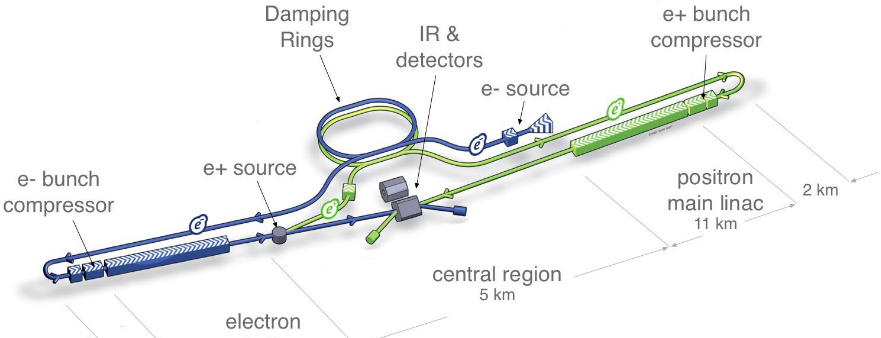
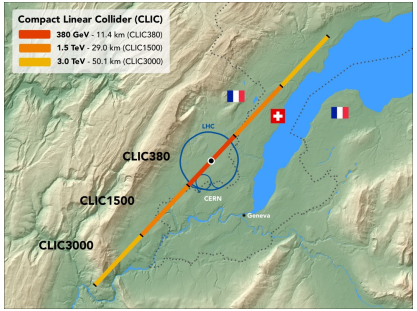
INTERNATIONAL WORKSHOP ON FUTURE LINEAR COLLIDERS

Argonne NATIONAL LABORATORY

Recent Developments in Detector Concept Studies

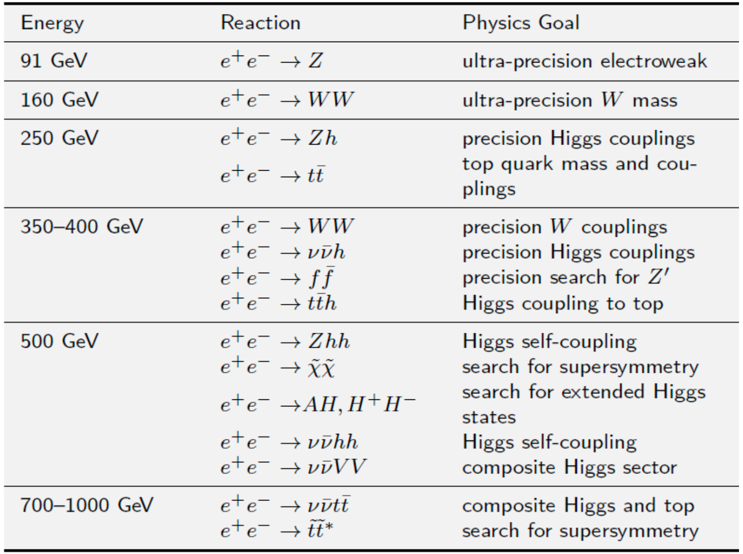




Jinlong Zhang
For CLIC, ILD, SiD

May 15, 2023

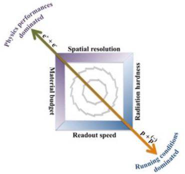
ILC Experimental Environment

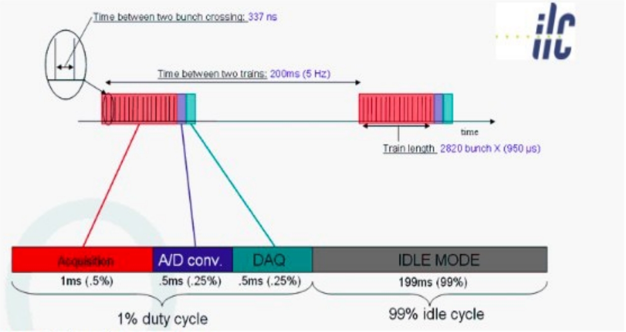


Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$ $e^+e^- \to t\bar{t}$	precision Higgs couplings top quark mass and couplings
350–400 GeV	$e^+e^- \to WW$ $e^+e^- \to \nu\bar{\nu}h$ $e^+e^- \to f\bar{f}$ $e^+e^- \to t\bar{t}h$	precision W couplings precision Higgs couplings precision search for Z' Higgs coupling to top
500 GeV	$e^+e^- \to Zhh$ $e^+e^- \to \tilde{\chi}\tilde{\chi}$ $e^+e^- \to AH, H^+H^-$ $e^+e^- \to \nu\bar{\nu}hh$ $e^+e^- \to \nu\bar{\nu}VV$	Higgs self-coupling search for supersymmetry search for extended Higgs states Higgs self-coupling composite Higgs sector
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}t\bar{t}$ $e^+e^- \to \tilde{t}\tilde{t}*$	composite Higgs and top search for supersymmetry

Lepton Colliders provide much cleaner experimental conditions, therefore, to maximize physics performance by pursuing ultimate detector performance

- much lower backgrounds
- much less radiation,





N.B. Final numbers may vary

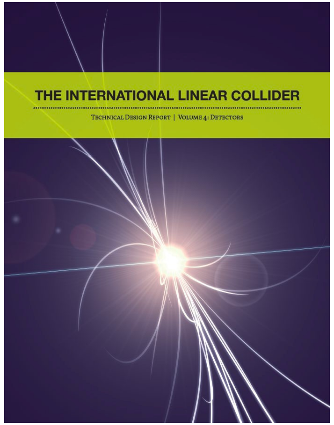
- Electronics switched on during > ~1ms of ILC bunch train and data acquisition
- Bias currents shut down between bunch trains

- Much smaller beam spot and beam pipe
  - first tracking layer at ~1cm of the IP
- Pulsed beam structure
  - Power pulsed electronics → low material budget
  - Triggerless operation → ALL events are recorded

ILC Detector Concepts

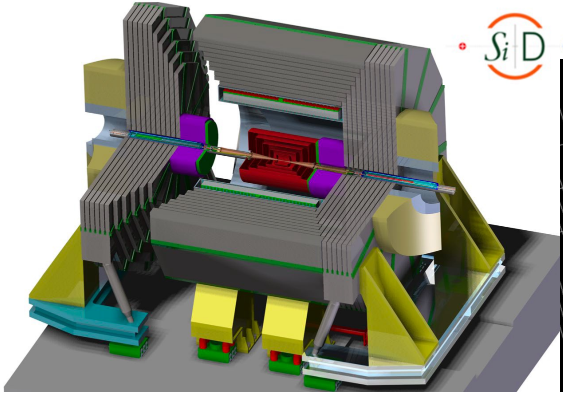
- Initial concepts in early 90s, developed in the early 2000s
- LOIs in 2009 (4 concepts)
- ILD and SiD validated by International Detector Advisory Group
- ILC TDR 2013 including Detailed Baseline Design (DBD) of ILD and SiD

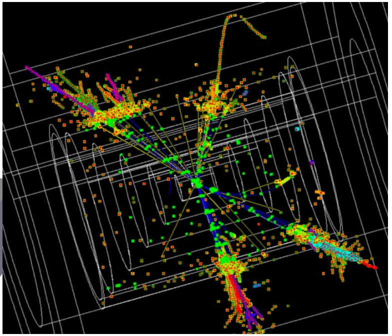
ILC is designed for two detectors in Push-Pull arrangement

