Grant PID2024-158190NB-C22 funded by

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Cofinanciado por la Unión Europea

AGENCIA ESTATAL DE INVESTIGACIÓN

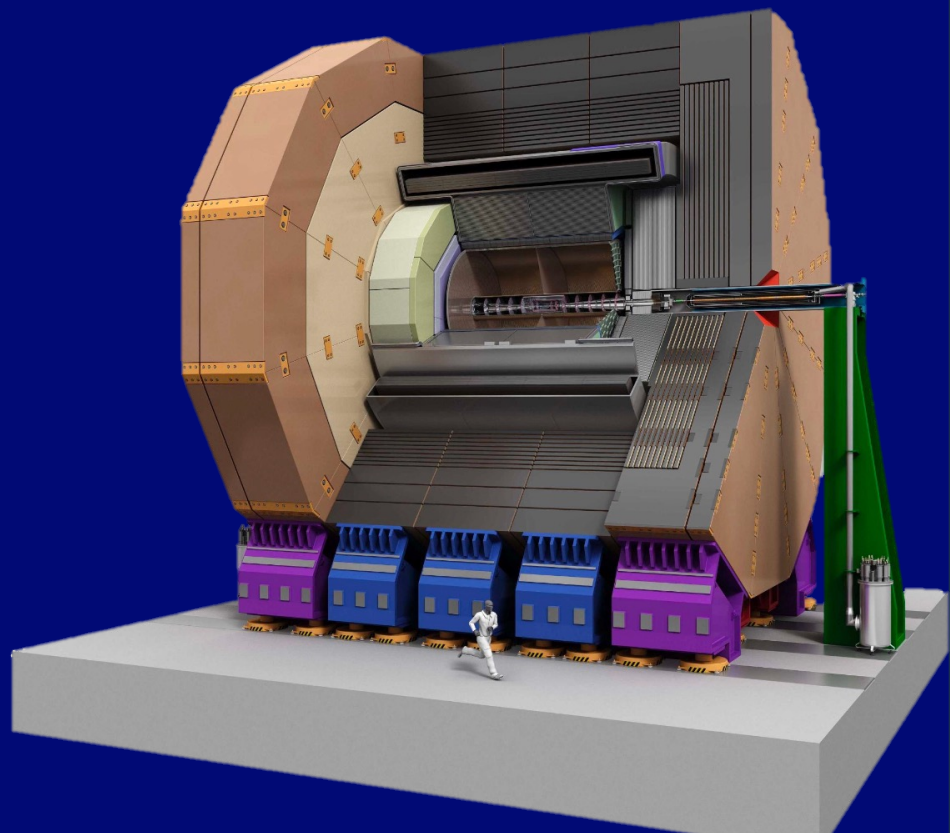
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

cfp CIEMAT física de partículas

ILD
International Large Detector

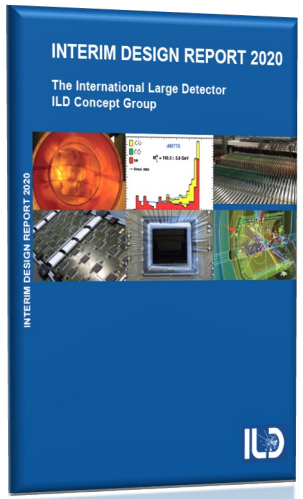
M.C Fouz
CIEMAT





The ILD Detector: A Versatile Detector for an Electron–Positron Collider at Energies up to 1 TeV

- ILD is a detector concept for e^+e^- colliders for precision physics from 90 GeV to ~1 TeV.
- ILD has been proposed both for linear and circular colliders, be it at CERN or elsewhere



https://doi.org/10.48550/arXiv.2003.01116

The concept was established more than 10 years ago in the context of the **ILC.**

(Part of the ILC TDR in 2013, ILD Interim Design Report (IDR) – 2020)

The design is now being revisited to adapt it to **FCC-ee** and take advantage of recent technological advances, particularly in silicon tracking and vertexing.

There is still room for improvement even beyond the **FCC-ee** additional requirements.

ILD remains open to innovation and continuous evolution

And it is open to new collaborators and to new ideas which can improve our detector including new technologies





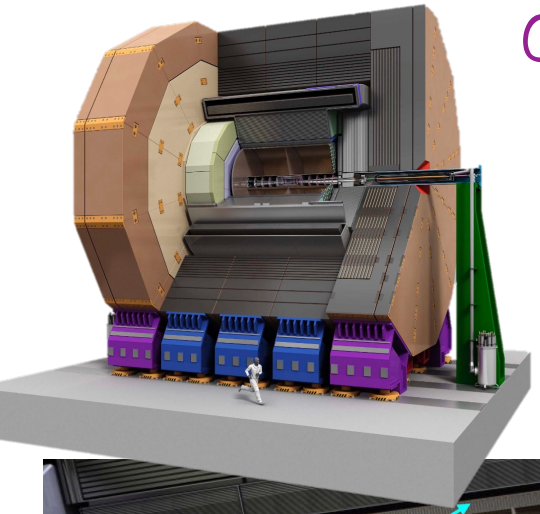
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The ILD group around the world



Memberships of Russian groups is currently suspended

The ILD "DNA" : Particle Flow

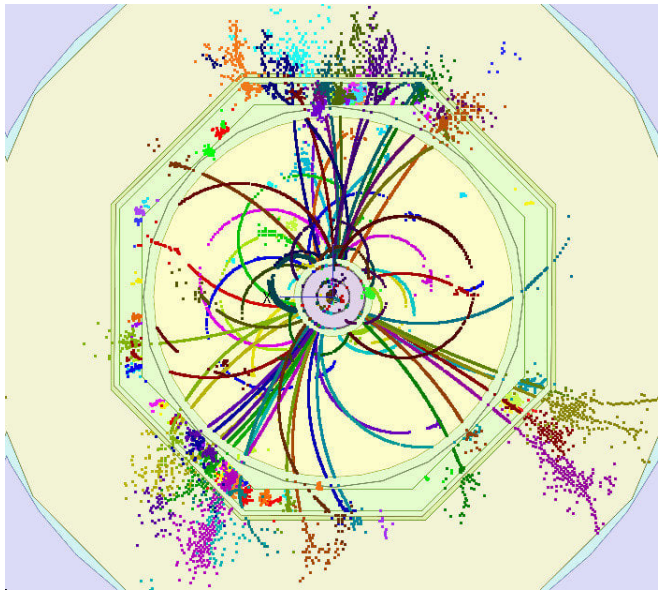


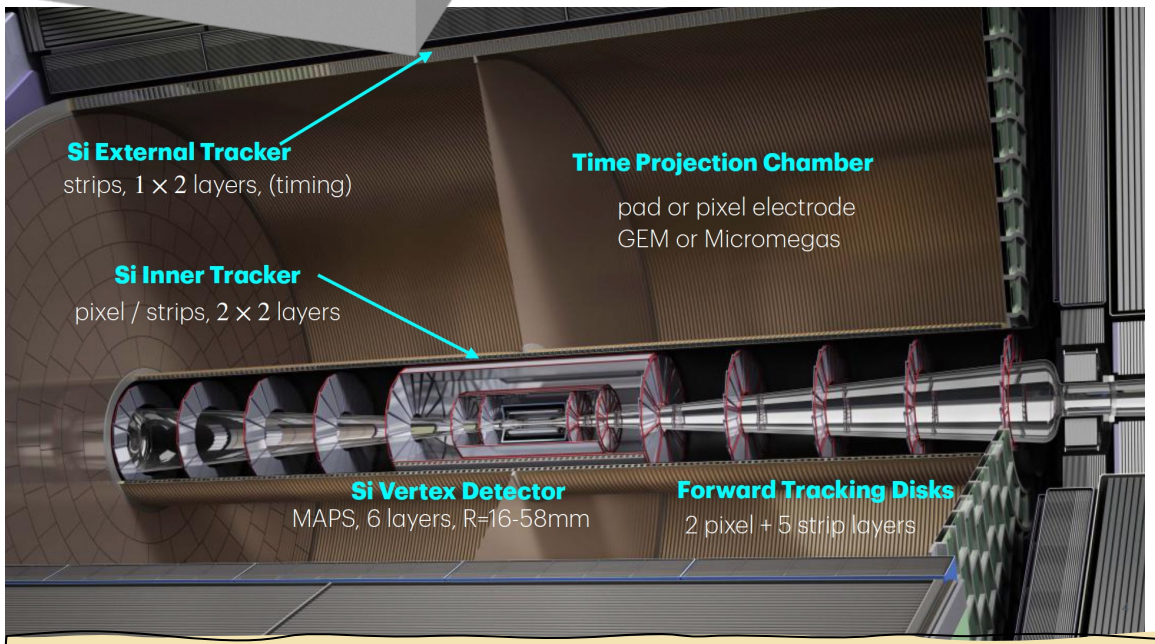
Optimized around Particle Flow: Granularity & Hermeticity

- Low-mass tracking system
  - Hybrid: Silicon – TPC tracking
  - Silicon Vertex
- Very high granularity calorimeter system

all inside a central solenoidal B field

➢ **PID in TPC** reinforced with timing







ILD has always evolved hand in hand with detector R&D collaborations (**CALICE**, **LC-TPC**, **FCAL**)
— today, in close connection with the **DRD** collaborations



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FCC-ee vs Linear Colliders: Key Differences Impacting Detector Design

From this Mogens Dam´s talk

FCC-ee parameters		Z	W^+W^-	ZH	ttbar
√s	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2} s^{-1}	**140**	20	7.5	1.5
Bunch spacing	ns	25	160	680	5000
		[. . .. .]			
Event rate	Hz	**100,000**	6	0.5	0.1

Luminosity and rates orders of magnitude larger at Z pole

Luminosity/IP (10^{34} cm^{-2}s^{-1})

	Z (91GeV)	HZ (240-250 GeV)
ILC	0.23	1.35 (2.7)
FCCee	140	7.5

Implications on detectors, electronics, DAQ: time resolution, event size, data handling….

- Up to two orders of magnitude tighter control of **systematics**

  Higgs Factory: $\mathcal{O}\,(10^{-3})$
  Tera Z: $\mathcal{O}\,(10^{-4} - 10^{-5})$

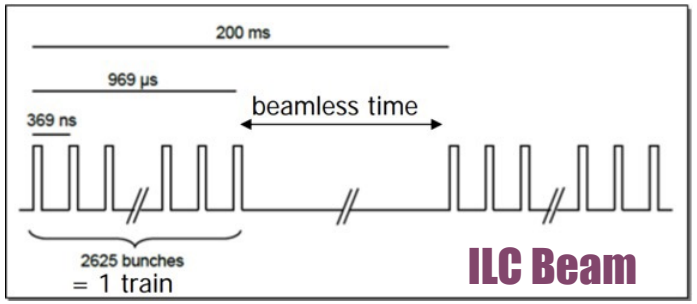
- **Luminosity precision** requirements relies on μm-level control of **luminometer geometry** and **acceptance** and high stability between center-of-mass energy scans

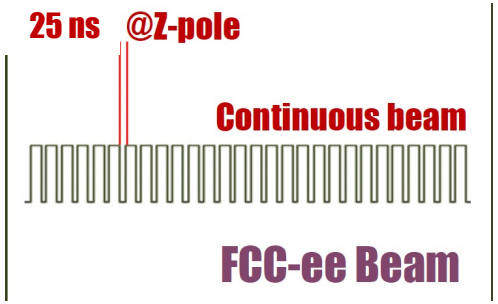
  IL 250 GeV: $\sim 10^{-3}$ (absolute)
  Tera-Z: $\sim 10^{-4}$ (absolute) $\sim 10^{-5}$ (relative)

- No power pulsing (electronics off between trains to reduce power dissipation)
  Cooling? Which one?
  This affects material budget, calorimetry homogeneity and compactness → Impact on performance?

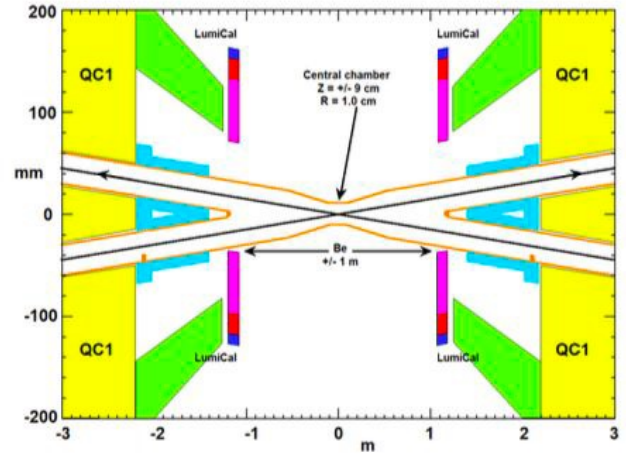
- Higher ionization rate and Ion backflow (IBF) in TPC (specific for ILD), no gating options → Efield distortions
  Additional second grid for IBF supresion?
  Offline space-charge corrections (à la ALICE)?

