Higgs Mass, cross-section & self-coupling at FCC-ee

Louis Portalès

FCC week 2023, London – 07/06/2023
Extensive Higgs physics program currently ongoing at (HL-)LHC

→ With impressive results, despite the harsh conditions of p-p collisions

→ Higgs mass, looking at $H \rightarrow ZZ^*$ and $H \rightarrow yy$
  ▪ O(%) uncertainties achieved by ATLAS+CMS
  ▪ Can expect ~10-20 MeV precision with HL-LHC

→ Higgs width, in $H \rightarrow ZZ^*$ on- & off-shell production
  ▪ ~ 50% uncertainties with Run 2
  ▪ Great achievement, but far from “precision” realm

→ Higgs self-coupling, mainly in $HH$ production
  ▪ ~ 50% uncertainty expected with full HL-LHC dataset
  ▪ Maybe pessimistic as not accounting for latest (+ future) tool developments, esp. object (b, taus, ...) tagging

Nat. Phys. 18, 1329-1334 (2022)

At FCC-ee, things will look much different

→ Two datasets enriched in ZH (@ 240 GeV) and VBF-H (@365 GeV) will be gathered
  ▶ “ZH” run @ 240 GeV: ~ 2 million ZH events, ~ 50,000 VBF-H events w/ 4IP
  ▶ “ttbar” run @ 365 GeV: ~ 400,000 ZH events, ~ 100,000 VBF-H events w/ 4 IP

→ ZH events will allow to study the Higgs boson inclusively, looking the associated Z boson
  ▶ Evaluating the Higgs “recoil” mass: $M_{\text{rec}}^2 = s - 2E_Z \sqrt{s} + M_Z^2$
  ▶ Clean Higgs peak to measure ZH cross-section and $m_H$
    → And unbiased access to $g_{HZZ}$ from production

→ With $g_{HZZ}$ precisely determined, can then constrain Higgs total width in $H \rightarrow ZZ$
  ▶ Through simple parametrisation of cross-section measurement:
    $$\sigma_{ZH} \text{BR}(H \rightarrow ZZ^*) \propto \frac{g_{HZZ}^4}{\Gamma_H}$$

→ Higgs self coupling will also be accessible, through loop effects
  ▶ And probed (mostly) inclusively
At FCC-ee, things will look much different

→ Two datasets enriched in ZH (@ 240 GeV) and VBF-H (@365 GeV) will be gathered
- "ZH" run @ 240 GeV: ~ 1 million ZH events, ~ 25,000 VBF-H events per IP
- "ttbar" run @ 365 GeV: ~ 200,000 ZH events, ~ 50,000 VBF-H events per IP

→ ZH events will allow to **study the Higgs boson inclusively**, looking the associated Z boson
  - Evaluating the Higgs “recoil” mass: \( M_{\text{rec}}^2 = s - 2E_Z\sqrt{s} + M_Z^2 \)
  - **Clean Higgs peak to measure ZH cross-section and \( m_H \)**

→ With \( g_{HZZ} \) precisely determined, can then **constrain Higgs total width in H→ZZ**
  - Through simple parametrisation of cross-section measurement:

\[
\sigma_{ZH} \times BR(H \rightarrow ZZ) \propto g_{HZZ}^6 \Gamma_H
\]

Covered by the ongoing prospect studies (and in the following slides)

Ang Li, Jan Eysermans, Gregorio Bernardi

→ **Higgs self coupling** will also be accessible, through loop effects:
  - And probed (mostly) inclusively
Higgs mass and ZH cross-section

Analysis focusing on $Z(\rightarrow \mu\mu)H$
- Small fraction of Z decays, but better resolution by far
- Allows for clean and narrow $M_{\text{rec}}$ peak

Using “standard” FCC-PED simulations:
- Simulated events from IDEA detector
  → Excellent tracking capability w/ drift chambers
- Assuming 10 $ab^{-1}$ of data

Analysis selection (in short):
- At least 2 SFOS leptons ($p_T > 20$ GeV)
  → at least one isolated lepton
- Selecting lepton pair from Z decay minimizing
  \[
  \chi^2 = 0.6 \times (m_{\ell\ell} - m_Z)^2 + 0.4 \times (m_{\text{rec}} - m_h)^2
  \]
- $86 < m_{\ell\ell} < 96$ GeV
- $20 < p_{\ell\ell} < 70$ GeV
- $120 < M_{\text{rec}} < 140$ GeV
- $|\cos(\theta_{\text{miss}})| < 0.98$ (mass measurement only)

→ ≤0.2% momentum resolution with IDEA drift chambers
→ Reduced for electrons due to bremsstrahlung (despite partial recovery)
Higgs mass and ZH cross-section

