A large Drift Chamber with Cluster Counting

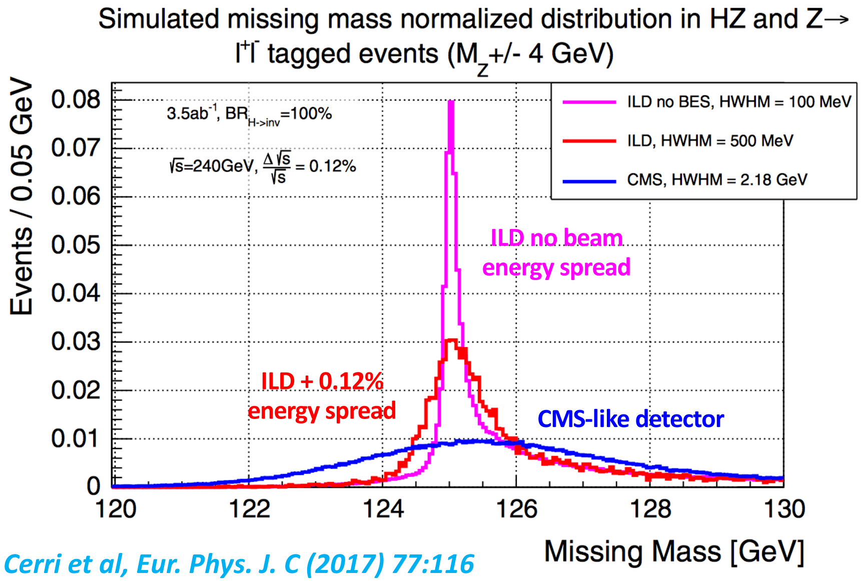
The IDEA Drift Chamber at FCC-ee and CEPC

F. Grancagnolo
INFN – Lecce, ITALY

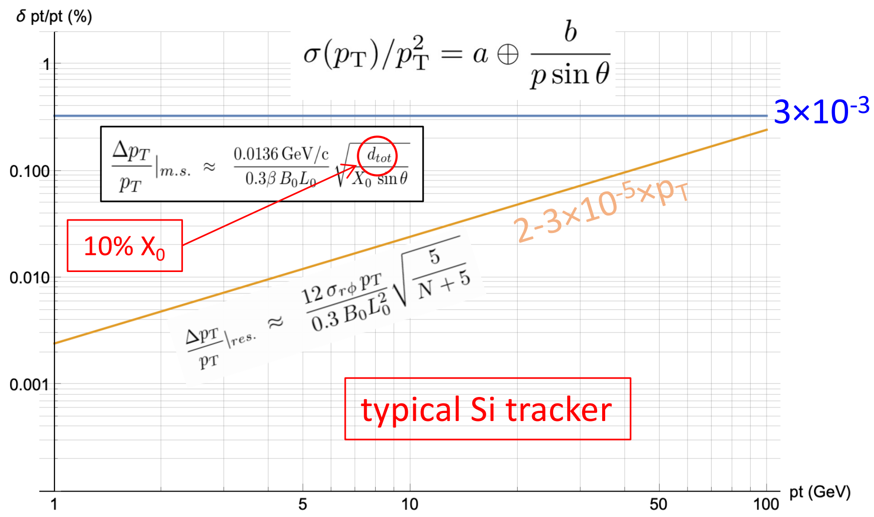
FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

21–23 Nov 2022 - IP2I Lyon

Requirements: momentum resolution



Cerri et al, Eur. Phys. J. C (2017) 77:116



Drasal, Riegler, https://doi.org/10.1016/j.nima.2018.08.078

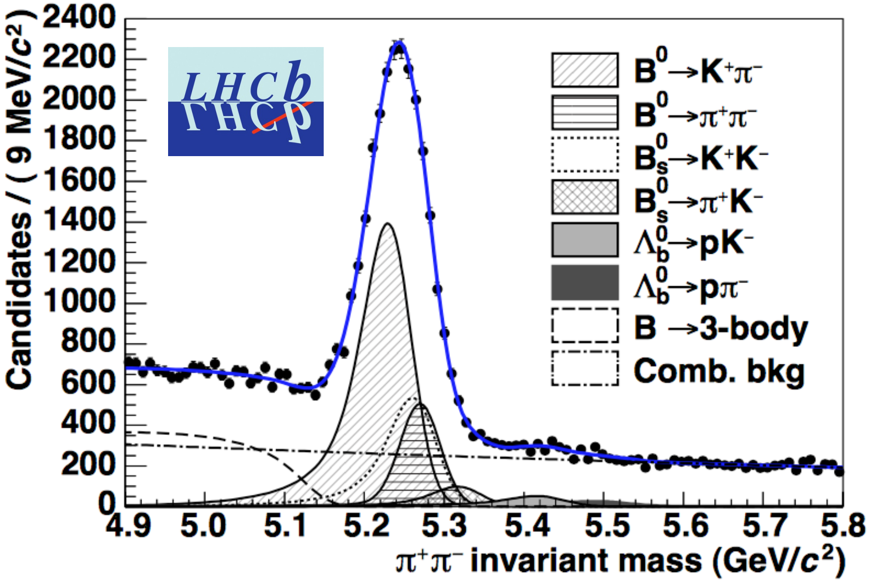
$$\sigma_{p_T}/p_T^2 \approx 2\times10^{-5}\ (GeV/c)^{-1}$$

PID mandatory to disentangle same topology final states.

