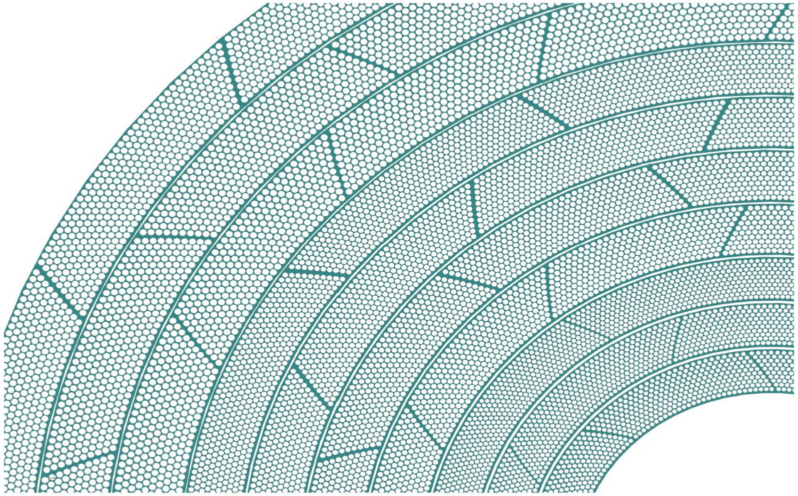
A Straw Tracker for the FCC-ee



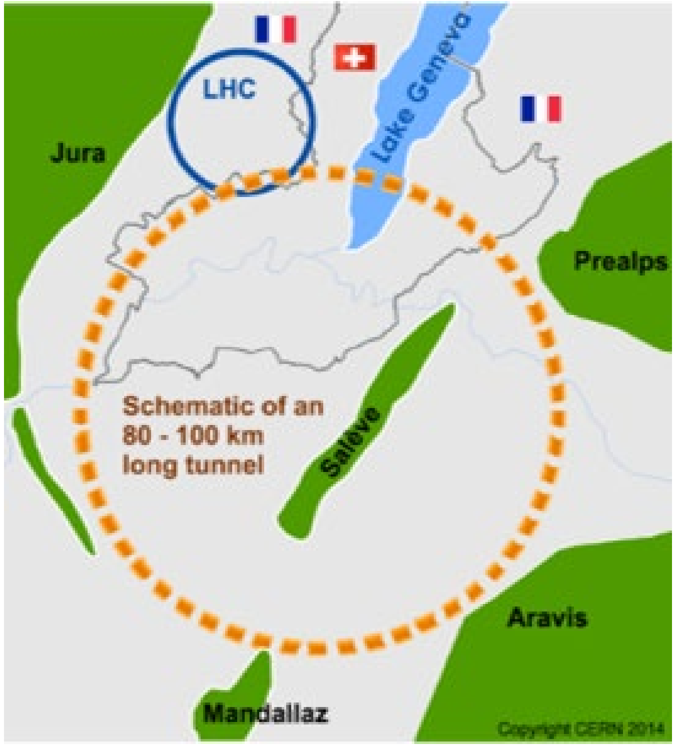
Jianming Qian
University of Michigan

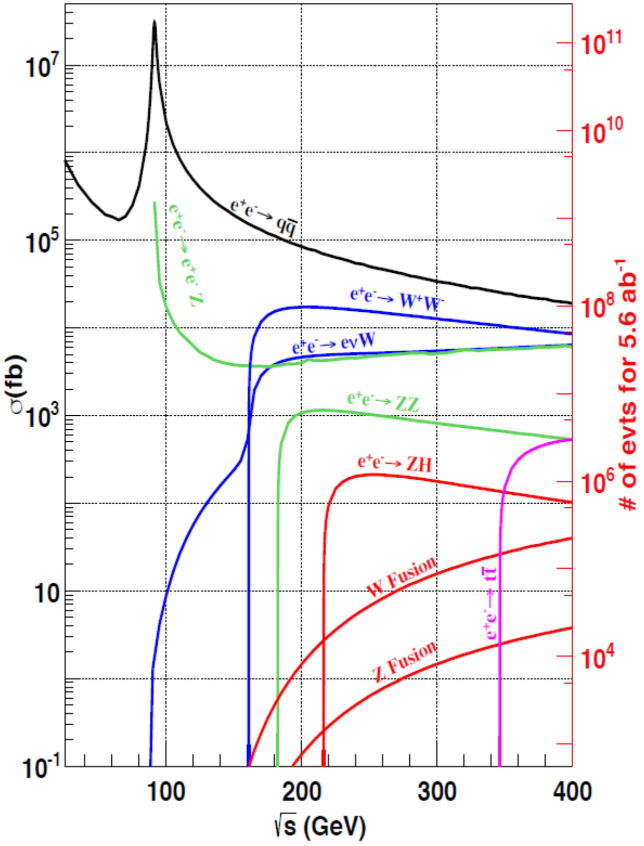
Groups with Interest

Michigan, MPI, Duke, Harvard, Michigan State, Tufts,
UC-Irvine, UMass, UT-Austin, …

DRD1 Collaboration Meeting, CERN, December 9, 2024

FCC-ee Collider



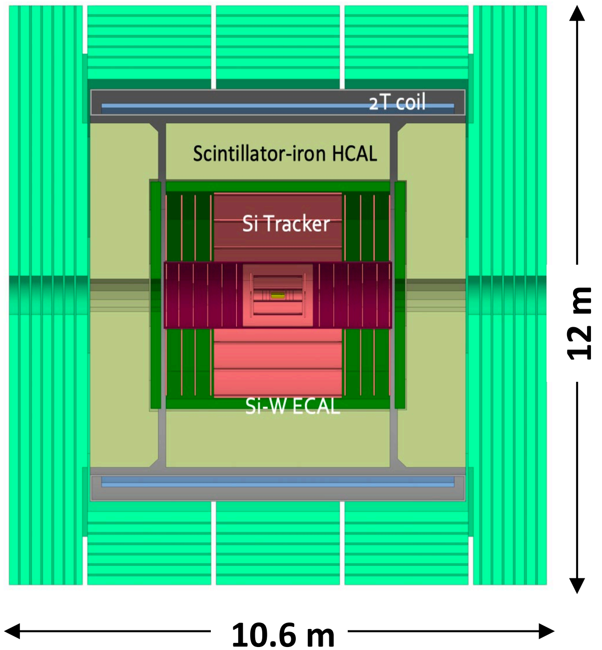


ZH maximum	√s ~ 240 GeV	3 years	10^6	$e^+e^- \to ZH$
$\bar{t}t$ threshold	√s ~ 365 GeV	5 years	10^6	$e^+e^- \to \bar{t}t$
Z peak	√s ~ 91 GeV	4 years	5×10^{12}	$e^+e^- \to Z$
WW threshold+	√s ≥ 161 GeV	2 years	$> 10^8$	$e^+e^- \to W^+W^-$
[s-channel H	√s = 125 GeV	5? years	~5000	$e^+e^- \to H_{125}$]

A multi-decade precision physics program to measure the properties of fundamental particles and study their interactions…

Detector Concepts

CLD



Based on CLIC detector design:

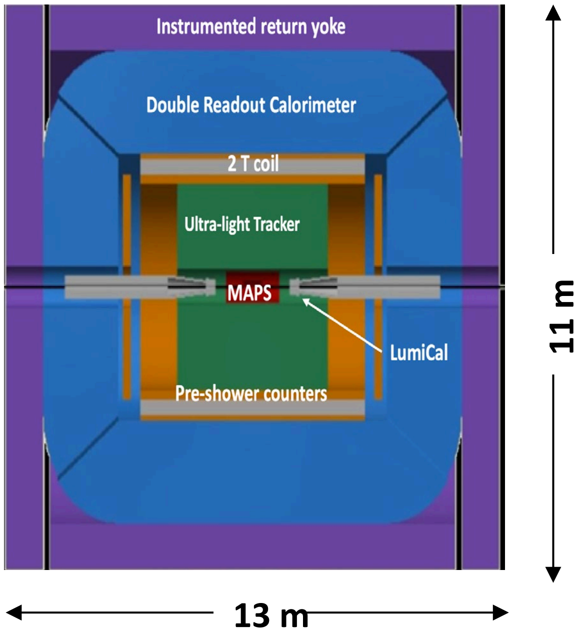
Silicon vertex detector;

All Silicon tracker;

High granular calorimeter;

....

IDEA



New, innovative, ...:

Silicon vertex detector

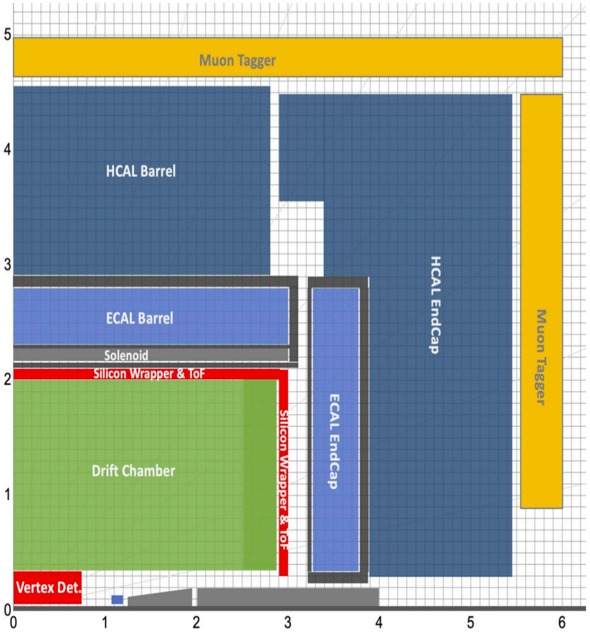
and outer wrapper;

Ultra-light drift chamber;

Dual-Readout calorimeter;

....

ALLEGRO



New Concept:

Silicon vertex detector

and outer wrapper;

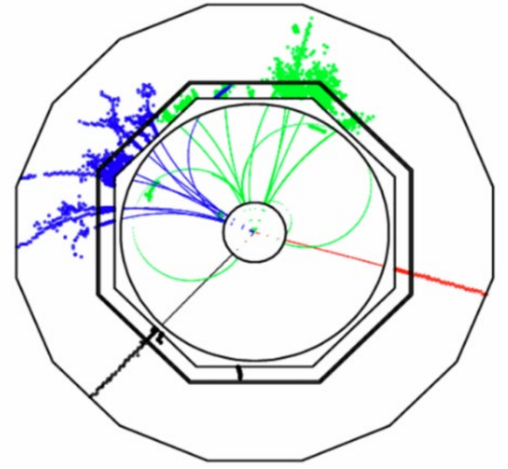
IDEA-like drift chamber;

High granular LAr ECAL,

....

Momentum Resolution Target

One of the key features of the Higgs physics program at the FCC-ee is to identify the Higgs boson through the recoil mass distribution, independent of the Higgs boson decay



$e^+e^- \to ZH \to \mu^+\mu^- + X$

Therefore, the $Z \to \mu^+\mu^-$ recoil mass distribution

$$M^2_{\text{recoil}} = \left(\sqrt{s} - E_{\mu\mu}\right)^2 - p^2_{\mu\mu}$$

of the $e^+e^- \to ZH \to \mu^+\mu^- + X$ events is often used to set the track momentum resolution target.

