WG2 - Simulation

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2nd ECFA Workshop on e^+e^- Higgs/EW/Top Factories

Oct. 13th, 2023 – Paestum

Based on material kindly provided by colleagues from C^3, CEPC, CLIC, FCC and ILC

CERN

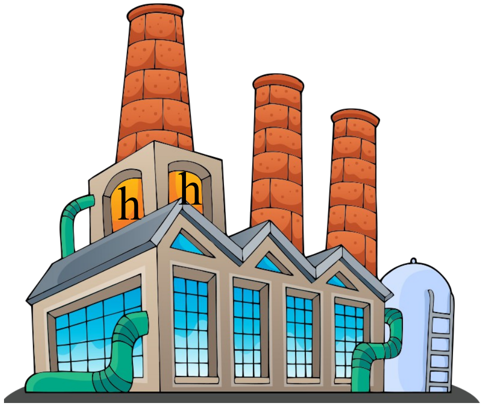
Content

- Assessment of a facility physics reach
- Detector geometry implementation
  - Highlighting flexibility and interoperability
- Simulation tips and tricks
- Detector optimization

Covering here a small subset of topics, chosen with my own bias

→ apologies to people whose work is not covered

Context



- The 2020 update of the European strategy for particle physics has identified an **electron–positron Higgs factory as the highest priority** collider after the LHC
- Several projects proposed: covering here **C^3, CEPC, CLIC, FCC and ILC**
- Though each facility features **different environments** and timelines, they must all **answer the same questions**
  - What is the **physics potential** of my collider?
  - What detector types are the most suitable?
  - What is the **optimal detector configuration**?
  - Uncertainties, technological feasibility, cost, …

  } What is the **physics reach** of my facility?
- **Answering the above questions requires simulation!**

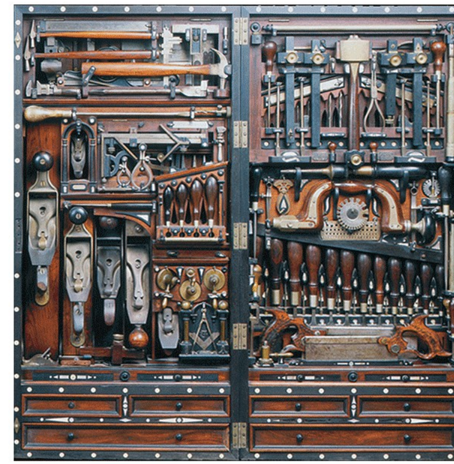
Simulation

… and can follow a sequential progression

Back of the envelope

Parametrized Simulation

Full(/Fast) Simulation



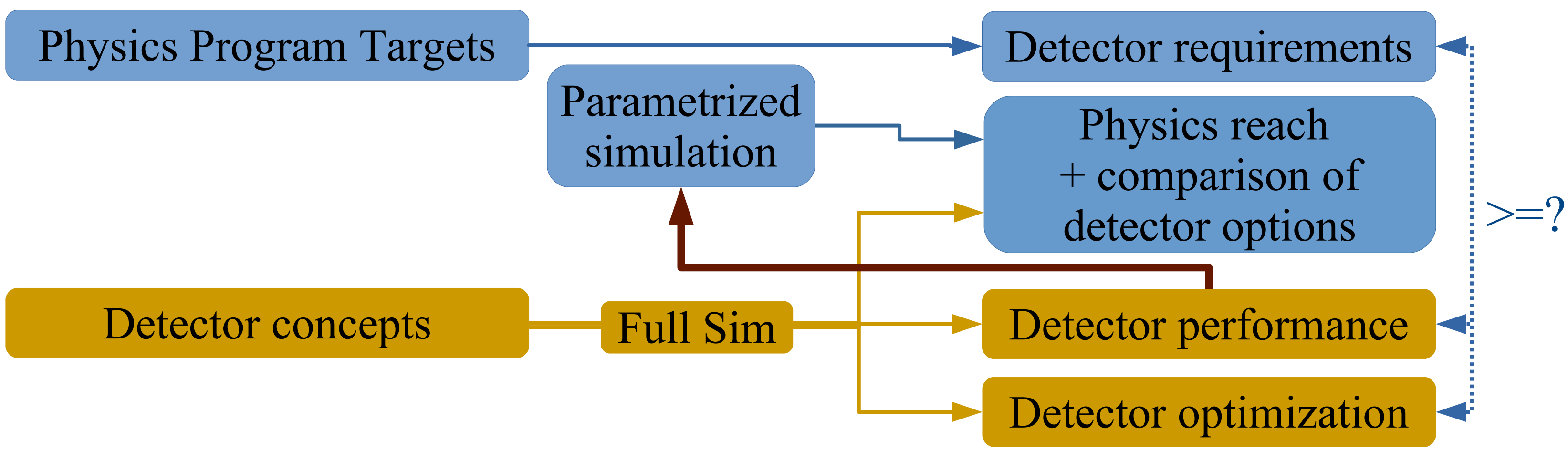
Why such complicated tools?

Real prototypes are expansive → allows us to explore many sub-detector options

No test beam with all sub-detectors together → enables exploration of their interplay (mat. budget, MS, calo leakage, global reco, ...)

…

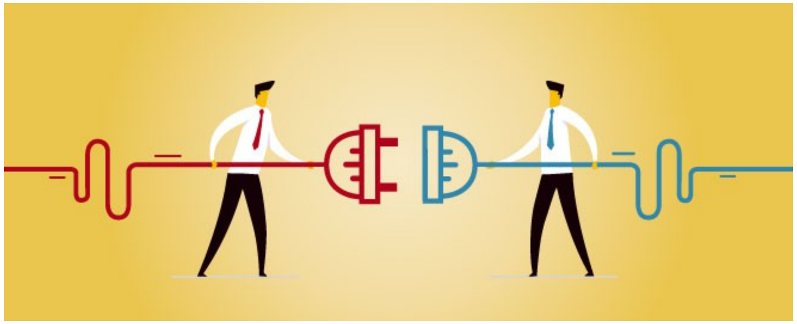
… or, for a more efficient usage of resources



This talk mostly **focuses on Full Simulation (+ digitization)**

- What are the solutions found to tackle the different simulation challenges?
- How can those solutions serve the entire community?

