



The International Large Detector

A Versatile Detector for an Electron-Positron Collider

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ILD : a Particle Flow (optimised) Detector



Detector layout

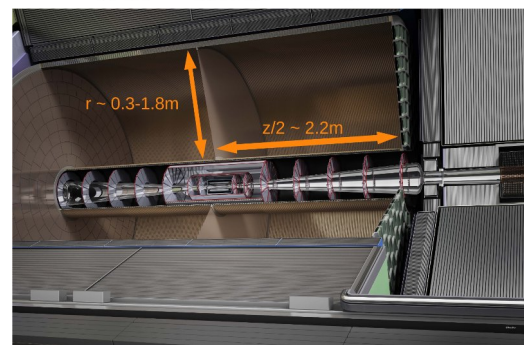
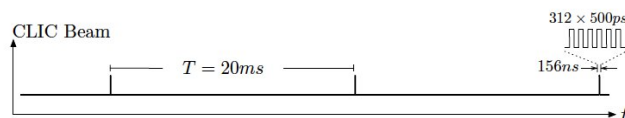
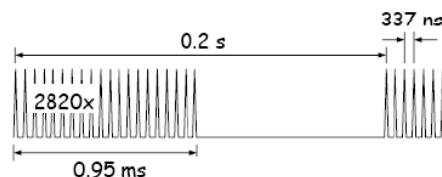
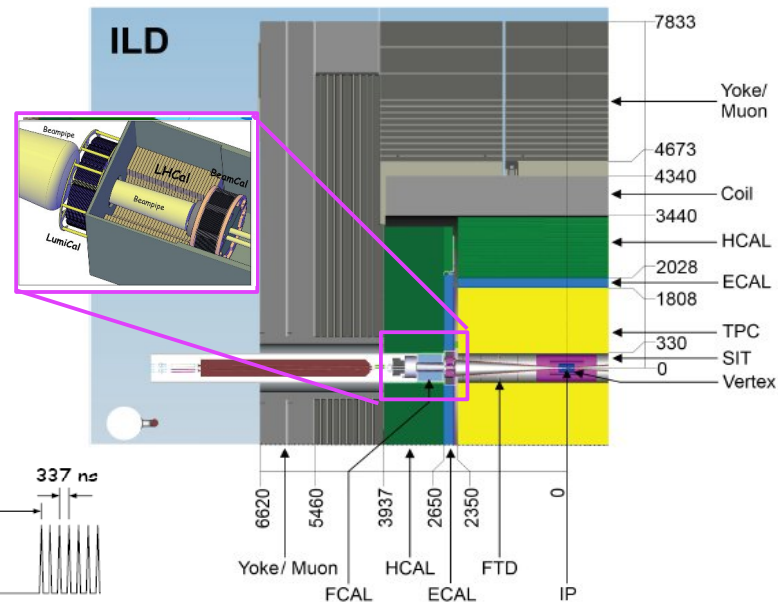
- Silicon Vertex (VTX) + Inner (FTD/SIT) Tracker
- Time Projection Chamber (TPC) as main tracker
 - Silicon External Tracker (SET) enhancing momentum resolution
- High-Granularity Calorimetry inside 3.5 T coil field $\leftrightarrow$ CALICE/DRD6
 - 4 options of calorimeters (Si | Scint)-W ECAL $\otimes$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

Functions:

- ToF from SET or (first layers of) ECAL
- DAQ: Triggerless & between trains
- Modest Irradiation ($\leq 10^{11}$ 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



- **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)

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

[illegible]

Time Projection Chamber

Tracking detectors should be as transparent as possible

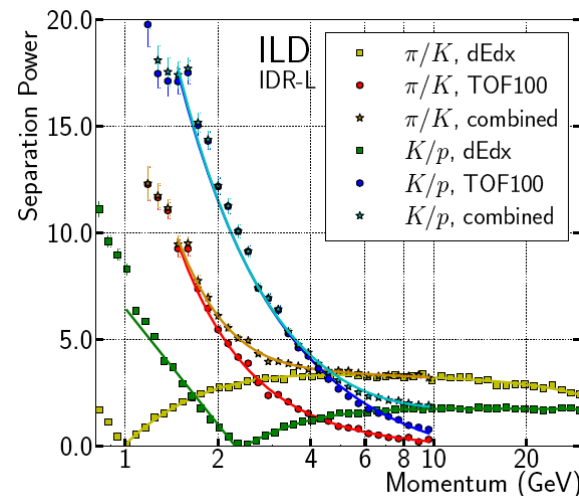
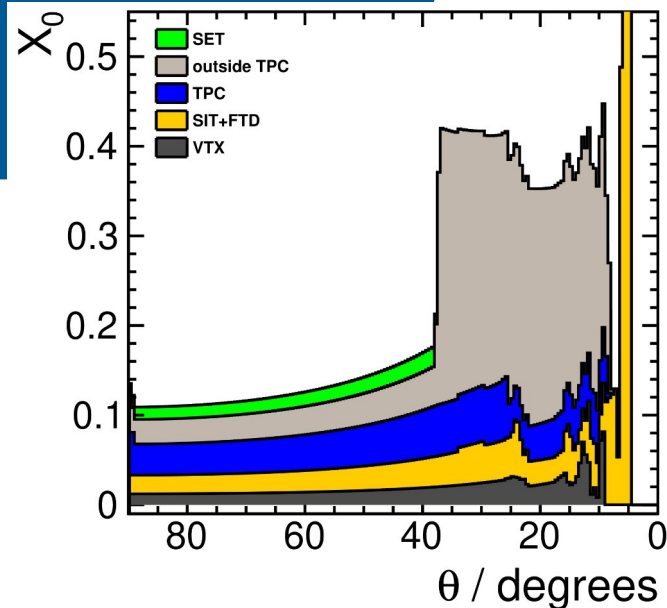
- Particle Flow → as little material as possible in front of ECAL
- Momentum resolution dominated by multiple scattering at low momenta
- TPC: Low in-volume material → high chance of uninterrupted track segment within TPC
- Readout in endcaps close the calorimeters : MPGD (GEM, μ Megas, ...)

