Adapted from summary talk by W. Chou
Higgs and the Standard Model

So far, consistent with the Standard Model
Higgs Factories

• Inexpensive

• Can produce Higgs particles at a rate of ~10,000 per year
  – Luminosity not the ideal measure of machine performance
  – Most comparisons will be done using Higgs production rates instead
Higgs Factories: Types

• Circular Collider
• Linear Collider
• Muon Collider
• $\gamma\gamma$ Collider
Circular Higgs Factory

• Advantages
  – Understood technology
  – Some designs can use existing tunnels
  – Can have more than one detector
  – Large tunnels can be reused for Hadron machines

• Disadvantages
  – Synchrotron Radiation
  – Beamstrahlung
  – Low Emittance lattices
  – Requires Positron source
Higgs factory

- Beam Energy = 120 GeV
- SR power, both beams = 100 MW
- Initial luminosity = $5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- $\beta_x^*, \beta_y^* = (20, 0.2) \text{ cm}$
- Beam-beam tune shifts = (0.067, 0.095)
- Beam current = 5 mA

Z Factory

- Beam Energy = 46 GeV
- SR power, both beams = 60 MW
- Initial luminosity = $3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Beam-beam tune shifts = (0.032, 0.045)
- Beam current = 134 mA

Fermilab Site Filler rings
Circumference = 16 km
Beyond HE-LHC: new tunnels in Geneve area

47 km – 80 km

1) 42 TeV c.o.m. with 8.3 T (present LHC dipoles)
2) 80 TeV c.o.m. with 16 T (high field based on Nb3Sn)
3) 100 TeV c.o.m with 20 T (very high field based on HTS)

Figure 9. Two possible location, upon geological study, of the 80 km ring for a Super HE-LHC (option at left is strongly preferred)
SuperTRISTAN

12/09/12 Krakow – ESG
C.Biscari - "High Energy Accelerators"

~ 2 B CHF
(only the tunnel)

13 Feb. 2012 K. Oide (KEK)
What is a (CHF + SppC)

- Circular Higgs factory (phase I) + super pp collider (phase II) in the same tunnel
Conclusion (Q. Qin)

• A CHF + SppC was proposed in IHEP for high precise probe of Higgs, and new discovery of physics as well.
• Main parameters and basic lattices are studied and further iterations are required.
• Budget and time schedule are not yet estimated.
LEP3/TLEP R&D items (F. Zimmermann)

- choice of RF frequency: 1.3 GHz (ILC) or 700 MHz (ESS)? & RF coupler
- SR handling and radiation shielding (LEP experience)
- beam-beam interaction for large $Q_s$ and significant hourglass effect
- IR design with large momentum acceptance
- integration in LHC tunnel (LEP3)
- Pretzel scheme for TERA-Z operation
How can one increase over LEP 2 (average) luminosity by a factor 500 without exploding the power bill?

Answer is in the B-factory design: a very low vertical emittance ring with higher intrinsic luminosity.

electrons and positrons have a much higher chance of interacting
  ➔ much shorter lifetime (few minutes)
  ➔ feed beam consitously with a ancillary accelerator
Top-up Injection: Schematic Cycle

beam current in collider (15 min. beam lifetime)

energy of accelerator ring

100%
99%

almost constant current

120 GeV
20 GeV

injection into collider

10 s

injection into accelerator
PEP-II/BaBar Top-Up Injection (Accelerator)

Improved peak and average luminosity.

Before Top-Up Injection

After Top-Up Injection

PEP-II: Luminosity and beam currents for a 24-hour period (a) before and (b) after the implementation of trickle injection.
Top-up injection will work for a Circular Higgs Factory.

A full energy injector is needed.

A synchrotron injector will work the best but is more than is needed. (60 Hz)

A rapidly ramped storage ring is likely adequate. (4 sec)

A slowly ramped storage ring injector doesn’t make the luminosity constant enough.

