Gaseous trackers at FCC-ee

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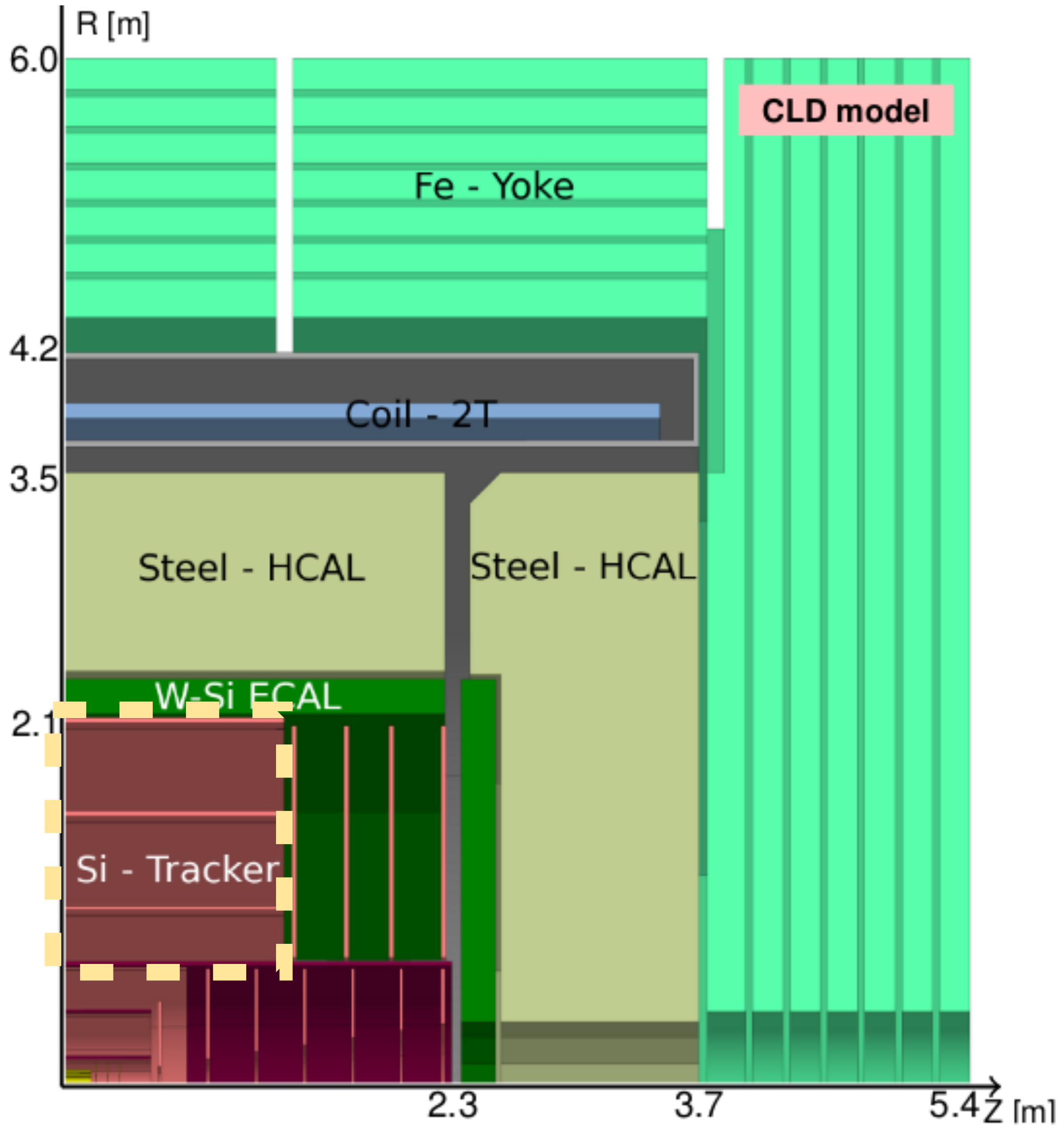
FCC Week - San Francisco
June 11, 2024

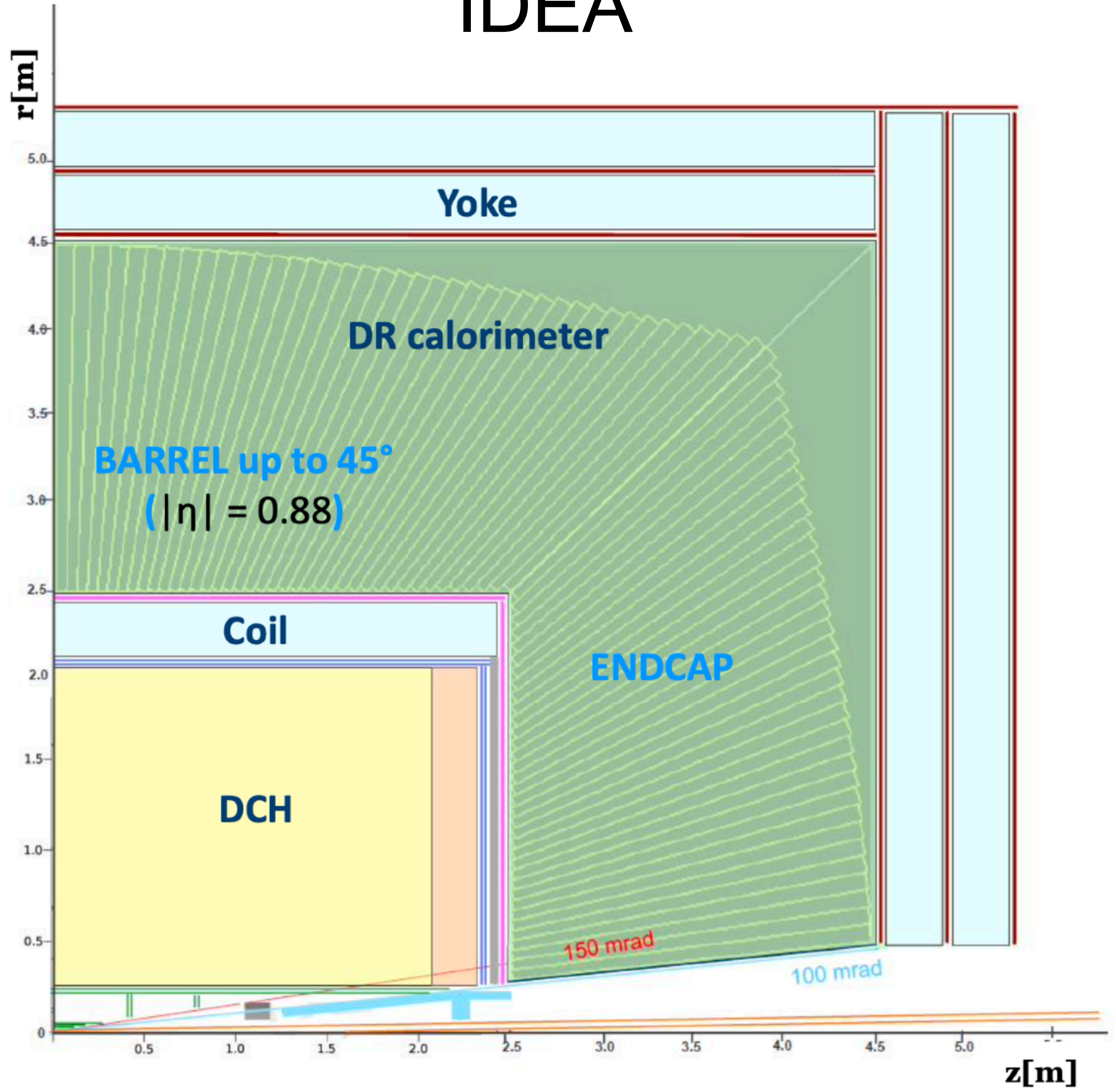
Detector concepts for FCC-ee - Focus on Trackers

CLD



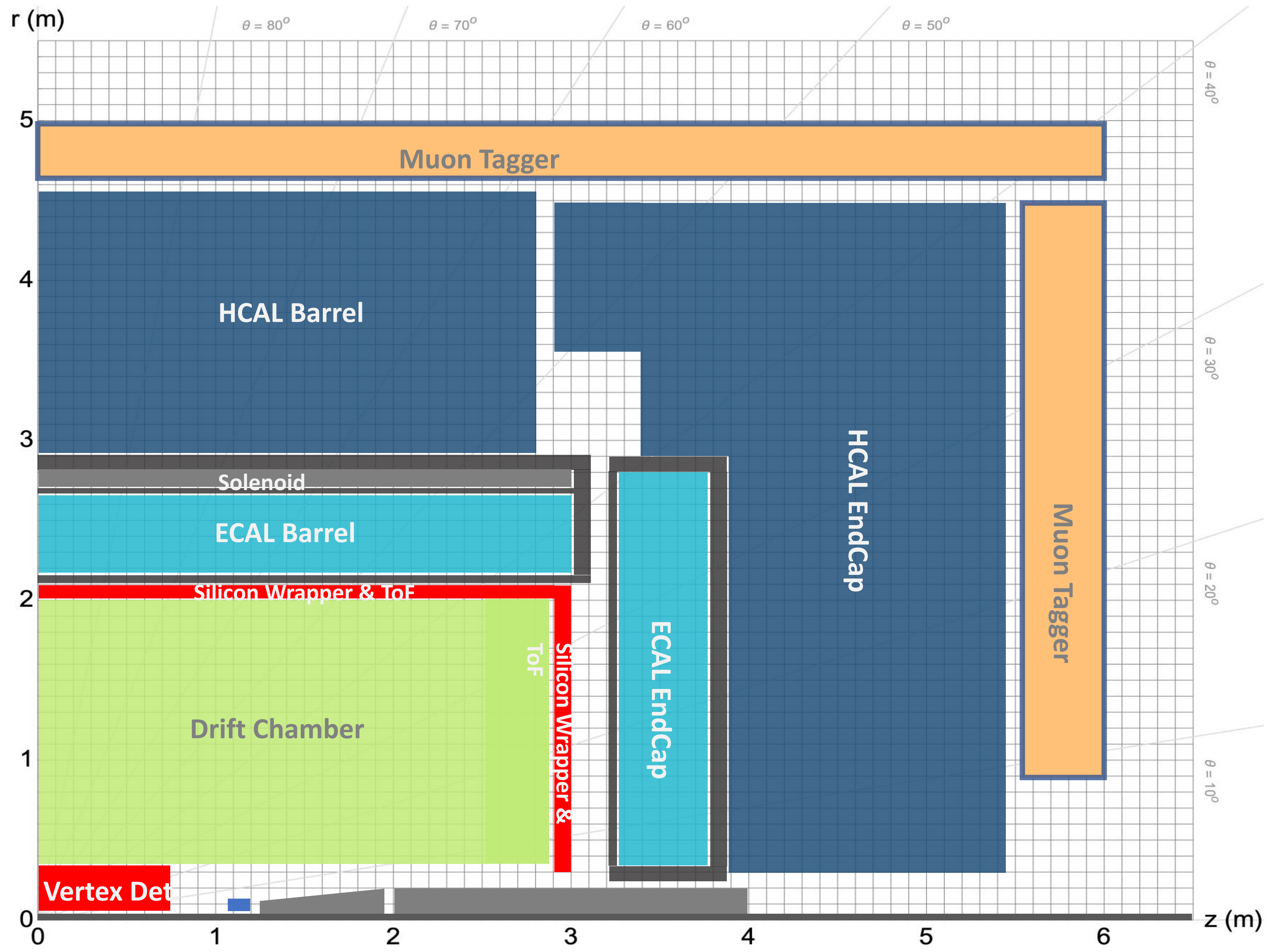
- All-silicon tracker
- Proposal of a TPC as main tracker
  - Recent proposal

IDEA



- Transparent Drift Chamber
- 112 layers
- **4m Long**
- R = 35-200cm
- (Outer Silicon wrapper for ToF)

ALLEGRO



- Transparent Drift Chamber or straw tubes
- **5m Long**
- R = 35-200cm
  - Basically follows the same layout with IDEA concept
- Tracker design open to new ideas and developments
- (Outer Silicon wrapper for ToF)