Continuous vs pulsed Beam

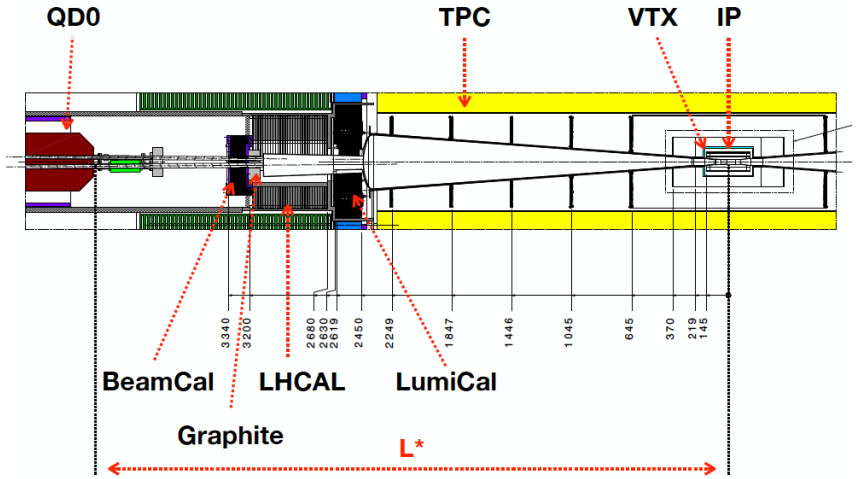




More challenging MDI for FCC-ee



Crossing angle 30mrad
L* 2m: Final Quadrupole **inside** the detector
Solenoid B field restricted to 2T maximum
Lumical at **~1m** from IP
Inner beam pipe radius 10mm
➔ Tracker acceptance: cosθ ~ 0.984



Crossing angle 14 mrad
L* 4.1 m: Final Quadrupole **outside** the detector
Solenoid magnetic field 3.5 – 4 T
Lumical at **~2.5m** from IP
Inner beam pipe radius 16 mm
Conical ➔ Tracker acceptance: cosθ ~ 0.996

How much the lower B field could impact on TPC reconstruction and PFA. Physics performance to be checked
Do we need a larger tracker?

Complication in forward detector design and background shielding

New ILD Models

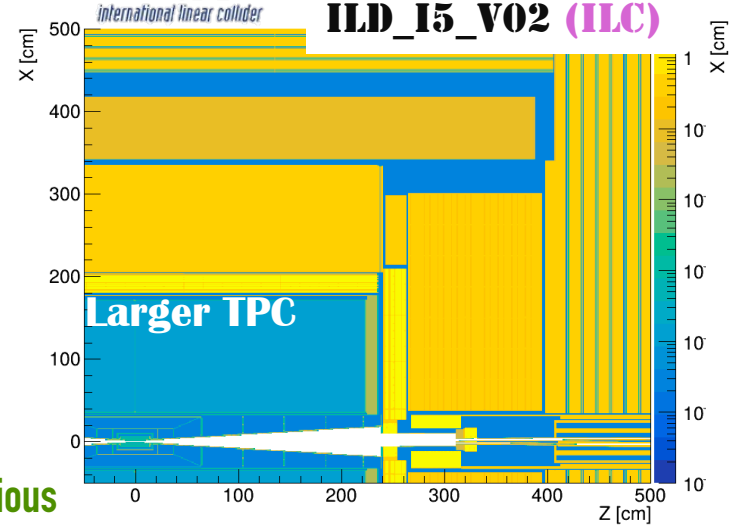
Common FCCee MDI
CLD-like silicon tracker

TPC innR= TPC Inner Radious

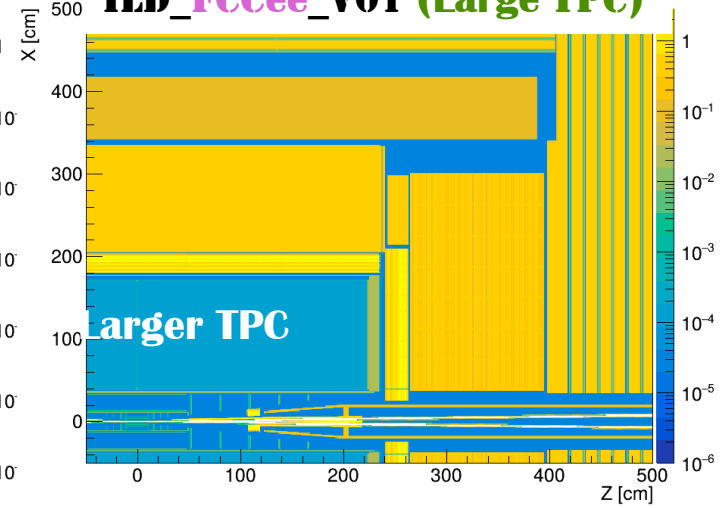
Beamstrahlung background decreases with increasing radius.

Realistic background conditions needed for reliable optimization.

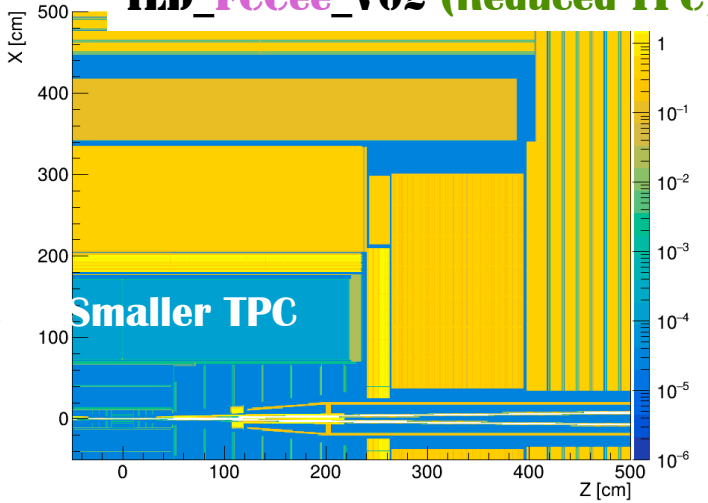
ILD_l5_v02 (ILC)

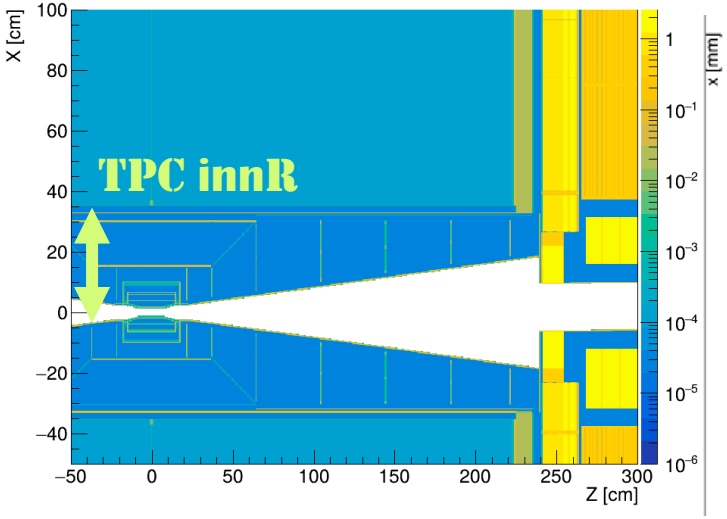


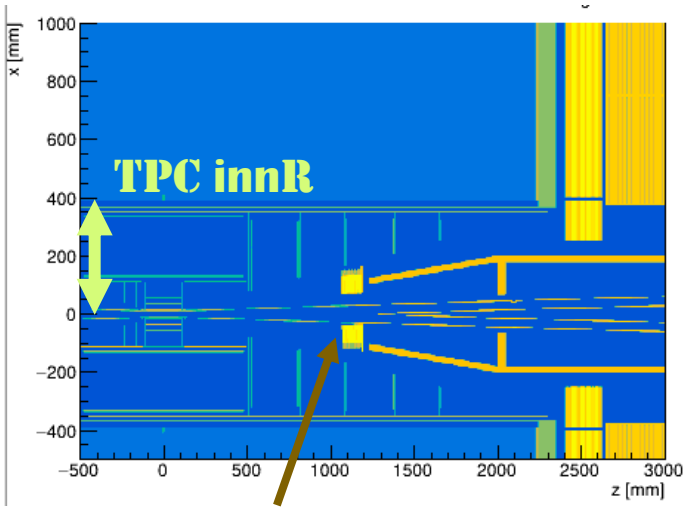
ILD_FCCee_v01 (Large TPC)



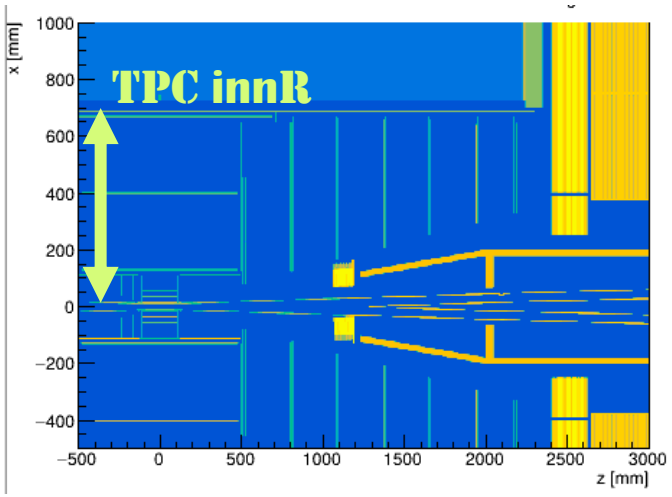
ILD_FCCee_v02 (Reduced TPC)







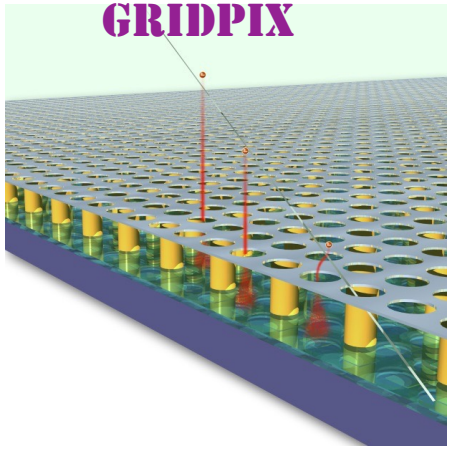
Beampipe forking



The TPC for ILD

A TPC provides high-precision tracking with a low material budget, making it ideal for Particle Flow reconstruction. It also offers excellent particle identification (PID) capabilities through dE/dx measurements.

The LC-TPC Collaboration has been developing and testing TPC technologies for ILD for many years, exploring different readout solutions based on GEMs, resistive-anode Micromegas, and, more recently, GridPix technology.



