Performance study of the IDEA detector

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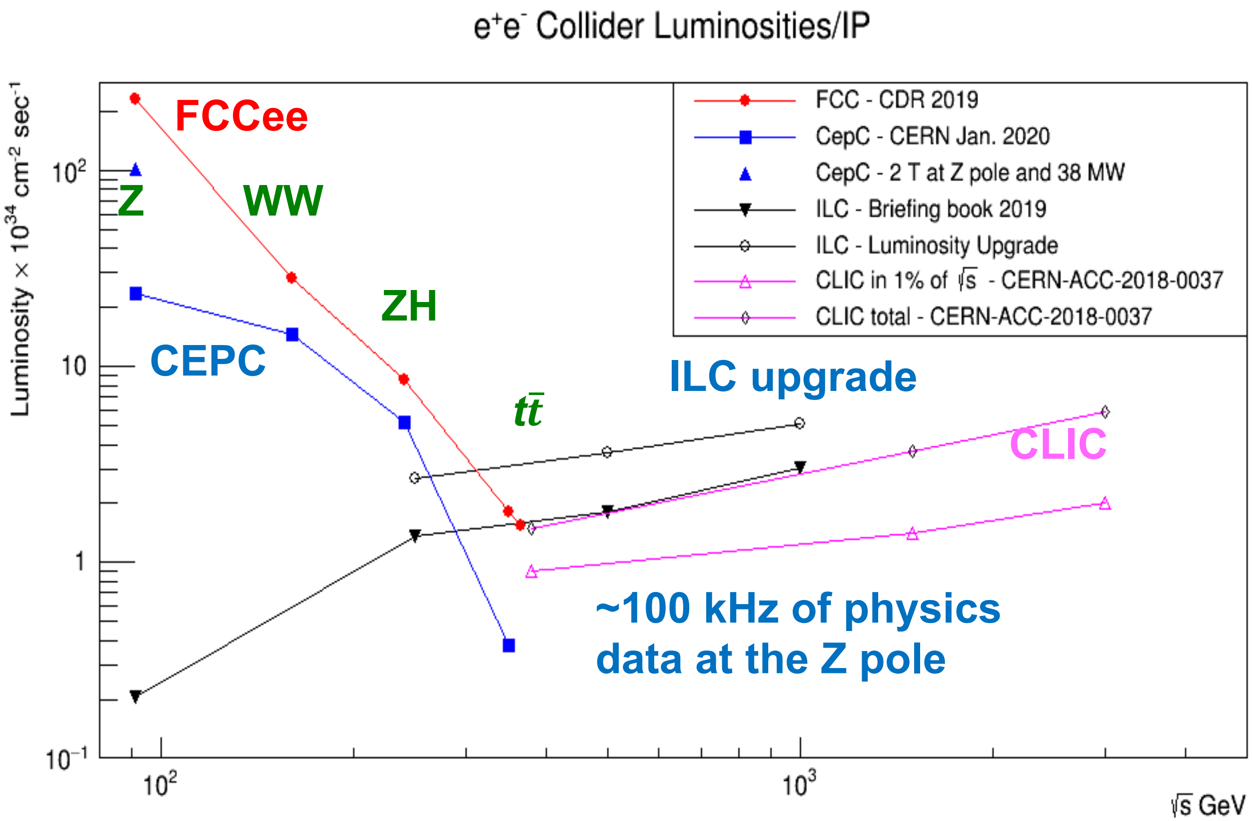
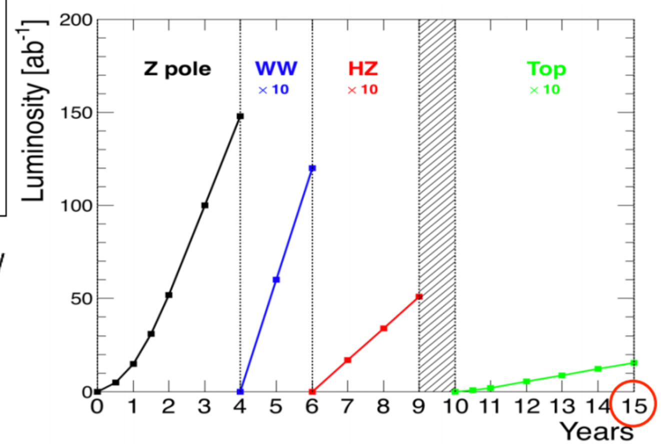
on behalf of the INFN team

The 2020 international workshop on the high energy Circular Electron-Positron Collider (CEPC) workshop
October 26-28, 2020

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- → $\tau+\tau-$
- Potential discovery of NP

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 (1)

Innovative Detector for E+e- Accelerator

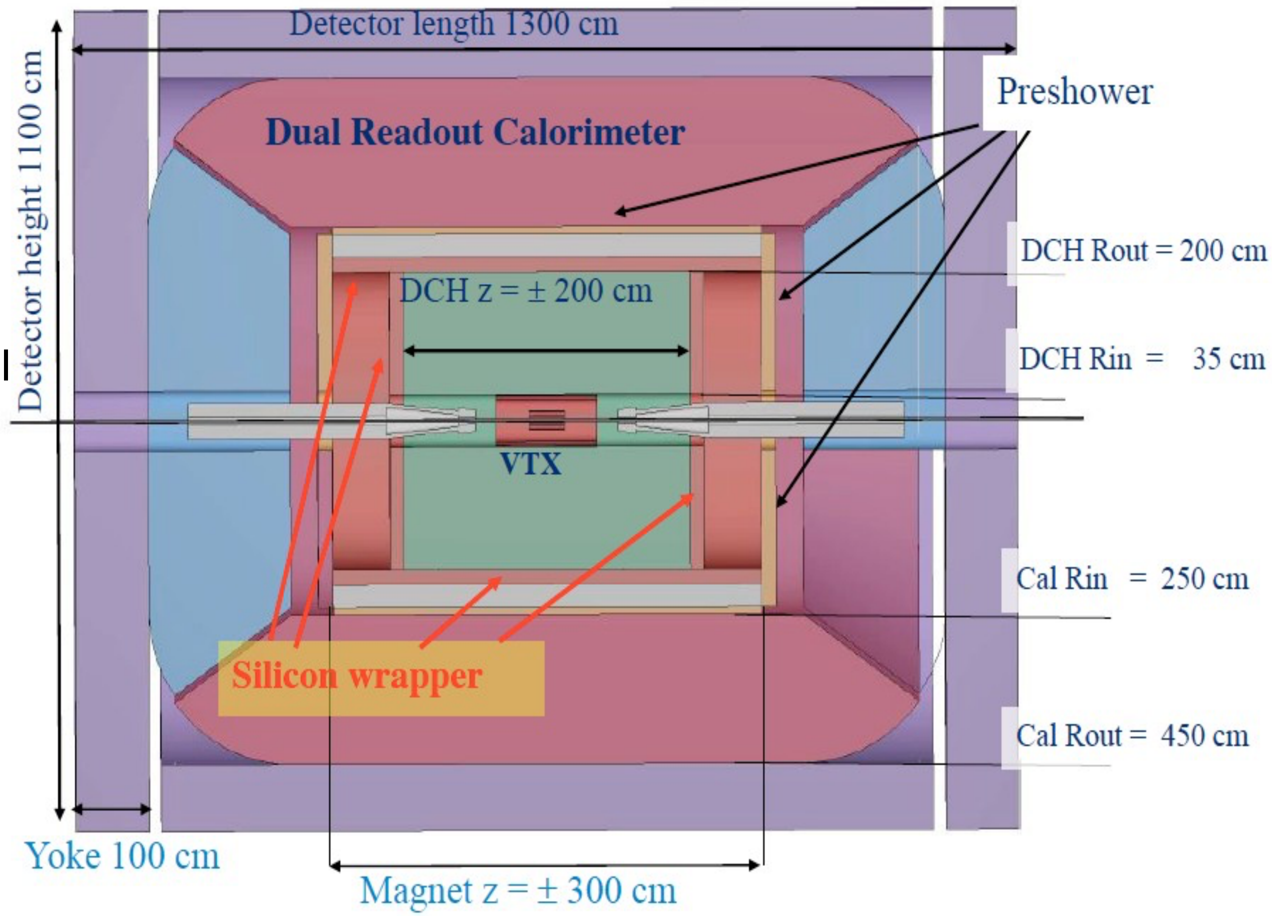
FCC-ee at CERN

CEPC at IHEP-China

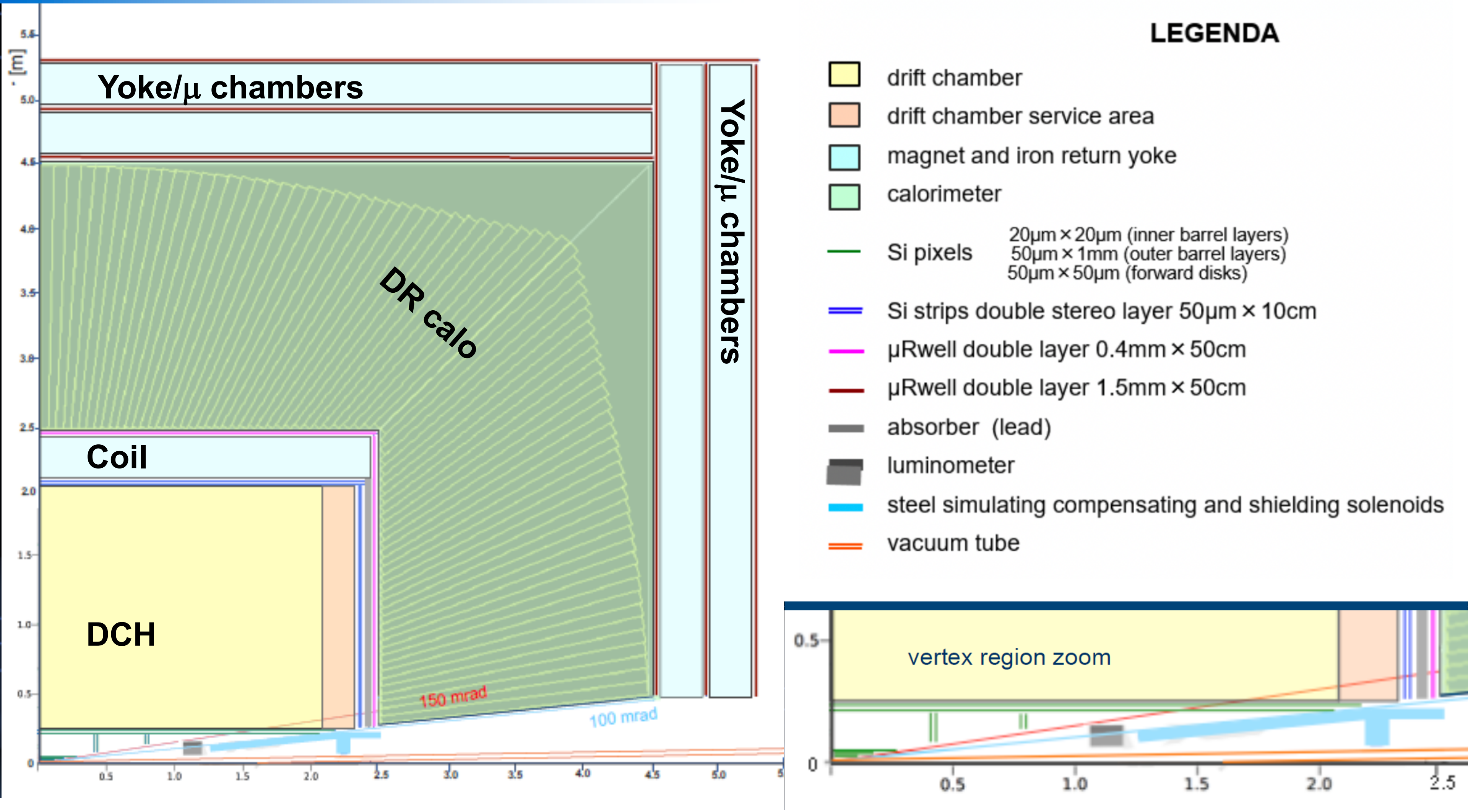
IDEA consists of:

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

Low field detector solenoid to maximize luminosity
→ optimized at 2 T



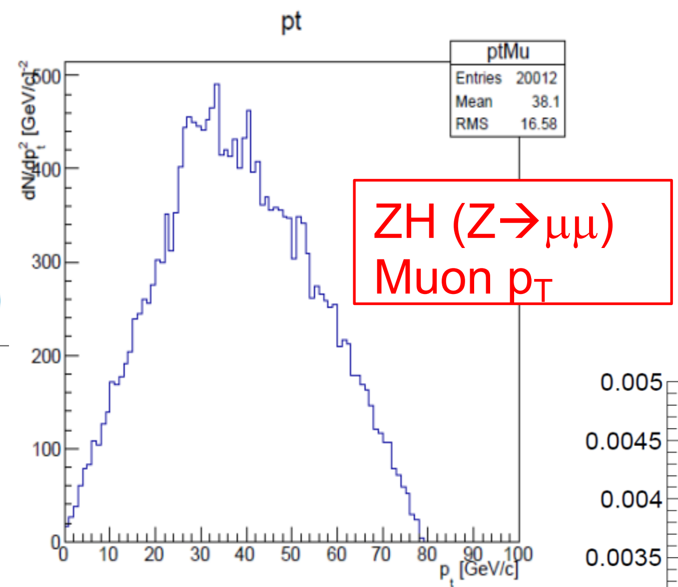
The IDEA detector at e$^+$e$^-$ colliders (2)

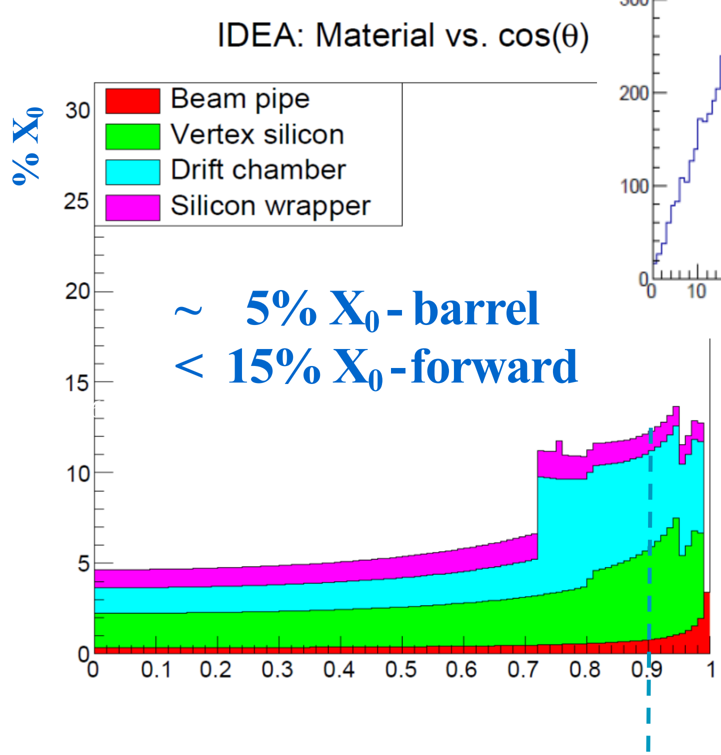


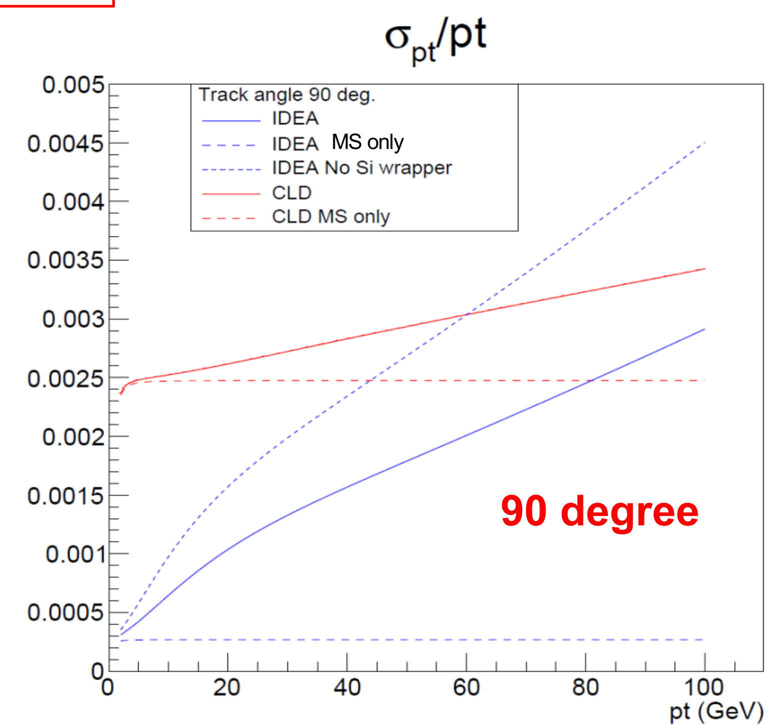
Tracking → 150 mrad → No material in front of luminometer
Calorimetry → 100 mrad

