A High-Precision, Fast, Robust, and Cost-Effective Muon Detector Concept for the FCC-ee

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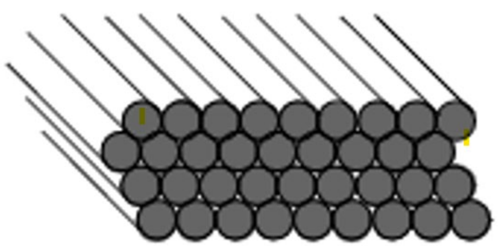
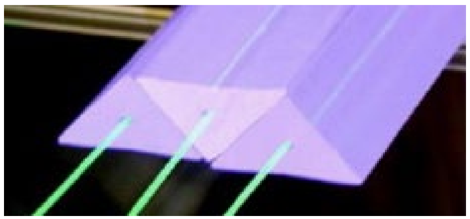
Groups with Interest:
Fermilab, Harvard, Michigan, MSU, Rome, SLAC, Tufts, UCI, UMass, …



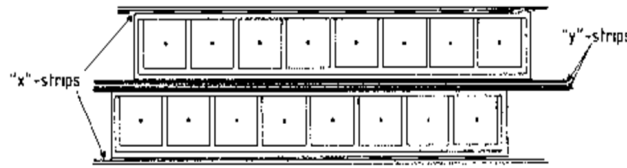


FCC Physics Workshop, January 15, 2025

Collider Muon Detectors

Historically, gaseous detectors have been the preferred choices for muon detectors at colliders, such as those used in the LEP and LHC experiments. These detectors are advantageous for several reasons:

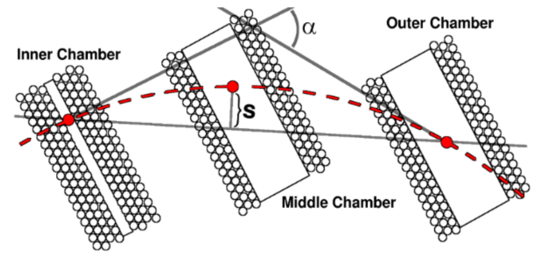
- Economical for large area coverage
- Provide good position resolutions
- Robust and can operate in magnetic fields



ALEPH Streamer tubes

The detectors are designed for

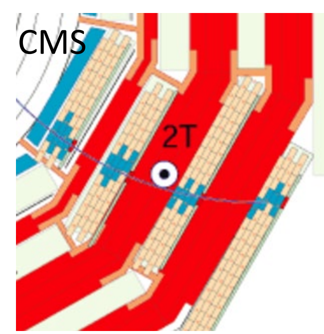
- Muon tagging to complement the precision momentum measurements from the inner tracker, with typical sub-cm hit resolutions. Examples: ALEPH, DELPHI, …



ATLAS muon detector

- Independent precision muon momentum measurement with typical ~100 μm hit resolution. Examples: L3, ATLAS

- Independent coarse momentum measurements with detectors typically instrumented inside the magnetic field return yoke, with typical sub-mm hit resolution. Examples: D0, CMS



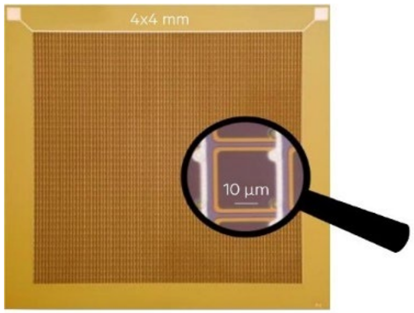
Some detectors have independent trigger capabilities.

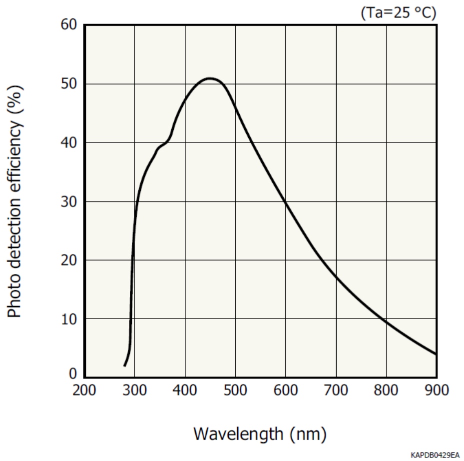
Advances in Detector Technologies

It has been decades since the design and construction of the last collider muon detectors. Since then, significant progresses have been made in new and improved detector technologies.

Several developments are particularly relevant for collider muon detectors:

- **Silicon photomultipliers (SiPMs)** with high quantum efficiency and high gain that are functional in magnetic fields has made scintillators viable options for muon tagging and timing.





Example: Hamamatsu S14160

- **Micro-Pattern Gaseous Detector (MPGDs):**
  -- Micro-Megas (MM), small-thin-gap-chamber (sTGC) and GEM are used for ATLAS and CMS muon detector upgrade in the endcap region to handle the HL-LHC rate
  -- µ-RWELL, a new type of gaseous detector, expected to have significantly improved capabilities in high-rate and high-intensity environments such as the HL-LHC.

