A Straw Tracker for FCC-ee

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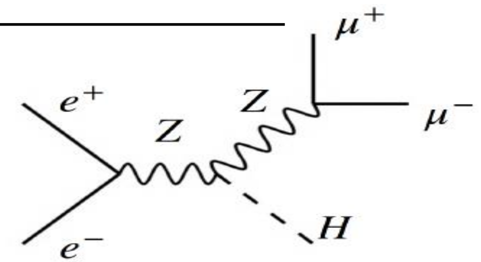
Momentum resolution requirement for FCC-ee

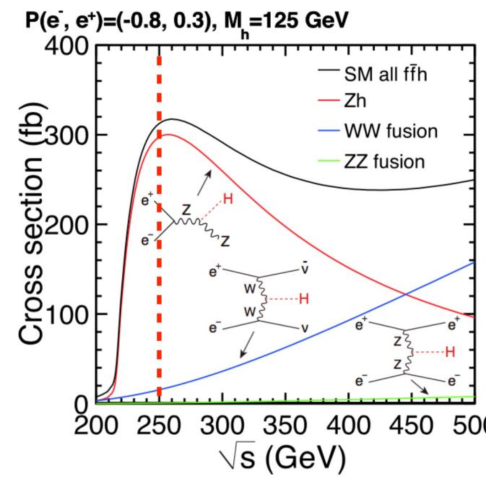
- Important to reconstruct the recoil mass distribution for the Higgs mass and ZH cross section measurements

$$M^2_{recoil} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$

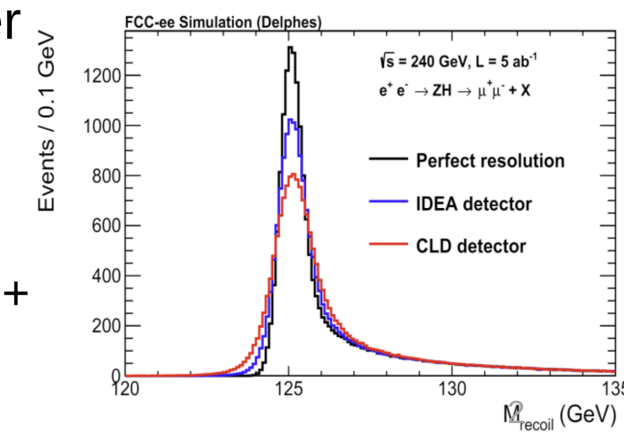
- Sensitivity dominated by the Z→μμ channel
- Required momentum resolution expected to be comparable to the beam energy spread (~0.16% @ 240 GeV)
  - $\sigma(p_T)/p_T$ ~ 0.2% at 45 GeV
  - 5/10 better than current CMS/ATLAS inner tracker p_T resolution @ 45 GeV
- Current proposals for FCC-ee experiment inner tracker:
  - CLD: full silicon pixel+strip (TPC under consideration)
  - IDEA/ALLEGRO: Silicon pixel + Drift Chamber + Outer silicon wrapper