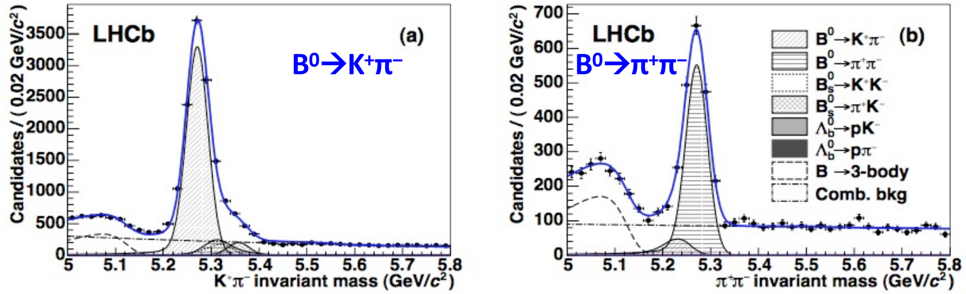
Example: 2-prongs B-decays

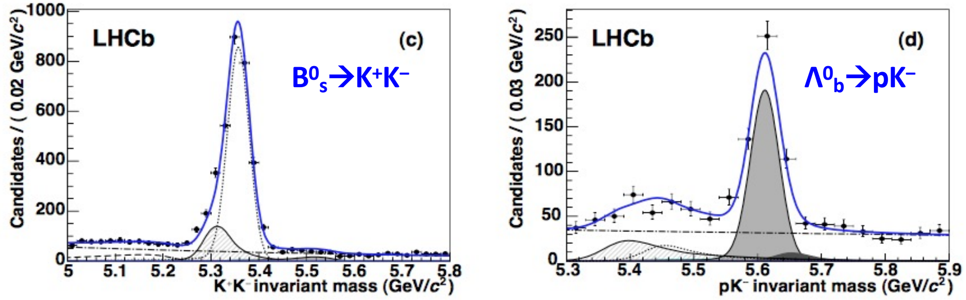
LHCb - JHEP 10 (2012) 037

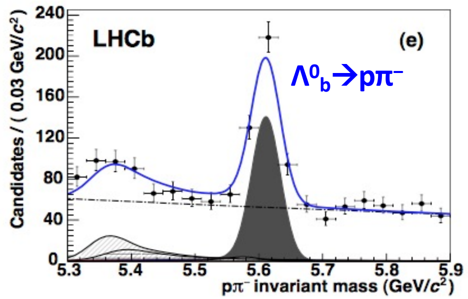
Without PId



with PId





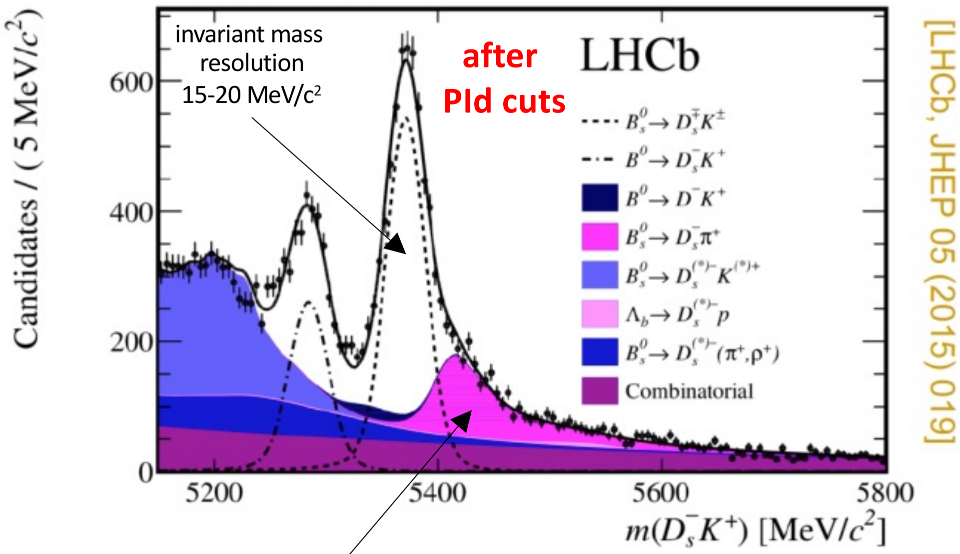


PId cut efficiency and misidentification

	$\pi^+\pi^-$	K^+K^-	$K^+\pi^-$	$p\pi^-$	pK^-
$B^0 \to \pi^+\pi^-$	43.1	0.33	28.6	1.53	0.13
$B_s^0 \to K^+K^-$	0.05	55.0	15.4	0.05	1.63
$B_{(s)}^0 \to K^+\pi^-$	1.40	4.17	67.9	0.72	0.06
$\bar{B}_{(s)}^0 \to \pi^+K^-$	1.40	4.17	2.09	0.02	0.85
$\Lambda_b^0 \to p\pi^-$	1.93	0.92	16.8	35.4	3.16
$\bar{\Lambda}_b^0 \to \pi^+\bar{p}$	1.93	0.92	0.95	0.03	0.18
$\Lambda_b^0 \to pK^-$	0.06	12.2	1.92	1.18	40.2
$\bar{\Lambda}_b^0 \to K^+\bar{p}$	0.06	12.2	4.51	0.03	0.18

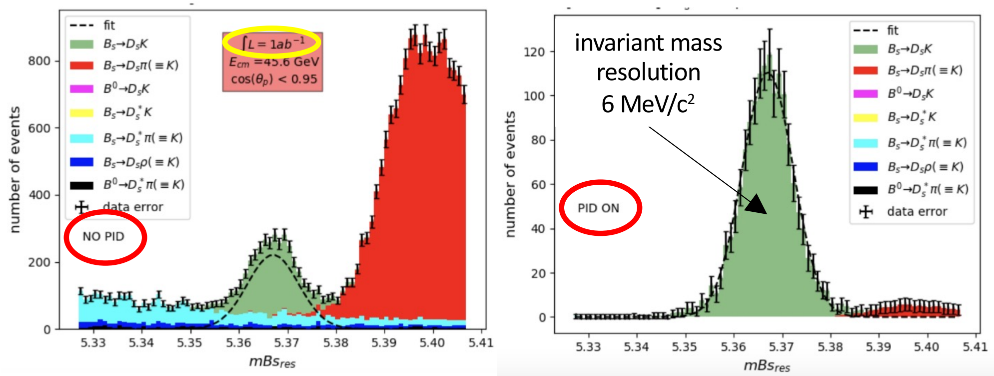
Requirements: particle identification

Example: $B_s^0 \to D_s^{\mp} K^{\pm}$



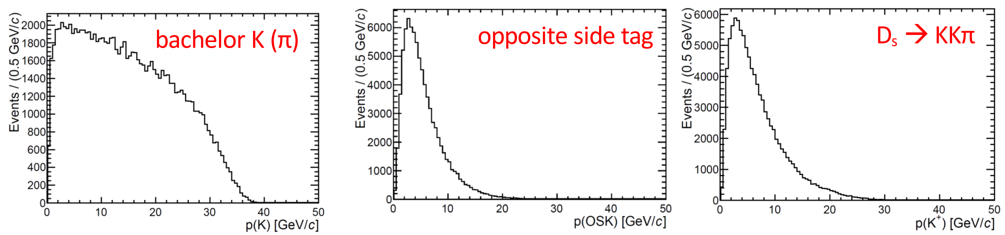
$B_s^0 \to D_s^- \pi^+$
contribution reduced by a factor x10
(60% efficiency – 1% contamination)

R. Aleksan , L. Oliver and E. Perez - arXiv:2107.02002v1 [hep-ph] 5 Jul 2021



PID at 5% and TOF at 100 ps

Range of momenta



Physics and Tracking Requirements

- Large **angular coverage**
- High **angular resolution** ($\Delta\vartheta \leq 0.1$ mrad for monitoring beam spread ($Z \rightarrow \mu\mu$))
- High **granularity** (to cope with occupancy at inner radii)
- High **tracking efficiency**
- High **momentum resolution**
  $\delta p/p^2 \leq$ few x 10^{-5}, small wrt 0.12% beam spread for
  - Higgs mass recoil
  - cLFV processes like $Z \rightarrow e\mu$,$e\tau$, $\mu\tau$ (BR ≈ $10^{-54} - 10^{-60}$)
    current exp. limits ($\leq 10^{-6}$) can be improved by > 5 orders of magnitude
- High capabilities for **Particle Identification** (dE/dx resolutions $\lesssim$ 3%)
  - Flavor Physics
  - CPV ($B_s \rightarrow D_s K$)
  - $A_{FB}(b)$, exclusive b-hadron decays reconstruction
  - Hadron spectroscopy
- High **V^0 and kink** capability for CPV (CP eigenstates usually long-lived particles)

