# HFCC Muon Detector R&D

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L2s: Marcus Hohlmann hohlmann@fit.edu and Bing Zhou bzhou@umich.edu
L3s: Reinhard Schwienhorst schwier@msu.edu – Drift tubes + Scintillator strips
Klaus Dehmelt kdehmelt@jlab.org – MPGD/μ-RWELL
Verena Martinez Outschoorn vimartin@umass.edu – Muon electronics

## The US institutes expressed interests and their expertise

Boston University (ATLAS MDT, FE, L0MDT)

Brookhaven National Laboratory (ATLAS CSC, MM, ASIC)

Florida Institute of Technology (CMS Muon, GEM)

Harvard University (ATLAS MDT, FE, MM TP)

Jefferson Lab (MPGD/μ-RWELL facility)

Michigan State University (ATLAS sMDT)

Northeastern University (CSM End-cap Muon system)

Tufts University (ATLAS Muon detector alignment)

SLAC (ATLAS CSC TDAQ, Silicon FE, Scintillator strips, SiPM)

University of California, Davis (CMS Forward Pixels, endcap muon)

University of California, Irvine (ATLAS CSC, TDAQ, L0MDT)

University of Florida (CMS CSC, muon gas system)

University of Massachusetts, Amherst (ATLAS NSW TP, L0MDT)

University of Michigan (ATLAS MDT/sMDT, ASIC, FE, TDAQ)

University of Wisconsin (CSM Muon, trigger system)

Fermilab (Scintillator strip extrusion facility)

Univ. of Washington (ATLAS MDT, DCS)

# Muon section agenda

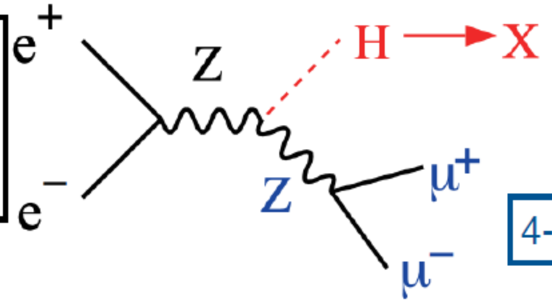
| | | | |
|---|---|---|---|
| **The uRWELL design for the muon system of the IDEA detector concept** | *Marco Poli Lener et al.* | *53/4-4006 - Tulare, SLAC* | 10:45 - 11:10 |
| **Scintillator/wavelength-shifter fiber/SiPM detectors for use in muon systems for a Higgs factory detector** | *Jim Freeman* | *53/4-4006 - Tulare, SLAC* | 11:10 - 11:35 |
| **A muon system with drift tubes and scintillators** | *Prof. Bing Zhou* | *53/4-4006 - Tulare, SLAC* | 11:35 - 12:00 |
| **A gas mixing station for R&D on gaseous muon detectors for a Higgs factory** | *Merrick Lavisnky* | *53/4-4006 - Tulare, SLAC* | 12:00 - 12:20 |
| **An MPGD production facility in the US: MPGD Resource and Development Center at TJNAF** | *Drew Weisenberger* | *53/4-4006 - Tulare, SLAC* | 14:00 - 14:20 |
| **SiPM and drift tube readout and DAQ** | *Yuxiang Guo* | *53/4-4006 - Tulare, SLAC* | 14:20 - 14:40 |
| **ATLAS muon detector upgrade TDAQ and R&D ideas for FCC-ee** | *Thiago Paiva* | *53/4-4006 - Tulare, SLAC* | 14:40 - 14:55 |
| **Discussion on input to European Strategy Update by US muon group and prioritization of muon R&D for 2025** | | *53/4-4006 - Tulare, SLAC* | 14:55 - 15:05 |

arXiv:1604.07524
arXiv:2203.07622

# How physics drives detector requirements

## Unprecedented precision unlocked with a well defined initial state

initial 4-momentum
- nominal CM energy +
- beam energy spread [ < 0.2%/beam ] +
- beamstrahlung energy loss




$$m^2_{recoil} = s + m^2_Z - 2 \cdot E_Z \cdot \sqrt{s}$$

4- momentum measured by detector

smearing due to Z momentum ~ smearing due to beam energy spread
$dp_T / p_T \sim$ few x $10^{-5}$ $p_T$ @ high momentum

SLAC Caterina Vernieri · US HF Planning @ SLAC · December 19, 2024 10

- **Muons are principal physics signals**
- **Never ignore or compromise the muon detector in HCFF experiment design!**

# Physics Driver of the Muon Detector Design

All proposed FCC-ee detector concepts have excellent inner tracking capabilities combined with state-of-the-art calorimetry. Muon momenta are considered being measured precisely in the inner detectors. Therefore, the primary functionalities of a muon detector are:

- Muon identifications (or tagging) – matching the outer muon tracks with the tracks in the inner tracker with high efficiency and low fake rate. It would not be so "easy" to satisfy this requirement
- Tail-catching of calorimeter showers, reject the punch through fake muons – crucial for muon detector design configuration

**The physics potential of a muon detector can be significantly enhanced with additional capabilities:**

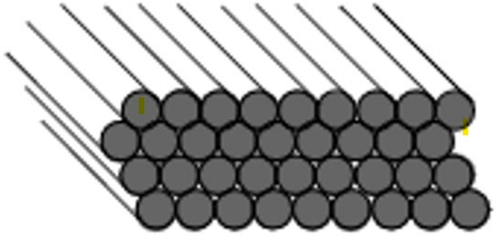
- **Tracking with good spatial resolutions**
  - -- Redundant muon momentum measurement, excellent matching with inner tracker
  - -- For the identification of long-lived particles (LLPs)
    - **-- $2^{nd}$ long particle decay vertices**
    - **-- energy/momentum and mass determination of LLP**
- **Fast timing**
  - **-- for independent triggers and search for massive stable particles.**
  - **-- for L1 muon trigger**

Both proposed detector technologies (drift tubes +scintillator strips, and MPGD/μ-RWELL) set the same design goal for a large muon system:

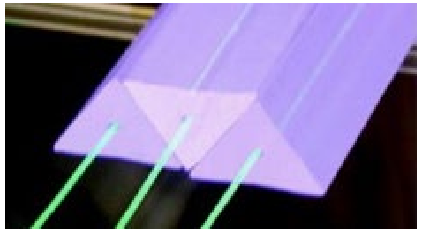
**high spatial resolution, fast timing, robust, and cost-effective.**

Proposed by Michigan, MSU, SLAC, and Fermilab +… to build a hybrid muon system

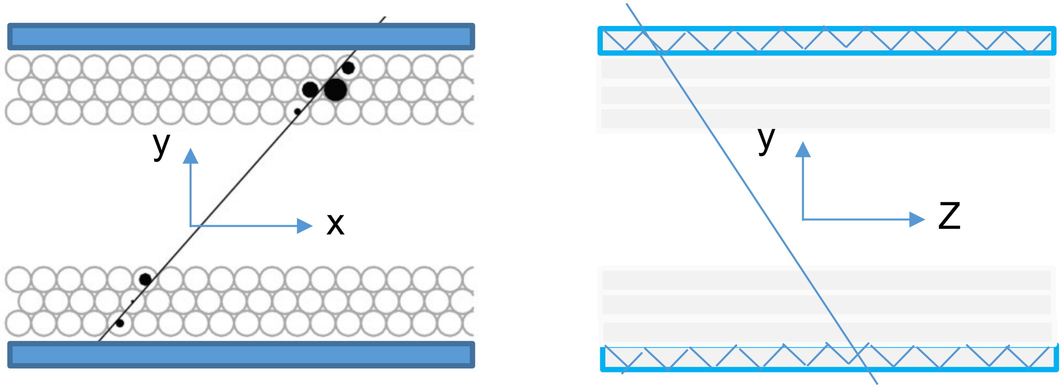
Drift tube area



Scintillator strips



An example of a muon detector module




- **High precision:** Precision position measurements from drift tubes
- **Fast:** Fast timing information from scintillators
- **Robust:** Reliable and robust to operate for long term
- **Cost-effective:** Inexpensive to construct and with a low channel count

# A Concept: Drift Tube and Scintillator Muon System

A combination of drift tubes and scintillators is a cost-effective option to meet the requirements of a muon detector at FCC-ee:

- Drift tubes and scintillator strips can be produced cost-effectively through extrusion
- Drift tubes provide good spatial resolutions
- Scintillators with **SiPM** readouts offer excellent timing information
- They have low channel counts and are robust!

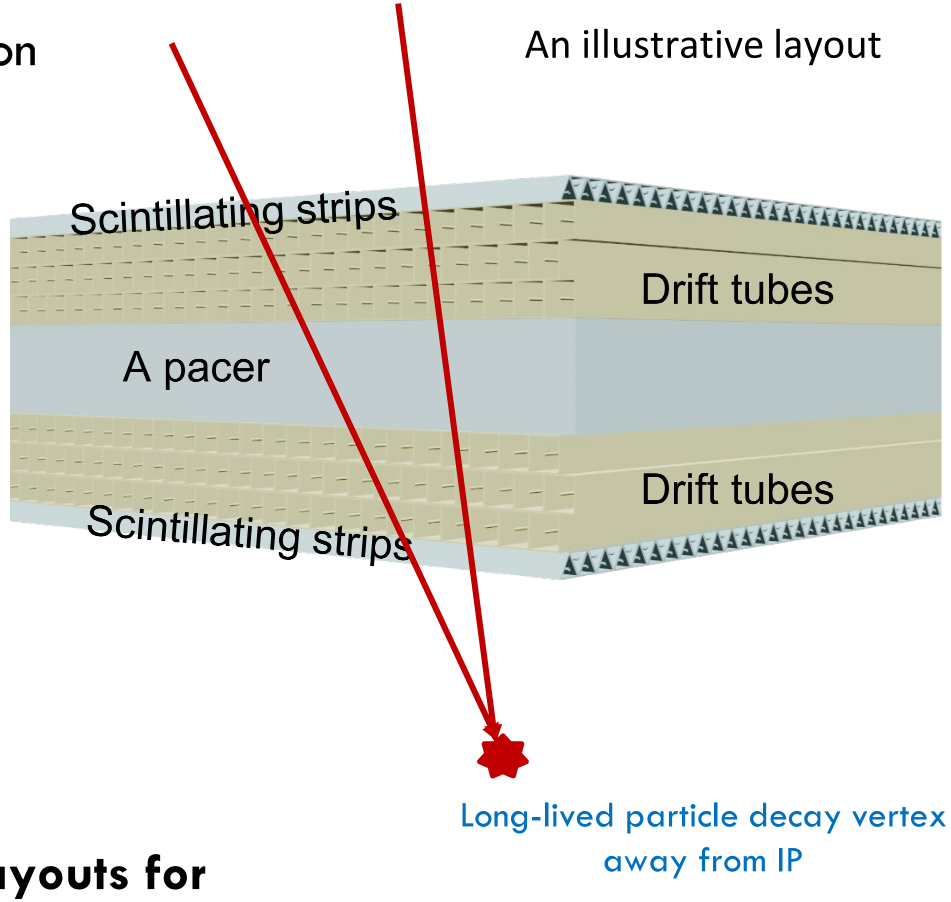
Multiple layers of drift tubes for bending-plane spatial measurements with a hit resolution of $\sigma_{xy}$~100μm

- Reconstruction of track segments,
- Reconstruction of decay vertices of long-lived particles

Triangular scintillator strip layers sandwiching the drift tubes for the z-coordinate and timing measurements with $\sigma_z$~1mm and $\sigma_t$~200ps

