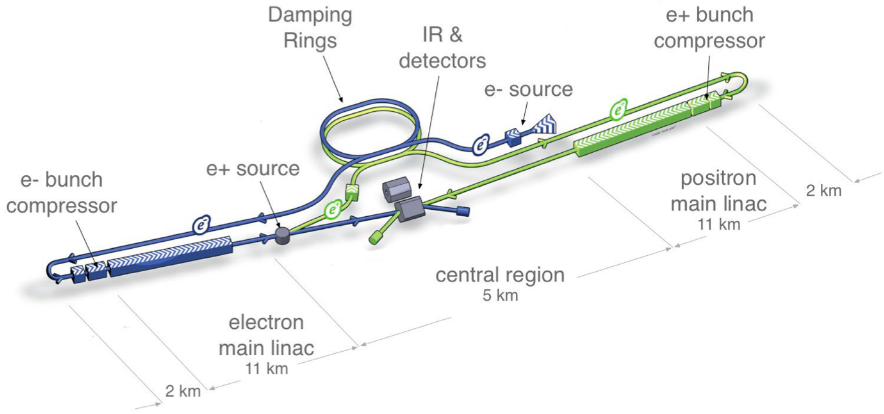
INTERNATIONAL WORKSHOP ON FUTURE LINEAR COLLIDERS

Recent Developments in Detector Concept Studies



Jinlong Zhang
For ILD, SiD

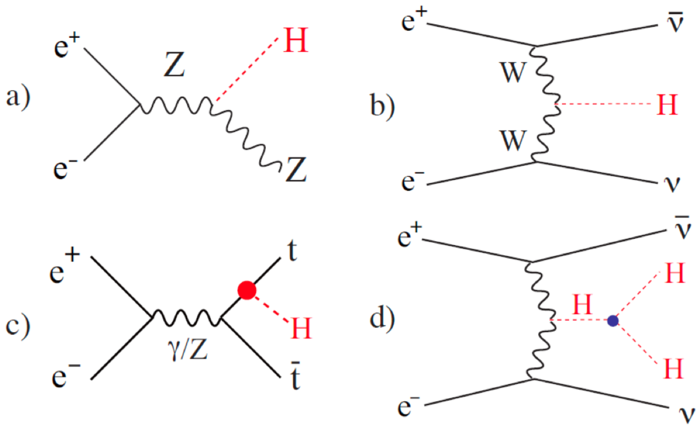
U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

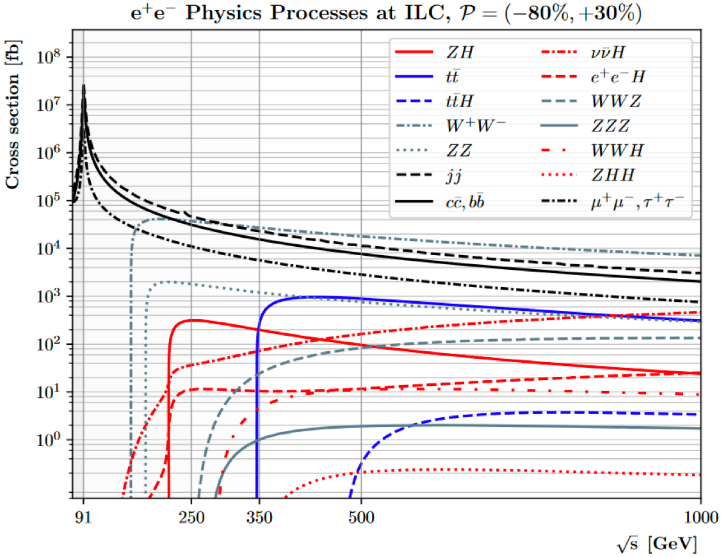
May 15, 2023

ILC Physics

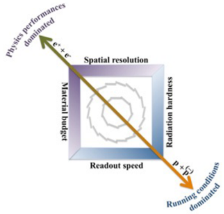
Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$ $e^+e^- \to t\bar{t}$	precision Higgs couplings top quark mass and couplings
350–400 GeV	$e^+e^- \to WW$ $e^+e^- \to \nu\bar{\nu}h$ $e^+e^- \to f\bar{f}$ $e^+e^- \to t\bar{t}h$	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



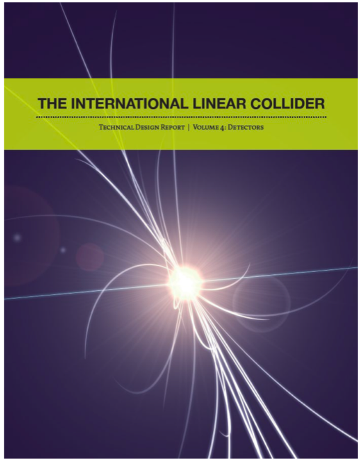


Detector Concepts

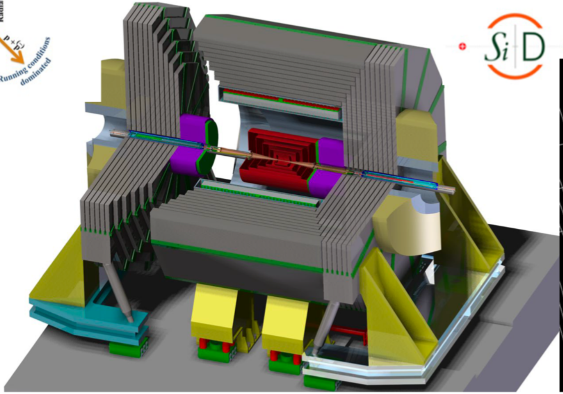


- Initial concepts in early 90s
- LOIs in 2009 (4 concepts)
- ILD and SiD validated by International Detector Advisory Group
- ILC TDR 2013 including Detailed Baseline Design (DBD) of ILD and SiD

