The International Large Detector

A Versatile Detector for an Electron-Positron Collider at Energies up to 1 TeV

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ÉCOLE POLYTECHNIQUE

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EPS-HEP25, 7–11 july 2025, Marseille

CNRS NUCLÉAIRE & PARTICULES

Particle Flow

Best Jet Energy Resolution obtained from Full Reconstruction of single particles

- Charged best measured mostly from the trackers
- Neutrals only measured from calorimeters

→ Large Tracker

- Precision and low X_0 budget
- Pattern recognition

→ High precision on Si trackers

- Tagging of beauty and charm

→ Highly Granular Imaging Calorimetry

- Track–Cluster Matching & Discarding
- Particle Identification

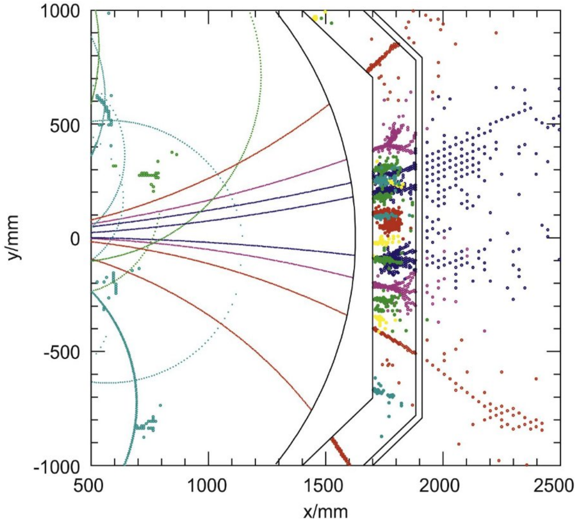
→ Large acceptance

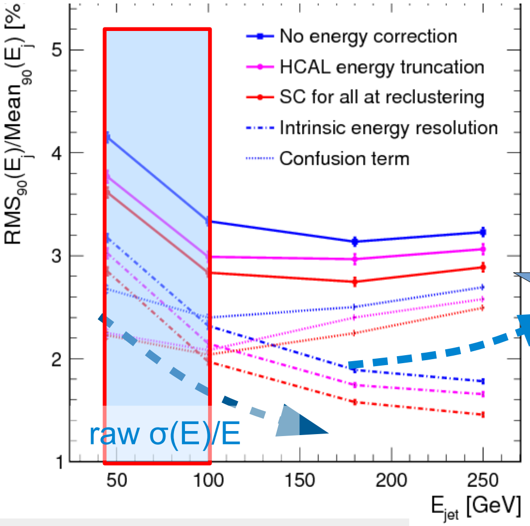
Particle Flow Algorithms :

- **Jets** = 65% Charged Tracks + 25% γ ECAL + 10% h^0 ECAL+HCAL
- **TPC** $\delta p/p \sim 2\text{-}5 \cdot 10^{-5}$; VTX $\sigma_{x,y,z} \sim 5–10$ µm

H. Videau and J. C. Brient, "Calorimetry optimised for jets," (CALOR 2002)

Pandora PFA: EPJ C77 (2017) 10, 698





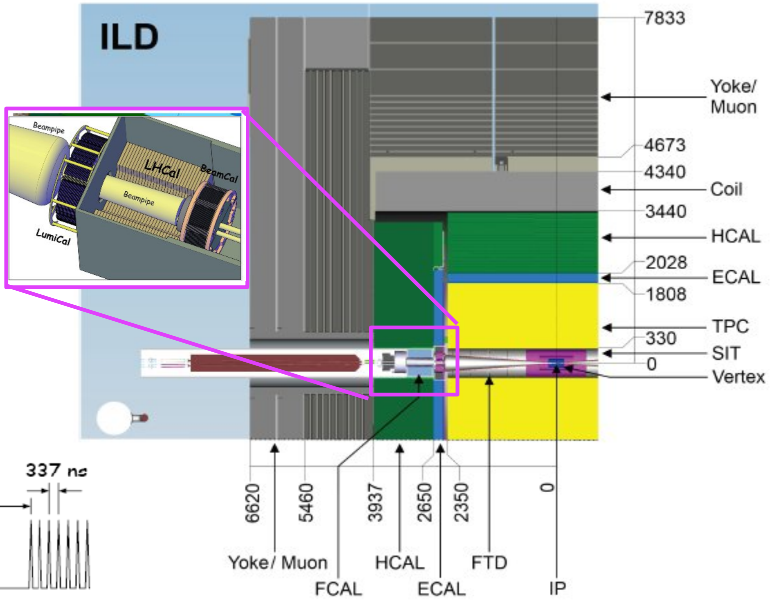
Software Weigthing

Confusion (cluster misattrib, merging)

Particle Flow Software

Low E jets ⇒ where PFA brings most

ILD : a Particle Flow (optimised) Detector

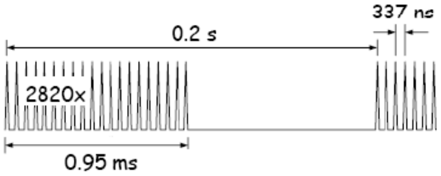


Detector layout

- Silicon Vertex (VTX) + Inner (FTD/SIT) Tracker
- Time Projection Chamber (TPC) as main tracker
  - Silicon External Tracker (SET) enhancing momentum resolution
- High-Granularity Calorimetry inside 3.5 T coil field ⬌ CALICE/DRD6
  - 4 options of calorimeters (Si | Scint)-W ECAL ⊗ (Scint A | RPC-SD)-HCAL
- Forward & Beam calorimetry: (Si | C | GaAs)-W ⬌ FCAL collaboration

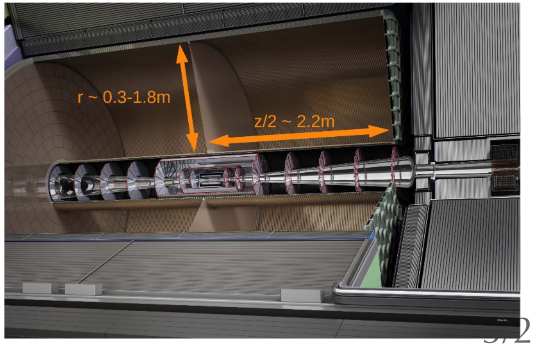
Functions:

- ToF from SET or (first layers of) ECAL
- DAQ: Triggerless & between trains
- Modest Irradiation (≤10^{11} n/cm²/yr, excl. FCAL)



Optimisations

- Designed for ILC500 [LoI: 2010; DBD(CDR): 2012; IDR: 2018]
  - Spin-off: CLIC-det (with SiD): ≤ 3 TeV
- Being adapted for Circular Coll. & HALHF
  - FCC-ee: CLD, ILD;   CEPC-Baseline