Main Higgs production process @ FCC-ee via Higgs-strahlung

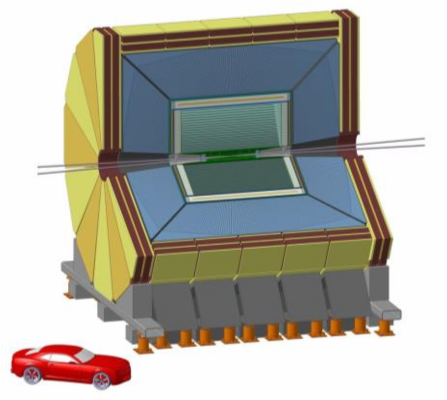


DeFilippis Higgs 2022



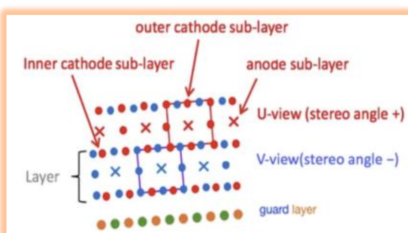
Eur. Phys. J. Plus (2021) 136:1195

IDEA Inner Tracker concept as an example

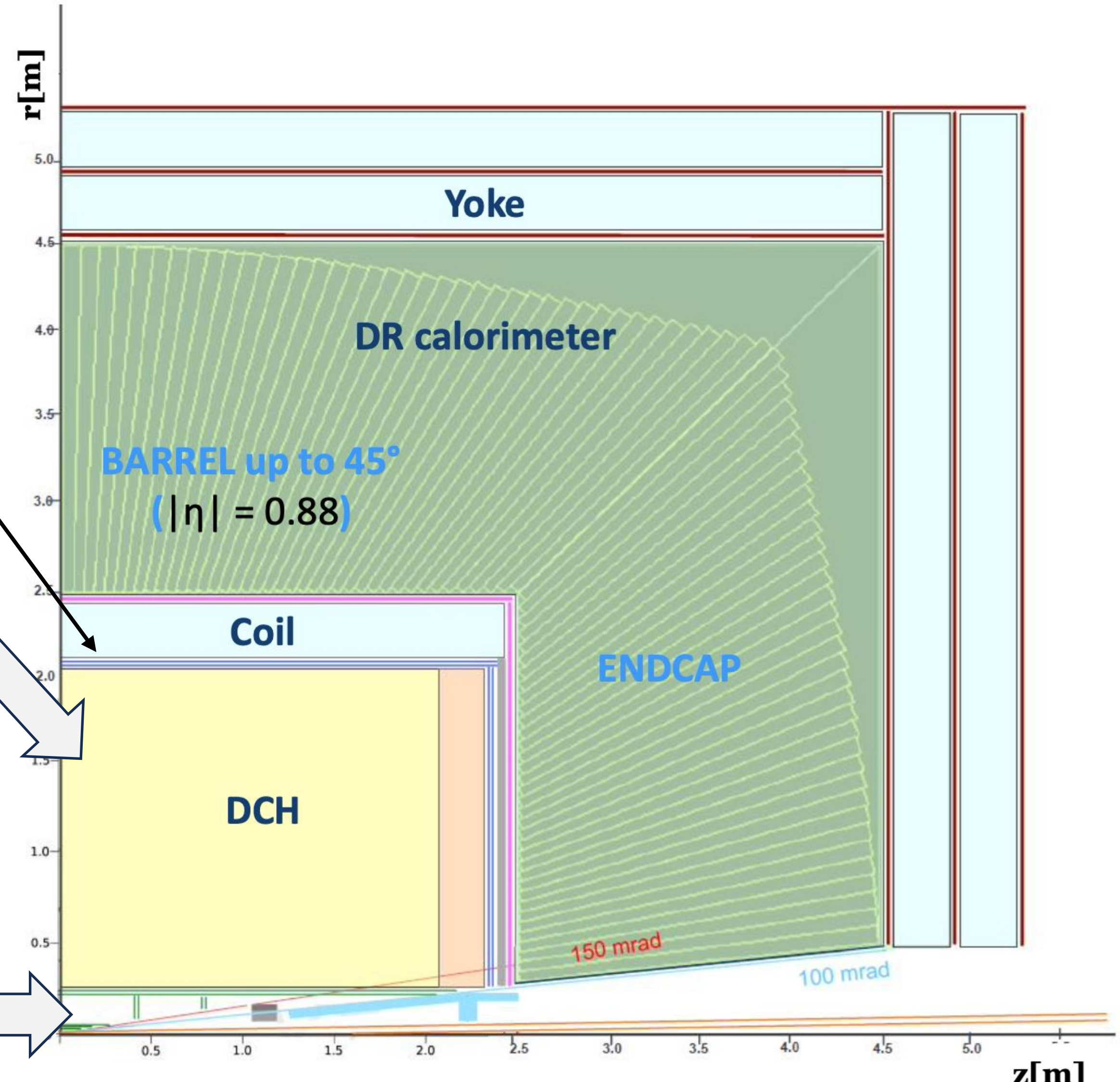


Outer Silicon wrapper:
50μm x 1mm pitch sensor

Drift Chamber: 112 layers
4 m long, R = 35-200 cm

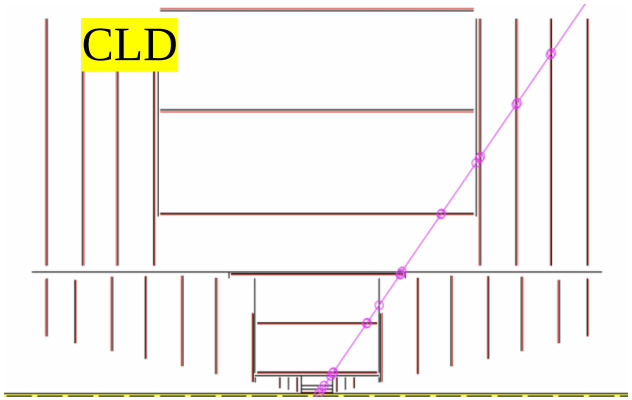


Vertex:
- 5 MAPS layers
- R = 1.37-31.5 cm



A straw tracker for FCC-ee

- We propose to have an ultra-light weight straw tracker (combined with pixel & silicon wrapper) for particle tracking at FCC-ee experiment:
  - Single hit resolution: 100-150 μm. Similar or better momentum resolution than the IDEA pixel-only detector -- more hits (N) and longer lever arm (L)
  - Low material and multiple scattering for low p_T
  - Complement silicon tracker for pattern recognition
  - Particle identification (π-K, K-p identifications)
  - Could provide hardware-level trigger primitives

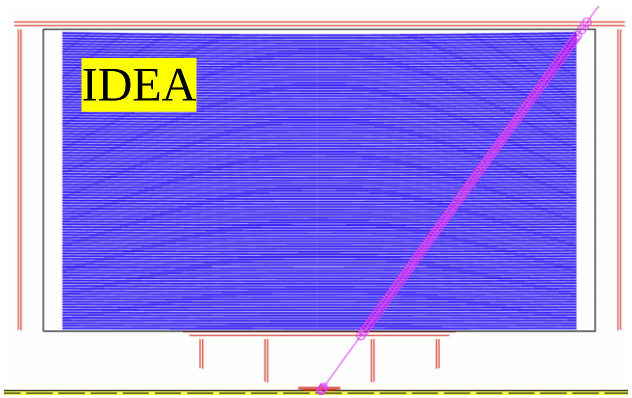


CLD tracking based on limited high-spatial resolution si-layers

p_T-resolution due to hit position resolution

$$\frac{\sigma_{p_T}}{p_T}\Big|_{meas} \simeq \sqrt{\frac{720}{N+4}}\,\frac{\sigma_x\, p_T}{0.3BL^2}$$

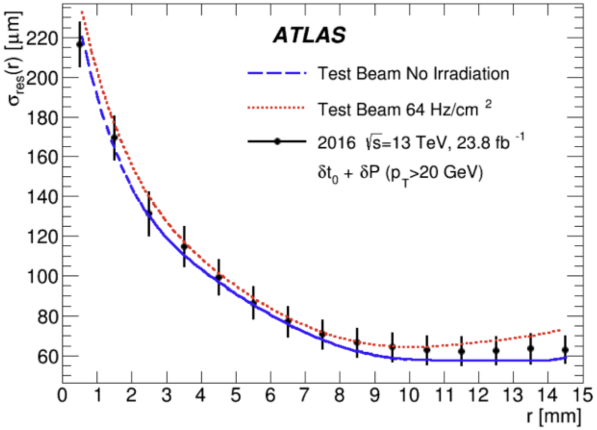
	Silicon Tracker	Gaseous Tracker
Single hit resolution (σ_x)	3-5 μm	100-150 μm
Measurements points (N)	6	100-120
Level arm (L)	0.3m	1.5m



IDEA tracking concept: large number of sampling along track

Straw tracker features

- Straw trackers could potentially provide robust high-performance tracking and particle identification.
  - Sense wire failures limited to single straws.
  - Radially symmetric electric field. Good spatial resolution, independent of particle incident angle
  - Different straw radii to optimize hit occupancy
  - Counting rate: a few kHz/cm^2 without significant gain drop (d=10-15mm drift tubes. Ref.). Single straw rate up to a few hundred kHz – matches Z-pole operation with O(100) kHz event rate.
  - Relatively low wire density: <1 wire/cm^2
  - Flexible layouts for central and endcap regions
  - Possibility to use different gas mixtures at the same time with optimization for tracking and PID.



ATLAS Muon Spectrometer drift tube position resolution. arXiv: 1906.12226

Straw tracker used in various experiments

- ATLAS
- LHCb
- PANDA
- CBM
- COMPASS
- Mu2e
- NA64
- SVD-2
- GLUEX
- COZY-TOF
- ..

- NA62
- COMET
- SHiP
- DUNE
- SPD NICA
- ,,

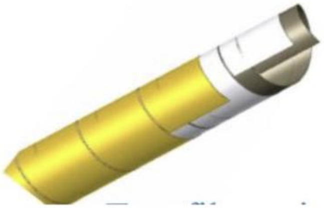
red color- straw tracker created with our participation

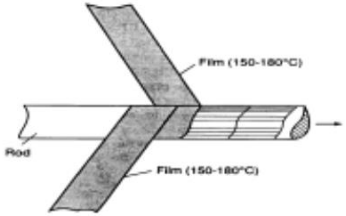
From Temur Enik https://indico.cern.ch/event/1307673/contributions/5608746/

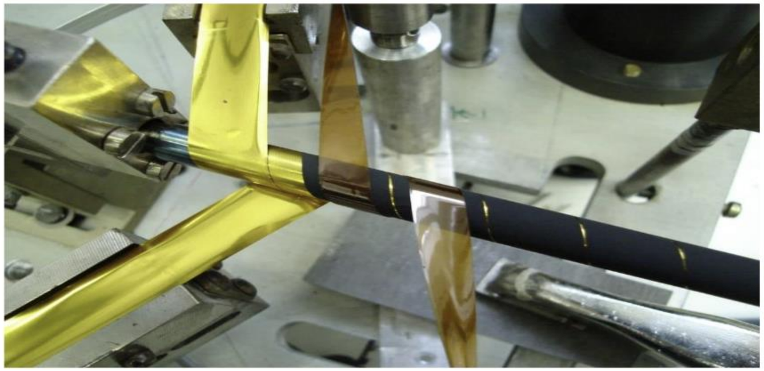
Straw construction technologies

Winding

- Production speed: 1 m/min
- Maximal length: 5.5 m
- Diameters: 2,4,6,10,20 mm
- Wall thickness: 15+ um