Community Effort



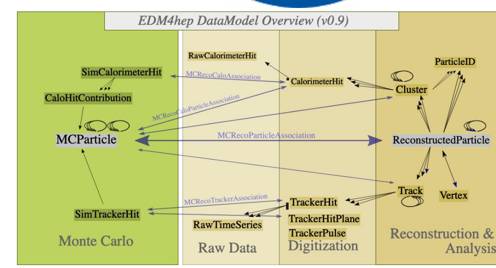
- Prospective studies have limited man power (w.r.t. operating experiments)
  - Important to exploit synergies through a common effort
- The Future Collider community decided to develop a **common software ecosystem**
  - **Key4hep** guiding principles
    - **Interoperability**
      - "What was developed by some should be useable by others" (with minimal modifications)
    - **Versatility:** should cover large spectrum of needs (serves diverse facilities and detectors)
    - **Flexibility:** everything is under development, need to adapt to evolving detector configurations, experimental conditions, etc

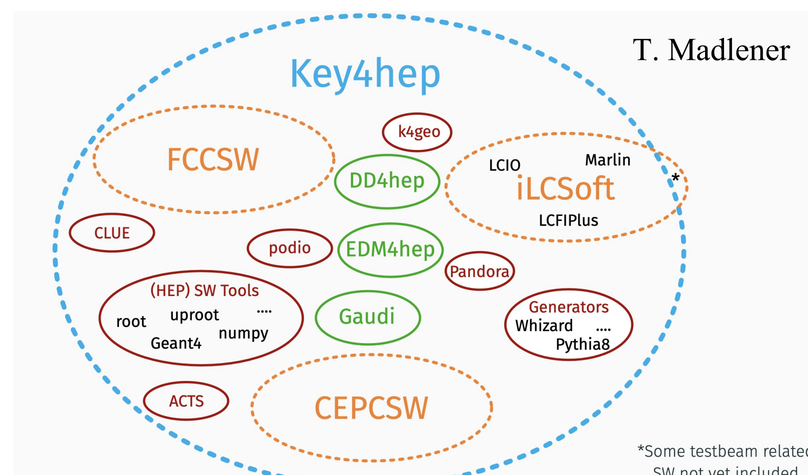
The Simulation Toolbox

Key4hep

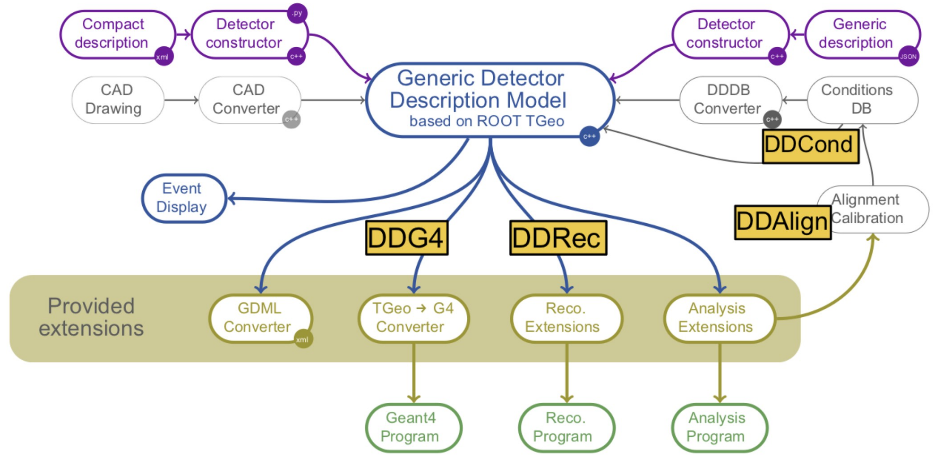
How do we realize the guiding principles of the Key4hep software ecosystem?

- **Interoperability**
  - Common algorithm orchestration framework: Gaudi (LHCb, ATLAS)
  - Common data format for algorithm input/output: edm4hep
  - Common detector geometry construction strategy: DD4hep
- **Versatility**
  - A set of packages of general interest in HEP is provided through the Spack package manager
  - Easily extended to meet everyone's need
- **Flexibility**
  - Provided by the above
    - Mainly DD4hep (more later)
  - Code factorization
- More details about Key4hep in Juan's talk



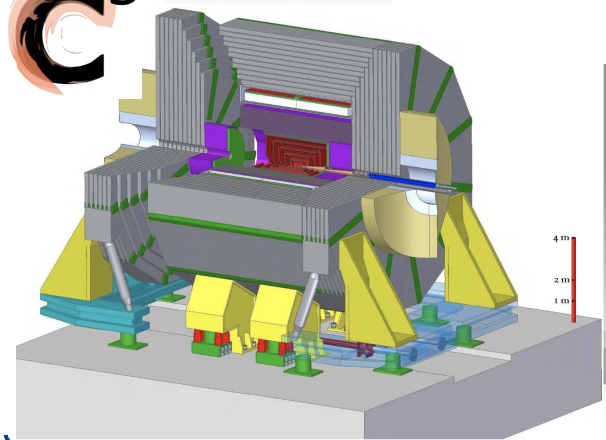


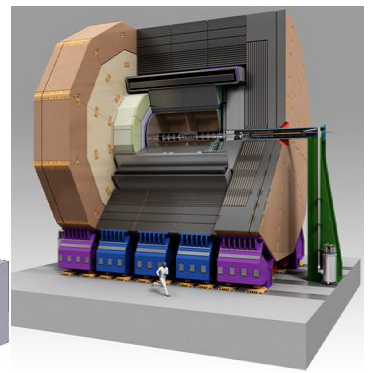
DD4hep

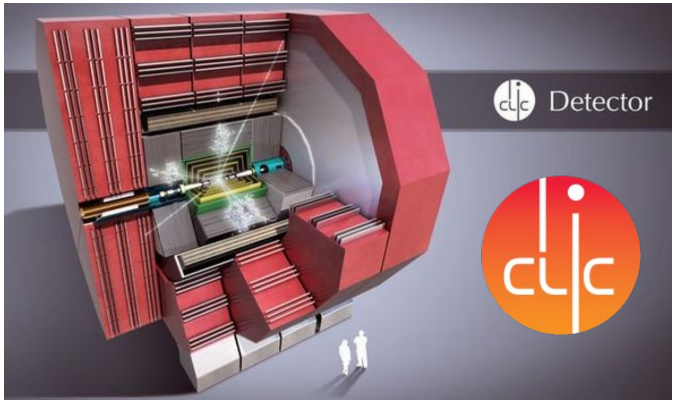


- DD4hep: generic detector geometry implementation framework supporting the full life cycle of the experiment
  - Conceptualization, optimization, construction and operations
- Whole detector description from a single source of information
  - Geometry, materials, readout, alignment, calibration, …
  - Accessible from simulation, visualization, reconstruction and analysis
- Now a **community standard:** CMS, LHCb, EIC, Future Colliders, …
- Convenient factorization enables the plug and play approach
  - C++ for generic geometry structure construction
  - Very simple XML configuration for detector specific implementations