Muon Detector Requirements for FCC-ee

Unlike the HL-LHC or FCC-hh, the FCC-ee is a **low-intensity** and **low-rate** environment, especially for muon detection outside the calorimeter. Thus, the requirements for muon detectors are similar to those at LEP.

Current proposed FCC-ee detector concepts all have excellent inner tracking capabilities paired with state-of-the-art calorimetry. Muon momenta will be measured precisely in the inner detectors. Therefore, the primary roles of a muon detector at the FCC-ee are:

- Muon identifications (or tagging) – matching the outer muon hits/tracks with the tracks in the inner tracker
- Tail-catching of leaking calorimeter showers

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

- Tracking with **good spatial resolutions** for the identification of long-lived particles
- **Fast timing** for independent triggers and search for massive stable particles.

A Concept: Drift Tube and Scintillator

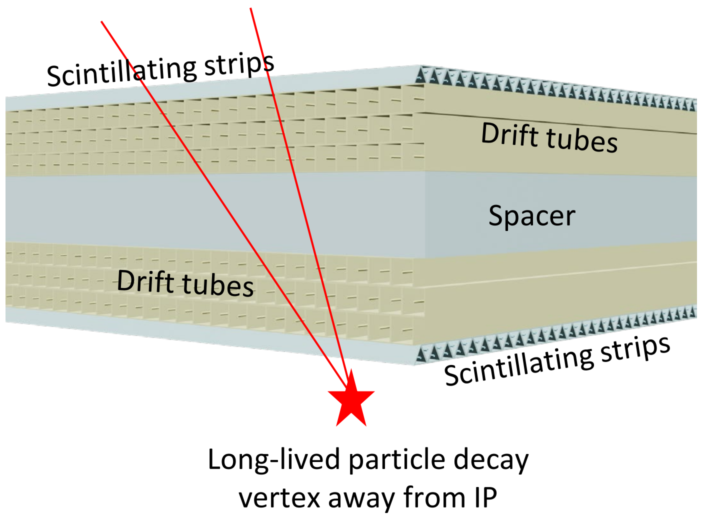
A combination of drift tubes and scintillators is a cost-effective option to meet the requirements of a muon detector at the FCC-ee:

- 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 to operate!

An Example Barrel Layout for Illustration:

Multiple layers of drift tubes along the beam line for bending-plane spatial measurements with a hit resolution of σ_{xy}~100µm

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



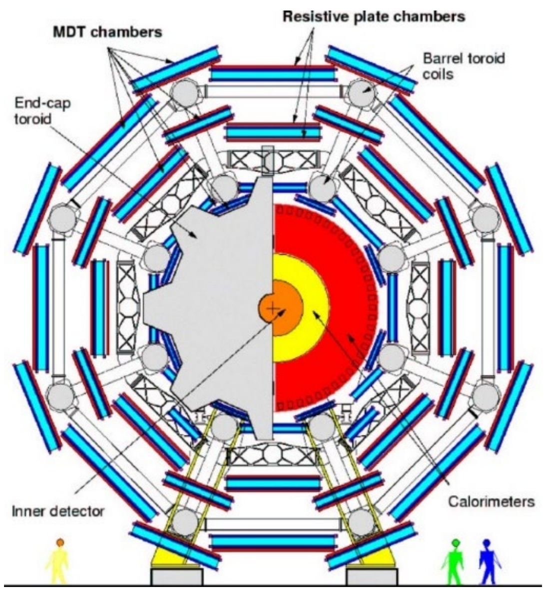
Triangular scintillator strip layers perpendicular to the beam line for the z-coordinate and timing measurements with σ_z~1mm and σ_t~200ps

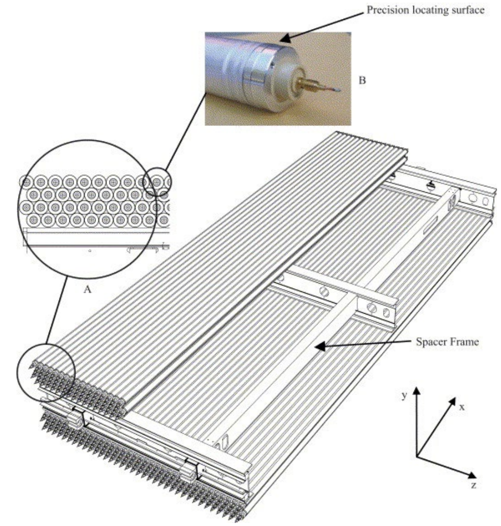
- Independent triggers for both beam and non-beam events
- Time-of-flight information for massive stable particles, …

This configuration can be readily expanded to 2-3 such super layers for independent momentum measurements (as the ATLAS and CMS muon system)

Drift Tubes: Repurpose ATLAS (s)MDT Chambers?

ATLAS has a large number of precision MDT/sMDT chambers (1200) of different sizes. Can these chambers be repurposed for the FCC-ee?