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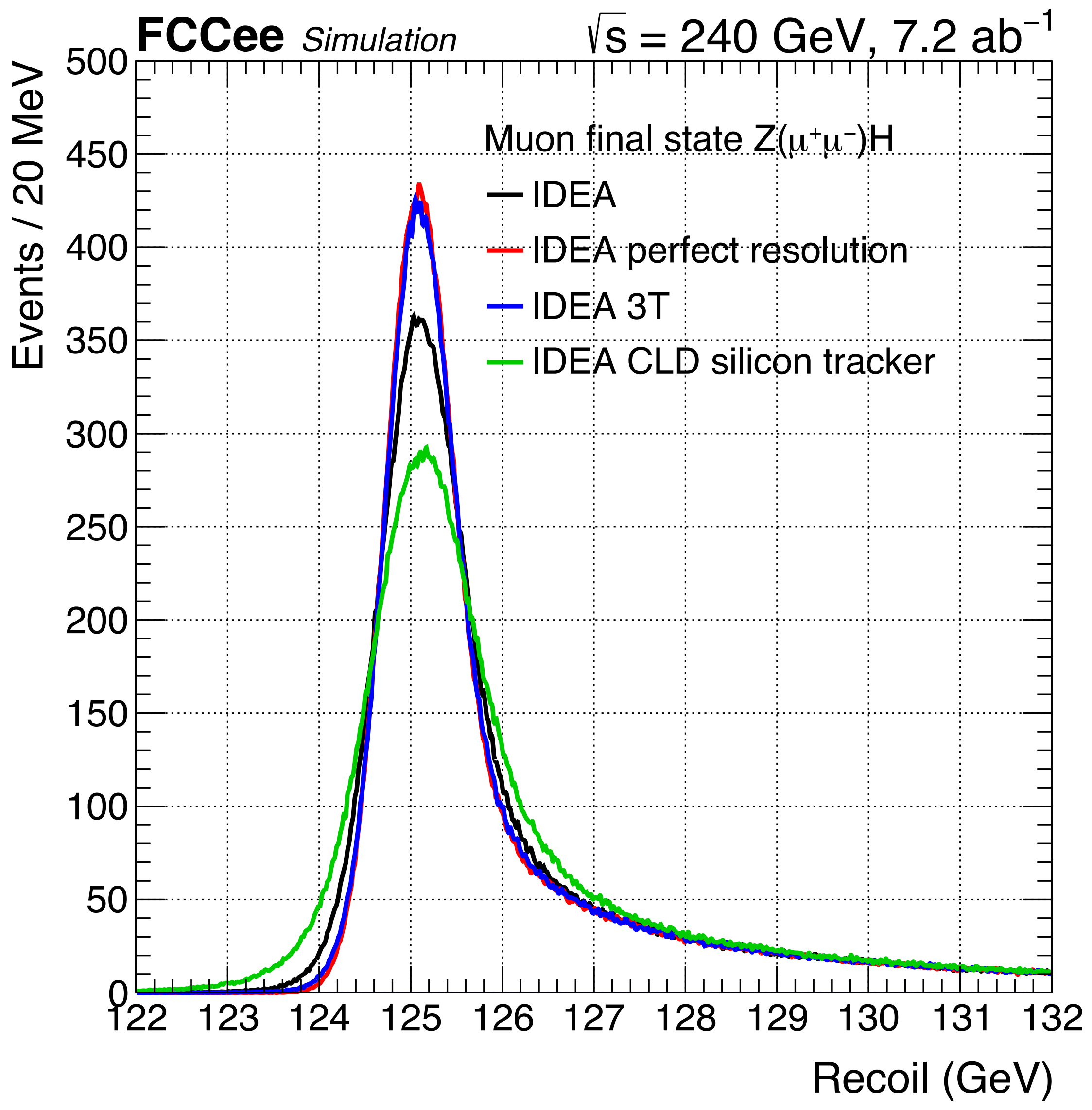
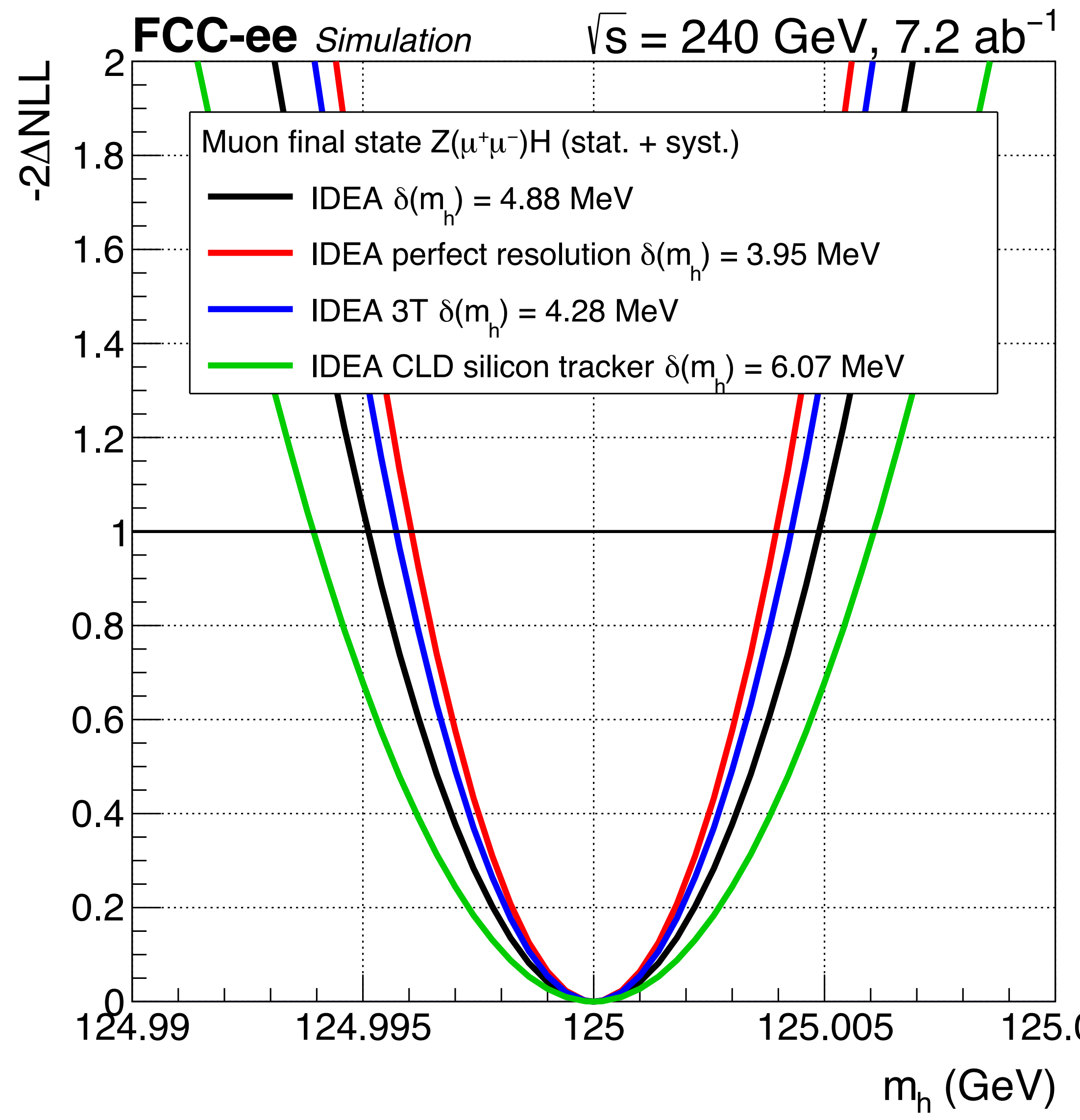
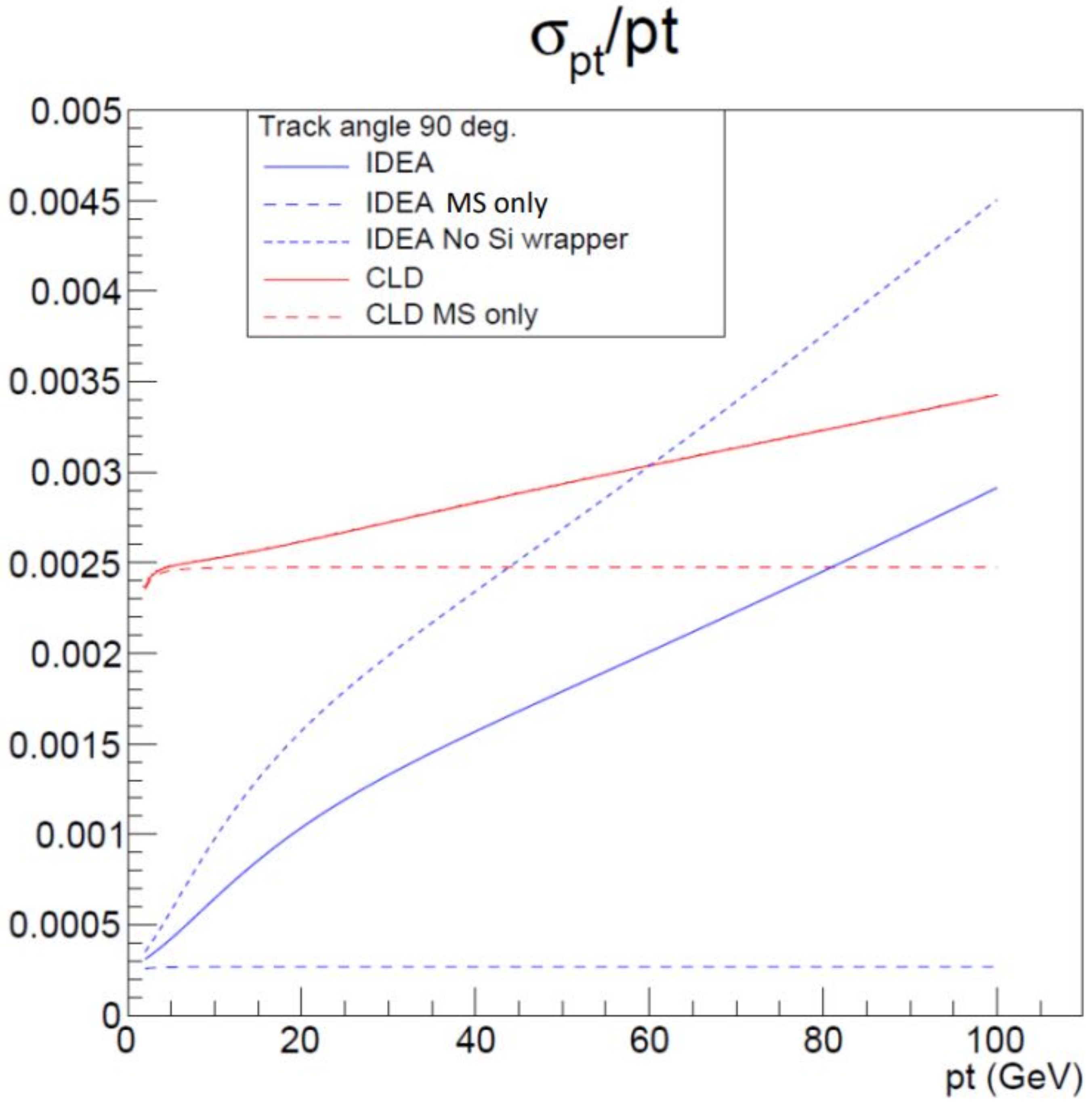
Requirements

- Tracking in FCC-ee crucial for many physics cases, precision measurements flavor physics, QCD, LLVs, *B* physics etc.
- Higgs mass measured at its intrinsic width (4 MeV)
- M_{recoil} for $Z(\mu^+\mu^-)H$ determined by BES (0.185%)
  - Momentum resolution should be at the same level ~ $\mathcal{O}(50)$ GeV σ_{p_T}/p_T~0.2%
  - Transparency of the tracker is 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



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Gaseous trackers - applications and advantages

- **Gaseous** detectors have been used in experiments for **tracking** applications for the last **~50y**,
  - MWPC, Drift chambers, TPCs, Straw tubes
- Tracking system should be as **light** as possible
  - **Momentum resolution** dominated by multiple scattering at low momentum
  - **Particle Flow** requires as little material as possible in front of ECAL
  - **PID** capabilities, over wide momentum range
- Tracking detectors though **do not measure** the full energy loss of a particle!

Facility	Experiment	Detector type
SPEAR	MARK2	Drift Chamber
	MARK3	Drift Chamber
DORIS	PLUTO	MWPC
	ARGUS	Drift Chamber
CESR	CLEO1,2,3	Drift Chamber
VEPP2/4M	CMD-2	Drift Chamber
	KEDR	Drift Chamber
	NSD	Drift Chamber
PETRA	CELLO	MWPC + Drift Ch.
	JADE	Drift Chamber
	PLUTO	MWPC
	MARK-J	TEC + Drift Ch.
	TASSO	MWPC + Drift Ch.
TRISTAN	AMY	Drift Chamber
	VENUS	Drift Chamber
	TOPAZ	TPC
PEP	MARK2	Drift Chamber
	PEP-4	TPC
	MAC	Drift Chamber
	HRS	Drift Chamber
	DELCO	MWPC
BEPC	BES1,2	Drift Chamber
LEP	ALEPH	TPC
	DELPHI	TPC
	L3	Si + TEC
	OPAL	Drift Chamber
SLC	MARK2	Drift Chamber
	SLD	Drift Chamber
DAPHNE	KLOE	Drift Chamber
PEP2	BaBar	Drift Chamber
KEKB	Belle	Drift Chamber

Facility	Experiment	Detector type
VEPP2000	CMD-3	Drift Chamber
	KEDR	Drift Chamber
BEPC2	BES3	Drift Chamber
S.KEKB	Belle2	Drift Chamber
LHC	ALICE	TPC
	ATLAS	Straw tubes
	LHCb	Straw tubes
CERN SPS	COMPASS	Drift Chamber + Straw
	NA35	TPC
	NA49	TPC
RHIC	STAR	TPC
	PHENIX	Drift Chamber
PSI	MEGII	Drift Chamber
ILC	ILD	TPC
	SiD	Si
FCC-ee	CLD	Si or TPC
	IDEA	Drift Chamber
	ALLEGRO	Drift Chamber, Straw
SCTF	BINP	Drift Chamber
	HIEPA	Drift Chamber

*not an exhaustive list

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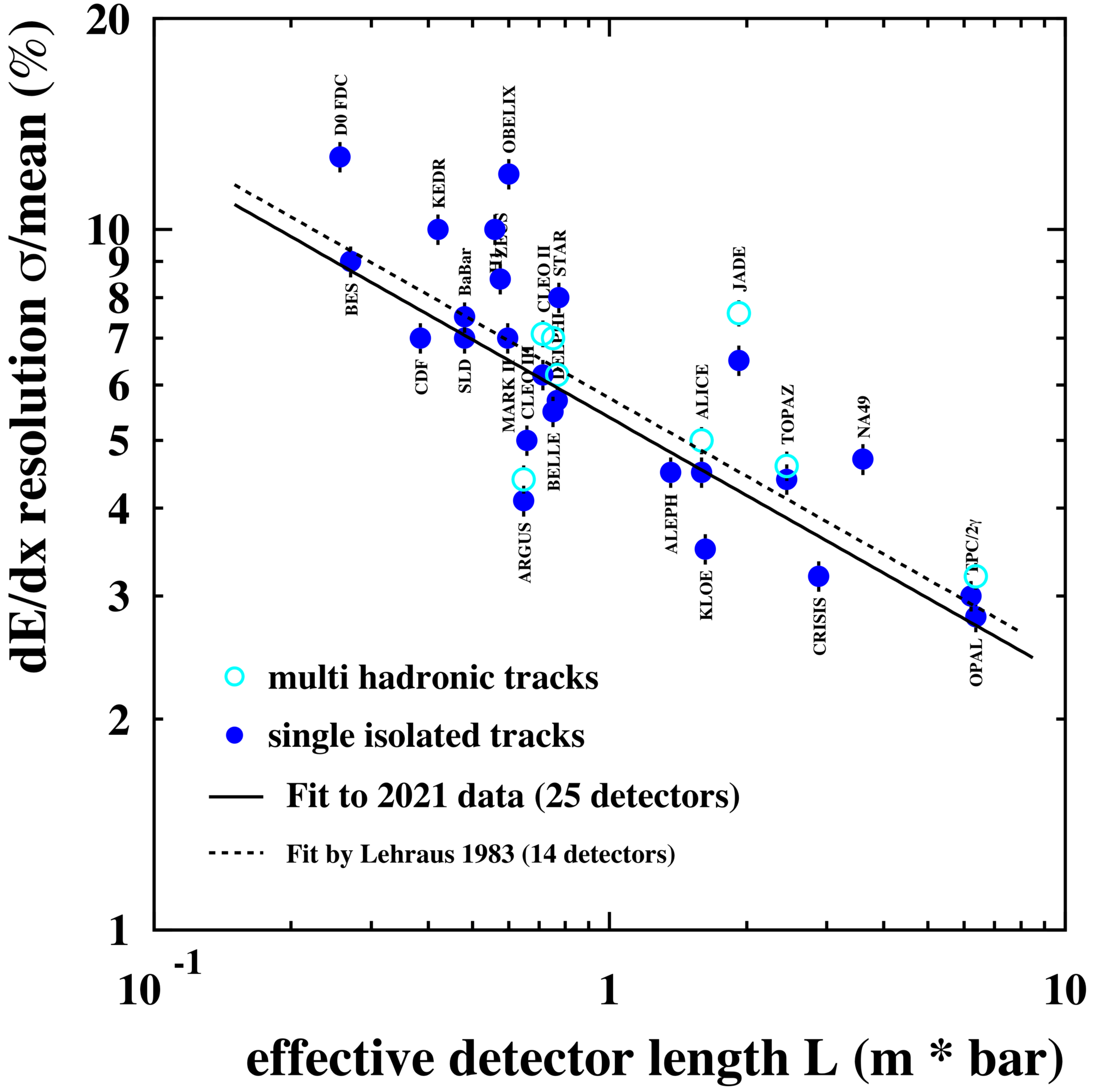
The d*E*/d*x* for gaseous detectors (trackers)



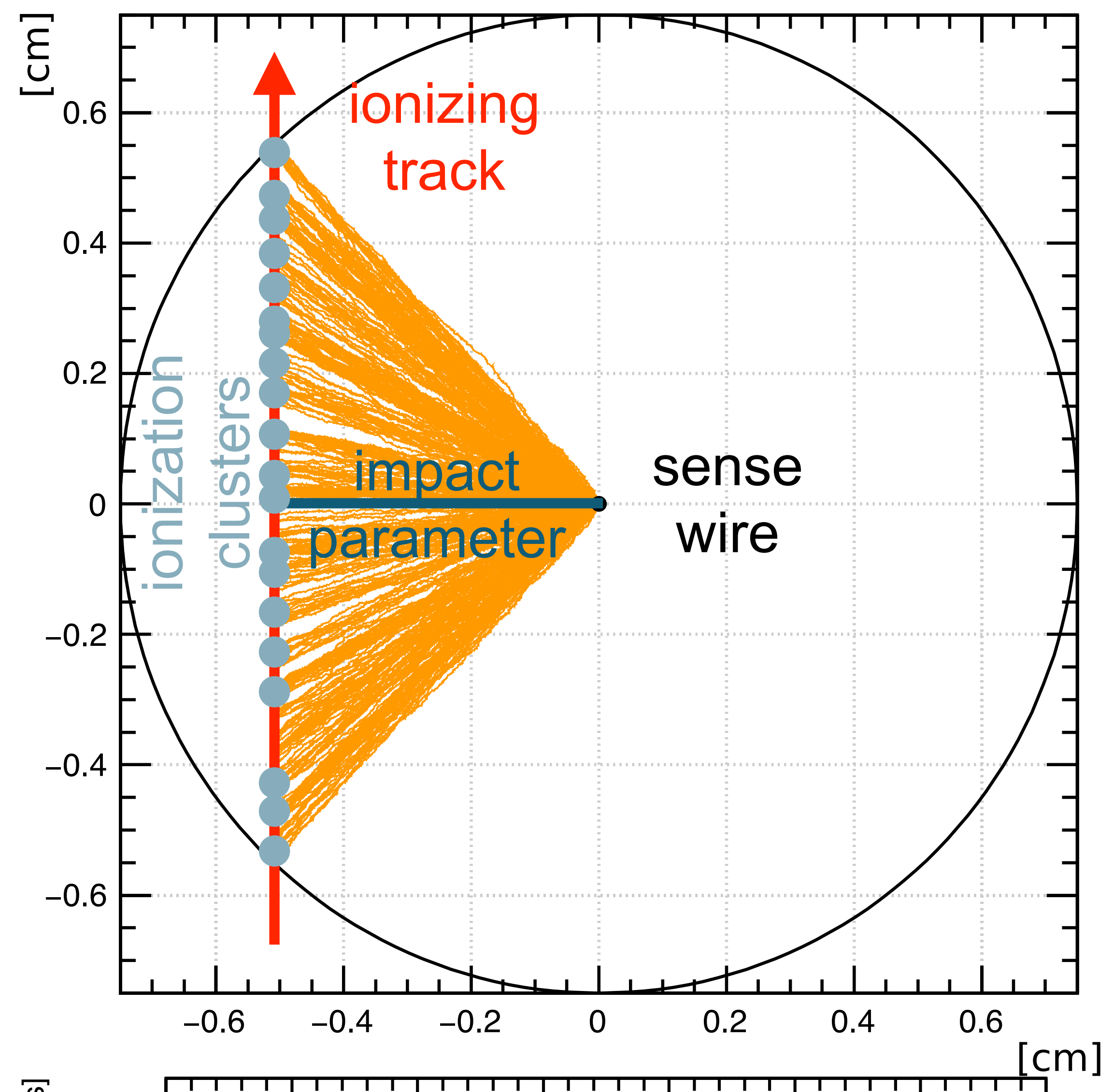
- In “modern” gaseous tracking detectors, the velocity dependence of the energy loss is used to infer the mass of the particle (PID) in combination with momenta measurement
- d*E*/d*x* resolution achieved in large detectors, mainly at e^+e^- colliders, at some hadron colliders and fixed target experiments
  - Truncated mean mostly used → empirically set
- Fit by Lehraus 1983 (14 detectors)
  - ➡ dE/dx res. $= 5.7 \cdot L^{-0.37} (\%)$
- Fit in 2021 (25 detectors):
  - ➡ dE/dx 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**

