This presentation is mainly based on
- “The International Linear Collider A Global Project” (arXiv:1903.01629)
  including their references and updates,
- “ILC implementation status and plans”
  (https://indico.cern.ch/event/789524/contributions/3340272/attachments/1827177/2990796/Lausanne_Apr_2019.pdf)
Outline

- Introduction to ILC
- Recent situation in Japan
- (SUSY related) physics cases at ILC
- Summary
What is ILC?

- **e+ e- linear collider with Superconducting RF cavities**
  - The design is the result of ~20 years effort by a broad, global community.
  - The successful construction and operation of the European XFEL at DESY, which uses the same SRF technology as ILC, provides confidence in realization.
  - A most promising candidate site: **Kitakami, Japan** (Stable ground, Many local supporters!)

  Find more about Kitakami:
  - [http://www.kitakami-kanko.jp/](http://www.kitakami-kanko.jp/)
  - [https://www.iwate-ilc.jp/eng/ktimes/](https://www.iwate-ilc.jp/eng/ktimes/)

- **As merits from e+ e- collider**
  - Provides controllable initial particle energy
  - Low QCD background (compared to hadron colliders)
  - Can naturally reduce the number of EFT parameters (EW interaction)

- **As merit from linear collider**
  - Provides controllable **beam polarization**
  - Energy extendability (e.g. 350 GeV, 500 GeV, 1 TeV)
Detectors at ILC

- **Two detector concepts proposed for ILC: SiD and ILD**
  - Replace detectors on the IP within a day ("push-pull" scheme.),
  - Low radiation levels at ILC allow the consideration of a wide range of materials and technologies for the tracking and calorimeter systems, and the innermost vertex detector can be very close to IP,
  - Good hermetisity (to ensure reconstruct missing objects),
  - To achieve ideal jet energy resolution (3% jet energy resolution above 100 GeV), detectors are optimized for Particle Flow Approach.

SiD: $R \sim 6m$, $B=5T$, Silicon tracker

ILD: $R \sim 8m$, $B=3.5T$, TPC
Beam polarization

- **One of the attractive features at linear colliders**
  - In circular colliders, very challenging to achieve high beam polarization, especially for longitudinal polarization.
  - A linear electron-positron collider naturally preserves longitudinal beam polarization.
  - Two polarizations for each beam provides 4 distinct datasets.

- **4 distinct datasets allow us to:**
  - Measure helicity-dependent electroweak couplings,
  - Suppress backgrounds and enhance signals (less running time/cost for same physics),
  - Cancel large parts of the experimental systematic uncertainties.

- **Polarimetry**
  - Laser-Compton polarimeters upstream and downstream of IP.
  - In-situ measurement with known SM processes (WW, W, γ, Z)
  - (see more detail: arXiv:1703.00214)
It should be noted that **FCCee** and **CEPC**: 2 IPs are expected (×2).

On the other hand, beam polarization increases effective luminosity for many processes. For example, 2ab⁻¹ of polarized data (Pe⁻/Pe⁺ = ±80%/±30%) were shown to be almost equivalent to 5ab⁻¹ of unpolarized data for Higgs coupling measurements (arXiv:1903.01629).

**Beam polarization can compensate for 2 IPs at FCCee and CEPC.**
ILC Running scenario

- **Ecm = 250 GeV**
  - Maximum of ZH production cross section.
  - 15 years running (L=2ab\(^{-1}\)) together with **HL-LHC results** and **EFT framework** will give powerful and model-independent constraints on the Higgs properties! (see more details in the reference.)

- **Energy upgrade**
  - Higgs self coupling, Top EW couplings
  - New particle searches
  - Great advantage in combining a data set taken at 250 GeV with data set at higher energies because some parameters in EFT have energy dependance.

![Integrated Luminosities graph](image)
Situation in Japan

Based on the slides at the Lausanne meeting from M. Yamauchi KEK DG
https://indico.cern.ch/event/789524/contributions/3340272/attachments/1827177/2990796/Lausanne_Apr._2019.pdf
Progress status

- **2019.3**: Japanese **MEXT** released its statement
  
  MEXT will continue to discuss the ILC project with other governments having an interest in the project. 
  International discussions at the government level 
  Funding plan discussion among governments 
  
  Now MEXT is strongly involved in the ILC project.