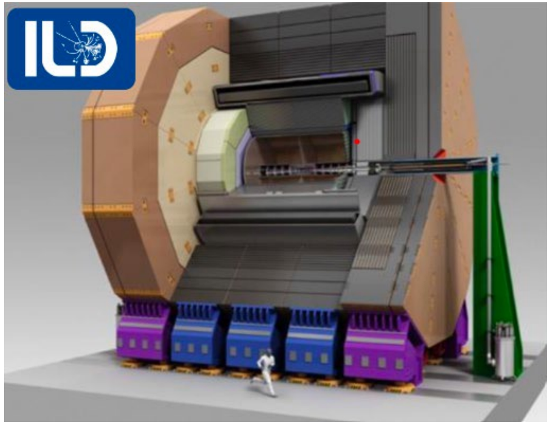


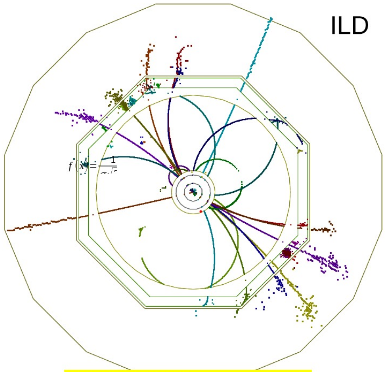
THE INTERNATIONAL LINEAR COLLIDER

Technical Design Report | Volume 4: Detectors



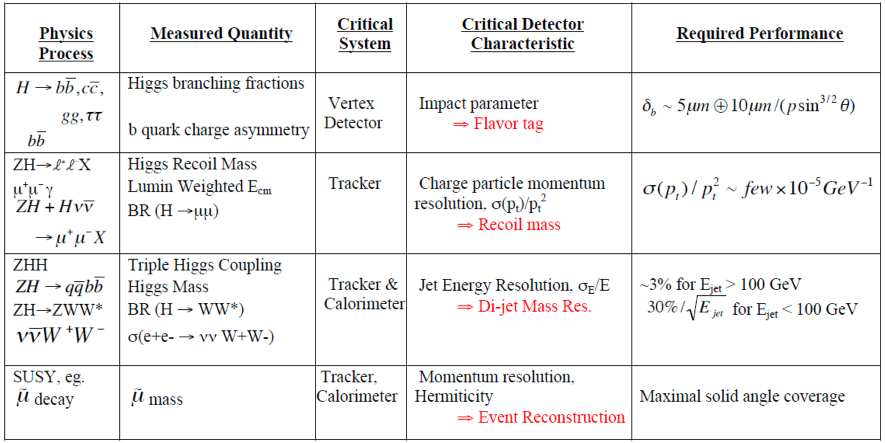






ECM = 250 GeV, $e^+e^- \rightarrow \mu^+\mu^- H$

ILC Detector Requirements



Physics Process	Measured Quantity	Critical System	Critical Detector Characteristic	Required Performance
$H \to b\bar{b}, c\bar{c}, gg, \tau\tau$ $b\bar{b}$	Higgs branching fractions b quark charge asymmetry	Vertex Detector	Impact parameter ⇒ Flavor tag	$\delta_b \sim 5\mu m \oplus 10\mu m/(p\sin^{3/2}\theta)$
$ZH \to \ell^+\ell^- X$ $\mu^+\mu^-\gamma$ $ZH + H\nu\bar{\nu} \to \mu^+\mu^- X$	Higgs Recoil Mass Lumin Weighted E_{cm} BR ($H \to \mu\mu$)	Tracker	Charge particle momentum resolution, $\sigma(p_t)/p_t^2$ ⇒ Recoil mass	$\sigma(p_t)/p_t^2 \sim few \times 10^{-5} GeV^{-1}$
ZHH $ZH \to q\bar{q}b\bar{b}$ $ZH \to ZWW^*$ $\nu\bar{\nu}W^+W^-$	Triple Higgs Coupling Higgs Mass BR ($H \to WW^*$) $\sigma(e+e- \to \nu\nu W+W-)$	Tracker & Calorimeter	Jet Energy Resolution, σ_E/E ⇒ Di-jet Mass Res.	~3% for $E_{jet} > 100$ GeV $30\%/\sqrt{E_{jet}}$ for $E_{jet} < 100$ GeV
SUSY, eg. $\tilde{\mu}$ decay	$\tilde{\mu}$ mass	Tracker, Calorimeter	Momentum resolution, Hermiticity ⇒ Event Reconstruction	Maximal solid angle coverage

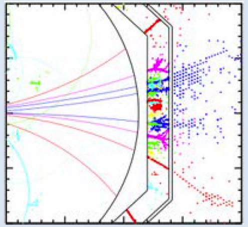
Robust silicon vertexing and tracking system – excellent momentum resolution, live for single bunch crossings.

Highly segmented "tracking" calorimeters optimized for Particle Flow.

Compact design with 5T field.

Iron flux return/muon identifier – component of SiD self-shielding.

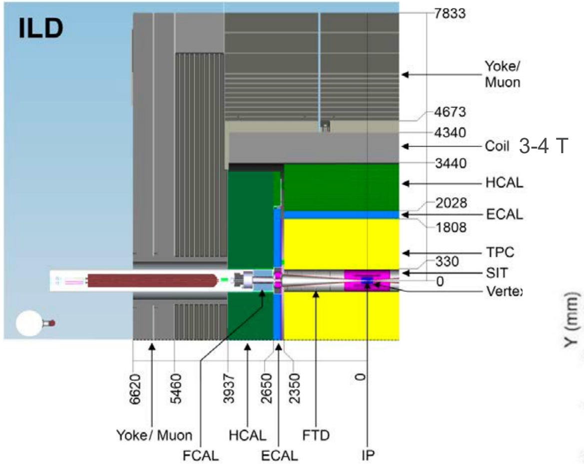
Detector Requirements ⟷		**Physics Studies**
Impact parameter resolution $\sigma(d_0) < 5 \oplus 10 / (p[\text{GeV}] \sin^{3/2}\theta)$ μm	~ LHC / 2	H→bb,cc,ττ
Transverse momentum resolution $\sigma(1/p_T) = 2 \times 10^{-5}\ \text{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_T \sin^{1/2}\theta)$	~ LHC / 10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



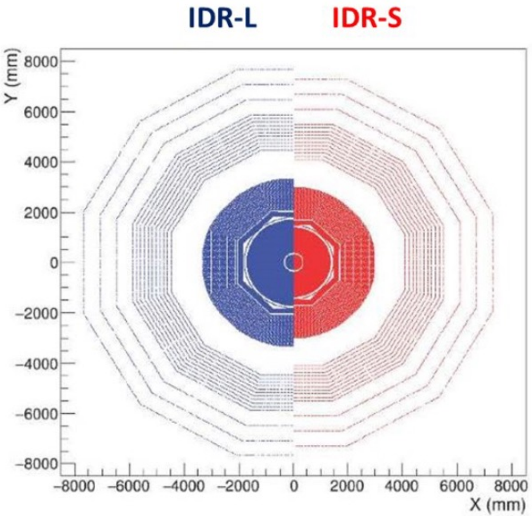
ILD is optimized around **particle flow**:
- Highly granular calorimeters
- Low-mass trackers
- Software reconstruction

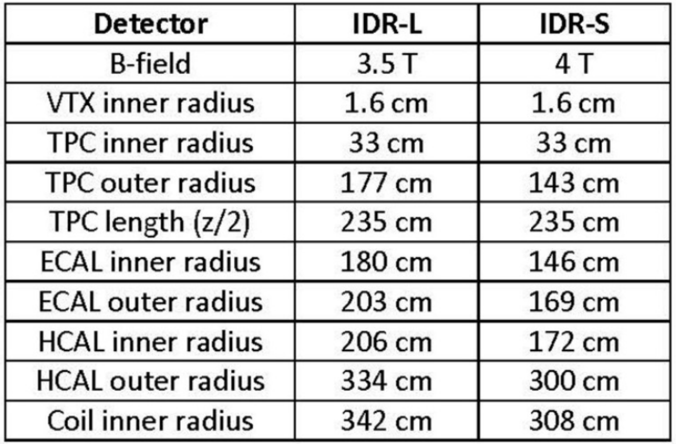
→ Separation of clusters at particle level

ILD Baseline



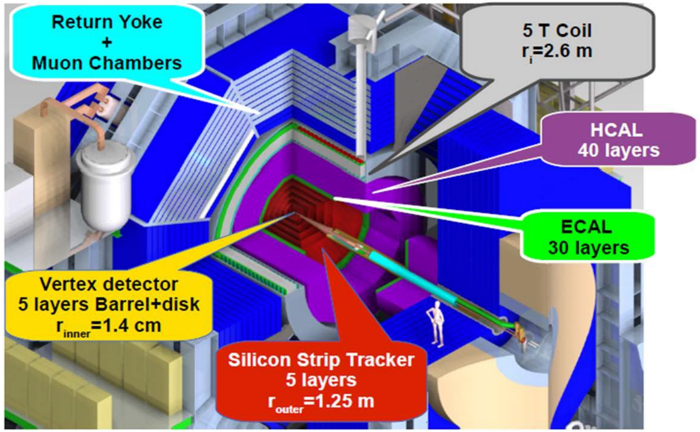
- Particle flow as the key design driver
- Excellent vertexing very close to the IP (~1cm)
- Hybrid tracking system optimized for excellent resolution at high energies and ultimate efficiency over a broad momentum range
- High granular calorimetry
- Up to and including the HCAL, all inside solenoidal coil of 3-4 T



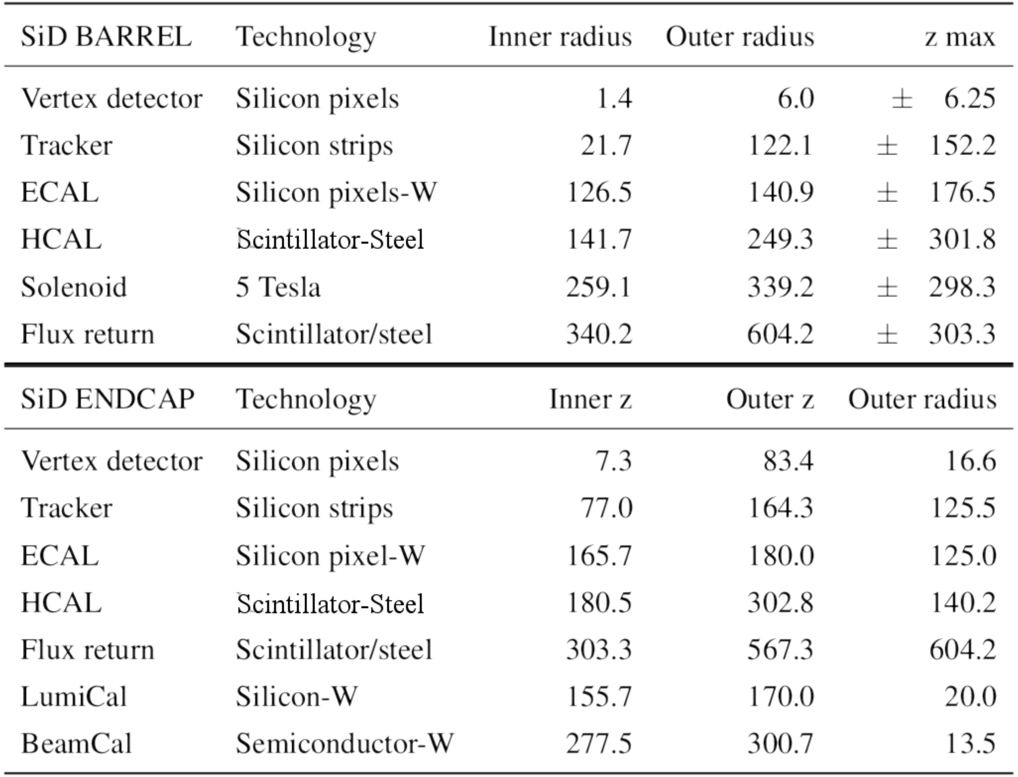


Detector	IDR-L	IDR-S
B-field	3.5 T	4 T
VTX inner radius	1.6 cm	1.6 cm
TPC inner radius	33 cm	33 cm
TPC outer radius	177 cm	143 cm
TPC length (z/2)	235 cm	235 cm
ECAL inner radius	180 cm	146 cm
ECAL outer radius	203 cm	169 cm
HCAL inner radius	206 cm	172 cm
HCAL outer radius	334 cm	300 cm
Coil inner radius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