Design guidelines: momentum resolution

- Z or H decay muons in ZH events have rather small/medium p_T
  - Transparency (against multiple scattering) more relevant than asymptotic resolution



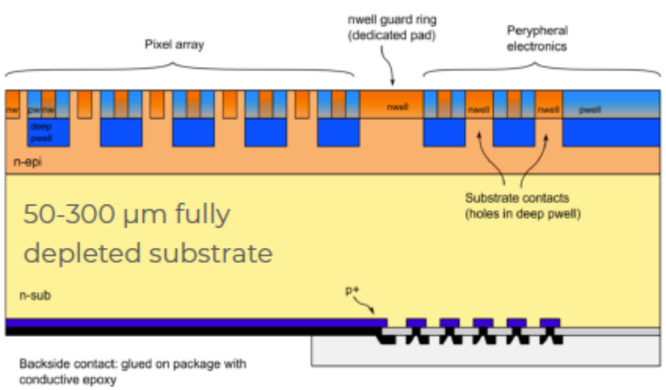


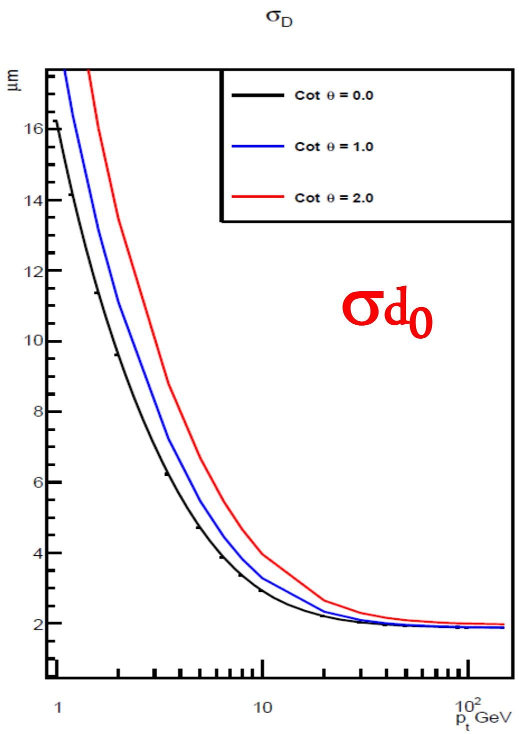


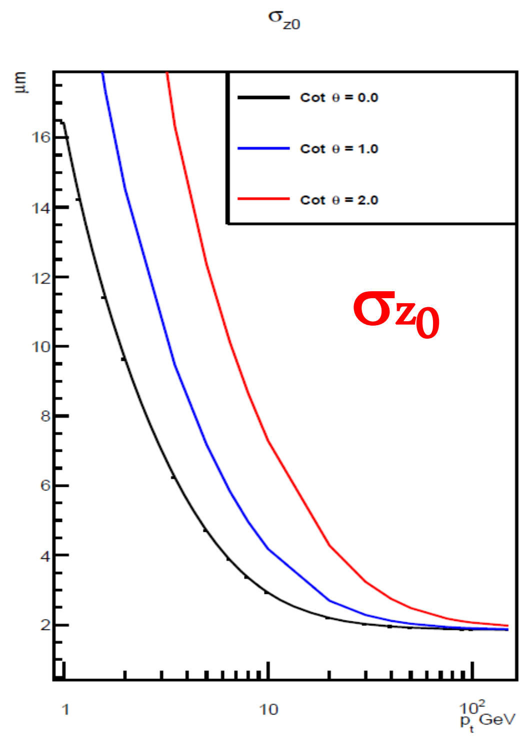
Design guidelines: vertex detector

ARCADIA (2019-2021)

- Transparency:
  - Low power (< 20 mW/cm^2) to allow air cooling
  - Pixel size 25μm x 25μm
- Resolution:
  - 5 μm shown by ALICE ITS (30 μm pixels)
  - Aim at ~20 μm pixels for ~ 3 μm point resolution
  - Monolithic Active Pixel Sensors (MAPS) able to provide the required resolution



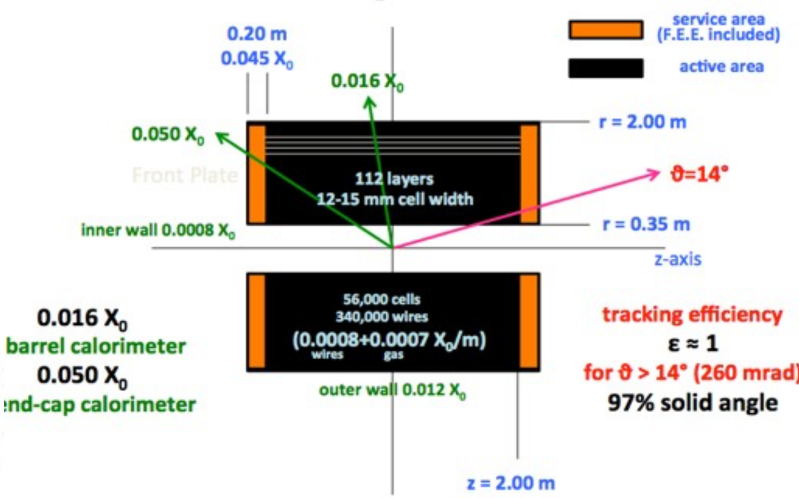


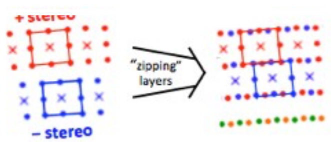


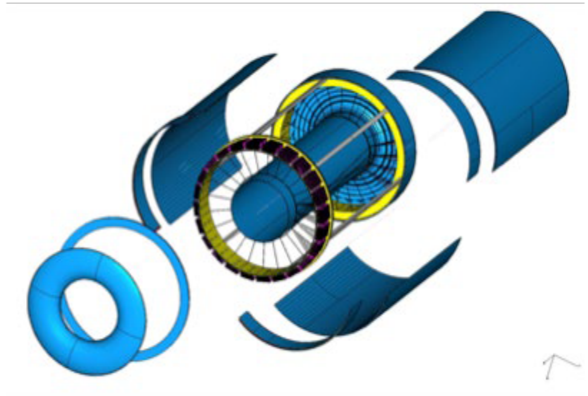
See also slide by P. Giubilato at silicon detector session yesterday

Design guideline: the Drift Chamber

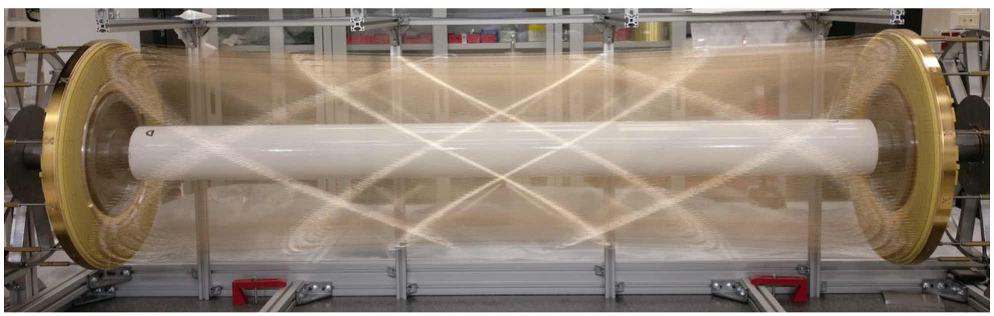
Drift Chamber







New concept of construction allows to reduce material to ≈ 10^{-3} X_0 for the barrel and to a few x 10^{-2} X_0 for the end-plates.



The wire net created by the combination of + and – orientation generates a more uniform equipotential surface

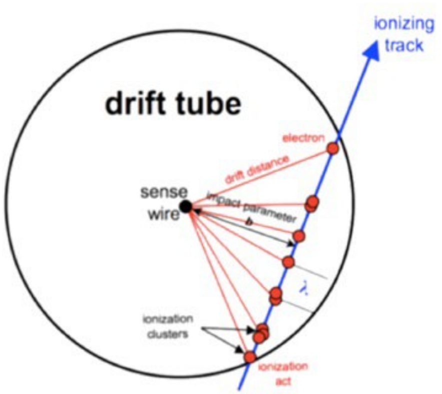
sense wires:	20 mm diameter W(Au) =>	56448 wires
field wires:	40 mm diameter Al(Ag) =>	229056 wires
f. and g. wires:	50 mm diameter Al(Ag) =>	58464 wires
	343968 wires in total	

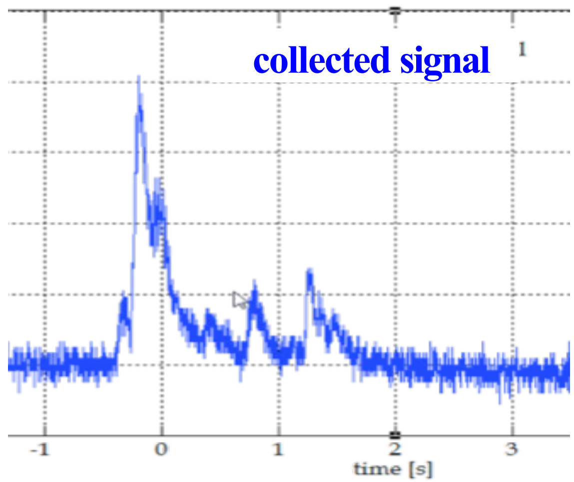
- High wire number requires a non standard wiring procedure and needs a feed-through-less wiring system.
- A novel wiring procedure developed for the construction of the ultra-light MEG-II drift chamber

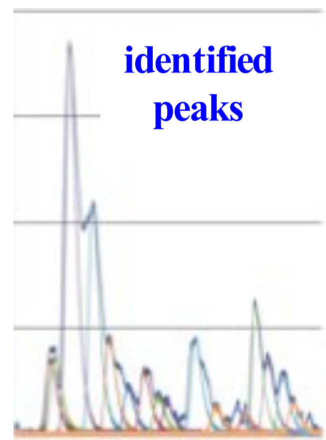
Cluster Counting/Timing and P.Id. principles

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.







- record the time of arrival of electrons generated in every ionisation cluster (≈12cm-1)
- reconstruct the trajectory at the most likely position

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%) reduces the amount of collected information. n = 112 and a 2m track at 1 atm give $\sigma \approx$ 4.3%

dN_{cl}/dx

δ_{cl}= 12.5/cm for He/iC_4H_{10}=90/10 and a 2m track give $\sigma \approx$ 2.0%

→ could improve also the spatial resolution

New studies about the Cluster Counting

Goal: Investigation of the potential of the C.C. (for He based drift chamber) with parametrization of the generation of ionization clusters

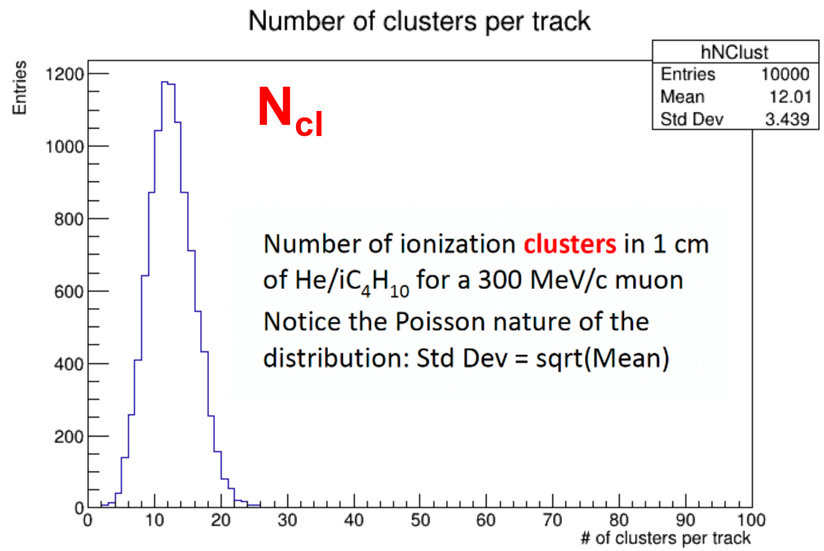
Studies done with a 1cm^3 box of gas (90% He and 10% iC_4H_{10})

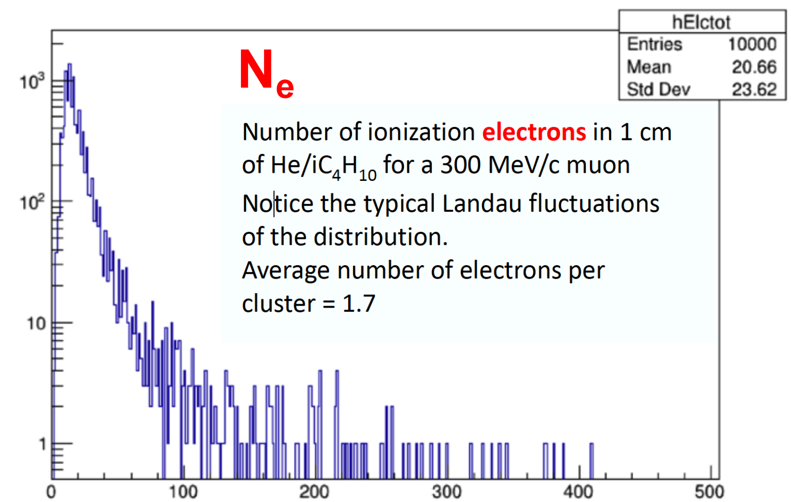
Garfield++:

- simulates the ionization process in a detailed way
- computes the gas properties (drift and diffusion coefficients as function of the fields value)
- solves the electrostatic planar configuration and simulates the free charges movements and collections on the electrodes.
- cannot simulate a full detector and collider events.

Geant4:

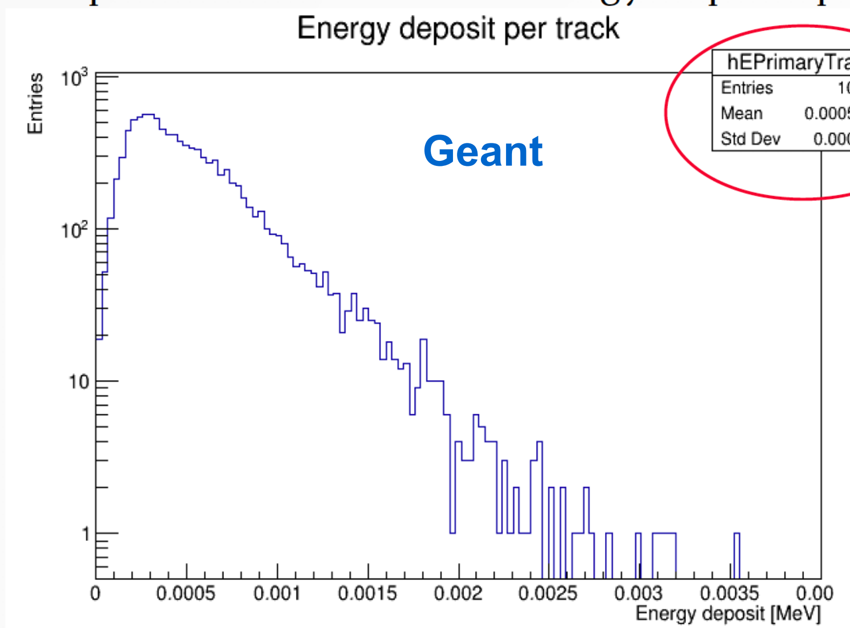
- simulates the particle interaction with material of a full detector.
- But...the fundamental properties and performance of the sensible elements (drift cells) are either parameterized or «ad-hoc» physics models have to be defined.