- **2019.3**: KEK submitted a proposal of ILC to SCJ master plan.
  SCJ master plan: Science Council of Japan (SCJ) calls for proposals of large-scale research projects every three years, and recommends “priority programs” to MEXT.
  MEXT Minister suggested the ILC to be evaluated in this process to provide an evidence of getting support by the broader academic community in Japan.

- **2019.9**: SCJ will recommend “priority programs” to MEXT
  Results of the evaluation will be publicized officially 2020.2.

- **2020.5?**: MEXT will show a new roadmap for next 3 years.
(SUSY related) Physics
What can ILC do on top of LHC?

- Precise Higgs/EW parameters
- LSP Dark Matter
- Z'
- R parity violation
- Additional Higgs
- Light Higgsino
- Loopholes free search

ILC will add many probes for SUSY!
Higgs/EW precision measurements

- **Higgs parameters**
  - Total decay width —> can discover decays to unknown particles.
  - Higgs mass —> $\Delta M_H \approx 14$ MeV together with $\Delta M_t \approx 0.3$ GeV (HL-LHC) can probe New Physics up to $10^{12}$ GeV considering the vacuum stability.
  - “Higgs recoil mass technique” —> **Model-independent** Higgs (or new scalars) coupling measurement.

- **EW parameters**
  - $M_W, \sin \theta_{\text{eff}}$ —> Assuming the center values remain as they are, ILC measurements would result in $3\sim4\sigma$ discrepancy, which indicate SUSY at TeV scale.
Pattern of Higgs boson couplings could tell us existence of SUSY
(arXiv:1708.08912)

Percent-level precision is the key!

ILC precision for Higgs mass (~14MeV) leads to 0.1% level of higgs coupling precisions to Z and W!
Phenomenological MSSM

The most general version of the R-parity conserving MSSM with a minimal set of experimentally motivated guiding principles gives many possible models depending on $\Gamma(H \rightarrow b\bar{b})$. 

![Graph showing the number of models as a function of $\Gamma(H \rightarrow b\bar{b})$. The graph includes different scenarios and data points for various luminosities and experiments such as LHC14, ILC500, and HL-ILC500.]
Higgs self coupling $\lambda$

- Could deviate by $\sim 20\%$ level if a new scalar boson exists.

**Two channels are complementary:**

\[
\frac{\lambda}{\lambda_{SM}} < 1 \quad \Rightarrow \quad \nu\bar{\nu}HH \quad (1\,\text{TeV}) \quad \text{is better}
\]

\[
\frac{\lambda}{\lambda_{SM}} > 1 \quad \Rightarrow \quad ZHH \quad (500\,\text{GeV}) \quad \text{is better}
\]

$\delta\lambda/\lambda \sim 10\%$

is feasible! $(\lambda \sim \lambda_{SM}, 1\,\text{TeV})$
Higgs CP properties

\[ \mathcal{L}_{H\tau\tau} = g\bar{\tau}(\cos \psi_{CP} + i\gamma_5 \sin \psi_{CP})\tau H \]

The CP phase angle \( \psi_{CP} \) can be determined using the transverse spin correlation (\( \Delta\Phi \)) between the two \( \tau \)s.

Possible to measure CP-phase better than 4°

ILD simulation: 250 GeV, \( e^- e^+ \), 0.9 ab\(^{-1}\)  \( Z \to e/\mu/q \)
Additional Higgs bosons

- Very precise and model-independent measurements of 125-GeV particle can probe far beyond the kinematic limit and beyond the reach of the LHC.
- ILC offers unique opportunities to directly produce additional lighter Higgs bosons (or any weakly interacting light scalar / pseudo-scalar particles).

\[ \theta : \text{Mixing angle of new scalar to } H_{SM} \]

