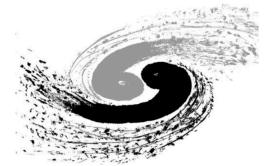


Search for low-mass dilepton resonance in Higgs boson decays to four-lepton final states at $\sqrt{s} = 13 \text{ TeV}$

China LHC Physics Workshop

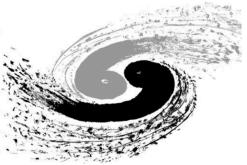
Nov. 6, 2020

Zebing Wang

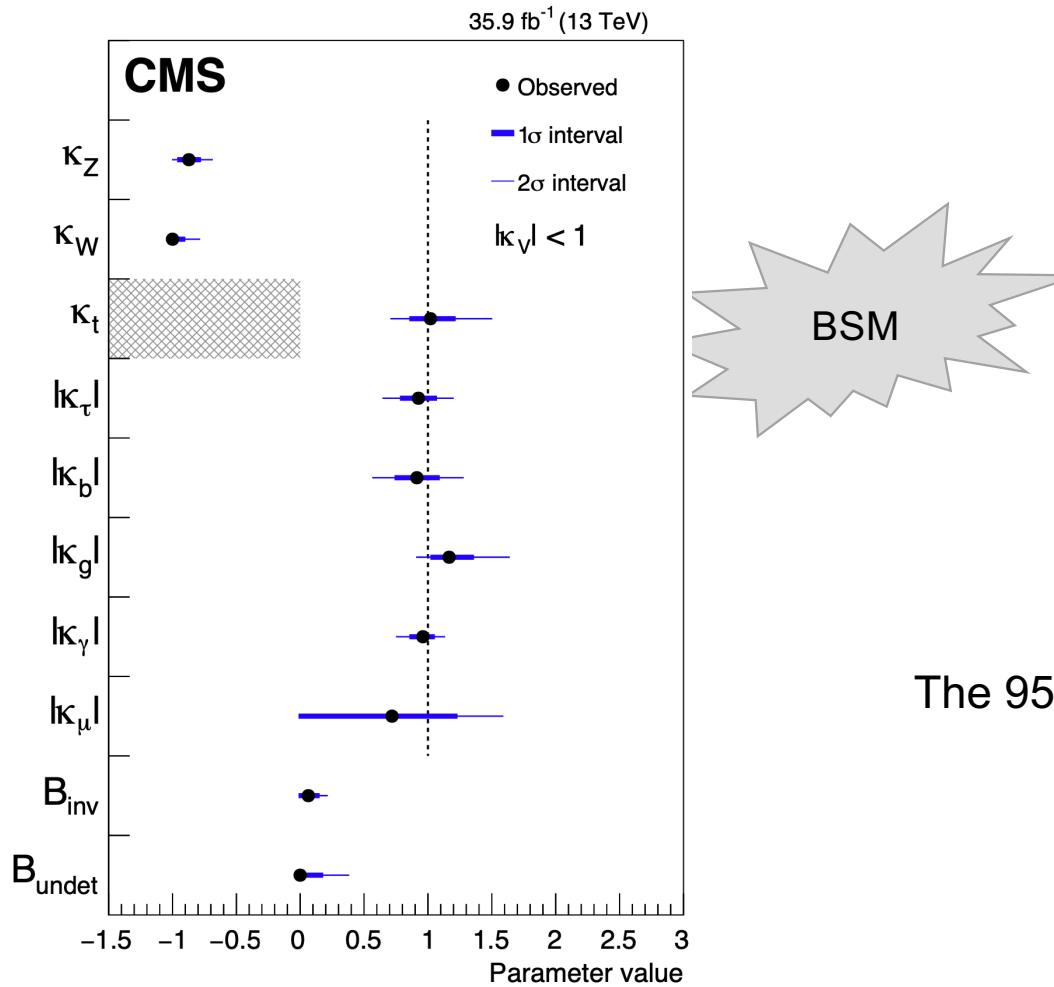


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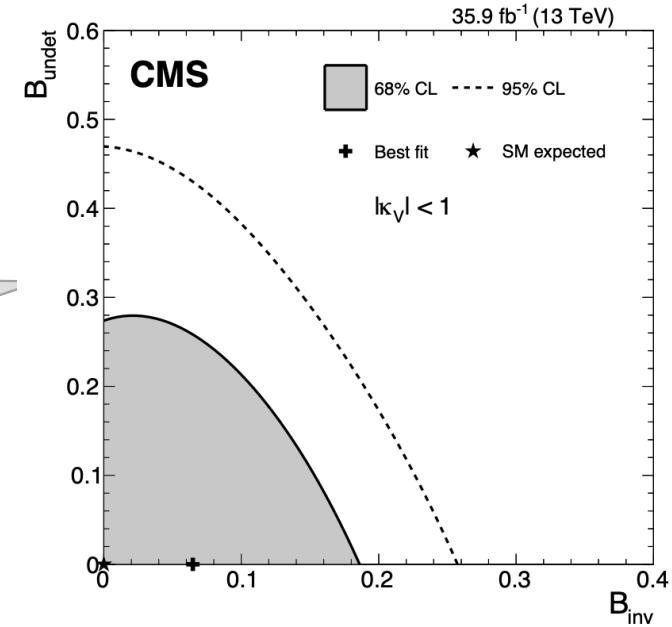


Introduction



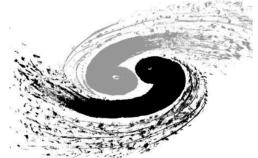
The 95% CL upper limit:
 $Br(h \rightarrow \text{undet}) < 0.38$
 $Br(h \rightarrow \text{inv}) < 0.22$

[arXiv:1809.10733](https://arxiv.org/abs/1809.10733)





Specific BSM Models

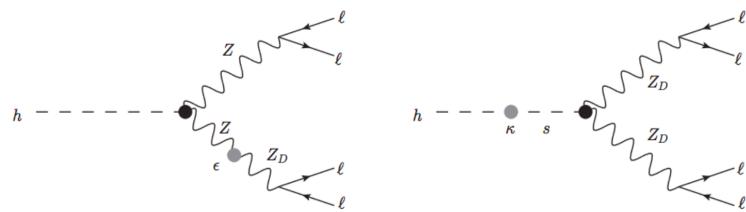


- **Hidden Abelian Higgs Model (HAHM)**
 - Dark gauge couplings, mass of Z_d , mass of h_d .