The detectors will need to mask out the buckets with damping injected bunches during data taking.
Linear Higgs Factory

• Advantages
  – Significant design work has already been performed on a global scale
  – Allows for high energy reach with Leptons

• Disadvantages
  – High Cost
  – Work remains on industrialization of major components
  – Requires positron production
ILC as a Higgs Factory

TESLA Cavity (DESY/FNAL)
- Blade Tuner (FNAL)
- Saclay Tuner (DESY)
- TTF-III Coupler (DESY/FNAL)

Tesla-like Cavity (KEK)
- Slide-Jack Tuner (KEK)
- STF-II Coupler (KEK)

Graph showing E-field [MV/m] for various cavities:
Proposal for Phased Execution of the ILC Project

The Japan Association of High Energy Physicists (JAHEP) accepted the recommendations of the Subcommittee on Future Projects of High Energy Physics\(^{(1)}\) and adopted them as JAHEP's basic strategy for future projects, in March 2012. Later in July 2012 a new particle consistent with a Higgs Boson was discovered at LHC, while in December 2012 the Technical Design Report of the International Linear Collider (ILC) will be completed by the worldwide collaboration.

On the basis of these developments and following the subcommittee's recommendation on ILC, JAHEP proposes that ILC shall be constructed in Japan as a global project based on agreement and participation by the international community in the following scenario:

(1) Physics studies shall start with precision study of "Higgs Boson" and will evolve into studies on top quark, "dark matter" particles, and Higgs self-couplings, by upgrading the accelerator. A more specific scenario is as follows:

(A) A Higgs factory with a center-of-mass energy of approximately 250 GeV shall be constructed as a first phase.

(B) The machine shall be upgraded in stages up to a center-of-mass energy of \(\sim 500\) GeV, which is the baseline energy of the overall project.

(C) Technical extendability to a 1 TeV region shall be secured.

**ILC - Global Project**

(2) A guideline for shares of the construction costs is that Japan covers 50% of the expenses (construction) of the overall project of a 500 GeV machine. The actual shares, however, should be left to negotiations among the governments.
Two Candidate Sites in Japanese mountainous locations

- GDE-CFS group visited two candidates sites, Oct. 14 and 15, 2011
TDR 500 GeV Baseline

15.4 km
(site length ~31 km)

1.1 km
10.8 km

Main Linac

\[ \langle G_{\text{cavity}} \rangle = 31.5 \text{ MV/m} \]
\[ G_{\text{eff}} \approx 22.7 \text{ MV/m} \]
(fill fact. = 0.72)

Cost: 100%
P_{\text{AC}}: 161 \text{ MW}
250 GeV staged (scenario 1)

Half the linac
Full-length BDS tunnel & vacuum (TeV)
½ BDS magnets (instrumentation, CF etc)
½ RTML LTL

Extended tunnel/CFS already 500 GeV stage

10Hz mode e- linac
250 GeV staged (scenario 2)

Half the linac
Full-length BDS tunnel & vacuum (TeV)
½ BDS magnets (instrumentation, CF etc)
1 RTML LTL
5km 125 GeV transport line

Extended tunnel/CFS already 500 GeV stage

10Hz mode e- linac
Summary (N. Walker)

• ILC (500 GeV) machine already “contains” a light Higgs factory
  – Luminosity: $7.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
  – (Possible to upgrade by factor 2)

• Standalone machine for LHF
  – reduced cost by ~35% ($P_{AC} \sim 100 \text{ MW}$)
  – reduces schedule by 12-18 months
    (perhaps a little more)

• Only really makes sense as part of a first-stage machine
  – scope of complete project still ~500 GeV
  – TeV upgrade remains optional
ILC Polarised-Positron Production

Uses primary electron beam to generate ~30 MeV photons in a SC helical undulator

Photons converted into e+e- pairs in “thin” titanium target

Positron production yield dependent on e- beam energy (and therefore $E_{cm}$)
147m helical undulator (TDR baseline)

Positron Yield

\[ E_{\text{beam}} = 125 \text{ GeV} \]

Wei Gai (ANL) et al
Positron Yield for a LHF

Recover yield by going to ~250 m of undulator

$E_{\text{beam}} = 125 \text{ GeV}$

Wei Gai (ANL) et al
Goal: Lepton energy frontier

Main Beam Generation Complex

Drive Beam Generation Complex

drive beam accelerator
2.4 GeV, 1.0 GHz

circumferences delay loop 73 m
CR1 293 m
CR2 439 m

819 klystrons
15 MW, 142 μs

819 klystrons
15 MW, 142 μs

delay loop

decelerator, 24 sectors of 878 m

Drive Beam

Main Beam

Main Beam Generation Complex

e⁻ main linac, 12 GHz, 100 MV/m, 21 km

e⁺ main linac

2.75 km

IP

2.75 km

BDS

BC2

BC2

TA

TA

CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump

D. Schulte, CLIC, HF 2012, November 2012
Energy choices made with Physics Group

Need to be reviewed when more LHC results become available

They are only an example

4 sectors equal 500GeV
12 sectors equal 1.5TeV
24 sectors equal 3TeV
31 km, ~100 m deep