Silicon Tracking

Original General Scheme: Technology evolves rapidly

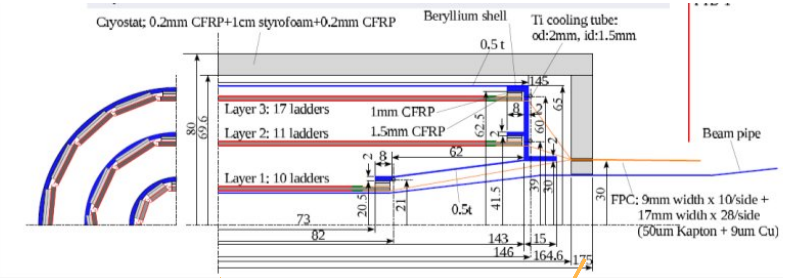
- **VTX** – 3 double layers of MAPS
- **FTD** – 7 discs
  - Inner 2 discs: pixel (similar to the vertex detector)
  - Outer 5 discs: strip (similar to SIT/SET)
- **SIT** – 2 double layers of strips between VTX & TPC

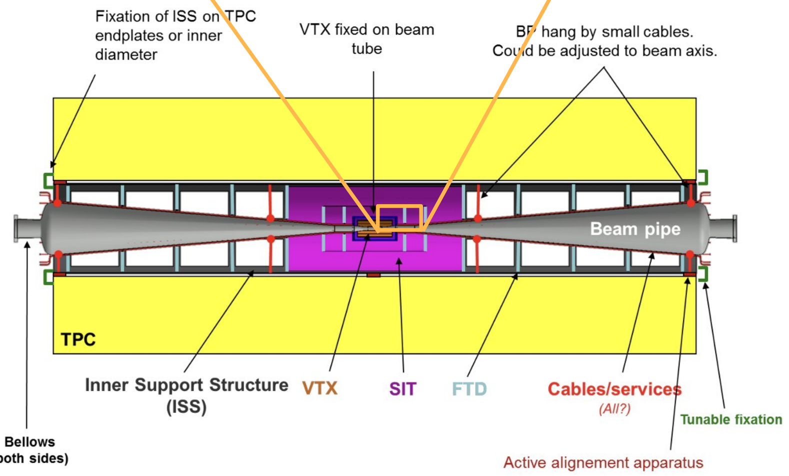
  TPC
- **SET** – 1 layer strip after TPC (barrel, endcap)

Functions / merits

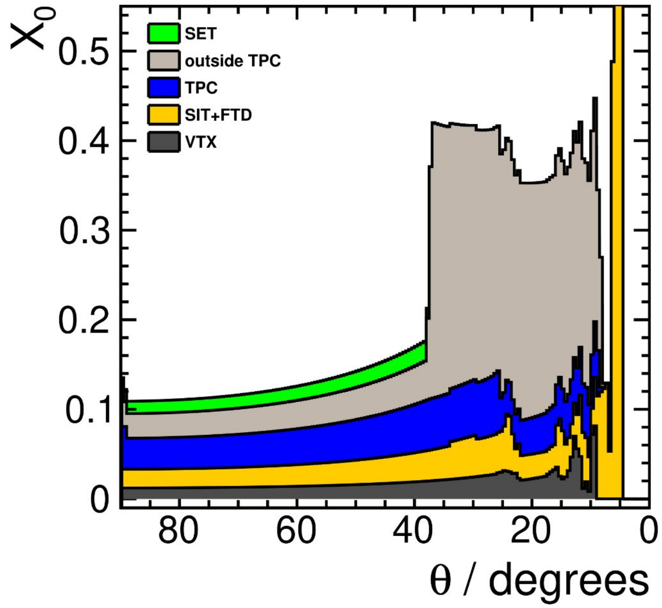
- Time stamping
- Precise points to connect VTX/TPC/ECAL
- Calibration of TPC

	R (mm)	$\|z\|$ (mm)	$\|\cos\theta\|$	σ (μm)	Readout time (μs)
Layer 1	16	62.5	0.97	2.8	50
Layer 2	18	62.5	0.96	6	10
Layer 3	37	125	0.96	4	100
Layer 4	39	125	0.95	4	100
Layer 5	58	125	0.91	4	100
Layer 6	60	125	0.9	4	100





Time Projection Chamber

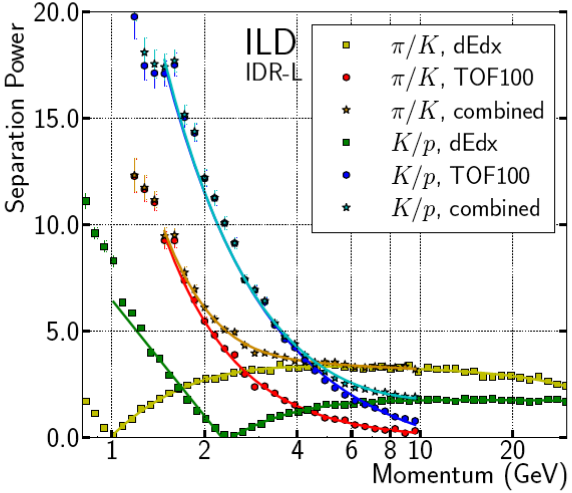


Tracking detectors should be as transparent as possible

- Particle Flow → as little material as possible in front of ECAL
- Momentum resolution dominated by multiple scattering at low momenta
- TPC: Low in-volume material → high chance of uninterrupted track segment within TPC
- Readout in endcaps close the calorimeters : MPGD (GEM, μMegas, ...)

Flavor studies require PID over wide momentum range

- Excellent charged hadron separation
- dE/dx or dN/dx (cluster counting) possible up to 50 GeV
- ToF data further improves low-momentum range



Detection of in-flight decays via continuous pattern recognition

- Important for BSM (See the two presentations from J. Klamka, and M.T. Núñez Pardo de Vera on staus and light scalars)

ILD : Calorimeters

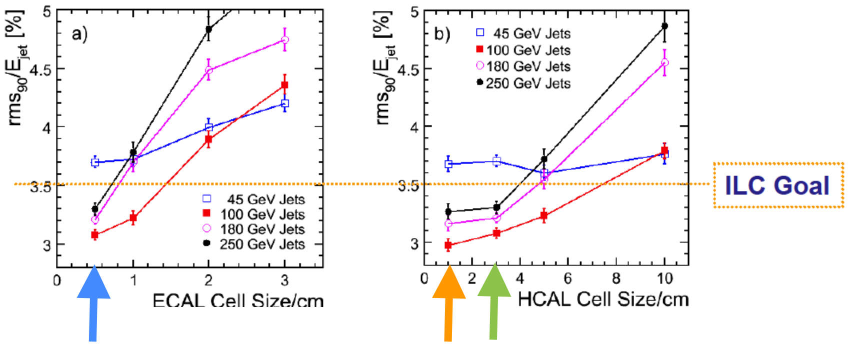
Particle Flow:

- Geometrically match high precision tracks with clusters ➞ Measure only neutral particles in Calo
  ⇒ Best Jet Energy Resolution (JER) and Boson Mass Resolution (BMR)

