# HF Muon Detector R&D

US-HFCC-muons@cern.ch in CERN e-groups.cern.ch

The US institutes expressed interest

Boston University,
Brookhaven National Laboratory,
Florida Institute of Technology,
Harvard University,
Jefferson Lab,
Michigan State University,
Northeastern University,
Tufts University,
SLAC,
University of California, Davis,
University of California, Irvine,
University of Florida,
University of Massachusetts, Amherst,
University of Michigan,
University of Wisconsin.

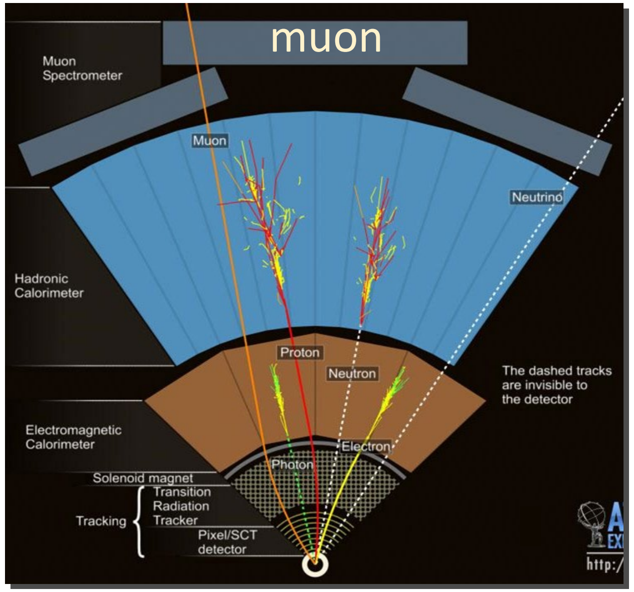
# Muons – Principal signal for discovery

Muon identification and detection in colliding beam experiments

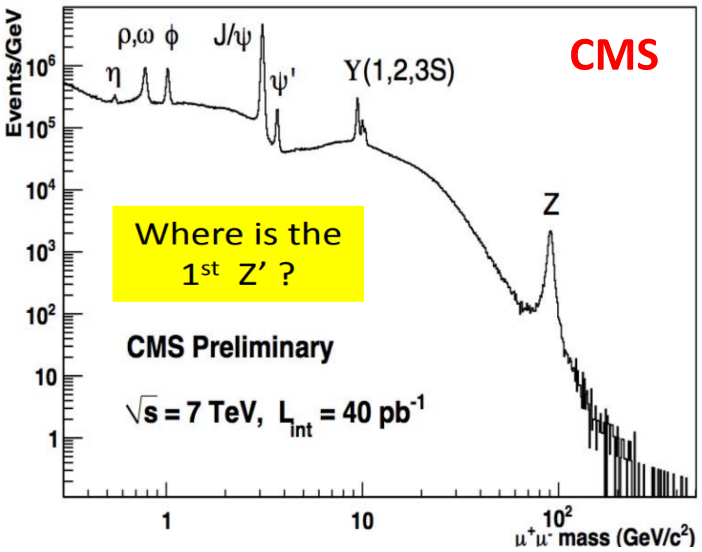
- Tracking (trigger) System, the outmost part of a detector (large volume)
- Front-end electronics (fast timing, and charge measurements)

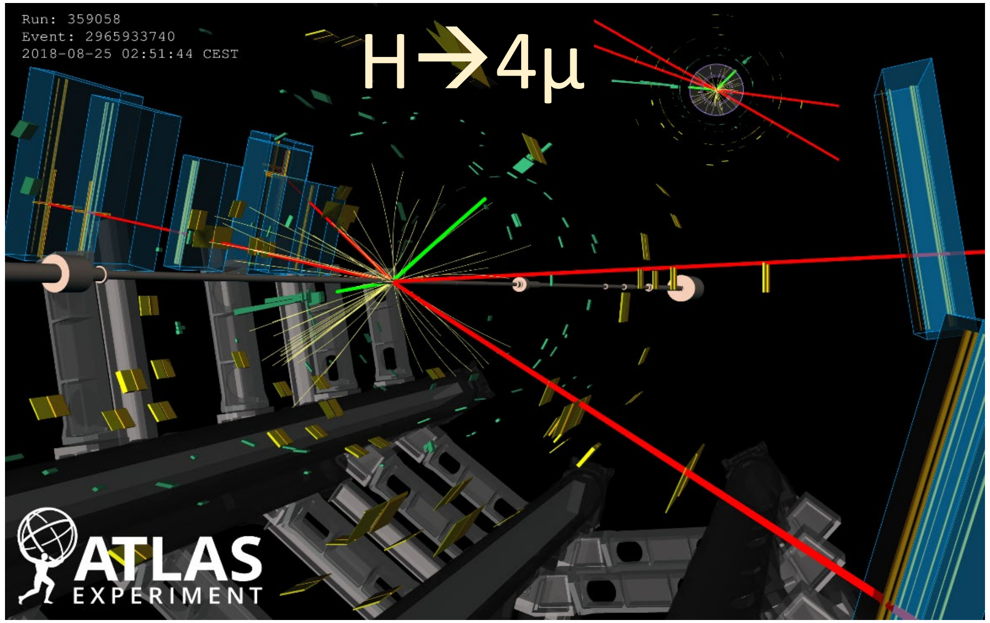
Combined with

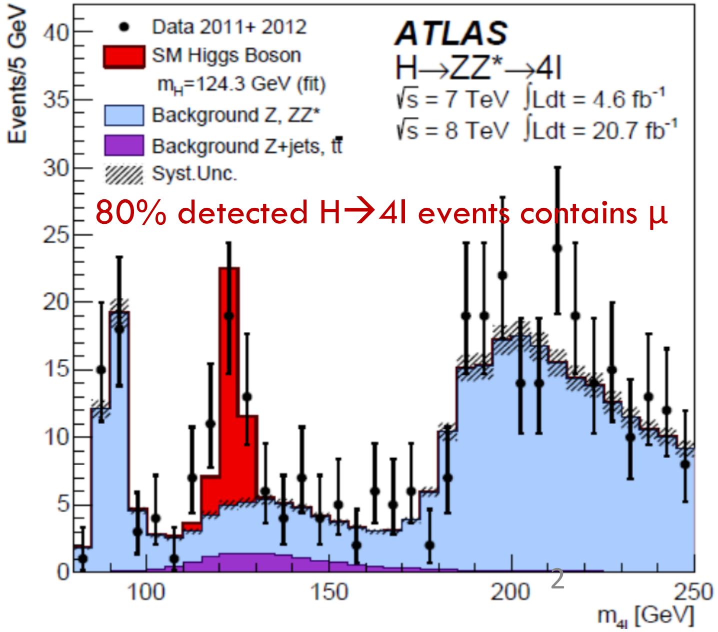
- Central tracker with interaction vertex determination
- EM/Hadron calorimeter & muon filter
- Magnetic field(s)




Standard candles



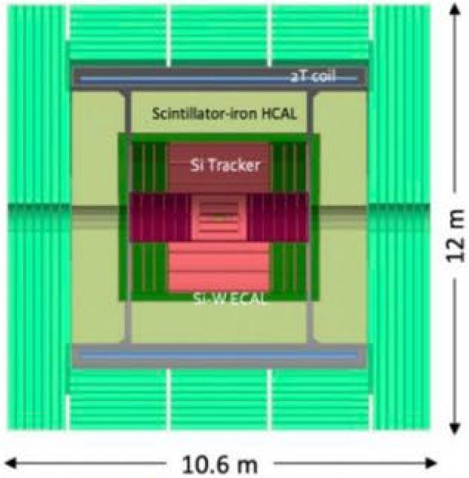



# Detector concepts for experiments at FCC-ee

https://indico.cern.ch/event/1291157/contributions/5888444/attachments/2900747/5086820/Abbrescia@ICHEP2024.pdf

