Physics at e+e- Colliders

Seminar 9.11.2017
Karlsruhe Institute of Technologies
Ties Behnke, DESY
- The case for lepton colliders
- Collider projects
- Physics at an e+e- collider
- Opportunities in Japan
The success of the Standard Model: Predictability

LEP: number of families
Indirect constraints

LHC: discovery of a Higgs particle

Many years of intense studies at electron positron (LEP, LEP2, SLC) and Hadron Colliders (Tevatron) paved the way to the discovery of the Higgs at the LHC.
Following the Route to Higgs

• The discovery of the Higgs boson at the LHC in 2012 marks the end of an era: All particles predicted to exist by the Standard Model of particle physics have now been observed.

• The discovery has been a triumph of the Standard Model, leading the way to the discovery.

BUT: for the first time in 40 years we are left without clear guidance.
Key Challenges

1. Use the Higgs Boson as a new tool for discovery

2. Pursue the physics associated with neutrino mass

3. Identify the new physics of dark matter

4. Understand cosmic acceleration: dark energy and inflation

5. Explore the unknown: new particles, interactions, and physical principles
Ways Forward at the Energy Frontier

Two main largely complementary strategies:

- Highest energy: Direct production of new particles
  - LHC, (FCC-hh, HE-LHC...)
- Highest precision: Detection of new phenomena in deviations from expectations
  - Energy frontier $e^+e^-$ colliders
    - ILC, CLIC (FCC-ee)
  - LHCb, Belle II, FCC-ee, ...

Linear $e^+e^-$ colliders - Combining precision and direct discovery potential
Lepton Collisions

LHC: pp scattering at $\leq 14$ TeV

- Scattering process of proton constituents with energy up to several TeV,
- strongly interacting
- huge QCD backgrounds,
- low signal–to–backgr. ratios

LC: e+e− scattering at $\leq 1$ TeV (3 TeV)

- Clean exp. environment:
  - well-defined initial state,
  - tuneable energy,
  - beam polarization, GigaZ,
  - $\gamma\gamma$, e\gamma, e−e− options, . . .
- rel. small backgrounds
- high-precision physics
Lepton Colliders

Long history of successful lepton colliders at the energy frontier:

- Last high energy colliders: SLC at SLAC, until 1998, LEP at CERN, until 2000
## Physics at Lepton Colliders

### Three main pillars:

<table>
<thead>
<tr>
<th>Higgs</th>
<th>t\text{(\text{op})}</th>
<th>New Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full exploration of the Higgs sector:</td>
<td>Precision measurements of top quark properties in theoretically well-defined schemes</td>
<td>Direct search for new particles complementary to the LHC: additional light Higgs bosons, electroweak states, Dark Matter candidates, ...</td>
</tr>
<tr>
<td>a model-independent measurement of all relevant Higgs couplings</td>
<td>Use of top quark observables as an indirect probe for New Physics at high mass scales</td>
<td>Indirect search for new force carriers at high mass scales</td>
</tr>
<tr>
<td>direct study of the Higgs potential: Measurement of the self coupling</td>
<td>electroweak precision measurements</td>
<td></td>
</tr>
</tbody>
</table>

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Ties Behnke, 9.11.2017

Lepton Colliders
The Higgs Menu

- $\sigma(e^+e^- \rightarrow HX)$ [fb]
- $\sqrt{s}$ [GeV]
- Energy range of $e^+e^-$ projects

- $\geq 250$ GeV
- $\geq 350$ GeV
- $\geq 500$ GeV
- $\geq 500$ GeV
- $\geq 1$ TeV
The TOP Menu

- Clean, highly efficient identification of top quark pair events

- Enables two classes of measurements:
  - Precise determination of top quark properties: mass, width, ...
  - Use top quarks as a tool: high mass makes top potentially very sensitive to new physics, strong connection to EWSB
  - $t\bar{t}H$ coupling

>380 GeV

>500 GeV
The New Physics Menu

- Two main paths for discovery
  - Direct detection of new particles
  - Observations of deviations from SM expectations, pointing to new phenomena at higher scales

- Irrespective of LHC results, both approaches are highly relevant:
  - Linear Colliders emphasize electroweak phenomena, cover regions of phase space not accessible at LHC
  - Indirect measurement in many cases can access scales which are not accessible at the LHC

But we do not know ... there are no guarantees

For ILC: recent summary paper in arXiv:1702:05333
How can we go there?