The large chamber
L = 6 m
W= 2 m

Chamber assembly at Michigan

Some of issues to be considered:

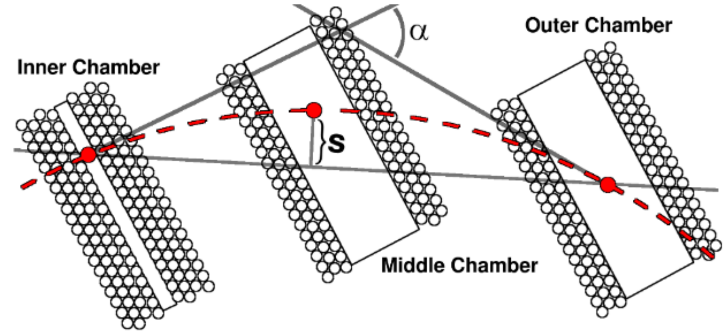
- Are there significant performance degradations due to aging?
- Can these chambers fit into the FCC-ee detector design, or what constraints do they impose on the design? Perhaps we could use them for most of the coverage, supplemented with some new chambers…
- Discuss with the ATLAS Collaboration.

Note: Tubes were glued together to form chambers. It is far more practical to repurpose entire chambers than individual tubes.

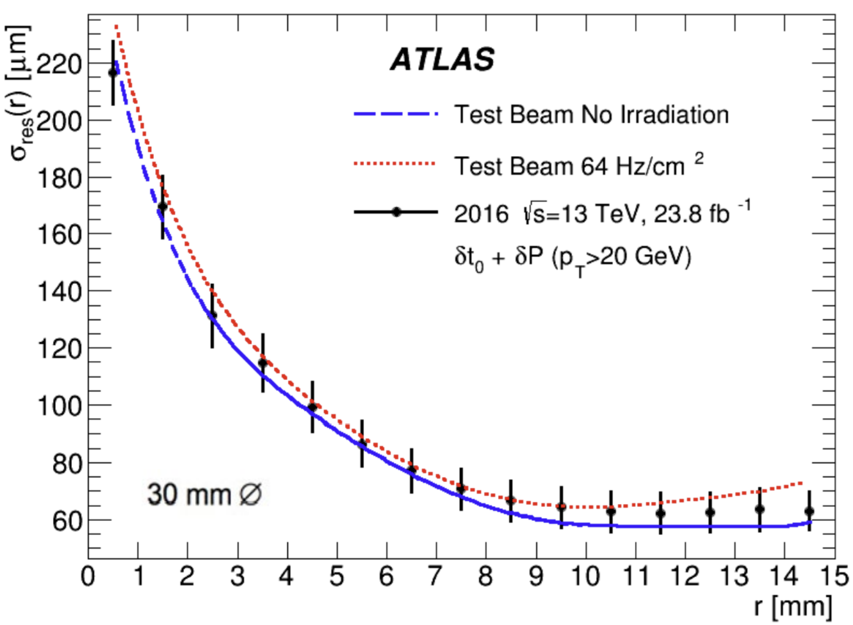
ATLAS Drift Tube Performances

ATLAS MDT muon chambers were designed for independent precision momentum measurements. Therefore, these round drift tubes have excellent spatial resolution: **σ~80μm**.

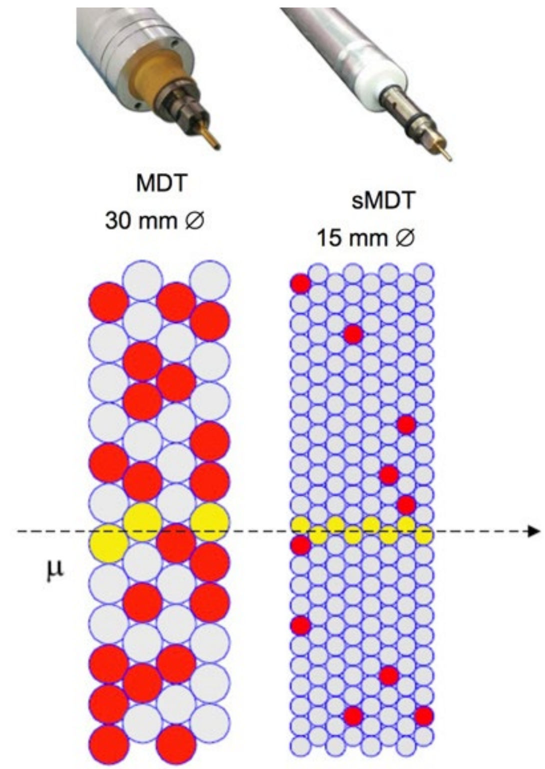
Most chambers have 30mm-diameter tubes while a small number of chambers have 15mm-diameter tubes (HL-LHC upgrade) with **100μm** spatial resolution.



Gas: Ar:CO2 (93:7), HV=3080V, p=3 bar, T_{max}= 750 ns



arXiv: 1906.12226

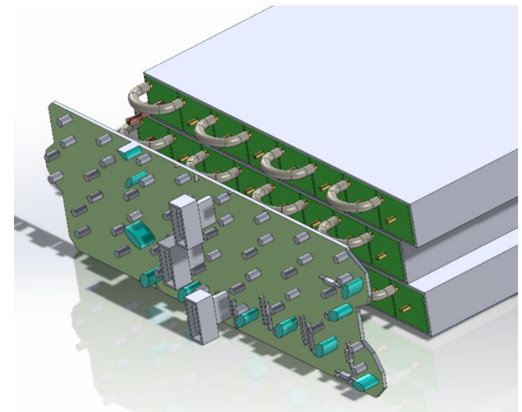


New Drift Tubes?

