Precision Higgs boson mass measurement using H → ZZ* → 4l decay mode

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On behalf of the CMS collaboration

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H → $Z_1 Z^*_2$ → 4l decay channel
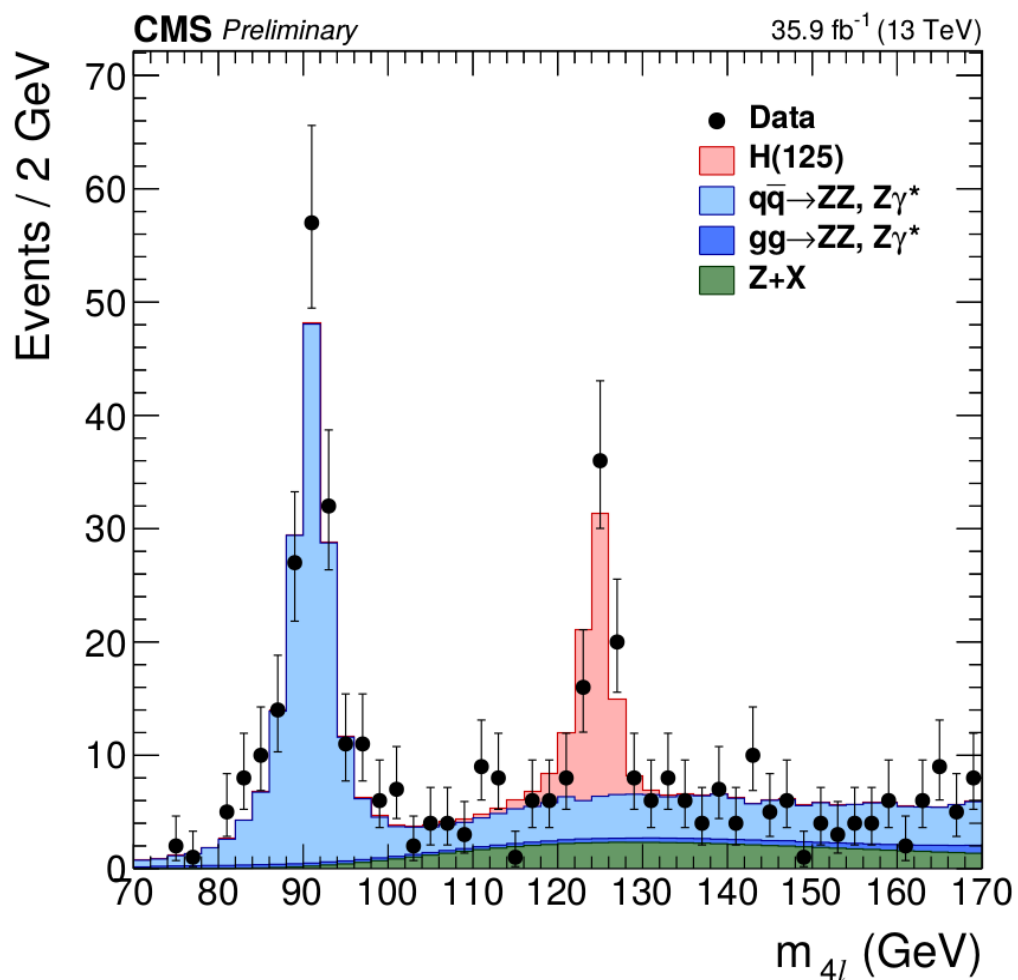
Event signature:
- 4 leptons (4e, 4μ, 2e2μ)
- Large S/B ratio (> 2:1)
- Good mass resolution (1-2%)