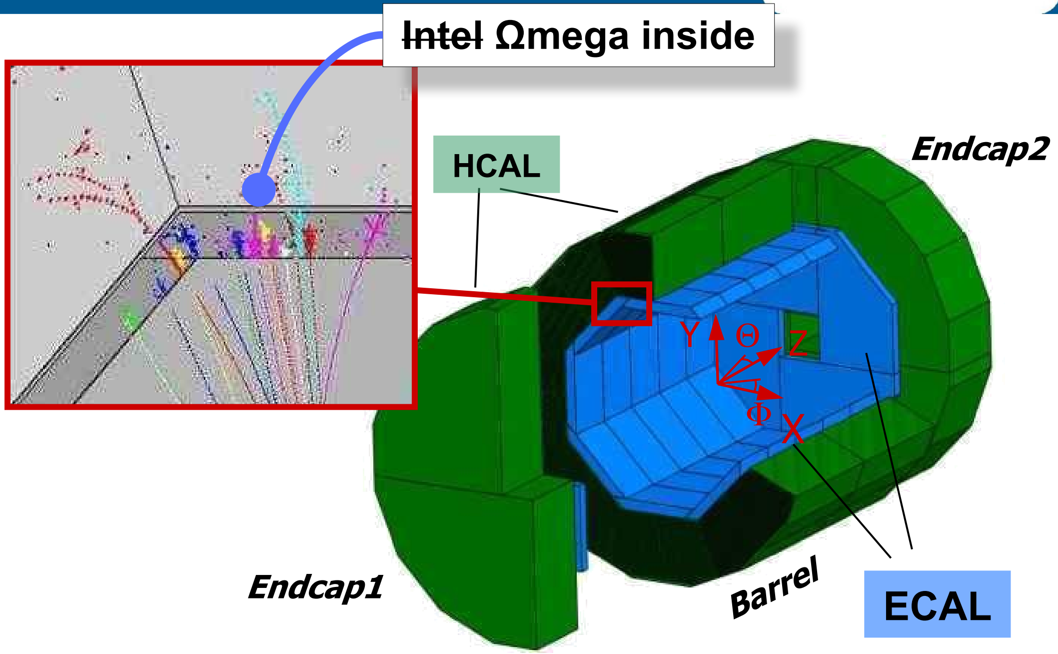
High Granularity Imaging Calorimeters

- "Optimal" granularity

★ In ILD detector model vary ECAL Si pixel size and HCAL tile size



- Designed for ILC
  - Power pulsing ➞ Passive cooling
  - Low occupancy ➞ Local memory, delayed Readout



ECAL: 30 layers

- SiW-ECAL": 0.5 × 0.5 cm² Si cells
- ScECAL 0.5 × 5 cm² Scint strips

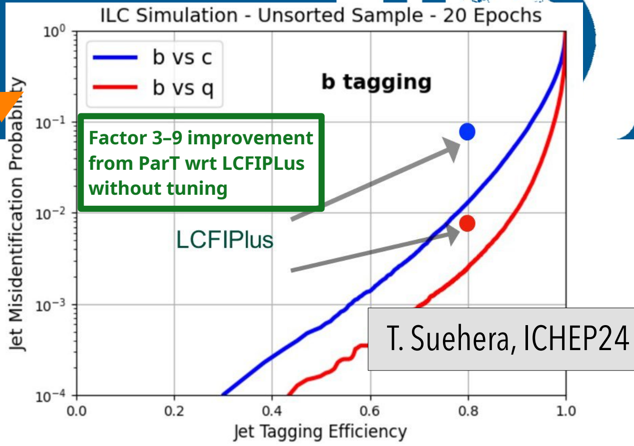
10–100M channels

HCAL: 48 layers

- AHCAL: 3×3 cm² Scint. cells
- ScECAL: 1×1 cm² RPC cells (Semi-Digital)

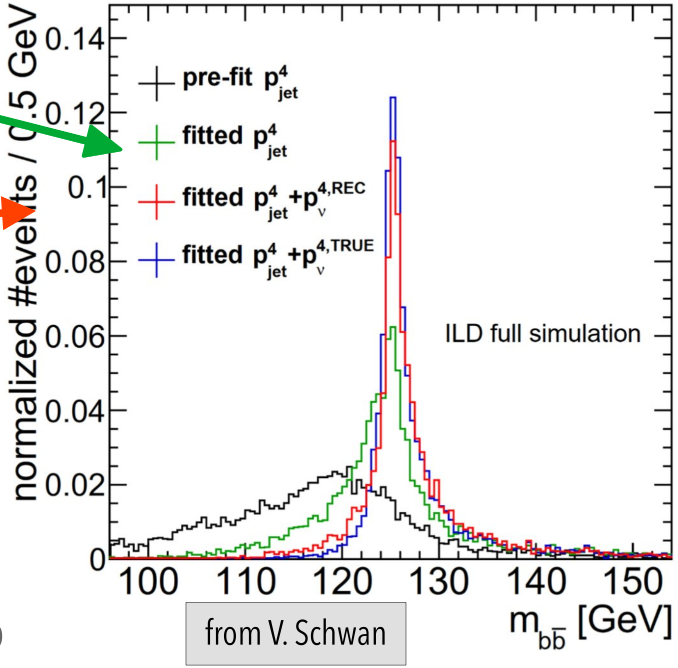
10–70M channels

Examples of Recent Improvements



Full simulation on b-jets

- **Flavor tagging**: Significant ML-driven gains over previous benchmark LCFIPlus (e.g. ParT)
- **Jet error estimation**: Now includes full covariance matrices of all PFOs
- **Kinematic fitting**: Supports physics hypothesis testing and improves reconstruction consistency
- **Semileptonic decay** correction: Enables neutrino 4-momentum reconstruction in many B-meson decays
- **Combined impact**: Di-jet mass resolution improved by factor ~ 2



On-going studies:

- Jet clustering confusion remains a key challenge — ML offers potential improvements
- (re)Development of Particle Flow algorithms with ML + Timing

List of Global Key requirements on ILD

Higgs physics

- Momentum resolution (for Higgs recoil against $Z \to \mu\mu$)
  - $\sigma(p_T)/p_T \approx 2 \cdot 10^{-5} \cdot p_T(\mathrm{GeV}/c) \oplus 0.2\,\%$
- for Z/W/H separation
  - Jet energy resolution ~3 % in multi-jet events
  - Particle Flow
- Precise impact parameter resolution for b- and c- quark tagging
  - $5\,\mu\mathrm{m} \oplus 10\,\mu\mathrm{m}/[p\,[\mathrm{GeV/c}] \cdot \sin^{3/2}\theta\,)$ hit resolution
- Hadron ID for s-quark tagging for $H \to s\bar{s}$

Electroweak and QCD

Tera-Z

- Absolute luminosity determination ~10^{-4}
- Acceptance definition ~10 µm
- Track angular resolution <0.1 µrad
- B field stability and mapping up to 10^{-6}

Heavy flavours

Tera-Z

- Impact parameter resolution
  - ~3 µm hit resolution
  - <0.1% X0 material budget per layer
- Beam pipe thickness <~0.35 mm @FCC-ee
  - Limiting ultimate material budget
- π^0/γ separation
  - High granularity ECAL and/or $\sigma(E)/E \approx$ % / (E)
- PID: π/K separation between 1–30 GeV and µ-ID

BSM

- Momentum resolution and impact parameter
- Detached vertices for long lived particles
  - Reconstruction of tracks up to meters
  - Photon direction
- Precise timing (~tens of ps)
- Detector hermeticity

(Adapted from P. Azzi & LCF vision)

Adaptation to FCC-ee

Adaptation to FCC-ee – Key elements

	ILC	FCC-ee
Crossing angles	14 mrad	30 mrad
L* (distance from IP to last accel. Focusing magnet)	4.1 m	2.0 m
Solenoid field	3.5 T	2.0 T
Addtional B-fields	anti-DID	− Compensating − Screening
Bunch separation	~350 ns @ 5–10 Hz	20–5000 ns cont.

