Physics at Photon Colliders

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Higgs Boson discovered in 2012 at the LHC using 8 TeV data and is still there at 13 TeV 😊
@LHC the Higgs is better detected in rare decays like γγ and ZZ → 4L
- Reflecting the power of Signal/Power
- Sensitivity of Higgs to fermions (g_F) comes from the gg to H production and dominated by the top quark
- See example for H to bb → we need to do this elsewhere like @γγC
The discovery of Higgs Boson has created as many questions as it has answer

1. Higgs boson mass ($M_H$) & decay width ($\Gamma_H$)
2. Higgs boson quantum numbers $J^{PC}$ and tensor structure
3. Higgs couplings to gauge bosons ($g_V$) and fermions ($g_F$)
4. Higgs potential - Higgs self-coupling ($\lambda$)

**The Standard Model Lagrangian - Higgs sector**

$$\mathcal{L}_{SM} = D_\mu H^+ D_\mu H + \mu^2 H^+ H - \frac{\lambda}{2} \left( H^+ H \right)^2 - (y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.})$$

**Couplings to EW gauge bosons**

$$[m_{W}^2 W^+ W^- + \frac{1}{2} m_Z^2 Z^\mu Z^\nu] \cdot (1 + \frac{h}{v})^2$$

- $2i \frac{m_W}{v} g^{\mu \nu}$

**Higgs self-couplings**

$$-\mu^2 h^2 - \frac{3}{2} v h^3 - \frac{1}{8} \lambda h^4$$

- $-3i \frac{m_W}{v}$

- $-3i \frac{m_Z}{v}$

**Couplings to fermions**

$$-\sum_f m_f \bar{f} f \left( 1 + \frac{h}{v} \right)$$

- $-i \frac{m_f}{v}$

$m_H = \sqrt{2} \mu = \sqrt{\lambda} v$ ($v =$ vacuum expectation value, 246 GeV)

Are (1)-(3) measured precise enough @ LHC to be sensitive the relevant PBSM?

(4) What is the exact shape of the Higgs potential?
Examples of the $M_H$ measurements/predictions before and after discovery

- Combination of precise measurements of $m_W$, $m_{\text{top}}$, $m_H$ provides critical test of SM if $\sigma(m_W) \lesssim 6$ MeV
- Huge challenge at LHC
- Recent ATLAS result: $\sigma(m_W) = 19$ MeV
- $m_W$ measurement is the bottleneck, where the experimental uncertainty is worse than the theoretical one

$\Rightarrow$ We need to do this elsewhere like @$\gamma\gamma$C
LHC Data making clear the need for future machines

• Discovered the Higgs Boson @125 GeV
• Excluded Physics Beyond the Standard Model (PBSM) at relatively low masses:
  < few TeV in many models
• Need to include Precision Electroweak measurements to have sensitivity to PBSM not accessible direct at the LHC
Already signs from new physics in the Higgs data by comparing $M_{\text{top}}$ with $M_H$?

- Dashed lines: Calculation of the regions of the $(m_H, m_{\text{top}})$ plane where the electroweak vacuum is stable, metastable or unstable, and yields the following estimate of the “tipping point” $\Lambda_I$, where $\lambda$ goes negative.

- The final result is an estimate:
  - $\log_{10} (\Lambda_I / \text{GeV}) = 9.4 \pm 1.1$

indicating to some experts that we are (probably) doomed, unless some new physics intervenes.
Based on what we have learned at the LHC

1. $E_{ee} = 160$ GeV or $E_{\gamma \gamma} = M_H$
   - We need a “low” energy $\gamma \gamma C$ to study the Higgs in more detailed
   - Branching ratios not accessible with precisions at the the LHC (i.e. $H \rightarrow bb$) and precision measurements of those that loop induced (i.e. $H \rightarrow \gamma \gamma$)
   - Look for new physics in the Higgs sector:
     - CP admixture
     - Flavor violating decays like $H \rightarrow e\mu$, $\mu\tau$ and $e\tau$
     - Dark sector $H \rightarrow$ dark photons $\rightarrow$ fermions
   - Precise measurements of $W$ properties ($m_W$, $\Gamma_W$ and $W$ Branching fraction) using $e^- \gamma \rightarrow W\nu$
   - Precise measurements of $\sin^2\theta_W$ from $e^-e^- \rightarrow e^-e^-$

