



Brookhaven
National Laboratory



**FUTURE
CIRCULAR
COLLIDER**



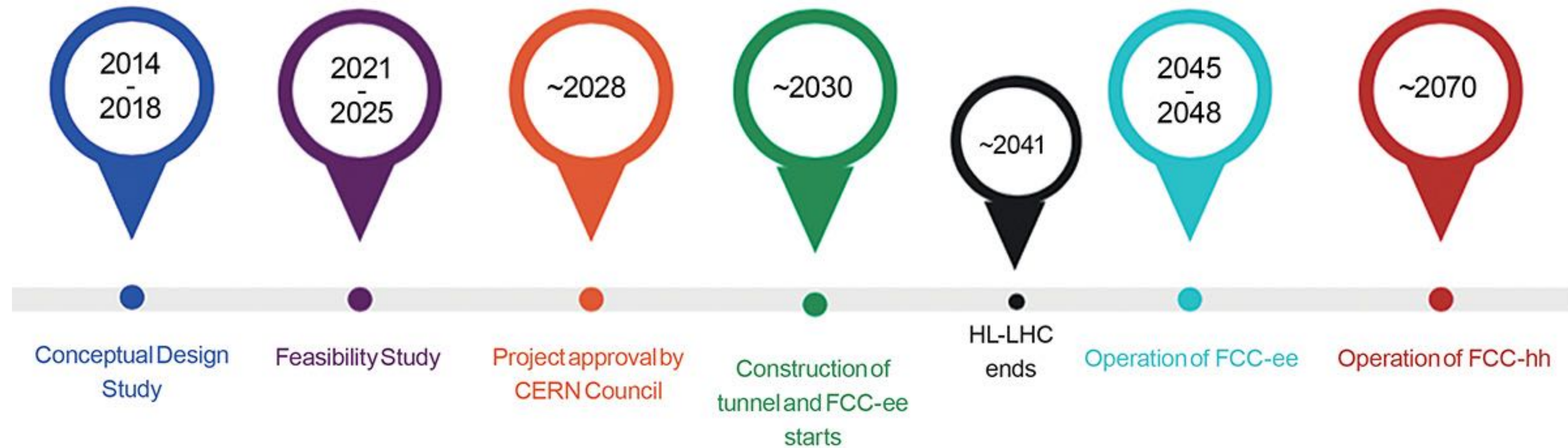
**U.S. DEPARTMENT
of ENERGY**

Tracking and Particle identification in future experiments for FCC-ee

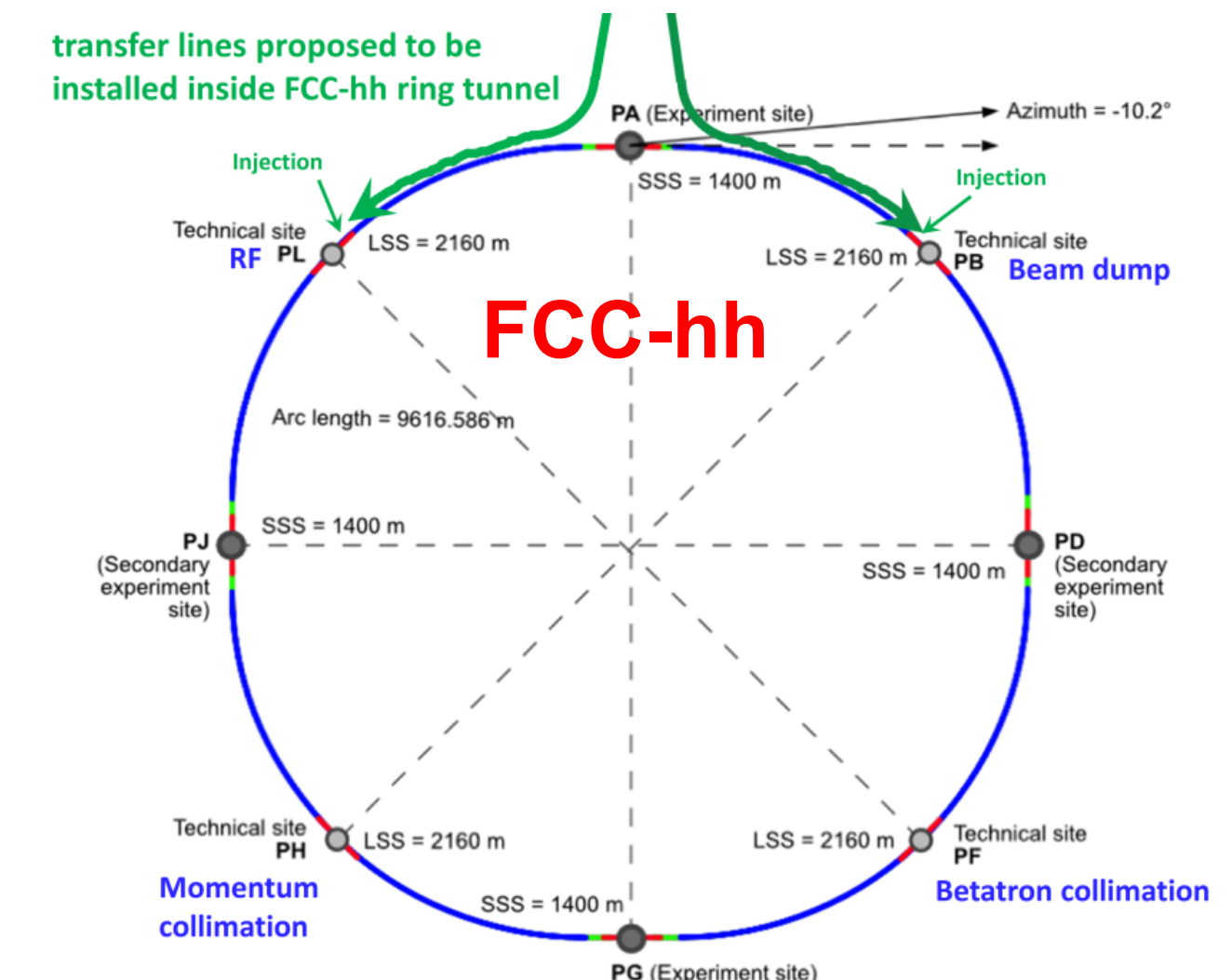
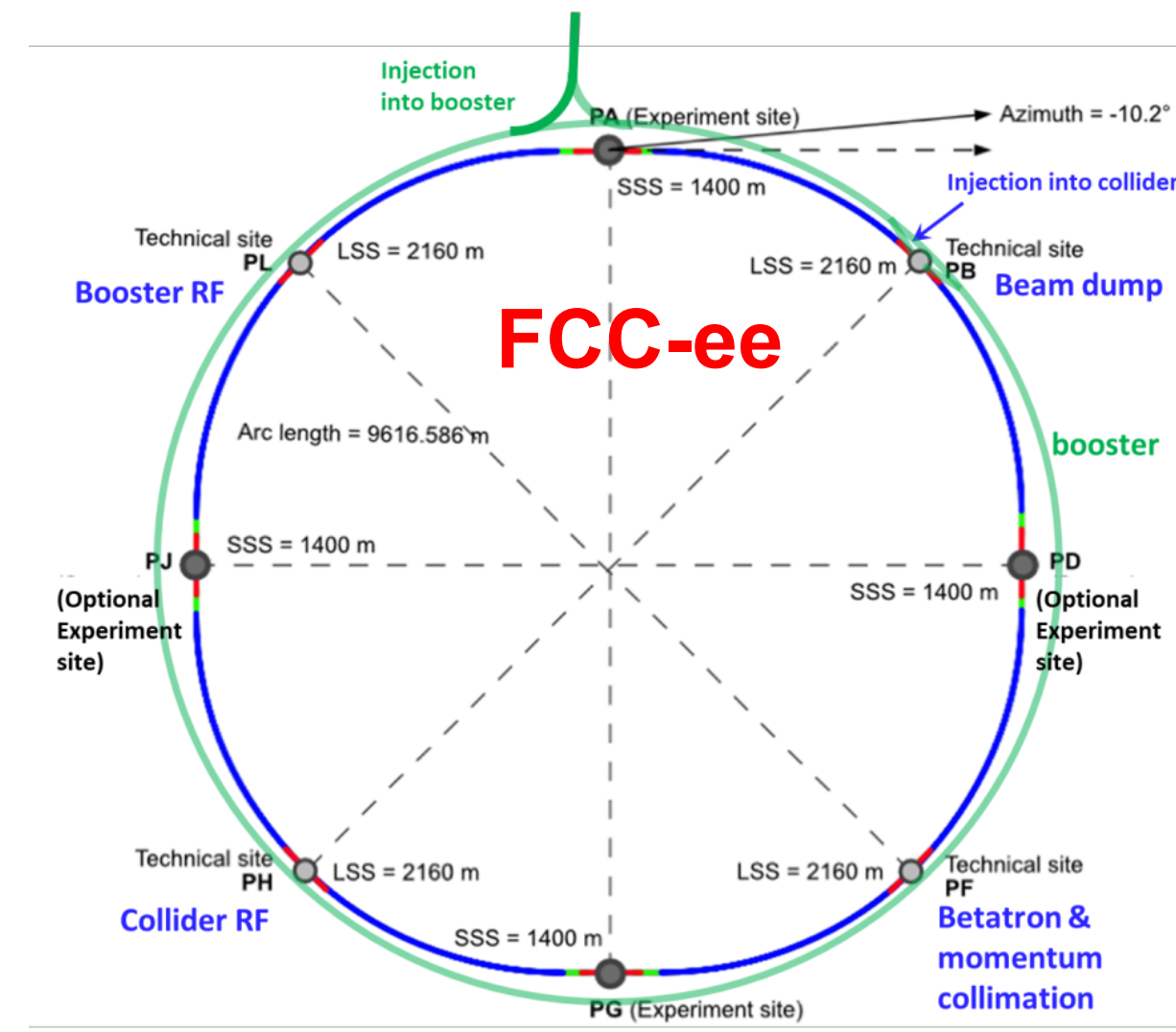
George Iakovidis, Valentina Cairo

*ILD meeting
September 2026 - CERN*

Timeline: FCC integrated program



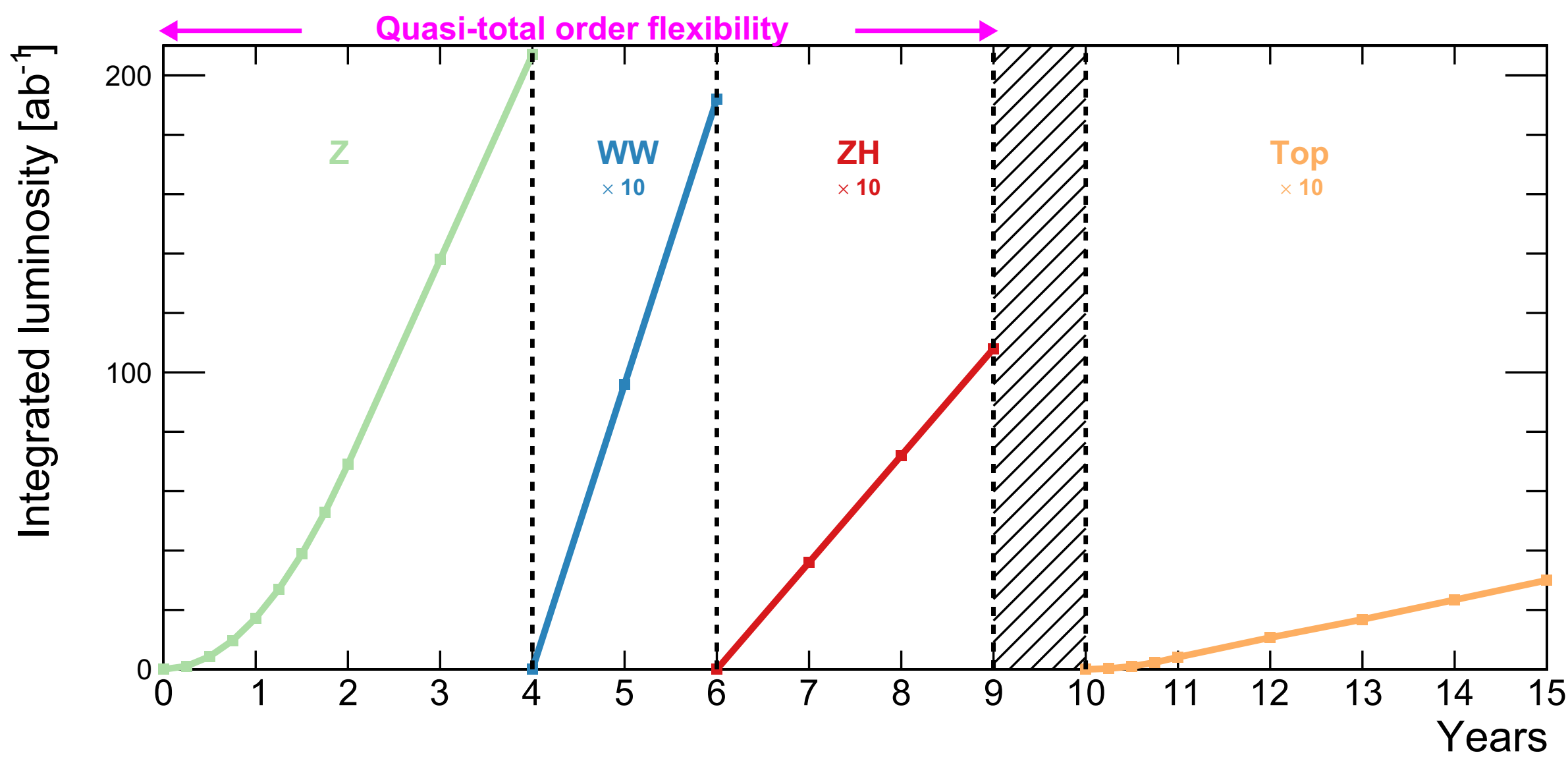
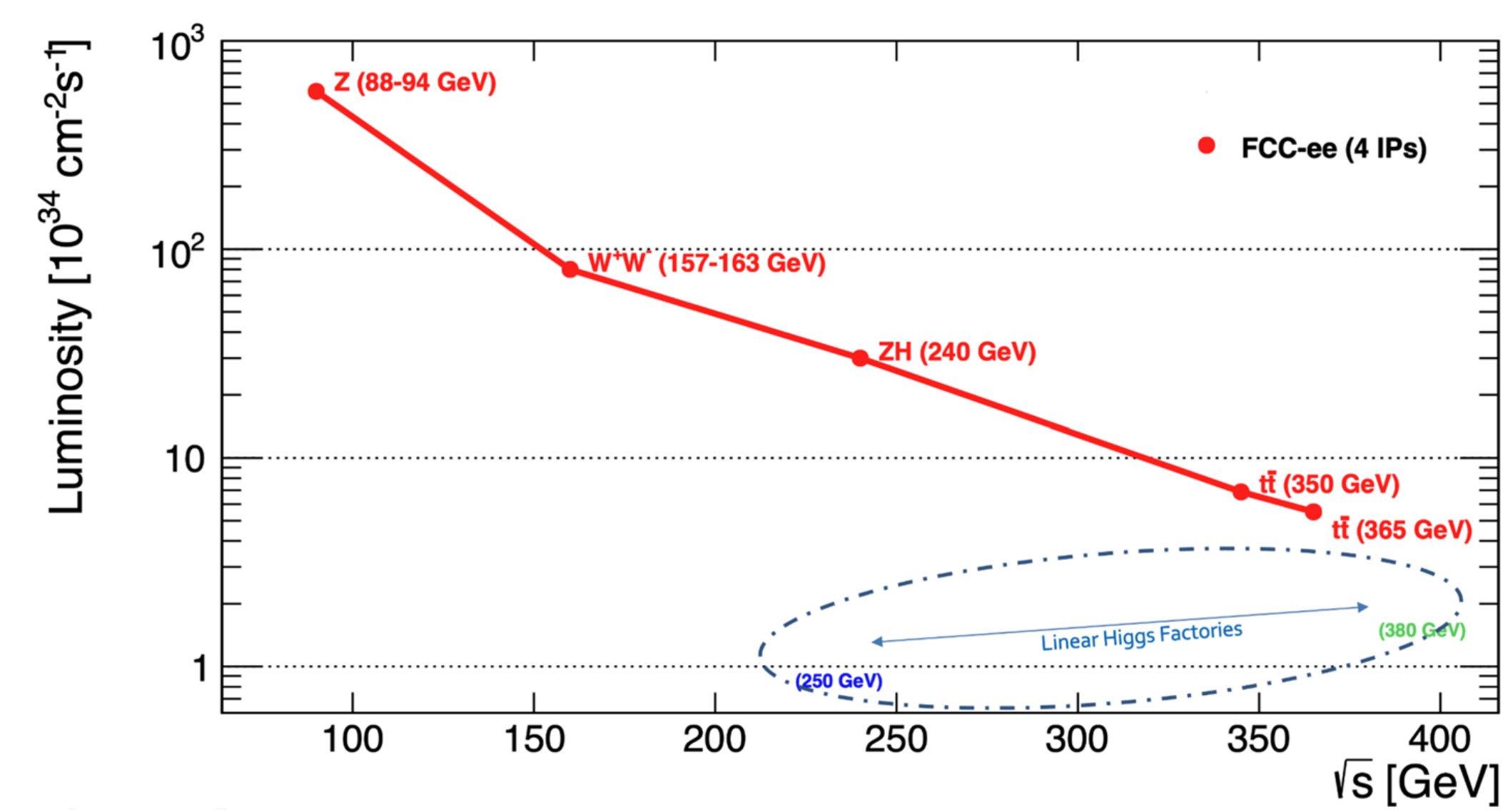
- Comprehensive **long-term program maximizing physics opportunities**
 - Stage 1: FCC-ee** ($Z, W, H, \bar{t}t$) as Higgs factory, electroweak & top factory at highest luminosities
 - Stage 2: FCC-hh** (~ 100 TeV) as natural continuation at energy frontier
- Highly **synergetic and complementary programme** boosting the physics reach of both colliders
- Common** civil engineering and technical **infrastructures**, building on and reusing CERN's existing infrastructure within a few years of the end of HL-LHC



2045 - 2065

2070 -

Focusing on the FCC-ee

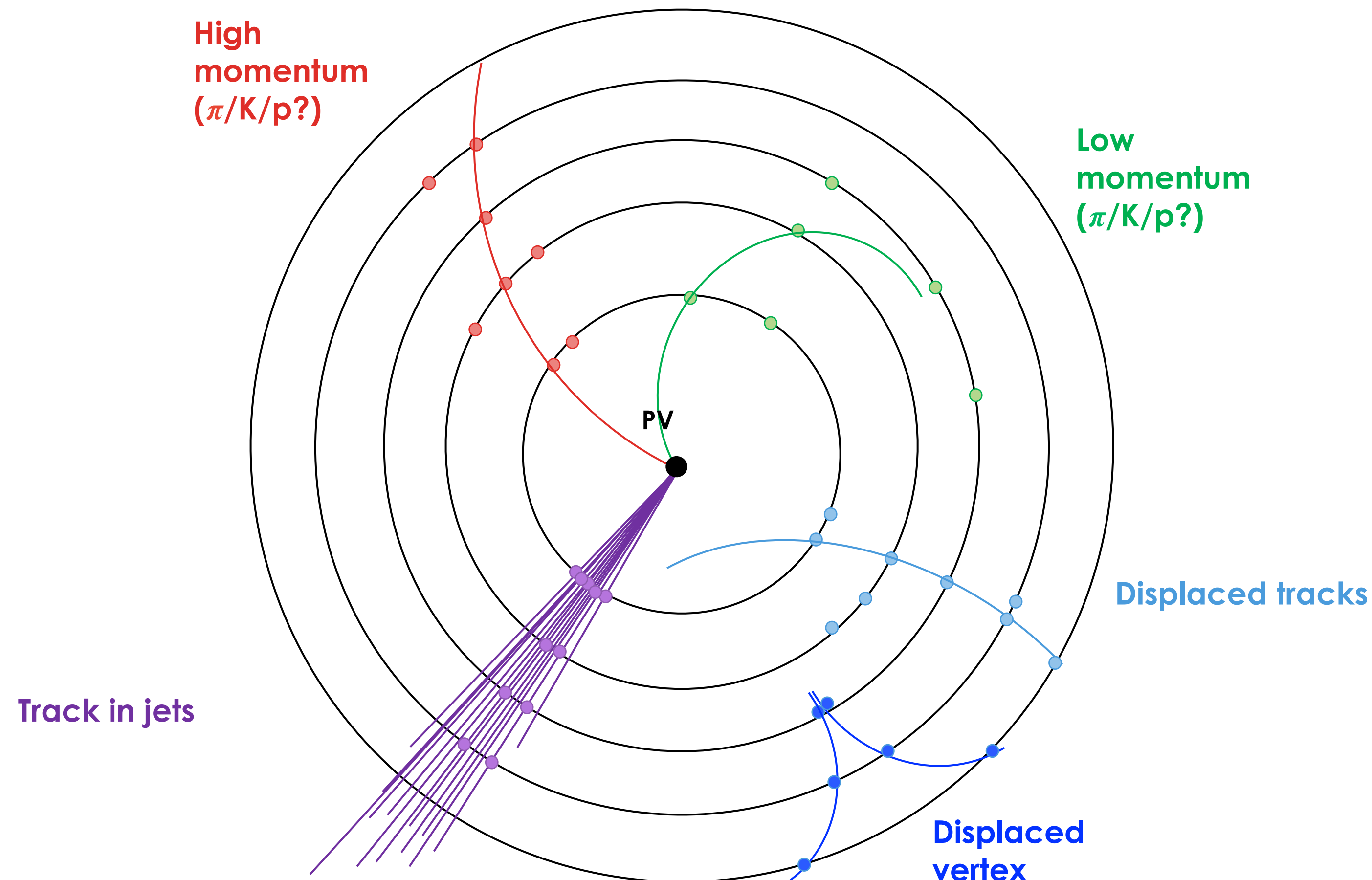


- **Exquisite luminosity** allows for **ultimate precision** well beyond LEP, opens **novel challenges** and **opportunities**:
 - **10^5 larger dataset** than LEP at the Z-pole can lead to **300x** improvement in statistical precision in **EWPO**
 - **$>10^6$** of extremely clean **H** and **t** can lead to **[0.1-1%]** **H , top couplings** precision and **mass and width 10x** better precision than LHC
- **how do we build optimal detectors?**

Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.67
Run time (year)	4	2	3	1	4
Integrated lumi. (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	6×10^{12} Z	2.4×10^8 WW	2.2×10^6 ZH + 65k WW $\rightarrow$ H	2×10^6 $t\bar{t}$ + 370k ZH + 92k WW $\rightarrow$ H	

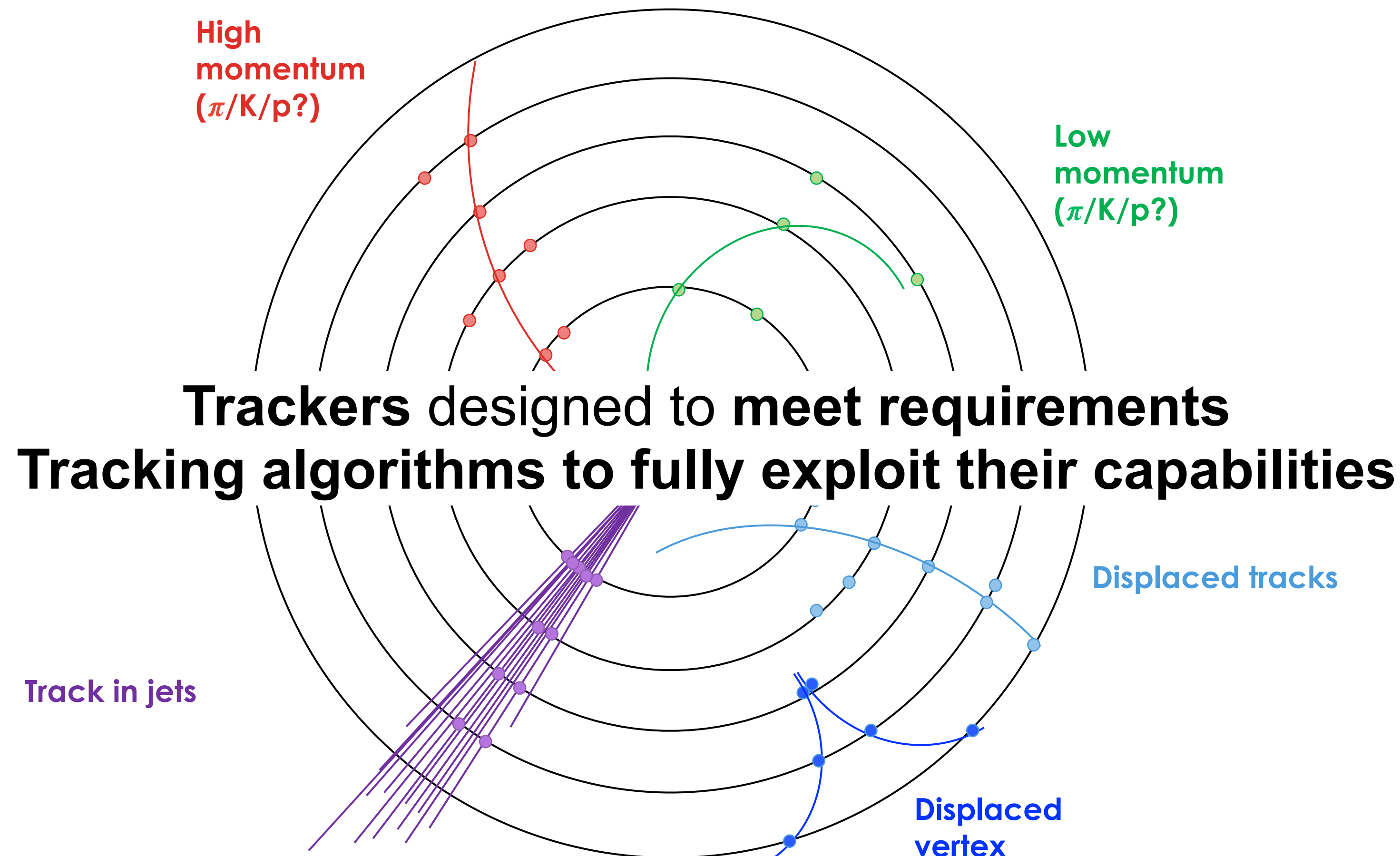
Focus on Tracking & Particle Identification

- Tracks and vertices are the building blocks of collider physics events. Identifying from which particle they originate is key for new physics studies.
- Demanding requirements on tracking systems from physics benchmarks.