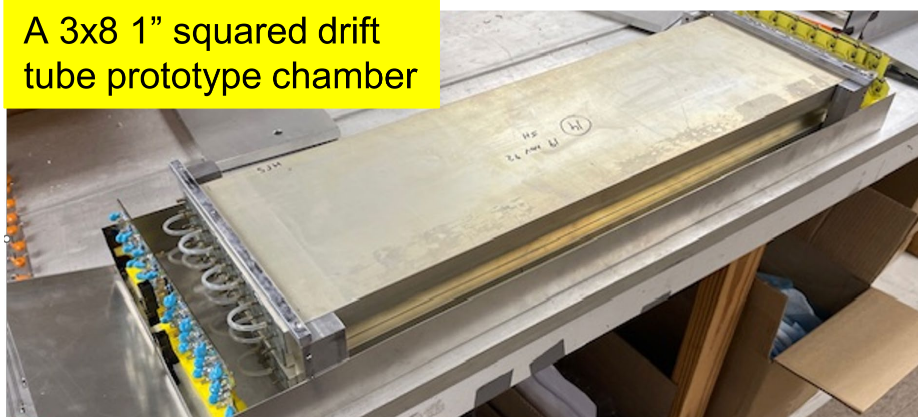
Concerted R&D efforts are needed to design new drift tubes and to demonstrate detector performances, develop construction techniques; optimize tube/chamber geometry in the context of the overall detector design, minimize cost,…

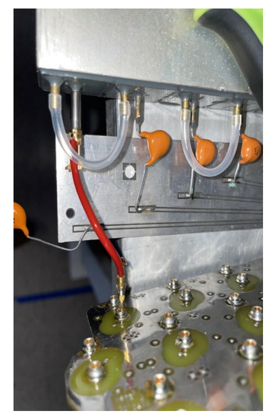
At Michigan, we have two dozen chambers with 1” square cells and plan to build a module with three layers for initial testing and studies:

- Using ATLAS MDT electronics for readout
- Exploring different gases
- Cosmic and beam test to characterize its performance.



A 3x8 1” squared drift tube prototype chamber





Using the ATLAS MDT front-end electronics (HH, mezzanine, CSM) and MiniDAQ for readout

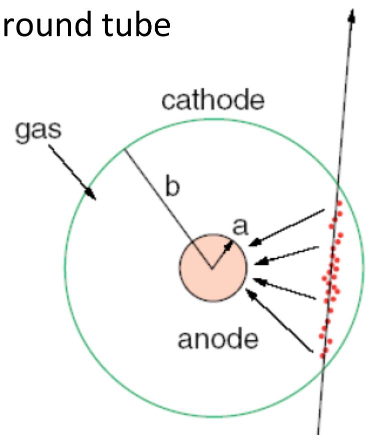
In collaboration with MSU, UMass, Tufts, Harvard, UCI, and others, we plan to develop new tube and chamber assemblies and their readout electronics, as well as study their performance. This work will be synergistic with the straw tracker R&D.

Drift Tube Cross-Sectional Shape

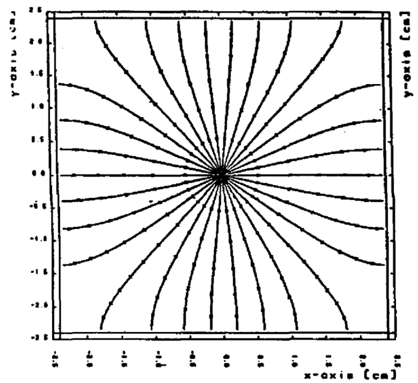
One R&D effort is to investigate the cross-sectional shape to optimize cost with performance.

Rectangular or even hexagonal tubes can be economically produced in large quantities simultaneously through extrusion, but their spatial resolution needs to investigated.