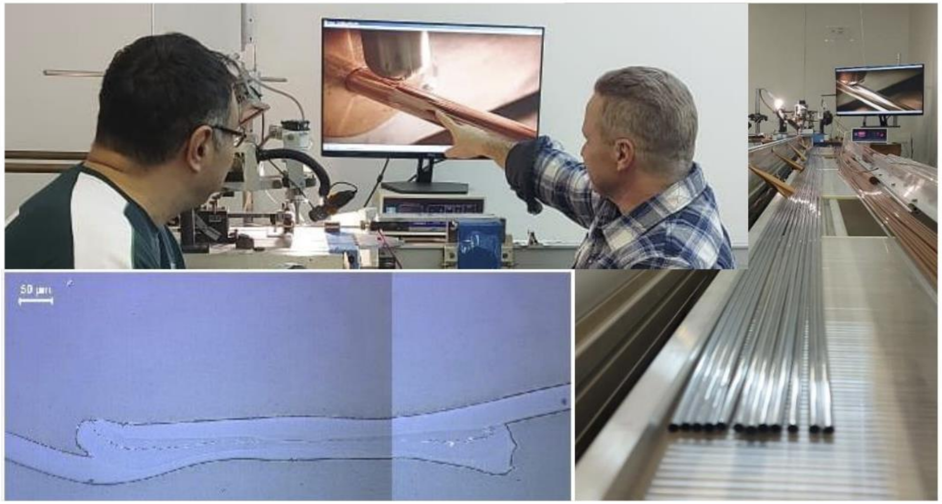




Example: [Mu2e]
- two layers 6 µm-thick Mylar, max length: 1.2 m
- 23k straws

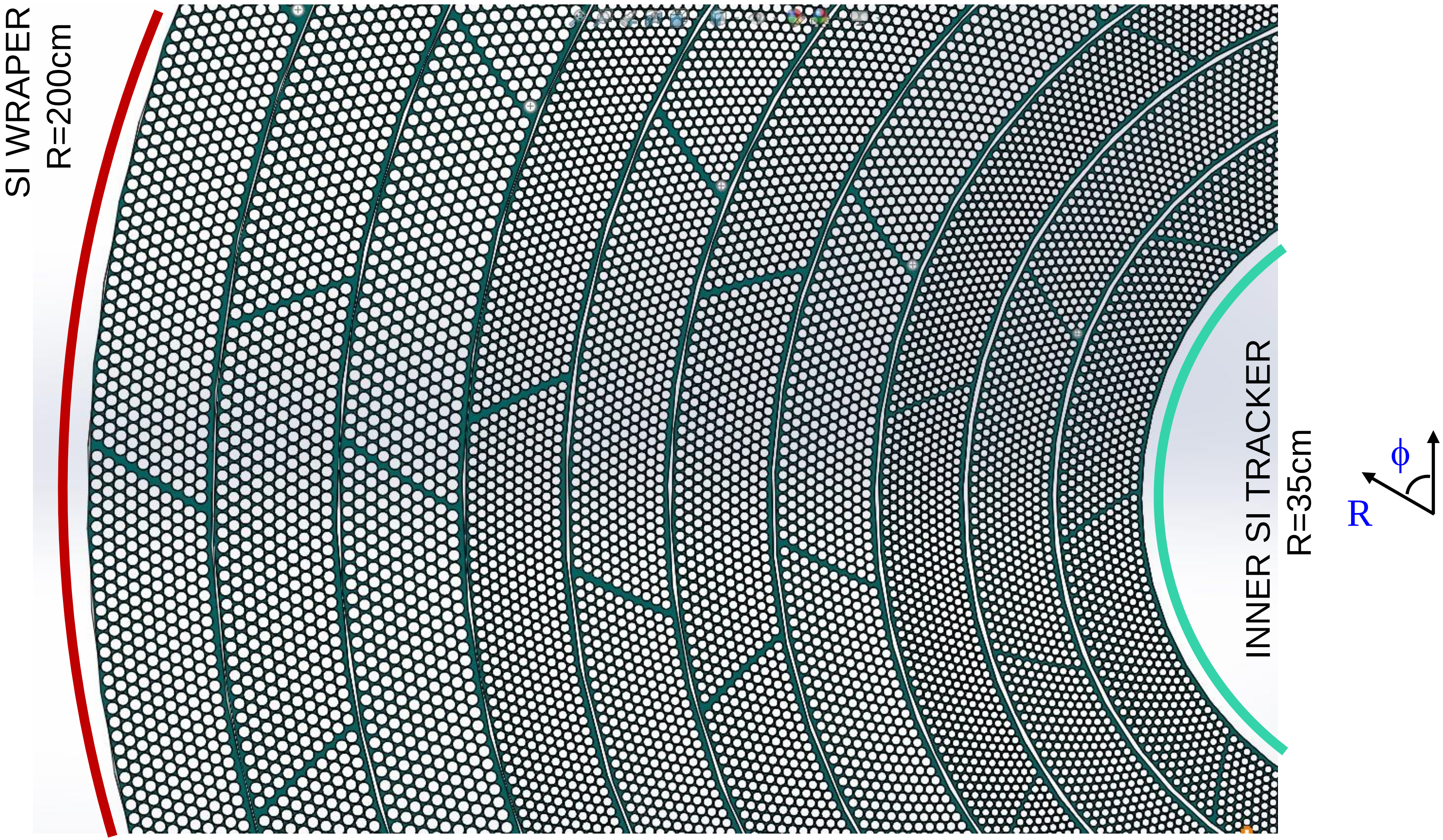
Ultrasonic welding

- Production speed: 1 m/min
- Maximal length: 5.5 m
- Diameters: 5,10,20 mm
- Wall thickness: 15, 20, 36, 50 um



Example: [DUNE]
- 19 µm-thick Mylar film, max length: 3.83 m
- 200k+ straws

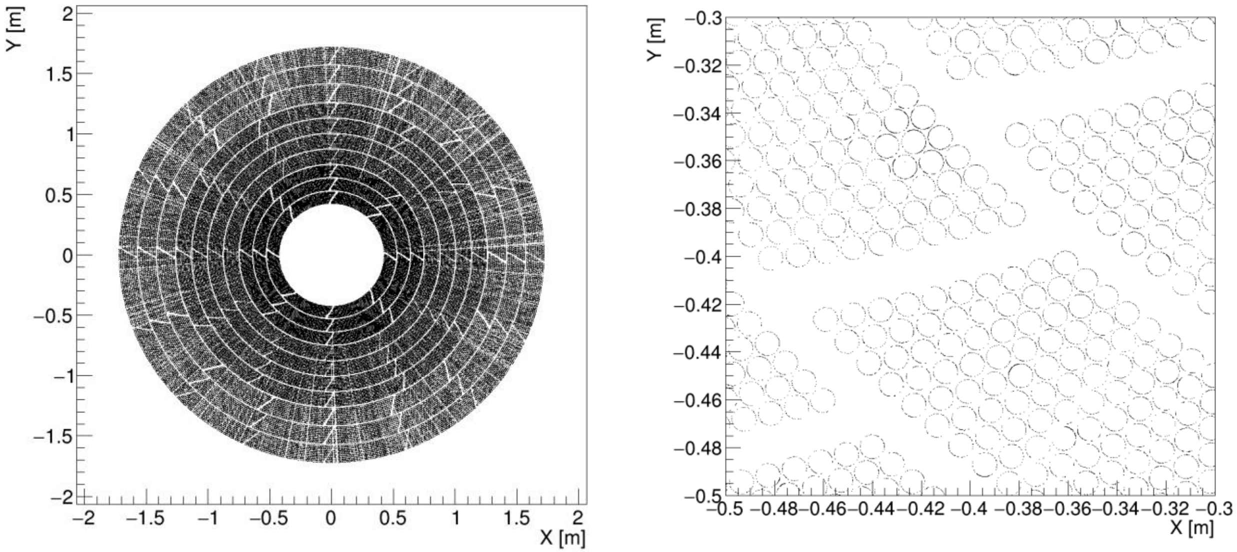
A strawman layout of the straw outer tracker



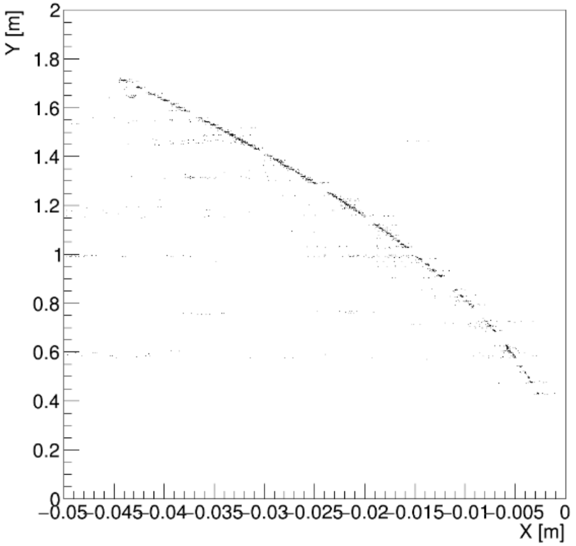
- 10 multi-layers
- 10 straw layers for each mulit-layer
- 10 -15 mm diameter straws
- O(100k) tubes

Straw tracker simulation in DD4HEP

- Incorporated toy straw modules in the DD4HEP framework to study geometries.
- Nominal geometry:
  - straws: 12 µm thick mylar wall (0.05 µm Al coating). 10µm-radius Tungsten wire.
  - straw modules: 10 multilayers x 10 straw (d=10-15mm) layer/per multilayer.
  - No Endplate supporting structure yet.