2. $E_{\gamma \gamma}$ above $2 \times M_W$ to $2 \times M_H$, that is 200 to 300 GeV
First steps: as discussed in the past, $\gamma\gamma C$ as **Higgs Factory** and associated $e^-e^-C$ and $e^-\gamma C$

- **Running of $\sin^2\theta_W$**
  - $e^-e^- \rightarrow e^-e^-$

- **$e^-\gamma C$**
  - $M_W$ & $\Gamma_W$, $e^-\gamma \rightarrow W\nu$ and $\gamma$-Structure

- **$\gamma\gamma C$**
  - Higgs CP Mixing and Violations

- Well defined CP-states, with linearly ($\lambda = 0$) polarized $\gamma$'s
  - $\gamma \parallel \gamma \parallel \Rightarrow$ CP-even
  - $\gamma \perp \gamma \parallel \Rightarrow$ CP-odd

See talk from Ziheng Chen
What is special about $\gamma\gamma C$?

• #1: Higher sensitivity due to higher cross sections and ability to manipulate the photon beam polarization to produce $J_z$ of $\gamma\gamma$ system is $= 0$ or $2$.
Example of Standard Model Processes
What is special about $\gamma\gamma C$?

- #2: Unique role in understanding CP structure due to the possibility of having linearly polarized beams that allow us to have:
  - Well defined CP-states, with linearly ($\lambda = 0$) polarized $\gamma$'s
  - $\Rightarrow (\gamma_\| \parallel \gamma_\|) \Rightarrow$ CP-even
  - $\Rightarrow (\gamma_\| \perp \gamma_\|) \Rightarrow$ CP-odd

- Change polarization of circularly polarized photon beams ($\lambda = \pm 1$) as needed to measure asymmetries for $J_z=0$ produced from:
  $$\lambda_1, \lambda_2 = (+, +) \text{ and } \lambda_1, \lambda_2 = (-, -)$$
What is special about $\gamma\gamma C$?

• #2: Unique role in understanding CP structure due to the possibility of having linearly polarized beams that allow us to have:

- **Well defined CP-states**, with *linearly* ($\lambda = 0$) polarized $\gamma$’s
  - $\Rightarrow (\gamma_{\|} \parallel \gamma_{\|}) \Rightarrow$ CP-even
  - $\Rightarrow (\gamma_{\|} \perp \gamma_{\|}) \Rightarrow$ CP-odd

We are still searching for the source of matter anti-matter asymmetry observed for visible matter in our universe; therefore looking for new sources of CP is crucial!
What is special about $\gamma\gamma C$?

• #3: Special role in understanding Higgs mechanism due to larger cross sections and the fact that Higgs is produced as a resonance:
Physics Motivation of $\gamma\gamma$C Higgs factory

- Important measurements that can only be done with high precision at the $\gamma\gamma$C assuming at least 10,000/year
  - $\Gamma_{\gamma\gamma}$ to 2% (Model independent)
    - Results in a 13% on $\Gamma_{\text{Total}}$
    - Results in a $Y_{\tau\tau}$ of 4%
  - Measure CP mixing and violation to better than 1%
  - At higher energies Higgs self coupling: $\lambda_{hhh}$ to a few %

Diagram:

- $\Gamma_{\gamma\gamma}$ proportional to $\Gamma_{\text{Fermions}} - \Gamma_{\text{Vectors}} - \Gamma_{\text{Scalars}}$
in the loop
Practical motivation of $\gamma\gamma C$ Higgs factory