14 km, ~100 m deep

Legend:
- CERN existing LHC
- CLIC 500 GeV
- CLIC 3 TeV
- ILC 500 GeV
- LHeC
TBTS: Two Beam Acceleration

Measured accelerating gradient

Maximum gradient 145 MV/m

Consistency between
• produced power
• drive beam current
• test beam acceleration

D. Schulte, CLIC, HF 2012, November 2012
**2012-16 Development Phase**
Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.

**2017-22 Preparation Phase**
Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement. Prepare detailed Technical Proposals for the detector-systems.

**2023-2030 Construction Phase**
Stage 1 construction of a 500 GeV CLIC, in parallel with detector construction. Preparation for implementation of further stages.

**2016-17 Decisions**
On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

**2022-23 Construction Start**
Ready for full construction and main tunnel excavation.

**2030 Commissioning**
From 2030, becoming ready for data-taking as the LHC programme reaches completion.

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D. Schulte, CLIC, HF 2012, November 2012
Note on Klystron-based First Stage

Klystrons-based design have been Developed in the past: NLC and JLC-X

They aimed at 75MW power, 1.6μs pulse length and 55% efficiency
-> reasonable limit of feasibility

Would need about 30,000 klystrons for CLIC at 3TeV
-> much more expensive than drive beam
But could be interesting at low energies
-> is being explored for first stage

D. Schulte, CLIC, HF 2012, November 2012
Muon Collider Higgs Factory

• Advantages
  – High Cross Section
  – Small size
  – No Synchrotron Radiation or Beamstrahlung
  – The future of the energy frontier for leptons

• Disadvantages
  – Unproven Technology
  – Cooling work needed
  – Constant decay of muons
  – Costs unknown
s-channel production of Higgs boson (Han and Liu)

• s-channel Higgs production cross section in a muon collider is 40,000 times larger than in an $e^+e^-$ collider
• Muon collider can measure the decay width $\Gamma$ directly without any theoretical assumption (a unique advantage) – if the muon beam energy resolution is sufficiently high
• But the required energy resolution is very demanding
Scale of facility

- Proton Ring
- Collider Ring
- Target + π→μ treatment
- Cooling line
- Linac
- RLA
8 GeV, 4MW Proton Source
- 15 Hz, 4 bunches $5 \times 10^{13}$/bunch

$\pi \rightarrow \mu$ collection, bunching, cooling
- $\varepsilon_{\perp,N} = 400 \pi \text{ mm-mrad}, \varepsilon_{\parallel,N} = 2 \pi \text{ mm}$
  - $10^{12} \mu$ per bunch

Accelerate, Collider ring
- $\delta E = 4 \text{ MeV}, C = 300 \text{ m}$
- Detector
- monitor polarization precession
- for energy measurement
  - $\delta E_{\text{error}} \rightarrow 0.1 \text{ MeV}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
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<tbody>
<tr>
<td>Collision Beam Energy</td>
<td>$E_{\mu^+}, E_{\mu^-}$</td>
<td>63 GeV</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$L_0$</td>
<td>$10^{31}$</td>
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<tr>
<td>Number of $\mu$ bunches</td>
<td>$n_B$</td>
<td>1</td>
</tr>
<tr>
<td>$\mu^+/\mu^-$ bunch</td>
<td>$N_{\mu}$</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>Transverse emittance</td>
<td>$\varepsilon_{\perp,N}$</td>
<td>0.0004 m</td>
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<tr>
<td>Longitudinal emittance</td>
<td>$\varepsilon_{\parallel,N}$</td>
<td>0.002 m</td>
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<tr>
<td>Energy spread</td>
<td>$\delta E$</td>
<td>4 MeV</td>
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<tr>
<td>Collision $\beta^*$</td>
<td>$\beta^*$</td>
<td>0.05 m</td>
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<td>Beam size at collision</td>
<td>$\sigma_{x,y}$</td>
<td>0.02 cm</td>
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<tr>
<td>Beam size (arcs)</td>
<td>$\sigma_{x,y}$</td>
<td>1.0 cm</td>
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<td>Beam size IR quad</td>
<td>$\sigma_{\text{max}}$</td>
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<td>Storage turns</td>
<td>$N_t$</td>
<td>1000</td>
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<tr>
<td>Proton Beam Power</td>
<td>$P_p$</td>
<td>4 MW</td>
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<tr>
<td>Bunch frequency</td>
<td>$F_p$</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Protons per bunch</td>
<td>$N_p$</td>
<td>$5 \times 10^{13}$</td>
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<tr>
<td>Proton beam energy</td>
<td>$E_p$</td>
<td>8 GeV</td>
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</tbody>
</table>
**Upgrade path (E and L)**

