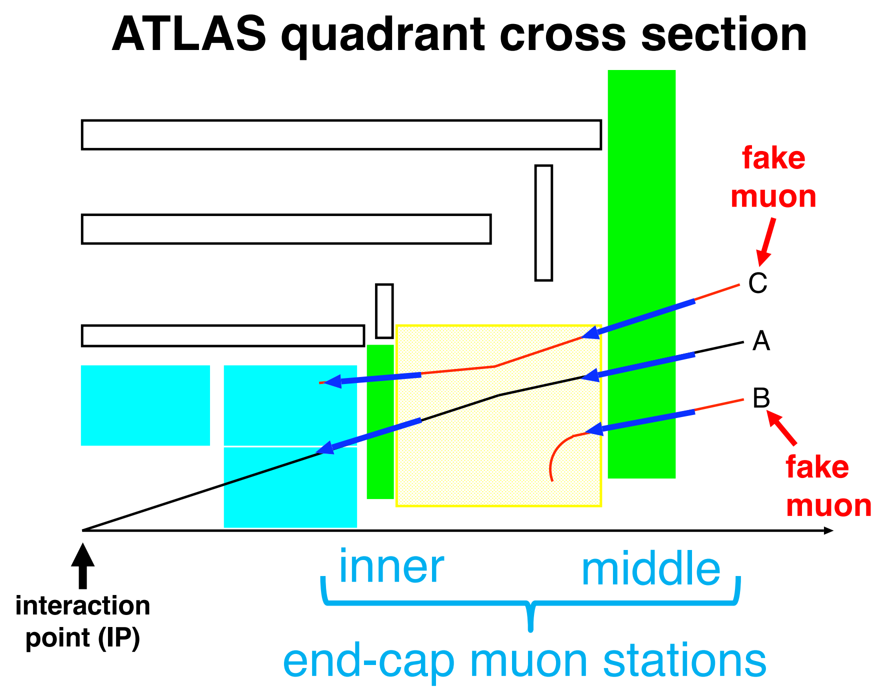


- Muon spectrometer divided in 3 stations: **Inner (I), Middle (M) and Outer (O).**
- **Barrel (B)** and **End-caps (E)** stations provide almost complete angular coverage.

- Precise offline muon momentum measurement.
  - Using hits from precision muon chambers: **Cathode Strip Chambers (CSC)** and **Monitored Drift Tubes (MDT).**
- Data acquisition trigger on events involving muons.
  - **Level-1 trigger (hardware)** using hits from muon trigger chambers: **Thin Gap Chambers (TGC)** and **Resistive Plate Chambers (RPC)**.
  - **High Level Trigger (software)** with hits from all muon detectors.

Challenges of High Luminosity Data Taking





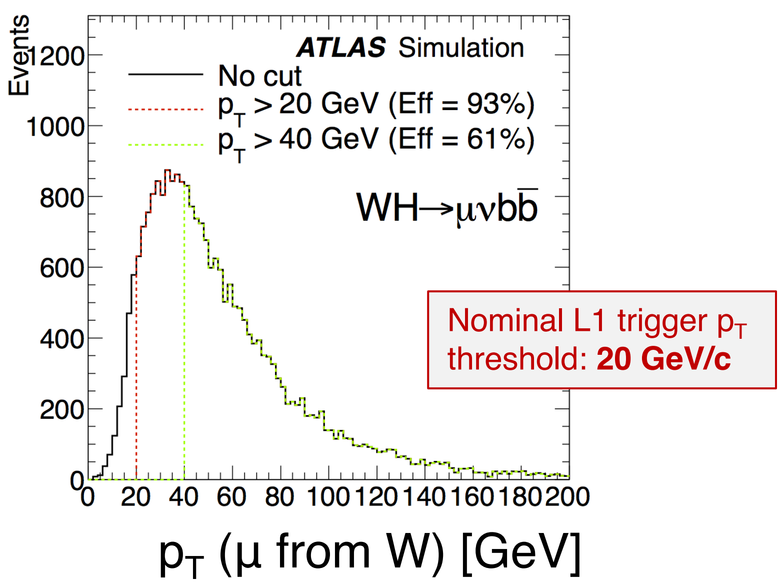
- **Problem at high luminosity:** Level-1 trigger rate will exceed the readout rate bandwidth (~1MHz after LS3) of the ATLAS data acquisition system.
- More than **90%** of muon candidates identified by the end-cap Level-1 trigger algorithm are from "**fake muons"** that are, in fact, background hits.
  - Background hits come from particles produced in the material between the inner and middle stations.
  - Current muon Level-1 trigger algorithm uses information only from the middle station.
- **Solution:** Use inner station hits to identify fake muons. Inner station track segment must point to the IP and match the middle station measurements.
- Current inner station detectors cannot achieve an online fake muon identification.
  - Coarse granularity of inner station trigger detectors.
  - The hit efficiency of CSC and MDT precision detectors is rate-limited.

Figure: CERN-LHCC-2013-006

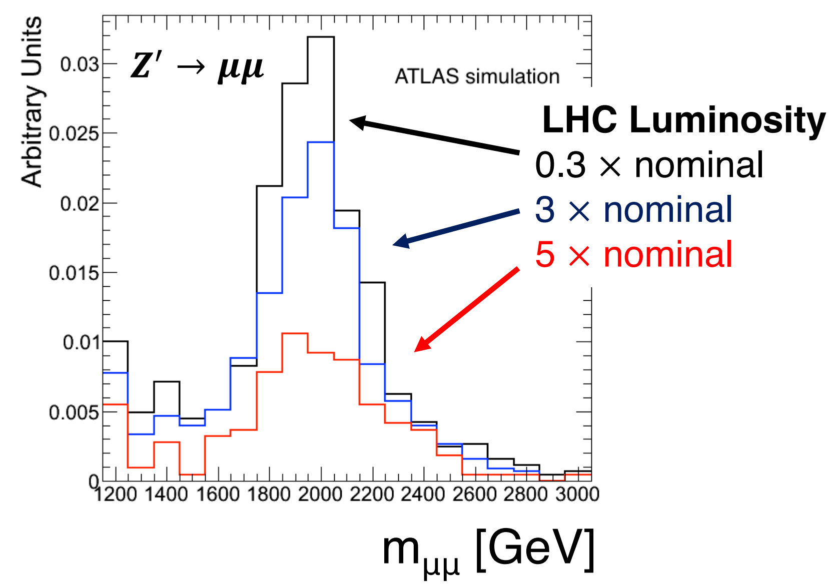
High luminosity physics with muons

- High luminosity operation enhances the discovery potential of ATLAS:
  - Increased precision of Standard Model measurements
  - Increased sensitivity to rare physics processes
  - More detailed studies of the electroweak symmetry mechanism
- Muons are an important signature for a plethora of physics processes.
- **The muon spectrometer overall performance must remain excellent at high luminosity to fulfill the ambitious ATLAS physics program.**