Collider Technologies
Circular Colliders@CERN

FCC: Future Circular Collider: 80-100 km ring at CERN

Main parameters under study:

- **e+e- collider (FCC-ee)**  
as potential (first?) intermediate step

- **pp-collider (FCC-hh)**  
defining infrastructure requirements

- **p-e (FCC-he) option**

Energy for e+e-: higgs factory, maybe top
CEPC e+e- collider

Proposal to build a 50-100 km ring in China.

Phase 1: e+e- Higgs factory
Phase 2: proton (anti)proton collisions

Similar to FCC proposal in Europe, though

Scope is somewhat reduced
Clear goal to have initial Electron – positron collisions

Status:
Pre-CDR finished, now some funding for R&D on accelerators and detectors available.
Two Beam Scheme

Drive Beam supplies RF power

- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

Main beam for physics

- high energy (9 GeV – 1.5 TeV)
- current 1.2 A

Technology is challenging
Intense R&D effort mostly at CERN

Up to 3 TeV E(cms) anticipated

---

CLIC: our option to reach multi-TeV energies in lepton collisions in the future.

Timescale 2030+
The International Linear Collider:

Electron Positron Collisions
Superconducting acceleration technology
High Luminosity at $E=250$ GeV to 1 TeV
About 31km site length at 500 GeV

Proven technology
Significant facilities exist or are under construction (XFEL)

$E = 250\text{GeV} \rightarrow 1\text{TeV}$
$L = 2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$
$500\text{fb}^{-1}$ in 4 years
How Does it Work?

Animation by T. Takahashi (Hiroshima)
Why Superconducting?

- Linear accelerator: Accelerate electrons in a long string of RF cavities
- ILC Gradient: 31.5MV/m → need 15.8km for 500GeV!
- For given total power (electricity bill!), luminosity proportional to efficiency
- ILC: total site power ~160MW @ 500GeV
- Superconducting cavities maximise RF-to-beam efficiency

Collider design is power constrained!
European XFEL @ DESY

Largest deployment of this technology to date
- 100 cryomodules
- 800 cavities
- 17.5 GeV

The ultimate ‘integrated systems test’ for ILC.

Successful commissioning 2017
Friendly user operation has started
ILC Performance

XFEL production line: maximum gradient reached

ILC baseline design

- Superconducting cavities
- 31.5 MV/m gradient
- Well developed, tested design of cryo modules, internationally accessible.
Large SCRF Community

European XFEL

ILC-SRF technology

Americas LCLS-II

PAPS@IHEP CFF/STF@KEK

Asia
SCRF Cavities: Almost a Stock Item

Niobium Superconducting Cavities
1.3 GHz 9-Cell ILC / TESLA

Niobium in stock for quick delivery!

Qualified vendors in all regions: America, Asia, and Europe

* Entry level niobium 3 months (other options available)

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Lepton Colliders
Graphic: Benno List, DESY
The ILC Proposal

Initial stage:

250 GeV, 4 ab$^{-1}$ in 15 years

Energy upgrade depending on findings

Linear Colliders are intrinsically energy upgradable.

Initial stage of 250 GeV is driven by cost: 40% cheaper than 500 GeV.
THE SCIENCE IN MORE DETAIL
The Higgs Menu
Higgs Physics: what we want

Comprehensive study of the Higgs Couplings

- Multi Jets in the final state
- need excellent jet-energy resolution to get decent measurement
### Precision needed

<table>
<thead>
<tr>
<th>Model</th>
<th>$\kappa_V$</th>
<th>$\kappa_b$</th>
<th>$\kappa_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet Mixing</td>
<td>$\sim 6%$</td>
<td>$\sim 6%$</td>
<td>$\sim 6%$</td>
</tr>
<tr>
<td>2HDM</td>
<td>$\sim 1%$</td>
<td>$\sim 10%$</td>
<td>$\sim 1%$</td>
</tr>
<tr>
<td>Decoupling MSSM</td>
<td>$\sim -0.0013%$</td>
<td>$\sim 1.6%$</td>
<td>$&lt; 1.5%$</td>
</tr>
<tr>
<td>Composite</td>
<td>$\sim -3%$</td>
<td>$\sim -(3 - 9)%$</td>
<td>$\sim -9%$</td>
</tr>
<tr>
<td>Top Partner</td>
<td>$\sim -2%$</td>
<td>$\sim -2%$</td>
<td>$\sim +1%$</td>
</tr>
</tbody>
</table>

2013 snowmass study, energy frontier report

Deviations from SM couplings are typically a few percent.

