Advancements in Tracking Techniques for Future Circular Collider Experiments

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University and INFN Bari
on behalf of the IDEA community

42nd International Conference on High Energy Physics

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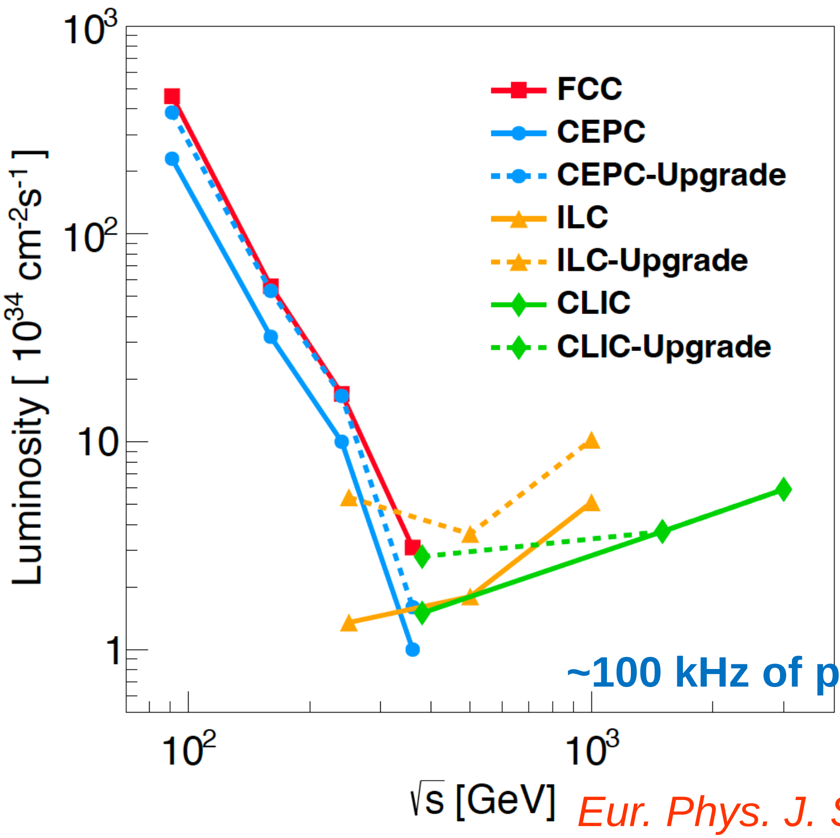
Machine luminosity at e+e- colliders



- Higgs factory:
  - 10^6 $e^+e^- \rightarrow HZ$
- EW & Top factory:
  - 3×10^{12} $e^+e^- \rightarrow Z$
  - 10^8 $e+e^- \rightarrow W^+W^-$
  - 10^6 $e^+e^- \rightarrow tt$
- Flavor factory:
  - 5×10^{12} e+e- → bb, cc
  - 10^{11} e+e- → **τ+τ-**

~100 kHz of physics data at the Z pole

Eur. Phys. J. Special Topics volume 228, pages 261–623 (2019)

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics	Extracted from FCC CDR
FCC-ee-Z	4	88-95 ± <100 KeV	150	3×10^{12} visible Z decays	LEP * 10^5
FCC-ee-W	2	158-162 <200 KeV	12	10^8 WW events	LEP * 2.10^3
FCC-ee-H	3	240 ± 2 MeV	5	10^6 ZH events	Never done
FCC-ee-tt	5	345-365 ± 5 MeV	1.5	10^6 $t\bar{t}$ events	Never done
s channel H	?	125 ± 2 MeV	10?	5000 events	Never done

Requirements of tracking system for an experiment at a leptonic collider

Central tracker system:

- state-of-the-art momentum and angular resolution for charged particles;
- B field limited to ≈ 2 T to contain the vertical emittance at Z pole. Large racking radius needed to improve momentum resolution.
- High transparency required given typical momenta in Z, H decays (far form the asymptotic limit where the Multiple Scattering contribution is negligible).
- Particle ID is a valuable additional ability.

Vertexing:

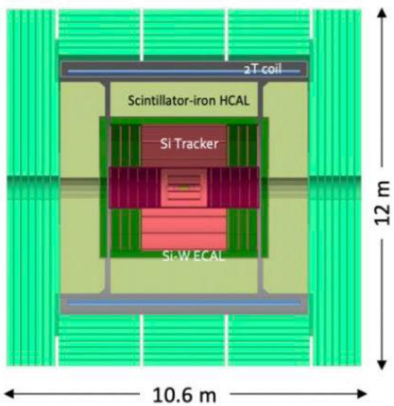
- excellent b- and c-tagging capabilities : few μm precision for charged particle origin;
- small pitch, thin layers, limited cooling, first layer as close as possible to IP.

Challenges:

- Physics event rates up to 100 kHz (at Z pole) → strong requirements on sub-detectors and DAQ systems

Detector concepts for experiments at FCC-ee

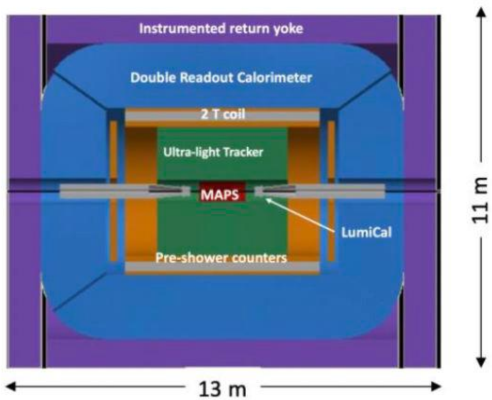
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

CDR

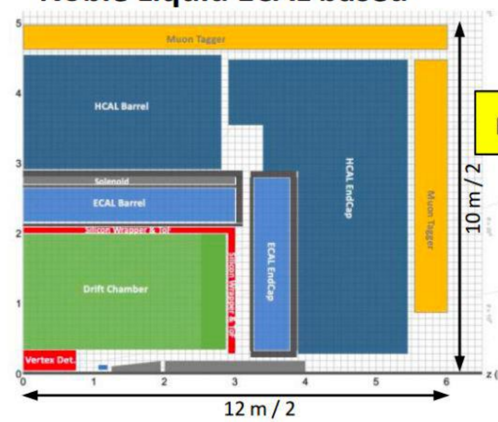
IDEA



- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

Noble Liquid ECAL based

new



- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

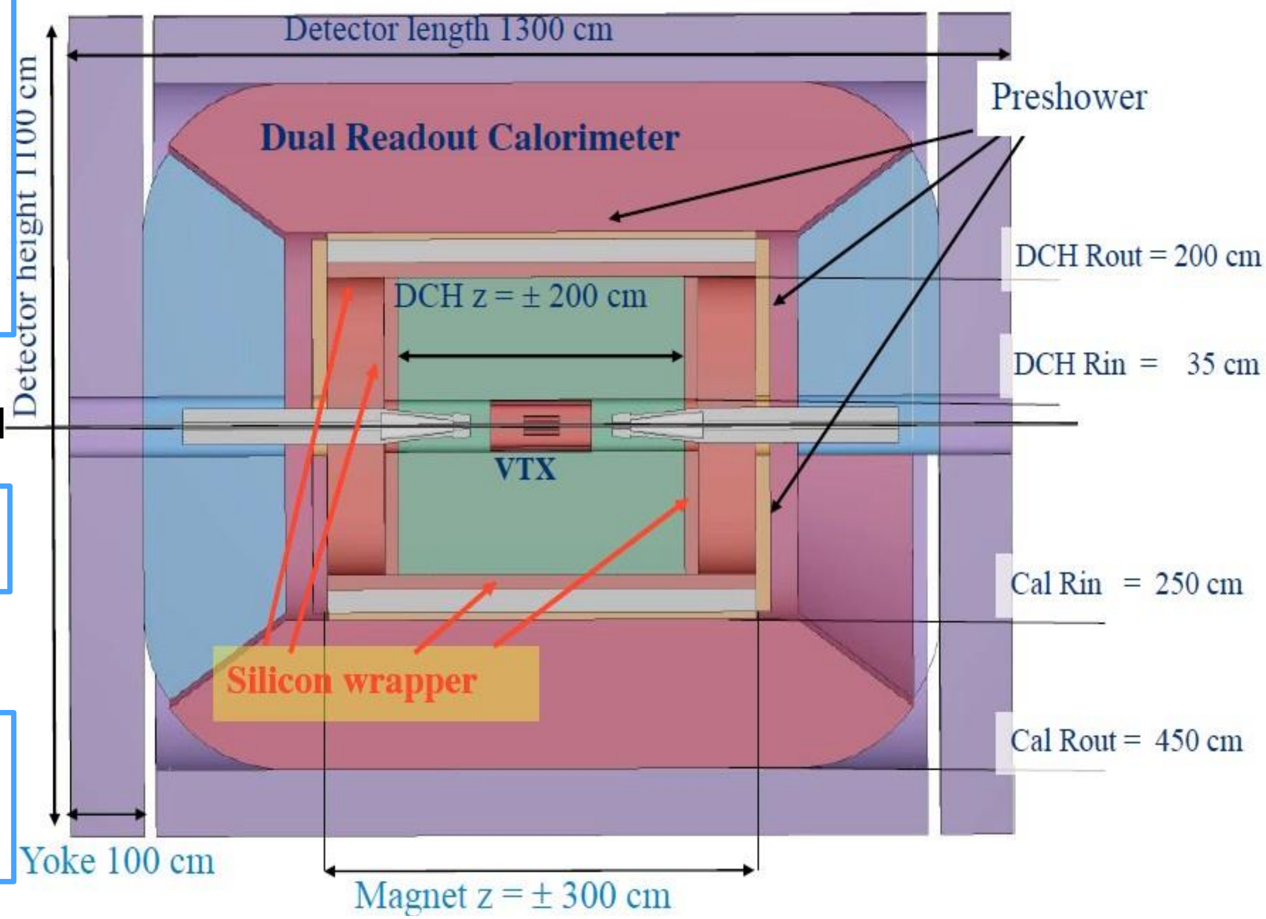
FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

The IDEA detector at e^+e^- colliders (1)

Innovative Detector for E+e- Accelerator

IDEA consists of:

- a silicon pixel vertex detector
- a large-volume extremely-light **drift chamber**
- surrounded by a layer of silicon micro-strip detectors
- a thin low-mass superconducting solenoid coil
- a preshower detector based on **μ-WELL technology**
- a dual read-out calorimeter
- muon chambers inside the magnet return yoke, based on **μ-WELL technology**



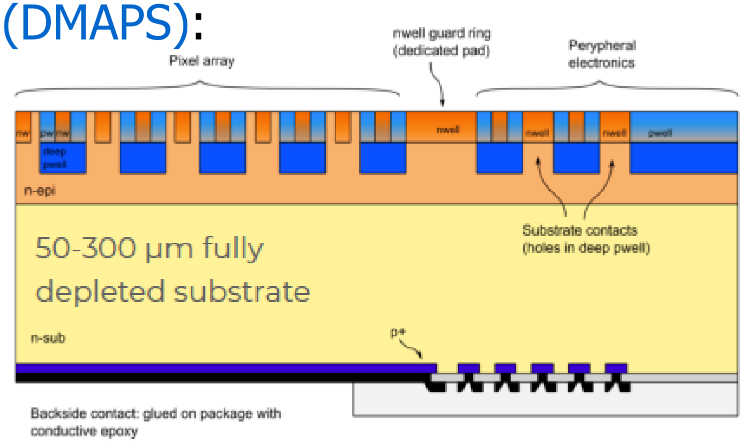
Low field detector solenoid to maximize luminosity (to contain the vertical emittance at Z pole).

→ optimized at 2 T

→ large tracking radius needed to recover momentum resolution

Vertex detector Insubria U.+ Milano U.

