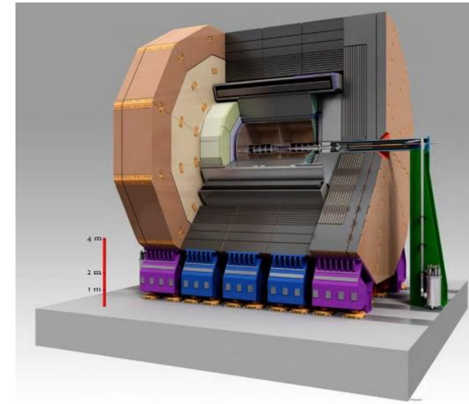
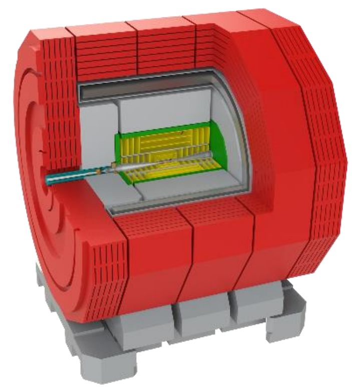
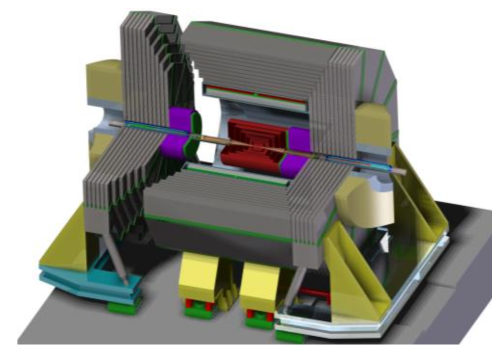
Ugrading and Updating Detector Concepts at linear colliders







With some bias towards ILD

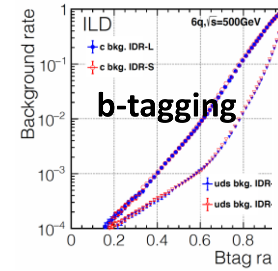
Ties Behnke

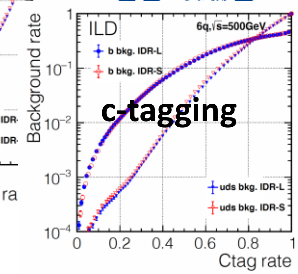
9.1.2025

For the ILD group, SiD group, CLICdp group

Driver: Precision

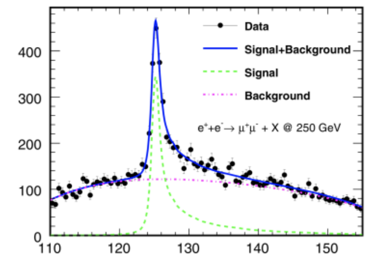
Slide heavily borrowed from Tomohiko Tanabe's 2020 ICHEP talk





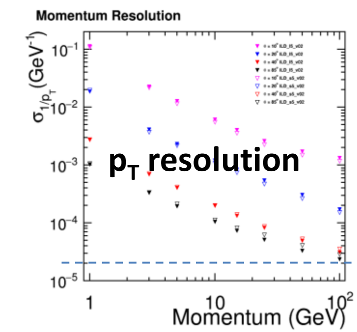
Detector Requirements ⟷ **Physics Studies**

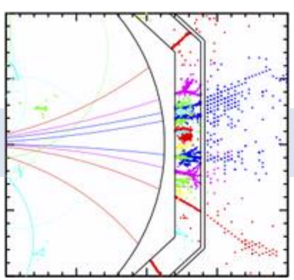
Detector Requirements		Physics Studies
• Impact parameter resolution $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)$ μm	~ LHC / 2	$H \rightarrow bb, cc, \tau\tau$
• Transverse momentum resolution $\sigma(1/p_T) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_T \sin^{1/2}\theta)$	~ LHC / 10	Total $\sigma(e+e- \rightarrow ZH)$
• Jet energy resolution 3-4% (around E_{jet} ~100 GeV)	~ LHC / 2	$Z/W/H \rightarrow jj$; $H \rightarrow$ invisible
• Hermeticity θ_{min} = 5 mrad	~ LHC / 3	$H \rightarrow$ invisible; BSM



Higgs recoil against $Z \rightarrow \mu\mu$

arXiv:2003.01116

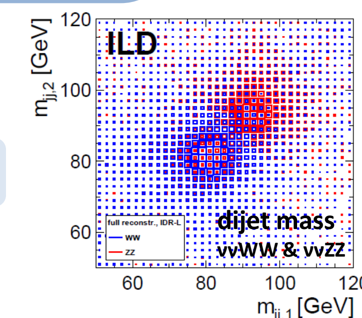


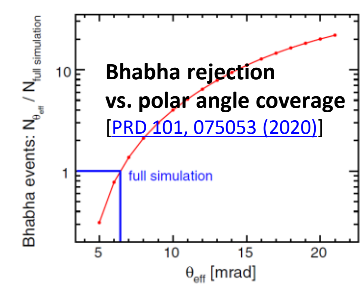


LC Concepts are optimized around **particle flow**:

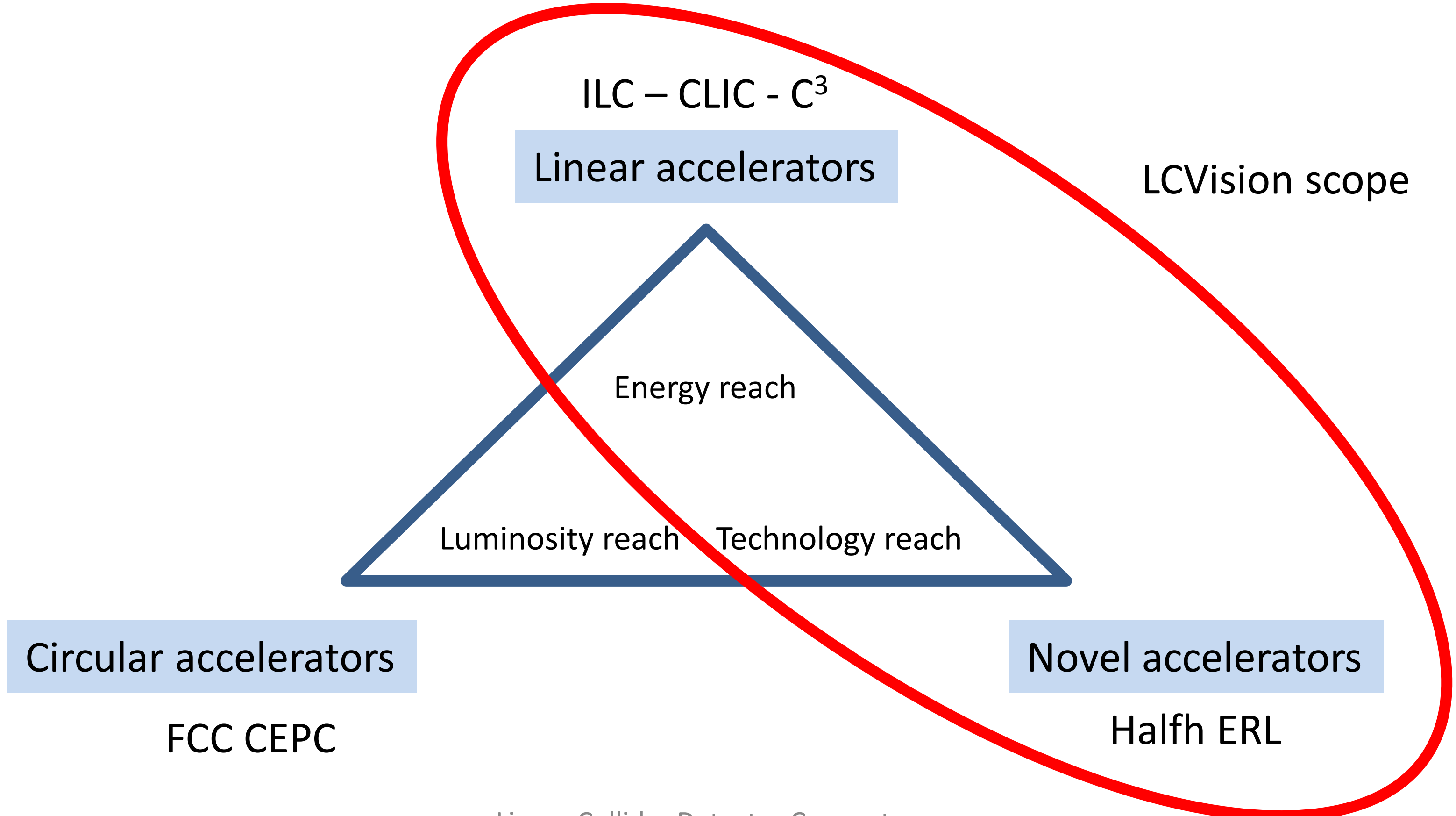
- Highly granular calorimeters
- Low-mass trackers
- Highly detailed software reconstruction