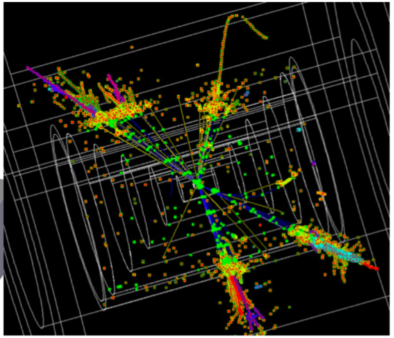
ILC is designed for two detectors in Push-Pull arrangement

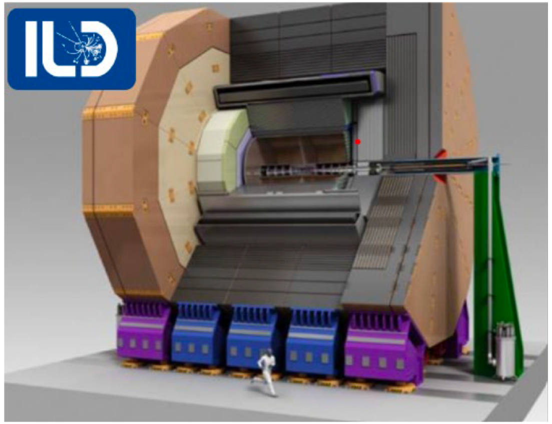

THE INTERNATIONAL LINEAR COLLIDER

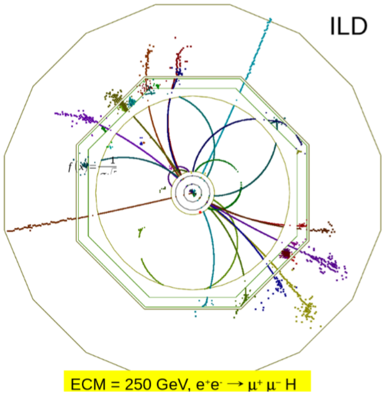
TECHNICAL DESIGN REPORT | VOLUME 4: DETECTORS



SiD

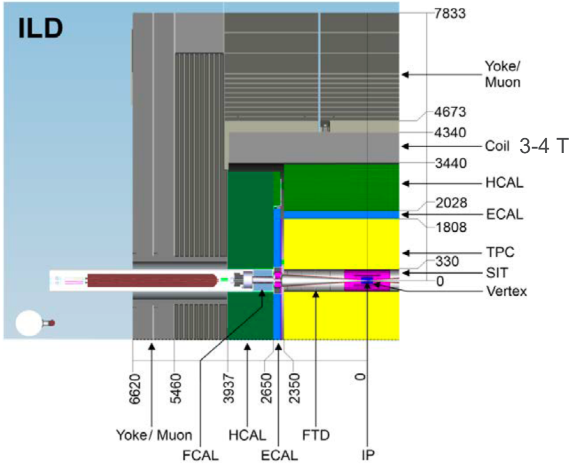






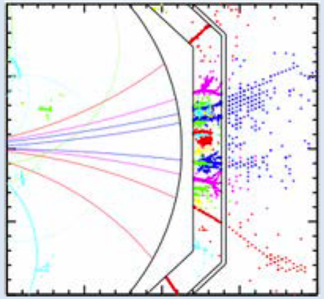
ECM = 250 GeV, $e^+e^- \rightarrow \mu^+\mu^- H$