$$\mathcal{L}_{\text{gauge,dark}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}Z_{D,\mu\nu}Z_D^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}B_{\mu\nu}Z_D^{\mu\nu}$$

$$V_0 = -\mu^2 |H|^2 + \lambda |H|^4 - \mu_D^2 |S|^2 + \lambda |S|^4 + \kappa |H|^2 |S|^2$$

- $h \rightarrow ZZ_d$ and $h \rightarrow Z_dZ_d$.



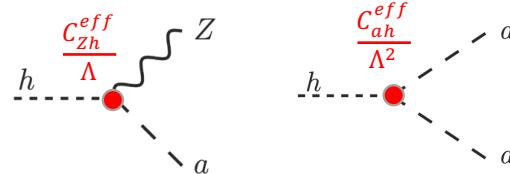
- Kinematic mixing ϵ and the Higgs mixing κ .

$$h \rightarrow ZZ_d : \kappa = 1.0 \times 10^{-9}, \epsilon = 0.02$$

$$h \rightarrow Z_dZ_d : \kappa = 1.0 \times 10^{-4}, \epsilon = 0.02$$

- **Axion-like particle Model (ALP)**

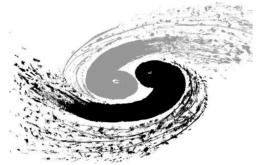
- Gauge-singlets pseudoscalar particles.
- $h \rightarrow Za$ and $h \rightarrow aa$.



- Two relevant Wilson coefficient: $\frac{c_{ah}^{eff}}{\Lambda^2}$ and $\frac{c_{Zh}^{eff}}{\Lambda}$.