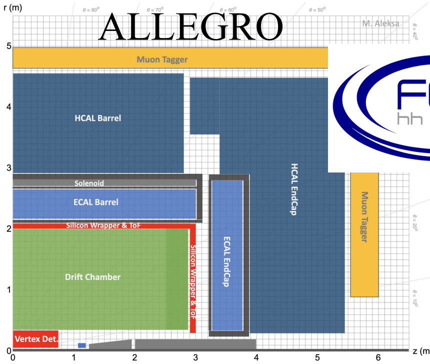
The Detector Zoo



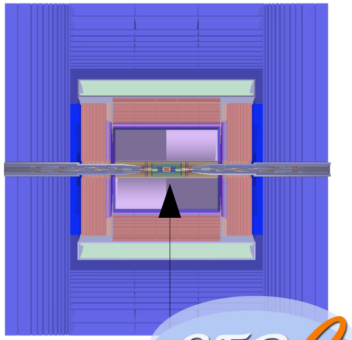




ALLEGRO

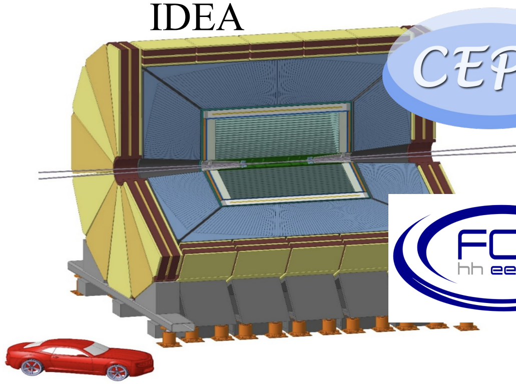


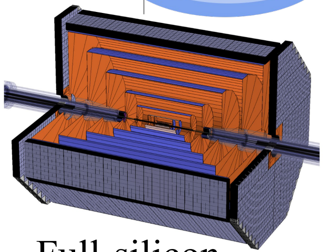
CRD's



ILD like

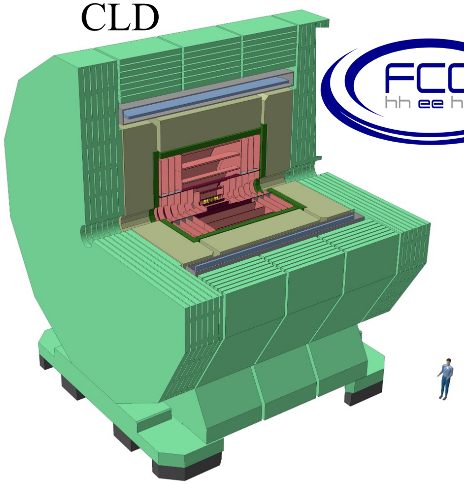
IDEA

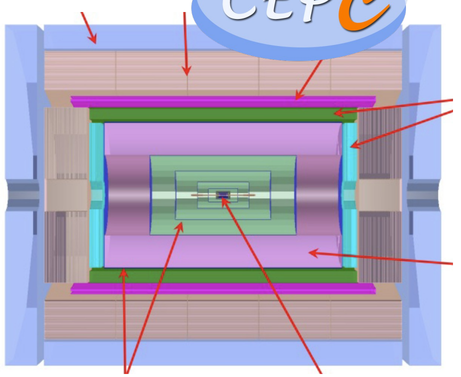




Full-silicon

CLD



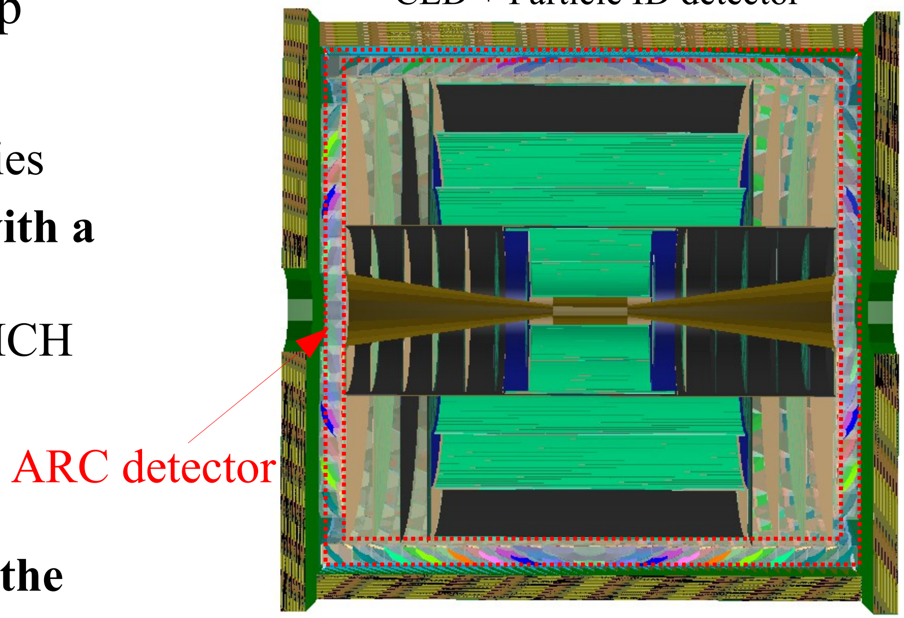


4th CEPC concept

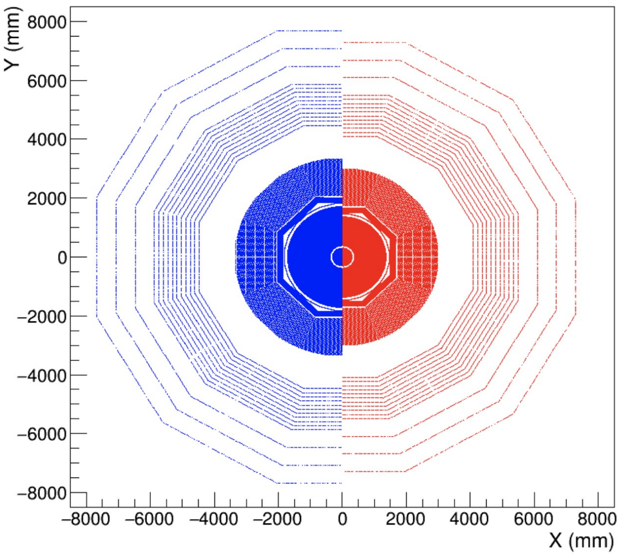
DD4hep Flexibility

- Further illustrations of the benefits from the DD4hep flexibility or 'plug-and-play' approach
  - CLD baseline has limited Particle ID (PID) capabilities
    - Very recently implemented an option of **CLD with a dedicated PID detector**
    - Shrink CLD tracker and squeeze the Array of RICH Cells (ARC) detector in front of the ECAL
      - It took only a few days! (excluding the implementation of the ARC itself)
    - Will allow us to **evaluate the gain on PID and the loss on tracking/Particle Flow performance**
  - ILD cost-performance optimization
    - Cost drivers: ECAL and coil/yoke system
    - "Small" ILD version with reduced TPC radius → smaller ECAL and coil