ICHEP2024

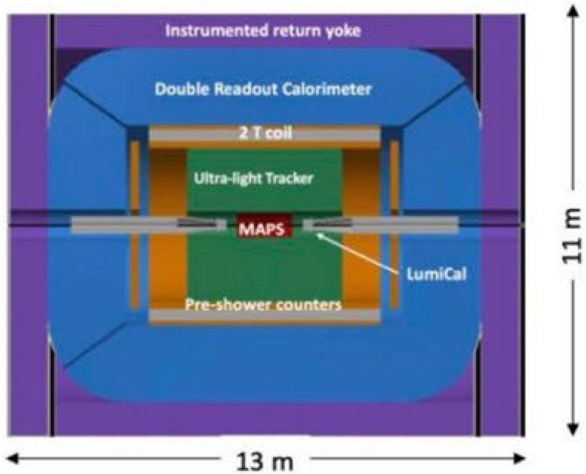
## CLD




- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system (RPC)
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - $\sigma_p/p$, $\sigma_E/E$
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

CDR

## IDEA

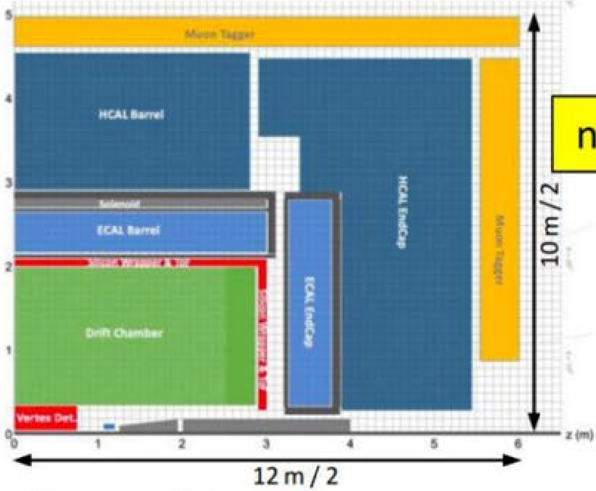



- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system (μ-RWELL)
- Very active community
  - Prototype designs, test beam campaigns, …

## ALLEGRO

## Noble Liquid ECAL based

new



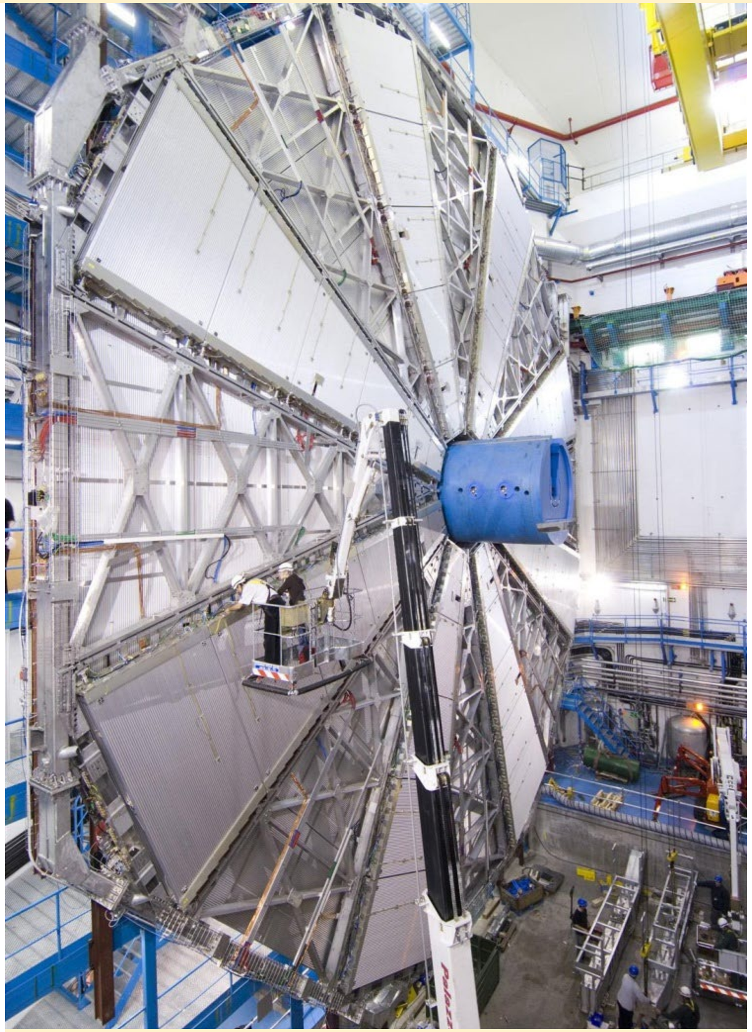

- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system. (**open in technology choice**)
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

# The FCC-ee Muon System R&D

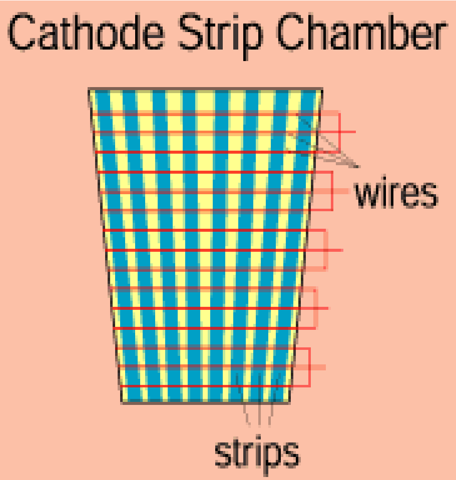
- The muon system is the largest sub-detector in colliding beam experiments. In the context of the FCC-ee detector concept design studies, the technology choices remain largely open, particularly for the new ALLEGRO experiment.
- US institutes possess strong technical expertise in muon system design and construction, drawing from experience with past and current high-energy physics experiments.

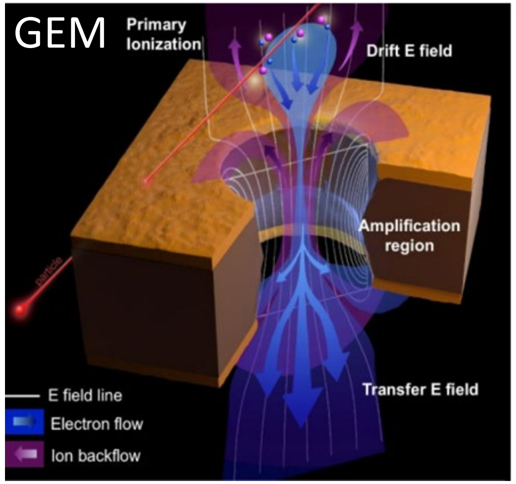
ATLAS precision muon detectors: **MDT** & **CSC**



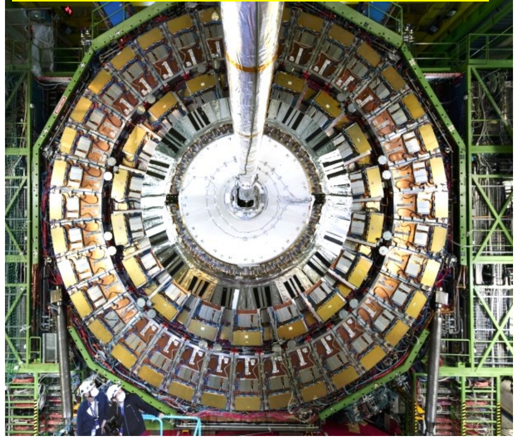
ATLAS Big Wheel MDT Muon detector built in the US

CMS precision endcap muon detectors: **Cathode Strip** & **Triple-GEM**




Endcap CSC disk Built by US



# The FCC-ee Muon System R&D

- ❖ Our highest priority is to develop robust, large-area muon/gaseous detectors with fast timing and high spatial resolution. The initial R&D will focus on the muon detector and electronics technology choice for the FCC-ee experiments
- ❖ Proposed R&D for FY2025, with modest funding request

**There are three muon detector R&D areas (L3's) in the US**

- **Drift tube based detector**
  - Study DT chamber gas mixture to meet the Eco-friendly gas requirement
  - Build 1" square drift tube prototype to study the resolution and efficiency, combined with gas studies
- **μ-RWELL (MPGD) based detector**
  - Begin developing MPGD production capabilities in the US
  - Study eco-friendly gas mixtures for μRWELL
- **Electronics for muon detection**
  - Study extensions of current drift tubes to satisfy 3D tracking & trigger requirements
  - Investigate new low-power electronics with precise timing resolution