- **More cooling**
  - $\varepsilon_{t,N} \rightarrow 0.0002$, $\beta^* \rightarrow 1\text{cm}$
  - $L \rightarrow 10^{32}$

- **Bunch recombination**
  - $60\text{Hz} \rightarrow 15\ ?$
  - $L \rightarrow 10^{32}$

- **More cooling**
  - low emittance
  - $\varepsilon_{t,N} \rightarrow 0.00003$, $\beta^* \rightarrow 0.3\text{cm}$
  - $L \rightarrow 10^{33}$

- **More Protons**
  - $4\text{MW} \rightarrow 8\ ?$
  - $15\text{Hz}$
  - $L \rightarrow 10^{34}$

- **more Acceleration**
  - $\rightarrow 4\text{ TeV or more} \ldots$
  - $L \rightarrow 10^{35}$

---

<table>
<thead>
<tr>
<th></th>
<th>Higgs¹</th>
<th>Design</th>
<th>Design</th>
<th>Extrap²</th>
<th>TeV</th>
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<tr>
<td>C of m Energy</td>
<td>0.126</td>
<td>1.5</td>
<td>3</td>
<td>6</td>
<td>$10^{34}$ cm$^{-2}$sec$^{-1}$</td>
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<tr>
<td>Luminosity</td>
<td>0.002</td>
<td>1</td>
<td>4</td>
<td>12</td>
<td></td>
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<tr>
<td>Muons/bunch</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>Total muon Power</td>
<td>1.2</td>
<td>7.2</td>
<td>11.5</td>
<td>11.5</td>
<td>MW</td>
</tr>
<tr>
<td>Ring circumference</td>
<td>0.3</td>
<td>2.6</td>
<td>4.5</td>
<td>6</td>
<td>km</td>
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<tr>
<td>$\beta^*$ at IP = $\sigma_z$</td>
<td>80</td>
<td>10</td>
<td>5</td>
<td>25</td>
<td>mm</td>
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<tr>
<td>rms momentum spread</td>
<td>0.004</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>%</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>30</td>
<td>15</td>
<td>12</td>
<td>6</td>
<td>Hz</td>
</tr>
<tr>
<td>Proton Driver power</td>
<td>4</td>
<td>4</td>
<td>3.2</td>
<td>1.6</td>
<td>MW</td>
</tr>
<tr>
<td>Muon Trans Emittance</td>
<td>300</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>Muon Long Emittance</td>
<td>2</td>
<td>72</td>
<td>72</td>
<td>72</td>
<td>mm</td>
</tr>
</tbody>
</table>
γγ Collider Higgs Factory

• Advantages
  – Lowest energy for Higgs Production, (160 GeV v. 240 GeV)
  – Can Provide CP violation information on the Higgs
  – Can be added to a normal linear collider
  – No Positrons required

• Disadvantages
  – Unproven Technology
  – Limited Physics reach
  – Requires very high power Laser
\[ \gamma \gamma \rightarrow h \text{ cross section} \]

**CLIC-based**

- **e**
- Laser \( \gamma \)
- detector
- Laser \( \gamma \)
- main linac
- drive beam decelerator
- drive beam
- delay loop
- combiner rings
- drive beam accelerator