→ Separation of clusters at particle level

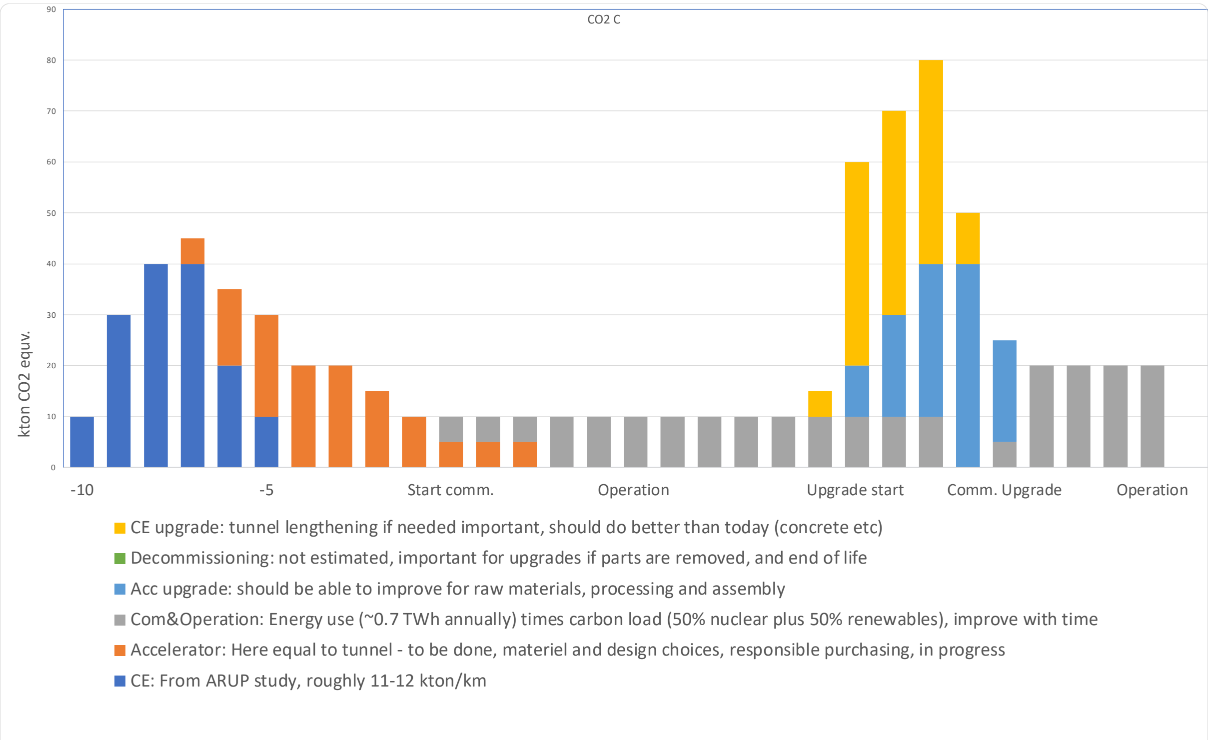




Driver: The Boundary Condition

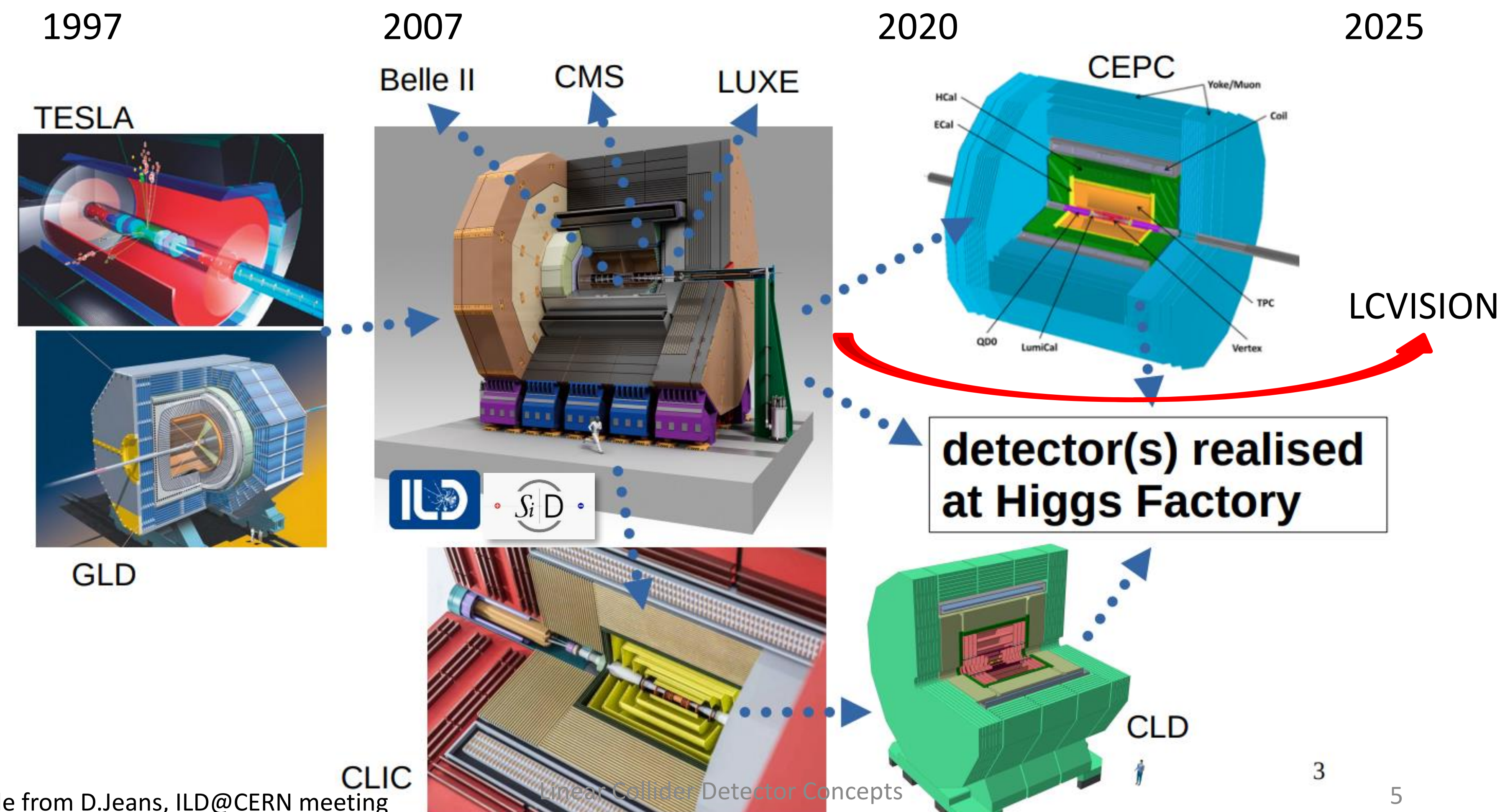


Driver: The Footprint



- Environmental impact of our projects
- Politically this is rapidly gaining importance
- This will need to be part of discussions of any project we consider in the future

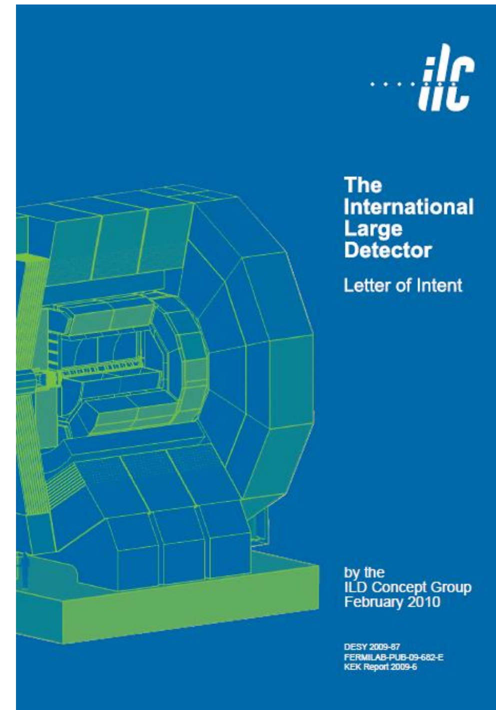
The LC Anchestry



Slide from D.Jeans, ILD@CERN meeting

The Development of the concepts

- ILC concepts: first phase developed until 2012, including down-select (LOI process) to SiD and ILD
- Part of the ILC TDR in 2013
- Continuous (funding limited) development since
- CLIC concept spins off from ILC concepts
- New collider concepts (C^3, HALHF) base on existing detector concepts
- The rise of circular options re-invigorated the concept discussions (somewhat)



The Collaboration

Following ILC TDR, concepts moved towards proto-collaborations.

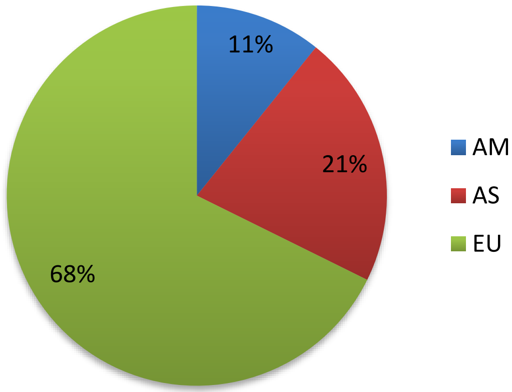
ILD example: Result of recent membership confirmation:

- 58 institutes confirmed ILD membership
- Around 10 institutes as guests members

ILD as a group got started in 2008
(first ILD workshop in DESY Zeuthen 2008)

ILD's main objective is to develop the best possible experiment for a Higgs/ Electroweak and beyond facility

institutes per region



ILD around the world

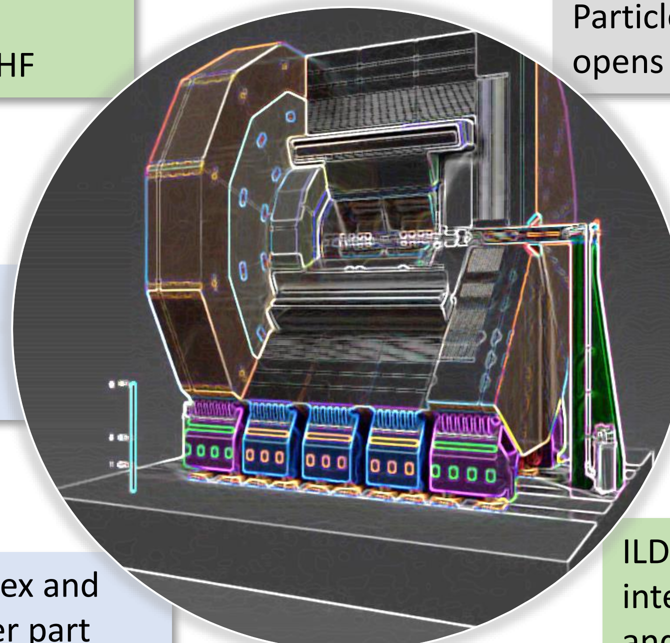
Memberships od Russian groups is currently suspended

ILD: fundamental choices

very similar arguments for SiD and CLICdp

Particle flow is the central paradigm to optimally reconstruct events at a HF

Particle ID in particular at the lower energies opens the route to an excellent flavor program



A gaseous central tracker ensures high efficiency high resolution tracking

A highly granular sampling calorimeter inside the coil ensures excellent particle flow performance

A high precision low mass vertex and tracking system forms the inner part

ILD is designed to be easily moved from the interaction point to allow for fast maintenance and open the possibility of push-pull