      - Allows us to put the performance loss in perspective with the cost reduction
      - Similar tracker size as CLICdet → also provides a comparison between full silicon and TPC

CLD + Particle ID detector



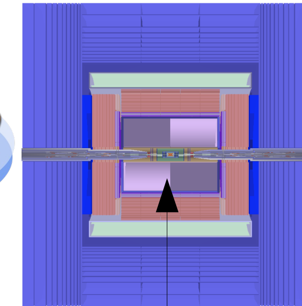
Large and Small versions of ILD

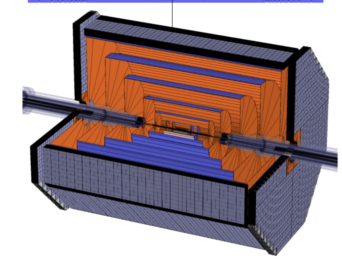


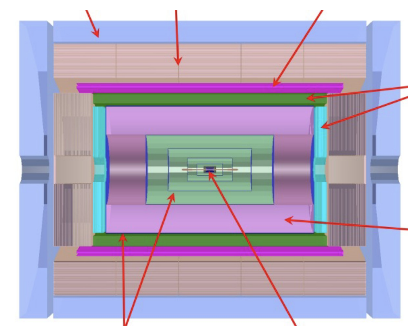
Highlights from the various Higgs Factories

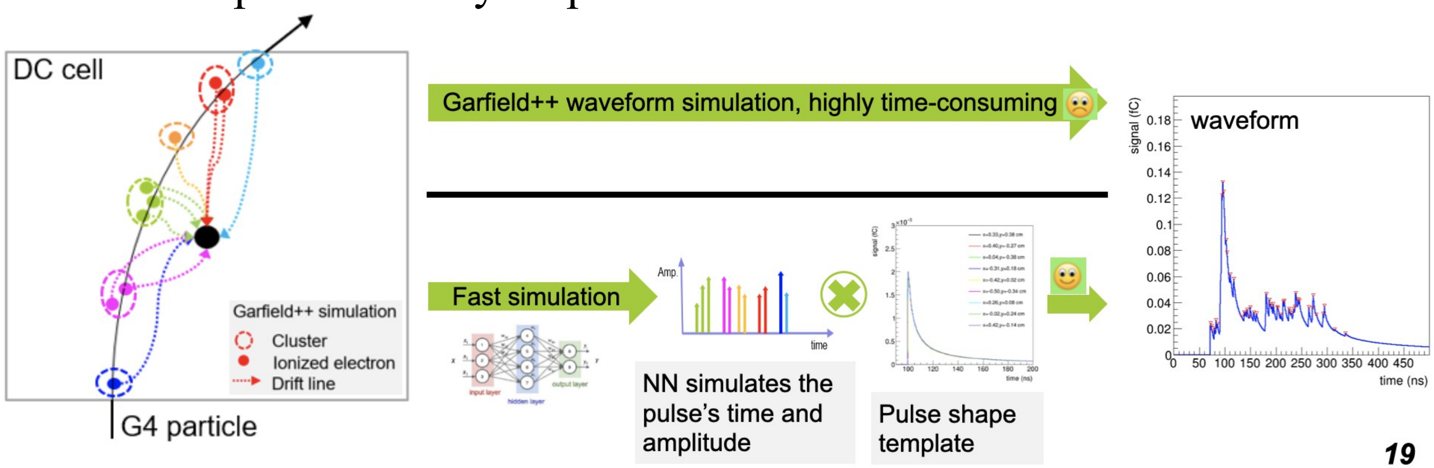
Highlights from CEPC

- 2 IPs, 4 detector concepts under development/optimization
  - The 3 CEPC Reference Detectors (CRD) are implemented in DD4hep, available in CEPCSW, part of Key4hep (+ IDEA)
- Complete simulation chain already available, currently **migrating** the Geant4 interface **to Gaussino** (LHCb): how to build
  - Better support for multi-threading, machine learning, fast simulation
  - Three-step plan: use it with LHCb dependencies, remove them and then migrate to the Key4hep version when available
- Drift chamber simulation
  - Cluster counting: Geant4 / Heed / Garfield++ → waveform (slow)
  - Used to train a ML-based 'fast' derivation of the waveform
  - Will be ported to Key4hep