Not just another large volume drift chamber, but an **ultra-light** drift chamber with unprecedented **particle identification** capabilities

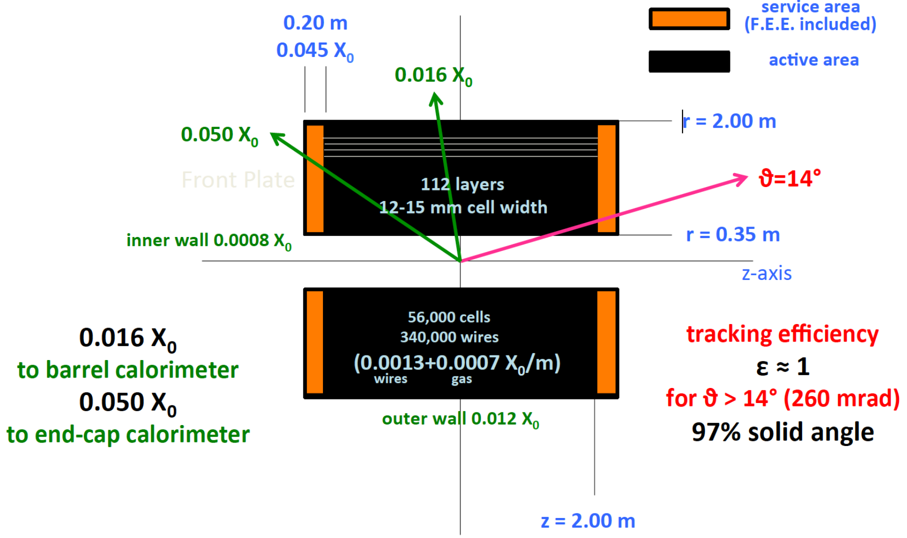
Genesis and evolution

- **Mark2 and Mark3** drift chambers at SLAC in the '80s
- **KLOE** ancestor chamber of a new He-based generation at INFN LNF Daφne ϕ factory (commissioned in 1998 and efficiently operated for over 20 years)
- **CMD-2** drift chamber at VEPP-2000 (2006, still in operation)
- **CluCou** chamber proposed for the **4th-Concept** at ILC (2009)
- **I-tracker** chamber proposed for the **Mu2e experiment** at Fermilab (2012)
- **CDCH** for **MEG2** at PSI (designed in 2014, built in 20128 and currently in data taking mode since 2021)
- **IDEA** drift chamber proposal for FCC-ee and CEPC (2017)

Innovations

- New mechanical assembly procedure by separating the **gas containment** from the **wire support** functions
- New concepts for **wire tension compensation** resulting in end caps with a 5% X_0 (including front end electronics and cables)
- A **larger number** of **thinner** (and **lighter** wires) resulting in less total stress on end plates
- No use of massive **feed-through**
- Use of **cluster counting** for particle identification
- Use of **cluster timing** for improving spatial resolution

Drift Chamber Layout and Material Budget

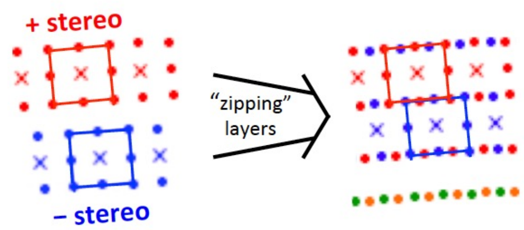


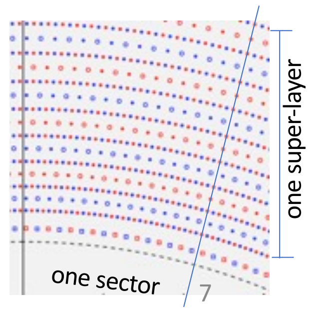
Conservative estimates on Material Budget

- Inner wall (from CMD3 drift chamber) — 8.4×10^{-4} X_0
  200 µm Carbon fiber
- Gas (from KLOE drift chamber) — 7.1×10^{-4} X_0/m
  90% He – 10% iC_4H_{10}
- Wires (from MEG2 drift chamber) — 1.3×10^{-3} X_0/m
  20 µm W sense wires 4.2×10^{-4} X_0/m
  40 µm Al field wires 6.1×10^{-4} X_0/m
  50 µm Al guard wires 2.4×10^{-4} X_0/m
- Outer wall (from Mu2e I-tracker studies) — 1.2×10^{-2} X_0
  2 cm composite sandwich (7.7 Tons)
- End-plates (from Mu2e I-tracker studies) — 4.5×10^{-2} X_0
  wire cage + gas envelope
  incl. services (electronics, cables, ...)

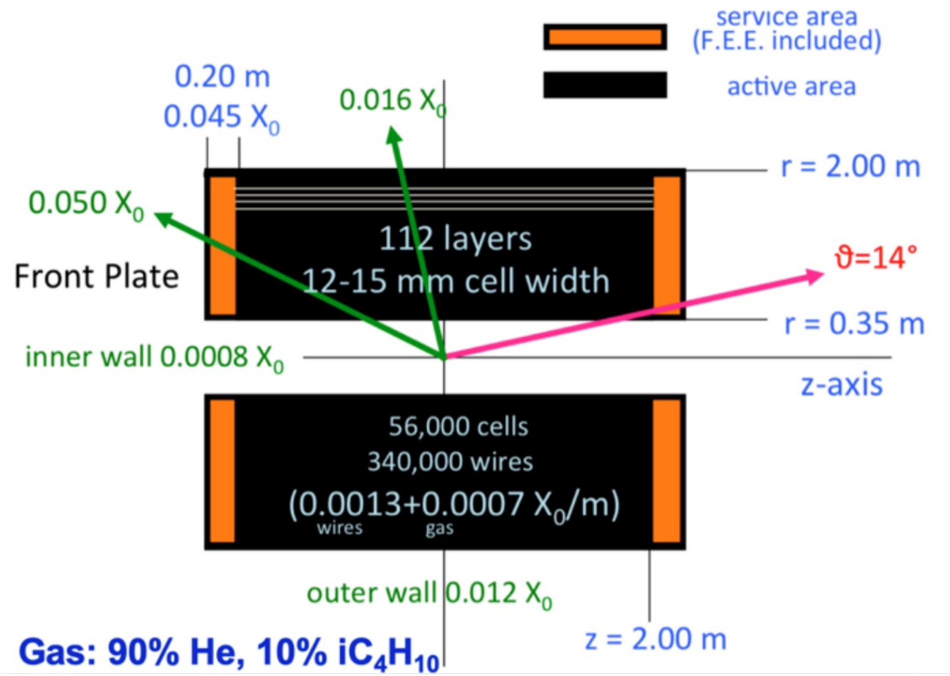
12 to 15 mm wide square cells, 5:1 field to sense wires ratio, 56,448 cells