• Development of compact $\gamma\gamma C$ starting from e$^-$e$^-$:
  • Based on already existing accelerator technology
  • Polarized and low energy e$^-$ beam: $E_e = 80$ GeV and ($\lambda_e = 80\%$)
  • Cost of building and operation is lower than other machines (excluding laser... to be discussed here)

• Required laser technology is becoming available
Designs that will produce \( \geq 10^7 \) Higgs/year

- **HFiTT:** Higgs Factory in Tevatron Tunnel (Fermilab specific)
- **SILC:** SLC-ILC-Style \( \gamma \gamma \) Higgs Factory (SLAC specific)
- **SAPPHiRE:** Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons (Can be built elsewhere)
- **CLICHÉ:** CLIC Higgs Experiment
- Plus designed to come out of this meeting

- Detector and beam environment not more difficult than what we are experiencing at the LHC

➔ 3 machines in 1: \( e^-e^- \), \( e^- \gamma \), \( \gamma \gamma \)
**Just for reference: Primary Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HFiTT</th>
<th>Sapphire</th>
<th>SILC</th>
<th>CLICHE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak $\gamma\gamma$ Energy</td>
<td>126 GeV</td>
<td>128 GeV</td>
<td>130 GeV</td>
<td>128 GeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>2e10</td>
<td>1e10</td>
<td>5e10</td>
<td>4e9</td>
</tr>
<tr>
<td>Bunches/train</td>
<td>1</td>
<td>1</td>
<td>1000</td>
<td>1690</td>
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<tr>
<td>Rep. rate</td>
<td>47.7 kHz</td>
<td>200 kHz</td>
<td>10 Hz</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Power per beam</td>
<td>12.2 MW</td>
<td>25 MW</td>
<td>7 MW</td>
<td>9.6 MW</td>
</tr>
<tr>
<td>$L_{ee}$</td>
<td>3.2e34</td>
<td>2e34</td>
<td>1e34</td>
<td>4e34</td>
</tr>
<tr>
<td>$L_{gg}$ ($E_{\gamma\gamma} &gt; 0.6 E_{cms}$)</td>
<td>5e33</td>
<td>3.5e33</td>
<td>2e33</td>
<td>3.5e33</td>
</tr>
<tr>
<td>CP from IP</td>
<td>1.2 mm</td>
<td>1 mm</td>
<td>4 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>Laser pulse energy</td>
<td>5 J</td>
<td>4 J</td>
<td>1.2 J</td>
<td>2 J</td>
</tr>
</tbody>
</table>

Total electric power $\leq 100\text{ MW}$

35-50 fb$^{-1}\text{s}^{-1}$

**$\gamma_{laser}$**: In all designs a laser pulses of a several Joules with a $\lambda \sim 350\text{nm}$ (3.53 eV) for $E_{e^-} \sim 80\text{ GeV}$
Idea of $\gamma\gamma C$ Based on Compton Backscattering (see Telnov’s talk)

With circularly polarized $\gamma_{\text{laser}}$ ($P_{C} = \pm 1$) & polarized $e^{-}$ ($\lambda_{e} = \mp 1$)

Example: $\gamma\gamma C$ Optimized as a Higgs Factory

$\sigma(\gamma\gamma \to H) > 200$ fb
$h^0 \rightarrow b\bar{b}$ and $h^0 \rightarrow \gamma\gamma$ \[\text{hep-ex/0110056}\]

2% measurement of \{$\Gamma_{\gamma\gamma} \times Br(h \rightarrow b\bar{b})$\} within a year!

21% measurement of \{$\Gamma_{\gamma\gamma} \times Br(h \rightarrow \gamma\gamma)$\} within a year!