Raising the muon Level-1 p_T threshold reduces the ATLAS sensitivity to Higgs physics

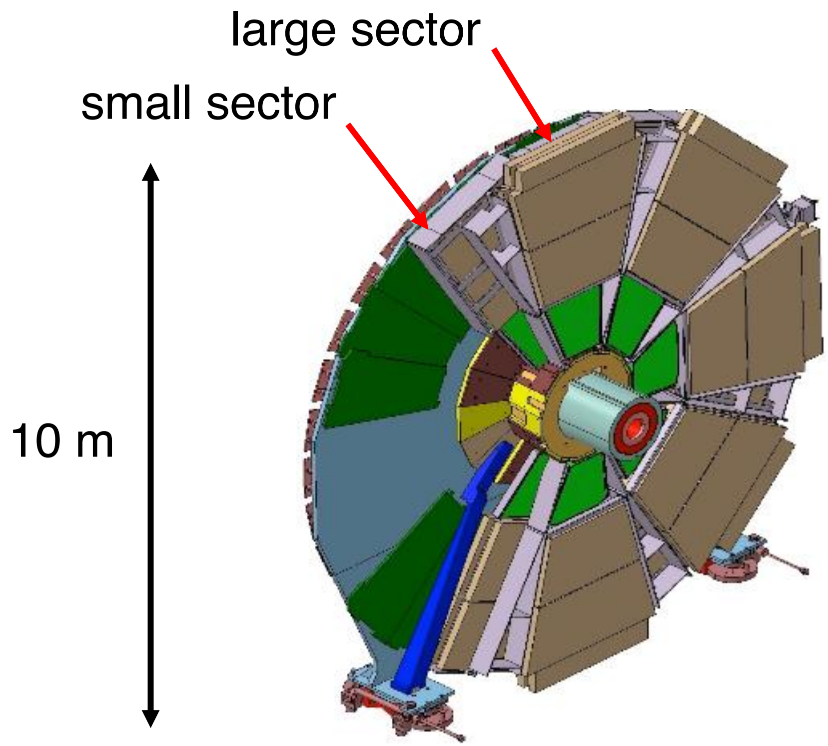


Effect of loosing precision space points from MDT at high particle fluences (Search for hypothetical Z' boson)



Figures: CERN-LHCC-2013-006

New Small Wheel (NSW)



- **New Small Wheel:** Detector arrangement replacing part of the end-cap inner station.
- Wheel arrangement of 8 “large” and 8 “small” pie-slice detector sectors.

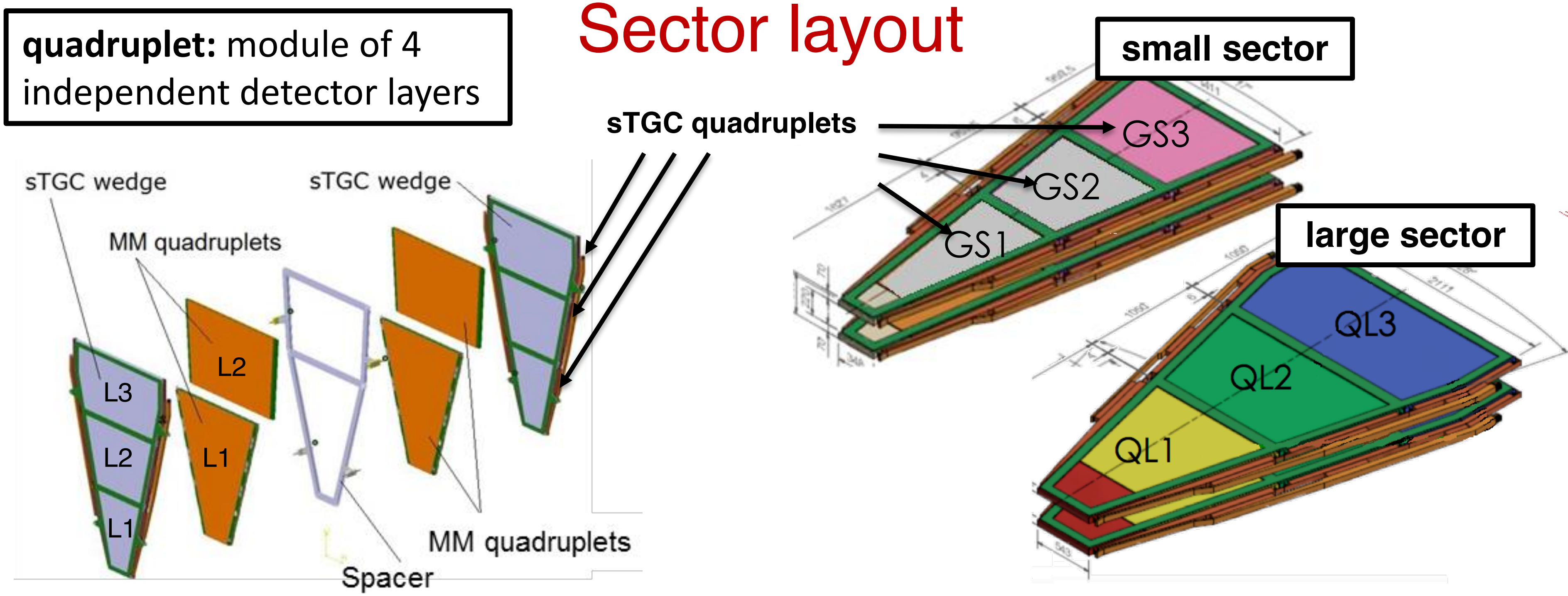
Specifications

- Online angular resolution better than 1 mrad.
- Stable overall performances up to a hit rate of 20 kHz/cm^2.
- Spatial resolution similar to that of the current inner station to maintain the current muon momentum resolution (10% @ p_T = 1 TeV/c)
- Time jitter better than 25 ns for bunch crossing identification.