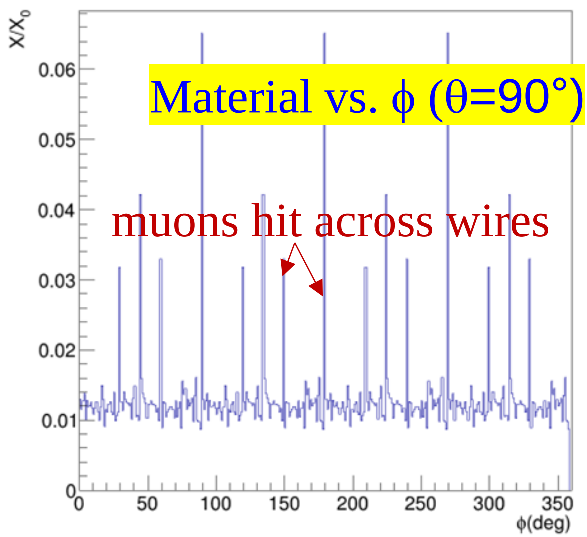
Hits for 5000 muons with p_T=20 GeV/c

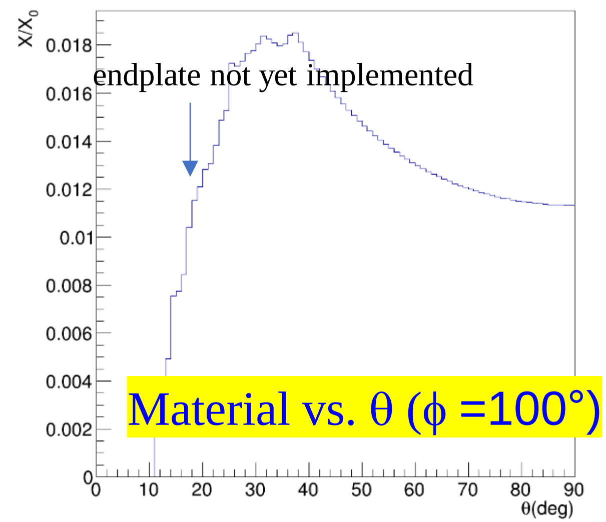


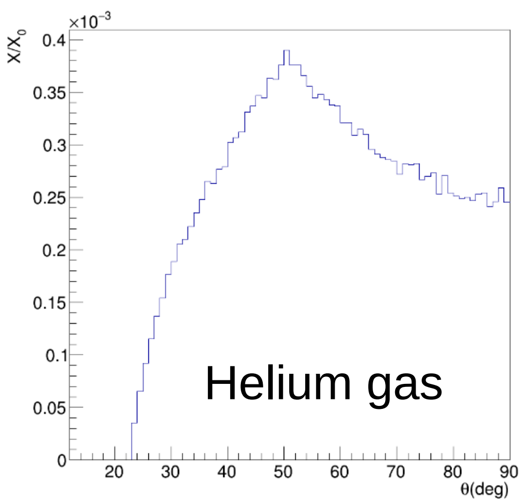
1000 muons (p_T=20 GeV/c) hits registered inside straws

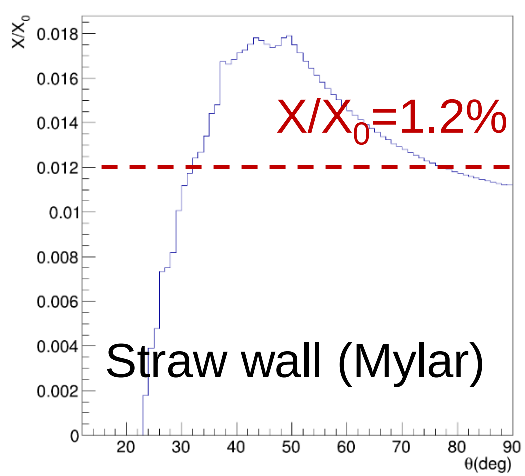
Material budget from simulation

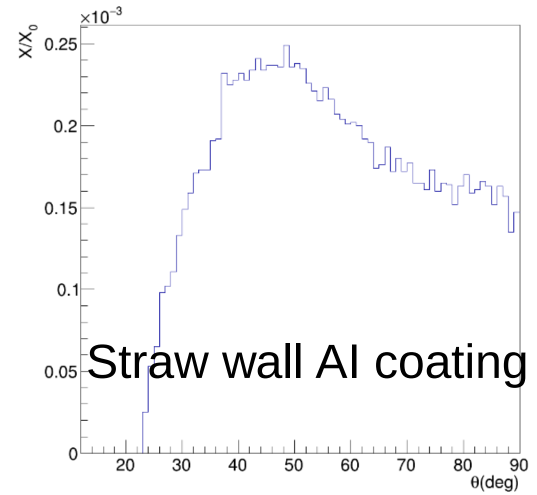
- Nominal geometry X/X_0: ~1.2% @ θ=90° (assume Helium gas).
- Material budget dominate by Mylar (X_0=39.95 g/cm^2)
- Break down of material contributions in straw trackers of 100 layers:







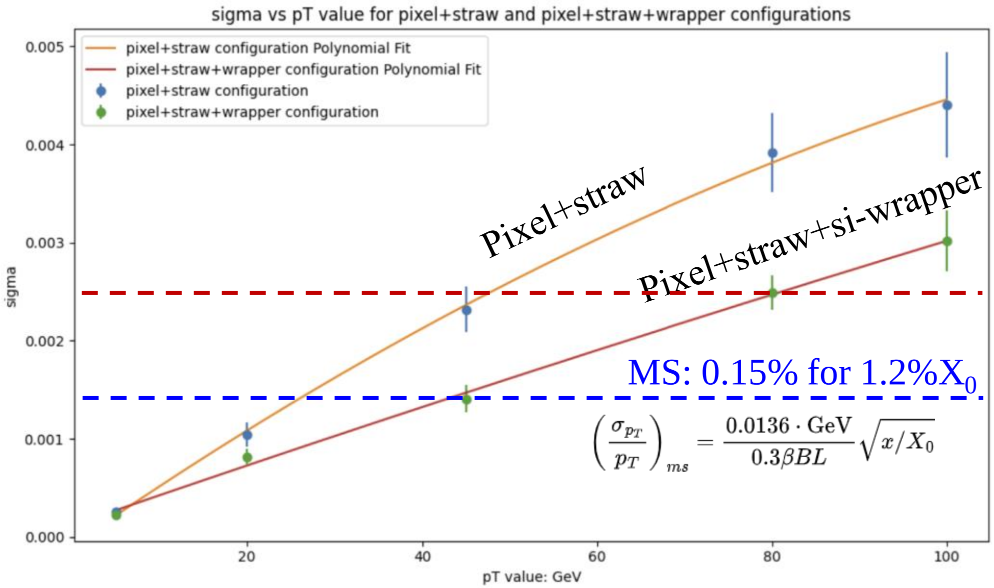


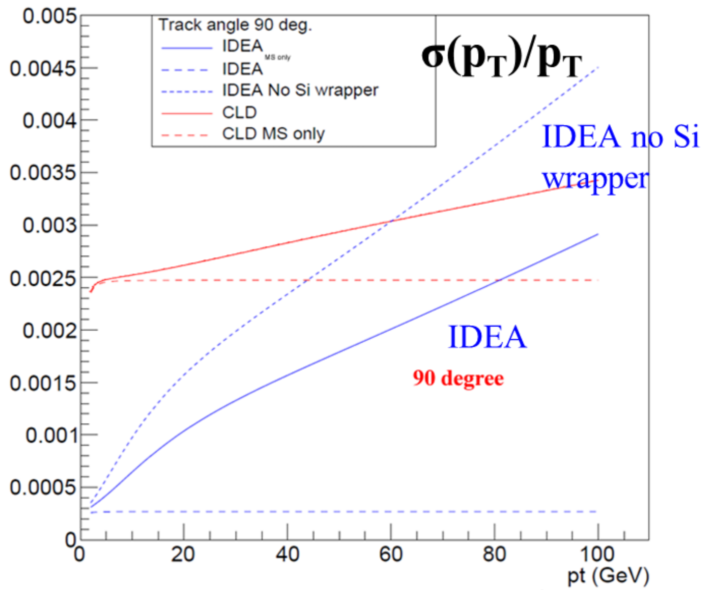


* For comparison: 1.5 m Ar = 1.5% X/X_0

Understanding momentum resolution

- A simple python simulation developed to understand the effect of hit locations and resolution on the track momentum resolution
  - 2 Tesla magnetic field
  - 5 layers of pixel from 5 cm to 30 cm (σ=5 μm), 112 layers of straws from 30 cm to 180 cm (σ=120 μm), and a silicon wrapper layer at 200 cm (σ=10 μm)
  - Smear hit according to the resolution in the respective layer
  - χ^2 minimization using scipy to calculate "measured" track p_T
- Ongoing work with ACTS to perform track fitting including detector and multiple scattering effects.

