ILD ILC Snowmass 2021

ILD concept group

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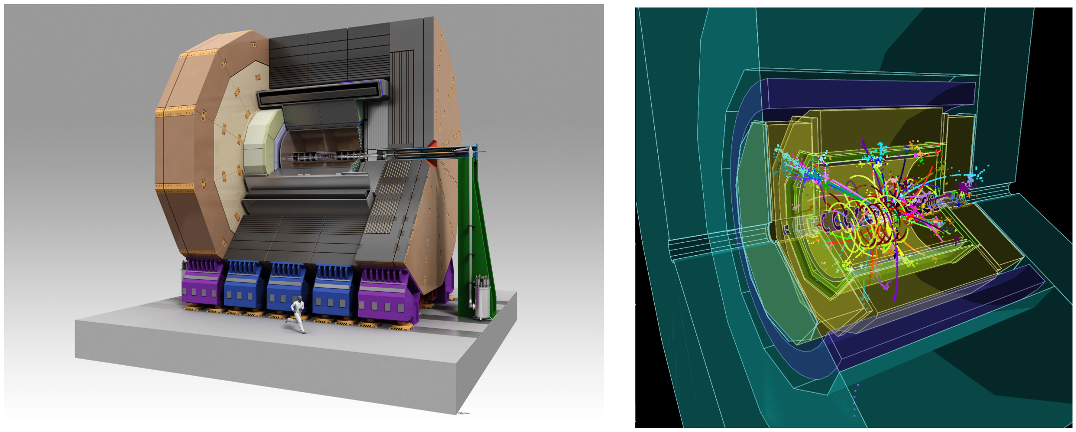

Figure 1: Left: Three-dimensional rendering of the ILD detector. Right: Event display of a simulated hadronic decay of a $t\bar{t}$ event in ILD. The colors of the tracks show the results of the reconstruction, each color corresponding to a reconstructed particle.

0.1 Detectors

0.1.1 The ILD Detector

The International Large Detector, ILD, is a proposal for a multi-purpose detector at the ILC. The design of ILD is the result of more than a decade of work by an international group of scientists and engineers. Throughout this time ILD has profited from and at the same time driven extensive technological developments which make the advanced ILD design possible.

A central role in ILD plays the concept of particle flow reconstruction [?], a method which can reconstruct complex events at collider experiments with unprecedented precision. ILD decided early on to adopt particle flow as the central guiding principle for its detector concept, and developed the ILD design around this paradigm.

The ILD concept has been described in a number of documents. The basic concept and its validation were first discussed in the ILD Detector Baseline Document (DBD) in 2013 [?]. ILD has recently published an update to the DBD, the Interim Design Report, IDR [?]. A three-dimensional image of the detector is shown in figure **??**, together with an event display of a simulated top–anti-top event within it.

Requirements for the ILD detector

The science which will be done at the ILC has been summarised earlier in this document. It is strongly dominated by the quest for ultimate precision in measurements of the properties of key particles like the Higgs boson, the weak gauge bosons, and, once the center-of-mass energy is beyond its production threshold, the top quark (see for example [?] or [?] for recent summaries).

The anticipated precision physics program drives the requirements for the detector. Many final states which will be analysed are hadronic final states, with many jets. Thus a precise reconstruction of jets is essential, which translates into an excellent jet energy resolution. Several studies that investigated the reconstruction of W and Z bosons suggest that a jet energy resolution of about 3% is needed to fully exploit the power of the collider. Such a resolution is almost two times more precise than the ATLAS and CMS detectors at the LHC have achieved. The concept of particle flow is currently believed to be the only practical approach through which this level of precision can be reached. Particle flow requires the reconstruction of charged and neutral particles with excellent efficiency over a large solid angle. A tracker with outstanding efficiency is a essential ingredient, combined with a calorimeter capable of reconstructing neutral particles with high efficiency. For ILD the choice has been made to combine a large volume hybrid tracking system, with a silicon tracking system with excellent position resolution, combined with a large gaseous tracker which promises excellent efficiency combined with low material, together with a highly granular calorimeter in both the electromagnetic and hadronic sections. To ease linking between the tracker and the calorimeter, the calorimeter is placed within the solenoid magnet which procides a 3.5 T field.