- Triggers
- Time-of-flight information for massive stable particles, …

An illustrative layout



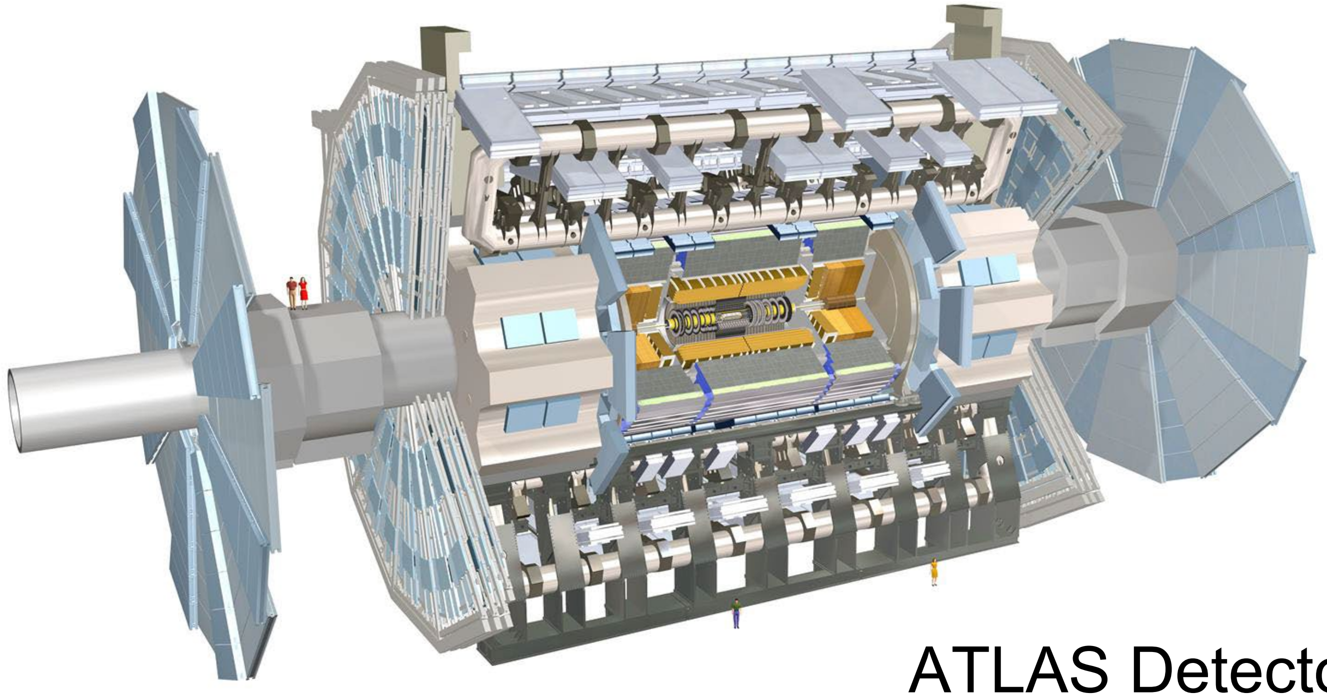

**This configuration design can be easily extended to 2-3 such layouts for independent momentum measurements (as ATLAS and CMS muon system)**

# ATLAS Muon Spectrometer with Drift Tubes

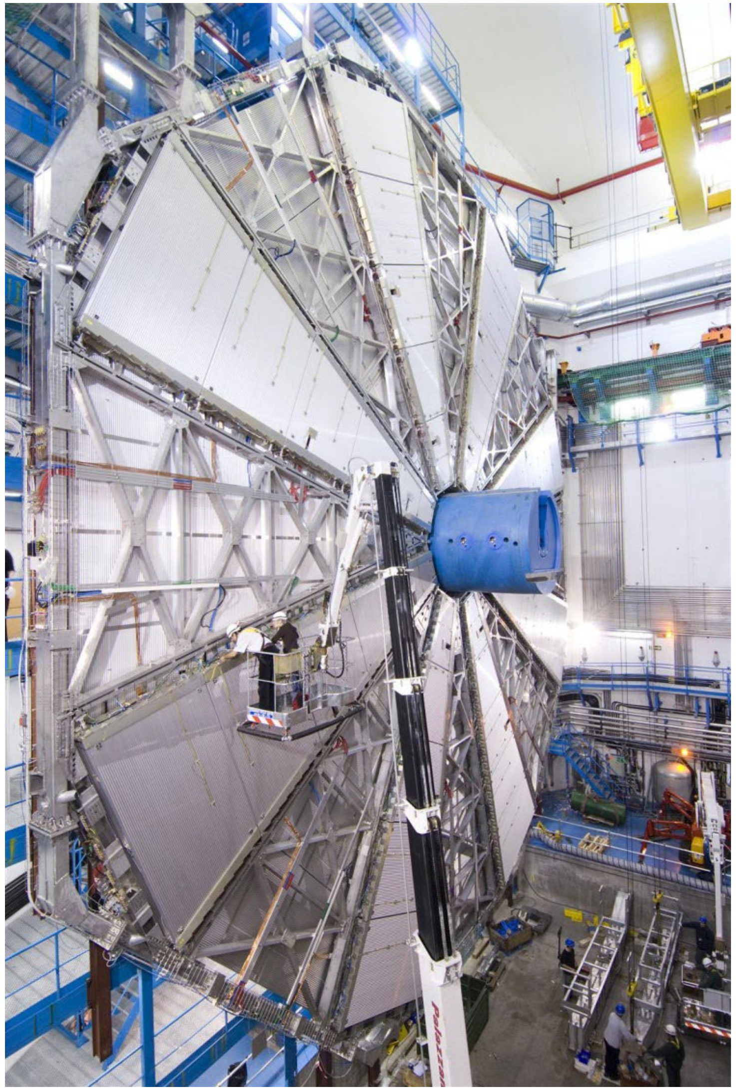
**US institutes designed, built, operated & upgraded Muon detectors**

- the end-cap precision detectors (MDT, and CSC, and alignment system)
- Phase 1 (NSW) and Phase 2 muon system (sMDT, FE, L0MDT) upgrade
- all the front-end electronics
- ATLAS Muon Project Leader (from Run 1 – Run 3, 12 years)

**Arizona, BNL, Brandeis, BU, Harvard, Michigan, MIT, MSU, Tufts, SLAC, UCI, UMass, U. Washington**



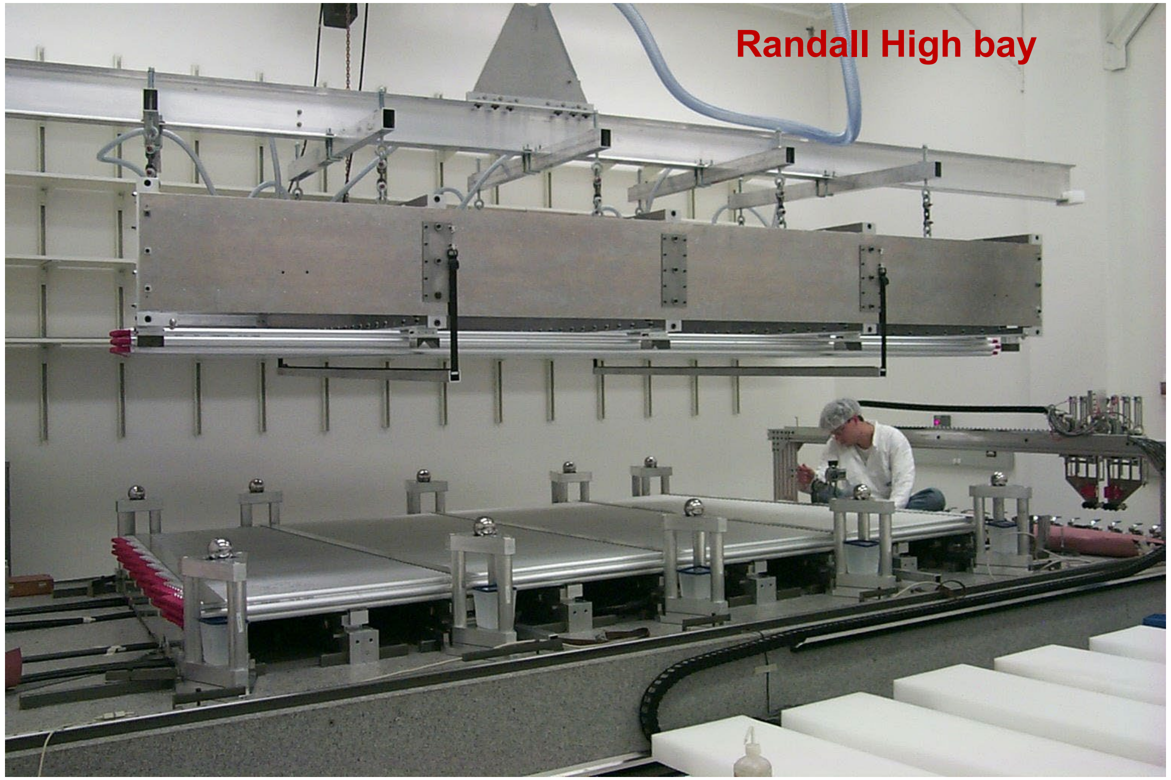
ATLAS Detector



Muon Big-Wheel built by the US groups

# Building the Largest Precision Muon Detectors

- R&D started in the SSC days to design a precision, radiation hard with high-rate capability, $4\pi$ coverage, cost effective muon spectrometer for hadron colliders
- There were four muon detector production sites in the US. As an example shown pictures below: building the large infrastructure and constructing large precision muon detectors at UM
- The facilities are still operational for ATLAS muon detector upgrade, and for FCC-ee muon detector R&D

# Design and Built Ultrafast Electronics For ATLAS Muon Detectors and Upgrades

## MDT front-end electronics

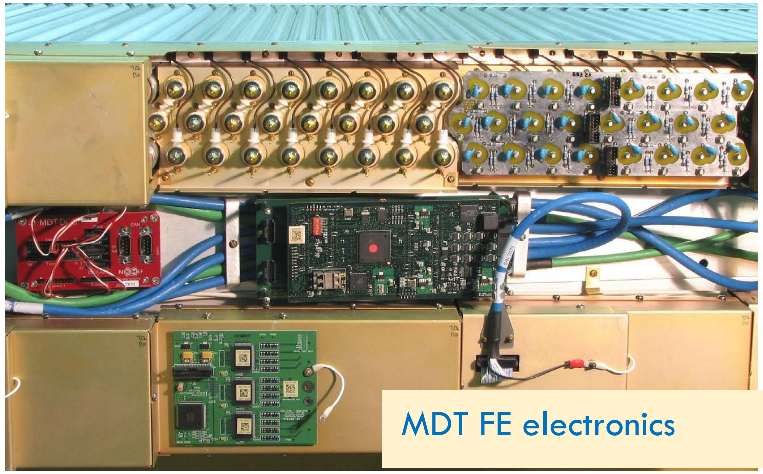
- Mezzanine (ASD, TDC ships)
- Chamber Service Module (CSM)
- MDM readout control unit

## Phase 1 upgrade

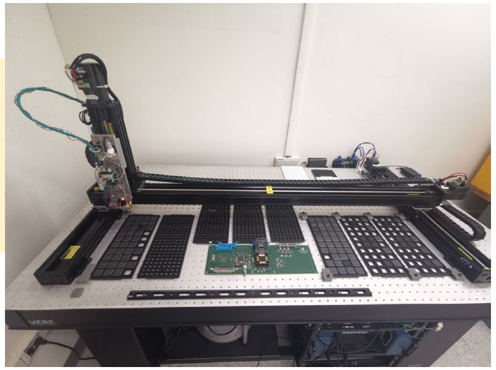
- MM and sTGC prototypes
- ASICs (VMM3, pTDS, sTDS)
- MM readout boards
- Trigger Router boards

## HL-LHC upgrade

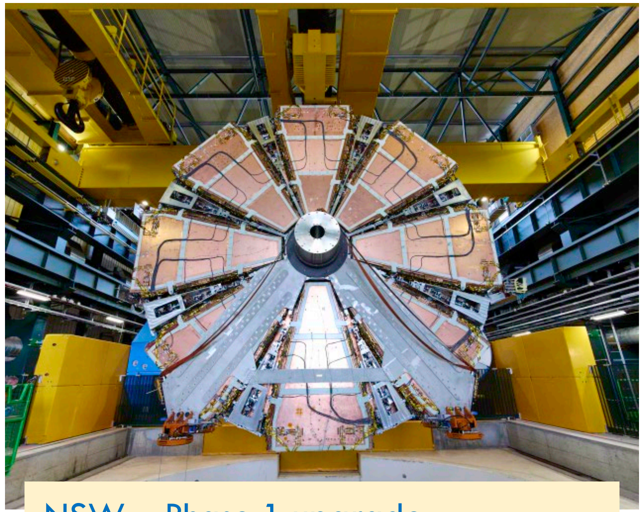
- sMDT chambers
- ASICs (TDC)
- CSM board
- L0MDT