New Small Wheel

Sector layout

quadruplet: module of 4 independent detector layers

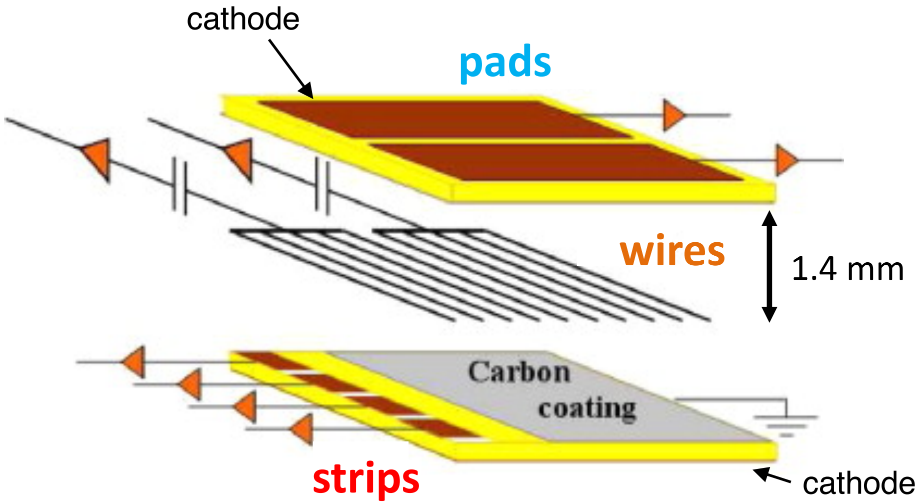


- Sectors combine **small-strip Thin Gap Chambers (sTGC)** and **Micromegas (MM)**[1]. Both technologies feature excellent high-rate track reconstruction and timing performances, required for the NSW.
- Both technologies use common readout electronics: the **VMM**
  - On-detector peak and time measurements of the detector signal.
  - Independent trigger and readout data paths.

[1]micro-mesh gaseous structure

small-strip Thin Gap Chamber (sTGC)
Detector technology

- **small-strip Thin Gap Chambers**: Multiwire chambers operating with a mixture of n-Pentane/CO_2.
- Operation in the quasi-saturated mode.
  - Gas gain ~10^5
  - Operating voltage = 2.9 kV
- **Strips:** Precise muon trajectory measurement in the bending plane.
  - Strip pitch = 3.2 mm
- **Pads:** Used for strip readout trigger and coarse measurement in the non-bending plane.
  - Pad area ~60 cm^2
- **Wires:** Coarse muon trajectory measurement in the non bending plane.
  - Wire pitch = 1.8 mm
  - Wires ganged in groups of 20
  - Wire channels not used for trigger

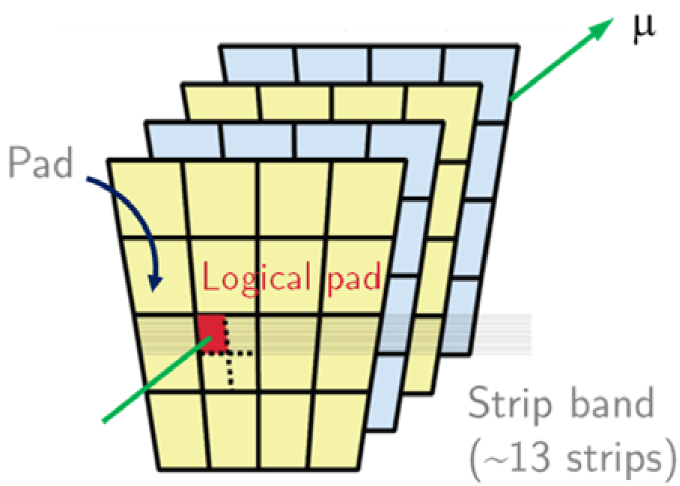


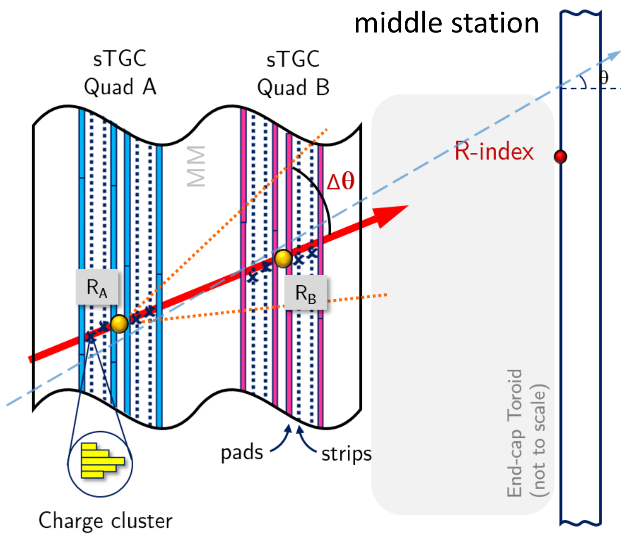
Strip, **pad** and **wire** electrodes are read out on NSW sTGC modules

Strip-cluster centroid obtained from the center of mass of the peak strip signals during online operation.

small-strip Thin Gap Chamber

Online track reconstruction





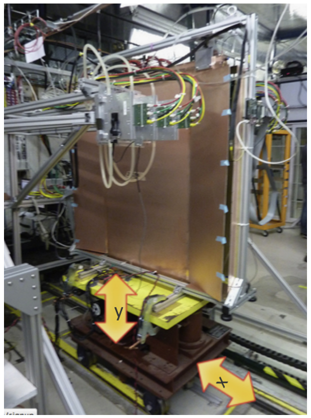
- sTGC readout pads are staggered between layers and define areas called ”logical pads” that trigger a band of strips.
- Muon position obtained from the centroid position of the strip charge clusters.
  - Centroid position obtained with a center-of-mass algorithm during online operation.
  - Strip clusters with more than 5 strips rejected because they originate from δ-rays.
- The centroid positions of each wedge are averaged. Candidate muon track segment obtained from average centroid of the wedges.

