Higgs Cross section and Mass measurements at CEPC

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On behalf of CEPC Higgs Study Group
Introduction

• The discovery of a Higgs boson in 2012 by ATLAS and CMS opened a new era in particle physics

• Subsequent measurements of the properties indicate Standard Model (SM) Higgs boson

• However, the SM does not predict the parameters in the Higgs potential.
  • Vast difference between the Planck scale and weak scale remains a major mystery

• Precision measurements of Higgs boson properties will be a critical component of any road map for high energy physics in the coming decades.
New Physics beyond the SM

• Deviations in the Higgs couplings from the SM expectations.

\[ \delta = c \frac{v^2}{M_{\text{NP}}^2} \]

- Vacuum expectation value of Higgs field
- Typical mass scale of new physics

• The HL-LHC will measure the Higgs boson couplings \( \sim 5\% \).
• Probing new physics significantly beyond the LHC reach require \( \sim \% \) level of Higgs coupling measurement. \( \rightarrow \) Need for Higgs factory.
CEPC - Circular Electron Positron Collider

- $E_{CM} = 240$ GeV
- 100 km ring
- Higgs production: $e^+e^- \rightarrow ZH$, recoil mass method
- Expected int. lumi: $5.6 \text{ ab}^{-1}$, 1M Higgs (7 years with two detectors)
- Higgs coupling to $Z$ accuracy $\sim 0.25\%$
- Model independent measurement of Higgs width

- CDR released on Nov 2018
  http://cepc.ihep.ac.cn/
- Input to European Strategy:
  arXiv: 1901.02170, 1901.03169
CEPC Detector Concept

- Higgs factory $\sqrt{s} = 240$ GeV 7 yrs $\rightarrow$ 1M Higgs, 1B Z, 100M W
- Z factory $\sqrt{s} = 91.2$ GeV $\rightarrow$ $10^{11} - 10^{12}$ Z bosons
- WW threshold scans $\sim \sqrt{s} = 161$ GeV $\rightarrow$ $10^7$ W
Object reconstruction and identification

• ARBOR particle flow
• Leptons
  • 7% H production with leptons
  • Lepton ID algo: LICH eff 99.9%
  • Dimuon mass reso. 0.16%
• Photons
  • H2 gg and H2Zg
  • Tau leptons and jets
  • Mass reso. 2.5%
• Jets
  • 70% H decay into jets (bb, cc, gg)
  • 22% through WW, * ZZ* cascades
  • JES: 3-5%, W and Z: 4.4%.
CEPCv4 and optimization

- Smaller solenoidal field 3T (14% degrades of momentum reso.)
- Reduced calorimeter dimensions
- ECAL readout sensor size changed from 5x5 to 10x10 mm²
- Add Time-of-Flight for flavor physics potential
Higgs production and decay

ZH associate production

W fusion

Z fusion

Vector Boson fusion (VBF)

- ZH process reaches maximum at ~250 GeV, decreases asymptotically as 1/s
- VBF proceeds through t-channel, increases logarithmically as \( \ln^2(s/M_V^2) \)
- VBF dominated by W fusion due to small neutral-current Zee coupling
Higgs Decay in Standard Model predictions

<table>
<thead>
<tr>
<th>decay mode</th>
<th>branching ratio</th>
<th>relative uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow b \bar{b}$</td>
<td>57.7%</td>
<td>+3.2%, −3.3%</td>
</tr>
<tr>
<td>$H \rightarrow c \bar{c}$</td>
<td>2.91%</td>
<td>+12%, −12%</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^-$</td>
<td>6.32%</td>
<td>+5.7%, −5.7%</td>
</tr>
<tr>
<td>$H \rightarrow \mu^+\mu^-$</td>
<td>$2.19 \times 10^{-4}$</td>
<td>+6.0%, −5.9%</td>
</tr>
<tr>
<td>$H \rightarrow WW^*$</td>
<td>21.5%</td>
<td>+4.3%, −4.2%</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^*$</td>
<td>2.64%</td>
<td>+4.3%, −4.2%</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$2.28 \times 10^{-3}$</td>
<td>+5.0%, −4.9%</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>$1.53 \times 10^{-3}$</td>
<td>+9.0%, −8.8%</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>8.57%</td>
<td>+10%, −10%</td>
</tr>
<tr>
<td>$\Gamma_H$</td>
<td>4.07 MeV</td>
<td>+4.0%, −4.0%</td>
</tr>
</tbody>
</table>