**Figure 1.3.1:** Spectrum of the Compton scattered photons for different polarisations of the laser and electron beams.

\[ \omega_m = \frac{x}{x + 1} E_0; \quad x \approx \frac{4E_0\omega_0}{m^2c^4} \approx 15.3 \left[ \frac{E_0}{\text{TeV}} \right] \left[ \frac{\omega_0}{\text{eV}} \right] \]
Issues for $\gamma \gamma$ colliders

• IR related
  – Beam crossing angle
  – Optics in the IR region
  – extraction line(e) and beam dump ($\gamma$)

• Lasers

(T. Takahashi)
Pulse Stacking Cavity for ILC

- total length \( \sim 100 \text{m} \)
- power enhancement \( \sim 100 \)

- \( L = n\lambda \)
- \( d L << \lambda / \text{enhancement} \)
- mode locked pulsed laser
  100MHz 0.1J/pulse
The entire $1\omega$ beamline can be packaged into a box which is 31 m$^3$ while providing 130 kW average power.
modified design approach
Yuhong Zhang
JLAB

thin laser target
• eliminates most useless and harmful soft $\gamma$ photons from multiple Compton scattering
• relaxed laser requirements (~factor 10)

high luminosity achieved through an increase of bunch repetition rate and higher e- beam current (~factor 10) with multi-pass recirculating linac and energy recovery
SAPPHiRE: a Small $\gamma \gamma$ Higgs Factory

SAPPHiRE: Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

scale ~ European XFEL, about 10-20k Higgs per year
Some challenges with 2-pass design!

- Final focii ~ 300 meters in length
- Laser beam from fiber laser or FEL
- Upgrade with plasma afterburners (what cms energy is possible?)

250 m

45 GeV, 1.5 km
or 85 GeV, 3 km

1 km radius
Schematic layout of the collider
HERA Tunnel Filler

- Laser or auto-driven FEL
- $\rho=564$ m for arc dipoles (probably pessimistic; value assumed in the following)
- 2x8+1 arcs
- 20-MV deflecting cavity (1.3 GHz)
- 3.6 GeV linac
- 2x1.5 GeV linac
- 0.5 GeV injector

F. Zimmermann, R. Assmann, E. Elsen,
DESY Beschleuniger-Ideenmarkt, 18 Sept. 2012
Possible Configurations at FNAL

Tevatron Tunnel Filler Options

1) Both versions assume an effective accelerating gradient of 23.5 MeV/m.

- Option 1: would require more civil construction, but would only require two sets of spreader/recombiner magnets, and only two linacs, for greater simplicity.

2) Option 2: would require 10 sets of spreader/recombiner magnets and 5 linacs but would achieve better beam parameters.

<table>
<thead>
<tr>
<th></th>
<th>Top Energy 80 GeV</th>
<th>Top Energy 80 GeV</th>
</tr>
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<tbody>
<tr>
<td><strong>2 Linacs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turns</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Avg. Mag. ρ</td>
<td>661.9 m</td>
<td>701.1 m</td>
</tr>
<tr>
<td>Linacs (2)</td>
<td>10.68GeV</td>
<td>8.64GeV</td>
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<tr>
<td>δp/ρ</td>
<td>8.84x10^-4</td>
<td>8.95x10^-4</td>
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<tr>
<td>ε_{nx} Growth</td>
<td>2.8μm</td>
<td>2.85μm</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Top Energy 80 GeV</th>
<th>Top Energy 80 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>5 Linacs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turns</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Magnet ρ</td>
<td>644.75 m</td>
<td>706.65 m</td>
</tr>
<tr>
<td>Linacs (5)</td>
<td>5.59GeV</td>
<td>4.23GeV</td>
</tr>
<tr>
<td>δp/ρ</td>
<td>6.99x10^-4</td>
<td>7.2x10^-4</td>
</tr>
<tr>
<td>ε_{nx} Growth</td>
<td>1.7μm</td>
<td>1.8μm</td>
</tr>
</tbody>
</table>
Summary

- Circular Colliders have the least technical risk, but aside from LEP3 would be very expensive.
- Linear colliders are furthest along in the design process, and already have a global support network.
- Muon Colliders offer room for growth, but are not mature enough for a near term facility.
- $\gamma\gamma$ Colliders offer low cost but are still an unproven technology that may lack sufficient physics reach for a dedicated facility.