A number of highly relevant physics processes require the precise reconstruction of exclusive final states containing heavy flavour quarks. This translates into the need for very precise reconstruction of the decay vertices of long lived particles, and thus implies a high resolution vertexing system close to the interaction region.

The excellent performance of the detector system depends critically on the amount of material in the inner part of the ILD detector. The total material budget in front of the calorimeter should be below 10% of a radiation length, for the barrel part of the detector acceptance.

The whole detector should be operated without a hardware trigger to maximise the sensitivity to new physics signals. This in turn places stringent requirements on the readout electronics, in terms of both speed and power consumption. The integration of ILD is faced with the additional complexity to allow for a rapid movement of the detector in and out of the interaction region, the so-called push-pull scheme. This scheme will allow the operation of two separate and complementary experiments at a single ILC interaction region.

The design drivers of the ILD detector can thus be summarized by the following requirements:

- **Impact parameter resolution:** An impact parameter resolution of $5\,\mu\mathrm{m} \oplus 10\,\mu\mathrm{m}/[p\,[\mathrm{GeV}/c]\sin^{3/2}\theta]$ has been defined as a goal, where θ is the angle between the particle and the beamline.
- **Momentum resolution:** An inverse momentum resolution of $\Delta(1/p) = 2{\times}10^{-5}$ $[(\mathrm{GeV/c})^{-1}]$ asymptotically at high momenta should be reached with the combined silicon–TPC tracker. Maintaining excellent tracking efficiency and very good momentum resolution at lower momenta will be achieved by an aggressive design to minimise the detector's material budget.
- **Jet energy resolution:** Using the paradigm of particle flow a jet energy resolution $\Delta E/E = 3-4\%$ for light flavour jets should be reached. The resolution is defined in reference to light-quark jets, as the R.M.S. of the inner 90% of the energy distribution.
- **Readout:** The detector readout will not use a hardware trigger, ensuring full efficiency for all possible event topologies.

- **Powering** To allow a continuous readout while also minimizing the amount of inactive material in the detector, the power of major systems will be cycled between bunch trains.

The ambitious requirements of the ILC detectors sparked a world-wide R&D program to develop and demonstrate the different technologies needed [?]. The R&D was mostly coordinated and executed within so-called R&D collaborations, which concentrated on particular technologies and sub-detector systems, and with which ILD has traditionally very close and collaborative relations. These collaborations operated outside the ILD concept group, serving, in many cases, several detector concept groups.

The ILD concept from its inception has been open to new technologies. No final decision on subdetector technologies has been taken, and in many cases several options are currently under consideration. ILD is actively inviting new groups to join the effort and propose new ideas or improvements to the current concept.

In the following paragraphs, the different components of the ILD concept are introduced and discussed.

Vertexing system

The system closest to the interaction region is a pixel detector designed to reconstruct decay vertices of short lived particles with great precision. ILD has chosen a system consisting of three double layers of back-thinned pixel detectors. The innermost layer is only half as long as the others to reduce the exposure to background hits. Each layer will provide a spatial resolution around 4 μm at a pitch of about 22 μm, and a timing resolution per layer of around 2–4 μs. R&D is directed towards improving this even further, to a point which would allow hits from individual bunch crossings to be resolved.

Over the last 10 years the CMOS pixel technology has matured close to a point where all the requirements (material budget, readout speed, granularity) needed for an ILC detector can be met. The technology has seen a first large scale use in the STAR vertex detector [?], and more recently in the upgrade of the ALICE vertex detector.

Other technologies under consideration for ILD are DEPFET, which is also currently being deployed in the Belle II vertex detector [?], fine pitch CCDs [?], and also less mature technologies such as SOI (Silicon-on-insulator) and Chronopix [?].

Very light weight support structures have been developed, which bring the goal of 0.15% of a radiation length per layer within reach. Such structures are now used in the Belle II vertex detector [?].