I-2 orders of magnitude improvement over LEP recoil results

500 GeV ILC covers larger mass region (\(<\sim 300 \text{ GeV})\).
A new gauge symmetry $U'(1)$

- **SUSY $U'(1)$ extension**
  - Solves the $\mu$ problem by replacing $\mu$ by a dynamical variable linked to the $U'(1)$ breaking, and the allowed MSSM parameter range would be extended.
  - $U'(1)$ has many possible implications for supersymmetry breaking and mediation, and for communication with a hidden sector.
  - $U'(1)$ occurs frequently in Superstring constructions.
  - It is natural to expect $M_{Z'}$ in TeV range if there is supersymmetry at TeV scale, then both the electroweak and $Z'$ scales are usually set by the scale of soft supersymmetry.
  - $e^+ e^- \rightarrow f \bar{f}$ can be used as the probe because s-channel resonance could affect the cross sections.
$Z'$ discovery reach

$\sqrt{s}$ at ILC

Study by Kyushu group and KEK group

500 GeV results were extrapolated from 250 GeV full simulation results.
Generic WIMP search

(http://bib-pubdb1.desy.de/record/417605/files/Moritz_Habermehl_PhD.pdf)

- General approach with effective operators
  - Setup and cross-section formulas from Chae and Perelstein (JHEP05(2013)138).
  - WIMP pair production in association with an ISR photon.

\[ \mathcal{L}^{\text{eff}} = \frac{1}{\Lambda^2} (\bar{f} \Gamma f) (\chi \Gamma \chi) \quad \Gamma = \left\{ \begin{array}{l} \frac{1}{\gamma^\mu} \\ \frac{1}{\gamma^5 \gamma^\mu} \end{array} \right\} \]

- Detailed detector simulation study for \( E_{\text{cm}} = 500 \text{GeV} \) has been done.

2\(\sigma\) expected exclusion limits
Loophole free searches

- **Draw attention to NLSP $\rightarrow$ LSP + SM particles**
  - Assuming R-parity conservation, NLSP must decay to LSP and SM partner of the NLSP.
  - NLSP pair production allows us to study entire space of models (if kinematically reachable and R-parity conserving).
  - This analysis was already carried out at LEP.
  - A few difficult cases (R-parity violation, Mixed NLSP, etc.) are discussed in arXiv:1308.1461 (In conclusion, none of them will represent a loophole).

![Graph showing exclusion and discovery regions for NLSP masses](image)

One of the experimentally most challenging case: 

\[
\text{NLSP} = \tilde{\tau}_1
\]

- Need to reject two $\tau$ background events.

Even in this most difficult case, most of the kinematically allowed area can be model-independently tested!
Light Higgsinos

- **Naturalness-motivated SUSY** requires Higgsino masses not to be far above Higgs mass even if the other SUSY particles are much heavier.
  - Mass differences within the higgsino sector are small (typically below 20GeV)
  - ILC can detect soft visible particles from such decays!

\[ \Delta M = 770 \text{MeV} \]

- Chargino pair production threshold

\[ \sqrt{s'}/\text{GeV} \]

Reduced centre-of-mass energy of the system recoiling against the ISR photon

\[ \Delta M = 20 \text{GeV} \]

ILD Preliminary

500 GeV, 500 fb^{-1}, P_{\gamma}^{80-30}

- Di-electron energy

\[ e^+ e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \]

\[ \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 e^+ e^- \]
Once SUSY particle has been found...

- ILC flexibly can react to the target of the new discoveries.
  - e.g. Higgs factory —> Higgsino factory, DM factory

- LSP Dark Matter properties
  - mass, couplings to SM particles, associated mediator particle

- Physics at GUT scale!
  - Natural SUSY + SUSY mass spectra measurements open possibility to study physics at GUT scale!
Summary

- **ILC is the most advanced future e+e- collider**
  - The technologies for ILC is well advanced (e.g. XFEL success).
  - Even at 250 GeV, it is feasible to be comparable to FCCee and CEPC in luminosity-wise thanks to the beam polarization.
  - ILC is being discussed now at governmental level as well as physicist level.