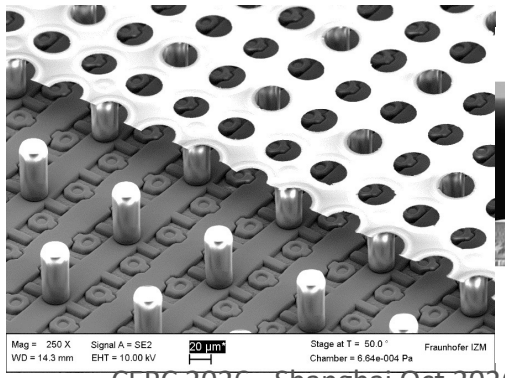
Pixel chip with integrated Grid (Micromegas-like)

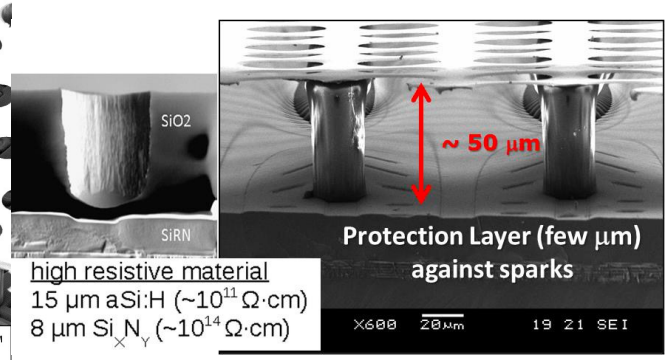
Timepix: 256 x256 pixes, size 55 μm

➔ can detect individual electrons

Aluminium grid 1μm thick, 35 μm holes, 55 μm pitch
Supported by 50 μm high pilars

HV: range: -600V to -300V

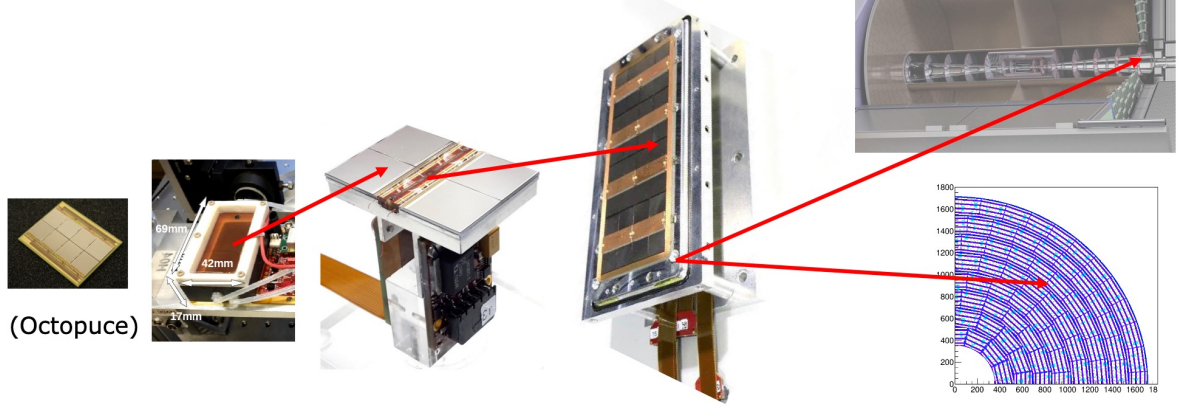




Quad: 4 TimePix3
All services located
under the detection surface

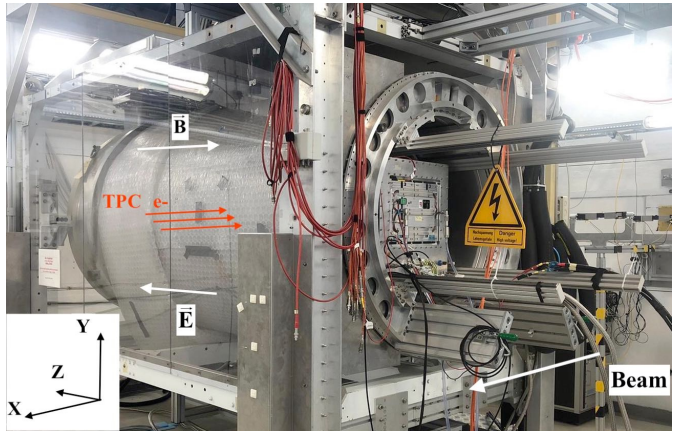
NIM A956 (2020) 163331

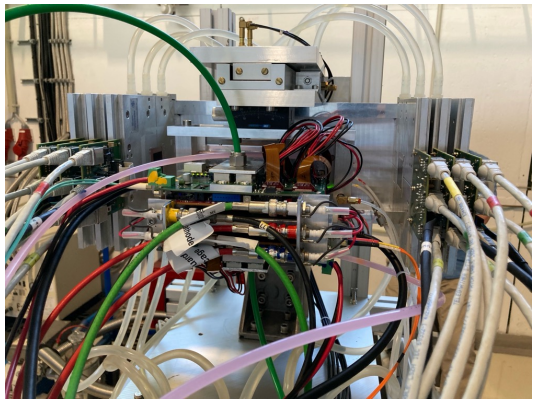
Pixel TPC

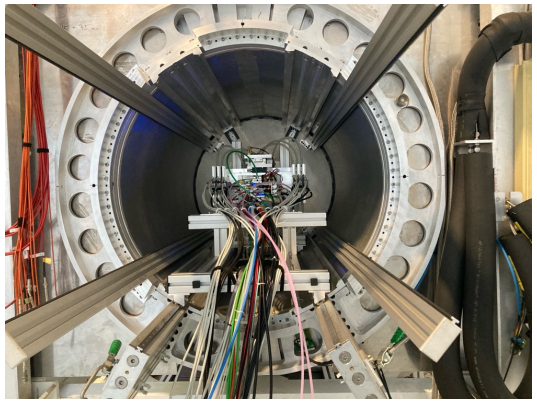


The TPC for ILD – GridPix studies

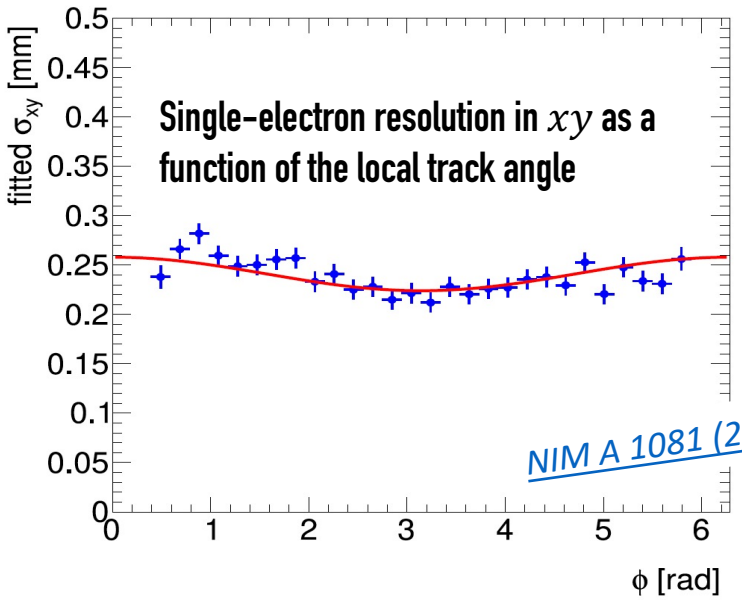
Different TPC readout technologies have been tested using the DESY test beam setup, which includes a TPC field cage and a B<1.2 T



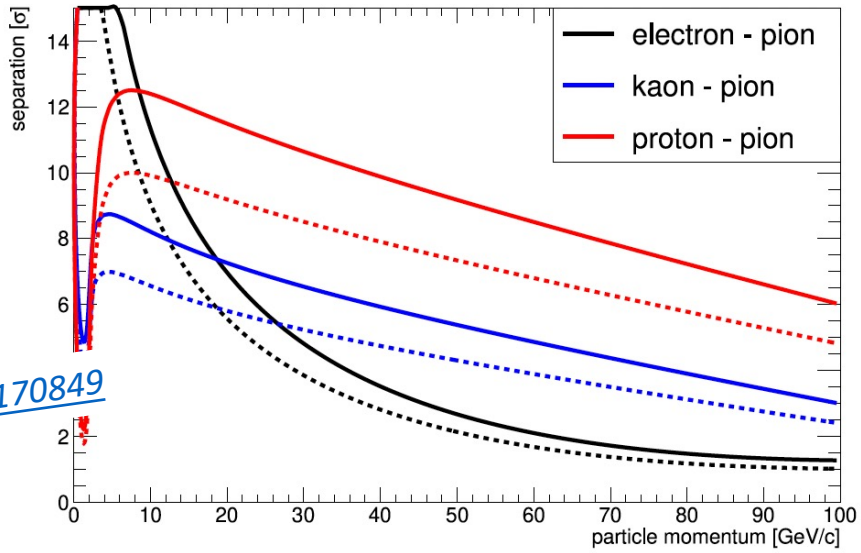




2021 TB: 32 GridPix Nucl. Instrum. Meth. A 1075 (2025) 345



NIM A 1081 (2026) 170849



Projected PID resolution for ILD at $\cos\theta = 0$

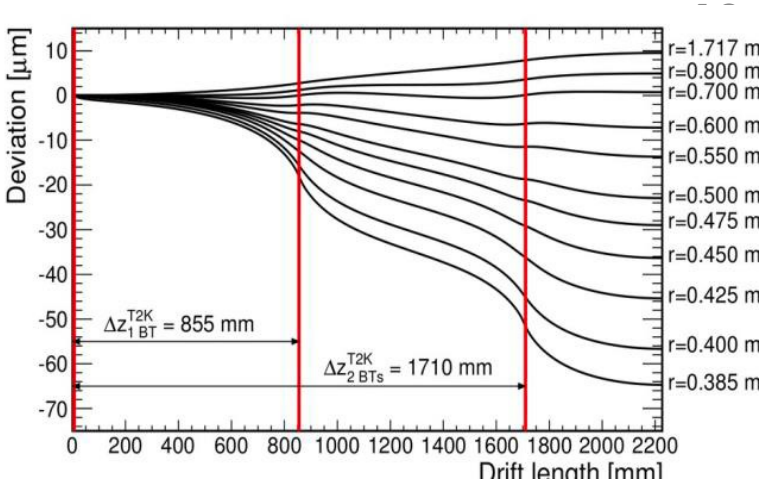
Dashed line
electron PID resolution 3.0% – truncation method
Continuous line
electron PID resolution 2.4% – templated fit

Fits distances between electrons to estimate the primary ionization cluster density.

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The TPC at the FCC-ee Zpole conditions

Distortions at ILC



Field distortion by ions caused by

- a large amount of the primary ions from ionization of the tracks from both Z-pole events and the machine background
- the backflowing ions generated in amplification.

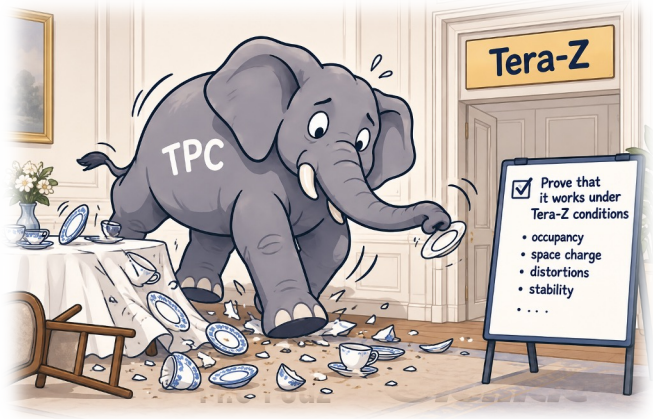
Due to the beam operation conditions gating is no possible

Simulation studies are ongoing

A good understanding of backgrounds is essential to assess TPC operational limits and optimize the ILD tracking design

Strategies to be evaluated

- Different TPC inner radius
- Map distortions (ALICE demonstrates effective correction)
- Study if including precise timing and position from dedicated silicon layers could help with the distortion corrections
- Possible mitigation strategies need to be explored
  - It has been reported recently that a combined Micromegas with GEM readout module could suppress ion backflow*.
  - Graphene membrane might be useful** (stops ions / transparent to electrons)
  - Optimization of field conditions (collection efficiency of primary ions can be also affected)
  - Using a Neon based gas
- ……



* https://indico.desy.de/event/33640/contributions/128390/attachments/77557/100324/ECFA_LCTPC_IHEP__Huirong_20220930.pdf

** Nuclear Inst. And Methods in Physics Research, A824 (2016) 571.
Nuclear Inst. and Methods in Physics Research, A 1031 (2022) 166521.
https://indico.cern.ch/event/1219224/contributions/5130761/attachments/2567723/4427337/MPGD_Conference_2022_CERN.pptx

Vertexing and silicon tracking

R&D developments along years on novel pixel sensors with different technologies, capable to achieve a spatial resolution and a material budget well beyond the LHC Standard.

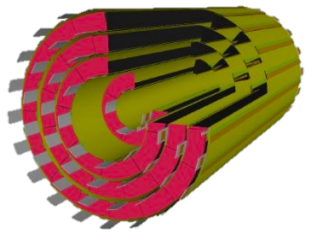
Aiming high timing resolution for the tracking. Baseline: LGAD/iLGAD (Low Gain Avalanche Detector)
Timing and pixelation could now play an even more important role in facilitating offline space-charge corrections.