# The Drift Tube Muon Detector R&D for HF

- **Simple, Robust,** and **inexpensive** suitable for large scale construction
- Capable of achieving **< 200 μm single wire resolution** for all muon incident angles
- Capable of determining $T_0$ with triggerless readout mode with ~ns time resolution, determine BCID

The proposed R&D with high priority; modest funding request in FY2025 ($50k)

- **Study of chamber drift gas mixture**
  - Climate change a growing concern; Greenhouse Gas emissions is one of the major problems. The search for new environmentally friendly gas mixtures is necessary to reduce GHG emissions and costs as well as to optimize detector's performance (alternative gas: $C_2H_2F_4$, $SF_6$, $CF_4$,…).
  - **build a four-channel gas mixture system to test various gas mixture performance on prototype DT chambers**
  - Using the existing MDT (sMDT) detector prototypes and the ATLAS MDT front-end electronics to study different gas mixture with cosmic rays and test beams, comparing with the ATLAS MDT performance (efficiency, resolution)

- **Construct and study the squared drift tube performance**

- **Build a prototype chamber** by using the existing UM squared-drift tubes to with redesigned end-plugs to locate wire with high precision, in a configuration of 2 multi-layers, each has 4 drift tube layers. To develop and study
  - An efficient wiring process with high precision, including an on chamber gas system
  - Measure the spatial resolution and efficiency using the ATLAS MDT electronics and MiniDAQ system with cosmic rays and test beams
  - Compare the test results with Garfield simulations

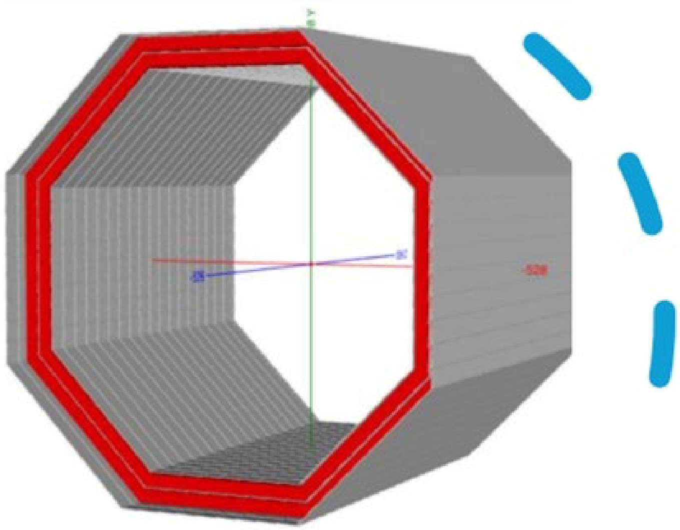
# The µRWELL Muon Detector R&D for HF

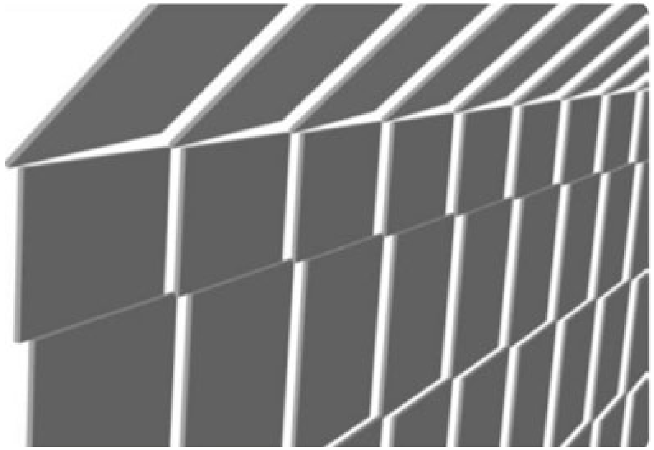
- A modern micro-pattern gas detector (MPGD) with single amplification stage
- Currently proposed by IDEA experiment for muon system

The Proposed R&D with high priority; modest funding request in FY2025

- **Begin developing MPGD production capabilities in the US**
  - Currently only CERN can provide MPGD components
  - Lead times for procurements are long (6-12 mos.) and increasing
  - Efforts in the past decade to develop commercial vendors (TechEtch, Mecaro, Tectra) have failed; presumably market too small
  - A national lab would be an appropriate location for a fabrication site to supply US researchers; JLAB is interested in developing a fabrication site
  - Use funding to enable JLAB to transfer MPGD production technology from CERN. Longer-term effort => need to start now to have production capability (even just for R&D) in a few years.
- **Study eco-friendly gas mixtures for µRWELL**
  - Using a gas mixing station developed with FY24 US-HF funds measure performance stability of small µRWELL as function of gas composition; in particular attempt to minimize $CO_2$ concentration.

IDEA Muon system

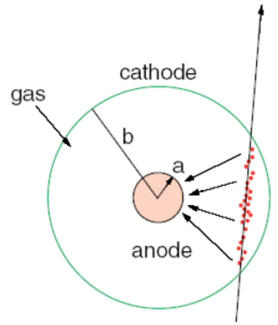


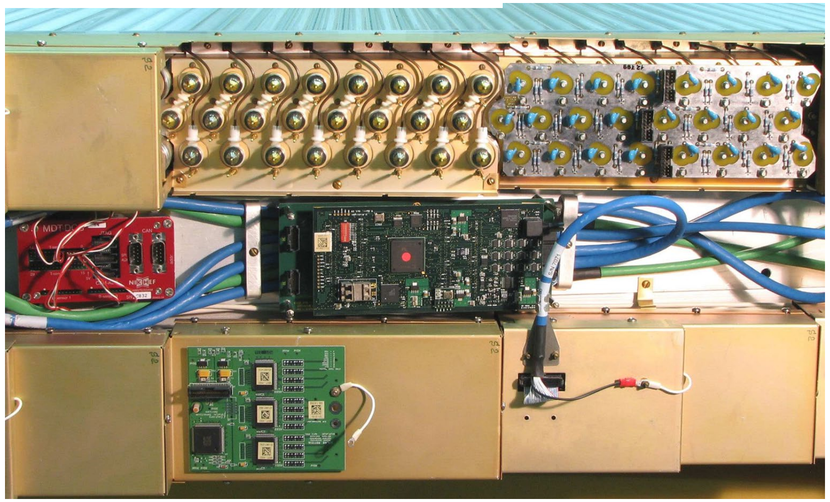


50cm x 50cm µRWELL modules

# The Muon Detector Electronics R&D

- Capable of **3D** tracking achieving **< 200 µm single wire resolution** and <**1cm in 2nd coord (along tube)**
- Capable of **trigger:** determining $t_0$ with triggerless readout mode with <ns time resolution, determine BCID



The Proposed R&D with high priority; modest funding request in FY2025 ($50k)

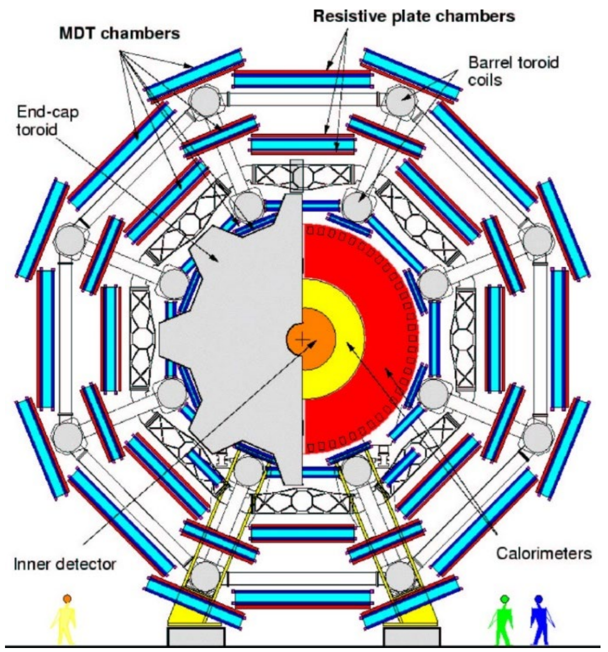
- **Study extensions of current drift tubes to satisfy 3D tracking & trigger requirements – would make it possible to use drift tubes as single technology for muons**
  - Explore use of drift tubes for 3D tracking, including the non-precision 2nd coordinate (along the tube direction. Investigate how to read out signal from both ends (currently only one is used) and extract position from time difference. **Study signals in simulation, build design and prototype new electronics hedgehog card**
  - Read out MDT signals using triggerless streaming mode and build events for data recording in an FPGA with **BCID determination using current electronics**
  - Study signals from **alternative gas choice and geometry** (e.g. square tube) and investigate changes in the **electronics requirements** using simulations.
- **Investigate new low-power electronics with precise timing resolution**
  - Simulations for pathfinding toward future low-power digital TDC designs with sub-200ps measurement resolution. Improved position and timing resolution for tracking and triggering.