Focus on Tracking & Particle Identification

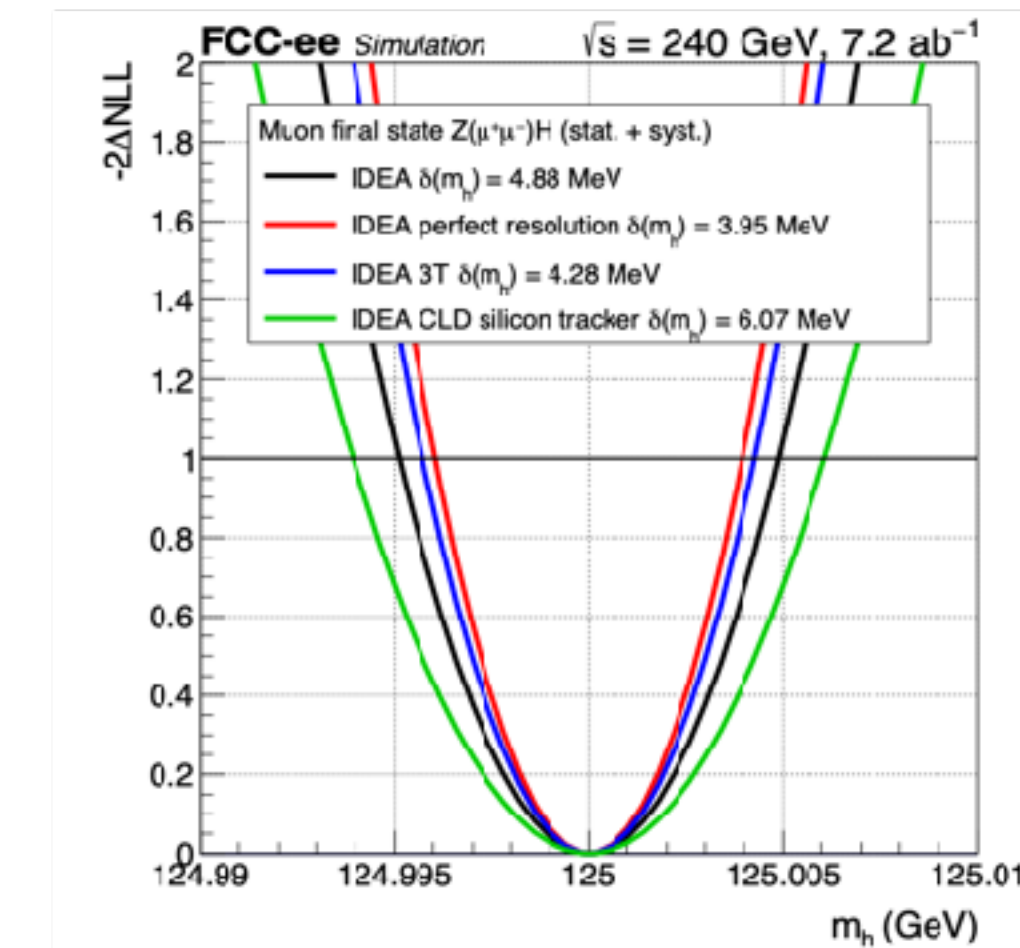
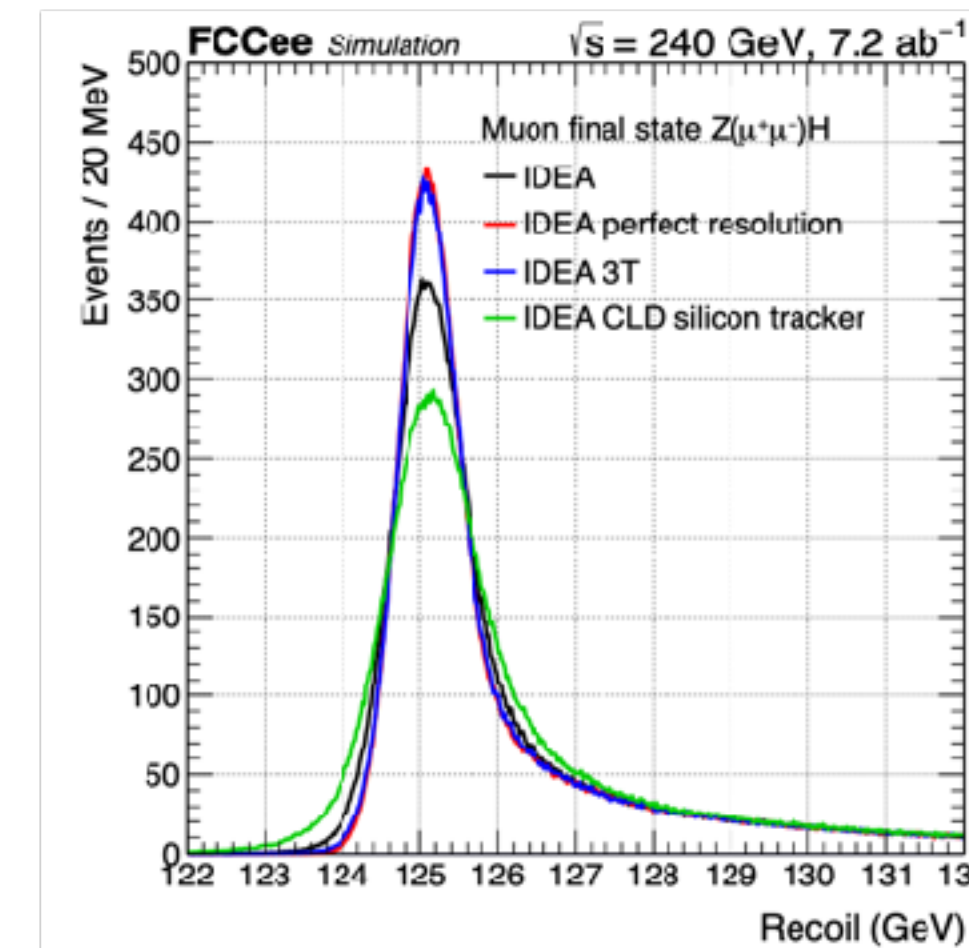
- Tracks and vertices are the building blocks of collider physics events. Identifying from which particle they originate is key for new physics studies.
- Demanding requirements on tracking systems from physics benchmarks.



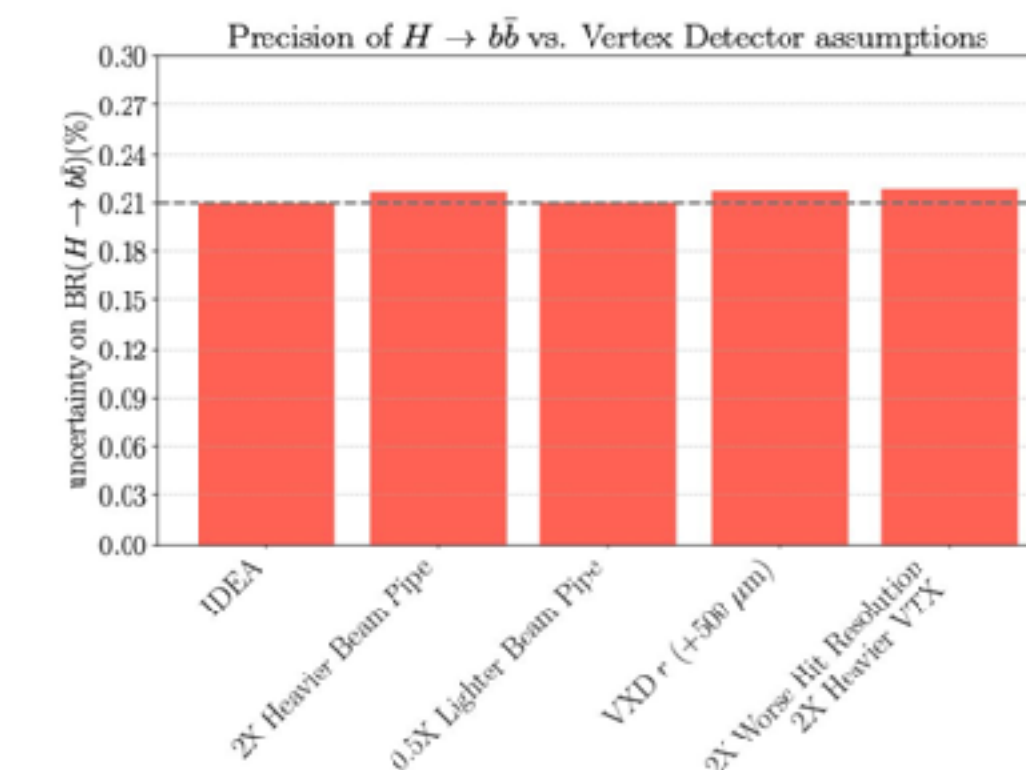
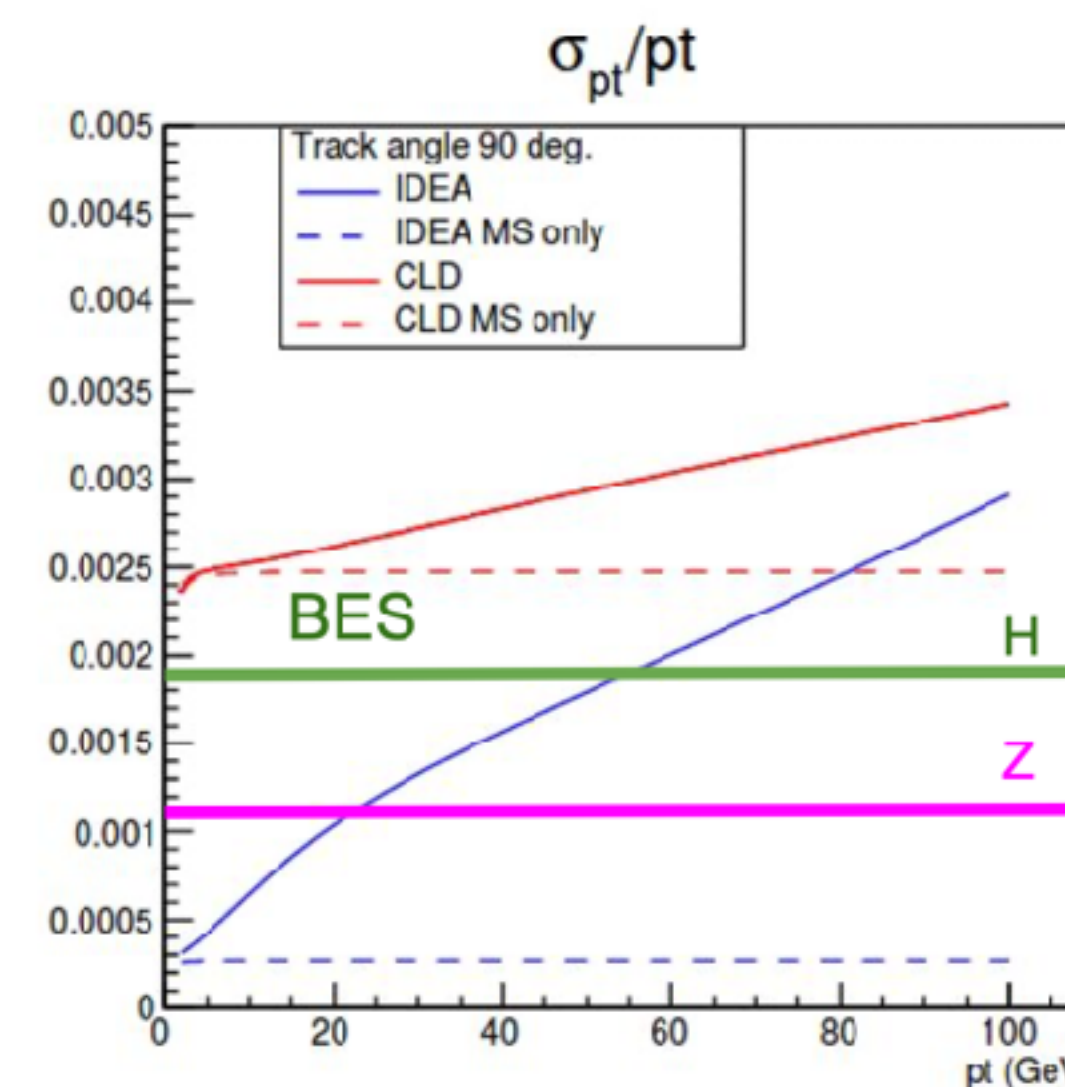
Physics requirements

In FCC-ee, tracking is crucial for many physics cases eg. Higgs, Flavor physics, QCD-EWK, BSM

- **Excellent impact parameter resolution** needed for charm- and b-jet tagging → Radial distance of first tracking layer is key
- PID Capabilities (e.g. $H \rightarrow s\bar{s}$)
- High acceptance, high efficiency, hermeticity
- Keep systematic uncertainties down to statistical errors
- **Excellent momentum resolution** → at the level $\sim \mathcal{O}(50)\text{GeV } \sigma_{p_T}/p_T \sim 0.2\%$
- Higgs mass measured at its intrinsic width (4 MeV)
- Sensitivity driven by m_{recoil} for $Z(\mu^+\mu^-)H$ determined by BES (0.185%)
- **Transparency** of the tracker crucial



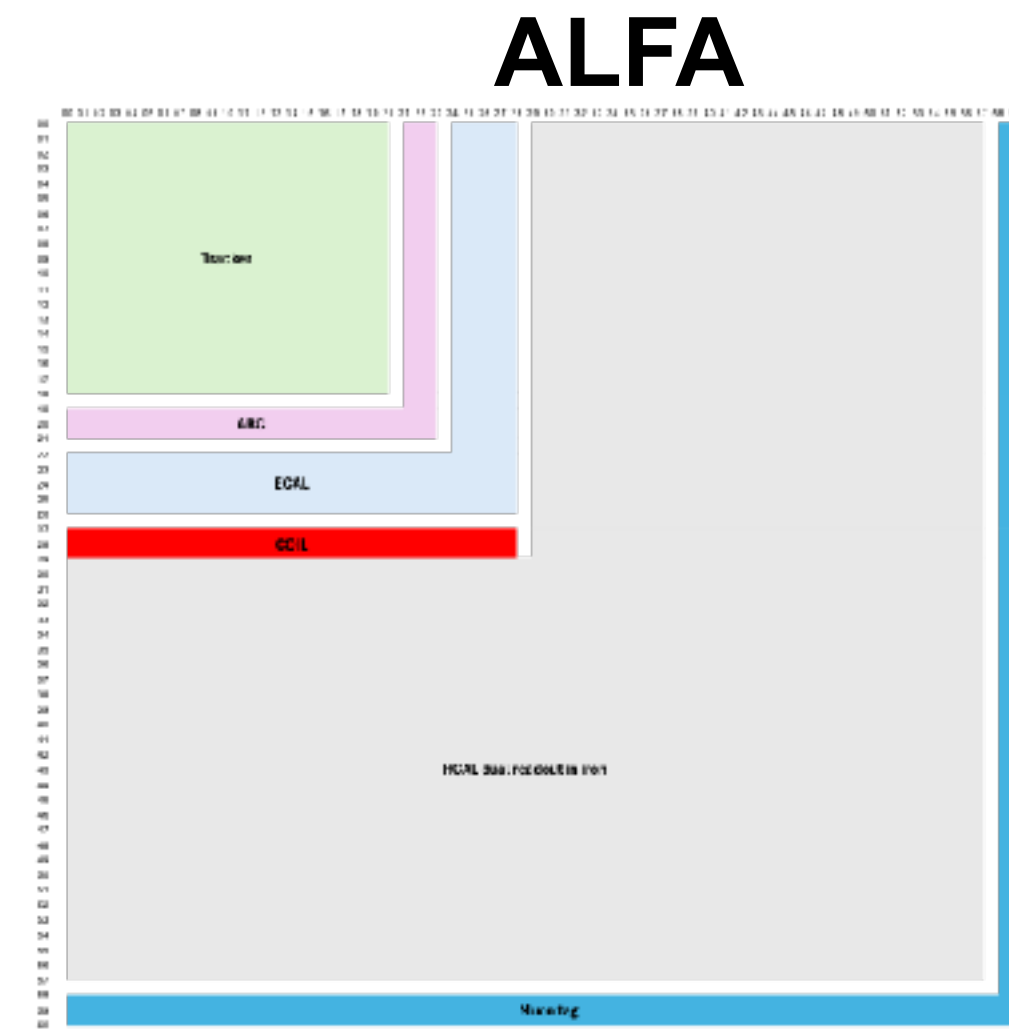
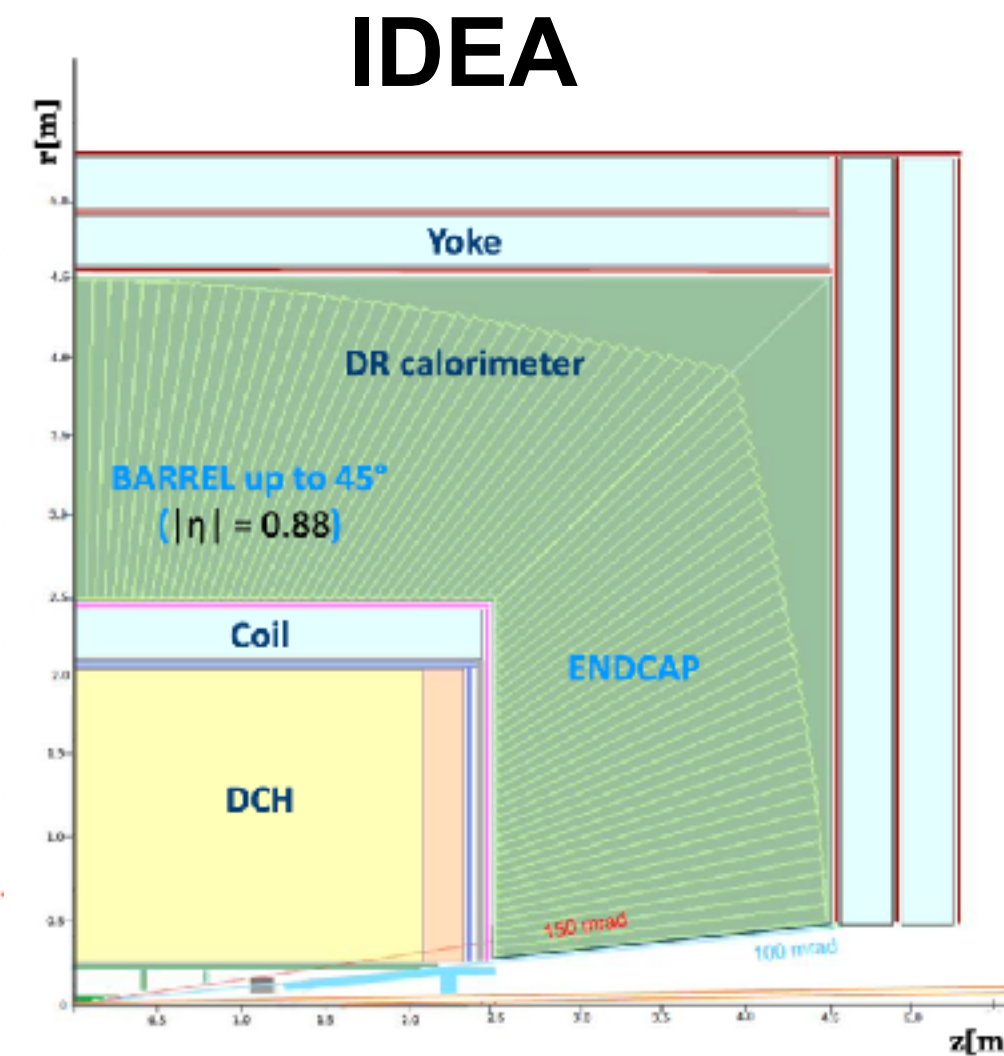
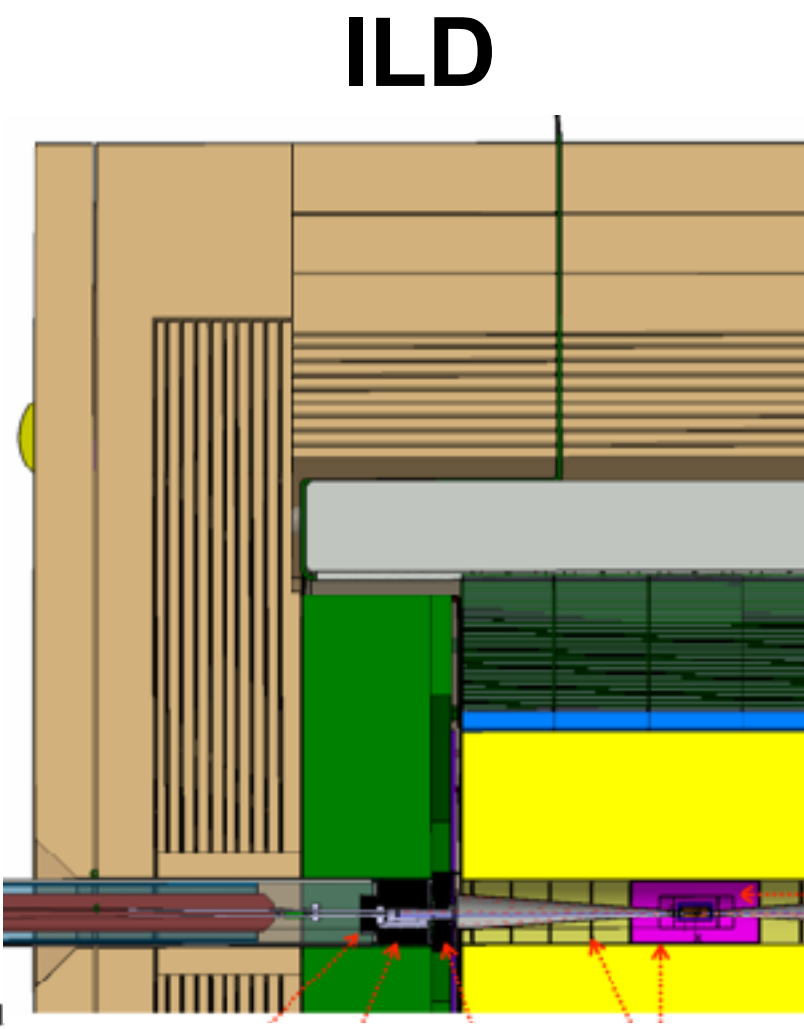
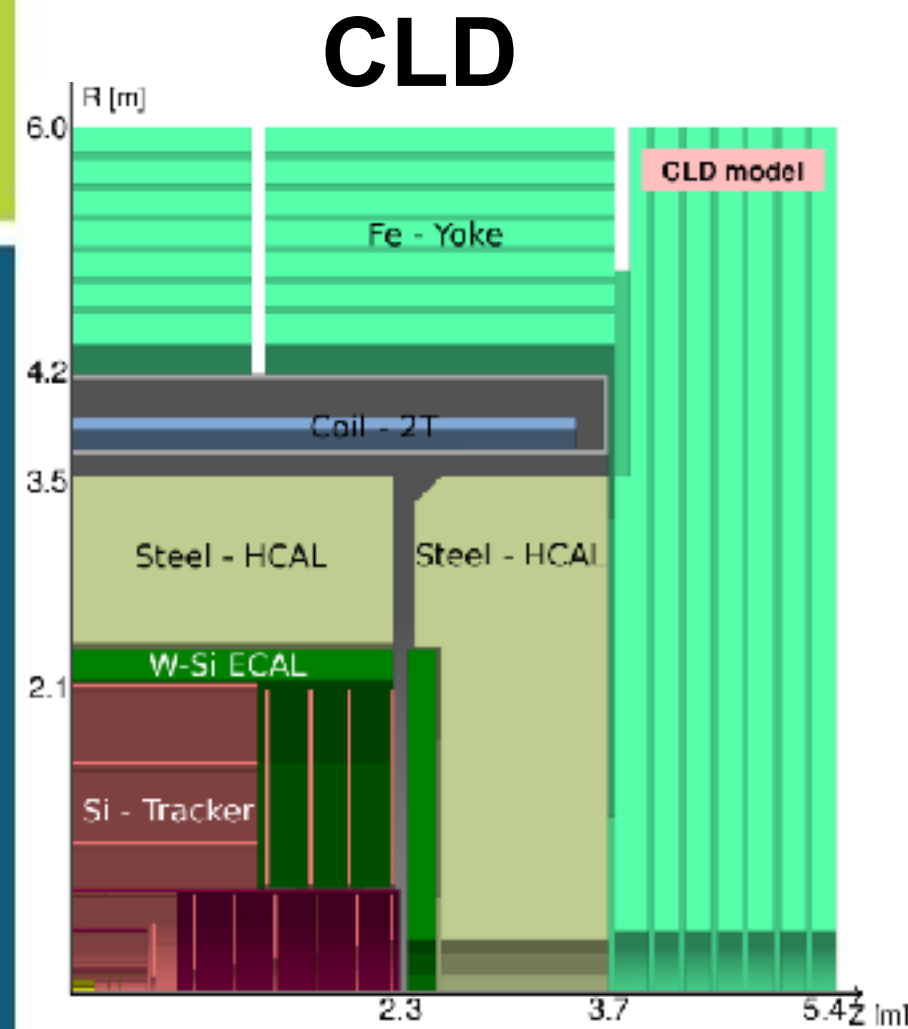
[J. Eysermans, A. Li, G. Bernardi, FCC note: Higgs boson mass and model-independent ZH cross-section at FCC-ee in the di-electron and di-muon final states](#)



[M. Selvaggi: Physics and Performance, Requirements on Tracking for future colliders](#)

Detector concepts - Tracking systems

Legend: Inner Tracker, Outer Tracker, Wrappers



- Evolved from CLIC detector
- Silicon vertex with 25 μ m pixels
- Geometry with ALICE ITS approximation $\rightarrow$ FCC-SEED
- Silicon tracker with 50 μ m strips
- Sensors plus ASICs or monolithic structure or MAPS
- ARC (Array of RICH Cells) Lightweight with 20cm radial depth
- Two radiators (gas + aerogel)

- Initial design for ILC
- Significant changes for FCC-ee
- Silicon Vertex
- Currently borrowed from CLD for simulations
- TPC as outer tracker
- Studying different layouts varying the inner Radii
- Silicon External Tracker for ToF + momentum resolution

- Conceived for FCC-ee
- Silicon vertex tracker
- Outer based on ATLASPix3 with 50x150 μ m² pixels
- Inner ARCADIA based 25x25 μ m² pixels
- Outer tracker based on low mass Drift Chamber
- 112 layers
- 4m Long
- R = 35-200cm
- Silicon wrapper
- either with MAPS with $\sim 10^{11}$ channels!
- or CMOS-LGADS ~ 40 ps