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](#) at EPS-HEP)



ILD : Calorimeters



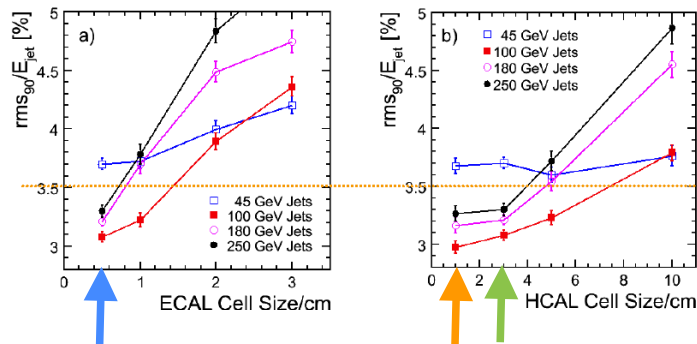
Particle Flow:

- 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

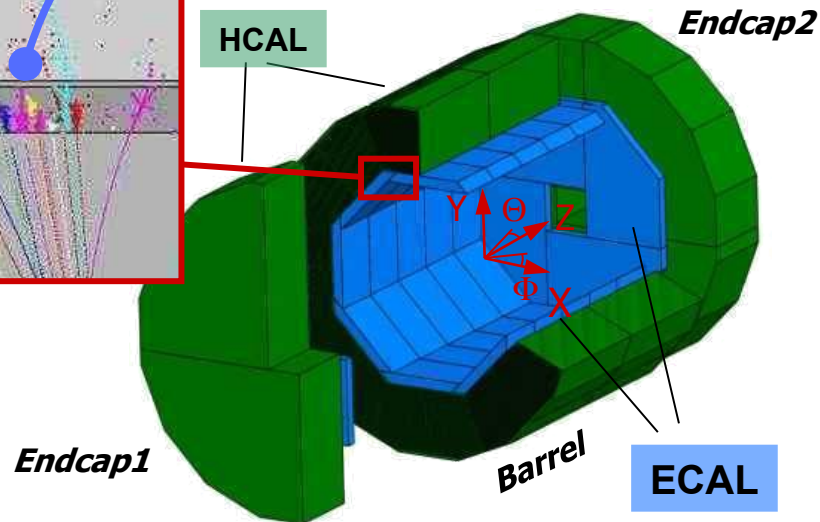
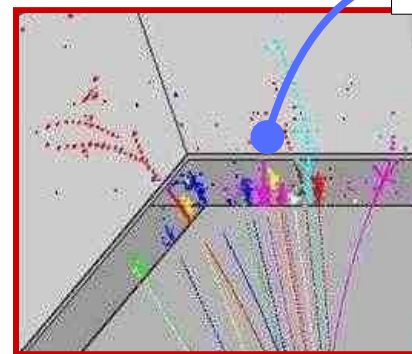
★ In ILD detector model vary ECAL Si pixel size and HCAL tile size



- Designed for ILC

- Power pulsing → Passive cooling
- Low occupancy → Local memory, delayed Readout

Intel Ω mega inside



ECAL: 30 layers

- SiW-ECAL: $0.5 \times 0.5 \text{ cm}^2$ Si cells
- ScECAL $0.5 \times 5 \text{ cm}^2$ Scint strips

10–100M channels

HCAL: 48 layers

- AHCAL: $3 \times 3 \text{ cm}^2$ Scint. cells
- ScECAL: $1 \times 1 \text{ cm}^2$ RPC cells (Semi-Digital)