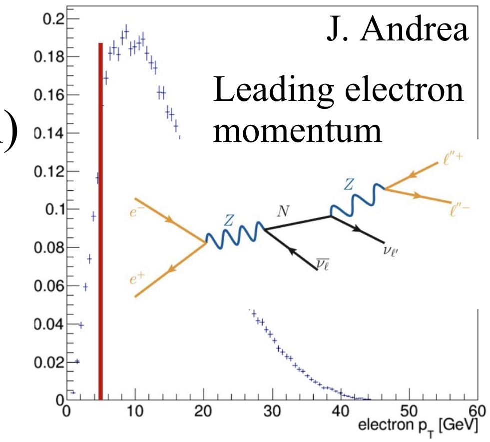


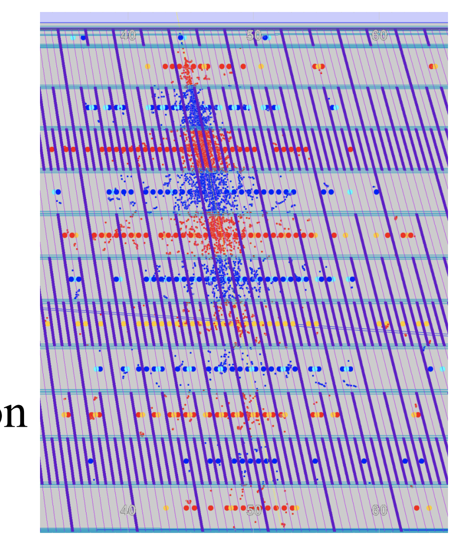




Highlights from FCC-ee

- 4 IP (baseline), 3 detector concepts (so far) under development/optimization
  - Detailed **beampipe**: **CAD drawing imported in DD4hep**, PR opened
    - Luminosity measurement studies starting
  - **CLD**: **fully available** in Key4hep (DD4hep, ddsim, ILCSoft reconstruction)
    - **First Full Sim physics analysis (HNL) starting!**
  - **IDEA**: many components were developed in standalone Geant4
    - Whole detector **being implemented in DD4hep/Key4hep**
    - Most sub-detectors are at the digitization/reconstruction step
  - **ALLEGRO**: new concept based on IDEA with different calorimeters
    - Started right away with Key4hep in mind
    - **ECAL and HCAL available**, will adapt the other IDEA sub-detectors
- Efficient **calorimeter granularity optimization** strategy
  - Time consuming Geant4 simulation with 'atomic' granularity
  - Multiple readout granularities defined at digitization step, from one simulation
  - Now possible to have different cell size per longitudinal layer
- Detector geometries ported in k4geo (already hosting ILC and CLIC detectors)



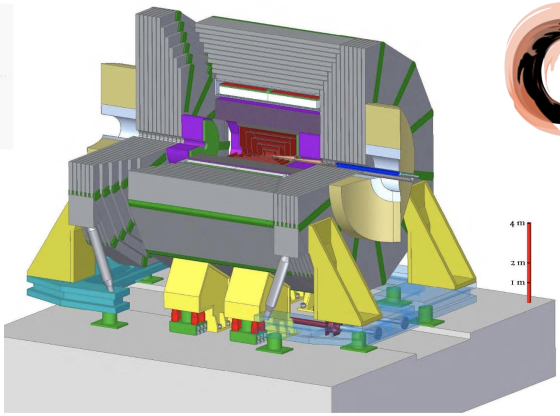


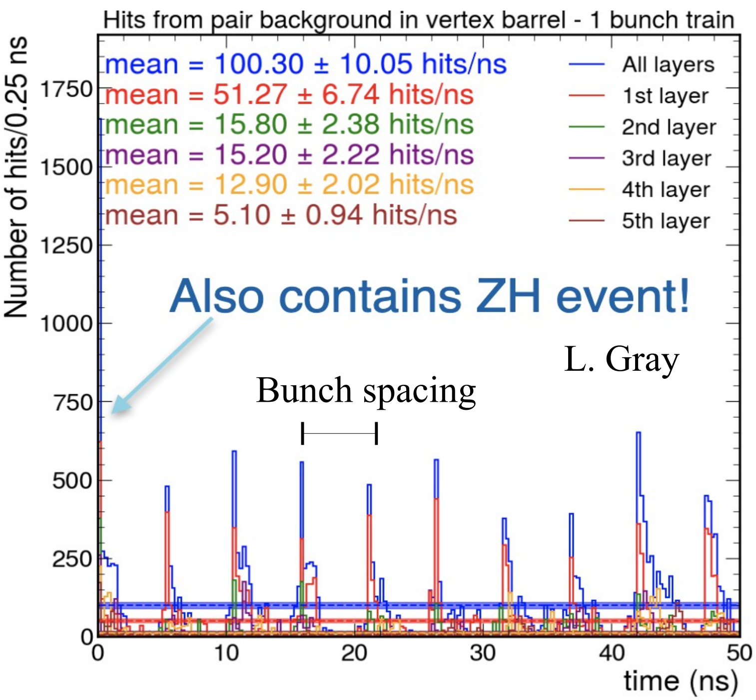
G. Marchiori

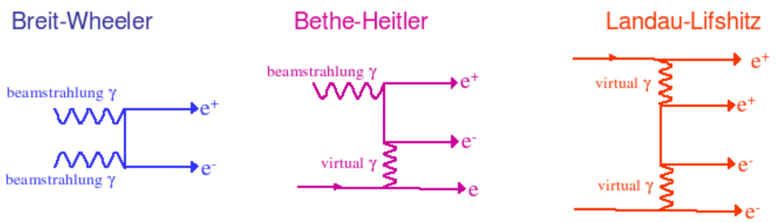
More details in Alvaro's talk

Highlights from C^3

- Recent effort gaining momentum fast!
- SiD (ILC) as a baseline detector
  - Will be re-optimized for the C^3 environment
- Main difference coming from bunch structure
- Focusing thus now on **background studies**
- Full bunch train $e^+ e^-$ pair production simulated with Guinea-Pig
  - Work ongoing to include hadron and muon backgrounds
- Z(μμ) H(all) + background overlay with ILCSoft wrappers
  - BeamCal backscattering from different BX's visible
  - Timing is consistent (BX every 5.25 ns)
  - Working on improving performances, retrieving 'past' BX's and randomizing the physics event position in the train
- Findings will be ported to Key4hep!



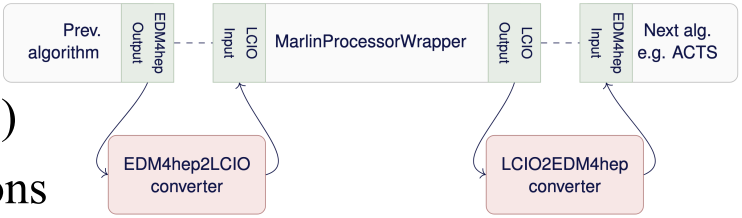




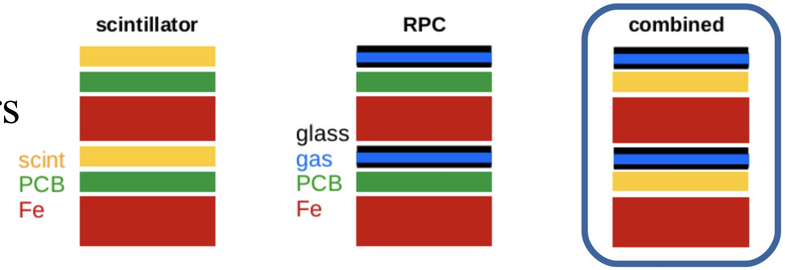
More details in Lindsey's talk and Dimitris' talk