SiD Baseline



- Compact high-field design
- All-silicon tracking
- B field 5 T, R_{ECAL}=1.25 m
- Robustness against backgrounds
- Integrated design
- Designed for Particle Flow Algorithm (PFA)

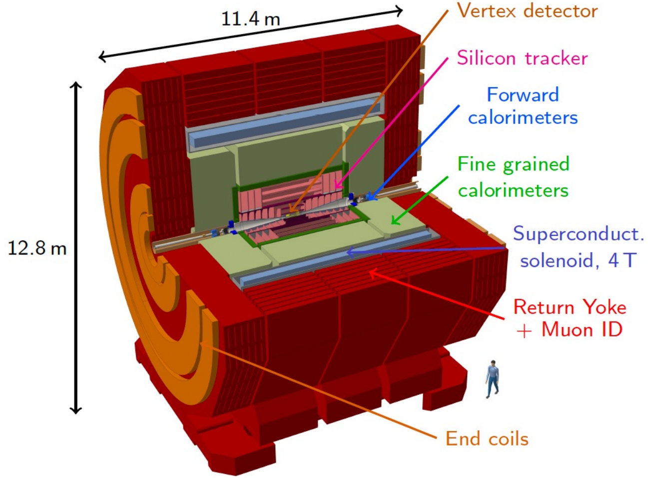


SiD BARREL	Technology	Inner radius	Outer radius	z max
Vertex detector	Silicon pixels	1.4	6.0	± 6.25
Tracker	Silicon strips	21.7	122.1	± 152.2
ECAL	Silicon pixels-W	126.5	140.9	± 176.5
HCAL	Scintillator-Steel	141.7	249.3	± 301.8
Solenoid	5 Tesla	259.1	339.2	± 298.3
Flux return	Scintillator/steel	340.2	604.2	± 303.3

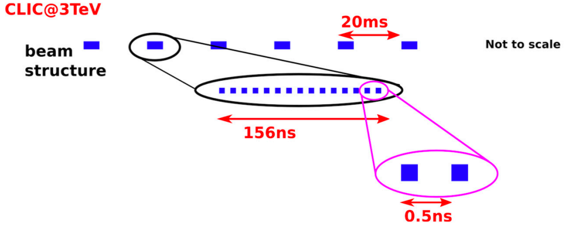
SiD ENDCAP	Technology	Inner z	Outer z	Outer radius
Vertex detector	Silicon pixels	7.3	83.4	16.6
Tracker	Silicon strips	77.0	164.3	125.5
ECAL	Silicon pixel-W	165.7	180.0	125.0
HCAL	Scintillator-Steel	180.5	302.8	140.2
Flux return	Scintillator/steel	303.3	567.3	604.2
LumiCal	Silicon-W	155.7	170.0	20.0
BeamCal	Semiconductor-W	277.5	300.7	13.5

CLICdet

- High-performing detector optimized for CLIC beam environment
- All-silicon vertex and tracking system, with spiral vertex endcaps for air cooling
- PFA calorimetry (ECAL and HCAL within CALICE)
- Full GEANT-based simulation, including beam-induced backgrounds, available for optimization and physics studies
- Mature reconstruction chain allows detailed performance characterization
  – e.g. displaced track reconstruction



- Momentum resolution
  - Higgs recoil mass, smuon endpoint, Higgs coupling to muons
  - → $\sigma_{p_T}/p_T^2 \sim 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$ above 100 GeV
- Impact parameter resolution
  - c/b-tagging, Higgs branching ratios
  - → $\sigma_{r\varphi} \sim a \oplus b/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}$
  - $a = 5\,\mu\mathrm{m}$, $b = 15\,\mu\mathrm{m}$
- Jet energy resolution
  - Separation of W/Z/H di-jets
  - → $\sigma_E/E \sim 5\% - 3.5\%$ for jets at 50 GeV – 1000 GeV
- Angular coverage
  - Very forward electron and photon tagging
  - → Down to $\theta = 10$ mrad ($\eta = 5.3$)
- Requirements from beam time structure and beam-induced background



Beam-induced backgrounds concentrated in very short bunch trains
→ High instantaneous hit rates (up to 6 GHz/cm^2 @ 3 TeV CLIC)

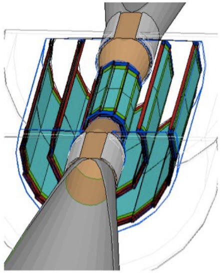
Time-stamping: **few ns @ 3 TeV CLIC** (compared with ~1-10 μs @ ILC)
→ Fast detector signals / frontend

→ **Detector R&D** targeted at specific CLIC requirements

Vertex Detector

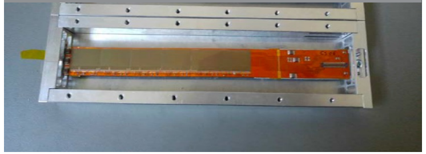
Final subdetector to be installed, R&D to continue until ~2030

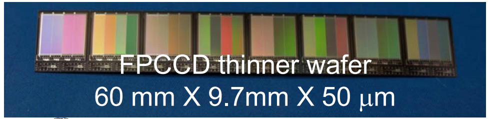
- 3 double layers, r_{min}=16 mm, 3 μm point resolution
- Main challenges: beam backgrounds, power consumption,
  material budget (0.2-0.3% X_0 per layer)
- Technology options: CPS, FPCCD, DEPFET



PLUME-2 CMOS

- Cu wire: 0.42% X_0
- Al wire: 0.35% X_0

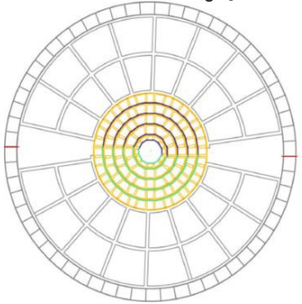




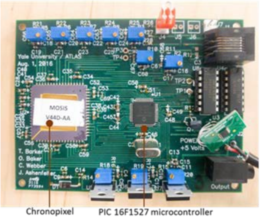
FPCCD thinner wafer
60 mm X 9.7mm X 50 μm

BELLE II
DEPFET
Vertex Detector

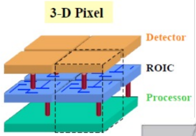
- Single bunch time resolution
- 5 layers, r_{min} = 14 mm, < 3 μm hit resolution
- Feature size ~20 μm
- <130 μW/mm^2
- ~0.1% X_0 per layer material budget

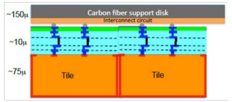


Chronopixel prototype 3 development board

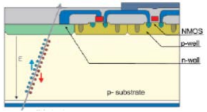


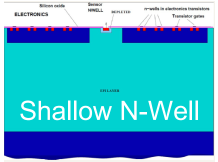
- monolithic CMOS design
  90 nm feature size,
  7 μm epitaxial layer
  280 μm thick chip
  10 ohm·cm
  manufactured by TSMC
- store up to 2 hits per pixel, 12 bit per timestamps
- 25 μm pixel pitch
- implements 6 sensor diode options





HVCMOS



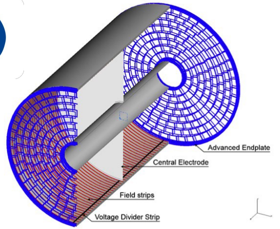


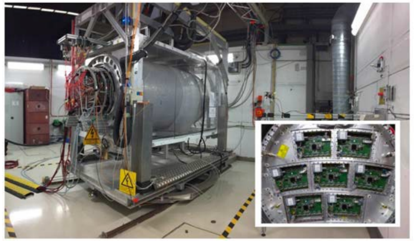
Shallow N-Well

Main Tracker

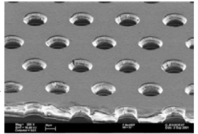
- ILD uses a Time Projection Chamber (TPC) as the central tracker
- TPC delivers up to 220 true 3D space points along a track
- Gaseous detector: low material budget (~0.05 X_0 barrel region)
- Particle identification with dE/dx
- Readout options: GEM, Micromegas, pixel
- Field distortion due to ion backflow mitigated using gating device to collect positive ions in-between bunch trains.