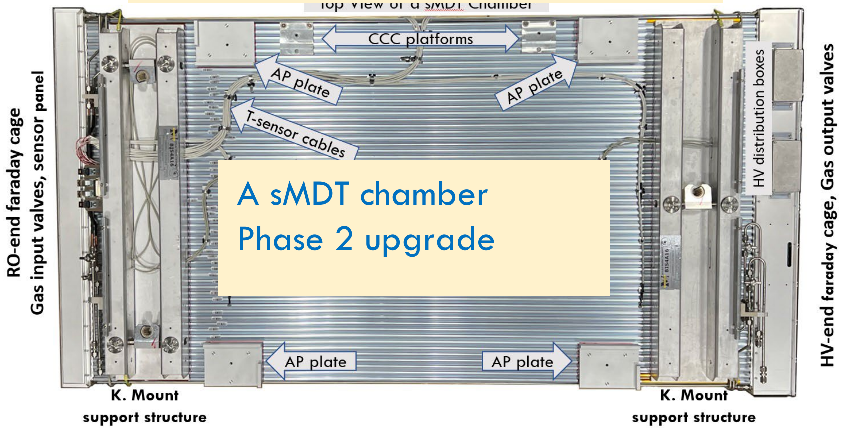
MDT FE electronics



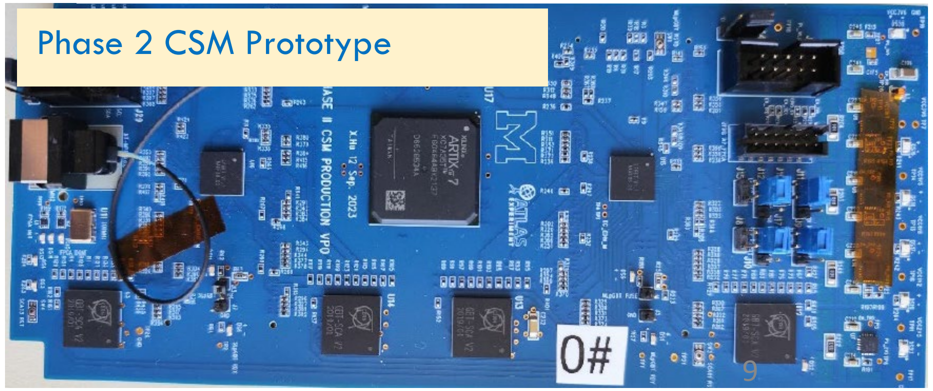
TDC ASIC automatic test station (UM)



NSW – Phase 1 upgrade




A sMDT chamber Phase 2 upgrade

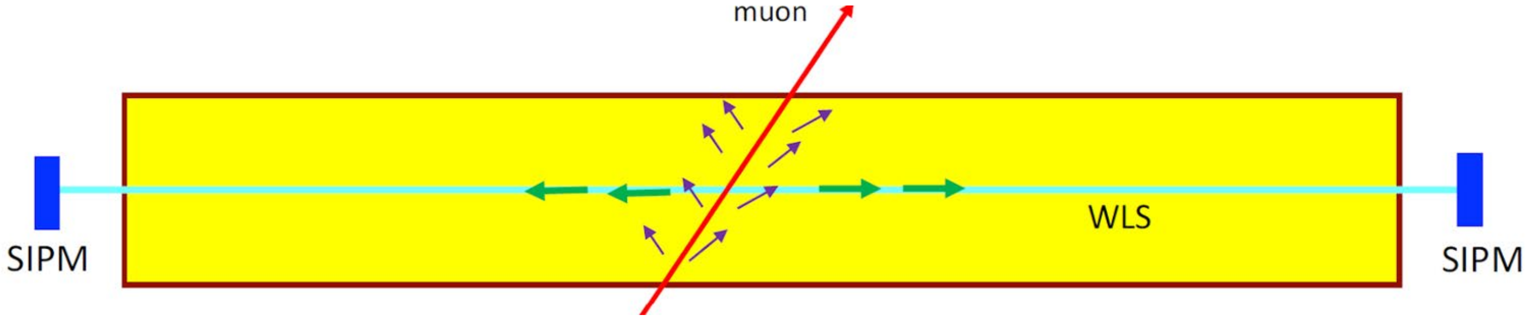


Phase 2 CSM Prototype

L0MDT electronics chain for Phase 2 upgrade

# Scintillator strips with WLS, readout by SiPMs

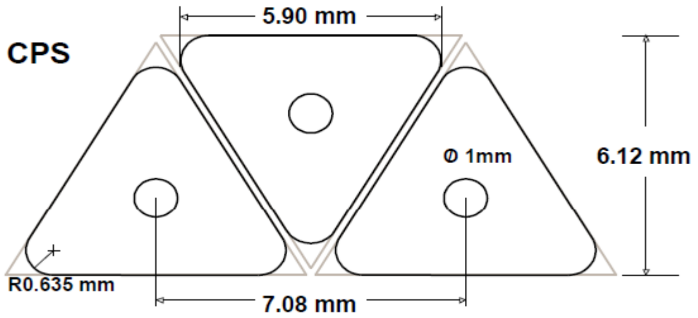
SLAC, Fermilab

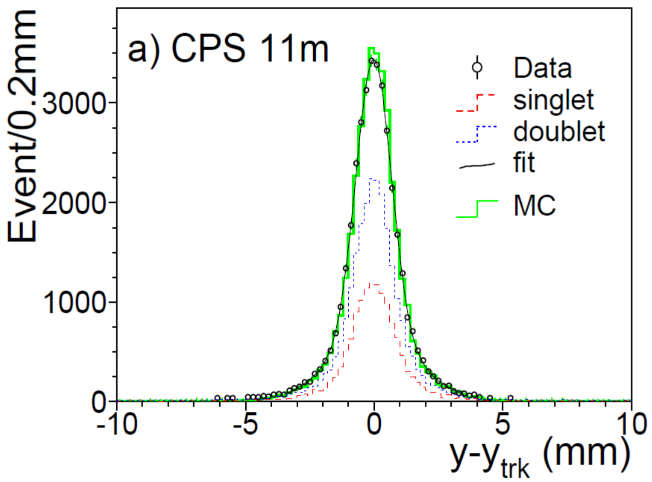



**Silicon photomultipliers (SiPMs)** with high quantum efficiency and high gain that are functional in magnetic fields

Work for the D0 preshower detector years ago

- **Extruded scintillator strips at Fermilab,** with holes in the middle to house wave-length-shifting fibers.
- Visible Light Photon Counters (VLPCs) were used as photodetectors (before the SiPM era). These were positioned outside the detector and connected with 10+m long clear fibers.
- The Vernier effect between neighboring strips significantly improved position measurements, achieved a resolution of ~8% of the strip base width.



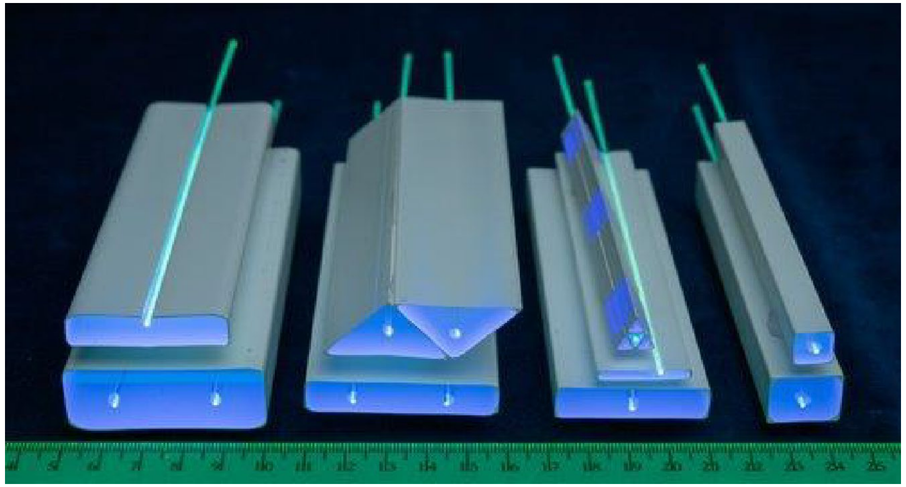

NIM A 378 (1996) 131
arXiv:hep-ex/0007026

**SiPMs have better specs than the VLPCs and are faster, should improve the performance! Readout both ends for "time-of-flight" information.**

# Unique Fermilab Scintillator Extrusion Facility

FNAL-NICADD Extrusion Facility

System 50m long, can extrude 75kg scintillators per hour



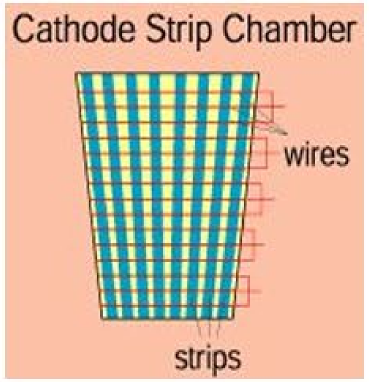
Scintillator development at Fermilab (Jim Freeman)

# MPGD – US expertise: CSC, MM, sTGC, GEM

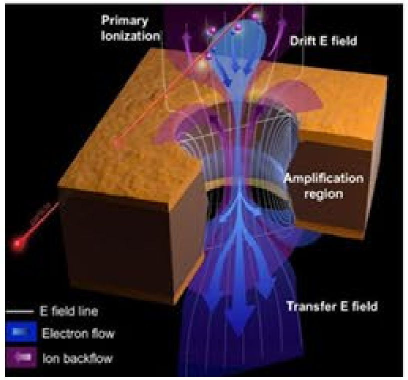
## US Muon Expertise - CMS

UMassAmherst

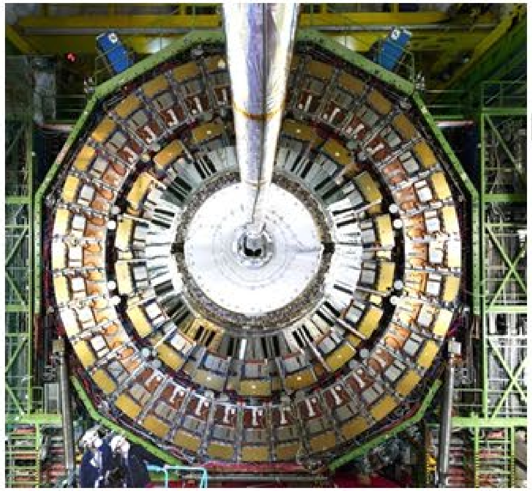
CMS precision endcap muon detectors: **Cathode Strip** & **Triple-GEM** Chambers




GEM

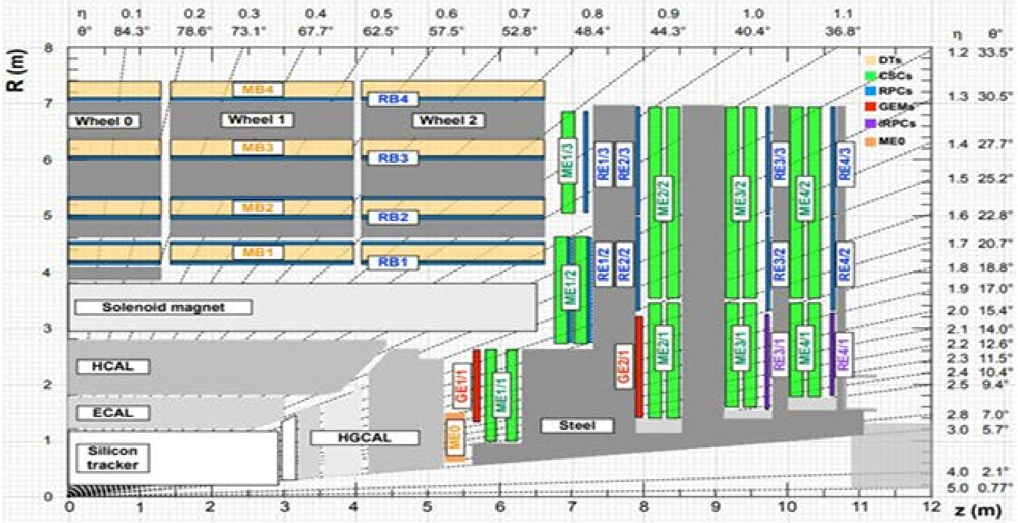



GE2/1 GEM Installation



Endcap CSC disk Built by US

| Muon subsystem | Cathode strip chamber (CSC) | Gas electron multiplier (GEM) |
|---|---|---|
| $\|\eta\|$ 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)<br>210 816 (wire groups) | 442 368 |
| Spatial resolution | 50–140 $\mu$m | 100 $\mu$m |
| Time resolution | 3 ns | $<$10 ns |

