Higgs Factory
Why, How, What?

Shufang Su • U. of Arizona

OSU, October 26, 2022
Higgs discovery

``BREAKTHROUGH of the YEAR'' - Science
Celebration!
Hunting the Last Missing Particle of the Standard Model

Shufang Su • Caltech

Feb 14, 2003
U Arizona Colloquium
Job Interview
First Hint: Dec 13, 2011
The Nobel Prize in Physics 2013

François Englert
Université Libre de Bruxelles, Belgium

Peter W. Higgs
University of Edinburgh, UK

"For the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider."
25 Yrs’ Work by thousands experimentalists
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Large Hadron Collider

S. Su
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S. Su
Why is Higgs puzzling? 
\[ \mu_h, \] measured, not predicted. 
Like phase transition in superconductor. However, not in known material. Nobody dials the temperature from "outside".

Parameters in \[ V(\mu) \] need to come from a (unknown) fundamental theory.

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The BCS ground state (named after John Bardeen, Leon Cooper and Robert Schrieffer, Nobel Prize, 1972) has spontaneously broken gauge symmetry. This means that, while the underlying Hamiltonian is invariant with respect to the choice of the electromagnetic gauge, the BCS ground state is not. This fact cast some doubts on the validity of the original explanation of the Meissner effect within the BCS theory, which, though well motivated on physical grounds, was not explicitly gauge invariant. Nambu finally put these doubts to rest, after earlier important contributions by Philip Anderson (Nobel Prize, 1977) [28] and others had fallen short of providing a fully rigorous theory. In the language of particle physics the breaking of a local gauge symmetry, when a normal metal becomes superconducting, gives rise to a finite mass for the photon field inside the superconductor. The conjugate length scale is nothing but the London penetration depth. This example from superconductivity showed that a gauge theory could give rise to small length scales if the local symmetry is spontaneously broken and hence to short range forces. Note though, that the theory in this case is non-relativistic since it has a Fermi surface. In his paper of 1960 Nambu [27] studied a quantum field theory for hypothetical fermions with chiral symmetry. This symmetry is global and not of the gauge type. He assumed that by giving a vacuum expectation value to a condensate of fields it is spontaneously broken, and he could show that there is a bound state of the fermions, which he interpreted as the pion. This result follows from general principles without detailing the interactions. If the symmetry is exact, the pion must be massless. By giving the fermions a small mass the symmetry is slightly violated and the pion is given a small mass. Note that this development came four years before the quark hypothesis.

Soon after Nambu's work, Jeffrey Goldstone [29] pointed out that an alternative way to break the symmetry spontaneously is to introduce a scalar field with the quantum numbers of the vacuum and to give it a vacuum expectation value. He studied some different cases but the most important one was that of a complex massive scalar field \[ \phi = \sqrt{\frac{1}{6}}(\phi_1 + i\phi_2) \] with a Lagrangian density of the form \[ L = \frac{1}{2} \partial\phi \partial\phi - \mu \phi^* \phi + \lambda \phi^6, \] where \[ \phi^* \] is the complex conjugate of \[ \phi, \] and the coupling constant \[ \lambda \] is positive. This Lagrangian is invariant under a global rotation of the phase of the field \[ \phi, \] \( \phi \rightarrow e^{-i\theta} \phi \), i.e., a \( U(1) \) symmetry as in QED, although not a local one. Suppose now that one chooses the square of the mass, \( \mu^2 \), to be a negative number. Then the potential looks like a "Mexican hat":

---

\[ \text{ATLAS} \]

Data
Sig+Bkg Fit (m_h=128.5 GeV)
Bkg (4th order polynomial)

---

\[ f_s=7 \text{ TeV}, \int L dt=4.8 \text{ fb}^{-1} \]
\[ f_s=8 \text{ TeV}, \int L dt=5.9 \text{ fb}^{-1} \]

---

\( H \rightarrow \gamma\gamma \)

---

\[ \text{Events} / \text{2 GeV} \]