Uncertainties include contributions from theoretical and parametric sources.
Background processes

- Bhabha scattering (ee)
- ISR return (Z gamma)
- Diboson (WW/ZZ)
- Single boson production (eeZ, evW)

- Considered interference effects in the simulation
- Assume stable W and Z
## Cross sections of Higgs and other SM processes

<table>
<thead>
<tr>
<th>process</th>
<th>cross section</th>
<th>events in 5.6 ab⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Higgs boson production, cross section in fb</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( e^+ e^- \rightarrow ZH )</td>
<td>204.7</td>
<td>( 1.15 \times 10^6 )</td>
</tr>
<tr>
<td>( e^+ e^- \rightarrow \nu_e \bar{\nu}_e H )</td>
<td>6.85</td>
<td>( 3.84 \times 10^4 )</td>
</tr>
<tr>
<td>( e^+ e^- \rightarrow e^+ e^- H )</td>
<td>0.63</td>
<td>( 3.53 \times 10^3 )</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td>212.1</td>
<td>( 1.19 \times 10^6 )</td>
</tr>
</tbody>
</table>

| background processes, cross section in pb                    |               |                    |
| \( e^+ e^- \rightarrow e^+ e^- (\gamma) \) (Bhabha)         | 850           | \( 4.5 \times 10^9 \) |
| \( e^+ e^- \rightarrow q\bar{q} (\gamma) \)               | 50.2          | \( 2.8 \times 10^8 \) |
| \( e^+ e^- \rightarrow \mu^+ \mu^- (\gamma) [\text{or} \tau^+ \tau^- (\gamma)] \) | 4.40         | \( 2.5 \times 10^7 \) |
| \( e^+ e^- \rightarrow WW \)                               | 15.4          | \( 8.6 \times 10^7 \) |
| \( e^+ e^- \rightarrow ZZ \)                               | 1.03          | \( 5.8 \times 10^6 \) |
| \( e^+ e^- \rightarrow e^+ e^- Z \)                        | 4.73          | \( 2.7 \times 10^7 \) |
| \( e^+ e^- \rightarrow e^+\nu W^- / e^-\bar{\nu} W^+ \)    | 5.14          | \( 2.9 \times 10^7 \) |

- Interference between ZH and \( \nu_e \bar{\nu}_e H \) and \( e^+ e^- H \)
- The cross sections can not be separated
- \( \sqrt{s} = 250 \text{ GeV} \)
- Assume stable W and Z
- ZZ, WW, and qqbar events used to characterize the detector performance
- Generated with WHIZARD, processed with MokkaC
Higgs tagging with recoil mass

- Higgsstrahlung (ee→ZH), Z decays to a pair of visible fermions (ff), the recoil mass against the Z:
  \[ M_{\text{recoil}}^2 = (\sqrt{s} - E_{ff})^2 - p_{ff}^2 = s - 2E_{ff}\sqrt{s} + m_{ff}^2 \]

- Higgs boson mass can be measured from the peak of the recoil resonance
- Resonance width dominated by the beam energy spread (ISR included) and energy/momentum resolution (if Higgs width is 4.07MeV)
- \( \sigma (ZH) \) can be extracted by the fitting of \( M_{\text{recoil}} \)
Z boson leptonic decays

• Easily identifiable and the lepton momenta can be precisely measured.
• Signal events with full detector simulation
• Background events with fast detector simulation
• SM process with at least 2 leptons in final states are considered as backgrounds

• Dimuon: (BDT)
  • Dimuon invariant mass 80 – 100 GeV
  • Recoil mass 120 – 140 GeV
  • Muon pair transverse momentum > 20 GeV, opening angle < 175°
  • Long high-mass tail due to ISR