10–70M channels

Examples of Recent Improvements

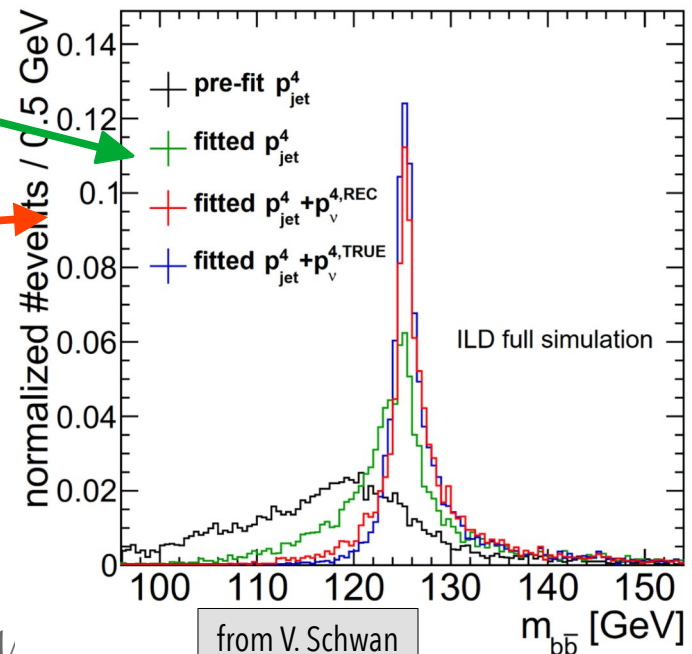
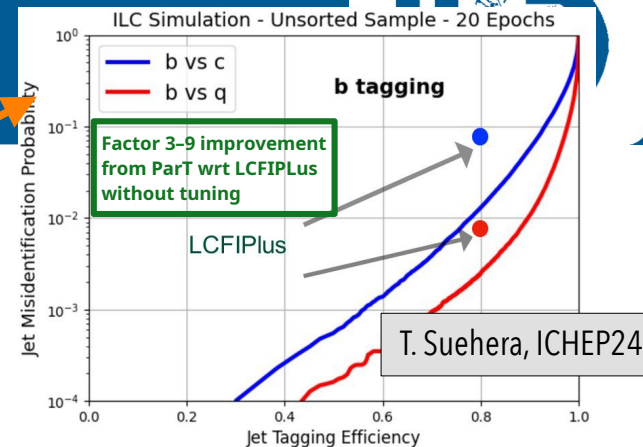
Full simulation on b-jets

- **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

See e.g. T. Pasquier, G. Marchiori



Adaptation to FCC-ee

Adaptation to FCC-ee – Key elements

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

- Collisions rates $\times \leq 20,000$
- $\neq$ Machine-Detector Interface
- Higher Machine Backgrounds

MDI / forward region

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

	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 (3 ?) T
Additional B-fields	anti-DID	– Compensating – Screening
Bunch separation	~350 ns @ 5–10 Hz	20–5000 ns cont.

Different bunch structure of beam

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

Miscellaneous

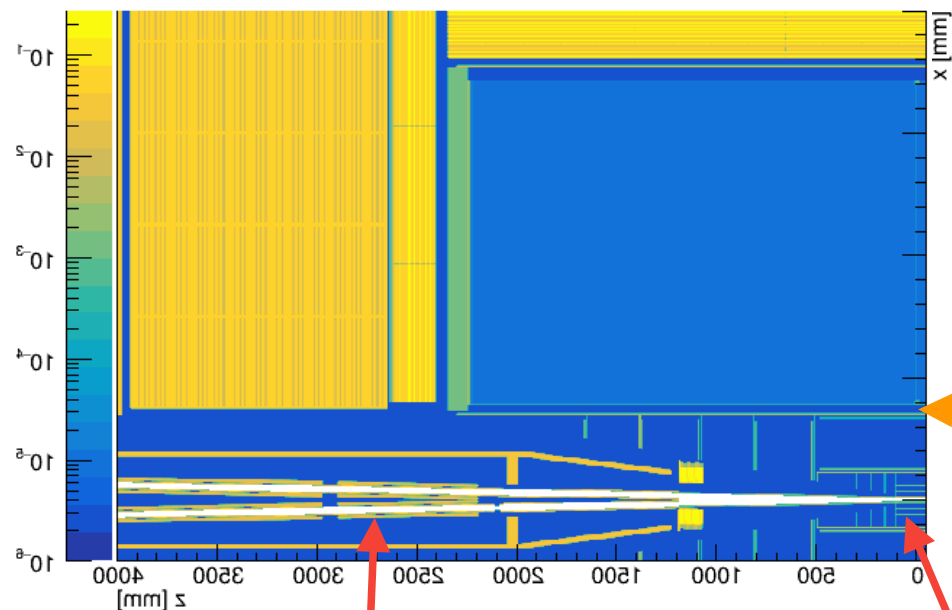
- Lower energies $\rightarrow$ less granular calorimeters ?
- No close-by detector (push-pull operation) $\rightarrow$ no need for self-shielding $\rightarrow$ thinner yoke ?
- If lower magnetic field (2T) $\rightarrow$ Do we need a larger tracker ?