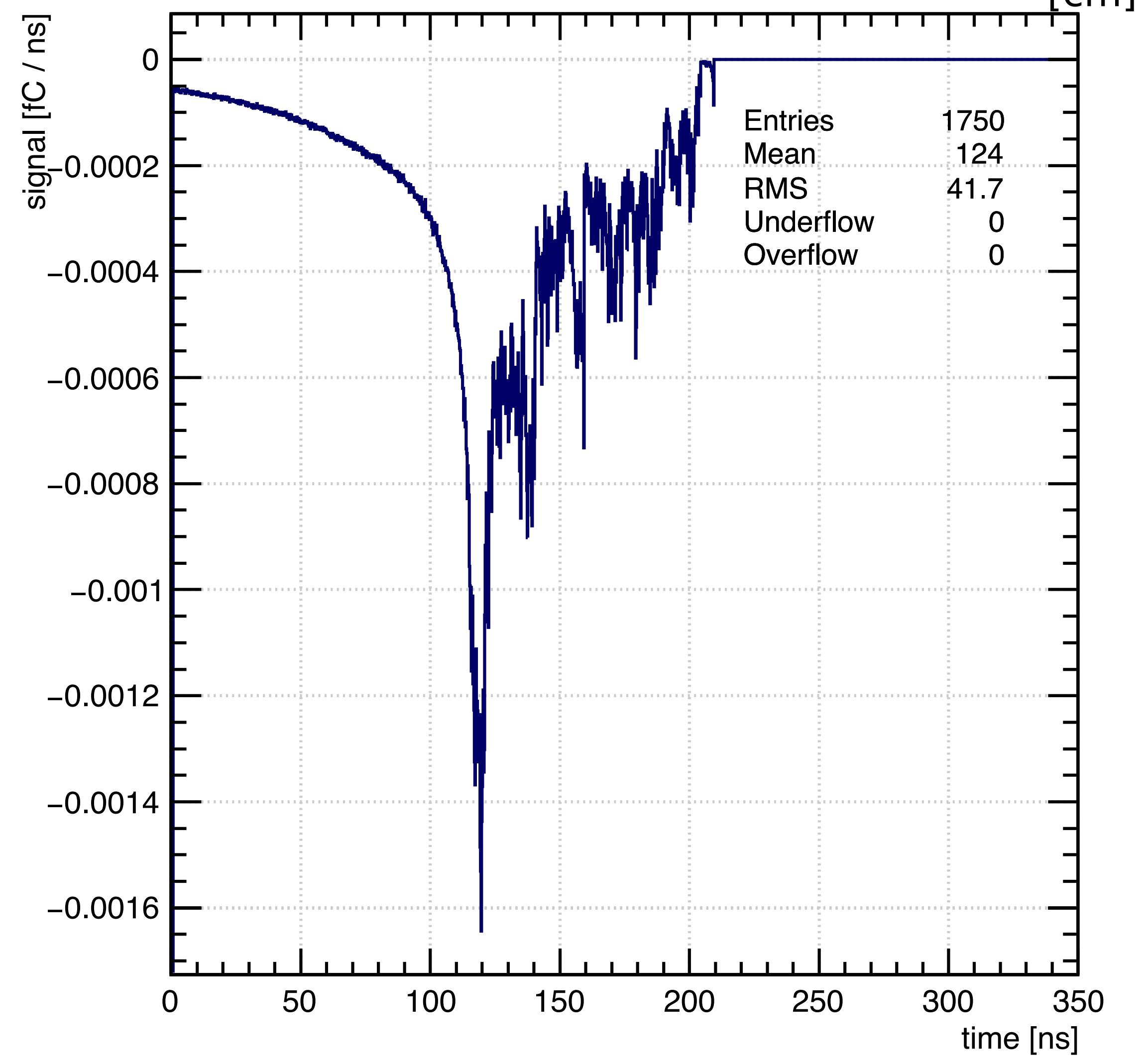
- [I. Lehraus, NIM, Vol 217, Issues 1-2, (1983)](#)
- [dE/dx, classical and with cluster counting](#)

The dN_{cl}/dx technique

- Based on A.H. **Walenta** research in 1980s who showed that **additional charge** comes from **number of primary clusters** and not from energy per cluster
- 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 resolution, timestamp etc)

Drift tube simulation
Garfield





dE/dx

$$\frac{\sigma_{\mathrm{d}E/\mathrm{d}x}}{(\mathrm{d}E/\mathrm{d}x)} = 0.41 \cdot n^{-0.43} (L_{\text{track}}[\text{m}] \cdot P[\text{atm}])^{-32}$$

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

$$\sigma \approx 4.3\,\%$$

IDEA DCH →

dN_{cl}/dx

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

$\delta_{\text{cl}} = 12.5/\text{cm}$ for He+10%iC_4H_{10} and 2m (Poisson distr.)

$$\sigma \approx 2.0\,\%$$

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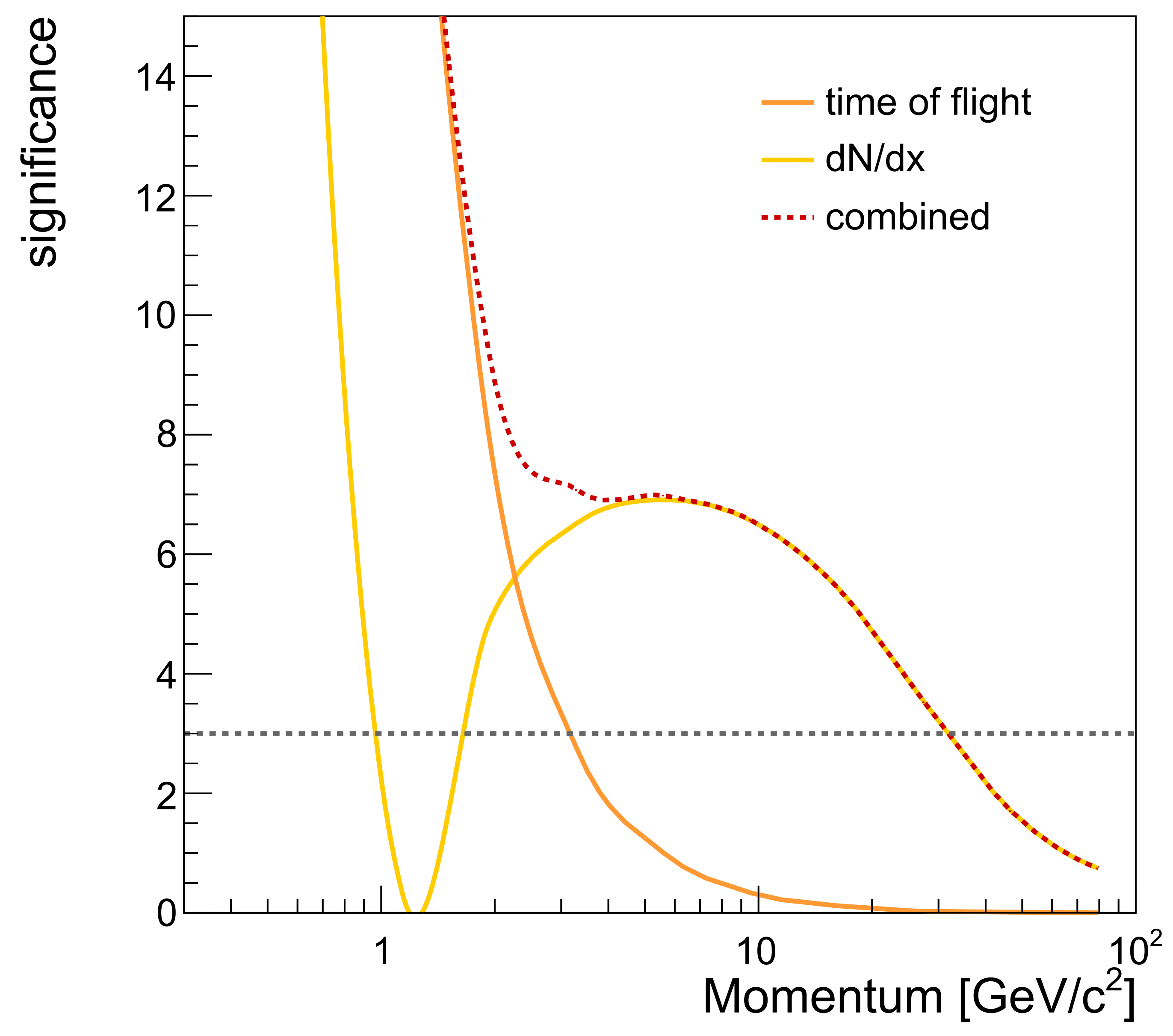
- G. Cataldi et al, NIM A 386 (1997) 458-469
- P. Rehak and A.H. Walenta, IEEE Trans. Nucl. Sci. vol. 27, no. 1, pp. 54-58, Feb. 1980
- F. Grancagnolo, AIDAinnova 3rd Annual meeting, 2024

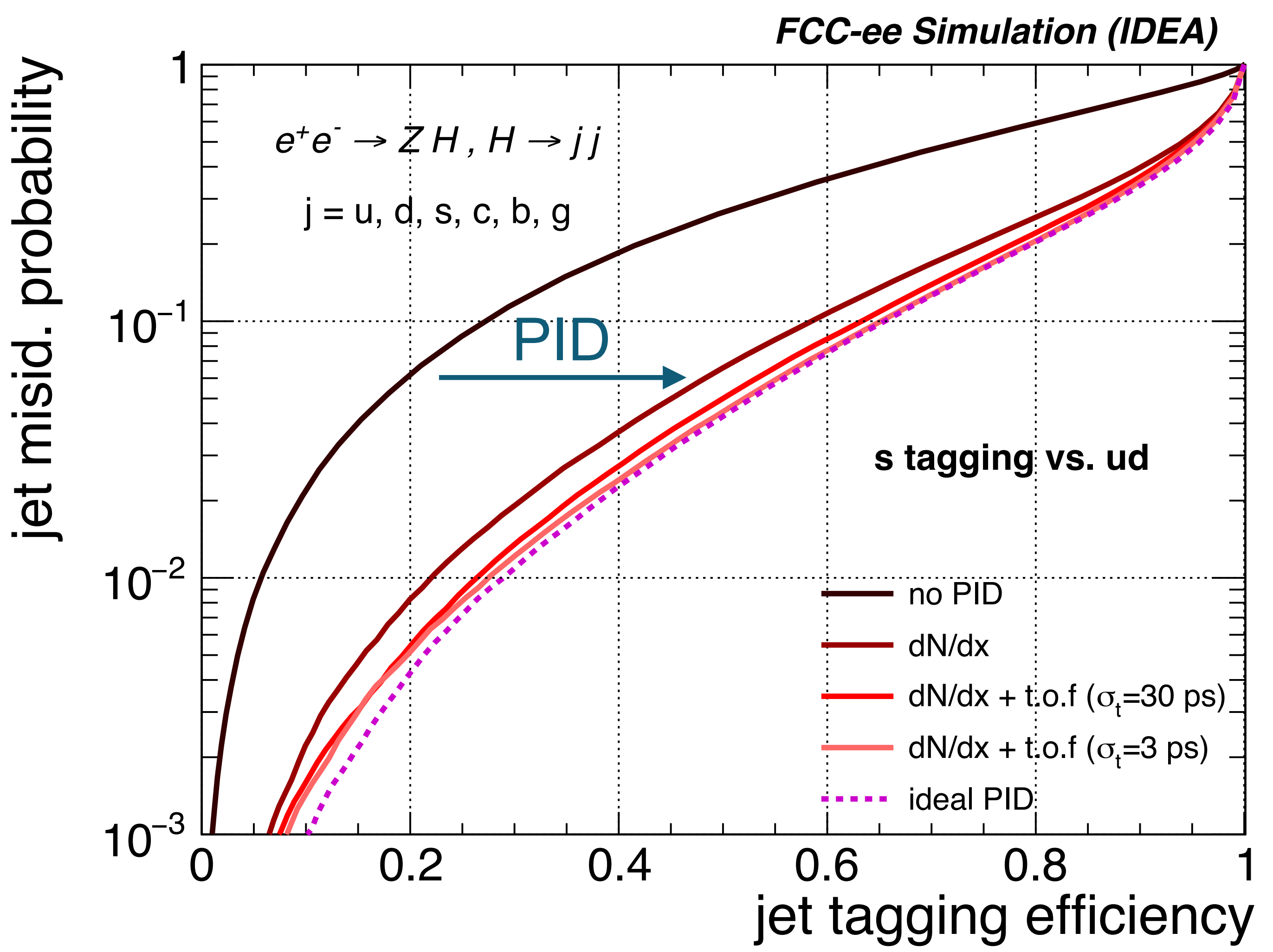
Challenge for electronics - GHz bandwidth !

The $\mathrm{d}N_{\mathrm{cl}}/\mathrm{d}x$ benefit

- The $\mathrm{d}N_{\mathrm{cl}}/\mathrm{d}x$ technique provide**s improved PID capabilities** to gaseous trackers for low momenta ~ 35 GeV/c (exc. region around $p \approx 1$ GeV/c)
  - Needs to be **complemented** by time of flight (**TOF**) measurement at the end of the tracker (~2m) (modified layout to provide time or silicon or ECAL) to compensate for the low velocity region and relativistic rise
  - 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 ~ **2m are required**

π, K separation of IDEA DCH along with a TOF measurement at 2m





Bedeschi, F., Gouskos, L. & Selvaggi, Eur. Phys. J. C 82, 646 (2022).