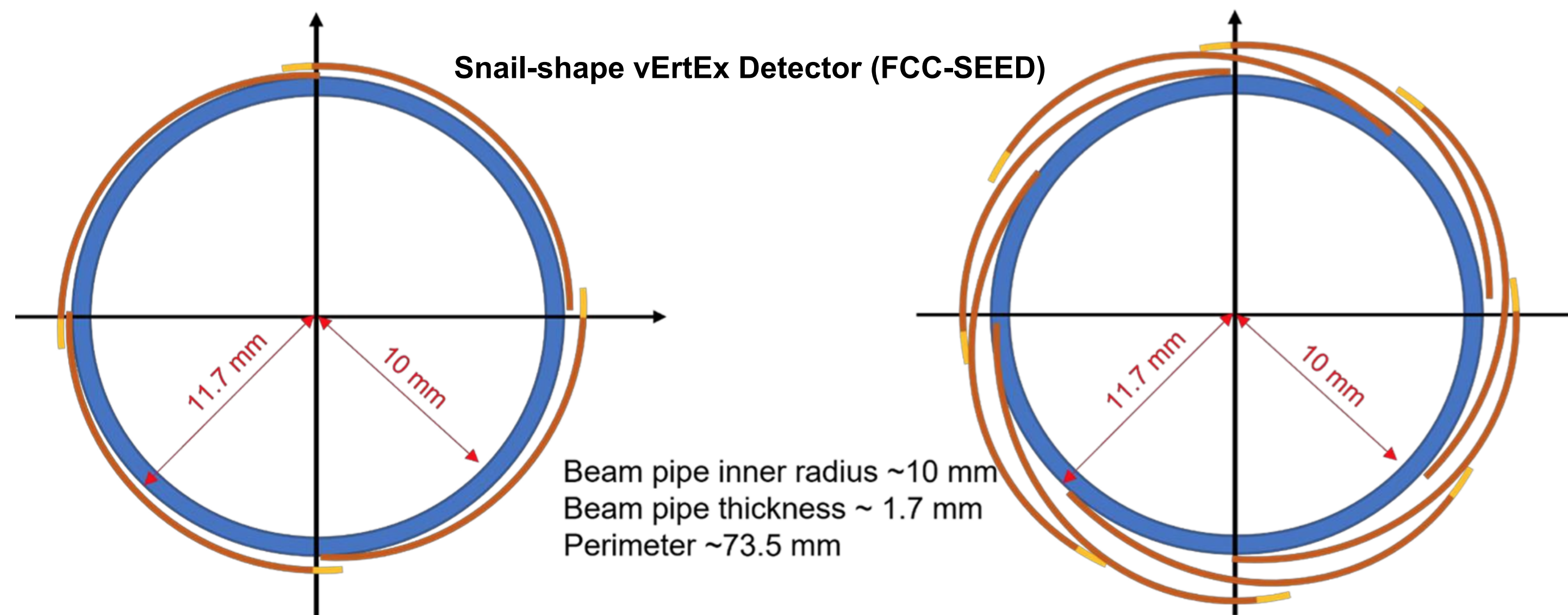
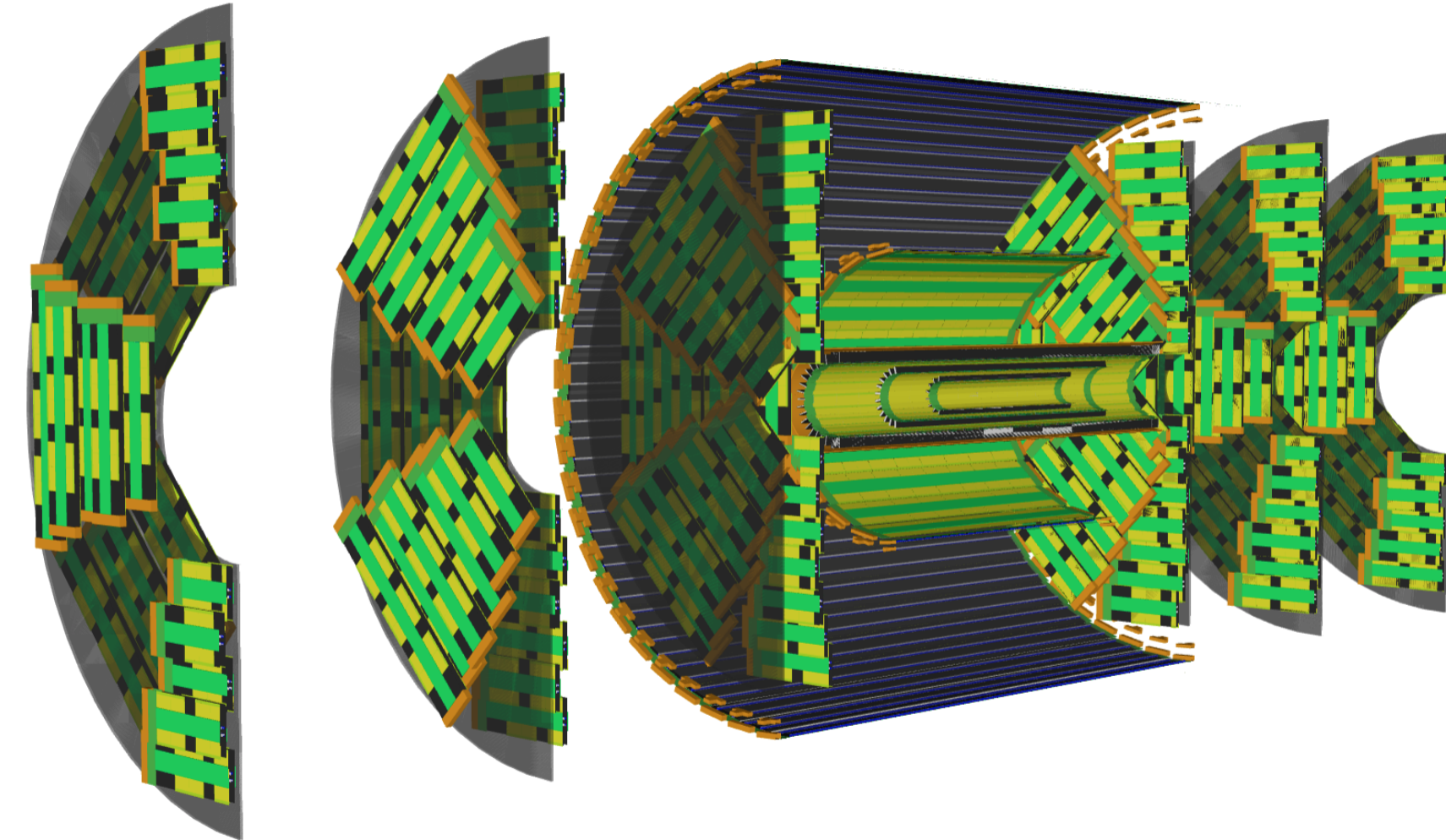
- Conceived for FCC-ee, started with a noble-liquid calorimeter
- Tracking system taken from IDEA
- Silicon Vertex with curved or straight sensors
- Outer tracker with
- Extended Drift Chamber
- Straw tubes
- Scintillating Fiber Tracker (SciFi)
- 5m Long
- R = 35-200cm
- Silicon wrapper
- Monolithic pixel or AC-LGADs

- Newly Conceived project for FCC-ee
- MAPS tracker following ALICE ITS3 developments
- Vertex curved MAPS 65 nm CMOS TPSCo 10x10 μ m² pixels
- Outer tracker Reticle-size MAPS,
 - 25x32 mm² to 50x128 mm² module
- ARC (Array of RICH Cells) Lightweight with 20cm radial depth
- Two radiators (gas + aerogel)

Inner Trackers - Vertex Detector

- Supreme impact parameter resolution: $\sigma_{d_0} = 3 \oplus 15/(p \sin^{3/2} \theta) \mu\text{m}$
 - Good single-hit resolution very close to the beam pipe
 - Material budget per layer of $\approx 0.3 \%X_0$ using Ultra-thin sensors
 - So far, only **Monolithic Active Pixel Sensors (MAPS)** are envisioned to deliver this (curved sensors R&D)
- Leverage on the assembly concept for ALICE ITS3

IDEA Vertex layout

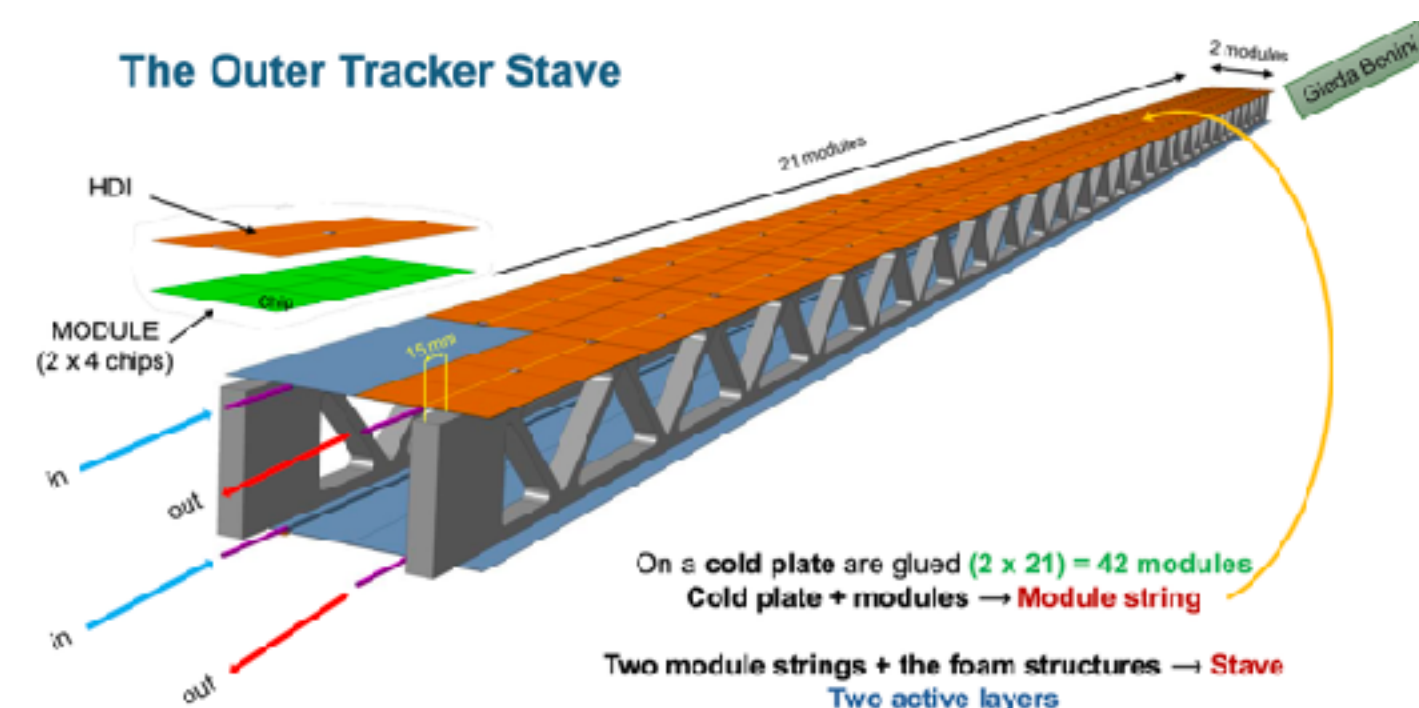
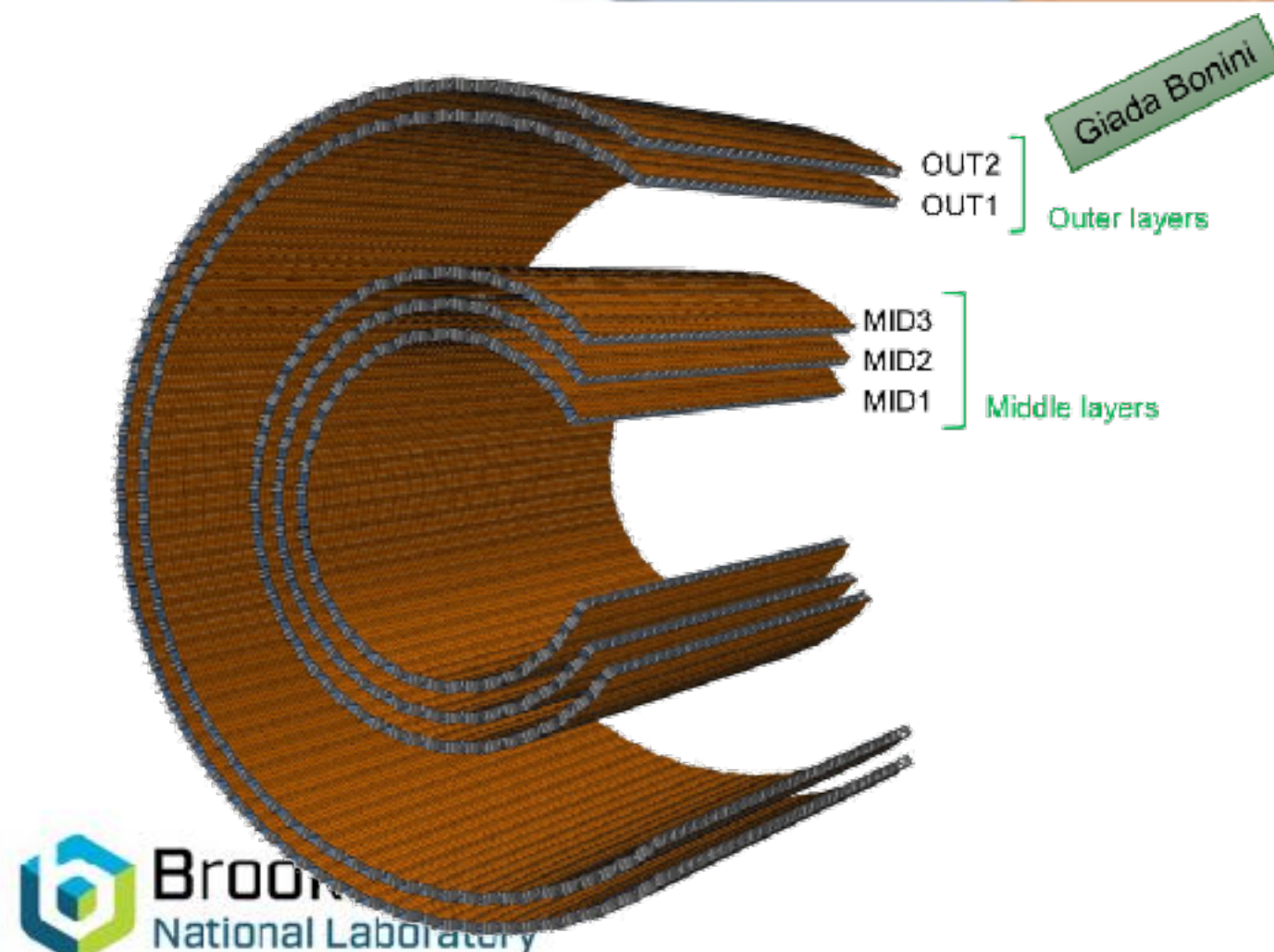
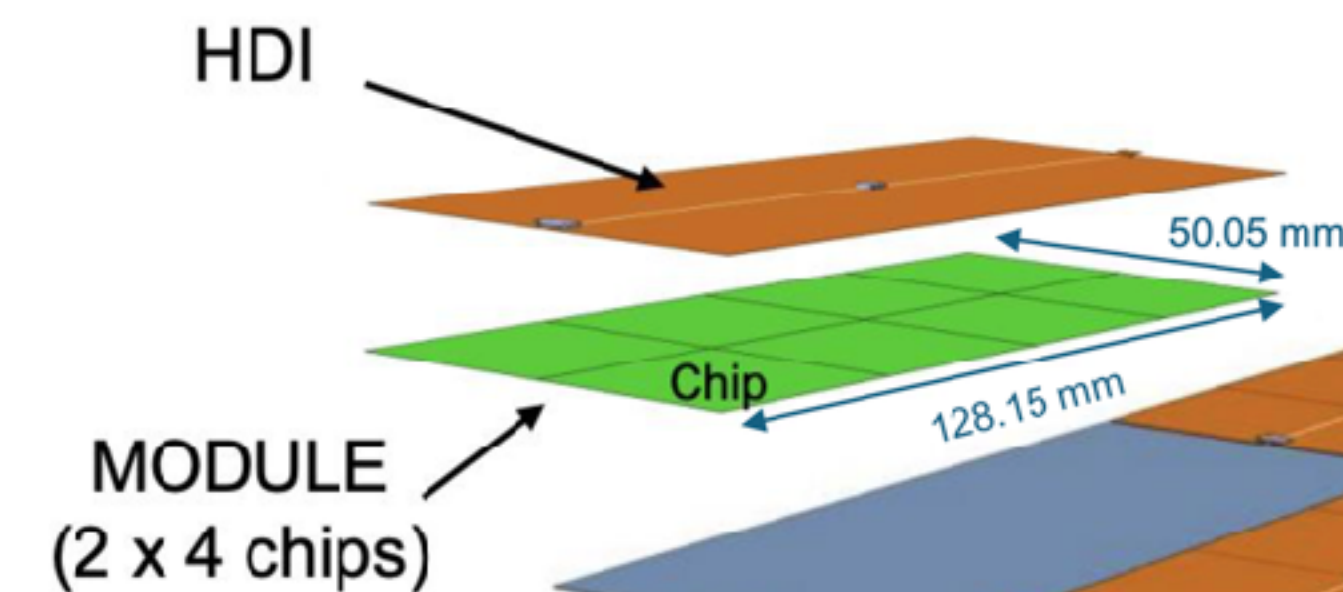


- Tower Semiconductor CMOS processes: R&D based on CMOS imaging technologies - from 180 nm to 65 nm (TPSCo)
 - smaller pixels, higher integration density, lower power, and faster readout.
- Stitched sensors: Large-area monolithic sensors fabricated by stitching multiple reticles
 - reduce dead regions, material, and assembly complexity.

Outer trackers - Silicon MAPS (ALFA)

- High-performance all-MAPS (10 μ m everywhere), from Vertex to Outer Tracker detector, including luminometers
- Challenges: keep sufficiently light, reasonable size and costs. **Lower rates thus slower front-end in outer layers, and eco-friendly cooling fluid.**
- Small collection electrodes are ideal: minimal capacity, minimal power density, minimal pixel size

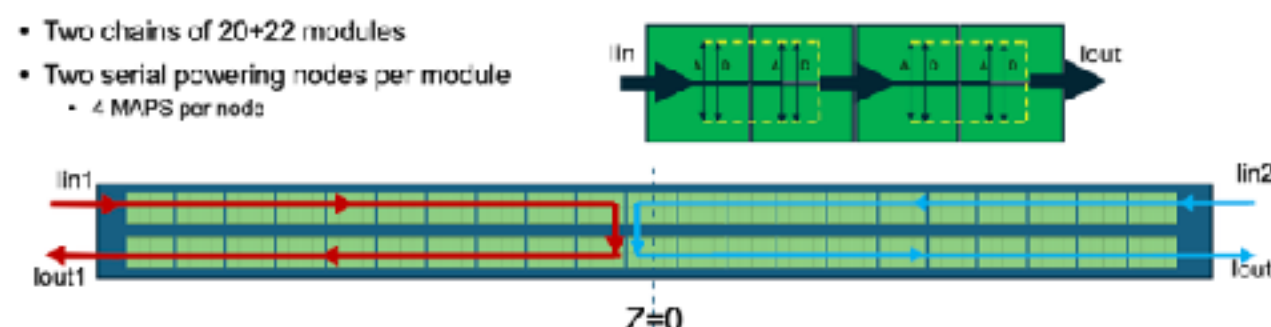
Building block for barrel stave



Serial powering is fundamental

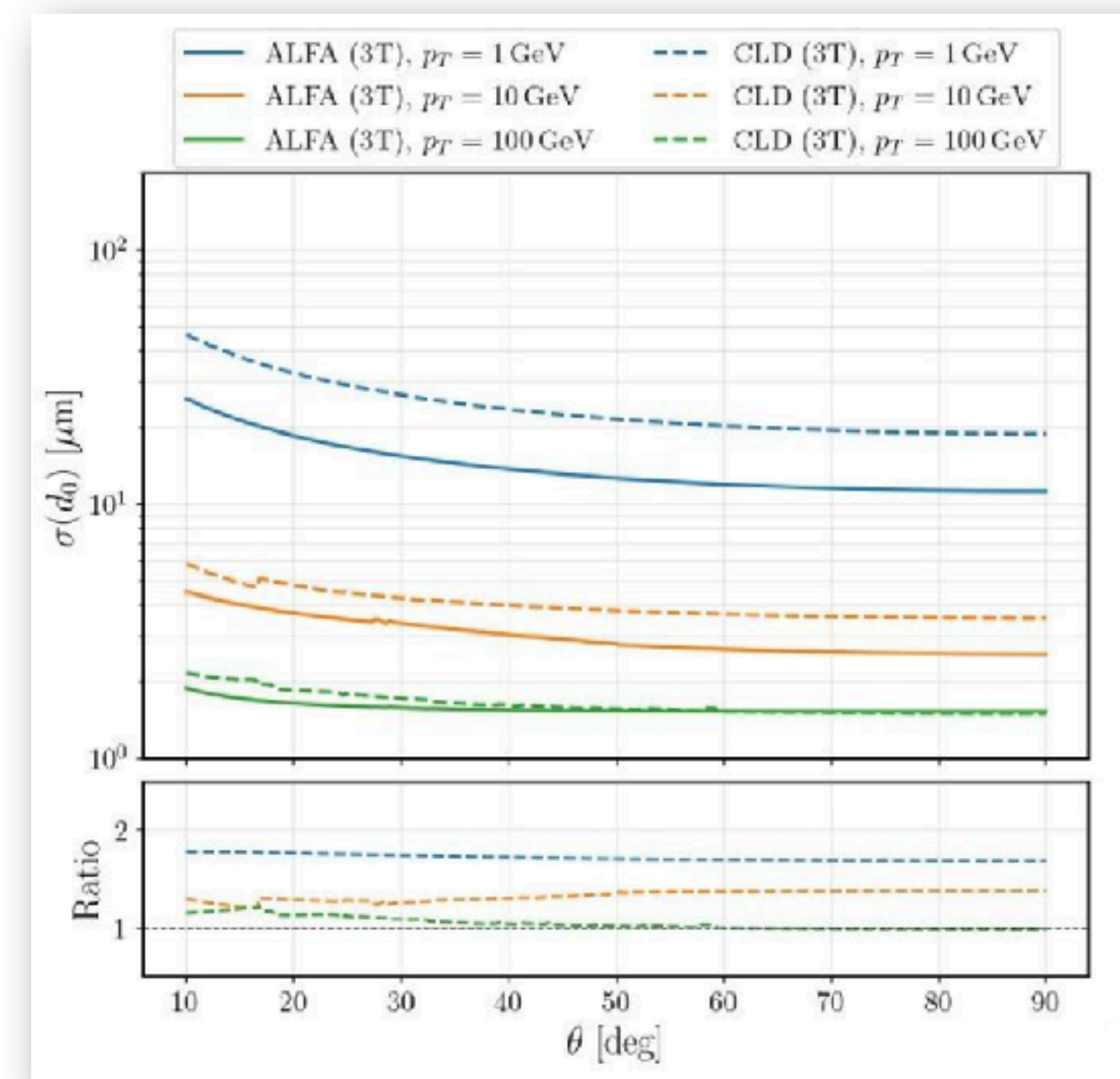
Implementing serial powering over a stave

- Two chains of 20+22 modules
- Two serial powering nodes per module
 - 4 MAPS per node



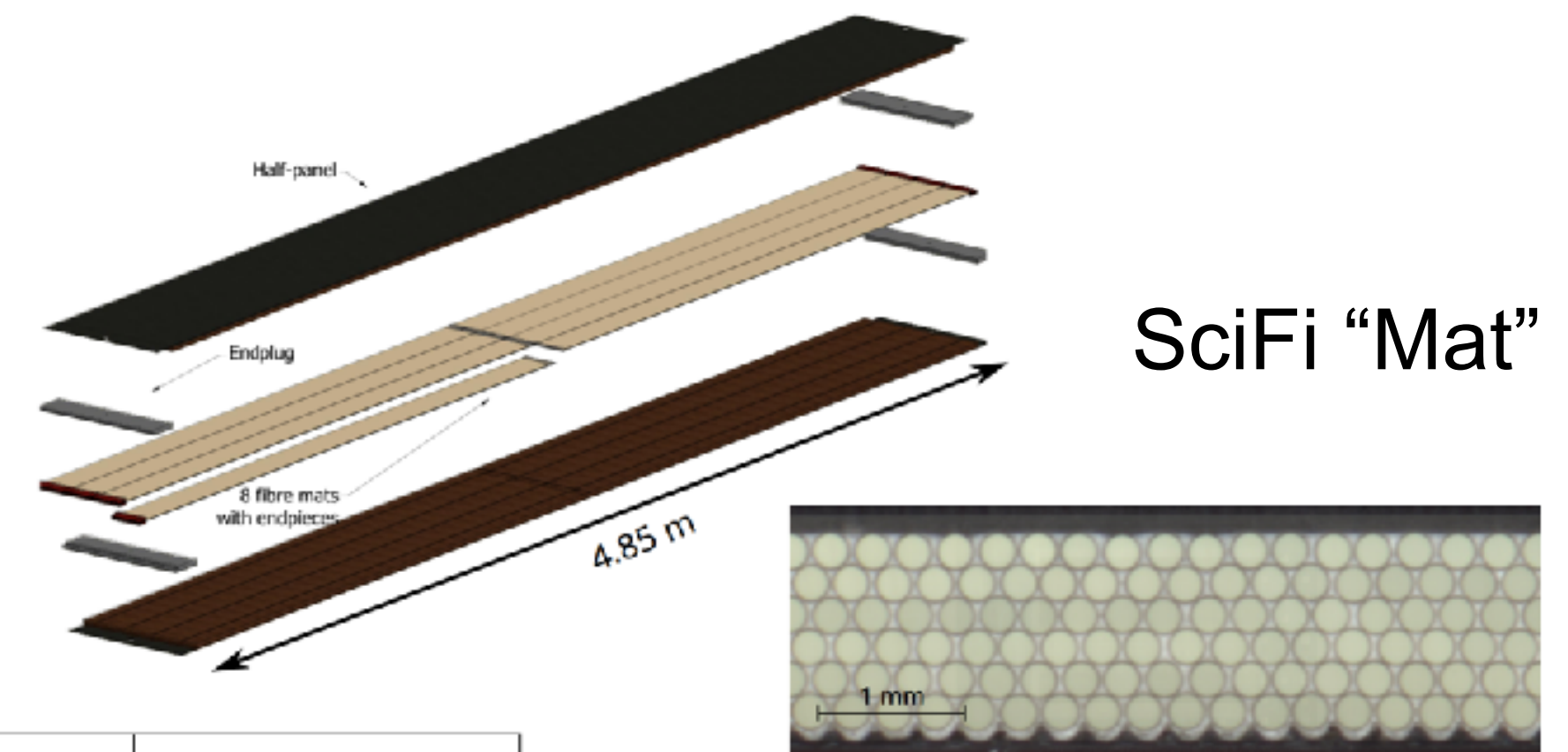
- Cooling pipes below the SLDO location to avoid hotspots
- Charge pump integrated on the periphery to bias the sensor (no extra bias line required)