Figures: ATL-COM-MUON-2015-062

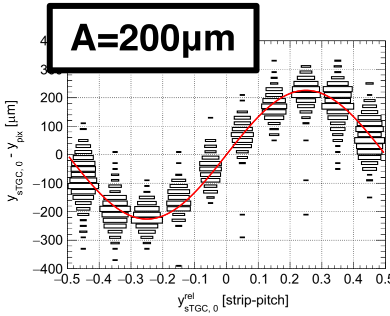
small-strip Thin Gap Chamber

Performance studies

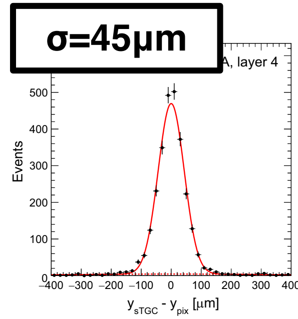
Test-beam at Fermilab in May 2014



Spatial resolution measurement with pixel telescope



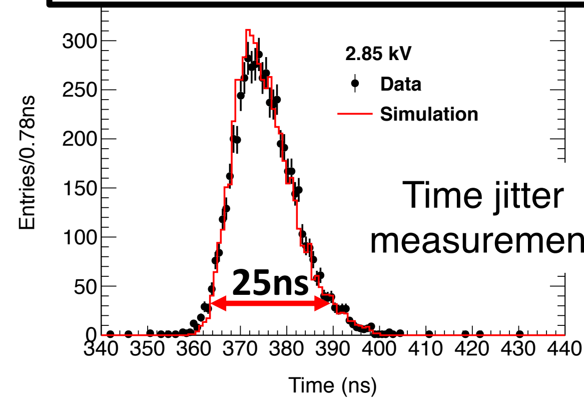
Differential non-linearity



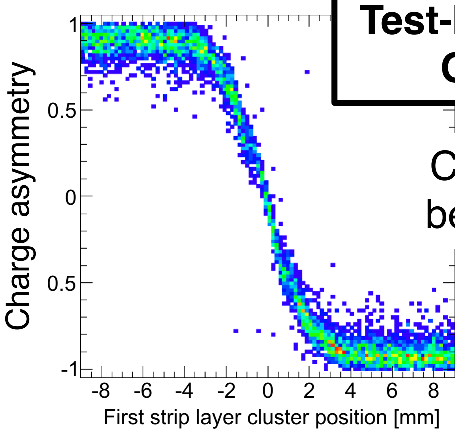
Resolution with perpendicular tracks

Full results: DOI: 10.1016/j.nima.2016.01.087

Test-beam at CERN in 2012



Test-beam at CERN in October 2014



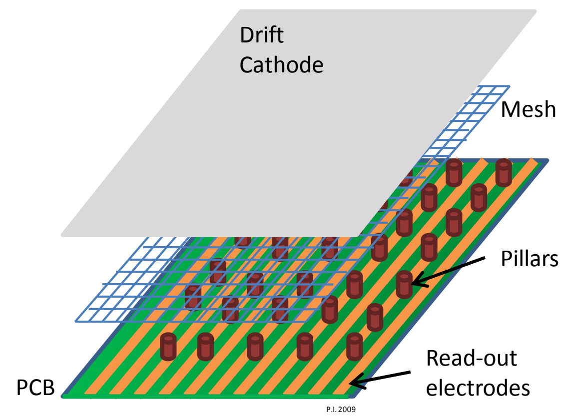
Charge sharing between 2 pads

Test-beam with final VMM prototype in October 2017

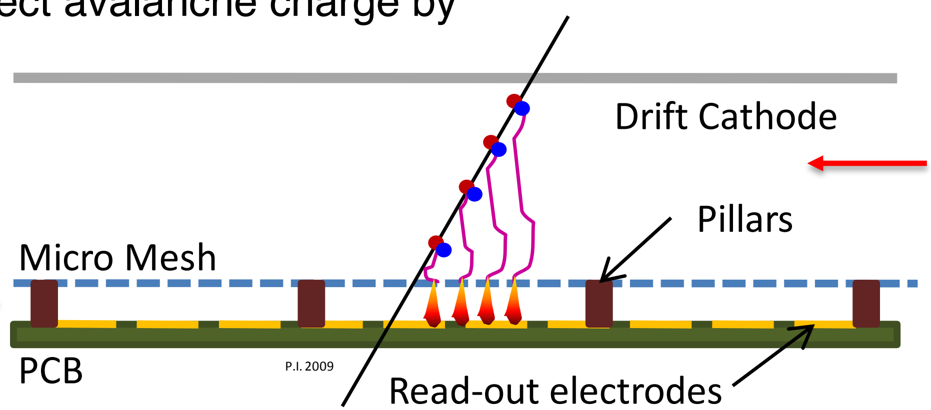
Figures: CERN-LHCC-2013-006, DOI:10.1016/j.nima.2016.01.087

Micromegas
Detector technology

- **Micromegas:** micro-pattern gaseous detectors that operate in 2 phases: *drift* and *amplification*.
- A micro-mesh, transparent to electrons, separates drift and amplification gaps.
- Primary ionization drifts to the mesh by the action of a moderate electric field.
  - Drift gap thickness: 5 mm
  - Drift field = 600V/cm
- Charge is multiplied by the strong electric field in the amplification gap.
  - Gain gain ~10^4, Amplification field = 40kV/cm
  - Amplification gap thickness: 128 µm
- Readout strips collect avalanche charge by induction.



Internal structure of a Micromegas

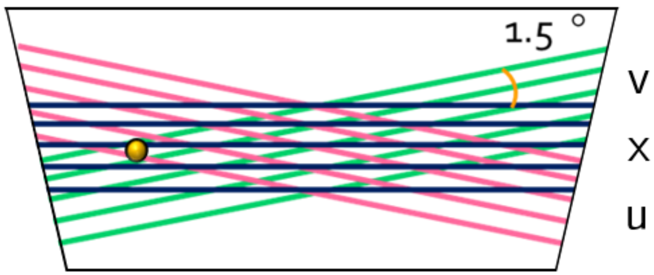


Operates with the principles of a time projection chamber.

Quick ion evacuation from the thin amplification gap

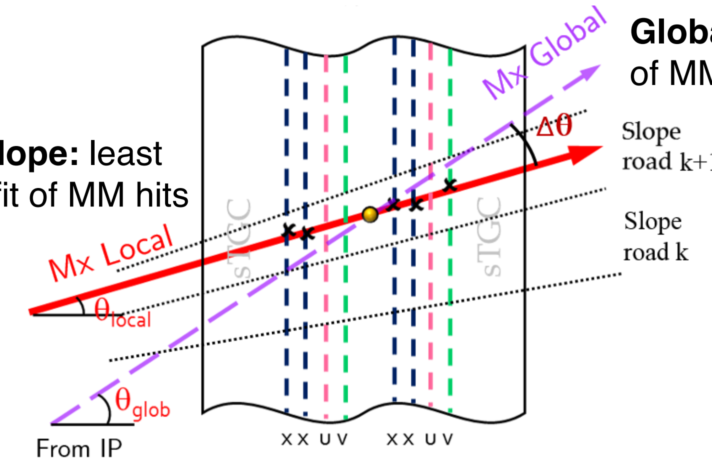
Micromegas
Track reconstruction and trigger

Stereo-strip configuration



x: horizontal strips (2 planes per Quad.)
u,v: stereo strips (1 each per Quad.)

Local slope: least square fit of MM hits



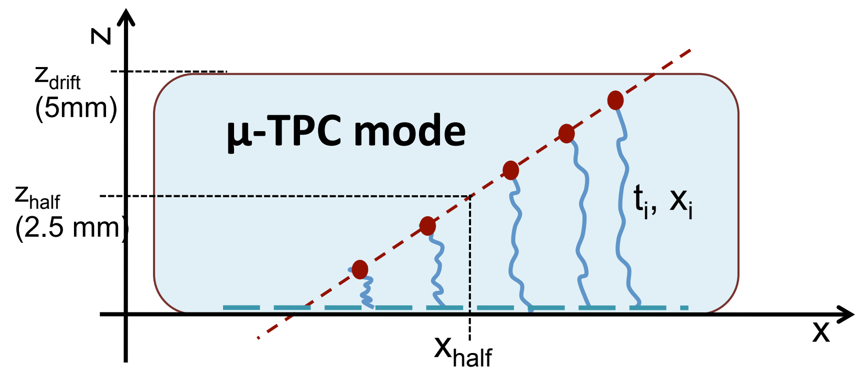
Global slope: avg. of MM hits to IP.

