Higgs boson mass measurement at CMS

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On behalf of the CMS collaboration
Run 1 Higgs mass

- Combination using two high precision channels: $\gamma\gamma$ and $4l$
- Statistical uncertainty dominates

Run 2 Higgs mass at CMS

Main topic of this talk

Higgs mass measurement using $H \to Z_1 Z_2^* \to 4l$ channel

- Perform 3D likelihood fit
  - $m_{4l}$
  - $D_{mass}^*: \text{mass uncertainty}$
  - $D_{kin}^{bkg}: \text{kinematic discriminant}$
- Introduce $Z_1$ mass constraint

arXiv:1706.09936
Observables

- 4 lepton invariant mass: $m_{4l}$
- Event-by-event mass uncertainty: $D_{\text{mass}} = \sigma_{m_{4l}} / m_{4l}$, propagated from individual lepton $p_T$ resolution (Corrected in data/MC using $Z \rightarrow ll$ events)
- Matrix element kinematic discriminant: $D_{\text{bkg}}^{\text{kin}} = \left[ 1 + \frac{\mathcal{P}_{\text{bkg}}^{qq} (\tilde{t} H \rightarrow 4\ell | m_{4\ell})}{\mathcal{P}_{\text{sig}}^{gg} (\tilde{t} H \rightarrow 4\ell | m_{4\ell})} \right]^{-1}$
Z₁ mass constraint

- Define Z₁ as l⁺l⁻ pair with mass closer to PDG mass
  - Significantly on-shell
- Perform kinematic fit using Z₁ mass as constraint
  - Four lepton invariant mass resolution is improved
  - Most useful for events with Z₁ → e⁺e⁻
- m₄l and D_mass are updated (m'₄l, D'_mass)

![Graph showing improvement in m₄l and D_mass]
Lepton energy scale uncertainty

- Dominant systematic uncertainty in mass measurement
- Calibrate scales using known dilepton resonances
  ➔ Use $J/\psi$ and $Z$ for muon, use $Z$ for electron
- $4l$ mass scale uncertainties:
  ➔ 0.04%, 0.3%, 0.1% for $4\mu$, $4e$, $2e2\mu$ final states
H → Z₁Z₂* → 4l results

Use per event mass uncertainty + ME-based kinematic discriminant + Z₁ mass constraint:

\[ 125.26 \pm 0.20 \text{ (stat.)} \pm 0.08 \text{ (sys.) GeV} \]

Run 1 ATLAS+CMS (4l, γγ) combination: 125.09 ± 0.21(stat.) ± 0.11(sys.) GeV

**Precision gain in mass measurement:**

- Use m4l alone: \( L(m_{4l}) \)
  - 9.8%

- + per-event mass uncertainty: \( L(m_{4l}, D_{\text{mass}}) \)
  - 3.1%

- + ME-based kinematic discriminant (CMS Run1 style): \( L(m_{4l}, D_{\text{mass}}, D_{\text{bkg}}^{\text{kin}}) \)
  - 8.1%

- + Z₁ mass constraint: \( L(m'_{4l}, D'_{\text{mass}}, D_{\text{bkg}}^{\text{kin}}) \)
BACKUP
Define $Z_1$ as intermediate $Z$ boson with mass closer to PDG mass

- Significantly on-shell
- Perform kinematic fit using $Z_1$ mass as constraint

**Likelihood to be maximized:**

$$L(p_T^{reco1}, p_T^{reco2}, \sigma_{p_T}^{1}, \sigma_{p_T}^{2}) = \text{Gauss}(p_T^{reco1}|p_T^{1}, \sigma_{p_T}^{1}) \cdot \text{Gauss}(p_T^{reco2}|p_T^{2}, \sigma_{p_T}^{2}) \cdot L(m_{12}|m_Z, m_H)$$

**Inputs:**

- $p_T^{reco1}, p_T^{reco2}$: reconstructed lepton $p_T$
- $\sigma_{p_T}^{1}, \sigma_{p_T}^{2}$: lepton $p_T$ resolution

**Outputs:**

- $p_T^{1}, p_T^{2}$: refitted lepton $p_T$
- $\sigma(p_T^{1}), \sigma(p_T^{2})$: refitted lepton $p_T$

**Constraint:**

$Z_1$ lineshape at generator level from SM Higgs sample with $m_H = 125$GeV

$m_{12}$ is calculated from $p_T^{1}$ and $p_T^{2}$

Use refitted lepton $p_T$ and uncertainty to recalculate $m_{4l}$ and $D_{mass}$
## Expected and observed results

<table>
<thead>
<tr>
<th></th>
<th>3D: $\mathcal{L}(m_{4l}, D_{\text{mass}}, D_{\text{bkg}}^{\text{kin}})$</th>
<th>2D: $\mathcal{L}(m_{4l}, D_{\text{mass}})$</th>
<th>1D: $\mathcal{L}(m_{4l})$</th>
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</thead>
<tbody>
<tr>
<td><strong>No $m(Z_1)$ constraint</strong></td>
<td></td>
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<tr>
<td>Expected $m_H$ uncertainty change</td>
<td>+8.1%</td>
<td>+11.2%</td>
<td>+21%</td>
</tr>
<tr>
<td>Observed $m_H$ (GeV)</td>
<td>125.28±0.22</td>
<td>125.36±0.24</td>
<td>125.39±0.25</td>
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<tr>
<td><strong>With $m(Z_1)$ constraint</strong></td>
<td></td>
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<tr>
<td>Expected $m_H$ uncertainty change</td>
<td>—</td>
<td>+3.2%</td>
<td>+10.7%</td>
</tr>
<tr>
<td>Observed $m_H$ (GeV)</td>
<td>125.26±0.21</td>
<td>125.30±0.21</td>
<td>125.34±0.23</td>
</tr>
</tbody>
</table>

- Observed uncertainty is smaller than the expected uncertainty by approximately 0.05GeV, which probability is about 18% determined from an ensemble of pseudo-experiments.
Other plots

- $p$-value for compatibility of different channels is 0.025