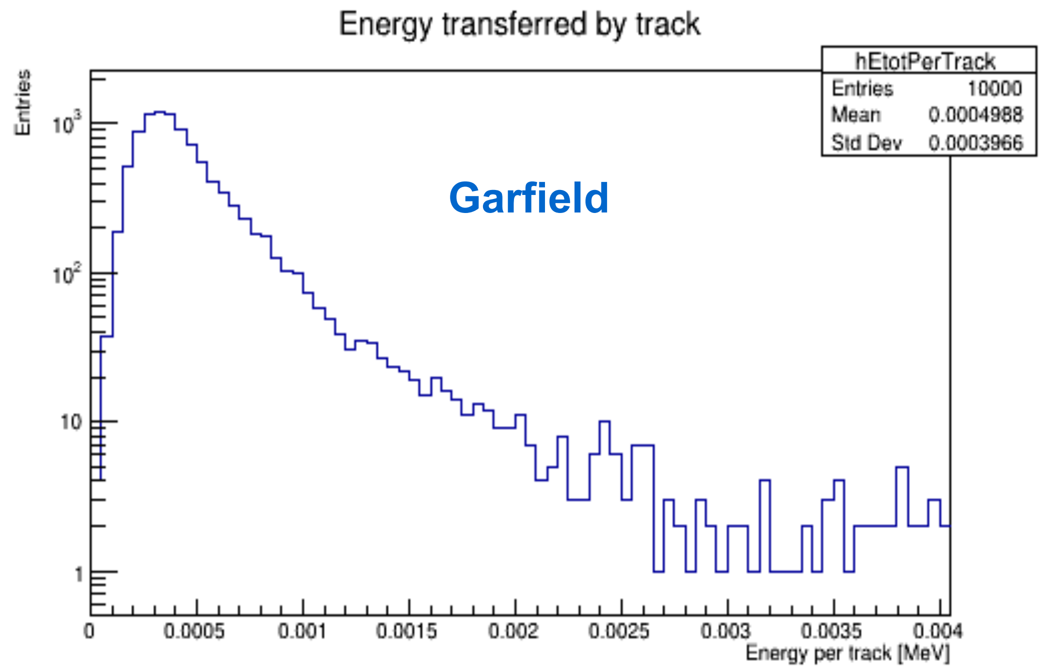
Garfield++ vs Geant4

Comparison between total energy deposit per track



Studies done with a 1cm^3 box of gas (90% He and 10% iC_4H_{10}), 1 cm track

PRELIMINARY

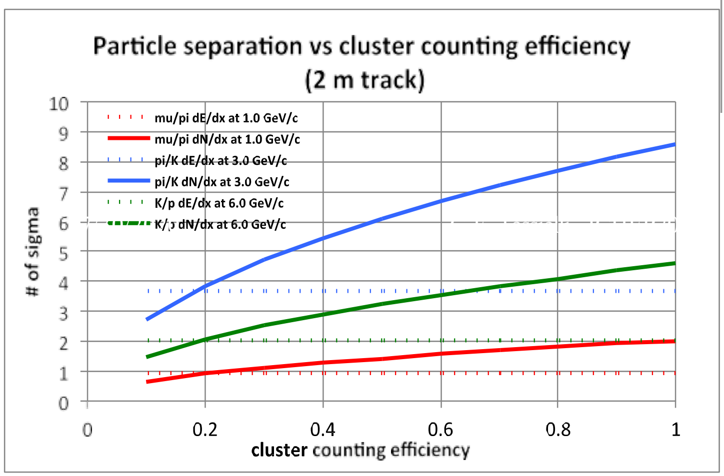


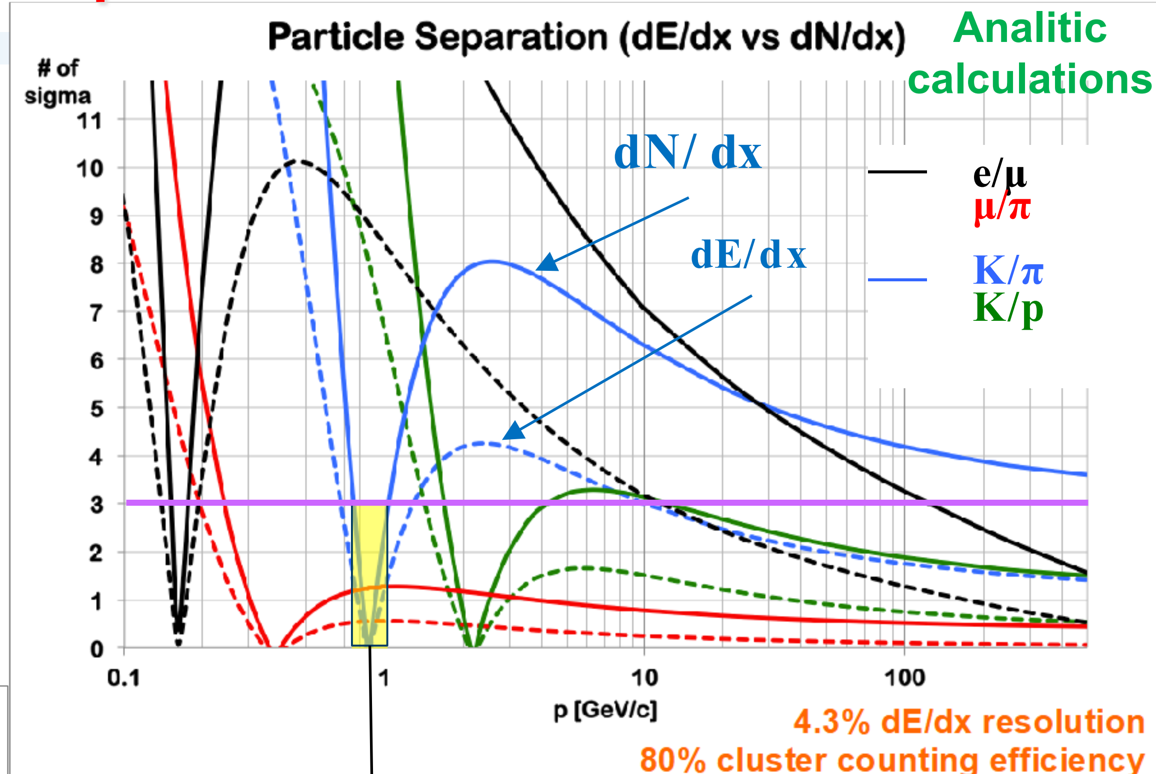
Similar mean and Std Dev.

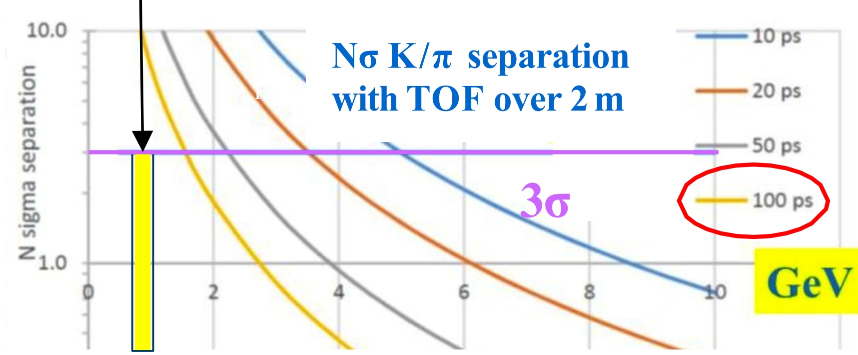
Design guidelines: particle identification

Cluster Counting/Timing in DCH for good P.Id. performance

- Expected excellent K/π separation over the entire range except 0.85<p<1.05 GeV (blue lines)
- Could recover with timing layer







Design guidelines: calorimeter

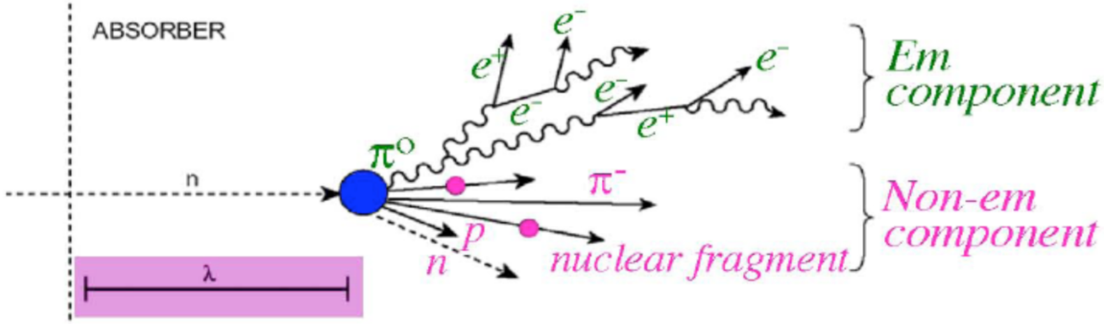
- Good, but not extreme EM resolution
  - ~ 10%/$\sqrt{E}$ sufficient for Higgs physics
- Jet resolution ~ 30-40%/$\sqrt{E}$
  - Clearly identify W, Z, H in 2 jet decays
- Transverse granularity < 1 cm for τ physics
- All electronics in the back to simplify cooling and services
- Dual Readout calorimeter satisfies all these requirements
  - EM & Hadronic calorimeter in a single package

References:

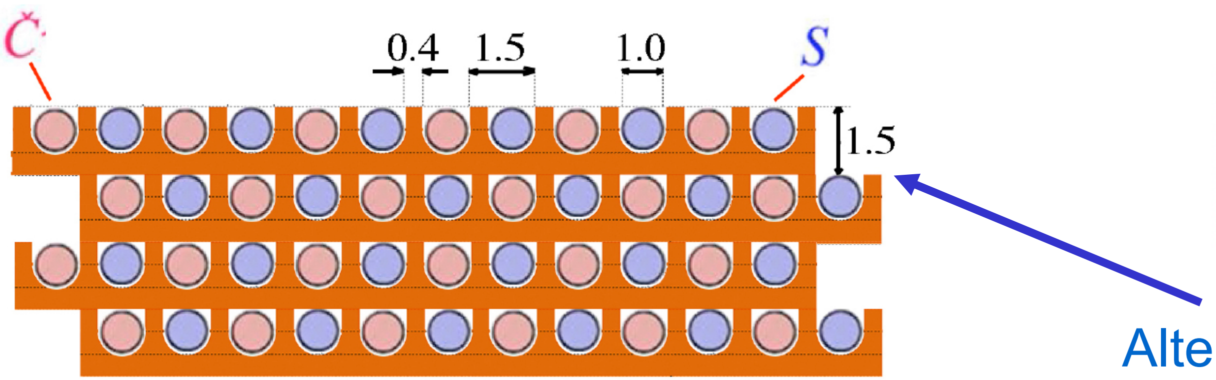
- "Dual-readout calorimetry", Sehwook Lee, Michele Livan, and Richard Wigmans, Rev. Mod. Phys. 90, 025002 – Published 26 April 2018
- L. Pezzotti, CHEF2019, Nov. 2019, Fukuoka, Japan

Principle of the Dual Readout calorimeter

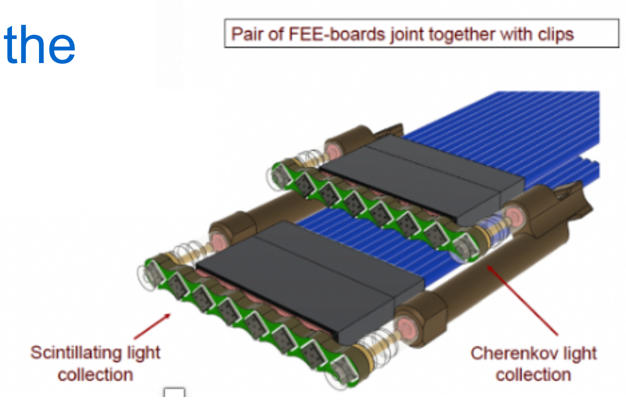
- Event by event correction for EM-had fluctuations
  - Principle demonstrated by DREAM/RD-52



- EM and hadron calorimeter in a single package
  - All electronics in back easy to cool and access
- Electrons/photons are independently sampled by the two kind of fibers (Scintillating and Cherenkov).



Fiber pattern RD52



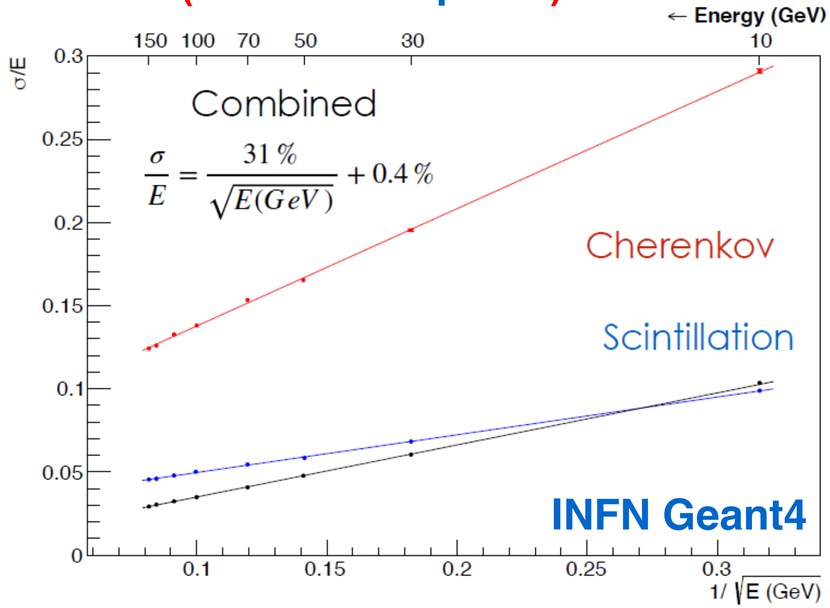
Alternating scintillating and clear fibers in metal matrix

More on slides by J. Vivarelli

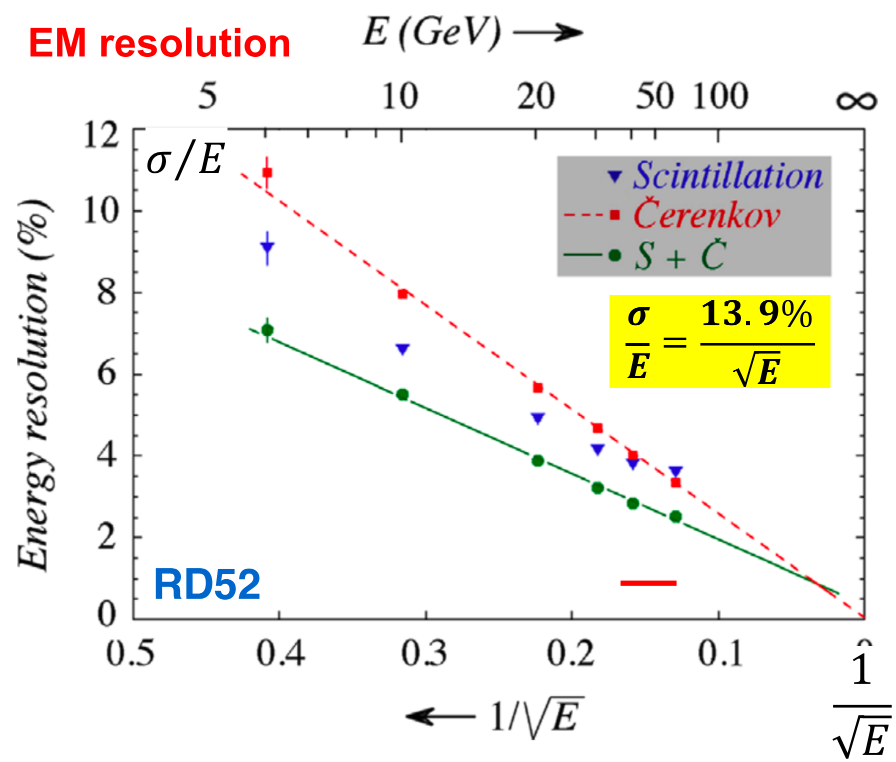
Dectector performance of the DR calorimeter