Performance compared to CLD

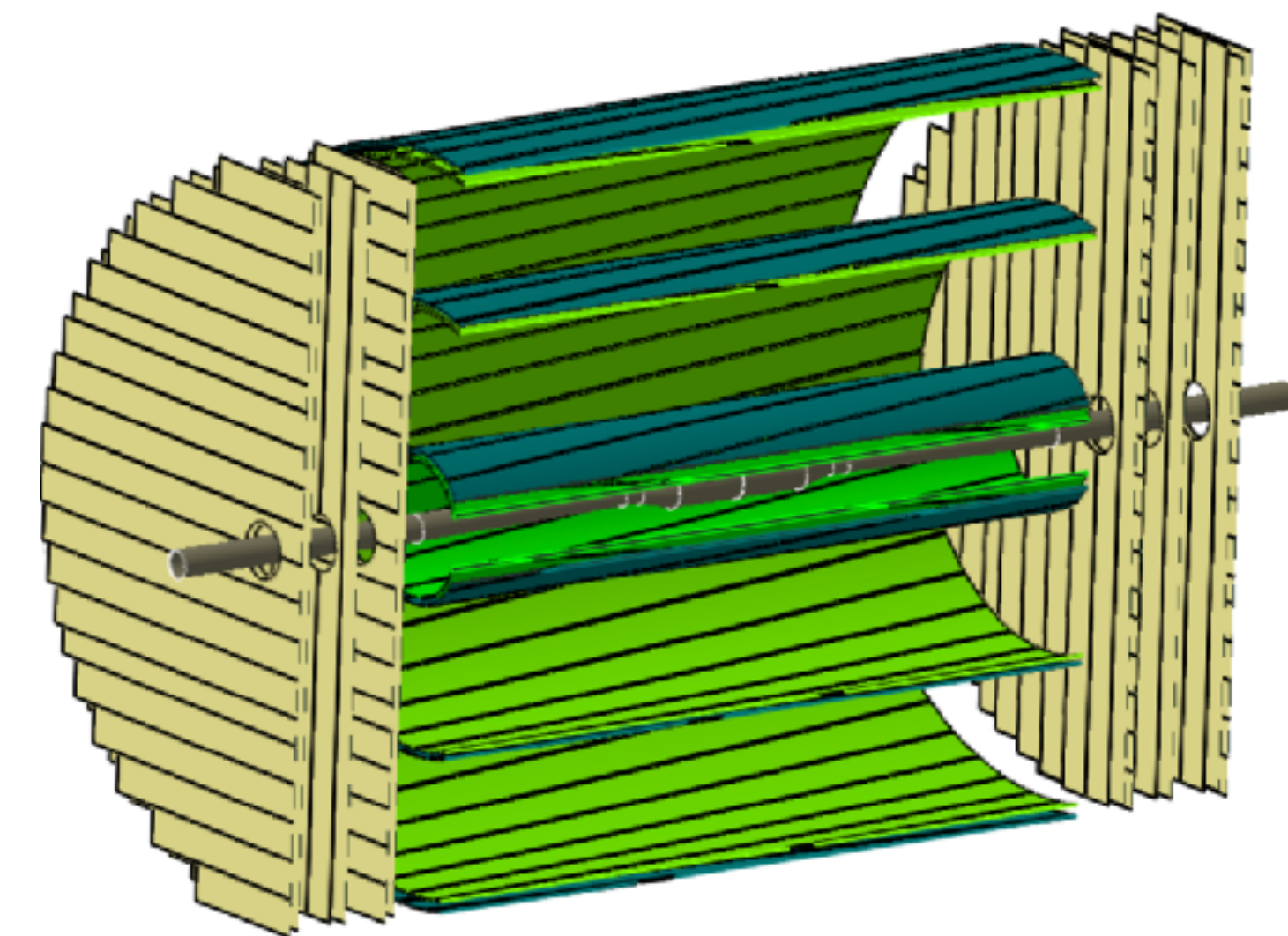


Scintillating Fiber Tracker (SciFi)

- A full-barrel **SciFi** tracker as the inner tracker is **proposed** for ALLEGRO
 - **Simulations** under IDEA geometry as well for **comparison**
- Development **driven** by the LHCb upgrade
- Main components are
 - **Scintillating fibers** for detection,
 - **SiPMs** as sensitive detectors to record the scintillation
- **Ongoing R&D** and simulations
 - SciFi stations with a **stereo** angle
 - **Dual-sided readout** to add timing and reduce background
 - New Fibers for **Radiation Hard(er)** SciFi



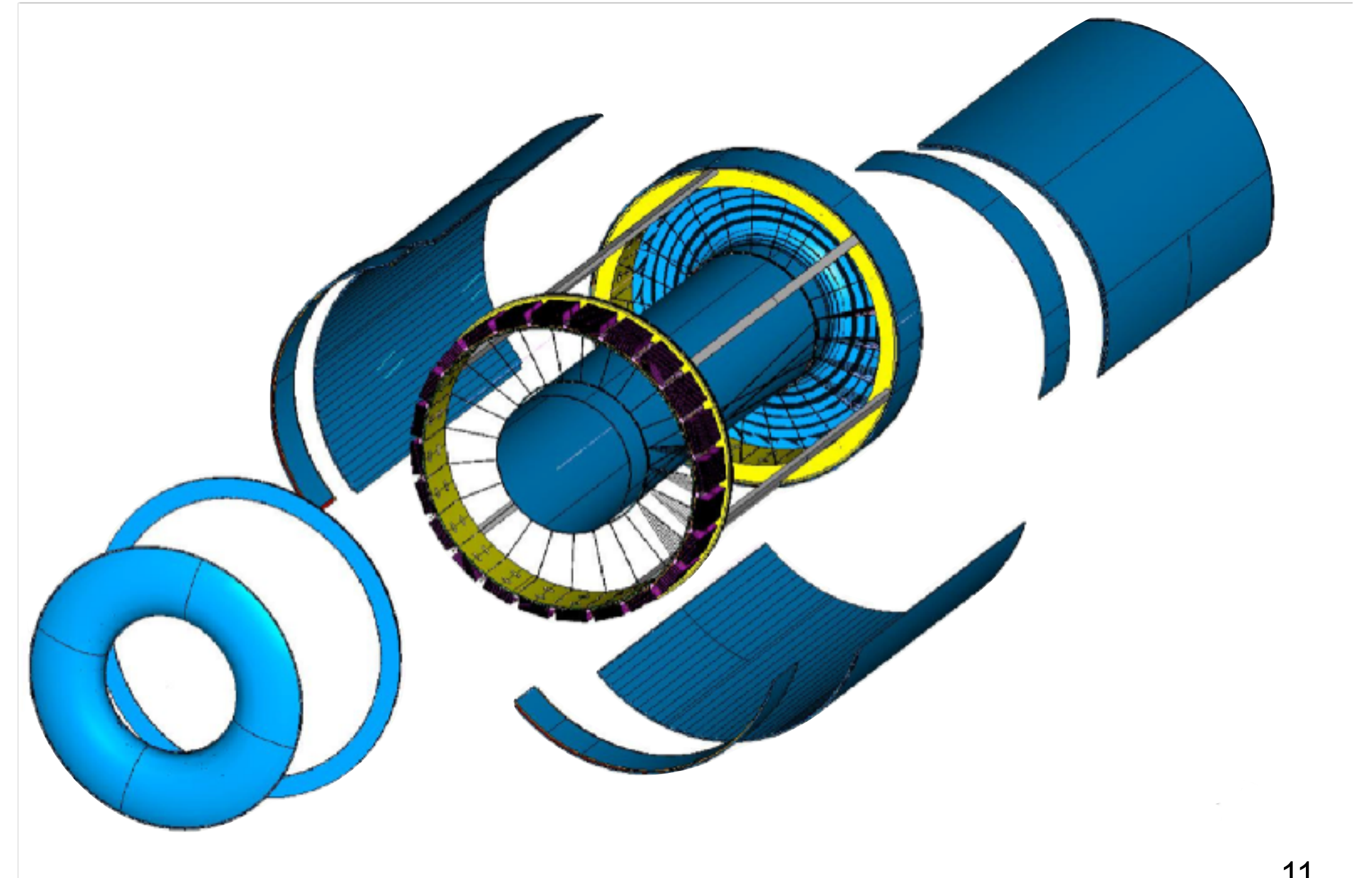
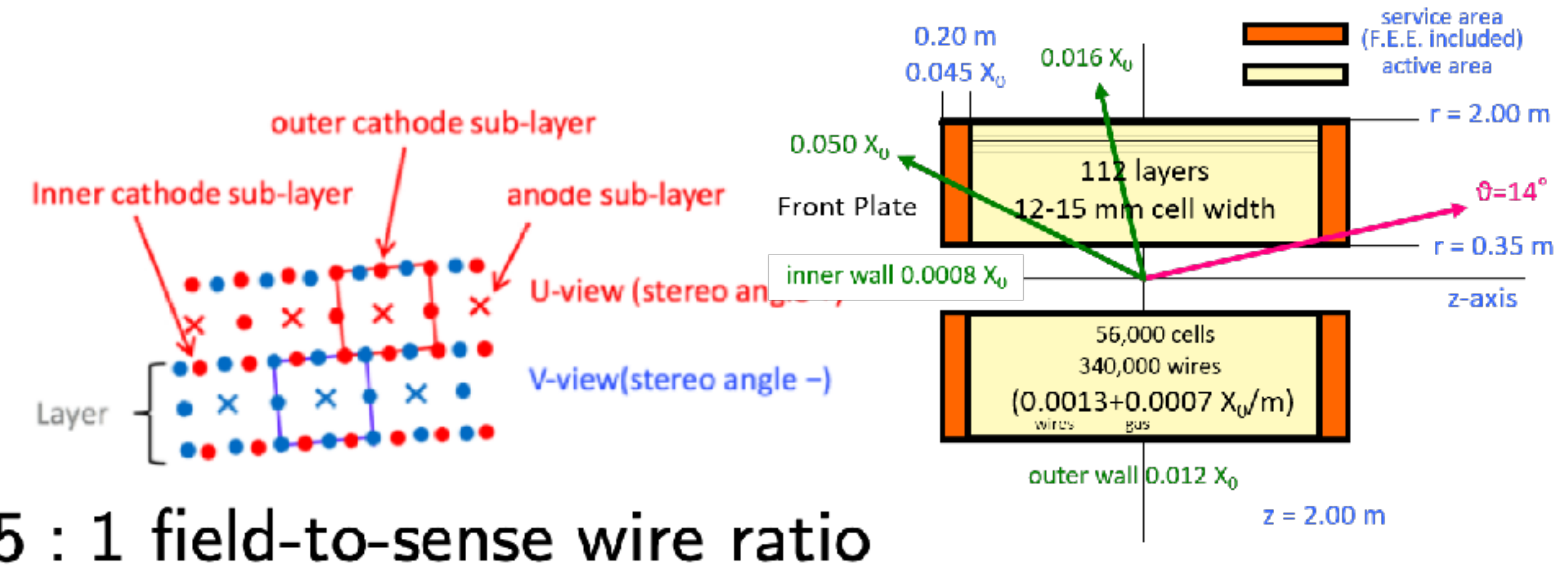
	For 6 Layer Mats with 10° stereo angle
Fiber Diameter	250µm
Mat Thickness	1.5mm
X Resolution Per Mat	30µm
Phi Resolution Per Station	21µm/R
Z Resolution @10 degrees Per Station stereo	300µm
Time Resolution Per Mat	300ps
Material Budget Per Station With Supports X/X ₀	1%
Material Budget Per Station Without Supports X/X ₀	0.41%



[Progress on Sci-fi tracker](#)

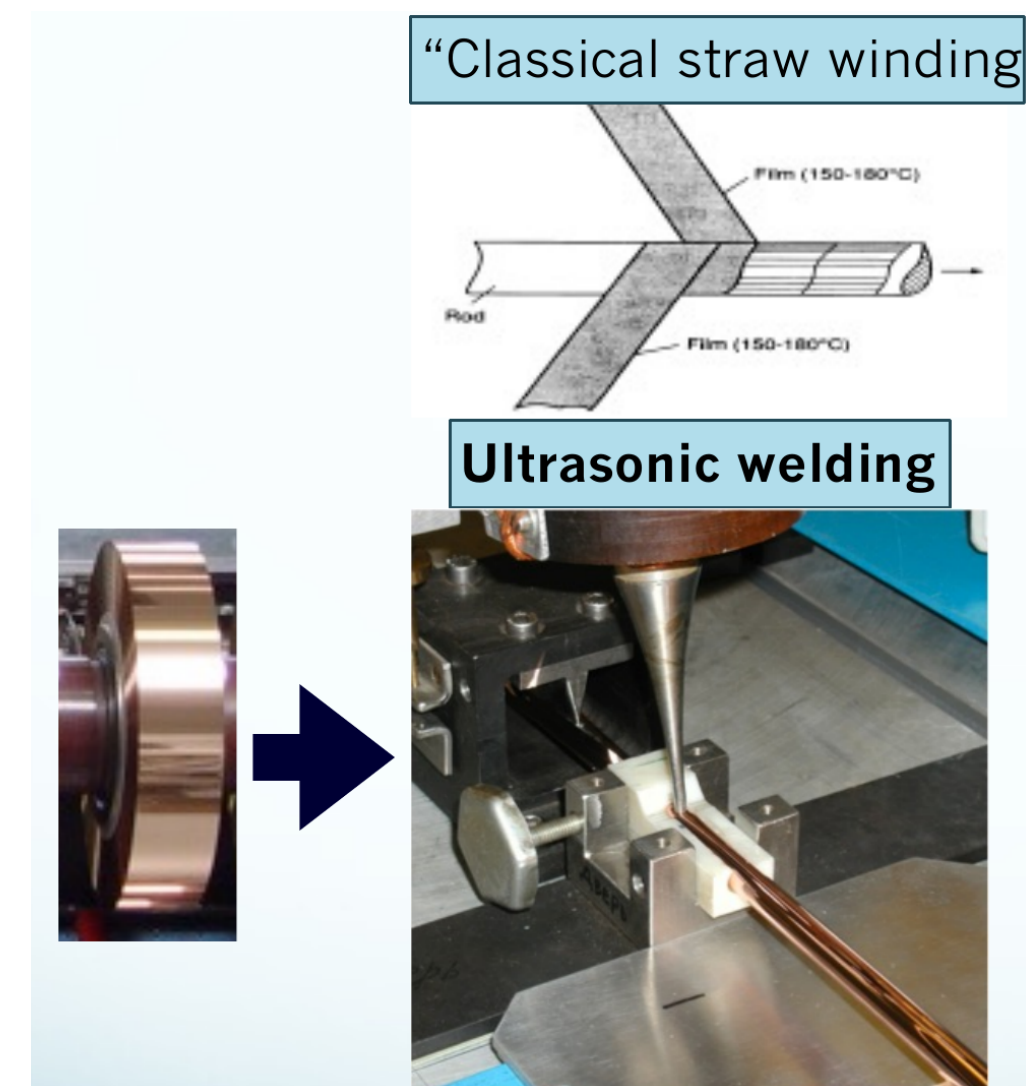
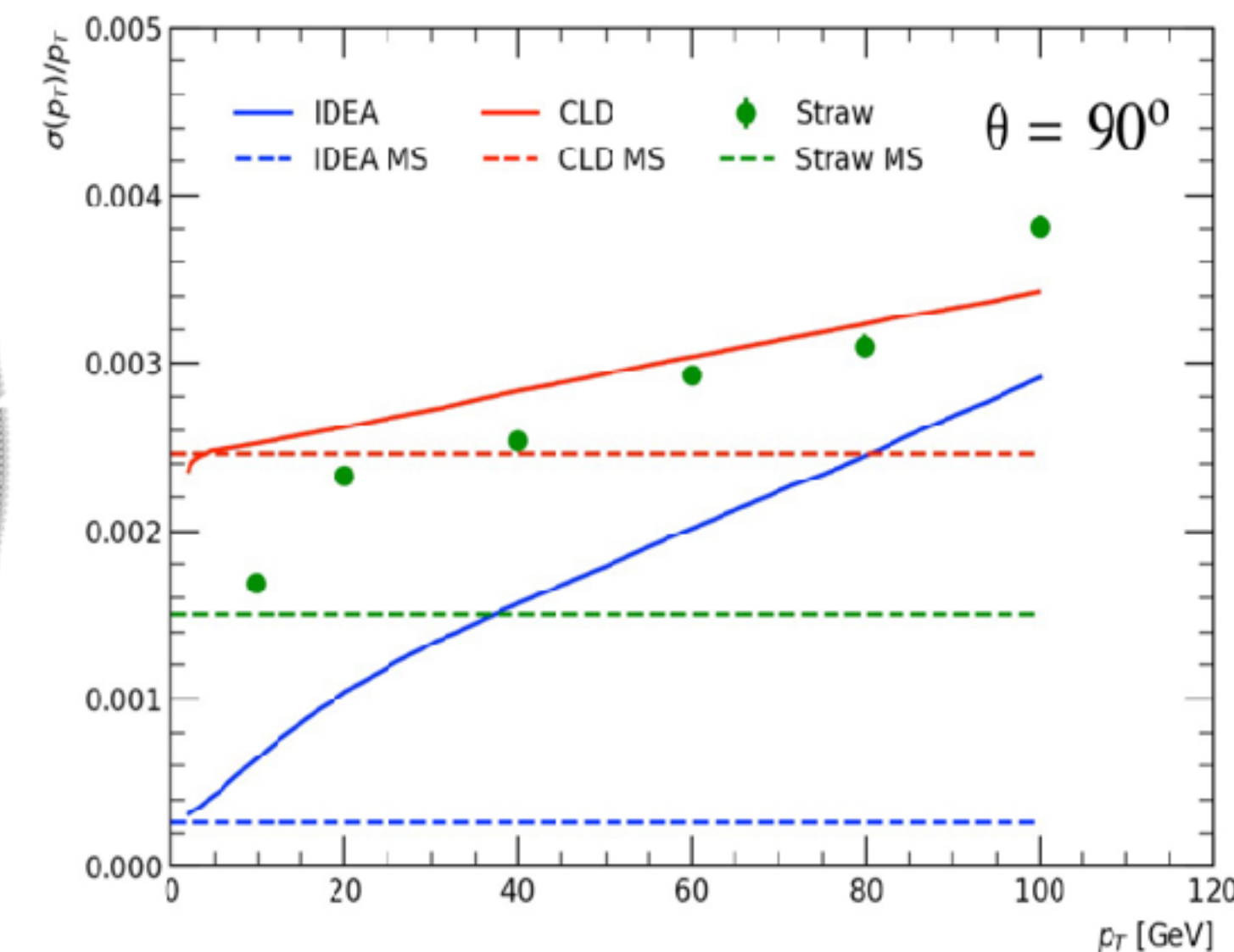
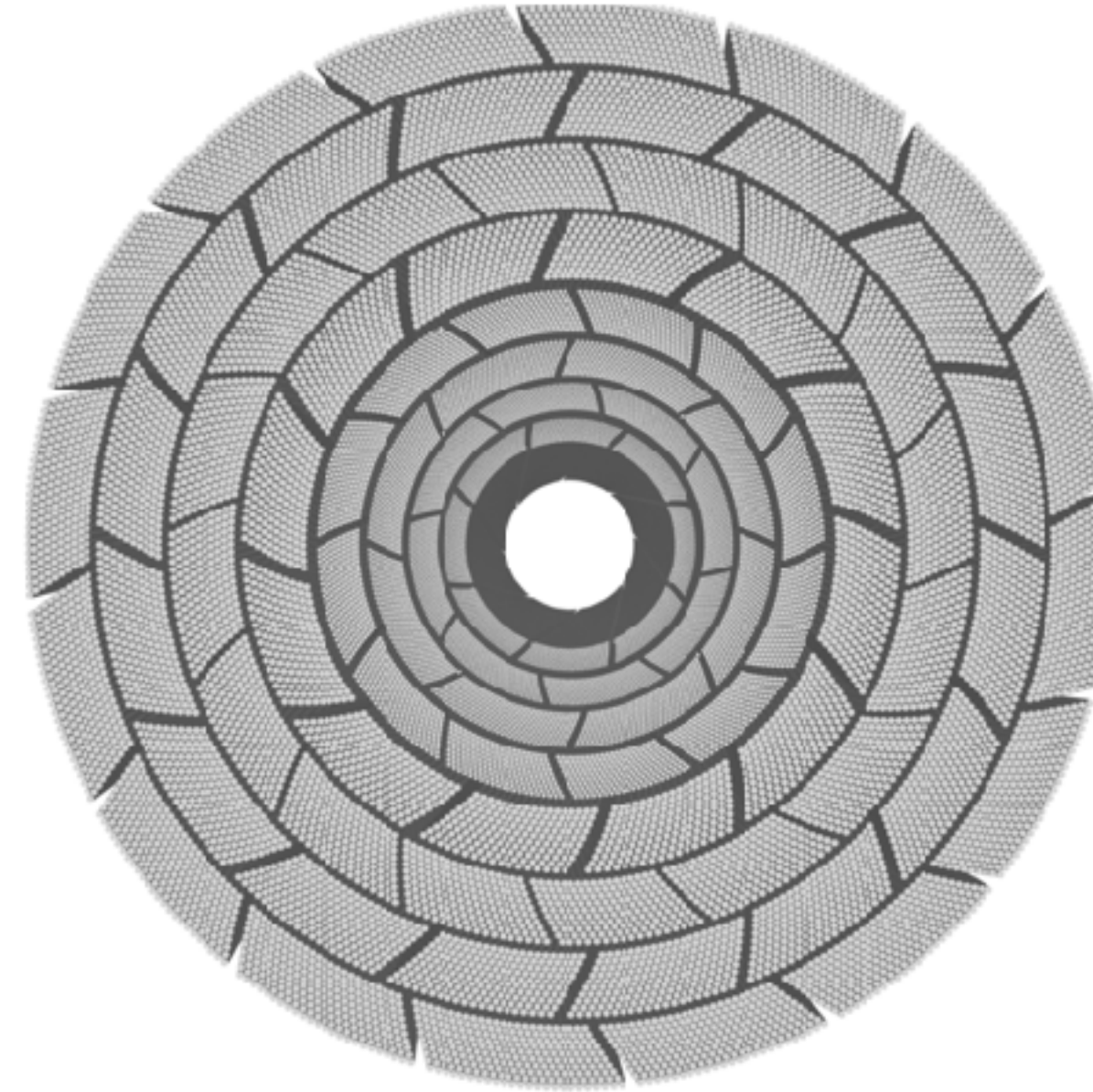
Drift Chamber

- Dimensions: **4 m long** (active volume), **35cm to 2m radius**
- **Low material budget**
 - Barrel: $\sim 1.6\% X_0$
 - Forward directions: $\sim 5\% X_0$
- Stereo layout with **~ 112 layers** ranging from 50 to 250 mrad
- Operating gas mixture: **He + 10% iC₄H₁₀**
 - Sense (anode): 20 μ m W(Au) $\rightarrow$ 56448 total
 - Field (cathode): 40 μ m Al(Ag) $\rightarrow$ 285504 total
 - Guard (cathode): 50 μ m Al(Ag) $\rightarrow$ 2016 total
- Active volume: 56448 almost squared drift cells (12 $\div$ 14.5 mm), with a 5 : 1 field-to-sense wire ratio for simpler time-to-distance relations
- Overall **expected resolution**: $\sigma_{xy} \sim 100 \mu\text{m}$ and $\sigma_z \sim 1 \text{ mm}$
- **Large scale prototype** is pursued to test the **mechanical** and **electrostatic** stability of the detector
- Challenges:
 - Endplates to support 5 tons due to tension of wires
 - Scaling up to 350k wires not trivial
 - Stable operation

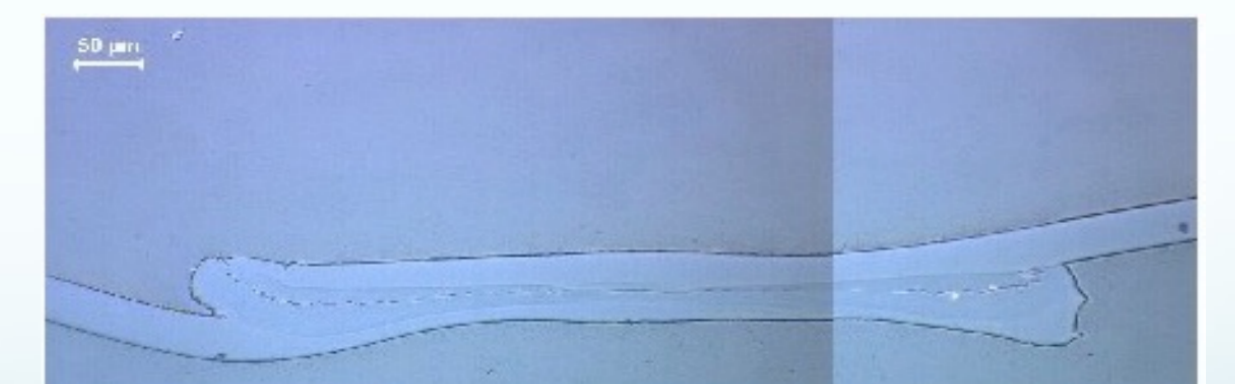
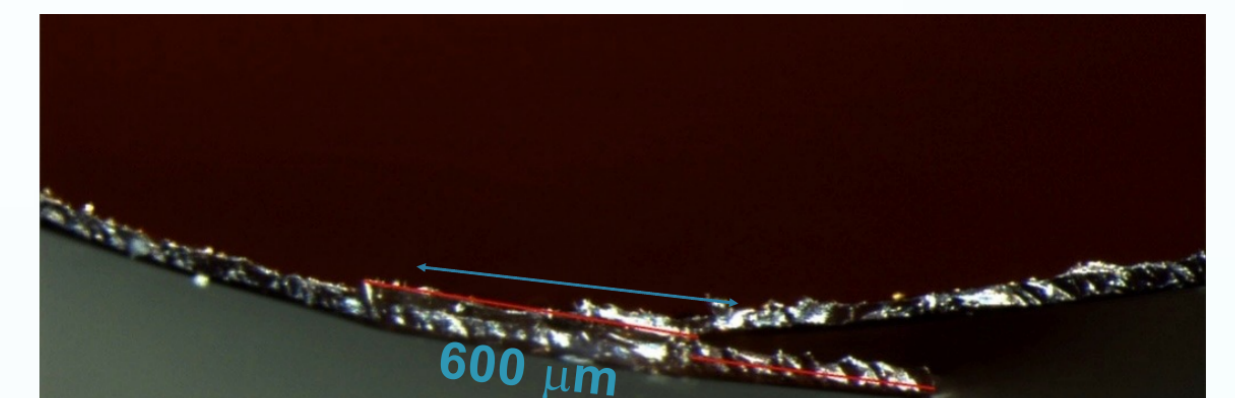


Straw tracker

- **Straw tracker** R&D is pursued
 - Implemented the **geometry** inside the FCC-ee **simulation** framework for ALLEGRO
- **Similar characteristics to drift tubes** but smaller radii $\sim 5\text{mm}$ and lower material budget
 - Targeting **Al + Mylar** ($\sim 15\mu\text{m}$ mylar, $0.05\mu\text{m}$ Al) and $25\mu\text{m}$ **tungsten** wires $\rightarrow \sim 1.2\%$ X_0 (structural support not included)
 - 5m ultrasonic **welding** techniques
- Building several **prototypes**, based on **NA62** experiment
- **Challenges:**
 - Increased Material especially when including supports
 - Stereo layout is not trivial
 - Operation with He based gases not trivial due to leaks