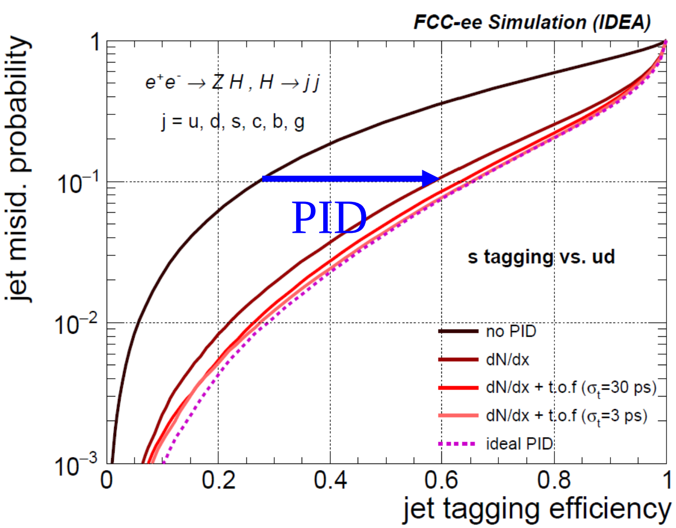


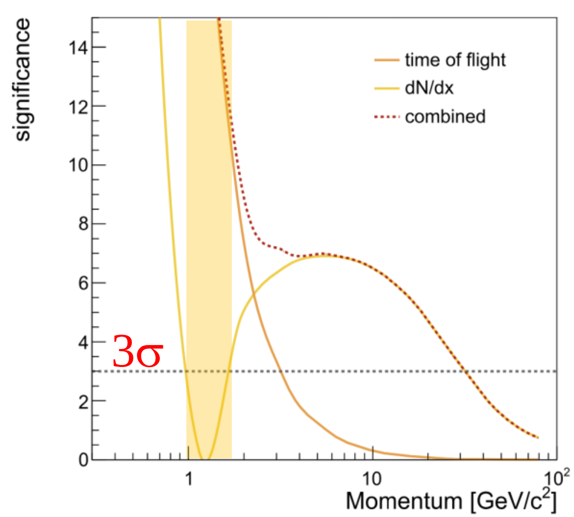


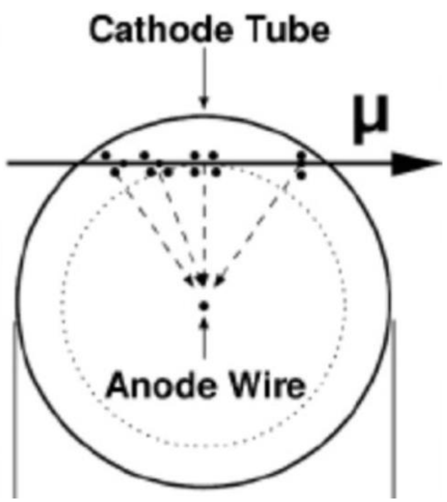
Particle Identification Capability

- Essential for flavor physics and bring significant benefits for other areas
  - Flavor physics measurements: $B^0_S \rightarrow D^{\pm}_S K^{\mp}$, $B \rightarrow K^* \nu\nu$, $B_s \rightarrow \phi\nu\nu$, …
  - s-quark jet identification → K identification ($H \rightarrow ss$, V_{ts}, V_{bs}, $H \rightarrow bs$, …)
- The straw tracker could provide PID at low momentum range based on d*E*/dx or d*N*/dx measurements, similar as the Drift Chamber (DCH).
- Induced current signal and timing properties are expected to be similar to DCH's.

Will hear from the next talk many details and progress already made with dN/dx





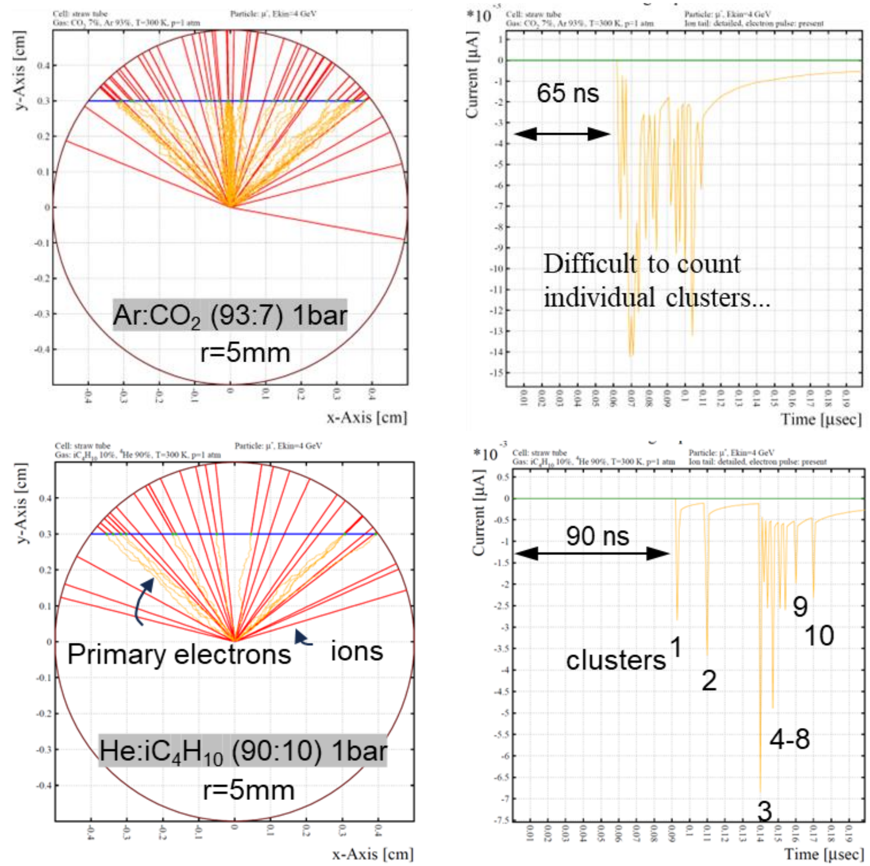


Straw Garfield simulation

- Ar-based gas: traditionally used for drift time-based tracking. High ionization density (~40 clusters/cm) and moderate electron drift velocity 40 μm/ns (@E~2 kV/cm). Mean cluster arrival time separation: ~6 ns
- He-based gas: lower ionization density (~15 clusters/cm) and 30 μm/ns (@E~2 kV/cm). Mean cluster arrival time separation: ~20ns