Discovery means 5$\sigma$, so need sub-percent accuracy
Higgs Physics

Higgs signals at LC are very clean:

Higgs recoil measurement (absolute width):
~ 235-260 GeV
(90+125+20 GeV)

Higgs branching ratios and tt threshold:
350 GeV = 2*175 GeV

Htt coupling, top physics,
Higgs self coupling:
≥ 500 GeV – 1000 GeV
(tth threshold:
2*175+125 = 475 GeV,
550 GeV for best rates)
What do we measure?

ILC and LHC: observe Higgs in specific decay mode: $\sigma \times \text{BR}$

ILC can measure independent of decay mode in recoil channel

Production cross section:

- Very difficult to measure at the LHC
- Precision measurements possible at the ILC (Higgs Recoil Method)

Only the $e^+e^-$ can provide a model independent measurement of the branching ratios!

Required mass precision:

$\delta M(H) = 0.1\%$

Driven by H-VV (W and Z) precision

Mass spectrum for recoil analysis at 250 GeV
Combined analysis (ILC + LHC) based on model independent EFT framework at the ILC.

End of LHC HL phase
End of first ILC phase
A word on numbers

When comparing results great care is needed to compare things on an equal footing.

The goal should be to be as model independent as necessary.

The impact on the results can be huge:

<table>
<thead>
<tr>
<th>error in $\Gamma_T$</th>
<th>unconstrained</th>
<th>$\sum BR = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILC 500</td>
<td>5.0%</td>
<td>1.6%</td>
</tr>
<tr>
<td>ILC 500 up</td>
<td>2.8%</td>
<td>0.75%</td>
</tr>
<tr>
<td>ILC 1000</td>
<td>4.6%</td>
<td>1.2%</td>
</tr>
</tbody>
</table>
The TOP Menu

- Clean, highly efficient identification of top quark pair events

- Enables two classes of measurements:
  - Precise determination of top quark properties: mass, width, ...
  - Use top quarks as a tool: high mass makes top potentially very sensitive to new physics, strong connection to EWSB
  - $t\bar{t}H$ coupling

500 GeV

$>380 \text{ GeV}$

$>500 \text{ GeV}$
Top at the Linear Collider

- Top mass: Fundamental SM parameter, leading contribution to radiative corrections
- **Threshold scan** measures mass in a `[theoretically very clean way](#) → gets rid of QCD uncertainties (~1 GeV) present in all measurements that sum up final state mass
- Important input for radiative correction measurements!
- Measure Z-tt vertex corrections -> tests new physics

Top performance:
- Mass*: 27MeV (0.019%)
- Width: 22MeV (1.7%)

Requires $E>350$ GeV: not at the first phase of ILC
Identifying Top Quarks

- Clean, highly efficient identification of top quark pair events

- Enables two classes of measurements:
  - Precise determination of top quark properties: mass, width, ...
  - Use top quarks as a tool: high mass makes top potentially very sensitive to new physics, strong connection to EWSB

EPJ C73 2530 (2013)
How important is the top mass measurement?

The dominant uncertainty [at the electroweak vacuum] will remain at the few percent level. The top quark mass will be determined at the LHC [this] year. Improved top quark measurements will be possible at a linear collider.

Physics beyond the Higgs

A linear collider is

- A top factory (if $E >$ threshold)
- A Standard Model physics center
- A discovery machine
250 GeV only marginally more than 209 GeV - nothing to expect?

• Closer look at ILC250 vs LEP2:
  • ~1000x more integrated luminosity

Examples:
• searches for additional light (Higgs) bosons with reduced couplings to the Z

Any search channel limited by rate will explore new territory even at ILC250!