Identical Physics : e^+e^- at 91, 165, 240, 360 GeV but

- Collisions rates × ≤ 20,000
- ≠ Machine-Detector Interface
- Higher Machine Backgrounds

MDI / forward region

- Mitigation of machine backgrounds — especially at high-luminosity Z-pole running

Different bunch structure of beam

- Impact on operation of Time Projection Chamber
- Thermal load management in subdetectors (no more power-pulsing)

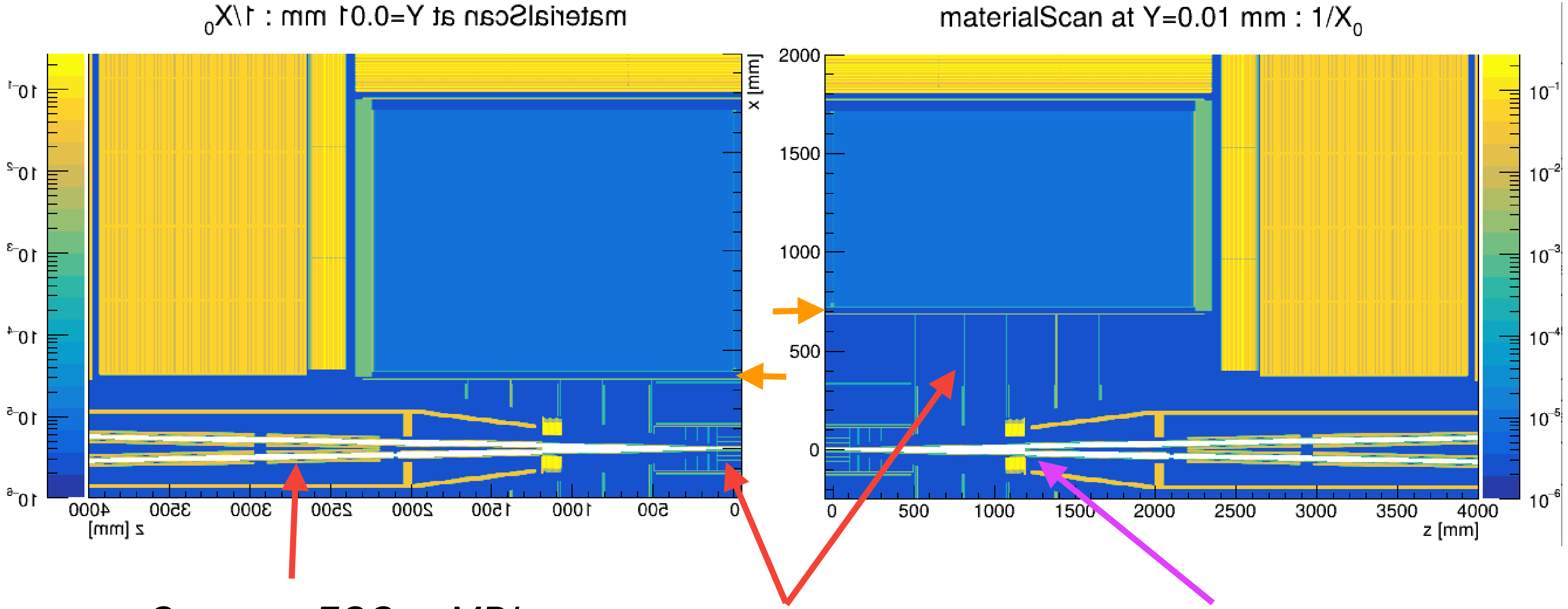
Miscellaneous

- Lower energies → less granular calorimeters ?
- No close-by detector (push-pull operation) → no need for self-shielding → thinner yoke ?
- If lower magnetic field (2T)→ Do we need a larger tracker ?

ILD FCC-ee in-developpment models

"o1": ILD-Like TPC

"o2": Shrinked TPC, more Si



Common FCCee MDI

Beampipe, LumiCal, quads, solenoids

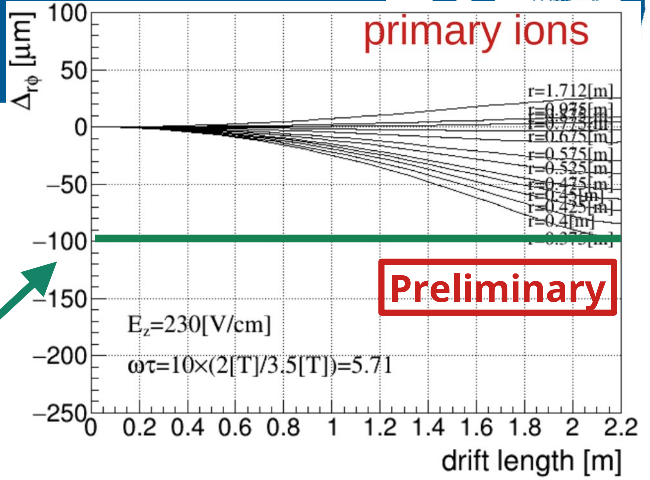
CLD-like silicon tracker

vertex, inner silicon

Beampipe forking

© D. Jeans

TPC: Estimating Magnitude of Distortions



Slow ion drift → space charge from many BXs (~20 000)

- Distorts the drift field
- Impacts the position resolution in $\Delta r\varphi$ (mostly in φ)
- Here: only primary ions considered (none from gas amplification)

Dominating source of primary ionization:

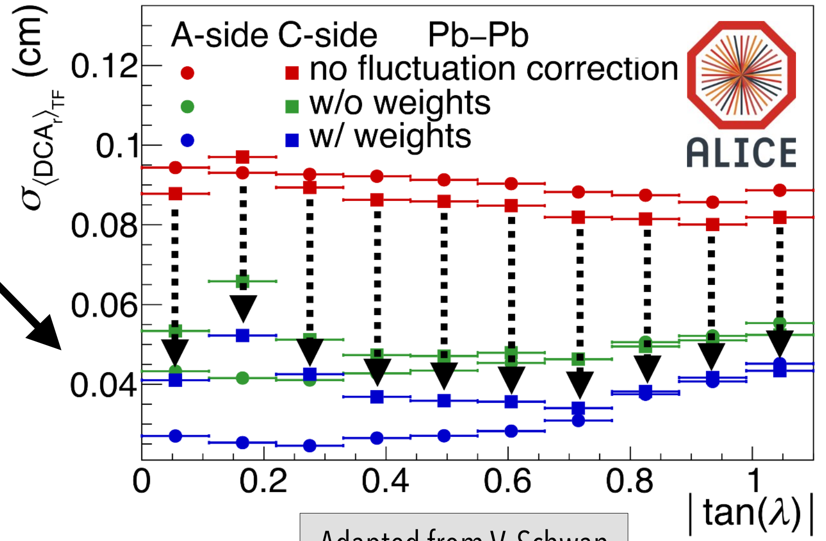
- Beamstrahlung dominates $e^+e^- \to qq$ (physics events) by two orders of magnitude
- Synchrotron radiation to be studied

Magnitude of distortions?