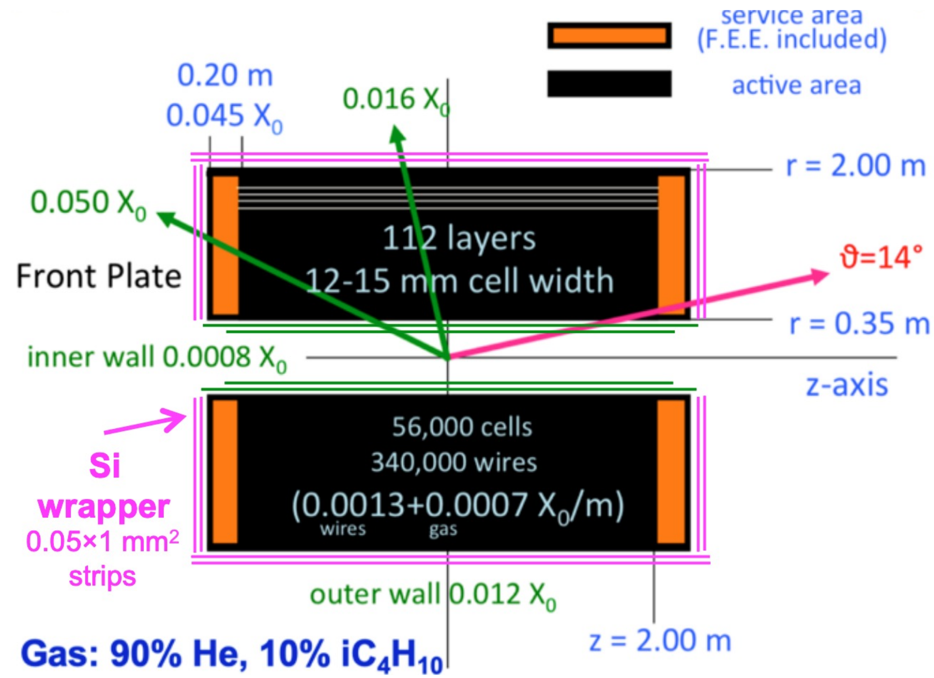
14 co-axial super-layers, 8 layers each (112 total) with alternating sign stereo angles ranging from 50 to 250 mrad, in 24 equal azimuthal (15°) sectors



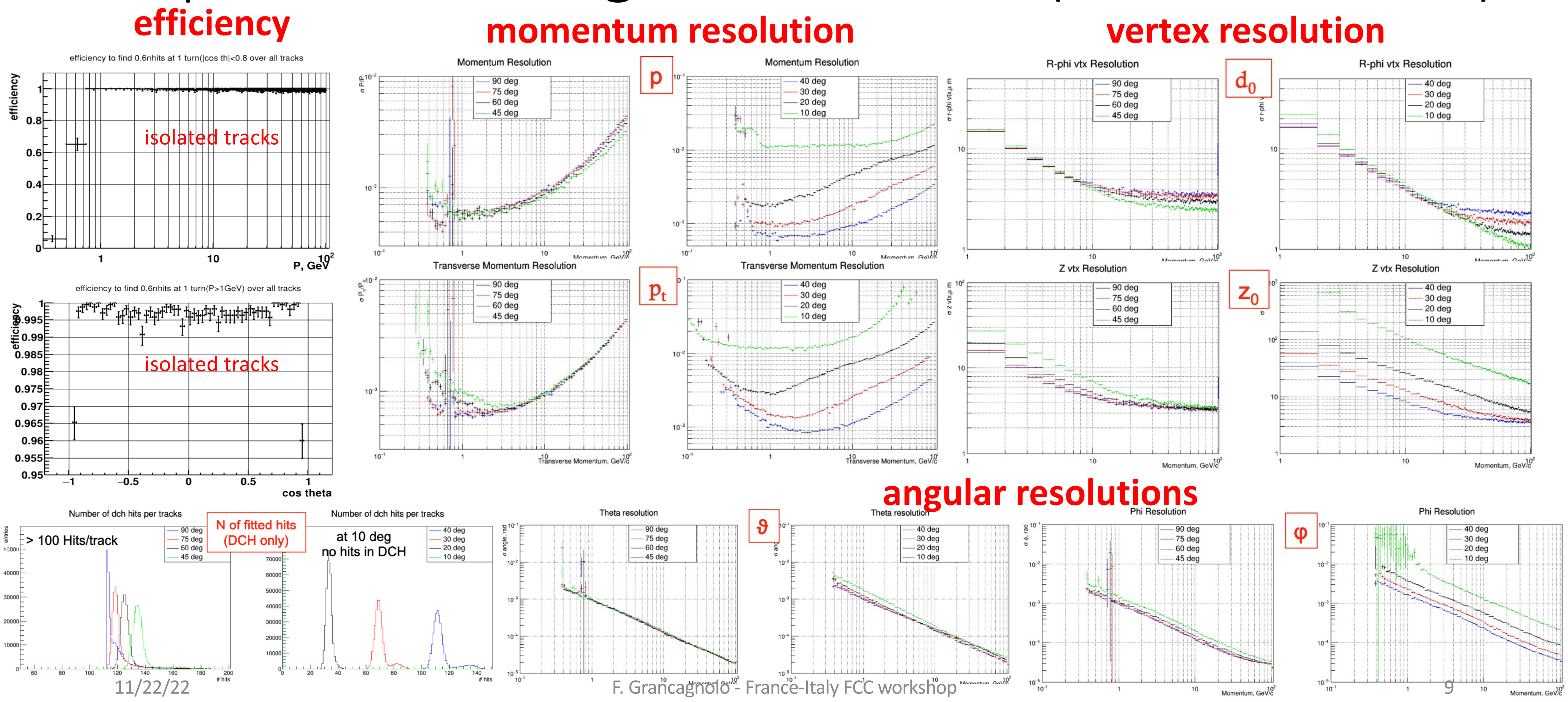


Full Tracking System: drift chamber + Si wrapper

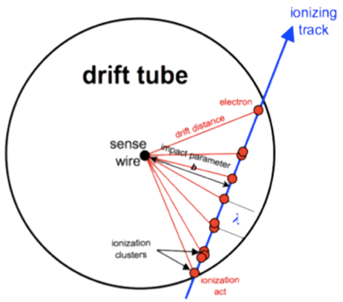




Expected Tracking Performance (full simulation)