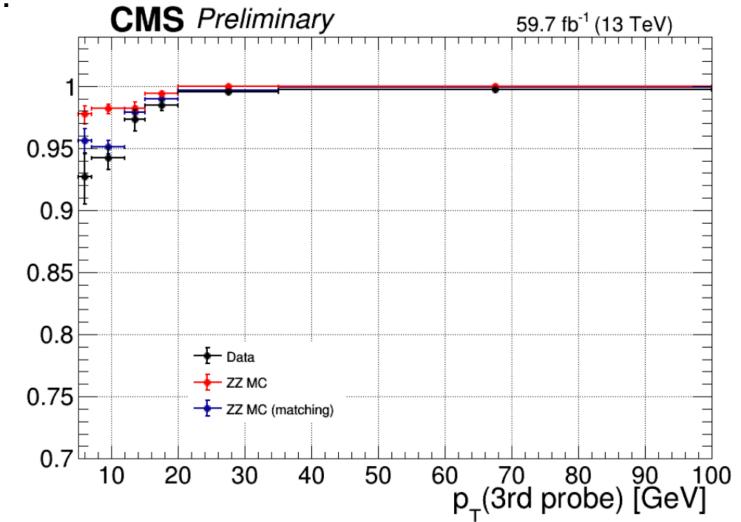
$$\Gamma(H \rightarrow aa) = \frac{v^2 m_h^3}{32\pi} \frac{c_{ah}^{eff2}}{\Lambda^4} \left(1 - \frac{2m_a^2}{m_h^2}\right)^2 \sqrt{1 - \frac{4m_a^2}{m_h^2}}$$

$$\Gamma(H \rightarrow Za) = \frac{m_h^3}{16\pi} \frac{c_{Zh}^{eff2}}{\Lambda^2} \lambda^{3/2} \left(\frac{m_Z^2}{m_h^2}, \frac{m_a^2}{m_h^2}\right)$$



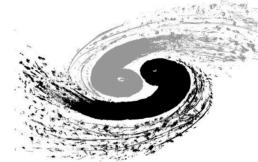
Datasets

- Datasets: Full-Run2 (2016+2017+2018 = 137 fb^{-1})
- MC Samples:
 - Signal: $h \rightarrow ZZ_d/Z_dZ_d \rightarrow 4l$ ($l = e, \mu$) mass point: **4, 7, 10, 15, 20, 25, 30, 35** GeV / **4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60** GeV (using LO MADGRAPH5, with the Hidden Abelian Higgs Model(HAHM)).
 - Backgrounds: $gg \rightarrow 4l$, $q\bar{q} \rightarrow 4l$ and SM Higgs boson processes.
- Trigger:
 - Single lepton + di-lepton + tri-lepton trigger.
 - Trigger efficiency measured by Tag and Prob method (>99%).

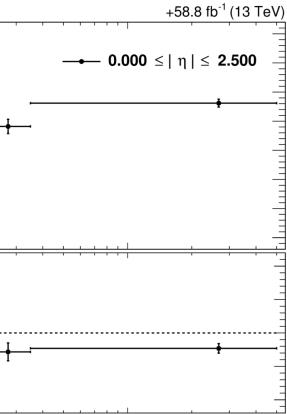
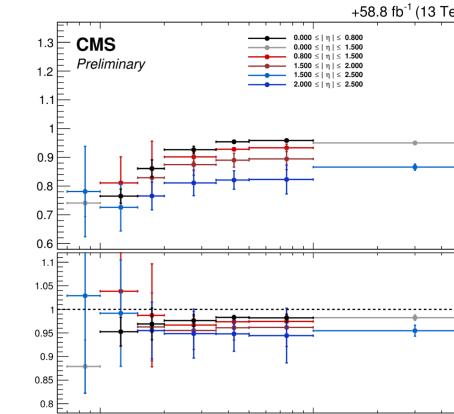
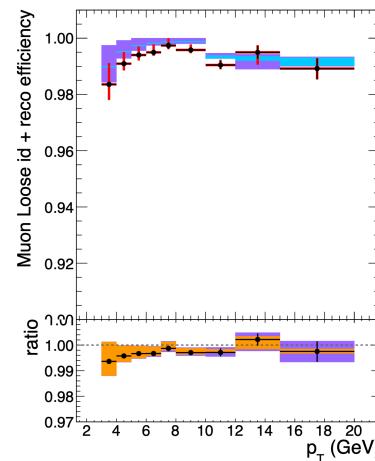
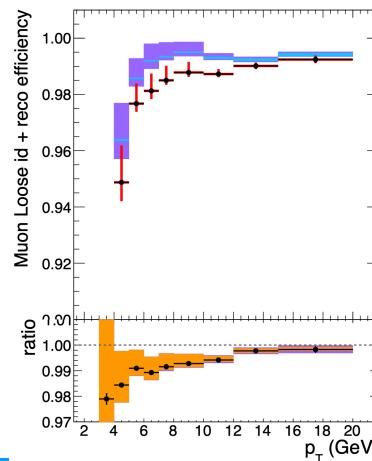