ARCADIA prototype



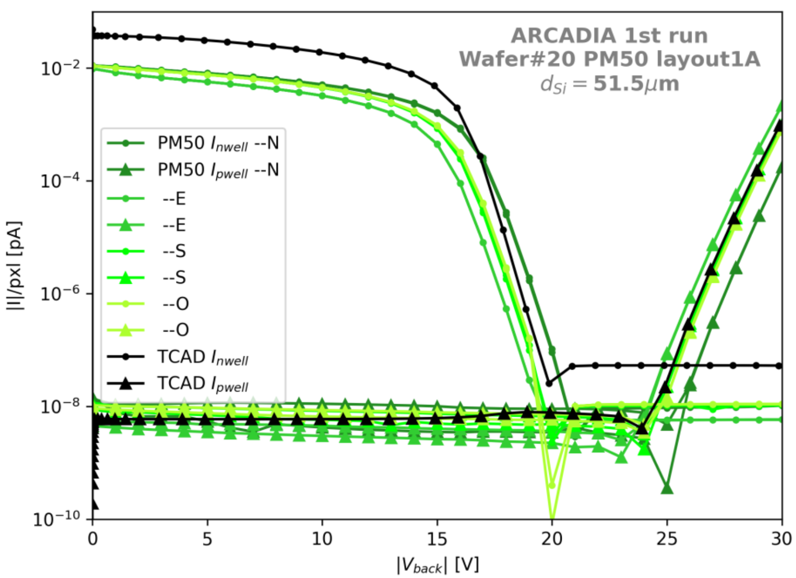
Technology: Depleted Monolithic Active Pixel Sensors (DMAPS):

- 25 x 25μm^2 pixel size for hit resolution ~ 3 μm
- 5 μm shown by ALICE ITS (30 mm pixels)
- prototype with thickness ~ 200 μm down to 50μm
- matrix 512x512
- low power consumption (< 20 mW/cm^2)

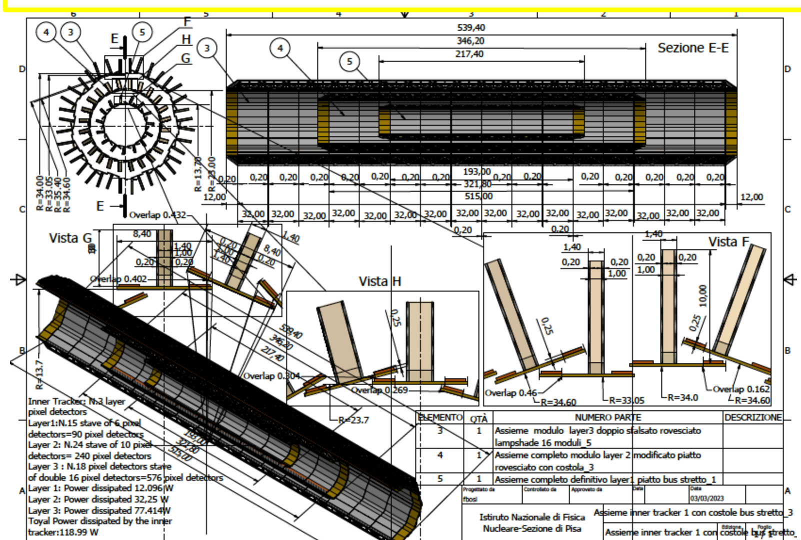
Tests of different design options:

- IV and CV measurements of test-structures from the first and second production run: proven functionality, stable operation at full depletion, and good agreement with TCAD simulations

A 2nd iteration prototype is working and will be tested soon at a test beam area



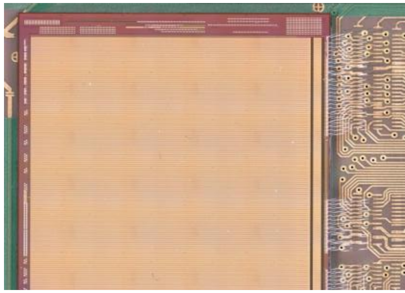
VTX mechanical strcture



Silicon medium and outer tracker KIT+UK+IHEP+INFN

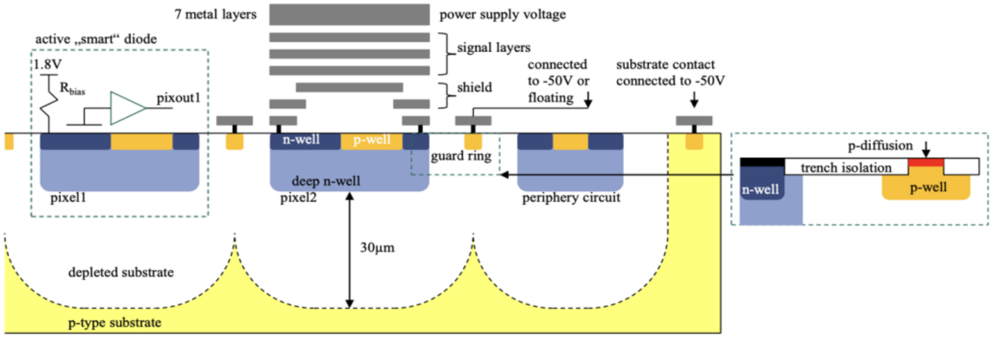
ATLASPIX3 modules: a full-size system on chip, targeting the medium and outer tracker

- quad module, inspired by ATLAS ITk pixels
- pixel size 50×150 μm^2 (25×165 μm^2 small size prototypes delivered)
- reticle size 20×21 mm^2
- TSI 180 nm process on 200 Ωcm substrate
- 132 columns of 372 pixels



Power consumption:

- ATLASPIX3 power consumption 150 mW/cm^2
- 600 mW/chip → 2.4 W/module → total FE power 130 kW
- additional power for on detector aggregation and de-randomizations ~2W/link



Complete system consists of 900'000 cm^2 area / 4 cm^2 chip = 225k chips (56k quad-modules):

- aggregation of several modules for data and services distribution is essential
- inner tracker will be 5-10% of this

See A. Andreazza talk for details

Data rate constrained by the inner tracker:

- average rate 10^{-4} - 10^{-3} particles cm^{-2} event^{-1} at Z peak
- assuming 2 hits/particle, 96 bits/hit for ATLASPIX3
- 640 Mbps link/quad-module (assuming local module aggregation) provides ample operational margin
- 16 modules can be arranged into 10 Gbps fast links: 3.5k links
- can also assume 100 Gbps links will be available: 350 links

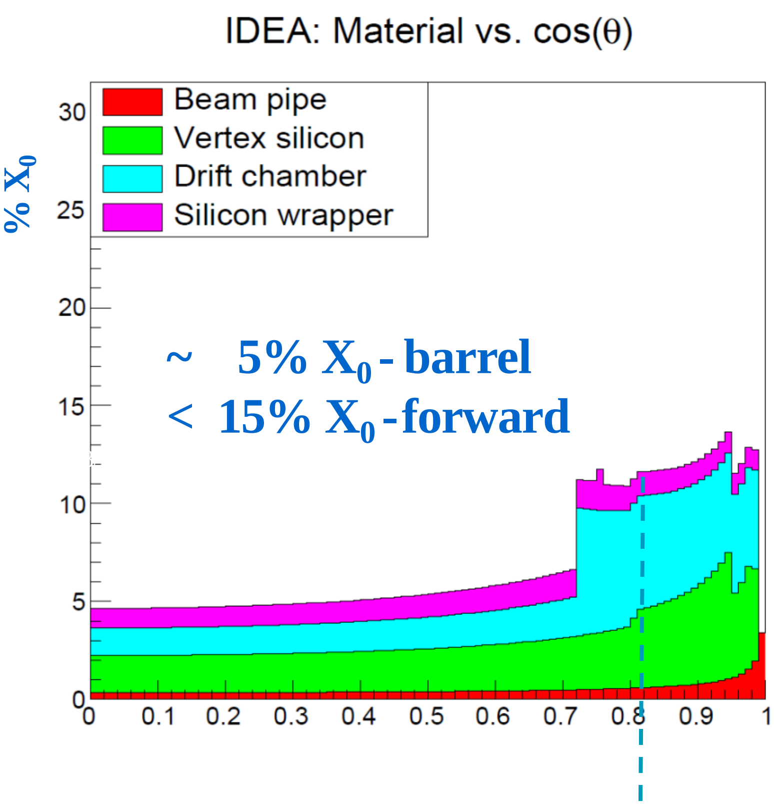
Design features of the IDEA Drift Chamber

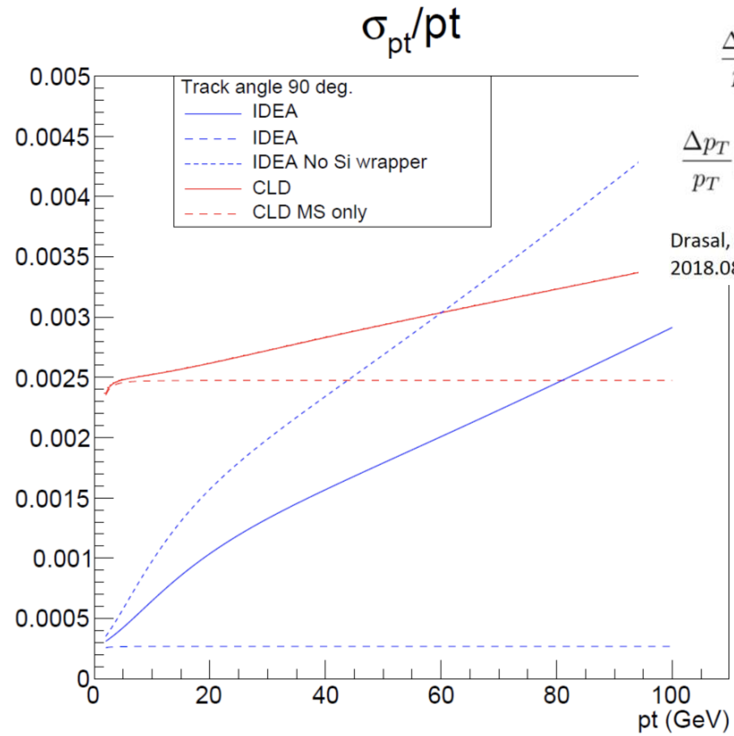
INFN Bari and Lecce, IHEP + contributions from UCL, NWU and FSU

For the purpose of tracking and ID at low and medium momenta mostly for heavy flavour and Higgs decays, the IDEA drift chamber is designed to cope with:

- transparency against multiple scattering, more relevant than asymptotic resolution
- a high precision momentum measurement
- an excellent particle identification and separation

Particle momentum range far from the asymptotic limit where MS is negligible





$$\frac{\Delta p_T}{p_T}\Big|_{res.} \approx \frac{12\,\sigma_{r\phi}\,p_T}{0.3\,B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\,B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$

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

The Drift Chamber

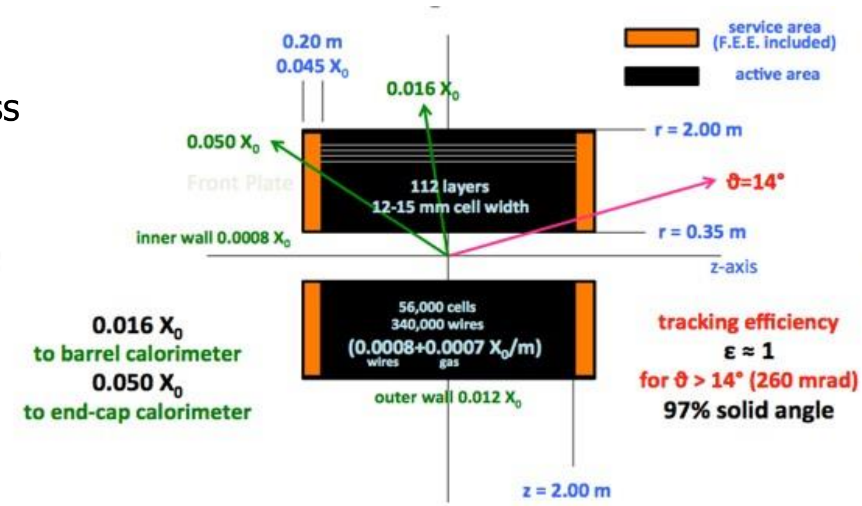
The DCH is:

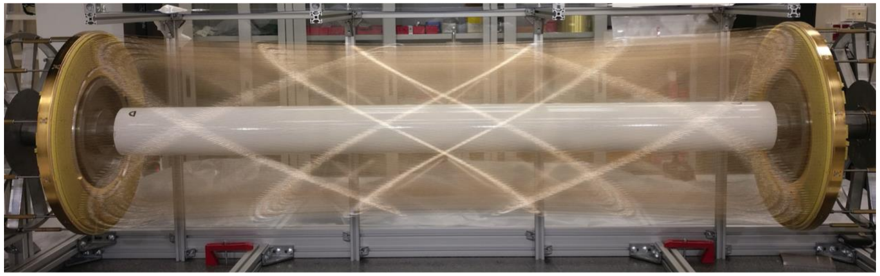
- a unique-volume, high granularity, fully stereo, low-mass cylindrical
- gas: He 90% - iC_4H_{10} 10%
- inner radius R_{in} = 0.35m, outer radius R_{out} = 2m
- length L = 4m
- drift length ~1 cm
- drift time ~150ns
- $\sigma_{xy} < 100\ \mu m$, $\sigma_z < 1$ mm
- 12÷14.5 mm wide square cells, 5 : 1 field to sense wires ratio
- 112 co-axial layers, at alternating-sign stereo angles, arranged in 24 identical azimuthal sectors, with frontend electronics
- 343968 wires in total:

  sense vires: 20 μm diameter W(Au) => 56448 wires

  field wires: 40 μm diameter Al(Ag) => 229056 wires

  f. and g. wires: 50 μm diameter Al(Ag) => 58464 wires





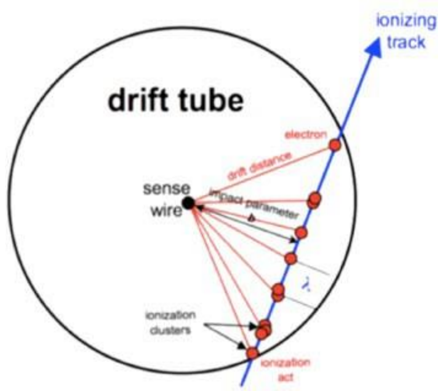
- the wire net created by the combination of + and – orientation generates a more uniform equipotential surface → better E-field isotropy and smaller ExB asymmetries)

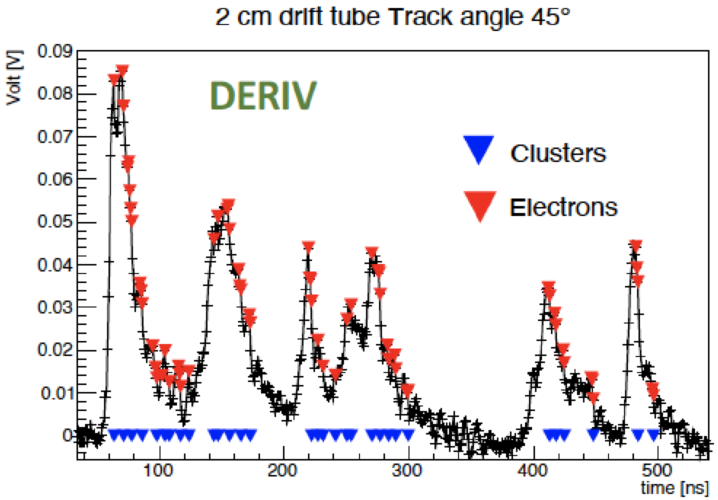
- a large number of wires requires a non standard wiring procedure and needs a feed-through-less wiring system → a novel wiring procedure developed for the construction of the ultra-light MEG-II drift chamber

The Drift Chamber: Cluster Counting/Timing and PID

Principle: In He based gas mixtures the signals from each ionization act can be spread in time to few ns. With the help of a fast read-out electronics they can be identified efficiently.