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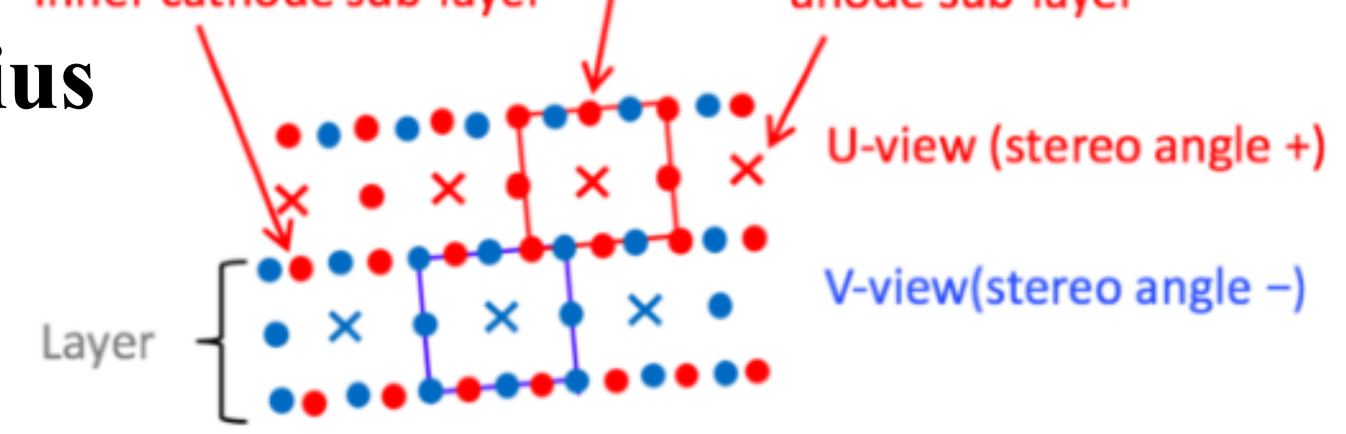
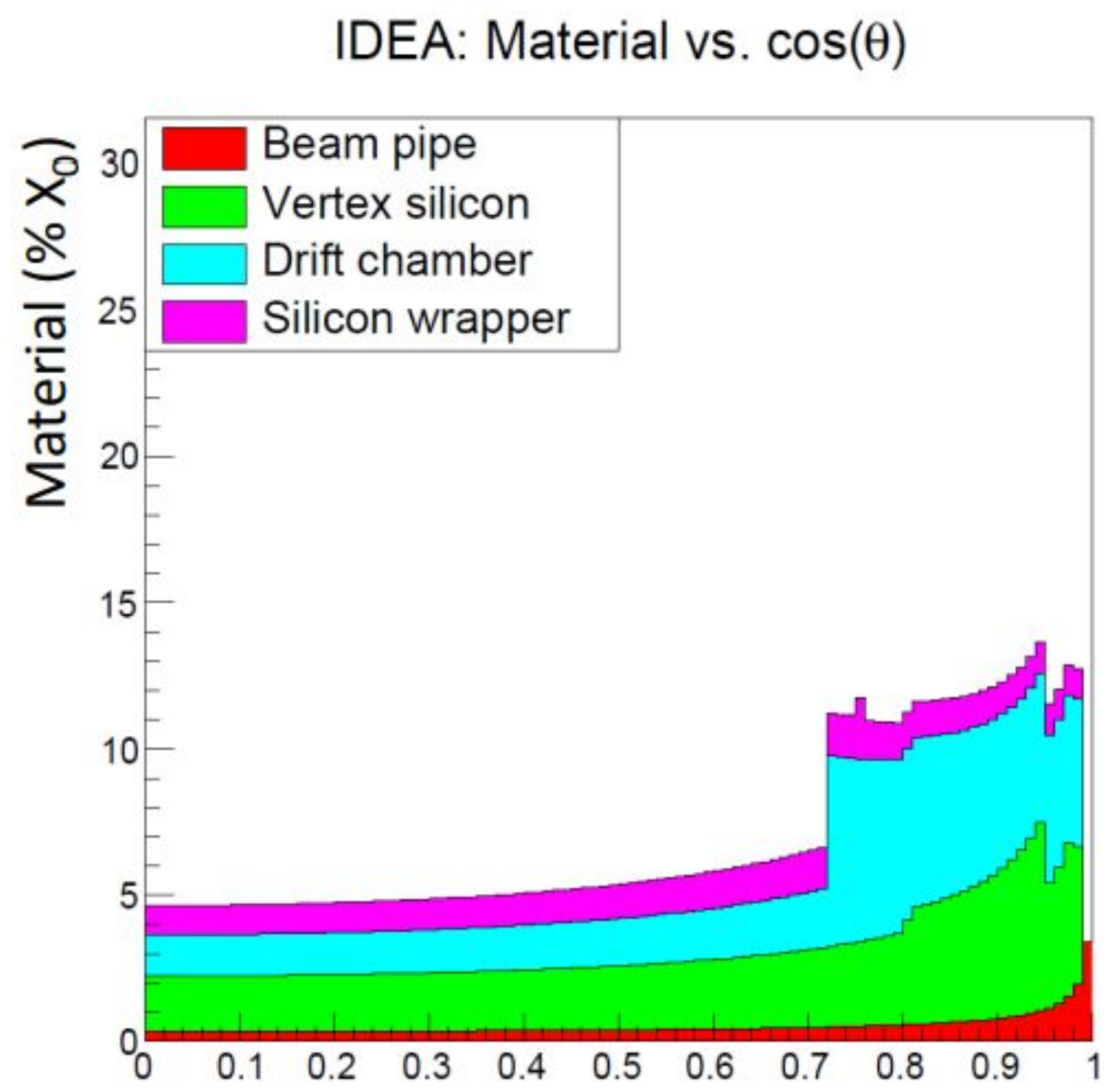
IDEA Drift Chamber

- Dimensions: **4 m long** (active volume), **35cm to 2m radius**
- **Low material budget**
  - Barrel: ~ 1.6% X_0
  - Forward directions: ~ 5% X_0
- Stereo layout
  - **112 layers** ranging from 50 to 250 mrad
- Operating gas mixture: **He + 10% iC_4H_{10}**
  - Average drift velocity of ~ 2 cm/µs → drift time $t_D < 400$ ns
  - Number of cluster (per m.i.p.) ~ 12.5 cm^{-1} avg. with ~ 1.6 electrons/cluster)
- Sense (anode): 20µm W(Au) → 56448 total
- Field (cathode): 40µm Al(Ag) → 285504 total
- Guard (cathode): 50µm Al(Ag) → 2016 total
- Active volume: 56448 almost squared drift cells (12 ÷ 14.5 mm), with a 5 : 1 field-to-sense wire ratio for simpler time-to-distance relations
- Overall **expected resolution**: σ_{xy} ~ 100 µm and σ_z ~ 1 mm

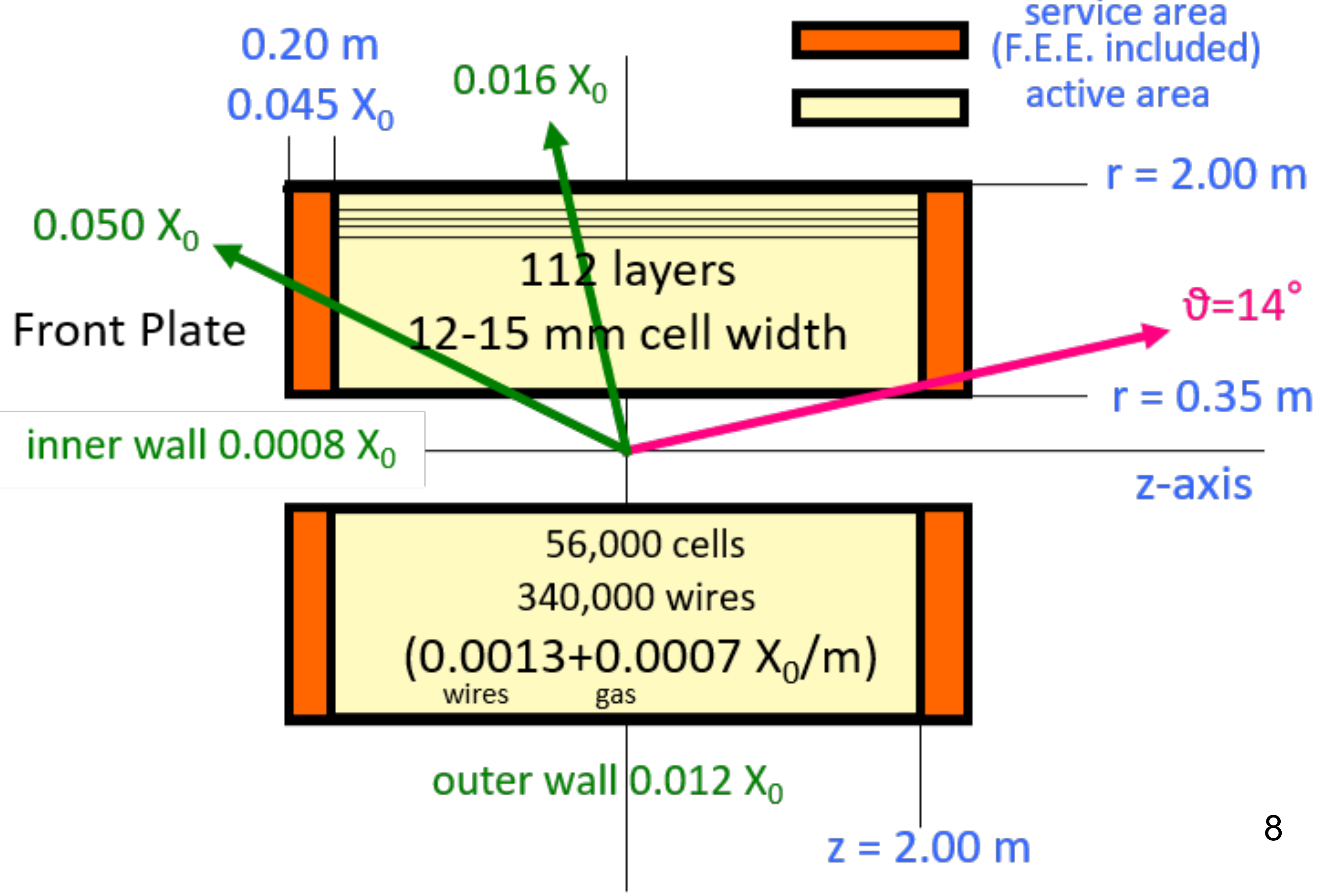


5 : 1 field-to-sense wire ratio



tracking efficiency ε ≈ 1 for ϑ > 14° (260 mrad)
97% solid angle

0.016 X_0 to barrel calorimeter
0.050 X_0 to end-cap calorimeter



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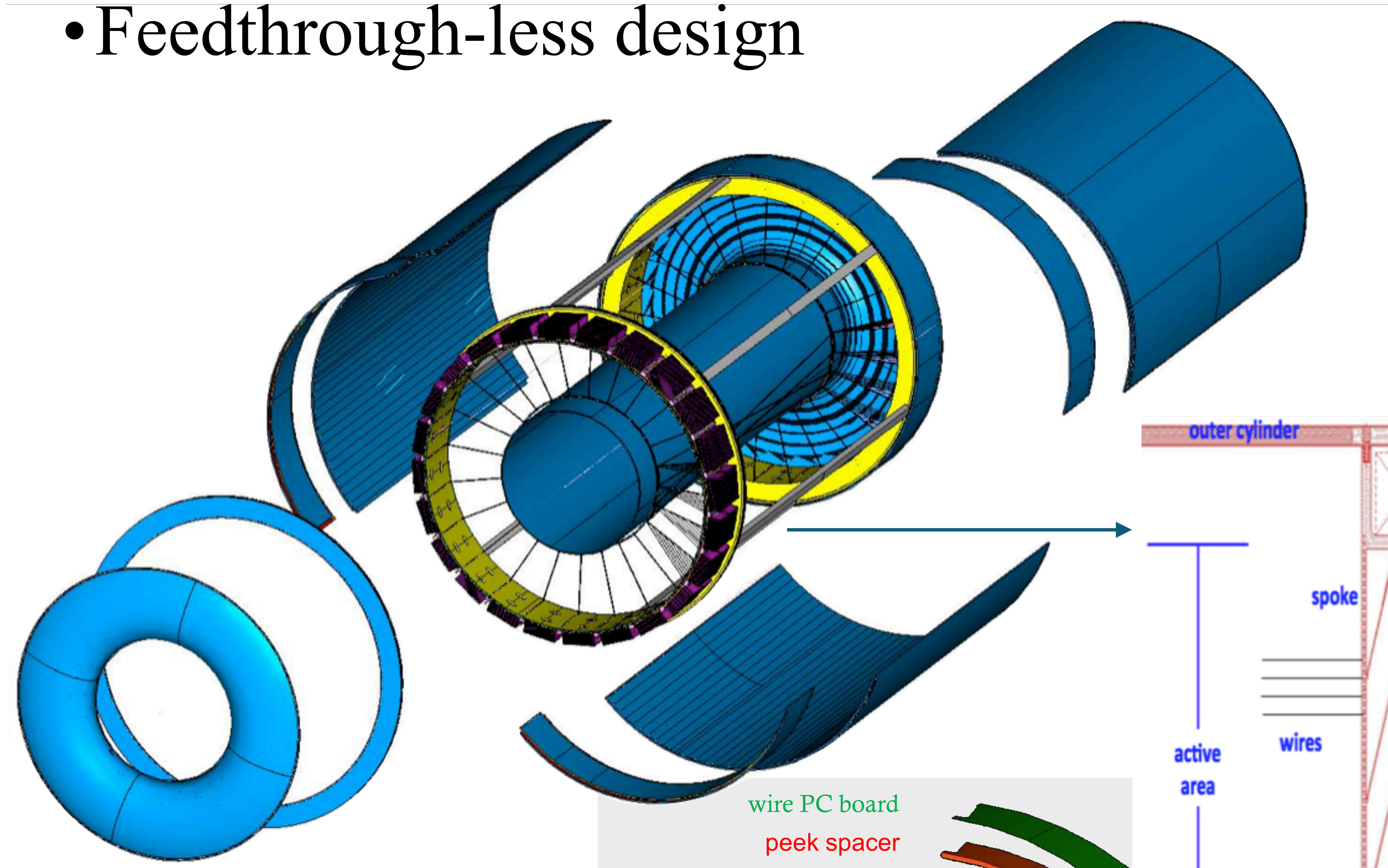
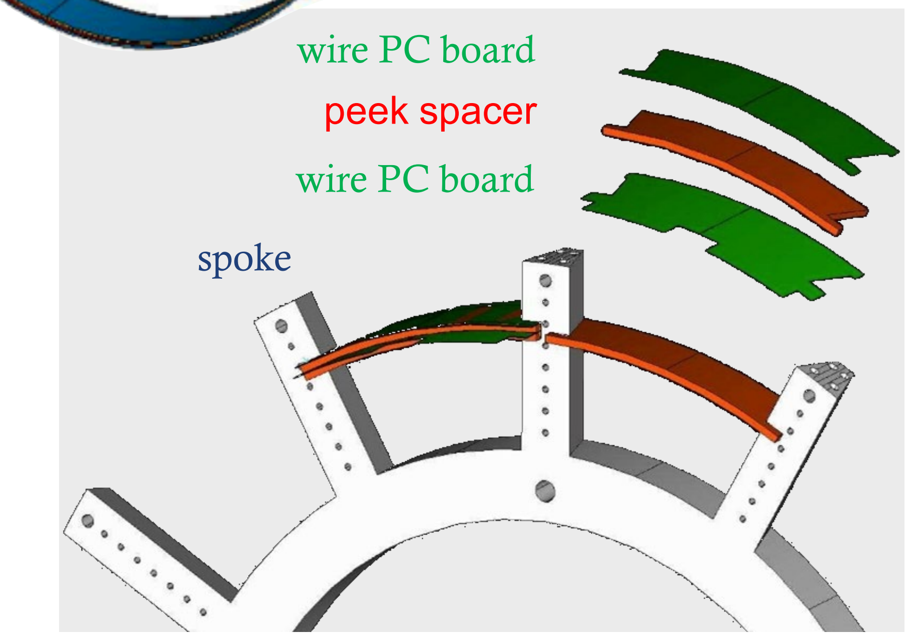
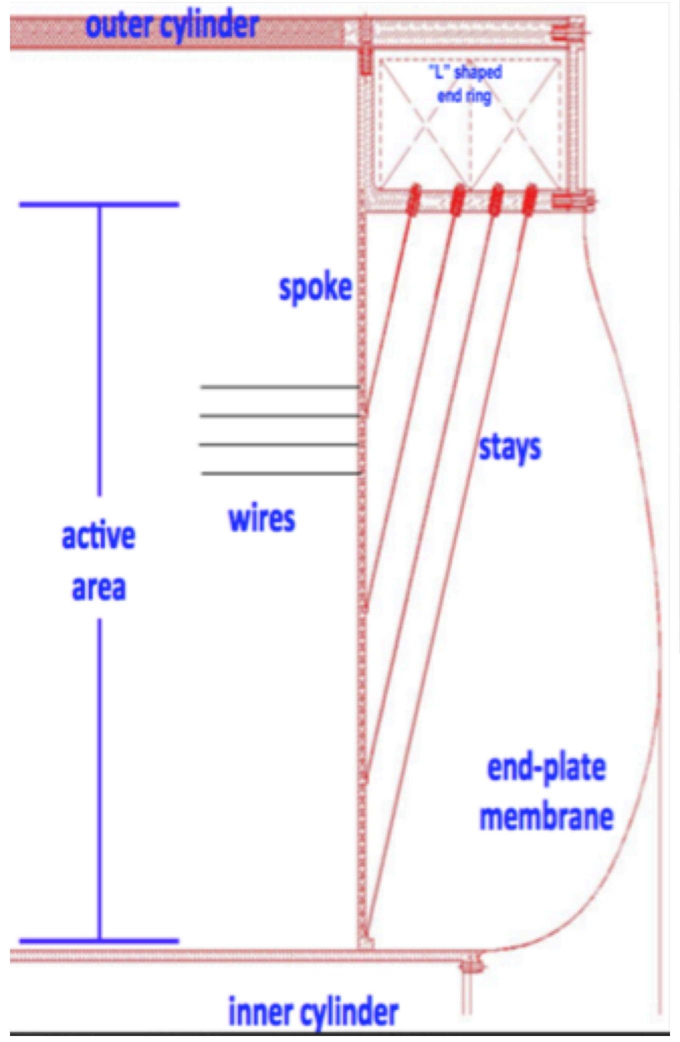
Mechanical design