→ 6 categories defined
• As a function of leptons flavor & $\theta$ (CC, CF & FF)
→ ~ classified according to expected peak resolution
→ Using parametric model for signal & backgrounds
• Signal: 2CBG (beyond double-sided crystal-ball):
  → combination of 2 single-sided crystal-ball and a gaussian:
  $$pdf_{\text{rec}} = c_1 CB(\mu, \sigma, \alpha_1, n_1) + c_2 CB(\mu, \sigma, \alpha_2, n_2) + \text{Gauss}(\mu_{gt}, \sigma_{gt})$$
• Background: 3$^{rd}$ order polynomial
→ Sufficient to model smooth sum of main background in SR
→ Signal extraction through likelihood fit:
• using CMS’ combine tool
• Signal PDF parametrised as a function of $m_H$
→ Including set of syst. uncertainties (BES, e/$\mu$ scales, $\sqrt{s}$)

Expecting $\delta m_H \sim 3.3$ MeV ( ~ 2.67 stat. only)
Detector & machine considerations

Some extended studies performed regarding detector effects

- Looking at impact on mH resolution
  → to be compared to stat-only (syst.) nominal estimates

~ Going from crystal calorimeter to Dual readout (tight artificial smearing applied to electrons)

Nominal 2 T field → 3 T (stronger field → better tracking)

IDEA drift chamber → CLD silicon tracker

Important impact of BES uncertainties AND nominal value

Assuming “perfect” (== gen-level) momentum resolution
  → Not so far off in some of the cases above!

<table>
<thead>
<tr>
<th>Fit configuration</th>
<th>$\mu^+\mu^-$ channel</th>
<th>$e^+e^-$ channel</th>
<th>combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>3.49 (4.27)</td>
<td>4.38 (4.72)</td>
<td>2.67 (3.28)</td>
</tr>
<tr>
<td>Inclusive</td>
<td>4.11 (4.79)</td>
<td>5.26 (5.73)</td>
<td>3.19 (3.89)</td>
</tr>
<tr>
<td>Degradation electron res.</td>
<td>3.49 (4.27)</td>
<td>5.09 (5.70)</td>
<td>2.82 (3.66)</td>
</tr>
<tr>
<td>Magnetic field 3T</td>
<td>2.89 (3.79)</td>
<td>3.59 (4.38)</td>
<td>2.20 (3.27)</td>
</tr>
<tr>
<td>CLD 2T (silicon tracker)</td>
<td>4.56 (5.32)</td>
<td>4.93 (5.48)</td>
<td>3.26 (3.99)</td>
</tr>
<tr>
<td>BES 6% uncertainty</td>
<td>3.49 (4.35)</td>
<td>4.38 (5.00)</td>
<td>2.67 (3.42)</td>
</tr>
<tr>
<td>Disable BES</td>
<td>1.92 (3.15)</td>
<td>2.52 (3.46)</td>
<td>1.50 (2.70)</td>
</tr>
<tr>
<td>Ideal resolution</td>
<td>2.67 (3.44)</td>
<td>3.29 (3.94)</td>
<td>2.02 (2.96)</td>
</tr>
<tr>
<td>Freeze backgrounds</td>
<td>3.49 (4.27)</td>
<td>4.38 (4.72)</td>
<td>2.67 (3.27)</td>
</tr>
<tr>
<td>Remove backgrounds</td>
<td>2.86 (3.69)</td>
<td>3.26 (3.47)</td>
<td>2.11 (2.64)</td>
</tr>
</tbody>
</table>
Higgs mass and ZH cross-section

→ **Similar selection as mass measurement**
  - Dropping $|\cos(\theta_{\text{miss}})|$ requirement
    → avoiding selection bias towards H decays w/ neutrinos
    → But lowers sensitivity to signal
  - Instead, trained a BDT using (Z) leptons kinematics
    → To help recover lost sensitivity

→ **Comparing fitted cross-section with $M_{\text{rec}}$ & BDT score**
  - Binned likelihood fit of distributions
    → With cut on BDT for $M_{\text{rec}}$ fit

**Expecting $\Delta \sigma \sim 0.61\%$ ( ~ 0.60% stat. only) fitting BDT score**

$\Delta \sigma \sim 0.93\%$ ( ~ 0.55 stat. Only) with $M_{\text{rec}}$
Higgs self-coupling

Involved in single-higgs processes at NLO

\[ \sigma_{i,NLO} = Z_H \sigma_{i,LO} \left(1 + \kappa \chi C_{1,i}\right) \]

→ Can be probed **exclusively**
  - Combined fit of all decay modes
  - Under consideration (@ BNL: A.Tishelman, E.Brost)
→ Or (partially) **inclusively**
  - With combined analysis @ 240 GeV & 365 GeV
→ Discussed in the following slides