- By counting the number of ionization acts per unit length (dN/dx), it is possible to identify the particles (P.Id.) with a better resolution w.r.t the dE/dx method.





- collect signal and identify peaks
- record the time of arrival of electrons generated in every ionisation cluster
- reconstruct the trajectory at the most likely position

- Landau distribution of dE/dx originated by the mixing of primary and secondary ionizations, has large fluctuations and limits separation power of PID → primary ionization is a Poisson process, has small fluctuations

- The cluster counting is based on replacing the measurement of an ANALOG information (the [truncated] mean dE/dX) with a DIGITAL one, the number of ionisation clusters per unit length:

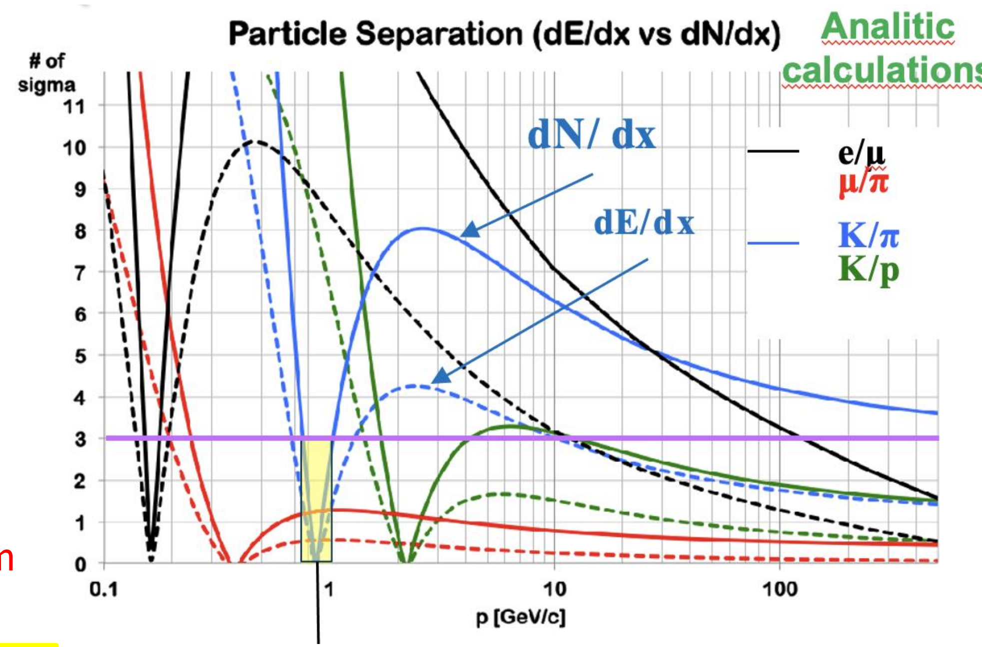
dE/dx: truncated mean cut (70-80%), with a 2m track at 1 atm give $\sigma \approx 4.3\%$

dN_{cl}/dx: for He/iC_4H_{10}=90/10 and a 2m track gives $\sigma_{dNcl/dx}$ **$/(dN_{cl}/dx)$** < 2.0%

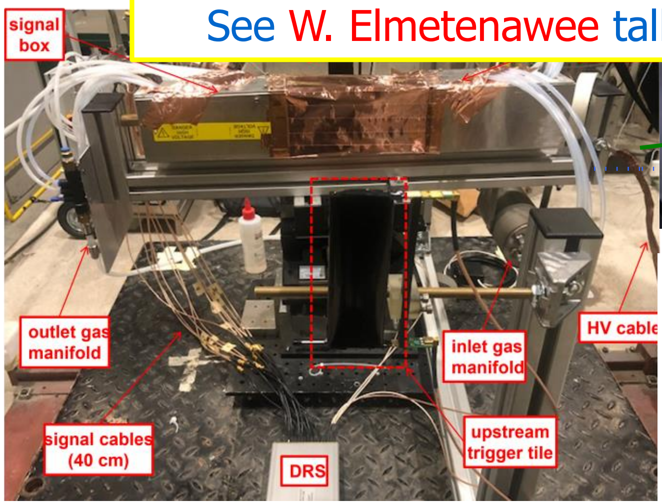
The Drift Chamber: Cluster Counting/Timing and PID

- Analitic calculations: Expected excellent K/π separation over the entire range except 0.85<p<1.05 GeV (blue lines)

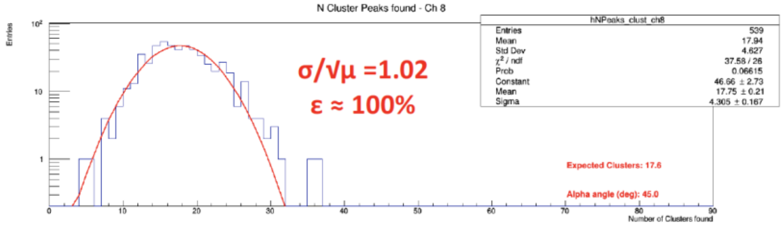
- Simulation with Garfield++ and with the Garfield model ported in GEANT4:
  - the particle separation, both with dE/dx and with dN_{cl}/dx, in GEANT4 found considerably worse than in Garfield
  - the dN_{cl}/dx Fermi plateau with respect to dE/dx is reached at lower values of βγ with a steeper slope
  - finding answers by using real data from beam tests at CERN in 2021 and 2022, and 2024



See W. Elmetenawee talk for details



$90\%He-10\%iC_4H_{10}$
nominal HV+20, 45°,
Gas gain ~ $2 \cdot 10^5$,
165 GeV/c



- Poissonian behaviour of the number of clusrers
- Meaurements vs predictions about the number of clusters are in very good agreement
- Same results in independent drift tubes

Data reduction and pre-processing of drift chamber signals

Issue: with about 60000 drift cells, assuming to digitise the signal at 12 bits and 2 GS/s, a throughput of about 1 Tb/s is hardly sustainable by modern equipment → is necessary to transfer all the data.

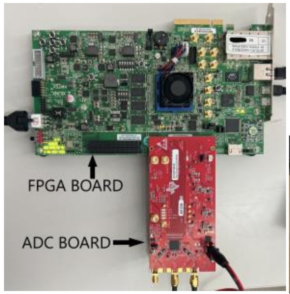
- with the cluster counting algorithms, by transferring only time and amplitude of each electron peak, these rates are reduced to about 60 Gb/s, resulting in a data reduction factor of more than one order of magnitude.

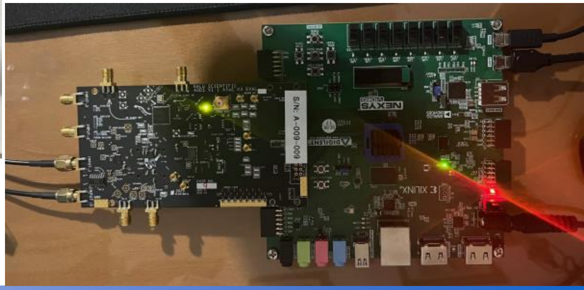
- Applying the cluster counting technique on FPGAs in real time has two main objectives:
  1. reduce transferred data
  2. reduce stored information

- A secondary advantage that allows us to reduce CPU usage during data analysis as the waveforms have already been analyzed in real time, saving only the necessary information

The objective of the new project is to implement, on a single FPGA, cluster counting algorithms for the parallel preprocessing of as many channels as possible in order to reduce the costs and complexity of the system and gain flexibility in determining the proximity correlations between hit cells for track segment search and for triggering purposes.

- For this purpose a card with multichannel reading is under development, testing different digitizers:
  - TEXAS INSTRUMENTS ADC32RF45 → implementation of cluster counting almost complete
  - CAEN digitzer
  - NALU SCIENTIFIC ASoCv3 → test with native acquisition program and then implementation of the cluster counting



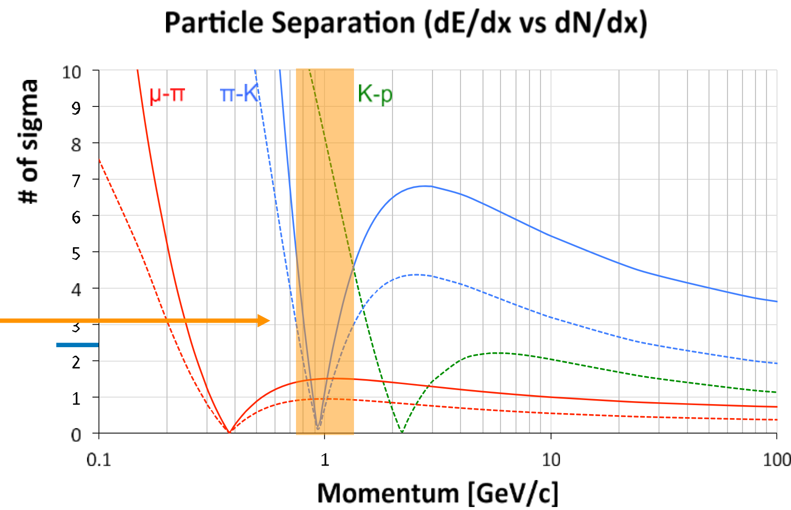


Silicon wrapper

INFN Genova

In IDEA concept, tracking and PID provided by the DCH (+ VTX + medium and outer T)

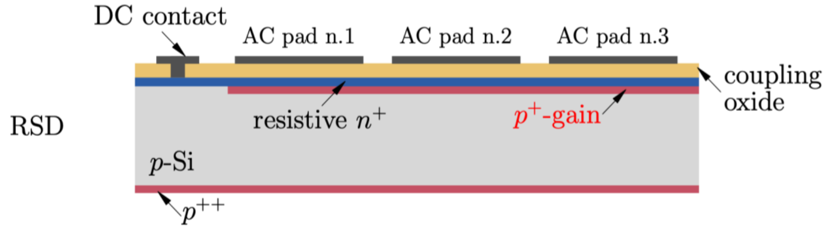
- Silicon wrapper for precise polar angle measurement
- Good K-p separation from dE/dx except for p ~ 1 GeV

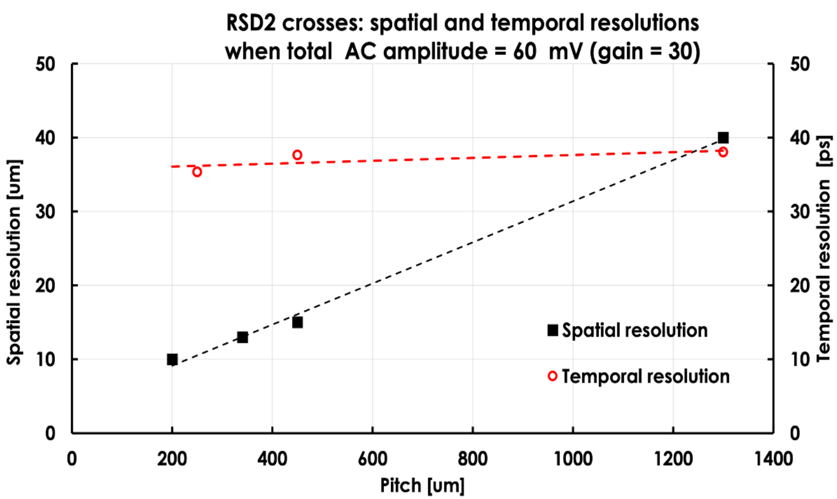


Baseline: ATLASPIX3 modules **BUT**

LGAD (Low-Gain Avalanche Diodes) with RSD (Resistive Silicon Detectors) technology are a possible option:

- TOF with excellent time resolution
- Position from pixel-like geometry or charge sharing resistive-layer design





Reconstruction of the position from the signal distribution between contiguous electrodes

Need to show that LGAD could be produced with acceptable cost

- Technology developed by INFN Turin group, production by FBK
- External funding also (ERC, PRIN)

Muon detectors for IDEA: guiding principles

INFN Frascati, Ferrara, CERN

Future colliders experiments require extremely large muon detectors :

- ~10000 m^2 in the barrel
- 3-5000 m^2 in the endcap
- 300 m^2 in the very forward region

PRESHOWER requirements:

- high-spatial-resolution layer between magnet and calorimeter
- charge measurement to help discriminating the electromagnetic nature of the clusters
- barrel + two endcaps

MUON CHAMBERS requirements:

- low particle rate
- rough resolution to detect muons behind the calorimeter
- with higher resolution could help detecting secondary vertices from Long-Lived Particles decaying into muons

Preshower:

- ✓ Efficiency > 98%
- ✓ Space Resolution < 100 μm
- ✓ Pitch = ~400 μm
- ✓ Strip capacitance ~70 pF
- ✓ 1.5 million channels
- ✓ FEE cost reduction —> custom ASIC
- ✓ Arranged in tiles 50x50 cm^2
- ✓ Mass production —> T.T.