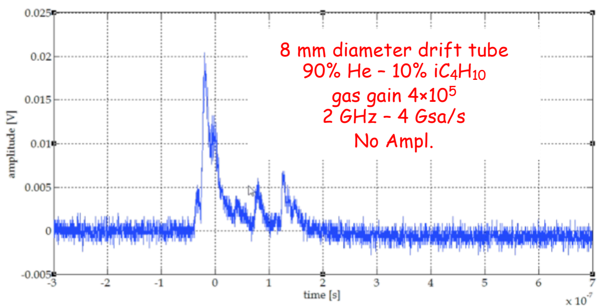


Cluster Counting

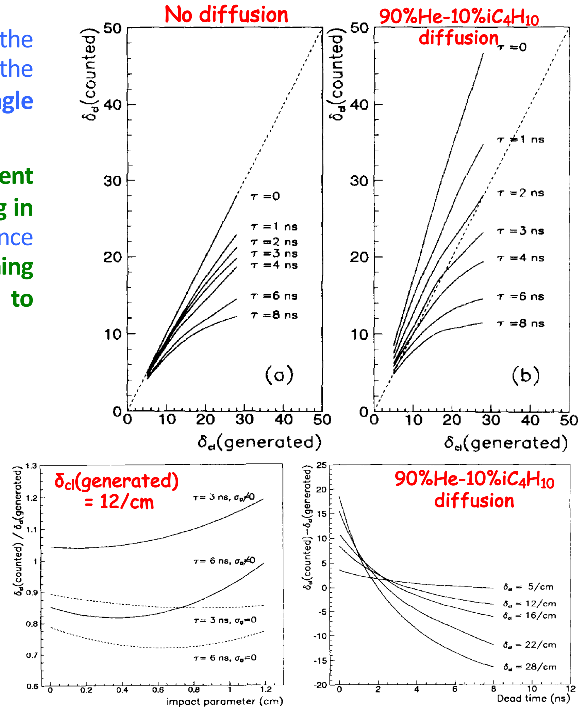


Single out, in every recorded detector signal, the **isolated structures** related to the arrival on the anode wire of the **electrons belonging to a single ionization act.**

Pulses from **electrons belonging to different clusters must have a little chance of overlapping in time** and, at the same time, the time distance between pulses generated by **electrons coming from the same cluster must be small enough to prevent over-counting**.



These requirements involve **incompatible time dependences**. The **optimal counting condition** can, therefore, be reached only as a result of the **equilibrium** between **cluster time resolution τ**, which forbids a fully efficient cluster detection, and **electron diffusion σ_D** causing the time spread among electrons of the same cluster.



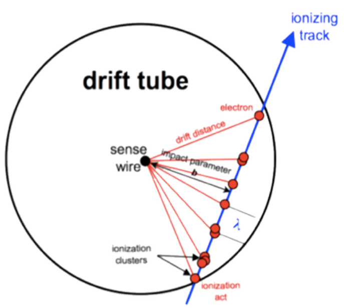
G. Cataldi, F. Grancagnolo and S. Spagnolo, Nucl.Instrum.Meth. A 386 (1997) 458-469

Once the parameters of the experimental set up, like **drift cell size** and **gas mixture** (primary ionization, drift velocity and diffusion) are set, one can define the optimal parameters for the **readout electronics** (frontend and digitizing).

In the case of He/iC_4H_{10} = 90/10 gas mixture and 1.2-1.5 cm cell size, like in the IDEA drift chamber, the optimal choice for the electronics parameters is:

- **analog bandwidth ≥ 1 GHz;**
- **pre-amplifier gain ≥ ×10;**
- **sampling rate ≥ 1.5 GS/s**
- **≥ 12 bit resolution**

Cluster Timing

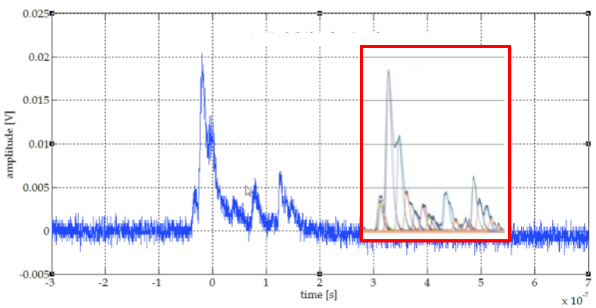


Determine, in the signal, the **ordered sequence of the electrons arrival times**:

$$\{t_j^{el}\} \qquad j=1,n_{el}$$

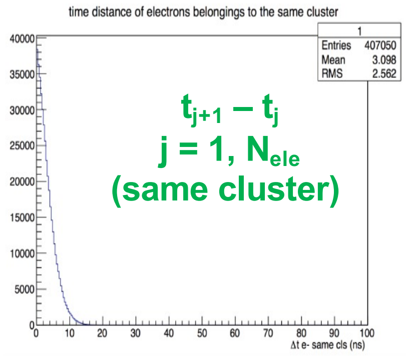
Based on the dependence of **the average time separation between consecutive clusters** and on the **time spread due to diffusion**, as a function of the drift time, **define** the **probability function**, that the ***j***th **electron** belongs to the ***i***th **cluster**:

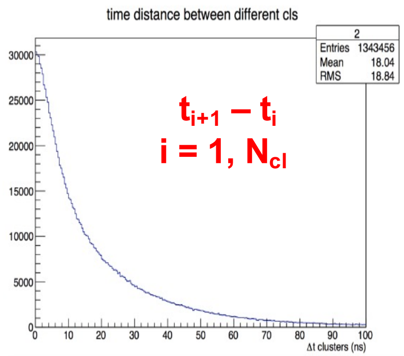
$$P(j,i) \qquad j=1,n_{el}, \quad i=1,n_{cl}$$



from this **derive** the most probable **time ordered sequence of the original ionization clusters:**

$$\{t_i^{cl}\} \qquad i=1,n_{cl}$$





For any given first cluster (**FC**) drift time t_1, the **cluster timing technique** exploits the drift time distribution of all successive clusters to statistically (**MPS**) or using **ML techniques**, determine, hit by hit, the most probable **impact parameter**, thus reducing the **bias** and improving the average **spatial resolution** with respect to that obtainable with the FC method alone:

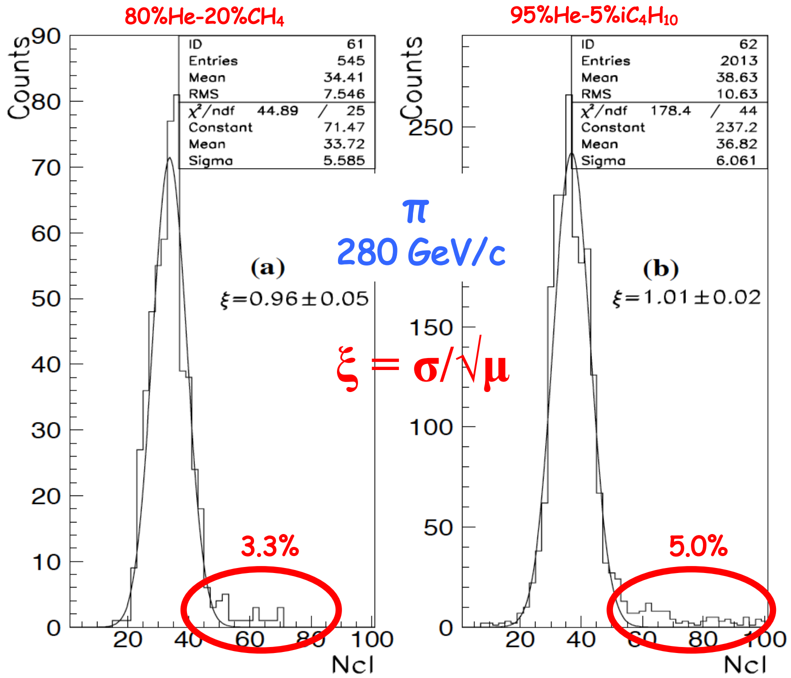
over a 1 cm drift cell, **spatial resolution** may improve by ≳ 20% **down to ≲ 80 µm**.

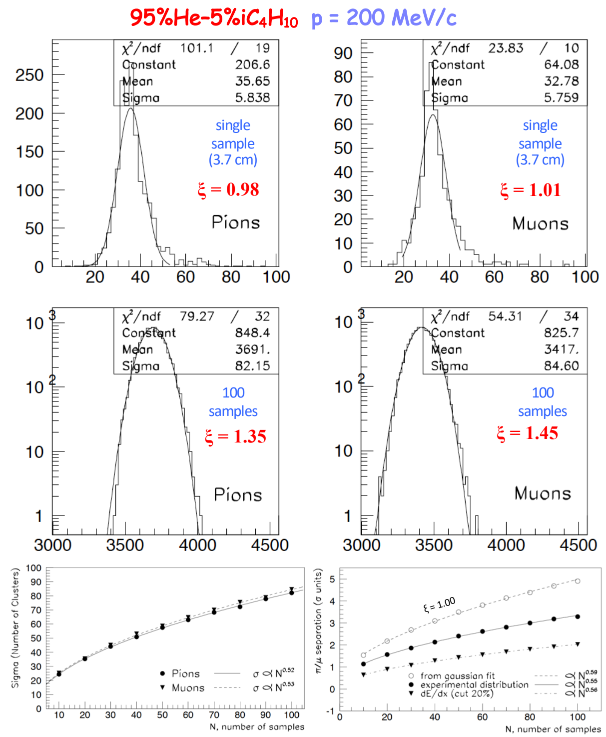
Fringe benefits of the cluster timing technique are:

- **event time stamping (at the level of ≈ 1 ns);**
- **improvements on charge division;**
- **Improvements on left-right time difference.**

Experimental Results

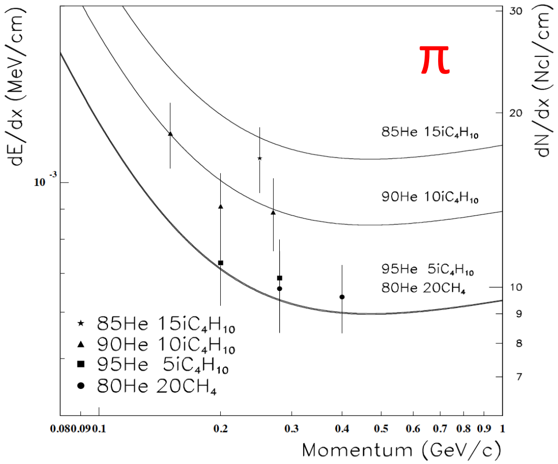
G. Cataldi, F. Grancagnolo and S. Spagnolo, Nucl.Instrum.Meth. A 386 (1997) 458-469





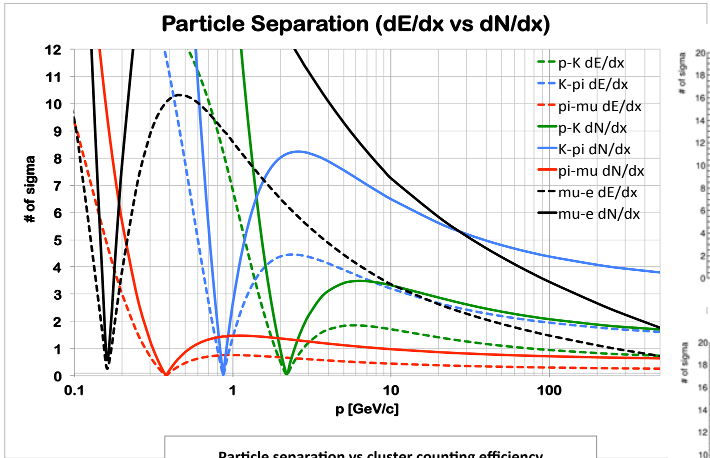
μ/π separation at p = 200 MeV/c
He/iC_4H_{10} = 95/5
100 samples
3.7 m track lenght

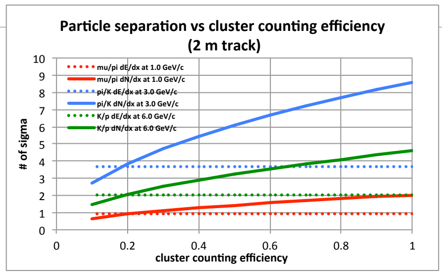
dN_{cl}/dx	3.2σ	(5.0σ ideal)
dE/dx	1.7σ	(2.8σ ideal)



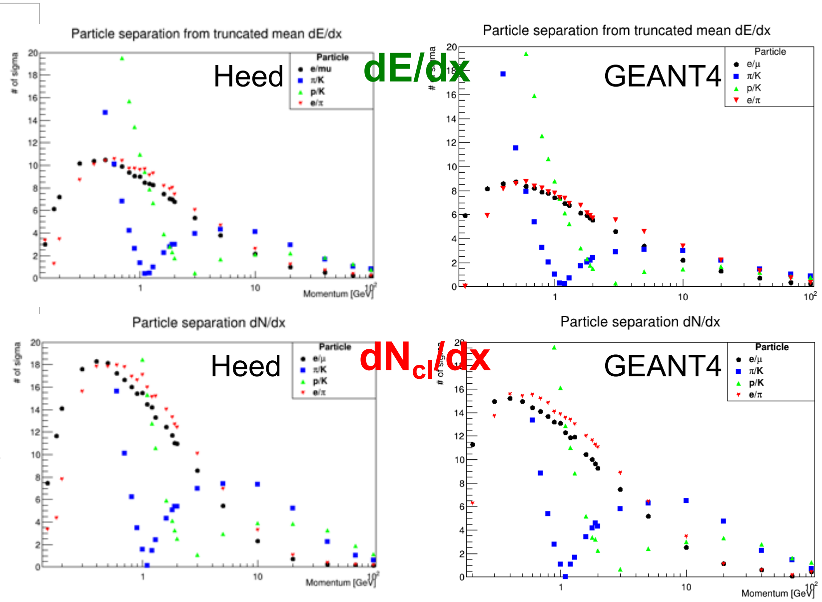
Expected Performance (2 m track length)

analytical calculations





full simulation



comments

dN/dx: consider π/K separation:

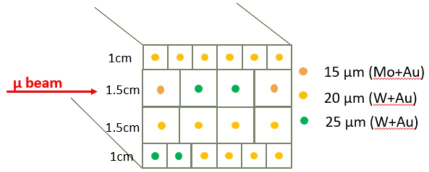
Heed (Garfield++) in reasonable **agreement with analytical calculations up to 20 GeV/c** momentum, then **falls much more rapidly at higher momenta**.

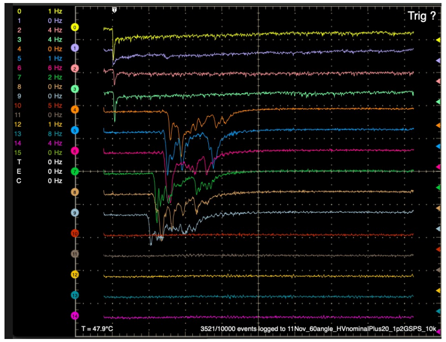
Despite **Geant4** uses the cluster density and the cluster size distributions from **Garfield++**, it **disagrees** from **Garfield++** and, therefore, from the **analytical calculations** also.

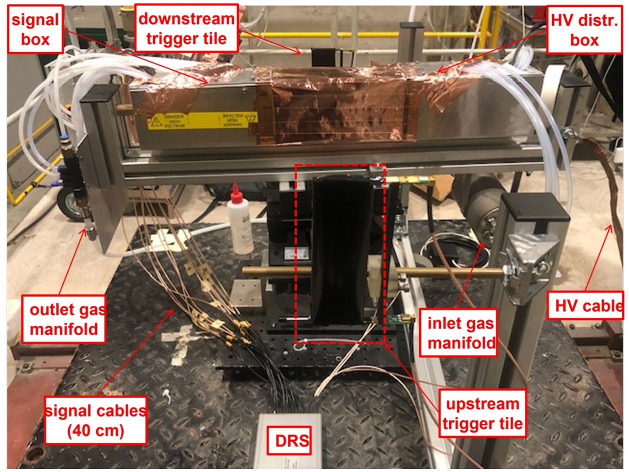
Unfortunately, lack of experimental data on cluster density and cluster population for He based gas. Particularly in the relativistic rise region to compare calculations.

Current R&D efforts: Beam tests

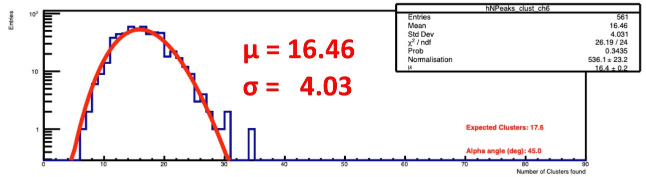
- Beam tests to experimentally asses and optimize the **performance of the cluster counting/timing** techniques in strict collaboration with the IHEP Beijing group
  - Two beam test performed at CERN-H8 ($\beta\gamma > 400$) in Nov. 2021 and July 2022
  - More tests planned in 2023 at CERN and PSI ($\beta\gamma = 1–4$) in 2023
  - Ultimate test at FNAL-MT6 with π and K ($\beta\gamma = 10–140$) to fully exploit the relativitic rise

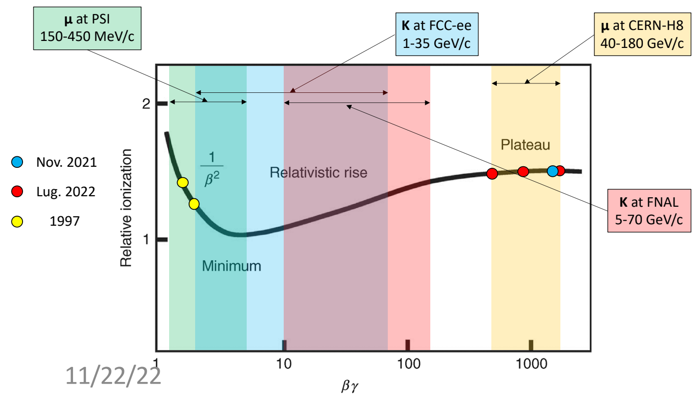


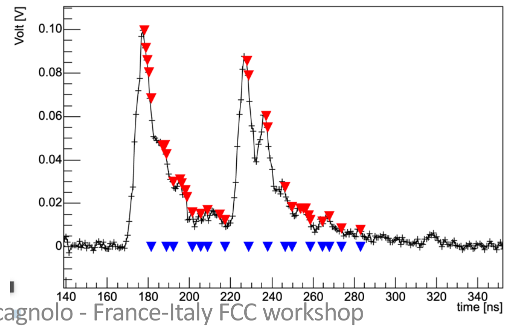


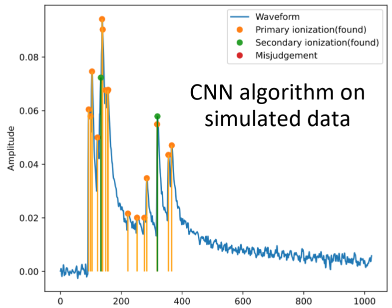


number of clusters

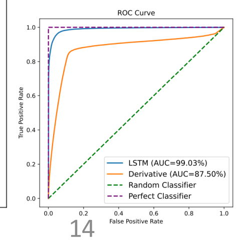








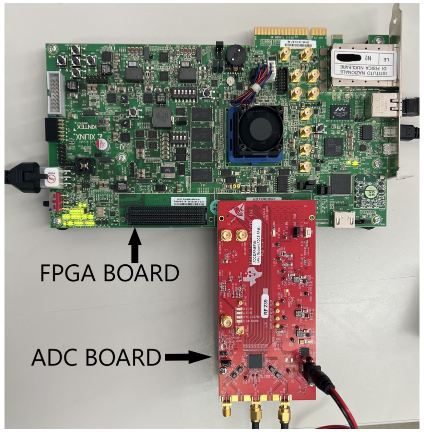
Credit to IHEP

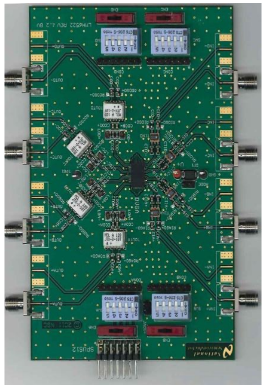


Current R&D efforts: DAQ

- Data readout and pre-processing board for **cluster counting/timing DAQ system** (sponsored by AIDA innova)
  - Successfully accomplished on a single channel board.
  - The objective is to be able to implement, on a single FPGA, CCT algorithms for the parallel pre-processing of as many (contiguous) channels as possible in order to define proximity correlations between hit cells, for track segment finding and for triggering purposes.
  - Further advantage is to reduces the data transfer rate and the amount of information stored.
  - Three different approaches are being attempted:
    - ADC TEXAS INSTRUMENT ADC32RF45
    - CAEN digitizer
    - NALU SCIENTIFIC ASoCv3