- ee→qq @ 90 GeV cause drift distortions in rφ of **~100 μm**
- Naive scaling to space charge density of beamstrahlung : **~20 mm**
- Consistent with ALICE TPC (Run 3): 20–120 fC/cm³ → **cm-level** distortions
  - ALICE demonstrates effective DCA correction

Small-TPC ILD@FCC model also looked at

- Distortion depends highly on inner radius.
- to be studied with full effects (secondary ions, event-by-event fluctuations and reconstruction)



Adapted from V. Schwan

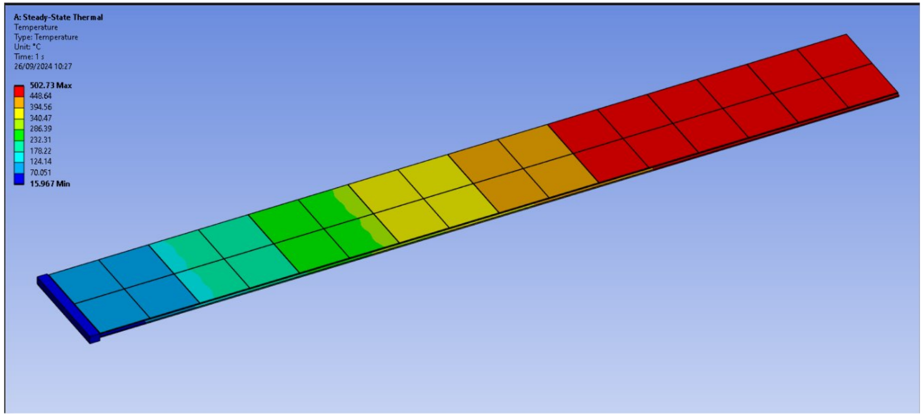
ECAL adaptation : Active cooling in SiW-ECAL Slabs

"Standart Slab":

- 8 ASU (1440mm), 8192 ch / 128 ASICs
- 128 W (1W/ASIC ~16 mW /ch)
- Adiabatic, heat bridge at one end

Passive cooling: Cu of 2mm (W, C ignored)

- Cont. mode ΔT = 500°C on Wafer surface at $t = \infty$
  - @ILC : power-pulsing 1 % Duty cycle ~ΔT ~ 6 °C, 0.5mm Cu



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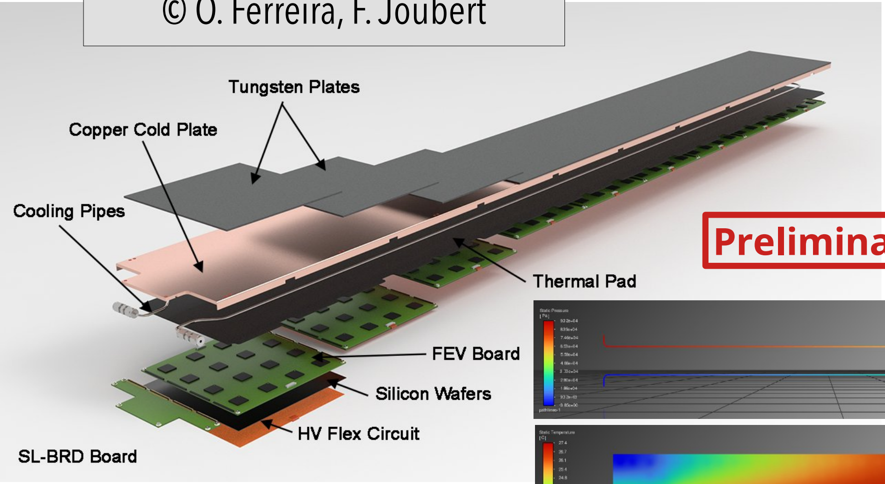
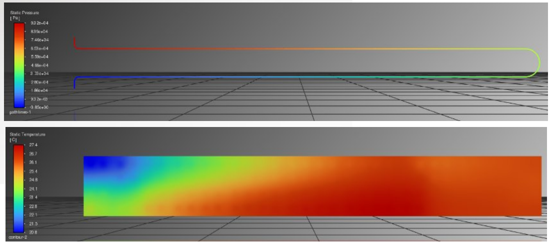


Preliminary



Active cooling (prelim.)

- 4mm Cu with 1/8″ steel tube,
- with 0.2 ℓ/min of water @ 15°C
- ΔP ~ 0,9 bar

ΔT = 6.6°C on Si surface at $t = \infty$

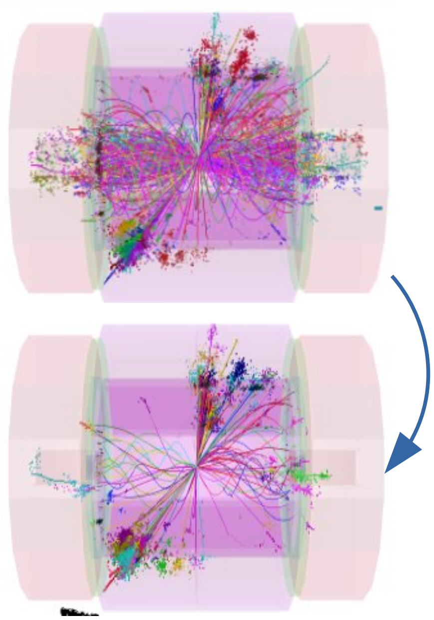
To be validated & investigated for HCAL's

Toward Centrimetric Time in Calorimeters (CTC)