• Electron-positron pair: (Cut based)
  • Larger backgrounds from Bhabha scattering and single boson production
  • Electron-positron pair invariant mass 86.2 – 96.2 GeV
  • Recoil mass 120 – 150 GeV
  • Dominant backgrounds: \( e^+e^- \rightarrow e^+e^-(\gamma), \ e^+\nu W^- (e^-\bar{\nu}W^+), e^+e^-Z \)
Z hadronic decays

- Benefits from larger $Z \rightarrow q\bar{q}$ decay branching ratio
- Suffers from worse jet energy resolution than tracks
- Ambiguity in selecting jets can degrade the analysis performance and introduce model-dependence
- Main backgrounds $Z\gamma$ and WW production
- Worse S/N and recoil mass resolution compared with leptonic decays
Measurements of $\sigma(ZH)$ and $m_H$

- Fit to recoil mass distributions of $e^+e^- \to Z + X \to \ell^+\ell^-/q\bar{q} + X$ to extract inclusive $\sigma(ZH)$ and Higgs boson mass $m_H$
- Modeled with Crystal ball + polynomial function
- Recoil mass distribution is insensitive to the intrinsic Higgs width
- Large statics $e^+e^- \to Z + X \to q\bar{q} + X$ dominates the cross section sensitivity

<table>
<thead>
<tr>
<th>$Z$ decay mode</th>
<th>$\Delta m_H$ (MeV)</th>
<th>$\Delta\sigma(ZH)/\sigma(ZH)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^-$</td>
<td>14</td>
<td>1.43%</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>6.5</td>
<td>0.86%</td>
</tr>
<tr>
<td>$q\bar{q}$</td>
<td>-</td>
<td>0.61%</td>
</tr>
<tr>
<td>Combined</td>
<td>5.9</td>
<td>0.5%</td>
</tr>
</tbody>
</table>
Summary

• The discovery of Higgs at LHC is a major breakthrough on both experiment and theory.

• The CEPC complements the LHC to study the Higgs in great detail with unprecedented precision.

• Higgs tagging using recoil mass of Z in the $e^+e^- \rightarrow ZH$ process could achieve an inclusive Higgs cross section uncertainty of 0.5% and Higgs mass uncertainty of 5.9MeV (combining all leptonic and hadronic channels with 5.6 ab$^{-1}$ data).
Extra Slides
## Basic parameters of CEPC-v1 detector

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>tracking system</td>
<td></td>
</tr>
<tr>
<td>vertex detector</td>
<td>6 pixel layers</td>
</tr>
<tr>
<td>Silicon tracker</td>
<td>3 barrel layers, 6 forward disks on each side</td>
</tr>
<tr>
<td>time projection chamber</td>
<td>220 radial readouts</td>
</tr>
<tr>
<td>calorimetry</td>
<td></td>
</tr>
<tr>
<td>ECAL</td>
<td>W/Si, $24X_0$, 5x5 mm$^2$ cell with 30 layers</td>
</tr>
<tr>
<td>HCAL</td>
<td>Fe/RPC, 6x1, 10x10 mm$^2$ cell with 40 layers</td>
</tr>
<tr>
<td>performance</td>
<td></td>
</tr>
<tr>
<td>track momentum resolution</td>
<td>$\Delta(1/p_T) \sim 2 \times 10^{-5}$ (1/GeV)</td>
</tr>
<tr>
<td>impact parameter resolution</td>
<td>$5 \mu m @ 10 \mu m/[(p/GeV)(\sin \theta)^{3/2}]$</td>
</tr>
<tr>
<td>ECAL energy resolution</td>
<td>$\Delta E/E \sim 16% / \sqrt{E}$/GeV@1%</td>
</tr>
<tr>
<td>HCAL energy resolution</td>
<td>$\Delta E/E \sim 60% / \sqrt{E}$/GeV@1%</td>
</tr>
</tbody>
</table>

![Diagram of CEPC-v1 detector concept](image)

Fig. 2. (color online) The layout of one quarter of the CEPC-v1 detector concept.
Simulated invariant mass distributions

CEPC 2018

ννH, H→μμ

–CEPC Simulation

CEPC 2018

ννH, H→γγ

–CEPC Simulation