SOFTWARE & PHYSICS ACTIVITIES IN RD-FCC (WP1)

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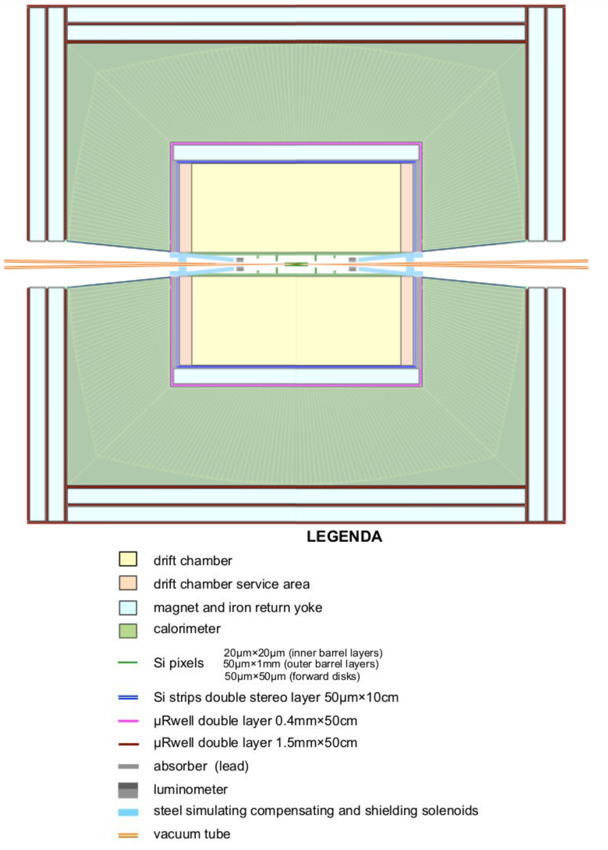
Outline 2023/24

- Tantissimi sviluppi a livello tecnico soprattutto di software legato alle performance del rivelatore per supportare il processo di avanzamento del design di IDEA
-
- Software [BA,BO,PI,MIB,PD, PV, UD]
  - Realization of the description of IDEA concept sub-detectors': silicon (vertex+wrapper), drift chamber, calorimeters (ECAL crystal + DR Calo), muon detector (and pre-shower) in DD4HEP
    - Geometry
    - Simulation
  - Initial development of Local & global Reconstruction & Performance studies
  - Test Beam analysis -> *risultati di TestBeam riportati nelle presentazioni dei rivelatori*
- Physics Studies
  - HZ hadronic analysis [BA]
  - HNL search [PD,PG,PV]
  - HH self coupling at FCC-hh[BA]

Innovative Detector for *e*+ *e*– Accelerator (IDEA)

IDEA detector concept consists of:

- Silicon pixel vertex detector.
- Large-volume extremely light drift wire chamber.
- Surrounded by a layer of silicon micro-strip detectors
- Thin low-mass superconducting solenoid coil.
- Pre-shower detector based on *µRWELL* technology
- Dual readout fiber calorimeter.
    - or a Dual Readout crystal calorimeter could be inserted before the hadronic calorimeter (WIP)
- Muon chambers based on *µRWELL* technology
- inside the magnet return yoke.



