Physics analyses review for future Higgs factories

Loukas Gouskos (Brown University)

LCHP 2024 @Boston
Introduction

BSM O(1TeV): Impact on H-couplings

<table>
<thead>
<tr>
<th>Model</th>
<th>$b\bar{b}$</th>
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$\frac{v^2}{\Lambda^2} \sim \frac{6\%}{\Lambda^2 (\text{TeV})}$

e.g. $\Lambda=1$ (5) TeV $\rightarrow$ 5 (0.1)%
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**HL-LHC:**
- **Direct searches:** O(5) TeV
- **H-couplings:**
  - Bosons/ 3rd-Gen fermions @ few %
  - 2nd Gen fermions: maybe evidence of $H \rightarrow cc$
  - Self-coupling $\sim 50\%$

**Future $e^+e^-$ collider:**
- Measure H-couplings at O(0.1)% level

$\frac{v^2}{\Lambda^2} \sim \frac{6\%}{\Lambda^2(\text{TeV})}$

e.g. $\Lambda=1 (5) \text{TeV} \rightarrow 5 (0.1)\%$

Details in S. Dawnson’s talk
Introduction

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Today: Focus on Higgs physics [just a subset] - $e^+e^-$: physics program extends well beyond Higgs

HL-LHC:
- Direct searches: O(5) TeV
- H-couplings:
  - 2nd Gen fermions: maybe evidence of $H \to cc$
  - Self-coupling~50%

Future $e^+e^-$ collider:
- Measure H-couplings at O(0.1)% level

Details in S. Dawson’s talk

$$\frac{\nu^2}{\Lambda^2} \sim 6\% \quad \frac{\Lambda^2}{\Lambda^2(\text{TeV})}$$
e.g. $\Lambda=1$ (5)TeV $\rightarrow$ 5 (0.1)%
Proposed future accelerators

Linear ($e^+e^-$) colliders

Circular ($e^+e^-/hh$) colliders
Proposed future accelerators

**Linear (e^+e^-) colliders**
- CLIC (CERN)
  - Normal-conducting acceleration
  - Up to 3 TeV collisions

**Circular (e^+e^-/hh) colliders**
- FCC-ee/-hh (CERN)
  - 100 Km tunnel
  - First: FCC-ee; up to 2*m_{top} collisions "standard" technology
  - Then: FCC-hh; 100 TeV collisions
    - challenge: 16T magnets

- ILC (Japan)
  - Super-conducting acceleration
  - 250 & 500 [1000?] GeV collisions

- CEPC/SppC (China)
  - 100 Km tunnel
  - Essentially an FCC-ee/ FCC-hh
  - More conservative lumi scenarios

- C^3 (SLAC)
  - Conducting acceleration
  - 250 & 550 GeV collisions

Details in E. Nanni’s talk
In a nutshell

- $e^+e^-$: Different strategies
  - Different luminosity and $E_{\text{CM}}$ scenarios

- FCC-ee/CEPC:
  - Study $Z$, $W$, $H$ and top with unprecedented precision
    - e.g. $10^{12}$ $Z$, $O(1\text{M})$ H-bosons

- CLIC/ILC/C^3:
  - Rich Higgs program
  - Direct access to HH

- Ultimate goal: $O(100\text{ TeV})$ pp collider
  - FCC-hh/SppC: use same tunnel constructed for FCC-ee/CEPC
Higgs as an exploration tool
Higgs production at $e^+e^-$

$E_{CM} \sim (240 \text{ GeV})$: ZH production dominates

$E_{CM} > 500 \text{ GeV}$: Hvv is dominant

$E_{CM} > 500 \text{ GeV}$: Opens direct access to HH
Model-independent measurements

- **ZH production in e^+e^-**
  - Unbiased tagging of Higgs boson
    - via $Z \rightarrow LL$, $m_{\text{recoil}}$, $E_{\text{beam}}$ constraints
    
    $$m_{\text{Recoil}}^2 = s + m_Z^2 - 2 \sqrt{s}(E_{\ell^+} + E_{\ell^-})$$

- **Strategy:**
  - **First:** measure ZH production
    - rate $\sim \kappa Z^2 \rightarrow \delta(\kappa_Z)/\kappa_Z \sim 0.1\%$
  - **Then:** measure ZH($\rightarrow ZZ$)
    - rate $\sim \kappa_Z^4/\Gamma(H) \rightarrow \delta(\Gamma(H))/\Gamma(H) \sim 1\%$

- Unique in e^+e^- machines @ZH
- “standard candle” for other Higgs measurements (incl. pp@100TeV)

O(10) improvement wrt HL-LHC
More on Higgs couplings

- Next step: Study as many as possible Higgs decays
  - **key:** identification of decay flavor

Novel Deep Learning based algorithms under development

![FCC-ee Simulation (IDEA)](image)

- $e^+e^- \rightarrow ZH, H \rightarrow jj$
- $j = u, d, s, c, b, g$

**better**

NB: example from FCC-ee; many other tools (e.g., 2202.03285, 2203.07535, 2310.03440)
More on Higgs couplings

- Next step: Study as many as possible Higgs decays
  - **key:** identification of decay flavor

Novel Deep Learning based algorithms under development

Signal extraction: 2D fit: $m_{rec}$ vs. $m_H$

<table>
<thead>
<tr>
<th>Final state</th>
<th>$Z(ll)H(jj)$ [%]</th>
<th>$Z(vv)H(jj)$ [%]</th>
<th>$Z(jj)H(jj)$ [%]</th>
<th>Comb. [%]</th>
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<td>$H \to bb$</td>
<td>0.81</td>
<td>0.36</td>
<td>0.3</td>
<td>0.22</td>
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<td>$H \to cc$</td>
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<td>2.6</td>
<td>3.5</td>
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<td>2.73</td>
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<td>$H \to ss$</td>
<td>?</td>
<td>?</td>
<td>?</td>
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NB: example from FCC-ee; many other tools (e.g., 2202.03285, 2203.07535, 2310.03440)
Towards $\mathcal{H} \rightarrow ss$