- Collaboration:
  - INFN (Italy), RBI (Croatia), Sussex (UK), Korea , etc..
- Activities:
  - Scalable mechanics and scalable SiPM readout
  - Performance demonstration with dedicated prototypes
  - Reproduced with Geant 4 simulation

Hadrons (10-150 GeV pions)



EM resolution

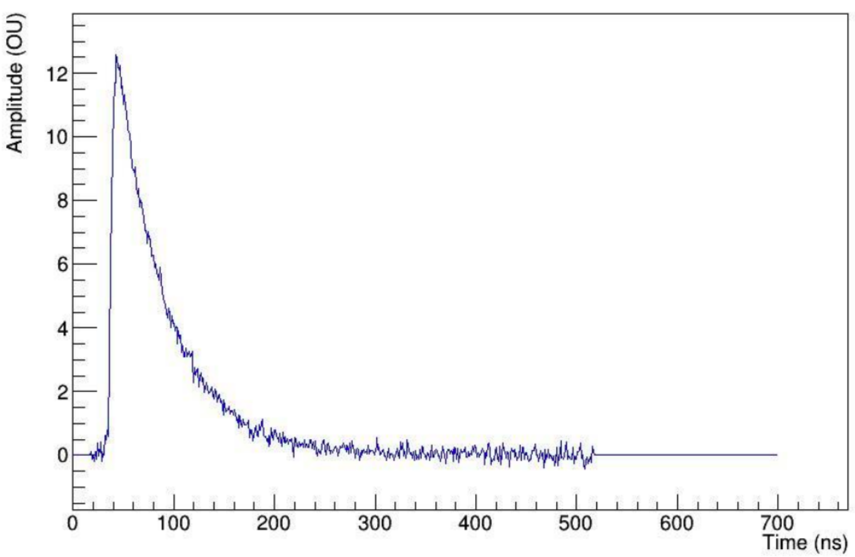


SiPM digitization for the DR calorimeter

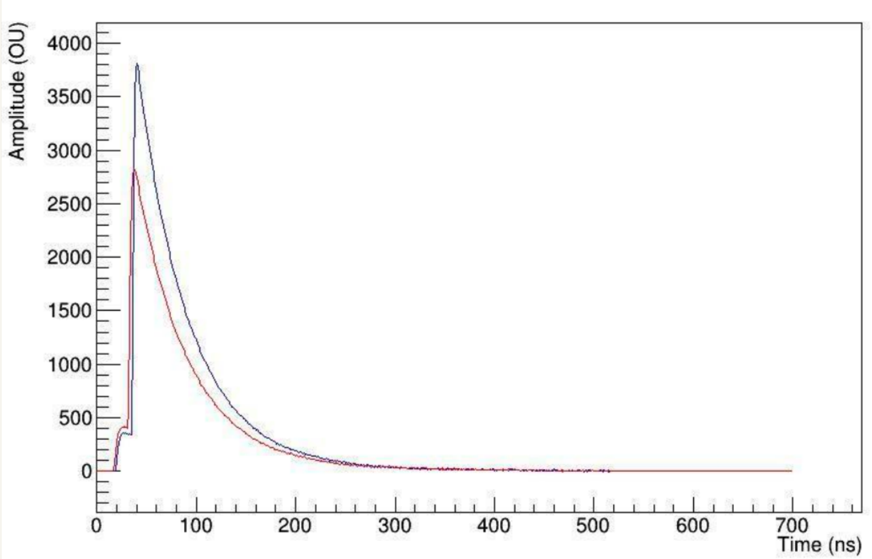
A python based SiPM digitization code has been developed to be used for timing studies

Digitization includes several effects (**electronic noise, dark counts, crosstalk probability, after pulses, etc**) and it makes possible to extract timing information of the whole digitized signal

Example: digitized signal from a single fiber with 12 p.e



Example: analog sum of Cherenkov signals from 40geV electrons and pions showering in the calorimeter



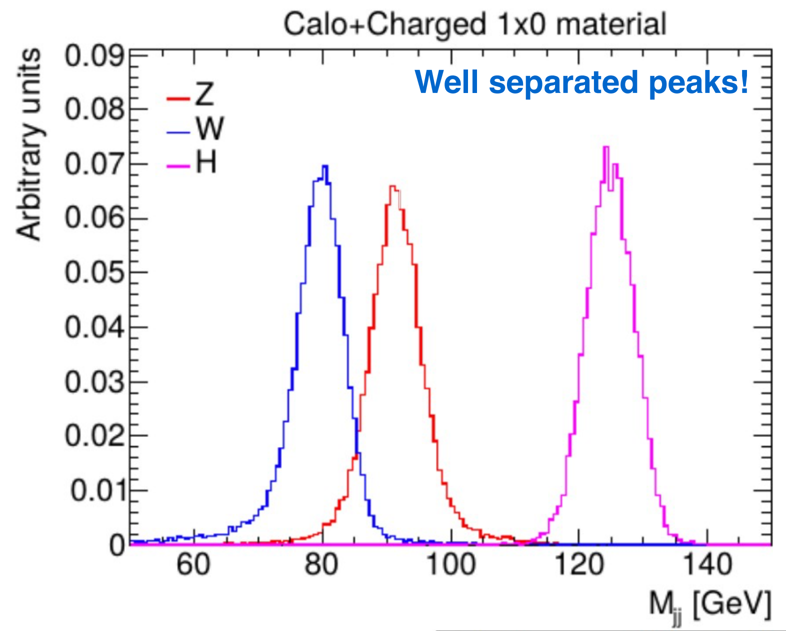
Physics performance of the DR calorimeter

$e^+e^- \rightarrow HZ \rightarrow \tilde{\chi}^0\tilde{\chi}^0 jj$ → Only decays to u,d,s,c
c semileptonic decays excluded

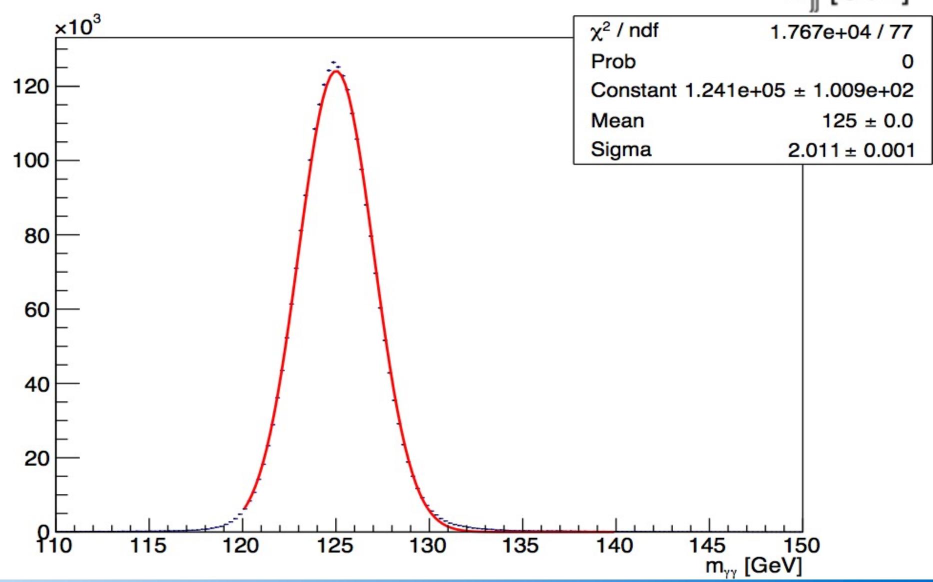
$e^+e^- \rightarrow WW \rightarrow \nu_\mu \mu jj$ → Contribution of tagged muon from Monte Carlo truth subtracted from the calorimeter signal
c semileptonic decays excluded

$e^+e^- \rightarrow HZ \rightarrow b b \nu\nu$ → b semi-leptonic decays excluded

$e^+e^- \rightarrow HZ \rightarrow \gamma\gamma\nu\nu$



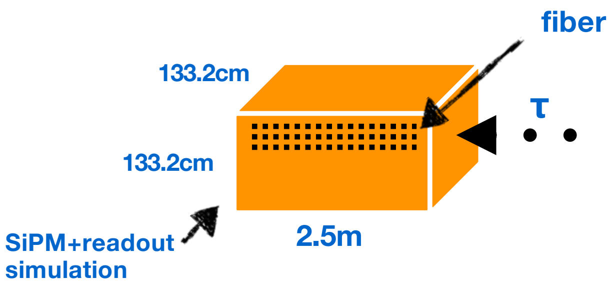
5 million events fully simulated at Sussex University.



Starting from calibration constants estimated with particle gun, after few energy corrections, the resolution on the mass term is consistent with the single photon energy resolution.

Deep Learning for τ ID with the DR calorimeter

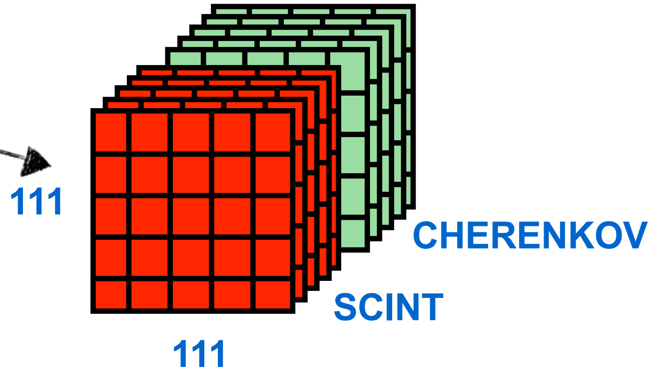
Initial study with ideal configuration: test-beam prototipe geometry module and the simplified task of identify different decays of τ all pointing to the center of the module



Data Preprocessing (needed to reduce data size and fit GPU memory)

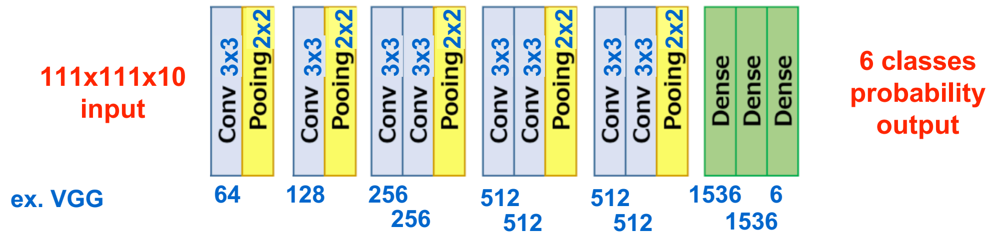
signals from fibers in each 1.2mmx1.2mm module integrated to obtain a 111x111 matrix

- each event represented as a 111x111x10 tensor
- 5 features for each matrix element:
  - signal integral, height, peak position, time of x-ing threshold , time over threshold
- independently for scintillation and Cherenkov fibers



Two different DNN Architectures studied:

VGG-like achitecture with batch normalisation / zero padding and Graph-NN

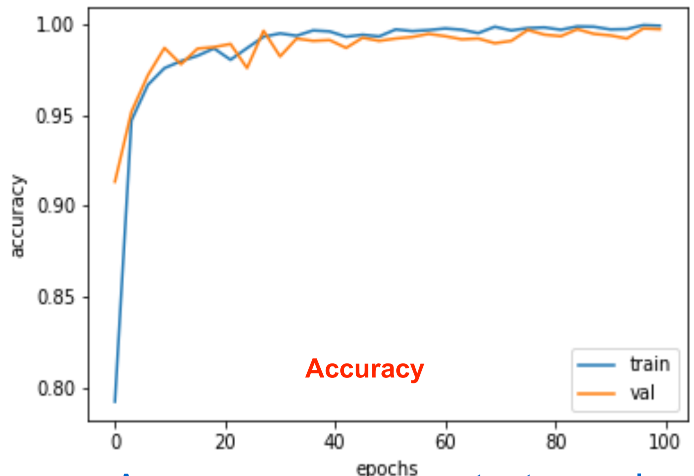


Performance for Deep Learning for τ ID

Training data:

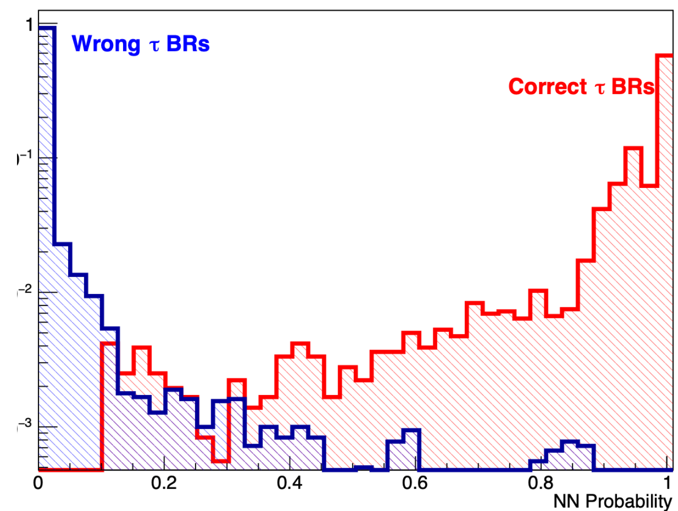
6 BR x 2000 evts = 12000 evts

	τ → final state
0	$\pi^0\pi^-\nu_\tau$
1	$e^-\bar{\nu}_e\nu_\tau$
2	$\mu^-\bar{\nu}_\mu\nu_\tau$
3	$\pi^-\nu_\tau$
4	$\pi^-\pi^-\pi^+\nu_\tau$
5	$\pi^0\pi^0\pi^-\nu_\tau$



Average accuracy on test sample:
97.3% (99.6% using GNN)

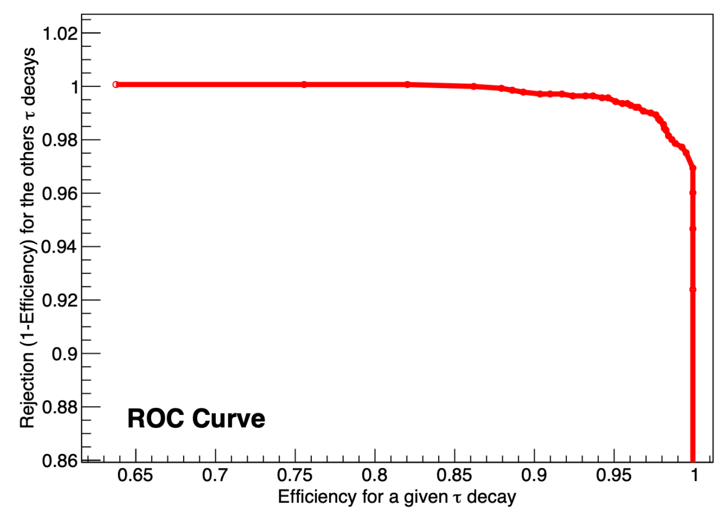
NN Output on test sample:



Truth BR \ Predicted BR	0	1	2	3	4	5
0	100%					
1	2%	95%	3%			
2			100%			
3			6%	91%	3%	
4					98%	2%
5						100%

Confusion Matrix
on test sample

ROC curve (test sample):