Detector technology, eg momentum resolution 1-2 orders of magnitude better, vertexing, highly granular calorimeter for tau ID, ....

From WW cross-section: expect 1-2 orders of magnitude improvement on mixing parameter

• ... and WIMPs!
BSM at a 250 LC

List of (some) models which would escape discovery at the LHC:

Even at 250 GeV, ILC does have a very complementary discovery scope than the LHC.
Potential increases of course with energy.
Where ILC Would Help

Higgsino-like LSP

Closing loopholes from near-degenerate masses

Understanding complex SUSY mass spectra

Elektroweakino Sector

Ties Behnke, 9.11.2017

Lepton Colliders
Conclusion Science

- Lepton Collisions at high energies have an enormous scientific potential
- Already 250 GeV will add significantly to the LHC
- The combination of high precision physics with discovery potential makes electron positron very attractive in the current situation.
- Higher collision energies will open up new regimes consecutively.

Disclaimer: I have only shown a small number of selected examples. There is much more.
REALISING THE ILC

The ILD detector
Design Philosophy

Particle flow as main reconstruction technique

- Imaging Calorimeters (CALICE)
  Extreme granularity wins over energy resolution,
in particular in the HCAL

High power tracking

- High efficiency, robust tracking in dense environments
- High precision vertexing for heavy flavour physics
The Particle Flow Paradigm

Particle flow is not new:
- LEP detectors (Aleph in particular)
- CDF
- CMS

Energy resolution is not the most important point

Pattern recognition in the Calorimeter

Linear Collider Goal:
Significantly better than CMS performance
Particle Flow

Energy resolution

Confusion

Particle flow is better than pure calorimetry

At high energies the advantage is lost.
Detector Layout

Typical multi-purpose detector
precision tracking
precision calorimetry
precision muon system
hermetic

ILD is one of two well developed (and complementary) concepts
Vertex Detectors

- Excellent spatial resolution
- Very low material budget

<table>
<thead>
<tr>
<th></th>
<th>ILC</th>
<th>Belle-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupancy</td>
<td>0.13 hits/μm²/s</td>
<td>0.4 hits/μm²/s</td>
</tr>
<tr>
<td>Radiation</td>
<td>&lt; 100 krad/year, 10¹¹ 1 MeV nₑₑ/year</td>
<td>&gt; 1Mrad/year, 2 x 10¹² 1 MeV nₑₑ/year</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>1/200</td>
<td>1</td>
</tr>
<tr>
<td>Frame time</td>
<td>25-100 μs (10 ns @ CLIC)</td>
<td>20 μs</td>
</tr>
<tr>
<td>Momentum range</td>
<td>All momenta</td>
<td>Low momentum (&lt; 1 GeV)</td>
</tr>
<tr>
<td>Acceptance</td>
<td>6°-174°</td>
<td>17°-150°</td>
</tr>
<tr>
<td>Resolution</td>
<td>Excellent 3-5 μm</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>(pixel size = 20 x 20 μm²)</td>
<td>(pixel size = 50 x 75 μm²)</td>
</tr>
<tr>
<td>Material budget</td>
<td>0.15 % X₀/layer</td>
<td>0.21 % X₀/layer</td>
</tr>
</tbody>
</table>
Vertex detector

- Excellent impact parameter resolution better than $5\oplus 10/pb \sin^{3/2}q$ is required for efficient flavor tagging
- 3 layers of double ladders (ca 100 um apart) (6 pixel layers)
  - Effect on pair-background rejection is expected, but not demonstrated yet
- Barrel only: $|\cos q|<0.97$ for inner layer and $|\cos q|<0.9$ for outer layer
- Point resolution $<3$um for innermost layer
- Material budget: $0.3\%X_0$/ladder=$0.15\%X_0$/layer
- Sensor options: CMOS, FPCCD, DEPFET
Vertex detector

- Excellent impact parameter resolution better than $5 \pm 10 / \rho \sin^{3/2} \phi$ is required for efficient flavor tagging.
- 3 layers of double ladders (ca 100 total)
  - Effect on pair-background
- Barrel only: $|\cos \theta| < 0.97$
- Point resolution <3μm
- Material budget: 0.3% of the LHC size
- Sensor options: CMOx
Tracking Detector