Object Selection



- Muon:
 - Loose: Global muon or tracker muon, $\text{Pt} > 5\text{GeV}$, $|\text{eta}| < 2.4$, $|\text{dZ}| < 1\text{cm} \& |\text{dxy}| < 0.5\text{cm}$
 - Tight: PF muon with isolation < 0.35.
- Electron:
 - Loose: $\text{Pt} > 7\text{GeV}$, $|\text{SC eta}| < 2.5$, $|\text{dZ}| < 1\text{cm} \& |\text{dxy}| < 0.5\text{cm}$
 - Tight: Dedicated HZZ MVA discriminant, isolation < 0.35.
- FSR photon recovery algorithm per lepton.
- Lepton efficiency and scale factors measured by TnP.

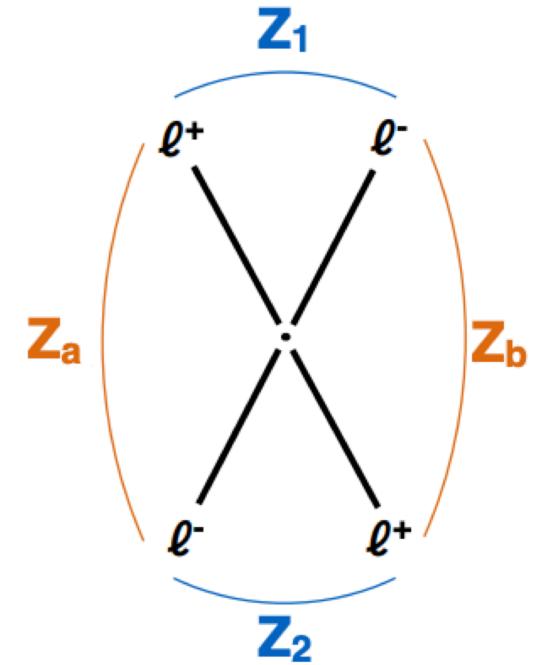


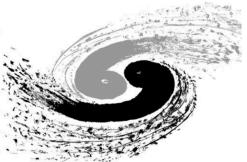


ZX Selection



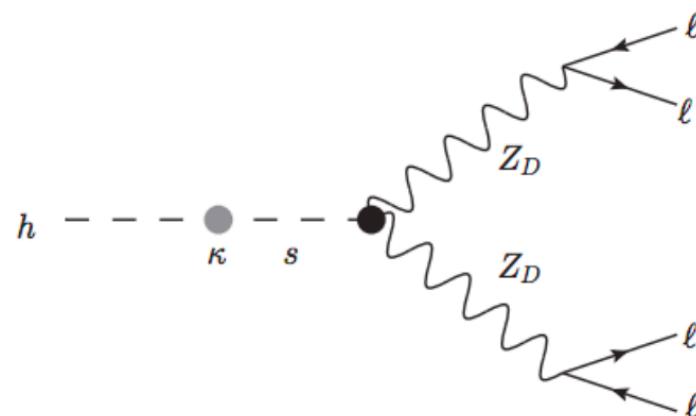
- Z selection:
 - Two SFOS leptons.
 - $4 < m_{ll(\gamma)} < 120 \text{GeV}/c^2$.
- ZZ Candidate:
 - Z1: m_{ll} closest to the nominal Z boson mass; Z2: The other one.
 - $m_{Z_1} > 40 \text{GeV}/c^2$.
 - $p_{T,i} > 20 \text{GeV}/c$ and $p_{T,j} > 10 \text{GeV}/c$.
 - $\Delta R(\eta, \phi) > 0.02$ between each of the four leptons.
 - $m_{ll} > 4 \text{GeV}/c^2$ for OS pairs (regardless of flavour).
 - Smart cut: *not* ($|m_{Z_a} - m_Z| < |m_{Z_1} - m_Z| \&\& m_{Z_b} < 12$).
 - $118 < m_{4l} < 130 \text{GeV}/c^2$.
- Exclude narrow mass window around Y states ($8.5 < m_Y < 11.0 \text{GeV}/c^2$).