ILD FCC-ee in-development models



“o1”: ILD-Like TPC

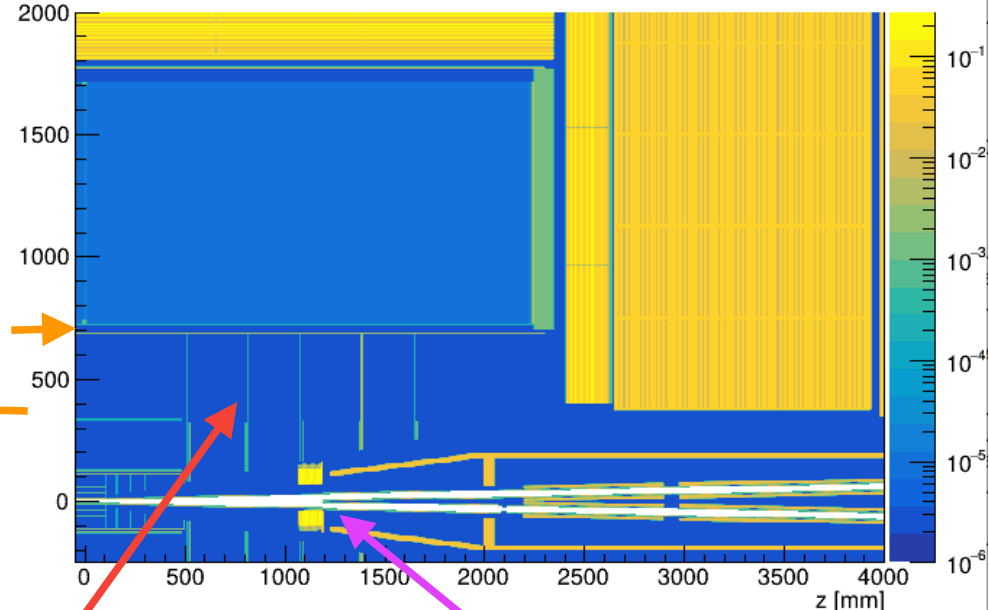
materialScan at $Y=0.01$ mm : $1/X_0$



*Common FCCee MDI
Beampipe, LumiCal,
quads, solenoids*

“o2”: Shrunk TPC, more Si

materialScan at $Y=0.01$ mm : $1/X_0$



*CLD-like silicon tracker
vertex, inner silicon*

*Beampipe
forking*

TPC: Estimating Magnitude of Distortions

Slow ion drift → space charge from many BXs ($\sim 20\,000$)

- Distorts the drift field
- Impacts the position resolution in Δr_ϕ (mostly in ϕ)
- Here: only primary ions considered (none from gas amplification)

Dominating source of primary ionization:

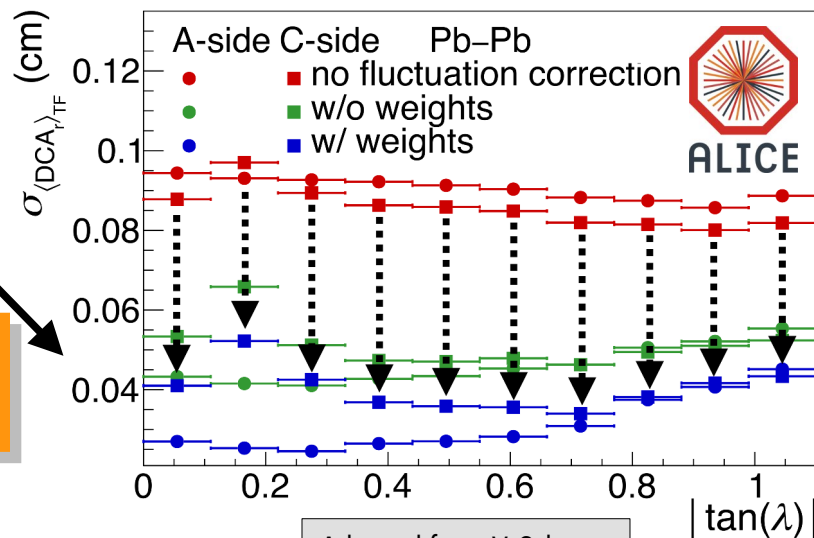
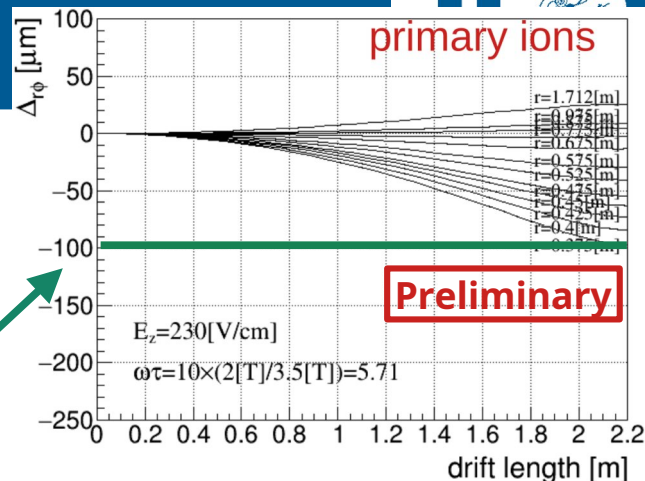
- Beamstrahlung dominates $e^+e^- \rightarrow q\bar{q}$ (physics events) by two orders of magnitude
- Synchrotron radiation to be studied

Magnitude of distortions?

- $ee \rightarrow q\bar{q}$ @ 90 GeV cause drift distortions in r_ϕ of $\sim 100\,\mu\text{m}$
- Naive scaling to space charge density of beamstrahlung : $\sim 20\,\text{mm}$
- Consistent with ALICE TPC (Run 3): $20\text{--}120\,\text{fC}/\text{cm}^3 \rightarrow \text{cm-level}$ 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)



See P. Colas for up-to-date info:
 Ar/He/Ne, 2/3T, Vd, ...