ILD Baseline



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

40
30
20
10

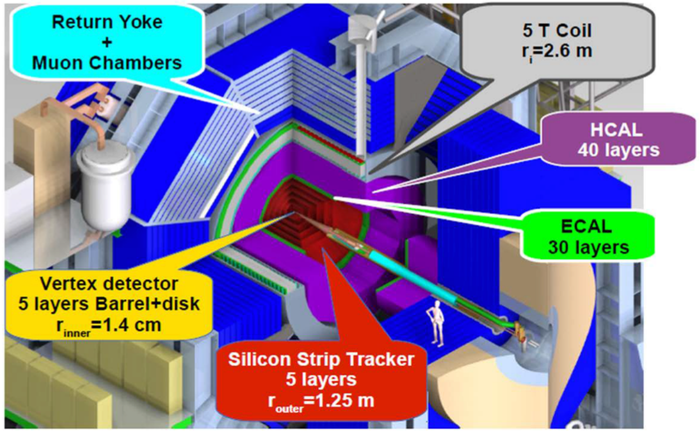


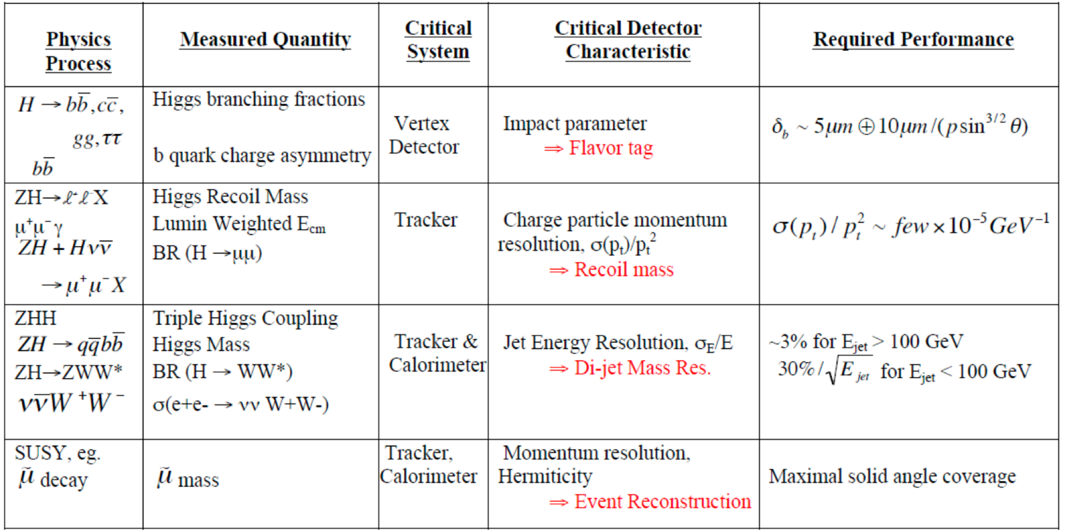
ILD is optimized around **particle flow**:

- Highly granular calorimeters
- Low-mass trackers
- Software reconstruction

→ Separation of clusters at particle level

SiD Baseline





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→$\ell^+\ell^-$X $\mu^+\mu^-\gamma$ $ZH + H\nu\bar{\nu}$ $\to \mu^+\mu^- X$	Higgs Recoil Mass Lumin Weighted E_{cm} BR (H →μμ)	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→ZWW* $\nu\bar{\nu}W^+W^-$	Triple Higgs Coupling Higgs Mass BR (H → WW*) σ(e+e- → νν 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

A compact, cost-constrained detector designed to make precision measurements and be sensitive to a wide range of new phenomena.

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

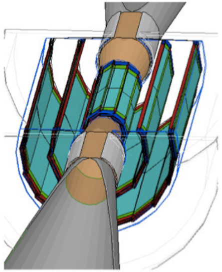
Highly segmented "tracking" calorimeters optimized for Particle Flow.

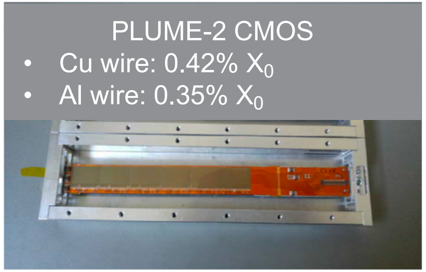
Compact design with 5T field.

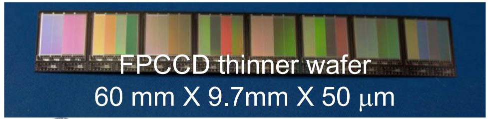
Detector is designed for rapid push-pull operation.

Vertex Detector

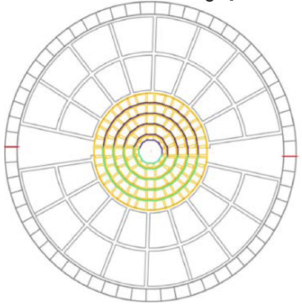
- Final subdetector to be installed, R&D to continue until ~2030
- 3 double layers, r_{min}=16 mm, 3 μm point resolution
- Main challenges: beam backgrounds, power consumption,
  material budget (0.2-0.3% X_0 per layer)
- Technology options: CPS, FPCCD, DEPFET



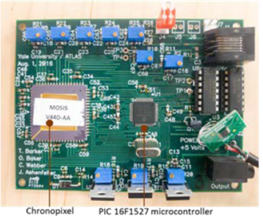

PLUME-2 CMOS
- Cu wire: 0.42% X_0
- Al wire: 0.35% X_0


FPCCD thinner wafer
60 mm X 9.7mm X 50 μm

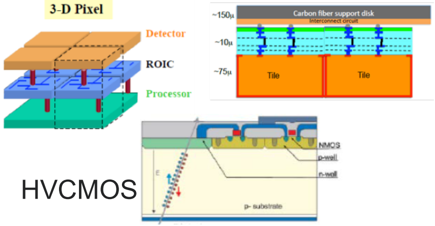
- Single bunch time resolution
- 5 layers, r_{min} = 14 mm, < 3 μm hit resolution
- Feature size ~20 μm
- <130 μW/mm^2
- ~0.1% X_0 per layer material budget



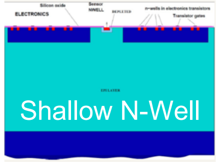
Chronopixel prototype 3 development board



- 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



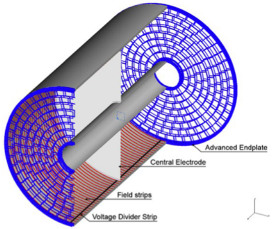
HVCMOS

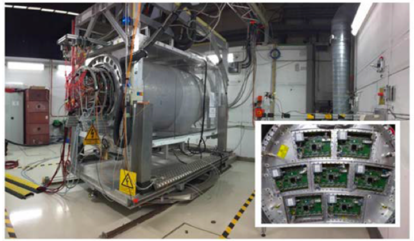


Shallow N-Well

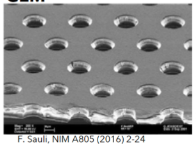
Tracker

- ILD uses a Time Projection Chamber (TPC) as the central tracker
- Drift time of ionized electrons → longitudinal position
- 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.