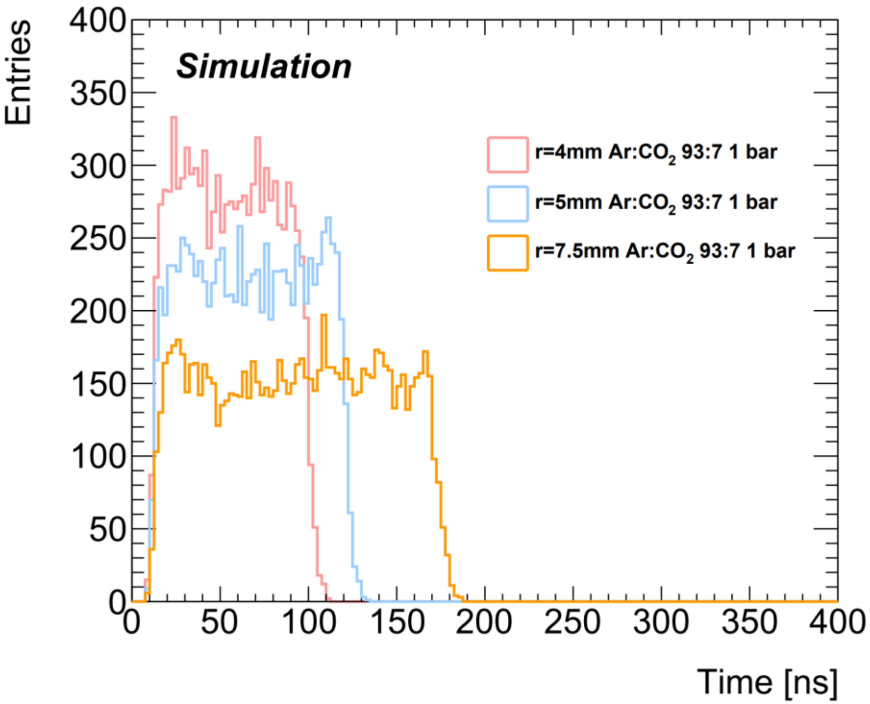
k	CH_4	Ar	He	CO_2
1	78.6	65.6	76.60	72.50
2	12.0	15.0	12.50	14.00
3	3.4	6.4	4.60	4.20
4	1.6	3.5	2.0	2.20
5	0.95	2.25	1.2	1.40
6	0.60	1.55	0.75	1.00
7	0.44	1.05	0.50	0.75
8	0.34	0.81	0.36	0.55
9	0.27	0.61	0.25	0.46
10	0.21	0.49	0.19	0.38
11	0.17	0.39	0.14	0.34
12	0.13	0.30	0.10	0.28
13	0.10	0.25	0.08	0.24
14	0.08	0.20	0.06	0.20
15	0.06	0.16	0.048	0.16
16	(0.050)	0.12	(0.043)	0.12
17	(0.042)	0.095	(0.038)	0.09
18	(0.037)	0.075	(0.034)	(0.064)
19	(0.033)	(0.063)	(0.030)	(0.048)
≥20	$(11.9/k^2)$	$(21.6/k^2)$	$(10.9/k^2)$	$(14.9/k^2)$

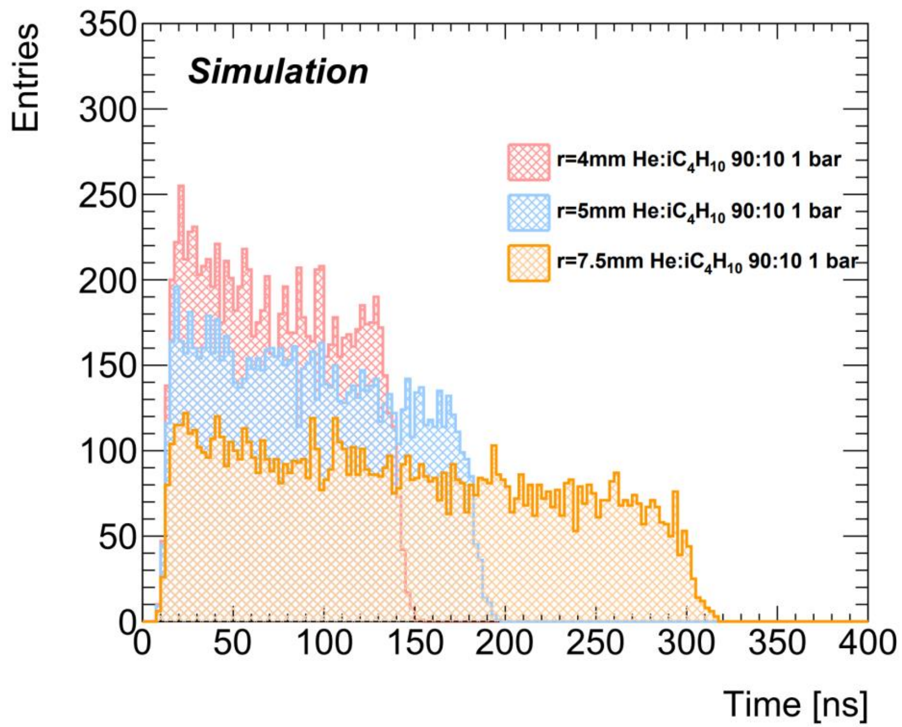
Number of electrons per cluster



Straw Garfield simulation

- Simulation of straw drift time (convolution of earliest cluster arrival time with the amplifier response) to understand electronics requirements :
  - 100-200 ns drift time in Ar-based gas.
  - ~50% longer drift time in He-based gas as expected.
  - Overall comparable with ATLAS sMDT drift time – expect similar rate behavior and specifications for readout electronics to do tracking (alone…)