Muon chambers:

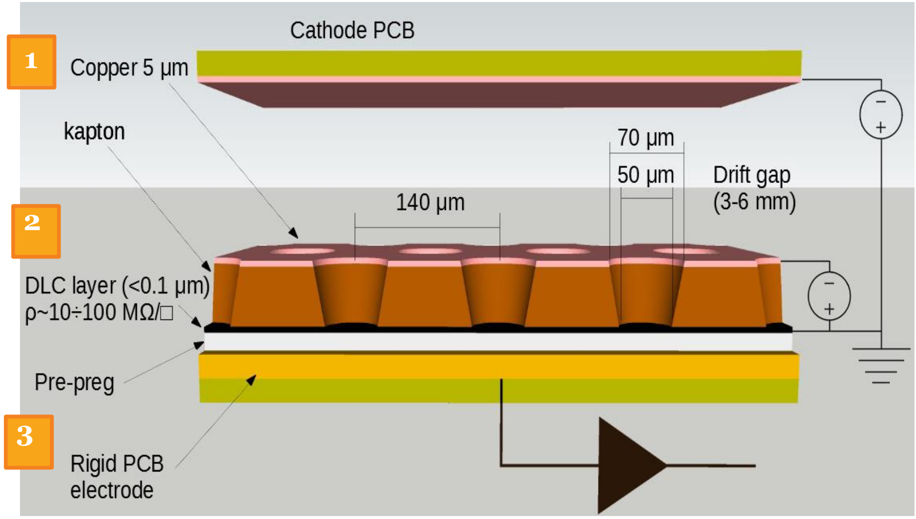
- ✓ Efficiency > 98%
- ✓ Space Resolution < 400 μm
- ✓ Pitch = ~1.5 mm
- ✓ Strip capacitance ~270 pF
- ✓ ~5 million channels
- ✓ FEE cost reduction —> custom ASIC
- ✓ Arranged in tiles 50x50 cm^2
- ✓ Mass production —> T.T.

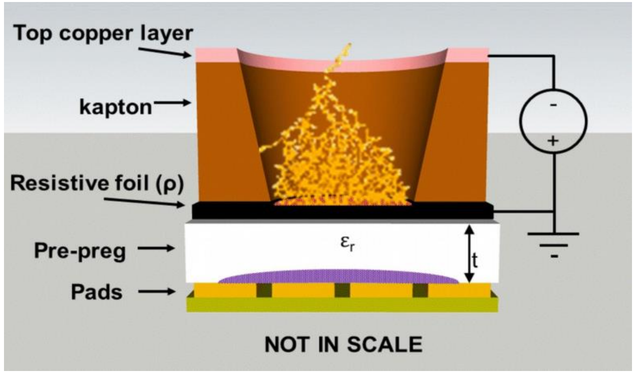
The μ-RWELL detector schema

R&D on μ-RWELL technology mainly motivated by the wish of improving:

- ✓ the stability under heavy irradiation (discharge suppression)
- ✓ the construction technology (simplifying the assembly)
- ✓ the technology transfer to industry (mass production)

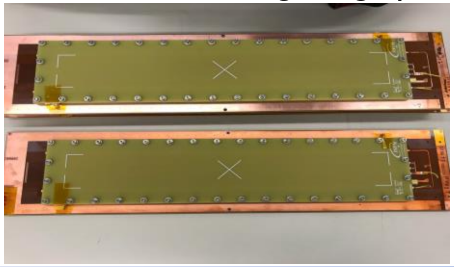
The μ-RWELL is a Micro Pattern Gaseous Detector (MPGD) composed of only two elements: the μ-RWELL_PCB and the cathode.





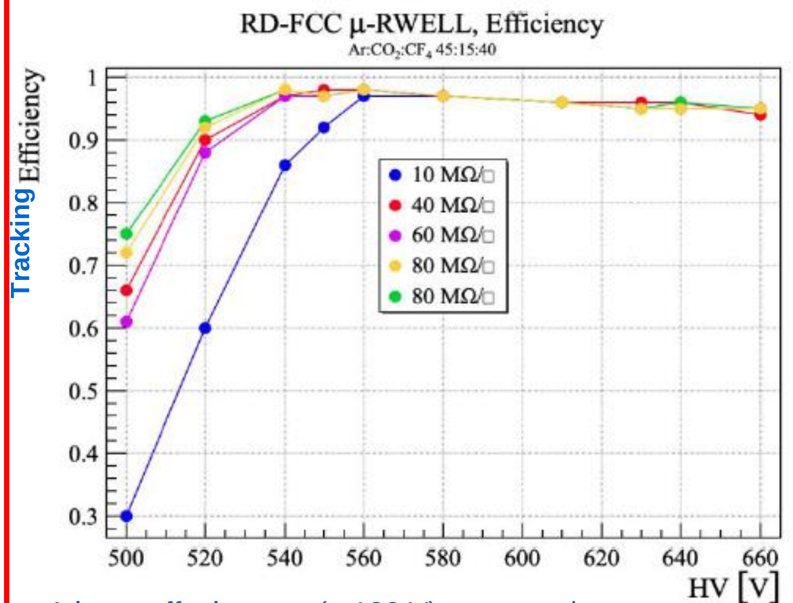
Applying a suitable voltage between the top Cu-layer and the DLC the WELL acts as a multiplication channell for the ionization produced in the conversion/drift gas gap.

1. A WELL patterned kapton foil acting as amplification stage (GEM-like)
2. a resisitive DLC layer (Diamond Like Carbon) for discharge suppression w/surface resistivity ~ 50÷100 MΩ/sq
3. a standard readout PCB

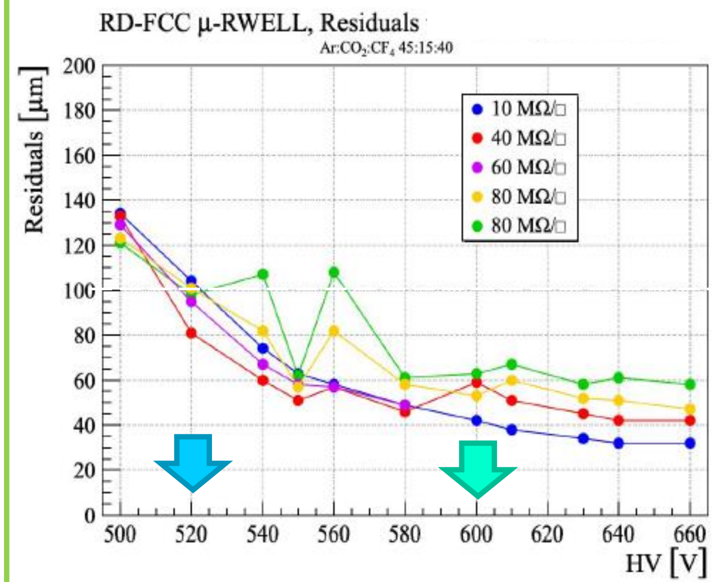


Test beam at CERN with μ-RWELL prototypes with
- 40cm long strips
- 0.4 mm strip pitch
- 1D readout

μ-RWELL test beam results and technology transfer



A large eff. pleateau (> 100 V) measured



With a pitch 0.4 mm at HV=520 V and with CL=1.5 → σ < 100 um

Technology transfer with ELTOS/CERN: flow chart

INFN LNF - DDG, Istituto Nazionale di Fisica Nucleare

Responsibility:

- Detector design (GERBER);
- Link with ELTOS
- Link with CERN-Rui
- Quality Control detector
- DLC Machine managment (>2023)

ELTOS

Responsibility:

- PCB RWELL production
- Cathode production
- DLC+PCB RWELL coupling

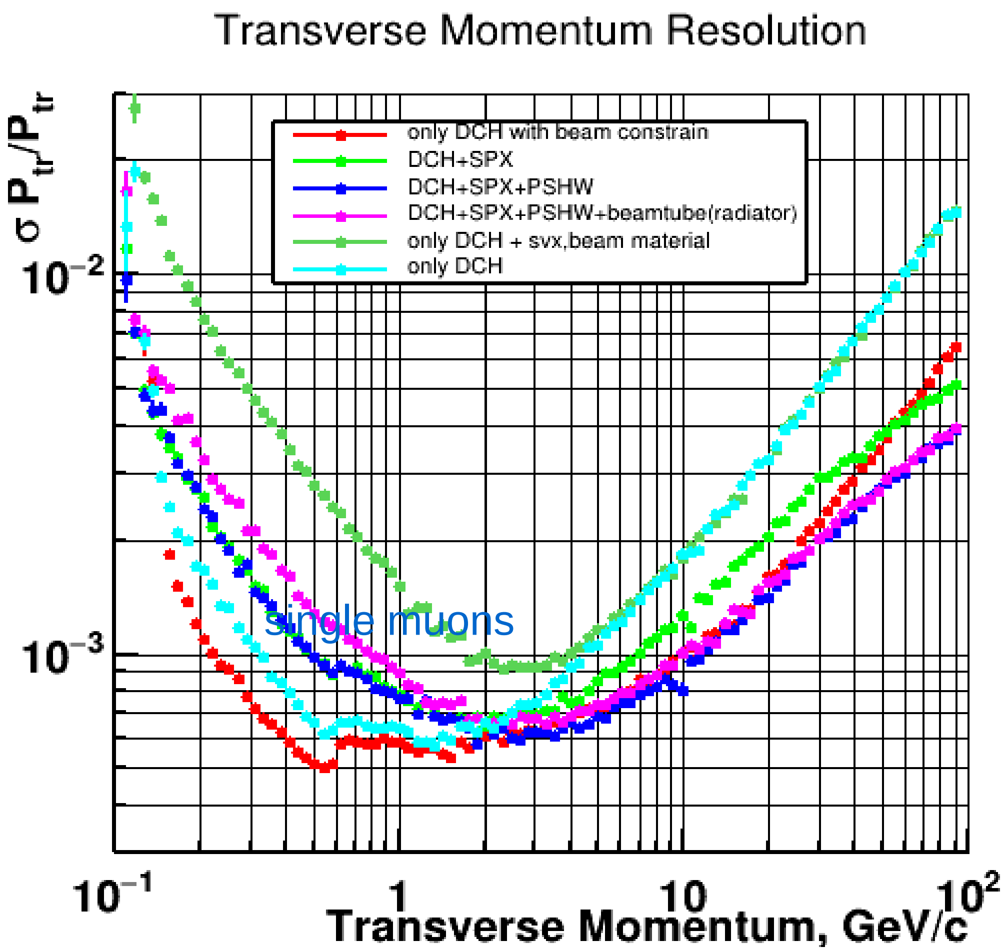
CERN

Responsibility:

- PCB RWELL finalization
- Hot Electrical Cleaning
- Detector closure

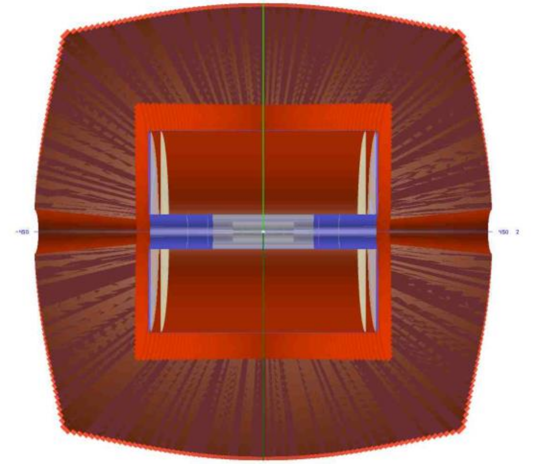
Simulation and performance of the IDEA tracking system

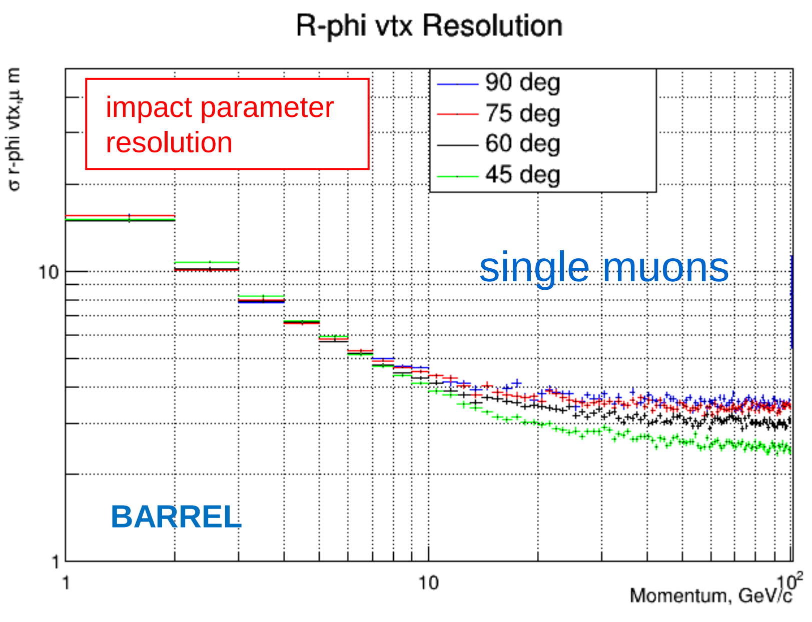
A full standalone Geant4 (and partially DD4HEP) simulation of the Silicon Vertex (and Si wrapper), DriftChamber, DR Calorimeter and Muon Preshower