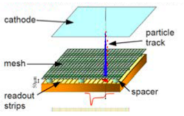


GEM



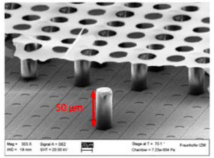
F. Sauli, NIM A805 (2016) 2-24

Micromegas



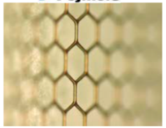
Y. Giomataris et al., NIM A376 (1996) 29-35

GridPix (NIKHEF)

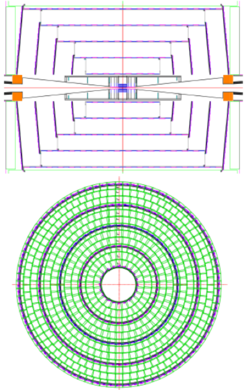


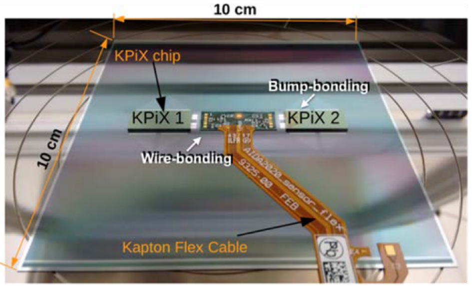
GEM Gating Grid

Fujikura



- 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





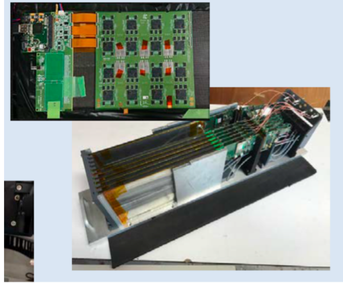
ECAL

High granularity imaging calorimetry

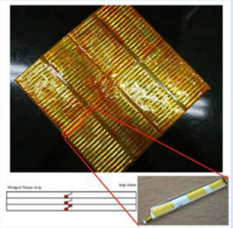
Silicon tiles (5x5mm^2)
or Scintillator strips (5x45mm^2)
with Tungsten absorber

Ultra-granular calorimeter:
10-100 million readout channels

Silicon ECAL prototype

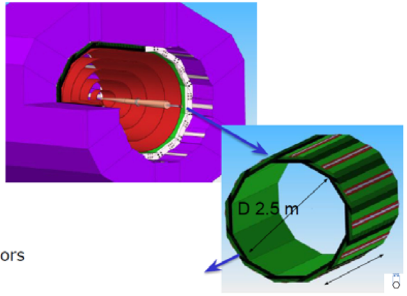


Scintillator ECAL prototype



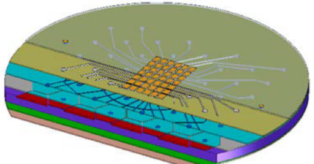
Baseline design: Slicon/Tungsten

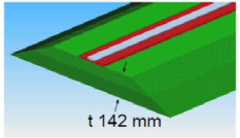
Compact Electromagnetic Calorimeter w 13 mm Moliere Radius

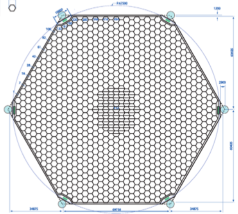


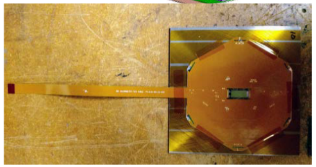
L 4.36 m

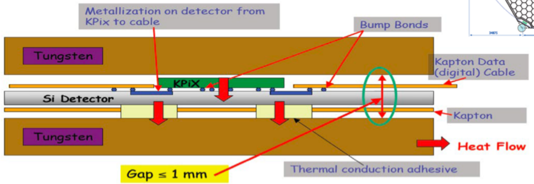
20 layers 2.5 mm W (5/7 X0)
10 layers 5 mm W (10/7 X0)
30 gaps 1.25 mm w Si pixels sensors
29 X_0; 1 λ
$\Delta E/E = 17\%/\sqrt{E}$