ILD will run without trigger and with minimum external cooling

Subdetector Status

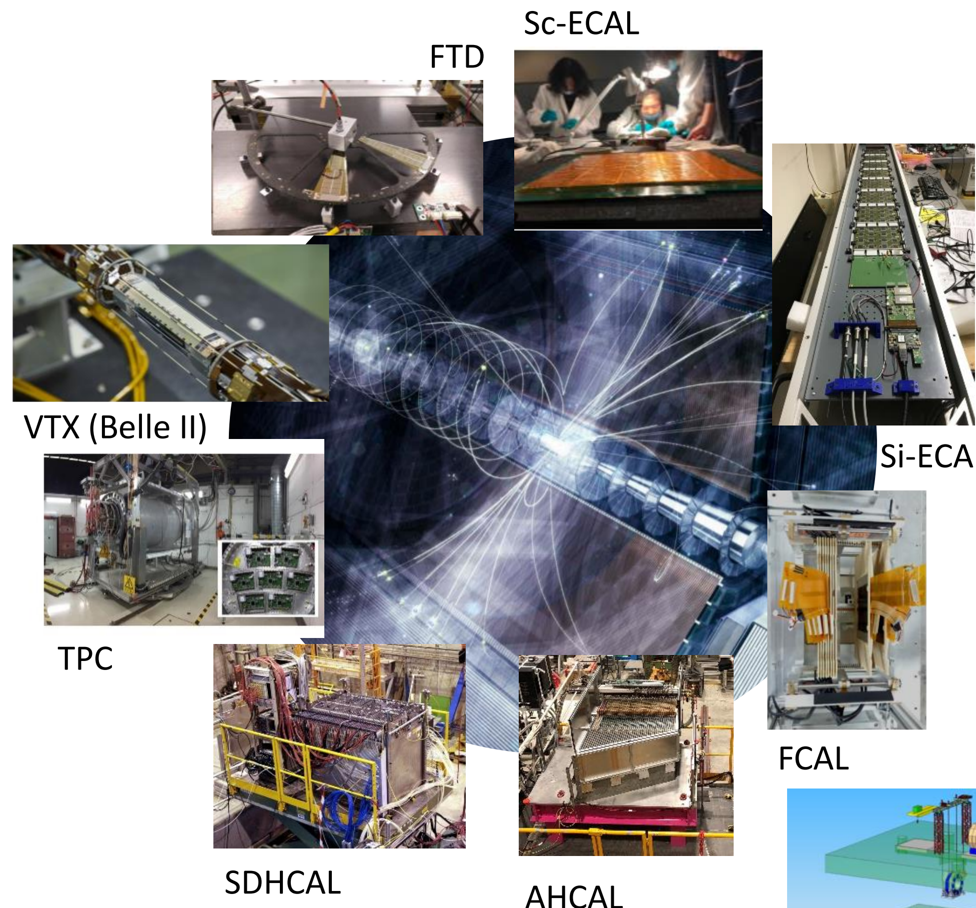
Taking ILD as an example

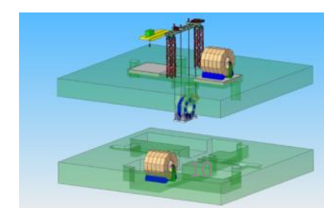
ILD has a concept of the detector,
well defined
with technological options where sensible

The main components of ILD
have been validated and
beam-tested.

A coherent System design has
been developed.

A complete and detailed
Geant4 model of ILD exists
and is used

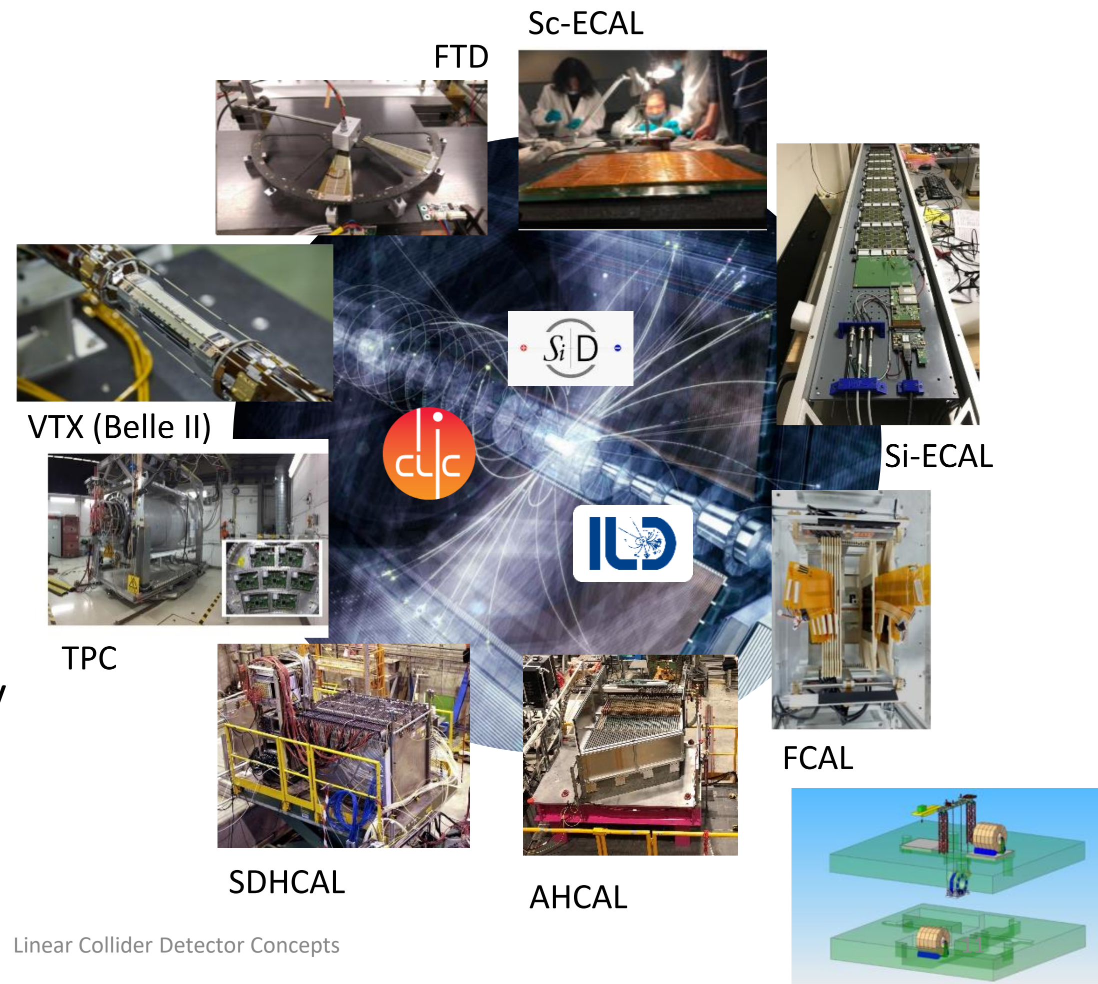




Technological Triggers

LC community has been a major technology driver

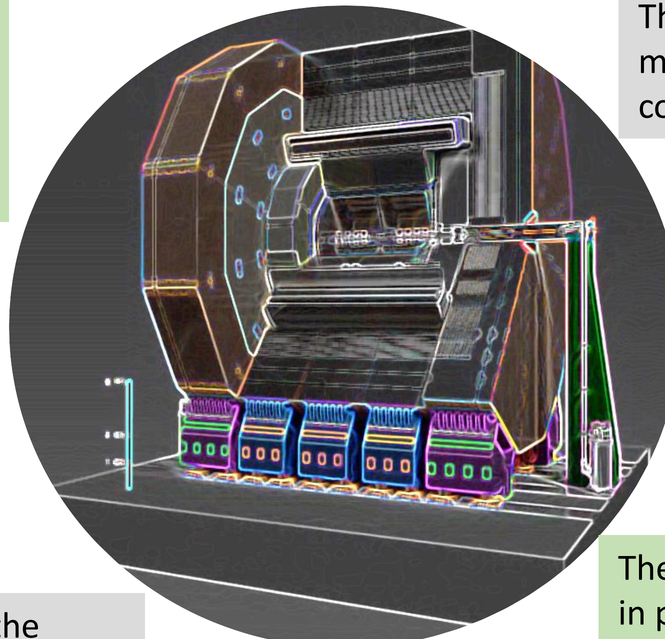
- MAPS VTX technology
- Micro-pattern TPC
- Silicon TPC
- Particle flow Calorimetry
- Silicon calorimetry
- Digital/ Semi-digital calorimetry
- Analogue Si-on-tile technology
- Triggerless running
- Software eco-system