- **ILC is powerful tool for searching/characterizing SUSY.**
  - well-defined initial state and low QCD backgrounds,
  - Beam polarization plays an important role for many analyses.
  - Has naturally energy extendability.

- **Some examples of SUSY related analyses are presented.**
  - Precise measurements of Higgs couplings and EW parameters
  - A new heavy gauge boson search
  - Model independent Dark Matter search
  - Loophole free search
  - Light higgsino search
LCWS2019

28 Oct. - 1st Nov. 2019
in Sendai/Japan.

Why not come to join us?

Find more about Sendai:
http://www.sendaimiyagidc.jp/en/
Backup
Particle Flow Approach (PFA)

- Requires individual particle reconstruction including jets in calorimeters so that each particle can be reconstructed with a best performance sub-detector (e.g. tracker, calorimeter).
- For instance, electron creates signals both in tracker and ECal but typically tracker gives better performance (depends on its energy) and in such a case tracker information is used in PFA.
- For photons, however, we have to rely on ECal. In this case, cluster hits made by charged particles must be removed to measure pure cluster hits by photons.
- **Track-cluster matching** is essential in PFA and this leads us to basic detector design: **low material budget for tracker** (to reconstruct low energy tracks), **high granularity for calorimeters** (to distinguish cluster hits depending on their origins).
AC Power vs Energy of Future $e^+e^-$ Colliders

- FCCee
- CEPC
- ILC baseline
- ILC luminosity upgrade
- ILC250 10 Hz operation
- CLIC
\[
\frac{\text{fraction with } \text{sgn}(P(e^-), P(e^+)) = (-,+) \quad (+,-) \quad (-,-) \quad (+,+) }{\%
\text{ [ ] } \%
\text{ [ ] } \%
\text{ [ ] } \%
\text{ [ ] } \%
}\]

<table>
<thead>
<tr>
<th>(\sqrt{s} )</th>
<th>(67.5)</th>
<th>(22.5)</th>
<th>(5)</th>
<th>(5)</th>
</tr>
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<tbody>
<tr>
<td>250 GeV (2015)</td>
<td>67.5</td>
<td>22.5</td>
<td>5</td>
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<tr>
<td>250 GeV (update)</td>
<td>45</td>
<td>45</td>
<td>5</td>
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<td>350 GeV</td>
<td>67.5</td>
<td>22.5</td>
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<tr>
<td>500 GeV</td>
<td>40</td>
<td>40</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

**TABLE V:** Relative sharing between beam helicity configurations proposed for the various center-of-mass energies. The update of the luminosity sharing for 250 GeV originates from the importance of the left-right asymmetry of the Higgsstrahlung cross section in the EFT-based Higgs coupling fit.
## Systematic Polarization Uncertainty

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Uncertainty $[10^{-3}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam and polarization alignment at polarimeters and IP (Δ$\theta_{\text{bunch}} = 50 , \mu\text{rad}$, Δ$\theta_{\text{pol}} = 25 , \text{mrad}$)</td>
<td>0.72</td>
</tr>
<tr>
<td>Variation in beam parameters (10% in the emittances)</td>
<td>0.03</td>
</tr>
<tr>
<td>Bunch rotation to compensate the beam crossing angle</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Longitudinal precession in detector magnets</td>
<td>0.01</td>
</tr>
<tr>
<td>Emission of synchrotron radiation</td>
<td>0.005</td>
</tr>
<tr>
<td>Misalignments (10 $\mu$) without collision effects</td>
<td>0.43</td>
</tr>
<tr>
<td><strong>Total (quadratic sum)</strong></td>
<td><strong>0.85</strong></td>
</tr>
<tr>
<td>Collision effects in absence of misalignments</td>
<td>&lt; 2.2</td>
</tr>
</tbody>
</table>