Pixel Vertex at small radii

Intermediate Silicon tracking

Large Volume TPC

Intense R&D effort
• Proof of concept done
• Performance reached
• Cost performance optimization ongoing
TPC/ Silicon Tracking

- Time Projection Chamber: The central tracker of ILD
- Tracks can be measured with many (~200/track) 3-dimensional r-f-z space points
- \(s_{rf} < 100\mu m\) is expected
- \(dE/dx\) information for particle identification
- Two main options for gas amplification: GEM or Micromegas
- Readout pad size \(\sim 1\times6\text{mm}^2 \rightarrow 10^6\) pads/side
- Pixel readout R&D as a future alternative
- Material budget: 5\%\(X_0\) in barrel region and <25\%\(X_0\) in endplate region
- Cooling by 2-phase CO2
- Backed up by extensive Silicon tracking in front and behind TPC
Calorimetry

Calorimetry is at the heart of any particle flow detector:

- Highly granular, thick, calorimeters
- Several technologies studied
  - Si-W
  - Scintillator based
  - RPC based

Performance simulations based on realistic detector models, background estimates, MC tuned to test beam data

M. Thomson, Calor 2010

Z → uds

RMS$_{90}(E)/\text{Mean}_90$ (%) vs $|\cos(\theta)|$
2012: Japanese HEP community proposes to build ILC in Japan

2015: results from an in-depth review in Japan are published:

- **Recommendation 1:** Share the cost internationally and Find a clear vision on the discovery potential of new particles.
- **Recommendation 2:** Closely monitor and analyze the development of the LHC experiments and Mitigate cost risk.
- **Recommendation 3:** Obtain general understanding by the public and science communities.

2016/2017: First international talks on ILC
- Review of the ILC cost
- US-Japan agreement on ILC related cost studies
- Siting studies in Japan
- extensive discussions in the community
Going ballistic

- Reports from several tasks forces have been received:
  - Costing
  - Human resources
  - Impact studies

- Statement by JAHEP on ILC, August 2017

The scientific significance and importance of ILC has been further clarified considering the current LHC outcomes. ILC250 should play an essential role in precision measurement of the Higgs boson and, with HL-LHC and SuperKEKB, in determining the future path of new physics. Based on ILC250’s outcomes, a future plan of energy upgrade will be determined so that the facility can provide the optimum experimental environment by considering requirements in particle physics and by taking advantage of the advancement of accelerator technologies. It is expected that ILC will lead particle physics well into the 21st century.

To conclude, in light of the recent outcomes of LHC Run 2, JAHEP proposes to promptly construct ILC as a Higgs factory with the center-of-mass energy of 250 GeV in Japan.
Where do we stand?

- Recommendation 1: Share the costs internationally and Find a clear vision on the discovery potential of new particles.
- Recommendation 2: Closely monitor and analyze the development of the LHC experiments and Mitigate cost risk.
- Recommendation 3: Obtain general understanding by the public and science communities.
2018: Make or Break

- From Japan: expect statement from government on ILC
  - Recent consultations with Abe
  - Statement: R&D money will increase significantly
- Preparations for European Strategy:
  - Clear statement is needed by the end of 2018
Northern Japanese Site

Geologically very stable area
Thinly populated, still well accessible through major roads and high speed rail roads
Closed big city: Sendai
ILC siting

Need to establish the IP and linac orientation
Then the access points and IR infrastructure
Then linac length and timing
Summary

A clear physics case exists for a lepton collider.

- Higgs physics
- Top physics
- BSM physics

If the 14 TeV LHC finds nothing new: we need to probe the Higgs boson and the top quark with ILC precision

If the 14 TeV LHC finds new physics: this might make the case for an ILC even stronger

The ILC design is mature and ready to go.

2018 will be decisive for the future of the ILC effort.

After the European Strategy, 2020+, the number of options for future facilities will be much reduced.
Japanese tunnel design
"Kamaboko" shape
How much does it all cost?

- Estimate from 2007 Reference Design Report, escalated to 2012 prices:
  $7.3 \cdot 10^9 \, \$ + 14k \, \text{years labor}$

- New estimate in 2013 Technical Design Report:
  $7.8 \cdot 10^9 \, \$ + 14k \, \text{years labor} \, (7\% \, \text{increase})$

- Dominated by Main Linac
Detector Integration

A detailed detector concept exists. It has been simulated in detail. Most technologies needed have been demonstrated. A preliminary engineering has been done.