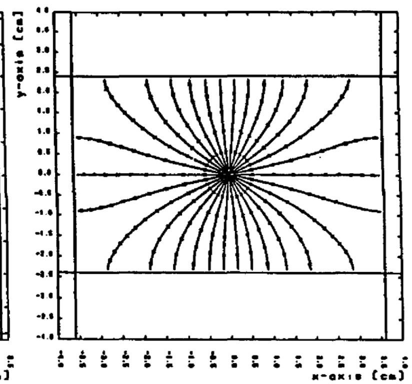
ATLAS round tube



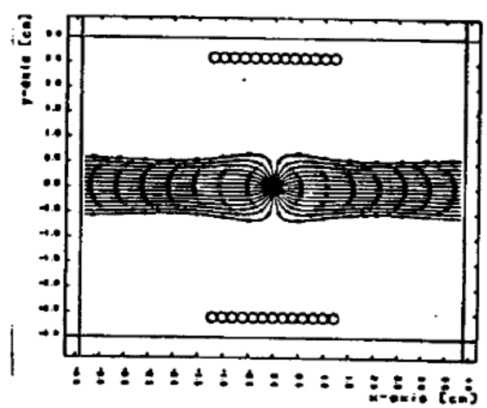
Squared tube

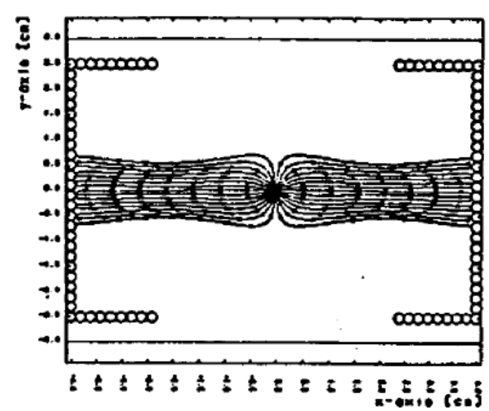


Rectangular tube

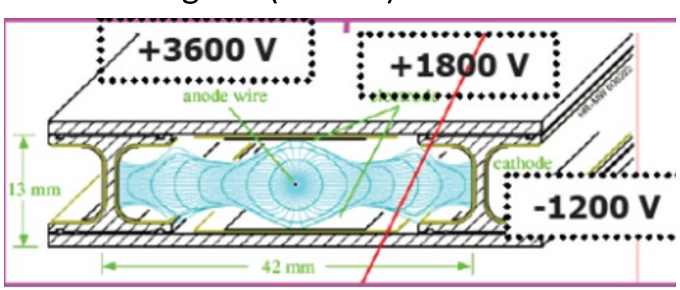


Shaping the fields can improve the resolution, but will increase the directional dependences.





CMS rectangular (I-beam) tube



Scintillator Strips

Scintillators have wide applications in particle physics. However, their use was previously limited to non-magnetic environments due to the constraints of classical photomultipliers.

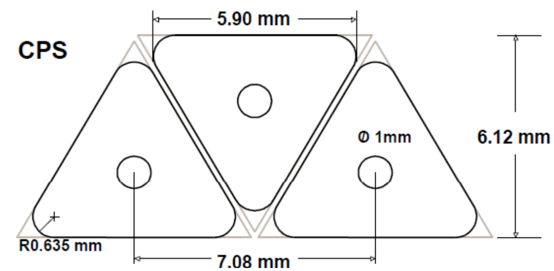
The development of Silicon Photomultipliers (**SiPMs**) has been a game changer for the application of scintillator detectors, making scintillator an attractive option for the FCC-ee muon detector.

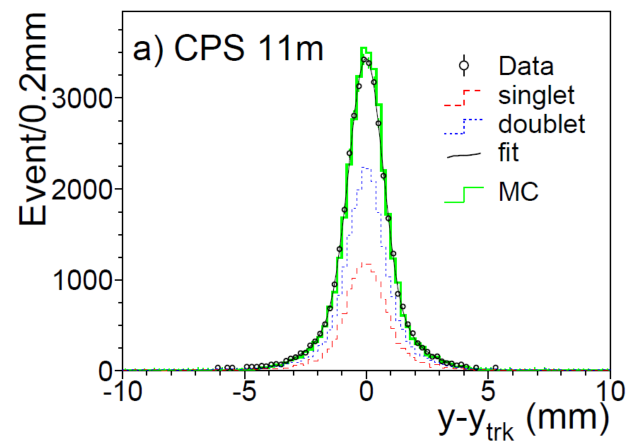
Work for the D0 preshower detector years ago

- **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 D0 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.

SiPMs have similar specs as the VLPCs, but the performance should improve without the long clear fibers! Readout both ends for "time-of-flight" information.

Interested groups include Fermilab, Rome, SLAC, …





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

Fermilab Scintillator Extrusion Facility

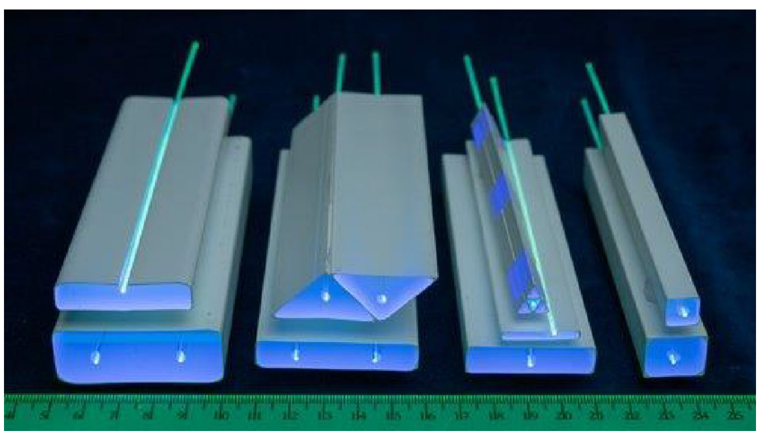
Fermilab Scintillator Extrusion and Injection Molding past/planned projects