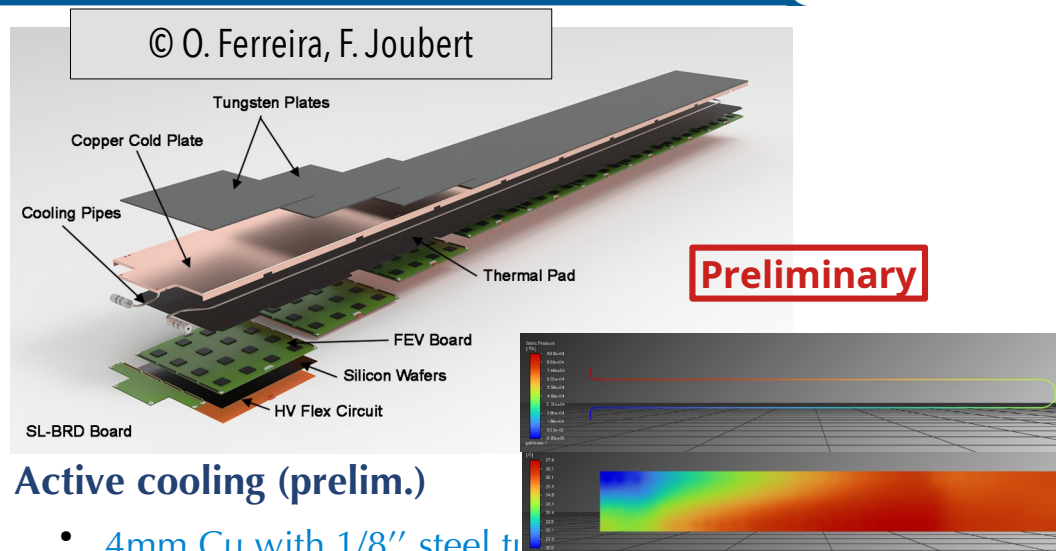
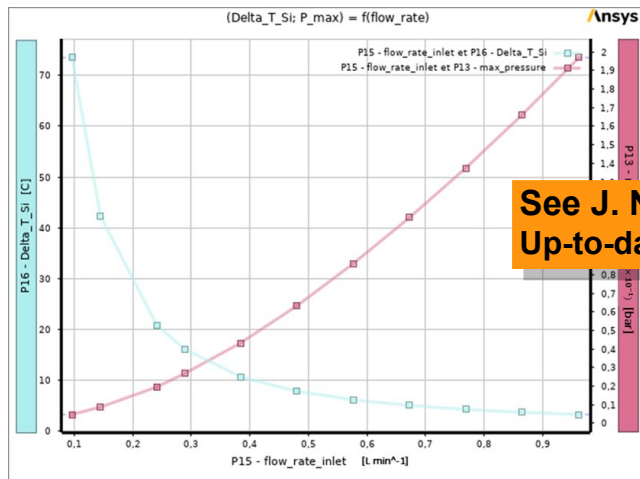
ECAL adaptation : Active cooling in SiW-ECAL Slabs

“Standard 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 $\Delta T = 500^{\circ}\text{C}$ on Wafer surface at $t = \infty$
 - @ILC : power-pulsing 1 % Duty cycle $\sim \Delta T \sim 6^{\circ}\text{C}$, 0.5mm Cu

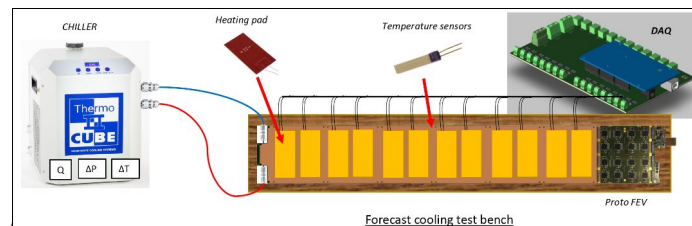


Active cooling (prelim.)

- 4mm Cu with 1/8" steel tube
- with 0.2 ℓ /min of water @ 15°C
- $\Delta P \sim 0,9$ bar

$\Delta T = 6.6^{\circ}\text{C}$ on Si surface at $t = \infty$

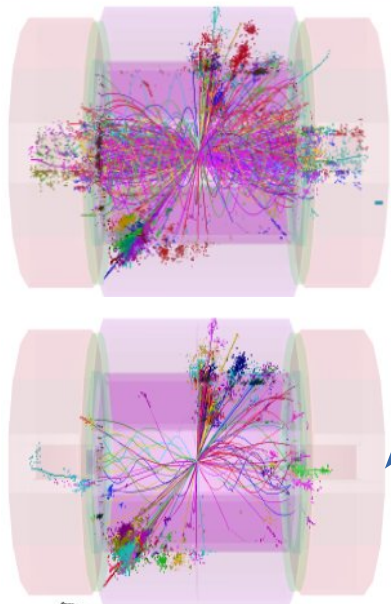
To be validated by prototype:



Toward Centrimetric Time in Calorimeters (CTC)