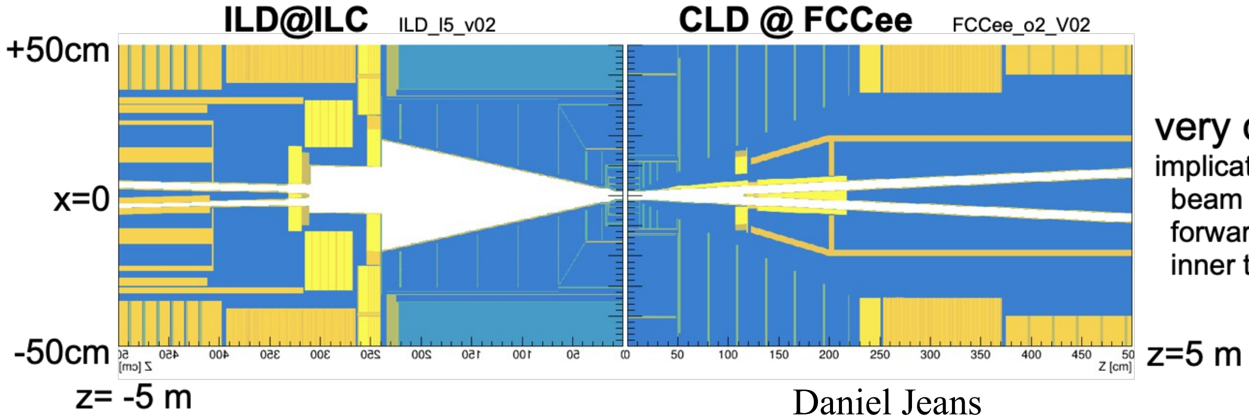
Highlights from ILC and CLIC

- Feature the most mature simulation studies (ILC TDR in 2013)
  - Influenced the design of central Key4hep components (DD4hep and edm4hep)
  - Simulation today: DD4hep, ddsim, MarlinProcessors
- Allowed Key4hep to profit from a pool of advanced simulation tools already in its early stages (MarlinWrappers + dataformat conversions)



- ILD can study **2 calorimeter** options with **one simulation**
  - Readout and active layers have similar thickness (mm and X_0)
  - Put both sensitive detectors (no readout), output two collections
- **ILD** being **adapted for circular colliders**!
  - Imported MDI from CLD, adapted CLD inner sub-detectors
  - Profit from common code (return on investment)





Daniel Jeans

very different MDI
implications for
beam pipe,
forward calorimetry,
inner tracking

Closing Thoughts

Why to invest in interoperability?

- Key4hep provides the simulation toolbox + guidelines to maximize interoperability
  - They are not “ready solutions guaranteeing full inter-operability”
  - The different facilities have to put efforts in their own implementations to ensure it
  - And provide documentation
- The main difficulty for this endeavor: why should “my facility” invest in this extra effort given the already limited manpower?
  - The big picture answer
    - Better usage of global resources
    - For the benefit of HEP, as a field driven by a common interest
    - Too philosophical?
  - The pragmatic answers
    - Generalizing software usually comes with a better code organization
    - Long term projects: your software will be used for many years, by many generation of physicist working on different detector versions → flexibility and documentation will pay off for your facility as well!

What is ahead of us?

- A lot of work has been done, but we still have a lot to do (applies more to some facilities than others)
  - **Validation** and fine tuning of the Full Sim with **test beam data**
    - Gain confidence in our models
  - Comprehensive detector **optimization**
    - Comparing detector concepts based on a few performance metrics is not enough
      - How do they combine together?
    - Optimization should ideally use a set of 'reference physics analyses benchmarks'
      - What improves some analyses may harm others
    - Performing all the Full Sim benchmark analyses for each detector options is unrealistic
      - Full and Parametrize simulation should keep playing together
    - Defining 'reference analyses' is a difficult exercise
      - Everyone has its favorite measurement/BSM search
  - …

Conclusions

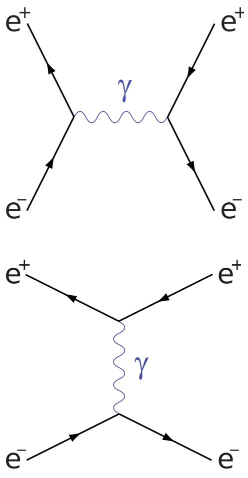
- The Future Collider community adoption of a common software development strategy/ecosystem (Key4hep) is important and growing
- The interoperability, enabled by the usage of a common framework, already paid back in many regards
- The Future Higgs Factories have implemented 10's of detector concepts, and much more sub-detectors
  - This will help us to find optimal detector solutions for the facility(ies) which will become a reality
  - And it will in turn maximize the physics we will make out of it

Thank you!

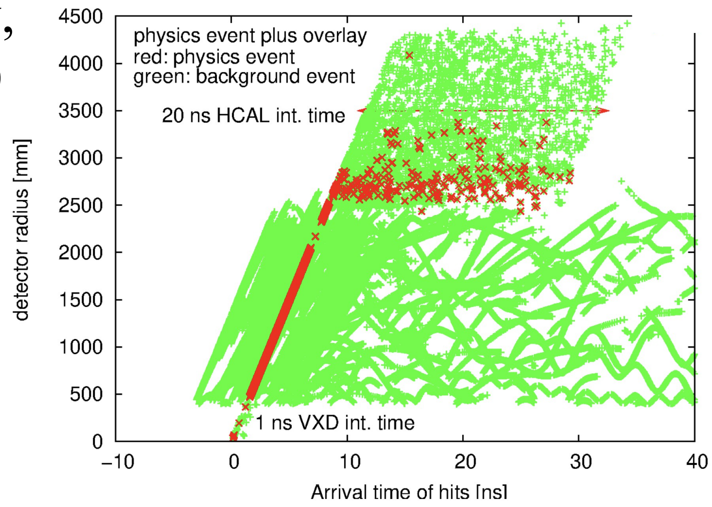
Additional material

Background Overlay

- In real experimental conditions, there is more than the hard process
  - Pair production, Bhabha scattering, synchrotron radiation, beam losses, …
- All facilities must assess the **impact of background on detector performance**
- Not practical to simulate the complete background for each physics event
  - Large CPU consumption
  - Bounds simulation to accelerator parameters
- The solution: simulate background contribution separately, overlay before digitization (reconstruction for some cases)
  - Tools available from ILCSoft: OverlayTimingGeneric
    - DD4hep compliant, need 'slcio' files
  - Work started to port it as Key4hep 'native' tool (k4Overlay)
- Machinery to handle this in Grid submission available through ILCDirac