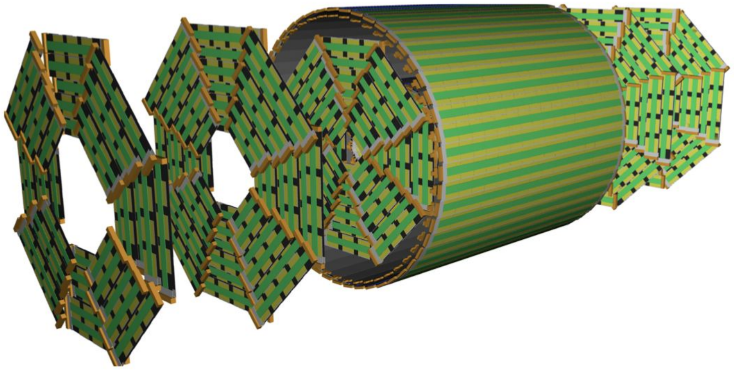
IDEA detector layout

IDEA definition is evolving toward a pre-CDR

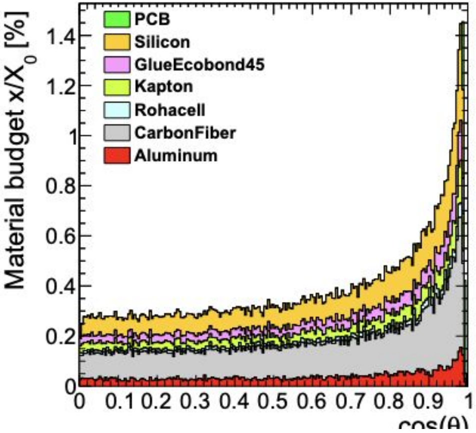
- The development of the geometry, simulation and reconstruction is being done in the key4HEP framework profiting of many modern tools.
- The detector geometry description is now inserted in classes in the k4geo repository
- this allows, for instance, to easily switch components, such as inserting the Drift chamber into an Liquid Argon calorimeter
- In particular the current baseline considers only a fiber Dual Readout calorimeter, but the proposal is to update this design adding a Dual Readout Crystal calorimeter that would ensure a very precise resolution as required by the flavor physics program of FCCee
  - The plan is to prepare a new baseline geometry for physics studies with FullSimulation that includes the precise ECAL Crystal
  - There are also new ideas for a different magnet design that can modify the design of the overall detector.

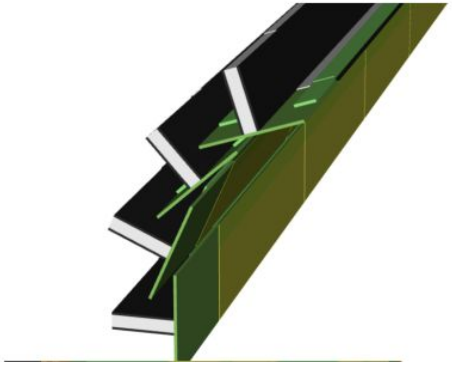
Vertex detector Geometry [PI+A. Ilg Zurich]

- A complete description for the detector is **available**
- Detailed and realistic description for the sensors & support structures
- Digitization algorithm in progress
- Material budget in line with 0.3% per layer at cos(θ) = 0 (CDR assumption)



DD4hep implementation of the IDEA vertex detector.

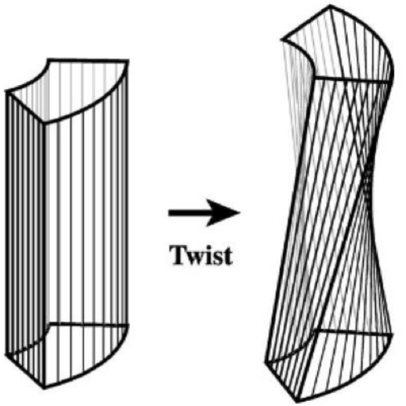


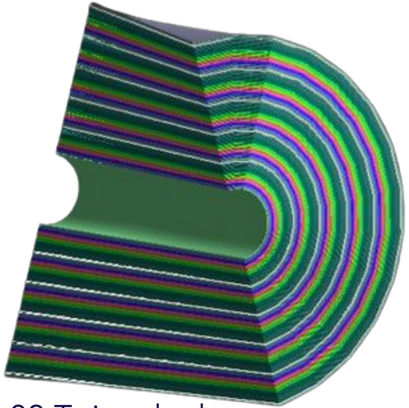


Drift Chamber [BA+LE+A.Tolosa(CERN)]

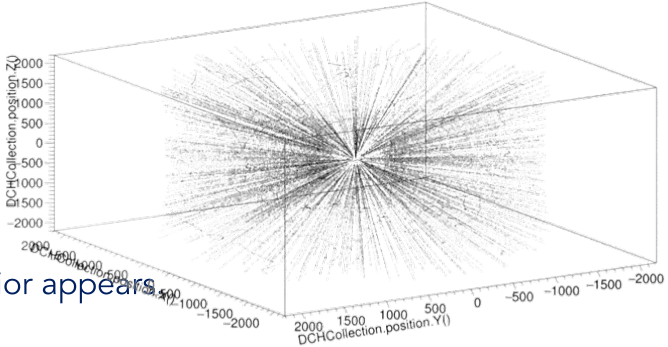
Large-volume extremely light drift wire chamber

- Old version of drift chamber (DriftChamber o1_v01) showed issues of large memory consumption That motivated a new implementation of the geometry.
- Cells are twisted tubes.These cells are the sensitive volumes!
- Field (x5) and sense (x1) wires inside each cell.
- **New digitizer being developed**
    - Test-beam data to be used to tune the simulation





l_v02 Twisted tubes.

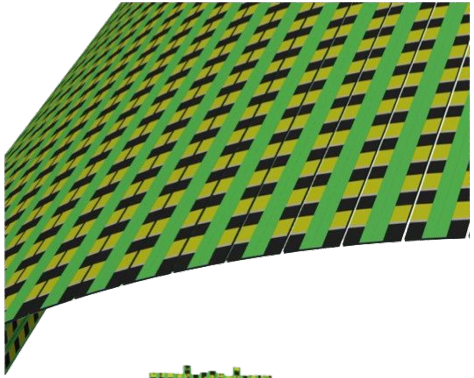


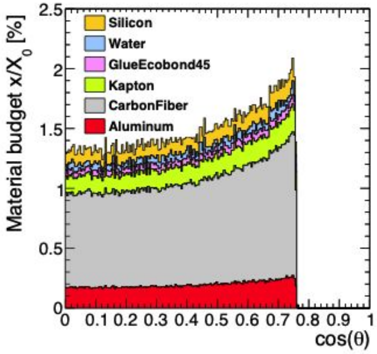
Expected behavior appears.