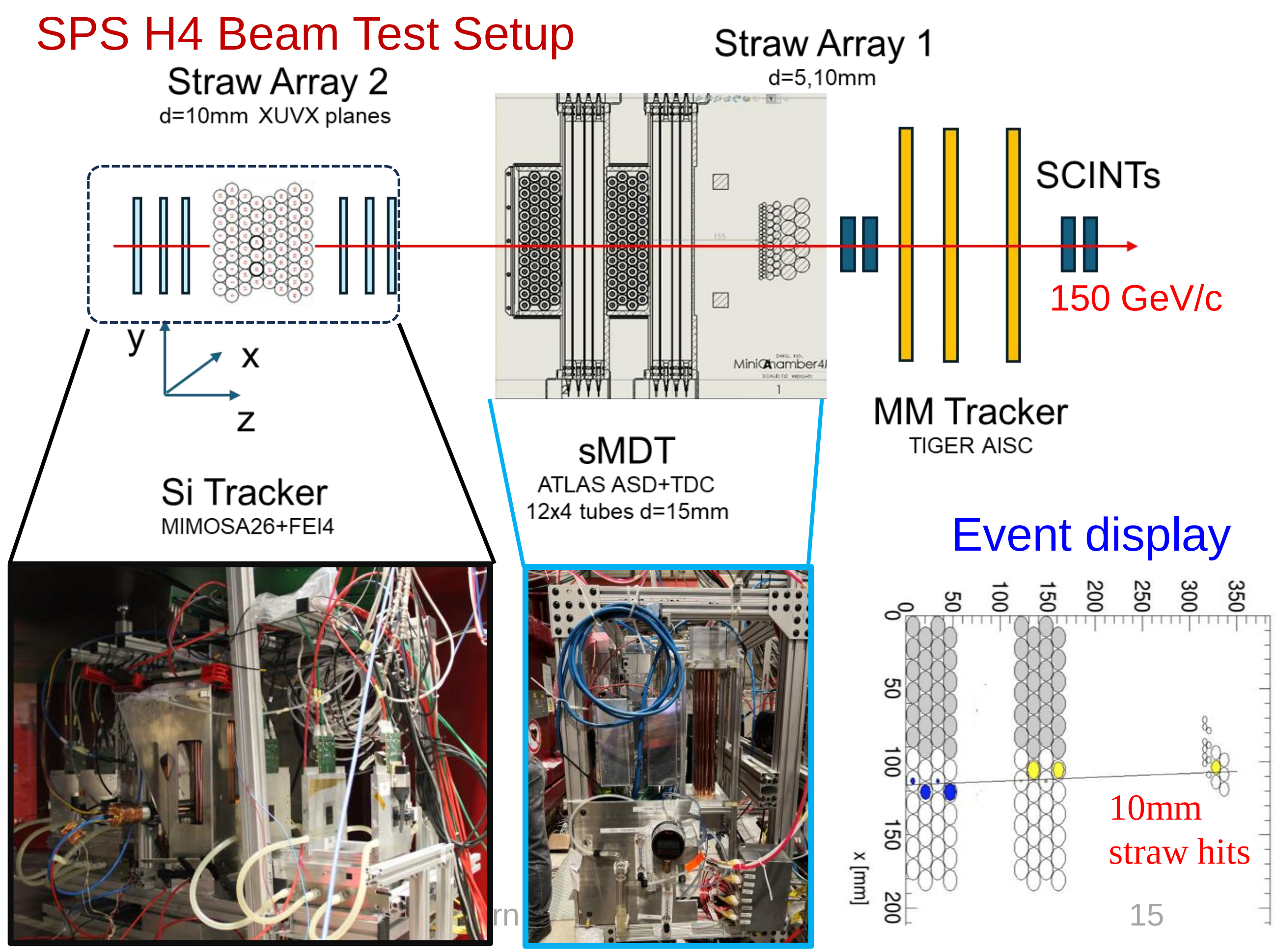




Straw tracker R&D activities

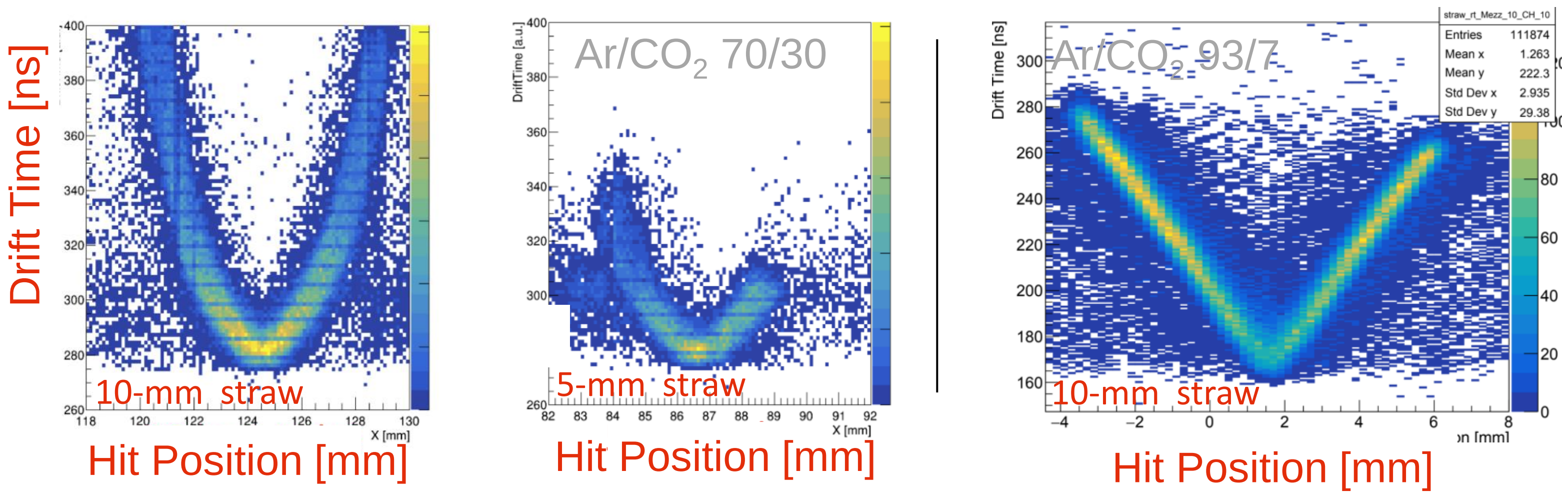
- R&D have been initiated recently to assess drift properties and position resolution from straws to provide baseline references for tracking performance evaluation.
- Beam test of straw prototype at CERN SPS beam line with ATLAS drift tube Front-end (ASD+TDC, well established for drift time-based tracking, 400 kHz hit rate)

- Straws: 5/10 mm diameter (20/36um Mylar wall)
- Gas: Ar/CO 93/7 or 70/30 (1-3 bar)
- Measurements:
  - charge gain
  - ADC/ToT mode operation
  - drift time vs. radius (r-t function)
  - position resolution



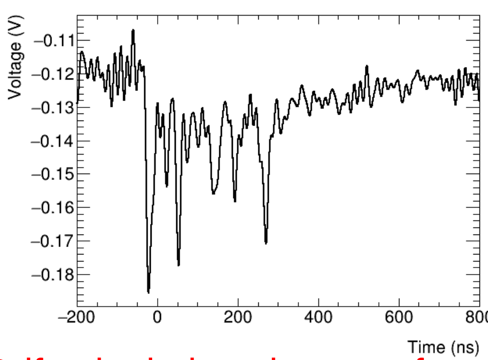
Straw tracker R&D activities

- Straw r-t characterized (impact parameter measured with precision tracker) to allow comparison with simulations and studies of intrinsic position resolution.

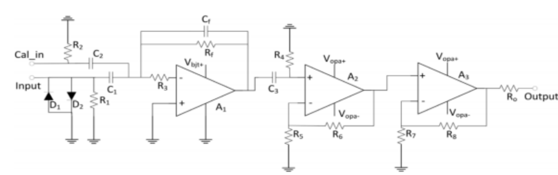


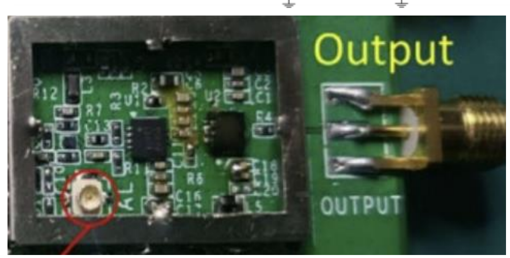
- Measurements of induced current from drift tubes in Ar-based gas ongoing to understand electronics requirements for cluster counting.

(drift tube, d=2.5 mm, Ar:CO2 93:7)



Drift tube induced current from one cosmic muon event





Identified fast amplifier:

- 40dB gain, 870MHz bandwidth for LGAD readout

Ge, J. J., et al. NIM A1040 (2022): 167222.

Conclusions

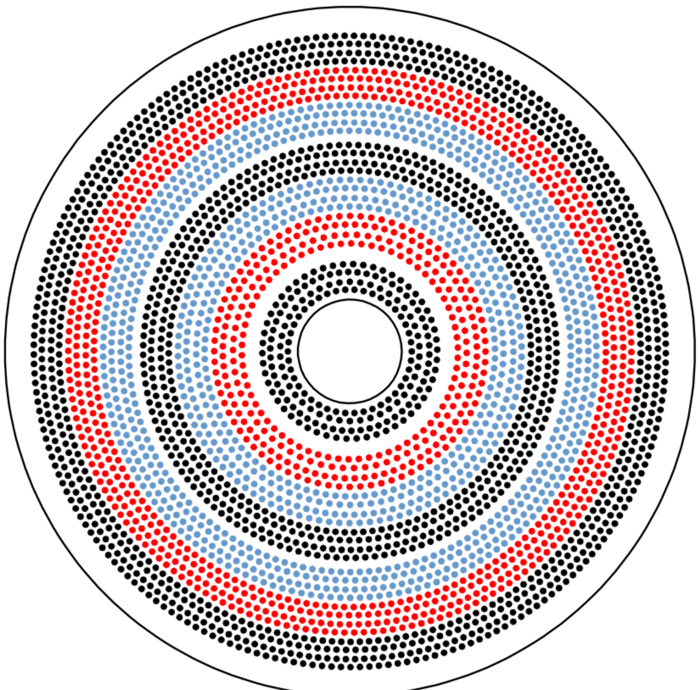
- A straw tracker could be a good option for FCC-ee experiments
  - Reasonable material budget (~1.2% X_0 for ~100 layers w. 12 μm Mylar wall)
  - Could use >4 m straws to extend the tracker volume
  - Robust technology used in many experiments
  - Could achieve high-performance tracking. Particle identification to be offered similar as Drift Chamber (DCH) (demonstration still needed).
- Still challenges. Many developments essential: thin-wall straw production, precision tracker mechanical assembly, optimal front-end electronics and gas for tracking and cluster counting.
- Synergies with DCH community on PID and endplate mechanics beneficial.
- R&D program ongoing within the DRD1 Community (under Work Package 3). Interested groups and individuals are encouraged to join the efforts!