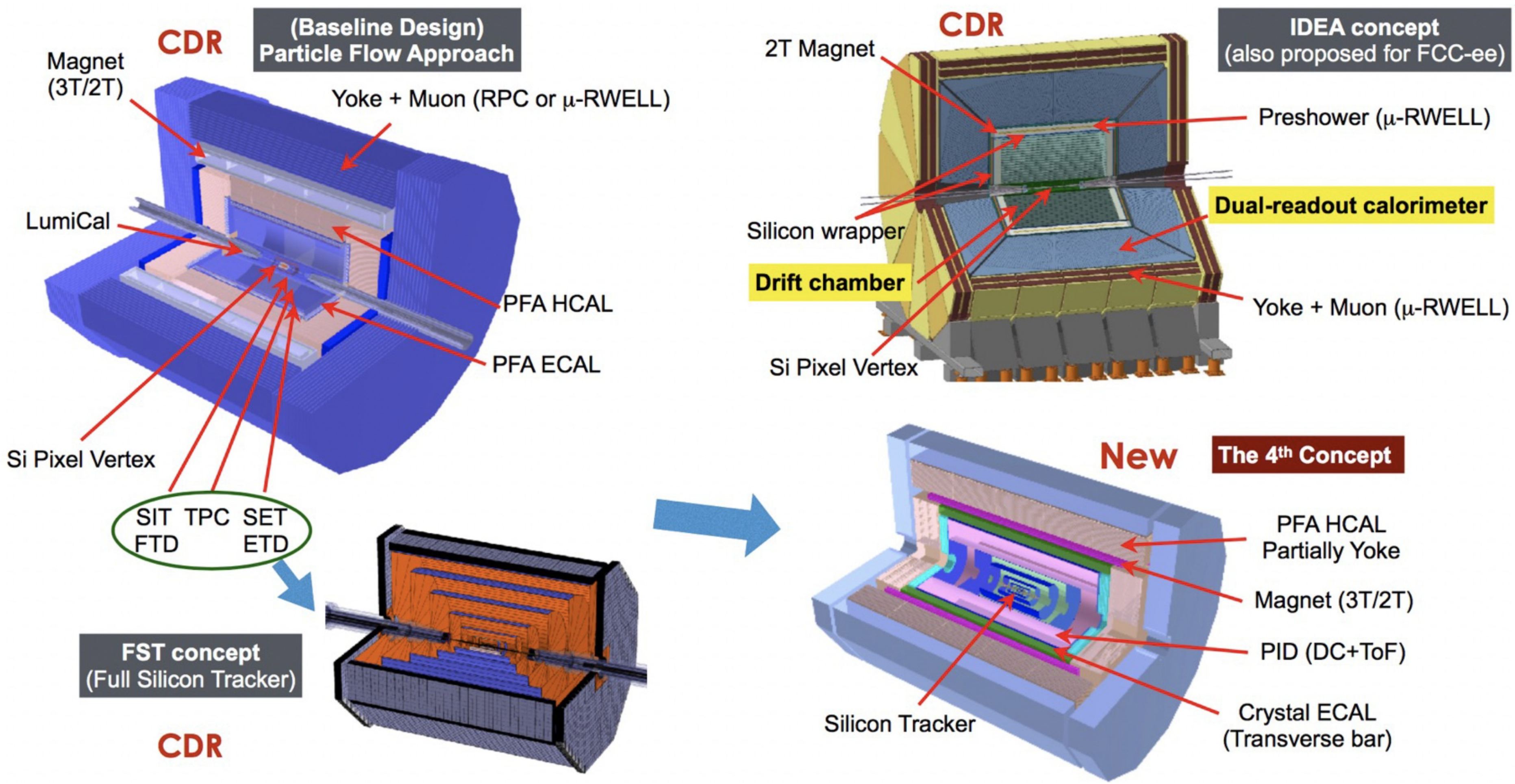


CLIC



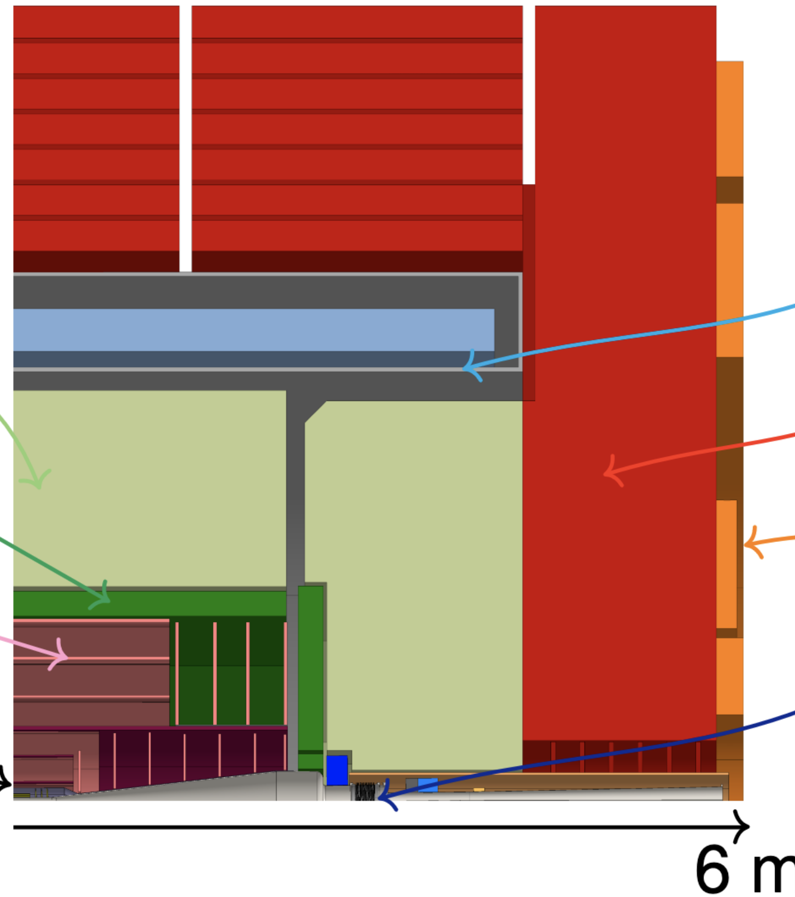
A. Sailer

CEPC Detectors



CLIC Detector

- Steel–Scintillator HCal with 3 cm cell-size
- Silicon–Tungsten ECal with 5 mm cell-size
- Silicon Tracker, mostly 50 μm pitch strips
- Vertex Detector with 25 μm pixels