- All Silicon Tracker
  - Using Silicon micro-strips
    - 25 µm pitch / 50 µm readout
    - v2 sensor prototype July 2017*
- 5 barrel layers / 4 disks
- Tracking unified with vertex detector
  - 10 layers in barrel
- Gas-cooled
- Material budget < 20% X_0 in the active region
- Readout using KPiX ASIC
  - Same readout as ECAL
  - Bump-bonded directly to the module



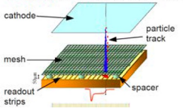


GEM



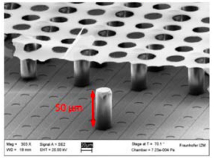
F. Sauli, NIM A805 (2016) 2-24

Micromegas



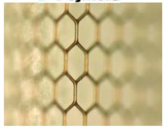
Y. Giomataris et al., NIM A376 (1996) 29-35

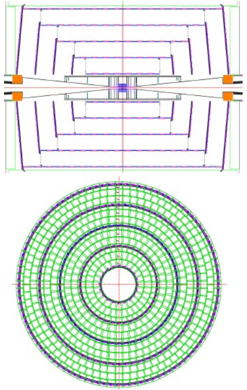
GridPix (NIKHEF)

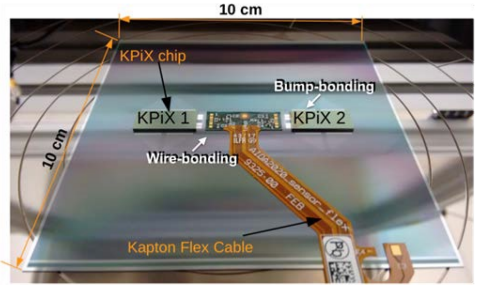


GEM Gating Grid

Fujikura







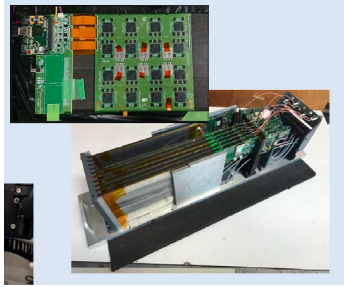
ECAL

High granularity imaging calorimetry

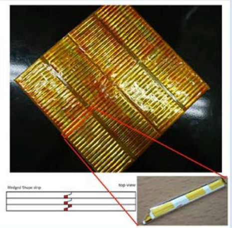
Silicon tiles (5x5mm^2)
or Scintillator strips (5x45mm^2)
with Tungsten absorber

Ultra-granular calorimeter:
10-100 million readout channels

Silicon ECAL prototype

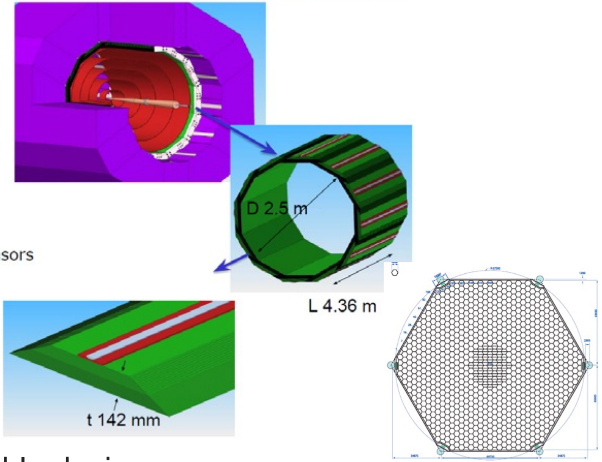


Scintillator ECAL prototype



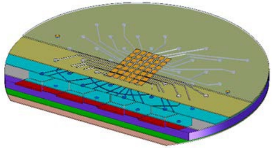
Baseline design: Silicon/Tungsten

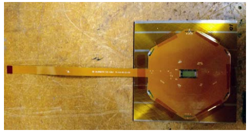
Compact Electromagnetic Calorimeter w 13 mm Moliere Radius

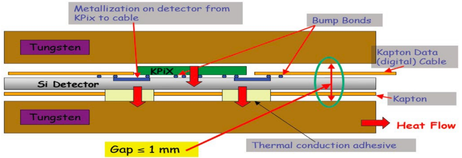


20 layers 2.5 mm W (5/7 X0)
10 layers 5 mm W (10/7 X0)
30 gaps 1.25 mm w Si pixels sensors
29 X_0; 1 λ
$\Delta E/E = 17\%/\sqrt{E}$

New sensor design, new cable design





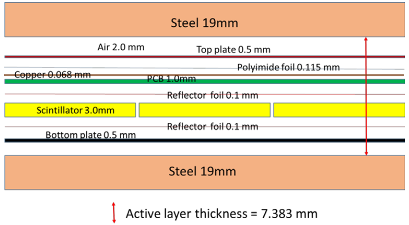


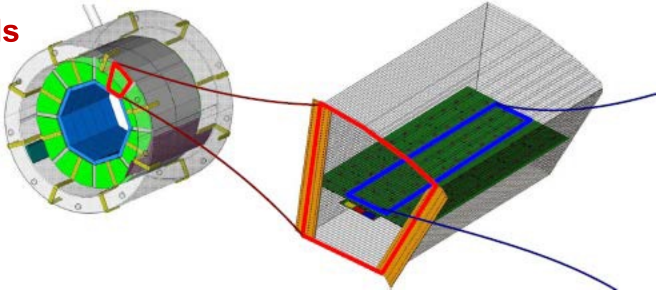
HCAL

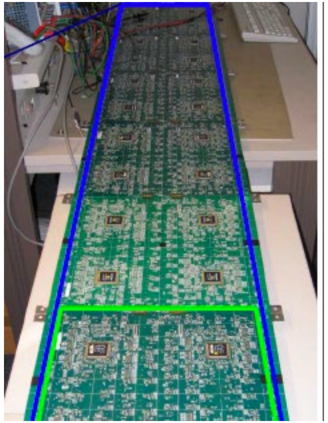
- **Two approached studied by CALICE**
  - **Analog HCAL: scintillator tile (3X3 cm^2) readout using SiPM**
  - **(Semi-)Digital HCAL: RPC with 1X1 cm^2 pads**

Baseline technology for the SiD HCal is Scintillator/SiPM/Steel

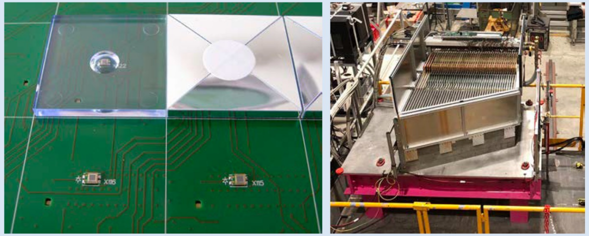
Scintillator tile (3x3 cm^2) or Gas RPC (1x1 cm^2) with Steel absorber for ILD



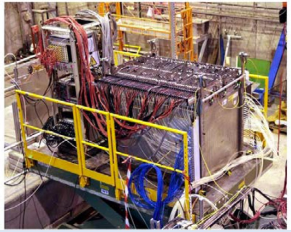




Analog HCAL prototype

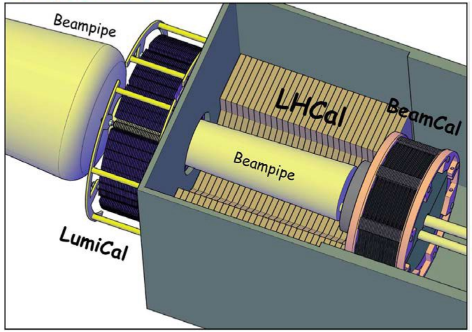


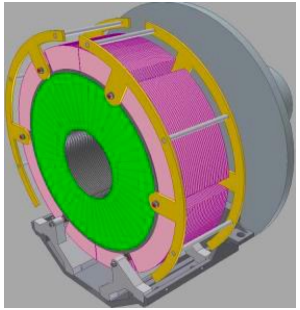
Semi-digital HCAL prototype



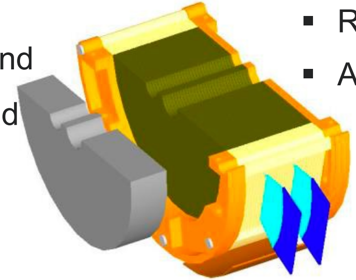
Forward Calorimeters

FCAL Collaboration
High precision design





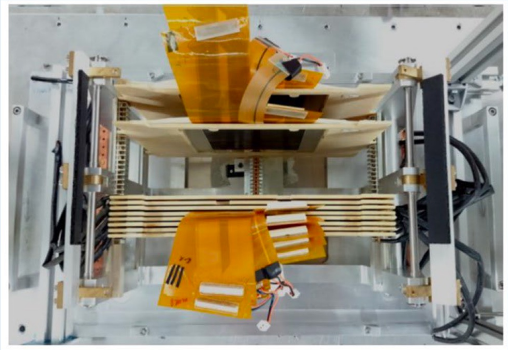
- Luminosity from low angle Bhabhas
- Reduce background
- -e/γ ID to few mrad

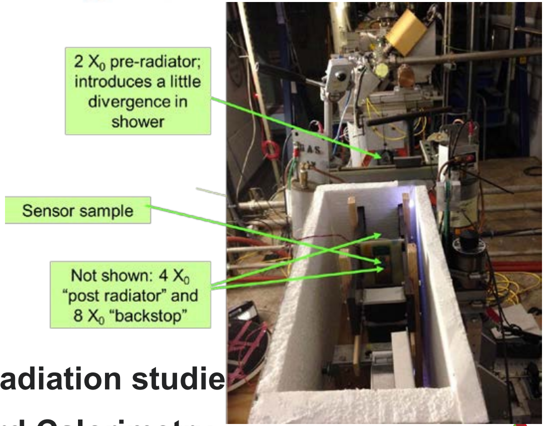


- Improve hermeticity
- Reduce backscatter
- Assist beam diagnostics

- Luminosity to 10^{-4}
- BeamCal radiation dose at inner radius ~100 Mrad/year
- Calorimetric hermeticity down to 6 mrad

