An ultra-light Drift Chamber with Particle Identification capabilities

F. Grancagnolo

INFN – Lecce, ITALY

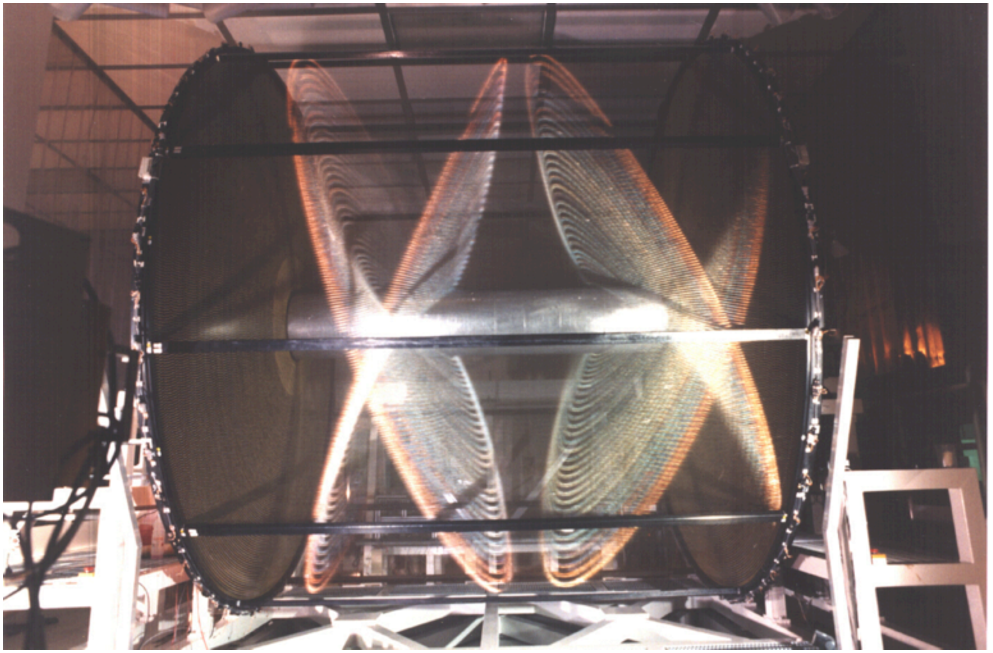
Practice Talk for CEPC CDR International Review

IHEP Beijing, Sept. 10, 2018

Road to IDEA D.C. proposal

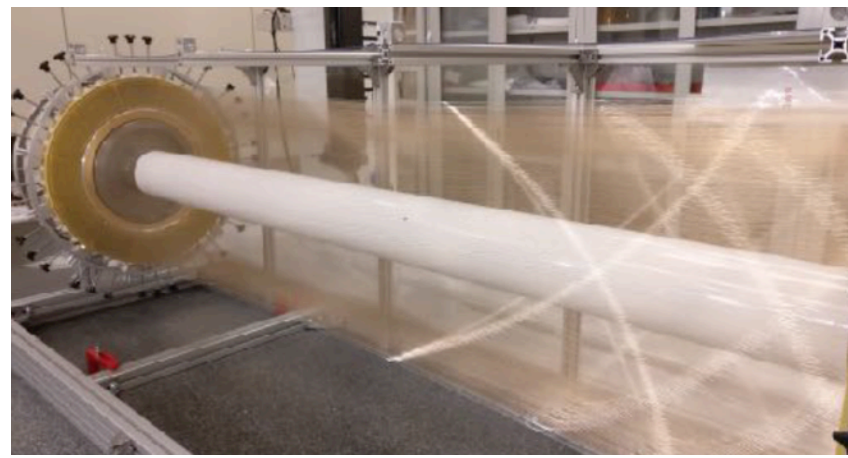
- Ancestor chamber: **KLOE** at INFN LNF Daϕne ϕ factory (commissioned in 1998 and currently operating)
- **CluCou** Chamber proposed for the **4th-Concept** at ILC (2009)
- **I-tracker** chamber proposed for the **Mu2e experiment** at Fermilab (2012)
- **DCH** for the **MEG2 upgrade** at PSI (under commissioning at PSI)

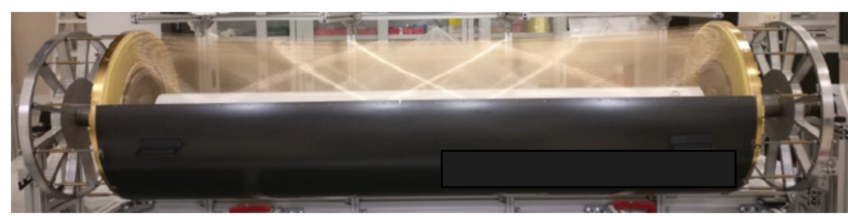
KLOE Drift Chamber

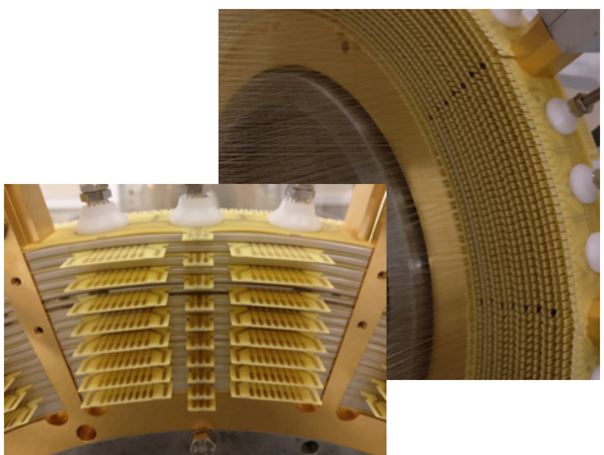


fully stereo
4 m diameter
3.3 m length
C-fiber structure
90% He – 10% iC_4H_{10}
12,000 sense wires
52,000 total wires
80 μm Al field wires
2x2 and 3x3 cm^2 cells