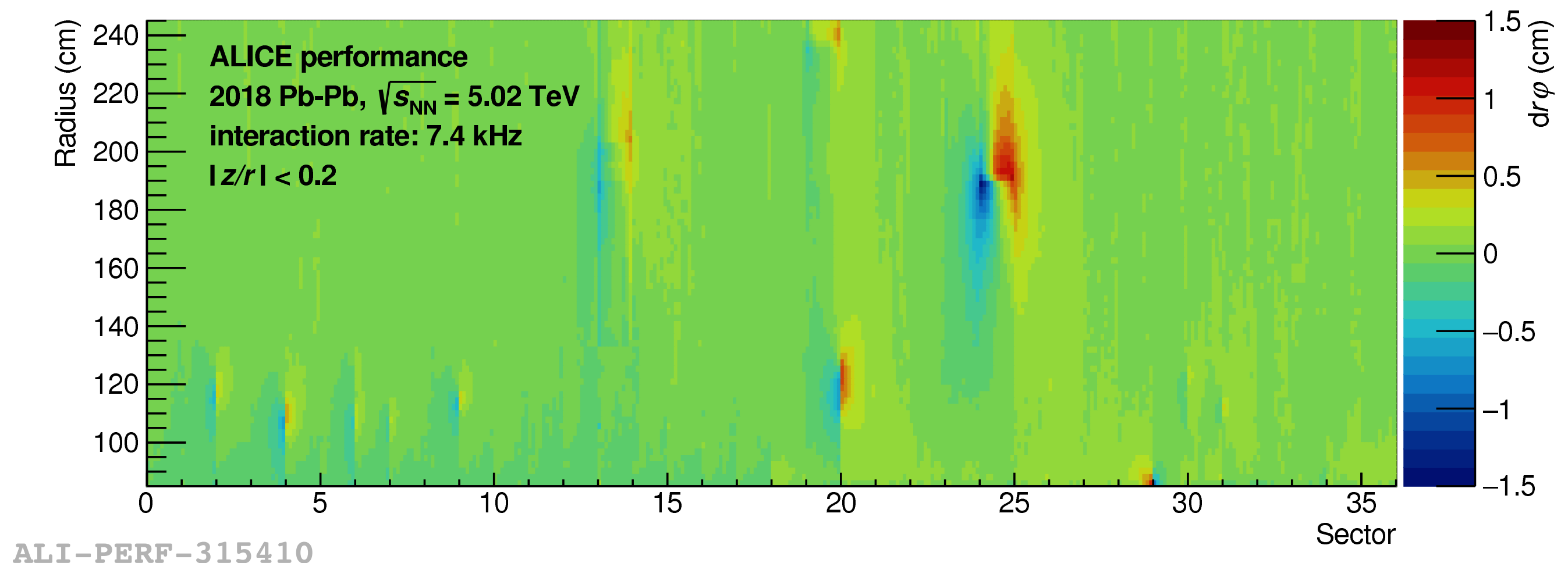
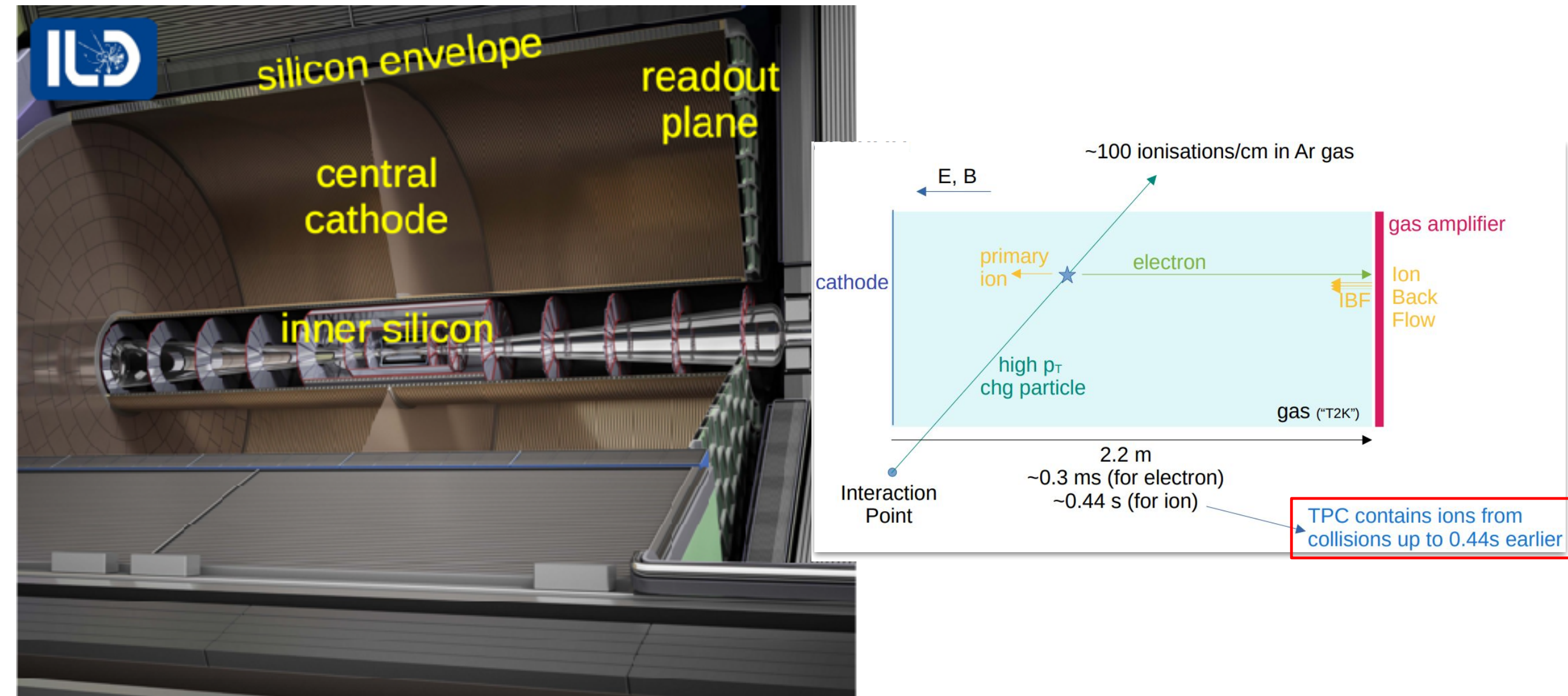


Microscope pictures of a straw cross-section for quality control of the weld



Time Projection Chamber (TPC)

- **TPC** as part of ILD's hybrid tracking system
- Readout plane: gas **amplification** GEM, micromegas, readout by **pads/pixels**
 - **GridPix** based on Timepix3 with $55 \times 55 \mu\text{m}^2$ **pixels** can detect one primary electron
- $\sim 3\%$ X_0 in barrel, higher in endcap
- **Operation challenges** at Z-pole due to space charge **distortions** and SR **backgrounds**
 - Gas choices still to be evaluated
 - **Backgrounds** are a concern for stable operation
 - Ways of reducing ion **backflow**, handle **distortions** is needed



Particle Identification (PID): Physics Drivers

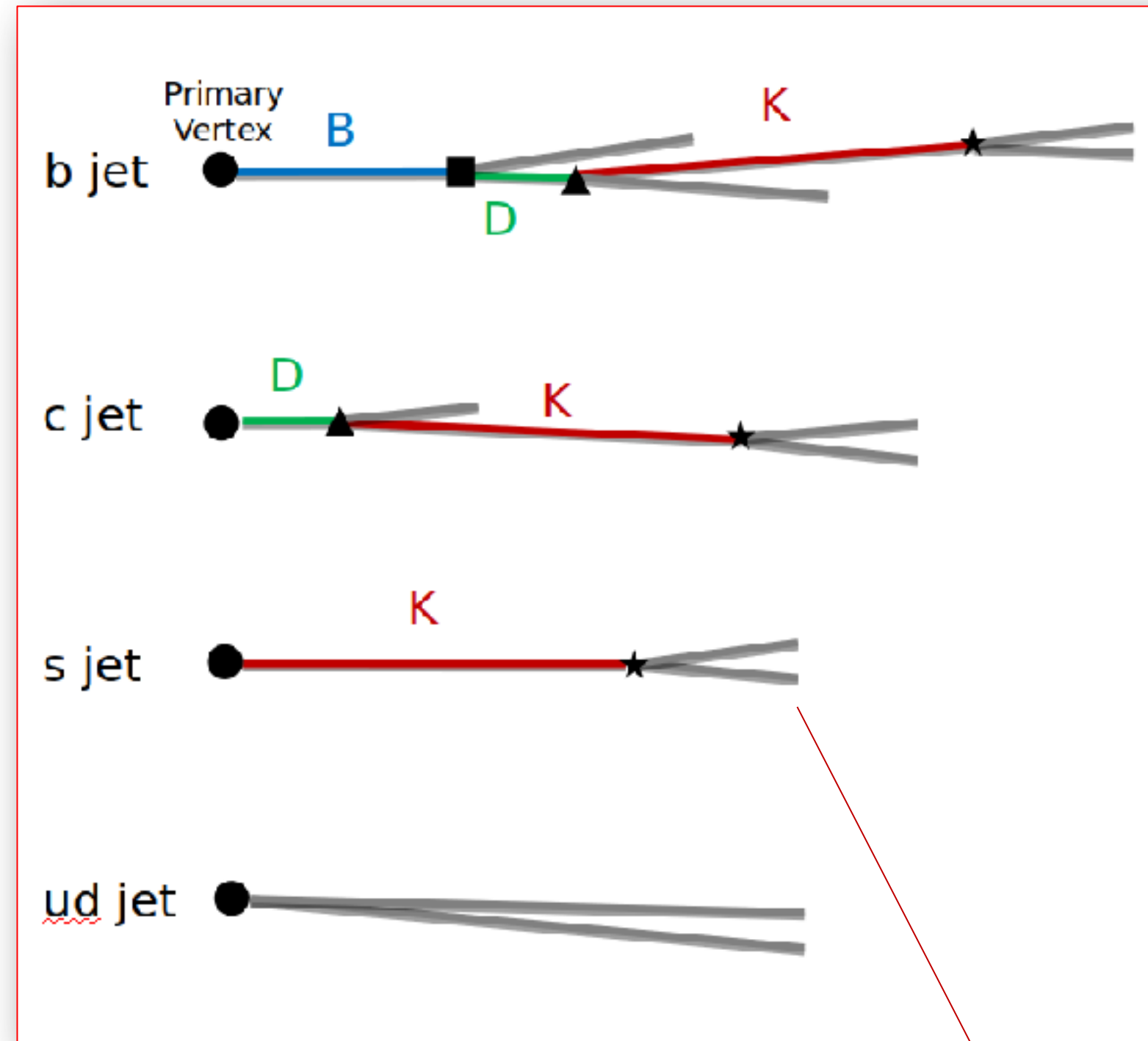
Particle identification: key feature to enhance flavour tagging and **distinguish strange-quark jets from other light jets**

Strange quarks as a probe for new physics at FCC-ee

- Probe Higgs light Yukawa couplings
- Study strange-quark fragmentation functions
- $Z \rightarrow s\bar{s}$
- Flavour physics

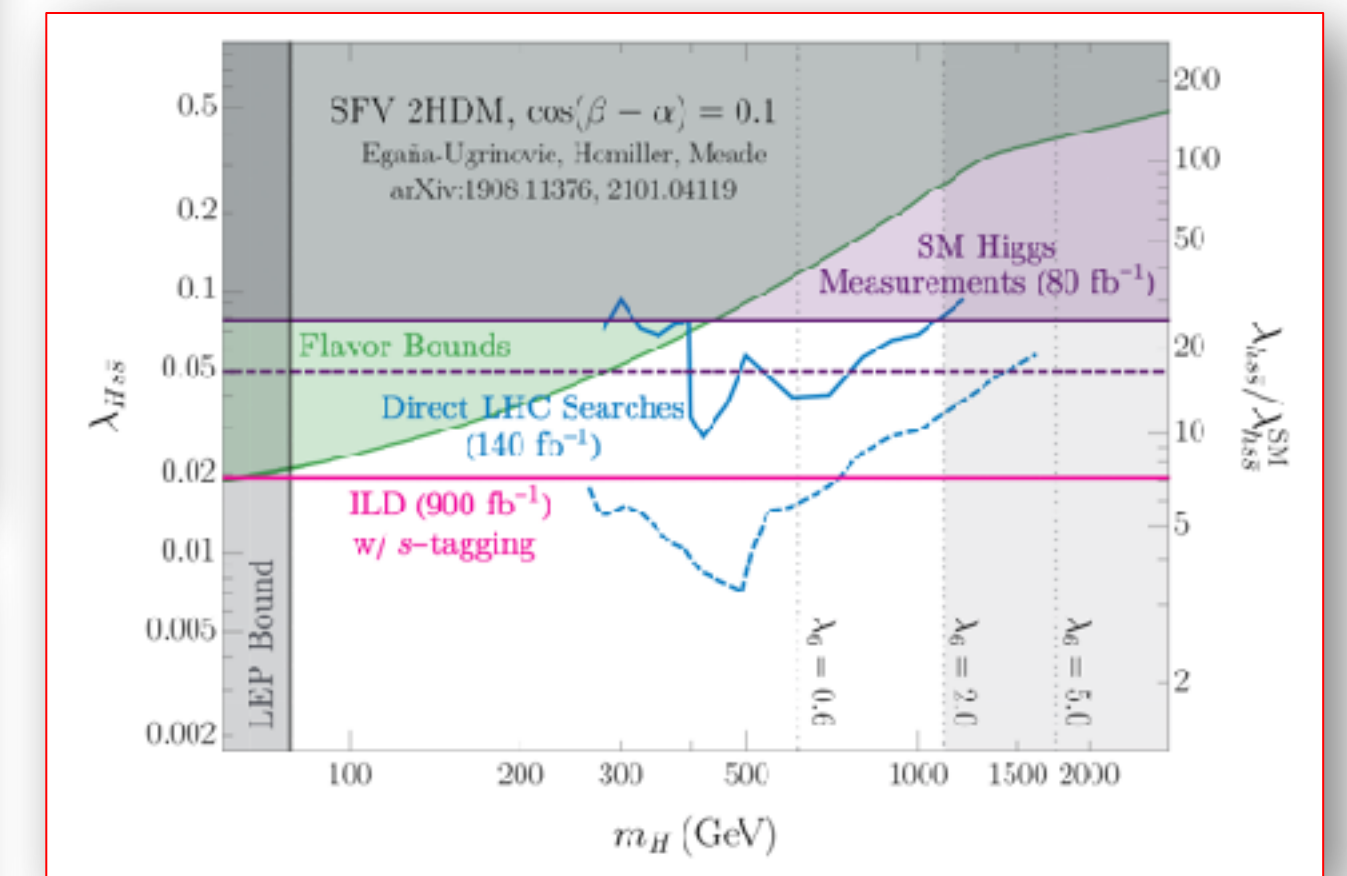
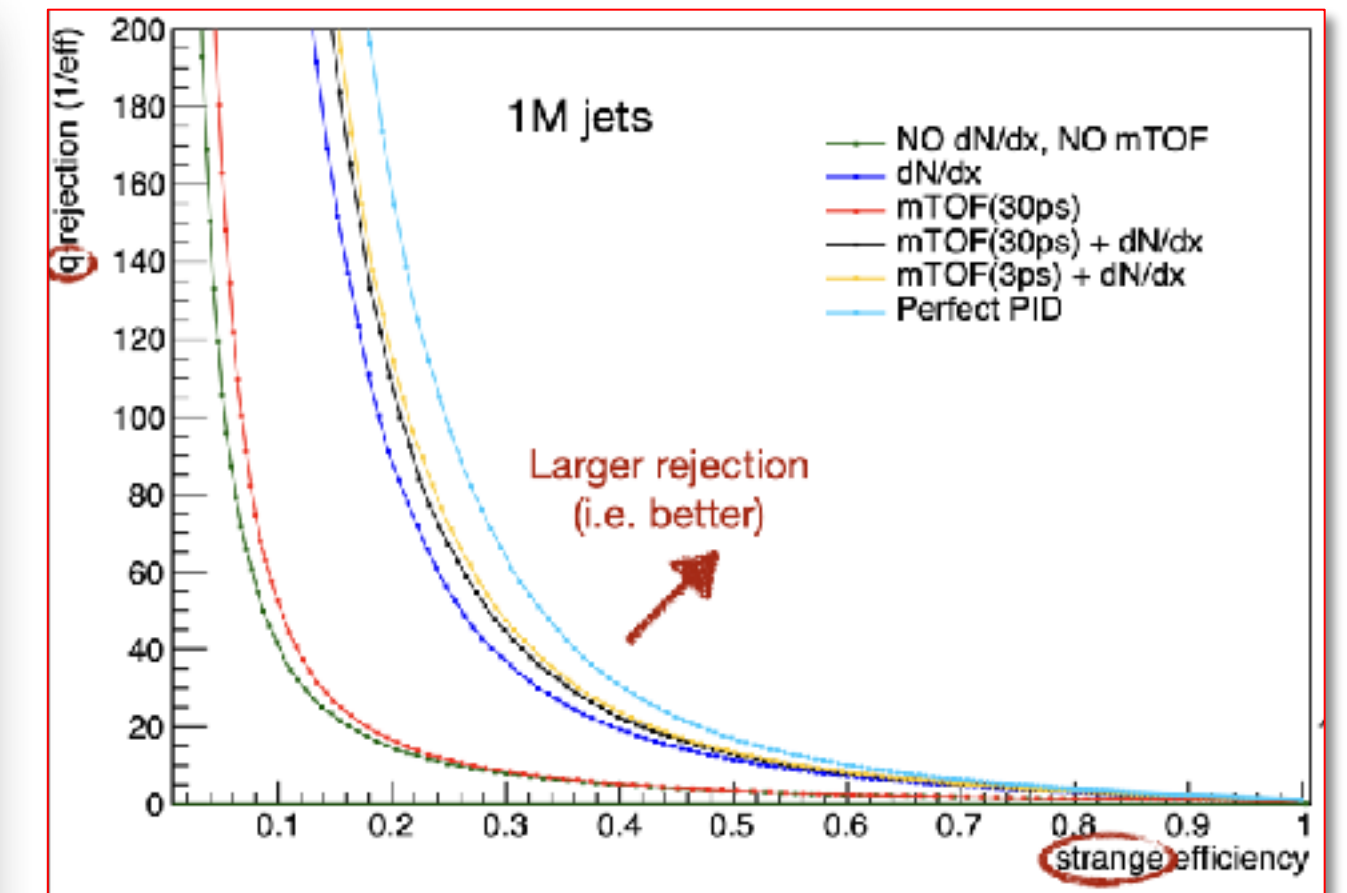
PID crucial for precision Higgs physics

- BSM models predict deviations in Higgs couplings at only the percent or sub-percent level
- The sensitivity of these measurements depends critically on identifying heavy-flavour final states



Strange Hadron reconstruction

- $K^\pm$ [PID]
- $K_S^0 \rightarrow \pi^+\pi^-$ [Vertex] (BF ~69.2%)
- $\Lambda^0 \rightarrow p\pi^-$ [Vertex] (BF ~64%)
- K_L^0 [Particle Flow]



precision measurements probe new physics well beyond the direct reach of the LHC

PID: Technologies

Hadrons identified by their mass, in turn determined by combining momentum and velocity.
Momentum inferred from radius of curvature in magnetic field, need to measure velocity.

Various technologies allow to identify hadrons in different momentum ranges

3 σ separation for π/K

dE/dx in silicon

≈ 5 GeV

Time-of-flight via
Fast Timing in
silicon envelopes
or calorimetry

≈ 5 GeV

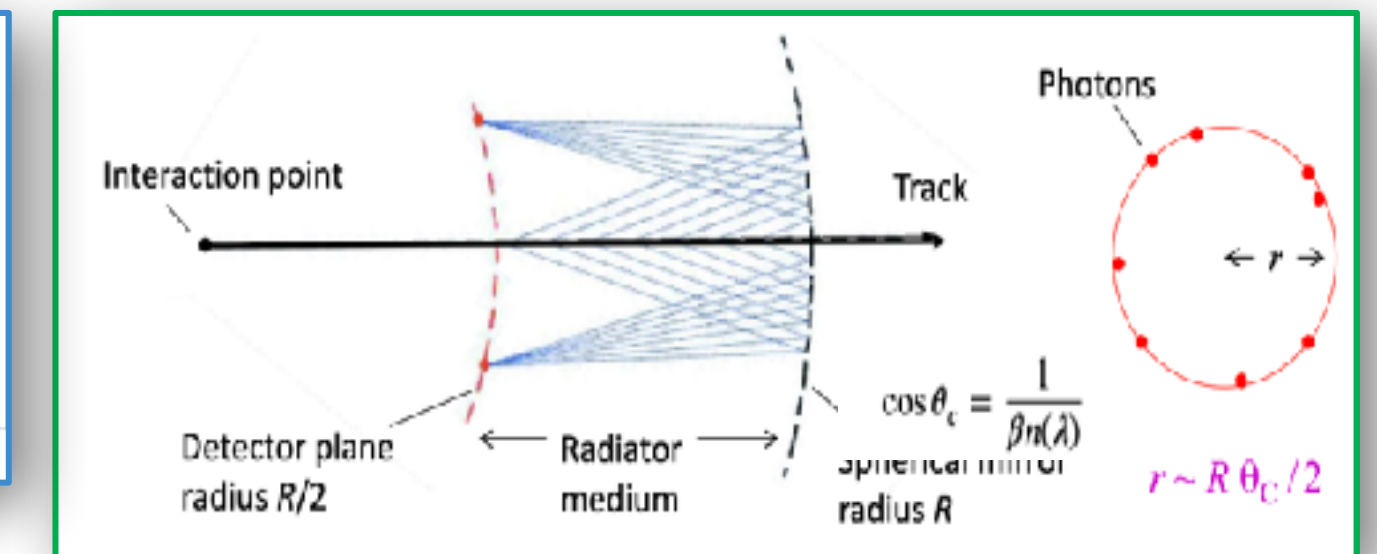
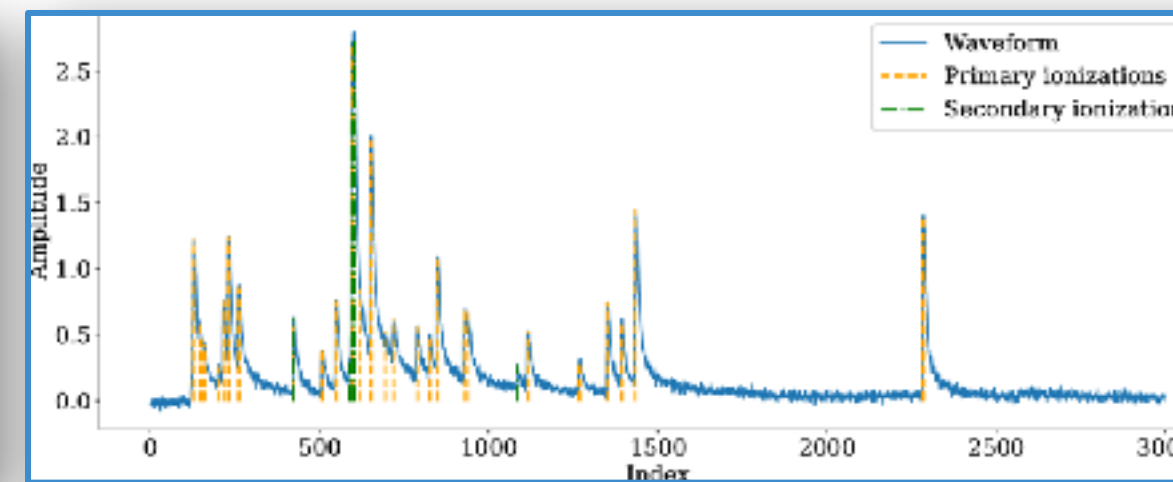
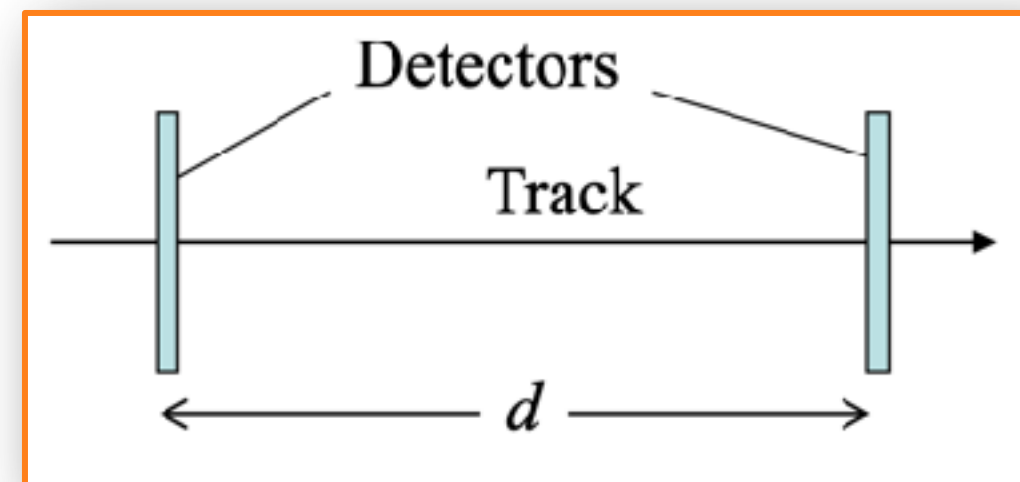
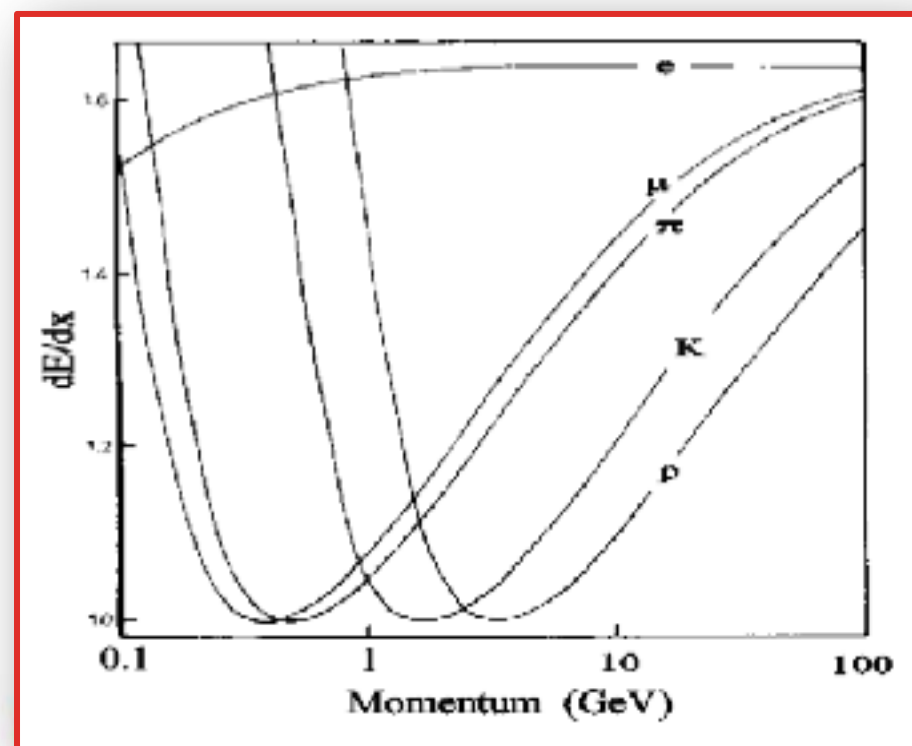
dE/dx or dN/dx in
Time Projection or
Drift Chambers