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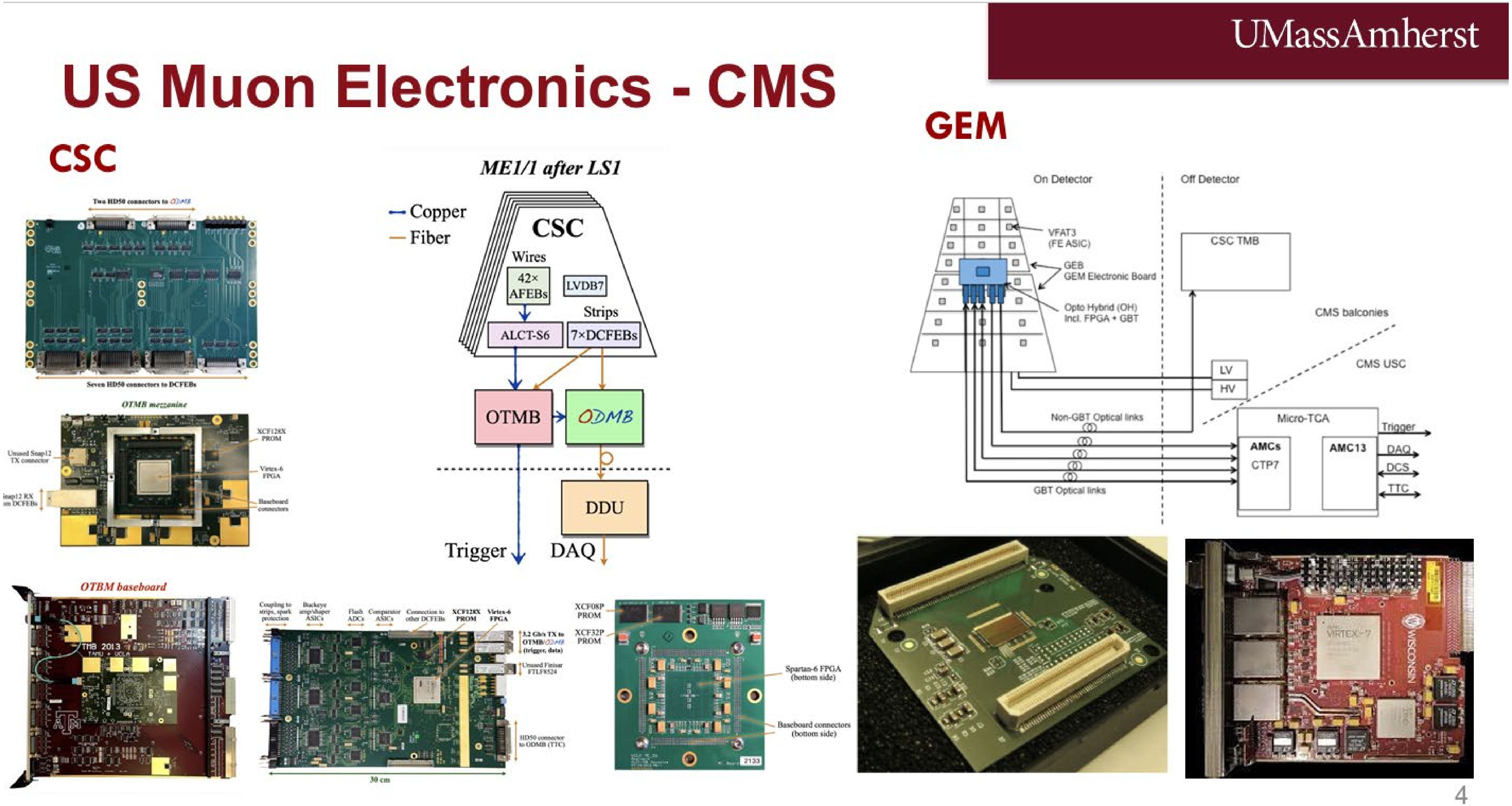
# Electronics for MPGD: VMM chip, FE, TP,…

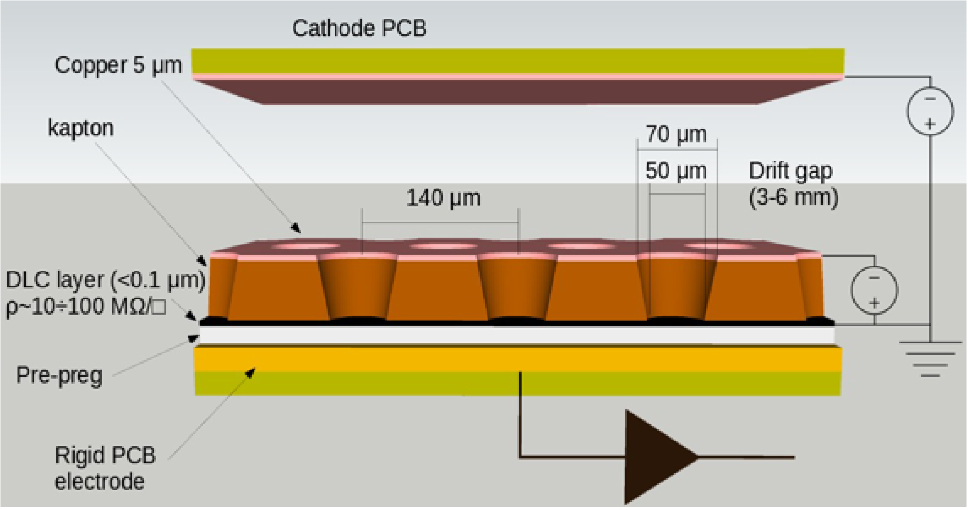


# The μ-RWELL

**μ-RWELL for the Muon system at IDEA**

Marco Poli Lener
on behalf of INFN – FCC group

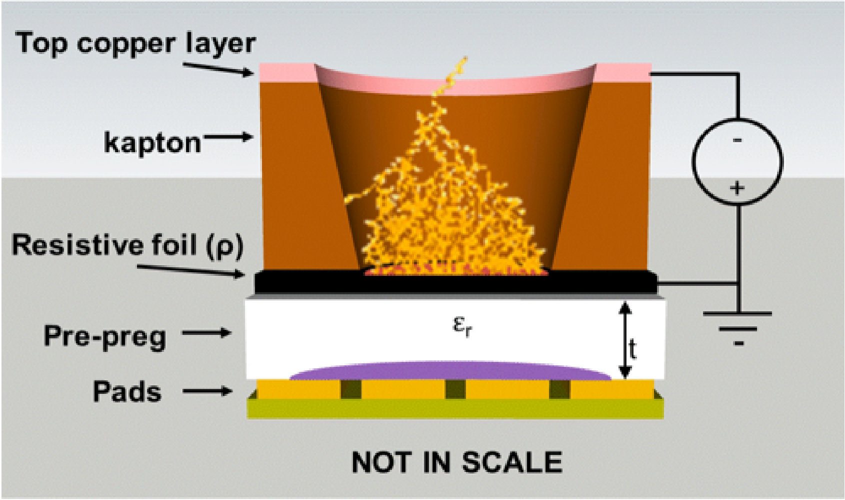
*G. Bencivenni et al., The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD, 2015 JINST 10 P02008*




The **μ-RWELL** is a **resistive MPGD** composed of two elements:

- **Cathode**
- **μ-RWELL_PCB:**
  - a **WELL** patterned **kapton foil** (w/**Cu-layer on top**) acting as **amplification stage**
  - a **resisitive DLC** layer(*) w/ **ρ~10÷100 MΩ/□**
  - a standard **readout** PCB with **pad/strip** segmentation

(*) DLC foils are currently provided by the Japan Company – BeSputter




The **"WELL"** acts as a **multiplication channel** for the ionization produced in the drift gas gap.

The **resistive stage** ensures the **spark amplitude quenching.**

**Drawback:** capability to stand high particle fluxes reduced, but **largely recovered** with appropriate **grounding schemes** of the **resistive layer**

# Why a MPGD Resource and Development Center at JLab?

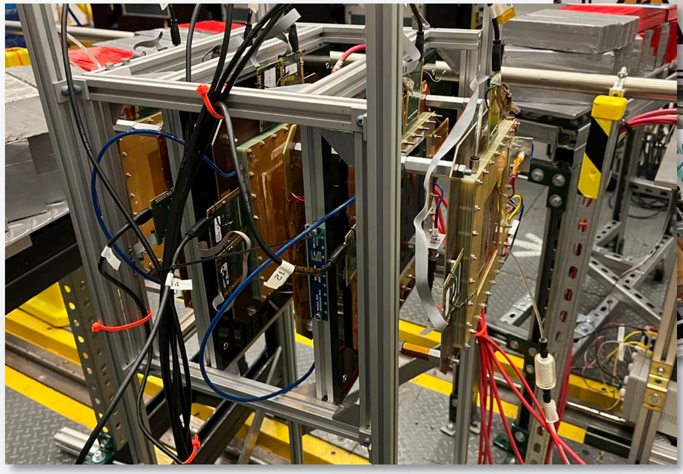
## Resources at JLab

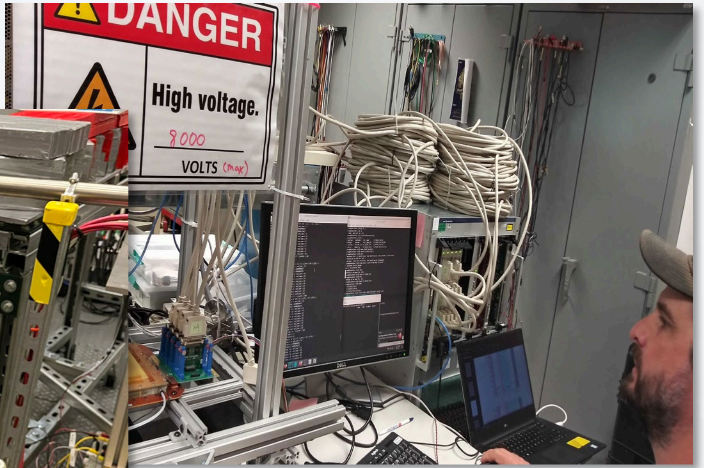
Drew Weisenberger

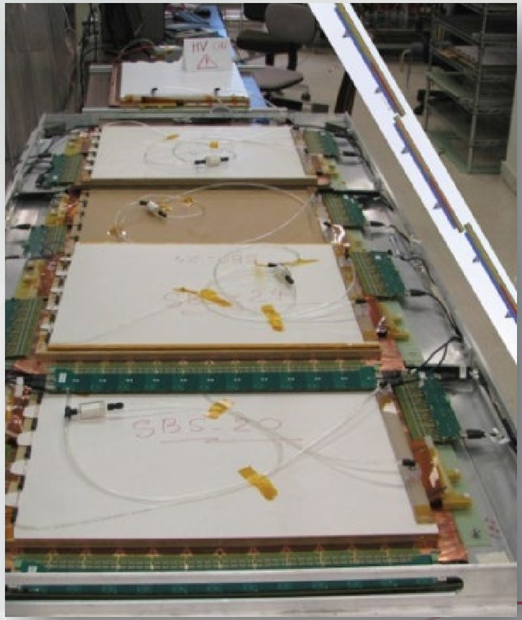
**JLab Nuclear Physics (NP) Division**
**JLab Radiation Detector and Imaging (RD&I) Group**

Fully equipped general detector R&D lab: test instrumentation, DAQs, power supplied, clean rooms, gas systems, ovens, scanning x-ray source, PMTs, etc