FNAL-NICADD Extrusion Facility

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

- FNAL experiments:
  - MINOS (supervision & QC)
  - MINERvA
  - Mu2e CRV
  - TMS – DUNE
  - Mu2e II
- Large projects:
  - K2K (Supervision & QC)
  - T2K: POD, ECal, INGRID
  - DoubleCHOOZ
  - Pierre Auger: CNEA, KIT
  - ICECUBE
  - IDEON – Canada
  - LDMX
  - MATHUSLA
- DOE complex:
  - ANL: STAR
  - JLAB: CLAS, CDet
  - LANL
- Smaller Projects
  - MURAVES – INFN Napoli
  - CANFRANC – Spain
  - SNOLAB -- Canada
  - INFN: Bologna, Brescia, Gran Sasso, Padova
  - Inst. Phys. Globe, France -- Volcano tomography Guadeloupe Soufrière
  - NYU – Abu Dhabi
  - Tel Aviv University – Erez City of David tomography
  - UIS – Colombia
  - Univ. Liverpool
  - LDMX Veto Prototype – Lund University
  - INO – mini ICAL Cosmic Veto
  - CMS
  - Naval Research Facility
  - MATHUSLA – U. Toronto
  - LHCB
  - INFN Catania
- Injection Molding (New capability as of this year)
  - CMS HGCAL
  - ePIC LFHCal – ORNL, BNL
  - Shashlik – HIKE calorimeter

9/25/2023 Jim Freeman IPRD23

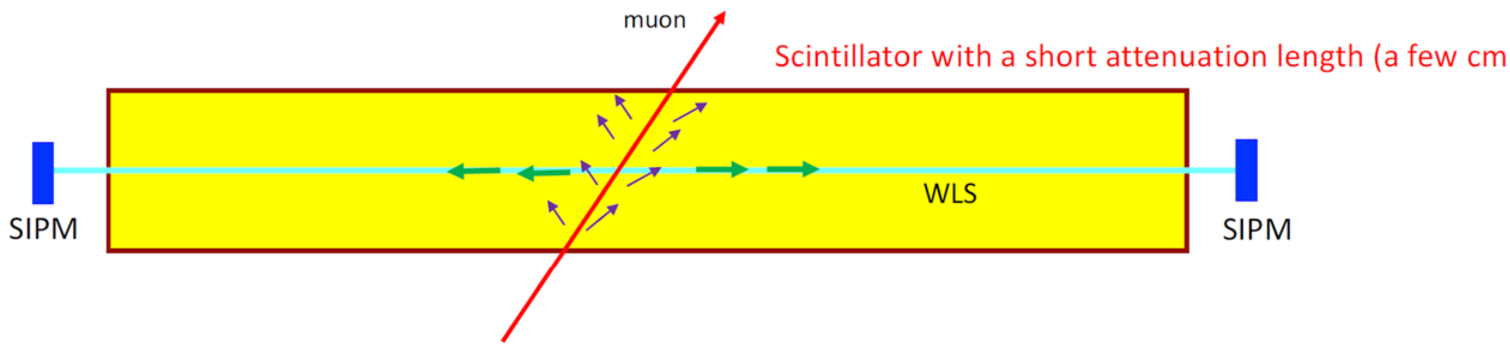


Scintillator development at Fermilab (Jim Freeman)

Proposal from INFN Roma 1 Group

A proposal for a Muon Detector based on Scintillators plus WaveLength Shifter

- The idea is to have something **reliable**, **simple**, **fast** and **not expensive** , that can be used for **trigger** and **tracking**.
- We propose to use scintillators with a wavelength shifter to guide the light to a silicon photon multiplier (sipm) for reading the signal.



- A similar solution has been proposed for the SiD detector at the International Linear Collider

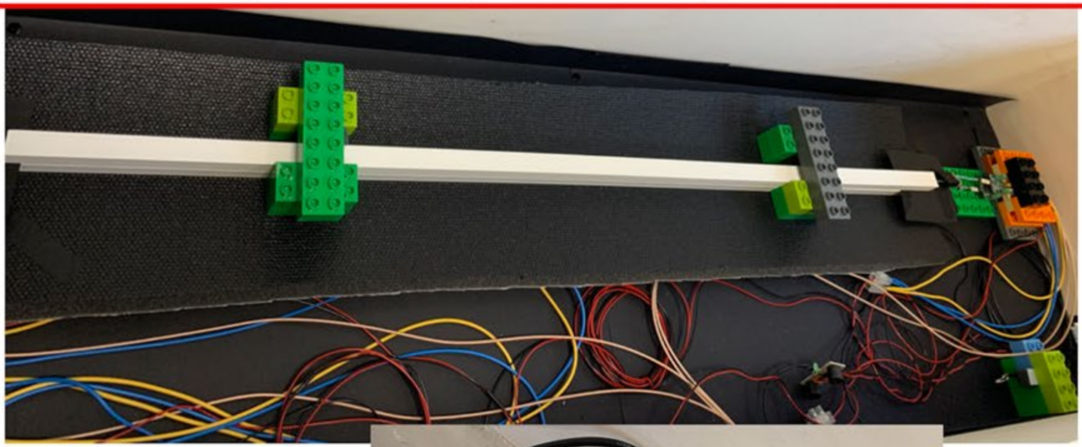
The SiD Detector for the International Linear Collider arXiv:1511.00134v1 [physics.ins-det] 31 Oct 2015