MEG2 Drift Chamber





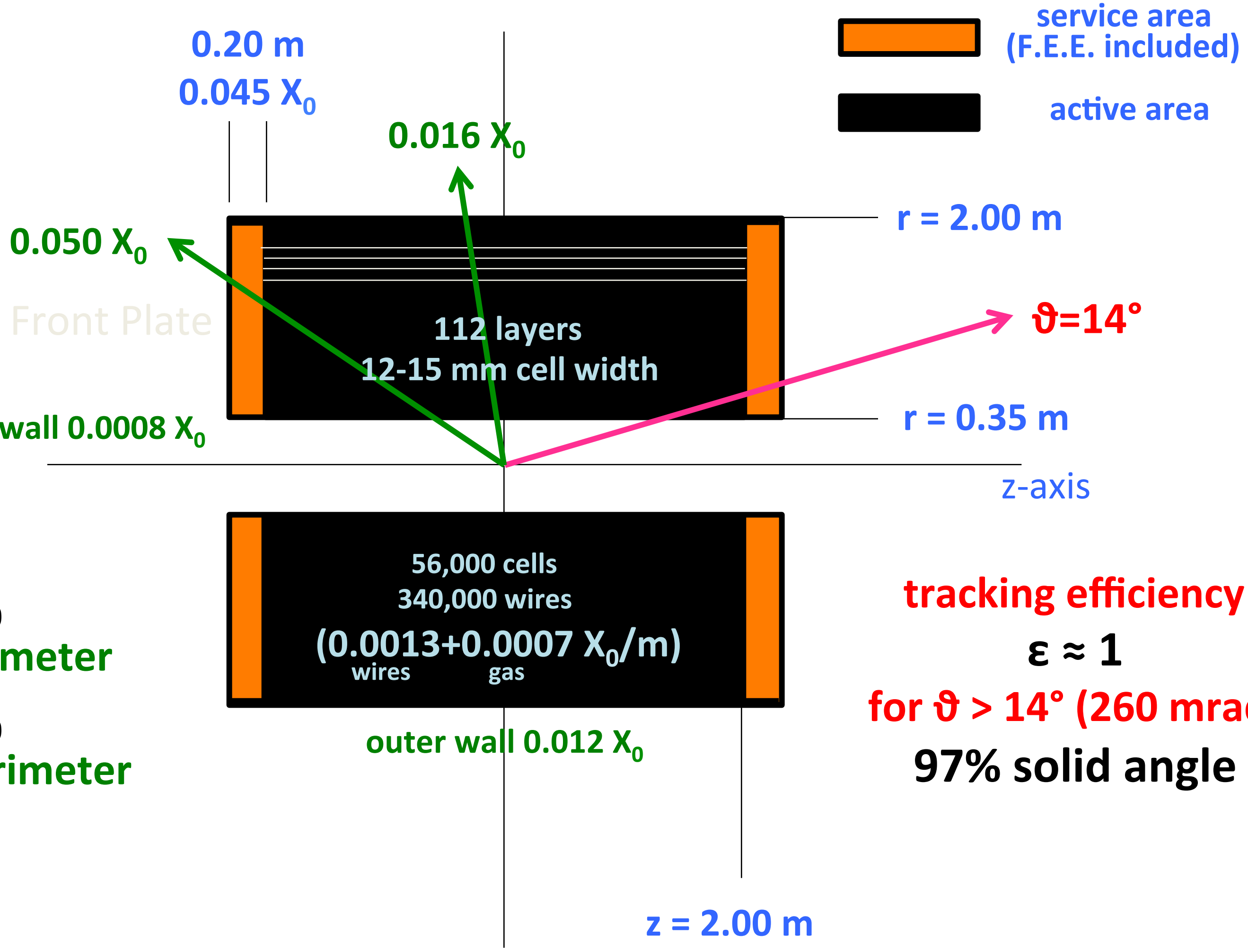


fully stereo
0.6 m diameter
2.0 m length
C-fiber structure
85% He – 15% iC_4H_{10}
2,000 sense wires
12,000 total wires
40 μm Al field wires
0.7x0.7 cm^2 cells
cluster tim/cou

IDEA D.C. "Innovations"

- **Gas containment** – **wire support** functions separation
  - allows to reduce material to **≈ 10^{-3} X_0 for the inner cylinder** and to **a few x 10^{-2} X_0 for the end-plates**, including FEE, HV supply and signal cables (Mu2e proposal design: 1.5×10^{-3} X_0 and 8×10^{-3} X_0, respectively).
- **Feed-through-less wiring**
  - allows to increase **chamber granularity** and field/sense wire ratio to reduce **multiple scattering** and **total tension on end plates** due to wires
- **Cluster timing**
  - allows to reach **spatial resolution < 100 µm** for 8 mm drift cells in He based gas mixtures (such a technique is going to be implemented in the MEG2 drift chamber under construction)
- **Cluster counting**
  - allows to reach **dN_{cl}/dx resolution < 3%** for particle identification (a factor 2 better than dE/dx as measured in a beam test)

IDEA D.C. Angular coverage



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

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

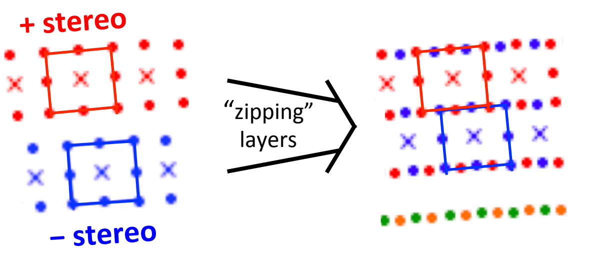
IDEA D.C. Material budget

Conservative estimates:

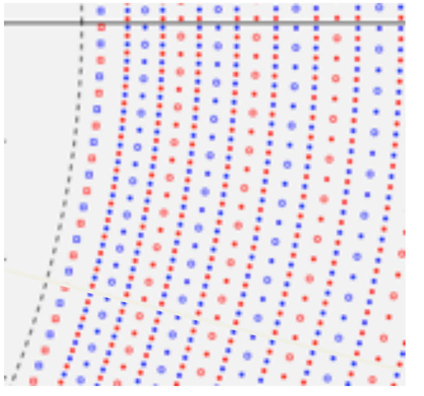
- Inner wall (from CMD3 drift chamber) **8.4×10^{-4} X_0**
  - 200 μm Carbon fiber
- Gas (from KLOE drift chamber) **7.1×10^{-4} X_0/m**
  - 90% He – 10% iC_4H_{10}
- Wires (from MEG2 drift chamber) **1.3×10^{-3} X_0/m**
  - 20 μm W sense wires 4.2×10^{-4} X_0/m
  - 40 μm Al field wires 6.1×10^{-4} X_0/m
  - 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, ...)

IDEA D.C. Layout

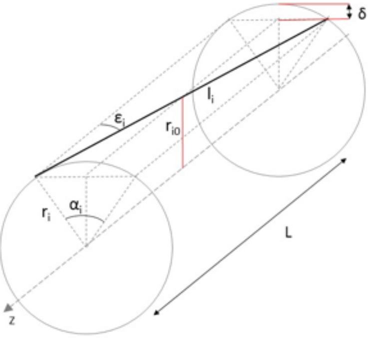
- **12÷15 mm wide square cells 5 : 1 field to sense wires ratio 56,448 cells**



- **14 co-axial super-layers, 8 layers each (112 total) in 24 equal azimuthal (15°) sectors (N_i = 192 + (i – 1) × 48)**



- **alternating sign stereo angles ranging from 50 to 250 mrad**



IDEA D.C. Electrostatic Stability

sagitta due to electrostatic forces on sense wire displaced by Δ from central symmetry position

$$\delta_{e.s.} = \frac{C^2 V_0^2 L^2}{4\pi\varepsilon T w^2}\Delta$$

C = wire capacitance per unit length
V_0 = wire voltage
L = wire length
T = wire mechanical tension
$w/2$= wire distance from ground plane
r = sense wire radius

$$C = \frac{2\pi\varepsilon}{\ln\left(\frac{\{2\}w}{2r}\right)}$$

stability condition

$$T \geq \frac{\pi\varepsilon V_0^2 L^2}{w^2\left(\ln\frac{w}{r}\right)^2}$$

For IDEA D.C.:

V_0 = 1500 V, L = 4 m,
***w = 12 mm, r = 20 μm*:**

$$T \geq 0.16N$$

or, for *T = 0.25 N*
(*$\delta_{grav.}$ = 400 μm*):

$$L \leq 4.9m$$

Smaller cell size (to mitigate higher occupancy at inner radius), e. g. *w = 7 mm*, would require higher tension: *T ≥ 0.48 N*, which is at the limit of elasticity for *20 μm* diameter tungsten sense wire (*YS ≈ 1500 MPa*):

⇨ shorten the wires (and loose angular coverage) and/or increase the wire diameter (and mult. scatt. and $\delta_{grav.}$) or **introduce new types of wires** (C wire?) with further improvement of drift chamber transparency

IDEA D.C. Expected resolution

Transverse Momentum Resolution

$$\frac{\Delta p_t}{p_t} = \frac{8\sqrt{5}\sigma_{xy}}{.3BR_{out}\sqrt{N}} p_t \oplus \frac{0.0523[GeV/c]}{\beta BL} \sin\theta \sqrt{\frac{L}{X_0}}$$