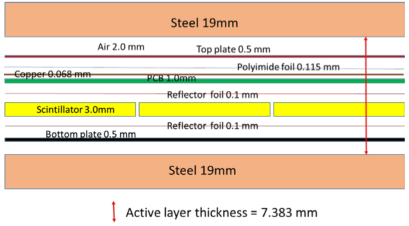


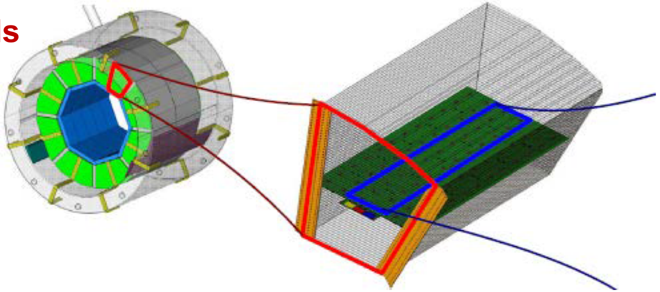
HCAL

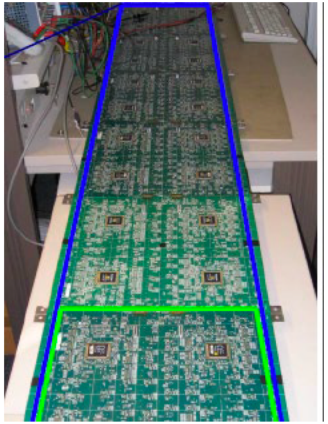
- **Two approached studied by CALICE**
  - **Analog HCAL: scintillator tile (3X3 cm^2) readout using SiPM**
  - **(Semi-)Digital HCAL: RPC with 1X1 cm^2 pads**

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

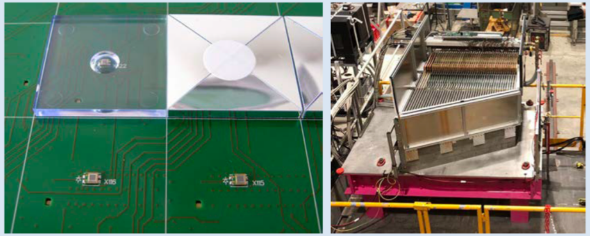
Scintillator tile (3x3 cm^2) or Gas RPC (1x1 cm^2) with Steel absorber for ILD



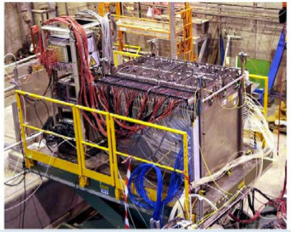




Analog HCAL prototype

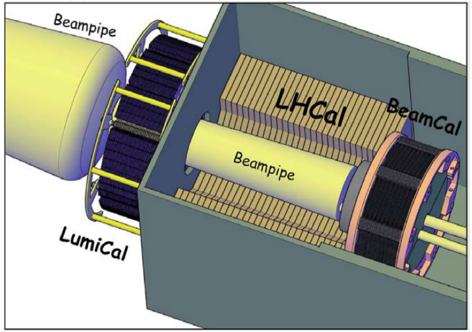


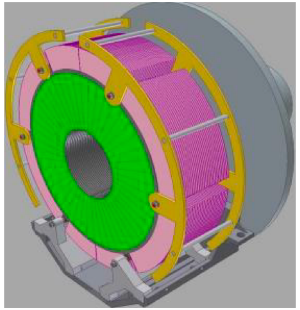
Semi-digital HCAL prototype



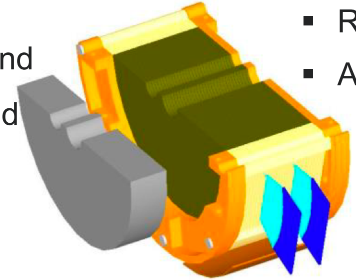
Forward Calorimeters

FCAL Collaboration
High precision design





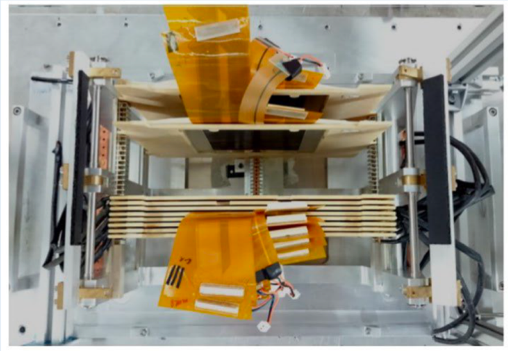
- Luminosity from low angle Bhabhas
- Reduce background
- -e/γ ID to few mrad



- 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

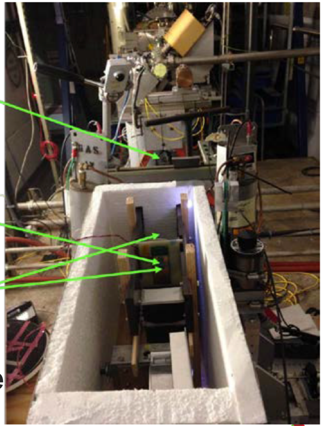
LumiCal prototype (DESY)



$2\ X_0$ pre-radiator; introduces a little divergence in shower

Sensor sample

Not shown: $4\ X_0$ "post radiator" and $8\ X_0$ "backstop"



Sensor irradiation studie for Forward Calorimetry

UPDATES SINCE DBD

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

October 20, 2021

Updating the SiD Detector concept

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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.