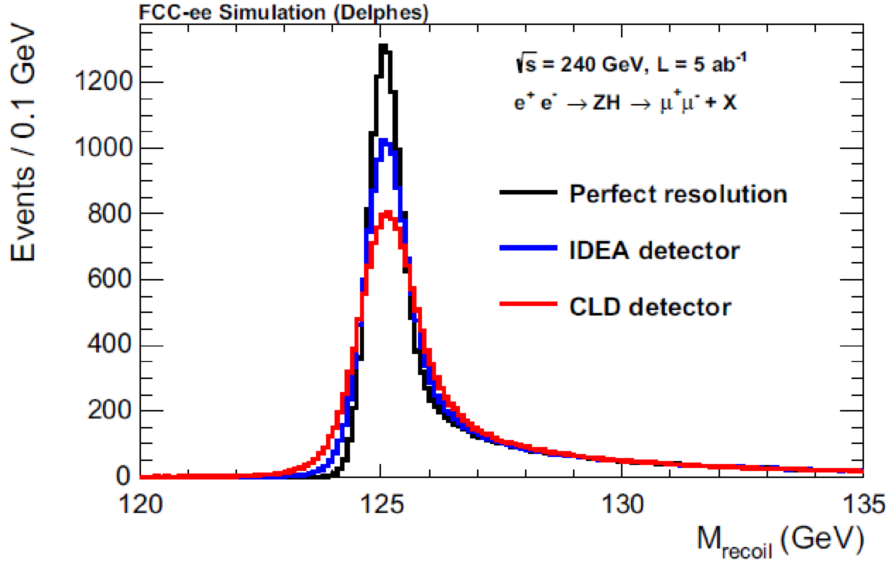
The contribution to the M_{recoil} spread from the momentum resolution should not be much worse than that from the $\sqrt{s}$ spread:

$\sim 0.16\%$ at $\sqrt{s} = 240$ GeV

$\Rightarrow$ a momentum resolution requirement

$$\frac{\Delta p_T}{p_T} \sim 0.16\% \ @ \ p_T \sim 50 \text{ GeV}$$

Or approximately $\Delta\left(\dfrac{1}{p_T\,(\text{GeV})}\right) \sim 3\times 10^{-5}$



Eur. Phys. J. Plus (2021) 136

Almost x10 better than the best of previous tracker!

Track Momentum Resolution

For a magnetic spectrometer, the resolution is mostly impacted by uncertainties in position measurements and by smearing due to multiple scatterings

$$\left(\frac{\Delta p_T}{p_T}\right)_{\text{meas}} \approx \frac{p_T}{0.3} \frac{\sigma_{\text{hit}}}{BL^2} \sqrt{\frac{720}{N+4}},$$

$$\left(\frac{\Delta p_T}{p_T}\right)_{\text{scat}} \approx \frac{0.0136}{0.3BL} \sqrt{\frac{X}{X_0}} \sqrt{C_N}$$

p_T in GeV, B in Tesla
L in meter (level-arm)
σ_{hit} in meter (single hit resolution)
N: the number of measurements
X/X_0: material in radiation length
$C_N \sim 1$

Position measurements assuming $B = 2$ T and $L = 2$ m:

$\sigma_{\text{hit}} \sim 10\mu\text{m}$ (silicon): $\left(\frac{\Delta p_T}{p_T}\right)_{\text{meas}} \sim 0.16\% \, p_T \Rightarrow N \sim 10$

$\sigma_{\text{hit}} \sim 100\mu\text{m}$ (gaseous): $\left(\frac{\Delta p_T}{p_T}\right)_{\text{meas}} \sim 0.16\% \, p_T \Rightarrow N \sim 1400$

Conclusion 1: Gaseous detector alone is not sufficient!

(Impractical to have this many measurements.)

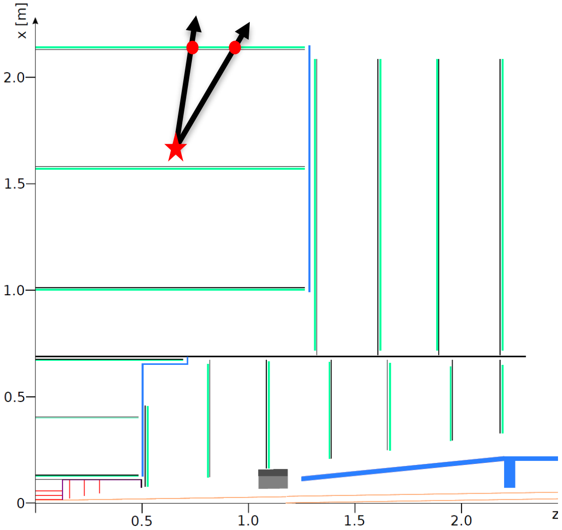
Multiple scatering assuming $B = 2$ T and $L = 2$ m:

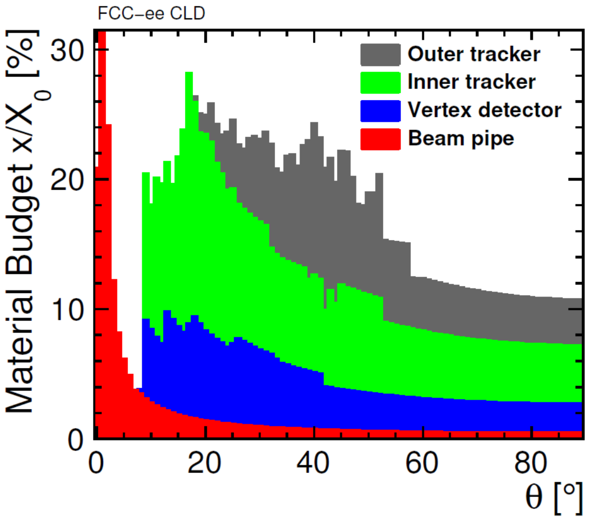
$$\left(\frac{\Delta p_T}{p_T}\right)_{\text{scat}} \sim 0.16\% \quad \Rightarrow \quad \frac{X}{X_0} \sim 2\%$$

Conclusion 2: Minimizing the material is a key!

Inner Tracker Concepts

CLD: Full Silicon





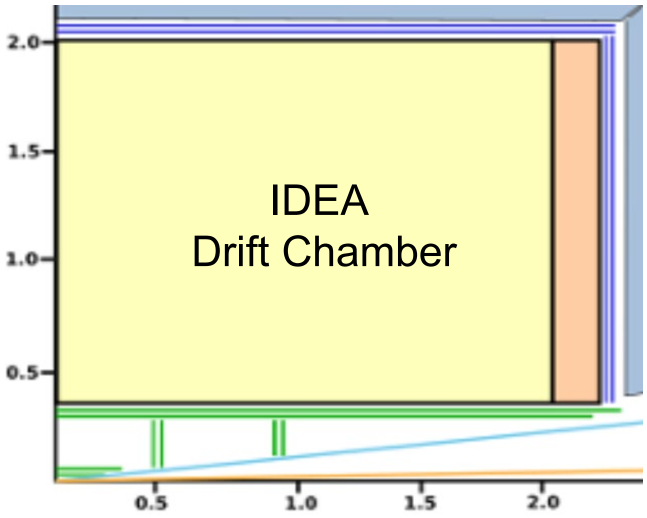
Pros:

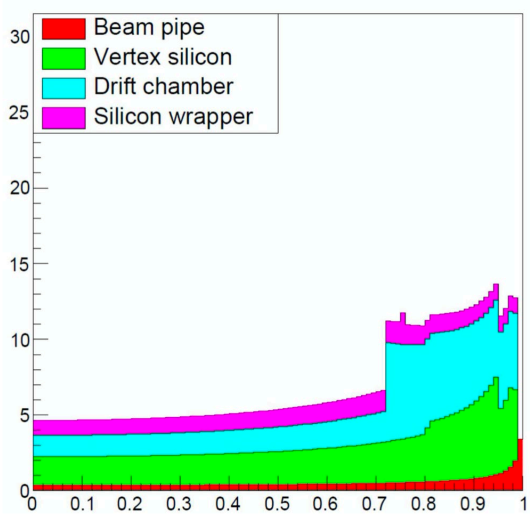
- Excellent singlet hit resolution
- No high voltage, no gas

Cons:

- Small number of hits
- Large material budget
- Limited dE/dx PID capability
- Likely more expensive

IDEA: Silicon vertex + Drift chamber + Silicon Wrapper





Pros:

- Very low material budget
- Large number of hits
- dN/dx PID potential

Cons:

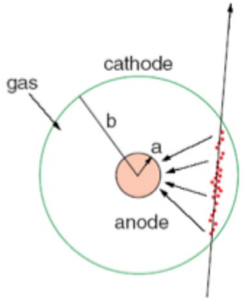
- Large number of wires, mechanical challenge
- High voltage, gas

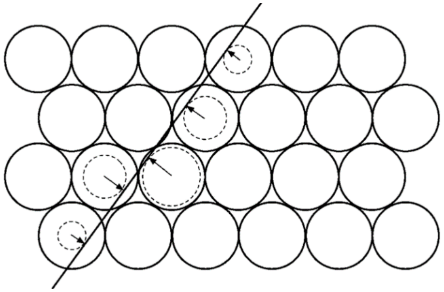
MDTs and Straw Tubes

Drift chambers have long been the preferred choices for gaseous trackers at lepton colliders. However, recent developments in very thin straws, coupled with the complexities of large drift chambers makes a straw tracker an attractive alternative.

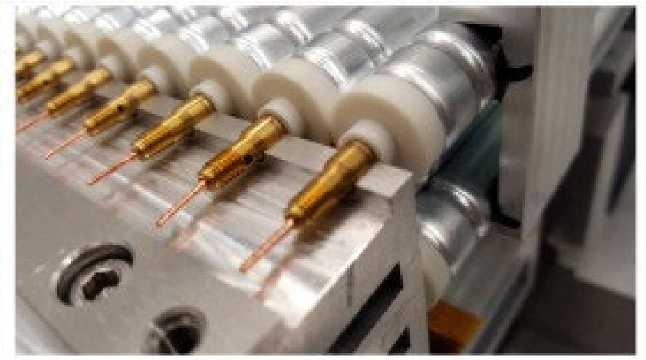
Straws are well-established technologies and are robust (even operatable in vacuum!). Our proposal for a straw tracker for the FCC-ee was first presented at: https://indico.cern.ch/event/1438815/

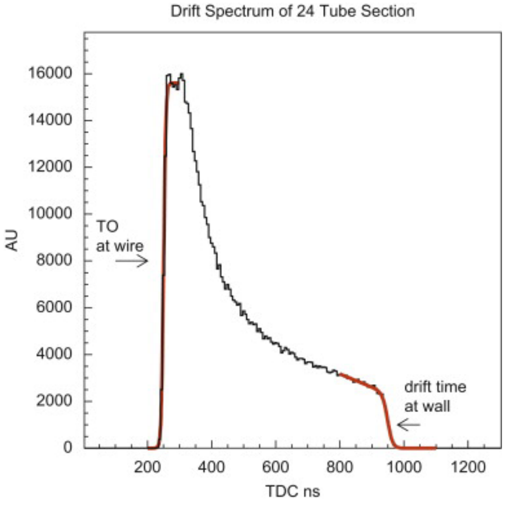
Straw tubes are thin-walled, smaller circular drift tubes that serve as gaseous detectors operating in the proportional mode with a typical position resolution of ∼100μm. They can be easily assembled into large chambers or trackers.