---

\[ -200 \quad 0 \quad 200 \quad 400 \quad 600 \quad 800 \quad 1000 \quad 1200 \quad 1400 \quad 1600 \quad 1800 \quad 2000 \quad 2200 \quad 2400 \quad 2600 \quad 2800 \quad 3000 \quad 3200 \quad 3400 \quad 3600 \quad 3800 \]

---

\[ \text{Events} - \text{Bkg} \]

---

\[ -100 \quad 0 \quad 100 \quad 200 \quad 300 \quad 400 \quad 500 \quad 600 \quad 700 \quad 800 \quad 900 \quad 1000 \]

---

Friday, October 11, 13
S. Su

10

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Friday, October 11, 13
50 Years’ work by numerous theorists
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\[ g_{Hff} = m_f \frac{1}{v} = (\sqrt{2} G_F)^{1/2} m_f \times (i) \]

\[ g_{HVV} = 2 M_H^2 / v = 2 (\sqrt{2} G_F)^{1/2} M_H^2 \times (-i g_{\mu\omega}) \]

\[ g_{HWW} = 2 M_W^2 / v^2 = 2 \sqrt{2} G_F M_W^2 \times (-i g_{\mu\omega}) \]

\[ g_{HHH} = 3 M_H^2 / v = 3 (\sqrt{2} G_F)^{1/2} M_H^2 \times (i) \]

\[ g_{HNN} = 3 M_H^2 / v^3 = 3 \sqrt{2} G_F M_N^2 \times (i) \]
50 Years' work by numerous theorists

Figure 1: Standard Model Higgs boson production cross sections at $E_{cm} = 7$ and $8$ TeV. Transition for VBF at $M_H = 300$ GeV at $8$ TeV is due to change from $ZWA$ to complex-pole-scheme. Right hand plot shows the total cross sections for $E_{cm} = 7$, $8$ and $14$ TeV.

Figure 2: Standard Model Higgs boson decay branching ratios and total width.
50 Years' work by numerous theorists

**Higgs Hunter's Guide**

**Collider Physics**

Associated production with $W/Z$: $qq \rightarrow V + H$

Vector boson fusion: $qq \rightarrow V^*V^* \rightarrow qq + H$

Gluon–gluon fusion: $gg \rightarrow H$

Associated production with heavy quarks: $gg, q\bar{q} \rightarrow Q\bar{Q} + H$

$$g_{HFF} = m_f/v = (\sqrt{2} G_F)^{1/2} m_f \times (i)$$

$$g_{VV} = 2 M_V^2/v = 2(\sqrt{2} G_F)^{1/2} M_V^2 \times (-g_\mu)$$

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- Truly a monumental triumph.
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SM Higgs does not have to be there…

Now that it actually IS…

Reached a deep understanding of nature!
Outline

๏ Why we need a Higgs factory?
๏ How to make a Higgs factory?
๏ What we can learn with a Higgs factory?
Why we need a Higgs Factory?
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To study Higgs, of course!
Why we need a Higgs Factory?
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Why is it important to study Higgs?
Quiz!!!
Quiz!!!

- Higgs is responsible for the mass of Universe
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dark matter and dark energies (96% of the Universe)
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Higgs mechanism: Yes. Higgs particle: No.
Elementary particles

SU(3)_c × SU(2)_L × U(1)_Y

The successful “Standard Model”
Elementary particles

\[ \text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_Y \]

The successful "Standard Model"

Quarks

\[ \begin{array}{cccc}
    u & c & t \\
    d & s & b \\
\end{array} \]

Leptons

\[ \begin{array}{cccc}
    e & \mu & \tau \\
    \nu_e & \nu_\mu & \nu_\tau \\
\end{array} \]

Forces

\[ m_\gamma = 0 \]

EM: long range force
SU(3)_c × SU(2)_L × U(1)_Y

The successful "Standard Model"

m_γ = 0
EM: long range force

m_{W,Z} \sim 100 \text{ GeV}
weak interaction: short range force
Higgs mechanism: historical profile

QED (1950's)

Yang-Mills Theory
[Yang, Mills, 1954]

EW unification theory
[Glashow, 1960]

Spontaneous symmetry breaking in particle physics
[Nambu, 1960; Goldstone, 1962]