1 cm/c = 30 ps

Cleaning of Events



CMS
HGCAL
Legacy

Particle ID by Time-of-Flight

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

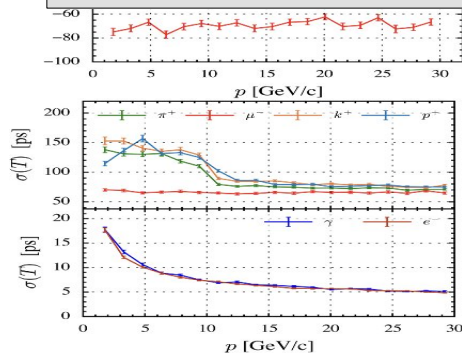
Ease Particle Flow with CTC

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

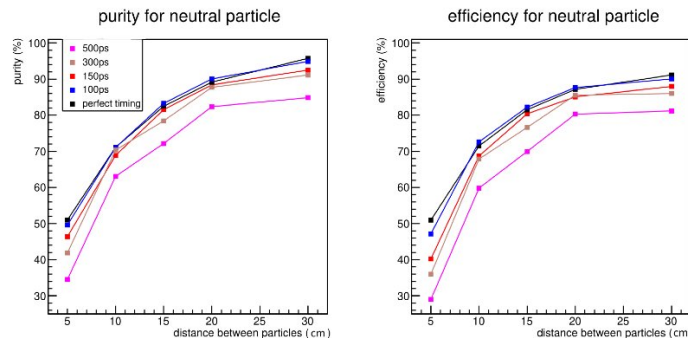
Power budget ?

[CLIC CDR: 1202.5940]
adapted from L. Emberger

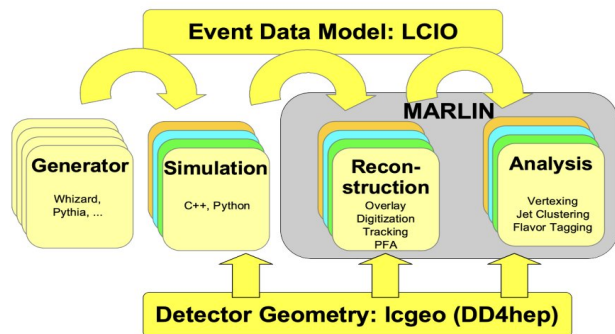
Y. Che et al. [Eur. Phys. J. C 83, (2023) 93]
from 'ILD-like' (CEPC/HGCAL) SiW-ECAL



Separation of 30 GeV $\tau\tau$ from 10 GeV KOL
in SDHCAL using APRIL
C. Devanne [ArXIV 2502.03555]

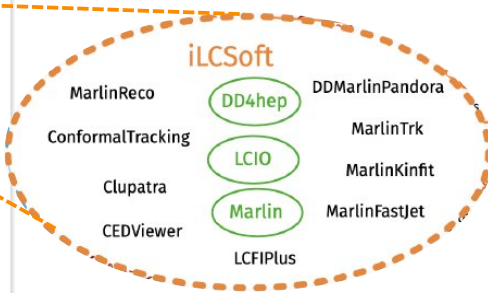
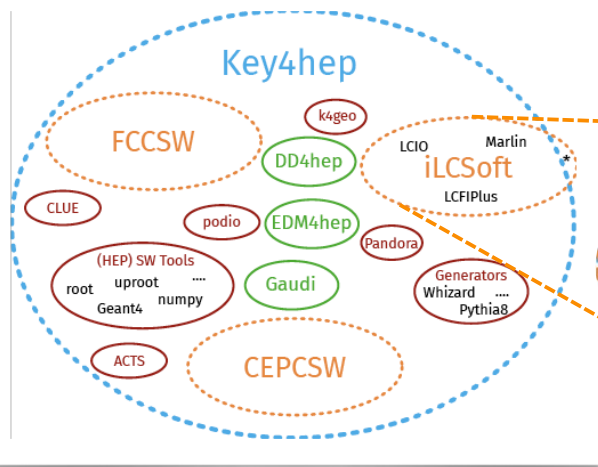
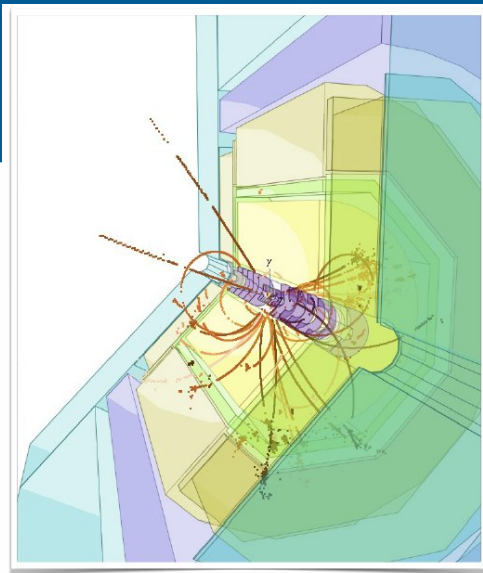


Software



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

- $\supset$ ILCSoft
 - Gaudi MarlinWrapper
 - LCIO $\leftrightarrow$ EDM4HEP converters
- Now standard for all concepts
- New dev: ACTS, ML