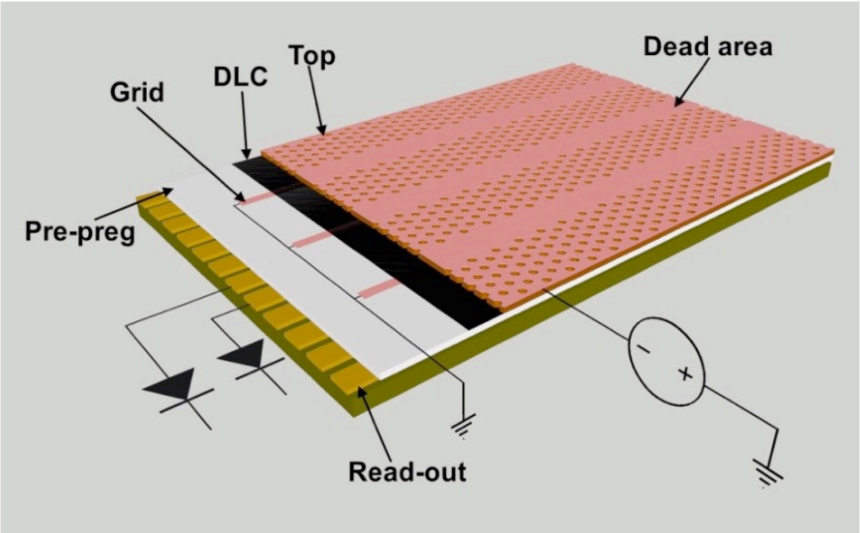
Preshower/Muon detector and simulation

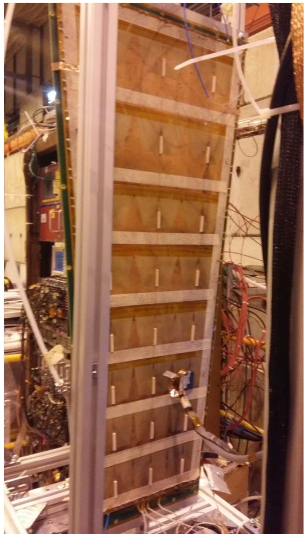
- A MPGD technology looks particularly promising for its characteristics and the possibility to be industrialised: the μ-RWell

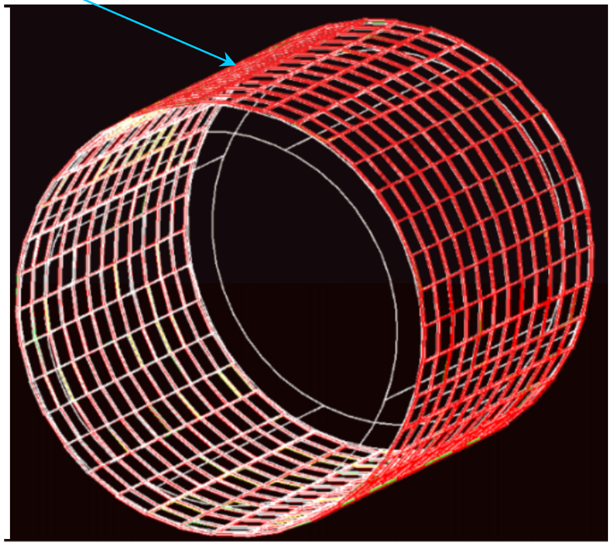
- A **μ-Rwell** essentially consists of:
- a patterned Kapton foil (amplification stage)
- a resistive layer sputtered on the back of the Kapton foil to quench the multiplication and avoid sparks (DLC = Diamond Like Carbon)
- a patterned PCB for readout
- the camera stands rates up to 35 kHz/cm^2 (simplest process)

time resolutions at the few ns level have been measured

- **Implementation of a μ-RWELL detector in Geant4**

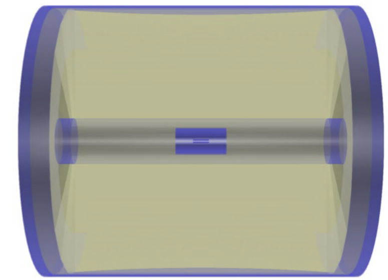


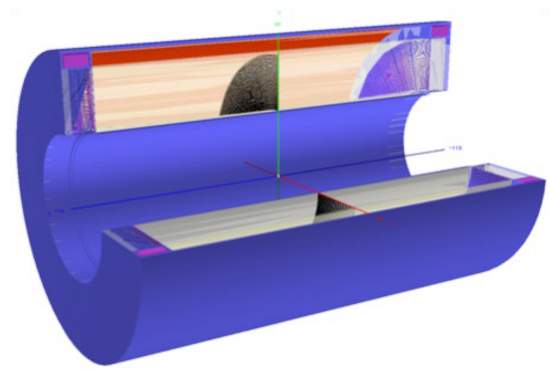




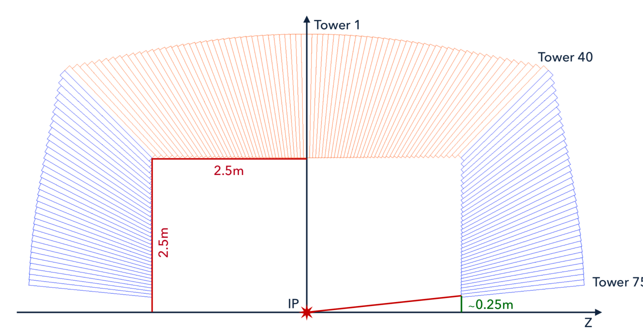
Geant4 full simulation of IDEA

A full standalone geant4 simulation of the IDEA **Silicon Vertex (and Si wrapper), DriftChamber, DR Calorimeter (and Muon)**

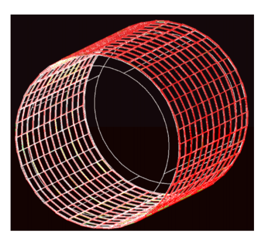




- The DCH is simulated at a good level of geometry details, including detailed description of the endcaps; hit creation and track reconstruction code available
- SVX and Si wrapper are simulated as simple layer or overall equivalent material
- Dual readout calorimenter simulated with geant4 too
  - Towers are trapezoidal physical volumes with slightly different shapes changing with θ.
  - Fibers are 1mm diameter tubes, 0.5 mm of absorber material (copper) between two adjacent
  - → 130 milion fiber for the whole IDEA detector



- Muon detector



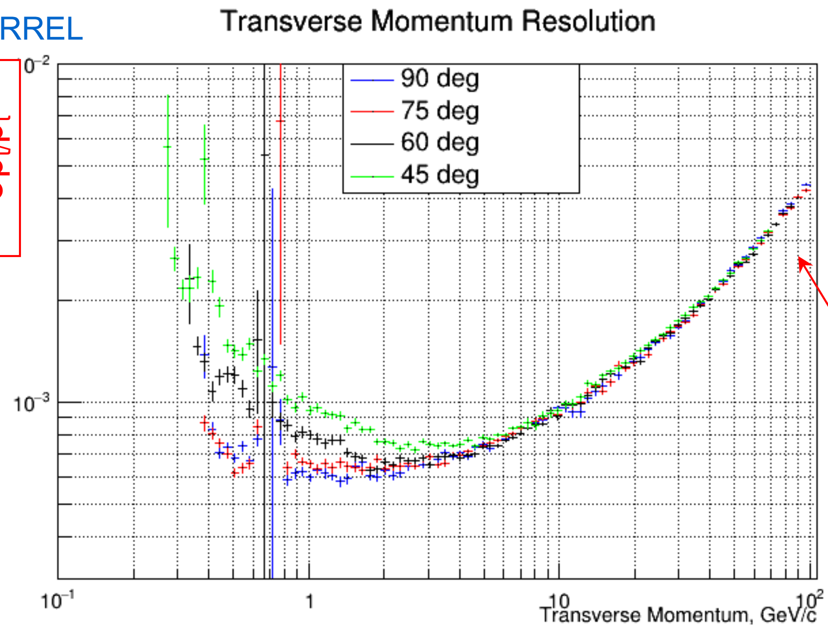
Integration of all the detectors on going

Expected tracking performance: full simulation with Geant4

DCH + SVX but no Si-Wrapper

BARREL

$\sigma p_t/p_t$



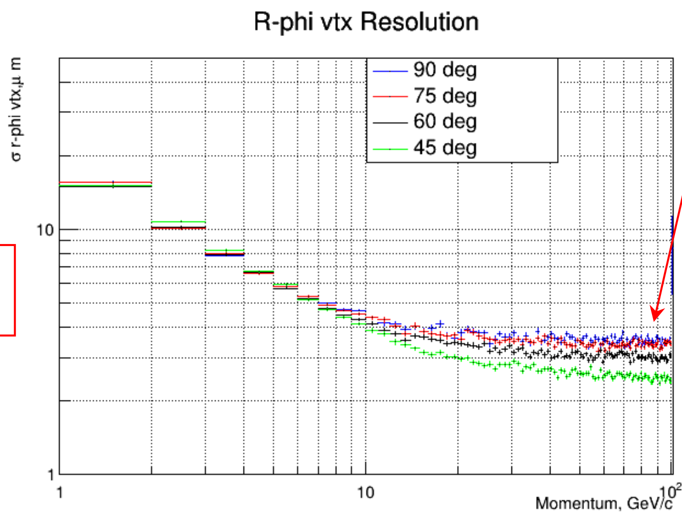
Recent studies with

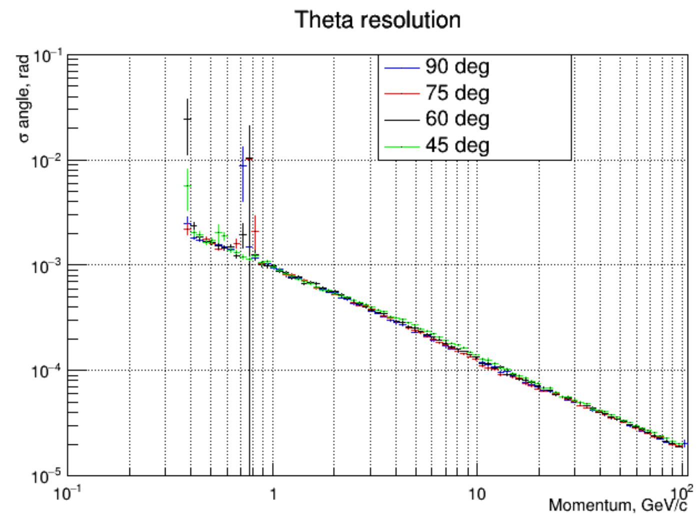
$\sigma(p_t)/p_t$ (100 GeV) = 3×10^{-3}

$\sigma(d_0)$ (100 GeV) = 2μm

BARREL

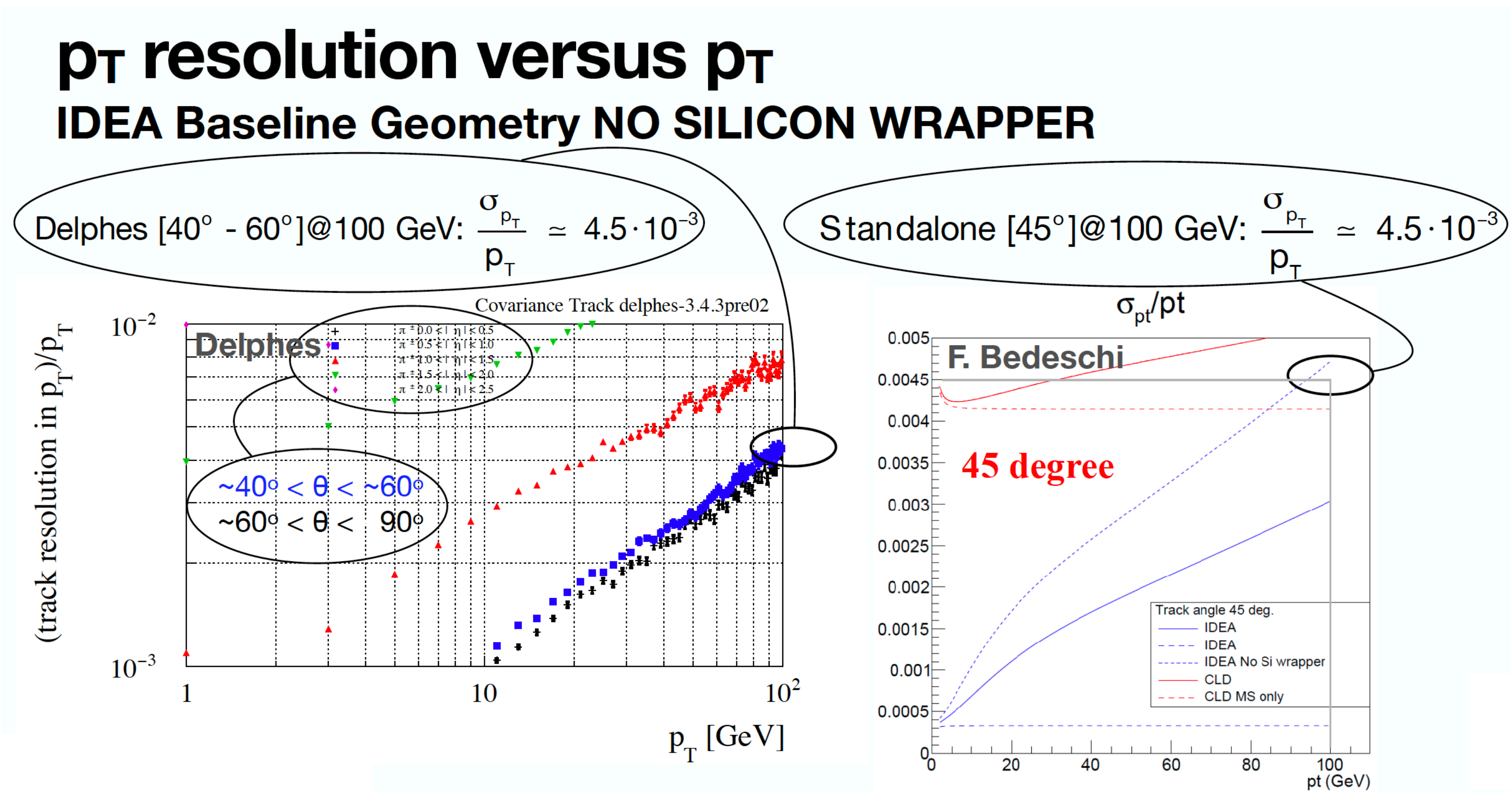
impact parameter



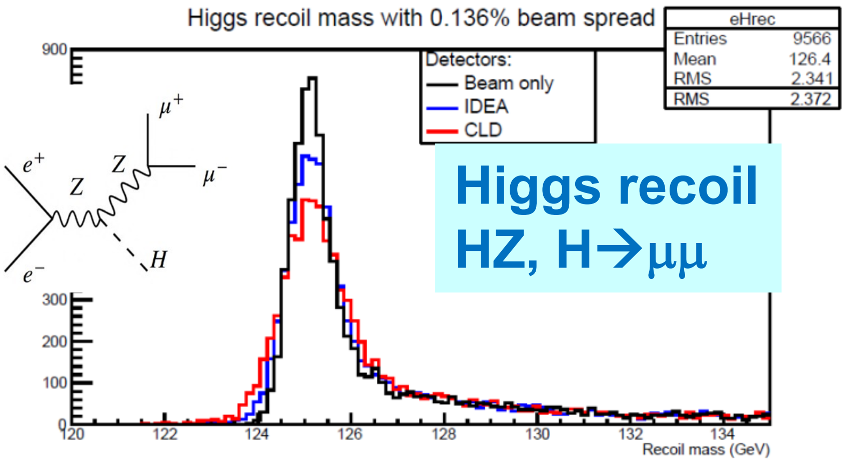


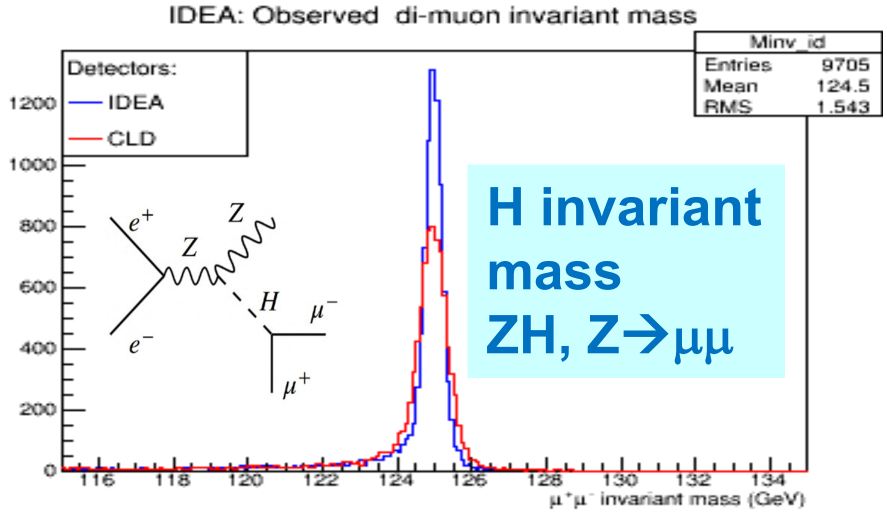
IDEA fast simulation with Delphes

- DELPHES provides the response of a detector in a parameterised way
- Addition to the official IDEA Delphes card (containing already the DR calo) of the covariance matrix description for tracks → validation plots below
- Crucial feature for improving development of b- and c-tagging algos in a more realistic way