ILD: a Range of Options

ILD has been conceived about 10 years ago It is now time to re-visit many of the choices and “modernize” ILD. There is no need to fundamentally change ILD

The well-known R&D collaborations are merging into the much larger DRD collaborations.

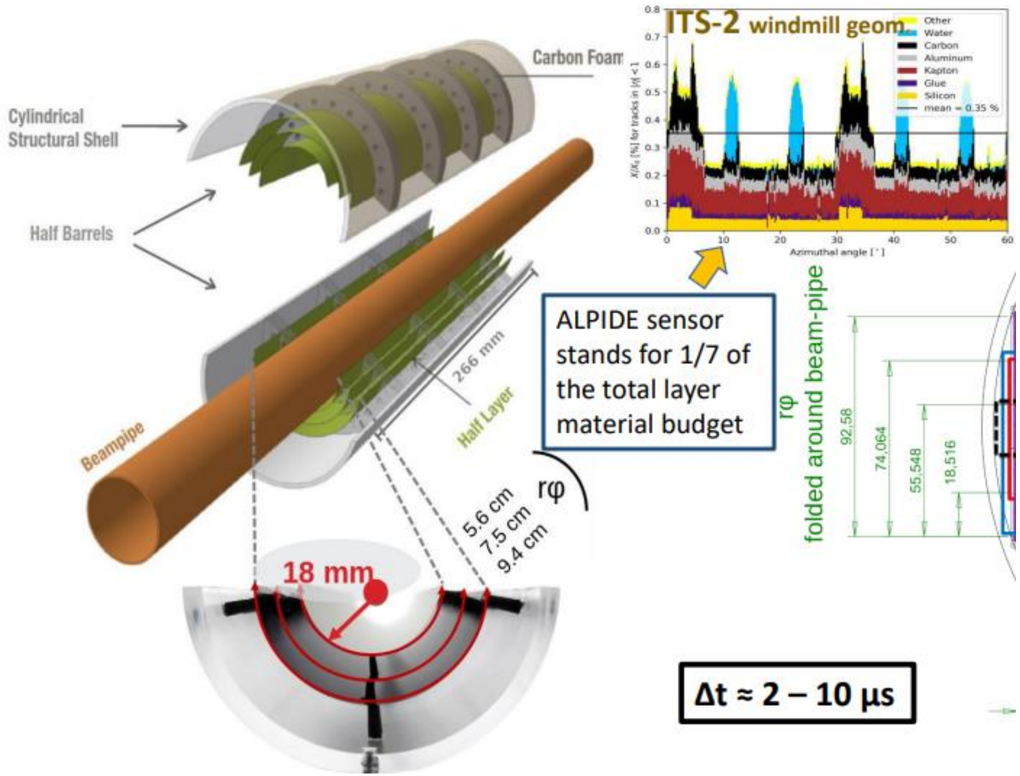


Is particle flow still the right paradigm for a detector at a Z or Higgs factory?

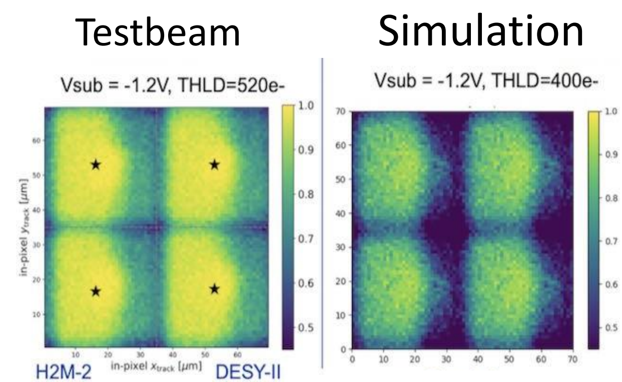
There has been tremendous progress in particular on semi conductor trackers: Significant upgrade of the trackers

The conditions in particular for the inner part of the detector are very different for different collider concepts

Vertex Technology



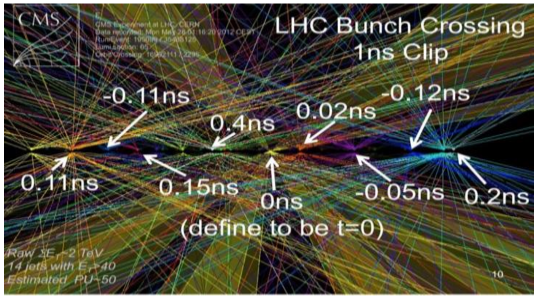
- Goal: ultra-thin fast sensors
- ALICE development:
    - Bent Silicon sensors
    - Unsupported
    - No active cooling
- Challenge: endcap development



65nm developments as a future route towards VTX detector

CERN-DESY-etc, DRD3

Timing: the missing dimension

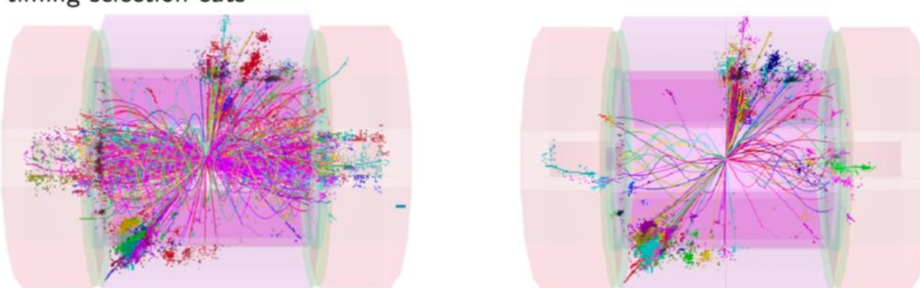


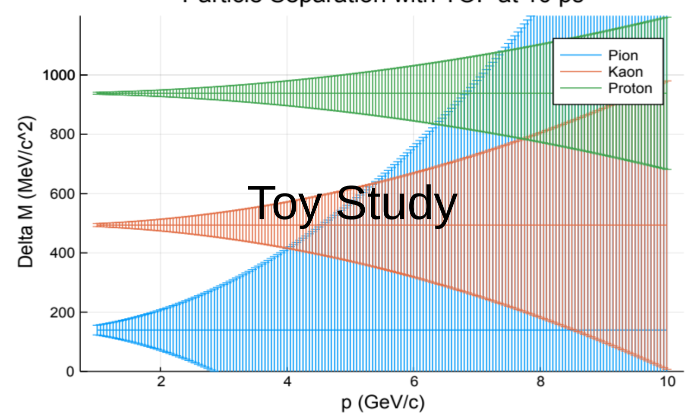
Timing in LC detectors

- Particle ID to supplement other technologies
- Timing layers for tracking
- Timing layers for particle ID