150 MeV mass measurement in 0.5 year!
## γγC Higgs-factory

**Table 1: Precision of measurements to be performed at HFfTT after 5 years of data taking**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Precision after 5 years of operation</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{\gamma \gamma} \times \text{Br}(h \rightarrow \bar{b}b)$</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{\gamma \gamma} \times \text{Br}(h \rightarrow WW^*)$</td>
<td>0.03</td>
<td>Leptonic decays only</td>
</tr>
<tr>
<td>$\Gamma_{\gamma \gamma} \times \text{Br}(h \rightarrow \gamma\gamma)$</td>
<td>0.12</td>
<td></td>
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<tr>
<td>$\Gamma_{\gamma \gamma} \times \text{Br}(h \rightarrow ZZ^*)$</td>
<td>0.06</td>
<td>One Leptonic and one hadronic decay</td>
</tr>
<tr>
<td>$\Gamma_{\gamma \gamma} \times \text{Br}(h \rightarrow Z\gamma)$</td>
<td>0.20</td>
<td>Leptonic and hadronic decays for Z</td>
</tr>
<tr>
<td>$\Gamma_{\gamma \gamma} \times \text{Br}(h \rightarrow \tau^+\tau^-)$</td>
<td>-</td>
<td>Work in progress</td>
</tr>
<tr>
<td>$\Gamma_{\gamma \gamma} \times \text{Br}(h \rightarrow \bar{c}c)$</td>
<td>-</td>
<td>Work in progress</td>
</tr>
<tr>
<td>$\Gamma_{\gamma \gamma} \times \text{Br}(h \rightarrow gg)$</td>
<td>-</td>
<td>Work in progress</td>
</tr>
<tr>
<td>$\Gamma_{\gamma \gamma} \times \text{Br}(h \rightarrow \mu^+\mu^-)$</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{\gamma \gamma}$</td>
<td>0.02</td>
<td>Using Br($h \rightarrow \bar{b}b$) as input</td>
</tr>
<tr>
<td>$\Gamma_{\text{total}}$</td>
<td>0.13</td>
<td>Using Br($h \rightarrow \bar{b}b$) as input</td>
</tr>
<tr>
<td>$H_{tt}$ Yukawa coupling</td>
<td>0.04</td>
<td>Indirect from $\Gamma_{\gamma \gamma}$</td>
</tr>
<tr>
<td>Mass measurement</td>
<td>60 MeV</td>
<td>From $h \rightarrow \gamma\gamma$</td>
</tr>
<tr>
<td>CP Asymmetry using $h \rightarrow \bar{b}b$</td>
<td>&lt;0.01</td>
<td></td>
</tr>
<tr>
<td>CP Asymmetry using $h \rightarrow WW^*$</td>
<td>0.04</td>
<td></td>
</tr>
</tbody>
</table>
\[ \gamma \gamma \text{ Ideal To Measure CP Mixing and Violation} \]

\[ \zeta_2 \text{ is the degree of circular polarization} \]

\[ (\zeta_3, \zeta_1) \text{ are the degrees of linear polarization} \]
In s-channel production of Higgs:

\[ |M_{H_i}|^2 = |M_{H_i}|_0^2 \left\{ [1 + \zeta_2 \tilde{\zeta}_2] + A_1 \left[ \zeta_2 + \tilde{\zeta}_2 \right] + A_2 \left[ \zeta_1 \tilde{\zeta}_3 + \zeta_3 \tilde{\zeta}_1 \right] - A_3 \left[ \zeta_1 \tilde{\zeta}_1 - \zeta_3 \tilde{\zeta}_3 \right] \right\} \]

- \( = 0 \) if CP is conserved
- \( = +1 \) (\(-1\)) for CP is conserved for a CP-Even (CP-Odd) Higgs

If \( A_1 \neq 0, A_2 \neq 0 \) and/or \( |A_3| < 1 \), the Higgs is a mixture of CP-Even and CP-Odd states.

Possible to search for CP violation in \( \gamma\gamma \rightarrow H \rightarrow \text{fermions} \) without having to measure their polarization.