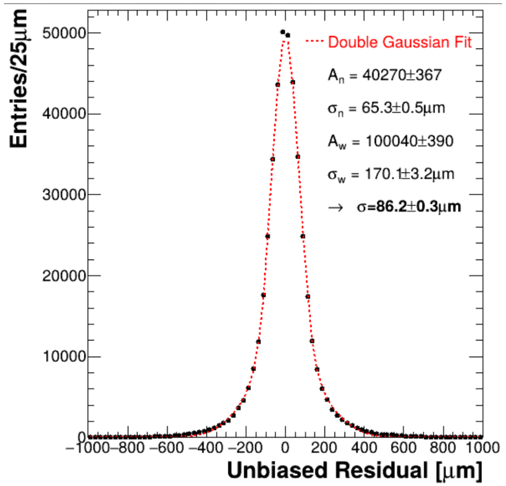




Our Michigan ATLAS group has extensive experience on the monitored drift tubes (MDT) of the ATLAS muon spectrometer, including the small-MDT for the HL-LHC upgrade.



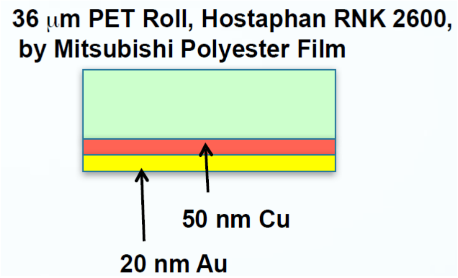




Straws and Straw Trackers

Unlike traditional drift tubes made from metals like aluminum, straws are constructed from light dielectric material such as Mylar (polyethylene terephthalate or PET). To function as drift tubes, straws need to be metalized.

Mylar is the preferred choice due to its high tensile strength, chemical stability, and excellent insulation against gas, moisture, and electric fields. Additionally, it is easy to metalize.



NA62 straw coating

In many ways, a straw tracker and a drift chamber are similar. Both are gaseous detectors with comparable spatial resolutions, similar dE/dx and dN/dx particle identification capabilities, and flexibility in optimizing drift cell or straw sizes;

However, there are significant differences. Each straw tube is an independent unit, making a straw tracker highly flexible in design, construction and operation, albeit at the cost of slightly more material than a drift chamber.

Design: Modular design allows better optimization and integration with the silicon detectors. For instance, a silicon layer can be placed between straw layers if warranted.

Construction: Straw trackers can be built in multiple functional units, have far smaller wire densities resulting in much less mechanical stress on the supporting structure.

Operation: Different gas mixtures can be used for different layers for various purposes, and individual tubes can be disabled if their wires are broken.

Straw Tracker Workshop

Mini-Workshop on Straw Tracker R&D for a Future Electron-Positron Higgs Factory

October 14-15, 2024
Department of Physics, University of Michigan
Ann Arbor, Michigan 48109, USA

Through European strategy studies and the US Snowmass process, a consensus on an electron-positron collider as the Higgs factory is emerging within the particle physics community. To explore the physics potential of such a collider, several detector concepts have been proposed, each necessitating a precision inner tracking detector. Popular options for this critical component include semiconductor detectors, drift chambers, time projection chambers, and their various combinations.

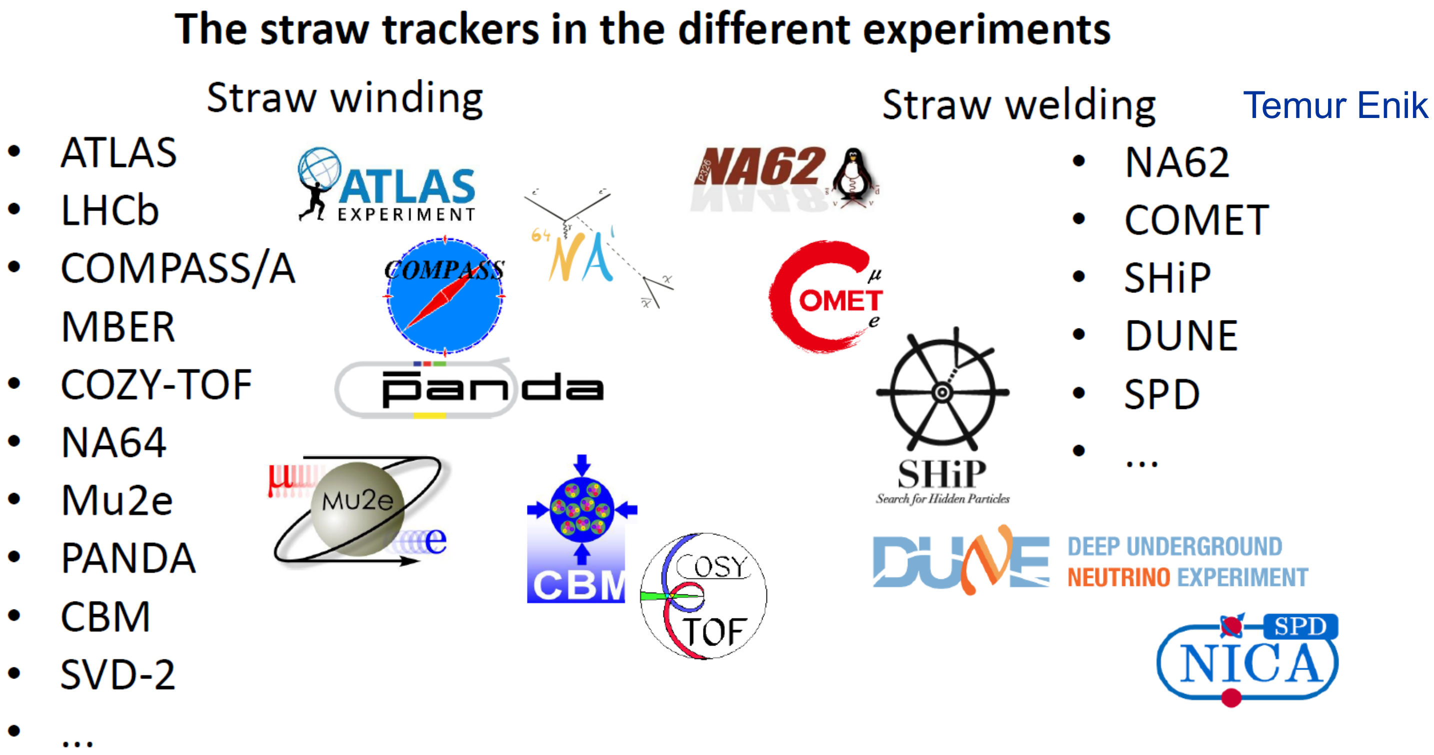
This workshop intends to bring together experts and interested parties to investigate the feasibility of incorporating a straw tracker into the inner detector. The topics for the workshop will encompass reviews of existing straw trackers and their latest developments, the requirements for a Higgs factory, critical R&D issues, as well as potential layouts for an inner detector that includes a straw tracker.

Approximately 35 physicists from 20 institutions participated in the workshop

Website: https://sites.google.com/umich.edu/strawtracker2024/home
Indico: https://indico.cern.ch/event/1408681/

Straw Trackers are Popular…

Straw trackers have been utilized in various recent and upcoming experiments, thanks to the technological developments in thinner straws and their versatilities in geometry and operating conditions.



The straw trackers in the different experiments

Straw winding

- ATLAS
- LHCb
- COMPASS/AMBER
- COZY-TOF
- NA64
- Mu2e
- PANDA
- CBM
- SVD-2
- …

Straw welding

Temur Enik

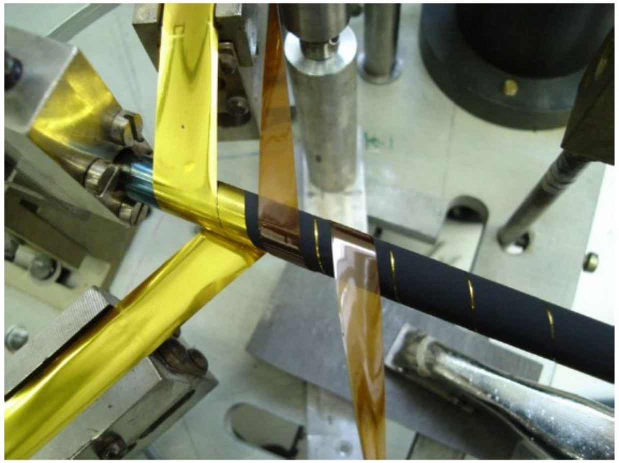
- NA62
- COMET
- SHiP
- DUNE
- SPD
- …

+ g-2
AMS

Those old enough may recall that a straw tracker was once proposed for the SDC detector at the SSC.

Straw Production Technologies

Straws for drift tube applications are primary produced through **winding** or **welding**.



Temur Enik

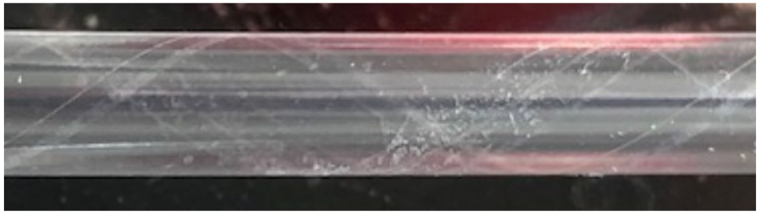
Hans Danielsson

(Classical) winding:
ATLAS, LHCb, NA64, Panda, Mu2e, …

(Relatively Recent) Welding:
NA62, Comet, SHiP, Dune, ….

For drift tube applications, straw material is a major contributor to particle multiple scattering. Currently, the Mu2e experiment has the thinnest straw tracker with a wall thickness of 15μm. There have been significant ongoing R&D efforts to develop thinner straws. The Mu2e-II experiment has produced 8μm thin straws through winding. Self-supporting these straws has become an issue.

3.5μm Mylar
1.5μm adhesive
3.5μm Mylar



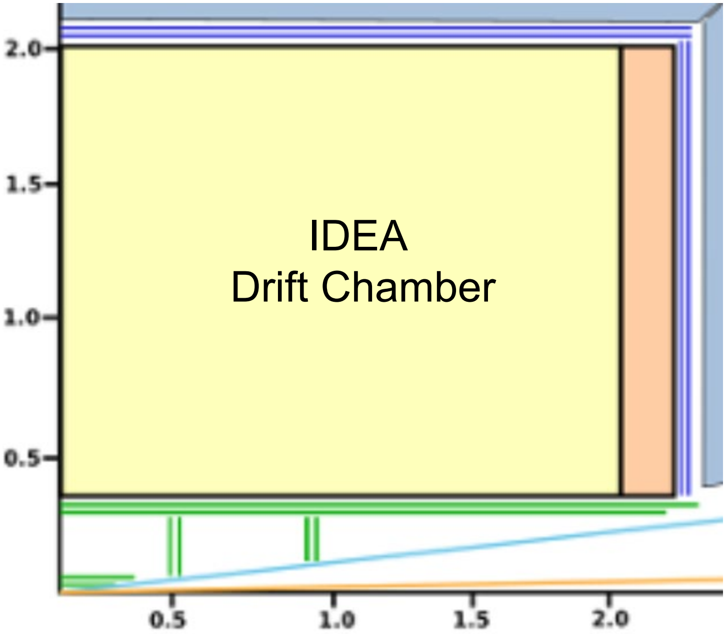
Pressurized 8 μm Mylar Straws

Kenneth Heller

Daniel Ambrose

A Strawman Layout

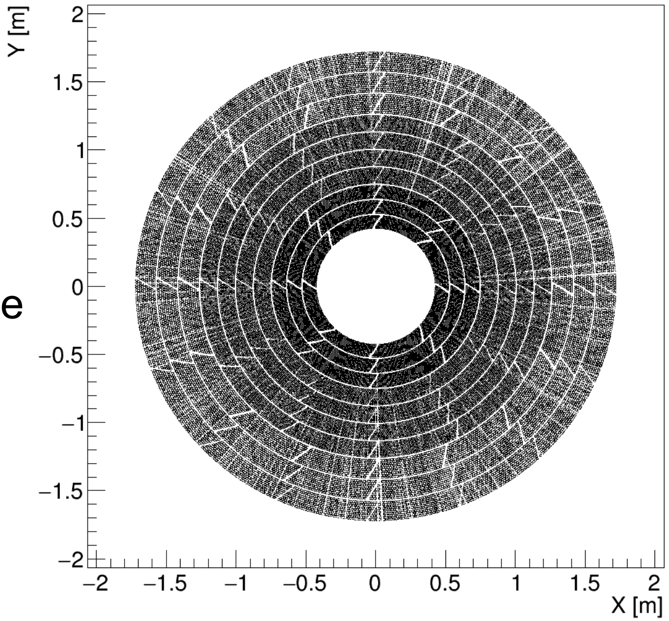
To understand the performance of a straw tracker and facilitate comparison with other options, we have implemented a strawman straw tracker in the FCC-ee simulation framework, replacing the drift chamber of the IDEA concept while keeping the same vertex detector and the inner and outer silicon layers.