In figure 2 the purity of the flavour identification in ILD is shown as a function of its efficiency. The performance for b-jet identification is excellent, and charm-jet identification is also good, providing a purity of about 70% at an efficiency of 60%. The system also allows the accurate determination of the charge of displaced vertices, and contributes strongly to the low-momentum tracking capabilities of the overall system, down to a few 10's of MeV. An important aspect of the

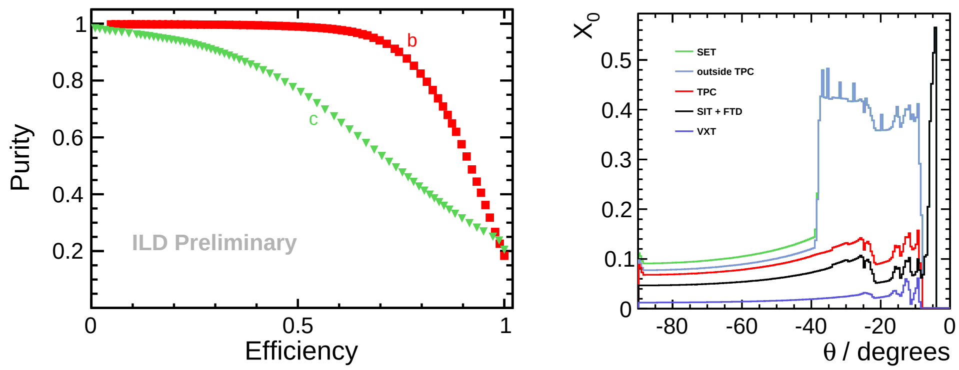

Figure 2: Left: Purity of the flavour tag as a function of the efficiency, for different flavours tagged. Right: Cumulative material budget in ILD up to the calorimeter, in fraction of a radiation length (figures from [?]).

system leading to superb flavour tagging is the small amount of material in the tracker. This is shown in figure 2 (right).

Tracking System

ILD has decided to approach the problem of charged particle tracking with a hybrid solution, which combines a high resolution time-projection chamber (TPC) with a few layers of strategically placed strip or pixel detectors before and after the TPC. The time-projection chamber will fill a large volume about 4.6 m in length, spanning radii from 33 to 180 cm. In this volume the TPC provides up to 220 three dimensional points for continuous tracking with a single-hit resolution of better than 100 μm in $r\phi$, and about 1 mm in z. This high number of points allows a reconstruction of the charged particle component of the event with high accuracy, including the reconstruction of secondaries, long lived particles, kinks, etc.. For momenta above 100 MeV, and within the acceptance of the TPC, greater than 99.9% tracking efficiency has been found in events simulated realistically with full backgrounds. At the same time the complete TPC system will introduce only about 10% of a radiation length into the detector [?].

Inside and outside of the TPC volume a few layers of silicon detectors provide high resolution points, at a point resolution of 10μm. Combined with the TPC track, this will result in an asymptotic momentum resolution of $\delta p_t/p_t^2 = 2 \times 10^{-5}$ ((GeV/c)$^{-1}$) for the complete system. Since the material in the system is very low, a significantly better resolution at low momenta can be achieved