Silicon Wrapper

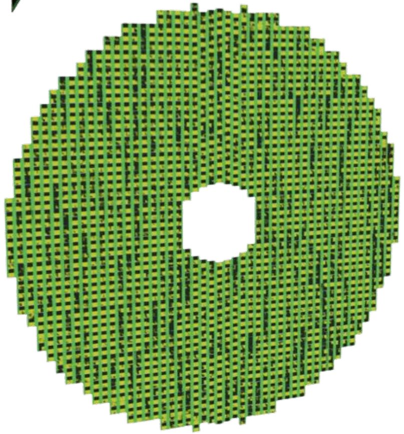
- using the same detector builder and digitizer as for the vertex detector, a first version of Si-Wrapper is ready.
- Large surface (112 m^2), tiled with ~ 4x4 cm^2 modules.
- A huge number of modules. Slow and large memory consumption.
- A second version which is lighter (memory consumption-wise) is implemented. For the moment a single-layer of 0.050 x 1 mm strips.
- Digitization at the moment is the same as for the silicon vertex.

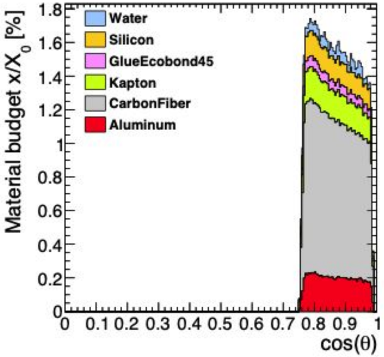
Barrel





Endcap





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Occupancy

Beam background

- **Dominated by incoerent pair production from these processes evaluated with GuineaPig at different √s**
  - physics contribution is negligible
  - Compared with different vertex designs present in simulation

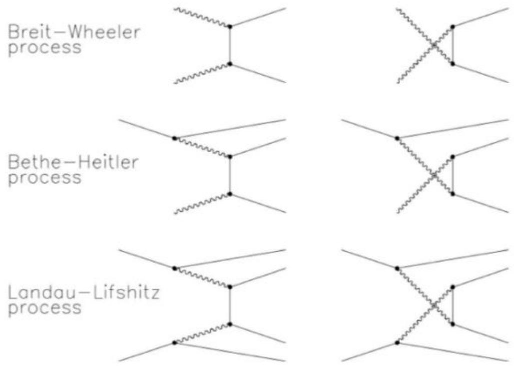
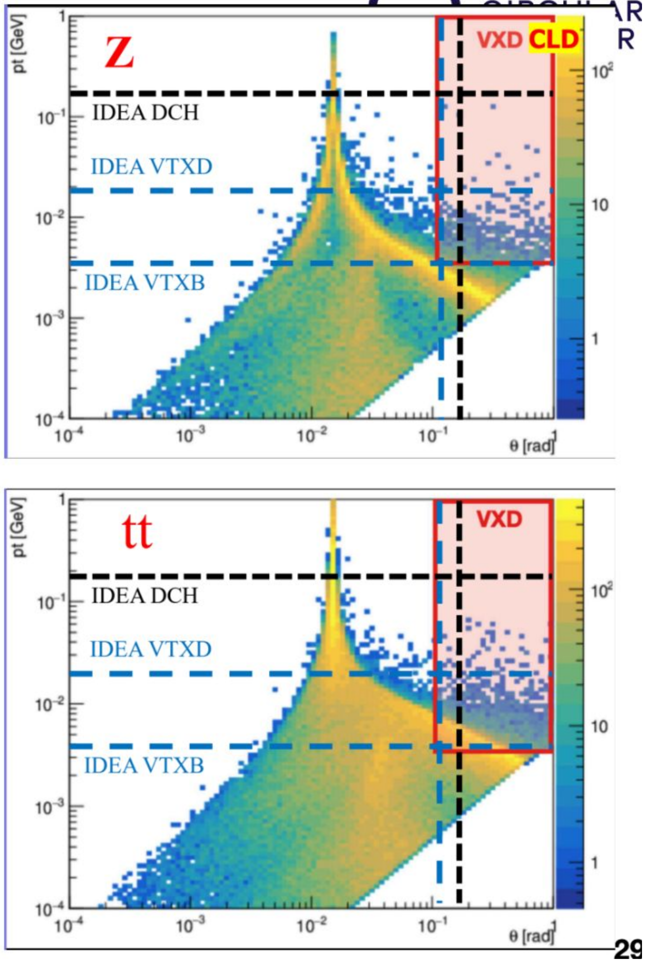