ILC vertex design: 3 double-layers (16, 37, 58 mm from IP). Spacial Resolution 3.0 μm, timing resolution 2-4 μs
Material Budget: 0.15% X_0 per layer (air cooling, enabled by power pulsing)
At FCC it could increase a factor 2 with liquid cooling as suggested by the CLD design assumptions

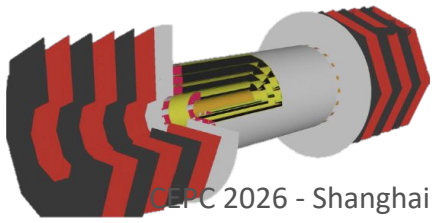
Design for FCC-ee to be revisited. New R&D developments ongoing to be evaluated

FCC Snail-shape vErtEx Detector (FCC – SEED)

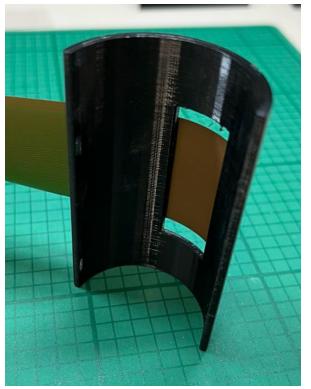
FCC-SEED
VERTEX DETECTOR
FOR FCC-ee

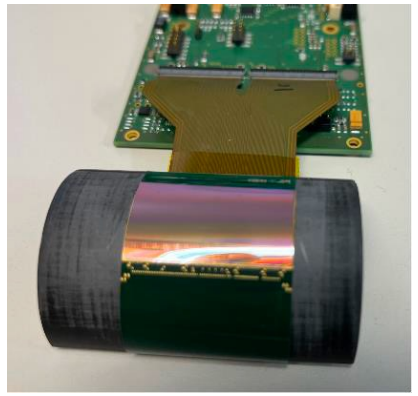


Overlapping curved sensors (a la ALICE).
1D Stiching MAPS (Octopus like)
5 layers, 0.15% X_0 per layer (single or double layer)
Barrel + Endcaps



Soon available in Key4hep full simulation framework
Pull request made to FCC.-SEED as option to ILD

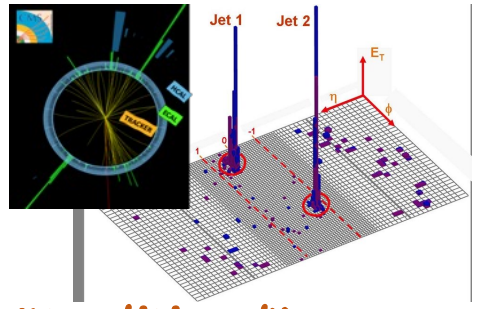




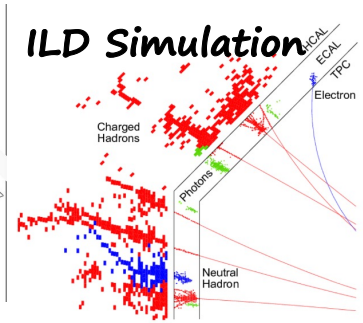
Using MIMOSIS chips for curved sensor tests

Highly segmented calorimeters optimized for PFA

Reconstruct **every** single particle in the event and measure it **only** with the detector providing the best resolution



"traditional" calorimeters



"tracking" calorimeters

High granularity calorimeter technological challenges

High precision mechanics to minimize dead spaces.
Tolerances over 1x3x1m^3 of <1mm

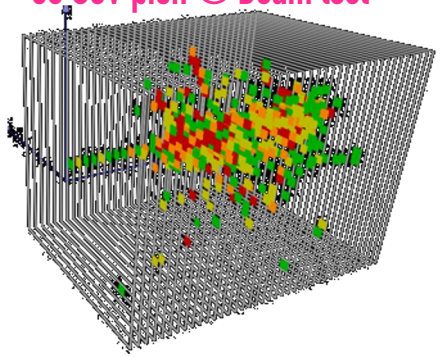
Compact electronics despite the huge number of channels
Embedded in the calorimeter

Precise timing ~100-200 ps resolution

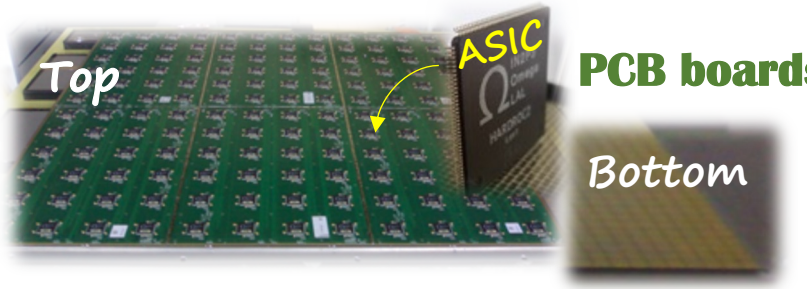
Low power consumption

5D -CALORIMETER
(E,x,y,z,t)

80 GeV pion @ Beam test



FE electronics is embedded into the layer structure



PCB boards

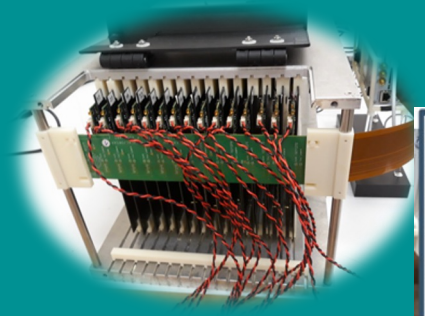
Bottom has the pads/strips
Top has ASIC chips

CALICE
drdcalo

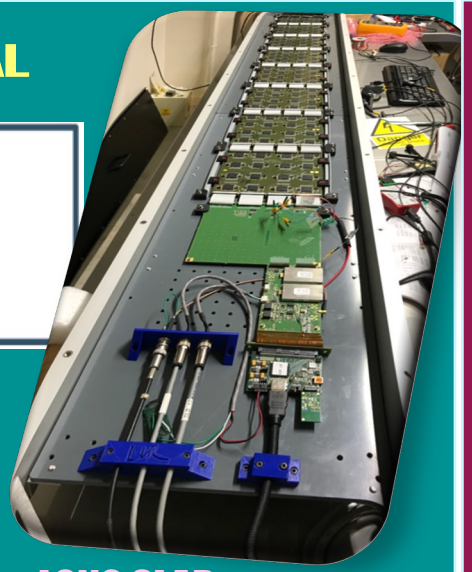
Calorimeters developed at CALICE, now at DRD Calo Technologies fully validated for ILC with large prototypes at test beams

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Silicon-W ECAL



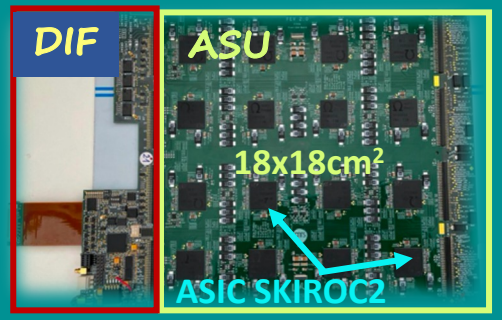
SiW-ECAL
- 15 layers 18×18 cm²
- 0.5×0.5 cm² Si cells
- 2.8+5.6 mm W (21 X_0)
- 100 kg, 0.4×0.4×80 cm³
- 15k channels



LONG SLAB ~150cm

7 ASU

Embedded electronics



Pads on bottom

ASU = ASIC+PCB+SiWafer

DIF = Detector InterFace:

Scintillator HCAL - AHCAL



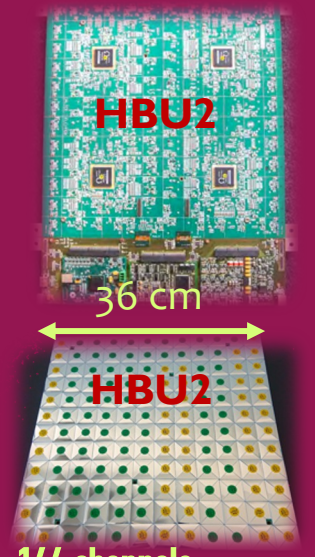
Tiles 3x3x0.3 cm³

38 layers 0.72 x 0.72 m²

~22.000 channels

ASIC SPIROC2E

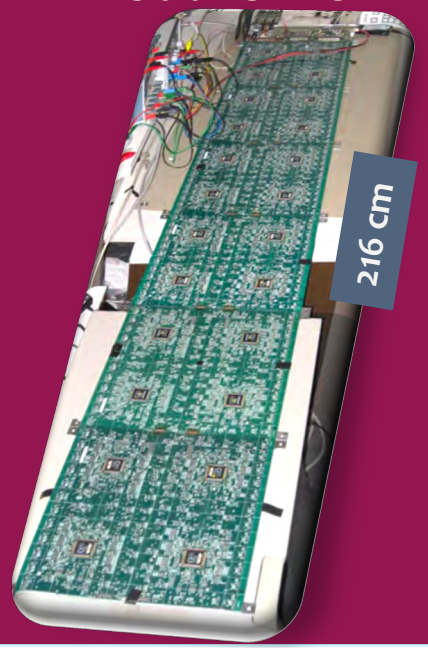
HBU: HCAL Base Unit



144 channels

Full extension

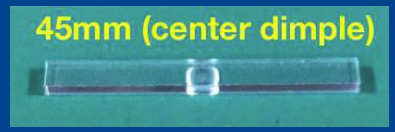
1 slab = 6 HBU2

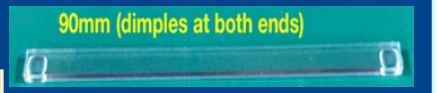


Scintillator-W ECAL



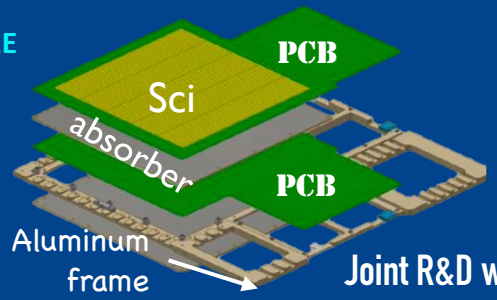
ASIC SPIROC2E

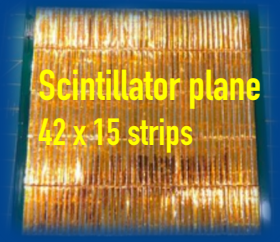




- ✓ SiPM in dimple of strip → better LY and uniformity
- ✓ Double SiPM readout considered → noise reduction, hit position reconstruction

ScW-ECAL
32 layers (23.4X_0)
22x22 cm²
0.5 x 4.5 cm² strips



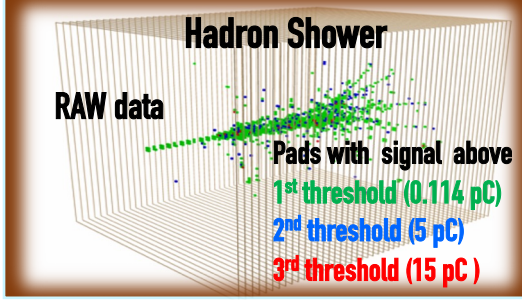


Joint R&D with CEPC-ECAL group

Semidigital HCAL – SDHCAL



- 48 GRPC layers (~6λ_I)
- 1 cm² pads – 3-threshold –Semi-digital Readout
- Self-supporting mechanical structure (<500 μm deformation)





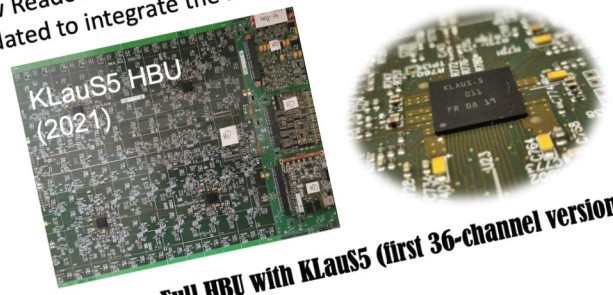
Many ongoing /planning R&D to improve the calorimeters and adapt them to FCC-ee
Here only few examples

Improving electronics
And… Why not include also precise (sub-ns) timing? (every channel? On some dedicated planes?

AHCAL from SPIROC2E to Klausv7

Based on H2GROC (CMS HGCAL)
Optimized for low gain SiPMs (~10mm pixel)
Low power
Precise timing (<100 ps)
lpGBT compatible
Allows power pulsing as well as continuous readout

New Readout scheme, readout needs also to be updated to integrate the new chip and functionalities



Full HBU with KLauS5 (first 36-channel version)

SDHCAL from HADROC to CALOROC
From SDHCAL to t-SDHCAL

Precision timing (<100 ps target): Exploiting the excellent timing capabilities of multigap RPCs.
Charge and time measurement: Combining energy information with precise hit timing.
High-rate, continuous operation: Addressing FCC-ee requirements without ILC-style power pulsing.
Improved readout architecture: Overcoming PETIROC limitations, particularly TDC precision and dead time.