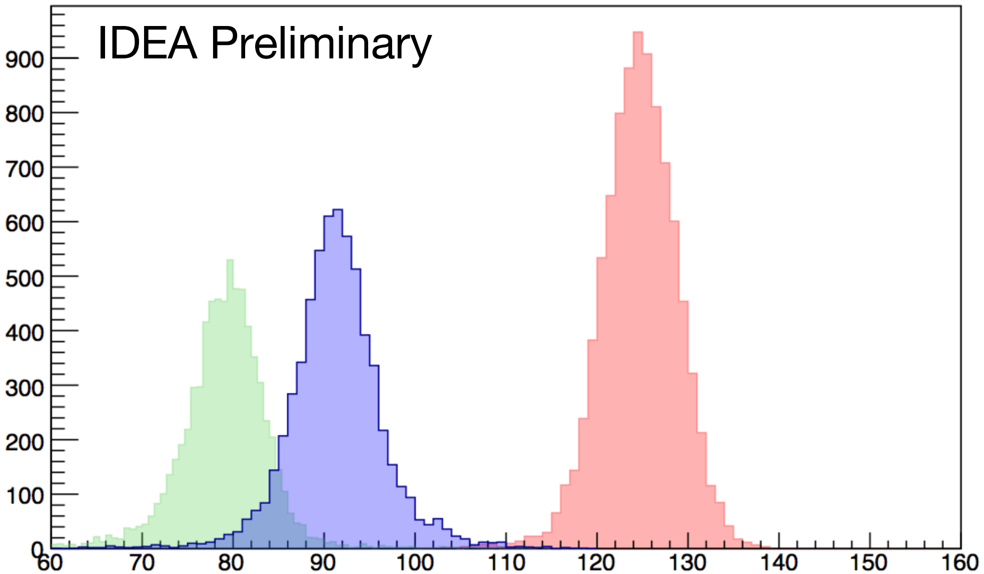
Kinematical observables – Fast simulation





- Beam only: assuming 0.136% beam spread and an ideal detector.
- CLD: a detector concept for FCC-ee with a full Si-tracker system, inspired by CLIC detector.

Jet-jet invariant mass resolution to separate W, Z, H in 2 jets



Conclusions

- Physics requirements impose guiding principles for detector design and performance:
  - High precision vertex detector
  - High transparency and momentum resolution
    - Good integrated PID with cluster counting
  - Excellent calorimetry
  - Light solenoid and minimal yoke
  - Tracking muon system
  - Excellent performance at all energies: Z, WW, ZH, tt

- Performance studies with Geant4 full simulation, Delphes fast simulation and analitic caculations have been performed

- More refined studies in progress both for DCH and DR Calo.

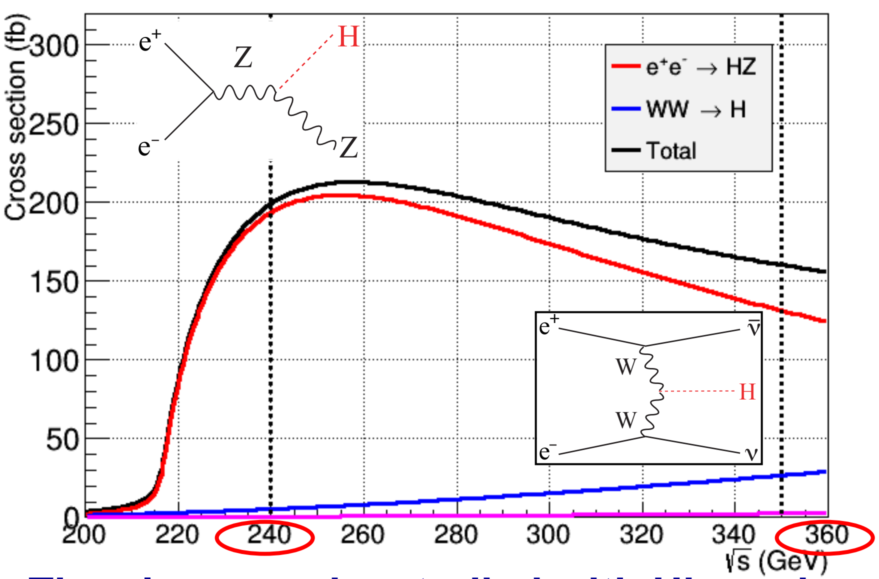
Backup

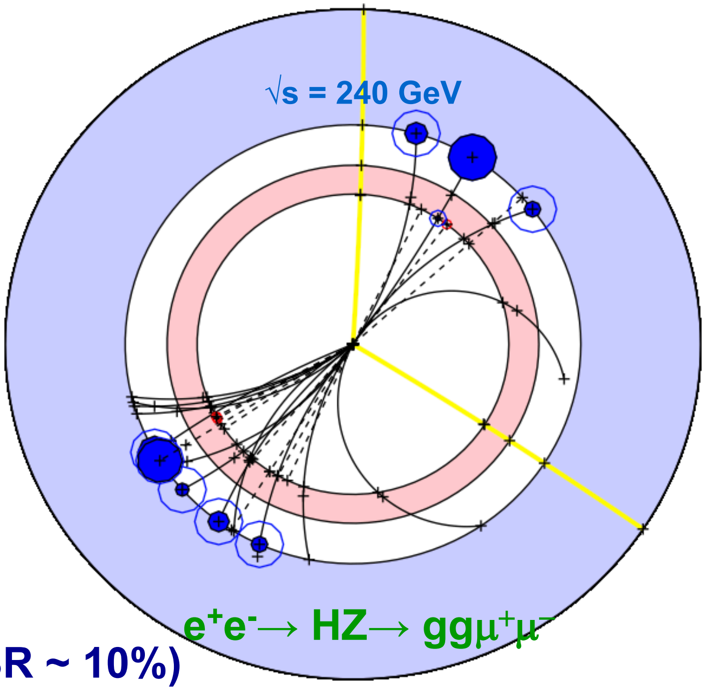
Motivation for e^+e^- colliders

e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be

FCC-ee/CepC: focus on a 90-360 GeV e^+e^- machine (100 km circumf.)
5 ab^{-1} integrated luminosity to two detectors over 10 years → 10^6 clean Higgs events
→ FCC-ee/CEPC will measure the Higgs boson production cross sections and most of its properties with precisions far beyond achievable at the LHC

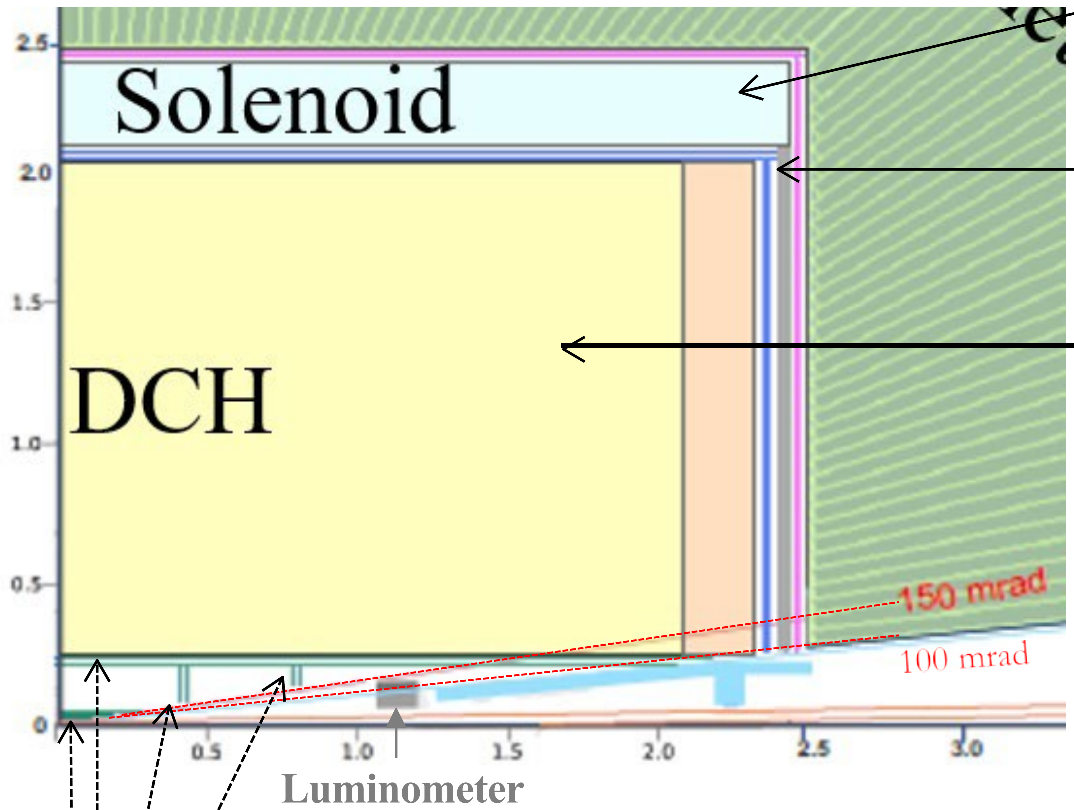
- **Higgs-strahlung (m_H = 125 GeV)**





- **The gluon can be studied with Higgs decays (BR ~ 10%)**

The IDEA tracking system



Solenoid: 2 T, length = 5 m, r = 2.1-2.4 m, 0.74 X_0, 0.16 λ @ 90º

Si Wrapper:
2 layers of µ-strips (50 µm x 1 mm) both barrel and forward regions

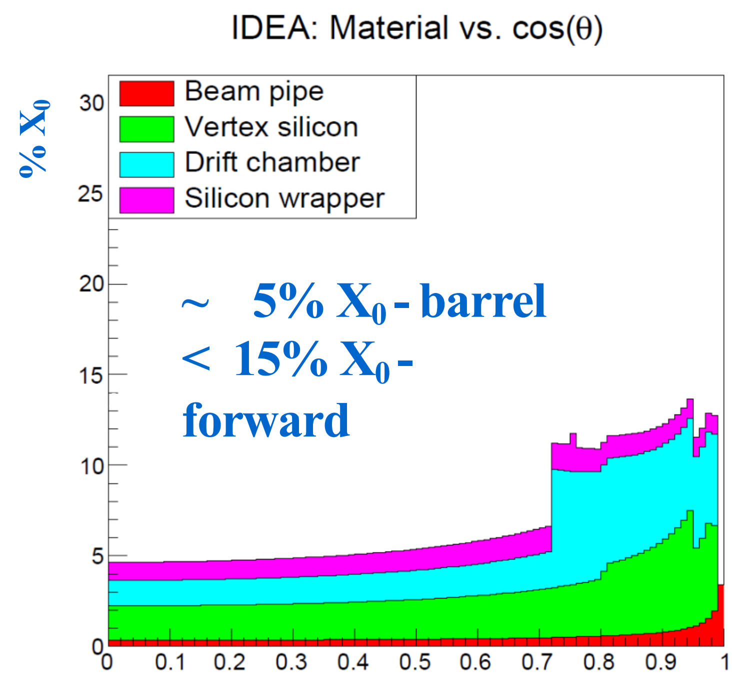
DCH: 56448 (~1.2 cm) cells
He based gas mixture (90% He – 10% i-C_4H_{10})

Vertex:

inner: 3 single Si pixel (20 µm x 20 µm) layers of 0.3% X_0

outer: 2 single Si pixel (50 µm x 50 µm) layers of 0.5% X_0

forward: 4 single Si pixel (50 µm x 50 µm) layers of 0.3% X_0



Tracking requirements

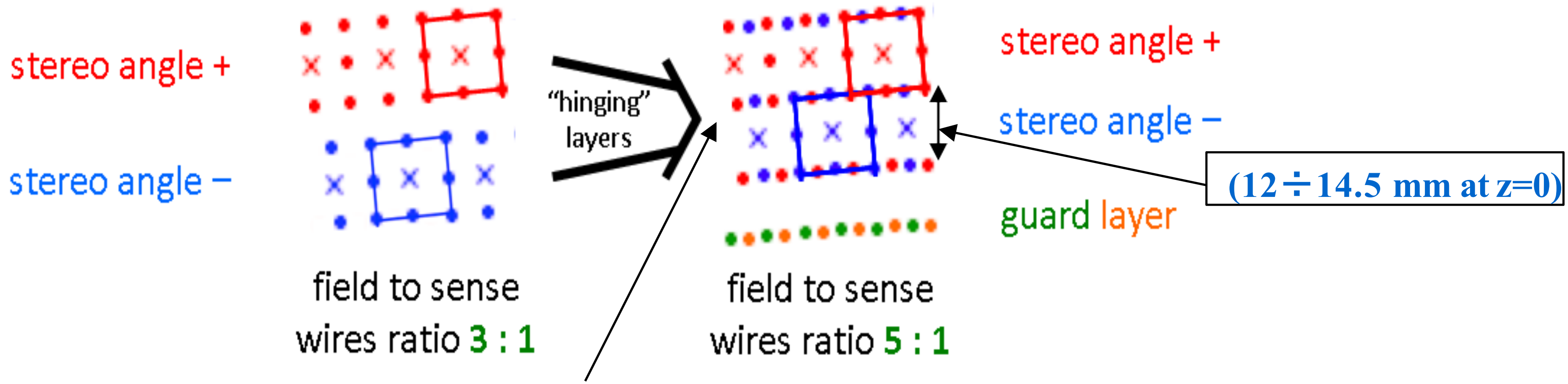
Central tracker system:

- 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 tracking radius needed to recover 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

The IDEA drift chamber



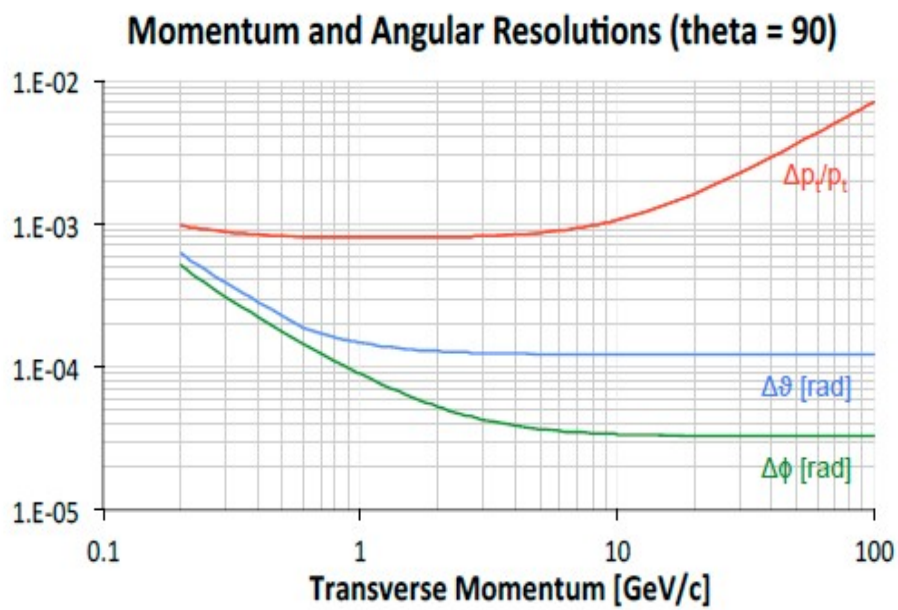
The wire net created by the combination of + and – orientation generates a more uniform equipotential surface

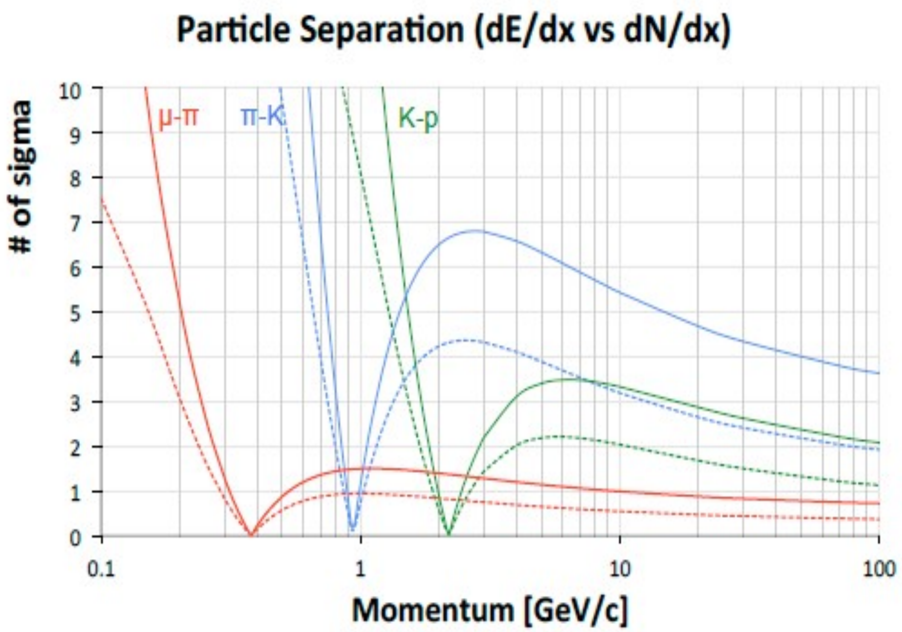
sense wires:	**20 mm diameter W(Au) =>**	**56448 wires**
field wires:	**40 mm diameter Al(Ag) =>**	**229056 wires**
f. and g. wires:	**50 mm diameter Al(Ag) =>**	**58464 wires**
	343968 wires in total	

High wire number requires a non standard wiring procedure and needs a feed-through-less wiring system. The novel wiring procedure developed and used for the construction of the ultra-light MEG-II drift chamber must be used.