Higgs mechanism and Higgs boson
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Higgs Mechanism (1964)
Elementary particles

\[ SU(3)_c \times SU(2)_L \times U(1)_Y \]

Quarks

\[
\begin{array}{cccc}
\text{up} & \text{down} & \text{charmed} & \text{top} \\
\text{d} & \text{s} & \text{b} \\
\text{quarks} & \text{strange} & \text{bottom} & \text{bottom}\end{array}
\]

Leptons

\[
\begin{array}{cccc}
\text{electron} & \text{muon} & \text{tau} \\
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\text{neutrinos} & \text{massive neutrinos} & \text{neutrino}\end{array}
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\[
\begin{align*}
\text{Z} & \quad \gamma \\
\text{W} & \quad g
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Higgs (mechanism)!
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**Higgs (mechanism) !**

- **Higgs mechanism** break electroweak symmetry spontaneously.
- **Higgs field** gives mass to e, W, Z,…
- The remaining Higgs boson spin 0 scalar
Higgs Mechanism **DOES NOT** require a Higgs boson!
Mass generation

Higgs Mechanism DOES NOT require a Higgs boson!

Higgs Mechanism: If a LOCAL gauge symmetry is spontaneously broken, then the gauge boson acquires a mass by absorbing the Goldstone mode.
Higgs Mechanism **DOES NOT** require a Higgs boson!

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The predicted Higgs boson is the **left-over particle!**
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Higgs field $\rightarrow 4 = 3$

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\[ 4 = 3 + 1 \]

Higgs field \( \rightarrow \) longitudinal modes of \( W^+, W^-, Z \) \( \uparrow \) physical Higgs Boson
THE HIGGS MECHANISM

1. To understand the Higgs mechanism, imagine that a room full of physicists quietly chattering is like space filled only with the Higgs field.

2. A well-known scientist, Albert Einstein, walks in, creating a disturbance as he moves across the room, and attracting a cluster of admirers with each step.

3. This increases his resistance to movement - in other words, he acquires mass, just like a particle moving through the Higgs field.

4. If a rumour crosses the room...

5. It creates the same kind of clusterings, but this time among the scientists themselves. In this analogy, these clusters are the Higgs particles.
Quiz!!!

- Higgs is responsible for the mass of Universe
  dark matter and dark energies (96% of the Universe)

- Higgs is responsible for the mass of your and me
  (and 4% of the Universe) QCD does it!

- Higgs is needed for the mass of elementary particles
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...... **THE END.**  Beginning of a new Era !!!
light, weakly coupled boson: $m_h = 125-126$ GeV, $\Gamma < 1$ GeV

$$V(\phi) = \frac{1}{2} \mu_h^2 \phi^2 + \frac{\lambda}{4} \phi^4$$

$$\langle \phi \rangle \equiv v \neq 0 \quad \rightarrow \quad m_W = g_W \frac{v}{2}$$

$$M_H^2 = -2\mu^2 = 2\lambda v^2$$
On the theory side...

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\[ \lambda_q \sim m_q/v \]
All couplings and parameters of the Higgs sector is determined in the SM.

To compare with measurements high precise needed!
- clean environments
- lots of Higgs

→ Higgs factory!
A light SM Higgs is puzzling...

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where \( \phi^* \) is the complex conjugate of \( \phi \), and the coupling constant \( \lambda \) is positive. This Lagrangian is invariant under a global rotation of the phase of the field \( \phi \), ie. a U(1) symmetry as in QED, although not a local one. Suppose now that one chooses the square of the mass, \( \mu^2 \), to be a negative number. Then the potential looks like a "Mexican hat":

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Higgs: a new kind of elementary particle!
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Nothing protects its mass. 😢

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A light SM Higgs is puzzling...

<table>
<thead>
<tr>
<th>particle</th>
<th>spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>quark: u, d,...</td>
<td>1/2</td>
</tr>
<tr>
<td>lepton: e...</td>
<td>1/2</td>
</tr>
<tr>
<td>photon</td>
<td>1</td>
</tr>
<tr>
<td>W,Z</td>
<td>1</td>
</tr>
<tr>
<td>gluon</td>
<td>1</td>
</tr>
<tr>
<td>Higgs</td>
<td>0</td>
</tr>
</tbody>
</table>

Higgs: a new kind of elementary particle!
Nothing protects its mass.