MPGD Detector Expertise:
- RD&I- Kondo Gnanvo, Eric Christy, Xinzhan Bai
- NP- Klaus Dehmelt, Ibrahim Albayrak, Florian Hauenstein
- NP Fast electronics Group-

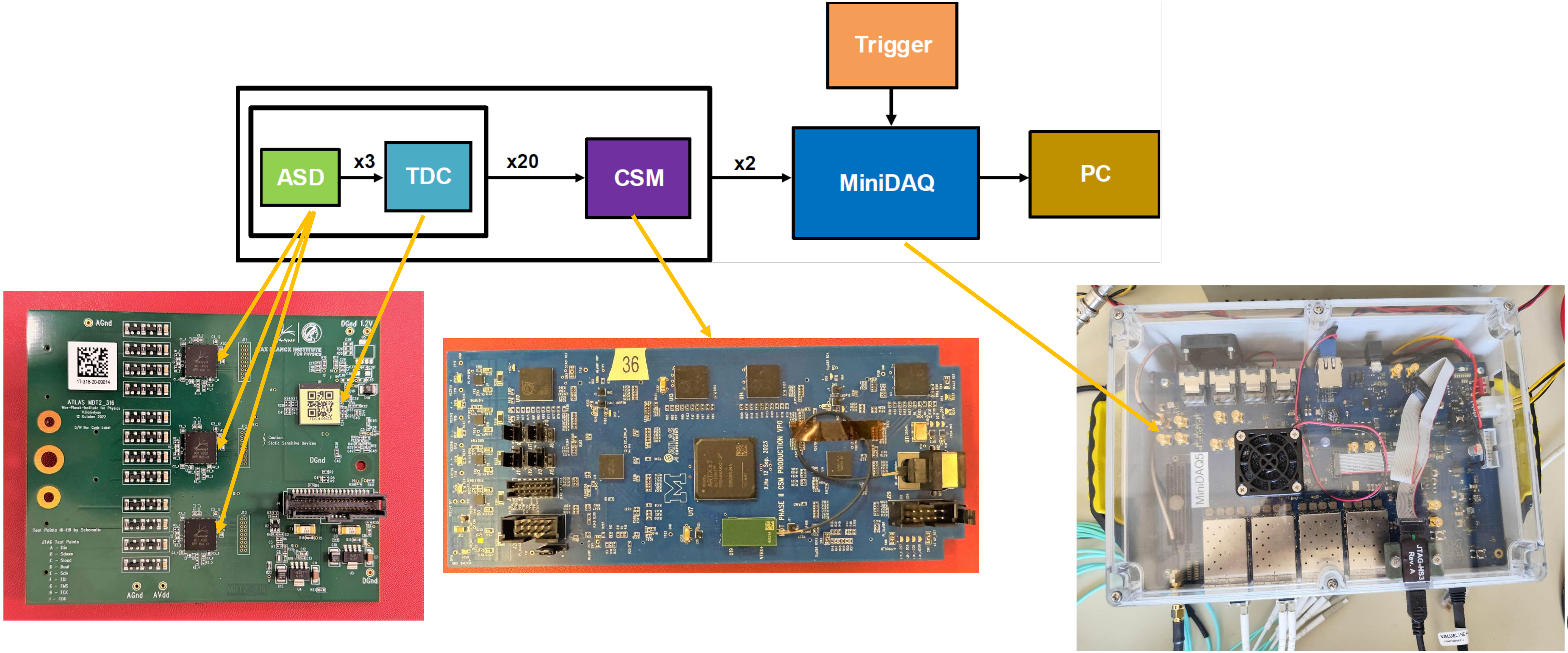




# A portable MiniDAQ system with MDT front-end electronics

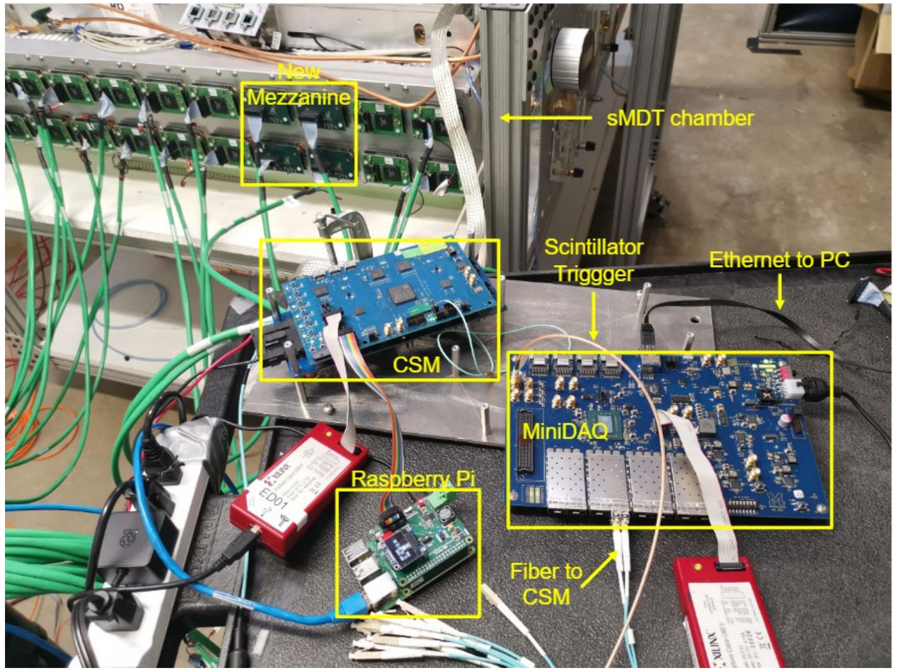
- ASD: Amplifier-shaper-discriminator circuit, 8 channels, peaking time 12 ns, small signal gain 18 mV/fC
- TDC: Time to digital converter, 24 channels, bin size 0.78 ns, 100 us dynamic range, output 2*320Mbps
- CSM: Chamber service module, 20 mezzanine readout and monitor, output 2*10.24Gbps
- MiniDAQ: 2 CSMs readout, mezz and CSM configuration, output 1Gbps



# MiniDAQ implementation

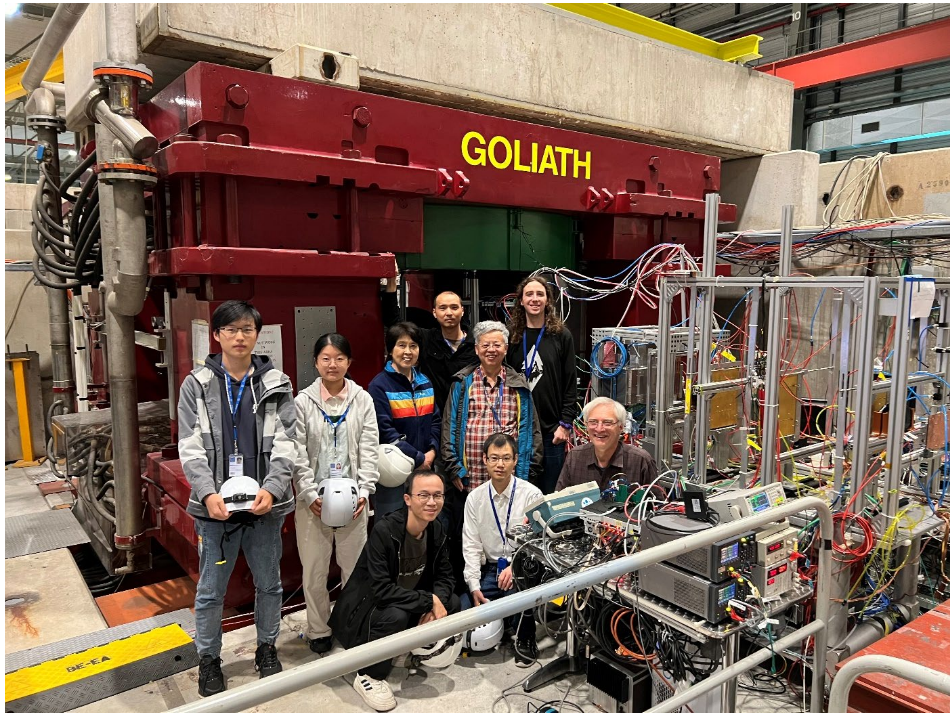
The system has been successfully used in:

- Michigan sMDT construction commissioning for 50 chambers
- MDT chamber cosmic test with new mezzanine, CSM, CSM-MB for PHase 2 upgrade
- CERN GIF++ test beam study for sMDT under high gamma rate (July 2021)
- CERN DRD1/WP3 test beam study for straw chamber (September-October, 2024)




sMDT construction commissioning

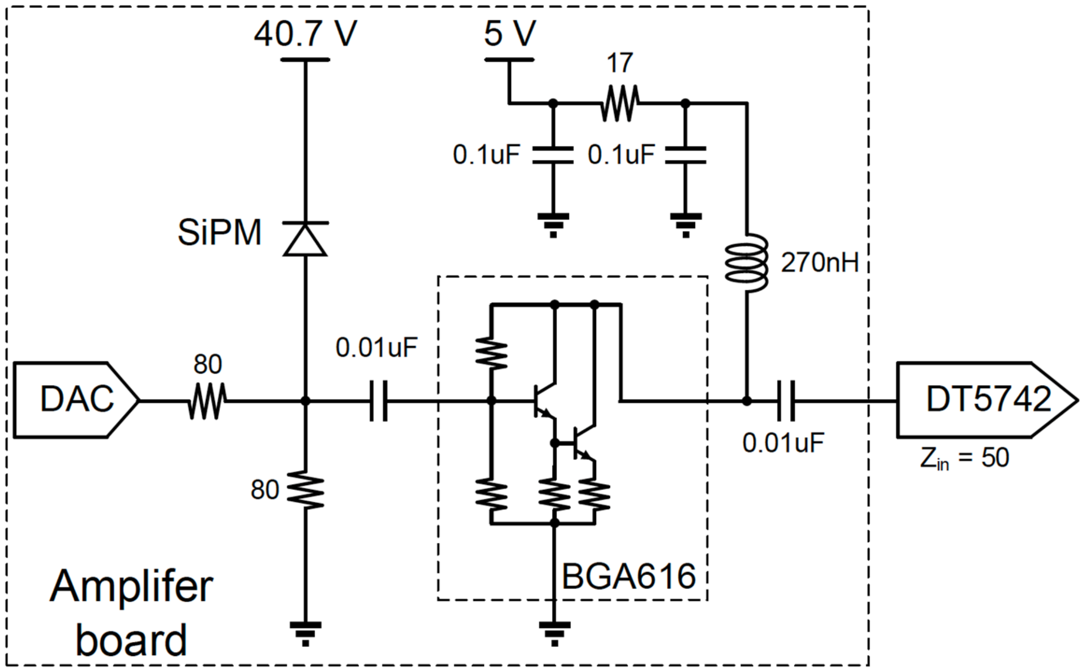
Testing at CERN GIF++



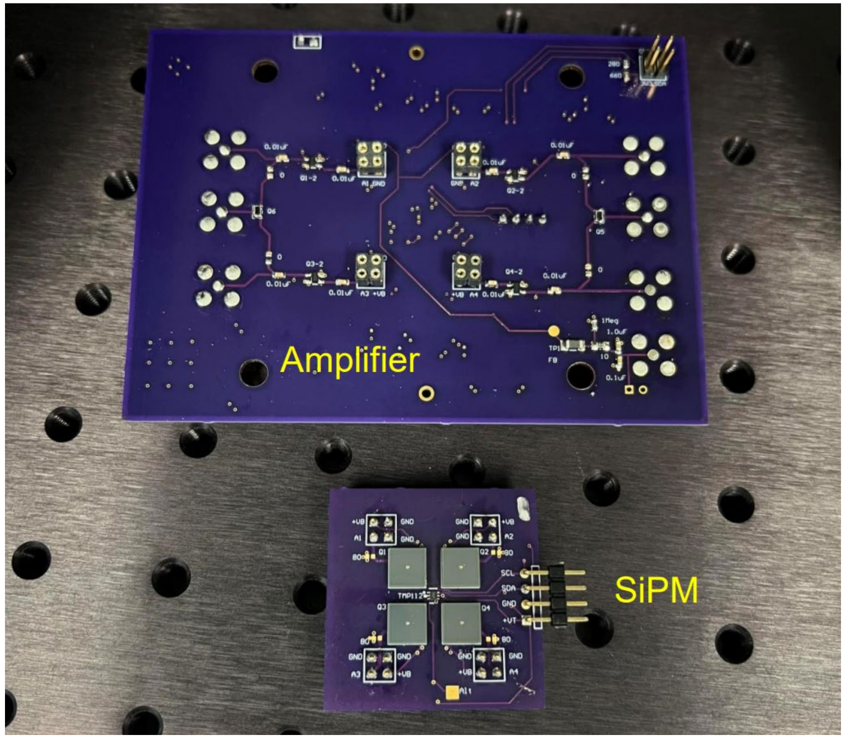

Testing at CERN H4 and T9

# SiPM readout in FCC-ee R&D CalVision dual readout project

- Boards designed by the University of Virginia group
- Four S14160-6050HS (6 x 6 mm2) SiPMs on board, micro-cell pitch 50 um
- Single-stage RF amplifier for each channel (gain ~10)
- Domino-ring sampler4 (DRS4) digitizer, 5 Gsps, 200 ns window, 16+1 channel maximum