$\sigma(p_t)/p_t$ (100 GeV) = 3×10^{-3}

but new studies ongoing





Summary/Conclusions

Advanced R&D effort on tracking detectors:

- vertex pixel detector, based on ARCADIA
- silicon medium and outer tracker, based on ATLASPIX3
- silicon wrapper, based on ATLASPIX3 (LGAD under evaluation)
- drift chamber design and cluster counting study, sinergy with MEG2
- muon chambers, synergy with LHCb upgrades

Plenty of areas for collaboration:

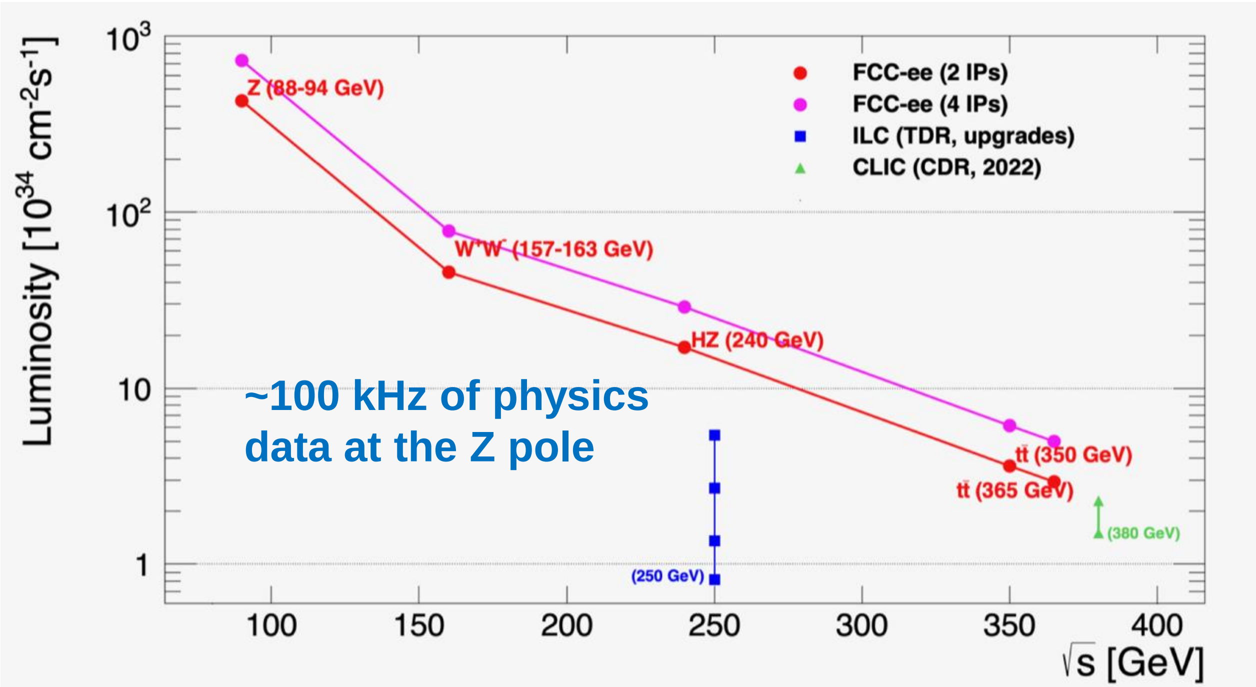
- detector design, construction, beam test, performance
- local and global reconstruction, full simulation
- physics performance and impact
- etc.

Effort to build international collaboration on going (in some areas well advanced) and to be enforced

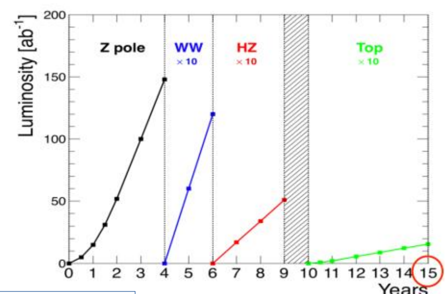
Manpower, funding under continuous discussion

Backup

Machine luminosity for physics at e^+e^- colliders



- Higgs factory:
  - 10^6 $e^+e^- \rightarrow HZ$
- EW & Top factory:
  - 3×10^{12} $e^+e^- \rightarrow Z$
  - 10^8 $e+e^- \rightarrow W^+W^-$
  - 10^6 $e^+e^- \rightarrow tt$
- Flavor factory:
  - 5×10^{12} e+e- → bb, cc
  - 10^{11} e+e- → $\tau+\tau-$



Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events

$$\approx \frac{\Delta_{LEP,Stat}}{500}$$

Physics requirements: Higgs, EWK and Heavy Flavour

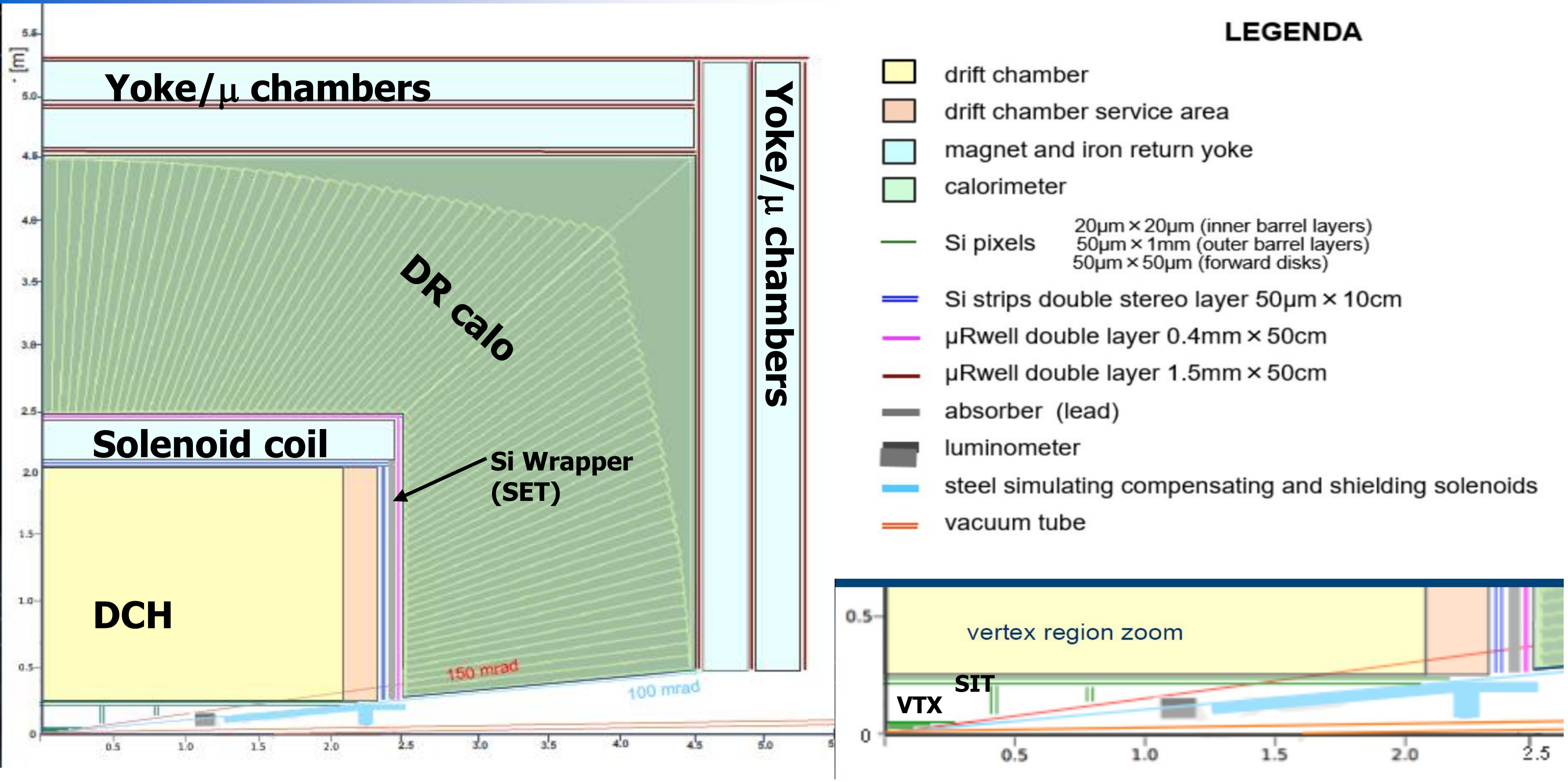
- Tracking:
  - Momentum resolution for Z recoil (and $H \rightarrow \mu\mu$)
    - Comparatively low momenta involved → transparency is important
  - Vertex resolution/transparency to separate g, c, b, τ final states
- Calorimetry:
  - Jet-jet invariant mass resolution to separate W, Z, H in 2 jets
  - Good π^0 ID for τ and HF reconstruction

Higgs boson sector

- EWK:
  - Extreme definition of detector acceptance
  - Extreme EM resolution (crystals) under study
    - Improved π^0 reconstruction
    - Physics with radiative return
- Heavy Flavour:
  - PID to accurately classify final states and flavor tagging

EWK and Heavy Flavour

The IDEA detector at e^+e^- colliders (2)



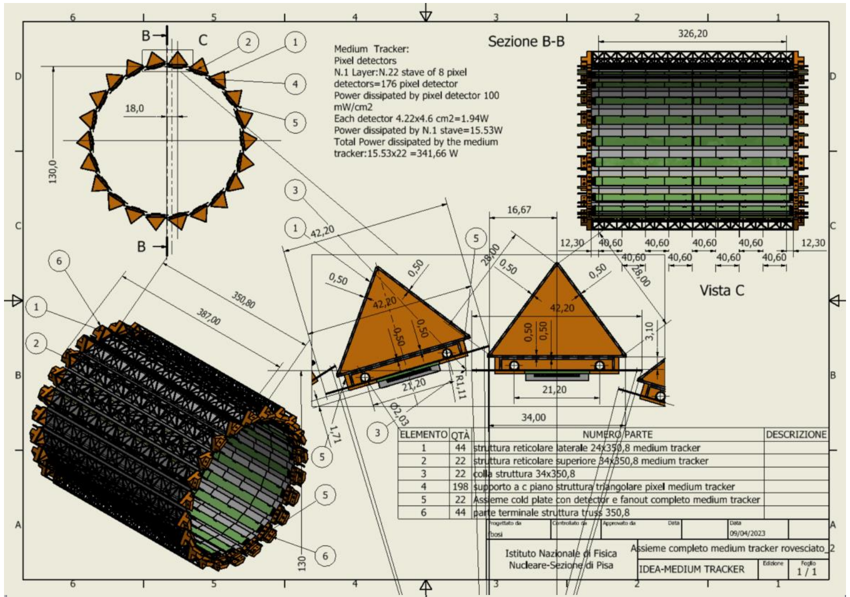
- Tracking coverage → 150 mrad → No material in front of luminometer
- Calorimetry → 100 mrad

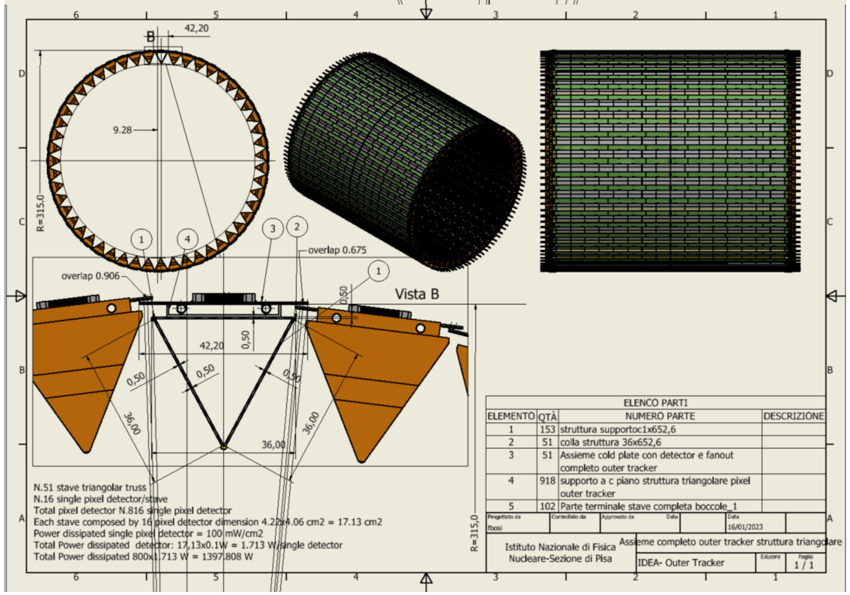
Goals of the IDEA tracking system:

- to preserve the momentum resolution for Z recoil (and $H \rightarrow \mu\mu$)
  - comparatively low momenta involved → transparency is important
- to preserve the vertex resolution/transparency to separate g, c, b, τ final states

Silicon medium and outer tracker

See F. Palla talk for details





Intermediate Tracker Barrel
At 13 cm radius

22 staves of 8 modules each.