LumiCal prototype (DESY)

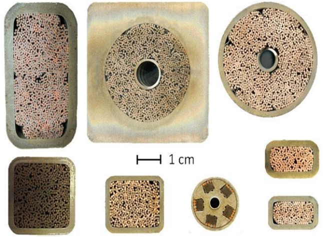


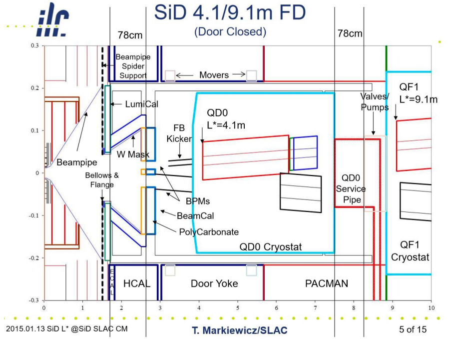


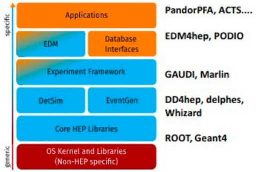
Sensor irradiation studie for Forward Calorimetry

Other ILC Items

- **Muon system**
  - **Baseline for both concepts: Long scintillator strips with WLS fiber and SiPM readout**
- **Coil**
  - **Looking into alternative conductors like CICC**
  - **Implications for field, Cost …**
- **MDI**
  - **The detectors do function for a range of L***
- **DAQ**
  - **Triggerless readout and reasonable data volume**
  - **With the “MAPSsification” the role of front-ends will change**
- **Detector calibration and alignment**
  - **Can’t be an afterthought in the time of push-pull**
- **Software and Computing**
  - **community wide software solutions (LCIO, DD4hep, etc) developed over 15 years**
  - **collaborating with other communities to modernize the software stack: key4hep**







ILC Detector Design Updates Since DBD

arXiv:2110.09965v1 [physics.ins-det] 19 Oct 2021

October 20, 2021

Updating the SiD Detector concept

M. Breidenbach and T. Markiewicz
SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA, USA

J.E. Brau
Department of Physics, University of Oregon, Eugene, OR 97403, USA

P. Burrows
Department of Physics, Oxford University, Oxford, UK

M. Stanitzki
DESY, Notkestrasse 85, 22607 Hamburg, Germany

J. Strube
University of Oregon, Institute for Fundamental Science, Eugene, OR 97403-5203

A.P. White
University of Texas Arlington, Arlington, TX 76019, USA

The SiD Detector is one of two detector designs for the future International Linear Collider (ILC) that were validated in 2012 SiD features a compact, cost-constrained design for precision Higgs and other measurements, and sensitivity to a wide range of possible new phenomena. A robust silicon vertex and tracking system, combined with a five Tesla central solenoidal field, provides excellent momentum resolution. The highly granular calorimeter system is optimized for Particle Flow application to achieve very good jet energy resolution over a wide range of energies. With a potential construction date of the ILC moving closer, it is now the time to review the design and technology decision that have been made during the DBD phase and reconsider them in the light of the recent technological advances. For each area of SiD development R&D topics and opportunities for participation will be discussed.

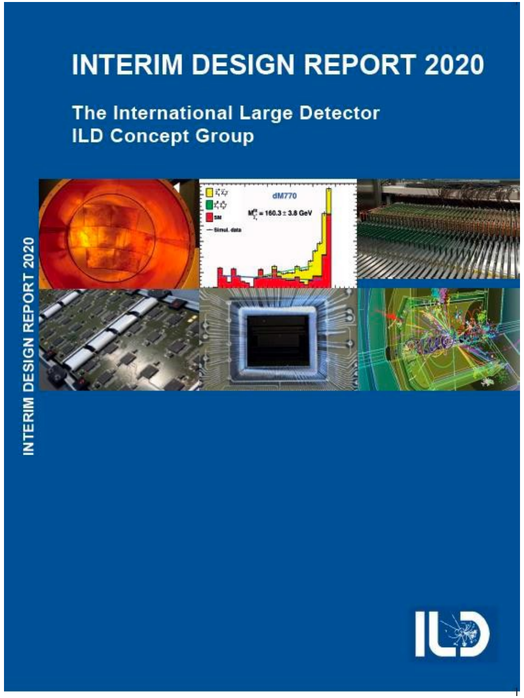
I. INTRODUCTION

The International Linear Collider (ILC) [1] is a proposed e^+e^- collider at the energy frontier. The ILC is a 20 km long linear accelerator using superconducting cavities with a initial baseline center-of-mass energy of 250 GeV. The ILC will provide polarized beams for both electrons (80%) and positrons (30%), which is a unique capability of linear colliders. The ILC project includes a clear upgrade path to center-of-mass energies of 1 TeV, or even slightly beyond. The ILC has a mature baseline design which has been summarized in the Technical Design Report (TDR), which was presented in 2012 [2, 3].

The ILC environment is unique and very different than at synchrotrons. The ILC accelerates a bunch train with 1300 bunches roughly 550 ns apart roughly every 200 ms, so collisions only happen during 1 ms followed by a quiet time of 199 ms. This allows to buffer the data on the front-ends, read out at the end of the bunch train and then to power down the front-ends (power-pulsing). This reduces the average power consumption by roughly a factor of 100.

SiD started as a detector concept for linear colliders almost twenty years ago [4, 5]. It was well documented in the ILC TDR Detailed Baseline Document (DBD) [6] in 2012. This note will first give a brief review on the current design and layout of SiD and then identify and highlight the improvements appropriate for a construction start in the late 2020s, and the new opportunities for R&D contributions. This note will not recapitulate the DBD in great details, and the reader should refer to the ILC TDR for a complete summary of the physics motivations [7], the ILC accelerator [3] and the conceptual detector designs[6]. For a review of the R&D activities in the Linear Collider Community, the Detector R&D Report [8] is an excellent summary.

https://arxiv.org/abs/2110.09965



INTERIM DESIGN REPORT 2020

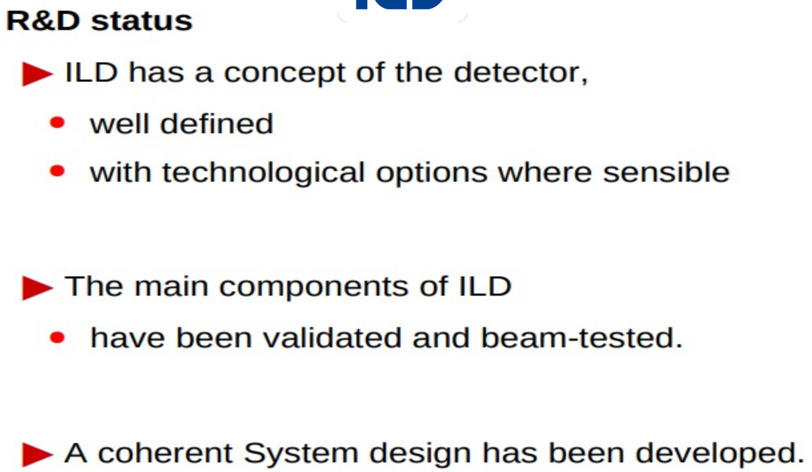
The International Large Detector
ILD Concept Group

INTERIM DESIGN REPORT 2020

https://arxiv.org/abs/2003.01116

Brief Status/Highlights of Progress

- SiD Tracker
  - Demonstrated desired point resolution of <7 µm
  - Charge-sharing design works very well
- SiD ECAL
  - Second generation sensor arrived and bump-bonded



R&D status

- 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.

- Both collaborations have been continuously pursuing physics studies for a wide range of possible signals at an LC, and detector performance studies
- Both collaborations were active in the Snowmass Studies
- Both collaborations are actively engaging with other Higgs factory studies
- A common software framework has been developed and is available to do studies and detector optimization studies, which is shared among ILD, SiD and CLIC (and increasingly also with FCC-ee and others).

R&D Progress for CLICdet

Calorimeter R&D => within CALICE and FCAL

Silicon vertex/tracker R&D:
- Working Group within CLICdp and strong collaboration with DESY + AIDAinnova
- Now integrated in the CERN EP detector R&D programme

A few examples:

Monolithic sensors:

CLICTD 180 nm monolithic sensor
- Target: CLIC tracker
- Exploring large parameter space of sensor-design modifications, substrate materials (epitaxial, high-resistivity Cz) and thicknesses (40-300 µm), in collaboration with ATLAS MALTA / STREAM
- Detailed TCAD/Geant4-based simulation studies (AllPix^2) to optimize sensor design

IEEE TNS 67.10 (2020): 2263-2272
NIM A 1006 (2021) 0165396
NIM A 1041 (2022) 167413

- Excellent performance observed in test-beam measurements and reproduced by simulations
- Results have served as input to sensor optimization, also for 65 nm process

R&D Progress for CLICdet

Calorimeter R&D => within CALICE and FCAL

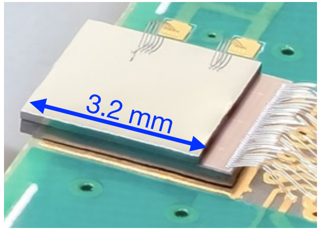
Silicon vertex/tracker R&D:
- Working Group within CLICdp and strong collaboration with DESY + AIDAinnova
- Now integrated in the CERN EP detector R&D programme

A few examples:

Hybrid assemblies:

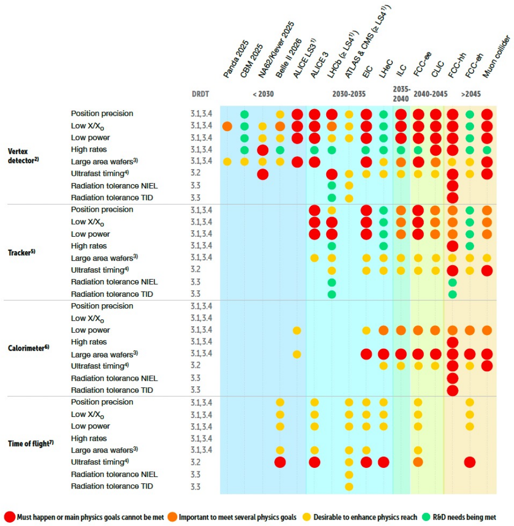
CLICpix2
- Target: CLIC pixel detector
- 65 nm with thin active-edge sensors (25 μm pitch)

CLICpix2 hybrid assembly



- Efficiency, spatial and timing resolution targets are achieved, but not yet simultaneously with material budget target –> need advanced sensors / smaller pitch (28 nm ASICs, also considered for HL-LHC)

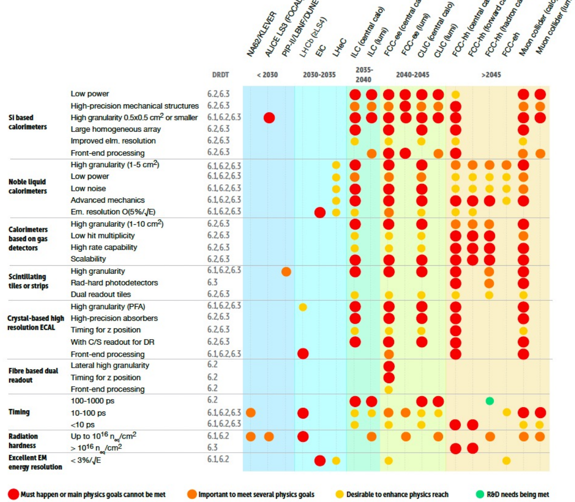
R&D Tasks in ECFA Detector R&D Roadmap



Columns: Panda 2025, CBM 2025, NA62/Klever 2025, Belle II 2026, ALICE LS3[1)] (< 2030); ALICE 3, LHCb (≥ LS4[1)]), ATLAS & CMS (≥ LS4[1)]), EIC, LHeC (2030-2035); ILC (2035-2040); FCC-ee, CLIC (2040-2045); FCC-hh, FCC-eh, Muon collider (>2045)

		DRDT
Vertex detector[2)]	Position precision	3.1,3.4
	Low X/X_0	3.1,3.4
	Low power	3.1,3.4
	High rates	3.1,3.4
	Large area wafers[3)]	3.1,3.4
	Ultrafast timing[4)]	3.2
	Radiation tolerance NIEL	3.3
	Radiation tolerance TID	3.3
Tracker[5)]	Position precision	3.1,3.4
	Low X/X_0	3.1,3.4
	Low power	3.1,3.4
	High rates	3.1,3.4
	Large area wafers[3)]	3.1,3.4
	Ultrafast timing[4)]	3.2
	Radiation tolerance NIEL	3.3
	Radiation tolerance TID	3.3
Calorimeter[6)]	Position precision	3.1,3.4
	Low X/X_0	3.1,3.4
	Low power	3.1,3.4
	High rates	3.1,3.4
	Large area wafers[3)]	3.1,3.4
	Ultrafast timing[4)]	3.2
	Radiation tolerance NIEL	3.3
	Radiation tolerance TID	3.3
Time of flight[7)]	Position precision	3.1,3.4
	Low X/X_0	3.1,3.4
	Low power	3.1,3.4
	High rates	3.1,3.4
	Large area wafers[3)]	3.1,3.4
	Ultrafast timing[4)]	3.2
	Radiation tolerance NIEL	3.3
	Radiation tolerance TID	3.3

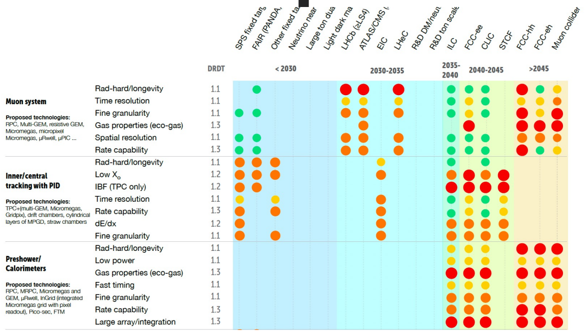
🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met



Columns: NA62/KLEVER, ALICE LS3 (FOCAL) (< 2030); PIP-II/LBNF/DUNE, LHCb (≥LS4), EIC, LHeC (2030-2035); ILC (central calo), ILC (lumi) (2035-2040); FCC-ee (central calo), FCC-ee (lumi), CLIC (central calo), CLIC (lumi) (2040-2045); FCC-hh (central calo), FCC-hh (forward calo), FCC-hh (hadron calo), FCC-eh, Muon collider (calo), Muon collider (lumi) (>2045)

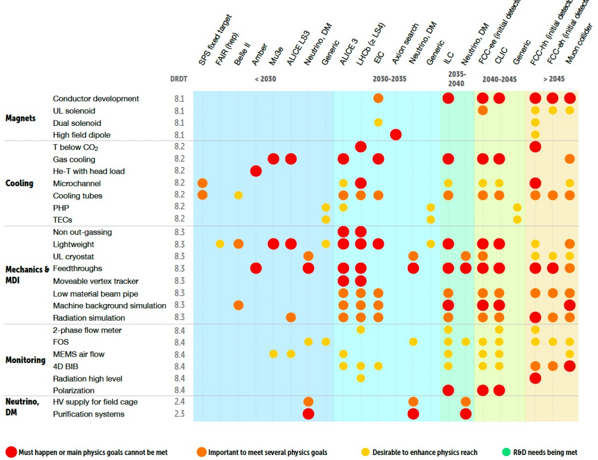
		DRDT
Si based calorimeters	Low power	6.2,6.3
	High-precision mechanical structures	6.2,6.3
	High granularity 0.5x0.5 cm^2 or smaller	6.1,6.2,6.3
	Large homogeneous array	6.2,6.3
	Improved elm. resolution	6.2,6.3
	Front-end processing	6.2,6.3
Noble liquid calorimeters	High granularity (1-5 cm^2)	6.1,6.2,6.3
	Low power	6.1,6.2,6.3
	Low noise	6.1,6.2,6.3
	Advanced mechanics	6.1,6.2,6.3
	Em. resolution O(5%/$\sqrt{E}$)	6.1,6.2,6.3
Calorimeters based on gas detectors	High granularity (1-10 cm^2)	6.2,6.3
	Low hit multiplicity	6.2,6.3
	High rate capability	6.2,6.3
	Scalability	6.2,6.3
Scintillating tiles or strips	High granularity	6.1,6.2,6.3
	Rad-hard photodetectors	6.3
	Dual readout tiles	6.2,6.3
Crystal-based high resolution ECAL	High granularity (PFA)	6.1,6.2,6.3
	High-precision absorbers	6.2,6.3
	Timing for z position	6.2,6.3
	With C/S readout for DR	6.2,6.3
	Front-end processing	6.1,6.2,6.3
Fibre based dual readout	Lateral high granularity	6.2
	Timing for z position	6.2
	Front-end processing	6.2
Timing	100-1000 ps	6.2
	10-100 ps	6.1,6.2,6.3
	<10 ps	6.1,6.2,6.3
Radiation hardness	Up to 10^{16} n_{eq}/cm^2	6.1,6.2
	> 10^{16} n_{eq}/cm^2	6.3
Excellent EM energy resolution	< 3%/$\sqrt{E}$	6.1,6.2

🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met



Columns: SPS fixed targ, FAIR (PANDA, Other fixed ta, Neutrino near, Large ton dua, Light dark ma (< 2030); LHCb (≥LS4), ATLAS/CMS (, EIC, LHeC, R&D DM/neut, R&D ton scale (2030-2035); ILC (2035-2040); FCC-ee, CLIC, STCF (2040-2045); FCC-hh, FCC-eh, Muon collider (>2045)

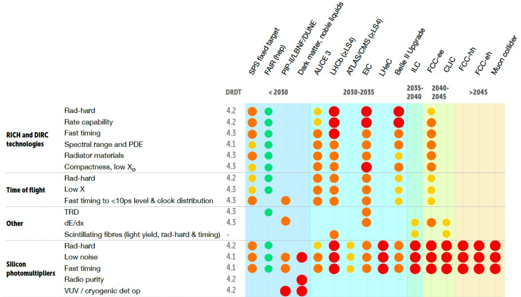
		DRDT
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, micropixel Micromegas, μRwell, μPIC ...	Rad-hard/longevity	1.1
	Time resolution	1.1
	Fine granularity	1.1
	Gas properties (eco-gas)	1.3
	Spatial resolution	1.1
	Rate capability	1.3
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1
	Low X_0	1.2
	IBF (TPC only)	1.2
	Time resolution	1.1
	Rate capability	1.3
	dE/dx	1.2
	Fine granularity	1.1
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, μRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM	Rad-hard/longevity	1.1
	Low power	1.1
	Gas properties (eco-gas)	1.3
	Fast timing	1.1
	Fine granularity	1.1
	Rate capability	1.3
	Large array/integration	1.3