This straw tracker covers a radius from 31.1cm to 184.2cm and includes

- 10 axial-view superlayers,
- 10 straw layers for each superlayer
- Three straw diameters: 1cm, 1.2cm, and 1.5cm, depending on the radius.

This results in a total of approximately 60k straws

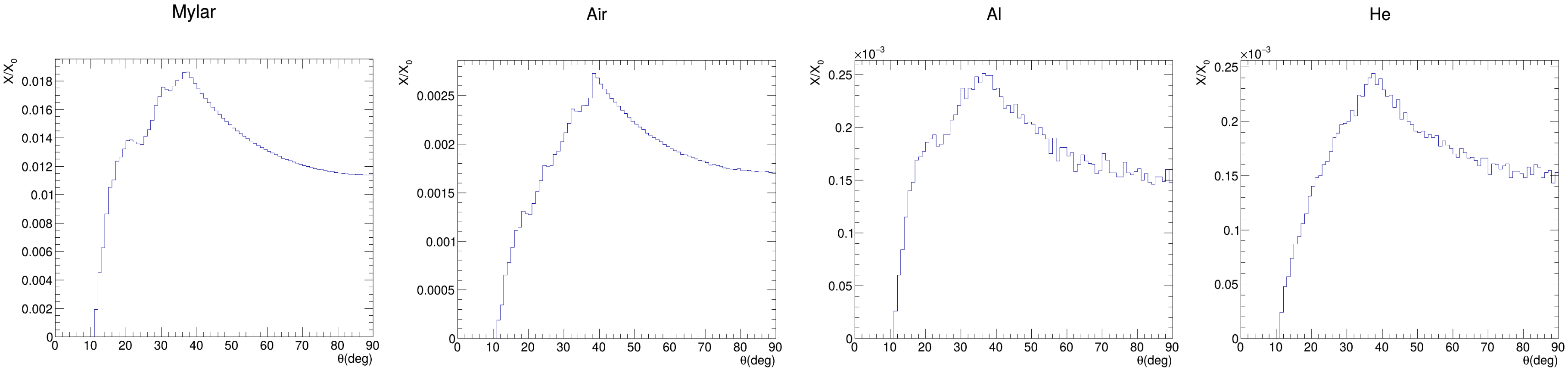


Stereo-view layers will be necessary for the z-coordinate measurements. A stereo angle of a few degrees should provide a precision of a few millimeters. These layers are not included in the current strawman implementation.

Material Budget Breakdowns

The straws are assumed to have a 12μm thick wall with a 50nm aluminum coating on the inner surface, and 10μm tungsten sense wires.

Assuming operating with helium gas at 1 atm, the tracker will have a material budget of 1.35%X_0 at 90 degrees, not including any mechanical structure.



The contribution is dominated by the mylar wall, followed by the gap-filling air, aluminum coating, and helium gas.

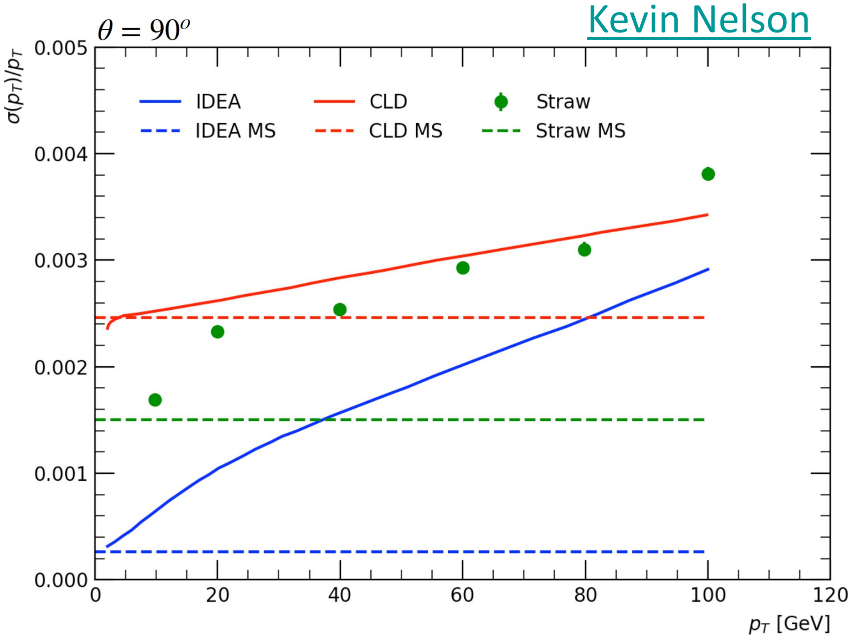
Heavy gases such as argon will significantly increase the material budget, potentially making their contribution comparable to that of the mylar.

Resolution Comparisons

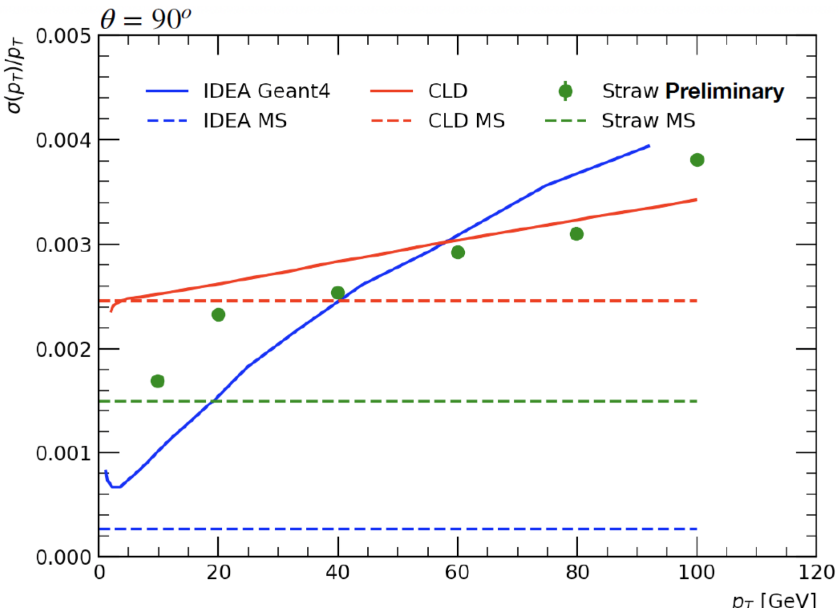
Hit resolution assumptions for the straw momentum resolution calculations:

- 5μm for the vertex detector, 120μm for straw tube, and 15μm for silicon wrapper

Kevin Nelson



CLD, IDEA: Analytical estimates
Straw: semi-Geant simulation



IDEA update: Geant simulation,
see the talk by Nicola de Filippis

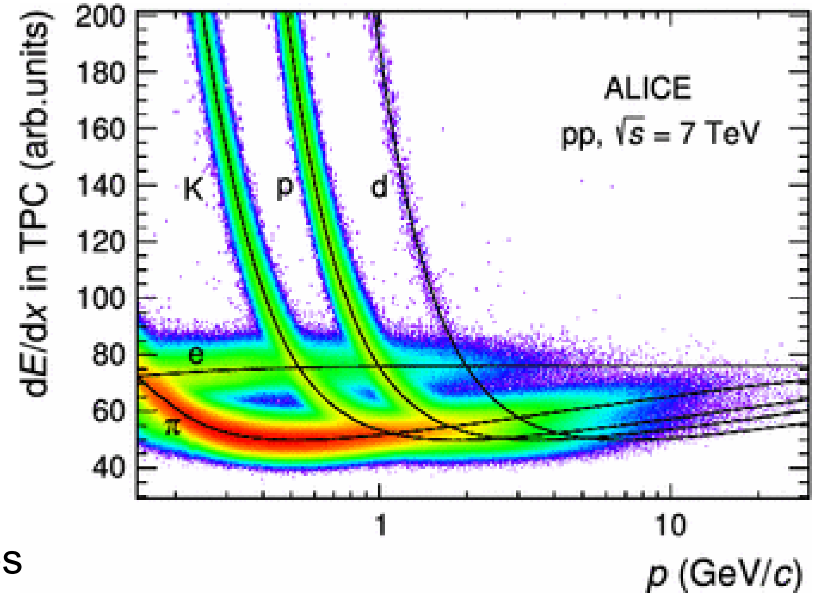
Observation 1: Track momentum resolution is adversely impacted by material
- Designing a tracker with minimal material is crucial.

Observation 2: Resolutions are not calculated with the same assumptions between the different proposals - Taking comparisons with a grain of salt.

This said, a straw tracker is expected to have a competitive momentum resolution!

Particle Identification

Proportional gaseous detectors are known for their good particle identification capability (PID) through the measurement of total ionization energy loss per unit length, known as dE/dx, combined with the momentum measurement.



However, PID with dE/dx are limited by

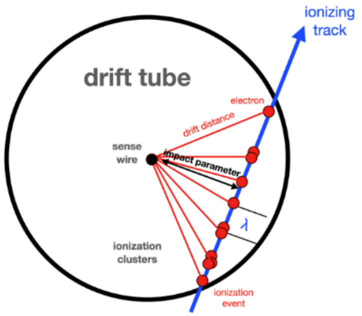
- The measured energy combines contributions from both primary and secondary ionizations;
- Long Landau tail of the dE/dx distribution, due to large fluctuations, washes out the differences between different particles to be identified.

The cluster counting method attempts to circumvent these limitations by replacing the analog dE/dx signal with a digital signal, the number of primary ionization clusters per unit length or dN/dx.

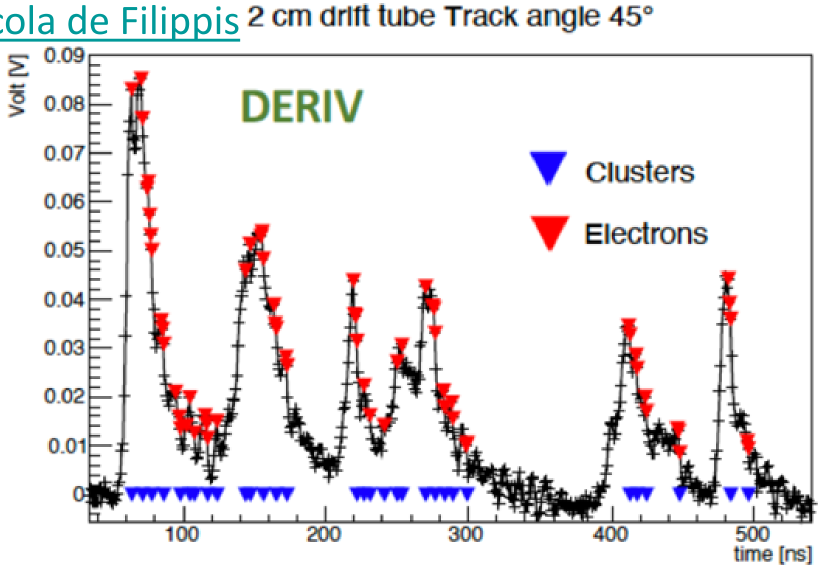
dN/dx is determined by Poisson statistics of the primary ionization, independent of the secondary ionizations and the energy fluctuation in each ionization.