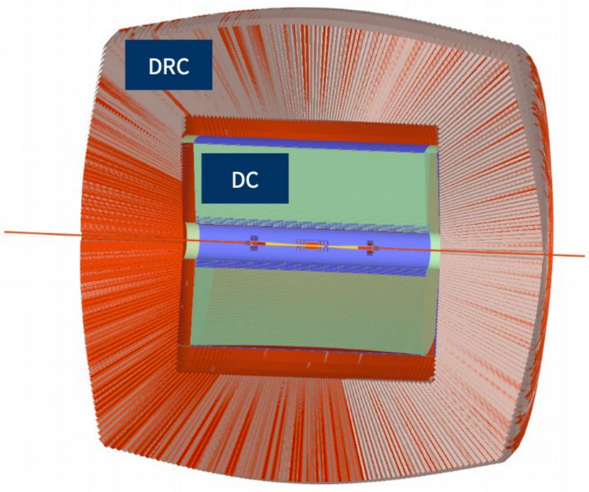
Table 2: Number of pairs produced per bunch crossing (BX) at the four working points, and maximum occupancy measured in the barrel and endcaps of the vertex detector and tracker (respectively VXDB, VXDE, TRKB, TRKE).

		Z	WW	ZH	$t\bar{t}$
1	Pairs/BX	1300	1800	2700	3300
10^{-6}	O_{max}(VXDB)	70	280	410	1150
10^{-6}	O_{max}(VXDE)	23	95	140	220
10^{-6}	O_{max}(TRKB)	9	20	38	40
10^{-6}	O_{max}(TRKE)	110	150	230	290

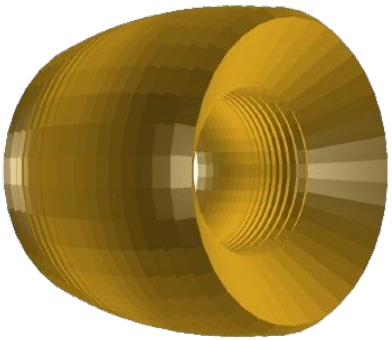


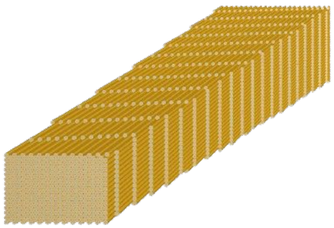
More complete studies will now be possible with full reconstruction

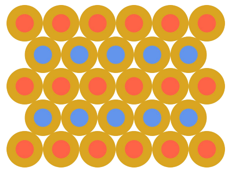
Fiber sampling dual-readout calorimeter [PV,BO+Korea,Sussex]

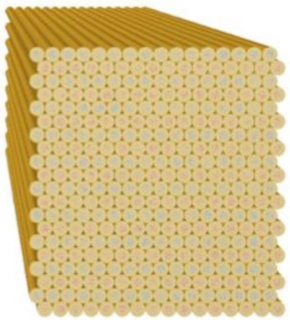


- Currently, the performance optimization of full simulation for full-scale production for FSR has one older version of the DR calorimeter (developement picked up by Korean colleagues)
- The full simulation of the new ***Bucatini*** modules fiber sampling DR-Calo is still under construction:
- The implementation of geometry and materials of the barrel part is ready.
- Ongoing work to implement the endcap in DD4HEP



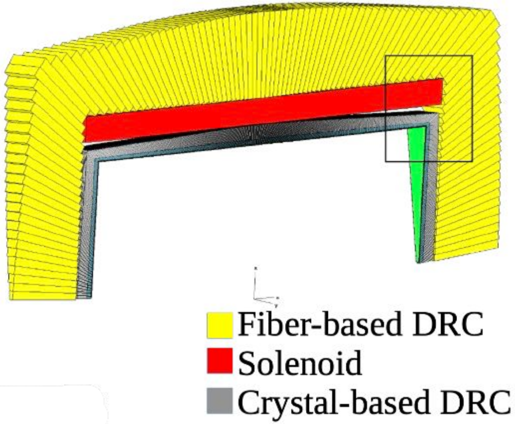


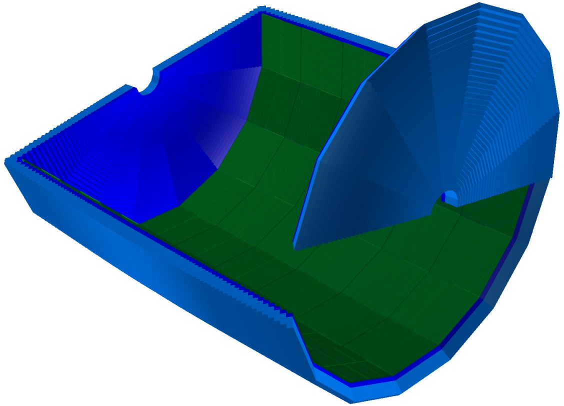




Crystal-based ECAL dual-readout calorimeter [MIB,NA+USA]