Background:
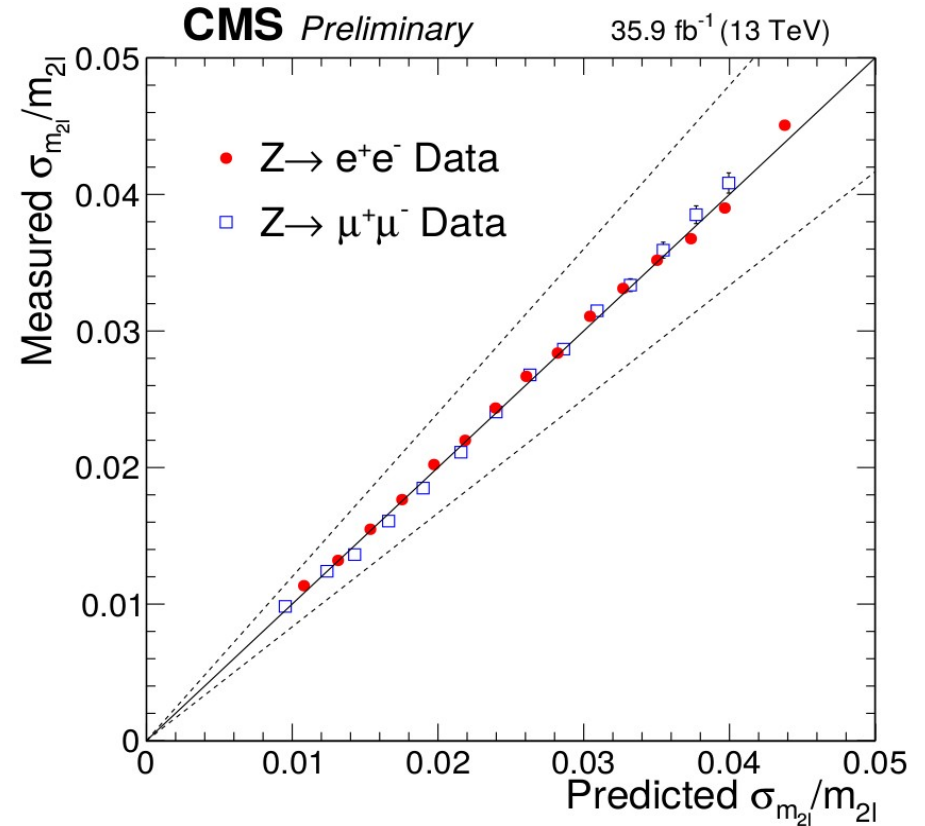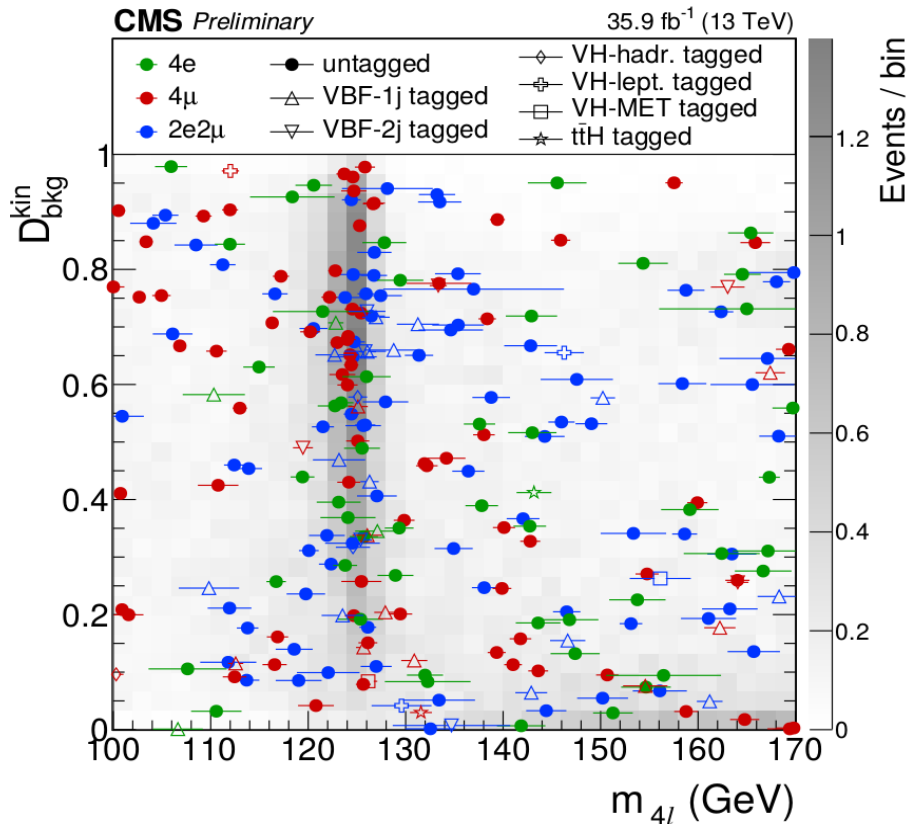- ZZ (main): estimated from MC
- Reducible background (data driven)