New physics beyond the SM
light, weakly coupled boson: $m_h = 125-126$ GeV, $\Gamma < 1$ GeV
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Experimentally ...
light, weakly coupled boson: \( m_h = 125-126 \text{ GeV} \), \( \Gamma < 1 \text{ GeV} \)

Experimentally …
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Experimentally …

- Is it a SM Higgs? Mass, width, spin, coupling, CP, …
light, weakly coupled boson: $m_h = 125-126$ GeV, $\Gamma < 1$ GeV

Experimentally ...

- Is it a SM Higgs? Mass, width, spin, coupling, CP, ...
- Is there more than one Higgs boson?
light, weakly coupled boson: \( m_h = 125-126 \text{ GeV}, \quad \Gamma < 1 \text{ GeV} \)

Experimentally …

- Is it a SM Higgs? Mass, width, spin, coupling, CP, …
- Is there more than one Higgs boson?
- Does this H decay to other things unexpected?
On the exp side...

light, weakly coupled boson: $m_h = 125-126$ GeV, $\Gamma < 1$ GeV

Experimentally …

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- Is there more than one Higgs boson?
- Does this H decay to other things unexpected?
- Can we use H to look for new physics?
light, weakly coupled boson: $m_h = 125-126$ GeV, $\Gamma < 1$ GeV

Experimentally …

- Is it a SM Higgs? Mass, width, spin, coupling, CP,…
- Is there more than one Higgs boson?
- Does this H decay to other things unexpected?
- Can we use H to look for new physics?
- Where is new physics? top partners? Dark matter?
On the exp side...

light, weakly coupled boson: $m_h = 125-126$ GeV, $\Gamma < 1$ GeV

Experimentally …

- Is it a SM Higgs? Mass, width, spin, coupling, CP, …
- Is there more than one Higgs boson?
- Does this $H$ decay to other things unexpected?
- Can we use $H$ to look for new physics?
- Where is new physics? top partners? Dark matter?
- …
syblings $H, A, H^\pm, \ldots$
syblings $H, A, H^\pm, ...$

partners Higgsinos $...$
friends stop, ...

syblings H, A, H^\pm, ...

partners Higgsinos ...

Higgs
friends stop, ... friends of friends, squarks, gluinos

Higgs

syblings H, A, H\(^{\pm}\), ...

partners Higgsinos ...

S. Su 26
friends stop, friends of friends, squarks, gluinos

syblings $H, A, H^\pm$, partners Higgsinos

Higgs
friends stop, ...

friends of friends, squarks, gluinos

NEW

syblings $H, A, H^\pm, ...$

partners Higgsinos

Higgs
S. Su

26

Higgs friends stop, ...

... syblings H,A,H\(^{\pm}\), ...

friends of friends, squarks, gluinos

partners Higgsinos

NEW
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Higgs friends

H,A,H±, ...

partners Higgsinos ...

friends of friends, squarks, gluinos
# New Physics Searches

## ATLAS Exotics Searches* - 95% CL Exclusion

<table>
<thead>
<tr>
<th>Model</th>
<th>$l$, $y$, $J$</th>
<th>$E_T^{miss}$</th>
<th>$l^p$</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell_1 + \ell_2 + \ell_3$</td>
<td>$\ell_1$, $\ell_2$, $\ell_3$</td>
<td>$E_T^{miss}$</td>
<td>+1</td>
<td>0.2</td>
</tr>
<tr>
<td>$\ell_1 + \ell_2 + \ell_3$</td>
<td>$\ell_1$, $\ell_2$, $\ell_3$</td>
<td>$E_T^{miss}$</td>
<td>-1</td>
<td>2.3</td>
</tr>
<tr>
<td>$\ell_1 + \ell_2 + \ell_3$</td>
<td>$\ell_1$, $\ell_2$, $\ell_3$</td>
<td>$E_T^{miss}$</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>$\ell_1 + \ell_2 + \ell_3$</td>
<td>$\ell_1$, $\ell_2$, $\ell_3$</td>
<td>$E_T^{miss}$</td>
<td>1</td>
<td>0.2</td>
</tr>
</tbody>
</table>

### Reference
- ATLAS Preliminary

## CMS SUSY

### Summary of CMS SUSY Results* in SMS framework

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

### CMS Preliminary

For example with intermediate mass $m_{\text{intermediate}}$:

$$m_{\text{intermediate}} = \sqrt{m_{\text{prod}}^2 + \Delta m^2}$$

---

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New Physics Searches

No New Physics Yet!