- **Online reconstruction:** muon position obtained from the first strip with signal.
- **Offline reconstruction:** use charge cluster centroid position or µTPC mode.
- Stereo-strip arrangement for muon measurement in two coordinates.
- For trigger: **global** and **local** slopes obtained and compared using hits from all 8 Micromegas layers.

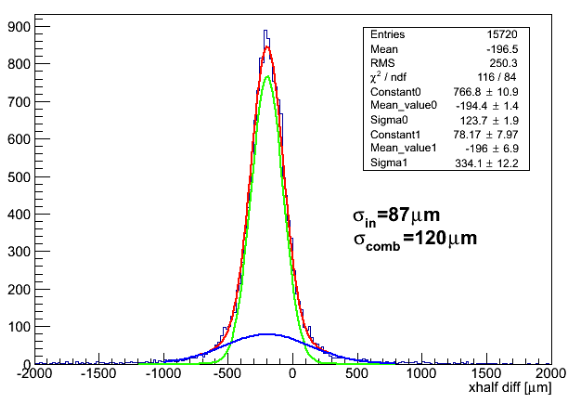
Figures: L. Guan

Micromegas
Performance studies

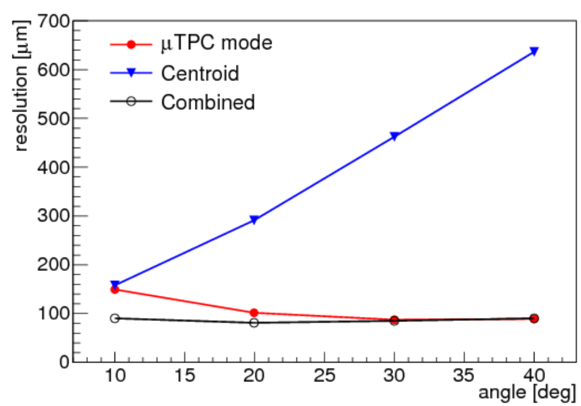
μ-TPC mode: use strip hit timing to reconstruct a muon track.
Centroid mode: strip-cluster centroid provides the muon position



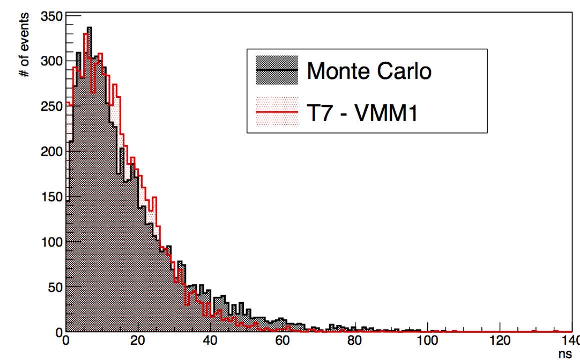
90μm spatial resolution with perpendicular tracks.



Spatial resolution improvement with angle using the μ-TPC mode.



Timing of first strip hit
All hits within ~3 bunch crossings



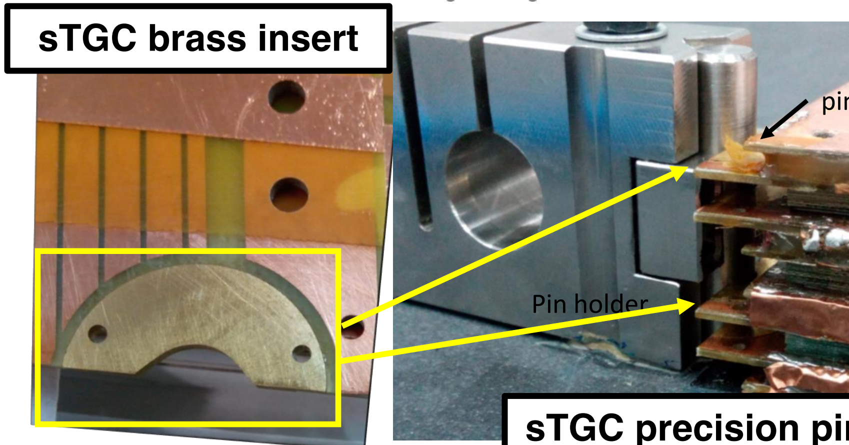
Figures: CERN-LHCC-2013-006

Detector production

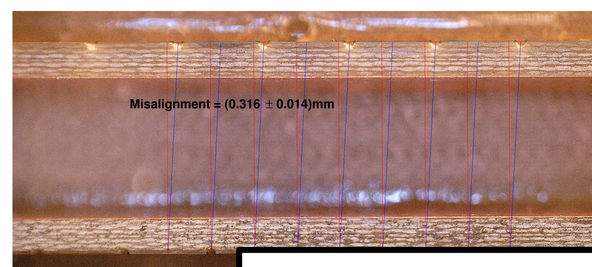
- sTGC and Micromegas are **trigger and precision detectors** manufactured with **stringent tolerances** on the geometry and location of readout strips.
- The planarity of the assembly is crucial for a uniform detector gain.
  - Most assembly steps carried out on a flat granite table.
  - All boards and frames controlled for thickness.
- Excellent alignment of strip boards required for a precise muon track reconstruction.
  - sTGC strip boards aligned using brass inserts and precision alignment pins.
  - Micromegas strip boards aligned with precision dowel pins.
- **Deviations from nominal of detector components known to within ~100 microns to meet the NSW specifications.**

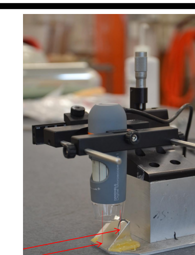
sTGC strip dimensional control with a CMM machine

sTGC brass insert



sTGC precision pin

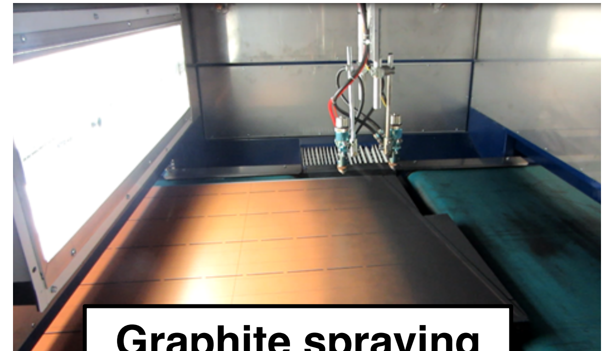




sTGC strip misalignment measurement with microscope

sTGC production
Overview

- Cathode board production in collaboration with industry.
- Quadruplet assembly: 5 production lines
  - Valparaiso/Pontifical, Chile (S1)
  - Shandong, China (S2)
  - TRIUMF/Carleton/McGill, Canada (L2,S3)
  - Weizmann/TAU/Technion, Israel (L1,S3)
  - PNPI, Russia (L3)
- Wedge assembly and final testing at CERN

