Gamma Gamma (gC) & e- Gamma Colliders

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April 23, 2004

Pleenary LCWS-2004 Paris
2002: @ Jeju it was discussed....

- **To make LC as versatile as possible:** a 2\textsuperscript{nd} IR capable of working as $\gamma\gamma$ & $e\gamma$ machine was desireable.

- **Concluded $\gamma\gamma$:**
  - Complemented in important ways the LC & the LHC program: *i.e.* precisions measurements of the light Higgs.
  - Provided unique opportunities: *i.e.* measurements of CP admixture (from polarization asymmetries).
  - Extended discovery reach: *i.e.* Heavy Higgs.
High event rate expected at a low energy

gC: Light SM Higgs

<table>
<thead>
<tr>
<th>Machine</th>
<th>$E_{e^+e^-}$(GeV)</th>
<th>$M_{h_{SM}}$(GeV)</th>
<th>Yield/year</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>* CLICHE</td>
<td>150</td>
<td>115</td>
<td>22.5k</td>
<td>hep-ex/0110056</td>
</tr>
<tr>
<td>CLICHE</td>
<td>160</td>
<td>120</td>
<td>23.6k</td>
<td>Correct for $\Gamma_{\gamma\gamma}$</td>
</tr>
<tr>
<td># TESLA</td>
<td>160</td>
<td>120</td>
<td>21.0k</td>
<td>hep-ex/0101056</td>
</tr>
<tr>
<td># NLC</td>
<td>160</td>
<td>120</td>
<td>11.0k</td>
<td>hep-ex/0110055</td>
</tr>
</tbody>
</table>

* Is a 10% CLIC TEST MACHINE # DESIGNS @ SNOWMASS
Example: $gC$ for 115-120 GeV SM Higgs

@ $gC$ in one year

$10^7 s$ - Design Luminosity

- $M_h = 115$ GeV
- Signal
- $bb(g)$
- $cc(g)$

$M_{2-Jet}$ Invariant Mass (GeV)

Events/2 GeV

- $\Gamma_{\gamma\gamma} \times Br(h \rightarrow bb)$
- $\Gamma_{\gamma\gamma} \times Br(h \rightarrow WW)$
- $\Gamma_{\gamma\gamma} \times Br(h \rightarrow \gamma\gamma)$

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{\gamma\gamma} \times Br(h \rightarrow bb)$</td>
<td>2%</td>
</tr>
<tr>
<td>$\Gamma_{\gamma\gamma} \times Br(h \rightarrow WW)$</td>
<td>5%*</td>
</tr>
<tr>
<td>$\Gamma_{\gamma\gamma} \times Br(h \rightarrow \gamma\gamma)$</td>
<td>22%*</td>
</tr>
</tbody>
</table>

* Only hep-ex/0110056 available

- **LC + gC** gives a precise value for
  - $\Gamma_{\gamma\gamma}$
  - $\Gamma_{\text{TOTAL}}$

- **LHC + gC** test anomalous couplings

- $bb$ study in great detail by several groups, all results are in agreement

-----> ASIA, EUROPE & USA
Resolved background photons is not a big effect in \( h \rightarrow bb \)!

Good progress since Jeju....
@ Praga all group converged on PYTHIA parameter for X-section

### TABLE III: Event Multiplicity Due to Resolved Photon Backgrounds.

<table>
<thead>
<tr>
<th>NLC: hep-0308103</th>
<th>160 GeV</th>
<th>500 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events/Crossing</td>
<td>0.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Tracks/Crossing ((p &gt; 0.2 \text{ GeV},</td>
<td>\cos \theta</td>
<td>&lt; 0.9))</td>
</tr>
<tr>
<td>Energy/Track ((p &gt; 0.2 \text{ GeV},</td>
<td>\cos \theta</td>
<td>&lt; 0.9))</td>
</tr>
<tr>
<td>Clusters/Crossing ((E &gt; 0.1 \text{ GeV},</td>
<td>\cos \theta</td>
<td>&lt; 0.9))</td>
</tr>
<tr>
<td>Energy/Cluster ((E &gt; 0.2 \text{ GeV},</td>
<td>\cos \theta</td>
<td>&lt; 0.9))</td>
</tr>
</tbody>
</table>
Other analysis can be more sensitive... needs to be study before making detector recommendations,... if any.