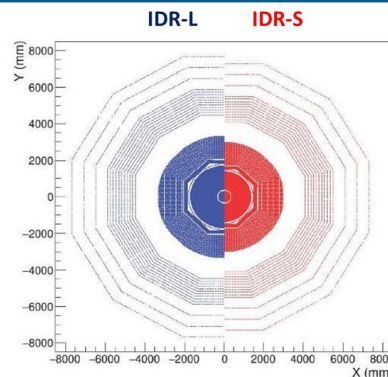
Skipped Topics

Engineering

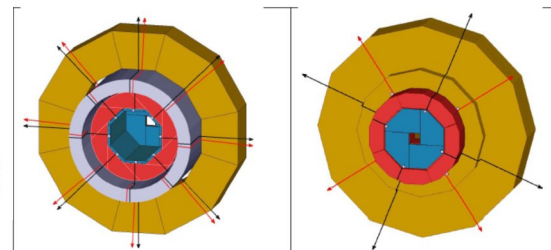
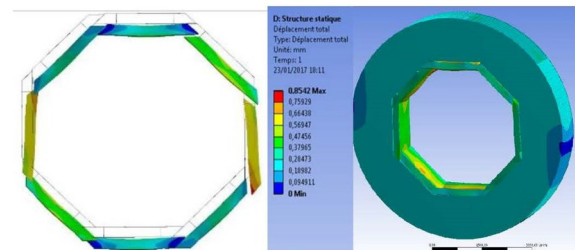
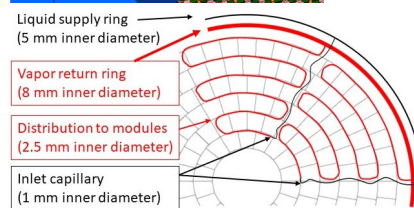
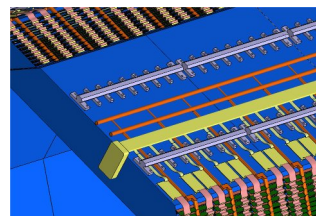
- Mechanical Stability ($\supset$ seismic)
- Services (cooling, DAQ, power)
 - Mechanical & GEANT4 Models
- Electronics & DAQ: rates and update of electronics

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 & Detailed 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

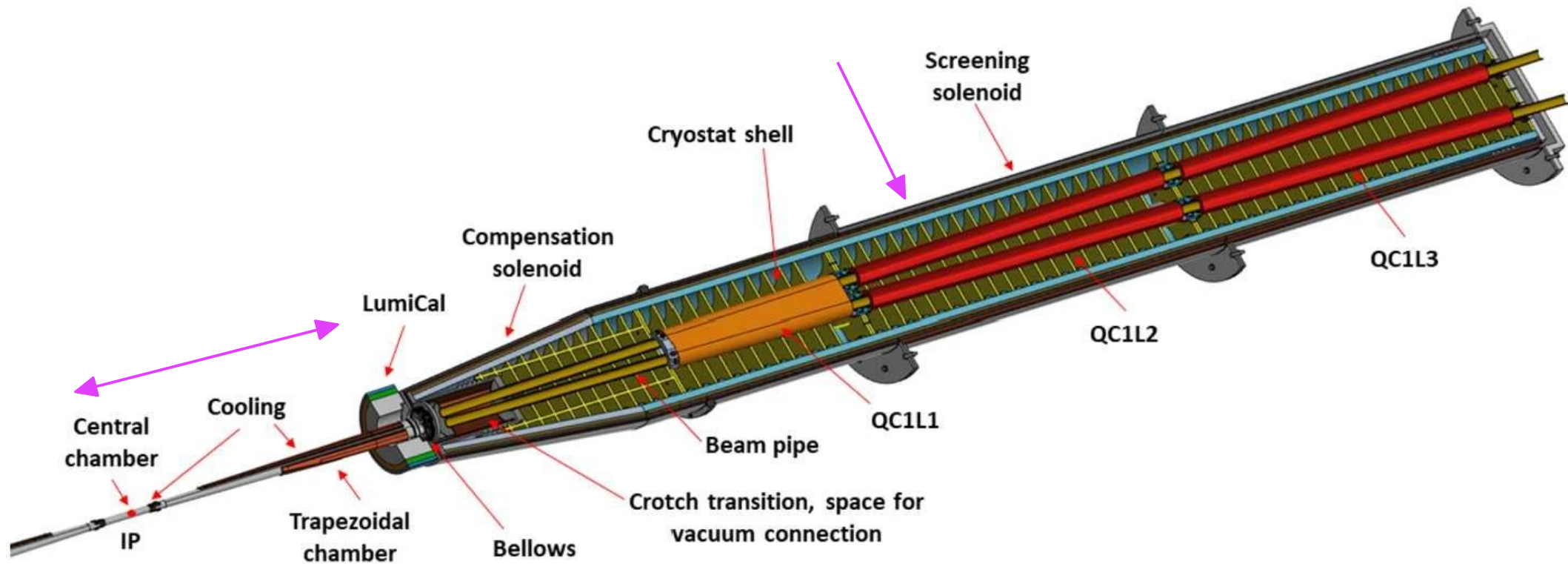
Re-design for the FCC-ee

- 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-optimize
- High precision, High granularity opens opportunities:
 - ML, go 4D (5D in calorimetry)
 - Jet clustering, tagging, PID, ...
- Open to new ideas and people: large MC fullsim samples available.