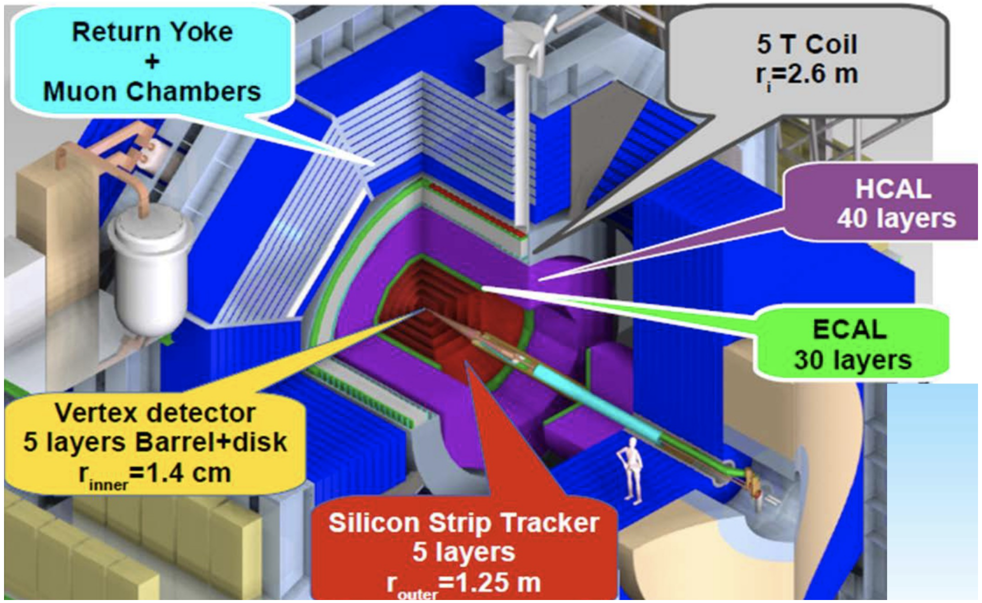


- Superconducting Solenoid of 4 T
- Iron Yoke with RPCs for Muon ID
- End-coils
- Forward calorimeters for EM coverage down to 10 mrad

ILC Detectors

Scintillator strips, WLS, SiPM

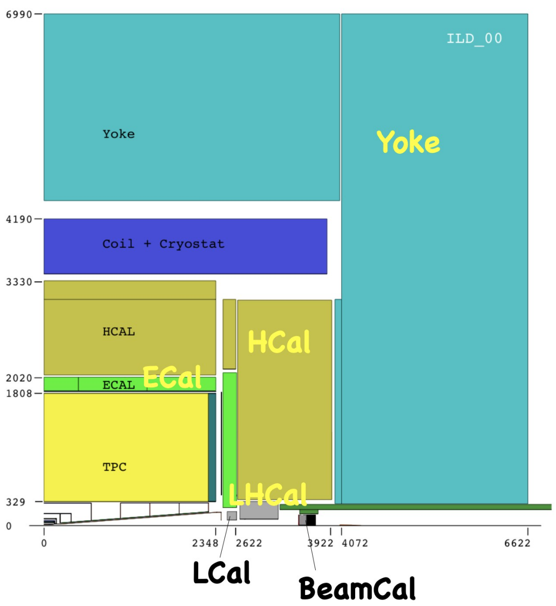
SiD



Scintillator
SiPM Steel

SiW

ILD



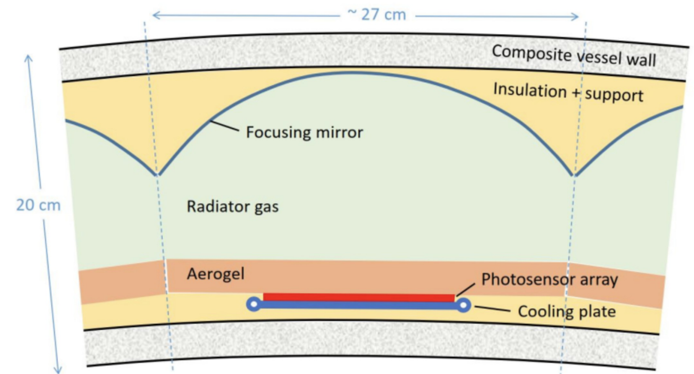
- ECal – options:
  - SiW: 0.5cm*0.5cm cells
  - SciW: 0.5cm*4.5cm tiles
- HCal – options
  - analogue: FeSci: 3cm*3cm tiles
  - semi-digital: Fe-RPC: 1cm*1cm cells
- Yoke: muon system
  - Fe-RPCs 1cm*1cm cells
- forward calorimeters:
  - LumiCal: W-Si
  - BeamCal: W-GaAs
  - LHCal: W-Si

Simulation Toolbox

- Geant4 remains the favorite tool to model the passage of particles through matter
- Key4hep hosts convenient interfaces to interact with Geant4
  - ddsim (ILC, from DD4hep)
  - k4SimGeant4 (FCCSW, Gaudi algorithm/tools)
  - DetSimAlg (CEPCSW, Gaudi algorithm/tools)
  - What is available?
    - Shipping of the detector geometry, sensitive actions, physics lists, …
    - Magnetic fields: homogeneous, from known geometries (e.g. solenoid) or by providing a full field map (e.g. to study field non uniformities)
    - Vertex position and smearing
    - Lorentz boost due to crossing angle
- What would we need more?
  - Beam energy spread should be done at the MC generator level
  - Crossing angle smearing?

PID Detectors

- Detector layouts are not frozen!
  - Exploring further sub-detector technologies
- Particle ID detectors can complement/replace dE/dx or dN/dx
  - Technology more mature then at the LEP time (DELPHI)
    - LHCb RICH
    - Less complex, lower material budget (target 5% X_0)
- Accurate and comprehensive estimation of what it brings needs Full Sim
  - Photon yield/collection, additional material budget
  - Quite difficult to implement
- Array of RICH Cells (ARC) implemented in DD4hep
- Readout available, reconstruction has started



ARC detector (one cell)