In the absence of a technology choice we need to do the studies on WARM and COLD in a consistent manner.
Measurement of \( \Gamma_{\gamma\gamma} \) is best at gC & give us tt-Yukawa couplings & access to new physics

\[ \Gamma_{\gamma\gamma} = 2\% \text{ in 1 year} \]

Higgs coupling to mass is an essential prediction in Higgs-theory. \( \Rightarrow \) We need to test it!!!

Dawson, \( \gamma\gamma \) WS2001.

\[ M_h = 120 \text{ GeV} \]

\( \gamma\gamma \rightarrow h \) depends on the \( tth \) coupling, and a 2\% measurement of this cross section results in a 4\% constraint on \( Y_t \).
SM heavy Higgs (200-350 GeV) @ gC can measure partial width and phase

\[ \gamma\gamma \rightarrow H \rightarrow WW, ZZ \]

From the simultaneous fit to the observed \( W^+W^- \) and \( ZZ \) mass spectra both the two-photon width \( \Gamma_{\gamma\gamma} \) and phase \( \phi_{\gamma\gamma} \) can be determined.

For SM: \( \Gamma_{\gamma\gamma} \) with precision \( \sim 4 - 9\% \), \( \phi_{\gamma\gamma} \) with precision \( 40 - 120 \) mrad

A.F. Zarnecki, ECFA/DESY workshop, November 2002, Praha (including systematic uncertainties)
gC also important for Higgs Physics

Beyond the SM

- SUSY (Now, \( h, H, A , H^+, H^- \))
  - Real MSSM (Heinemeyer, Weiglein, et al, Logan, et al, etc)
  - Real NMSSM (Gunion, Szleper, \( h \rightarrow aa \rightarrow bbbb, bb\tau\tau, \tau\tau\tau\))
  - Etc...

- 2HDM (Ginzburg, Osland, Krawczyk, etc.)

- Littlest Higgs (Logan, etc.)

- Exotic Higgs-Radion mixing (Cheung, Gunion, Hewett, etc.)

Most of the work is on: How gC complement the other Machines in the case of all the above? Exception --> Heavy Higgs, also seen as discovery machine.
@ Jeju: Neutral Heavy Higgs analysis in gC fills LHC wedge!

Asner, Gromberg, Gunion
FIG. 12: On the left: The effective cross section for $\gamma\gamma \rightarrow H^+ H^-$ for the two beam configurations. The center and right plots show the number of accepted events per $\text{BR}(H^+ \rightarrow \tau^+ \nu_{\tau})^2$ per Snowmass year, as a function of $m_{H^\pm}$. The dashed horizontal line shows the number of accepted background $\gamma\gamma \rightarrow W^+ W^-$ events.
gC besides, that could help to distinguish among SUSY model, complements LHC/LC measurements of $\tan \beta$.

- Error on $\Delta(\tan \beta) \sim 1$ for $\tan \beta > 10$
- All tools available to make the experimental study (Szleper, $h_2 \rightarrow h_1 h_1$)
CP violation... Special role for gC

- Model independent at gC vs Model dependent at LC

- Significant Progress in CP violation detection:
  - Light & Heavy

- With Linear and Circularly polarized beam
  - Linearly polarized beam designed made two times better with respect to what was shown at SNOWMASS by using 10 µm laser increasing beam energy by a factor of two (Higher degree of linear polarization and luminosity).
Complex MSSM: we have MASS and CP Eigenstates

- CP Eigenstates
  - h, H (CP-EVEN)
  - A (CP-ODD)

- Mass Eigenstates
  \[ M_{h_1} < M_{h_2} < M_{h_3} \]

\[ VV\phi : c_V \frac{g m_W^2}{m_W} g_{\mu\nu} = 0 \]

\[
\begin{pmatrix}
h_1 \\
h_2 \\
h_3 \\
\end{pmatrix} =
\begin{pmatrix}
u_{11} & u_{12} & u_{13} \\
u_{21} & u_{22} & u_{23} \\
u_{31} & u_{32} & u_{33} \\
\end{pmatrix}
\begin{pmatrix}
h \\
H \\
A \\
\end{pmatrix} \equiv U
\begin{pmatrix}
h \\
H \\
A \\
\end{pmatrix}
LC & LHC can study the CP quantum #’s from angular correlations...But only gC could see CP admixture in a model independent way