1 cm/c = 30 ps

CMS HGCAL Legacy

Cleaning of Events

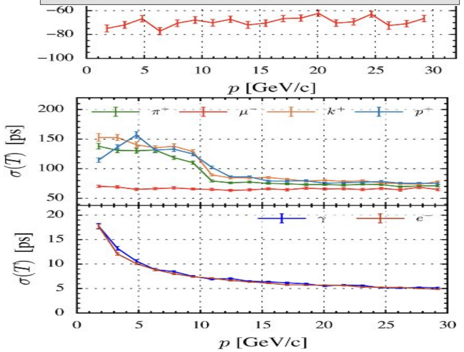


[CLIC CDR: 1202.5940]
adapted from L. Emberger

Particle ID by Time-of-Flight

- Complementary to dE/dx
- From : dedicated layers or CTC

Y. Che et al. [Eur. Phys. J. C 83, (2023) 93]
from 'ILD-like' (CEPC/HGCAL) SiW-ECAL

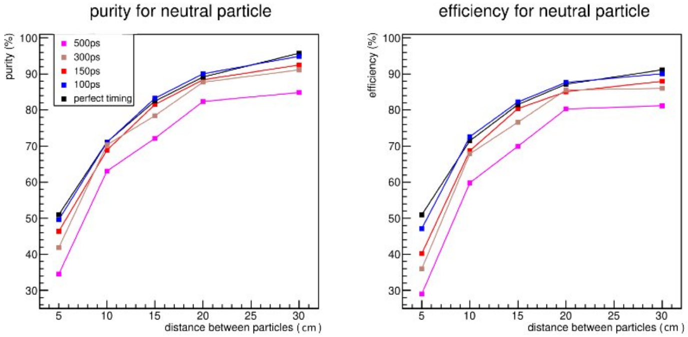


Ease Particle Flow with CTC

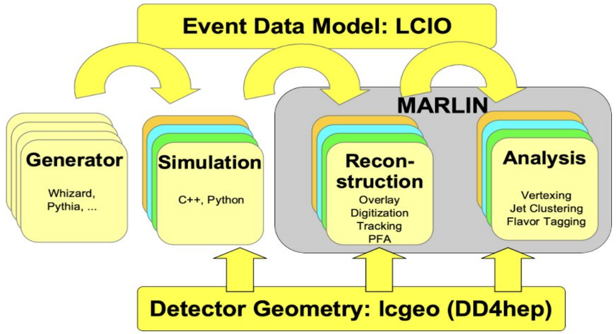
- Cleaning of late neutrons & back scattering (ns)
- Identify primers in showers
- Help against confusion
  better separation of showers
  - Requires '4D clustering'

Power budget ?

Separation of 30 GeV π- from 10 GeV K0L
in SDHCAL using APRIL
C. Devanne [ArXiV 2502.03555]

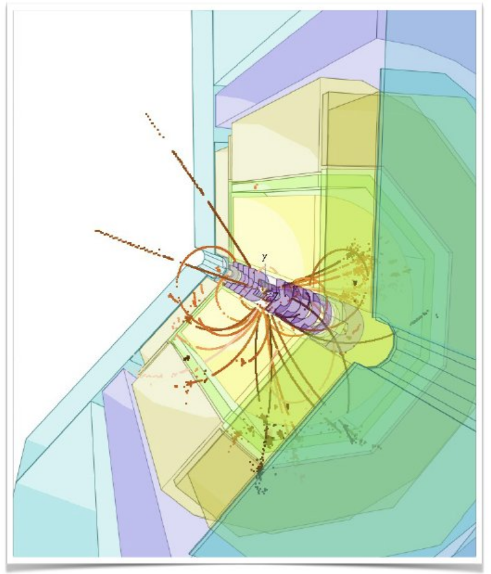


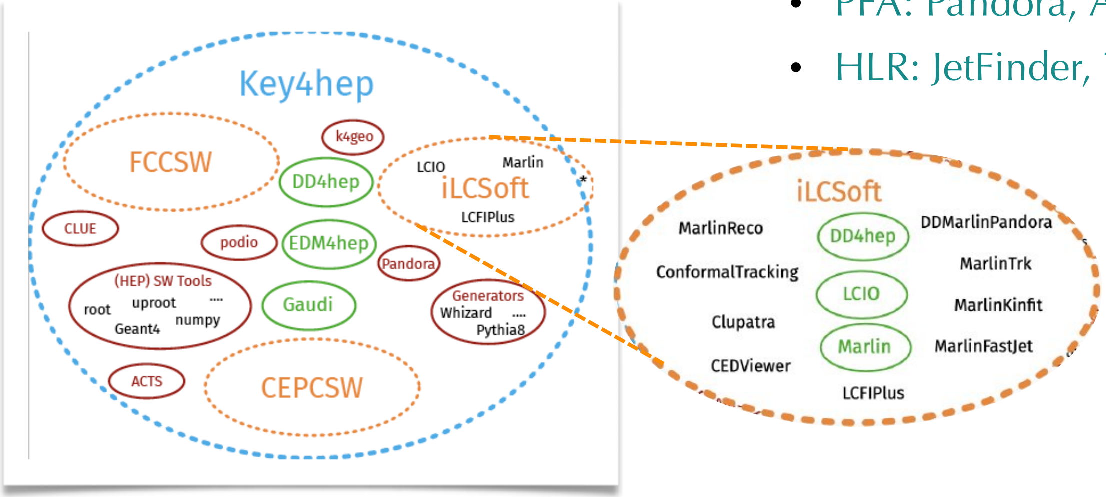
Software



From ILCSoft…

- Complete framework
- DD4Hep for geometry
- Many HL analysis package in Marlin
  - Tracking: conformal, Kalman,
  - PFA: Pandora, Arbor/APRIL,
  - HLR: JetFinder, ToF, PID, tagging





… to Key4HEP smoothly

- ⊃ ILCSoft
  - Gaudi MarlinWrapper
  - LCIO ⬌ EDM4HEP converters
- Now standard for all concepts
- New dev: ACTS, ML

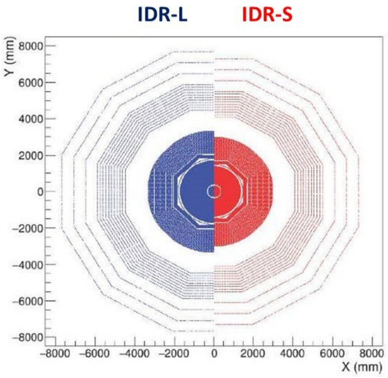
Skipped Topics

Enginering

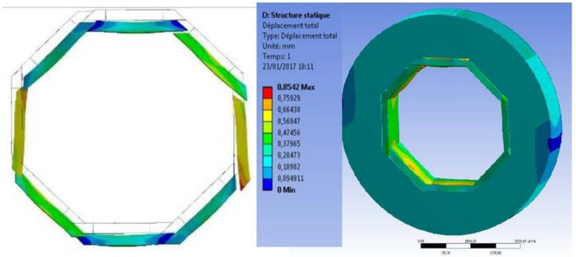
- Mechanical Stability (⊃ seismic)
- Services (cooling, DAQ, power)
  - Mechanical & GEANT4 Models
- Electronics & DAQ: rates and update of electronics

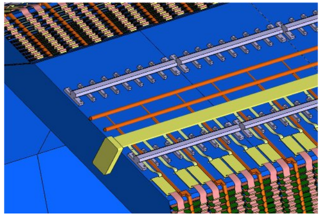
Costing

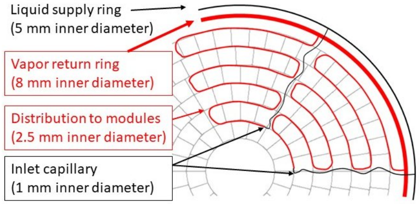
- Full Costing done for the DBD(CDR): 2012, updated in 2018 (IDR)
  - Including manpower and mounting procedures
  - 330 ~ 380 M€(2018)
    - Needs update
    - Option with reduced radius (and calorimeter layers)