≈ 30 GeV
(scales with volume)

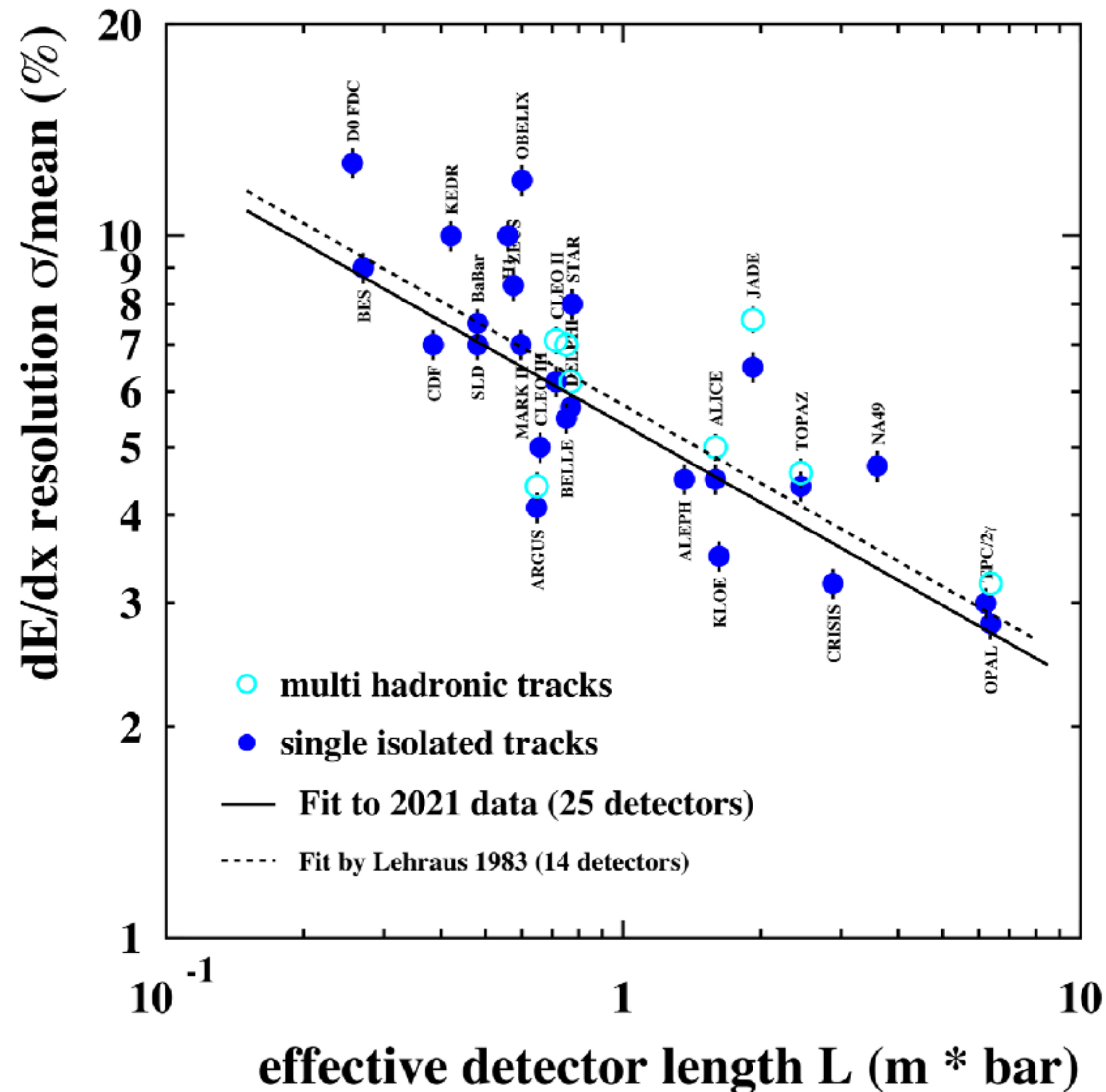
**Ring Imaging
Cherenkov
Detectors**

O(tens of GeV)

Momentum



PID: The dE/dx for gaseous detectors (trackers)



- dE/dx resolution achieved in large detectors, mainly at e^+e^- colliders, at some hadron colliders and fixed target experiments
- Truncated mean mostly used → empirically set
- Fit by Lehraus 1983 (14 detectors)
 - ➔ $dE/dx \text{ res.} = 5.7 \cdot L^{-0.37}(\%)$
- Fit in 2021 (25 detectors):
 - ➔ $dE/dx \text{ res.} = 5.4 \cdot L^{-0.37}(\%)$
- 5.4% typical dE/dx resolution for 1 m track length
 - ➔ no significant change to 1983

Performance of present generation of detectors as predicted ~40 years ago

PID: The dN_{cl}/dx technique

- A.H. Walenta research in 1980s →

It was experimentally confirmed that the relativistic rise is mainly due to the increased number of the primary clusters, rather than due to the energy of clusters.

- Technique is to **define ionization clusters** from the signal formation **distribution** within the track footprint
 - Ordered in time electrons (average time separation within clusters)
 - Electrons per cluster (primary & secondary ionizations)
 - Number of clusters per track
- Further improvement by adding the cluster timing (spatial res., timestamp etc)

dE/dx

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 0.41 \cdot n^{-0.46} (x[\text{cm}] \cdot P[\text{atm}])^{-0.32}$$

trunc. mean (80%), n=112, 2m at 1atm (Walenta-Allison/Cobb, param.)

$$\sigma \approx 4.0 \%$$

IDEA DCH →

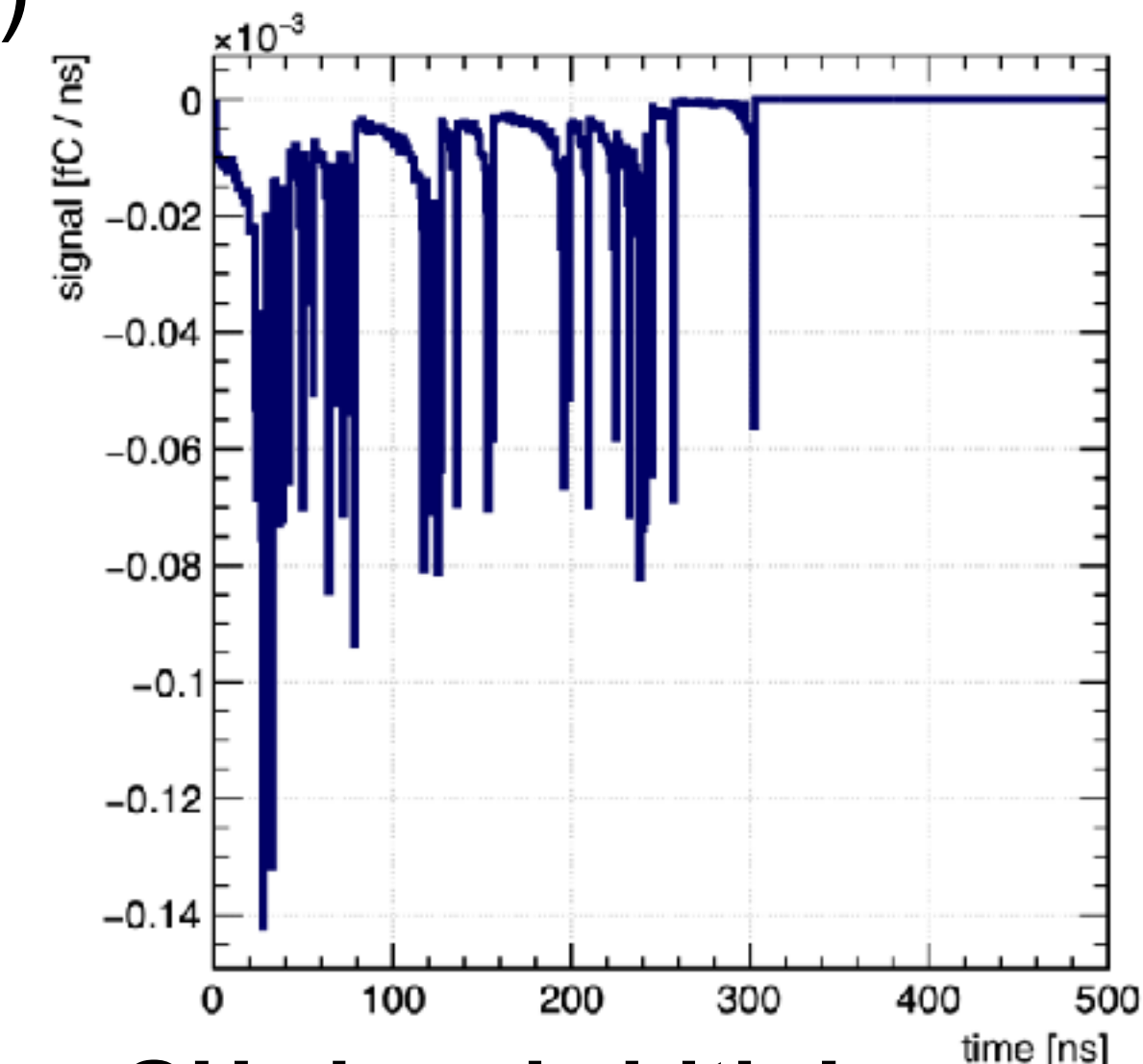
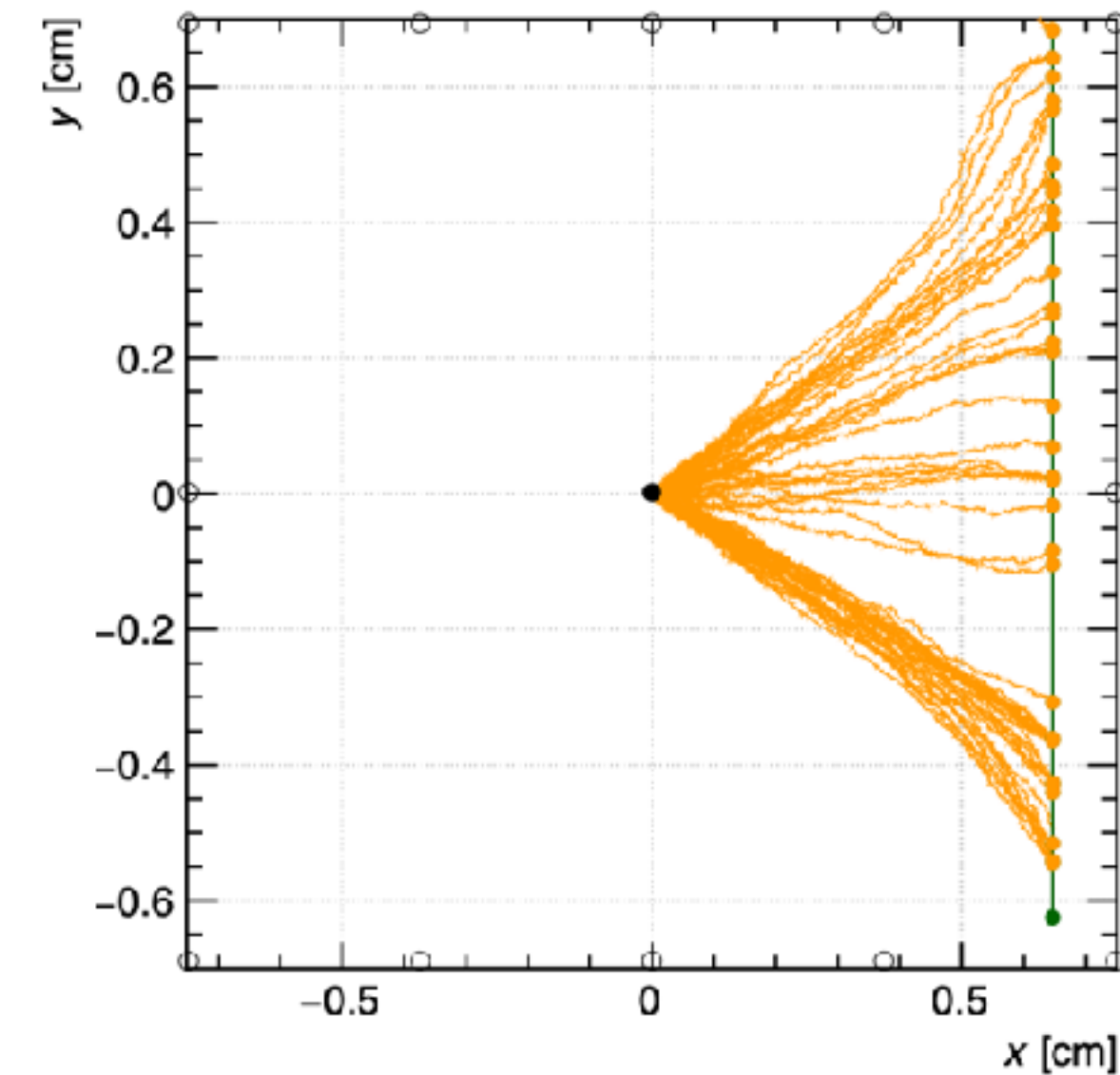
dN_{cl}/dx

$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = (\delta_{cl} \cdot L_{\text{track}})^{-1/2} = N_{cl}^{-1/2}$$

$\delta_{cl} = 12.5/\text{cm}$ for He+10% $i\text{C}_4\text{H}_{10}$ and 2m (Poisson distr.)

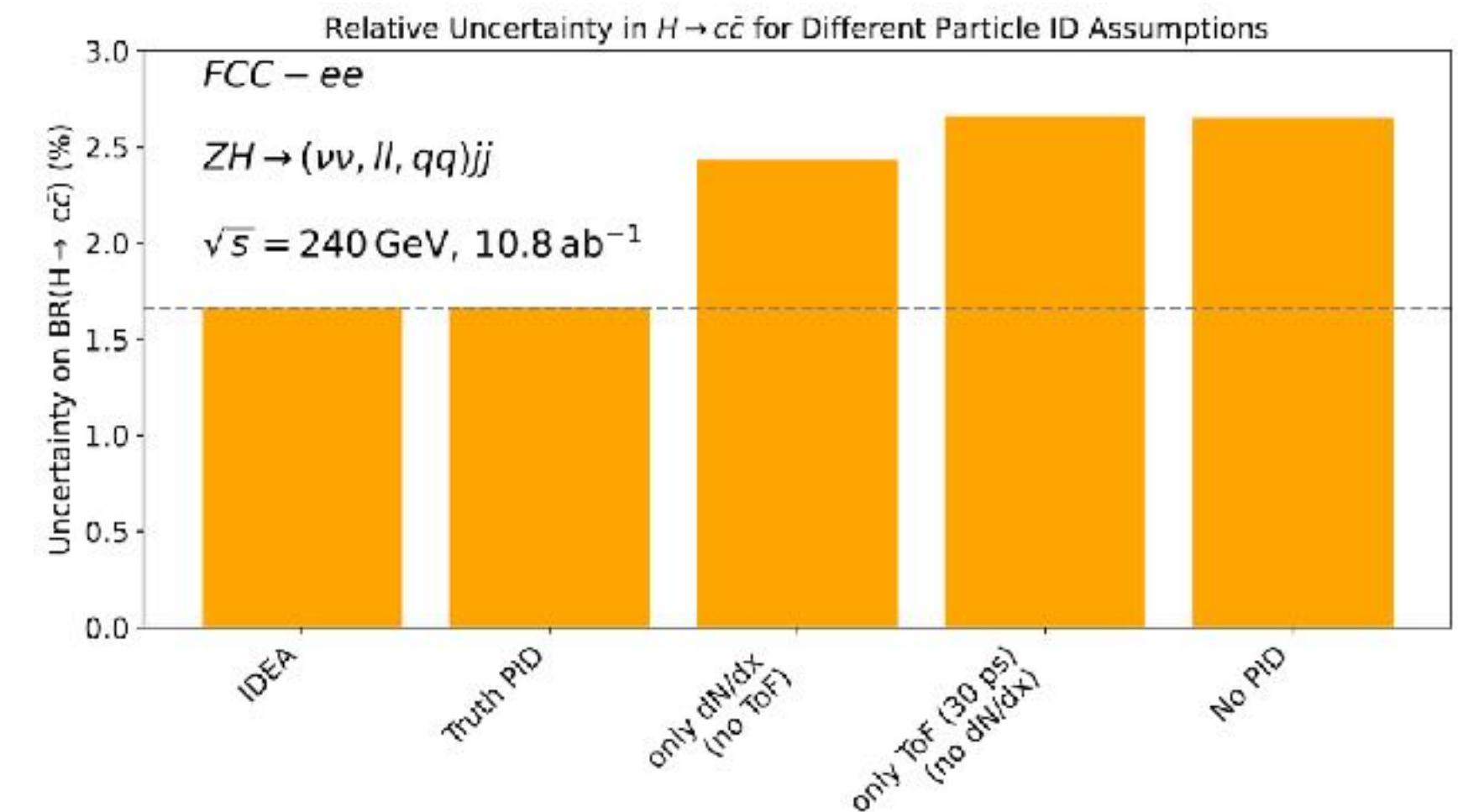
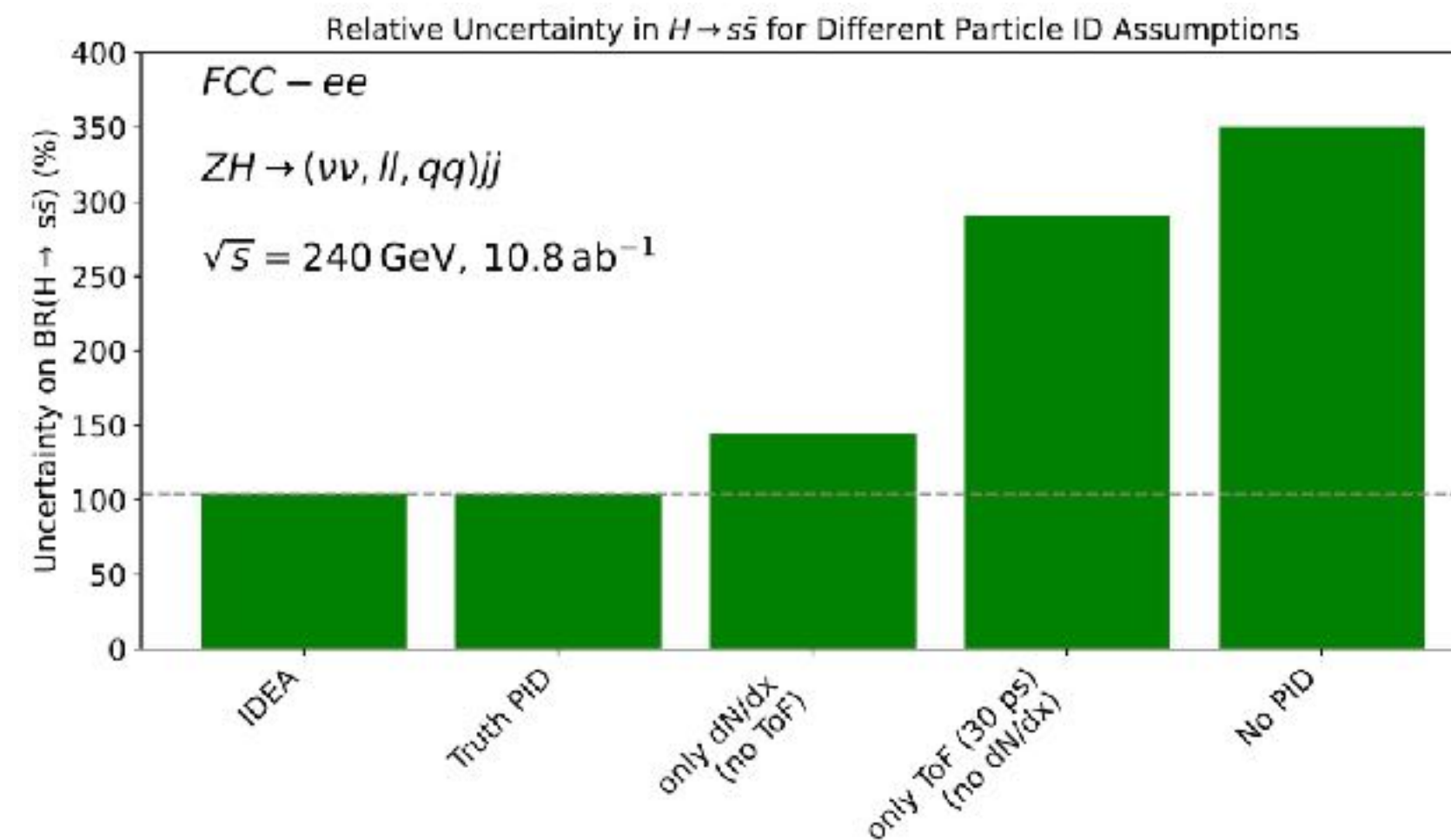
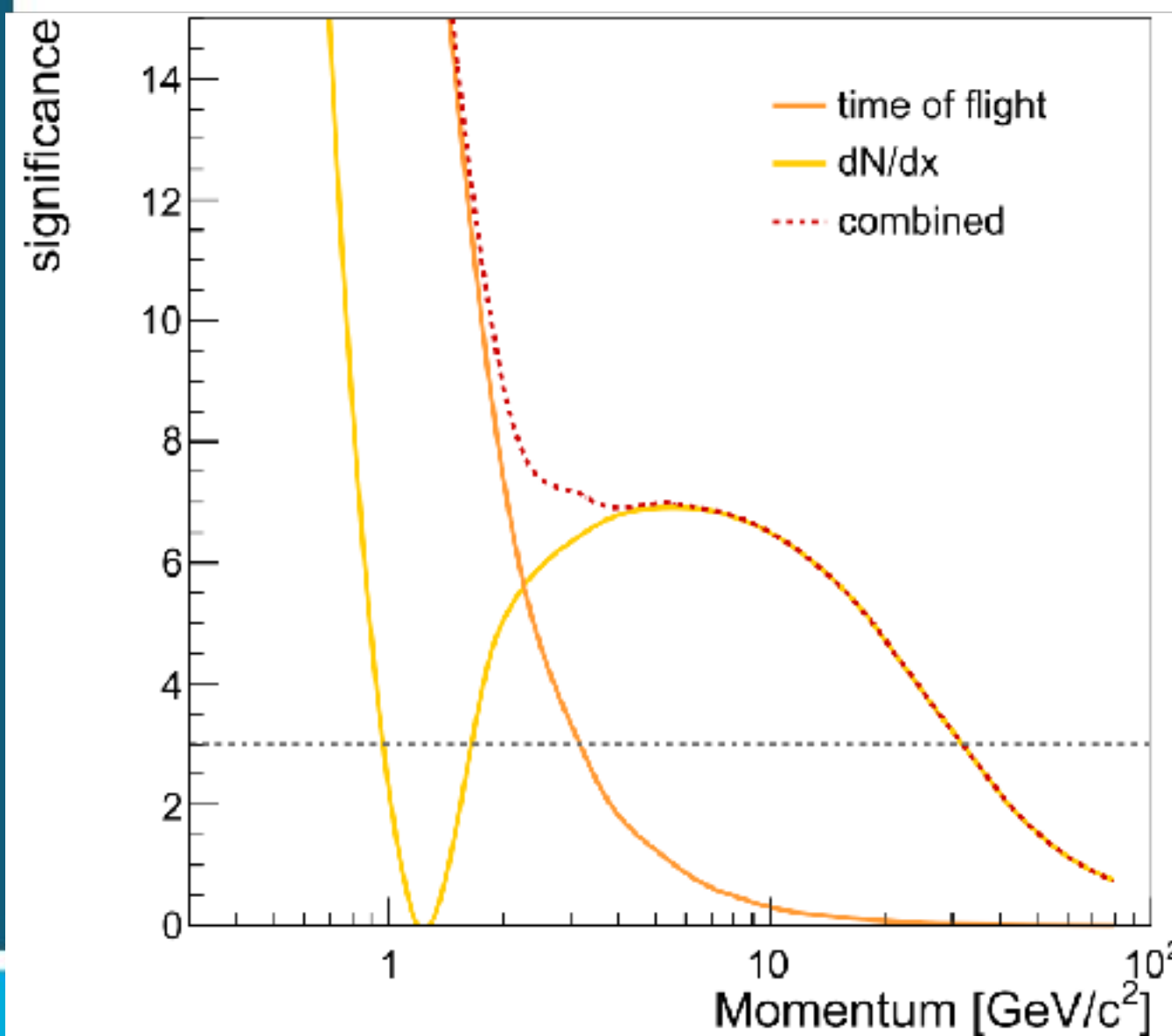
$$\sigma \approx 2.0 \%$$

Drift cell simulation
Garfield



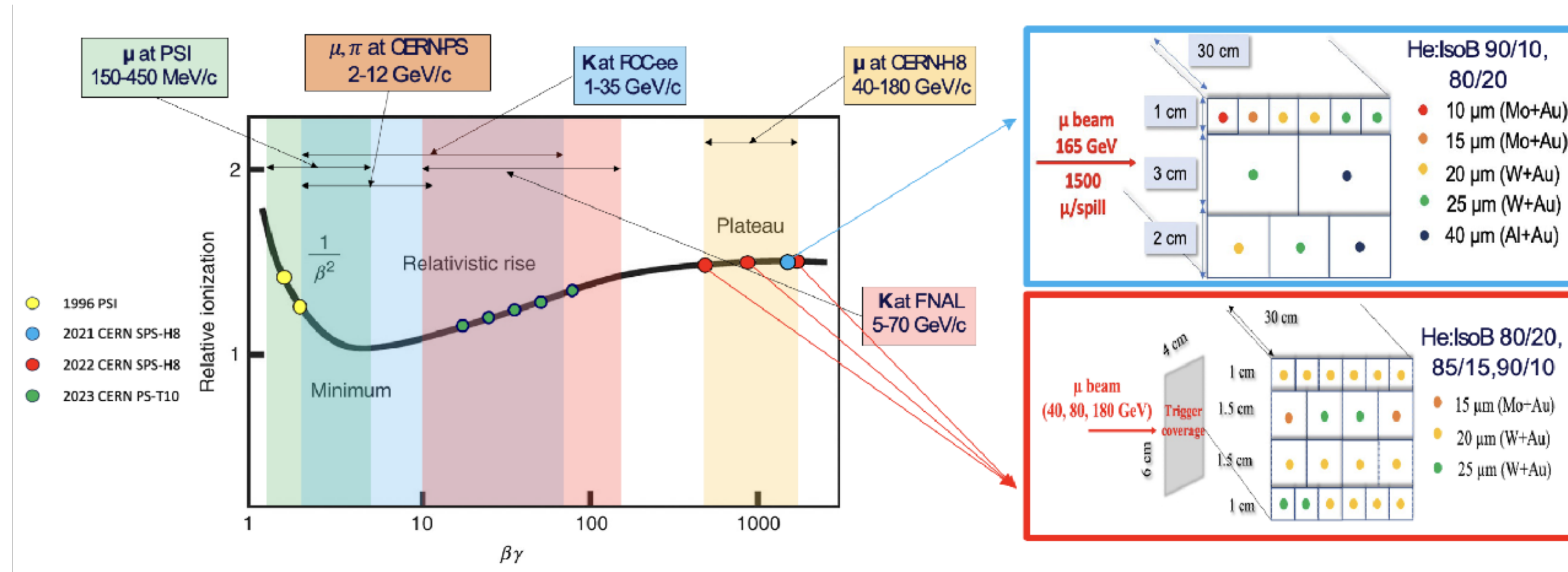
PID: dN_{cl}/dx and TOF impact

- dN_{cl}/dx provides **improved PID capabilities** to gaseous trackers for momenta up to $\sim 35\text{GeV}/c$ (exc. region around $p \approx 1\text{GeV}/c$)
 - To be **complemented** by TOF measurement at the end of the tracker ($\sim 2\text{m}$) (modified layout to provide time or silicon or ECAL)
At high momenta Fermi plateau is reached, energy loss of a particle traversing the gas no longer increases with increasing particle energy
 - Identification on the 'logarithmic rise' requires **approximately 100 measurements** over a detector length of close $\sim 2\text{m}$
- **Impact on $H \rightarrow s\bar{s}$ and $H \rightarrow c\bar{c}$** shows high dependance on the dN_{cl}/dx capability of the detector, ToF still complements (more important on the momentum resolution)
- **Assessment on the impact on other physics analysis is needed**

