Opportunities for **Higgs Physics**

at Future **Electron-Proton Colliders**

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A Critical Point in Search of New Physics

• Experimental status:
  • **SM+GR** consistent with all observations so far.

• Theoretical side:
  • **Naturalness** is highly debated.

• Note: Issues like DM, neutrino mass do not necessarily imply new physics which can be probed at foreseeable colliders.
A Critical Point in Search of New Physics

• With no definite experimental clue and irrefutable theoretical guideline at hand, measuring precisely what we already have (eg. Higgs) could become progressively important, both as precision tests of SM and avenues to NP.
The Phenomenological Higgs Landscape

- Mass
- Width
- Spin-Parity
- Coupling
  - $hVV, hff$
  - $3h, 4h, hhVV$
  - FCNC Higgs coupling
- Exotic Higgs Decay
  - $h \rightarrow$ invisible
  - $h \rightarrow 4b$
  - ...

Collider Type Considerations

- (HL-)LHC
  - Large signal cross sections
  - Large backgrounds
  - Large pile-up
    - Higher thresholds needed to control systematics
    - Significant impact on the performance of objects like jet and MET

- Electron-positron collider
  - Small backgrounds
  - Pile-up negligible
  - Small signal cross sections
  - Probably available after the end of HL-LHC

Significant impact on exotic Higgs decay searches due to soft objects involved
Collider Type Considerations

- LHeC
  - Small backgrounds
  - Pile-up negligible
  - Small signal cross sections
Case Study: Invisible Higgs Decay @ LHeC

(Based on 1508.01095, Yi-Lei Tang, Chen Zhang and Shou-hua Zhu)

• Important and well-motivated signature in many types of BSM & regular constraint on DM models, complementary to DM direct detection.

• LHeC parameters used in the study:
  • 7 TeV proton
  • 60 GeV electron (-0.9 polarized)
  • Integrated luminosity up to 1 ab\(^{-1}\)
  • Very large pseudorapidity coverage (up to 5.0)
Case Study: Invisible Higgs Decay @ LHeC

(Based on 1508.01095, Yi-Lei Tang, Chen Zhang and Shou-hua Zhu)

Signal

\[ e^- \rightarrow e^- h(E_T) \]

\[ q \rightarrow Z \rightarrow h(E_T) \]

\[ q \rightarrow Z \rightarrow h(E_T) \]

Signal cross section \( \sim 20 \text{fb} \) before Higgs decay & cuts

Backgrounds

- Wje
- Wjν
- Zje
- Other (top quark, photoproduction, e+multijet etc.)

**No Alpha_s @LO!**
Case Study: Invisible Higgs Decay @ LHeC

(Based on 1508.01095, Yi-Lei Tang, Chen Zhang and Shou-hua Zhu)

**Signal** (100% invisible)~1.8fb

**Total background**~2.7fb

\[ C^2_{\text{MET}} = \kappa^2 \times \text{Br}(h \rightarrow \text{invisible}) \]

<table>
<thead>
<tr>
<th>Cross Section (fb)</th>
<th>Basic Cuts</th>
<th>$p_T &gt; 70$ GeV</th>
<th>$I &gt; 1$</th>
<th>$\eta_j - \eta_e &gt; 3.0$</th>
<th>$\Delta\phi_{ej} &lt; 1.2$</th>
<th>$\eta_e \in [-1.2, 0.6]$</th>
<th>$y \in [0.06, 0.5]$</th>
<th>Lepton Veto</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal ($C^2_{\text{MET}} = 1$)</td>
<td>16.1</td>
<td>8.80</td>
<td>8.23</td>
<td>4.68</td>
<td>2.37</td>
<td>2.16</td>
<td>1.77</td>
<td>1.77</td>
</tr>
<tr>
<td>$Wje$</td>
<td>816</td>
<td>158</td>
<td>143</td>
<td>51.7</td>
<td>13.9</td>
<td>11.3</td>
<td>9.13</td>
<td>1.96</td>
</tr>
<tr>
<td>$Wj\nu$</td>
<td>192</td>
<td>102</td>
<td>101</td>
<td>5.68</td>
<td>2.36</td>
<td>1.33</td>
<td>0.387</td>
<td>0.387</td>
</tr>
<tr>
<td>$Zje$</td>
<td>42.7</td>
<td>13.8</td>
<td>12.1</td>
<td>1.64</td>
<td>0.683</td>
<td>0.464</td>
<td>0.326</td>
<td>0.326</td>
</tr>
</tbody>
</table>

**TABLE I:** The cross section (in unit of fb) of the signal and major backgrounds after application of each cut in the corresponding column. Other backgrounds contribute less than 0.1 fb in total after all cuts and are not displayed in the table.

**FIG. 2:** Left: $\eta_e$ distribution of the signal and major backgrounds just before the $\eta_e$ cut. Middle: $y$ distribution of the signal and major backgrounds just before the $y$ cut. Right: $\tau$ lepton pseudorapidity distribution of the $Wje(W \rightarrow \tau\nu)$ background just before the lepton veto.

\[ \text{Br}(h \rightarrow \text{inv}) = 6\% @ 2\sigma \text{ level with } 1 \text{ ab}^{-1}, \text{ exceeding ZH@HL-LHC!} \]
More General Considerations

- Lepton-hadron colliders are suited to studying those exotic Higgs decays which suffer from large backgrounds at hadron-hadron colliders, such as $h \to 4b$. (Work in progress)
The Phenomenological Higgs Landscape (Revisited)

Future ep colliders could make important contribution to Higgs physics!

- Mass
- Width (via VV scattering)
- Spin-Parity
- Coupling
  - hVV, hff
  - 3h, 4h, hhVV
  - FCNC coupling
- Exotic Higgs Decay
  - h to invisible
  - h to 4b
  - ...
  - Reducing PDF & Alpha_s uncertainties in Higgs measurements

See also:
M. Kumar et al., 1509.04016
U. Klein, talk given at LHeC Workshop 2015

Philosophy could be traced back to
FCC-he Case

• Most Higgs analyses done at LHeC could be extended to FCC-he in a straightforward manner, with better sensitivity expected.

• Some new channels (e.g. double-Higgs) could be probed at FCC-he (while LHeC does not have enough sensitivity).

• FCC-he might play a role which is unprecedentedly important in boosting precision Higgs studies in conjunction with the concurrent FCC-hh.
Summary

• LHeC is shown to offer promising sensitivity to probe invisible Higgs decay.

• Future electron-proton colliders are suited to studying a lot more well-motivated exotic Higgs decay processes.

• We should not forget high-energy electron-proton colliders when considering future precision Higgs projects.
Thank you!