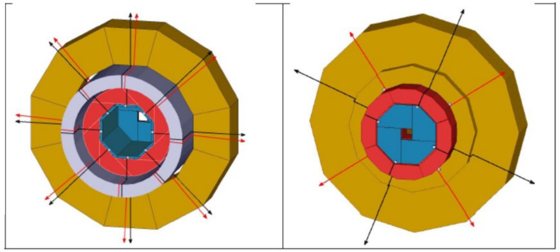


Detector	IDR-L	IDR-S
B-field	3.5 T	4 T
VTX inner radius	1.6 cm	1.6 cm
TPC inner radius	33 cm	33 cm
TPC outer radius	177 cm	143 cm
TPC length (z/2)	235 cm	235 cm
ECAL inner radius	180 cm	146 cm
ECAL outer radius	203 cm	169 cm
HCAL inner radius	206 cm	172 cm
HCAL outer radius	334 cm	300 cm
Coil inner radius	342 cm	308 cm









Conclusions & Perspectives

Complete Design for the ILC

- Full & Detailled Simulation Models
- Advanced Reconstruction & Performance tools
- Elements being/ to be revisited:
  - Readout electronics for calorimeters
  - Global Addition of timing
    - Particle Flow Code and non-Code (AI)
  - Estimate for Cost, Mounting operations

Re-design for the FCC-ee

- MDI & backgrounds
- Sharing of TPC vs Si tracking for Z-pole
- Re-evaluation of rates in sub-detectors
  - Cooling → Re-optimisation of ECAL

Versatile Detector:

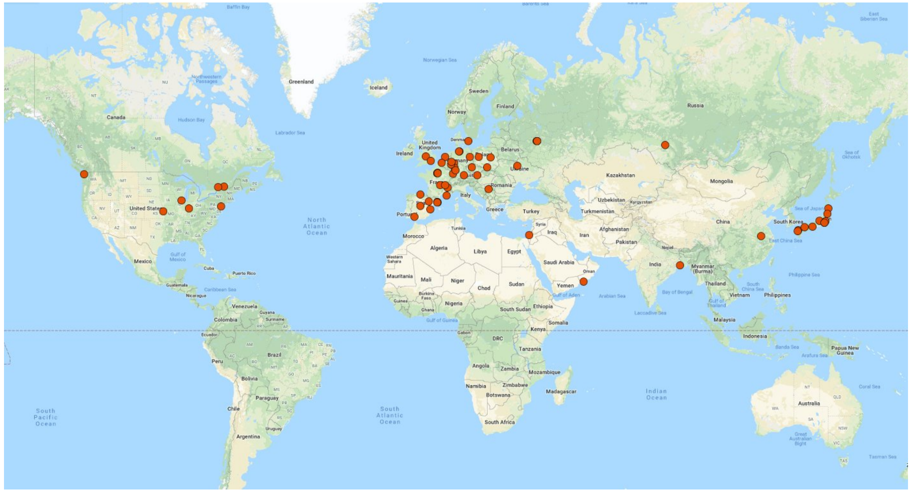
- Do not over-optimise
- High precision, High granularity opens opportunities:
  - ML, go 4D (5D in calorimetry)
  - Jet clustering, tagging, PID, …
- Open to new ideas: large MC samples avail.

Collaboration

58 institutes + ~10 guest members

Open:

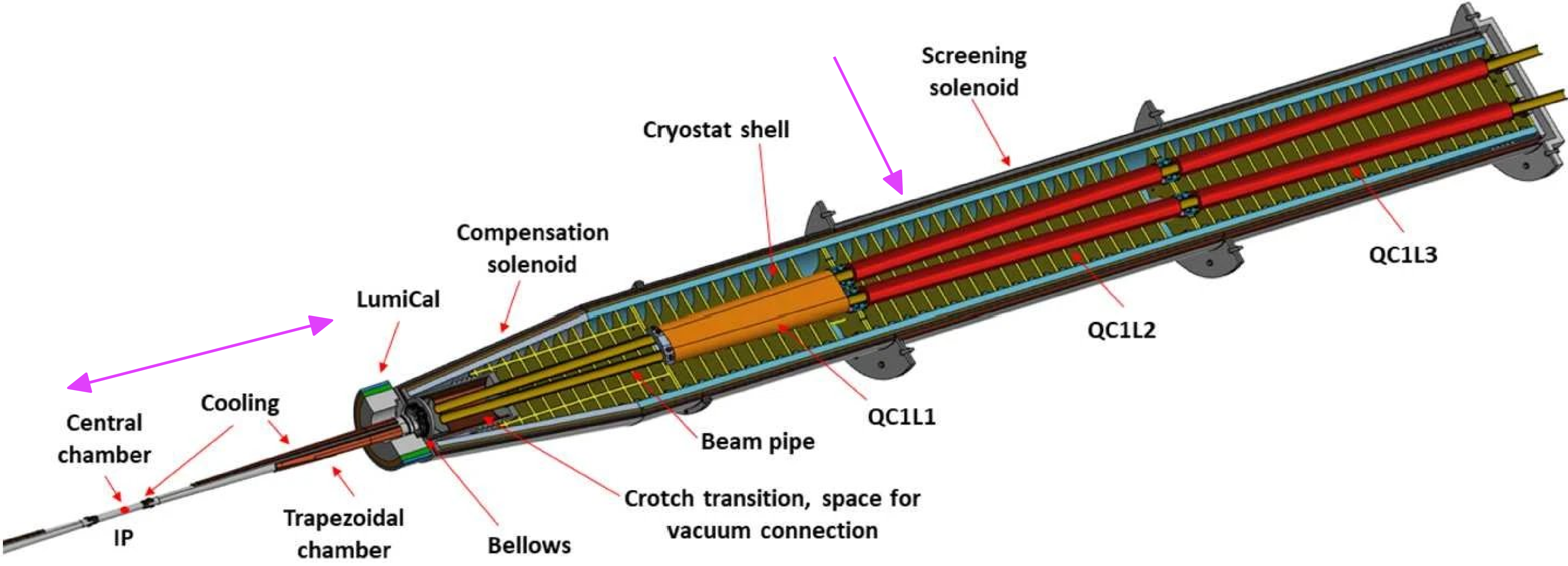
- Technologies not fixed — ILD offers a flexible platform for integrating emerging detector technologies
- Many opportunity to test innovative techniques (Det. Optimisation, ML, etc…)
- Guest Membership for Dedicated studies (large MC sample)
- Contact us for further collaboration



ILD-related contributions at EPS-HEP25

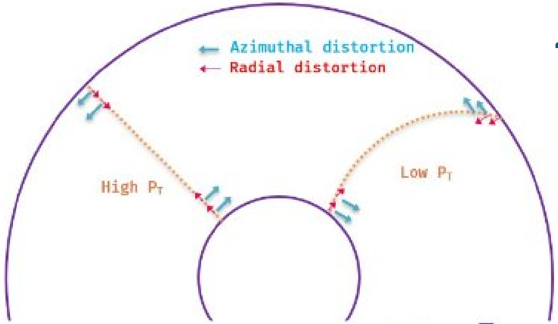
- J. Klamka: Long-Lived Particle Searches at a Future Higgs Factory with the ILD experiment
- J. Klamka: BSM searches at the linear collider facility
- M. Nunez Padro de Vera, *Prospects for light exotic scalar measurements at the e+e– Higgs factory*
- K. Mekala: *Determination of the first-generation quark couplings at the Z-pole*
- K. Mekala: *Top and Electroweak physics at the linear collider facility*
- M. Nunez Padro de Vera, *Stau searches at future e+e– colliders*
- G. Moortgat-Pick: *A Linear Collider Vision for the Future of Particle Physics*
- Poster: *A Silicon-Tungsten ECAL for Higgs Factory Detectors*