Single-channel schematic

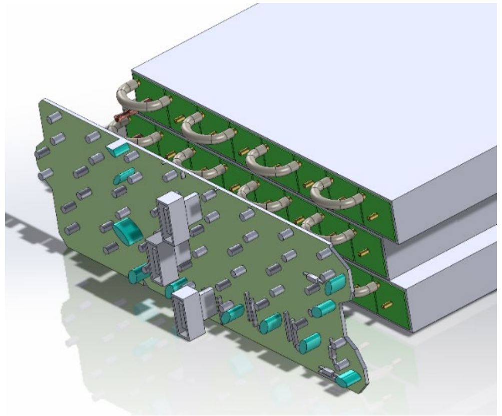


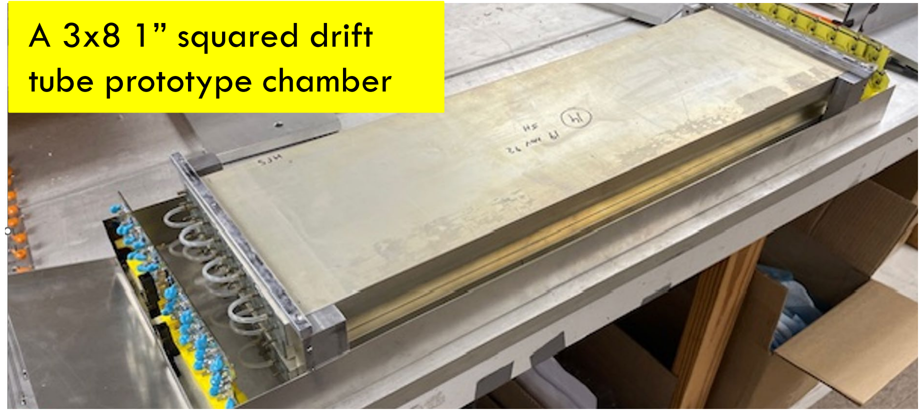

4-channel amplifier board and SiPM board

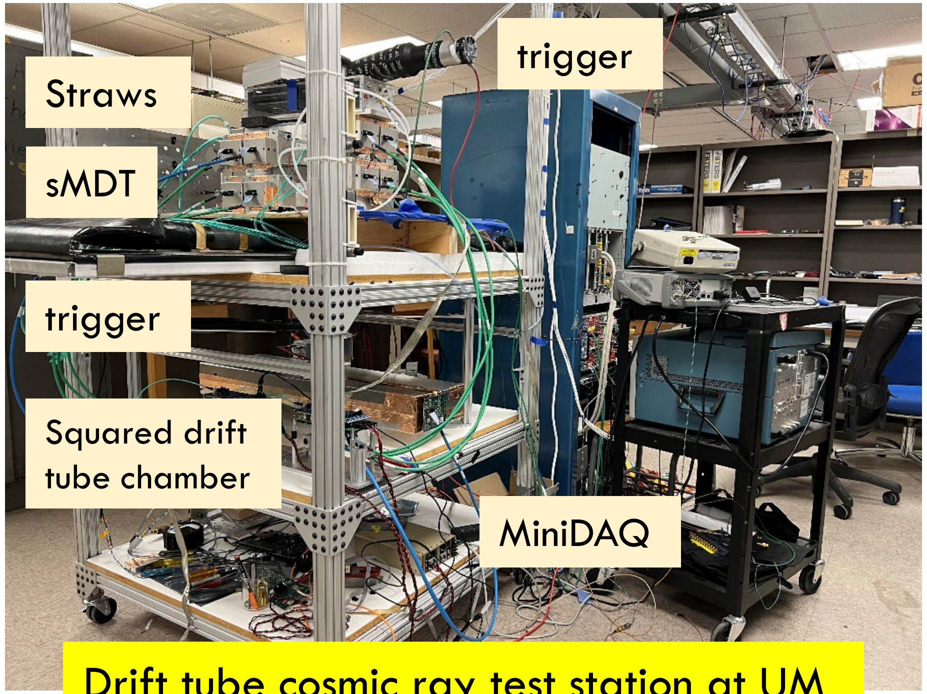
# R&D on Drift Tube Muon Detector

- Build and study squared drift tube chamber

**Squared drift tubes can be economically produced through extrusion**

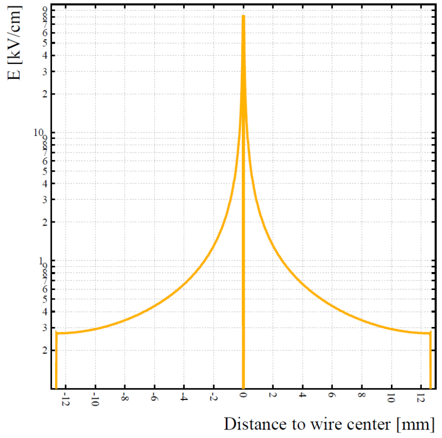


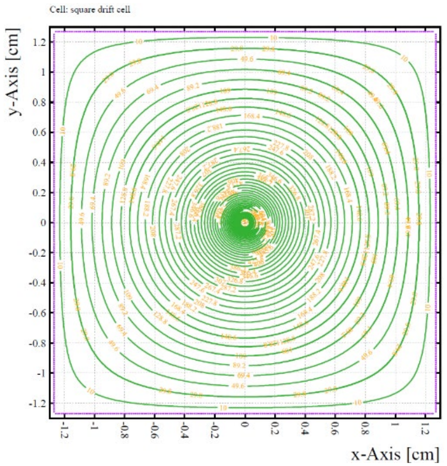


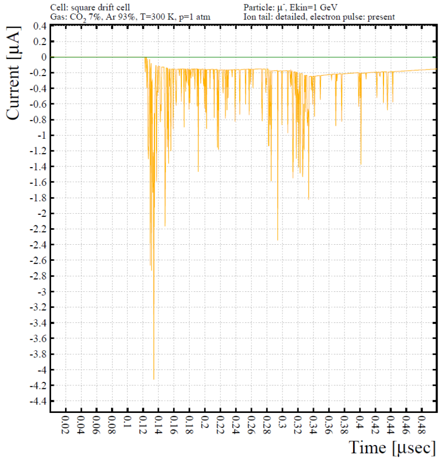



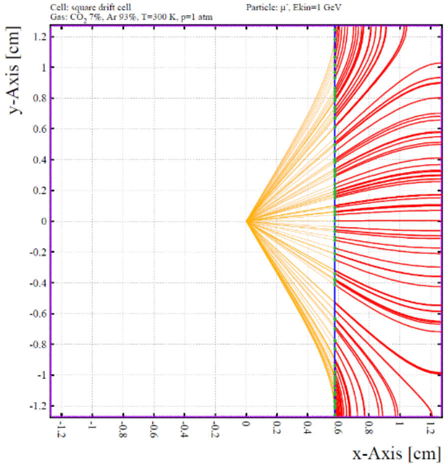

Drift tube cosmic ray test station at UM

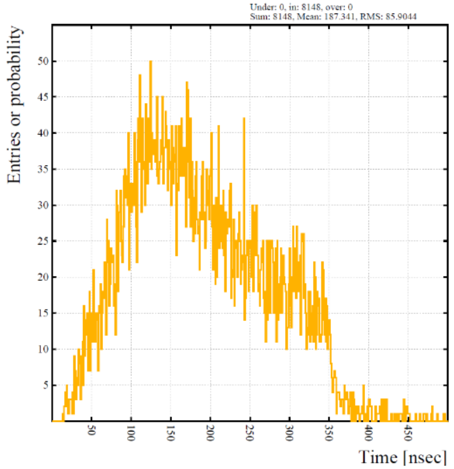
- Simulations with Garfield and Geant4



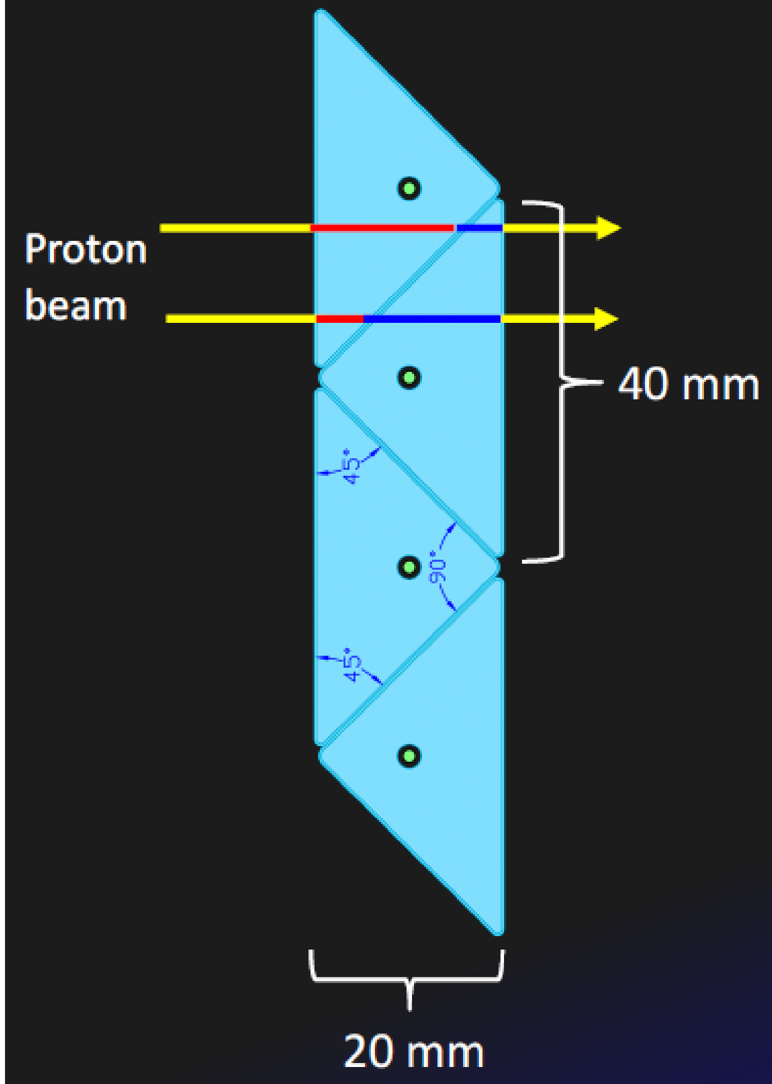



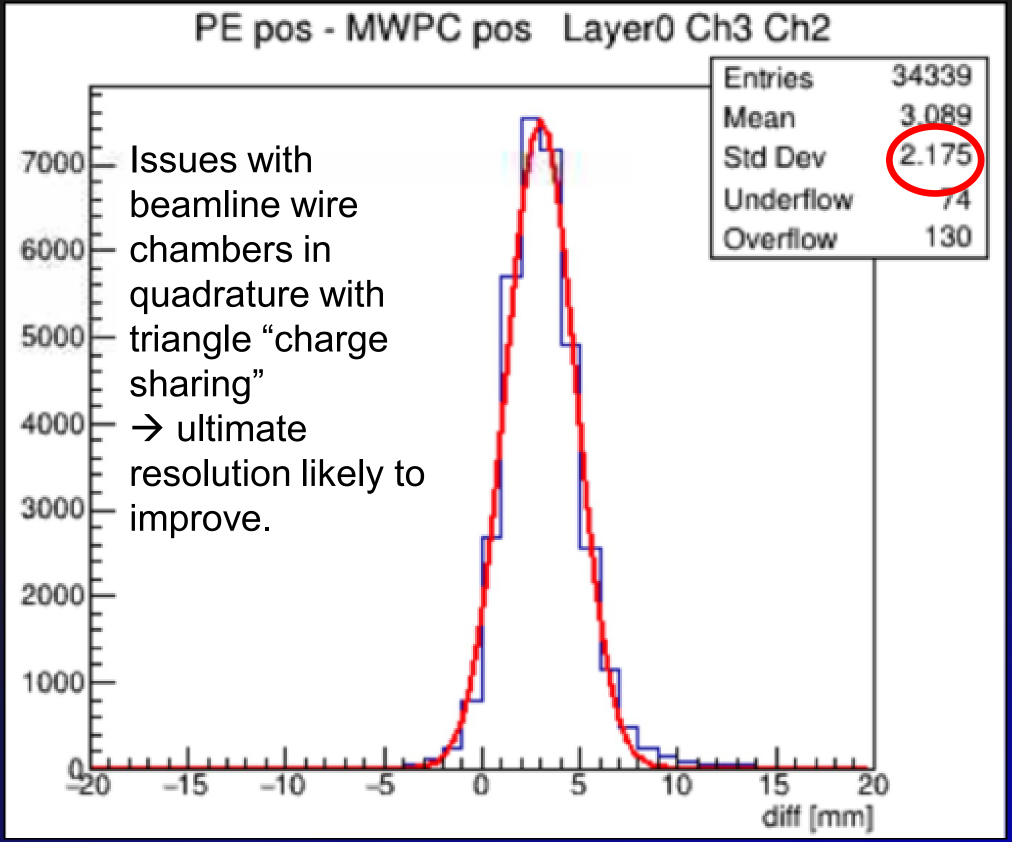



# Using Light Sharing to Determine Beam Position Transverse to Fiber




By measuring the relative light yield from the two counters we can determine the impact position of the proton beam

**We find that at 0° incident angle we get σ ~ 2 mm**




Issues with beamline wire chambers in quadrature with triangle "charge sharing" → ultimate resolution likely to improve.

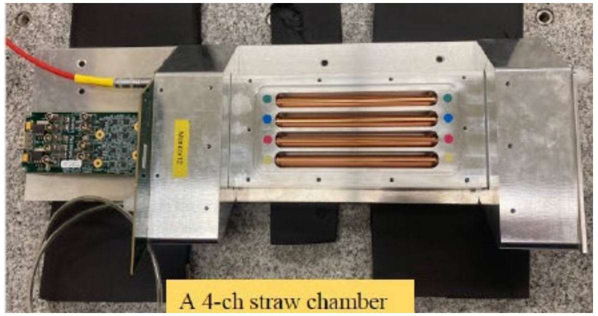
# R&D on Drift Tube Gas Mixture system

- Gas mixture studies