Higgs mass measurement
- Perform 3D fit : $L\left(m_{4l}, D_{mass}, D^{kin}_{bkg}\right)$
- NEW • **Introduce Z_1 mass constraint**

Observables

- 4 lepton invariant mass : m_{4l}

- Event-by-event mass uncertainty : $D_{mass} = \sigma_{m_{4l}}/m_{4l}$, propagated from individual lepton p_T resolution (Corrected in data/MC using Z → ll events)

- Matrix element kinematic discriminant: $\mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}} = \left[1 + \dfrac{\mathcal{P}_{\mathrm{bkg}}^{q\bar{q}}(\vec{\Omega}^{H\to 4\ell}|m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}^{gg}(\vec{\Omega}^{H\to 4\ell}|m_{4\ell})} \right]^{-1}$

Z_1 mass constraint

- Define Z_1 as l^+l^- pair with mass closer to PDG mass
  - Significantly on-shell
- Perform kinematic fit using Z_1 mass as constraint
  - Four lepton invariant mass resolution is improved
  - Most useful for events with $Z_1 \to e^+e^-$
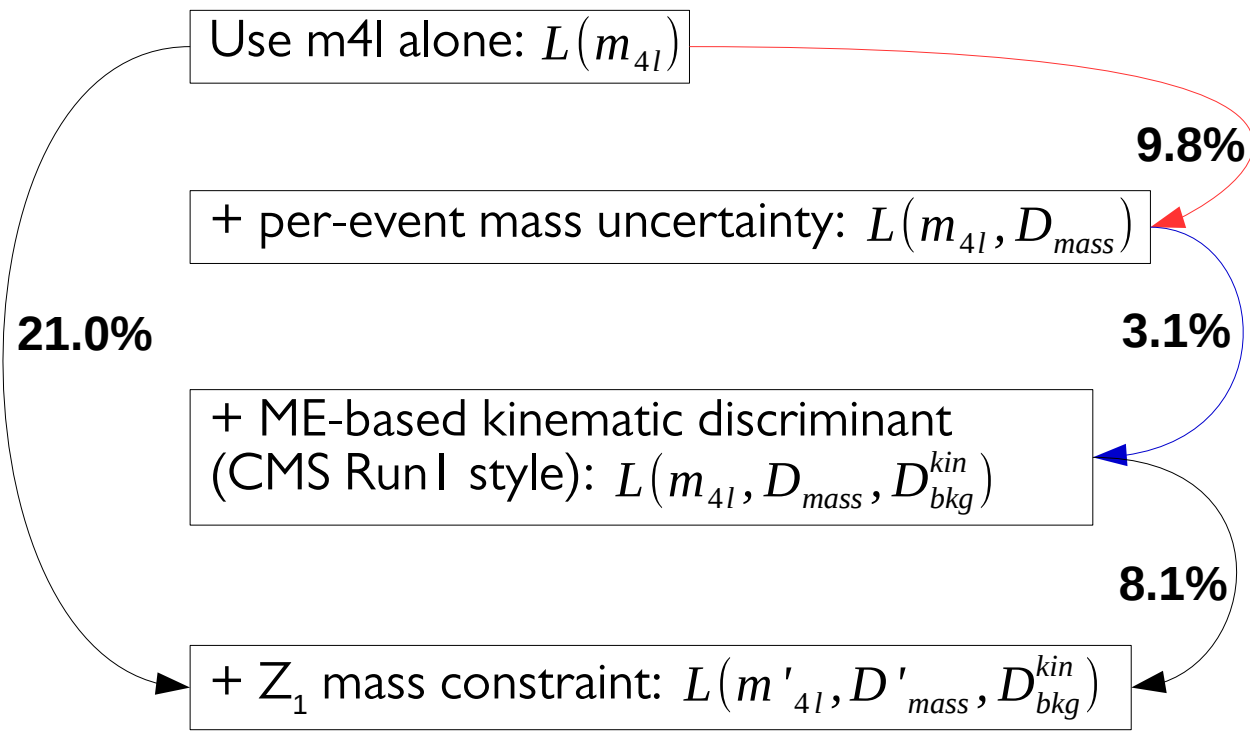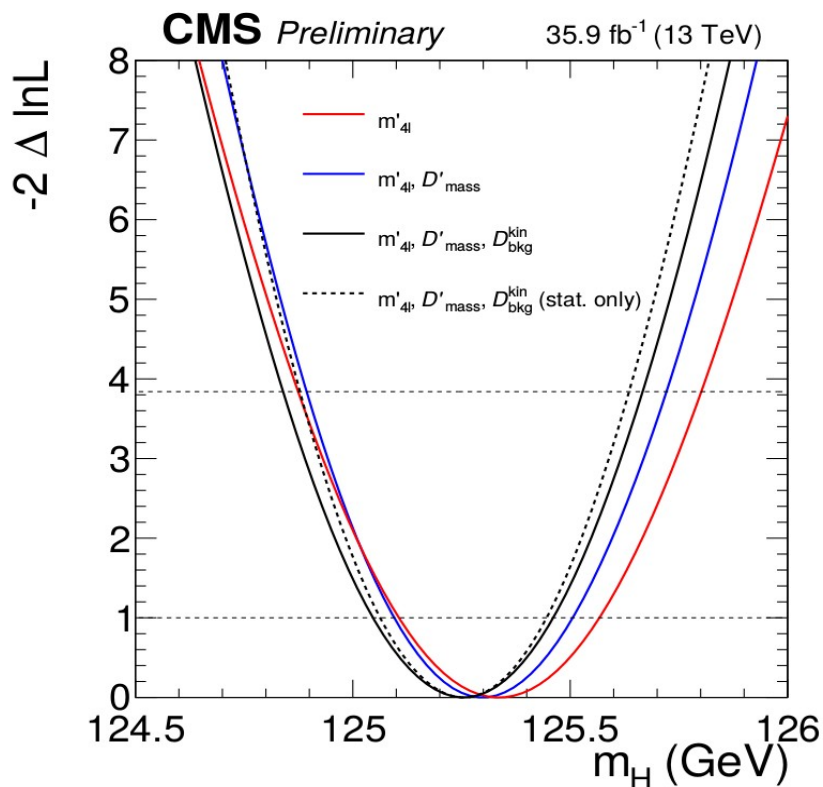 - m_{4l} and D_{mass} are updated (m'_{4l}, D'_{mass})
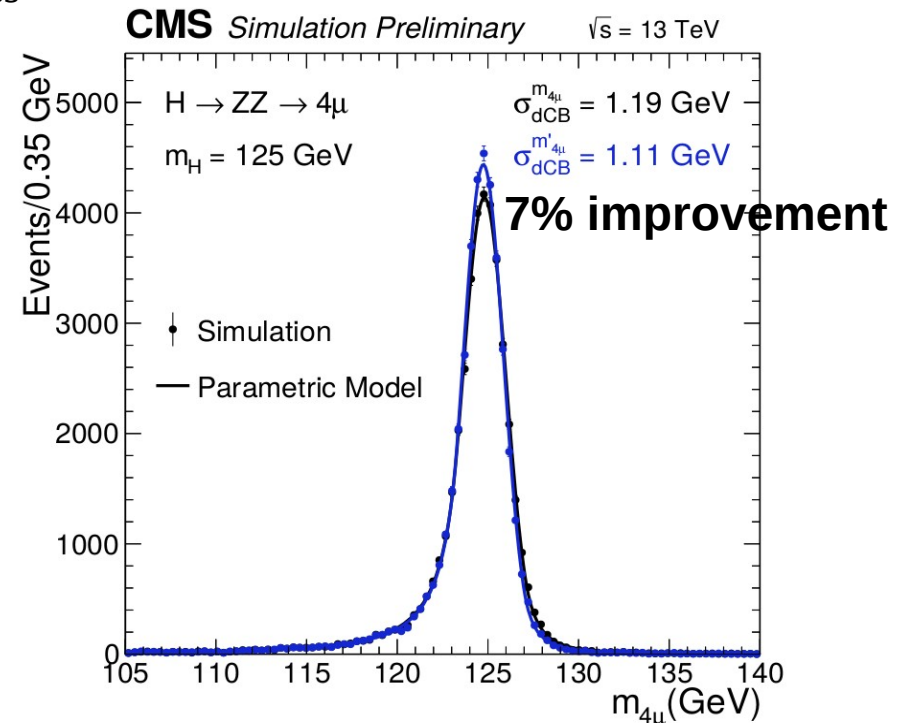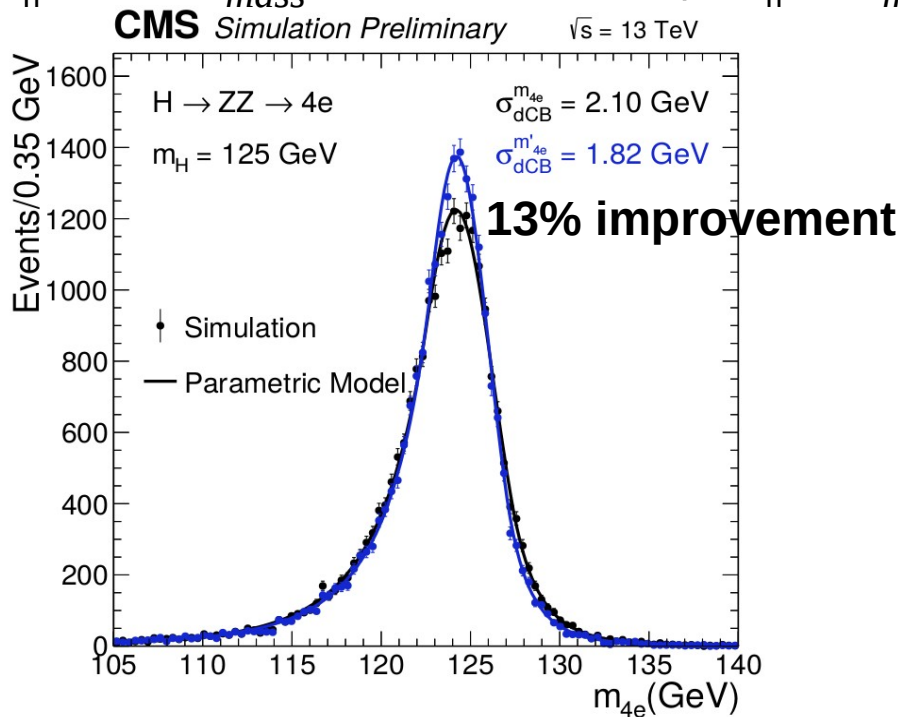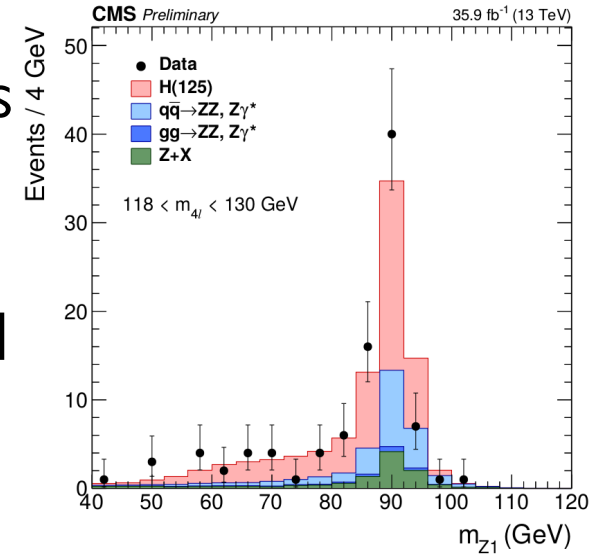
Results