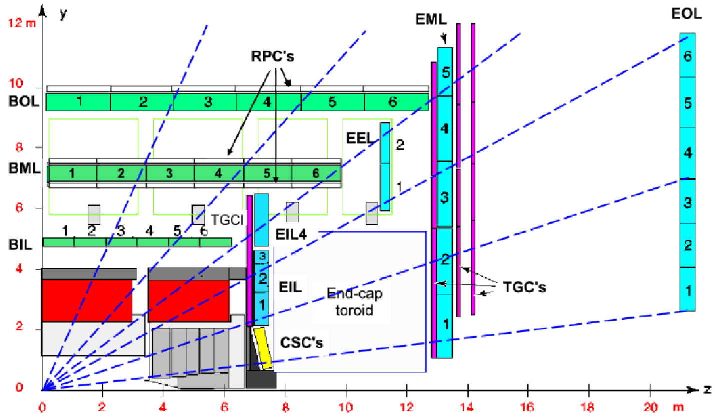
- Spare slides

# US Muon Expertise - ATLAS Muon Spectrometer

Precision muon detectors: Monitored Drift Tube (MDT) chambers +CSC

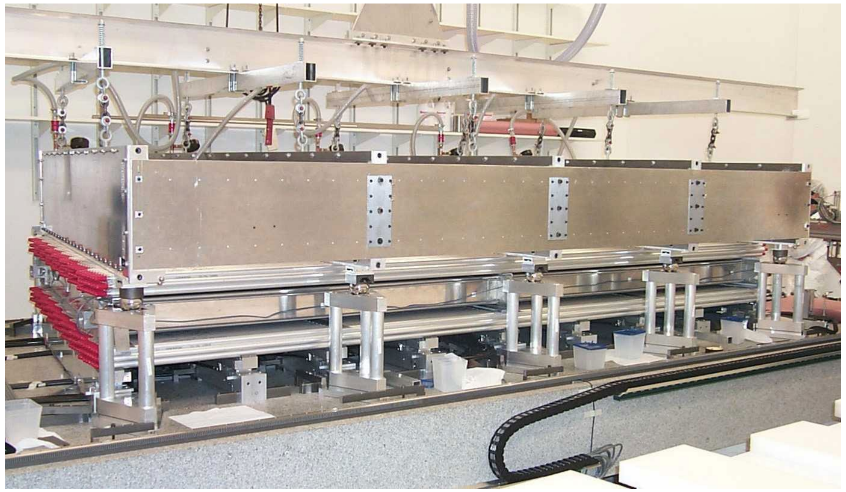
MDT Drift gas: Ar:CO2 (93:7), p=3 bar, max drift time 750 ns



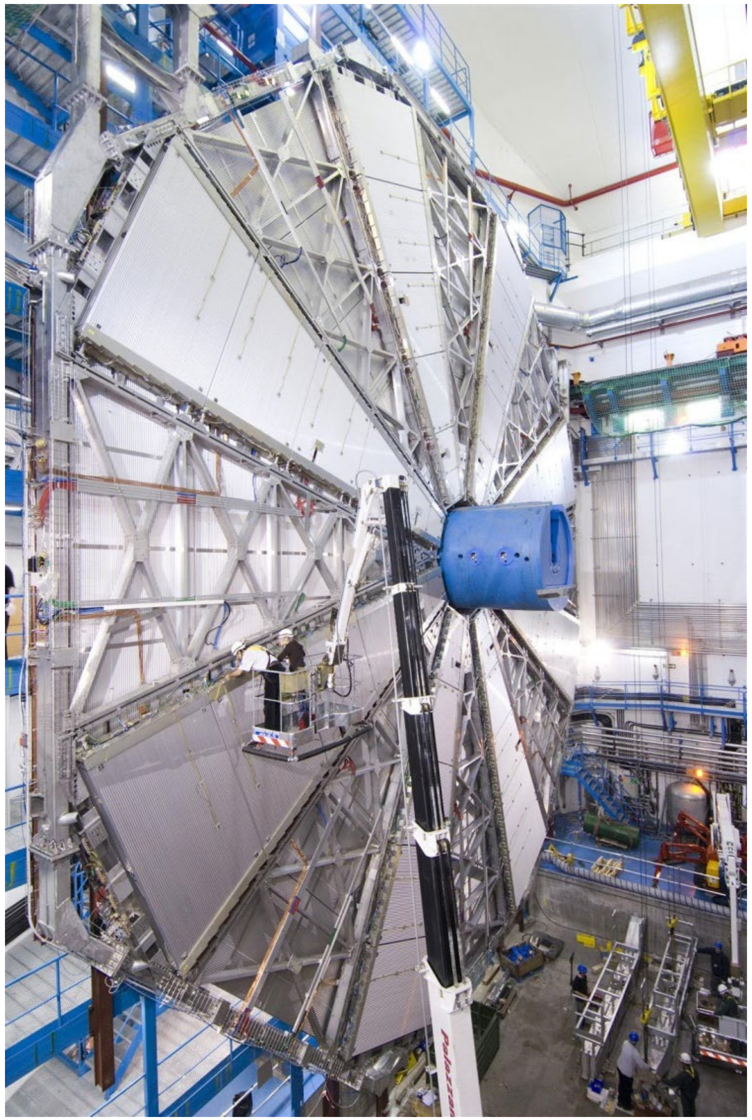




Magnet: Solenoid (inner) + Toroid (outer)

Muon MDT chamber, tube d=3 cm, 80µm/wire



Large chamber construction at UM

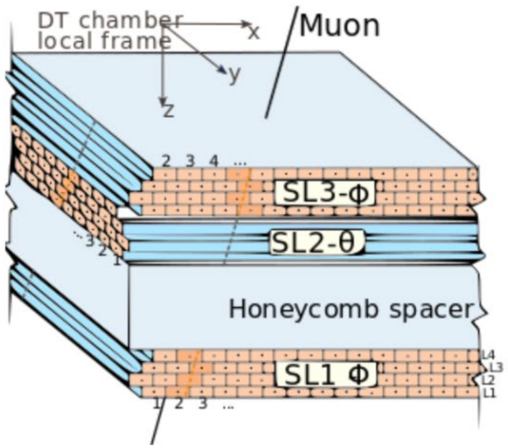


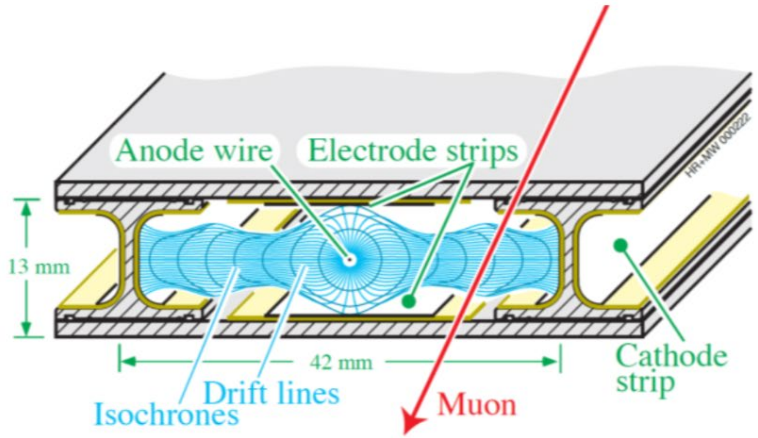
Big Wheel (endcap) built in the US, installation in ATLAS