Extruded scintillator strips from Fermilab, WLS fibers from Kuraray

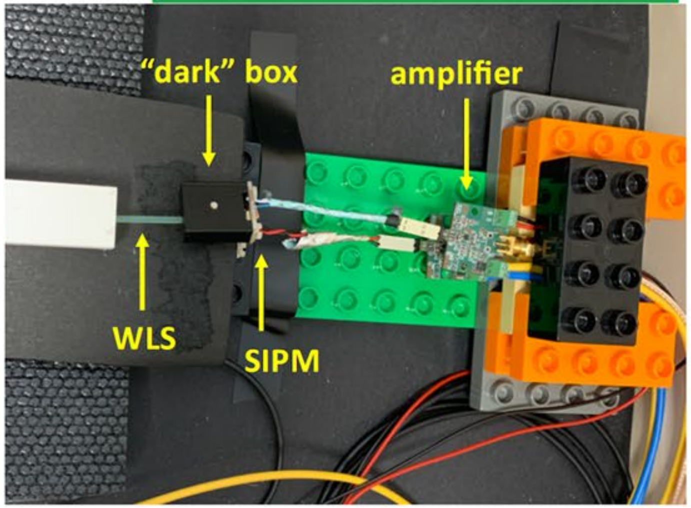
Roma 1: Prototype Strips

Little prototype realised in Rome

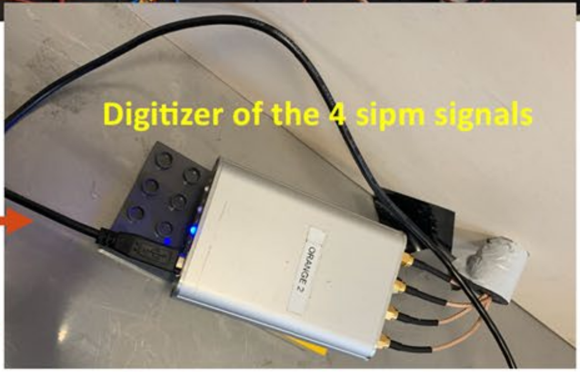
Two scintillator bar, about 1 m long and 1 cm thick, placed one on top of the other



The amplifier has been developed at Rome a few years ago for a CLIC R&D study.