- Potential new baseline with the addition of a dual readout crystals ECAL.
- For themoment leave drift chamber untouched, push out fiber DR calo.
- Add a PbWO4 crystals + LYSO timing layer.
- With 1x1cm crystal faces/thickness:
  - ~1.12 million barrel crystals
  - ~400,000 endcap crystals
  - ~30,000 timing crystals

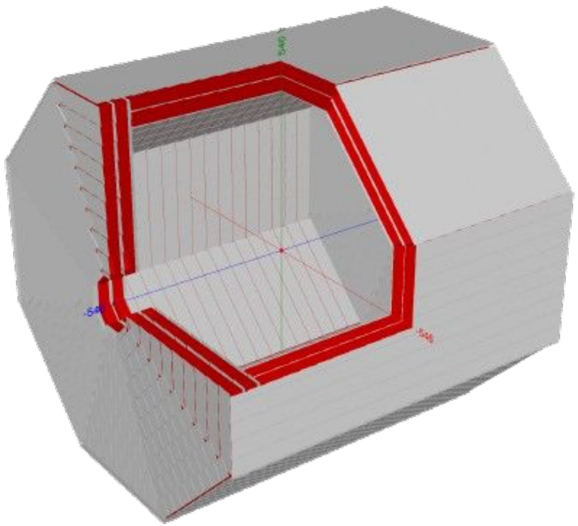




Crystal-based calorimeter would provide better EM resolution than fiber-based plus longitudinal segmentation [JINST2020]

Muon system [BO]

- IDEA muon system primarily composed of 3 sensitive stations. Each station will consist of a large mosaic of μRWELL technology detectors.
- The basic μRWELL ”tile” will have an active area of 50 × 50 cm^2.
- The layers are placed between layers of the iron yoke that closes the magnetic field.
- A strip pitch ~ 1.2 mm and 500 mm length.
- A 2D readout system for each individual chamber.
- **New studies are ongoing for the determination of requirements from physics on the details of the muon detector design: for instance using the standalone reconstruction of very displaced tracks/vertices to increase the sensitivity to BSM processes.**

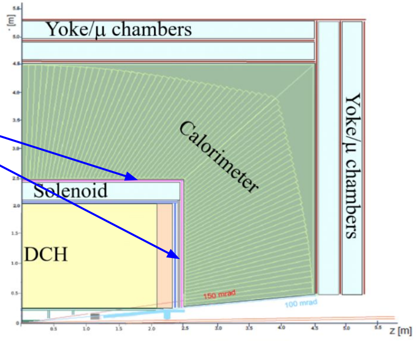


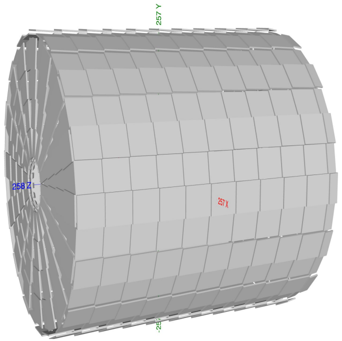
- A simple digitization algorithm is now ready which smears the hit position in the local μRWELL chamber plan in 2D, with the space resolution of the chamber ~ 400 μm, and more features to be added (simulates the efficiency, fake rate (noise)).
- Currently working on reconstruction (Standalone muon system alg.).

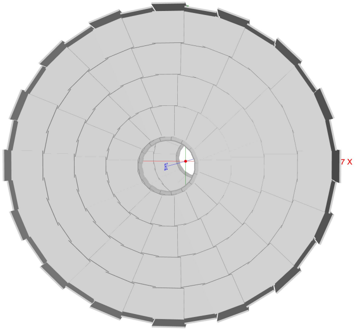
Preshower based on *μRWELL* technology [UD+BO]

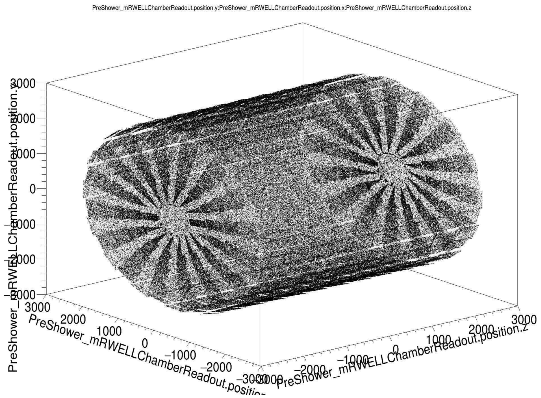
- IDEA detector envisages one layer preshower system utilizing μRWELL technology.
- Pitch between readout strips: 400 μm
- A 2D readout system for each individual chamber.
- The implementation is ready in DD4hep
- It uses the same digitization of the muon system.
- A reconstruction algorithm needs to be implemented.