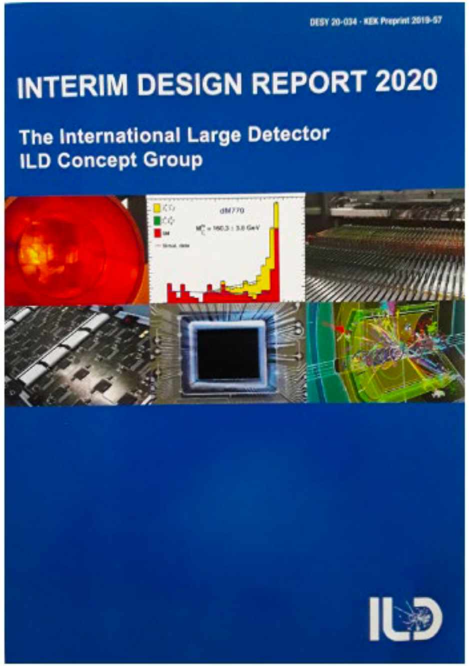
I. INTRODUCTION

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.

2020

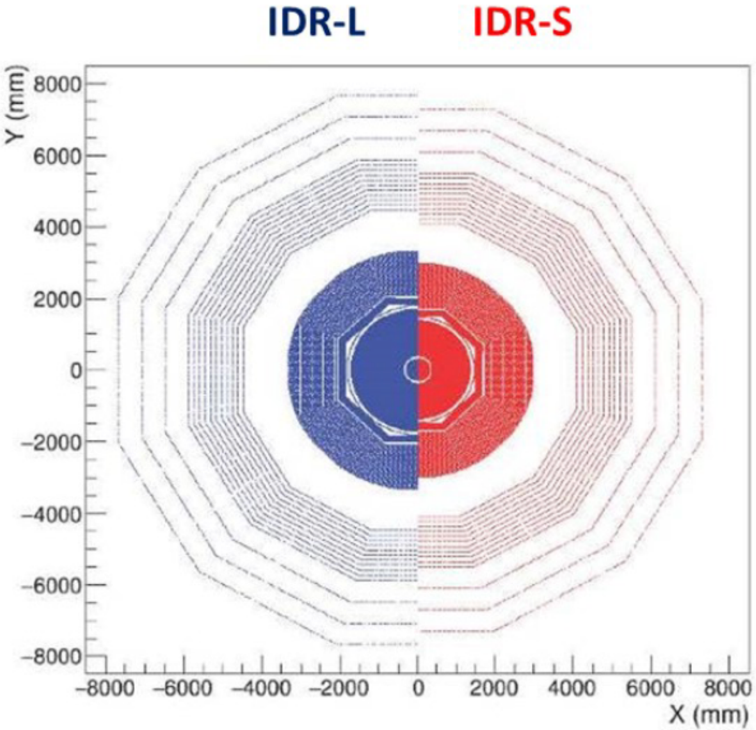


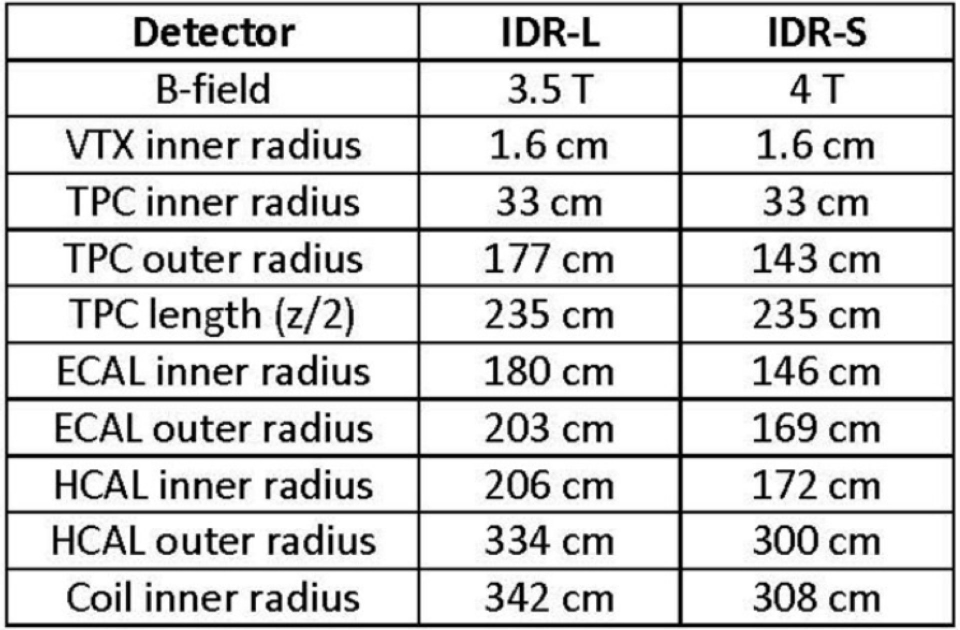
DESY 20-034 · KEK Preprint 2019-57

INTERIM DESIGN REPORT 2020

The International Large Detector
ILD Concept Group

ILD OPTIMIZATION

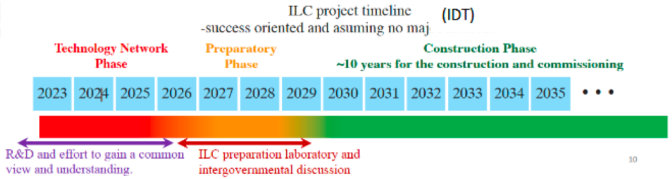




Detector	IDR-L	IDR-S
B-field	3.5 T	4 T
VTX inner radius	1.6 cm	1.6 cm
TPC inner radius	33 cm	33 cm
TPC outer radius	177 cm	143 cm
TPC length (z/2)	235 cm	235 cm
ECAL inner radius	180 cm	146 cm
ECAL outer radius	203 cm	169 cm
HCAL inner radius	206 cm	172 cm
HCAL outer radius	334 cm	300 cm
Coil inner radius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