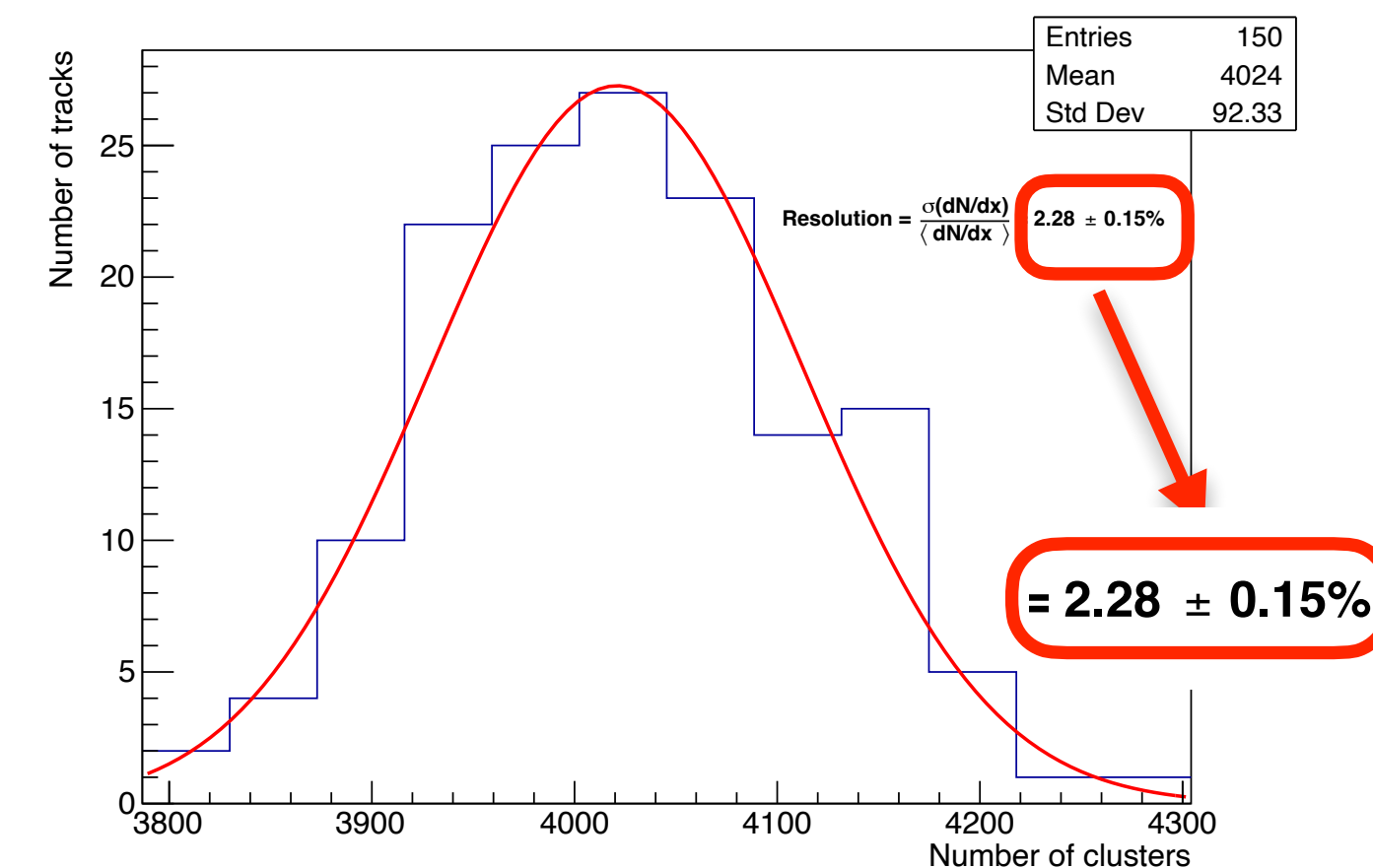


dN_{cl}/dx measurements

- Several **test beams with prototype drift cells** to experimentally assess and optimize the performance of the cluster counting/timing techniques covering big range of $\beta\gamma$ range
- Several **improvements** achieved with improved algorithms
 - Experimental **demonstration** of $\sim 2.3\%$ cluster-counting resolution
- Similar **effort ongoing** with the straw tubes prototype, electronics developed for cluster counting, analysis is ongoing

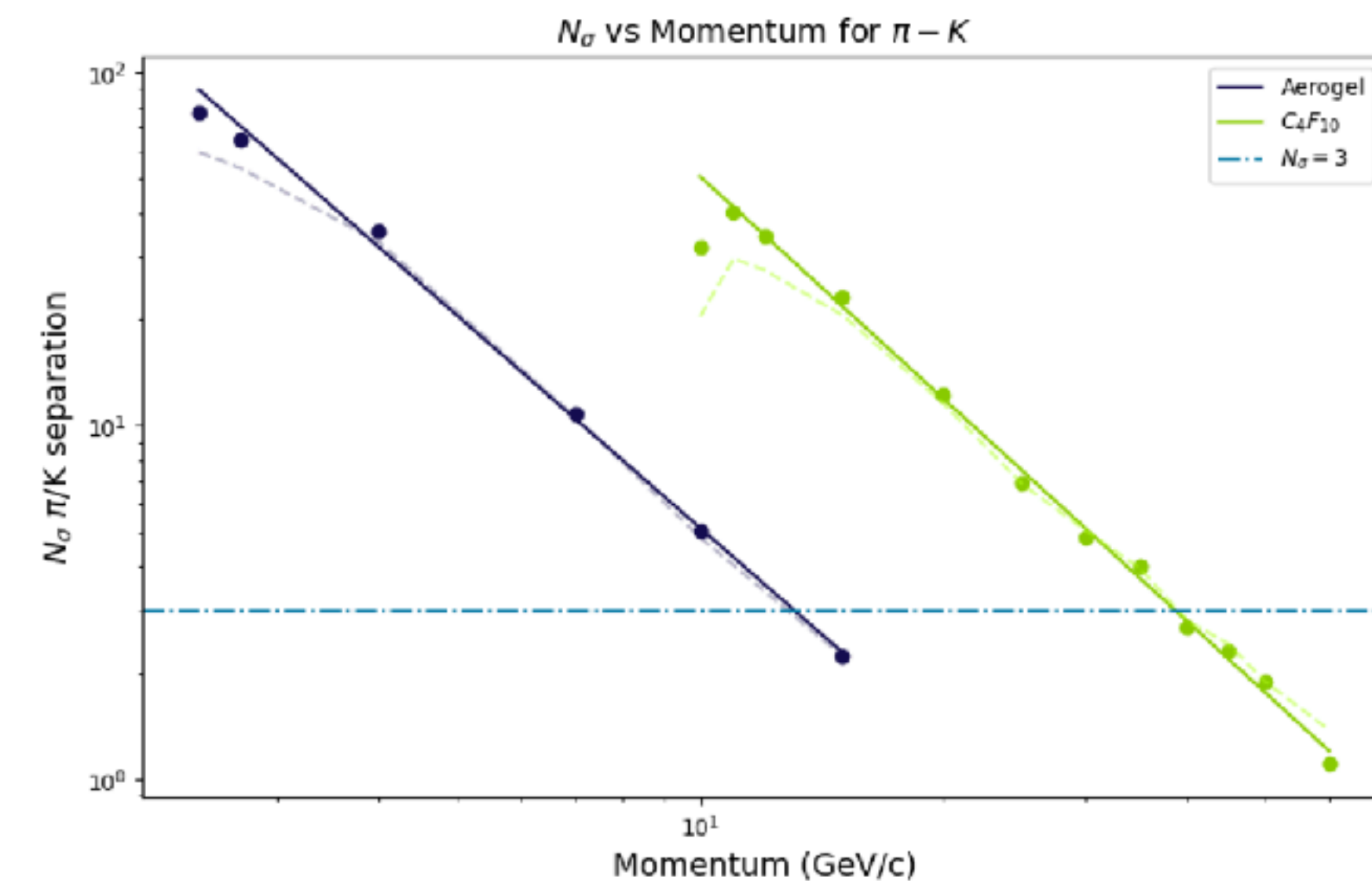
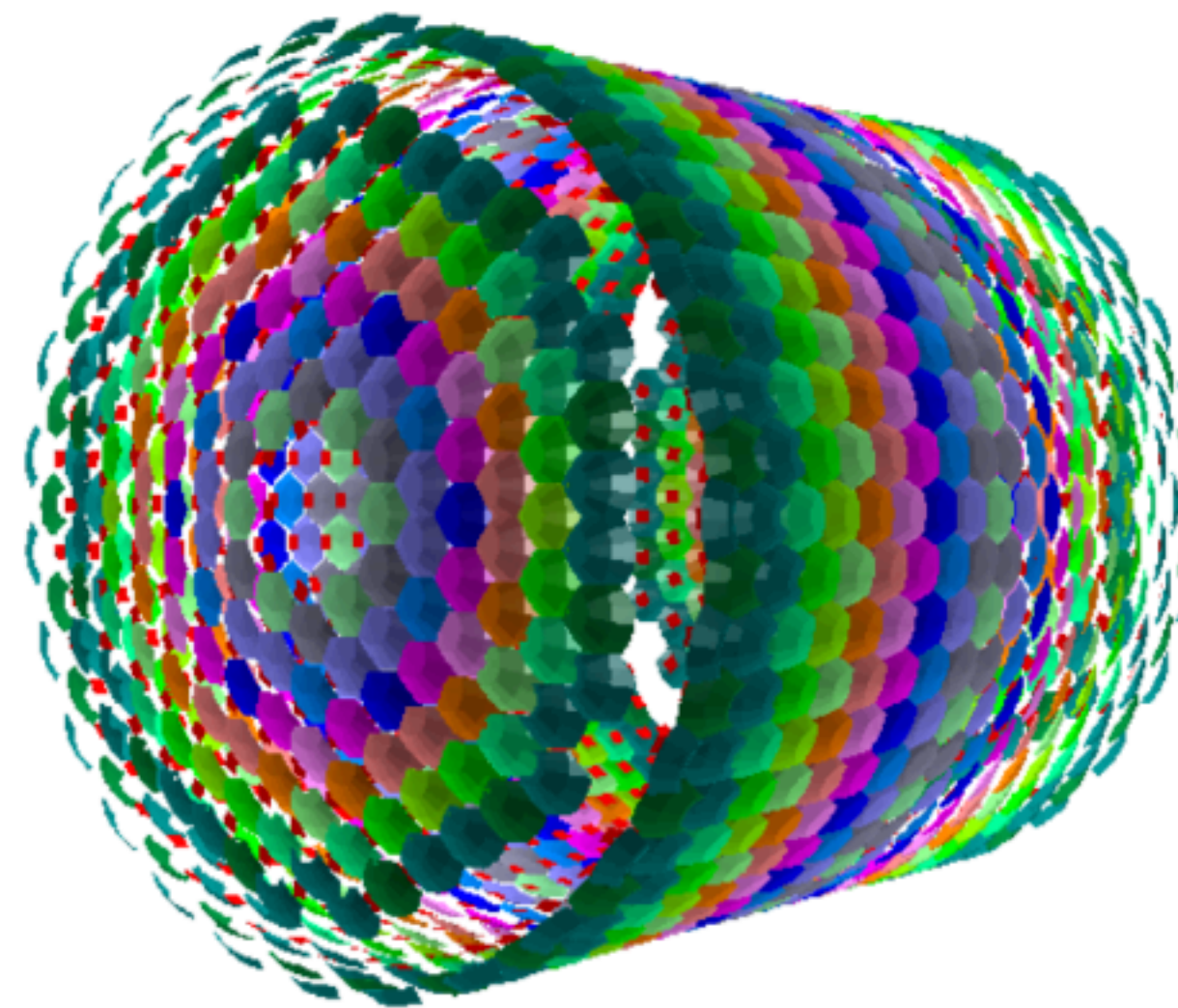
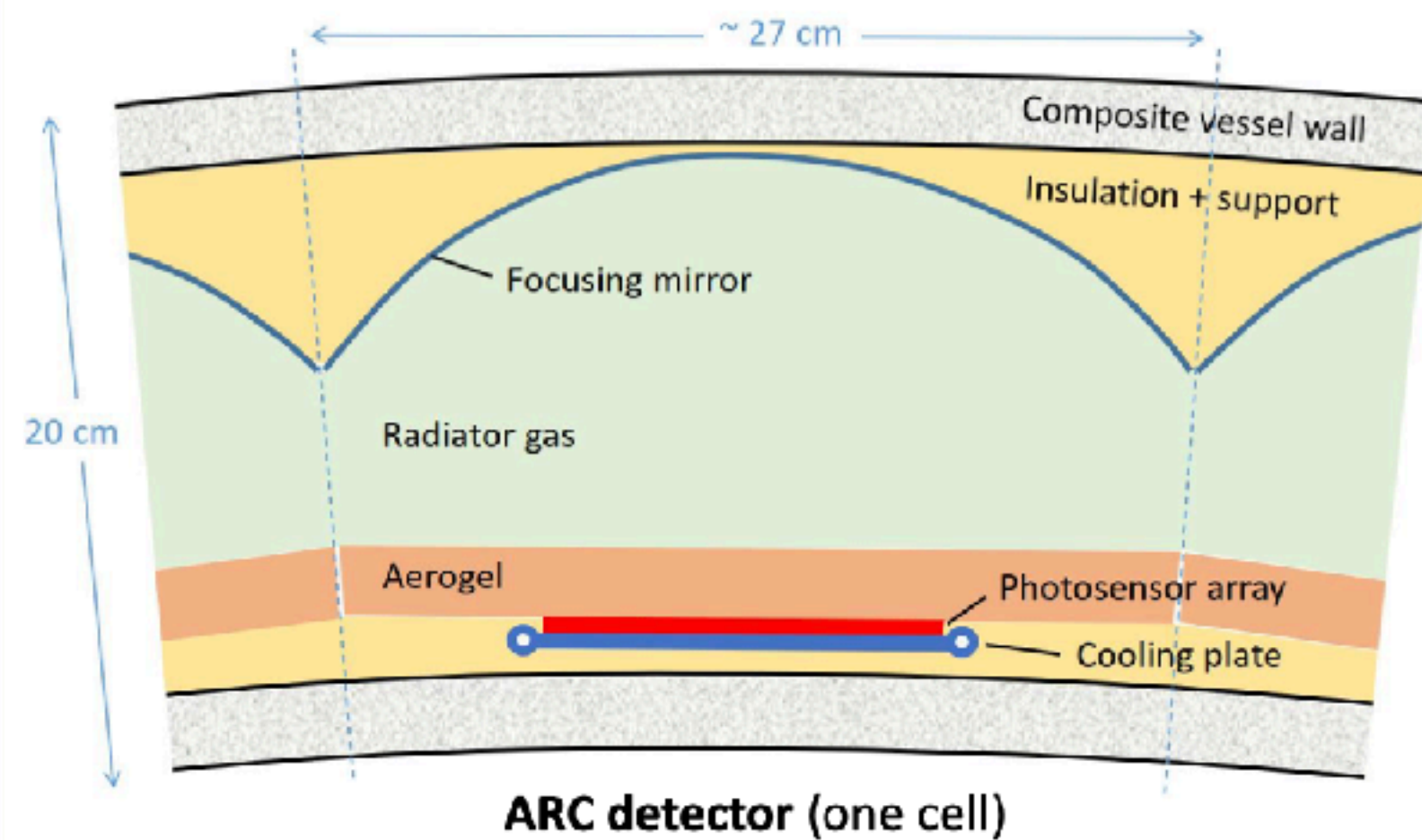
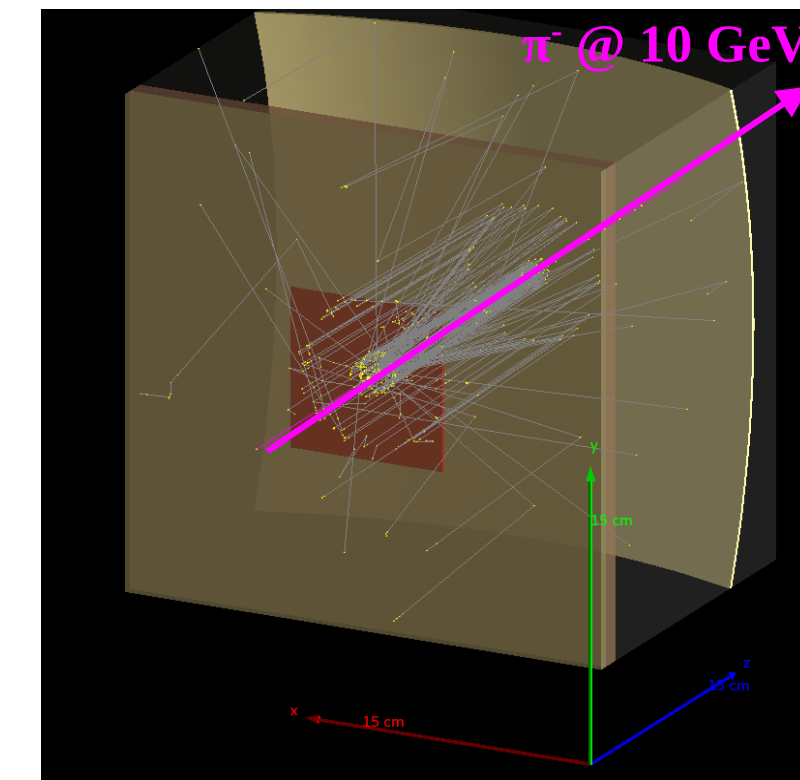


W. Elmetenawee et al 2025 JINST 20 P11019



Wrappers: Ring Imaging Cherenkov - RICH

- For silicon trackers where PID is limited, wrappers have been proposed
- Modernized RICH compact & lightweight, leverage SiPMs for photodetection
 - ARC (Array of RICH Cells)



Adapted for the [CLD and ALFA](#) detector concepts, occupying 10% of the tracker volume:
Material budget target: below 0.1 X₀

Detector geometry implemented in [Geant4](#)

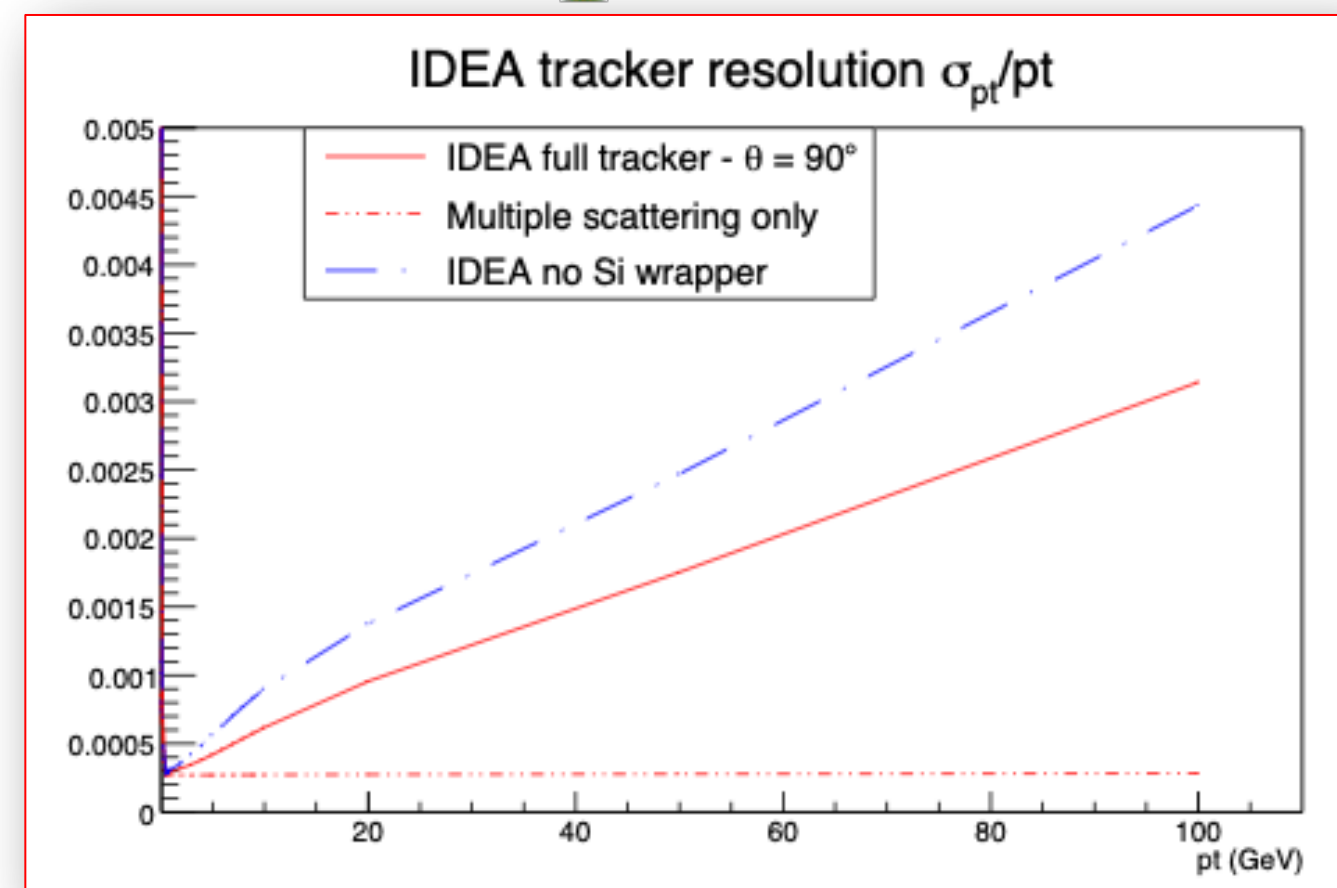
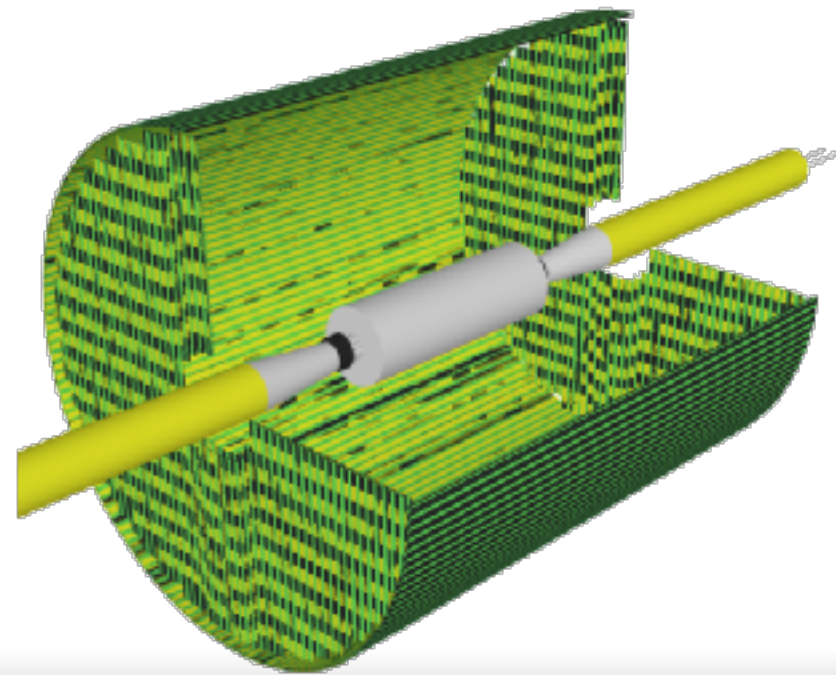
Pion/Kaon separation $> 3\sigma$ up to $\sim 40 \text{ GeV}$

Wrappers for p resolution & time-of-flight

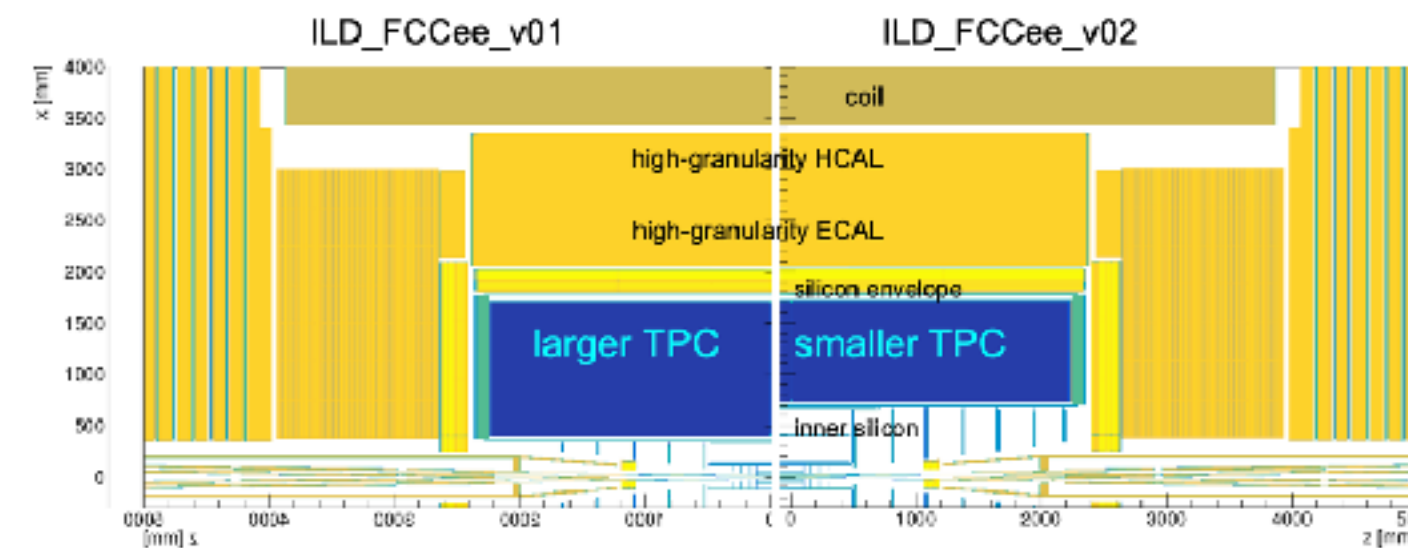
Silicon Wrappers with timing capabilities (100ps) foreseen in several detector concepts with gaseous central trackers

- Candidate technologies include **MAPS** and **LGAD**-based sensors
- Requirements include high spatial granularity for improved track momentum resolution, together with precise timing capabilities for TOF and background rejection.