ATLAS exotic

CMS SUSY
Where Are We Now?

- Our wish list has not changed much from 10 years ago.
- Discovery of Higgs
  - Exclude technicolor
  - Narrow down parameter space
- Non-discovery of anything else
  - New physics gets heavier
  - A bit uncomfortable, big picture unchanged
What Do Theorists Say?

More tricks

More fine tuning
What Do Theorists Say?

Ideal. But simple ones ruled out.

More tricks

More fine tuning
What Do Theorists Say?

More tricks

More fine tuning

Ideal. But simple ones ruled out.

Our models
What Do Theorists Say?

Last 20 years. Many many models. Run I ruled out some. But most could still work.

Ideal. But simple ones ruled out.

Our models

More tricks

More fine tuning
What Do Theorists Say?

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More tricks

Our models

More fine tuning

Ideal. But simple ones ruled out.
Where is New Physics? larger mass? Small Coupling? Both?

- Indirect search
  - e+e-

- direct search
  - pp
Where is New Physics? larger mass? Small Coupling? Both?

- Indirect search
  - e+e-

- direct search
  - pp

$E_{cm}$
Current and Future Colliders

Where is New Physics? larger mass? Small Coupling? Both?

- Indirect search
- Direct search

- $e^+e^-$
- $pp$

$L$

$E_{cm}$
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**pp**
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- e+e-
- pp

direct search

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**Current and Future Colliders**

Where is New Physics? larger mass? Small Coupling? Both?

- Indirect search
- direct search

**Diagram:**
- e+e-
- pp

**Axes:**
- $E_{cm}$
- $L$

**Author:** S. Su
Current and Future Colliders

Where is New Physics? larger mass? Small Coupling? Both?

- Indirect search
  - e+e-
  - L
  - small coupling

- direct search
  - pp
  - L
  - larger mass

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Current and Future Colliders

Where is New Physics? larger mass? Small Coupling? Both?

- Indirect search
  - e+e-
- Direct search
  - pp

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L
small coupling

E_{cm}

Precision
Higgs study

L

larger mass
E_{cm}
How to Make a Higgs Factory?
Large Hadron Collider

- pp collider, 27 km
- 7 TeV beam
  0.99999999 c
- stored energy:
  ~ Giga Joule
Large Hadron Collider (LHC)

- LHC pp collider, 27 km
- 7 TeV beam
- 0.99999999 c
- Stored energy: ~ Giga Joule
Large Hadron Collider (LHC)

- **stored energy:**
  - ~ Giga Joule

**Highest energy, probing smallest distance (10^{-10} \text{ nm})**
Particle Detector

- 150 MP
- 600 million snapshots / second
Particle Detector

- 150 MP
- 600 million snapshots / second
- 7000 scientists
- $10 billion
FCC

- HE-LHC
  - 27 km, 20T
  - 33 TeV

- FCC-ee
  - 80/100 km
  - 90 - 400 GeV

- FCC-hh
  - 80 /100 km, 16/20T
  - 100 TeV
CEPC-SPPC

CEPC
e+e-: 240 GeV
SPPC
pp: 70-100 TeV

---

CEPC Site Selections

1) Qinhuangdao, Hebei Province (Completed in 2014)
2) Huating, Shandong Province (Completed in 2017)
3) Shenzhou, Guangdong Province (Completed in 2016)
4) Baoding (Xiong an), Hebei Province (Started in August 2017)
5) Huzhou, Zhejiang Province (Started in March 2018)
6) Chongqing, Jilin Province (Started in May 2018)
7) Changsha, Hunan Province (Started in Dec. 2018)
Muon Collider