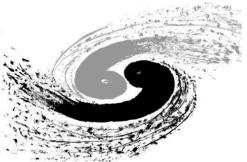




XX Selection

- Same as ZX selection except:
 - $4 < m_{Z_1}, m_{Z_2} < 62.5 \text{GeV}/c^2$.
 - Z1: Larger m_{ll} ; Z2: The other one.
 - No smart cut.
- Exclude narrow mass window around Y states ($8.5 < m_Y < 11.0 \text{GeV}/c^2$).



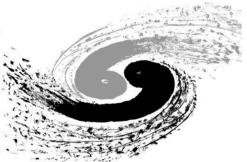


Irreducible and Reducible Background

	Irreducible	Reducible
Process	SM Higgs boson processes $q\bar{q} \rightarrow 4l$ $gg \rightarrow 4l$	Z+X
Method	Simulation	OS method (Fake factor method)

Z+X: one or more mis-identified non-prompt leptons.

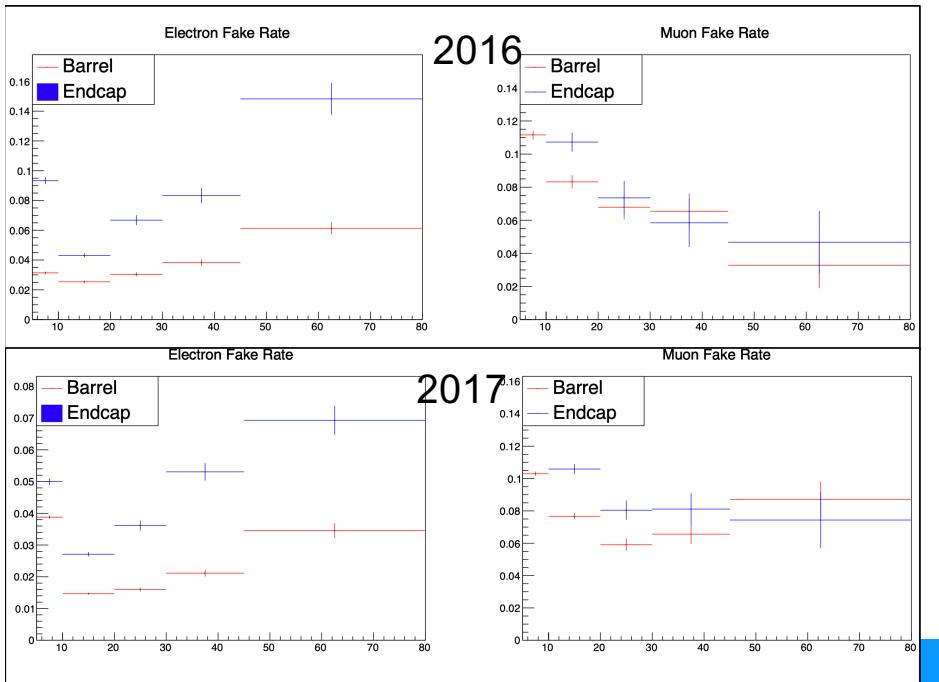
Non-prompt leptons: non-isolated electrons and muons from heavy-flavour hadrons; mis-identified jets and electrons from photon conversion.

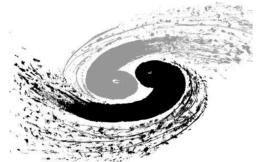


Z+X Background Estimation

- Opposite sign method:
 - Two control region: 2P2F and 3P1F.
 - Measure lepton fake rate with tight selection in lepton Pt bins.
 - Reweighting events in the 2P2F and 3P1F control region with the measured lepton fake rate.