Example LHC: sub-ns timing needed for overlay reduction

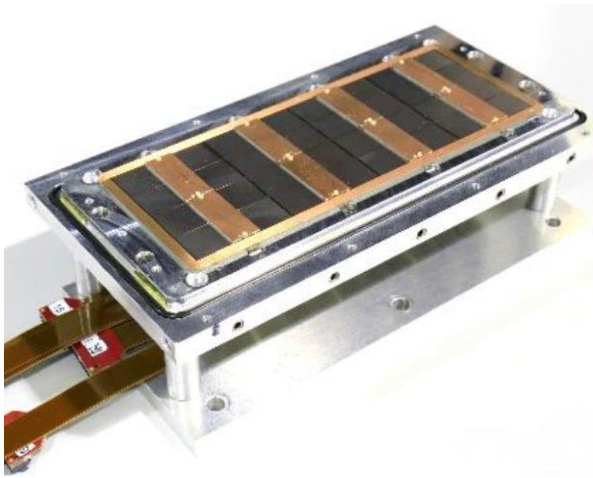
$e^-e^+ \to HH$ with $\gamma\gamma \to$ hadron background overlaid before and after *tight* timing selection cuts



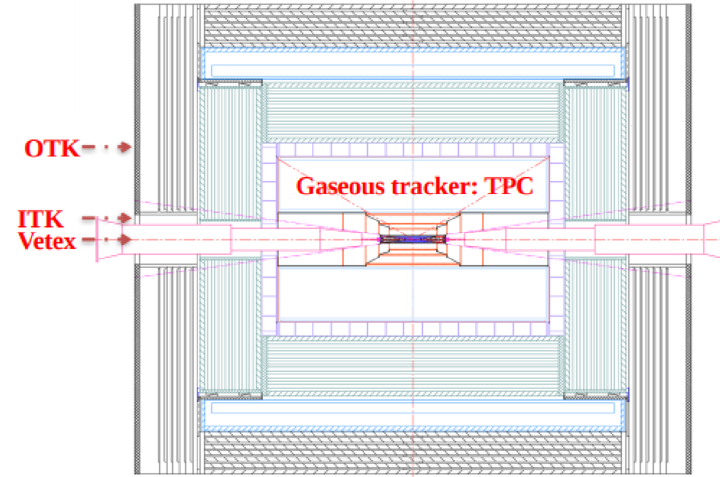


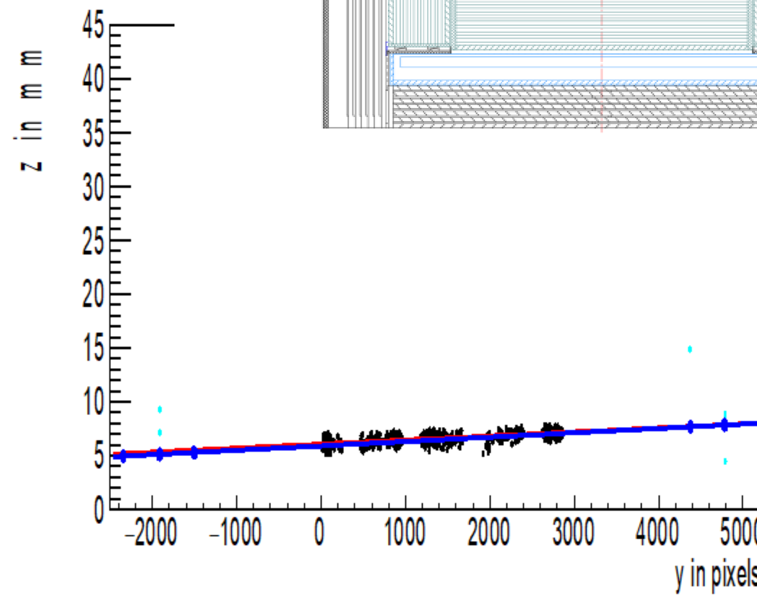
Pixel TPC

TPC: baseline option for ILD as the large volume central tracker
is this still a viable option?



Highly pixelated readout plane
Cluster counting possible
But relatively poor area coverage

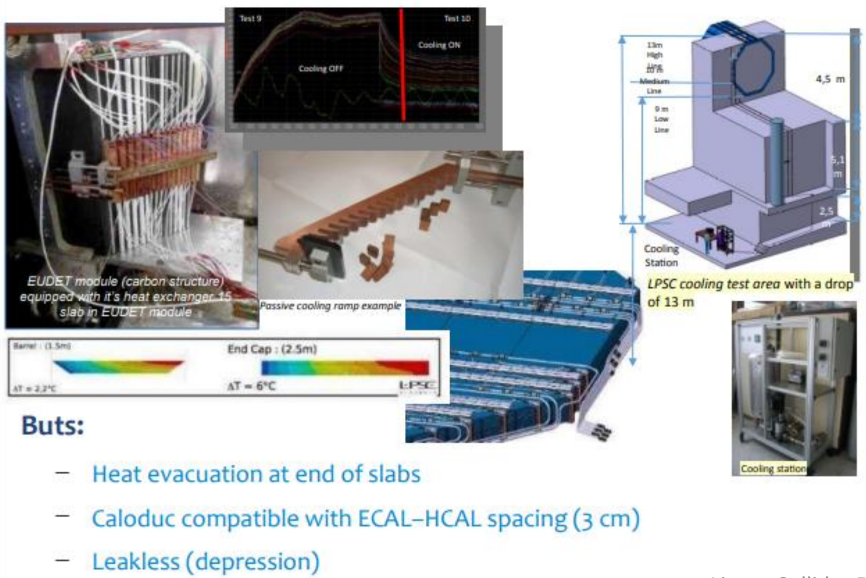


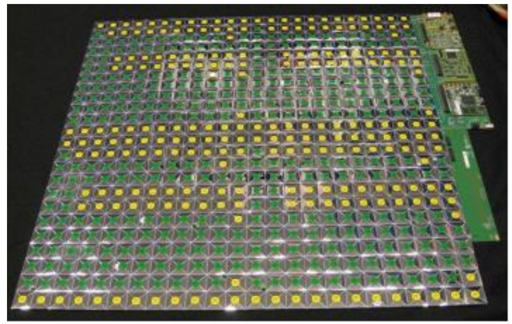


Example picture of a track recorded at DESY in the pixel TPC.