Use per event mass uncertainty + ME-based kinematic discriminant + Z_1 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:

CMS *Preliminary* 35.9 fb^{-1} (13 TeV)

- m'_{4l}
- m'_{4l}, D'_{mass}
- m'_{4l}, D'_{mass}, D^{kin}_{bkg}
- m'_{4l}, D'_{mass}, D^{kin}_{bkg} (stat. only)

Use m4l alone: $L(m_{4l})$

9.8%

+ per-event mass uncertainty: $L(m_{4l}, D_{mass})$

3.1%

21.0%

+ ME-based kinematic discriminant
(CMS Run1 style): $L(m_{4l}, D_{mass}, D^{kin}_{bkg})$

8.1%

+ Z_1 mass constraint: $L(m'_{4l}, D'_{mass}, D^{kin}_{bkg})$

BACKUP

Z_1 mass constraint

- 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 :

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

Inputs :

p_T^{reco1}, p_T^{reco2} : reconstructed lepton p_T
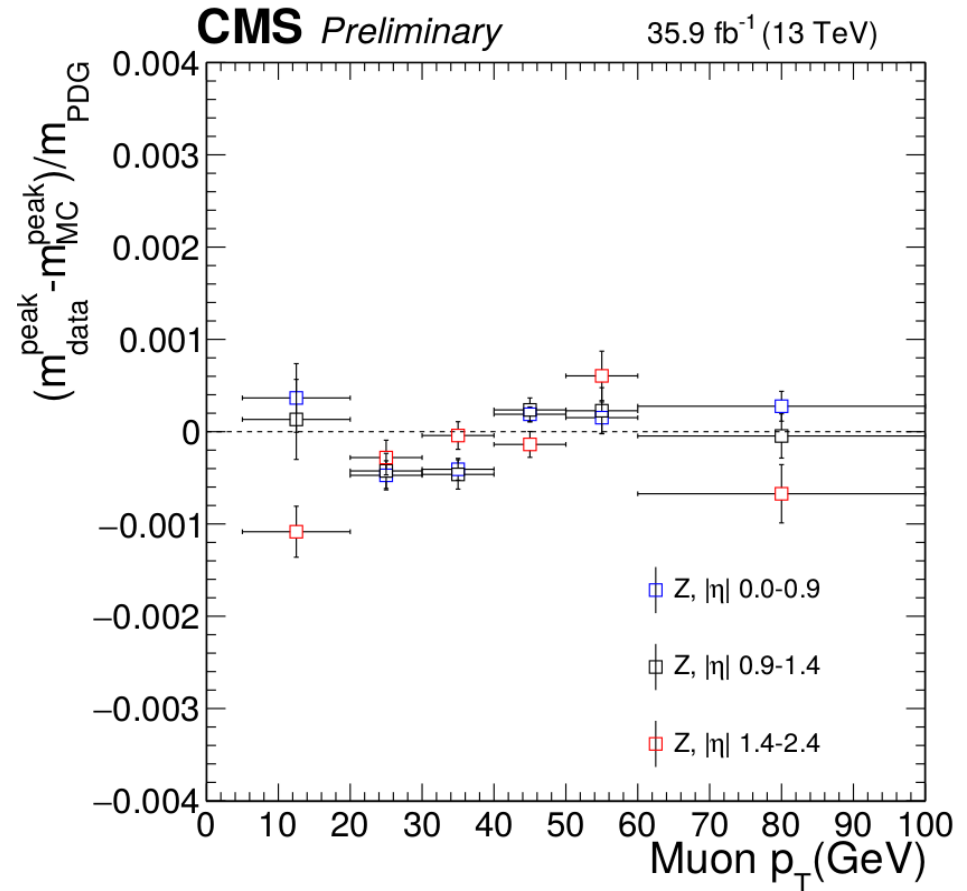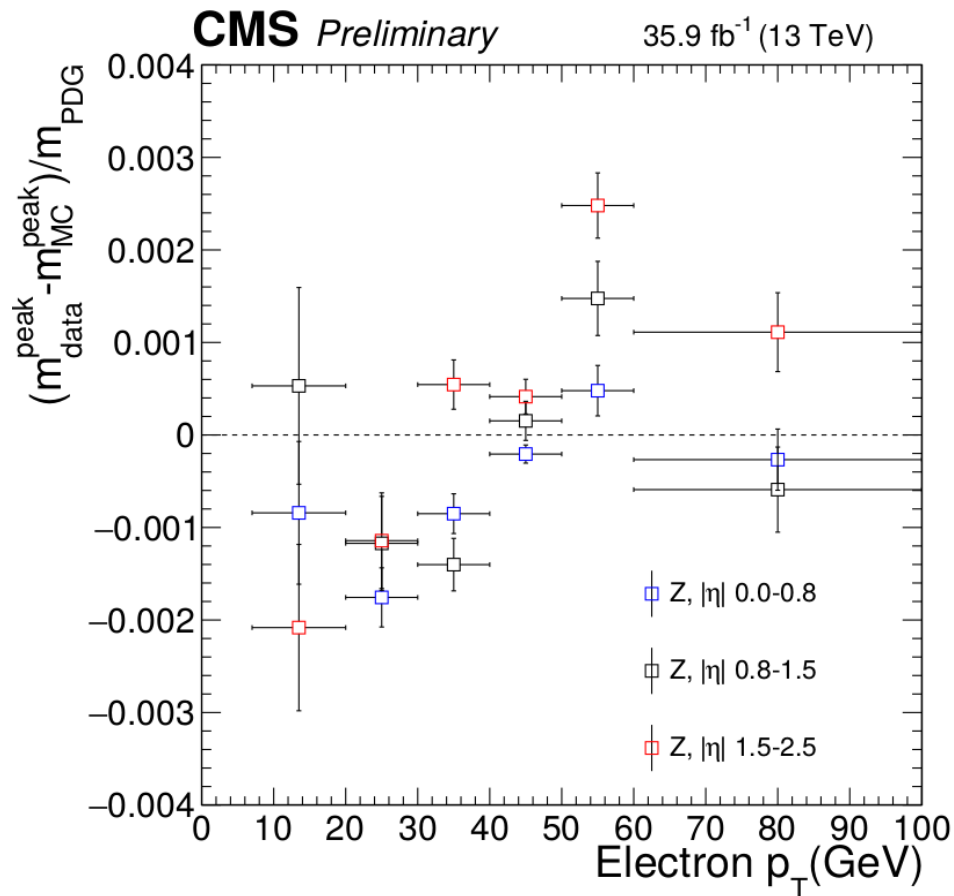σ_{pT}^1, σ_{pT}^2 : lepton pT resolution