R&D Needs for a 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

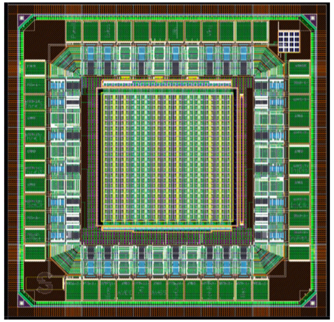
ALCC subgroup - 31 Mar 2023

- 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

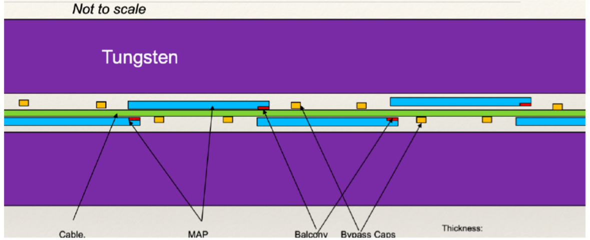
Monolithic Active Pixel Sensors (MAPS) for tracking and electromagnetic calorimeter

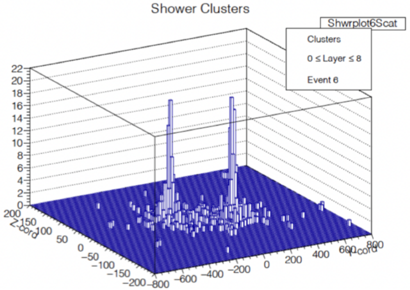
- Potential for providing higher granularity, thinner, intelligent detectors at lower overall cost
- Significantly lower material budget, with sensors and readout electronics integrated on the same chip
- Stitching for large scale sensors and reduced dead areas, towards the wafer-scale chip
- Lower power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



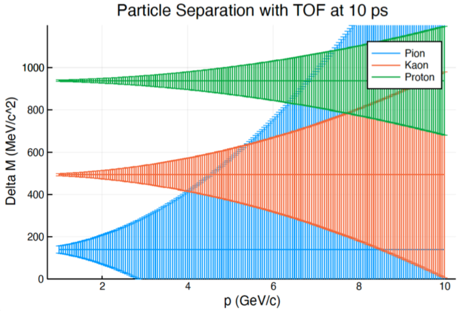
Parameter	Value
Min. Threshold	140 e^-
Spatial resolution	7 μm
Pixel size	25 x 100 μm^2
Chip size	10 x 10 cm^2
Chip thickness	300 μm
Timing resolution (pixel)	~ns
Total Ionizing Dose	100 kRads
Hit density / train	1000 hits / cm^2
Hits spatial distribution	Clusters
Power density	20 mW / cm^2

Table 1: Target specifications for 65 nm prototype.





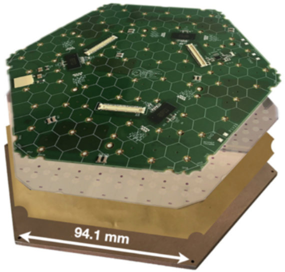
FAST TIMING

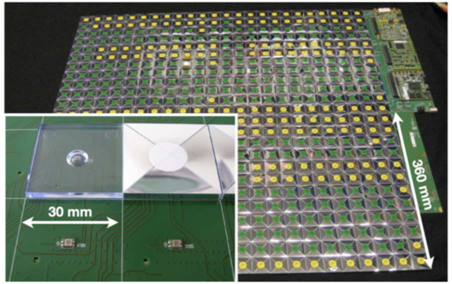


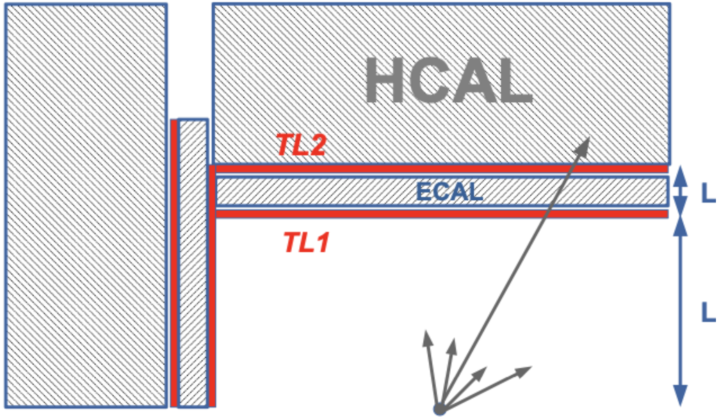
Precision timing at the level of 10-30ps is a new capability to enhance PID and calorimeter measurements

- ***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
- ***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

- How can precision timing be best used in PFA or DR
- What level of precision timing can make a real difference to calorimeter performance