Calorimetry

- Have a well developed system for ILC-like environment
- Major proof-of-concept experiments through HL-LHC (e.g., CMS upgrade)
- Continuous development to continuously improve the system
- Explore impact of different collider options



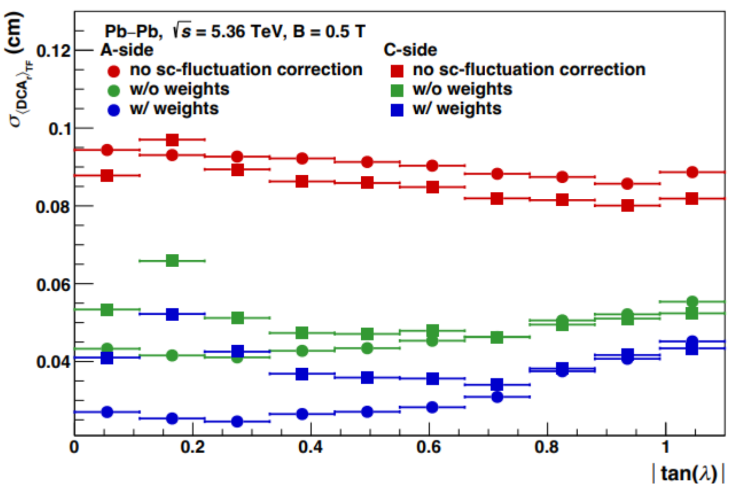


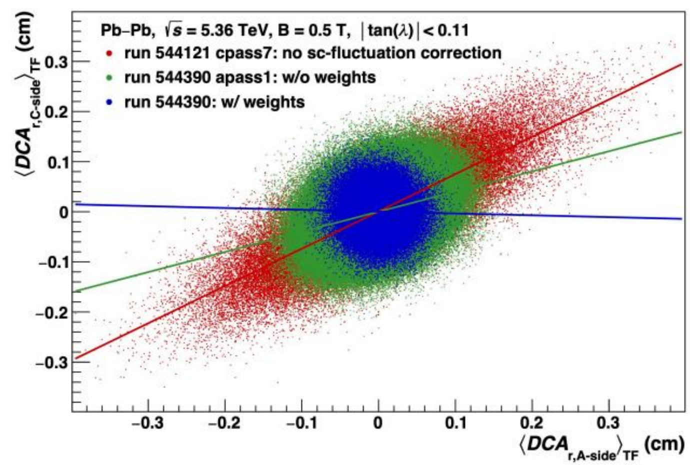
Base-board for HGCAL module
at CMS (based on ILD technology)

Ongoing R&D on a cooling system for the Si-W ECAL as one example of current key R&D

Calibration Concept

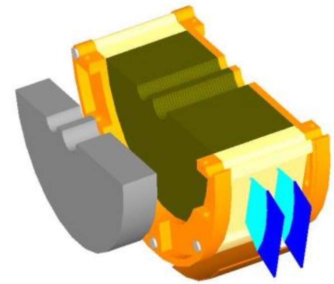
- In general we have not made progress in this area over the past few years
- High precision experiments require high precision alignement
  - Need to understand the limits
  - The combination of high backgrounds with extreme stability requirements is highly non-trivial

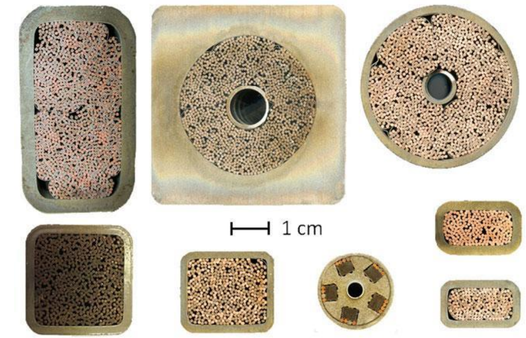




ALICE: example of calibration for TPC in high occupancy conditions

Not your traditional subdetector





Cable-in-Conduit Conductors

DAQ

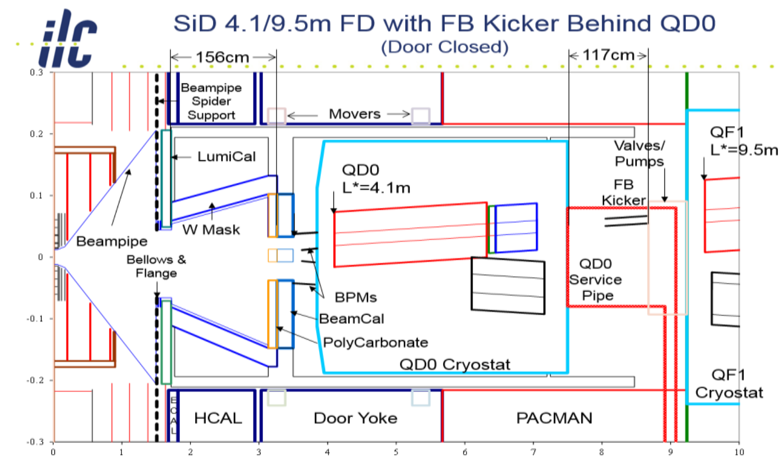
- With the “MAPSsification” the role of front-ends will change
- ASICS will most likely move to purely digital

Coil

- Looking into alternative conductors
- Implications for field, Cost … needs to be studied