One layer encapsulate the solenoid



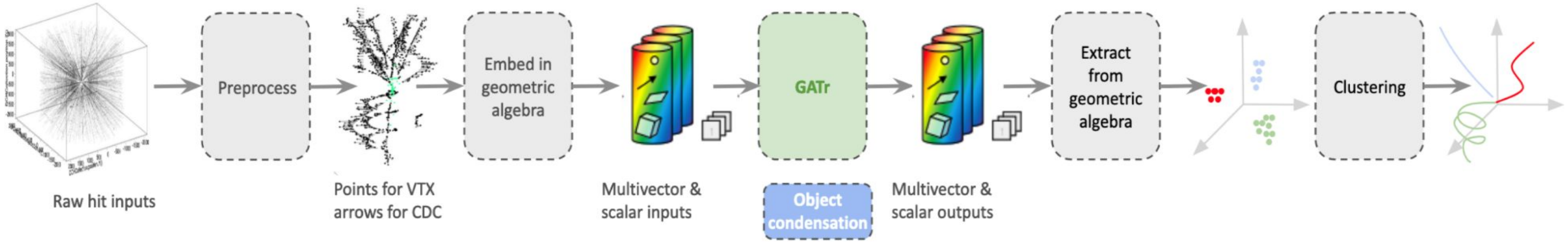






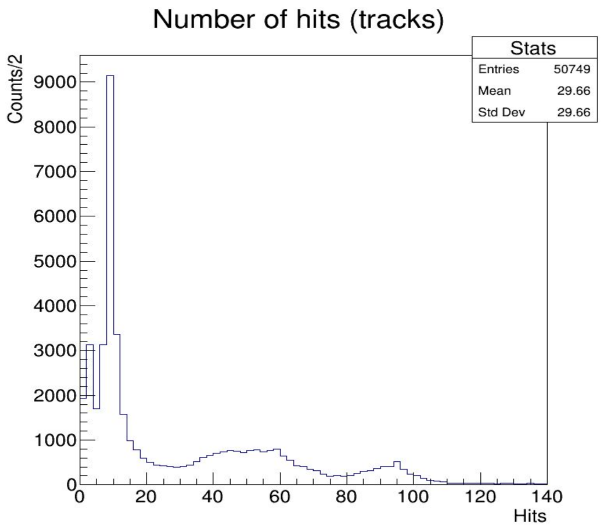
Tracking and Reconstruction[PD,PG+CERN]

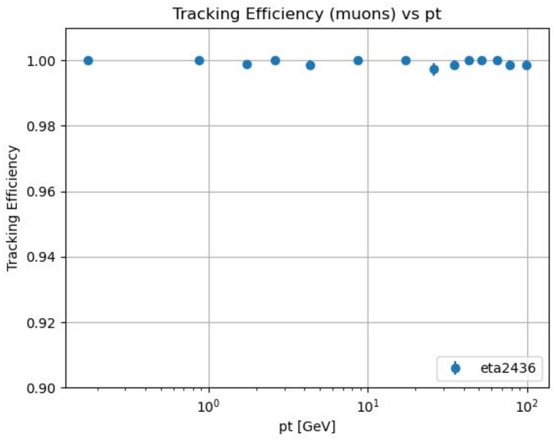
- CERN is leading the development of reconstruction with ML. Italian students are working with them to help with algorithm developments and a validation suite.
- A new track reconstruction effort is based on TFGG, a generalised geometric track finding approach to allow for more complex tracking detectors which involve multiple tracking technologies. Specifically, our end-to-end pipeline considers the hits from all tracking systems and outputs a set of tracks.