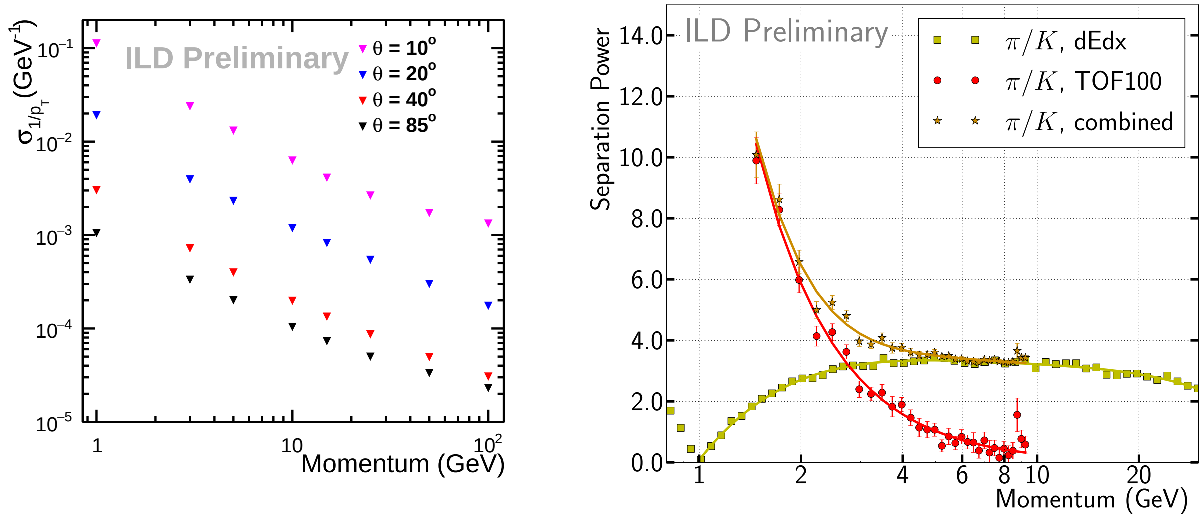

Figure 3: Left: Simulated resolution in $1/p_t$ as a function of the momentum for single muons. The different curves correspond to different polar angles. Right: Simulated separation power (probability for a pion to be reconstructed as a kaon) between pions and kaons, from dE/dx and from timing, assuming a 100 ps timing resolution of the first ECAL layer (figures from [**?**]).

than is possible with a silicon-only tracker. The achievable resolution is illustrated in figure 3, where the $1/p_t$-resolution is shown as a function of the momentum of the charged particle. In the forward direction, extending the coverage down to the beam-pipe, a system of two pixel disks (point resolution 5μm) and five strip disks (resolution 10μm outside of the TPC, and 5μm inside the TPC) provide tracking coverage down to the beam-pipe.

The time-projection chamber also enables the identification of the particle type by the measurement of the specific energy loss, dE/dx, for tracks at intermediate momenta [**?**]. The achievable performance is shown in figure 3 (right). If the inner and/or outer silicon layers or the first calorimeter layers in addition provide timing with 100 ps resolution, time of flight measurements can provide additional information, which is particularly effective in the momentum regime which is problematic for dE/dx, as it is shown in figure 3 (right).

The design and performance of the TPC has been the subject of intense R&D over the last 15 years. A TPC based on the readout with micro-pattern gas detectors has been developed, and tested in several technological prototypes. The fundamental performance has been demonstrated, and solutions to construct a TPC with the required low mass have been developed. Most recently the performance of the specific energy loss, dE/dx, has been validated in test beam data. Based on these results, the TPC technology is sufficiently mature for use in the ILD detector, and can deliver the required performance (see e.g. [**?**, **?**]).

Calorimeter- and Muon-System

A very powerful calorimeter system is essential to the performance of a detector designed for particle flow reconstruction. Particle flow stresses the ability to separate the individual particles in a jet, both charged and neutral. This puts the imaging capabilities of the system at a premium, and pushes the calorimeter development in the direction of a system with very high granularity in all parts of the system, both transverse to and along the shower development direction. A highly granular sampling calorimeter is the chosen solution to this challenge [?]. The conceptual and technological development of the particle flow calorimeter have been largely done by the CALICE collaboration (for a review of recent CALICE results see e.g. [?]).

ILD has chosen a sampling calorimeter readout with silicon diodes as one option for the electromagnetic calorimeter. Diodes with pads of about (5×5) mm^2 are used, to sample a shower up to 30 times in the electromagnetic section. In 2018 a test beam experiment demonstrated the large scale feasibility of this technology, by showing not only that the anticipated resolution can be reached. A very similar system has been adopted by the CMS experiment for the upgrade of the endcap calorimeter, and will deliver invaluable information on the scalability and engineering details of such a system.

As an alternative to the silicon based system, sensitive layers made from thin scintillator strips are also investigated. Orienting the strips perpendicular to each other has the potential to realize an effective cell size of 5×5mm^2, with the number of read-out channels reduced by an order of magnitude compared to the all silicon case.

For the hadronic part of the calorimeter of the ILD detector, two technologies are studied, based on either silicon photo diode (SiPM) on scintillator tile technology [?] or resistive plate chambers [?]. The SiPM-on-tile option has a moderate granularity, with 3×3 cm^2 tiles, and provides an analogue readout of the signal in each tile (AHCAL). The RPC technology has a better granularity, of 1×1 cm^2, but provides only 2-bit amplitude information (SDHCAL). For both technologies, significant prototypes have been built and operated. Both follow the engineering design anticipated for the final detector, and demonstrate thus not only the performance, but also the scalability of the technology to a large detector. As for the ECAL the SiPM-on-tile technology has been selected as baseline for part of the upgrade of the CMS hadronic end-cap calorimeter, and will thus see a major application in the near future.

A rendering of the barrel calorimeter is shown in figure 4 (left).