New Boards under development
MultiGap RPC → Precise timming

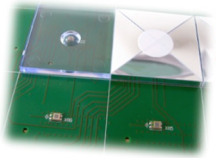
AHCAL: From Tiles to Megatiles

Huge number of channels for the full detector

Single tile

Scintillator tiles wrapped individually in reflective foil

Glued on board one by one!!

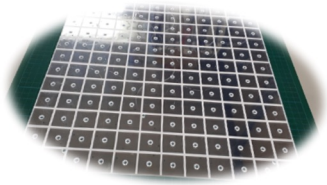


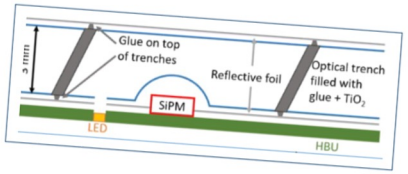
Light Tightness 👍
Dead areas between tiles 👎

Megatile design:

Large scintillator plate optically separated by trenches

Plated wrapped in reflective foil
No dead area

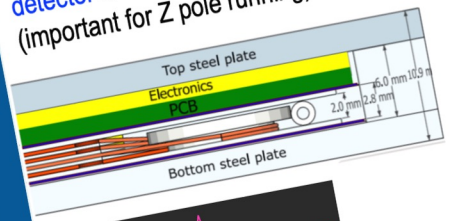


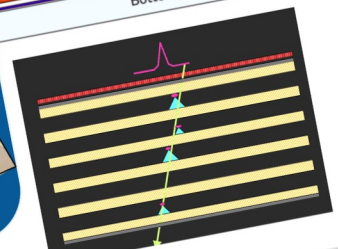


Easier assembly and no dead areas👍
Optical crosstalk and uniformity is a challenge 👎
Several generations produced.
Last shows reasonable uniformity and light yield and low crosstalk ~3%
Optimization is ongoing

SDHCAL: From Glass RPCs to multigap GRPCs

improve the intrinsic timing of the detector and its rate capabilities.
(important for Z pole running)







M.C Fouz Ciemat

And…. what about the cooling

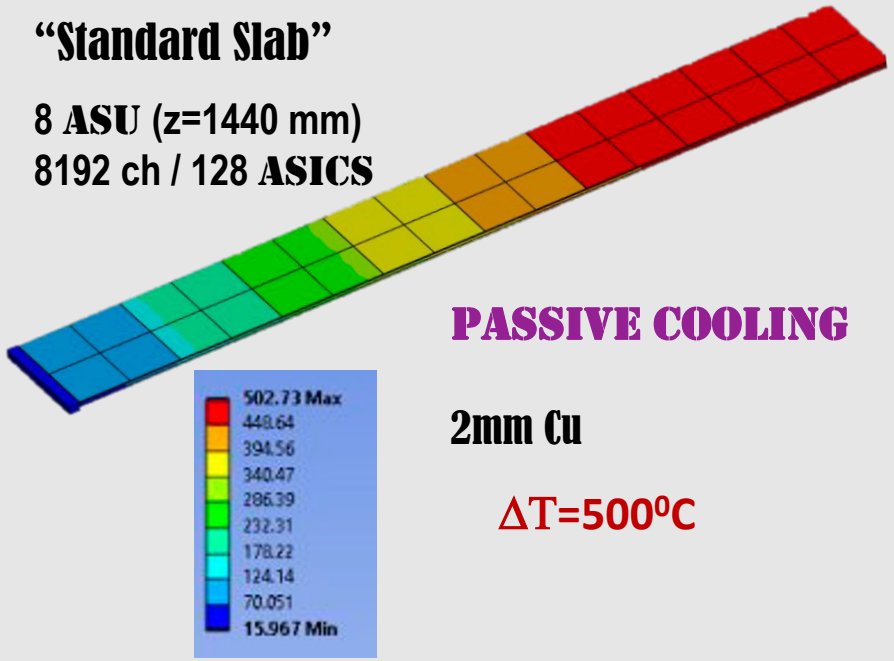
The compactness and uniformity in calorimeters is important for high performance.
It is challenging to maintain it when including active cooling.

Several preliminary simulations has been done in the different calorimeters,
based on the present electronics used for the prototypes.

SiWCAL

"Standard Slab"

8 ASU (z=1440 mm)
8192 ch / 128 ASICS

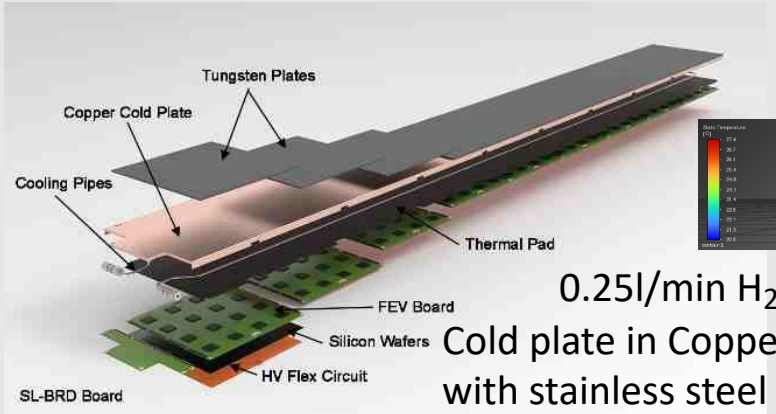


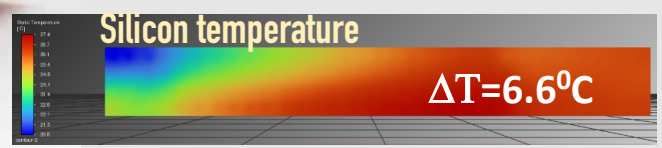
PASSIVE COOLING

2mm Cu

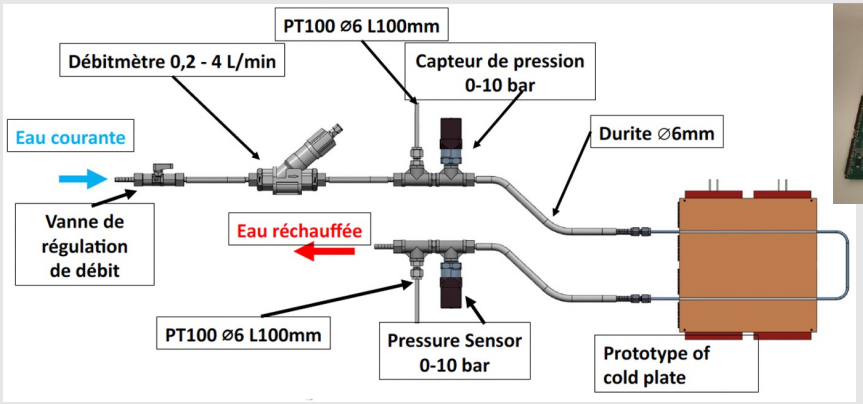
ΔT=500⁰C

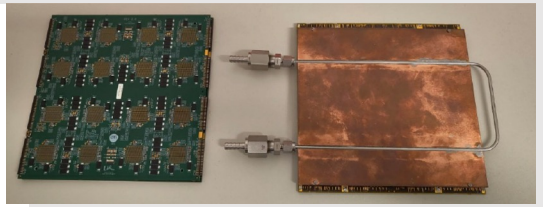
ACTIVE COOLING





0.25l/min H_20@ 15⁰C
Cold plate in Copper with grooves
with stainless steel pipe (1/8")





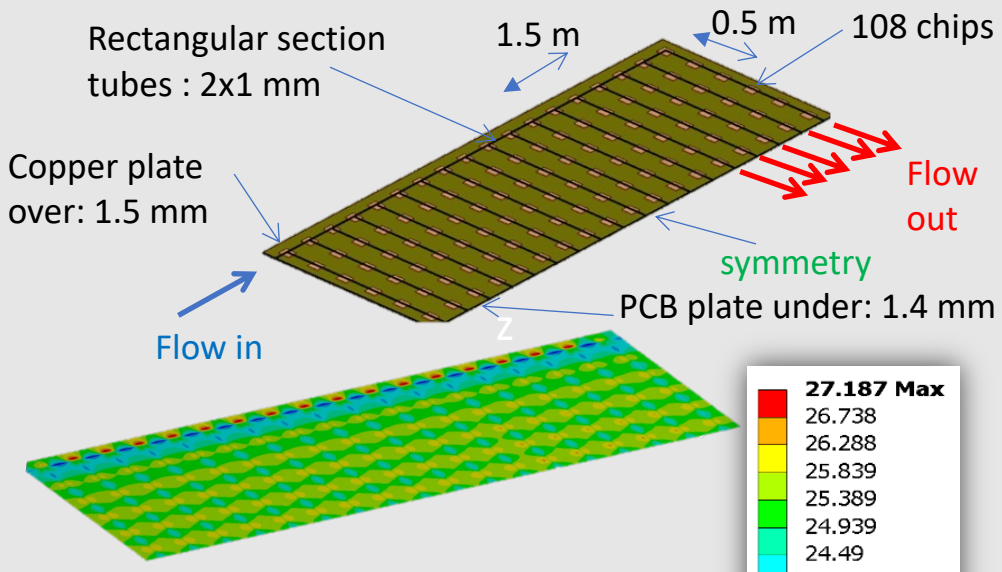
Test bench being mounted

And…. what about the cooling

The compactness and uniformity in calorimeters is important for high performance.
It is challenging to maintain it when including active cooling.

Several preliminary simulations has been done in the different calorimeters, based on the present electronics used for the prototypes.

SDHCAL water circulation in copper pipes

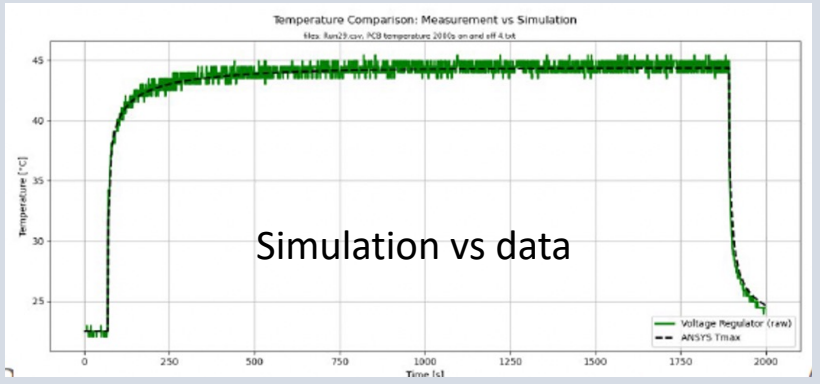


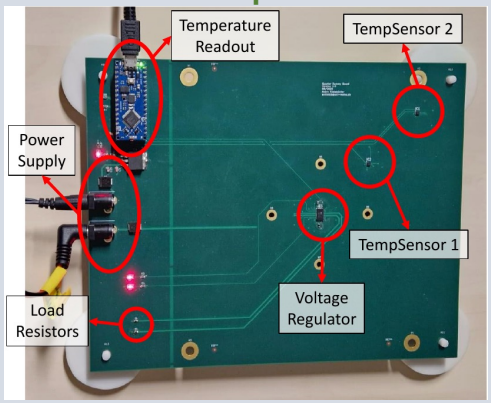
0.8 mW/chip with power pulsing
vs 80 mW/chip without

AHCAL Copper plate on one side in direct contact to ASIC via thermal pad/paste
Screws close to ASICs for good contact pressure with Cu plate

Cooling Material	Thickness	T max (°C)	ΔT (°C)
Copper plane in the PCB	35 µm	614.1	596.4
Copper plane in the PCB	140 µm	165.9	152.7
Copper plate	1 mm	36.2	16.4
Copper plate	3 mm	22.5	5.6
Copper plate	5 mm	19.6	3.4
Stainless Steel Absorber	19 mm	44.6	22.6
Copper Plate + Stainless Steel	1 mm + 19 mm	27.7	9.8
Copper Plate + Stainless Steel	3 mm + 16 mm	21.3	4.7

Dummy HBU to mimic ASIC heat production





The luminometer

Developments in the framework VFCAL collaboration, CALICE and DRDCalo.
Tight mechanical precision requirements, extreme compactness
Si or GaAs/W sandwich calorimeters,

Ultra thin layers <1mm for minimal Moliere Radius
High granularity calorimeter but without embedded electronics
Higher radiation levels