  - Baseline: Ar:$CO_2$ – two-component fractions need to be optimized

  Based on our recent beam test using sMDT and straw tubes, we observed that the spatial resolution for Ar:$CO_2$ (70:30) is a factor of 2 better compared to the ATLAS gas mixture Ar:$CO_2$ (93:7), which was optimized on the aging consideration at the LHC

  - Climate change a growing concern; Greenhouse Gas (GHG) 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 the control system and calibrate a gas mixture device

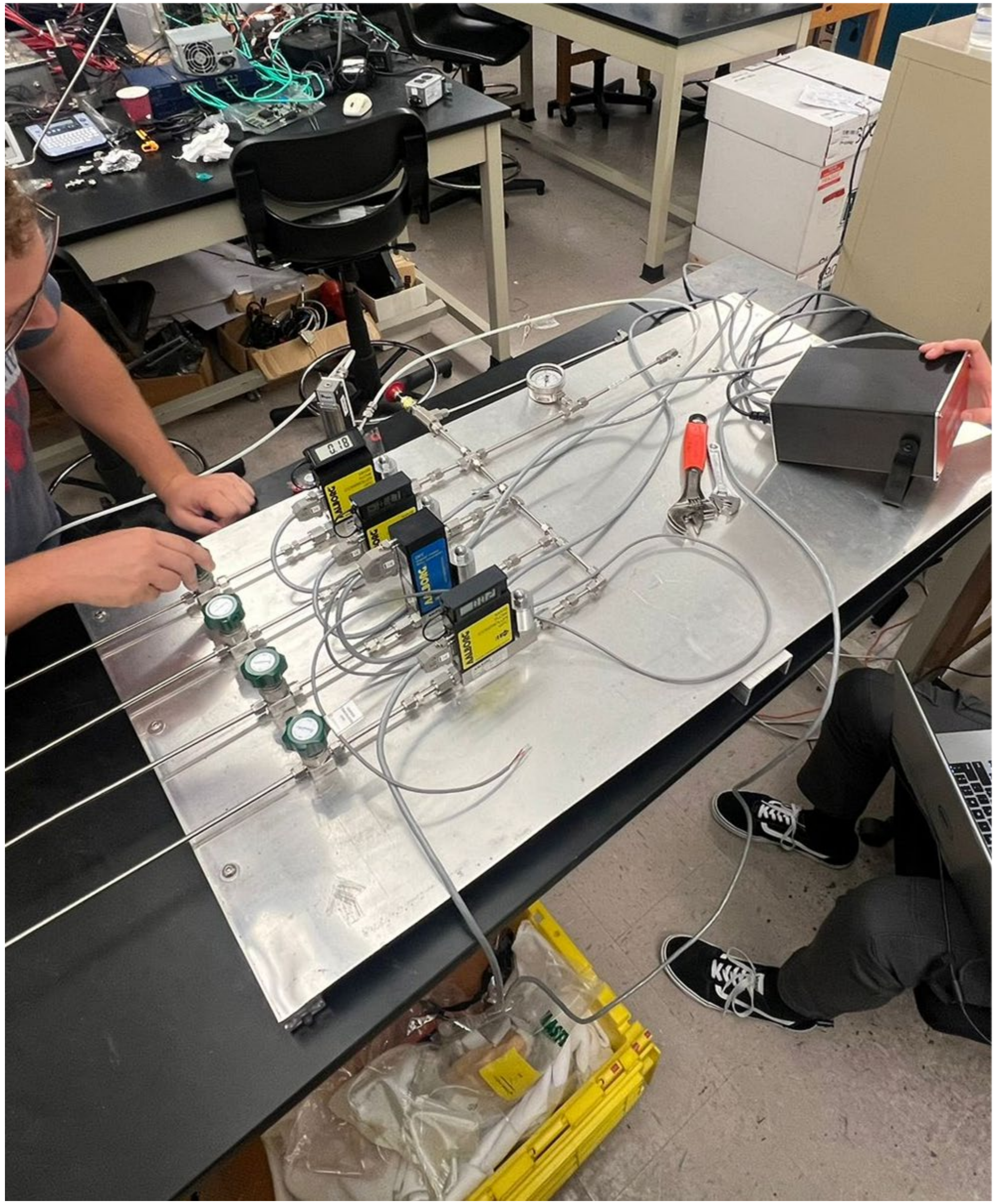
Hardware from early drift gas studies at UM with four input gas lines. Study of gas gain and working points using a straw monitor chamber



# Gas mixture study for PMGD

Merrick Lavinsky

- Designed and built four-channel gas mixing station
- Calibrated flow rates in all four channels
- Tested totalizer mode to ensure accurate volume and timing
- Initial ratio calibration testing performed, but preliminary results show some issues with experiment

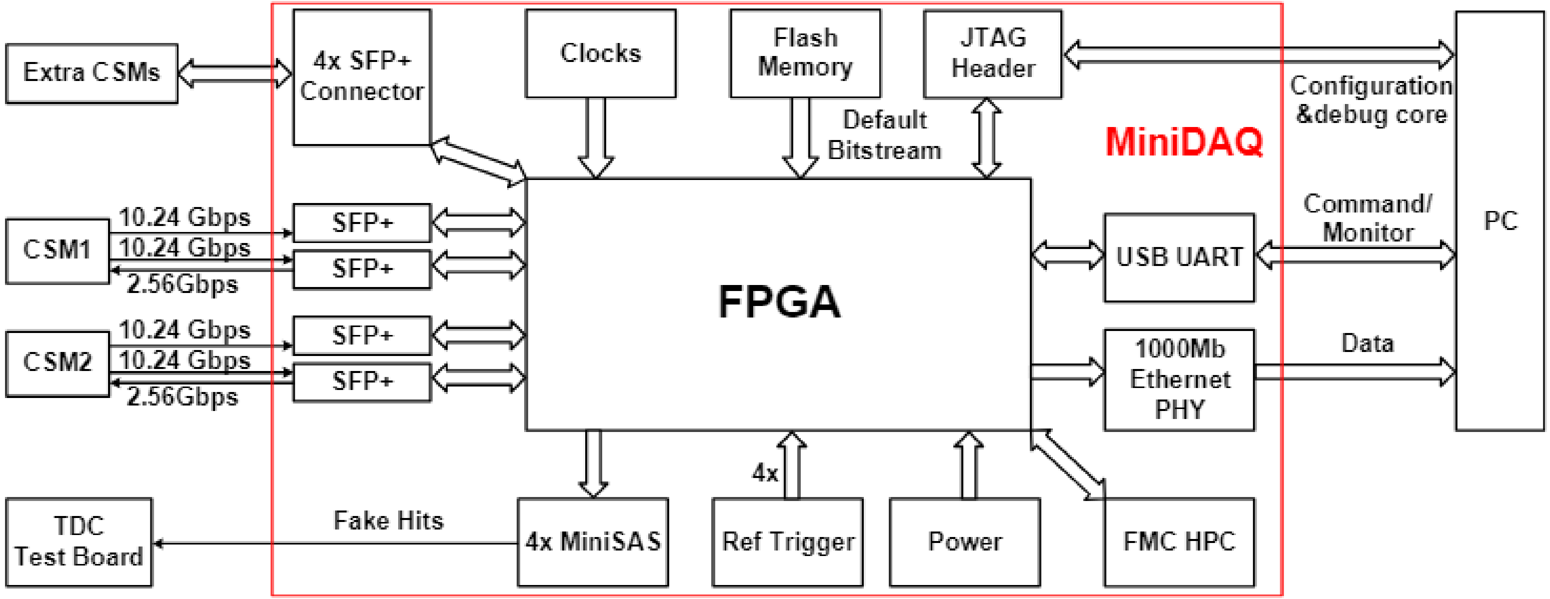


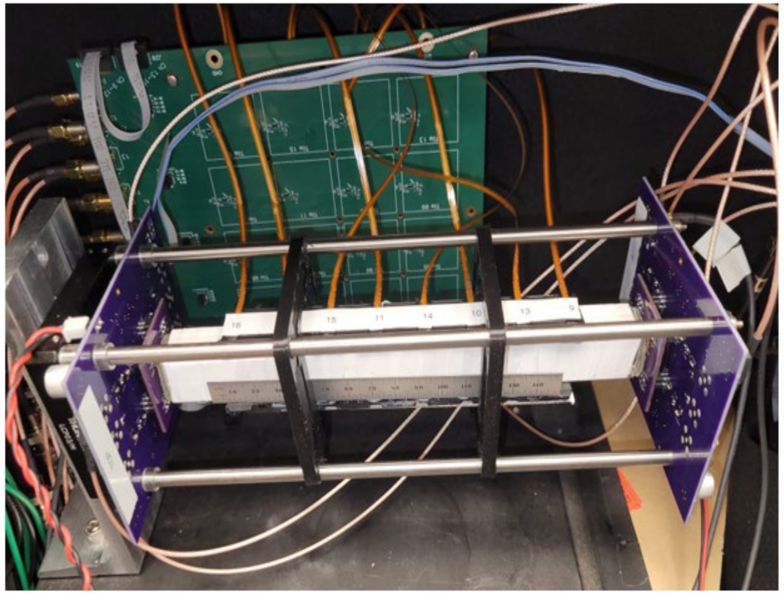
# Future Testing Plans

- Redo ratio calibration with narrower tube and longer fill times
- Test more ratio combinations and potentially three gas combinations