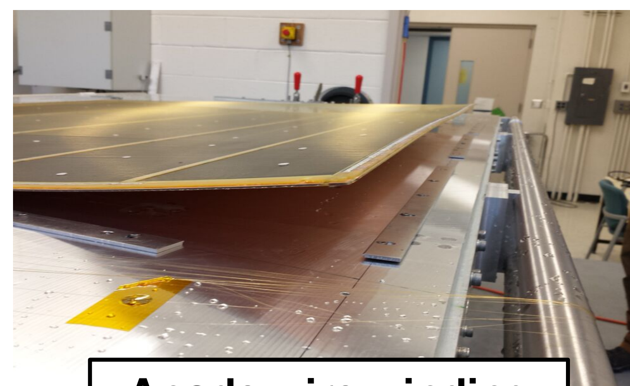


Graphite spraying

Graphite polishing

sTGC Wedge Assembly

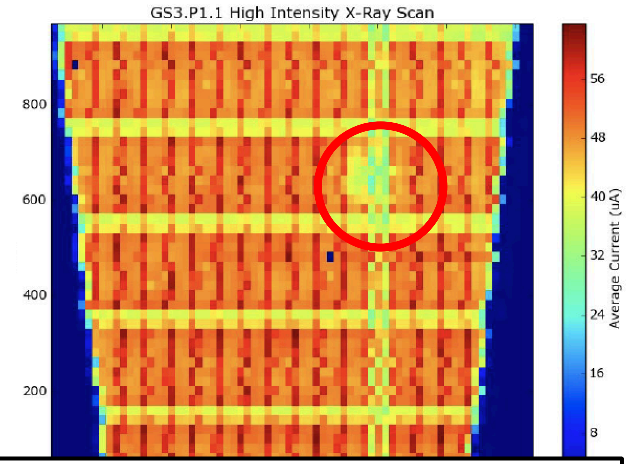
Finished QS3 quadruplet



Anode wire winding

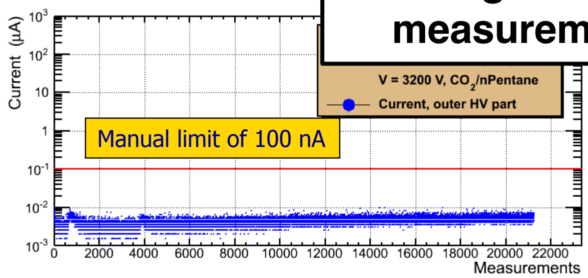
sTGC production
Status

- Quadruplet prototype produced in all construction sites.
- Production is well underway in all construction sites.
  - Production of cathode boards and other parts in parallel.
  - More than 50% of cathode boards manufactured to this day.
  - End of cathode board production in Fall 2018.
- First prototype sTGC wedge complete.
  - Wedge production will start this Summer.
- QA/QC tests have been defined for assembled detectors:
  - x-ray scan
  - cosmic-ray testing

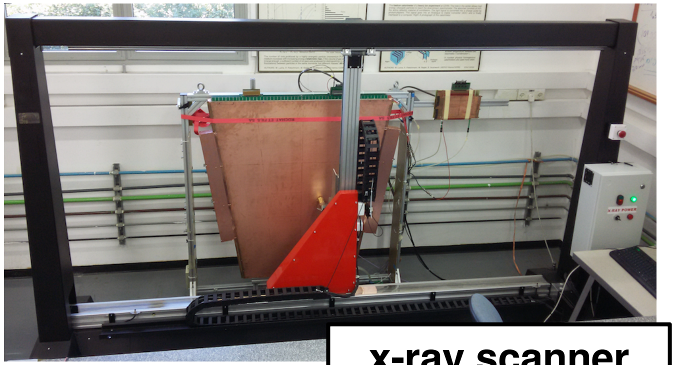


x-ray gain uniformity map

Leakage current measurement



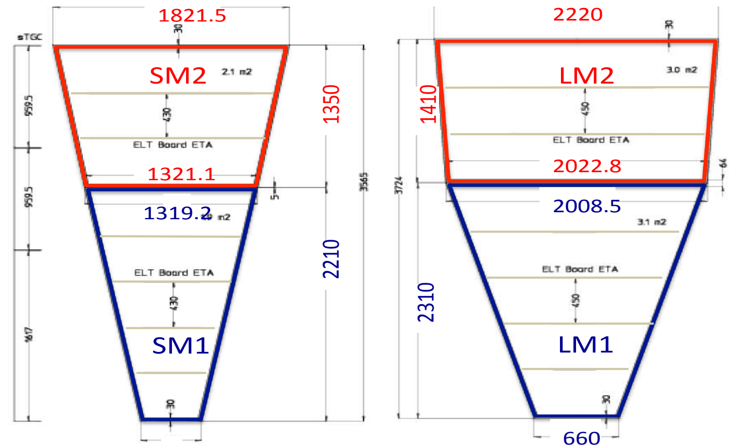
Cosmic-ray testing facility



x-ray scanner

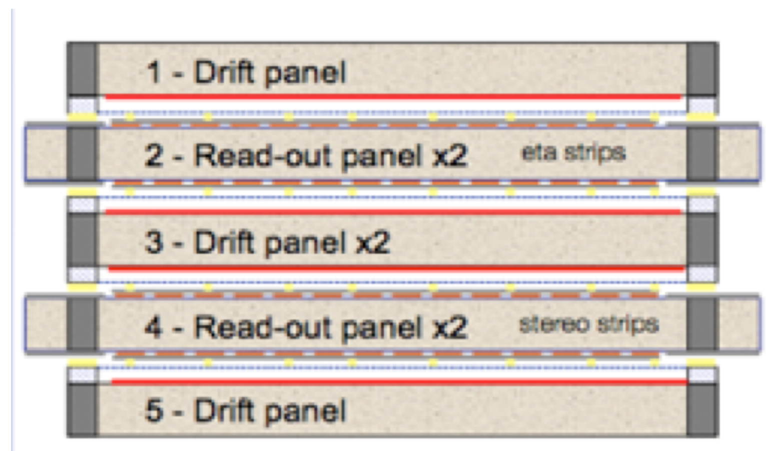
Micromegas production
Overview

- 2200 readout (RO) boards production in PCB factories.
- Quadruplet assembly in 5 production lines
  - INFN, Italy: SM1
  - BMBF, Germany: SM2
  - Paris-Saclay, France: LM1
  - JINR, Russia: LM2
  - Thessaloniki, Greece: LM2
- CERN is a central point for quality control and procurement.