- unique combination of higher energy and clean environment
- smaller ring

$m_\mu \sim 200 \, m_e$
How to make a Higgs

- $e^+e^-$ collider
- $\mu^+\mu^-$ collider
How to make a Higgs

e+e- collider

μ+μ- collider
How to make a Higgs

e+e- collider

µ+µ- collider
How to make a Higgs

$e^+e^-$ collider

$\mu^+\mu^-$ collider
How to make a Higgs

e+e- collider

\[ e^+ e^- \rightarrow Z \rightarrow H \]

µ+µ- collider

\[ \mu^+ \mu^- \rightarrow Z \rightarrow H \]
How to make a Higgs

\[ e^+e^- \text{ collider} \]

\[ \mu^+\mu^- \text{ collider} \]

\[ H \]

\[ Z \]
How to make a Higgs

e+e- collider

µ+µ- collider

Z

H

µ+

µ-
How to make a Higgs

$e^+e^-$ collider

$\mu^+\mu^-$ collider

$Z$
What we can learn with a Higgs Factory?
Why is Higgs puzzling

- \( \mu_{\text{H}} \), measured, not predicted.
- Like phase transition in superconductor. However, not in known material. Nobody dials the temperature from "outside".
- Parameters in \( V(\phi) \) need to come from an (unknown) fundamental theory.

### BCS Theory

That the BCS ground state (named after John Bardeen, Leon Cooper, and Robert Schrieffer, Nobel Prize, 1972) has spontaneously broken gauge symmetry. This means that, while the underlying Hamiltonian is invariant with respect to the choice of the electromagnetic gauge, the BCS ground state is not. This fact cast some doubts on the validity of the original explanation of the Meissner effect within the BCS theory, which, though well motivated on physical grounds, was not explicitly gauge invariant. Nambu finally put these doubts to rest, after earlier important contributions by Philip Anderson (Nobel Prize, 1977) and others had fallen short of providing a fully rigorous theory.

In the language of particle physics, the breaking of a local gauge symmetry, when a normal metal becomes superconducting, gives rise to a finite mass for the photon field inside the superconductor. The conjugate length scale is nothing but the London penetration depth. This example from superconductivity showed that a gauge theory could give rise to small length scales if the local symmetry is spontaneously broken and hence to short range forces. Note though, that the theory in this case is non-relativistic since it has a Fermi surface.

In his paper of 1960, Nambu studied a quantum field theory for hypothetical fermions with chiral symmetry. This symmetry is global and not of the gauge type. He assumed that by giving a vacuum expectation value to a condensate of fields, it is spontaneously broken, and he could show that there is a bound state of the fermions, which he interpreted as the pion. This result follows from general principles without detailing the interactions. If the symmetry is exact, the pion must be massless. By giving the fermions a small mass, the symmetry is slightly violated and the pion is given a small mass. Note that this development came four years before the quark hypothesis.

Soon after Nambu's work, Jeffrey Goldstone pointed out that an alternative way to break the symmetry spontaneously is to introduce a scalar field with the quantum numbers of the vacuum and to give it a vacuum expectation value. He studied some different cases but the most important one was that of a complex massive scalar field \( \phi = \sqrt{\frac{1}{2}}(\phi^0 + i\phi^1) \) with a Lagrangian density of the form

\[
L = \frac{1}{2} \partial \phi^\dagger \partial \phi - \frac{1}{2} m^2 (\phi^0)^2 - \frac{1}{4} \lambda (\phi^0)^2,
\]

where \( \phi^\dagger \) is the complex conjugate of \( \phi \), and the coupling constant \( \lambda \) is positive. This Lagrangian is invariant under a global rotation of the phase of the field \( \phi \), \( \phi \rightarrow e^{i\theta} \phi \), i.e., a \( U(1) \) symmetry as in QED, although not a local one. Suppose now that one chooses the square of the mass, \( m^2 \), to be a negative number. Then the potential looks like a "Mexican hat".
Why is Higgs puzzling - $\mu_h$, measured, not PREDICTED. - Like phase transition in superconductor. However, not in known material. Nobody dials the temperature from "outside". - Parameters in $V(\mu_h)$ need to come from a (unknown) fundamental theory.