FLAME (FcaL Asic for Multiplane rEadout) ASIC

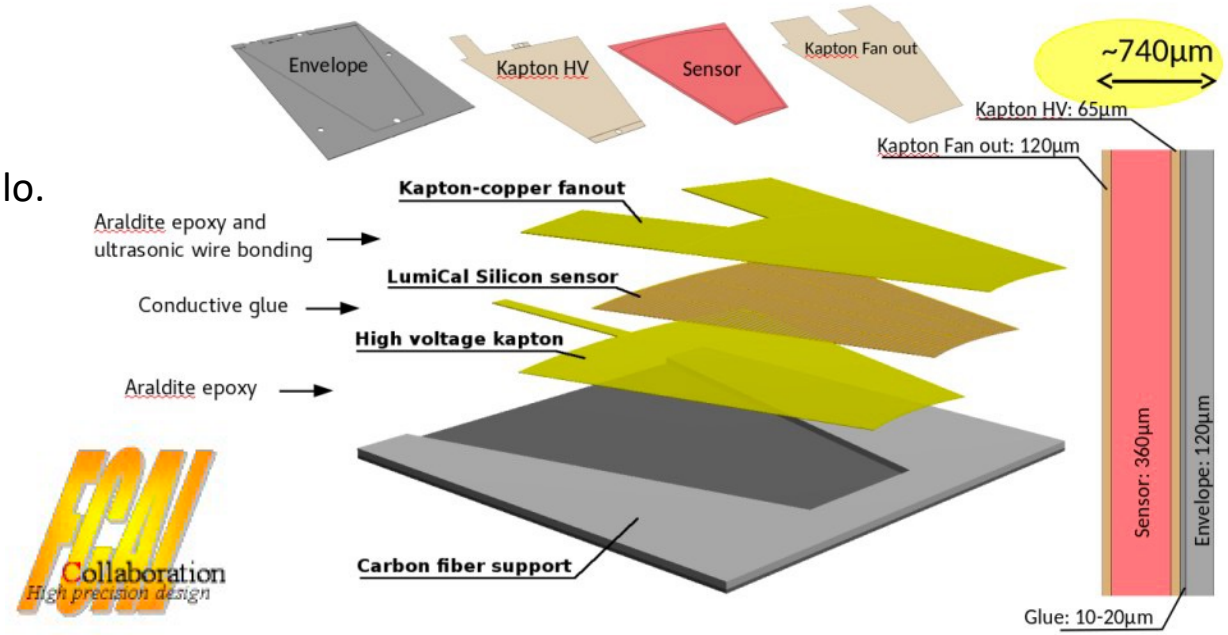
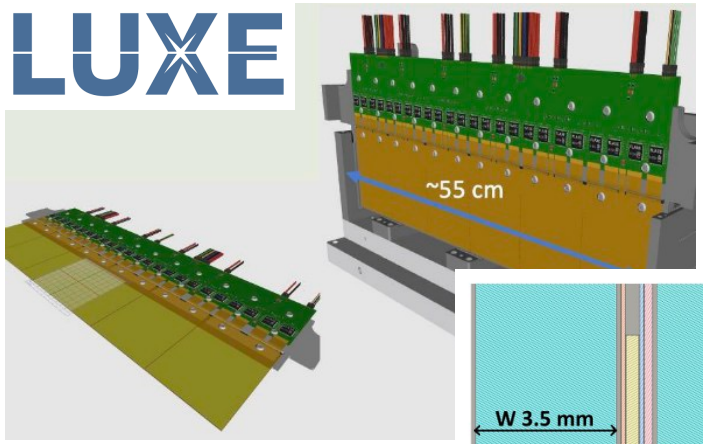
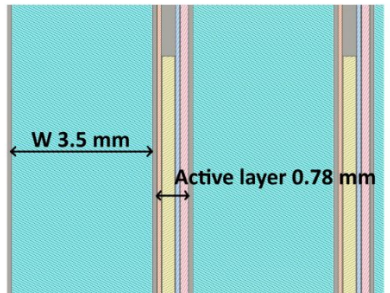


Figure 5.13. Structure of a sensitive layer of the LumiCAL calorimeter.

Large sinergiy with the LUXE ECALp (**HighCompactCalo - FCAL**)

Front end boards above sensors

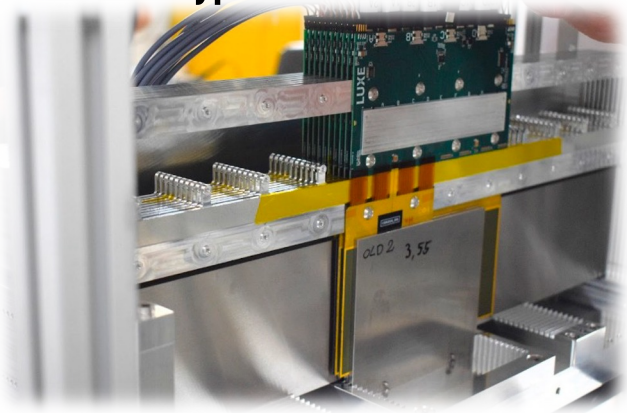




ECALp mechanical housing



Prototype at Testbeam



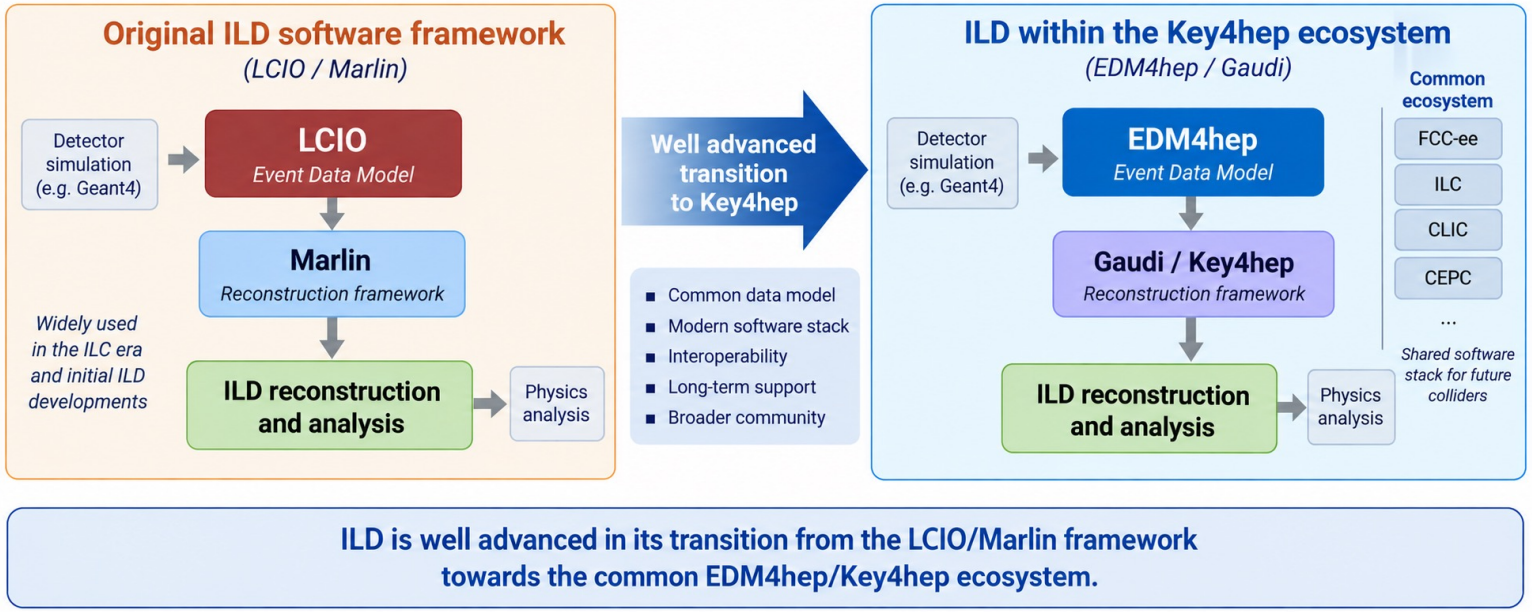
M.C Fouz Ciemat

ILD Software – Simulation & Reconstruction

ILD has a long-standing commitment to common software frameworks, from ILCSoft to the Key4hep ecosystem.

ILD software is entirely in Key4hep
Full simulation & reconstruction producing EDM4hep exists
Full reconstruction available via Marlin Wrapper
Marlin processor migration is ongoing

The new developments should use Gaudi and EDM4hep
New data samples to be generated directly within Key4Hep



Beyond migration to the new software ecosystem significant opportunities remain for improving reconstruction.
See recent Uli Eihaus´ talk on reconstruction

ILD Software and analysis. Exploring the use of machine learning

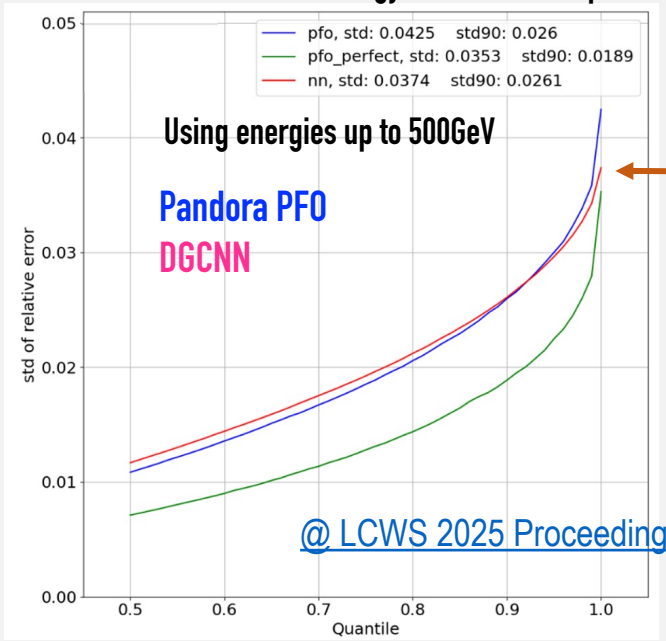
Modern machine learning approaches are also being explored to improve reconstruction and develop novel methods for physics analyses.

Examples of reconstruction studies

Energy reconstruction using Dynamic Graph Convolutional Neural Network

WORK IN PROGRESS

Width of the reconstructed energy distribution vs quantile

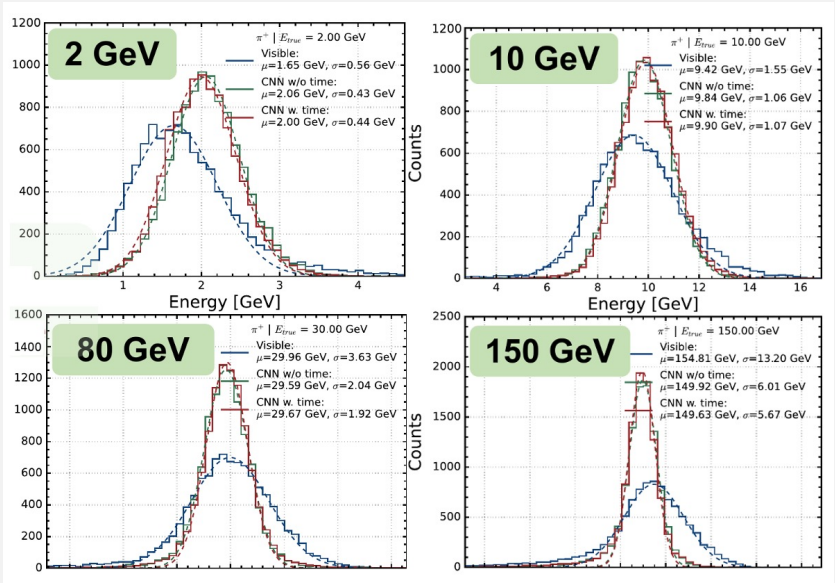


improvement for the full distribution with DGCNN

→ helps to correct bias and outliers

@ LCWS 2025 Proceedings

Energy reconstruction using Convolutional Neural Network



(*) Visible
CNN w/o timing
CNN w timing

CNN improves resolution 40–60%

@ILD Software meeting

(*) Visible - Summing all visible hits energy (SiECAL + AHCAL)