- Tiny $\text{BR} \sim 10^{-4}$: e.g., $O(100)$ expected at FCC-ee (@ZH)

**Key points:**
- Enhanced **Kaon** fraction; Strange tagging critical
- Need powerful identification up to $O(30-40)$ GeV
Towards $H \rightarrow ss$

- Big effort to design optimal PID detectors and algorithms to exploit their full potential [e.g., ECFA $H \rightarrow ss$ team, Wiki]

- Achieve $3\sigma$ $\pi/K$ separation for up to $\sim 30$ GeV momenta

Details in D. Bortoletto’s talk
Towards $H \rightarrow ss$

- Big effort to design optimal PID detectors and algorithms to exploit their full potential [e.g., ECFA $H \rightarrow ss$ team, Wiki]

But:
We need to carefully access impact of detector proposals to the full Higgs [and not only] physics program in general

Achieve $3\sigma$ $\pi/K$ separation for up to $\sim 30$ GeV momenta

Details in D. Bortoletto’s talk
Towards $H \rightarrow ss$

- Strong dependence on detector design, jet tagging, Lumi..
  - Most sensitive results currently $\sim 2\sigma$ (CEPC/FCC-ee)

Opportunity to **fully establish second generation** charged fermions!
→ Impossible at the HL-LHC/hadron colliders
Unique at Circular Colliders: $H \to ee$

- **FCC-ee/CEPC**: Resonant Higgs production
  - Tiny signal $\text{BR}(H \to ee) \sim 10^{-9}$ vs. huge BKGs
  - but: large luminosity at FCC-ee
    - $20 \text{ ab}^{-1}/\text{year/IP} \to \sim 10\text{K} \ Higgs$

- **Key points**:
  - Beam spread ($\sim \text{MeV}$) $\to$ monochromatization
  - Precise $m_H \to$ from ZH run

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2107.02686  
$g, \ W, \ Z, \ ...$

- 1 year, 2 IPS: $2\sigma$
- 3 years, 4 IPS: $\kappa_e @ 15\%$
Higgs to invisible

- Portal to Dark Matter (DM)
  - SM: $\text{BR}(H \rightarrow ZZ^* \rightarrow 4\nu) \sim 0.1\%$

**Goal:** Reach neutrino floor

**SM $H \rightarrow \text{inv}$ reach**

- Possible at the HL-LHC
- NS: $s=240$ GeV, $L=10$ ab$^{-1}$
- SM BF $H \rightarrow \text{invis.}$ = 0.106%
- $\pm 0.141\%$, $\pm 0.124\%$, $\pm 0.042\%$, $\pm 0.133\%$, $\pm 0.110\%$, $\pm 0.035\%$

**5\sigma discovery potential**

- NB: 5% poorer $\sigma_{E/E(\text{Had})}$
- $\rightarrow$ 80% increase in $\delta(H \rightarrow \text{inv})$
- Keep in mind for detector design/choice
Higgs self coupling ($\lambda$) @ $e^+e^-$
(a) Via loops (FCC-ee/CepC)

Key points:
- Precise $\kappa_Z$ measurement
- Different collision energies

Relative enhancement of ZH production

O(10-20%) precision on $\lambda$
[other couplings at SM-values]
(b) Direct access (ILC/C$^3$/CLIC)

\[ \sigma \text{ [fb]} \]

\[ \sqrt{s} \text{ [GeV]} \]

H self coupling ($K_{\lambda}$)

HHVV coupling ($K_{2V}$)

$H H W^* W^*$

$H H Z Z$
(b) Direct access (ILC/C^3/CLIC)

Use $m_{HH}$ to disentangle $\kappa_\lambda - \kappa_{2V}$
(b) Direct access (ILC/C^3/CLIC)

- **Higgs → 4b, bbWW; Z → leptonic+hadronic decays**

- **ZHH: ILC/C^3: δ(κ_λ)~20-30%; CLIC: ZHH observation ~6σ**

- **HHvv: >3σ evidence @CLIC E_{CM}=1.4 TeV**
Higgs-self coupling summary

2209.07510

<table>
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<th>collider</th>
<th>Indirect-$h$</th>
<th>$hh$</th>
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<td>HL-LHC [78]</td>
<td>100-200%</td>
<td>50%</td>
<td>50%</td>
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<tr>
<td>ILC$_{250}/C^3$-250</td>
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<td>ILC$_{500}/C^3$-550</td>
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**e$^+e^-$ vs. HL-LHC**
- O(10) improved precision on $\kappa_Z$
- Up to 2-3x improvement on $\kappa_\lambda$

**e$^+e^-$: Potential to probe several baryogenesis models**
Summary

- Unique situation: no clear direction of where to look for New Physics
  - but we have very strong reasons to believe it exists

- We need a new colliders… Which one?
  - $e^+e^-$: provide precision $O(10)$ times better than HL-LHC
    - particularly for challenging decay modes (e.g., charm, strange..)
  - $e^+e^-$ program extends well beyond Higgs physics
    - Z-pole, ttbar, axions, LLPs, right-handed neutrinos,…

- Far from “over-subscribed”
  - Lot’s of room of innovation and out-of-the-box thinking in several areas
    - Detector design, event reconstruction, physics analyses, …