<table>
<thead>
<tr>
<th>Decay Modes</th>
<th>( C_1^\Gamma ) [%]</th>
<th>( \gamma \gamma )</th>
<th>ZZ</th>
<th>WW</th>
<th>( f \bar{f} )</th>
<th>gg</th>
</tr>
</thead>
<tbody>
<tr>
<td>on-shell ( H )</td>
<td>0.49</td>
<td>0.83</td>
<td>0.73</td>
<td>0</td>
<td>0.66</td>
<td></td>
</tr>
</tbody>
</table>

\[ C_{1}^{\Gamma_{tot}} = \sum_{j} \text{BR}^{SM}(j)C_{1}^{\Gamma}(j) \sim 2.3 \times 10^{-3} \]

Higgs self-coupling – Analysis

→ **Analysis setup:**

- **Spring 2021 samples** (older baseline w/ IDEA detector)
  → to be updated!

→ **Categorization tuned for the two energy points (240, 365 GeV)**

- 18 orthogonal categories
  → 2x2 $Z(\text{ee/}\mu\mu)H$ categories – similar to mass & xsec analysis
  → 2x6 $Z(\text{qq})H$ categories – per qq flavor
  → Additional $\text{eeH}(\rightarrow \text{bb})$ & $\nu\nuH(\text{bb})$ categories @ 365 GeV
Inclusive $\lambda$ measurement – ZH selection

→ Similar selection as $m_H$/cross-section analysis for $Z\to ee/\mu\mu$
  - (looking for the same process)

→ Tuned selection for $Z\to qq$
  - 6 flavor categories ($bb, cc, ll, bc, bl, cl$)
    → Assuming ad-hoc tagging efficiencies
    → Dedicated $Z\to cc$ optimisation ongoing (@BNL)
  - $86 < m_{qq} < 96$ GeV
  - $120 < M_{rec} < 140$ GeV
  - $|\cos(\theta_{miss})| < 0.90$

→ BDT used for selection
  - One per flavor category
    → Using only $Z\to qq$ kinematics
Inclusive $\lambda$ measurement – VBF selection

→ Recoil mass not sufficient to properly isolate a Higgs peak in VBF

- Instead, looked at VBF $H\to bb$

→ Exclusive measurement, some model-dependance introduced

→ Defining selection adapted to VBF

- No $\mu\mu$ pair reconstructed ($\nu\nu H$: no ee pair either)
- 2 b-tagged jets
- $H_T > 20$ GeV, $|\Delta\eta_{bb}| < 3$ (vvH: + MET>20 GeV)
- $|M_{ee} - M_\tau| \geq 6$ GeV (eeH)
- $|M_{qq} - M_H| \leq 30$ GeV ($\nu\nu H$)

→ Still using $M_{rec}$ as template variable for the fit

- Cutting on BDT discriminants, using (b-)jet kinematics and multiplicity as inputs
Inclusive $\lambda$ measurement – combined fit

- **Measuring cross-section & coupling modifier**
  - Parametrised cross-section as a function of $\kappa_\lambda$
  - Fitting all categories (ZH + VBF) together

- **Assuming:**
  - 0.1% luminosity uncertainty
  - 1% selection efficiency uncertainty
  - 2.8 MeV uncertainty on CoM energy
  - $m_H = 125.38 \pm 0.14$ GeV (latest CMS result)
  - Higgs decay BRs ($H \rightarrow bb$) fixed to SM values

- **Reaching $\delta\kappa_\lambda \sim 30\%$ (~20% with 10 ab$^{-1}$)**
  - Combining with HL-LHC expected constraints
  - Sensitivity driven by Z(qq)H categories
  - Adding ZH@365GeV resolves degenerated minima
  - Negligible impact from VBF-H

Work in Progress
Conclusion & take-away

Prospective study of Higgs parameters (mass, cross-section, self-coupling) @ FCCee

- Mainly targeting inclusive ZH production @ 240 GeV (+ exclusive VBF-H @ 365 GeV for $\lambda$)
- Reaching excellent precisions assuming baseline scenario (IDEA detector & 10 ab$^{-1}$)

Excellent playground to understand detector requirement

- Detector/beam performance impact probed in mH measurement:
  - Clear gains from higher field (better lepton momentum resolution) & better control of BES
  - Ecal design would impact $Z\rightarrow$ee category, but sensitivity driven by $Z\rightarrow$\mu\mu
- Jet performance would significantly influence sensitivity to $\lambda$ (driven by $Z\rightarrow$qq categories)
  - Good physics usecase to compare calorimeter designs

Room for fine-tuning and to get to a better understanding/more educated design choices

- Include more (and more realistic) systematics in the studies (esp. mH measurement)
- Refresh analyses with state-of-the-art tools (e.g. ParticleNet), latest samples & detector performance estimates (esp. $\lambda$ measurement)
Back up