ILD integration study.
ILD simulation model
Tracking performance

- Performance goal
  - $s_{1/pT} \sim 2 \times 10^{-5} \text{GeV}^{-1}$
  - $s_{rf} = 5 \pm 10 / \text{psin}^{3/2} \mu\text{m}$

- Tracking efficiency for $t \bar{t}$ events
- Impact parameter resolution
- Pt resolution for muon tracks
Flavor-tag performance

- Sophisticated multi-variable tagging algorithm (LCFIplus)
- Continuous improvement
- Based on full simulation.
PFA performance

- Performance goal
  - Jet energy resolution < 3.5% for efficient separation of W, Z, and Higgs in hadronic mode
  - $s_E/E = a/\sqrt{E}$ is not applicable because particle density depends on $E_{\text{jet}}$
  - Jet energy resolution is slightly better than LOI due to improvement of reconstruction software

<table>
<thead>
<tr>
<th>Jet energy</th>
<th>$\sigma_{E}/E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 GeV</td>
<td>3.66%</td>
</tr>
<tr>
<td>100 GeV</td>
<td>2.83%</td>
</tr>
<tr>
<td>180 GeV</td>
<td>2.86%</td>
</tr>
<tr>
<td>250 GeV</td>
<td>2.95%</td>
</tr>
</tbody>
</table>

$Z \rightarrow u,d,s$ events

$|\cos \theta| < 0.7$
Vertex detector

- Excellent impact parameter resolution better than $5\times10/pb\sin^{3/2}q$ is required for efficient flavor tagging
- 3 layers of double ladders (ca 100 um apart) (6 pixel layers)
  - Effect on pair-background rejection is expected, but not demonstrated yet
- Barrel only: $|\cos q|<0.97$ for inner layer and $|\cos q|<0.9$ for outer layer
- Point resolution <3um for innermost layer
- Material budget: $0.3\%X_0$/ladder=$0.15\%X_0$/layer
- Sensor options: CMOS, FPCCD, DEPFET
Vertex detector

- Excellent impact parameter resolution better than $5 \oplus 10/pbs \sin^{3/2}q$ is required for efficient flavor tagging.
- 3 layers of double ladders (ca 100 ladders):
  - Effect on pair-background.
- Barrel only: $|\cos q| < 0.97$ for hadronic events.
- Point resolution < 3μm.
- Material budget: 0.3%.
- Sensor options: CMO, GEM.

Cryostat: 0.2mm CMO

Beam pipe:
- FPC: 9mm width x 10/side + 17mm width x 28/side (50μm Kapton + 9μm Cu)
Vertex detector

- **CMOS option**
  - Pixel size: 17x17(L1), 17x85(L2), 34x34(L3-6)
  - Frame readout time: 10us~100us
  - Power consumption: 600W → 10W by power pulsing
- **FPCCD option**
  - Pixel size: 5x5 (L1-2), 10x10(L3-6)
  - Readout between trains
  - Power consumption: ~40W (no power pulsing)
- **DEPFET option**
  - Experience at Belle-II
  - Frame readout time: 50us~100us
  - 5-single layer of all-Si ladder option
- **Cooling**
  - CO2 cooling for FPCCD
  - Additional material budget is small: 0.3%X0 in end-plate 0.1%X0 in cryostat
  - Air cooling for CMOS/DEPFET
Silicon tracking system

- Silicon tracking system
  - SIT (Silicon Inner Tracker)
  - SET (Silicon External Tracker)
  - ETD (Endcap Tracking Detector)
  - FTD (Forward Tracking Detector)

- Role of Silicon tracking system
  - Additional precise space points
  - Improvement of forward coverage
  - Alignment of overall tracking system
  - Time stamping

- SIT/SET/ETD
  - Two/one/one false double-sided layers of Si strip
  - Material budget: 0.65%X₀/layer
  - Same silicon strip tiles of 10cmx10cm with 50um pitch, 200um thick, edgeless sensors will be used
  - Point resolution of ~7um
Forward Silicon tracking system