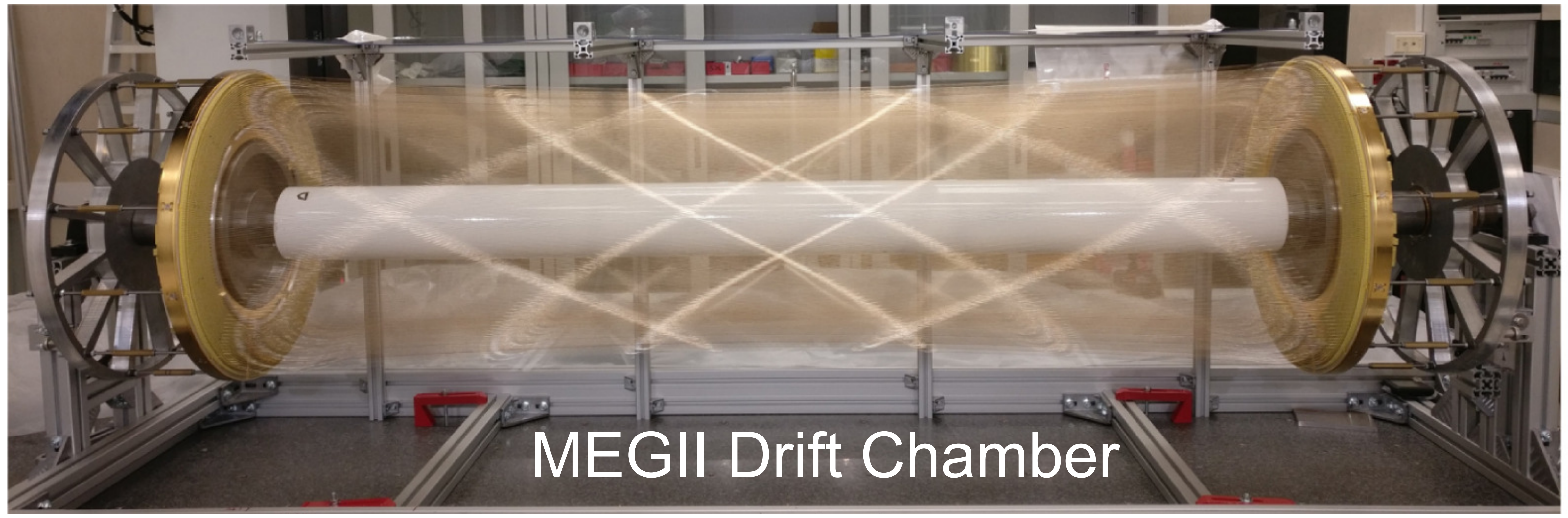
- IDEA DCH **separating wire support**, by counterbalancing the wire tension (external stays) from the gas containment → Ultra-light structure
- Deformations on the Gas vessel have no impact on the wire position
- **New wiring strategy**: inner and outer cylinder connected to 48 spokes, forming 24 identical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







Comparison to MEGII and IDEA DCH	Comparison to BELLEII and IDEA DCH
• 12k → 340k wires • 9 → 112 layers • 2 → 4 m (Even 5m for ALLEGRO)	• 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

- Commissioning and preliminary performance of the MEG II drift chamber

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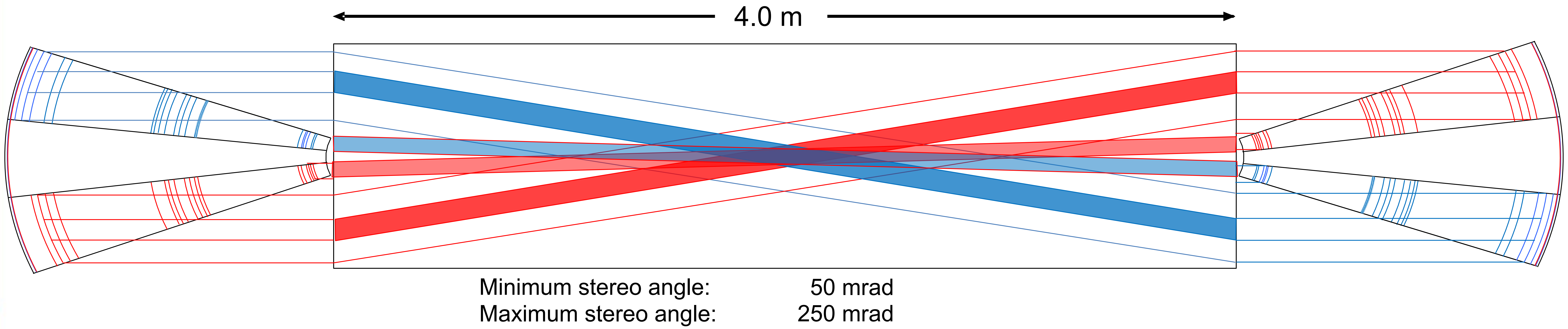
Towards a full length prototype

- Conceptual design of full chamber completed as of today by a collaboration of EnginSoft and INFN-LE mechanical service
- Full design of full-scale prototype completed by summer 2024
  - Preparation of samples of prototype components (molds and machining) ready by fall 2024
  - All mechanical parts (wires, wire PCBs, spacers, end plates) ready by end of 2024
  - MEG2 CDCH2 Wiring robot transported from INFN-PI refurbished and re-adapted, to be operational by spring 2025
  - Prototype built by end of 2025 (+6 months contingency) and ready to be tested during 2026



TOTAL LAYERS: 10
Sense wires: 168
Field wires: 965
Guard wires: 264

Type	Wires	Wire Boards
Sense	168	8
Field	965	22
Guard	264	12
Total	1397	42

From Nicola De Filippis

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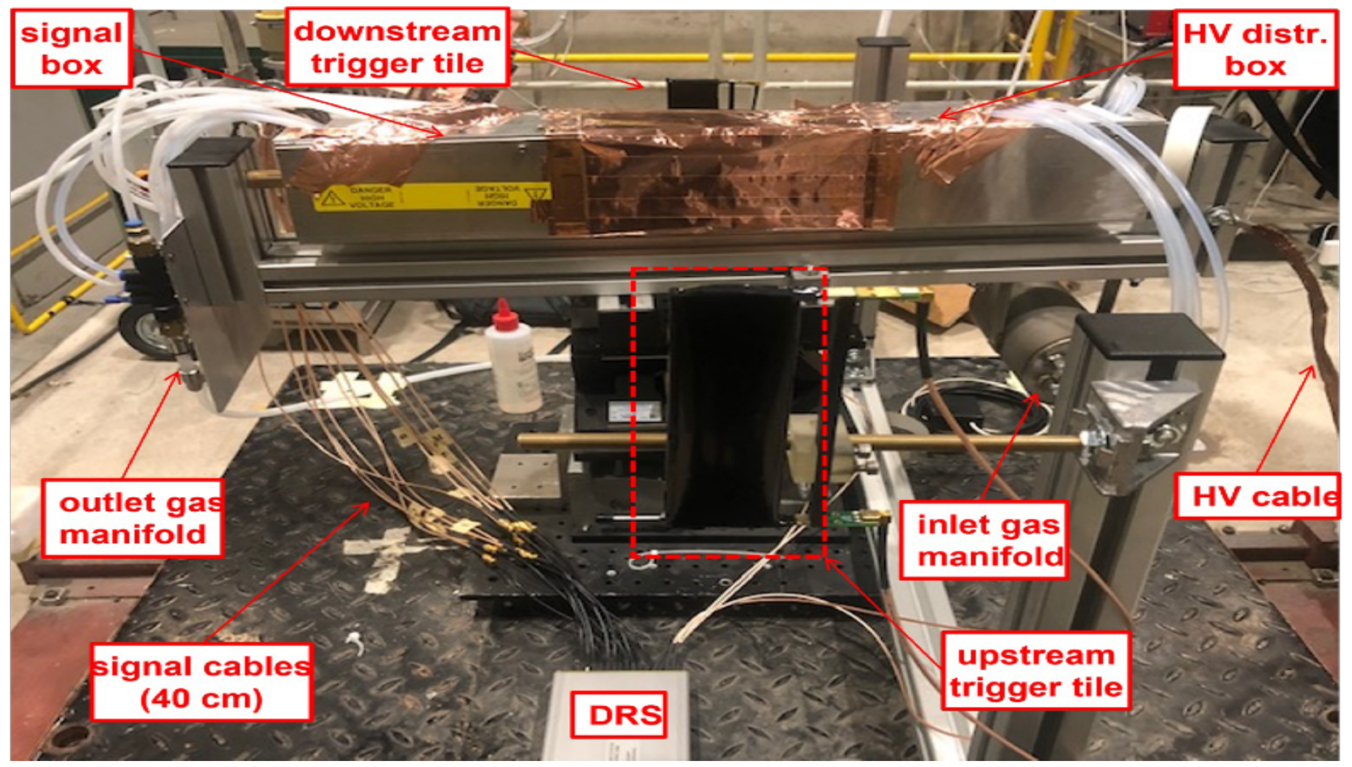
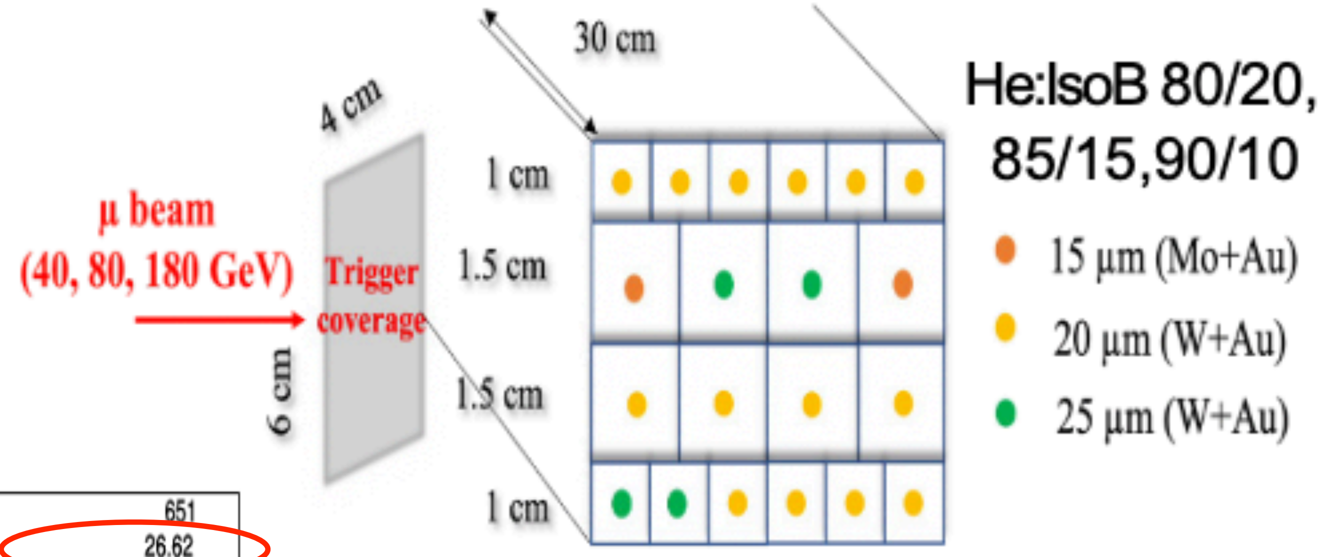
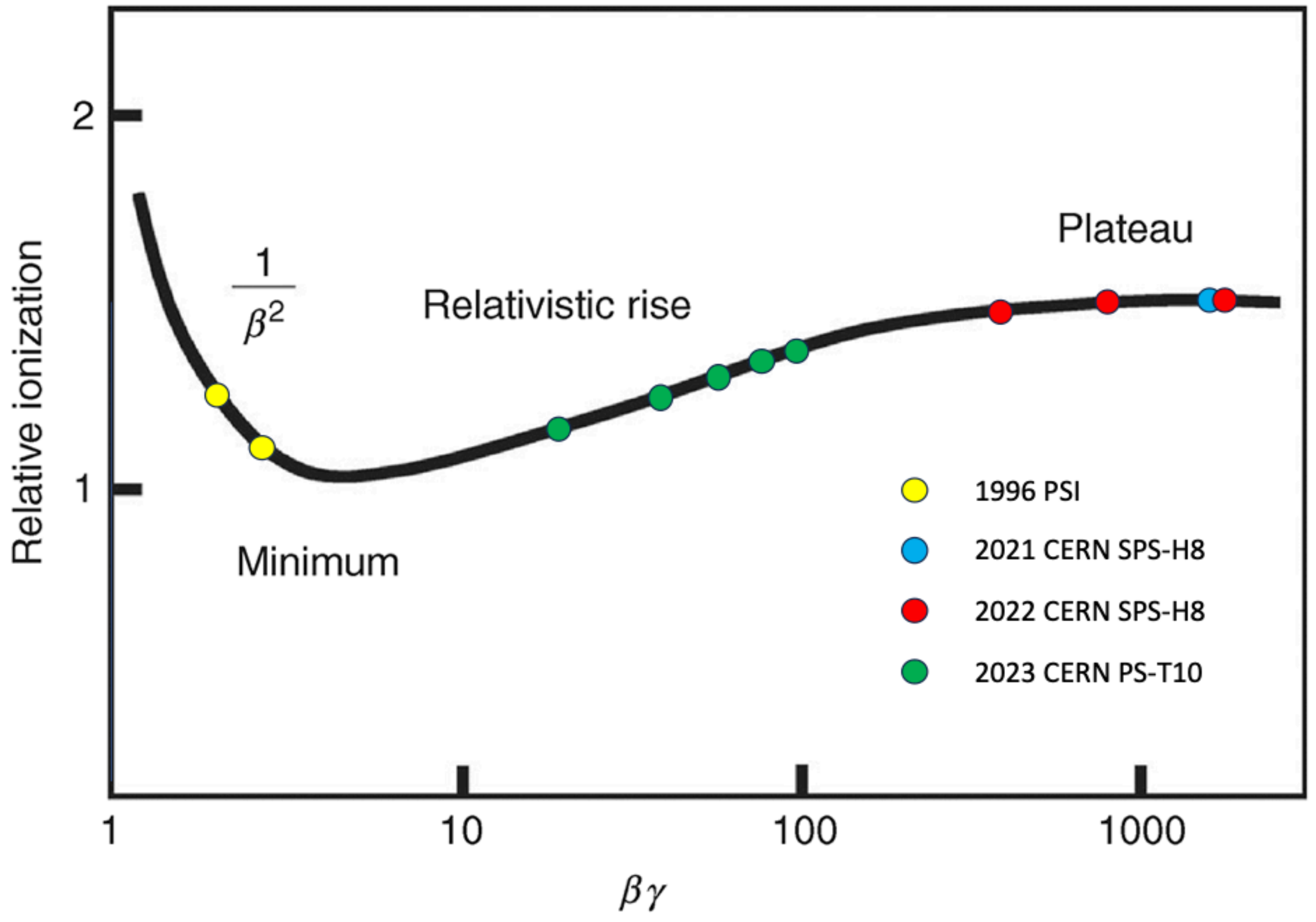
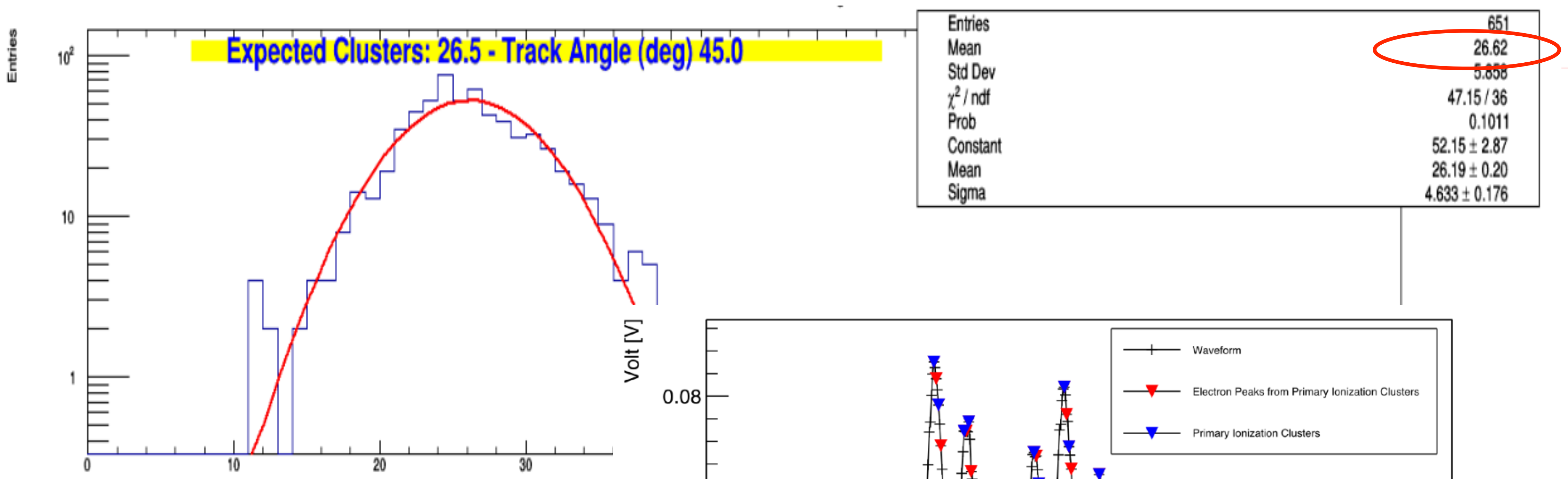
Reconstruction techniques, test-beam results