The iron return yoke of the detector, located outside of the coil, is instrumented to act as a tail catcher and as a muon identification system. Several technologies are possible for the instrumented layers. Both RPC chambers and scintillator strips readout with SiPMs have been investigated. Up to 14 active layers, located mostly in the inner half of the iron yoke figure 1 for more details) could be instrumented.

Three rather specific calorimeter systems are foreseen for the very forward region of the ILD detector [?]. LumiCal is a high precision fine sampling silicon tungsten calorimeter primarily designed to measure electrons from Bhabha scattering, and to precisely determine the integrated luminosity [?]. The LHCAL (Luminosity Hadronic CALorimeter) just outside the LumiCal extends

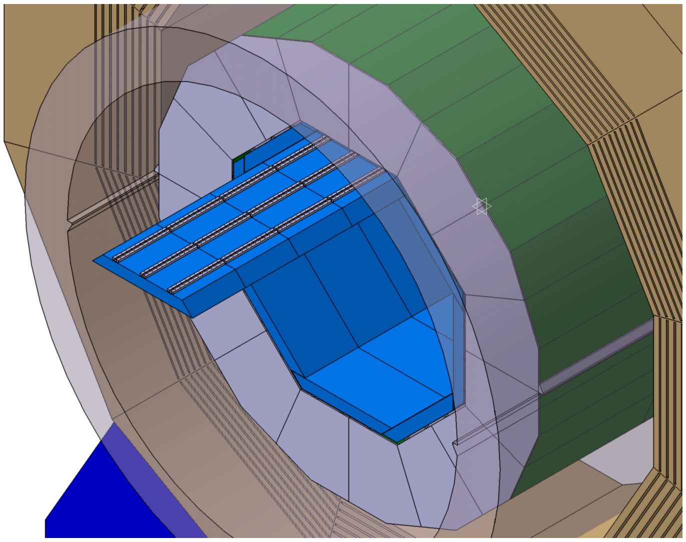

Figure 4: Left: Three-dimensional rendering of the barrel calorimeter system, with one ECAL module partially extracted. Right: Prototype module of the lumical calorimeter.

the reach of the endcap calorimeter system down to smaller angles relative to the beam, and closes the gap between the inner edge of the ECAL endcap and the luminosity calorimeter, LumiCal. Below the LumiCal acceptance, where background from beamstrahlung rises sharply, BeamCal, placed further downstream from the interaction point, provides added coverage and is used to provide a fast feedback on the beam position at the interaction region. As the systems move close to the beam-pipe, the requirements on radiation hardness and on speed become more and more challenging. Indeed this very forward region in ILD is the only region where radiation hardness of the systems is a key requirement. A picture of a prototype of the Lumical calorimeter is shown in figure 4(right).

Detector Integration and Costing

One of the major goals of the ILD concept group was from the beginning to develop the detector concept from a collection of technological ideas to a real detector that can actually be built, commissioned, and operated within given engineering and site-dependent constraints.

The main mechanical structure of the ILD detector is the iron yoke that consists of three barrel rings and two endcaps. The yoke provides the required shielding for radiation and magnetic fields and supports the cryostat for the detector solenoid and the barrel detectors, calorimeters and tracking system.

A common concept for the detector services such as cables, cooling, gases and cryogenics has been developed. The requirements are in many cases based on engineering prototypes of the ILD sub-systems.

The main detector solenoid is based on CMS experience and can deliver magnetic fields up to

4 T. A correction system for the compensation of the crossing angle of the ILC beam, the Detector Integrated Dipole, has been designed and can be integrated into the main magnet cryostat.

The cost of the ILD detector has been estimated at the time of the ILD interim design report, IDR. The total detector cost is about 379 Million EUR in 2018 costs. The cost of the detector is strongly dominated by the cost of the calorimeter system and the yoke, which together account for about 60% of the total cost. The total cost of ILD scales weakly with the overall size of the detector.

Future Developments of the ILD Detector

0.1.2 Science with ILD

ILD has been designed to operate with electron-positron collisions between 90 GeV and 1 TeV. The science goals of the ILC have been described in detail in [?], and results of numerous studies are reported in the following chapters of this document. It should be pointed out that the analyses which have been performed within the ILD concept group are based on fully simulated events, using a realistic detector model and advanced reconstruction software, and in many cases include estimates of key systematic effects. This is particularly important when estimating the reach the ILC and ILD will have for specific measurements. Determining, for example, the branching ratios of the Higgs at the percent level depends critically on the detector performance, and thus on the quality of the event simulation and reconstruction.