Lightweight reticular support structure (ALICE/Belle-II like)

Outer Tracker Barrel
At 31.5 cm radius

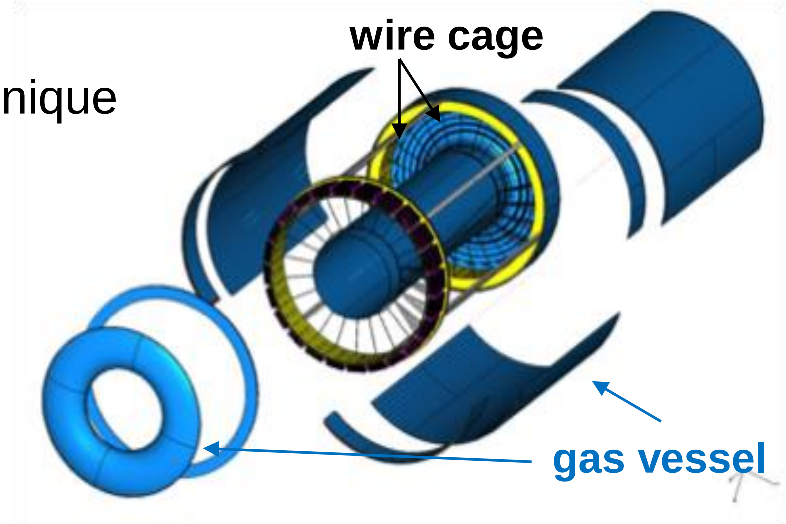
51 staves of 16 modules each

Lightweight reticular support structure (ALICE/Belle-II like)

Design features: the Drift Chamber

Novel approach at construction technique of high granularity and high transparency Drift Chambers

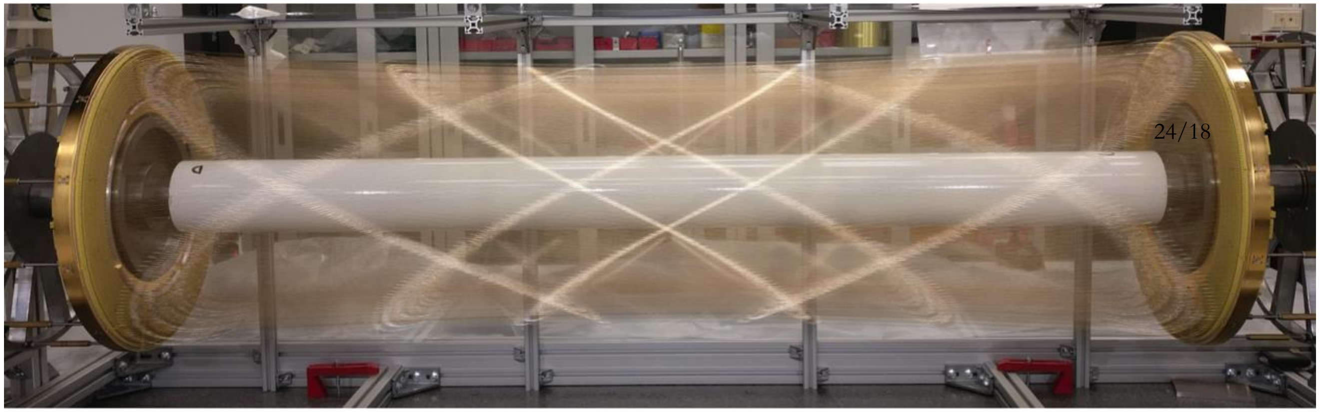
Based on the MEG-II DCH new construction technique the IDEA DCH can meet these goals:

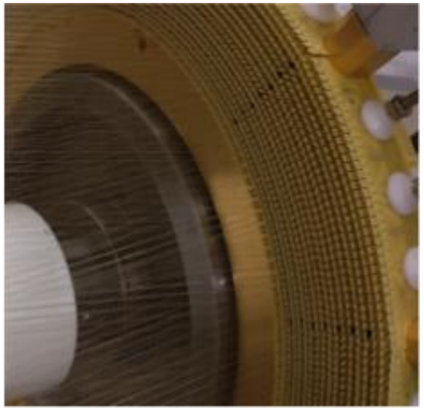


- Gas containment – wire support functions separation:

  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
- 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 by using thinner wires





Chamber Layout (the IDEA drift chamber)

Radii (at z = 0)		
Inner Cylinder	350	mm
Guard wires layer	354	mm
First active layer	356	mm
Last (112th) active layer	1915	mm
Guard wires layer	1927	mm
Outer Cylinder	2000	mm

Radii (at end plate)		
Inner Cylinder	350	mm
Guard wires layer	366	mm
First active layer	369	mm
Last (112th) active layer	1982	mm
Guard wires layer	1995	mm
Outer Cylinder	2000	mm

Active length	2000	mm
Number of super-layers (8 layers) Number of sectors	(14x8) = 112 24	
Number of cells per layer / per sector	192÷816 / 16	
Cell size (at z=0)	11.8 ÷ 14.9	mm
2α angle	30°	
Stereo angle	43 ÷ 223	mrad
Stereo drop	12.5 ÷ 68.0	mm

sense wires	56 448
field wires	284 256
guard wires	2 016
Total wires	342 720

Wire Layout (the IDEA drift chamber)

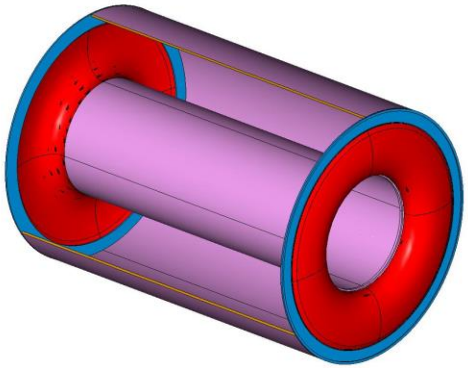
- 112 co-axial layers (grouped in 14 superlayers of 8 layers each) of para-axial wires in 24 azimuthal sectors;
- stereo angles from ±43 mrad to ±223 mrad;
- rotational hyperboloid for each layer
- 192 (at inner layer), 816 (at outer layer) square drift cells (16 per sector);
- cell size ranging from 11.8 mm at the innermost layer, to 14.9 mm at the outermost one;
- ratio of field wires to sense wires = 5 : 1;
- 56 448 sense wires – 284 256 field wires – 2 016 guard wires;
- sense wires 20 μm diameter gold plated Mo (30 g tension);
- field and guard wires, 40 and 50 μm diameter silver plated Al (30 g);
- total wire tension 10 Ton.

Mechanical construction scheme

On going: Finite element analysis in collaboration with a company (EnginSoft) and Politecnico Un. in Turin.

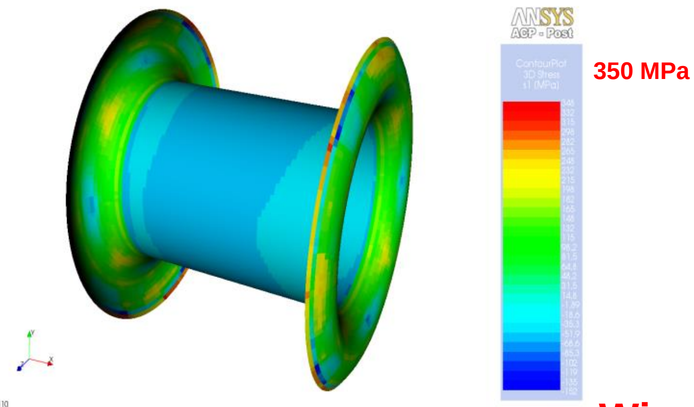
Gas containment

Gas vessel can freely deform without affecting the internal wire position and mech. tension.



Static solution

stress

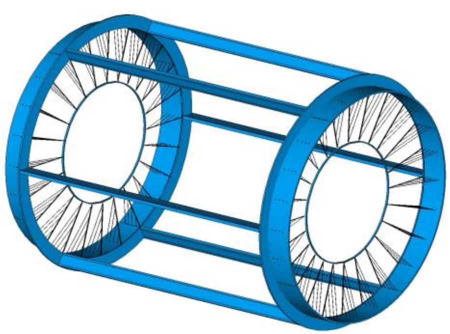


Inner cylinder sandwich:
2 C-fiber skins, 2-ply each,
HM M30S 53 ET443 51%
+ C-foam core, 5 mm total
Grafoam® FPA-10
(0.100 g/cm^2 total)

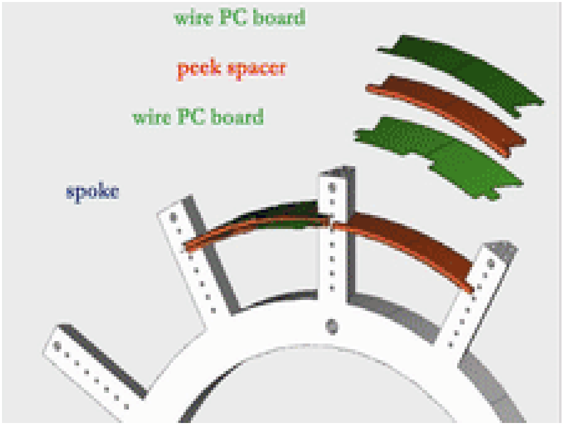
End plates: 4-ply orthotropic (0-90-90-0)
HM M30S 53 ET443 51%
60 µm/ply - 0.0053 g/cm^2
(0.021 g/cm^2 total)

Wire support

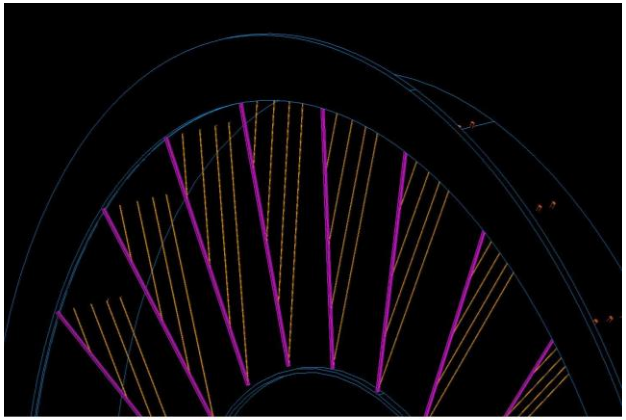
Wire support structure not subject to differential pressure can be light and feed-through-less.



Analogy with MEG2 drift chamber



Wire tension recovery scheme



Plan for 2023/2024:

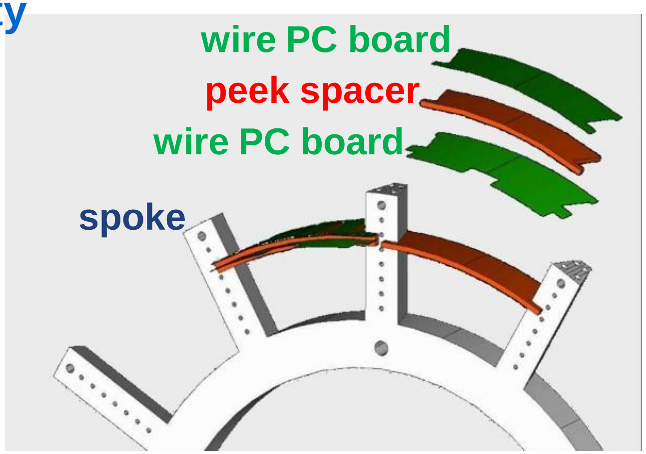
- construct a full-size prototype (4m long) to test different wire choices and the relative electrostatic stability and to validate the proposed tension recovery scheme of the endplates.