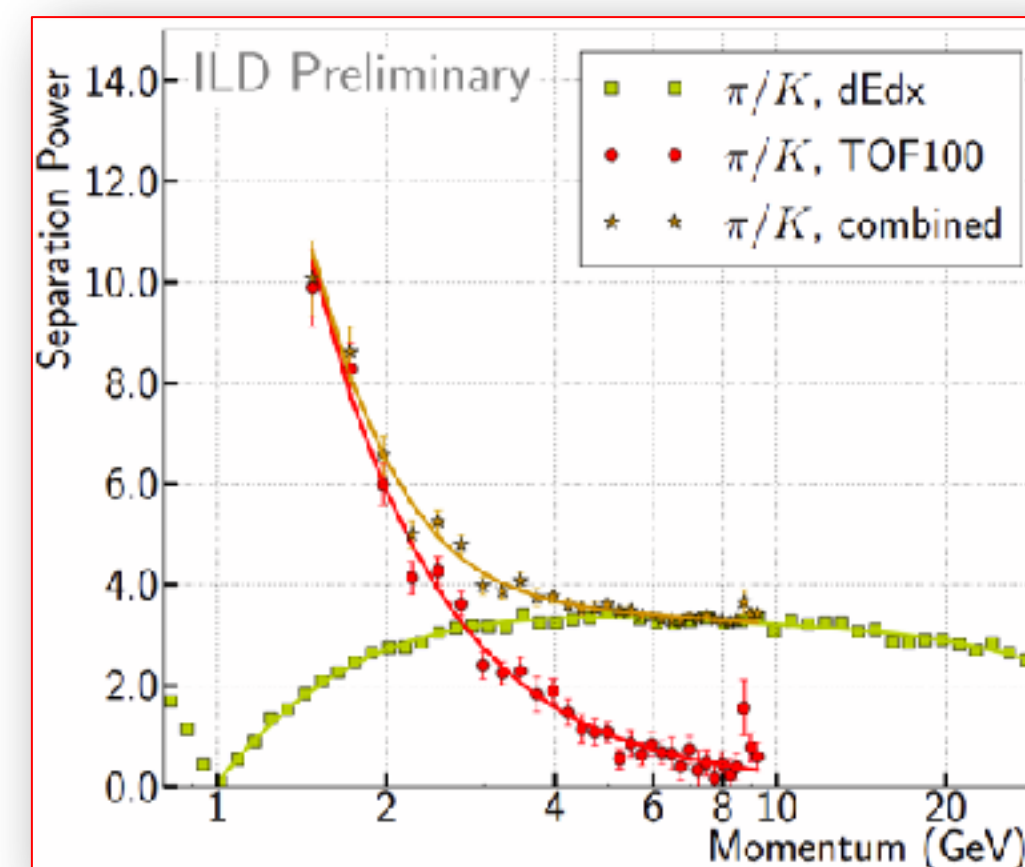
IDEA



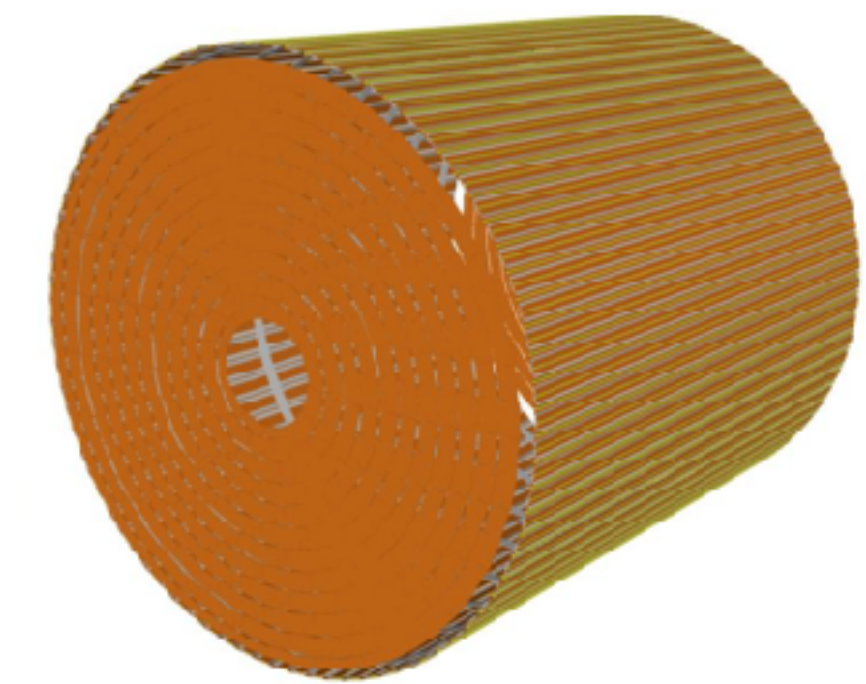
ILD



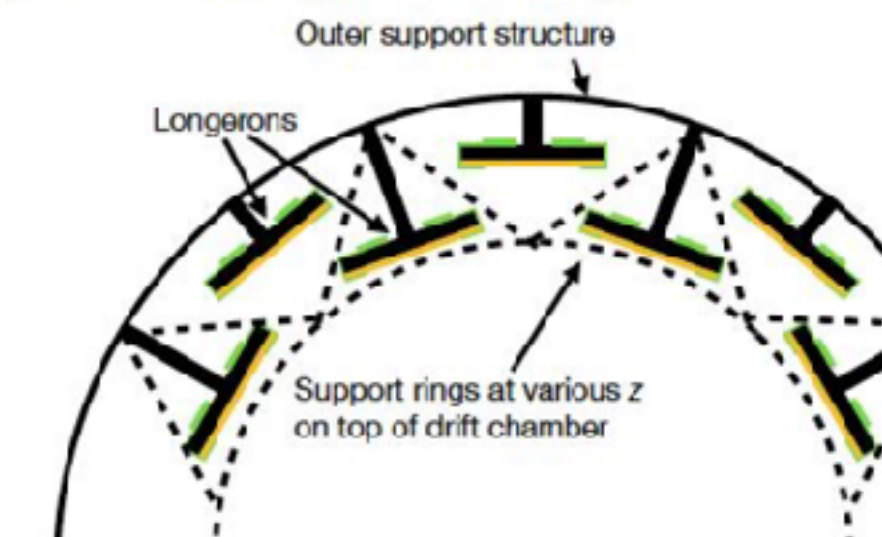
[Behnke's talk](#)



ALLEGRO



Complete SiWr
(SiliconWrapper-01-v01)



Conclusions

Tracking systems for the FCC-ee: highly challenging R&D that might enable the next generation of discoveries

- The Ambitious level of precision in FCC-ee physics program demand advanced tracking detectors
- Active R&D in
 - Silicon vertex detectors and outer silicon trackers and wrappers
 - Gaseous technologies with big challenges in scaling
 - Particle identification capabilities that include several technologies

**A rich and exciting roadmap lies ahead
for both detector innovation and physics exploration.**

Workshop on Tracking and PID, Registration and Abstract submission is open

- Next workshop during the week of Nov. 16 at CERN. Explore detector technologies for FCC-ee in the following topics.
 - Vertex,
 - Outer Tracking,
 - Wrappers
 - Particle Identification (PID),
 - Conjunction with Machine–Detector Interface (MDI).

Cross-cutting perspective connecting detector R&D, Physics Performance, and Software Developments.

Agenda: <https://indico.cern.ch/event/1660971/>



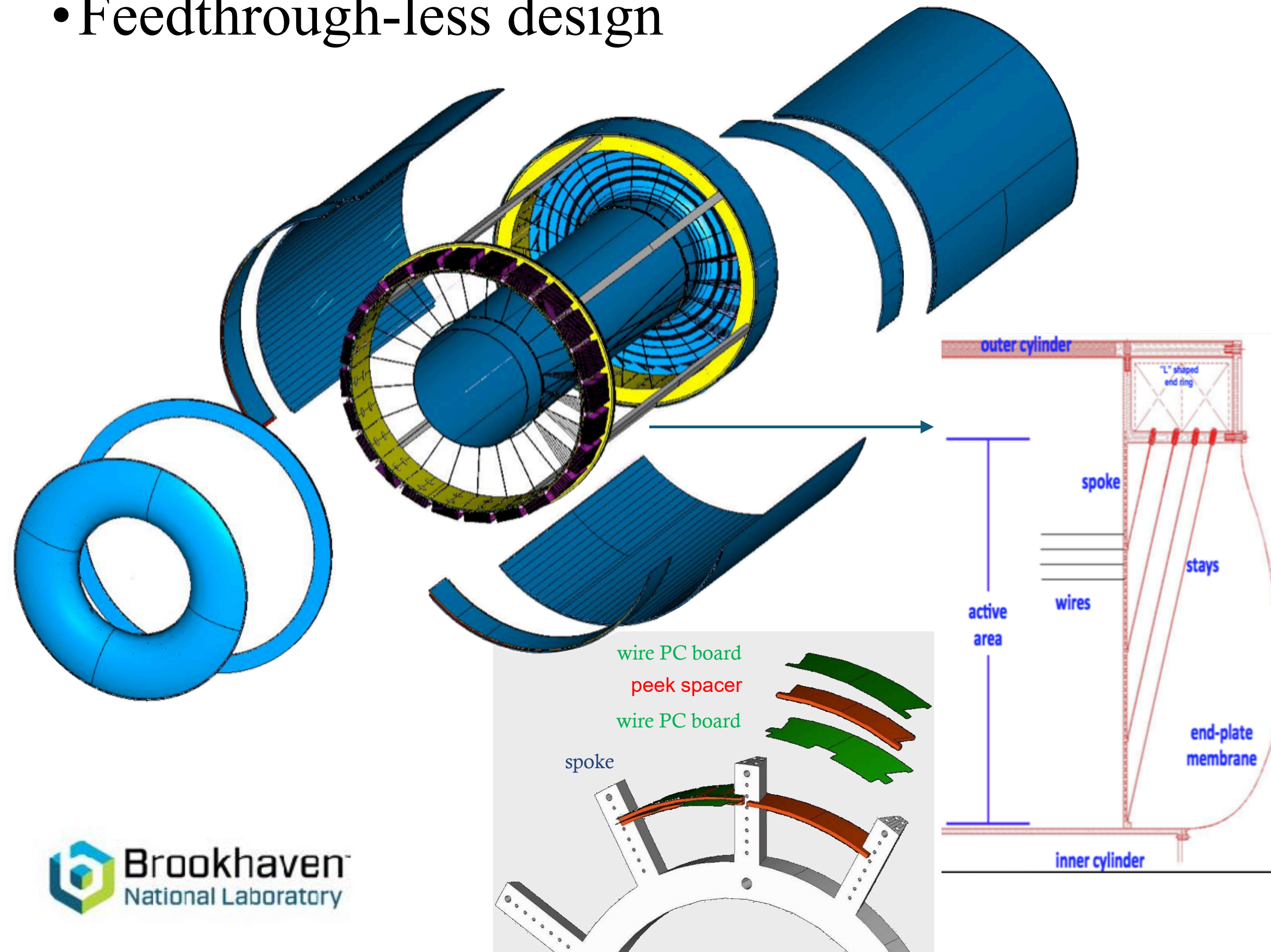
Mark your calendar!

Reach us: fcc-ped-detectorconcepts-tracker-conveners@cern.ch
Sign up to list: [FCC-PED-DetectorConcepts-Tracker](https://indico.cern.ch/event/1660971/)

Backup

Mechanical design

- IDEA DCH separating wire support, by counterbalancing the wire tension (external stays) from the gas containment → Ultra-light structure
- Deformations on the Gas vessel have no impact on the wire position
- **New wiring strategy:** inner and outer cylinder connected to 48 spokes, forming 24 identical sectors
- Feedthrough-less design



Comparison to MEGII and IDEA DCH

- 12k → 340k wires
- 9 → 112 layers
- 2 → 4 m (Even 5m for ALLEGRO)

Comparison to BELLEII and IDEA DCH

- 57k → 340k wires
- 65 → 112 layers
- 2.3 → 4 m (Even 5m for ALLEGRO)

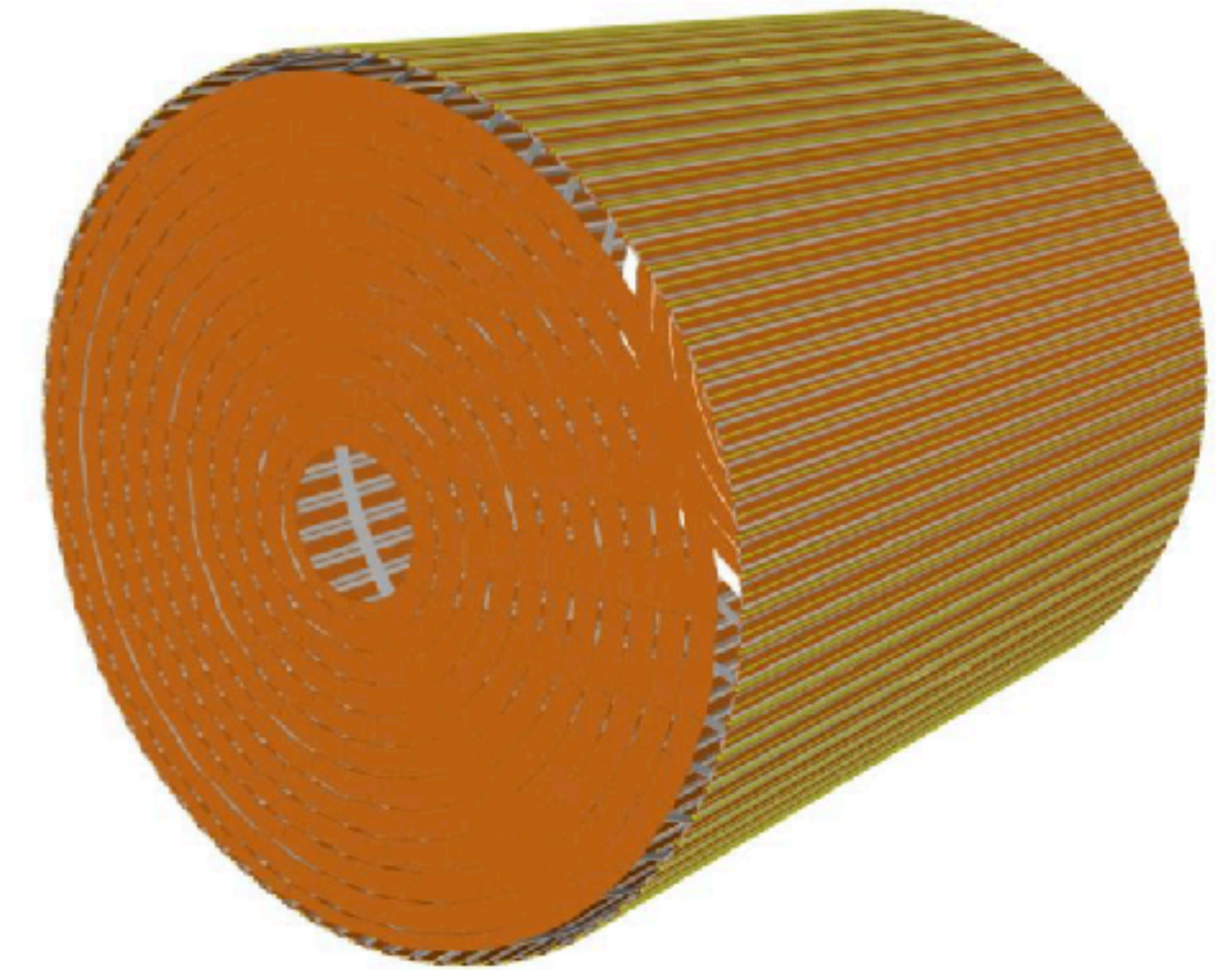


Lessons learnt from MEGII & BELLE II

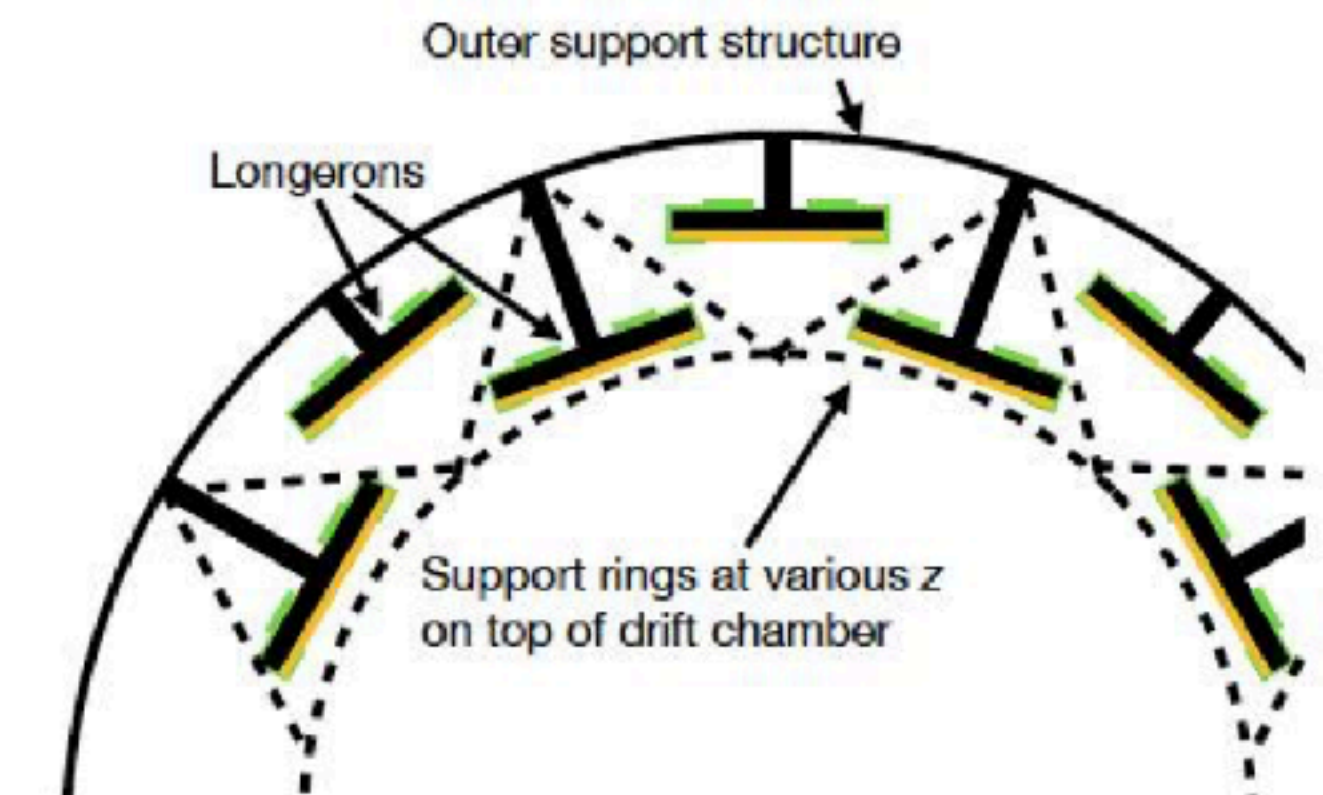
- Corrosion and breakage of 107 aluminum wires in presence of 40-65% humidity level → Problem fully cured by keeping CDCH in dry atmosphere
- Anomalously high currents experienced → CDCH operation recovered by using additives
- Beam induced background challenging at high luminosities

Silicon Wrapper

- Present baseline: Monolithic pixels with a pitch of $50 \times 1000 \mu\text{m}^2$
- Aim to implement timing pixels with a spatial resolution of $10 \mu\text{m}$ and timing resolutions of 30 ps per hit
 - Possible technologies: AC-LGADs with 300-500 μm pixel cell size or monolithic timing sensors
- **Study the spatial and timing resolution with single or double layers in SiW**
- Investigate which are the minimal requirements in terms of spatial and timing resolution to achieve a good Kaon/Pion separation via Time-of-Flight
- Timing for the last Vertex layer ?
 - A suitable technology could be monolithic sensors with a gain layer (e.g. Cassia or MadPix)
 - Study the possible improvement also in terms of PID for low momentum particles since only particles with momentum larger than 1 GeV reach the Silicon Wrapper



Complete SiWr
(SiliconWrapper_o1_v01)



Electronics & readout with drift chamber

PROBLEM

For the IDEA drift chamber, however, given:

- > 56,000 active cells, readout at both ends;
- 1.5 cm drift length, max drift time: ~ 500 ns;
- $Z \rightarrow$ hadrons trigger rate: ~ 100 KHz;
- charged tracks multiplicity: 20 tracks/hadronic event;
- average of 130 hit cells/track;
- Digitization: 12 bits at 2 Gsa/s:

$$20 \text{ track/event} \times 130 \text{ cell/track/side} \times 2 \text{ side} \times 10^5 \text{ event/s} \times 5 \times 10^{-7} \text{ s/cell} \times 2 \times 10^9 \text{ byte/s} =$$

$$= 0.5 \text{ TB/s}$$

plus $\gamma\gamma$, Bhabha, beam background, noise, ...

$\Rightarrow$ Transfer rate at Z-pole $\gtrsim 1 \text{ TB/s!}$

some data reduction is mandatory!

SOLUTION

A possible solution consists in transferring, for each hit drift cell, only the minimal information relevant to the application of the cluster timing/counting techniques, i.e.: **amplitude** and **arrival time** of each peak associated with each individual ionization electron, instead of the full digitized **signal waveform**:

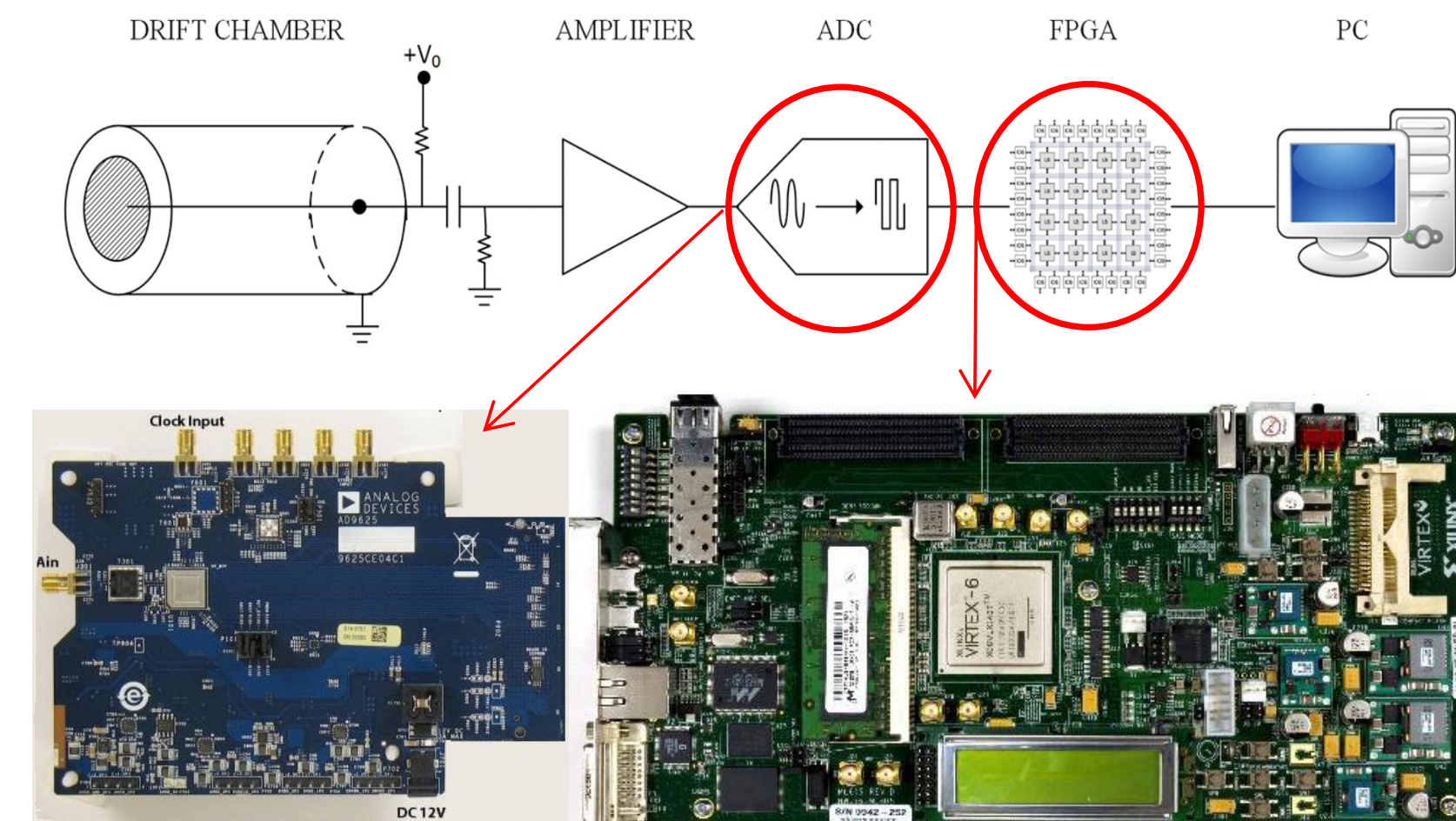
$$20 \text{ track/event} \times 130 \text{ cell/track/side} \times 2 \text{ side} \times 10^5 \text{ event/s} \times 30 \text{ peaks/cell} \times 2 \text{ byte/peak} =$$

$$= 30 \text{ GB/s}$$

This can be accomplished with the use of simple algorithms on a **FPGA** for the real time pre-processing of the digitized data generated by the drift chamber.

Moreover, background and noise can easily be filtered out by the same algorithm.

Single channel implemented solution



A fast readout algorithm (**CluTim**) for identifying, in the digitized drift chamber signals, the individual ionization peaks and recording their time and amplitude was developed as a **VHDL/Verilog** code implemented on a **Virtex 6 FPGA**, allowing for a maximum input/output clock switching frequency of **710 MHz**. The hardware setup included also a 12-bit monolithic **pipeline sampling ADC** at conversion rates of up to **2.0 GSPS**.

[F. Grancagnolo, A 4-channel electronics board for Cluster Counting](#)