In many cases the performance assumed in the detector simulation has been cross checked with prototype test results. The key performance numbers for the vertexing, tracking and calorimeter systems are all based on results from test beam experiments. The particle flow performance, a key aspect of the ILD physics reach, could not be fully verified in the absence of a large scale detector prototype, but key aspects have been shown in experiments. This includes the single particle resolution for neutral and charged particles, the particle separation in jets, the linking power between tracking and calorimetry, and detailed shower reconstruction important for particle flow.

While the physics case studies are based on the version of the ILD detector presented in the detector volume of the ILC DBD [?], ILD ~~has recently~~ initiated a systematic benchmarking effort to study the performance of the ILD concept, and to determine in particular the correlations between science objectives and detector performance. The list of benchmark processes which have been studied is given in table 1. Even if the ILC will start operation at a center-of-mass energy of 250 GeV, the ILD detector is being designed to meet the more challenging requirements of higher center-of-mass energies, since major parts of the detector, e.g. the coil, the yoke and the main calorimeters will not be replaced when upgrading the accelerator. Therefore, most of the detector benchmark analyses were performed at a center-of-mass energy of 500 GeV, and one benchmark even at 1 TeV. The assumed integrated luminosities and beam polarisation settings followed the canonical running scenario [?]. In addition to the well-established performance aspects of the ILD detector, the potential of new features not yet incorporated in the existing detector prototypes, e.g. time-of-flight information, have also been evaluated.

The results of these studies were published in the ILD Design Report [?]. They ~~will~~ form the basis for the definition of a new ILD baseline detector model, which has been used for a new physics-oriented Monte-Carlo production for 250 GeV. Sample production with the most recent beam parameters of the accelerator [?] and significantly improved reconstruction algorithms~~, and~~ is expected to lead to further improvements of the expected results of the precision physics program of the ILC [?].

Further ILD performance and physics potential studies are ongoing. Special attention is paid to understanding of systematic effects. Significant reduction of systematic uncertainties is possible in combined analysis of different channels, in particular when combining data taken with different beam polarisation settings.

0.1.3 Integration of ILD into the experimental environment

ILD is designed to be able to work in a push-pull arrangement with another detector at a common ILC interaction region. In this scheme ILD sits on a movable platform in the underground experimental hall. This platform allows for a roll-in of ILD from the parking position into the beam and vice versa within a few hours. The detector can be fully opened and maintained in the parking position.

The current mechanical design of ILD assumes an initial assembly of the detector on the surface, similar to the construction of CMS at the LHC. A vertical shaft from the surface into the underground experimental cavern allows ILD to be lowered in five large segments, corresponding to the five yoke rings.

ILD is self-shielding with respect to radiation and magnetic fields to enable the operation and maintenance of equipment surrounding the detector, e.g. cryogenics. Of paramount importance is the possibility to operate and maintain the second ILC push-pull detector in the underground cavern during ILC operation.

0.1.4 The ILD Concept Group

The ILD collaboration initially started out as a fairly loosely organised group of scientists interested to explore the design of a detector for a linear collider like the ILC. With the delivery of the DBD in 2013, the group re-organised itself more along the lines of a traditional collaboration. The group imposed upon itself a set of by-laws which govern the functions of the group, and define rules for the membership of ILD.

In total 65 groups from 30 countries signed the letter of participation in 2015. At present (2021), 68 institutions are members, and a number of individuals have joined as guest members of ILD. A map indicating the location of the ILD member institutes is shown in figure 5.