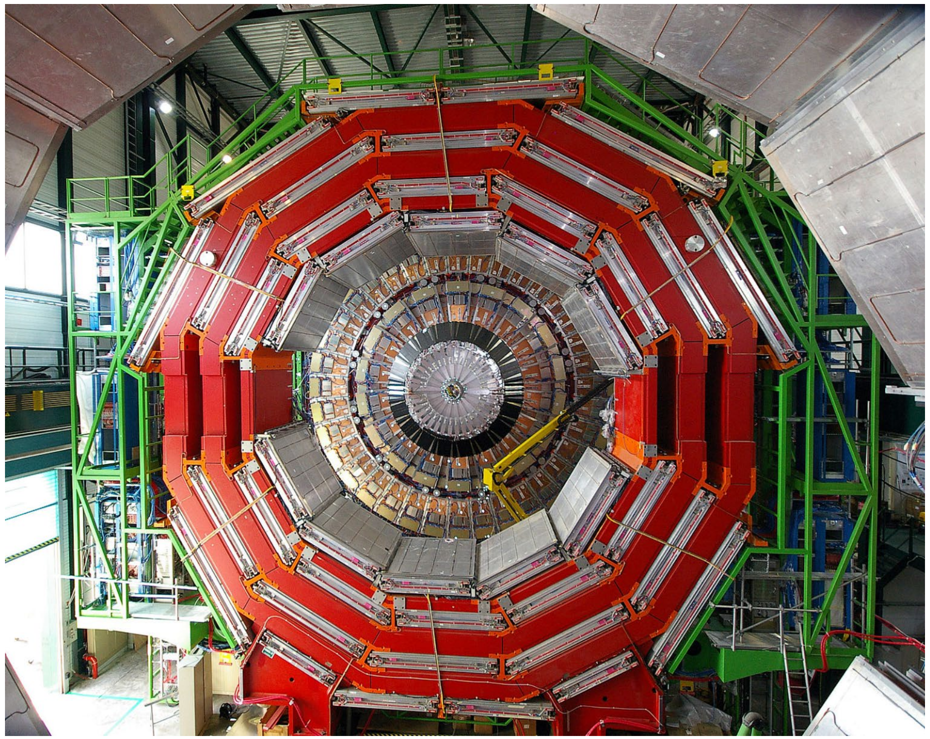
# The CMS Muon Spectrometer

CMS precision muon detector: Squared Drift Tube chambers (barrel)

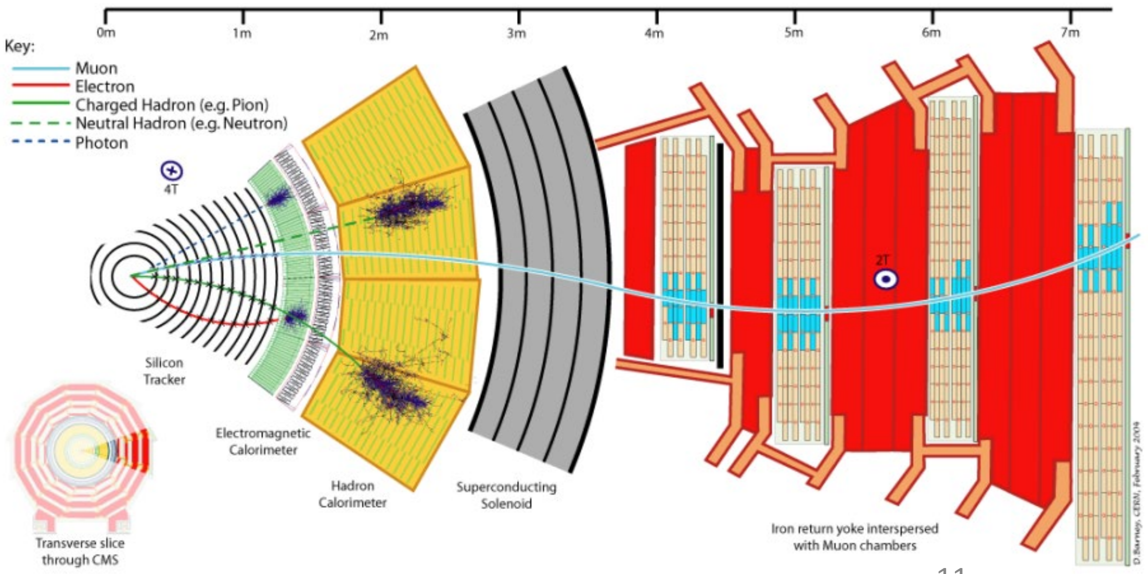
Drift gas: Ar:CO2 (85:15), max drift time 380 ns



The sizes of drift tube chambers range from 2m x 2.5m to 4m x 2.5m, approximately. Each chamber consists of 8 or 12 aluminum layers, arranged in two or three superlayers, each up with up to 90 tubes: the middle superlayer measures the coordinate along the direction parallel to the beam and the two outside superlayers measure the perpendicular coordinate, thus providing a combined 3D measurement of the muon track.



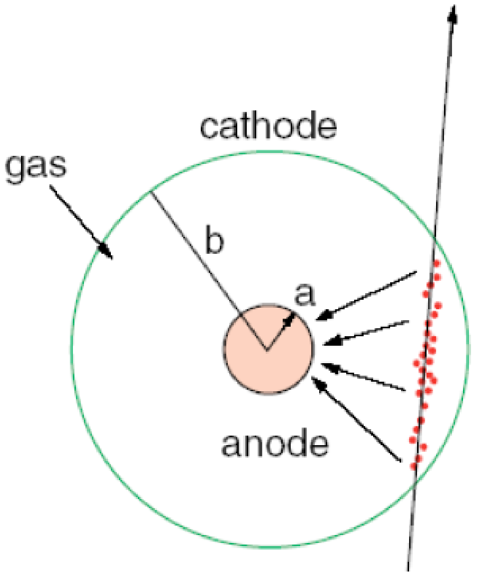

Cell resolution < 250 µm, chamber resolution~100 µm

Magnet: Solenoid (inner) + Ion return York

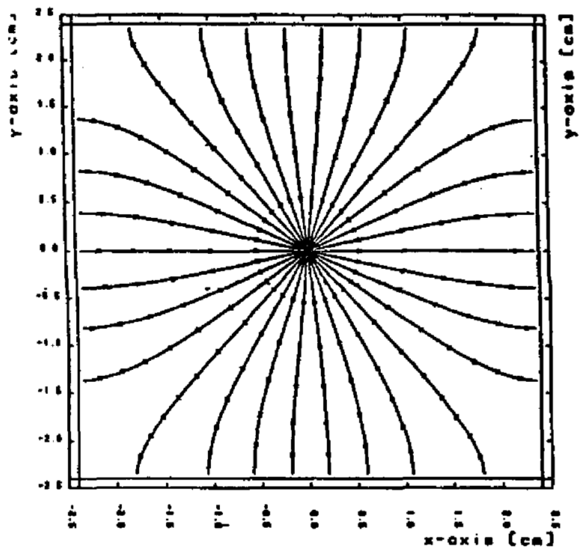
# Drift tube shapes and the electric field lines

ATLAS round tube

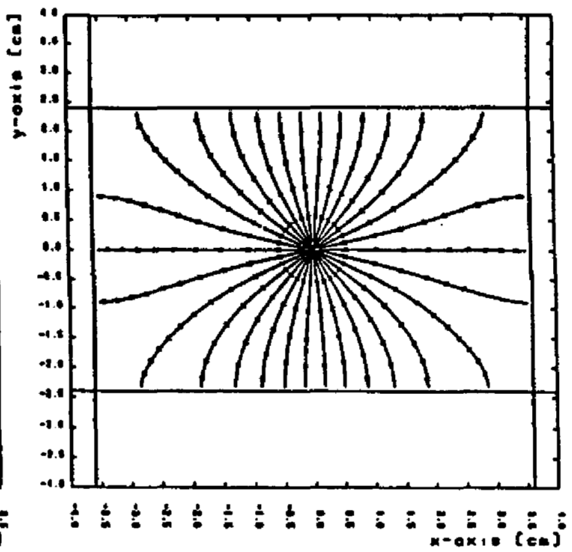
Tube diameter: 3 cm
Length: 1 – 6 meters
Gas pressure: 3 Bar
Anode wire HV=3080V
Gain: 20,000