Developing a validation suite

- Very first plots of hits on tracks and efficiency…
- Tracking in IDEA is a milestone that will allow to move to more advanced performance studies, hopefully for the European Strategy



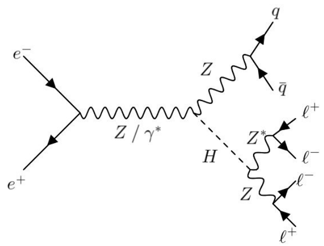


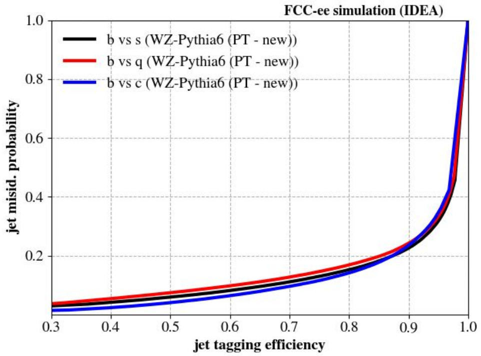
VERY PRELIMINARY

Physics Analysis - Higgs Physics (BA)

Motivation:

FCC-ee -> Higgs factory allowing for measurement of Higgs couplings with a cleaner environment than in LHC.



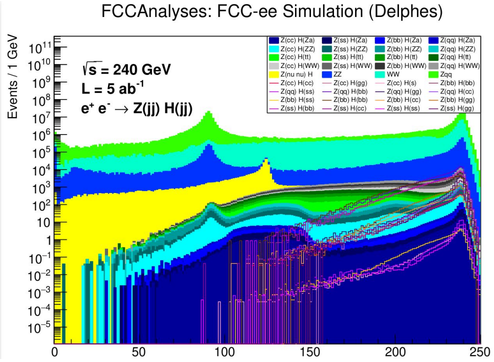


Channel :

2jets + 4l from Z(jj)H(ZZ) - ZZ->4l

Samples:

Produced by WHIZARD+PYTHIA for event generation Delphes (IDEA detector card) for detector simulation. Samples available <u>Here</u>.



Expected Background: At least 2l+2j

ZZ,Zqq, llH(jj), jjH(ll), ZH(Za), ZH(WW), llH(ZZ), vvH(ZZ)

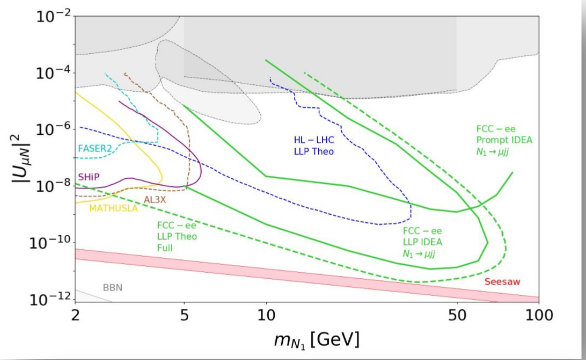
Analysis strategy:

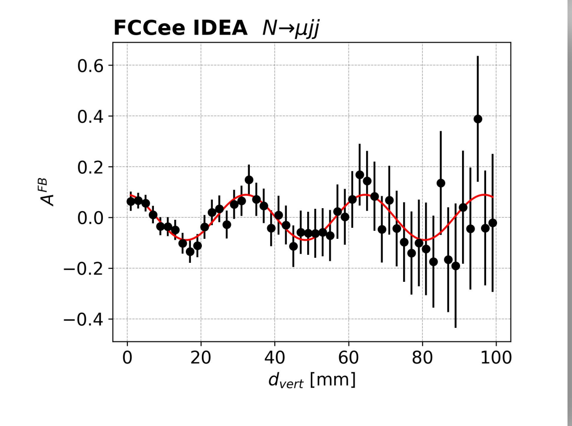
- Jet reconstruction algorithm: Durham kt algorithm for number of jets = 2
- Jet flavour tagging: Particle net tagger (c,s,b,g,u,d)
- Same flavour, oppositely charged lepton pairs.
- The On-shell Z is reconstructed by finding the pair of leptons that minimizes $|M_{ll} - M_Z|$, the other 2 highest pt leptons reconstruct the off-shell Z.

Physics Analysis - Heavy neutral leptons at FCC-ee [PV]

Study of production of heavy neutrinos, and characterization of the model parameters

- Channel: $Z \to N\nu, N \to \mu jj$
- Simulated in IDEA to extract reach, sensitivity limits and detector requirements (hadronic resolution, timing)
- Various analyses already developed:
  - Discovery potential, across the full mass spectrum accessible at the FCC-ee Z-pole run [1]
  - Mass measurement via neutrino time-of-flight [2]
  - Sensitivity to measurement of $N \to \overline{N}$ oscillation
- Further developments:
  - In-depth characterization of signatures of lepton-charge asymmetry (mainly for HNL oscillation and Dirac/Majorana nature discrimination)
  - Improved statistical models and application of ML techniques
  - Analysis of the signal with a full simulation (to validate fast-sim, and constrain detector requirements)