- FTD
  - Two pixel discs and five false double-sided strip disks
  - Pixel sensor options: CMOS, FPCCD, DEPFET
  - Power consumption: 2kW/disk → 100W/disk by power pulsing
TPC

- Time Projection Chamber: The central tracker of ILD
- Tracks can be measured with many (~200/track) 3-dimensional r-f-z space points
- $s_{rf} < 100\,\mu m$ is expected
- $dE/dx$ information for particle identification
- Two main options for gas amplification: GEM or Micromegas
- Readout pad size $\sim 1 \times 6 \, mm^2 \rightarrow 10^6$ pads/side
- Pixel readout R&D as a future alternative
- Material budget: $5\%X_0$ in barrel region and $<25\%X_0$ in endplate region
- Cooling by 2-phase CO2
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- Material budget: 5%$X_0$ in barrel region and <25%$X_0$ in endplate region
- Cooling by 2-phase CO2
Sampling calorimeter of tungsten absorber / Si or scintillator-strip sensitive layer sandwich
- 30 layers / $24X_0$
- Si sensor: 5x5mm$^2$ pixel size
- Scintillator strip: 5x45mm$^2$, read out by MPPC
- Leak-less water cooling

Detailed design exists, prototyped
Discussions with industry are ongoing on production and costing.
PFLOW ECAL

Typical granularity for ECAL: 0.5cmx0.5cm to 1cmx1cm, SI detectors, Tungsten absorbers

- 30 layers, 24 $\lambda_0$

CALICE prototype

Extreme segmentation:
MAPS sensors in the ECAL

Allows "tracking" in the calorimeter

Very detailed shower images
HCAL

- Sampling calorimeter with steel absorber (48 layers, 6l₁)
- Two options for the active layer
  - Scintillator tiles with analog readout → AHCAL
  - Glass RPC with semi digital (2-bits) readout → SDHCAL
AHCAL

- 3x3cm$^2$ segmentation of 3mm thick scintillator read out by SiPM through wavelength shifting fiber (Elimination of WLS under study)
- Software compensation (e/p ~1.2) technique was shown to work well through beam tests: $58%/E^{1/2} \rightarrow 45%/E^{1/2}$
- Test beam results are also used for evaluation of GEANT4 physics list
SDHCAL

- Active layer: GRPC with 1.2mm gap with 1x1cm² signal pick-up pads
- Demonstrated to work with power-pulsing in 3T B-field
- Test beam at CERN PS and SPS
Forward calorimeters

- **LumiCal**
  - Precise ($<10^{-3}$) luminosity measurement
- **BeamCal**
  - Better hermeticity
  - Bunch-by-bunch luminosity and other beam parameter measurements (~10%)  
- **LHCAL**
  - Better hermeticity for hadrons

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<th>Technology</th>
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<td>LumiCal</td>
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Muon system

- Active layers (14 for barrel, 12 for endcap) interleaved with iron slabs of return yoke
- Baseline design adopts scintillator strips + WLS fiber + SiPM readout as the active layer
- RPC is considered as an alternative
- Used for muon identification and as a tail catcher of the HCAL
Detector integration

- Detector assembly
  - Non-mountain site: CMS style
    - Pre-assembled and tested on surface
    - Large pieces (3 barrel rings + 2 endcaps) are lowered through vertical shaft
    - 3500t crane for the vertical shaft
  - Mountain site: Access through horizontal tunnel
    - Yoke rings are assembled underground
    - 250t crane in the underground experimental hall

- Detector service path
  - Detector services (cables and tubes) are considered seriously for ILD
  - Barrel detectors
    - services go through gap of central yoke rings
  - Endcap detectors
    - gap between endcap yoke and barrel yoke
  - Forward detectors
    - along the QD0 support structure
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Calibration/Alignment

• **Alignment procedure**
  – Accurate positioning during construction of sub-detectors by coordinate measuring machine
  – Alignment at the installation phase by standard survey technique
  – Hardware alignment system during operation
  – Ultimate micro-meter order alignment by "track-based alignment"

• **Alignment techniques under R&D**
  – IR laser alignment for Si strip detectors
  – Fiber Bragg Grating (FBG) sensors for mechanical structure alignment → Smart support structure

• **Large Potential to profit from LHC upgrades!**