[Ref.: Thesis Moritz Beckmann (http://bib-pubdb1.desy.de/record/155874)]
1. Measurement of the time-resolved beam polarization before and after the $e^- e^+$ IP
   ▶ Via laser-Compton polarimeter
   Ref.: Jenny List, Annika Vauth, and Benedikt Vormwald:
   A Quartz Cherenkov Detector for Compton-Polarimetry at Future $e^+ e^-$ Colliders (https://bib-pubdb1.desy.de/record/221054)
   A Calibration System for Compton Polarimetry at $e^+ e^-$ Colliders(https://bib-pubdb1.desy.de/record/289025)

2. Extrapolating the beam polarization to the $e^- e^+$ IP
   ▶ Via Spin Tracking
   Ref.: Moritz Beckmann, Jenny List, Annika Vauth, and Benedikt Vormwald:
   Spin transport and polarimetry in the beam delivery system of the international linear collider

3. Determination of the luminosity-weighed averaged polarization from collision data
   ▶ Calculating the polarization from known standard model processes
   ⇒ Discussed in the following
Higgs-strahlung at lepton colliders

- Powerful channel for unbiased tagging of Higgs Events
- Absolute normalisation of Higgs couplings
- Sensitivity to invisible Higgs decays

Well measurable decay leptons from Z
- μ Pairs, e pairs

No assumption on Higgs decay modes

Higgs Recoil Mass: \[ M_h^2 = M_{\text{recoil}}^2 = s + M_Z^2 - 2 E_Z \sqrt{s} \]

- Clean and sharp peak in Z recoil spectrum
- Illustrates precision that can be expected from e+e- colliders
for ZHH, interference is constructive, enhanced $\lambda$ will increase the total $\sigma$, and improve sensitive factor as well, e.g. if $\lambda = 2\lambda_{SM}$ $\sigma$ increase by 60%, $F$ decrease by half, $\delta\lambda / \lambda \sim 15\%$, $\rightarrow$ we may finish the $\lambda$ story at 500 GeV ILC

for $\nu\nuHH$, interference is destructive, enhanced $\lambda$ will decrease $\sigma$, minimum when $\lambda \sim 1.5\lambda_{SM}$, $\delta\lambda / \lambda$ degrade significantly if $\lambda / \lambda_{SM} \in (1.3, 1.7)$

but if $\lambda < \lambda_{SM}$, more difficult to use ZHH, have to rely on more on $\nu\nuHH$

two channels are complementary in terms of $\lambda$ measurement in BSM
The CP phase angle $\Psi_{CP}$ can be determined using the transverse spin correlation between the two $\tau$, which gives different $\Delta \phi$ distributions for different values of $\Psi_{CP}$.

Possible to measure CP-phase better than 4°.
FIG. 76: Projected Higgs boson coupling uncertainties for selected scenarios from Table XVIII. In particular it shows that at $\sqrt{s} = 250 \text{GeV}$, 2 $\text{ab}^{-1}$ with polarised beams yield comparable results to a much larger data set of 5 $\text{ab}^{-1}$ with unpolarised beams.
Generic WIMP search

http://bib-pubdb1.desy.de/record/417605/files/Moritz_Habermehl_PhD.pdf

Running scenario

Vector, $M(\chi)=1$ GeV

ILD $250\text{GeV}+500\text{GeV}$

250 GeV unpolarised

350 GeV unpolarised

500 GeV H20 pol. mix.

(40/40/10/10)

$\Lambda_{95}$ [GeV]

250 GeV unpolarised (45/45/5/5)

2ab$^{-1}$

10ab$^{-1}$

10ab$^{-1}$

1.5ab$^{-1}$

4ab$^{-1}$
Actions to be done by KEK

- Organize the international working group with close consultation with MEXT.

- Promote activities to gain a better understanding of the broader academic community in Japan.
  - Propose the ILC project to the SCJ Master Plan
  - Organize a symposium

- Cooperate MEXT to establish the governmental level discussion groups with France and Germany. Also, we need to strengthen the discussion group with the US DOE.

- Conducts R&D program at ATF, STF and CFF facilities collaborating with the international teams.