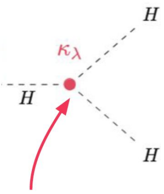


[1] https://doi.org/10.17181/9pc9x-kcn56
[2] https://arxiv.org/abs/2406.05102

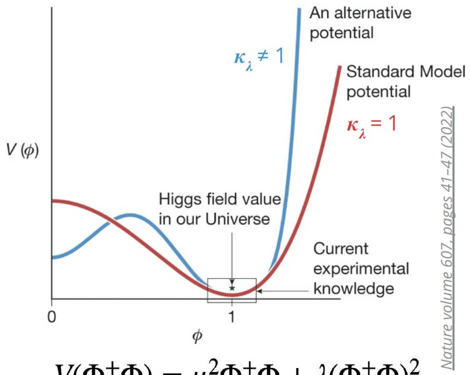
Interest in BSM also from PD,TS,UD

Physics Analysis - FCC-hh (BA+CERN+US)

Measuring the Higgs self-coupling allows us to gain insight into the nature of the Higgs potential and electroweak symmetry breaking



Higgs self-coupling modifier: $\kappa_\lambda = \lambda^{meas}/\lambda^{SM}$



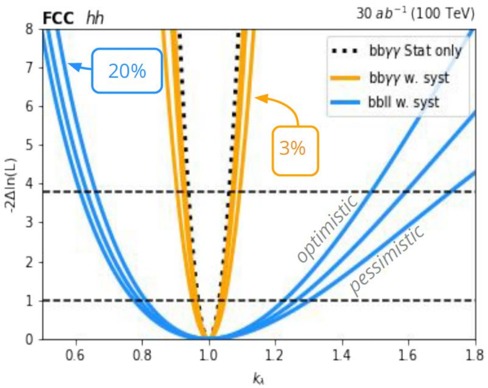
$$V(\Phi^{+}\Phi) = \mu^2\Phi^{+}\Phi + \lambda(\Phi^{+}\Phi)^2$$

Current and future status at the LHC :

Experiment	95% CL limit
ATLAS - *HH* - *H+HH*	 $-0.6 < \kappa_\lambda < 6.6$ $-0.4 < \kappa_\lambda < 6.3$
CMS - *HH*	 $-1.2 < \kappa_\lambda < 6.5$
	$\delta\kappa_\lambda$ (68% CL)
HL-LHC	~50%
FCC-hh	3%

FCC-hh: pp-collisions at 100 TeV, 30 ab^{-1} in ~25 years

Final state	Description
$b\bar{b}\gamma\gamma$	• High precision, despite small BR: Clean signature with well reconstructed objects
$b\bar{b}ll+E_T^{miss}$	• Summing contributions from $b\bar{b}WW(l\nu l\nu)+b\bar{b}\tau\tau(l\nu l\nu)+b\bar{b}ZZ(ll\nu\nu)$ • Larger BR, but more background contaminated, limited precision



Source of uncertainty	Syst. 1	Syst. 2	Syst. 3
Common systematics			
b-jet ID / b-jet	0.5%	1%	2%
Luminosity	0.5%	1%	2%
Signal cross-section	0.5%	1%	1.5%
$b\bar{b}\gamma\gamma$ systematics			
γ ID / γ	0.5%	1%	2%
$b\bar{b}\ell\ell + E_T^{miss}$ systematics			
Lepton ID / lepton	0.5%	1%	2%
Data-driven bkg. est.	-	1%	1%
Data-driven bkg. est.	-	-	1%

- In view of the European Strategy the effort on the physics of FCC-hh and its complementarity with FCC-ee has restarted both for FCC and inside INFN. Kick-off Meeting FCC-hh 03/09 (virtual). INFN Meeting in LNF 1-4/10
- We expect new interest in some FCC-hh studies to arrive in the next months.

Executive Summary

- Focus of activities in 2023 and until the FSR (December 2024) and European Strategy (March 2025) on the full simulation and reconstruction of the IDEA detector in order to perform physics studies.
- Excellent progress in the last months. Test Beam results essential to tune the performance.
- Some focused interest in physics analyses and performance studies. Will likely increase with the availability of new MC datasets
- Effort on computing in place as well to help with the incoming needs of MC generation

BACKUP

Algorithm pipeline

- **Preprocessing:** Each set of hits X = {Xvxt,Xcdh} has to be converted into a graph of multivectors in 16 dimensions, where each node corresponds to an hit. In the so called embedding space, tracks are supposed to be are easily separable.
- **Geometric Algebra Transformer (GATr)**: Each multivector graph is transformed with a GATr, a multiple block transformer, which exploits the symmetries of the detector through geometric algebra transformations.
- **Object Condensation Approach:** Each transformed graph is analysed to return a pair (beta, co-ordinates) for each node. Beta is a scalar used to define a potential that attracts hits belonging to the same track and rejects those belonging to different tracks.
- **Clustering:** From the clusters in the embedding space, tracks can be obtained using the HDBSCAN clustering algorithm.