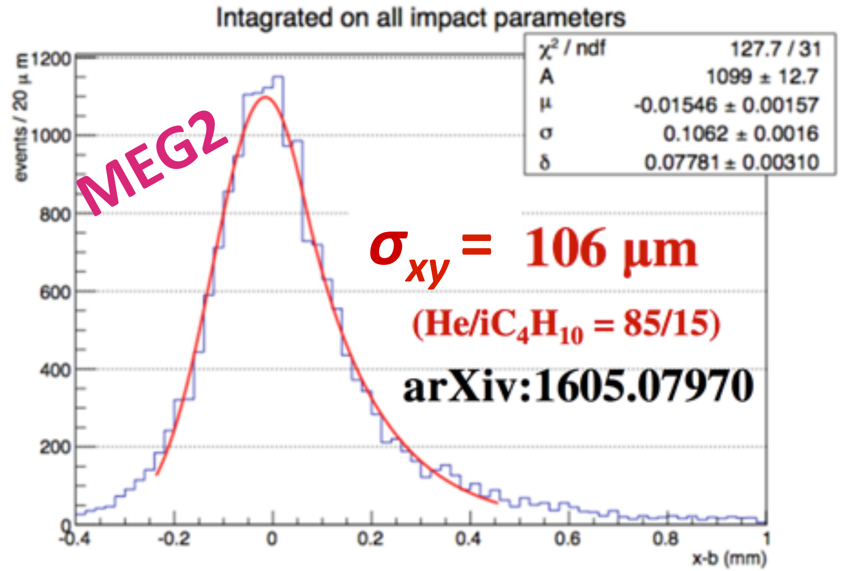
Angular Resolutions

$$\Delta\varphi_0 = \frac{4\sqrt{3}\sigma_{xy}}{R_{out}\sqrt{N}} \oplus \frac{0.0136[GeV/c]}{\beta p} \sqrt{\frac{L}{X_0}}$$

$$\Delta\theta = \frac{\sqrt{12}\sigma_z}{R_{out}\sqrt{N}} \frac{1+\tan^2\theta}{\tan^2\theta} \oplus \frac{0.0136[GeV/c]}{\beta p} \sqrt{\frac{L}{X_0}}$$

Momentum Resolution

$$\frac{\Delta p}{p} = \frac{\Delta p_t}{p_t} \oplus \frac{\Delta\theta}{\tan\theta}$$

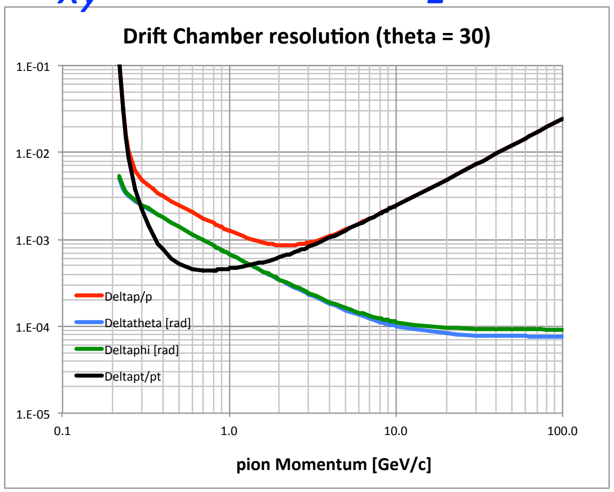


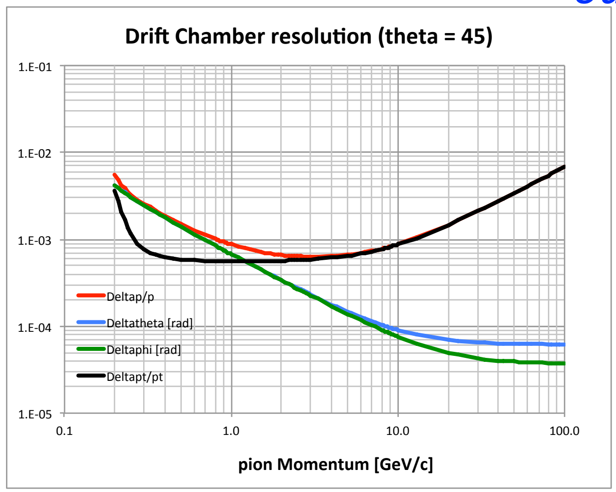
no cluster timing, 7x7 mm²
12x12 mm² ≤ 100 µm
cluster timing -> -20%

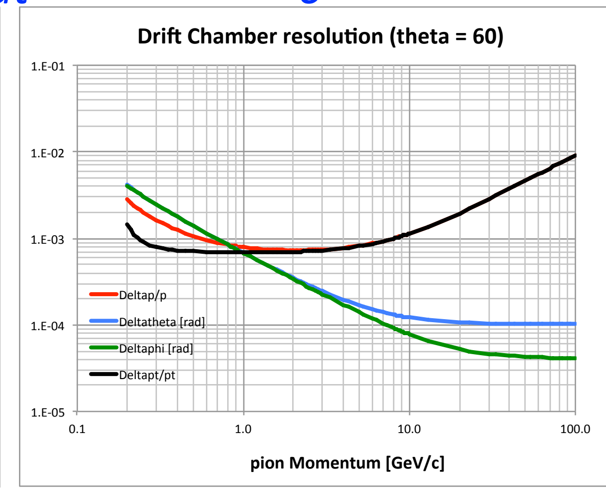
IDEA expected $\sigma_{xy} \approx 80$ µm

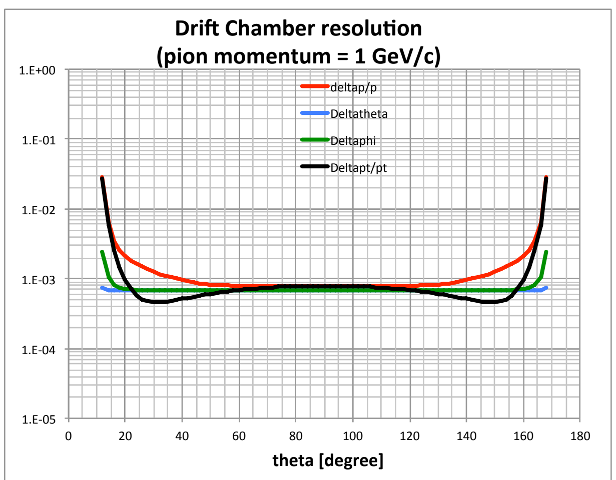
IDEA D.C. Expected resolution

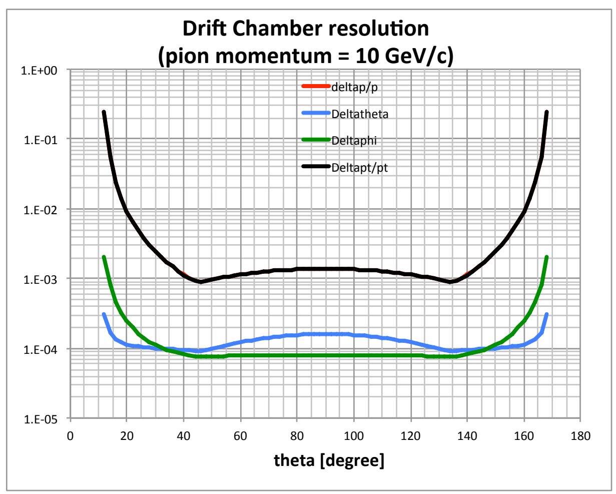
σ_{xy}=100μm, σ_z=1.0mm, N=112, B=2T, R_{out}=2m, $L/X_0=2.5\times10^{-3}$