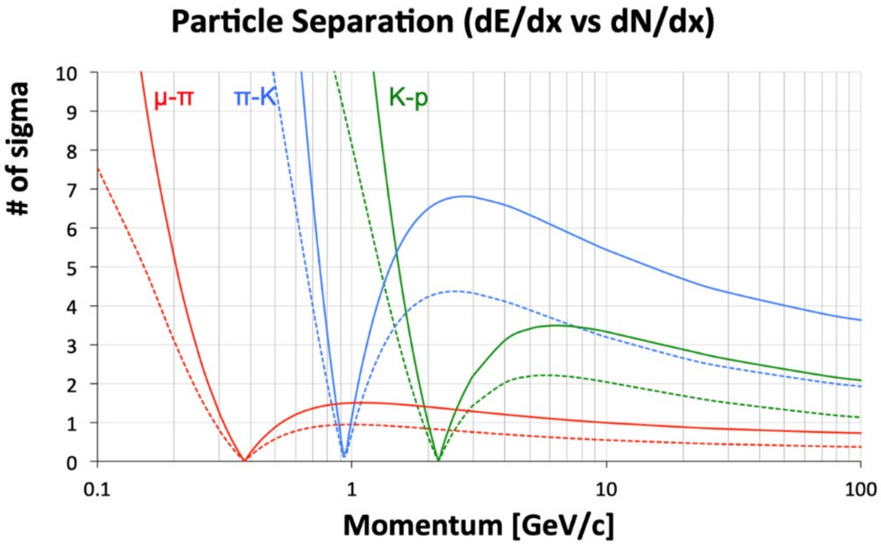
Cluster Counting Method

Signals from primary ionization clusters produced in non-isochrone drift cells, such as drift tubes, are spread out over time, ranging from a few to hundreds of nanoseconds.



Nicola de Filippis





Instead of measuring the total ionization energy, the dN/dx method attempts to count the number of individual ionization clusters per unit length. This is made possible by the modern fast readout electronics.

Some estimates suggest that dN/dx can be determined with a factor of two better resolution than dE/dx, thereby significantly improve the PID capability.

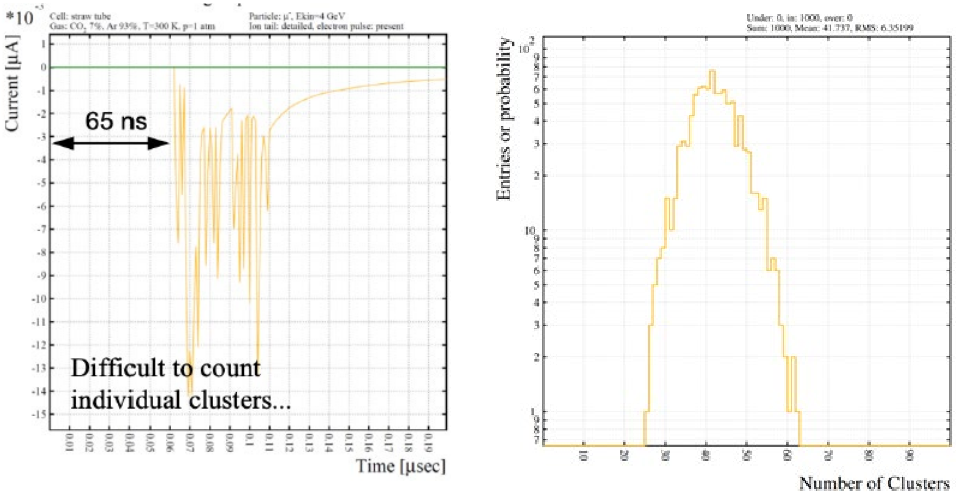
However, the method needs to be demonstrated. Significant R&D efforts, common to both drift chambers and straw trackers, are needed.

Garfield Cluster Simulation

The number of clusters produced and their timing distributions are strongly dependent on the gas mixture and its operation conditions.

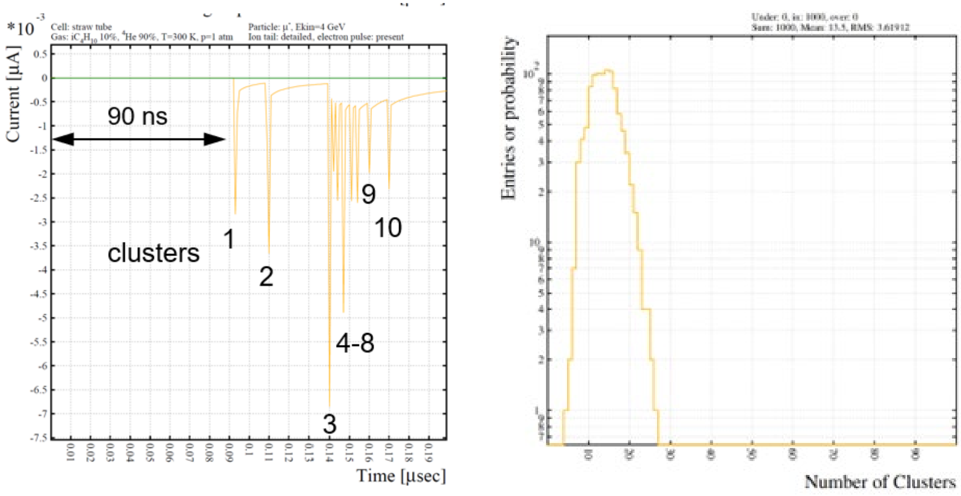
There are multiple competing factors to consider. For instance, a high ionization density is preferred as it reduces statistical fluctuation. However, it also reduces the time separation between clusters, making them harder to count.

However, in general slow gas will be ideal. (also good for position measurement).



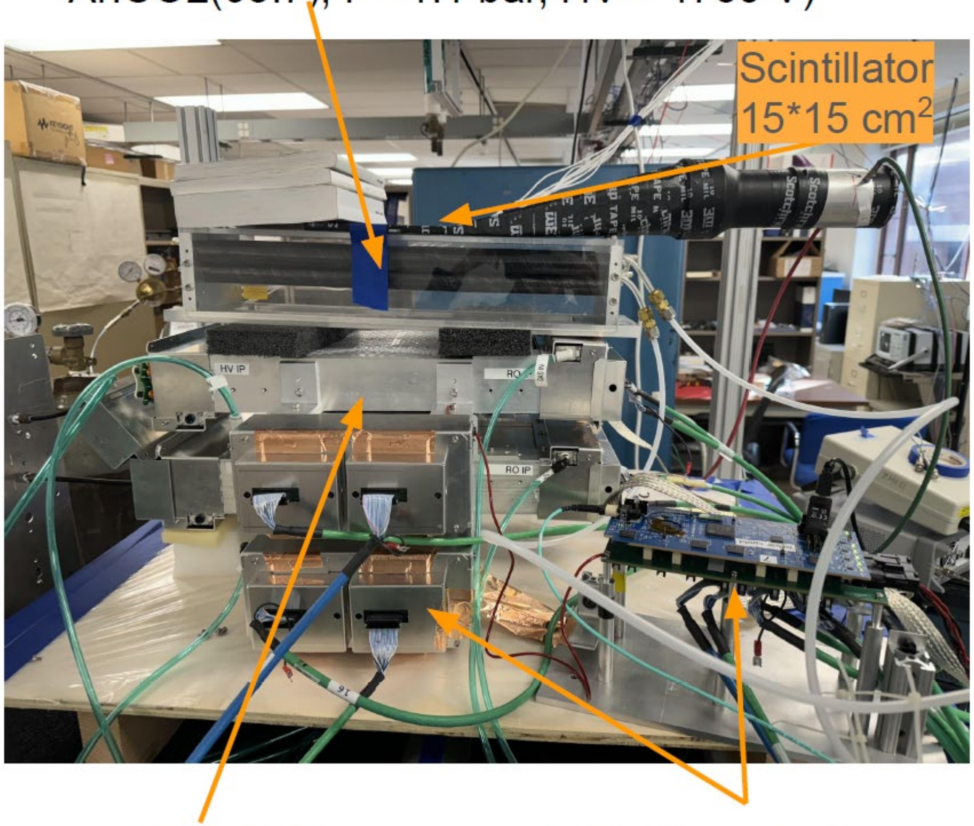
Difficult to count individual clusters...

Ar:CO2 (93:7): 40 clusters/cm, ~5 ns separation



He:iC_4H_{10} (90:10): 20 clusters/cm, ~15ns separation

Cosmic Tests at Michigan



Straw Tube d =24 mm, d_{wire} = 30 um,
Wall-thickness = 33 um mylar + 6 um Al),
Ar:CO2(93:7), P =1.1 bar, HV = 1750 V)

Scintillator 15*15 cm^2

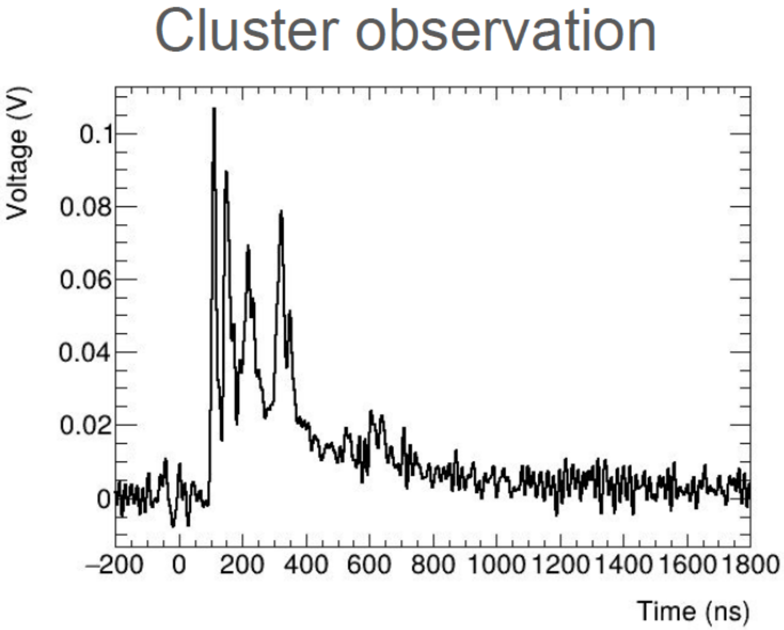
Mini-sMDT
Ar:CO2 (93:7) at 3 Bar

sMDT FE readout

Straw chambers from old balloon experiment

ATLAS mini-sMDT chambers for tracking

Study waveforms for cluster counting (dN/dx)