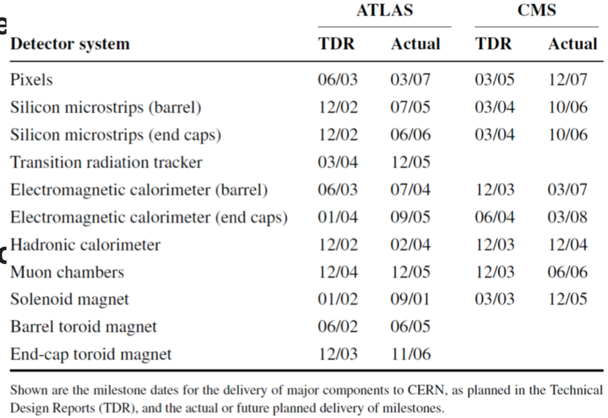






(Some) Lessons Learned from (HL-)LHC

- Long timeline and different project phases
  - Planning with project management despite (large) uncertainties
  - Early investments in critical detector R&Ds
  - Necessity of early readiness 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 expe
  - Optimization between design and buildability
    - Physicists and 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 resourc
- International and distributed collaboration
  - System engineering and technical coordination
  - Communicate and document well (and the mistakes)



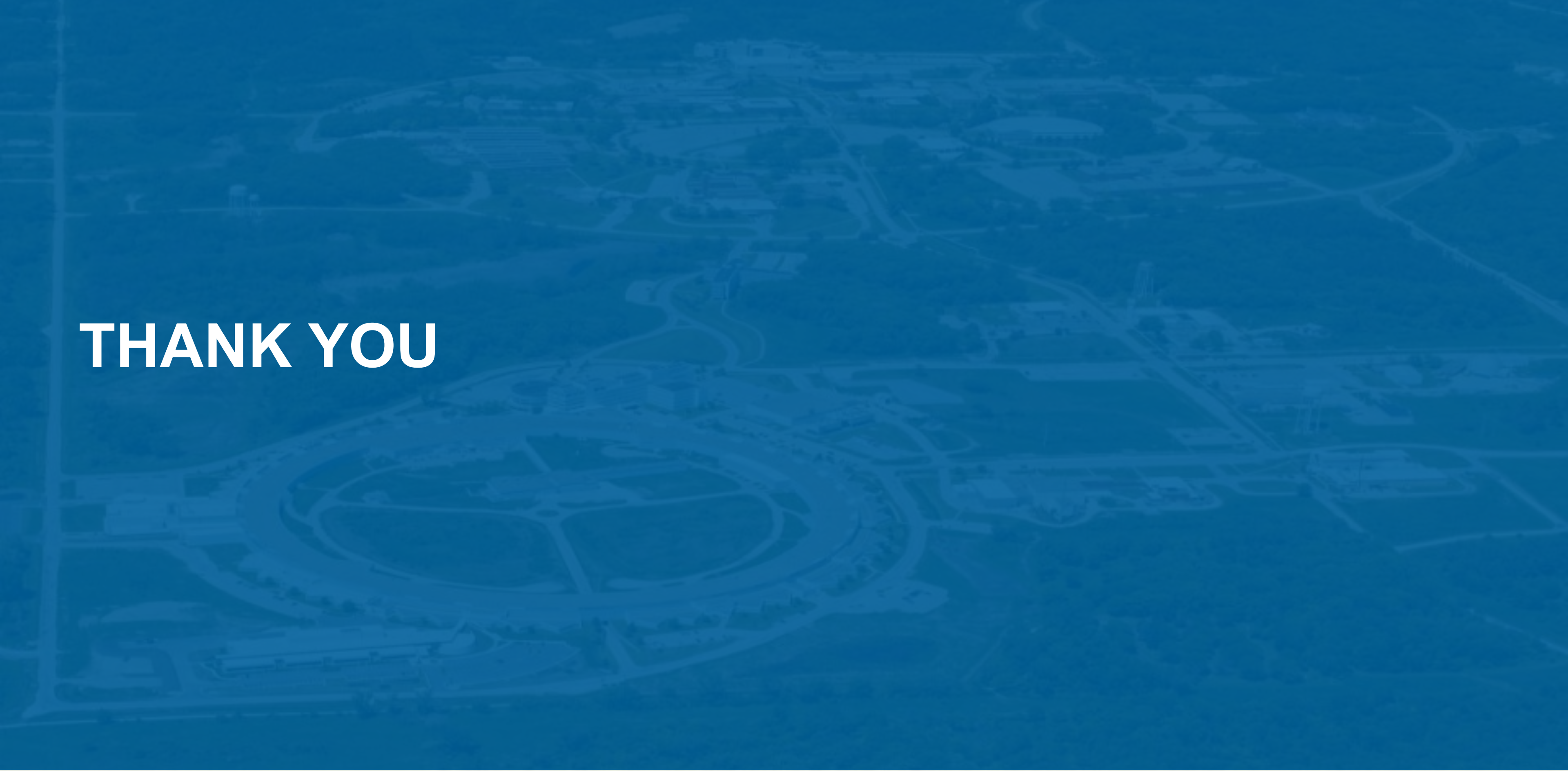
	ATLAS		CMS	
Detector system	**TDR**	**Actual**	**TDR**	**Actual**
Pixels	06/03	03/07	03/05	12/07
Silicon microstrips (barrel)	12/02	07/05	03/04	10/06
Silicon microstrips (end caps)	12/02	06/06	03/04	10/06
Transition radiation tracker	03/04	12/05		
Electromagnetic calorimeter (barrel)	06/03	07/04	12/03	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

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



THANK YOU

ILD & SID