Extras


Screening
solenoid
Cryostat shell
Compensation
solenoid
LumiCal
QC1L3
QC1L2
QC1L1
Cooling
Central
chamber
Beam pipe
Crotch transition, space for
vacuum connection
IP
Trapezoidal
chamber
Bellows

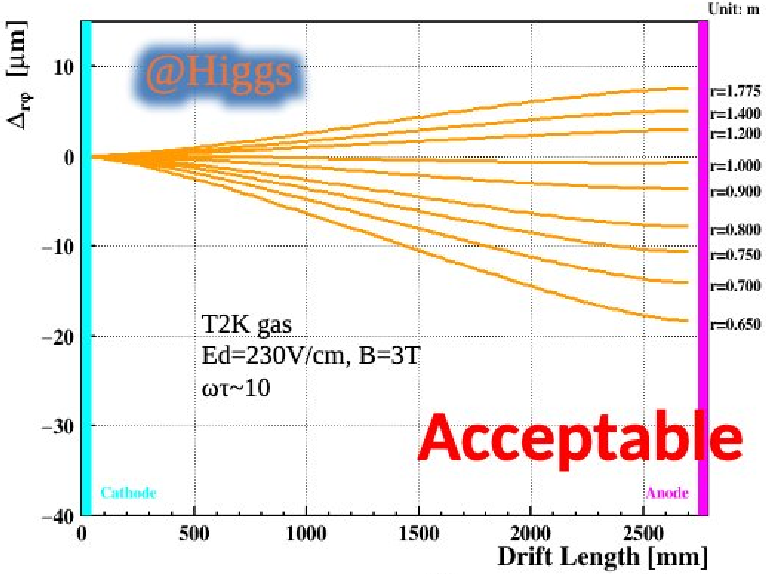
TPC distortion caused by primary ions

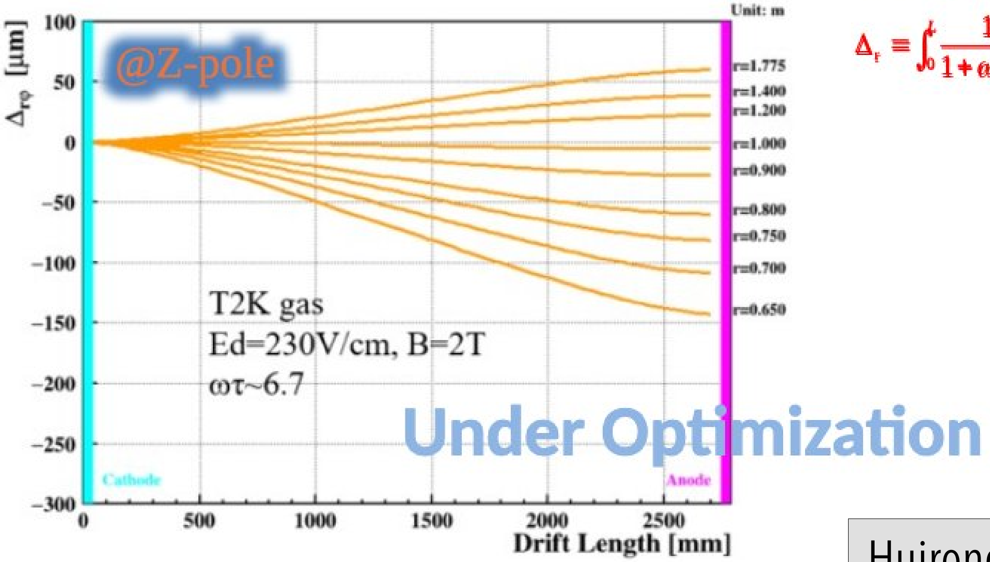
- Radial distortion (Δ_r) is much smaller than azimuthal distortion, almost imperceptible when along the track for most P_T track **IBF×Gain=1, same primary ion level**
  - Azimuthal distortion ($\Delta_{r\varphi}$) has much more serious impact both on high/low P_T track
  - The maximum $\Delta_{r\varphi}$ is 20μm@Higgs (**acceptable**)
  - The maximum $\Delta_{r\varphi}$ is 150μm@Z-pole (**need to optimization of MDI**)
    - Including Pair + Single Beam



$$\Delta_{r\varphi} = \int_0^L \frac{\omega\tau}{1+\omega^2\tau^2} \times \frac{E_r}{E_z} dz$$

$$\Delta_r = \int_0^L \frac{1}{1+\omega^2\tau^2} \times \frac{E_r}{E_z} dz$$





Numerical calculation results of TPC distortion based on Green's function

Huirong Qi

Detector Parameters

Technology	Detector	Start (mm)	Stop (mm)	Comment
Pixel detectors	Vertex	$r_{in} = 16$	$r_{out} = 58$	3 double layers of silicon pixels
	Forward tracking	$z_{in} = 220$	$z_{out} = 371$	2 Pixel disks
	SIT	$r_{in} = 153$	$r_{out} = 303$	2 double layers of Si pixels
Silicon strip	Forward tracking	$z_{in} = 645$	$z_{out} = 2212$	5 layers of Si strips
	SET	$r_{in} = 1773$	$r_{out} = 1776$	1 double layer of Si strips
Gaseous tracking	TPC	$r_{in} = 329$	$r_{out} = 1770$	MPGD readout, 220 points along the track, Alternative: pixel readout
Silicon tungsten calorimeter	ECAL option	$r_{in} = 1805$	$r_{out} = 2028$	30 layers of 5×5 mm^2 pixels
	ECAL EC option	$z_{in} = 2411$	$z_{out} = 2635$	30 layers of 5×5 mm^2 pixels
	Luminosity calorimeter	$r_{in} = 83$ $z_{in} = 2412$	$r_{out} = 194$ $z_{out} = 2541$	30 layers
Diamond tungsten or GaAs calorimeter	Beam calorimeter	$r_{in} = 18$ $z_{in} = 3115$	$r_{out} = 140$ $z_{out} = 3315$	30 layers
SiPM-on-Tile	ECAL alternative	$r_{in} = 1805$	$r_{out} = 2028$	30 layers, 5 mm strips, crossed
	ECAL EC alternative	$z_{in} = 2411$	$z_{out} = 2635$	30 layers, 5 mm strips, crossed
	HCAL option	$r_{in} = 2058$	$r_{out} = 3345$	48 layers, 3×3 cm^2 pixels
	HCAL EC option	$z_{in} = 2650$	$z_{out} = 3937$	48 layers, 3×3 cm^2 pixels
RPC	HCAL option	$r_{in} = 2058$	$r_{out} = 3234$	48 layers, 1×1 cm^2 pixels
	HCAL EC option	$z_{in} = 2650$	$z_{out} = 3937$	48 layers, 1×1 cm^2 pixels
SiPM on scintillator bar	Muon	$r_{in} = 4450$	$r_{out} = 7755$	14 layers
	Muon EC	$z_{in} = 4072$	$z_{out} = 6712$	up to 12 layers