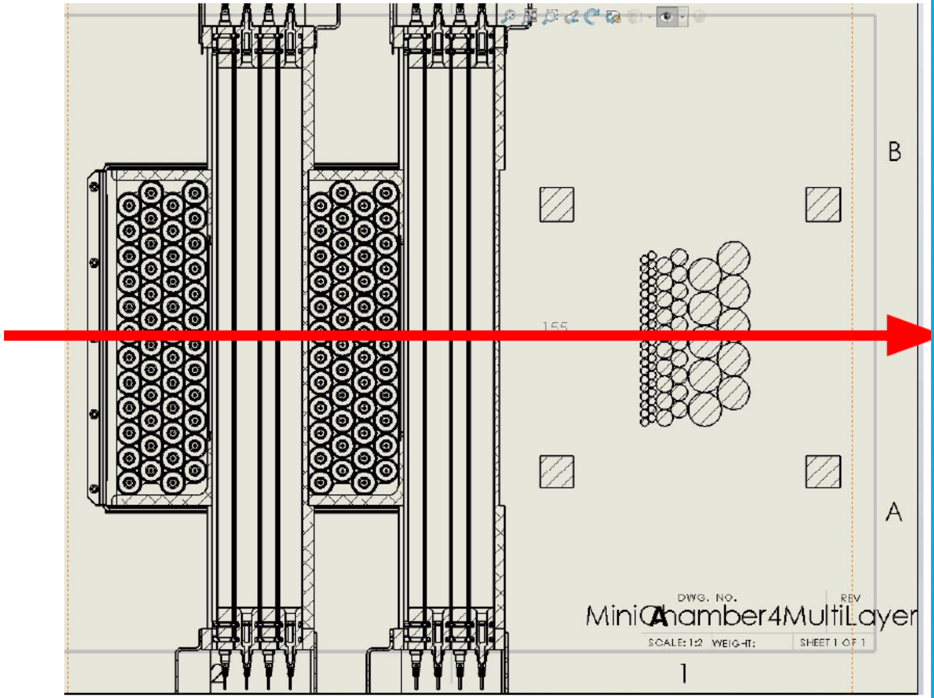
Cluster observation

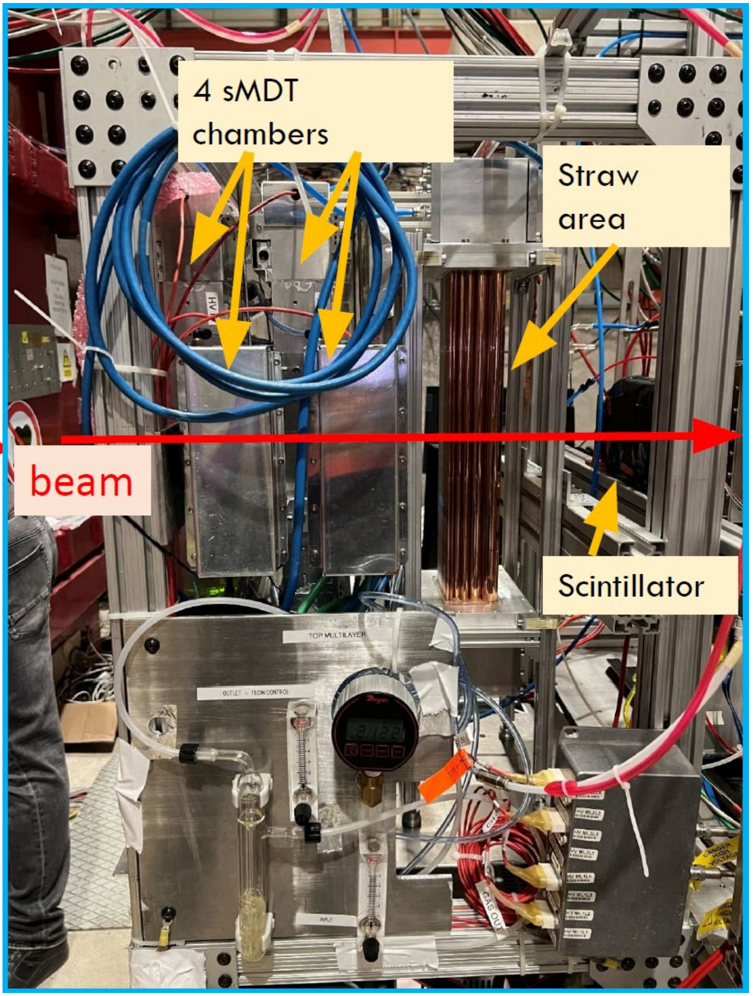
A typical muon waveform

Test Beam at CERN

Joined the DRD1-WP3 beam tests at CERN, completed two months ago. Tested two configurations:

1. sMDT + straws (5mm, 10mm, 20mm)
2. Si-tracker + sMDT + straw (10mm)



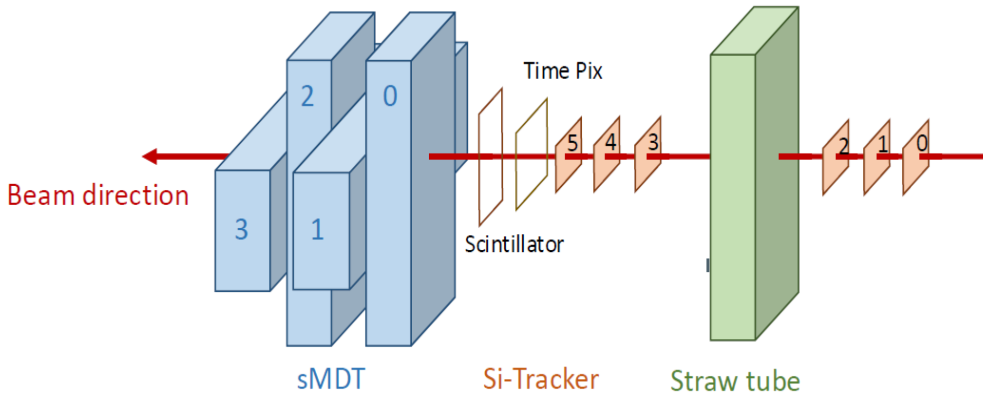


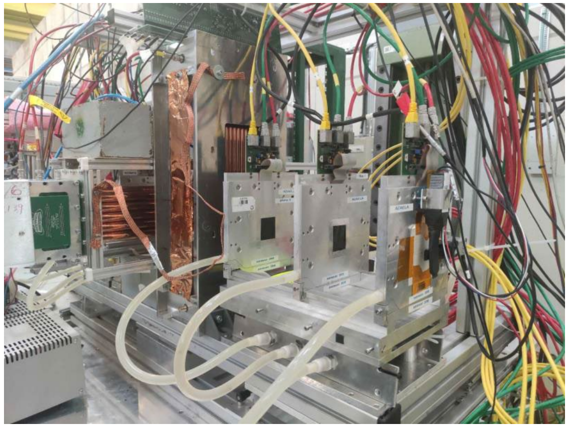
Four ATLAS mini-sMDT chambers as a beam telescope, tube diameter15mm

NA62 straws: 36μm thick, coated with 20nm of gold and 70nm of copper, and have 30μm diameter wires

Test Beam at CERN

Configuration 2:

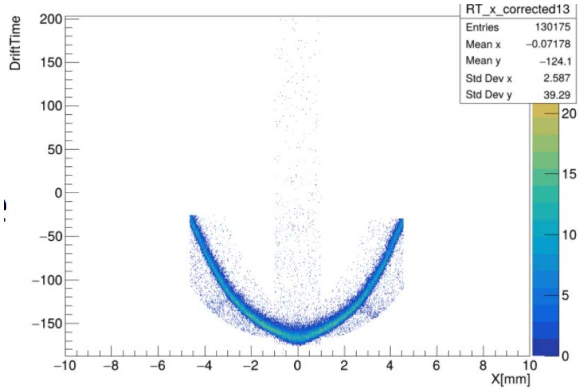




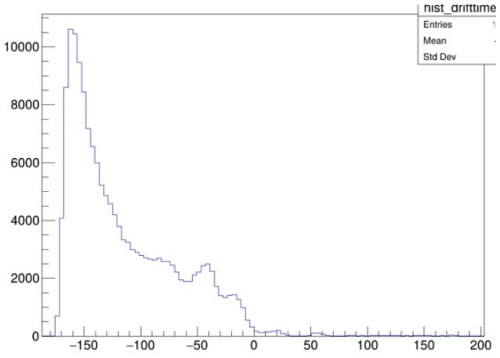
- Configuration 2: Si-tracker, Straw tubes and mini-sMDT chambers
- 120 GeV muon beam
- sMDT and straws are readout by miniDAQ, Si-tracker by a different DAQ
- Operation condition: Gas=Ar:CO2 (70:30) at 1 bar, HV=1750 GeV

Preliminary results for 10mm straws:

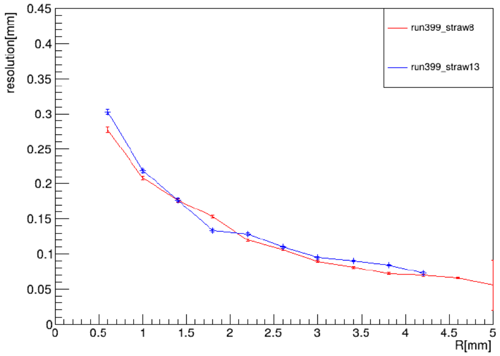
Linnuo Zhang



x-t spectrum



Drift time spectrum



Resolution vs radius

R&D Study Tasks

- Overall detector configuration optimization through Geant simulations:
  number of layers, number of stereo layers and stereo angle, integration with silicon and other detector components, …
- Single straw production and assembly:
  work with vendors for straw production including wall thickness, straw lengths and radii, end-plug design, metal coating, wire specifications, assembly procedures and mechanical stability, …
- Gas mixture optimization through testing and Garfield simulations:
  material budget vs ionization density, drift velocity and operation voltage, evaluation of gas mixtures for different requirements, ….
- Detector module prototype:
  assembly procedures, cosmic and beam tests for performance characterization, …
- Readout electronics and particle identification:
  front-end electronics for both dE/dx and dN/dx measurements, cluster counting algorithms,…
- Mechanical structure and engineering:
  modular detector design, overall detector assembly and support structures