Gas Vessel (tentative procedure)

- **End-plate profile optimization**
  - **Use isotropic material (1 mm thick Aluminum) solid rotational plates + inner cylinder (ideal joints)**
  - **Assume infinitely rigid outer cylinder**
  - **Parameterize geometry by:**
    - **constraining inner cylinder radius**
    - **constraining inner cylinder length**
    - **constraining outer cylinder radius**
    - **varying middle point of a 3 point-spline profile for the end plates**
  - **Optimize dynamic properties:**
    - **minimum stress at inner boundary**
    - **minimum of maximum stress**
    - **maximum safety factor**
  - **Replace isotropic material with light composite material**
  - **Detailed FEM analysis**
- **Solve buckling instabilities**
- **Measure mechanical properties of chosen material**
- **Build a scale model and characterize it**

Design features: the Drift Chamber

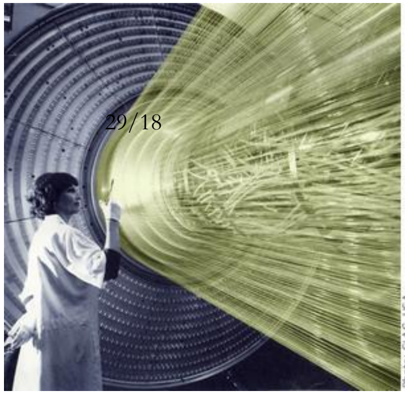
Novel approach at construction technique of high granularity and high transparency Drift Chambers

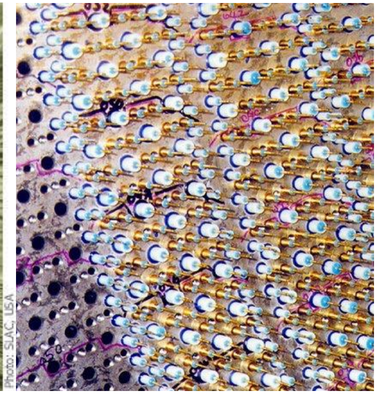


The solution adopted for MEG II:

- end-plates numerically machined from solid Aluminum (mechanical support only);
- Field, Sense and Guard wires placed azimuthally by a Wiring Robot with better than one wire diameter accuracy;
- wire PC board layers (green) radially spaced by numerically machined peek spacers (red) (*accuracy < 20 μm*);
- wire tension defined by homogeneous winding and wire elongation (*ΔL = 100μm corresponds to ≈ 0.5 g*);
- Drift Chamber assembly done on a 3D digital measuring table;
- build up of layers continuously checked and corrected during assembly;
- End-plate gas sealing done with glue.

(~ 12 wires/cm^2) impossible to be built with a conventional technique based on feedthrough:

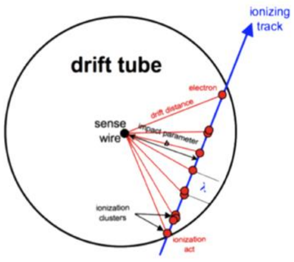


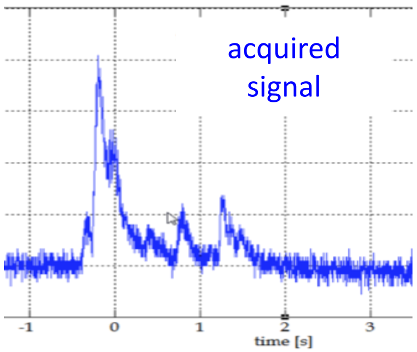


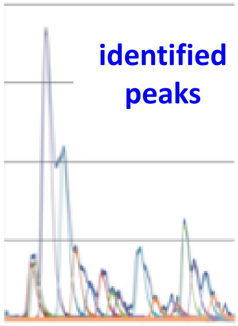
Cluster counting/timing performance

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:

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







dE/dx

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

from *Walenta parameterization (1980)*

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

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

from *Poisson distribution*

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.

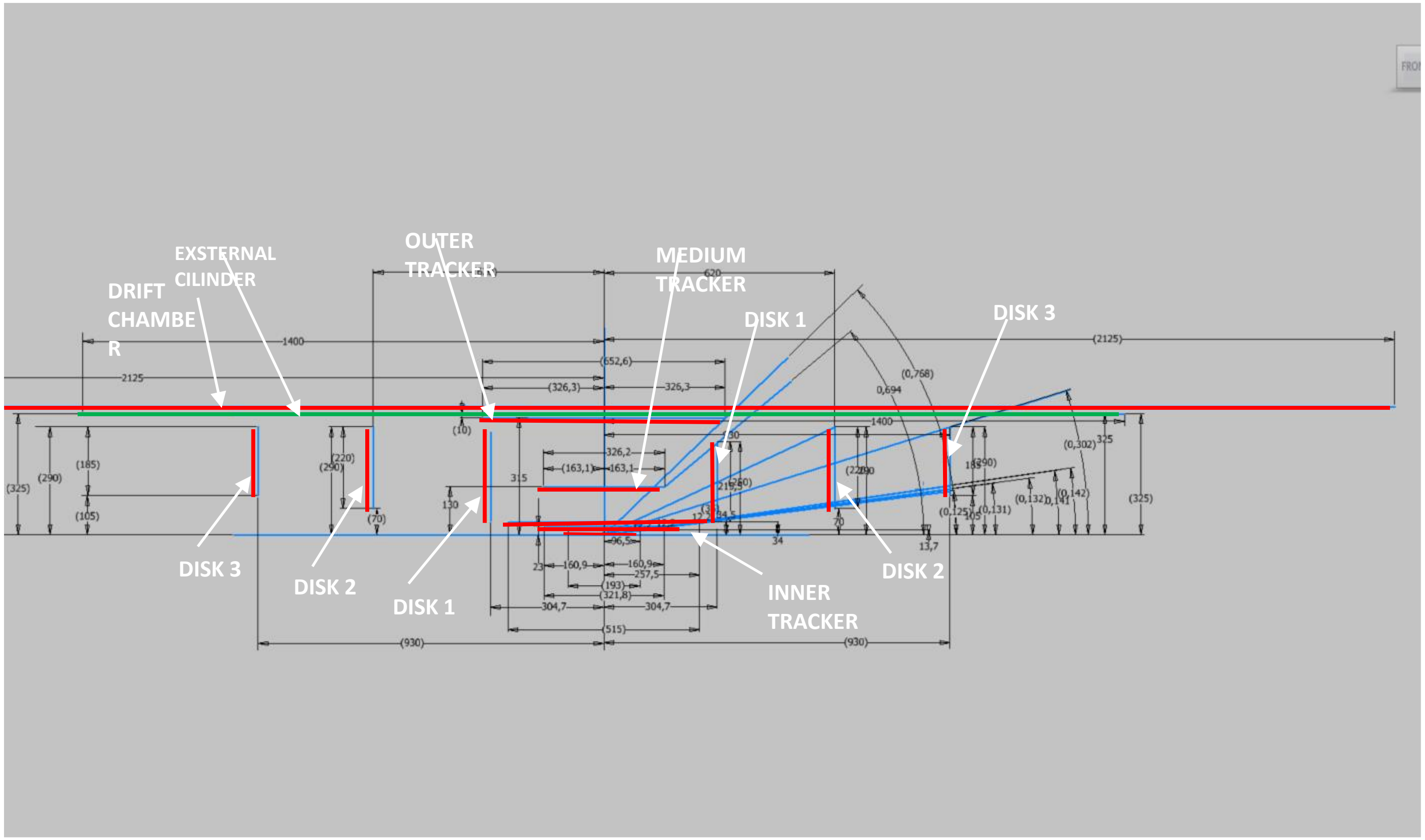
Moreover, C.C. allows can improve the spatial resolution < 100 μm for 8 mm drift cells in He based gas mixtures

Silicon detectors for precision measurements:

- vertex detector/inner tracker (VTX)
- silicon medium and outer tracker
- silicon wrapper (SET)

+ design of the mechanical structure (light-weight staves)

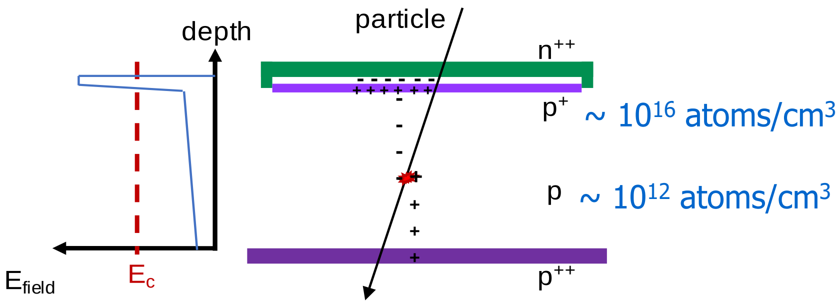
+ activity with the MDI group for the integration of the vertex detector



Silicon wrapper

INFN Genua

- Low-Gain Avalanche Diodes (LGADs) are n-in-p silicon sensors
- Operated in low-gain regime (~ 20) controlled by the external bias
- Critical electric field $E_C \sim 20 - 30$ V/μm → gain layer region
- Detector ion resistive substrate (RSD) suitable for the si-Wrapper, combining tracking and TOF



The p^+ dopant concentration of the gain implant gets reduced by irradiation and LGADs loose their multiplication power above ~ $3 \cdot 10^{15}$ n_{eq}/cm^2

An innovative design of the gain implant has been designed to extend signal multiplication up to ~ 10^{17} n_{eq}/cm^2

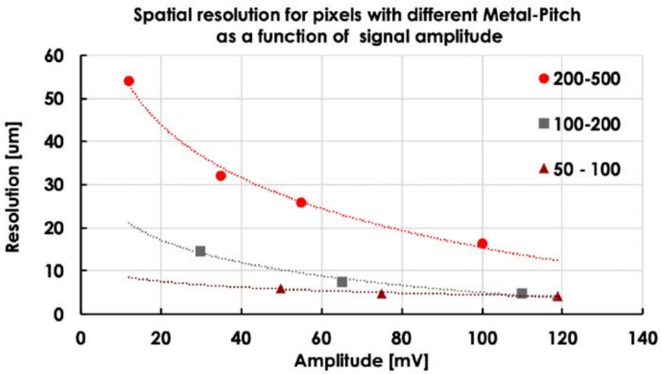
→ Compensated LGAD

→ A 3 years project has been accepted for funding by AIDAinnova as Blue Sky R&D to investigate and develop the compensated LGAD design

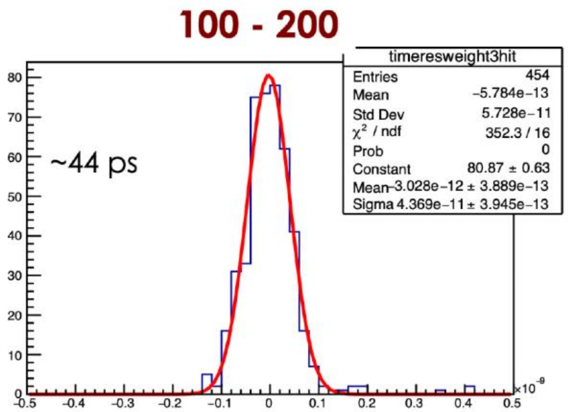
Silicon wrapper

INFN Genua

- **Risoluzione Spaziale**
  - dipende da molti fattori: pitch, geometria degli elettrodi rumore dell'elettronica, digitalizzazione del segnale, algoritmo di ricostruzione…
  - Si possono raggiungere risoluzioni pari a circa il **3% del pitch** degli elettrodi



- **Risoluzione Temporale**
  - I sensori RSD mantengono le eccellenti caratteristiche di risoluzione temporale degli LGAD
  - misura ottenuta dalla combinazione dei segnali distribuiti;
  - contributo aggiuntivo dal ritardo di propagazione del segnale;
  - ottima uniformità osservata sull'area attiva
  - Test su fascio su geometrie della prima produzione hanno mostrato risoluzioni di **40-45 ps** (~20 ps da test con laser)

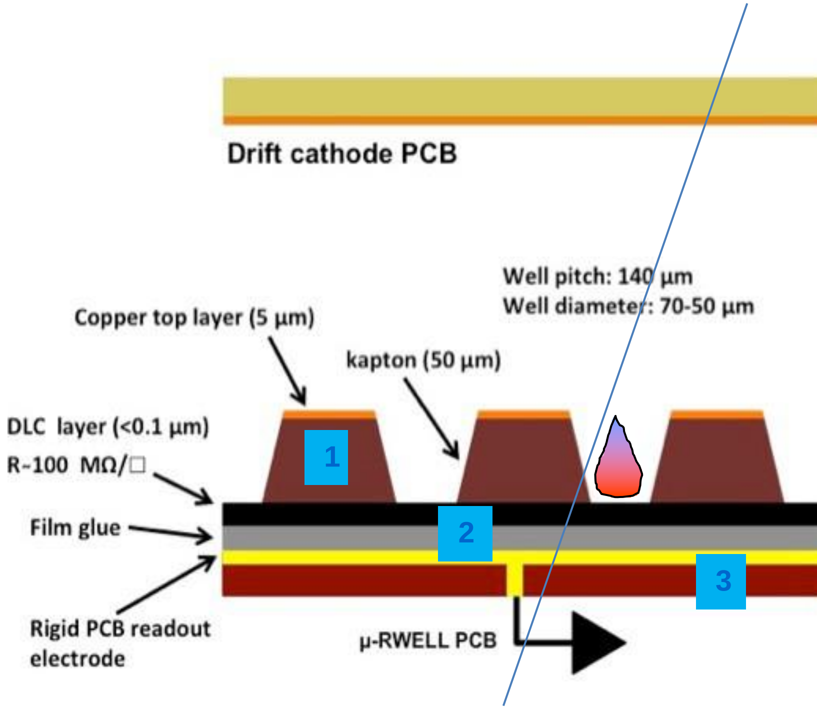


The μ-RWELL: the detector architecture

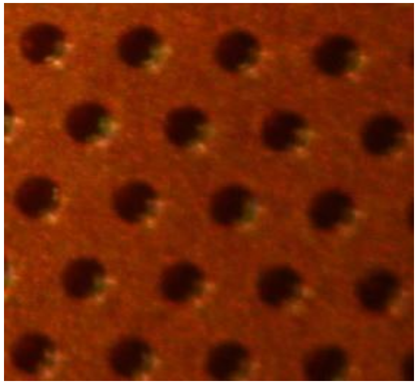
The μ-RWELL is composed of only two elements:
the μ-RWELL_PCB and the cathode