Constraint :

$L(m_{12} | m_Z, m_H)$: Z_1 lineshape at generator level from SM Higgs sample with m_H = 125GeV

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

Outputs :

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

Use refitted lepton p_T and uncertainty to recalculate m_{4l} and D_{mass}

Lepton energy scale uncertainty

- Events are separated into categories based on the p_T and η of one of the two leptons in data/MC
- Fit di-lepton mass distributions to a Breit-Wigner parameterization convolved with a double-sided Crystal Ball (CB) function
- Extract offset in the measured peak position with respect to the nominal Z-boson mass
- Relative difference between data and simulation is propagated to the reconstructed four-lepton mass from simulated Higgs-boson events
- The uncertainty is determined to be 0.04% (0.3%) for the 4μ (4e) channels, respectively

Expected and observed results

No $m(Z_1)$ constraint	3D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\text{mass}}, \mathcal{D}_{\text{bkg}}^{\text{kin}})$	2D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\text{mass}})$	1D: $\mathcal{L}(m_{4l})$
Expected m_H uncertainty change	$+8.1\%$	$+11.2\%$	$+21\%$
Observed m_H (GeV)	125.28 ± 0.22	125.36 ± 0.24	125.39 ± 0.25

With $m(Z_1)$ constraint	3D: $\mathcal{L}(m'_{4l}, \mathcal{D}'_{\text{mass}}, \mathcal{D}_{\text{bkg}}^{\text{kin}})$	2D: $\mathcal{L}(m'_{4l}, \mathcal{D}'_{\text{mass}})$	1D: $\mathcal{L}(m'_{4l})$
Expected m_H uncertainty change	—	$+3.2\%$	$+10.7\%$
Observed m_H (GeV)	125.26 ± 0.21	125.30 ± 0.21	125.34 ± 0.23