MEG-II: muon to e-gamma search experiment at Paul Scherrer Institut - “The design of the MEG II experiment”, Eur. Phys. J. C (2018) 78:380 - https://doi.org/10.1140/epjc/s10052-018-5845-6

The Drift Chamber for the IDEA experiment





$\Delta p_t/p_t = (0.7p_t + 8.3) \times 10^{-4}$

$\Delta\vartheta = (1.1 + 9.4/p) \times 10^{-4}$ rad

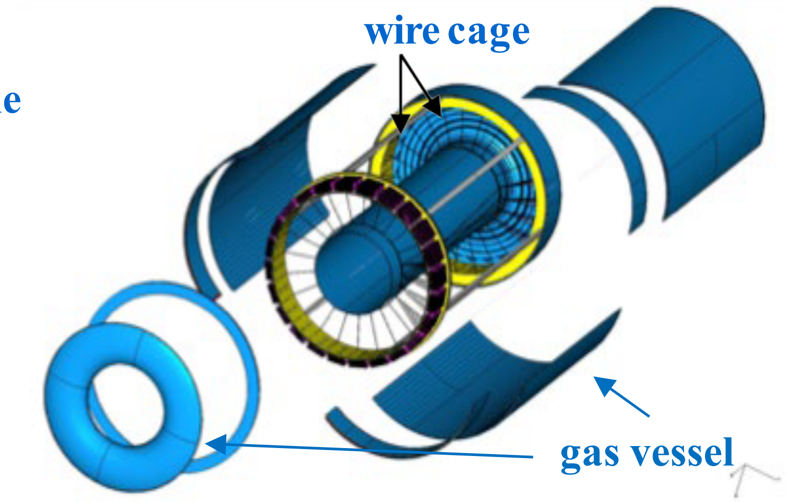
$\Delta\varphi = (0.33 + 9.4/p) \times 10^{-4}$ rad

dE/dx = 4.3 %

dN/dx = 2.2 % (at ε_N = 80 %)

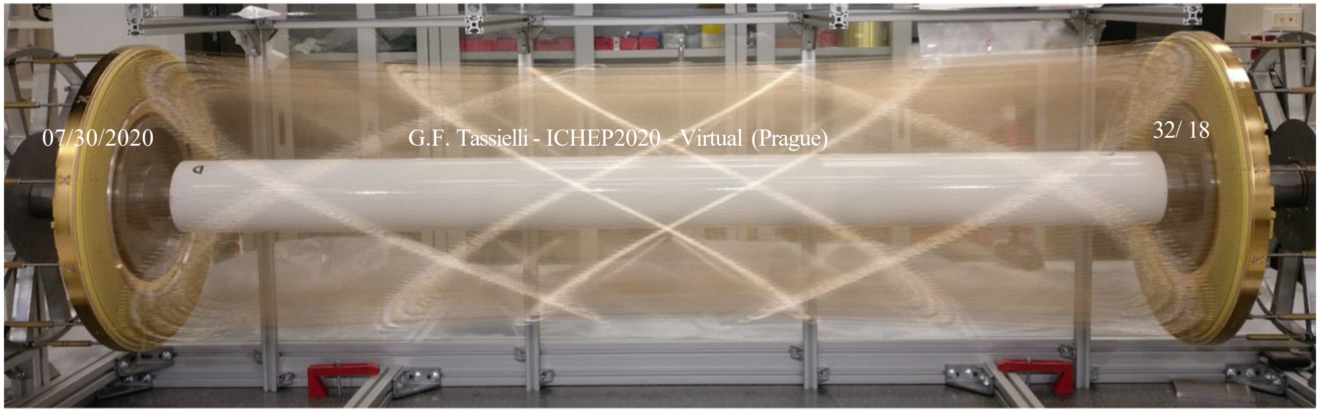
Novel approach at construction technique of high granularity and high transparency Drift Chambers

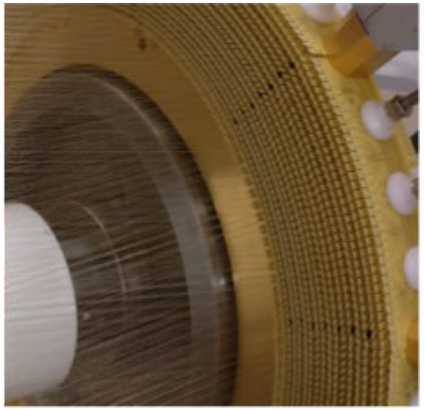
Based on the MEG-II DCH new construction technique the IDEA DCH can meet these goals:



- **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

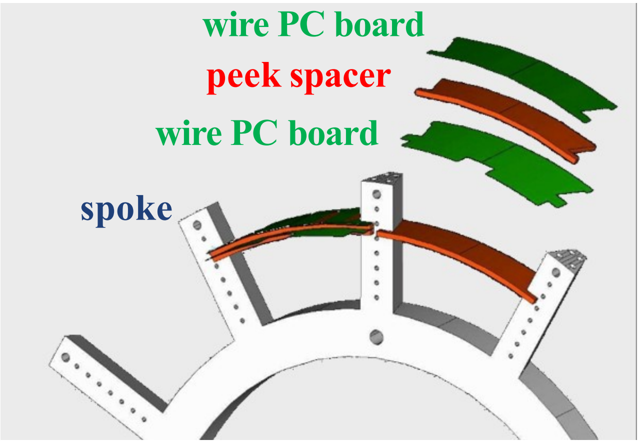




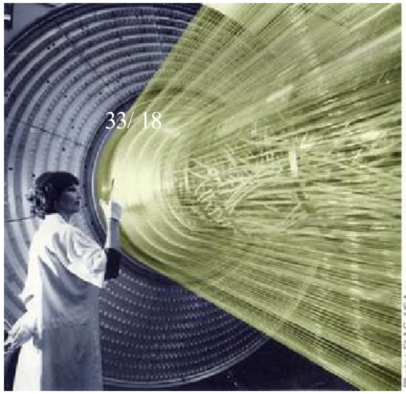
The solution adopted for MEG II:

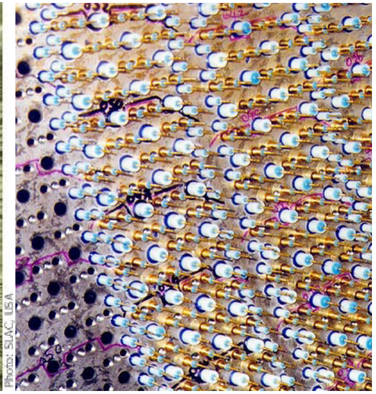
- end-plates numerically machined from solid Aluminum (mechanical support only);
- Field, Sense and Guard wires placed azimuthally by a Wiring Robot with better than one wire diameter accuracy;
- wire PC board layers (green) radially spaced by numerically

  machined peek spacers (red) (*accuracy < 20 μm*);
- wire tension defined by homogeneous winding and wire elongation (*ΔL = 100μm corresponds to ≈ 0.5g*);
- 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.

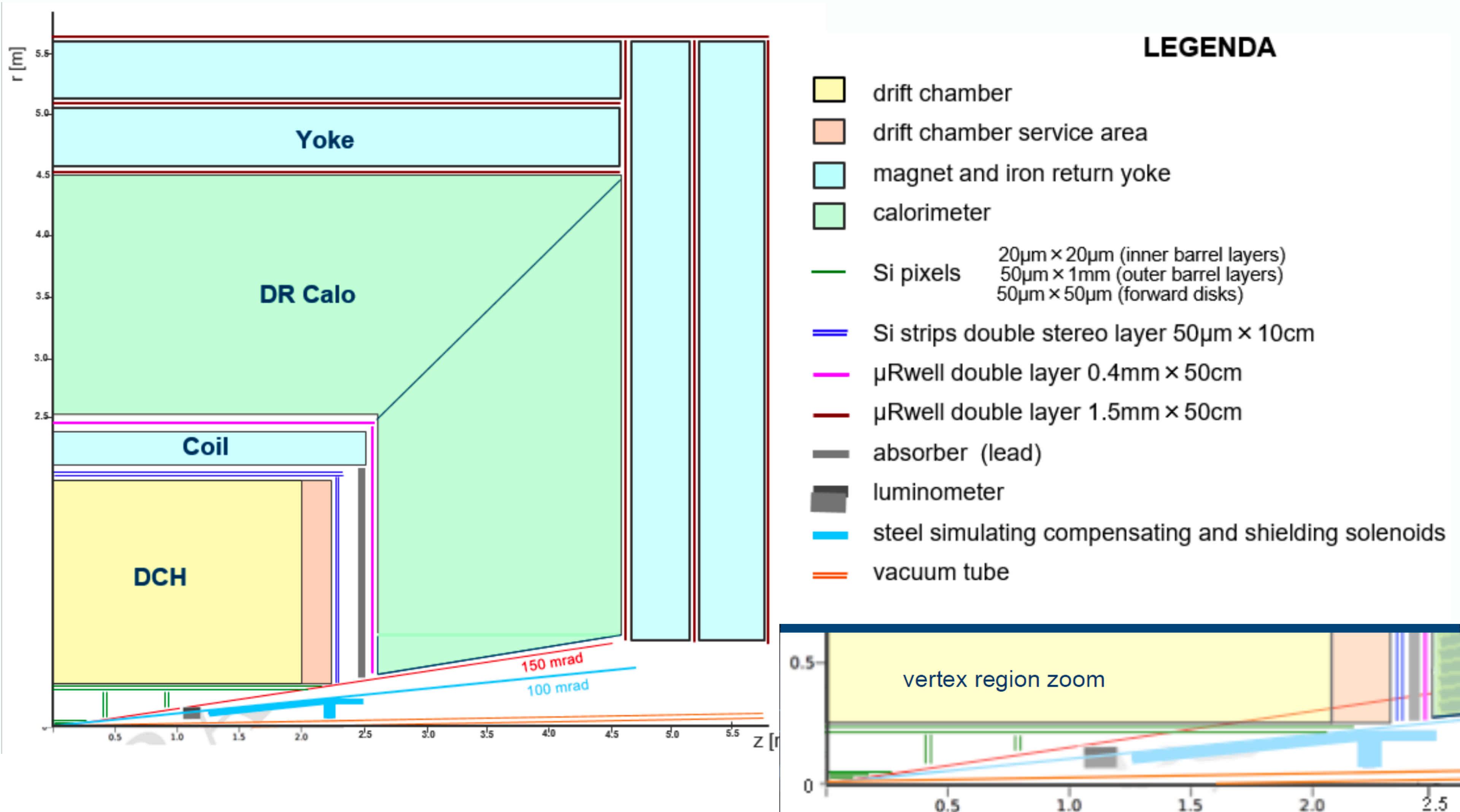


(~ 12 wires/cm^2) impossible to be built with a conventional technique based on feedthrough:



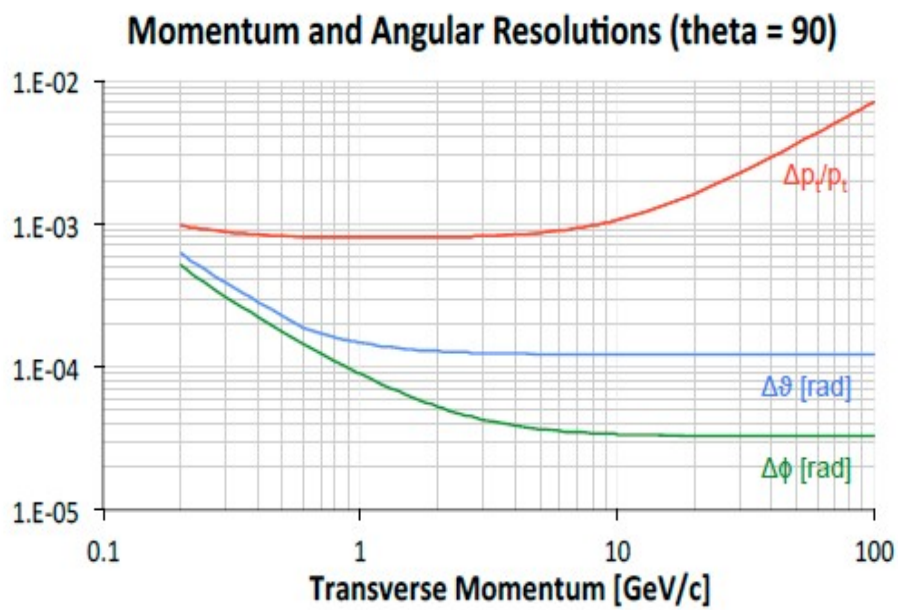


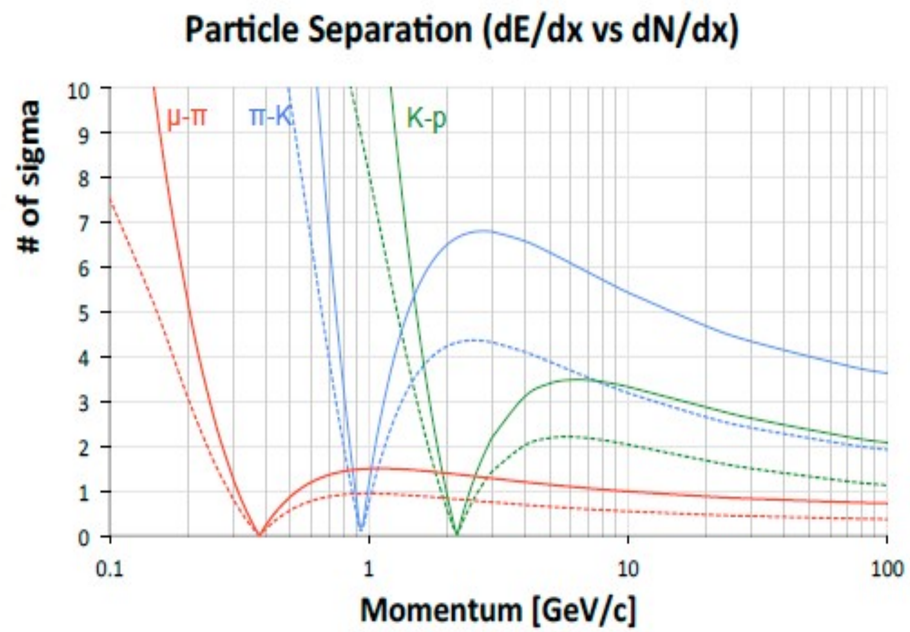
The IDEA detector at e^+e^- colliders (2)