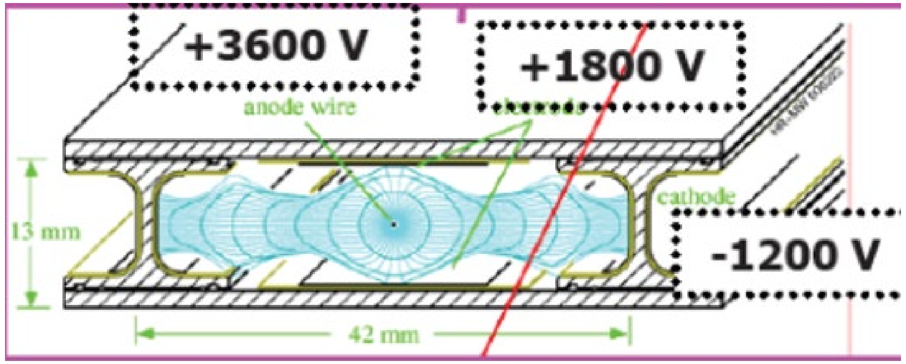

Squared tube

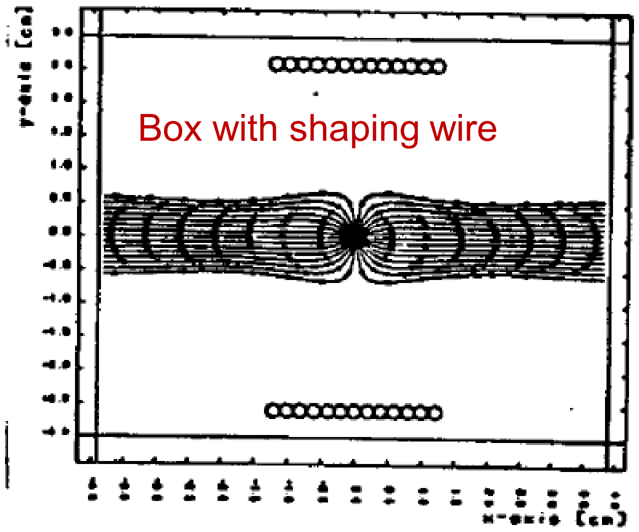


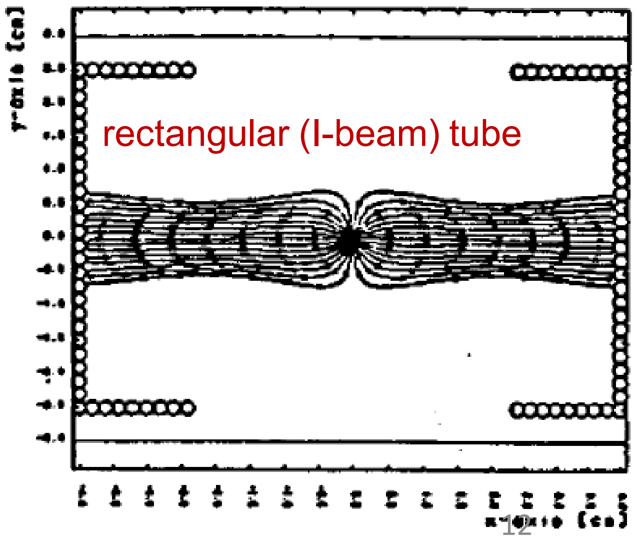

rectangular tube




CMS rectangular (I-beam) tube (2.5 – 4 m long)