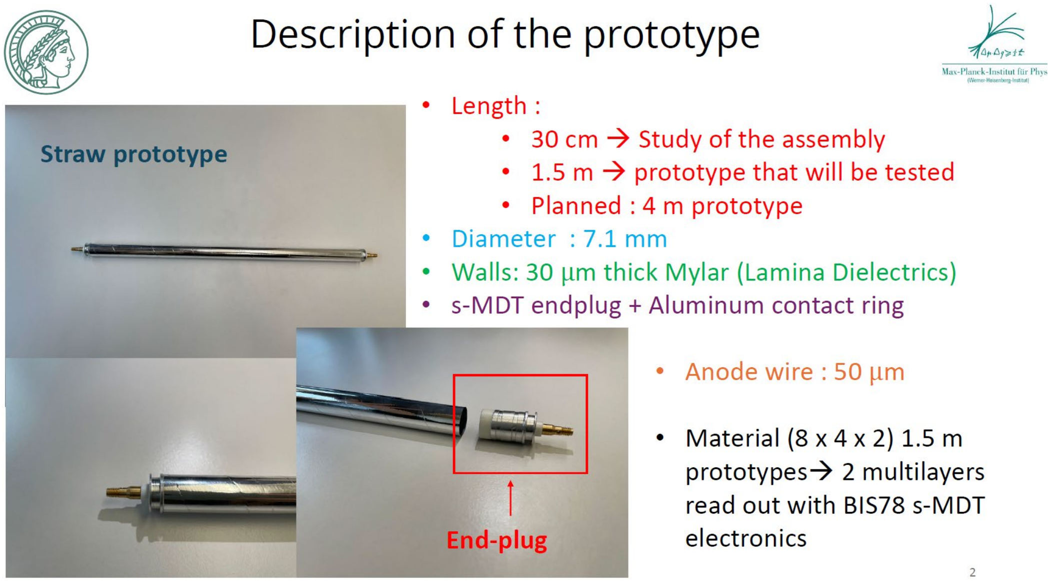
Ongoing Activities

Monthly FCC-ee straw tracker meetings under DRD1-WP3 organized by

Oliver Kortner (MPI-Munich)
Junjie Zhu (Michigan)

to coordinate the R&D efforts

First meeting on Dec. 2, 2024:
https://indico.cern.ch/event/1483060/



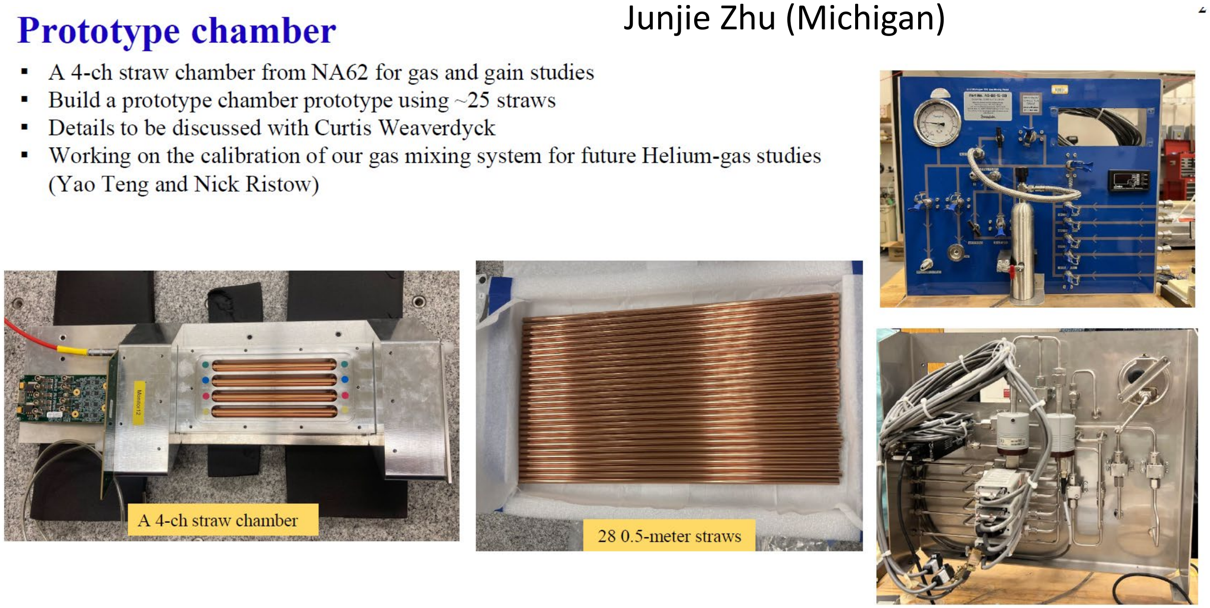
Description of the prototype

- Length :
  - 30 cm → Study of the assembly
  - 1.5 m → prototype that will be tested
  - Planned : 4 m prototype
- Diameter : 7.1 mm
- Walls: 30 μm thick Mylar (Lamina Dielectrics)
- s-MDT endplug + Aluminum contact ring
- Anode wire : 50 μm
- Material (8 x 4 x 2) 1.5 m prototypes→ 2 multilayers read out with BIS78 s-MDT electronics

2

Giorgia Proto (MPI)

Junjie Zhu (Michigan)



Prototype chamber

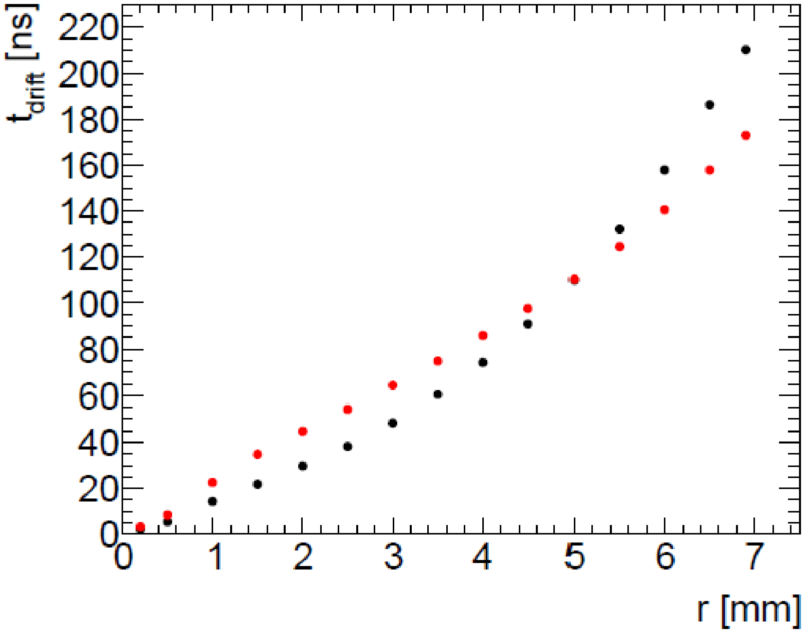
- A 4-ch straw chamber from NA62 for gas and gain studies
- Build a prototype chamber prototype using ~25 straws
- Details to be discussed with Curtis Weaverdyck
- Working on the calibration of our gas mixing system for future Helium-gas studies (Yao Teng and Nick Ristow)

Straw Tube Simulation

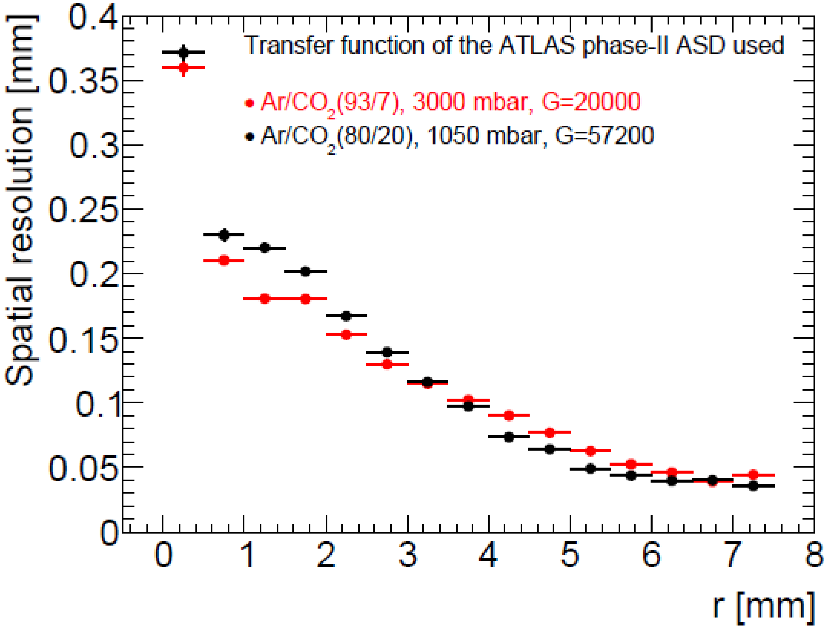
First results from Garfield simulation from the planned prototype at MPI. Investigating gas mixture, operational pressure and gains, comparing gas pressure of 1bar and 3bar:

- Approximately the same spatial resolution of 100μm
- Comparable maximum drift times: 180ns at 3bar and 220ns at 1bar.