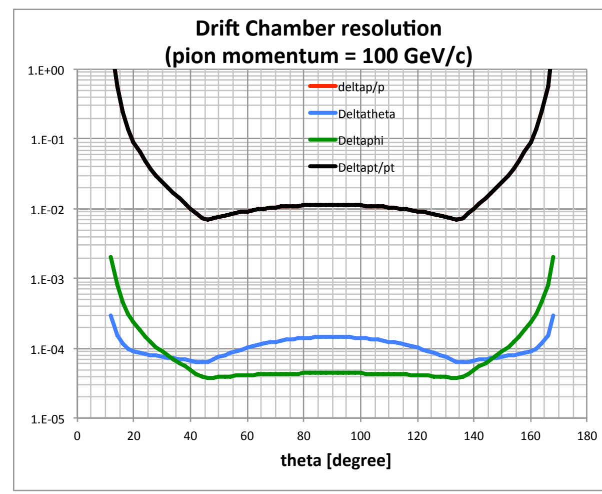




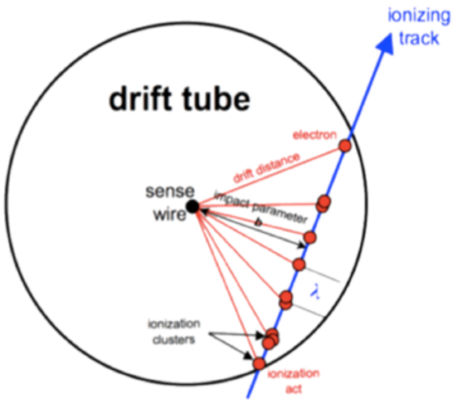




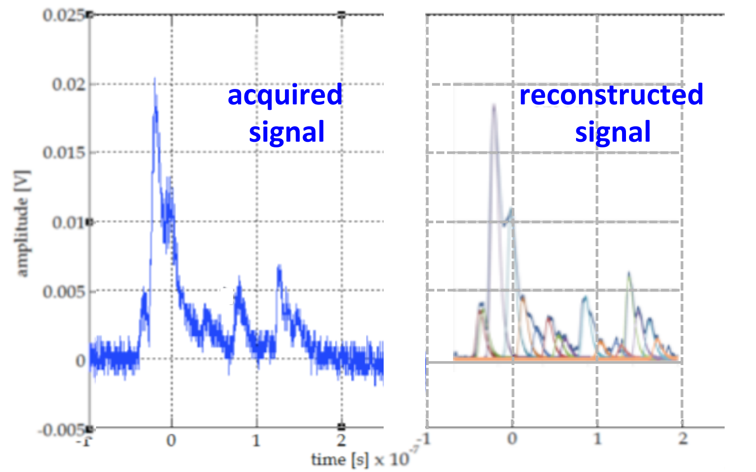


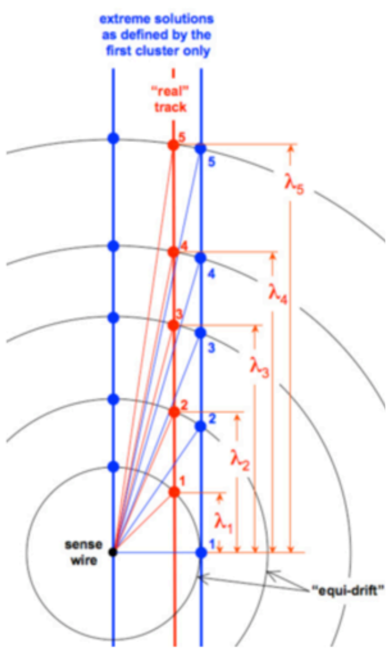


Cluster Timing/Counting

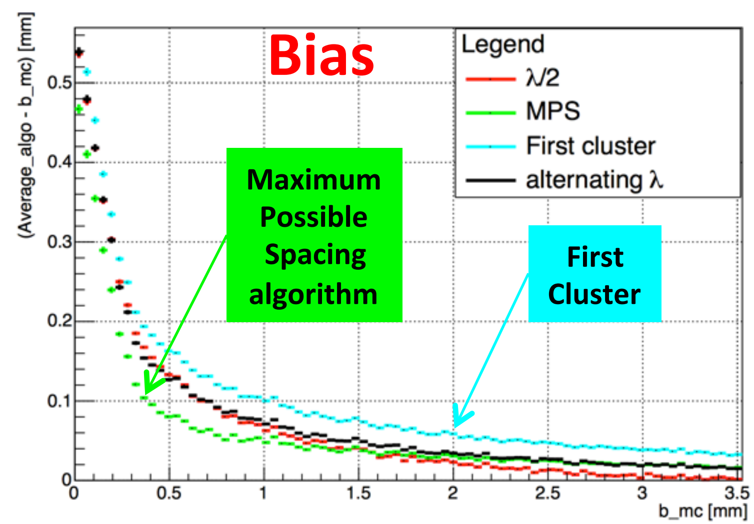


From the **ordered sequence of the electrons arrival times**, considering the average time separation between clusters and their time spread due to diffusion, **reconstruct the most probable sequence of clusters drift times:** $\{t_i^{cl}\} \quad i = 1, N_{cl}$





For any given first cluster (**FC**) drift time, the **cluster timing technique** exploits the drift time distribution of all successive clusters $\{t_i^{cl}\}$ to determine the most probable impact parameter, thus reducing the **bias** and the average **drift distance resolution** with respect to those obtained from with the FC method alone.



Particle Identification (in theory)

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 0.41 \cdot n^{-0.43} \cdot \left(L_{track}[m] \cdot P[atm]\right)^{-0.32}$$

from *Walenta parameterization (1980)*

versus

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

from *Poisson distribution*

dE/dx

truncated mean cut (70-80%) reduces the amount of collected information

***n* = 112** and a **2m track** at **1 atm** give

σ ≈ 4.3%

Increasing ***P*** to 2 atm improves resolution by 20% (σ ≈3.4%) but at a **considerable** cost of multiple scattering contribution to momentum and angular resolutions.

dN_{cl}/dx

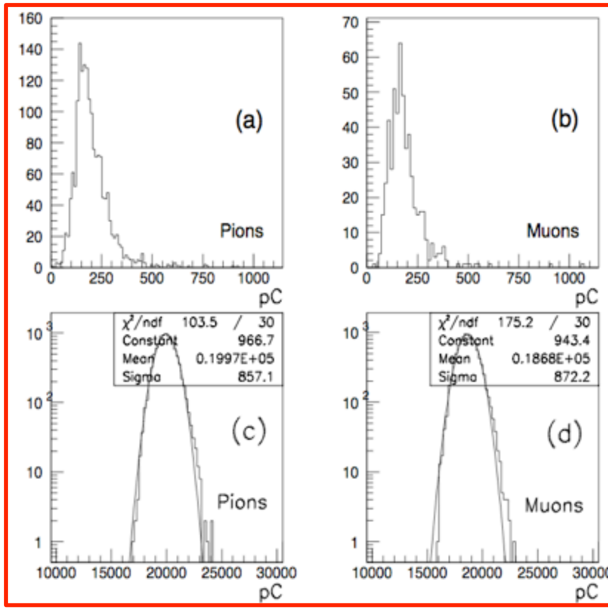
***δ_{cl}* = 12.5/cm** for He/iC_4H_{10}=90/10 and a **2m track** give

σ ≈ 2.0%

A small increment of iC_4H_{10} from 10% to 20% (*δ_{cl}* = 20/cm) improves resolution by 20% (σ ≈1.6%) at only a **reasonable** cost of multiple scattering contribution to momentum and angular resolutions.

μ/π separation at 200 MeV/c (exp.)

The data shown refer to a beam of **μ and π at 200 MeV/c**, taken with a gas mixture **He/iC_4H_{10}=95/5**, **δ_{cl} = 9/cm**, **100 samples**, **2.6 cm** each **at 45°** (for a **total track length of 3.7 m**, corresponding to **N_{cl} = 3340**, **$1/\sqrt{N_{cl}}$ = 1.7%**).



dE/dx

100 samples 3.7 cm

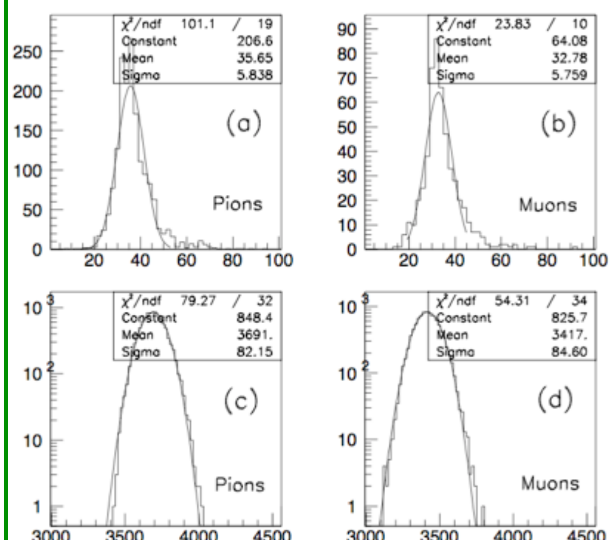
theory:
(σ = 0.41 $n^{-0.43}$ (L[m]P[atm])$^{-0.32}$)
σ = 3.7%
≈ 2.0σ separation

experiment
20% truncated mean
σ = 4.5%
≈ 1.4σ separation

Setup:

25 μm sense wire
(gas gain 2x10^5),
through a high BW preamplifier
(**1.7 GHz**, **gain 10**),
digitized at
2 GSa/s, 1.1 GHz, **8 bits**

(*NIM A386 (1997) 458-469* and references therein)