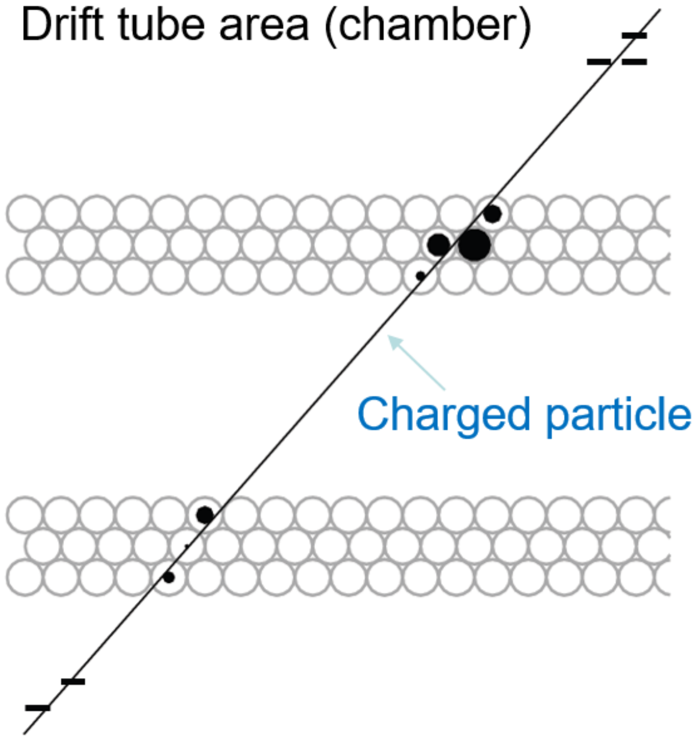


# Tracking of the Round and Squared tube Chambers

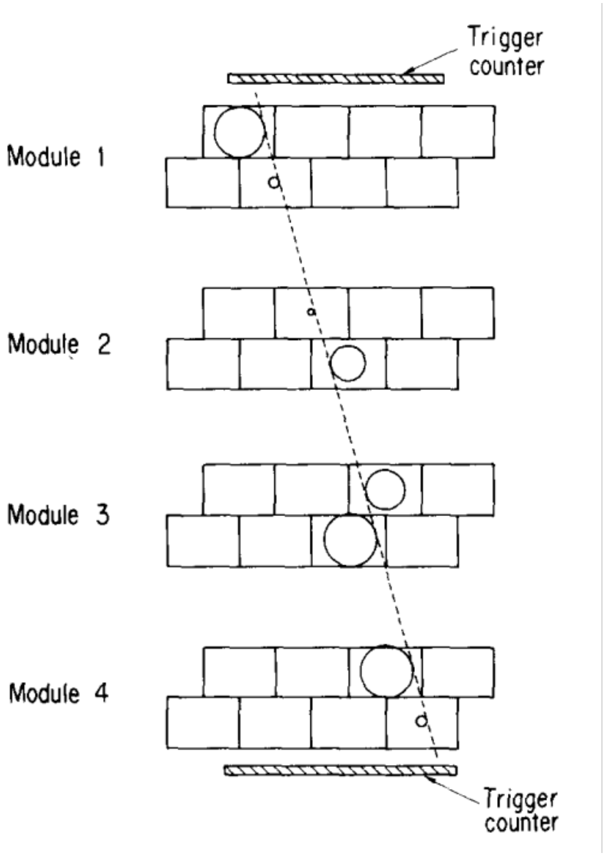
**Simple** and **inexpensive**




**Record drift time**

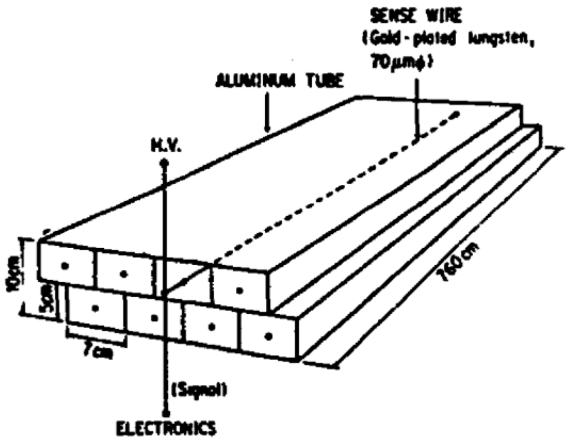
**Covert to drift distance**

ATLAS MDT chamber cosmic ray test



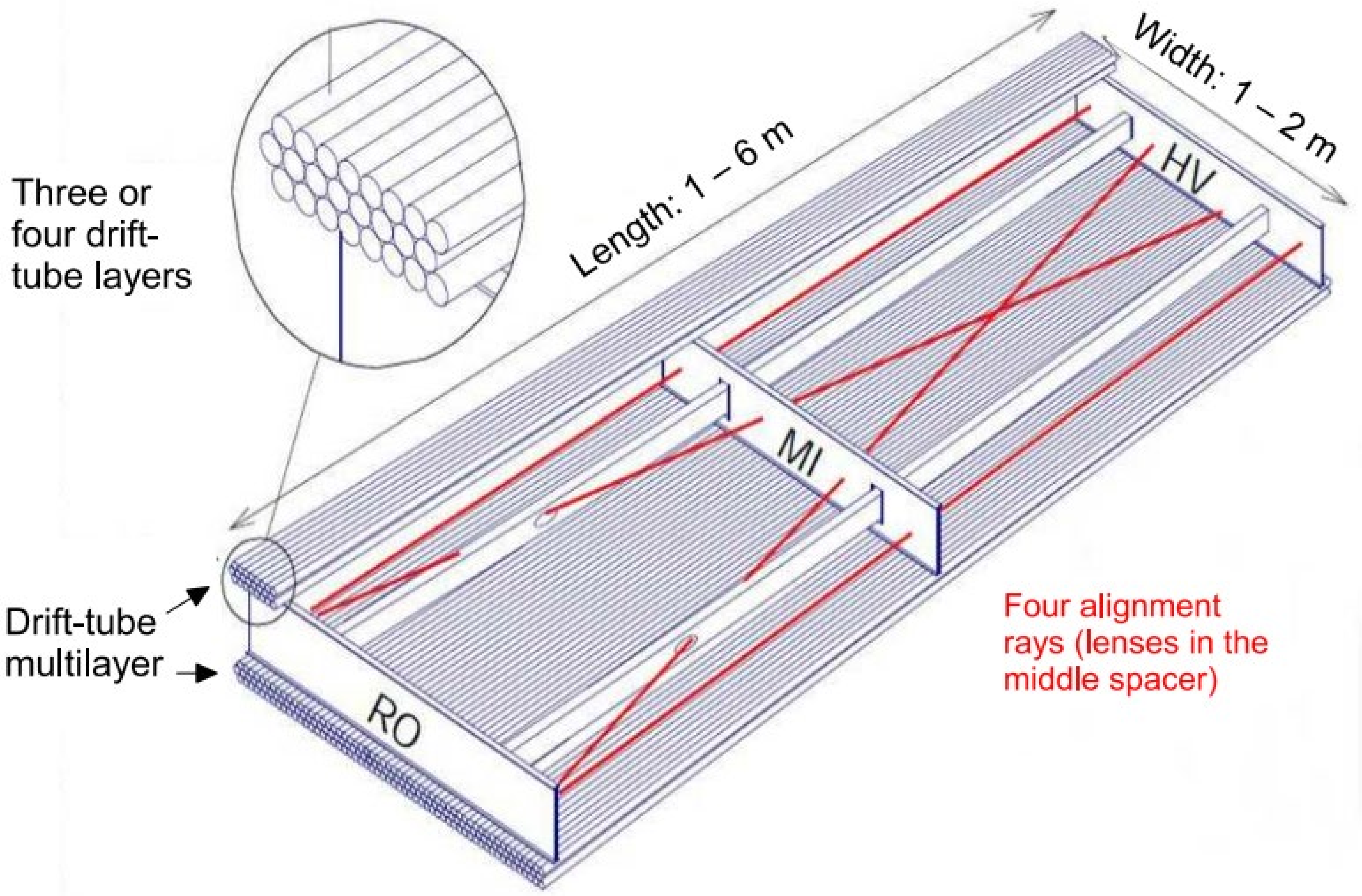

Y. Asano et al NIM A259 (1987) 430

Cosmic ray tests of 7.6 m drift-tube counters and the readout electronics system of the VENUS muon detector




1” Squared tube area at UM

# ATLAS MDT chamber



# R&D – Study of Chamber Drift Gas

The total chamber gas volume of the muon system is very large. If filled with 50/50 Argon/Ethane (UA1, L3, CDF, ZEUS,…) more than one ton of ethane gas are needed. However, thus saturated gas mixtures (linear RT function) contain large portions of hydrocarbon, the safety requirements may prohibit their use.

The non-explosive Argon/$CO_2$ are non-saturated gas mixture (non-linear RT function) and widely used at the LHC experiments. However, experiments use gas mixtures mainly due to their properties necessary for optimal detector performance and long-term operation. The drift velocity in a non-saturated gas mixture is strongly affected by the electric field uniformity, the gas mix fractions, and the environment factors (temperature, pressure, RH). The chamber electrical stability is also worse without hydrocarbon quenchers. The gas gain has to be relatively low resulting in small signal size. All these disadvantages of non-saturated gas mixture make the chamber design more difficult.

Climate change a growing concern; Greenhouse Gas emissions is one of the major problems. The search for new environmentally friendly gas mixtures is necessary to reduce GHG emissions and costs as well as to optimize detector/s performance (alternative gas: $C_2H_2F_4$, $SF_6$, $CF_4$,…).

**We plan to build a four-channel gas mixture system to test various gas mixture performance on prototype DT chambers**

# R&D – Study the Drift Tube Detector Performance

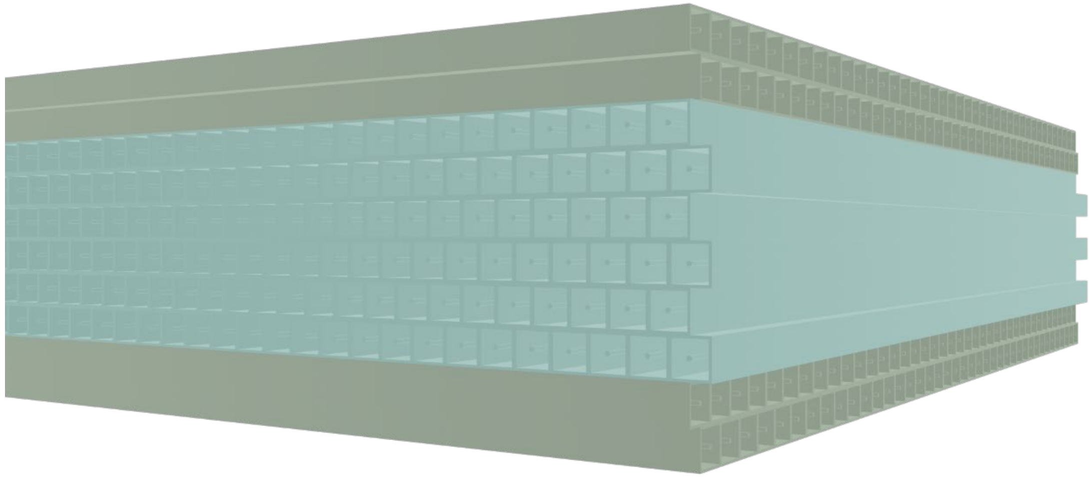
- Using the existing MDT (sMDT) detector prototypes and the ATLAS MDT front-end electronics to study different gas mixture with cosmic rays and test beams, comparison with the ATLAS MDT performance (efficiency, resolution) with the "standard" ATLAS gas mixture and operation working points (HV, gain, threshold…)

- **Using the UM squared-drift tube areas (1" square tubes) to build a prototype chamber with redesigned end-plugs to locate wire with high precision, in a configuration of 2 multi-layers, each has 4 drift tube layers. To develop and study**
    - An efficient wiring process with high precision, including gas system
    - Measure the spatial resolution and efficiency using the ATLAS MDT electronics and MiniDAQ system with cosmic rays and test beams
    - Compare the test results with Garfield simulations

- Perform Garfield simulations on different rectangular drift tube performance

- Find vendors to produce the rectangular drift tube areas and compare the costs

- Study the configuration of the muon detector layout and estimate channel numbers and costs