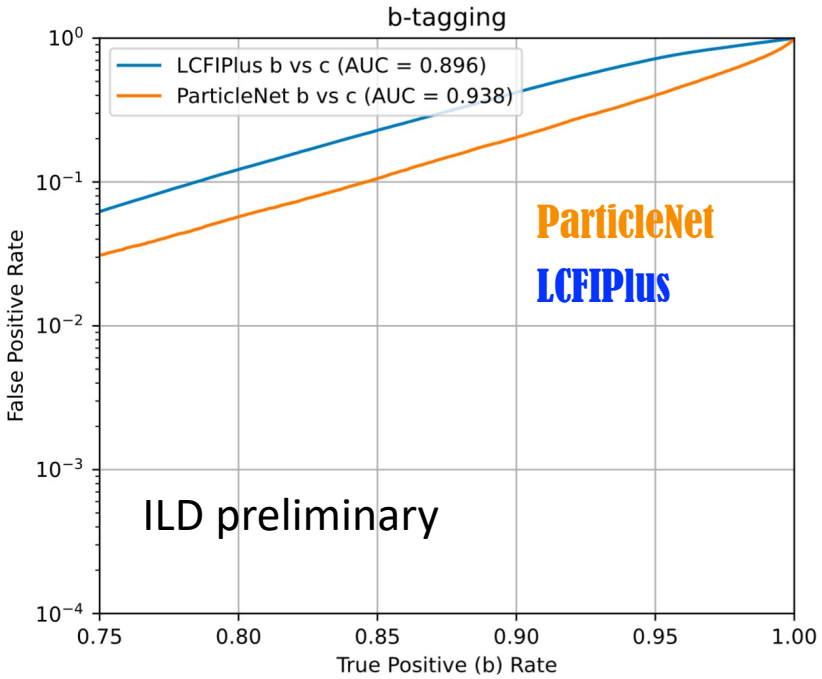
M.C Fouz Ciemat

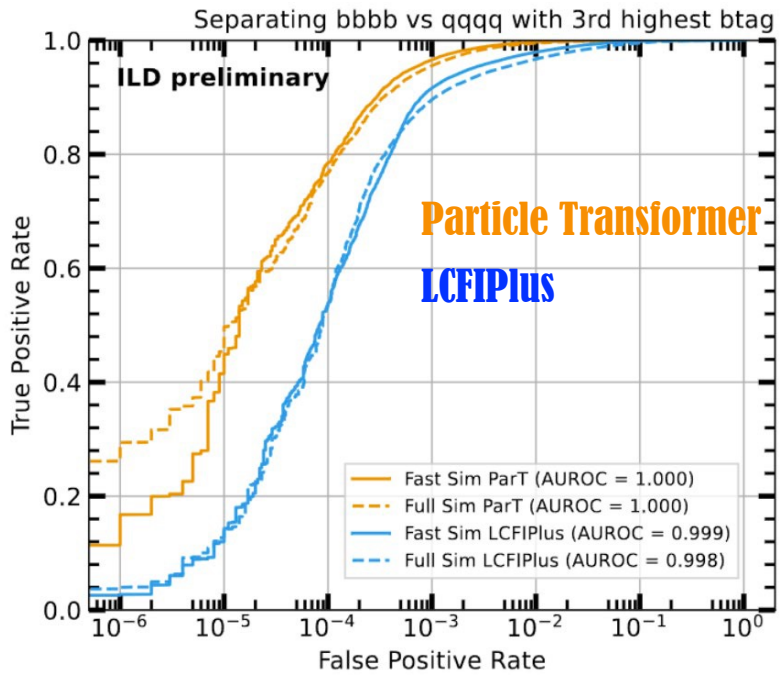
ILD Software and analysis. Exploring the use of machine learning

Modern machine learning approaches are also being explored to improve reconstruction and develop novel methods for physics analyses.

Flavour tagging

B-tagging performance with c-background





Significant improvements using new ML-driven methods

~10-12% higher tagging accuracy at same background rejection

@Higgs Pairs Workshop 2025

ILD Physics analysis

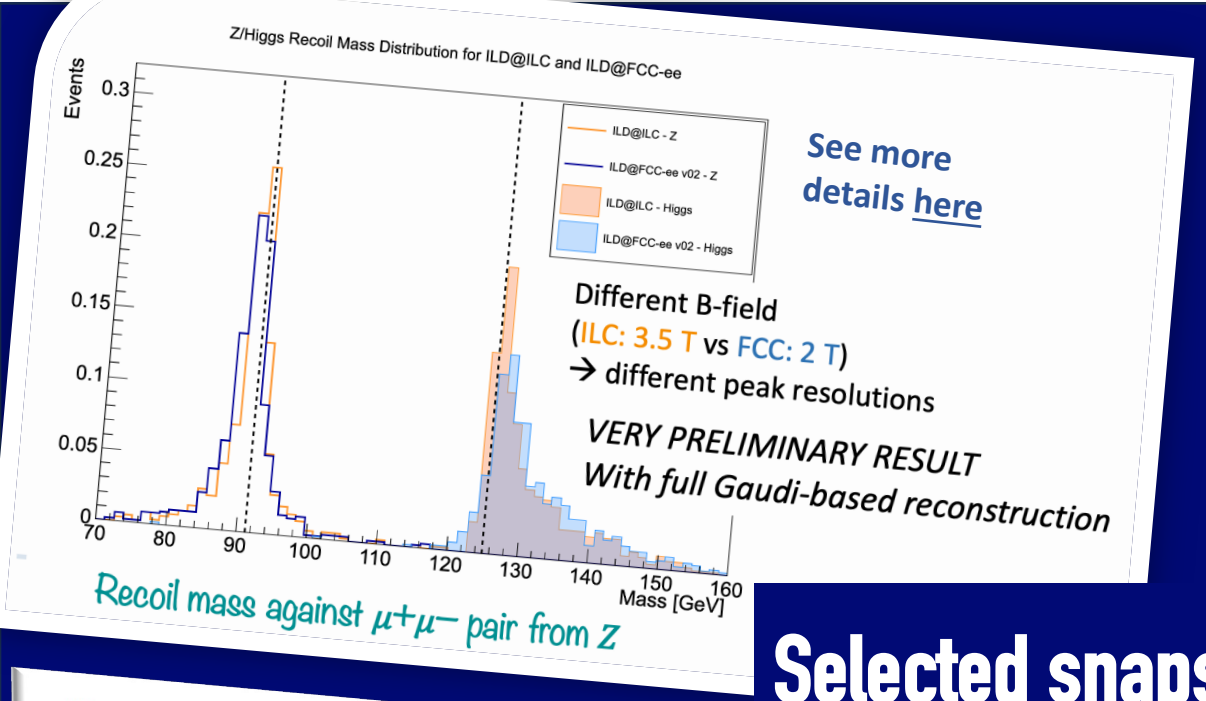
The ILD community has long been actively engaged in physics studies for e^+e^- Higgs factories, making significant contributions to the ECFA Higgs, Electroweak and Top Factory Study and the European Strategy for Particle Physics Update (ESPPU)

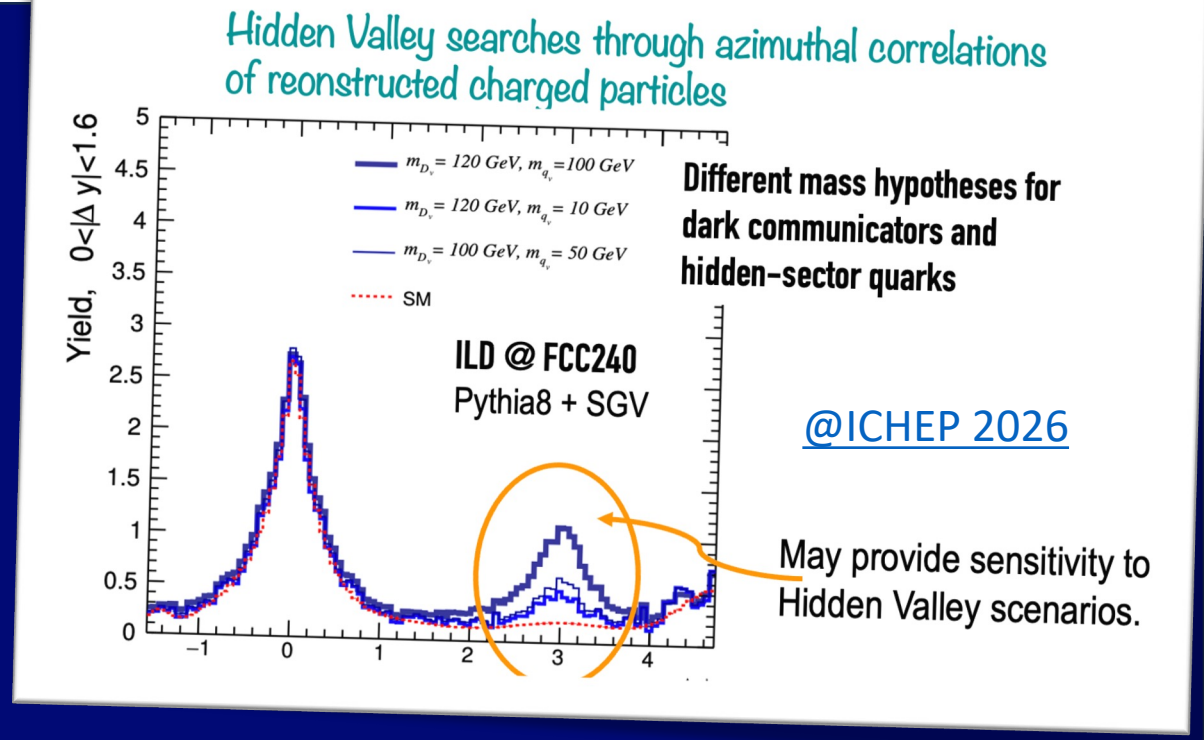
Most of these studies have focused on energies above 230–240 GeV.

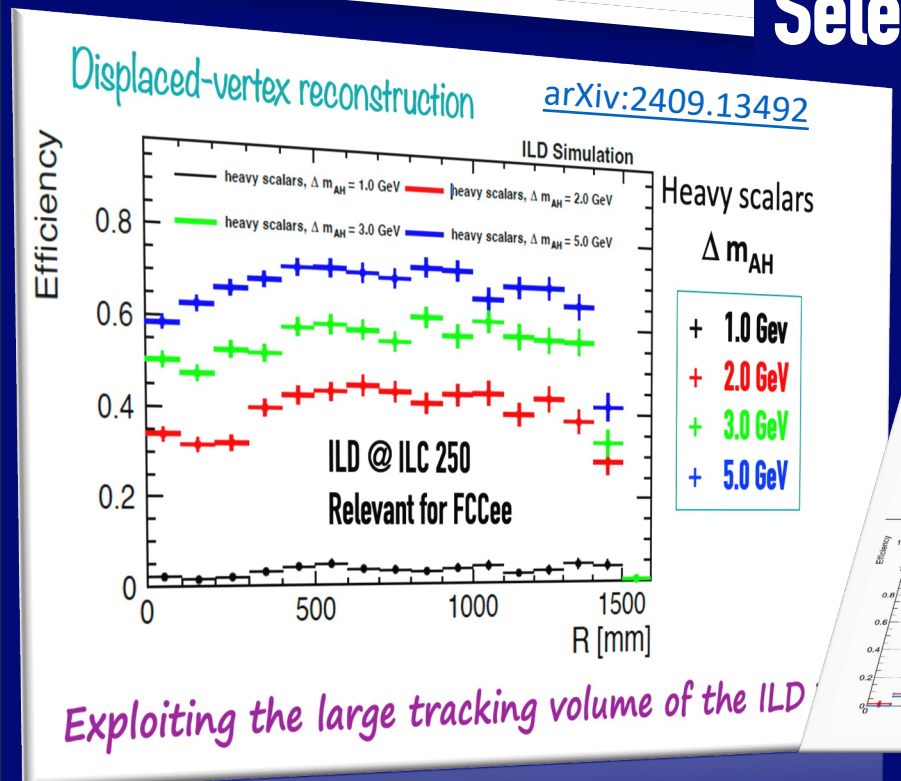
More recently, the ILD community has started to extend its physics studies to the Z-pole region of FCC-ee