- ... and so on.
Processes and Approximate Timelines Toward Realization of ILC (Physicists’ view)

2018.12
- Announcement by Japanese government
  - MEXT panel
  - Summarize opinions of relevant ministries

Government Level

2019.3
- Discussion among governments
  - Exchange of information
  - Strengthen US-Japan Discussion Group, cost reduction R&D, governance discussion

Establish Discussion Group with the European partners

2020.5
- Start negotiations among governments on international sharing
- Agreement on governance, operation, sharing of cost and human resources
- Full-scale negotiation among governments – specification of conditions and processes
- Critical decision process

Start construction of ILC

2024-
- MOU among research labs on start of the preparation phase under approval by each government
- Final agreement among governments on construction
- ILC pre-lab (4 years)

Physicists Level

3/7
- LCB/ICFA mtgs. @ Tokyo
- SCJ Master Plan
- SCJ committee on ILC

European Particle Physics Strategy Update
- Establish KEK International WG
  - Produce draft for international sharing of human and material resources
- Draft proposal by researchers on international cost sharing
- Talks with other countries

Good enough design for the final approval of construction, resolution of remaining technical issues

* ICFA: international organization of researchers consisting of directors of world’s major accelerator labs and representatives of researchers
* ILC pre-lab: International research organization for the preparation of ILC based on agreements among world’s major accelerator labs such as KEK, CERN, FNAL, DESY etc.
Science Council of Japan (SCJ) is an organization that represents the Japanese scientists. It has no policy-making or budgetary authority.

SCJ calls for proposals of large-scale research projects every three years, and recommends “priority programs” to MEXT. In the latest one in 2017, 20 programs were selected from 200 proposals.

MEXT Minister suggested the ILC to be evaluated in this process to provide an evidence of getting support by the broader academic community in Japan.

Following this suggestion, we submitted a proposal of ILC with a recommendation letter from Barry Barish.

Results of this evaluation will be publicized officially in February 2020.
Top mass Higgs mass and BSM

- Precise Top (and W) mass crucial to test compatibility of measured Higgs mass
- SM might not be sufficient to explain Higgs mass
- LHC may not reach sufficient discriminative power
- A lepton collider will for sure
Electroweak top couplings and discovery reach

New physics reach for typical BSM scenarios with composite Higgs/Top and/or extra dimensions
Based on phenomenology described in Pomerol et al. arXiv:0806.3247

95% Exclusion Limit

5σ discovery

ILC@500 has discovery potential up to 10 TeV for typical BSM scenario
More cms e.g. at CLIC would of course help a great deal (also for disentangling effects)
New physics below tt threshold? - Example b quark couplings

\[ A_{FB}^b \sim 3\sigma \] in heavy quark observable

- Is tension due to underestimation of errors or due to new physics?
- High precision e+e- collider will give final word on anomaly
  - In case it will persist polarised beams will allow for discrimination between effects on left and right handed couplings
  - Randall Sundrum Models generate basically automatically a symmetry group of type SU(2)_R

Randall Sundrum Models Djouadi/Richard '06
Higgs self-coupling – Precisions at LC

Cross section vs CM energy (e+e-)

Expected precision based on full detector simulation studies:

<table>
<thead>
<tr>
<th></th>
<th>ILC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>500 GeV, 4 ab-1</td>
<td>1.4 TeV, 1.5 ab-1</td>
</tr>
<tr>
<td></td>
<td>$\delta \lambda = 27%$</td>
<td>$\delta \lambda = 21%$</td>
</tr>
<tr>
<td></td>
<td>&amp; 1 TeV, 8 ab-1</td>
<td>&amp; 3 TeV, 2 ab-1</td>
</tr>
<tr>
<td></td>
<td>$\delta \lambda = 10%$</td>
<td>$\delta \lambda = 10%$</td>
</tr>
</tbody>
</table>

References:
- J. Tian, LC-REP-2013-003
- M. Kurata, LC-REP-2014-025
- C. Duerig, Ph.D. thesis at DESY, 2016

HH\textrightarrow bbbb, bbWW* combination

References:
- arXiv: 1307.5288
- HH\textrightarrow bbbb only, upgrade in progress including bbWW*