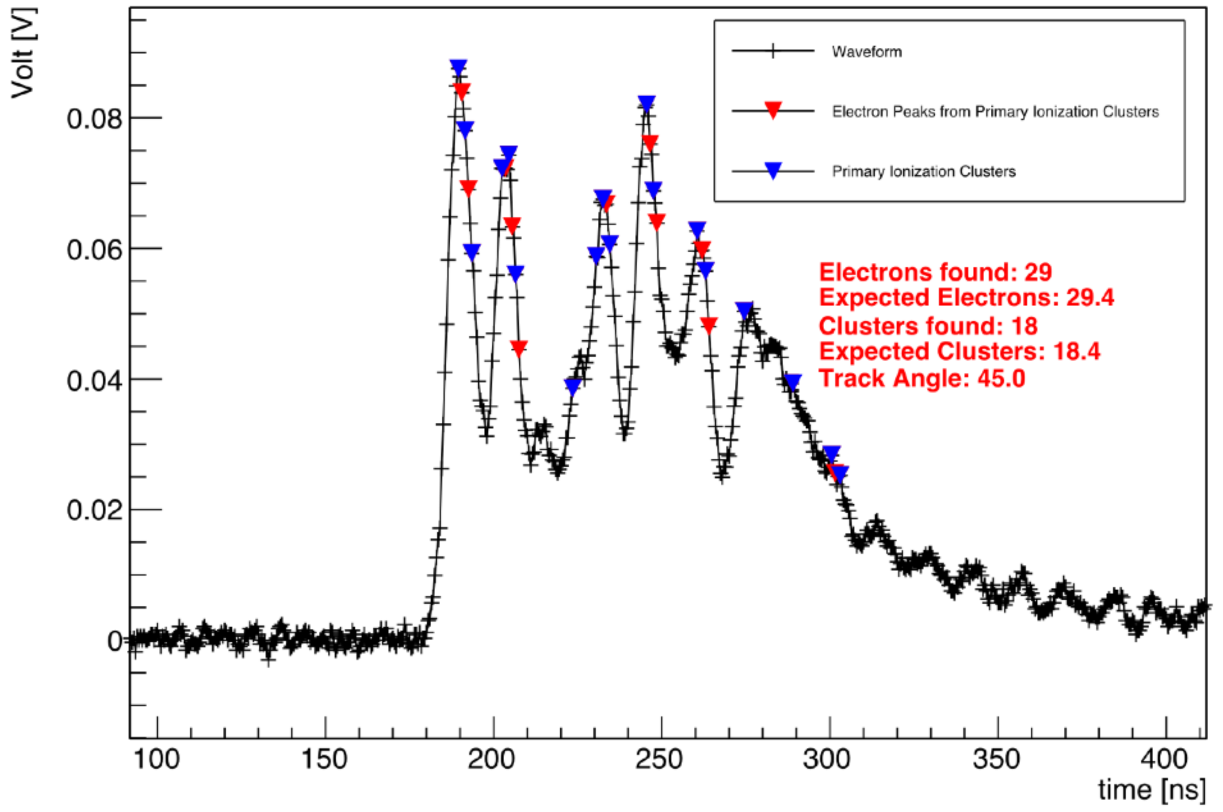
- Several **test beams** to experimentally assess and optimize the performance of the cluster counting/timing techniques covering big range of $\beta\gamma$ range
- **Several algorithms under testing**
  - Derivative Algorithm (DERIV)
  - Running Template Algorithm (RTA)
  - Long short-term memory (LSTM) (Recurrent Neural Network - RNN) for peak finding & Dynamic Graph Convolutional neural networks (DGCNN) to identify electrons in the same primary cluster

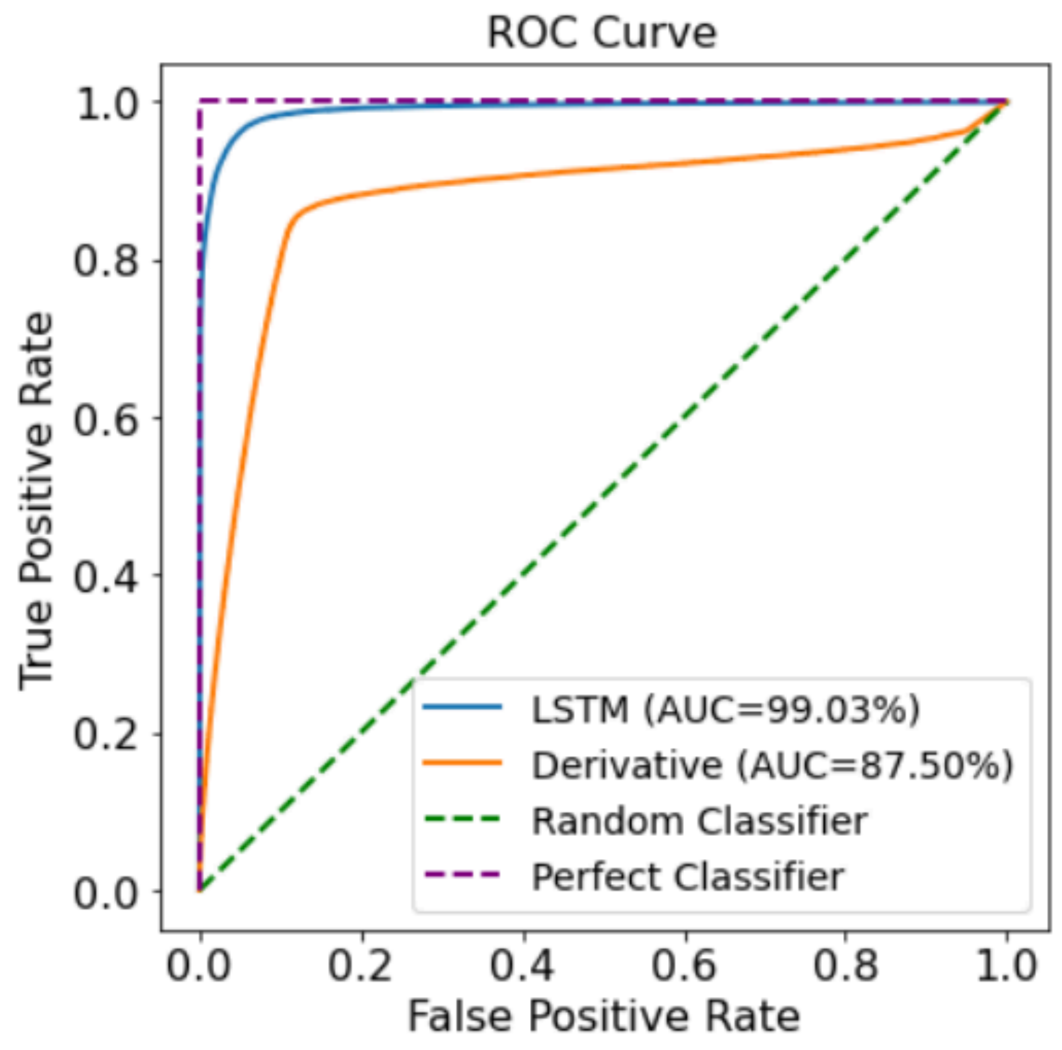












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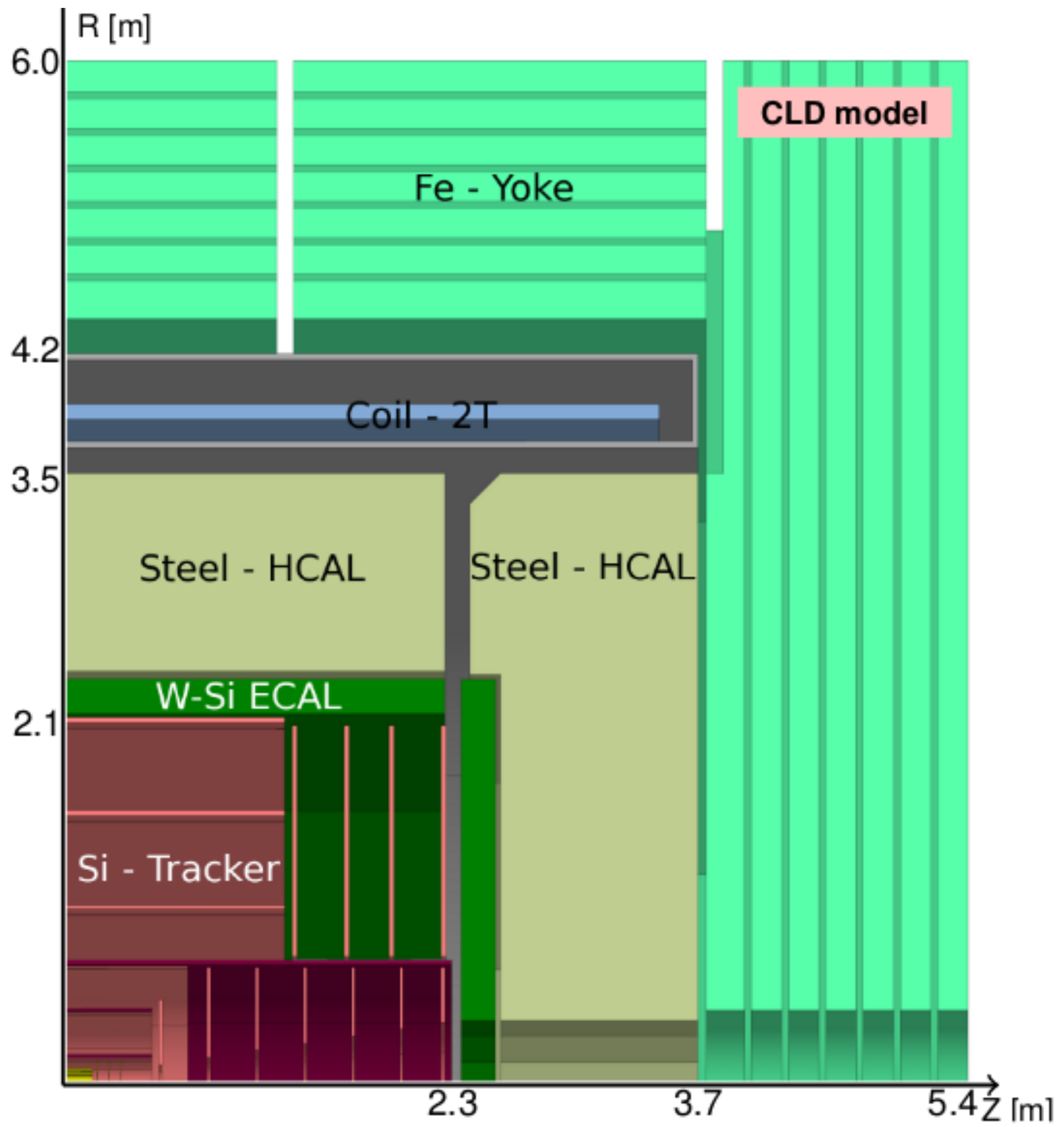
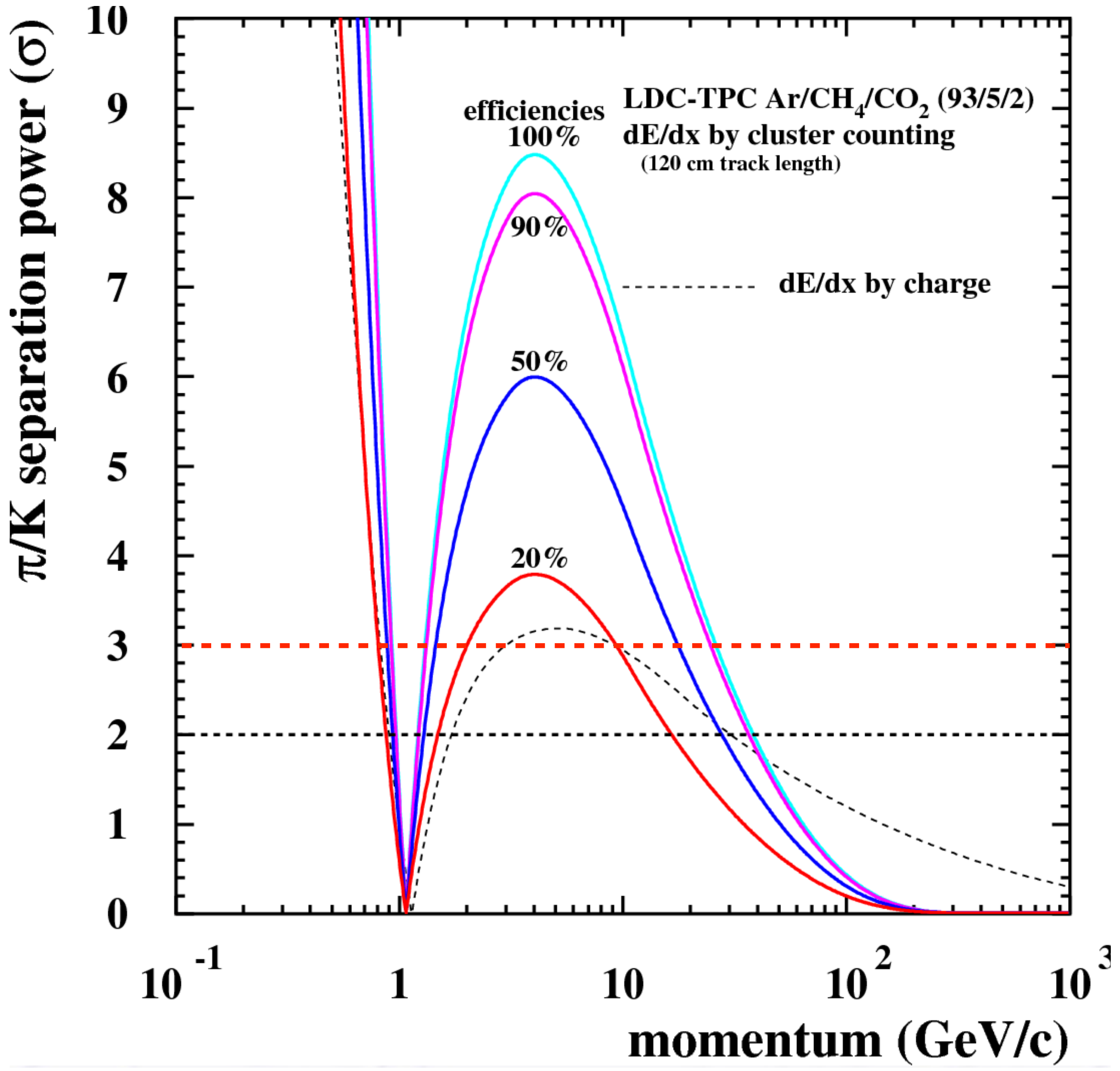
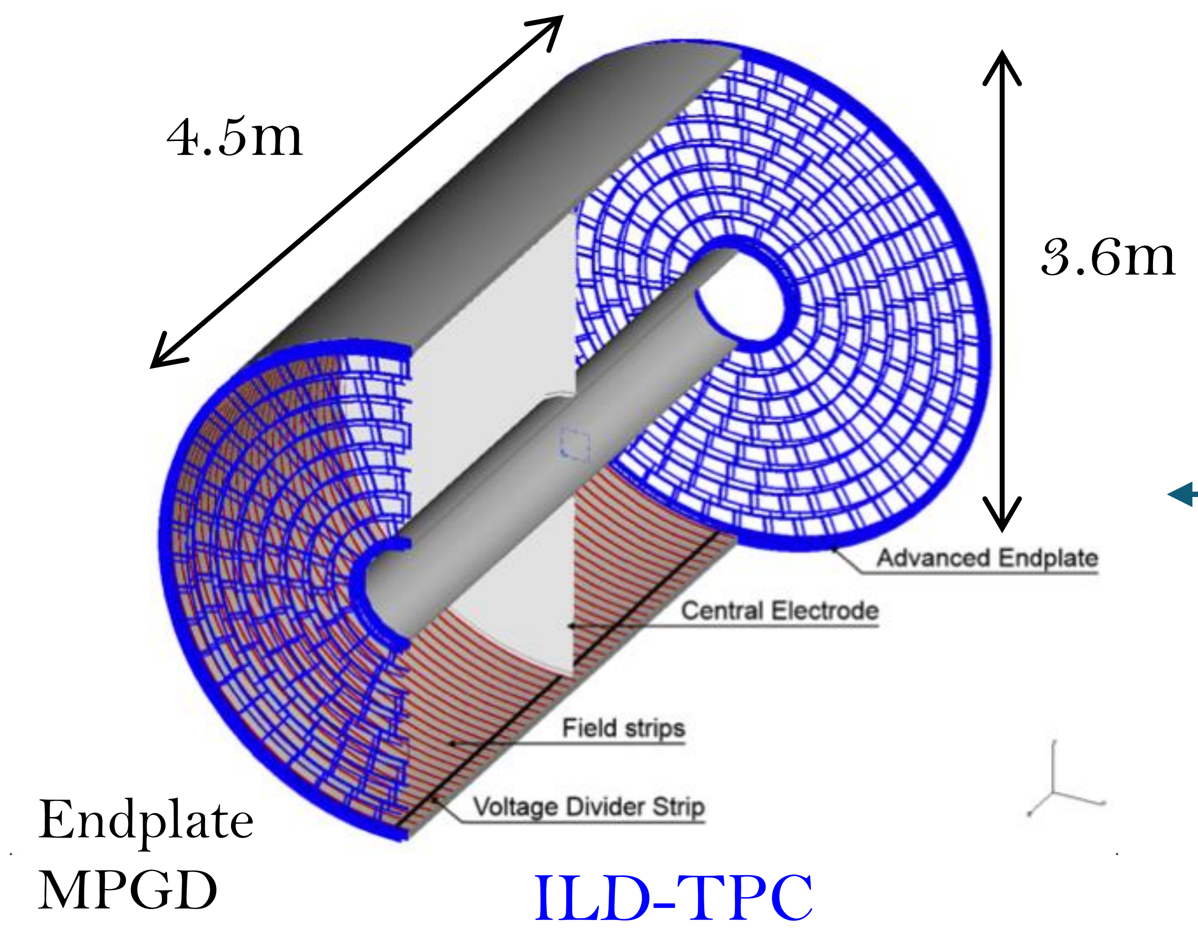
TPC as a main tracker at CLD