FPGA + ASoC

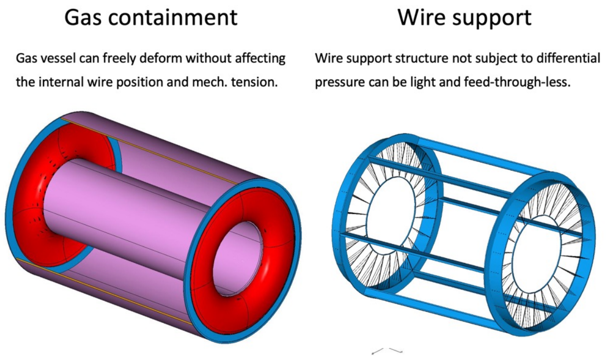


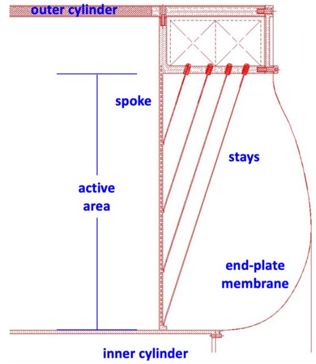


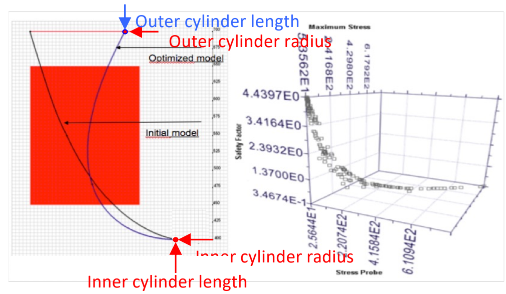
LMH6522

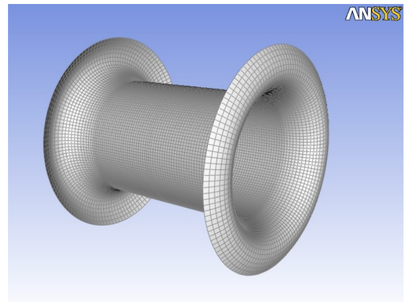
Current R&D efforts: Mechanical structure

- Model of the drift chamber **mechanical structure** (sponsored by eurizon European network for developing new horizons for RIs).
  - Simulation of the mechanical components of the wire cage structure has just started in the framework of ANSYS in collaboration with EnginSoft and Politecnico di Torino (expect to complete a Master Thesis by April 2023 and a PhD thesis by 2025).
  - Goal is to provide a solid base for the design of a full length prototype to verify the electrostatic stability of different wire types (aluminum, titanium and carbon monofilamets for field and guard wires and tungsten and molibdenum for sense wires) of different diameters.
  - Also, to optimize the wire tension compensation scheme proposed to minimize the end-plates material budget.
  - Lastly, to minimize the material budget of the carbon fiber gas vessel by the proper choice of the envelope profile.







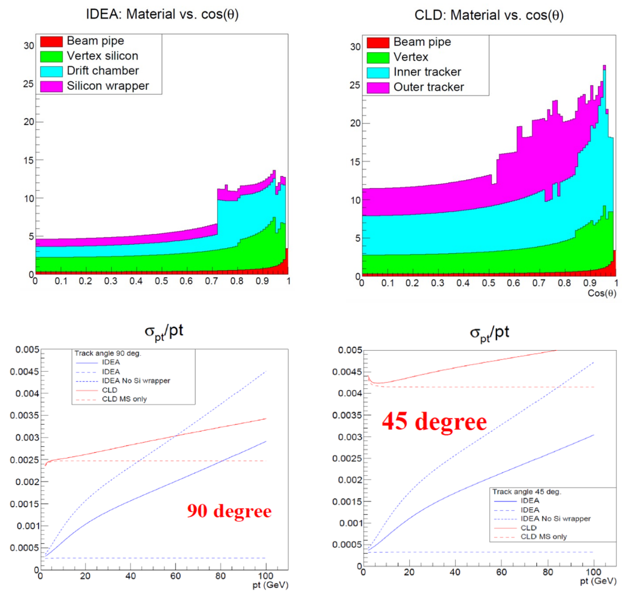


parameters	Initial model	Optimized model
Maximum stress	357.5 MPa	58.7 MPa
Stress at inner boundary	267.4 MPa	26.6 MPa
Safety factor	0.783	4.44

For more details see: *F. Grancagnolo, "Mechanical features of the IDEA drift chamber", Kick-Off Workshop on Detector Optimization and Benchmarking for FCC-ee, 23.06.2022*

Conclusions

- Excellent momentum resolution for low momenta thanks to the reduced material budget (one order of magnitude wrt a solid state tracker).
- Excellent asymptotic momentum resolution thanks to a solid state wrapping tracker
- Unprecedented particle identification capability thanks to the cluster counting technique (a factor 2 improvement over traditional dE/dx).
- Specific R&D on three different fronts:
  - Beam tests for optimizing the particle identification performance
  - Data readout and pre-processing of cluster counting/timing electronics
  - Mechanical structure design to further improve on material budget.



	$\frac{\Delta p_t}{p_t}\times 10^3$	at $p_t = 1GeV$	$\frac{dE}{dx} \Big/ \frac{dN}{dx}$
KLOE	$0.5p_t \oplus 2.6$	2.6×10^{-3}	5%
BaBar	$1.3p_t \oplus 4.5$	4.7×10^{-3}	7.5%
Belle	$2.8p_t \oplus 3.5$	4.5×10^{-3}	6.9%
BelleII	$1.9p_t \oplus 2.9$	3.5×10^{-3}	6.4%
BESIII	$2.7p_t \oplus 4.7$	5.1×10^{-3}	6 – 7%
Cleo3	$1.0p_t \oplus 9.0$	9.1×10^{-3}	5%
IDEA	$0.1p_t \oplus 0.8$	0.8×10^{-3}	2.2 %