- 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
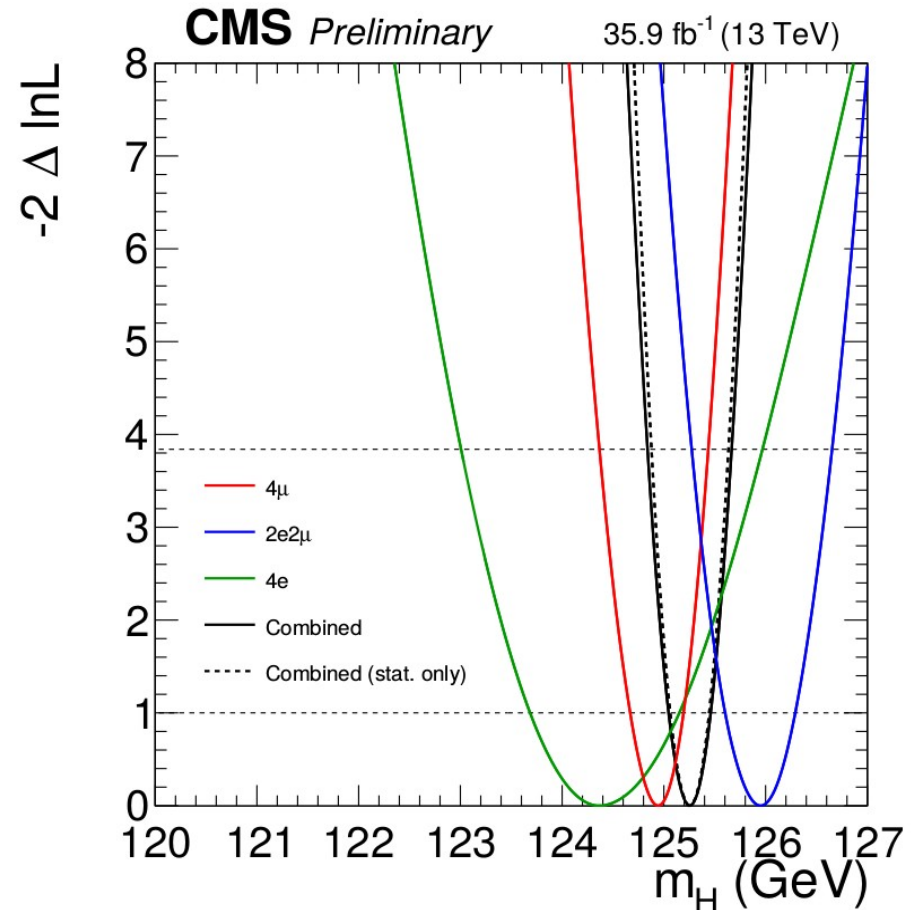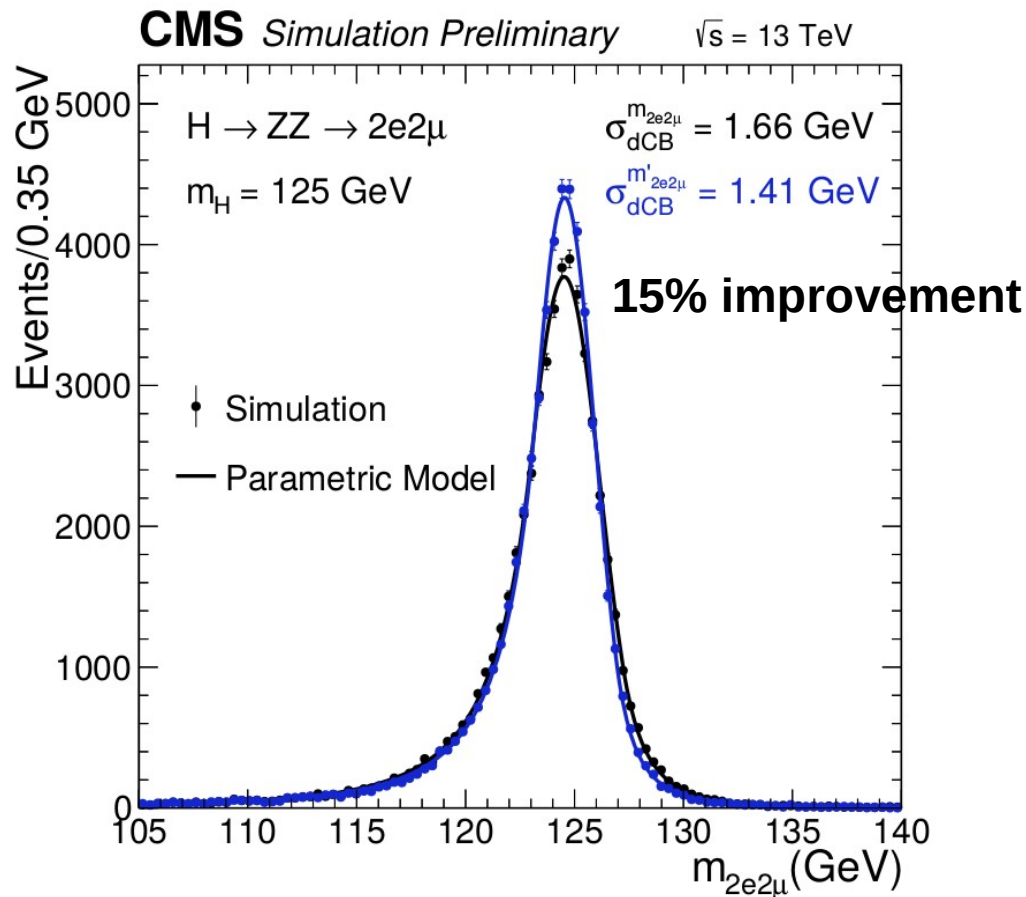
- p-value for compatibility of different channels is 0.061