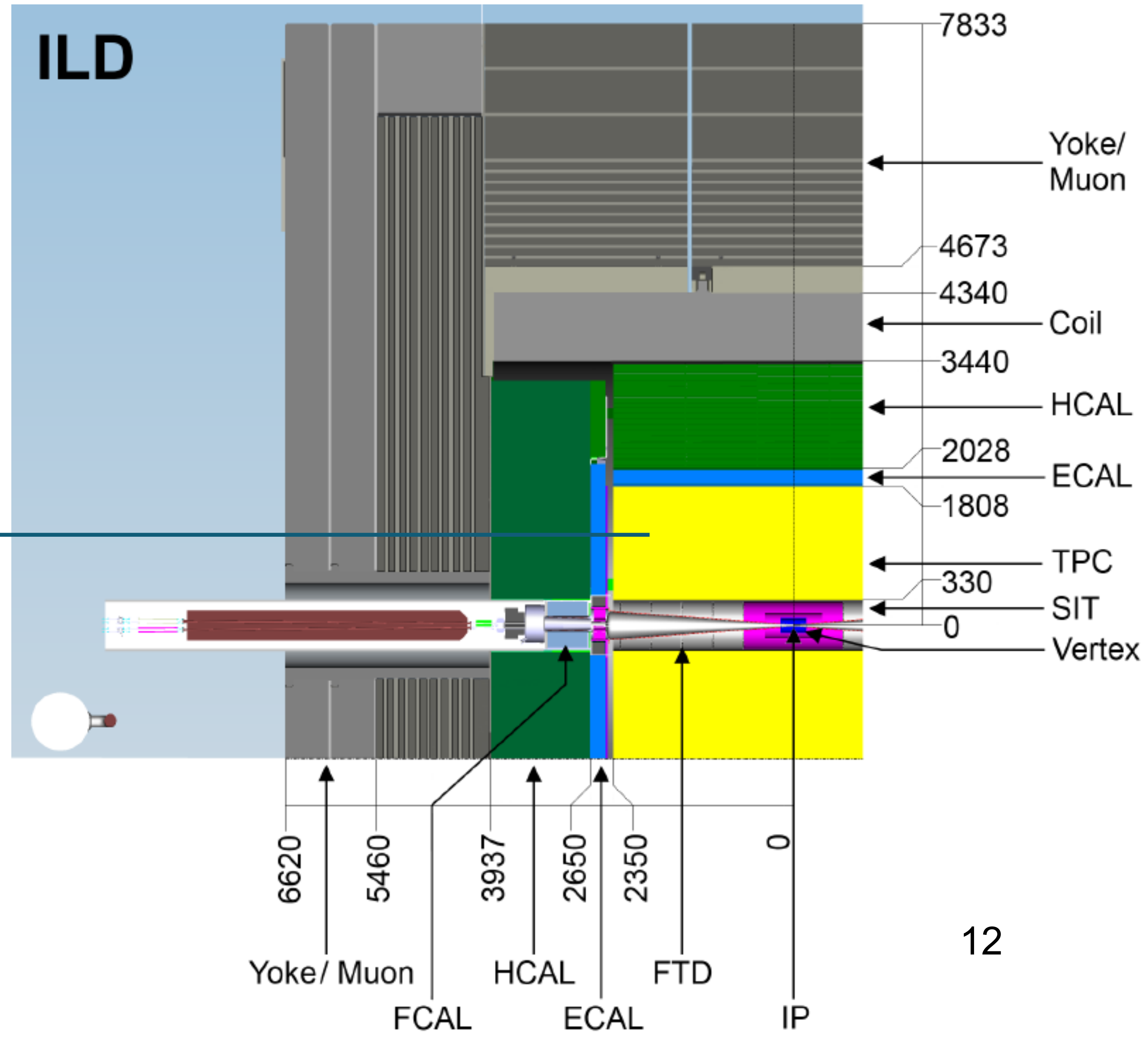
- During the 7th FCC Physics Workshop in Annecy, the ILD/CLD concept studies with a TPC were presented
- Proposal of a TPC based the developments for ILD using MPGDs like Triple/Double GEMs, Resistive Micromegas or GridPix (a must have for dN_{cl}/dx to work)
- 5% X_0 in barrel 25% X_0 in endcap
- **Differences between ILC and FCC-ee operations:**
  - ILC consisting of 1312 bunches (0.73 ms total) in a bunch train spaced every ~0.5μs and a 199 ms with no activity
  - FCC-ee up to 170 times more luminosity at Z-pole with bunch spacing of 20-25ns

➡ Imposes big challenges for a TPC operation



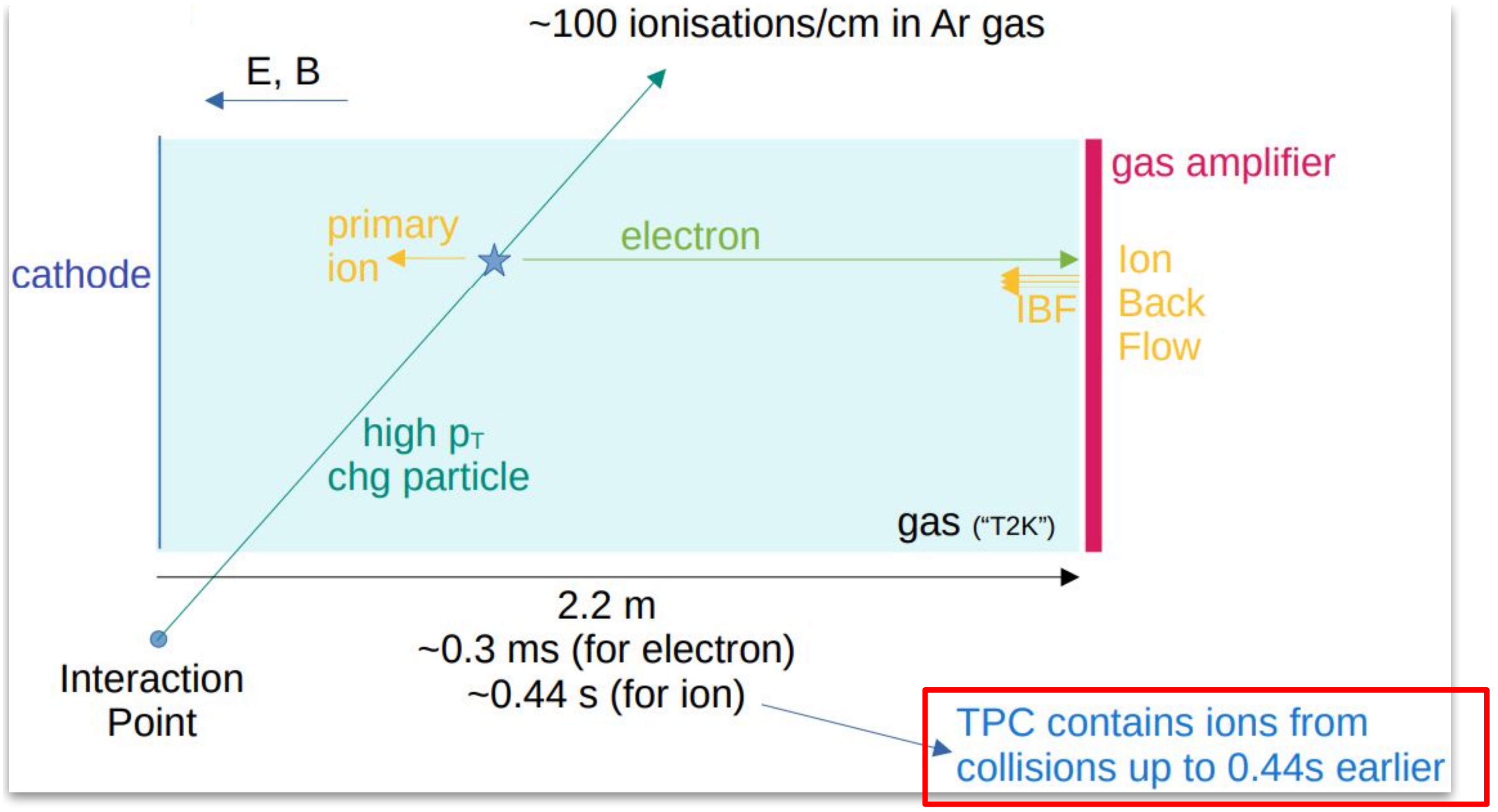






TPC Challenges

- Using a TPC in a triggerless system requires the management of the very large out-of-bunch pile-up and its operation in continuous mode
- At instant luminosity of $\sim 10^{36}$ cm^{-2} s^{-1}, an ion back flow control of percent level (Z bosons will be produced at 60-100 kHz)
  - Distortion can be as large as ~ cm at the inner most TPC layer at the which is orders of magnitude larger than the intrinsic TPC spatial resolution of 100 µm.
  - Ion back flow control technology (InGrid?)
  - Dedicated distortion correction algorithm
  - Adequate track finding algorithm using the vertex detector
  - diffusion plays key role, needs good cluster finding algorithm large systematics expected, e.g. depending on drift length



PRELIMINARY RESULTS!

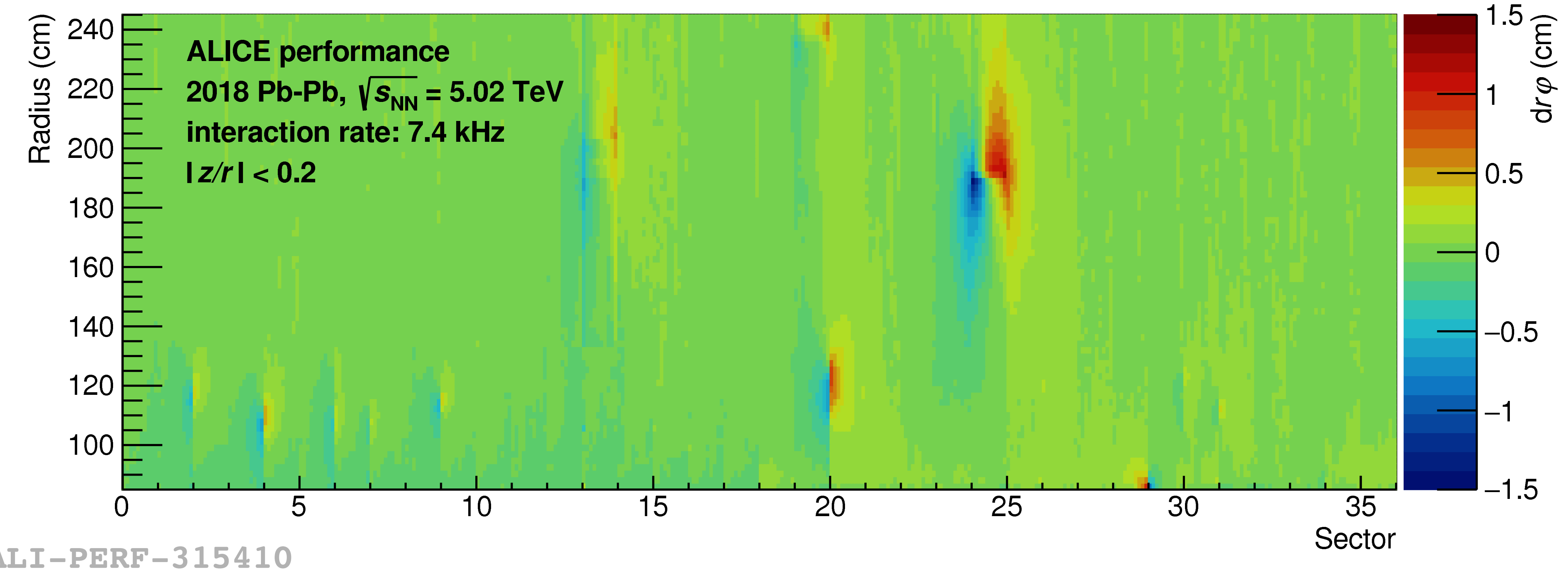
model	B-field [T]	MDI	FCCee-91	FCCee-240	ILC-250
			thousand ions / bunch crossing mean ± RMS		
ILD_l5_v02	3.5 (uniform)	ILC	6.5 ± 19.9	14 ± 14	960 ± 150
ILD_l5_v02_2T	2.0 (uniform)	ILC	6.9 ± 11.1	15 ± 11	4700 ± 300
ILD_l5_v03	3.5 (map)	ILC	5.7 ± 7.9	14 ± 11	1100 ± 200
ILD_l5_v05	3.5 (map, anti-DID)	ILC	0.6 ± 1.5	3.7 ± 9.7	450 ± 110
ILD_l5_v11β	2.0 (uniform)	FCCee	390 ± 120	1000 ± 170	110000 ± 2400
ILD_l5_v11γ	2.0 (map)	FCCee	270 ± 100	800 ± 140	100000 ± 1900