Micromegas wedges

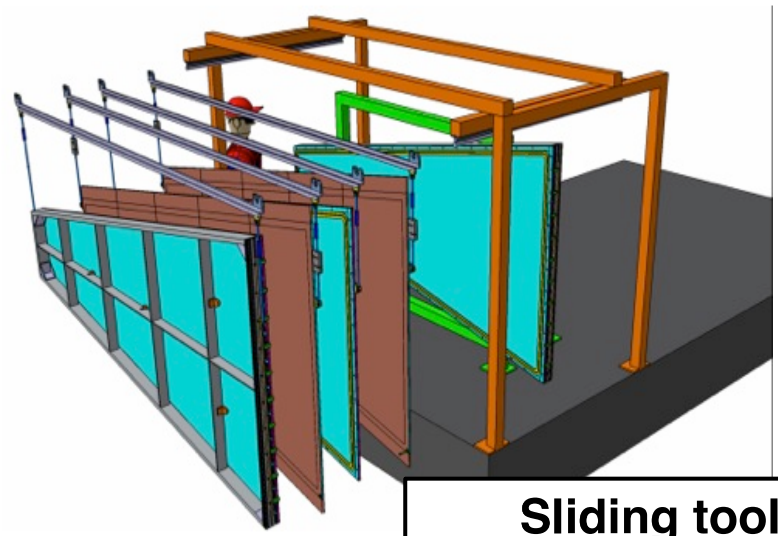
LM1/SM1: 5 PCB RO boards
LM2/SM2: 3 PCB RO boards



Micromegas cross-section

Micromegas production
Status

- ~50% of readout boards ready for quadruplet production.
  - Entered series production of drift and readout panels.
- Quadruplet production has started in construction sites.
  - Completion of first production module in all construction sites.