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

The Drift Chamber for the IDEA experiment





$\Delta p_t/p_t = (0.7p_t + 8.3) \times 10^{-4}$

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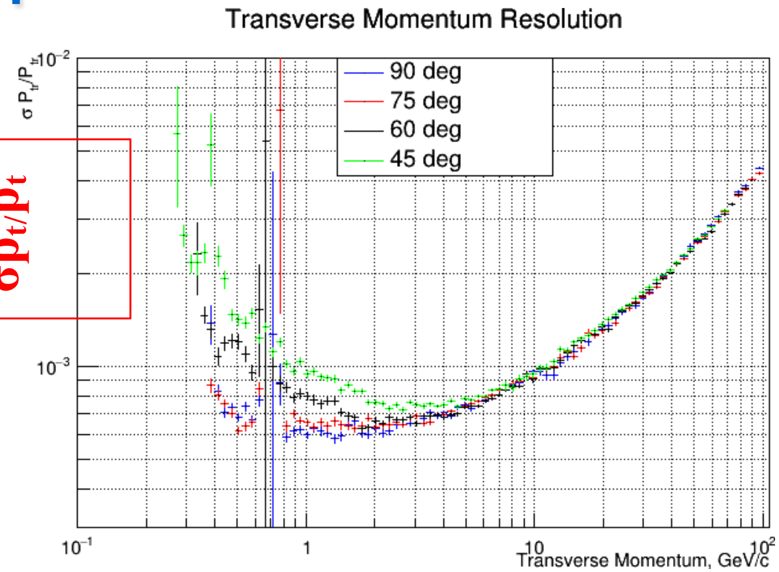
dE/dx = 4.3 %

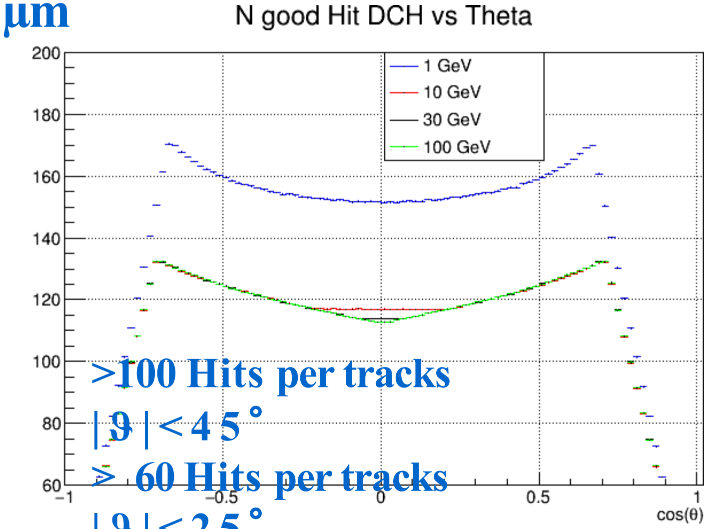
dN/dx = 2.2 % (at ε_N = 80 %)

Expected simulated performance

assumed: σ_d = 100 μm and (conservative for Si) σ_{Si} = pitch/√12 μm

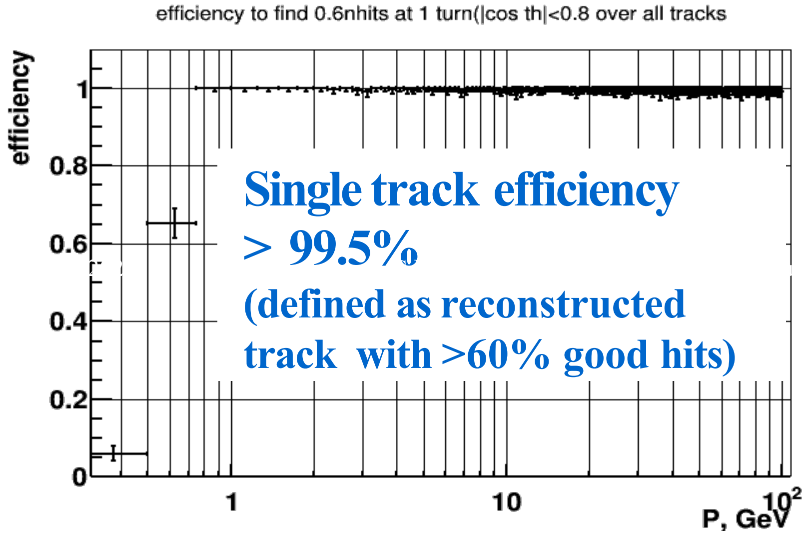
$\sigma p_t / p_t$





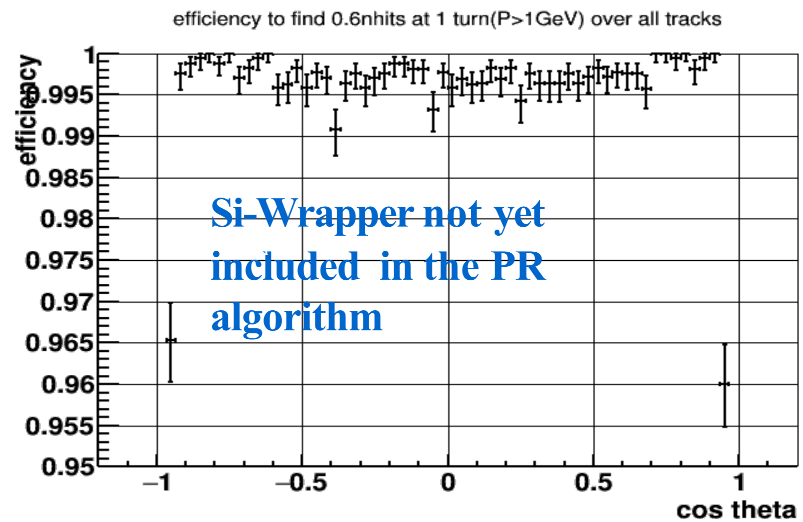
>100 Hits per tracks $|\vartheta| < 45°$

> 60 Hits per tracks $|\vartheta| < 25°$



Single track efficiency > 99.5%

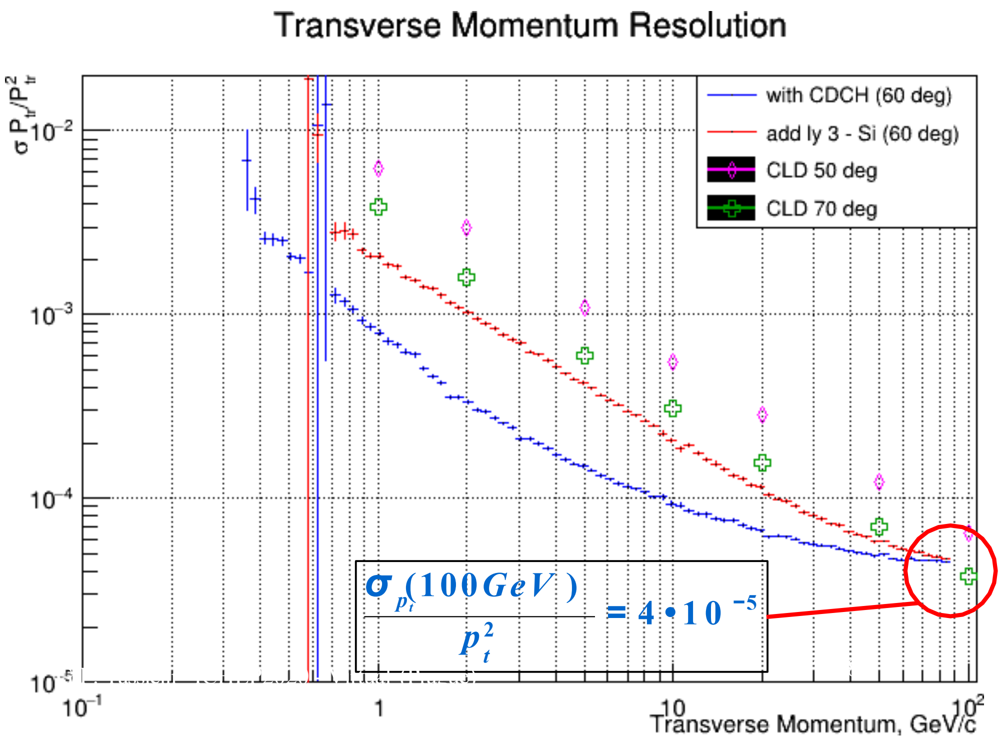
(defined as reconstructed track with >60% good hits)



Si-Wrapper not yet included in the PR algorithm

Expected simulated performance

Transparency more relevant than asymptotic resolution, the particle range is far from the asymptotic limit where MS is negligible.

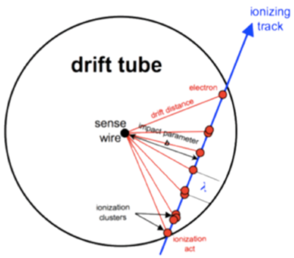


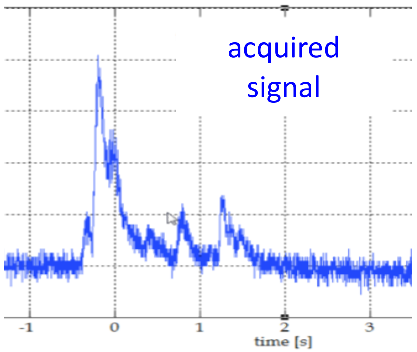
CLD: a detector concept for FCC-ee with a full Si-tracker system, inspired by CLIC detector.

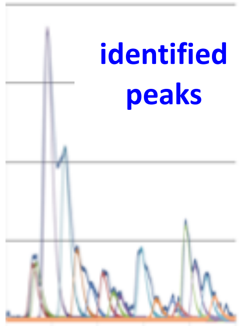
Cluster Counting/Timing and P.Id. expected performance

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:

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







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

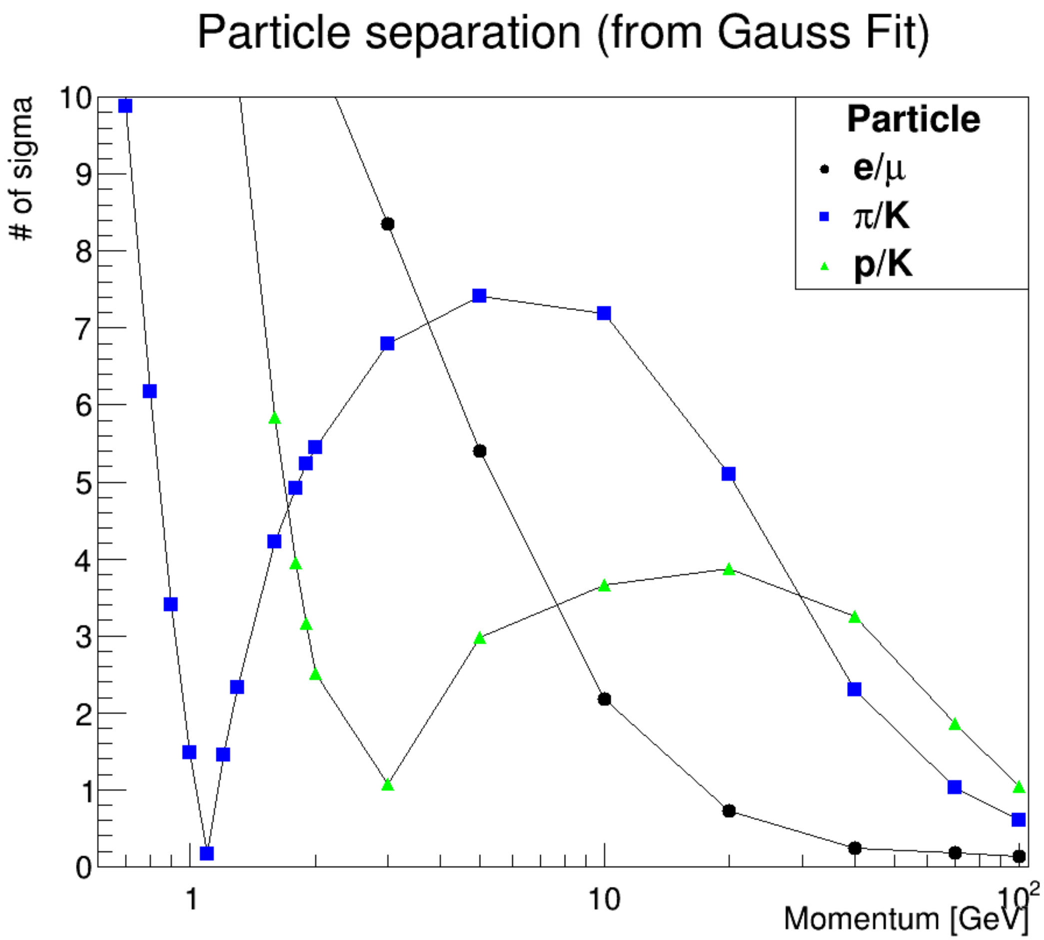
σ ≈ 2.0%

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

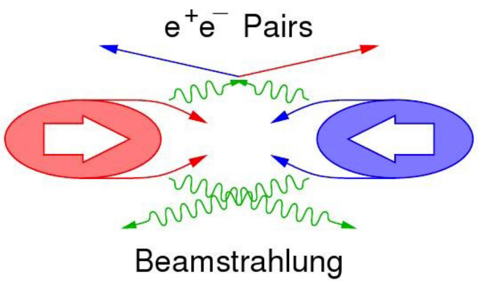
Particle separation in 1cm of gas with Garfield++

Number of σ vs p

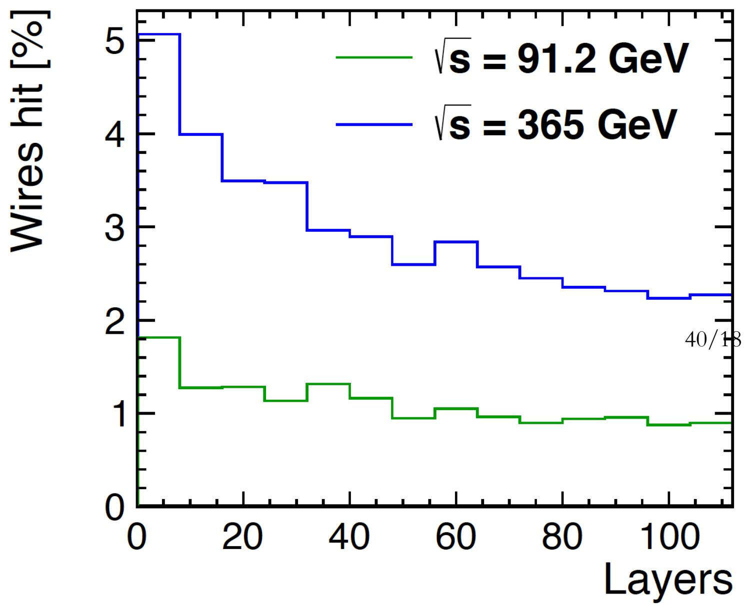


VERY PRELIMINARY

Expected simulated performance



Background	Average occupancy	
	$\sqrt{s}$ = 91.2 GeV	$\sqrt{s}$ = 365 GeV
e^+e^- pair background	1.1%	2.9%
$\gamma\gamma \rightarrow$ hadrons	0.001%	0.035%
Synchrotron radiation	negligible	0.2%



G.F. 40/18

Prospects for deep Learning for τ ID

- Analysis of ideal configuration (test-beam prototipe geometry module): DONE
  - almost perfect identification of different tau decays using state of the art ConvNet
- Ongoing step: move to IDEA detector with realistic conditions
  - several MC samples produced: $Z \rightarrow \tau\tau$ (principal decay modes) and $Z \rightarrow qq$ events with full sim in two scenarios:
    - no magnetic field and no material before the dual readout calorimeter
    - magnetic field and material
- Ongoing design and training of different ANN architectures (results will be ready soon):
  - conventional CNN
  - graph-NN and point-cloud networks
- Two initial tasks:
  - discrimination tau - jets
  - tau decay identification