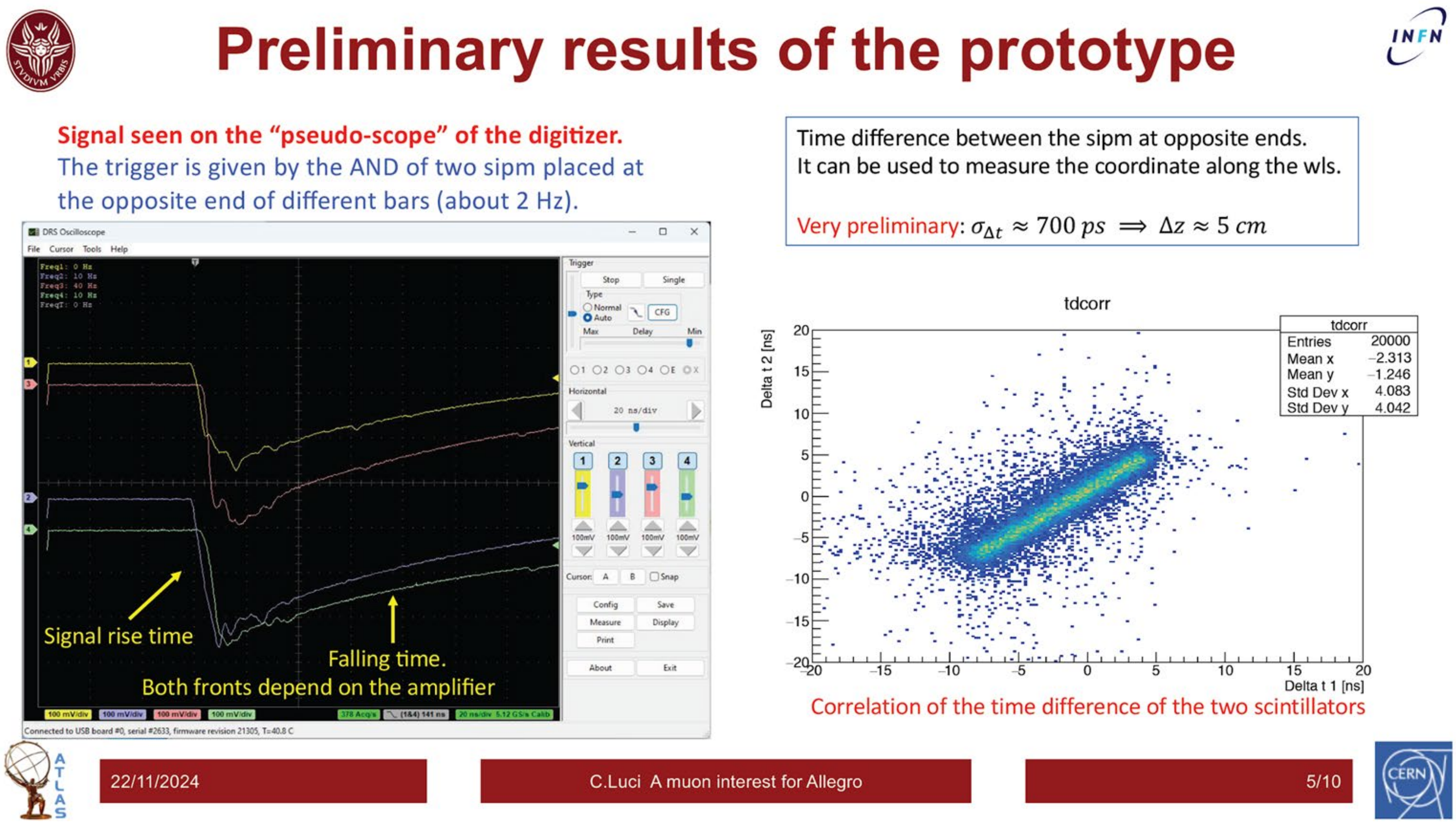


DRS4 evaluation board developed at PSI. 0.7 to 5 GSPS with a 700 MHz bandwidth.
It has a programmable trigger based on combination of the four input.



We have also a different kind of scintillator (ELJEN EJ-200) with 4 m attenuation length, whose light can be red with a SIPM without using any WLS.
We plan to test it and make a comparison with this setup.

Roma 1: Preliminary Results



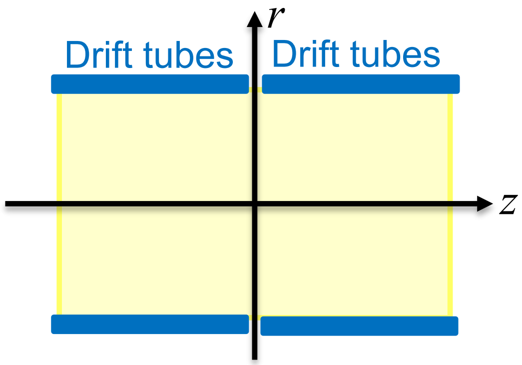
See the presentation by Claudio Luci at the ALLEGRO concept meeting for more details.

Some Numbers

Number of drift tubes (barrel): 17,000 (For new tubes)

- At a radius of ~5.5m outside the calorimeter
- 6 layers of 1” square-cell tubes along the beam direction
- 2 segments in Z (along the beam)

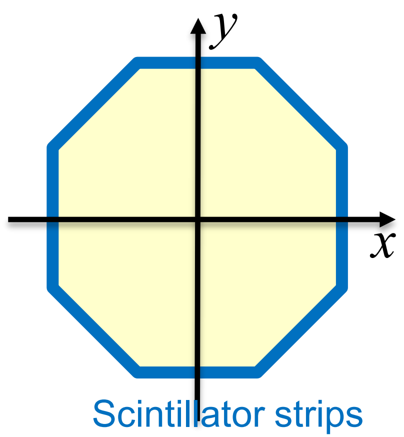
Double that to include endcaps leads to a total of 35,000 tubes (as a reference, ATLAS has 350,000 drift tubes in the muon system)



Number of scintillating strips (barrel): 16,000

- 2 layers (top/bottom) of strips perpendicular to the beam,
- Triangular strips with 2cm base width
- 10m coverage along Z, 8 segments (octants) in ϕ

Double that to include endcaps leads to a total of 32,000 strips.



R&D to characterize the performance of drift tubes and scintillators/SiPMs…

Refine the design based on performance assessments and simulation studies.

In particular, optimizing the sizes of the tubes and strips, as well as the number of layers, could result in an even smaller total number of channels.

Summary

We propose a **high-precision, fast, robust, and cost-effective** muon detector for an FCC-ee experiment by combining drift tubes and extruded scintillator strips with SiPM readout. Such a detector could offer precision tracking (σ_{xy}~100μm) and fast timing (σ_t~200ps) capabilities with a total channel count of fewer than 100k !

High-precision: Precision position measurements from drift tubes
Fast: Fast timing information from scintillators
Robust: Mature technologies, reliable and robust to operate
Cost-effective: Inexpensive to construct and with a far smaller channel count!

The specific configuration of the muon detector must be optimized together with the overall detector design, taking into account the inner tracker, calorimeter, and magnetic field setup.

We are currently drafting a white paper to outline the proposal, which will serve as both a reference and as input to the European Strategy studies. Furthermore, we are also recruiting new groups to further develop the concept and to plan and execute out R&D tasks. These tasks will include simulations, prototyping, construction techniques, and performance evaluations using cosmic rays and test beams.