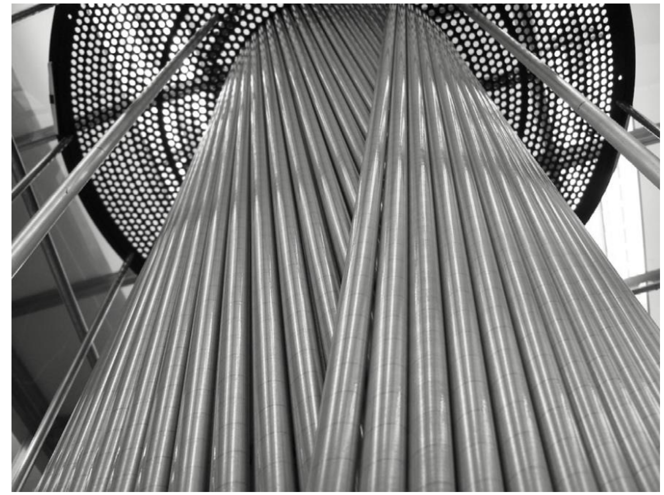
Backup

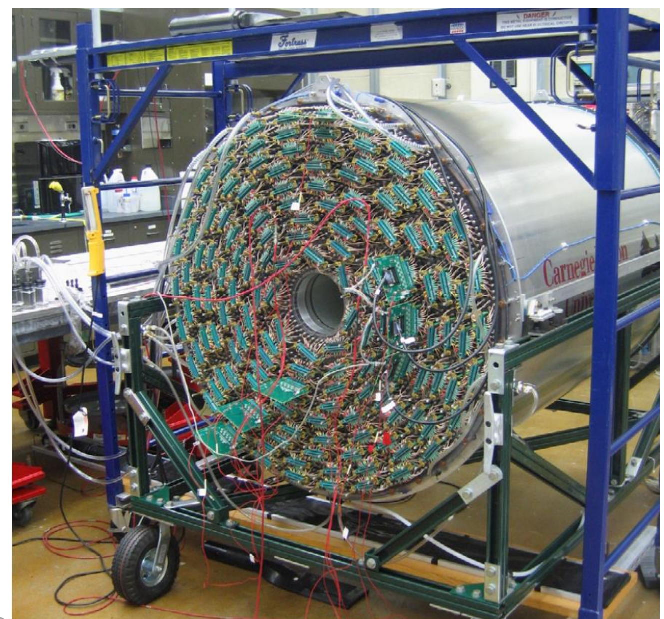
Second coordinate measurements can be achieved with stereo angle straw arrangement

Example: GlueX experiment central tracker

Reference: https://doi.org/10.1016/j.nima.2020.163727







Black: Axial straws

Red: +6° stereo layers

Blue: -6° stereo layers

Resolution

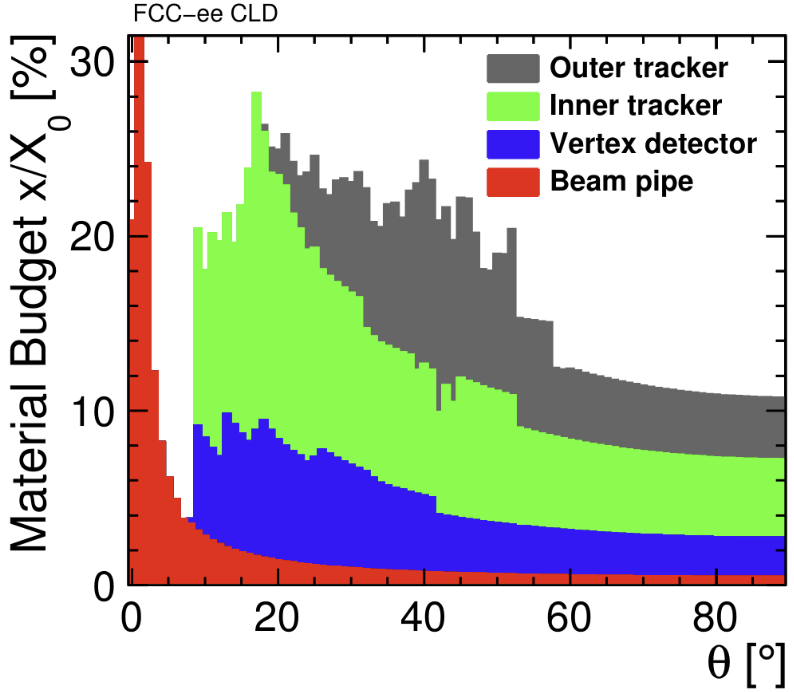
$$\sigma_\phi = \sigma_\eta \frac{\sqrt{1+\cos^2\theta}}{\sin\theta}$$

$\sigma_\phi = 1.4$ mm with $\sigma_\eta = 100\mu m$, 6° stereo angle

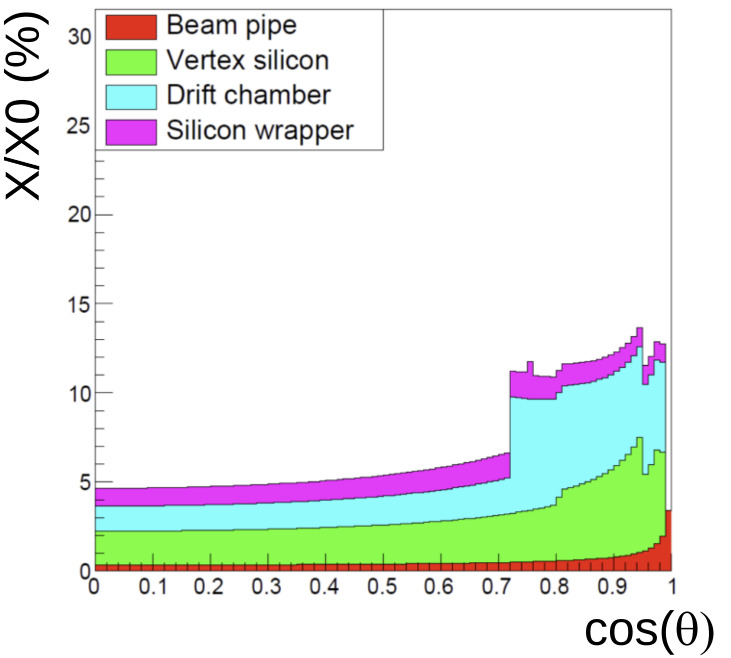
Backup

Material Budget

CLD

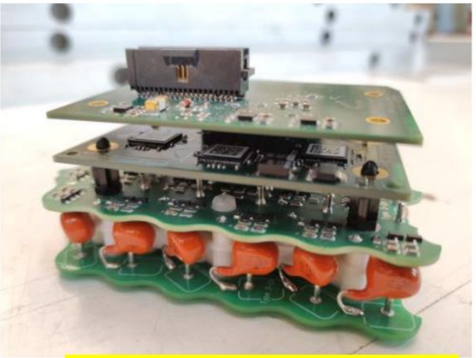


IDEA



Backup

ATLAS sMDT/MDT Front-end Mezzanine card and Front-end electronics for straw readout



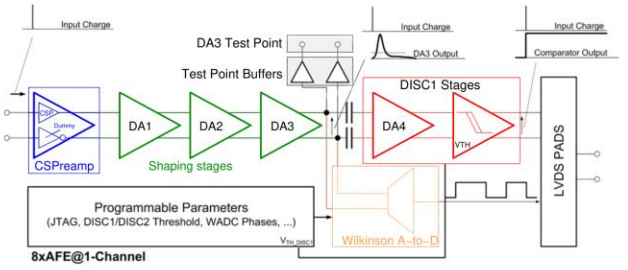
Stacked mezzanine card

Flat mezzanine card

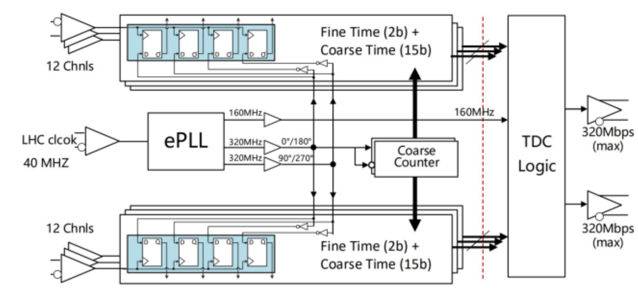
ATLAS sMDT ASD Spec.	
Technology	CMOS 130nm
#. of channels	8
Power consumption	10 mA/ch
Input capacitance	60pF
Shaper	bipolar
Peaking time	12 ns
Dynamic range	5-100 fC
sensitivity	8 mV/fC
ENC	1 fC
Charge readout	ADC, ToT

ATLAS sMDT TDC Spec.	
Technology	CMOS 130nm
#. of channels	24
Package	BGA 144
TDC LSB	0.78 ns
Nonlinearity	+- 80 ps
Power consumption	360 mW per chip
Dynamic range	17 bits (102μs)
Output data rate	320 Mbps x 2
Max. hit rate	400 kHz/ch
Mode	Lead/trail edge, pair

ASD schematic



TDC schematic



Backup

Number of clusters per 1cm track (left) and cluster size (Garfield/HEED)

Electron drift Velocity