Sliding tool for quadruplet assembly

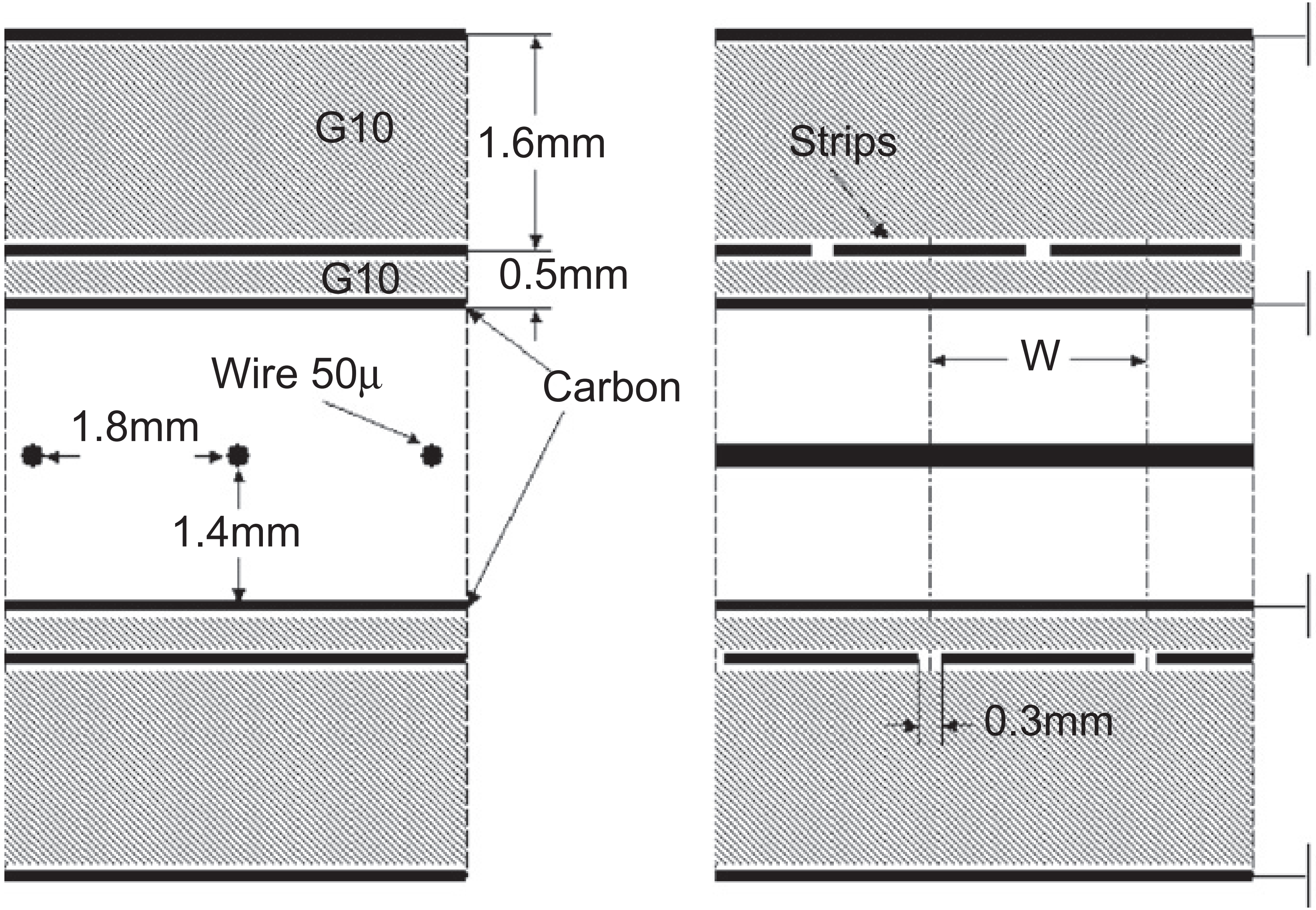
Gluing of mesh frame

Mesh stretching

Summary

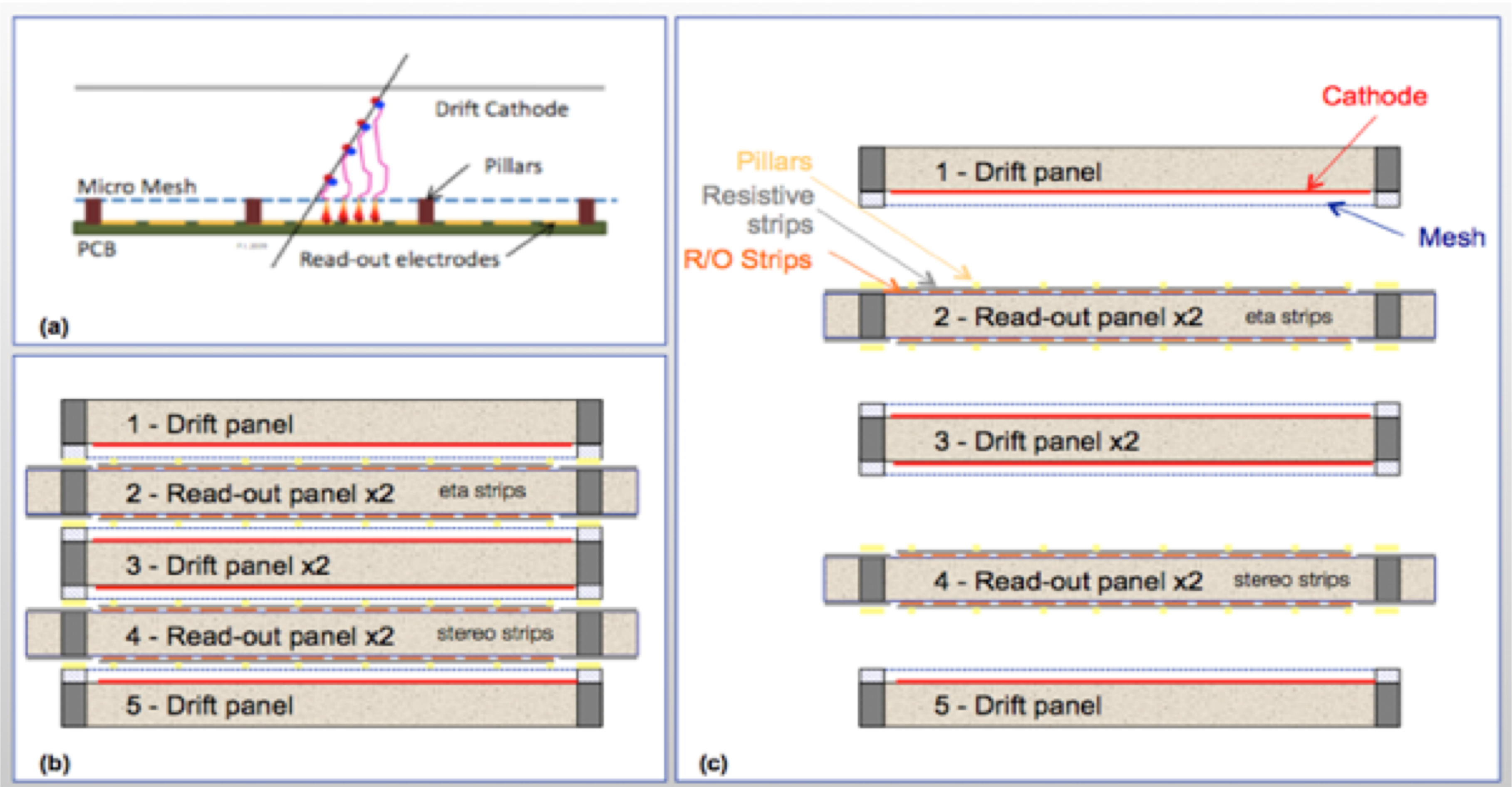
- Incremental upgrades of the LHC are planned.
  - Five to seven fold increase in luminosity expected.
  - More physics opportunities for the LHC experiments.
- The Phase-I upgrade will improve the online muon identification capabilities of the ATLAS detector in anticipation of the increased LHC luminosity.
- The NSW combine the sTGC and Micromegas detector technologies.
- Detector construction is ongoing with stringent manufacturing specifications.
  - End of NSW installation scheduled by the end of LS2.

Back-up slides

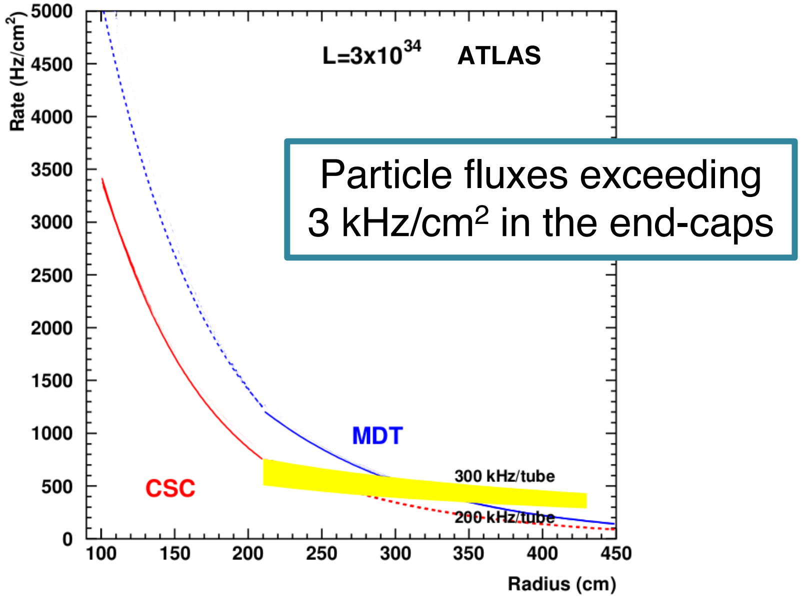


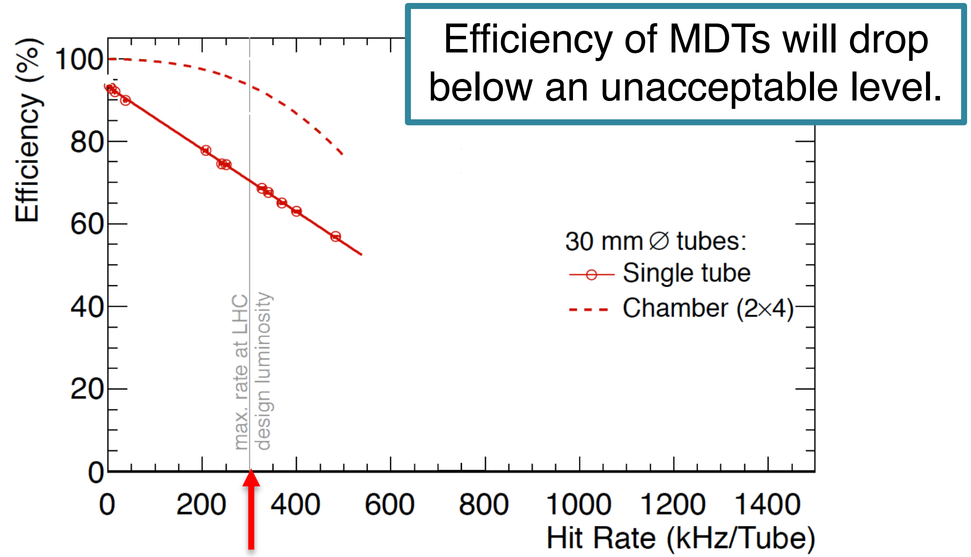
Cross-section of a sTGC gas volume

Cross-section of a Micromegas quadruplet



Muon detectors high-rate performance





Rate per tube at
$\mathcal{L} = 1\times10^{34}$ **cm^{-2} s^{-1}**

- Performance of muon end-cap detectors compromised by the high particle fluences expected at high luminosity.
- Current muon detector technologies reaching rate limitations:
  - Cathode Strip Chambers (CSC)
  - Monitored Drift Tubes (MDT)
- The expected performance degradation of end-cap detectors at high LHC luminosity will impact the trigger efficiency and precision of physics measurements involving muons.

Figures: CERN-LHCC-2013-006

ATLAS Muon Detectors