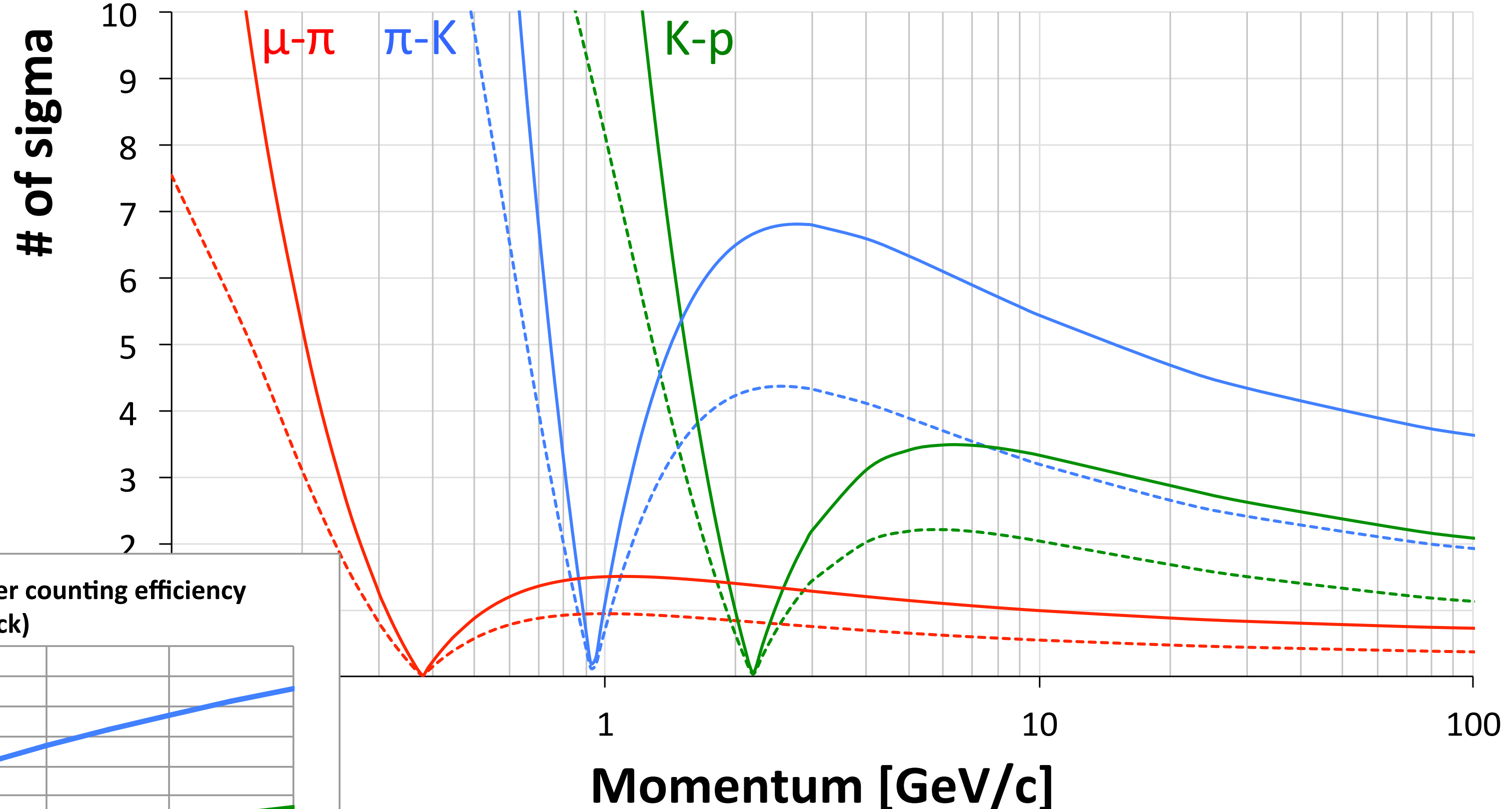
dN_{cl}/dx

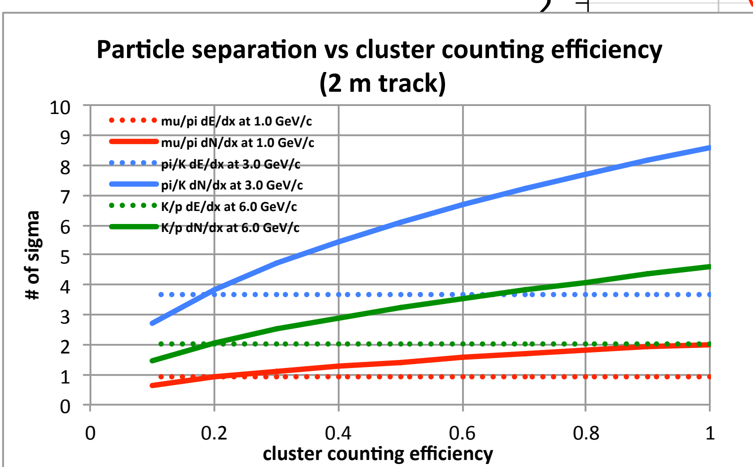
theory
Poisson distribution
σ = 1.7%
≈ 5σ separation

experiment
σ = 2.5%
≈ 3.2σ separation

IDEA D.C. expected Particle Id.

Particle Separation (dE/dx vs dN/dx)





Cluster Timing/Counting Read Out

Recipe for cluster timing/counting in He based gas mixtures:
FEE: 1 GHz BW, x10 gain (S/N ratio ≈ 8)
digitizer: 2 GSa/s sampling rate, >8 bits

However:

suppose a trigger rate of 10 kHz, an average occupancy of 20% over the 56,000 drift cells, a maximum drift time of 250 ns readout at 2 GSa/s =>

500 GB/s ! (<u>unsustainable</u>!)

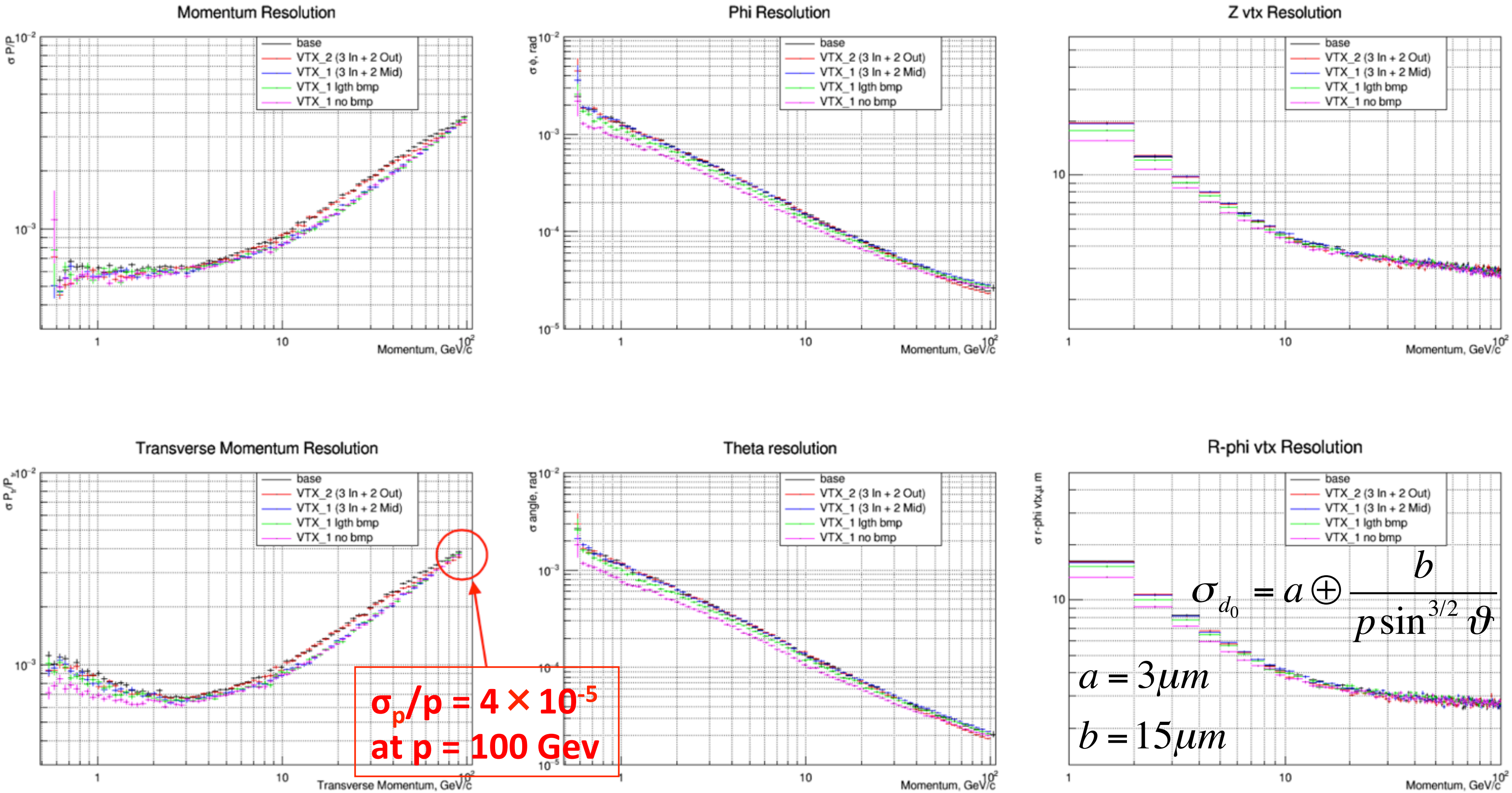
Solution:

analyze in real time the signal waveform: find the ionization peaks; register and transfer only the time and amplitude of each peak with a short relative delay with respect to the trigger. This represents a data reduction of about 50, equivalent to a data transfer of

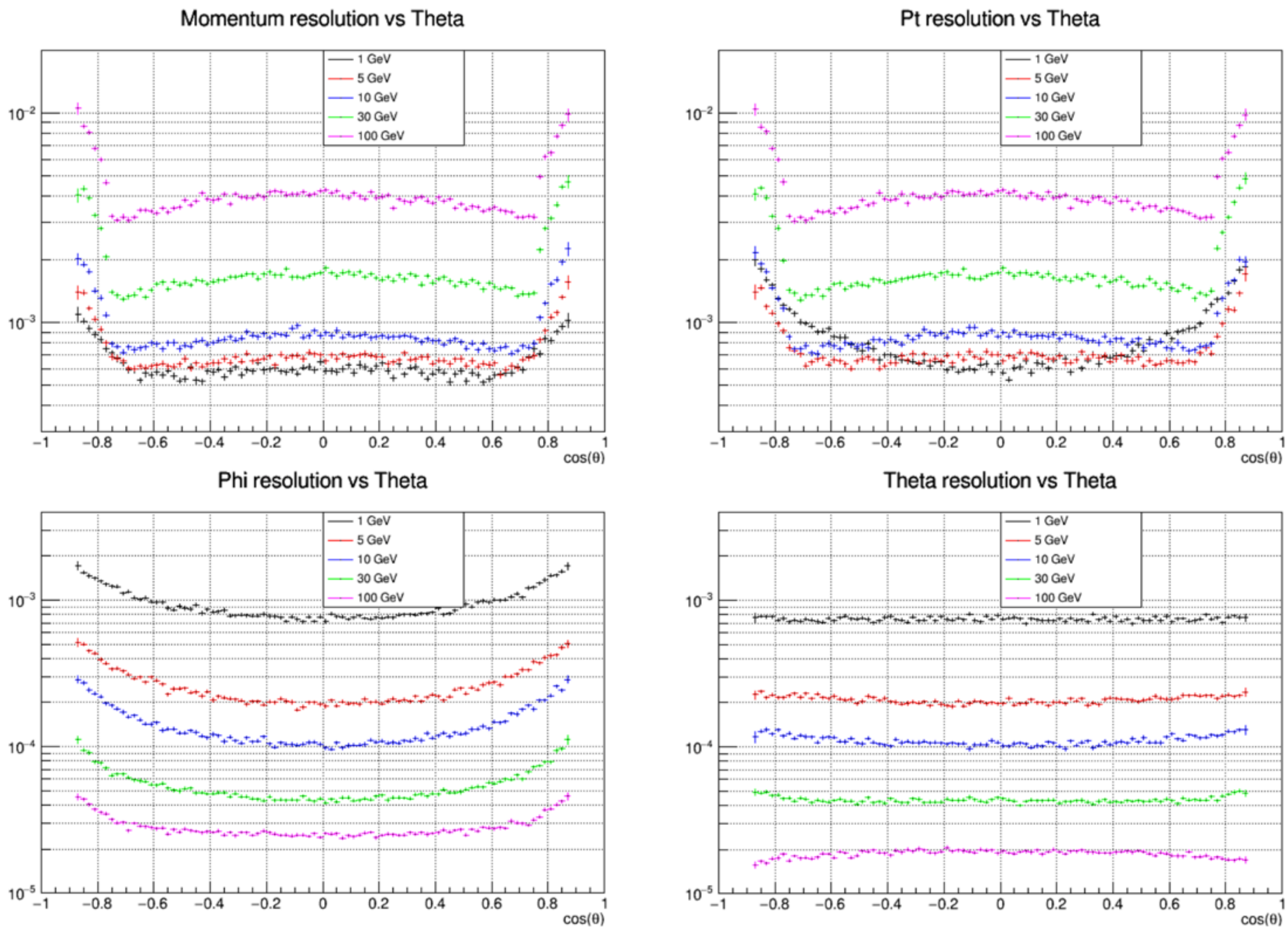
10 GB/s (<u>manageable</u>!)