Columns: SPS fixed target, FAIR (hep), Belle II, Amber, Mu3e, ALICE LS3, Neutrino, DM, Generic (< 2030); ALICE 3, LHCb (≥ LS4), EIC, Axion search, Neutrino, DM, Generic (2030-2035); ILC, Neutrino, DM (2035-2040); FCC-ee (initial detectors), CLIC, Generic (2040-2045); FCC-hh (initial detectors), FCC-eh (initial detectors), Muon collider (> 2045)

		DRDT
Magnets	Conductor development	8.1
	UL solenoid	8.1
	Dual solenoid	8.1
	High field dipole	8.1
Cooling	T below CO_2	8.2
	Gas cooling	8.2
	He-T with head load	8.2
	Microchannel	8.2
	Cooling tubes	8.2
	PHP	8.2
	TECs	8.2
Mechanics & MDI	Non out-gassing	8.3
	Lightweight	8.3
	UL cryostat	8.3
	Feedthroughs	8.3
	Moveable vertex tracker	8.3
	Low material beam pipe	8.3
	Machine background simulation	8.3
	Radiation simulation	8.3
Monitoring	2-phase flow meter	8.4
	FOS	8.4
	MEMS air flow	8.4
	4D BIB	8.4
	Radiation high level	8.4
	Polarization	8.4
Neutrino, DM	HV supply for field cage	2.4
	Purification systems	2.3

🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met



Columns: SPS fixed target, FAIR (hep), PIP-II/LBNF/DUNE, Dark matter, noble liquids (< 2030); ALICE 3, LHCb (≥LS4), ATLAS/CMS (≥LS4), EIC, LHeC, Belle II Upgrade (2030-2035); ILC (2035-2040); FCC-ee, CLIC (2040-2045); FCC-hh, FCC-eh, Muon collider (>2045)

		DRDT
RICH and DIRC technologies	Rad-hard	4.2
	Rate capability	4.2
	Fast timing	4.3
	Spectral range and PDE	4.1
	Radiator materials	4.3
	Compactness, low X_0	4.3
Time of flight	Rad-hard	4.2
	Low X	4.3
	Fast timing to <10ps level & clock distribution	4.3
Other	TRD	4.3
	dE/dx	4.3
	Scintillating fibres (light yield, rad-hard & timing)	-
Silicon photomultipliers	Rad-hard	4.2
	Low noise	4.1
	Fast timing	4.1
	Radio purity	4.2
	VUV / cryogenic det op	4.2

- Identified a set of detector R&D areas and defined the most important themes (DRDTs), and made general strategic recommendations (GSR)
- To implement, the long-term R&D efforts into newly established Detector R&D (DRD) Collaborations

R&D Needs for the New Timeline

- Technology R&D
  - Superconducting Coil(s): wire and winding techniques, project with industry
  - MAPS for Tracking and ECAL: stitching for large scale sensors and reduced dead areas
  - Pixel readout for TPC: GridPix dE/dx from cluster counting
  - Fast timing/power requirements: benefits for tracking/calorimetry?
- Detector Concept development
  - Major subsystems: main calorimeters, magnet return yoke, …
  - Concept major parameters: overall dimensions, magnet field strength, MDI, services
  - Strategy for assembly and installation of detectors

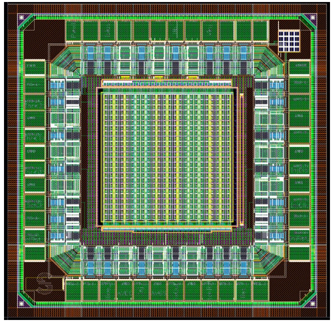
Possible ILC Detector Timeline

ALCC subgroup - 31 Mar 2023

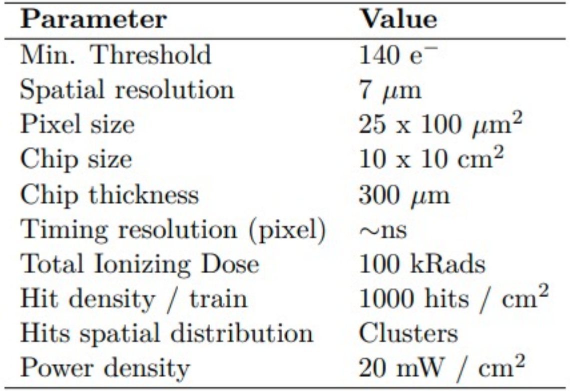
- Q1 2024 - Q3 2030 - Detector R&D
  - R&D ramps up now since TDRs require 2 years effort, building on and during R&D,
- Q1 2027 - Formation of Preparatory Phase
- Q1 2027 - Formation of ILCC
- Q1 2027 - Call for Detector LOIs - due Q4 2027
- Q1 2028 - Q2 2028 Review of LOIs by ILCC
  - Down select of LOIs to proceed to TDR phase
- Q3 2028 - Initiate TDR efforts (to be completed before Q3 2030)
  - Detector R&D continues until Q3 2030
- Q1 2030 - ILC Construction Begins
- Q3 2030 - TDRs submitted at beginning of Q3 2030
- Q3 2030 - Q4 2030 - Review of TDRs
- Q1 2031 - Start of detector component production
- Q1 2036 - Start of detector installation
- Q1 2039 - Start of integrated detector commissioning
- Q1 2039 - ILC Commissioning starts
- Q1 2040 - First physics running at 250 GeV

MAPS

Monolithic Active Pixel Sensors (MAPS) for tracking (Vertex Detector, Main Tracker) and electromagnetic calorimeter (ECAL)



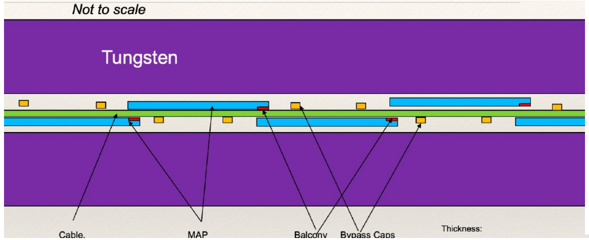
- **Potential for providing higher granularity, thinner, intelligent detectors at lower overall cost**
- **Significantly lower material budget, with sensors and readout electronics integrated on the same chip**
- **Stitching for large scale sensors and reduced dead areas, towards the wafer-scale chip**
- **Lower power**
- **Fully-depleted MAPS/CMOS for faster charge collection, higher efficiency, less cross-pixel charge sharing**

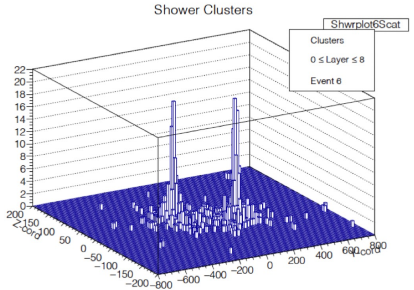


Parameter	Value
Min. Threshold	140 e$^-$
Spatial resolution	7 μm
Pixel size	25 x 100 μm^2
Chip size	10 x 10 cm^2
Chip thickness	300 μm
Timing resolution (pixel)	~ns
Total Ionizing Dose	100 kRads
Hit density / train	1000 hits / cm^2
Hits spatial distribution	Clusters
Power density	20 mW / cm^2

Table 1: Target specifications for 65 nm prototy

- Follow closely to CERN-lead 65 nm MAPS program
- Start designing prototypes targeted for SiD
- R&D on Stitching is essential, spearheaded by ALICE
- Inform Vertex Detector R&D





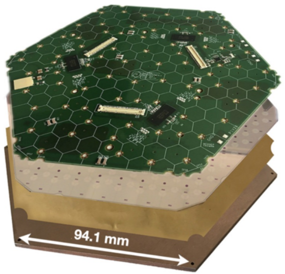
Precision Timing

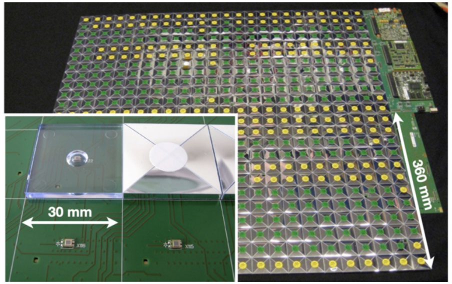
Precision timing at the level of 10-30ps is a new capability to enhance PID and calorimeter measurements

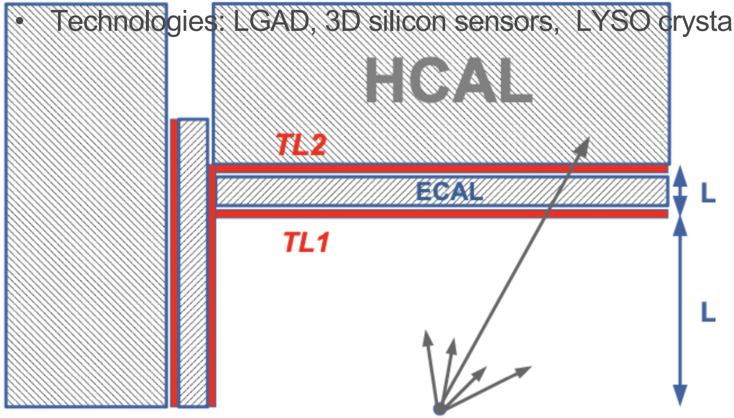
- **Large-radius Timing Layers in the in front of the calorimeter can provide Time-of-Flight (ToF) for PID**

- ***Volume timing***: good time resolution on the cell level in highly granular calorimeters
  - requires technologies that can provide this timing; significant implications for electronics
  - potential compromises in timing for objects
  - Technologies: LGAD or silicon tiles