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Higgs Production @ e+e-
is achieved for the leptonic boson physical width is about 4 MeV and resonance is largely determined by the energy and momentum resolution of the detector as the Higgs fermion pair. The recoiling against the adjustable. For a Higgsstrahlung event where the unlike hadron colliders, the center of mass energy at an measurements are expected to be small.

W_{125} GeV Higgs boson. (b) Higgs boson decay branching ratios as functions of Figure 2.6

At the ILC, the SM Higgs boson is produced mainly via production mechanisms such as the W-boson fusion process (Middle) and the top-quark association (Right). The corresponding production cross section at the ILC are, respectively, the total energy, momentum and invariant mass of the associated Higgs boson production and double Higgs boson production mechanisms. The Standard Model values of branching ratios of bosonic decays of the Higgs boson for each value of m_h are, respectively, the total energy, momentum and invariant mass of the Higgs boson mass values of the total decay width of the Higgs boson are also listed. It is quite interesting that with each particle shown in Fig. 1.1 can be well tested by measuring these branching ratios as well as the total decay width accurately at the ILC. For example, the top Yukawa coupling and the triple Higgs vertex.

S. Su

Precision of Higgs coupling measurement (7-parameter Fit)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Relative Error</th>
<th>HL-LHC S1/S2</th>
<th>CEPC 240 GeV at 5.6 ab^{-1} wi/wo HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_b</td>
<td>10^{-3}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K_t</td>
<td>K_c</td>
<td>10^{-2}</td>
<td></td>
</tr>
<tr>
<td>K_g</td>
<td>10^{-2}</td>
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</tr>
<tr>
<td>K_W</td>
<td>10^{-2}</td>
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</tr>
<tr>
<td>K_T</td>
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<tr>
<td>K_Z</td>
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<tr>
<td>K_Y</td>
<td>10^{-2}</td>
<td></td>
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</tr>
</tbody>
</table>
Tree-level 2HDM fit

2HDM, LHC/CEPC fit

Figure 2. The allowed region in the plane of $\tan\beta$ vs. $\cos(\beta-\alpha)$ at 95% C.L. for the four types of 2HDM, given LHC and CEPC Higgs precision measurements. For future measurements, we assume that the measurements agree with SM predictions. The special “arm” regions for the Type-II, L and F are the wrong-sign Yukawa regions. See text for more details.

Here $x$ is $d, e$ in the Type-II, $e$ in the Type-L and $d$ in the Type-F. Therefore, the survival parameter space at large $\tan\beta$ is reduced significantly in all these three types.

For the Type-II at the upper right panel of Fig. 2, as a result of larger $\tan\beta$ enhancement from $d,e$ and small $\tan\beta$ enhancement from $u$, the region around $\tan\beta = 1$ accommodates the allowed parameter space from CEPC and HL-LHC.

Han, Li, SS, Su, Wu (2020)
EW baryogenesis

- Baryon asymmetry ⇔ baryogenesis ⇔ strong 1st order EWPT
- SM: 125 GeV, 2nd order EWPT ⇒ no EW baryogenesis
- BSM with strong 1st order EWPT ⇒ large deviation in HHH
  ⇒ HHH > 20% or more, 100 TeV pp
  ⇒ ggH coupling, LHC
  ⇒ HZZ coupling, e+e−
The discovery of Higgs is a remarkable triumph in particle physics.

- A light weakly coupled Higgs argues for new physics beyond SM.

- Search for new physics calls for both high precision machine and high energy machine.

- Higgs factory: precise measurement of Higgs properties
  - Higgs coupling to sub-percent level
  - Indirect approach for new physics beyond the SM
  - Cosmo connection, dark matter, SM physics...
Why is Higgs puzzling

- $\mu_h$, measured, not predicted.
- Like phase transition in superconductor. However, not in known material. Nobody dials the temperature from "outside".
- Parameters in $V(\phi)$ need to come from a (unknown) fundamental theory.

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DPF community planning exercise

P5

Particle Physics Project Prioritization Panel

HEPAP

High Energy Physics Advisory Panel

US Government Funding Agency
Beginning of new era ...
Beginning of new era ...

Thank you!