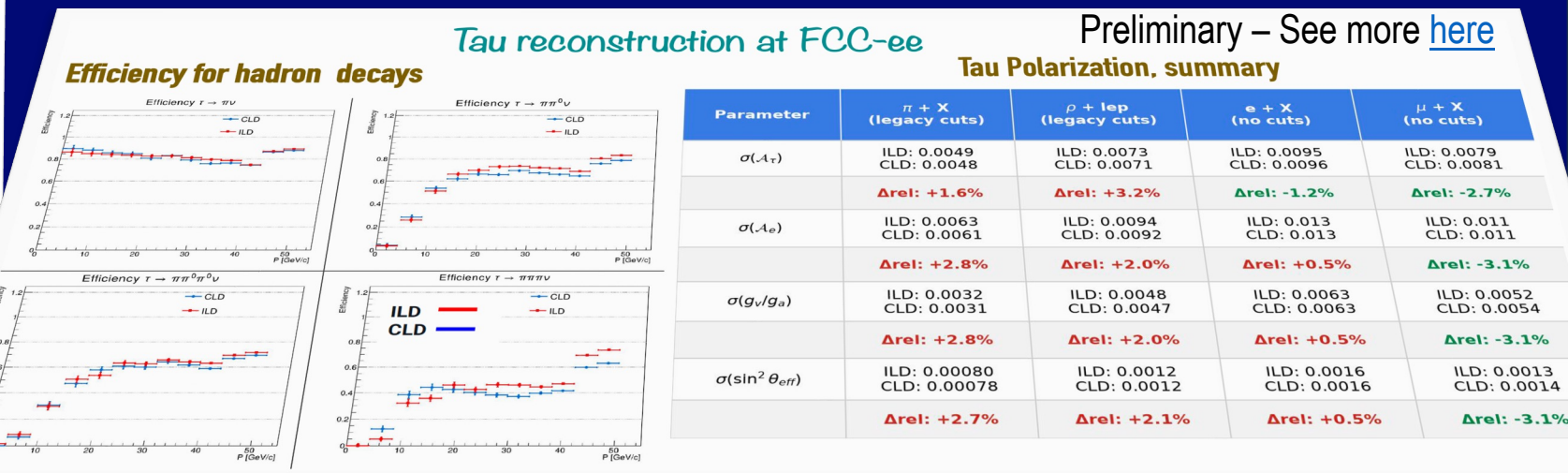
These studies serves not only to explore the physics potential at the FCC-ee Z pole, but are also also essential for optimizing the reconstruction and detector design to meet the stringent precision requirements needed to fully exploit the unprecedented Z-pole statistics. The ILD detector has not yet been fully optimized for these operating conditions

Selected snapshots of ongoing ILD physics studies relevant to FCC-ee









Parameter	π + X (legacy cuts)	ρ + lep (legacy cuts)	e + X (no cuts)	μ + X (no cuts)
$\sigma(\mathcal{A}_\tau)$	ILD: 0.0049 CLD: 0.0048	ILD: 0.0073 CLD: 0.0071	ILD: 0.0095 CLD: 0.0096	ILD: 0.0079 CLD: 0.0081
	Δrel: +1.6%	Δrel: +3.2%	Δrel: -1.2%	Δrel: -2.7%
$\sigma(\mathcal{A}_e)$	ILD: 0.0063 CLD: 0.0061	ILD: 0.0094 CLD: 0.0092	ILD: 0.013 CLD: 0.013	ILD: 0.011 CLD: 0.011
	Δrel: +2.8%	Δrel: +2.0%	Δrel: +0.5%	Δrel: -3.1%
$\sigma(g_v/g_a)$	ILD: 0.0032 CLD: 0.0031	ILD: 0.0048 CLD: 0.0047	ILD: 0.0063 CLD: 0.0063	ILD: 0.0052 CLD: 0.0054
	Δrel: +2.8%	Δrel: +2.0%	Δrel: +0.5%	Δrel: -3.1%
$\sigma(\sin^2\theta_{eff})$	ILD: 0.00080 CLD: 0.00078	ILD: 0.0012 CLD: 0.0012	ILD: 0.0016 CLD: 0.0016	ILD: 0.0013 CLD: 0.0014
	Δrel: +2.7%	Δrel: +2.1%	Δrel: +0.5%	Δrel: -3.1%

Summary

ILD is a mature and robust detector concept, originally designed and optimized for the ILC, and now evolving to meet the challenges of FCC-ee operation, particularly at the Z pole.

Particle Flow remains at the heart of ILD's DNA, while the concept continues to embrace new technologies and maintain strong links with detector R&D collaborations, with the ultimate goal of building the best possible detector to fully exploit the physics potential of future colliders.

ILD has a very active software community, which has contributed to the development of the new FCC software ecosystem. We are now working towards completing the migration of the ILD software to this new framework.

ILD also has a strong tradition of physics studies, with significant contributions to the ECFA studies and the European Strategy for Particle Physics Update (ESPPU). While our studies have traditionally focused on energies above 230–240 GeV, the enormous statistics expected at the FCC-ee Z pole open up exciting new physics opportunities, but also pose unprecedented challenges.

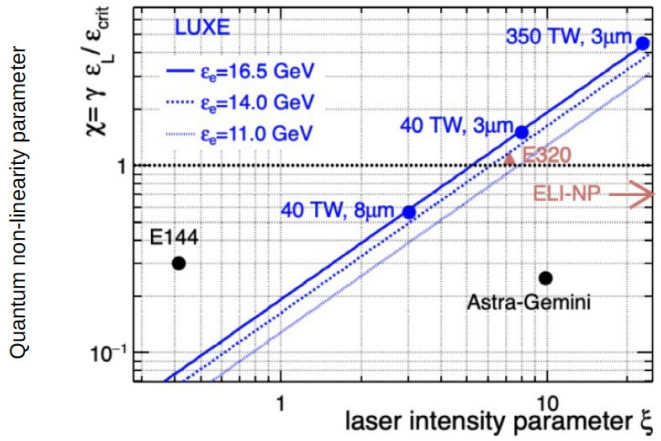
Expanding our physics program to lower energies, particularly the Z pole, is therefore a key priority. These studies will allow us to explore the full physics potential of this regime while guiding the further optimization of ILD to achieve the demanding detector performance required at the Z pole.

There is a lot of exciting work ahead of us, and we would be delighted to have more people joining us in this journey.
Everyone interested in contributing to the future of ILD is very welcome

Back-up

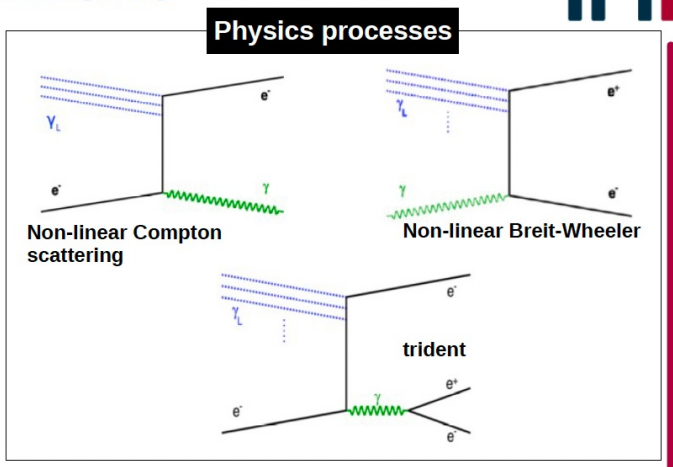
LUXE: Laser Und XFEL Experiment

- Experiment based at **DESY-XFEL**
- **Strong EM field**: 30-350TW laser & 16.5 GeV e- beam
  - e- / laser interaction mode and γ /laser interaction mode
- **Ambitious time-scale** (start data taking in 2027)
  - CDR published, TDR in arxiv since 2023

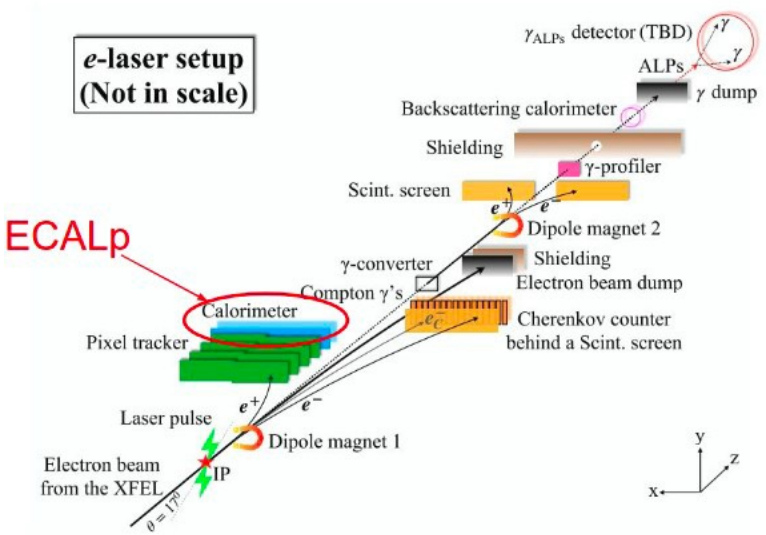


Field intensity parameter

$$\xi = \sqrt{4\pi\alpha}\left(\frac{\varepsilon_L}{\omega_L m_e}\right) = \frac{m_e \varepsilon_L}{\omega_L \varepsilon_{cr}}$$

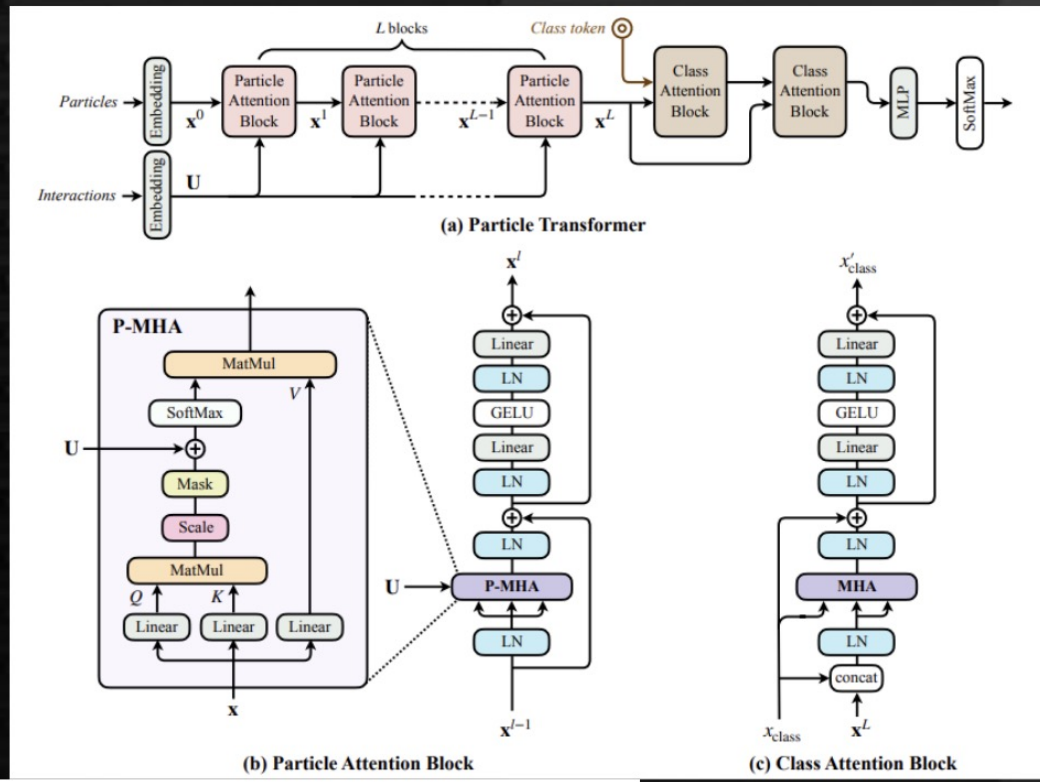


First experiment to try this E144 @ SLAC in 1990s.
Nowadays experiments : SLAC-E320 (US), Astra Gemini (UK), ELI-NP (RO)



Particle Transformer (ParT)

- Transformer: self-attention-based algorithm intensively used for NLP (e.g. chatGPT)
  - Weak biasing: possible to train big samples efficiently (with more learnable weights) but demanding big training sample for high performance
- ParT is a new Transformer-based architecture for Jet tagging, published in 2022.
  - Pair-wise variable (angle, mass etc.) is added to plain Transformer encoder to boost attention
- Surpasses the performance of ParticleNet
  - ParticleNet only looks “neighbor” particles while Transformer uses attention to learn where to look



	All classes	
	Accuracy	AUC
PFN	0.772	0.9714
P-CNN	0.809	0.9789
ParticleNet	0.844	0.9849
ParT	**0.861**	**0.9877**

Performance with JetClass event classification (100M sample)

https://agenda.linearcollider.org/event/11033/contributions/59588/attachments/41057/65491/260915-ildmtg-flavortag-suehara.pdf