IDEA integrated track simulation

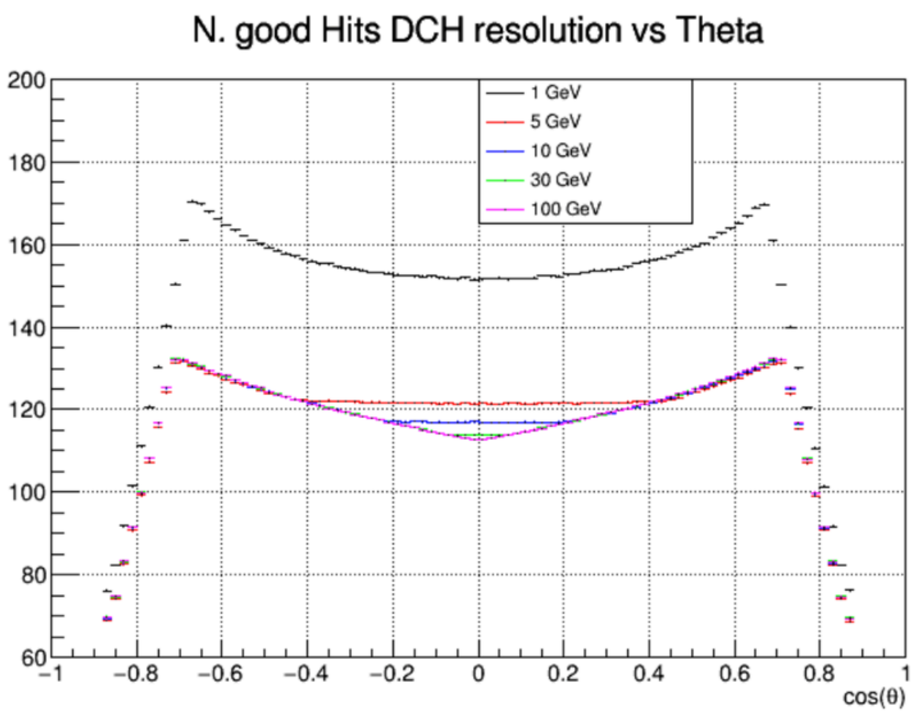
μ at $\vartheta = 65°$

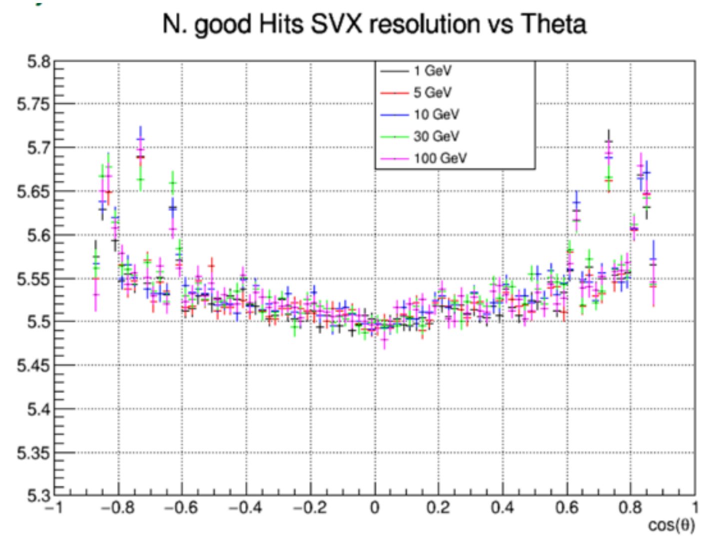


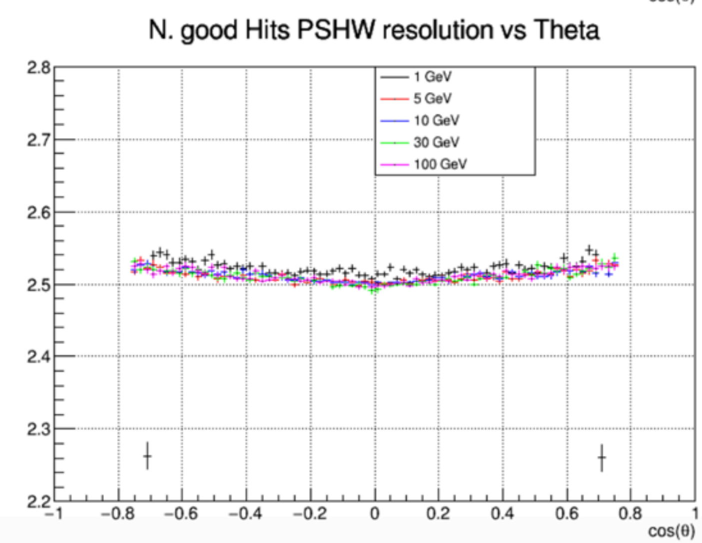
IDEA integrated track simulation



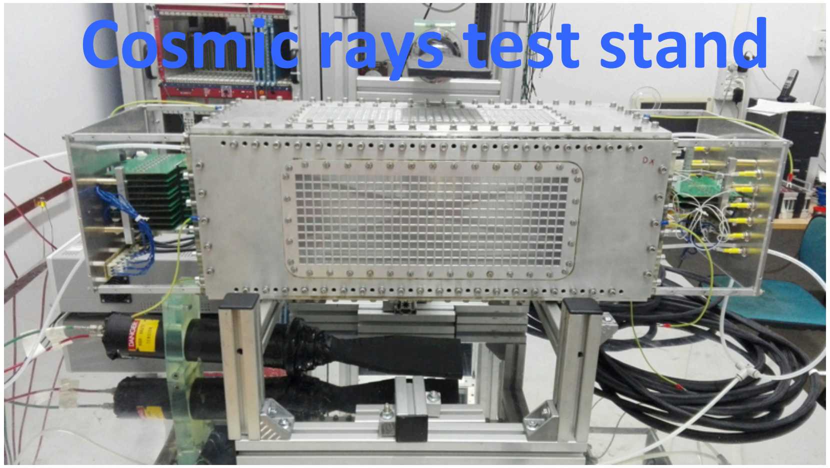
IDEA integrated track simulation

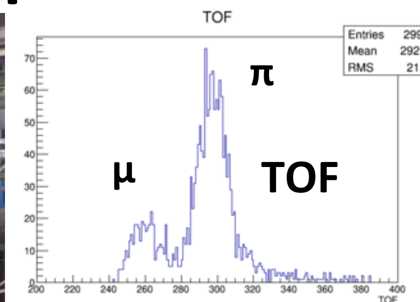






60 cm, 144 cells prototype





Beam test at PSI
last September

Beam test at CERN of a full IDEA slice: drift chamber, pre-shower, D.R. calo. μ-counter.

this week

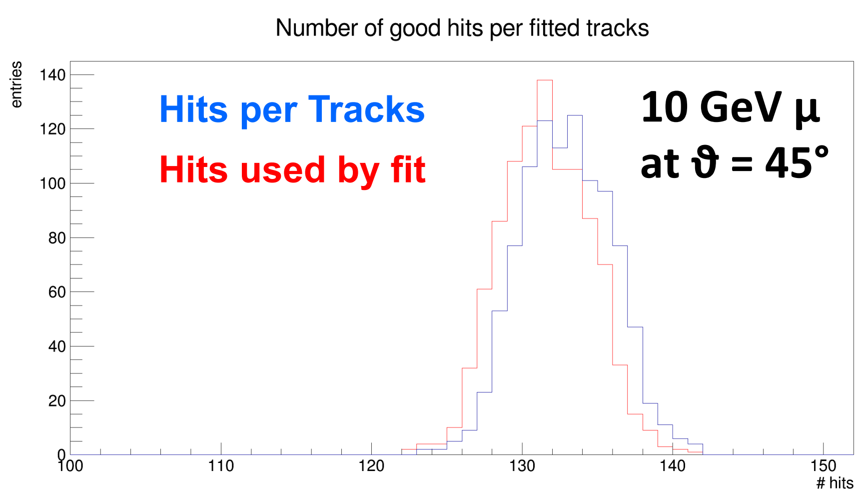
Conclusions

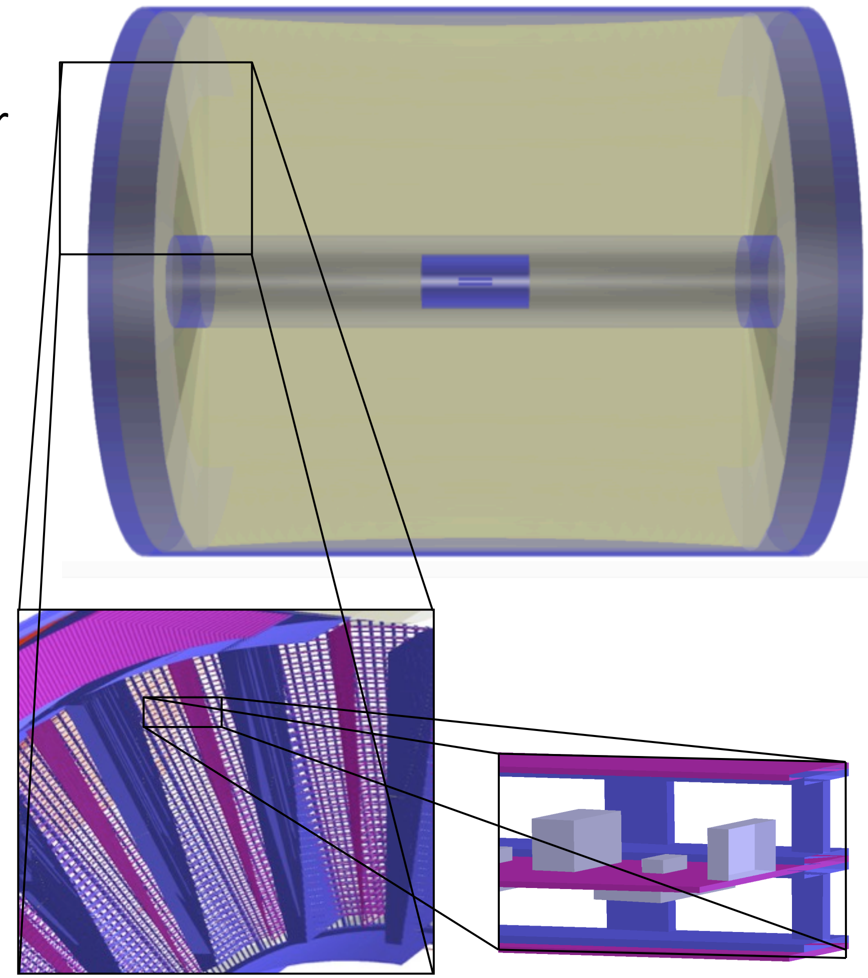
- We have presented an innovative tracking system for the IDEA detector at CEPC, based on a "**ultra-light drift chamber with peculiar particle identification capabilities**" using cluster timing/counting techniques.
- It consists of a full stereo, single sense wire, square cells drift chamber:
  - **R_{in} = 35 cm**; **R_{out} = 200 cm**; **L = 400 cm**; **112 layers**; **56,000 cells (12 to 15 mm)**;
    stereo angles ranging from **50 mrad to 150 mrad**;
    fully efficient down to **$\cos\vartheta = 0.97$**;
  - **2% X_0 in the barrel region**
  - **5% X_0 (including services) to the end cap region**
- Expected spatial resolutions: **$\sigma_{r\varphi} < 100\ \mu m$, $\sigma_z < 1$ mm**
- Expected momentum resolutions: **$\Delta p/p^2 = 4\times10^{-5}\ (GeV/c)^{-1}$,**
  angular resolutions: **$\Delta\vartheta = 2.0\times10^{-5}$ rad** and **$\Delta\varphi = 3.0\times10^{-5}$ rad at p=100 Gev/c**
  (with vertex detector and pre-shower)
- Expected π/κ separation **> 3σ for p < 850 MeV/c and p > 1050 MeV/c**