Planned squared-tube chamber prototype configuration

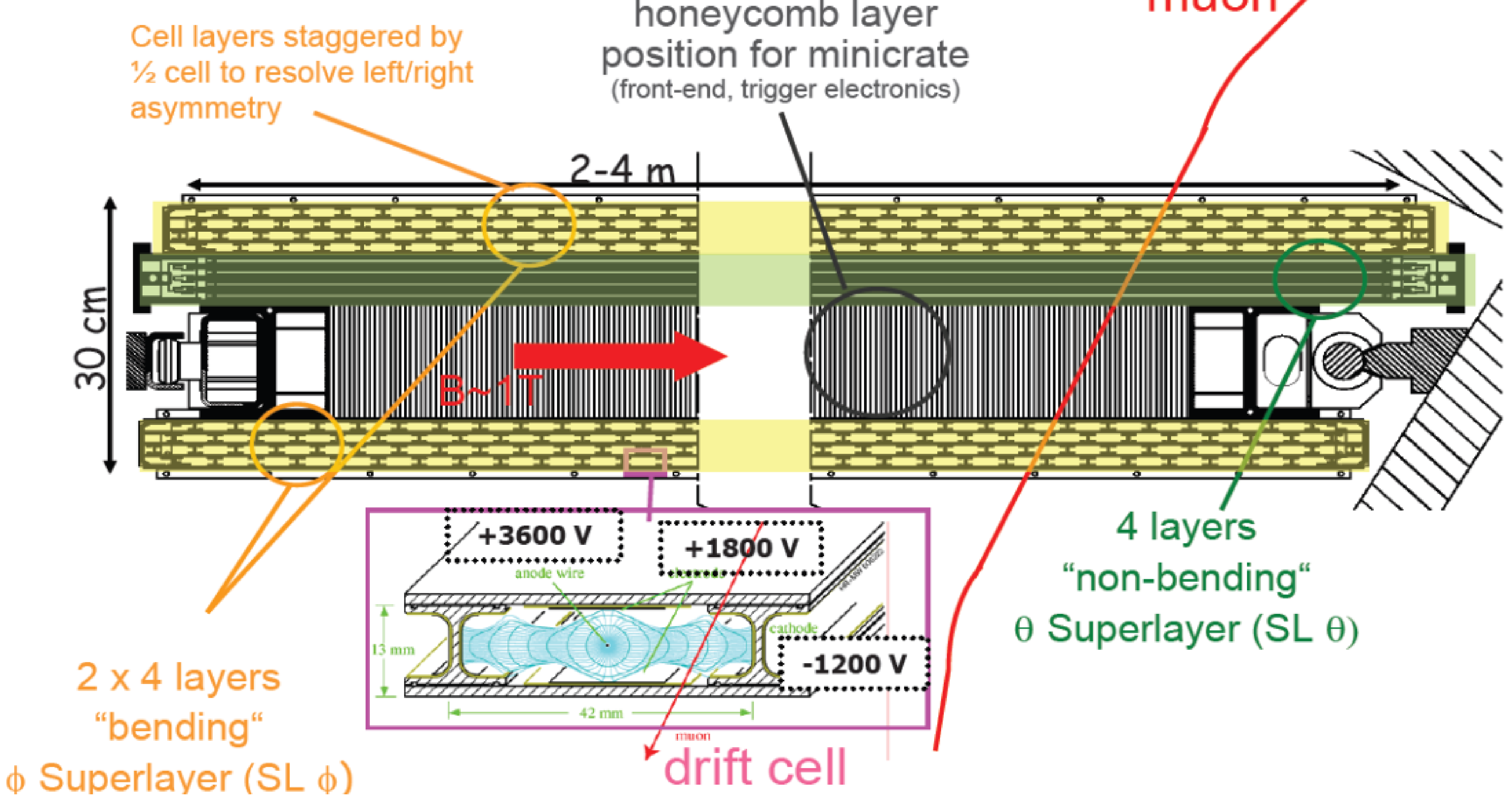
# CMS Drift tube muon chamber

12 layers per chamber: 4 z, 8 (r,$\phi$)

Gas: Ar(85%) $CO_2$(15%), max $t_{drift}$=380ns

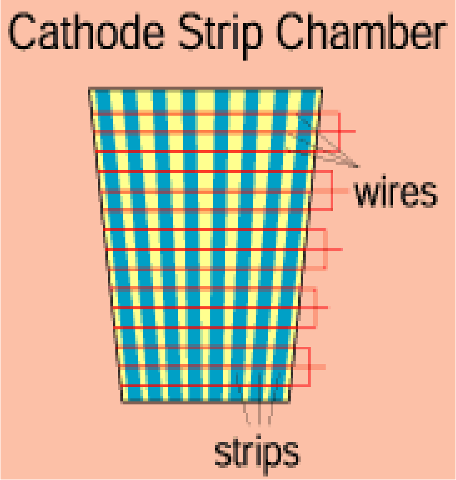
Cell resolution (r$\phi$) <250$\mu$m, chamber (r$\phi$) ~100$\mu$m

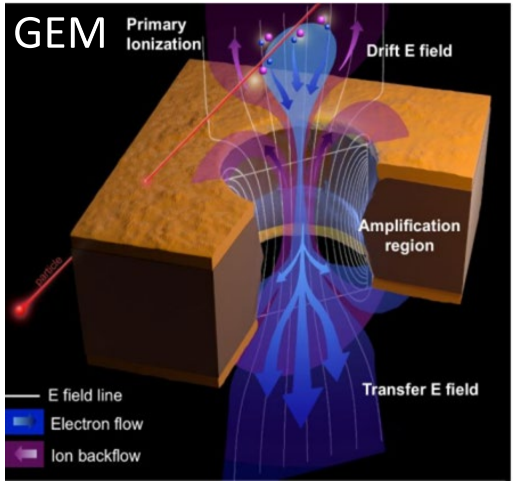
BX assignment efficiency >99%



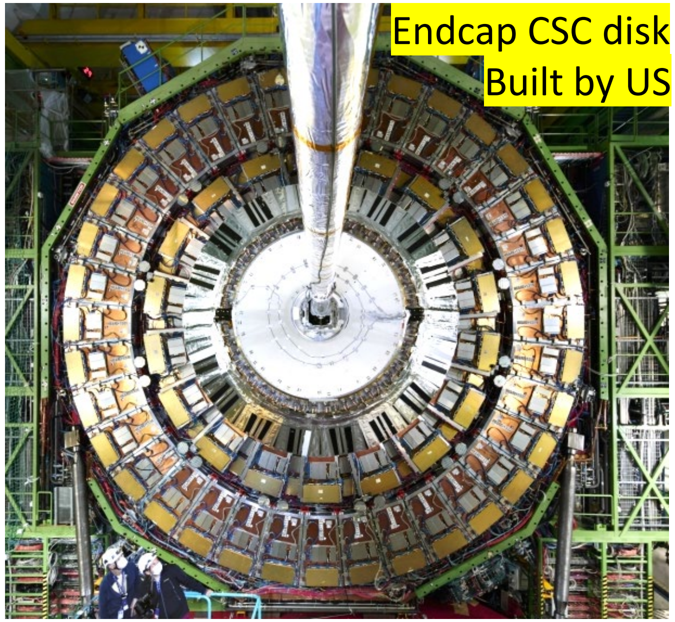
# US Muon Expertise - CMS Muon Spectrometer

CMS precision endcap muon detectors: **Cathode Strip** & **Triple-GEM** Chambers








| Muon subsystem | Cathode strip chamber (CSC) | Gas electron multiplier (GEM) |
|---|---|---|
| $\lvert\eta\rvert$ range | 0.9–2.4 | 1.55–2.18 |
| Number of chambers | 540 | 72 |
| Number of layers/chamber | 6 | 2 |
| Surface area of all layers | 7000 $m^2$ | 60 $m^2$ |
| Number of channels | 266 112 (strips) 210 816 (wire groups) | 442 368 |
| Spatial resolution | 50–140 $\mu m$ | 100 $\mu m$ |
| Time resolution | 3 ns | <10 ns |