- Linear polarization $\propto \zeta_1, \zeta_3$
- Circular polarization $\propto \zeta_2$

$$A_3 > (<) 0 \text{ for CP EVEN(ODD)}$$

$$dN = dL_{\gamma\gamma}d\Gamma\frac{1}{4}(|M_{++}|^2 + |M_{--}|^2) \left\{ (1 + \langle \zeta_2 \tilde{\zeta}_2 \rangle) + \langle \zeta_2 \rangle + \langle \tilde{\zeta}_2 \rangle A_1 + (\langle \zeta_3 \tilde{\zeta}_1 \rangle + \langle \zeta_1 \tilde{\zeta}_3 \rangle) A_2 + ((\zeta_3 \tilde{\zeta}_3) - \langle \zeta_1 \tilde{\zeta}_1 \rangle) A_3 \right\},$$

$$A_1 = A_2 = 0 \text{ if there is no CP admixture}$$

Grzadkowski & Gunion (1992)
In Models where LC cannot see $h \rightarrow h_2 h_1'$

gC will do the job...

LHC: Could see some of them, but will not be able to measure their masses.

$\Rightarrow$ Worries for when coupling to the $Z$ gets lost by $h$ & $H$ & $h_1, h_2, h_3$ close in mass (small $M_{H^+}$).

Now available... clear signal.
CP violation bigger @ gC than @ LC in bb
decay & filling regions difficult @ LHC

MSSM
- LHC Suppression
- LC Small Effect
- gC Enhancement

Heinemeyer Velasco Wood
Only in gC can we exploit interference effects to extract phases needed to study CP violations in an effective way.

- Exploit interference:
  - W+W-, Warsaw & Krawczyk
  - Top pairs, Asakawa et al, Godbole et al, Lee et al

Large interference effects are expected in the considered mass range.
New idea: CP violation for Light Higgs in the MSSM using interference & tau polarization (no need for mass peak)

Scan over MSSM parameters

Predicted change in the tau polarization measurable in regions of parameter space not excluded by LEP

Godbole & Krans

Experimental error 1 order of magnitude smaller than the expected effect
Exotic... Tecni-pion best at gC

Cheung, Hioki, Hewett, Rizzo, Gunion, Pietrello, etc...

- Light-by-light scattering and $\gamma\gamma \rightarrow ZZ$ proceed via box diagrams in the SM.

- Large extra dimensions: continuous spectrum of graviton exchanges.

- Randall Sundrum model, discrete unevenly spaced graviton resonances.

- RS radion has an anomalous coupling to photons, giving rise to large production. **Combine with LHC --> gluon anomalous coupling**

- $\gamma\gamma \rightarrow G_{\mu\nu}^{(n)} \rightarrow h\phi$ can test for the Higgs-radion mixing.

- Universal extra dimenion model: KK states of quarks and leptons give rise to multijet or multi-lepton plus missing energies.

- Technicolor models: anomaly-type coupling of techni-pion to photons.
All technologies have advanced designs
Serious prototyping will start after technology decision

Snowmass design: exploits small bunch spacing of warm machine

TESLA: Exploit long bunch spacing to save laser power

• ATF in Japan planning to do a $\gamma\gamma$ interaction region as part of their machine R&D

Takahashi
Conclusion I

- Physics motivations continue to get stronger:
  - OLD: Precision measurements of the Higgs ...
  - OLD: Extend physics reach of heavy Higgs searches
  - NEW: Sensitivity to CP violation in Higgs by exploiting interference effects in both light & heavy Higgses
  - NEW: Measurement of SUSY parameters like $\tan \beta$
  - NEW: Unique opportunities in NEW-PHENOMENA
    - Techni-pion
    - Anomalous coupling of the radions
    - Light-on-Light Scattering...
Conclusion II

- Once technology decision is made:
  - Prototyping of gg technology will begin
  - Detector issues will be made in details

- Strong reason to believe that gC will be an important program in the future, either as:
  - An option of one of the 2 IR,
  - Or, as a 10% test of CLIC technology, while providing physics information that will complement the LHC & e+e- program.