ILC and FCCee similar: O(100k) - O(1M) primary ions / BX

Collider	FCCee-91	FCCee-240	ILC-250
Detector model	ILD_l5_v11γ	ILD_l5_v11γ	ILD_l5_v05
average BX frequency	30 MHz	800 kHz	6.6 kHz
primary ions / BX	270 k	800 k	450 k
primary ions in TPC at any time	1.8×10^{12}	1.4×10^{11}	6.5×10^{8}
average primary ion charge density nC/m^3	6.8	0.54	0.0025

primary ion density in TPC (wrt ILC): x2500 @FCCee-91
x200 @FCCee-240

Space-charge distortions in ALICE TPC at 7.4kHz interaction rate



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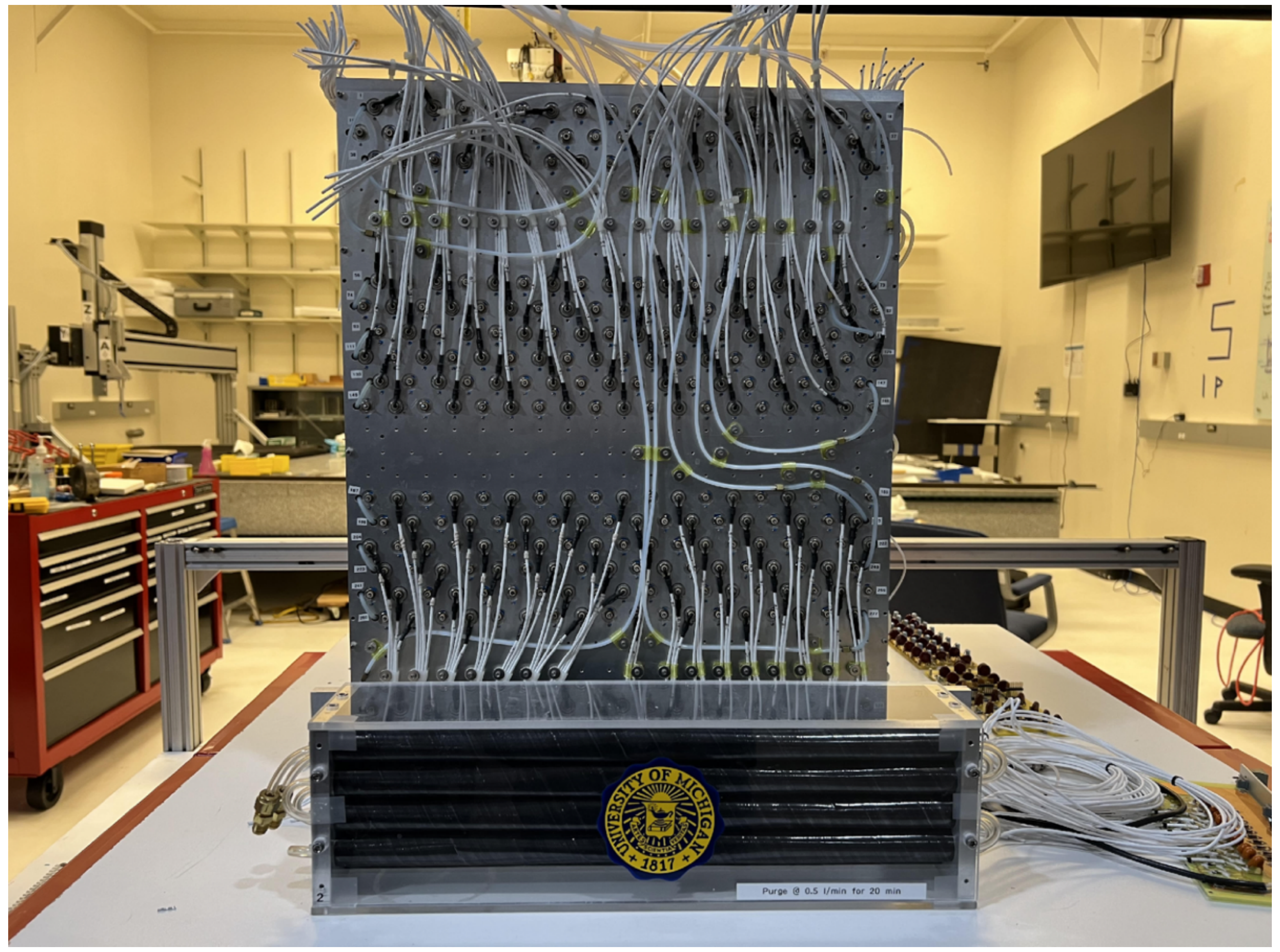
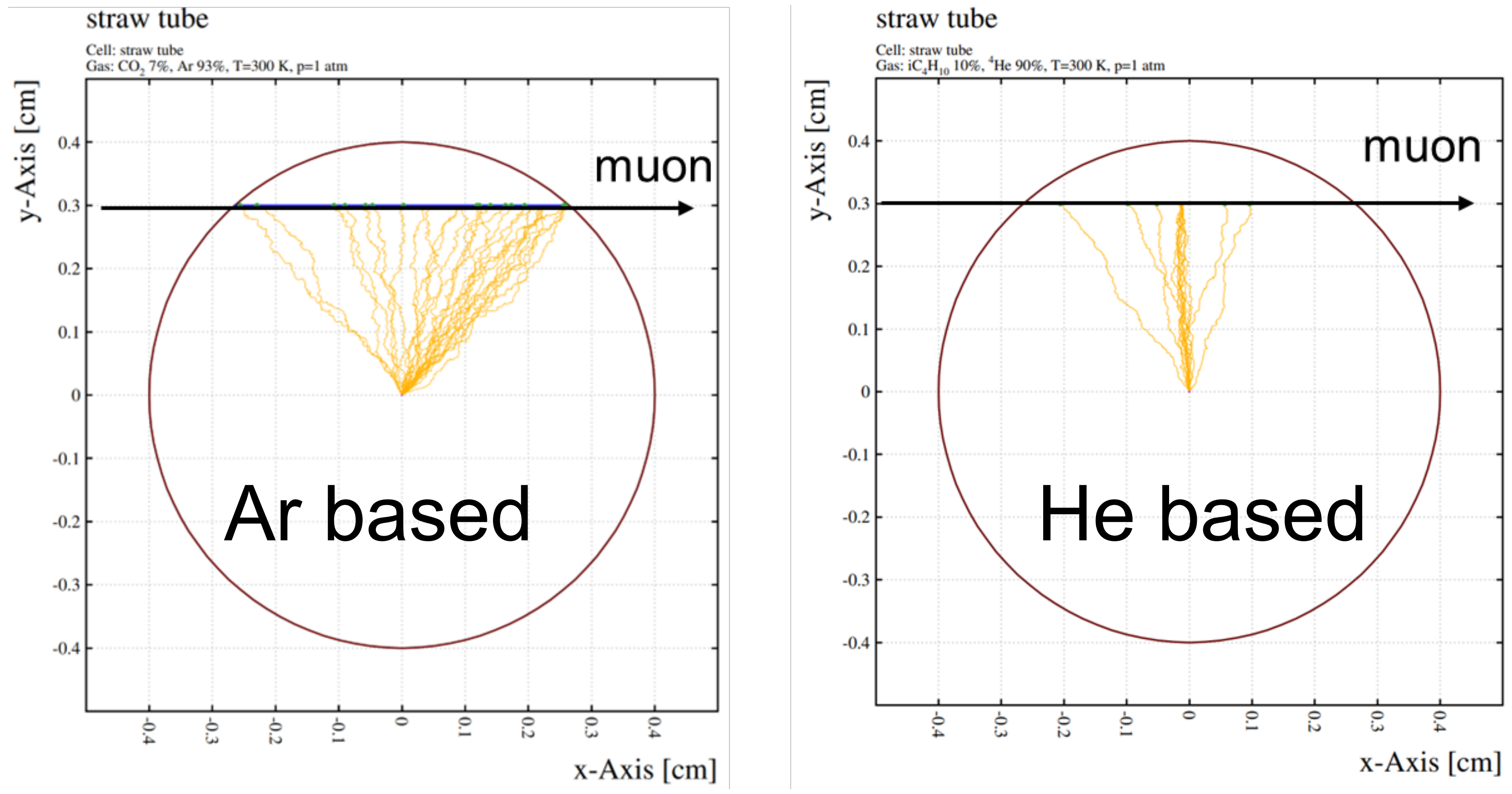
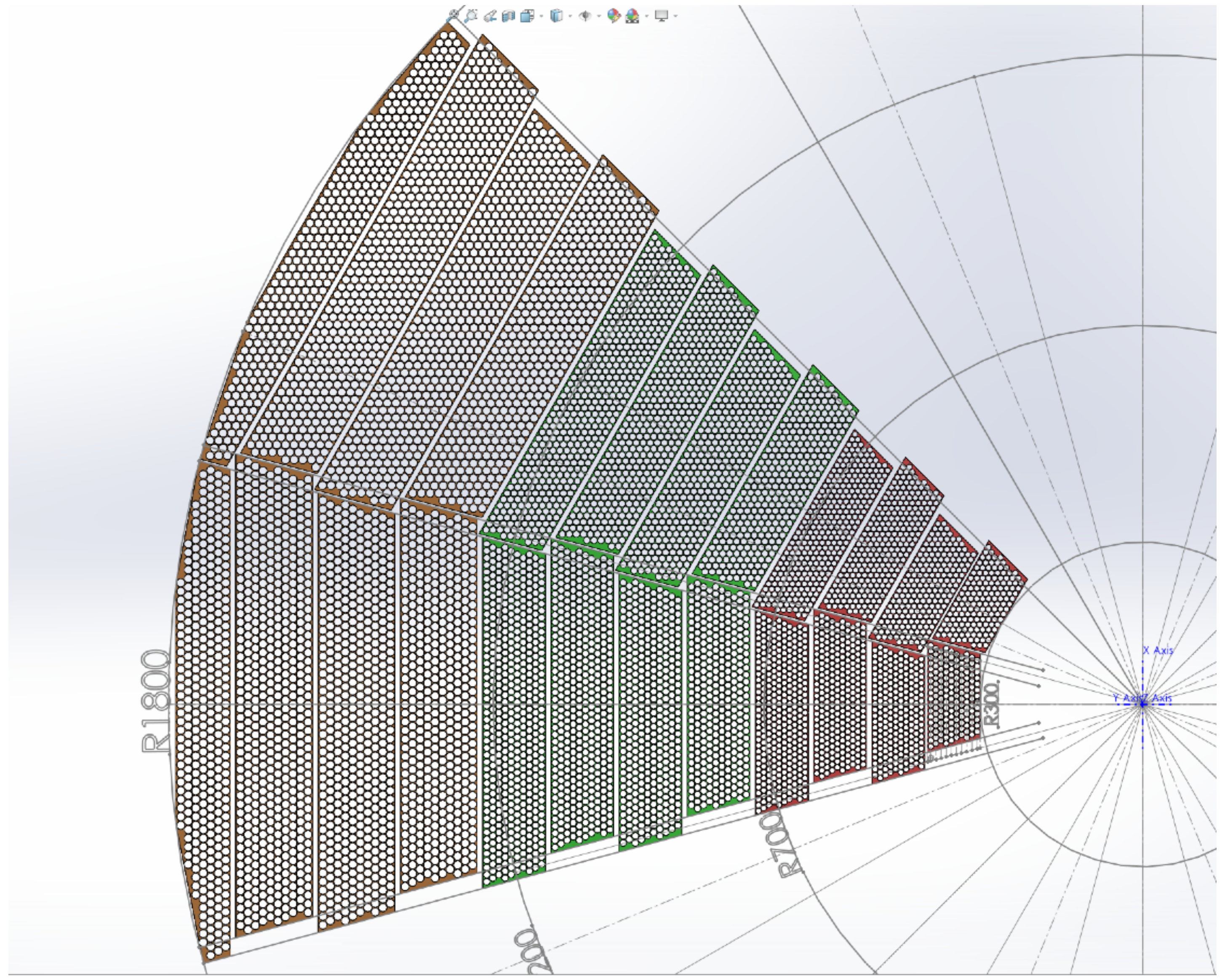
Straw tubes

- Recent proposal to explore the **possibility of a straw tube tracker**
- Variable diameter (inner to outer) → optimise occupancy
- Similar characteristics to drift tubes but lower material budget
  - Assuming **Aluminized Mylar** (15µm mylar, 0.05µm aluminum) and 25µm **tungsten** wires →~1.2% X_0
    - **Not including** mechanical supports on the estimation
    - **Challenging** for long straws of 4m (construction and transmission wise)
      - Termination to improve signal ? Noise ?
  - Operating gas? Ar based →0.15% X_0 not ideal for cluster counting compared to He based →0.035% X_0 , signal small though due to density, optimization is needed!
- Group is looking to build a small prototype with 20-50 straws and perform various studies



A straw tracker at the UM ATLAS muon detector construction lab





More on Junjie's talk on Thursday

Remarks

- Gaseous detectors have a long history as trackers not a surprise that have been proposed for the FCC-ee experiments
- Low material budget is one of the most important factors
  - Light structures, light gas
- $\mathrm{d}E/\mathrm{d}x$ demonstrated over the years, key is volume/pressure
  - $\mathrm{d}N_{\mathrm{cl}}/\mathrm{d}x$ provides improvement ~x2, been around as a method, realization challenging, advanced algorithms and electronics
- Three technologies proposed so far in FCC-ee detectors:
  - Drift chamber: advance layout and design, active group pursuing test beams, in pursue of electronics design and full scale prototype
  - TPC: Recent proposal, inherited from ILC, FCC-ee is rather harsh environment, techniques needed to handle space charge and material budget
  - Straw tubes: Recent proposal as well, promising material budget, prototyping is needed to demonstrate feasibility at the length required

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  - Drift chamber: advance layout and design, active group pursuing test beams, in pursue of electronics design and full scale prototype
  - TPC: Recent proposal, inherited from ILC, FCC-ee is rather harsh environment, techniques needed to handle space charge and material budget
  - Straw tubes: Recent proposal as well, promising material budget, prototyping is needed to demonstrate feasibility at the length required
- Important for any technology to learn from existing applications !

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I believe that all these challenges are what makes it fun to pursue !

Backup

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

= 0.5 TB/s

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

⟹ Transfer rate at Z-pole ≳ **1 TB/s!**

some data reduction is mandatory!

SOLUTION

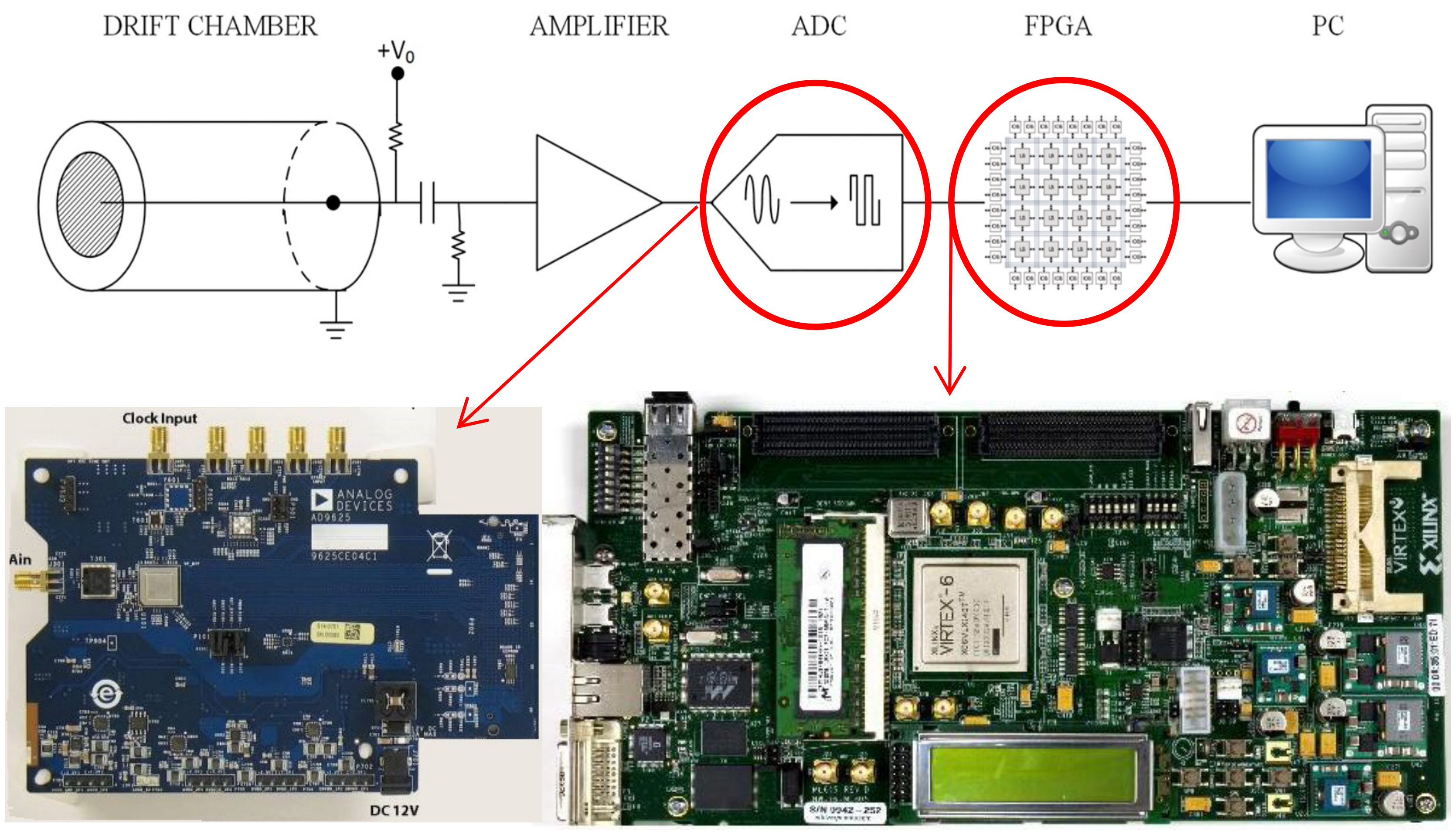
A possible solution consists in transferring, for each hit drift cell, only the minimal information relevant to the application of the cluster timing/counting techniques, i.e.: **amplitude** and **arrival time** of each peak associated with each individual ionization electron, instead of the full digitized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

20 track/event × 130 cell/track/side × 2 side × 10^5 event/s × 30 peaks/cell × 2 byte/peak =

= 30 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

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Data throughput manageable but careful assessment is need for a trigger-less or triggered operations !