In \( bb \), a \( \leq 1\% \) asymmetry can be measured with 100 fb\(^{-1} \) that is, in 1/2 years.

arXiv:0705.1089v2
$M_W$ from $e^-\gamma \rightarrow W^-\nu$

Mass measurement from $W \rightarrow$ hadron events scan can provide an error $< 5$ MeV.
$$\text{Mass measurement and width might be event better to work at } \gamma\gamma \rightarrow \text{WW threshold}$$
Comment: Interests in W branching fraction to improve tests of lepton universality

- Lepton universality tested at 1% level
  - $\tau BR \sim 2.7 \sigma$ larger than $e/\mu$

q/ l universality at 0.6%
Higher center of mass

• Upgrade: Increase energy of the e-beam from 80 GeV to 150 GeV to measure Higgs self coupling

• The Higgs self couplings measurements one of key topics for the future -- ILC (30%) and LHC (20%) cannot do the full job:
  - only way to reconstruct the Higgs potential:

\[ V_H = \mu^2 \Phi^+ \Phi + \eta (\Phi^+ \Phi)^2 \rightarrow \frac{1}{2} m_H^2 h^2 + \sqrt{\frac{\eta}{2}} m_H h^3 + \frac{\eta}{4} h^4 \text{ with } : \]

\[ m_H^2 = \eta v^2 / 2 \text{ and } v^2 = -\mu^2 / \eta \]

\[ \lambda_{SM} = \sqrt{\frac{\eta}{2}} m_H \]

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Higgs Self-Coupling

Final goal: Study of Higgs self-coupling

\[ \lambda = \lambda^{SM} (1 + \delta \kappa) \]

Self-coupling constant in the SM Parameter of deviation from the SM

A $\gamma\gamma$ Collider with a center of mass around 300 GeV and ILC characteristics, will produce 80 events in $b\bar{b}b\bar{b}$ channel for a 120 GeV Higgs

Possible to suppress background and have large significance after 5 years of data taking

Disclaimer

• Many of these results are old.

• Better simulation and detector designs available

• If a new “official” design comes out of this meeting, I recommend that we repeat and expand these studies
**γγC Summary**

- The Higgs factory γγC Physics program is
  - Complementary to other programs (LHC & e-e+)
    - $\Gamma_{\gamma\gamma}$ to 2% (Model independent)
      - Results in a 13% on $\Gamma_{\text{Total}}$
      - Results in a $Y_{tt}$ of 4%
  - AND nevertheless unique:
    - Precise measurements of CP-admixture < 1% in Higgs
- More physics topics that go well beyond Higgs
  - Other examples: $\tau$ factories including g-2
    - $e^-e^-\rightarrow e^-e^+\tau^+\tau^-$, $e\gamma \rightarrow W\nu \rightarrow \tau \nu \nu$, $\gamma\gamma \rightarrow \tau \tau \gamma$
    - $[\sigma(\gamma \gamma \rightarrow \tau \tau \gamma) > 100 \text{ pb}]$
  - $e^-e^-\rightarrow e^-e^-$ and $e\gamma \rightarrow W\nu$ also important
BACKUP
## More Primary Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HFiTT</th>
<th>Sapphire</th>
<th>SILC</th>
<th>CLICHE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_x / \varepsilon_y$ [µm]</td>
<td>10/0.03</td>
<td>5 / 0.5</td>
<td>6 / 5</td>
<td>1.4 / 0.05</td>
</tr>
<tr>
<td>$\beta_x / \beta_y$ at IP [mm]</td>
<td>4.5/5.3</td>
<td>5 / 0.1</td>
<td>0.5 / 0.5</td>
<td>2 / 0.02</td>
</tr>
<tr>
<td>$\sigma_x / \sigma_y$ at IP [nm]</td>
<td>535/32</td>
<td>400 / 18</td>
<td>140 / 125</td>
<td>138 / 2.6</td>
</tr>
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