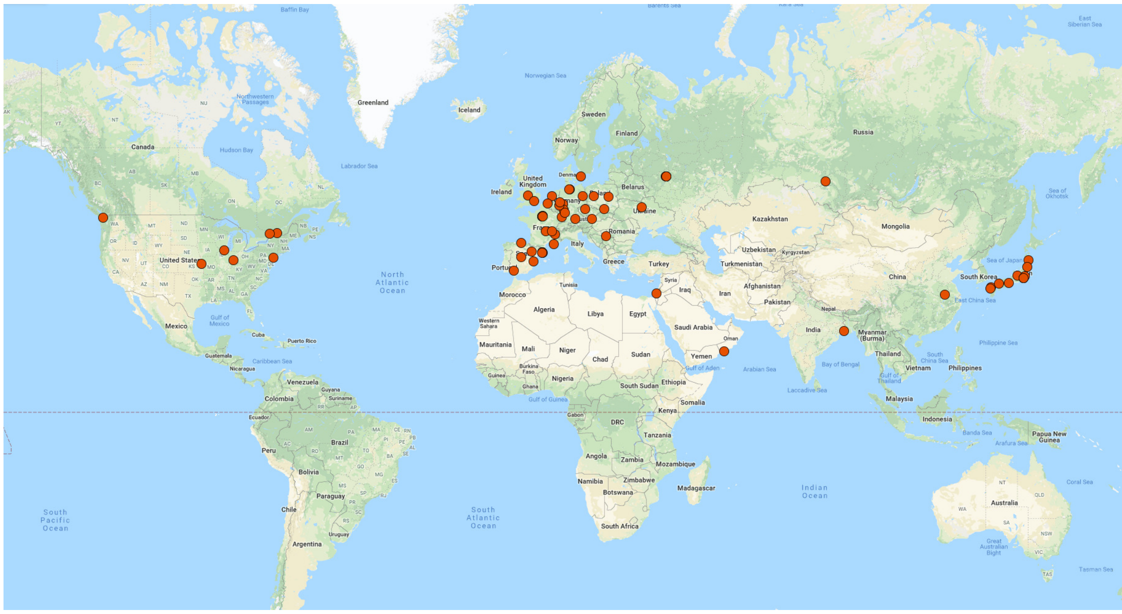

Figure 5: Map with the location of the ILD member institutes indicated.

0.1.5 Conclusion and Outlook

The ILD detector concept is a well developed integrated detector optimised for use at the electron-positron collider ILC. It is based on advanced detector technology, and driven by the science requirements at the ILC. Most of its major components have been fully demonstrated through prototyping and test beam experiments. The physics performance of ILD has been validated using detailed simulation systems. A community interested in building and operating ILD has formed over the last few years. It is already sizeable, encompassing 72 institutes from around the world. The community is ready to move forward once the ILC project receives approval.

Measurement	**Main physics question**	**main issue addressed**
Higgs mass in $H \to b\bar{b}$	Precision Higgs mass determination	Flavour tag, jet energy resolution, lepton momentum resolution
Branching ratio $H \to \mu^+\mu^-$	Rare decay, Higgs Yukawa coupling to muons	High-momentum p_t resolution, μ identification
Limit on $H \to$ invisible	Hidden sector / Higgs portal	Jet energy resolution, Z or recoil mass resolution, hermeticity
Coupling between Z and left-handed τ	Contact interactions, new physics related to 3rd generation	Highly boosted topologies, τ reconstruction, π^0 reconstruction
WW production, W mass	Anomalous triple gauge couplings, W mass	Jet energy resolution, leptons in forward direction
Cross section of $e^+e^- \to \nu\nu qqqq$	Vector Bosons Scattering, test validity of SM at high energies	W/Z separation, jet energy resolution, hermeticity
Left-Right asymmetry in $e^+e^- \to \gamma Z$	Full six-dimensional EFT interpretation of Higgs measurements	Jet energy scale calibration, lepton and photon reconstruction
Hadronic branching ratios for $H \to b\bar{b}$ and $c\bar{c}$	New physics modifying the Higgs couplings	Flavour tag, jet energy resolution
A_{FB}, A_{LR} from $e^+e^- \to b\bar{b}$ and $t\bar{t} \to b\bar{b}qqqq/b\bar{b}qql\nu$	Form factors, electroweak coupling	Flavour tag, PID, (multi-)jet final states with jet and vertex charge
Discovery range for low ΔM Higgsinos	Testing SUSY in an area inaccessible for the LHC	Tracks with very low p_t, ISR photon identification, finding multiple vertices
Discovery range for WIMPs in mono-photon channel	Invisible particles, Dark sector	Photon detection at all angles, tagging power in the very forward calorimeters
Discovery range for extra Higgs bosons in $e^+e^- \to Zh$	Additional scalars with reduced couplings to the Z	Isolated muon finding, ISR photon identification.

Table 1: Table of benchmark reactions which are used by ILD to optimize the detector performance. The analyses are mostly conducted at 500 GeV center-of-mass energy, to optimally study the detector sensitivty. The channel, the physics motivation, and the main detector performance parameters are given.