# Electronics and MiniDAQ R&D

- MiniDAQ is a lightweight portable  readout system, currently used for ATLAS MDT phase 2 upgrade chamber commissioning and for straw tube test beam experiment at CERN
- 960 channel basic, 1920 channel with expandable port, MiniDAQ can easily handle one or more drift chamber
- SiPM readout has been studied for CalVision dual readout



**Next step**

- Same scheme can be adopted for scintillator strips/WLS coupled with SiPM and readout by MiniDAQ
- Prepare to use this system for beam test (straws, drift tubes+scintillator strips) at CERN in 2025

# Summary

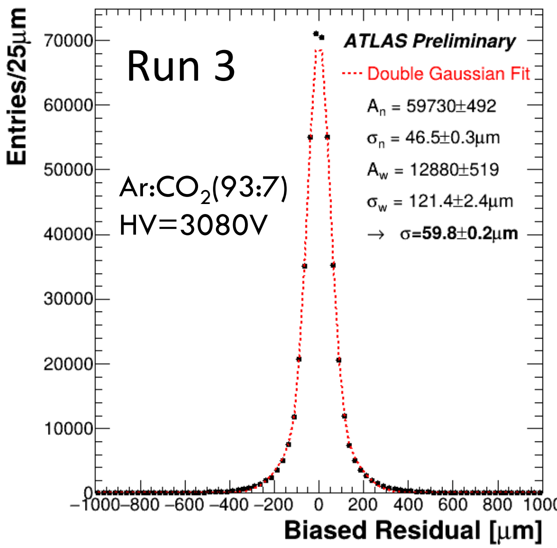
- There are a large number of US institutes expressed interests to develop **a high precision, fast, robust, and cost-effective muon system** for HFCC experiments. These institutes have had over three decades experience in design and building the muon system with continues R&D efforts.
- The HFCC muon detector R&D activities are ramping up.
- New ideas continued being developed, such as combine the precision drift tubes with fast timing scintillator strips, taking fully the advantage of the unique scintillator strip extrusion facility at Fermilab.
- Our strategy is focusing on the detector technology development, demonstrate the performance with prototypes and tests with cosmic rays and test beams, also perform detailed simulations at different levels, to guide the R&D.
- Modest  funding (~$150k) in 2025 will be very helpful! Enable us to make a major impact on the HFCC muon detector design.

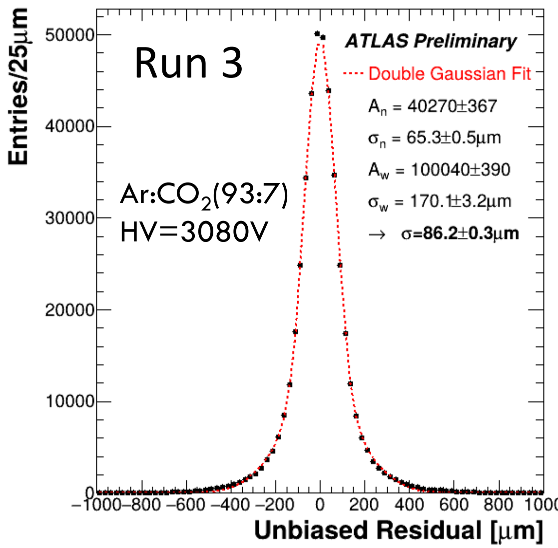
# Additional slides

# Excellent Performance and Precision Measurements

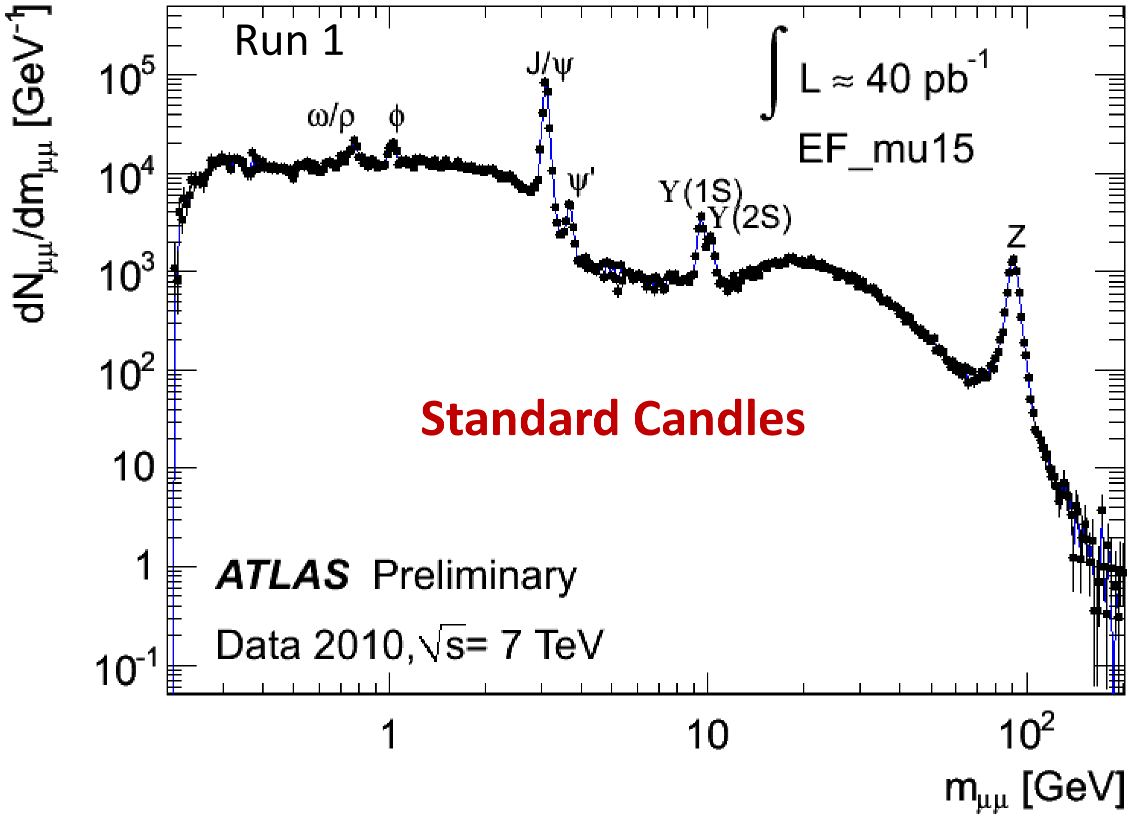
**The detector worked! Excellent performance**

- ✓ **Momentum scale accurate to 0.1%**
- ✓ **Resolution reached design goal: ~80 μm per tube**
- ✓ **TDAQ efficiency close to 100%**
- ✓ **Crucial for Higgs boson discovery and property measurements!**

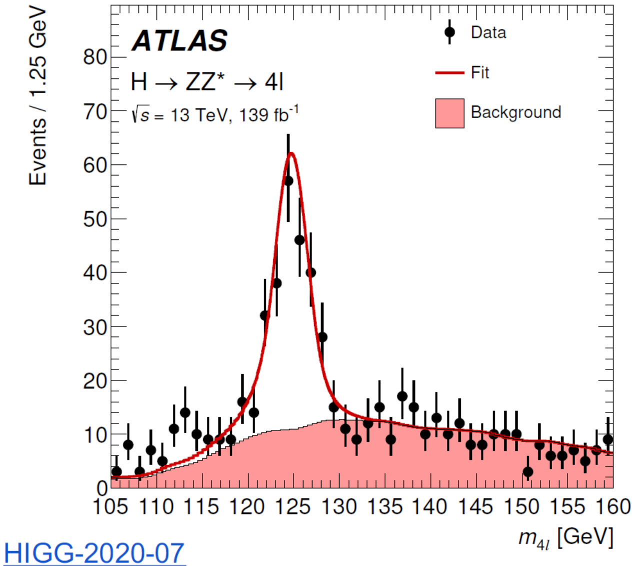


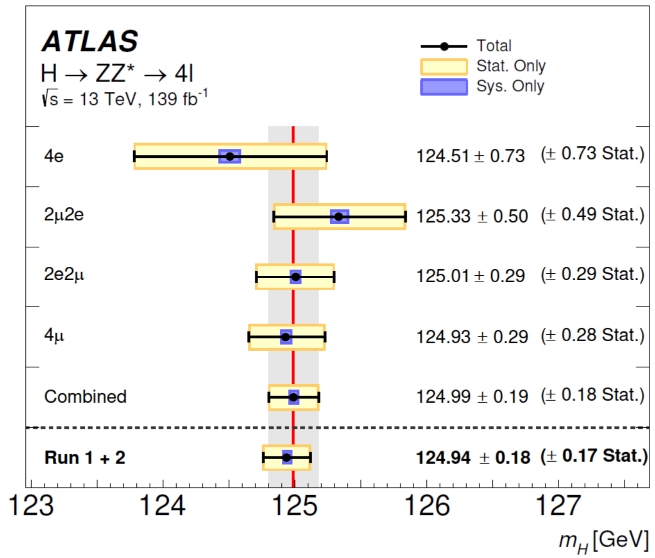




First observation at the LHC turn on




**Higgs boson**

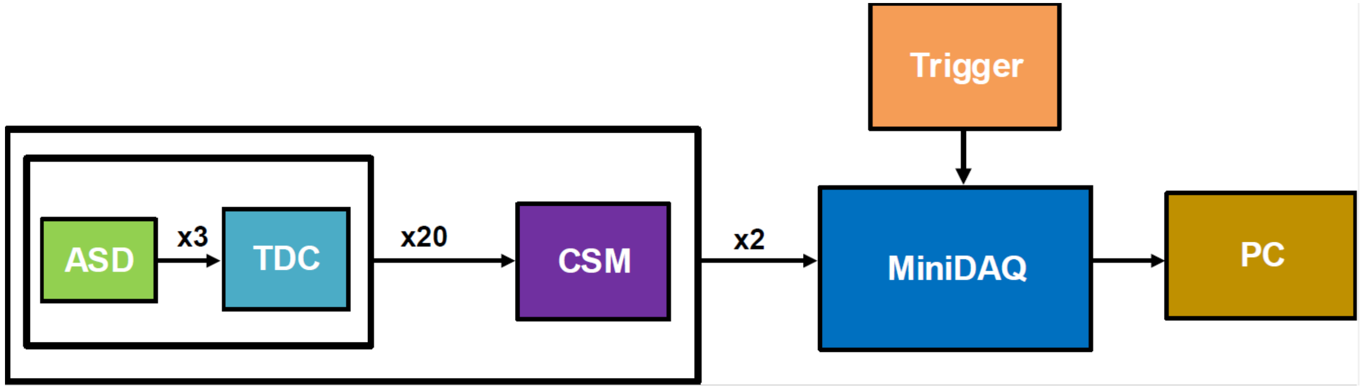



HIGG-2020-07

# A portable MiniDAQ system with MDT front-end electronics

- New front-end electronics and DAQ developed for ATLAS MDT phase-2 upgrade to cope with HL-LHC requirements
- This MiniDAQ system is also used for FCC-ee R&D for straw tracker and drift chamber tests with cosmic rays and test beams
- ASICs, front-end PCBs and MiniDAQ boards produced by various institutions
- System is lightweight and portable
- User friendly GUI is developed and maintained on git repo
- Basic readout channels = 960, data rate to DAQ = 40.96 Gbps, DAQ offline dump rate = 1 Gbps
- Readout channels and data rate can be doubled by adding one SFP+ FMC module
- Front-end voltage and temperature are monitored




The MiniDAQ readout system used to read out data from 2 CSMs

# Test beam study for $PbF_2$ at Fermilab

- $PbF_2$ crystal sits on a rotating platform
- Angular dependence studied for Cherenkov light with SiPM waveform
- If only leading edge info is needed (waveform digitization not required), can use MiniDAQ system as readout (such as scintillator strips with SiPM)