Back up slides

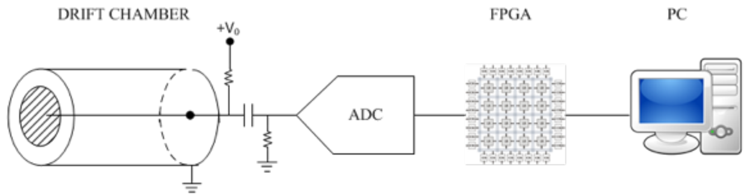
IDEA D.C. full simulation

- Detailed **geometry** description (Geant4 stand alone **and** Mokka (Yin Xu – CEPC note))
- Amount of **materials** accurately accounted for
- Simple model of **hit generation**, no time-to-d, gaussian resol.(detailed model in progress)
- **Cluster timing/counting** to be simulated (no particle id. yet)
- **Track finding** algorithms at preliminary stages
- **Track fitting** (Genfit2 Kalman filter)

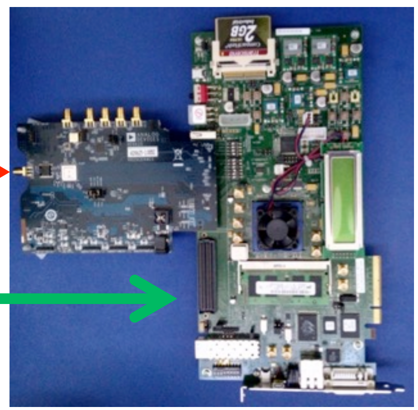




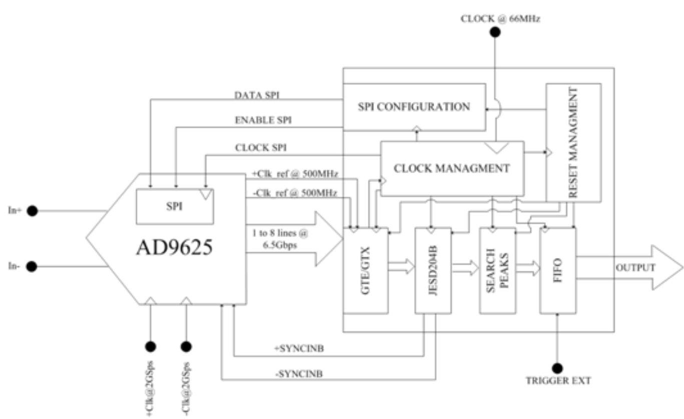
Cluster Timing/Counting Read Out

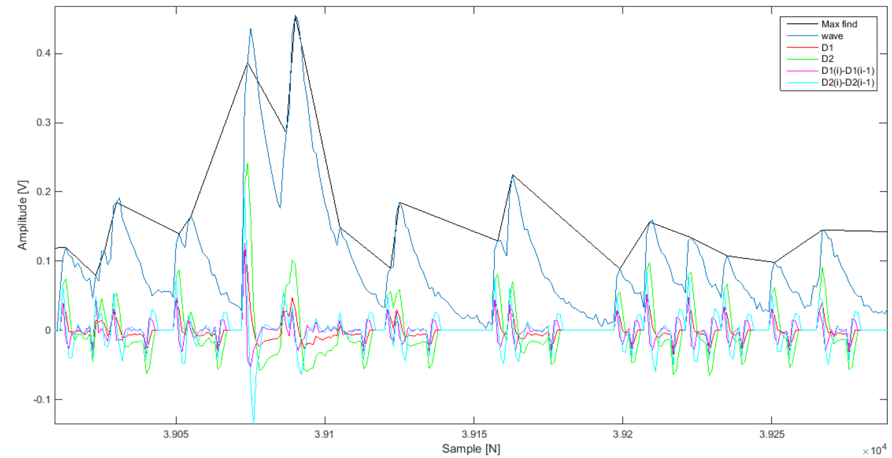


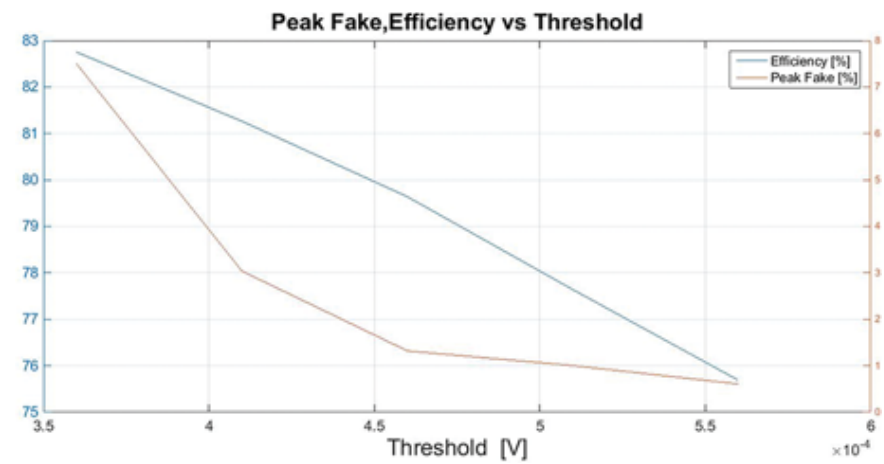
ANALOG DEVICES
AD9625-2.0EBZ



XILINX®
UG534 ML605







IDEA integrated track simulation

Geometry description (baseline):

- Beam pipe: **15.6 mm** radius, **0.0 X_0** – **0.24% X_0** – **0.48% X_0** thick (**0-0.8-1.6 mm Be**)
- Vertex detector: **17 – 23 – 31 – 180 – 200 – 330 – 340 mm** radii (20 µm pixels)
  0.3 – 0.3 – 0.3 – 1.0 – 1.0 – 1.0 – 1.0 % X_0 thick (incl. cooling)
  250 – 800 – 1500 mm long
- Tracker: **IDEA D.C.**
- Pre-shower: **2004 – 2014 mm** radii Pb radiators, **1.0 – 2.0%X_0** thick, **4800 mm** long
  2010 – 2027 mm radii pixel planes (70 µm), **1.0 – 1.0%X_0** thick, **4800 mm** l.

Configurations comparisons:

baseline vertex detector versus vertex detector without mid-stations
baseline vertex detector versus vertex detector without outer-stations
vertex detector without outer-stations versus thinner beam pipe
vertex detector without outer-stations versus no beam pipe

IDEA integrated track simulation

A lot to be done yet:

- Detailed hit creation and ionization clusters formation
- Time-to-distance relations in 2T B-field
- Signal waveform generation
- More efficient waveform analysis for timing and counting clusters
- More efficient track finding algorithms
- Realistic geometries for vertex detector (forward disks) and pre-shower counters (endplate regions)
- Hit creation and digitization (technologies)
- Full validation of Mokka simulation with Geant4 standalone version