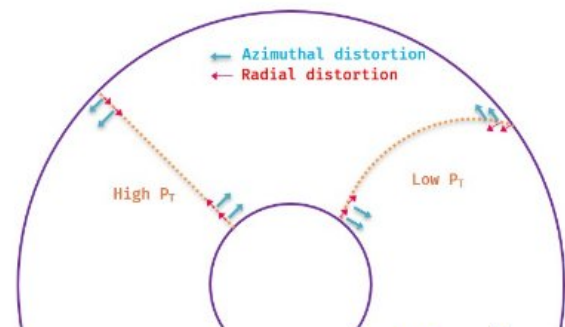
Extras



TPC distortion caused by primary ions

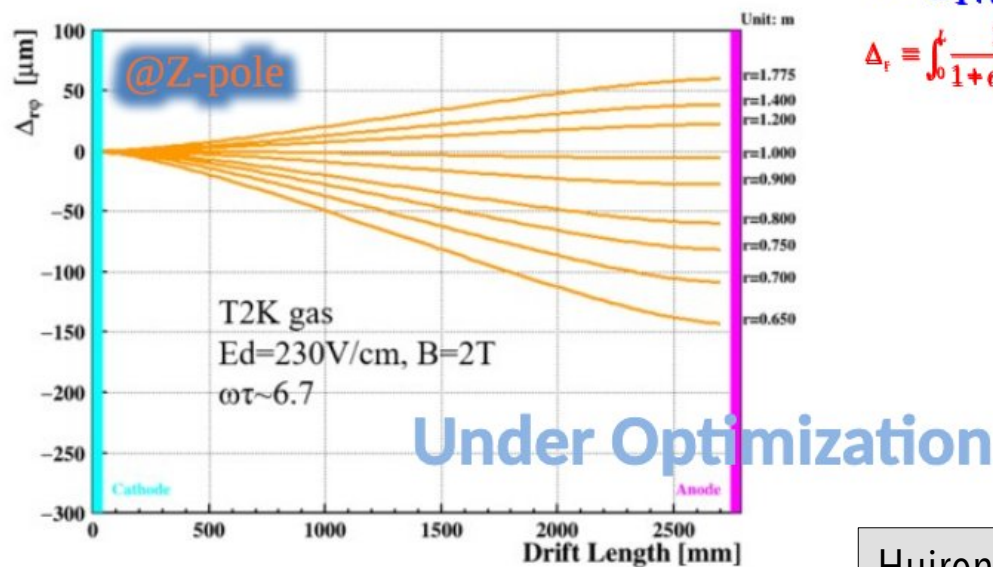
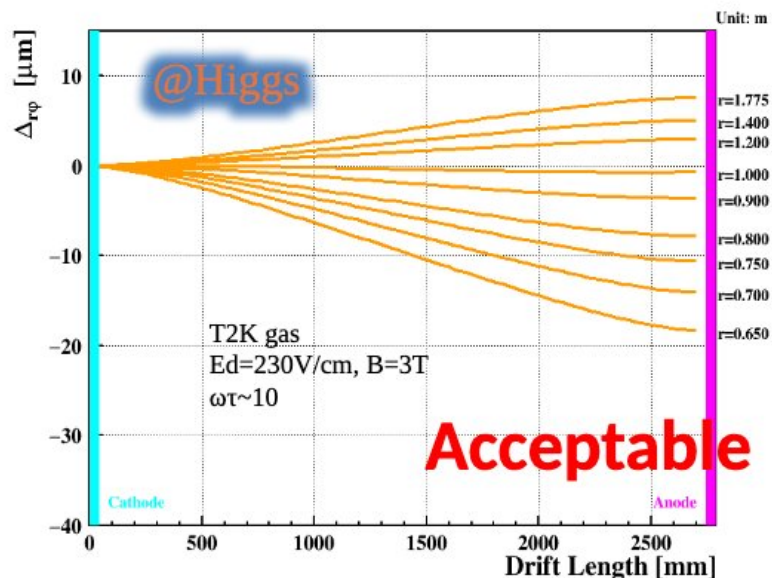
- Radial distortion (Δ_r) is much smaller than azimuthal distortion, almost imperceptible when along the track for most P_T track

IBF×Gain=1, same primary ion level
- Azimuthal distortion ($\Delta_{r\phi}$) has much more serious impact both on high/low P_T track
- The maximum $\Delta_{r\phi}$ is $20\mu\text{m}@$ Higgs (**acceptable**)
- The maximum $\Delta_{r\phi}$ is $150\mu\text{m}@$ Z-pole (**need to optimization of MDI**)
 - Including Pair + Single Beam



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

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



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

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 $5 \times 5 \text{ mm}^2$ pixels
	ECAL EC option	$z_{in} = 2411$	$z_{out} = 2635$	30 layers of $5 \times 5 \text{ mm}^2$ pixels
	Luminosity calorimeter	$r_{in} = 83$	$r_{out} = 194$	30 layers
		$z_{in} = 2412$	$z_{out} = 2541$	
Diamond tungsten or GaAs calorimeter	Beam calorimeter	$r_{in} = 18$	$r_{out} = 140$	30 layers
		$z_{in} = 3115$	$z_{out} = 3315$	
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, $3 \times 3 \text{ cm}^2$ pixels
	HCAL EC option	$z_{in} = 2650$	$z_{out} = 3937$	48 layers, $3 \times 3 \text{ cm}^2$ pixels
RPC	HCAL option	$r_{in} = 2058$	$r_{out} = 3234$	48 layers, $1 \times 1 \text{ cm}^2$ pixels
	HCAL EC option	$z_{in} = 2650$	$z_{out} = 3937$	48 layers, $1 \times 1 \text{ cm}^2$ 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