- ***Timing layers***: extreme timing in a few selected layers inside of the calorimeter system
  - can be combined with a wide range of technologies
  - excludes applications that require timing in the full shower volume, rather than on object level
  - Technologies: LGAD, 3D silicon sensors, LYSO crystals

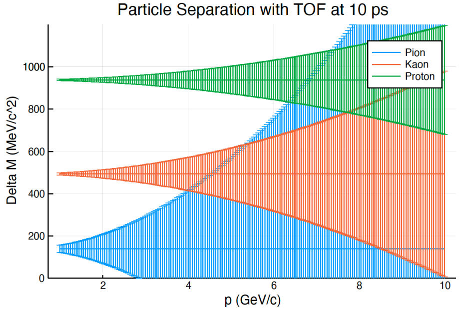






Precision Timing @ ILC

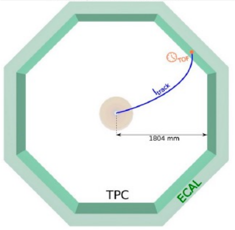
- Integrated time-stamping in the trackers
  - e.g. Background rejection in the Vertex Detector
    - Requiring ns-level resolution (intra-bunching timing)
    - Doable already today
- Timing measurements for shower development in calorimeters
  - Neutral and slow components
    - Requiring ~ns precision
    - Reachable today by reading out the cells
- Dedicated Timing Layers
  - Full 4D Tracking in the ILC environment
    - Nothing like the LHC
  - What about 5D calorimetry
    - How can precision timing be best used in PFA
    - What level of precision timing can make a real difference of calorimeter performance
  - Time-of-Flight systems for PID
    - 10 ps resolution as a goal to be competitive
  - What kind of physics does this enable and what are the Instrumentation implications
    - For a detector designed for 250-1000 GeV

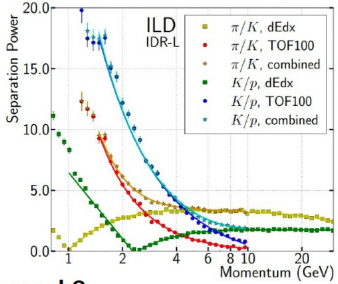


TOF in the ECAL – Particle ID

- ▶ "Standard" silicon sensors could reach O(100-300ps)
- ▶ LGAD sensors could get us to O(10ps) Drawback: high power consumption.

Example for ILD@ILC



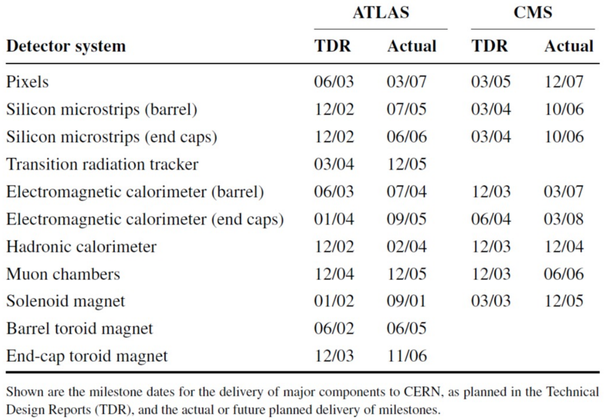


Impact in the physics reach?

- ▶ Could be a game changer for s-quark measurements
  - $Z/\gamma/Z' \rightarrow s\bar{s}$ or $H \rightarrow s\bar{s}$

(Some) Lessons Learned from (HL-)LHC

- Long timeline and different project phases
  - Planning with project management despite (large) uncertainties
  - Early investments in critical detector R&Ds
  - Necessity of proper transition from technology demonstration to TDR-level prototyping
  - Well-defined production phase
- Large complex detectors
  - Balance between conventional and novel technical solutions, and between adoption of diverse technical solutions and risk mitigation
  - Development of common solutions across subsystems and experiments
  - Optimization between design and buildability
    - Physicists vs Engineers: How to Strike the Right Balance?
  - Tests, tests, tests
    - Do systematical tests of all materials used
    - It is always the low tech (plumbing problems)
  - Integration, Installation and commissioning always more resource-consuming than expected
- International and distributed collaboration
  - System engineering and technical coordination
  - Multi-dimensional optimization of resource, expertise, schedule, deliverables



	ATLAS		CMS	
Detector system	**TDR**	**Actual**	**TDR**	**Actual**
Pixels	06/03	03/07	03/05	12/07
Silicon microstrips (barrel)	12/02	07/05	03/04	10/06
Silicon microstrips (end caps)	12/02	06/06	03/04	10/06
Transition radiation tracker	03/04	12/05		
Electromagnetic calorimeter (barrel)	06/03	07/04	12/03	03/07
Electromagnetic calorimeter (end caps)	01/04	09/05	06/04	03/08
Hadronic calorimeter	12/02	02/04	12/03	12/04
Muon chambers	12/04	12/05	12/03	06/06
Solenoid magnet	01/02	09/01	03/03	12/05
Barrel toroid magnet	06/02	06/05		
End-cap toroid magnet	12/03	11/06		

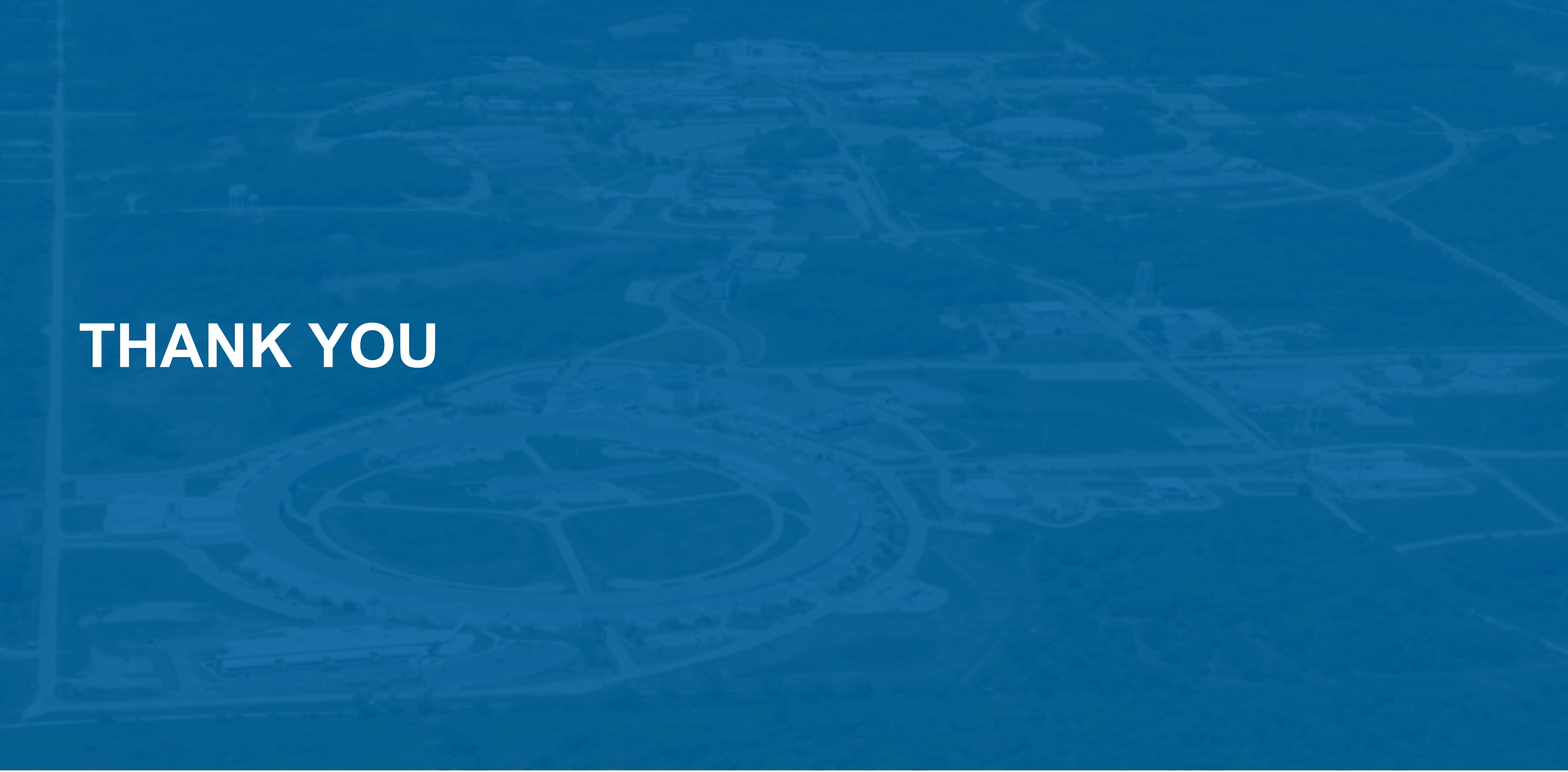
Shown are the milestone dates for the delivery of major components to CERN, as planned in the Technical Design Reports (TDR), and the actual or future planned delivery of milestones.

https://doi.org/10.1146/annurev.nucl.54.070103.181209

Summary

- **CLICdet, and two ILC detector concepts, ILD and SiD, have been developed and optimized for an extended period**
- **All have excellent performance for the full range of CLIC/ILC physics program**
- **All are open to new ideas/technologies and welcome new collaborators**

Many Thanks to CLIC Collaboration, ILD Collaboration and SiD collaboration, particularly Ties Behnke, Aidan Robson, Marcel Stanitzki and Andy White, for making the materials readily available and preparing this presentation. All inaccuracies and omissions are my own.



THANK YOU

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