Space drift-time relationship



Spatial resolution



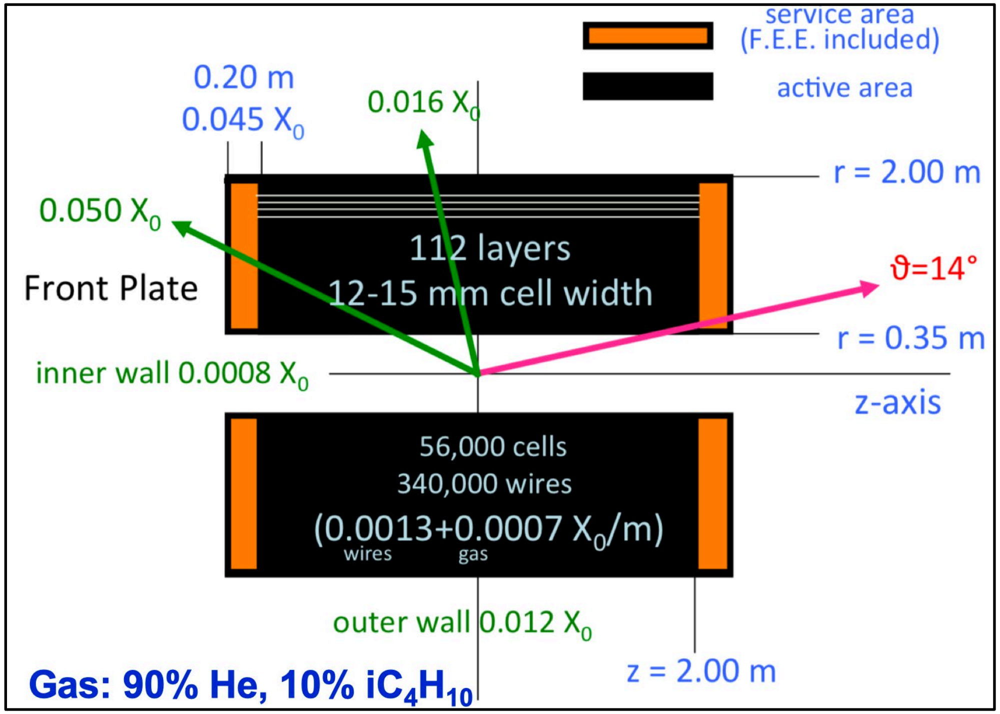
Oliver Kortner

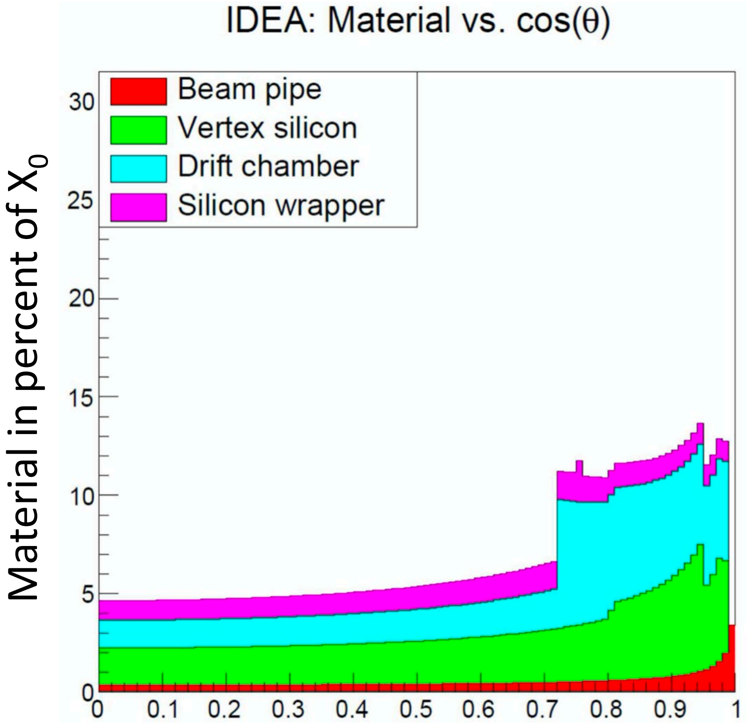
Concluding Remarks

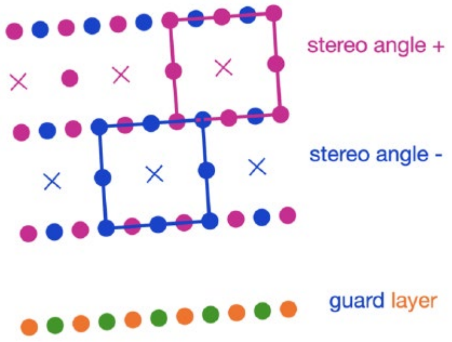
- Preliminary studies of a straw tracker show promising performances comparable with other options (full silicon, drift chambers) and meet the requirements for the FCC-ee.
- There are significant ongoing and planned R&D efforts to
  - Optimize the tracker layout and design mechanical structures
  - Study the tracker performances alone and within a full detector concept
  - Develop thinner straws,
  - Explore different gas options
  - Design readout electronics and study algorithms for cluster counting
  - Develop construction procedures
  - Build and test prototype modules, …
- There is strong interest from the community, including
  Michigan, MPI, Duke, Harvard, Michigan State, Tufts, UC-Irvine, UMass, UT-Austin, …
  We will continue to recruit and build a community, with monthly informal meetings under the auspices of DRD1-WP3 for updates, discussions, and coordination of critical R&D issues.
- Close collaboration with the drift chamber community to study common issues, such as gas and cluster counting etc., as well as the community at large for readout electronics and TDAQ system.
- Discussions are ongoing towards a full detector concept incorporating a straw tracker, with several discussions with ALLEGRO proponents already. Plan to prepare a document in response to the EoI call by the FCC-ee detector concept group and as an input to the European Strategy Studies.

Back ups

Drift Chamber





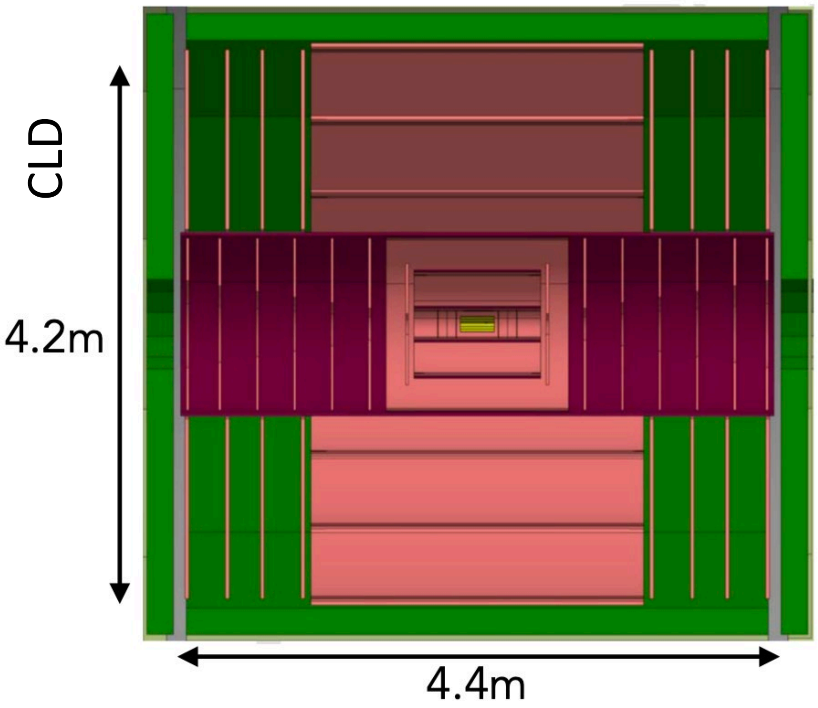


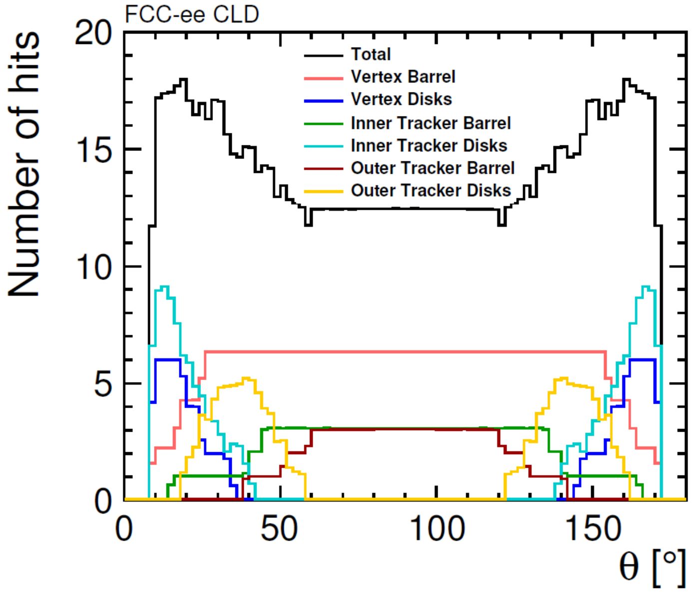
A cross-sectional segment

IDEA: Extremely transparent Drift Chamber based on MEG2

- GAS: 90% He – 10% iC_4H_{10}
- Total thickness: 1.6% of X_0 at 90°
  Tungsten wires dominant contribution
- Full system includes Si VXT and Si “wrapper”
- Solenoid field limited to 2T

CLD – Inner Tracker



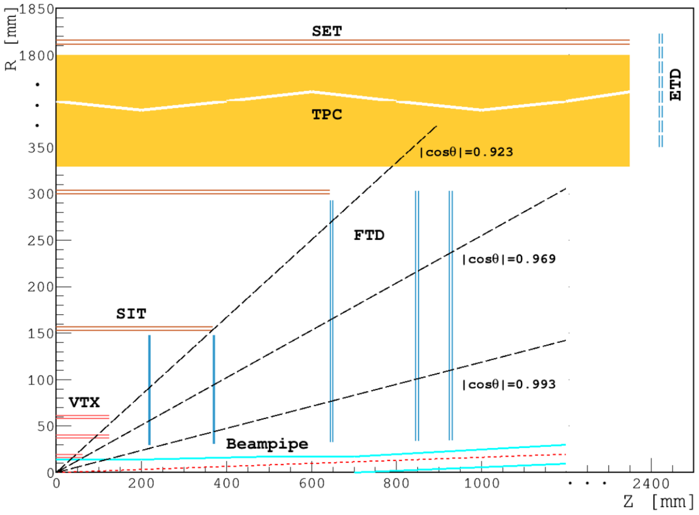


Full Silicon tracker for CLD

Partial silicon tracker for CEPC

CLD: All silicon pixel (innermost) + strips

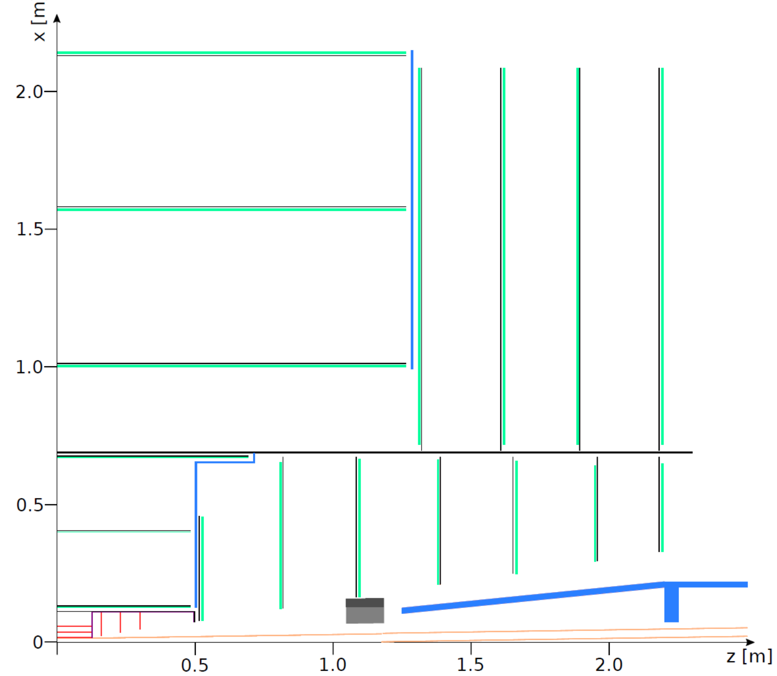
- Inner: 3 (7) barrel (fwd) layers (1% X_0 each)
- Outer: 3 (4) barrel (fwd) layers (1% X_0 each)
- Support tube (2.5% X_0)

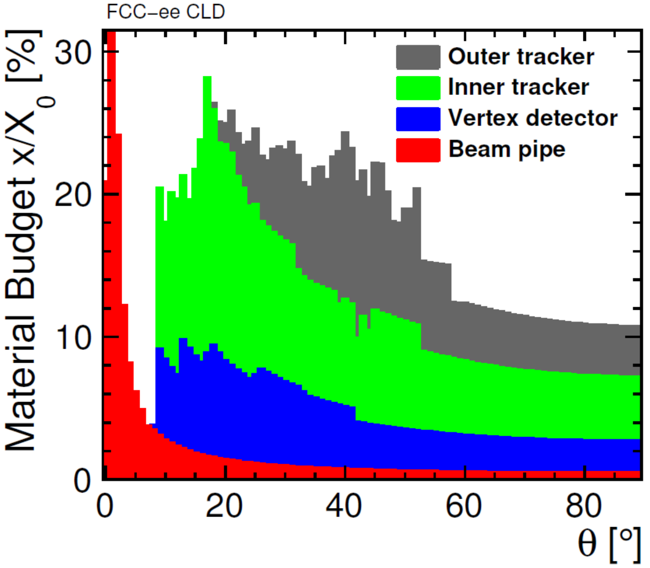


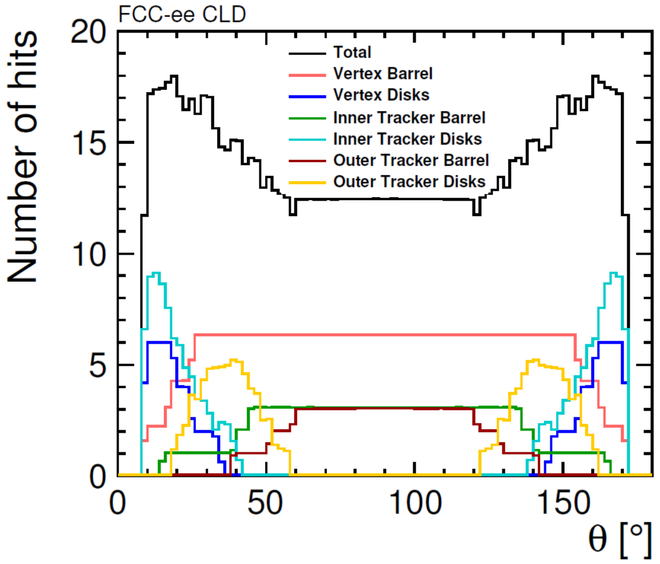
CEPC baseline

CLD Tracking Concept

Full Silicon







Pros:

- Excellent singlet hit resolution
- Vertex/

Cons:

- Small number of hits
- Large material budget
- Limited dE/dx PID capability
- Likely costly