MDI & CFS

- impact of siting on detector integration



Stolen from Marcel Stanitzki

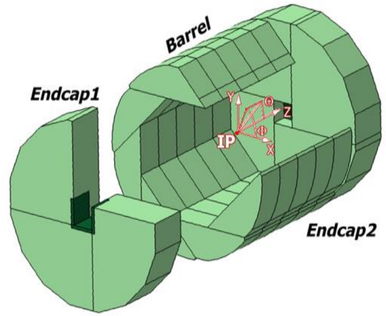
Reality

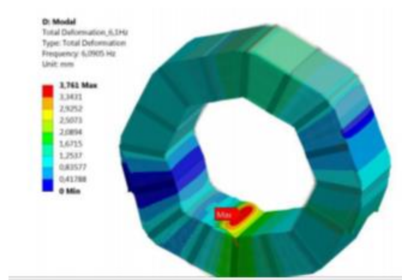
Prototyping

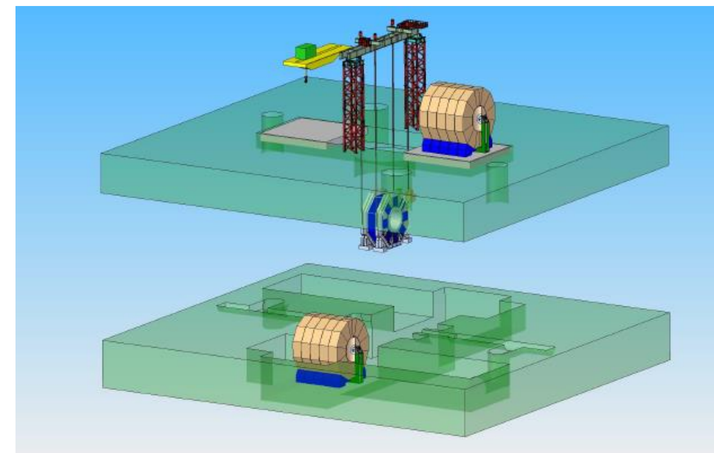
Engineering

Integration

Demonstrating



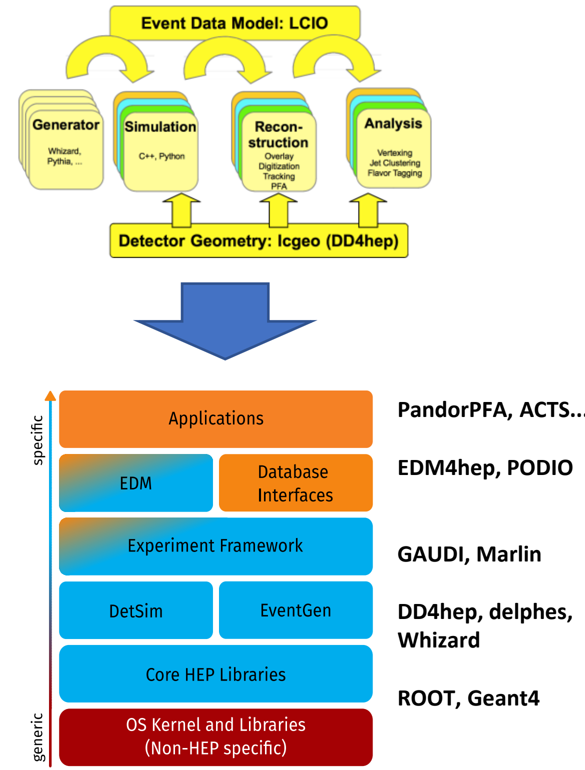




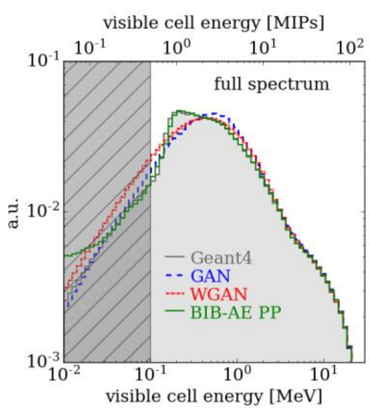
ILD and Software

ILD, with SiD and CLIC, has done a lot on the software and reconstruction side:

- We are a central player in pushing community wide software solutions in particular with **iLCSoft** (LCIO, DD4hep, etc) developed over 15 years
- We are deeply engaged already with communities (linear, circular, FCC-hh) to modernize our software stack: **key4hep** (DD4hep, EDM4hep,...)



There is enormous progress out there in the community on computing, computing models, computing implementations, analysis methods and tools:



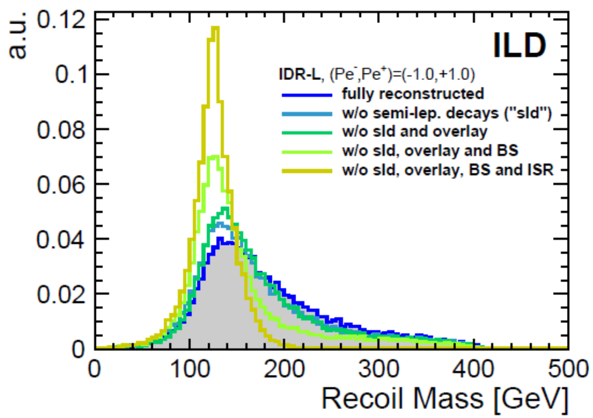
- parallelisation, multi-threading
- GPU based computing
- Machine Learning and AI
- Quantum computing

F. Gaede, E.Eren et al.: Use of GAN's to simulate photon showers in the ILD Calorimeter (2005.05334)

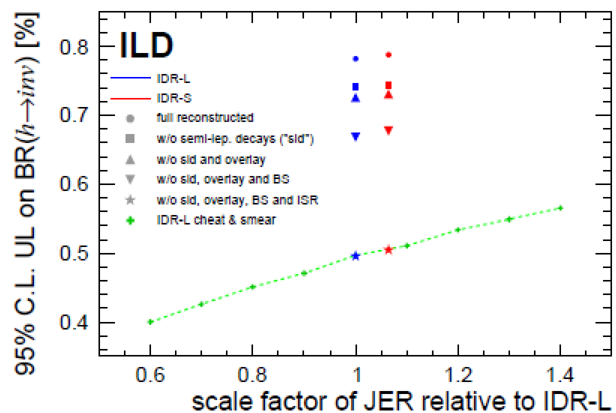
Physics

Continued strong effort on analysis in the ILD context;

- Nearly all analyses done in full simulation
- Very active role by ILD in intn'l processes like snowmass, LCC, now IDT
- Comprehensive list of projects:



Recoil mass spectrum (invisible Higgs search) for different reconstruction conditions



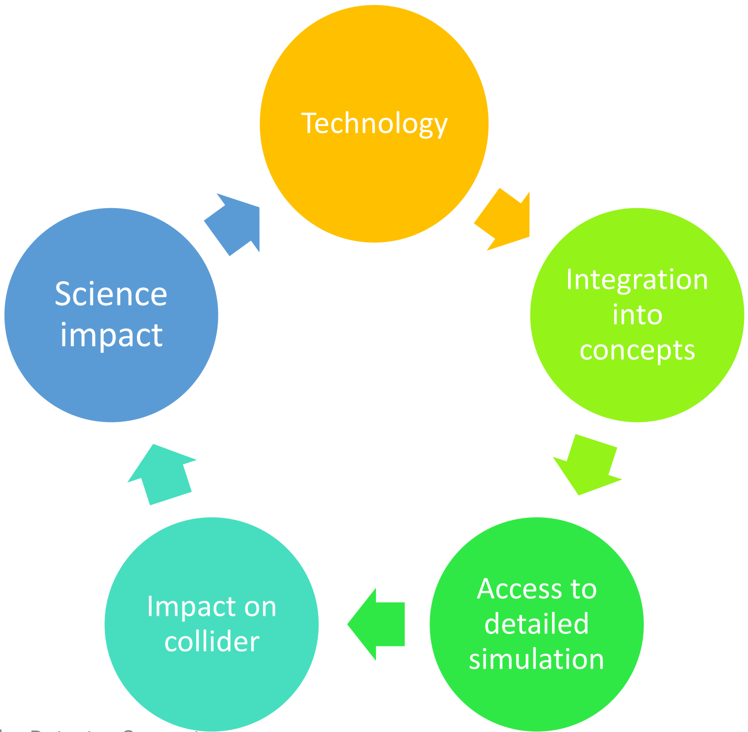
Impact of a detector indicator (JER resolution) on physics observable

This is just meant as a teaser and to demonstrate the power of a well developed platform like ILD

Future Opportunities

Well established concepts provide platforms for technology development

- Provide scientific guidance
- Provide means to check system aspects
- Put scientific questions into a realistic context
- Allow efficient interaction in the more global optimization loop



Summary/ Outlook

The linear collider based concepts have developed a range of highly developed particle-flow based detector concepts

These concepts are powerful platforms for technology, algorithm and science developments

We need to ensure as a community that we can maintain the effort in concepts for the coming years to come.

Many thanks to Aidan and Marcel for providing input
Apologies for the ILD bias