The μ-RWELL_PCB, the core of the detector, is realized by coupling:

1. a WELL patterned kapton foil as amplification stage
2. a resistive layer(*) for discharge suppression:
   i. Single resistive layer (SRL) <100 kHz/cm²: single resistive layer ➔ surface resistivity ~100 M Ω / □ (SHiP; CepC, Novosisbirsk, EIC, HIEPA)
   ii. Double resistive layer (DRL) >1 MHz/cm²: for LHCb-Muon upgrade
3. a standard readout PCB



G. Bencivenni et al., 2015_JINST_10_P02008



(*) DLC = Diamond Like Carbon
highly mechanical & chemical resistant

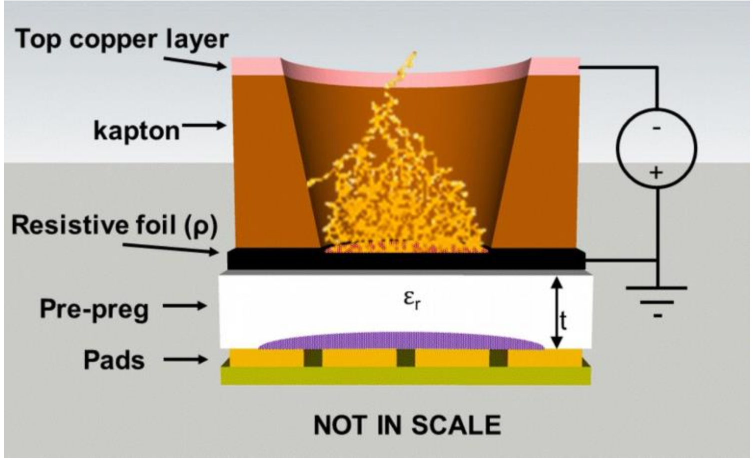
The μ-RWELL: principle of operation

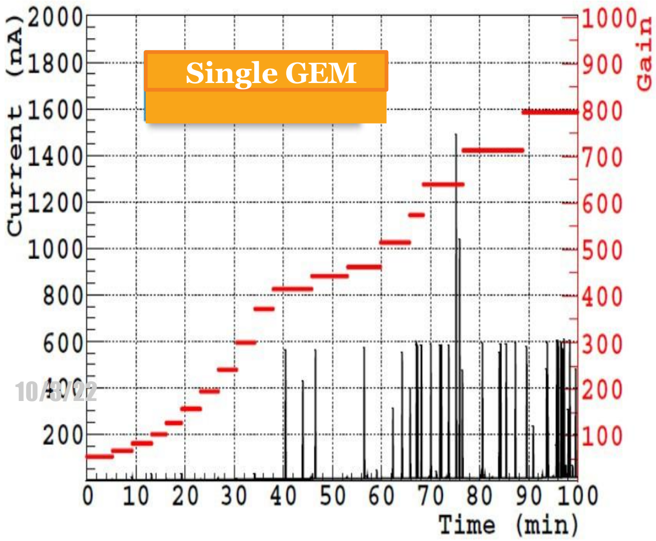
Applying a suitable voltage between the top Cu-layer and the DLC the WELL acts as a multiplication channell for the ionization produced in the conversion/drift gas gap.

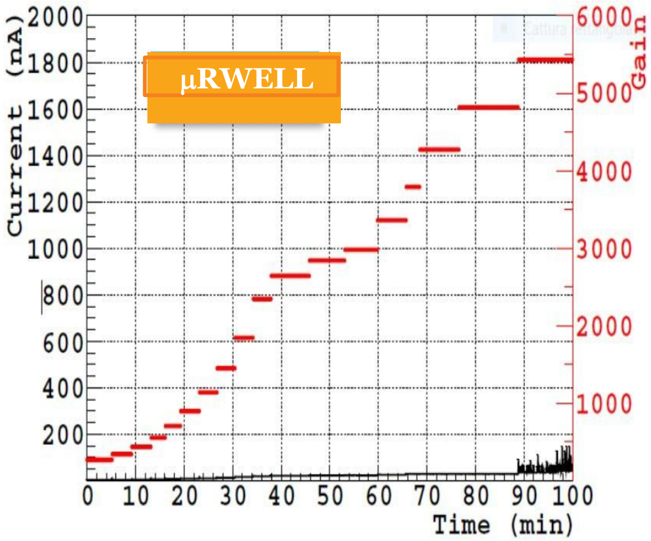
Introduction of the resistive stage:

Pros: suppression of the transition from streamer to spark
→Spark amplitude reduction

Cons: reduction of the capability to stand high particle fluxes. But an appropriate grounding schemes of the resistive layer solves this problem







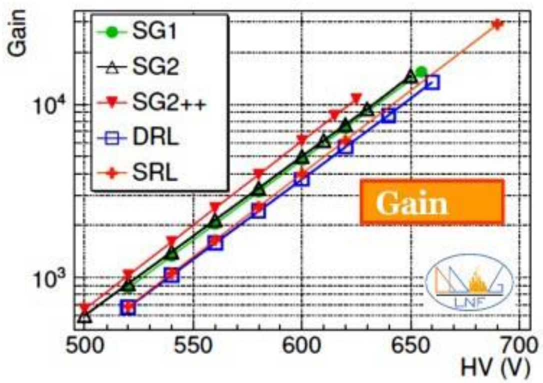
Comparison between the current drawn by a single GEM and a μ-RWELL at various **gas gain.**

The black spikes are the sparks in the detectors, clearly dumped in the μ-RWELL for higher gains

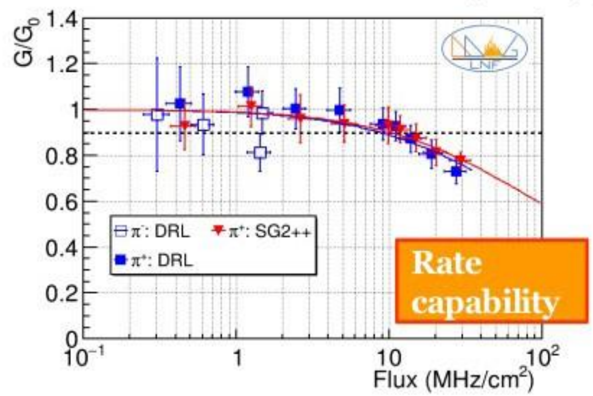
The μ-RWELL: overview of performance

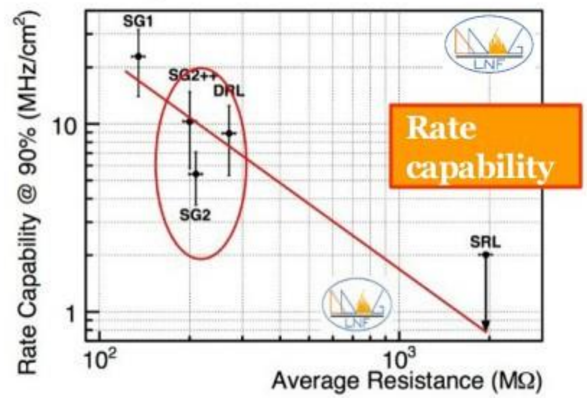
Results with 2017 testbeam data at PSI lab

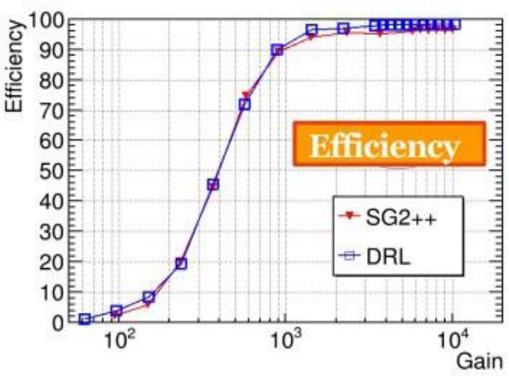
Gain up to 10^4



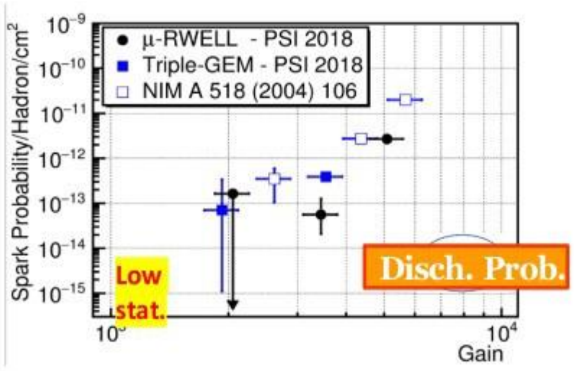
Rate Capability (@ G= 5000) ~ 5-10 MHz/cm^2



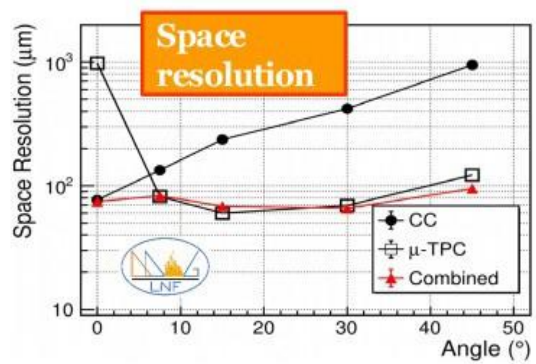




Efficiency ~ 98%



Discharge probability ~ 10^{-13} @ 4000

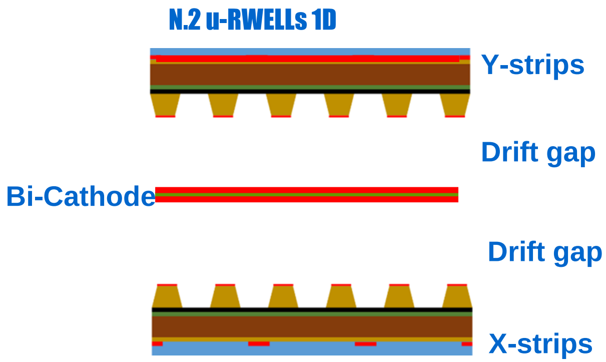


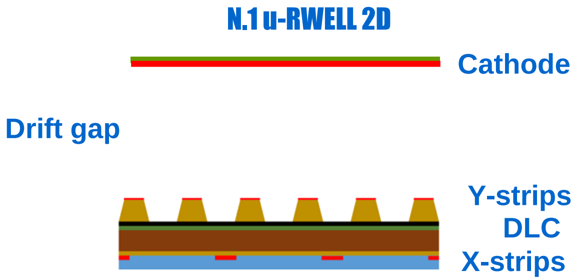
Space resolution ~ 100 μm

Plans for 2022/203

R&D for the 2022 foreseens the production of μ-RWELL with X-Y readout → beamtest In October 2022 (SPS-H8-CERN)

Detector layouts 2D





Y coordinate on the TOP of the amplification stage

These layouts allow to operate at lower gain with respect to the GEM detectors in «COMPASS»

Easy production technlogy for both layouts.
Bi-dimensional space resolution to be verified with Beam Test

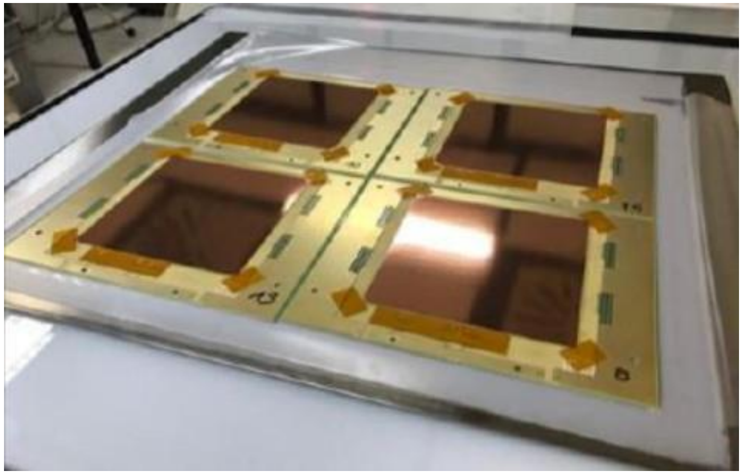
Technology transfer with ELTOS/CERN: flow chart

DLC sputtering with new INFN- CERN machine @ CERN

Step 1: producing µ-RWELL_PCB

-with top patterned (pad/strip)

-without bottom patterned



Step 2: DLC patterning

-in ELTOS with BRUSHING-machine

Step 3: DLC foil gluing on PCB

-double 106-prepreg (~2x50 □m thick) (already used in ELTOS)

-pre-smoothing + 106-prepreg (~50 µm thick)

-single 1080-prepreg (~75 µm thick)

Step 4: top copper patterning

Step 5: Kapton etching on small PCB

Finalization

Detector @ CERN for final preparation

Technology transfer with ELTOS/CERN: flow chart

Responsibility:
- Detector design (GERBER);
- Link with ELTOS
- Link with CERN-Rui
- Quality Control detector
- DLC Machine managment (>2023)

Responsibility:
- PCB RWELL production
- Cathode production
- DLC+PCB RWELL coupling

Responsibility:
- PCB RWELL finalization
- Hot Electrical Cleaning
- Detector closure