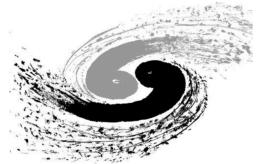
$$N_{\text{SR}}^{\text{bkg}} = \left(1 - \frac{N_{\text{3P1F}}^{\text{ZZ}}}{N_{\text{3P1F}}} \right) \sum_j^{N_{\text{3P1F}}} \frac{f_a^j}{1 - f_a^j} - \sum_i^{N_{\text{2P2F}}} \frac{f_3^i}{1 - f_3^i} \frac{f_4^i}{1 - f_4^i}$$



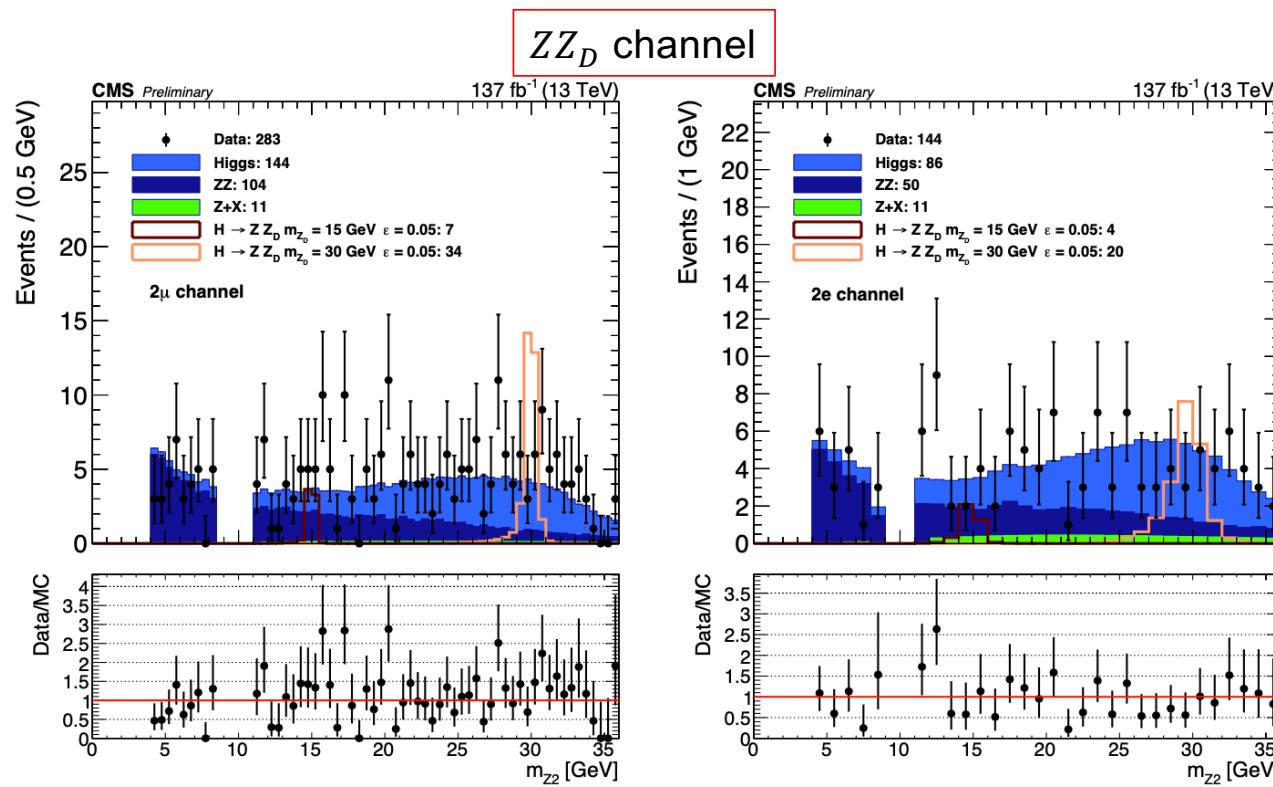


Systematic Uncertainties

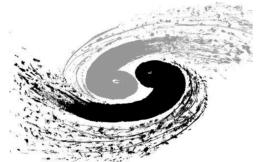
- Luminosity:
 - 2.3% - 2.5%.
- Lepton identification and reconstruction efficiency:
 - 2.5% - 16.1%
- Reducible background:
 - 48% - 100%
- Theoretical:
 - renormalization and factorization scales
 - PDF
 - branching fractions of Higgs to four leptons via ZZ_D and Z_DZ_D



Discrimination Distribution

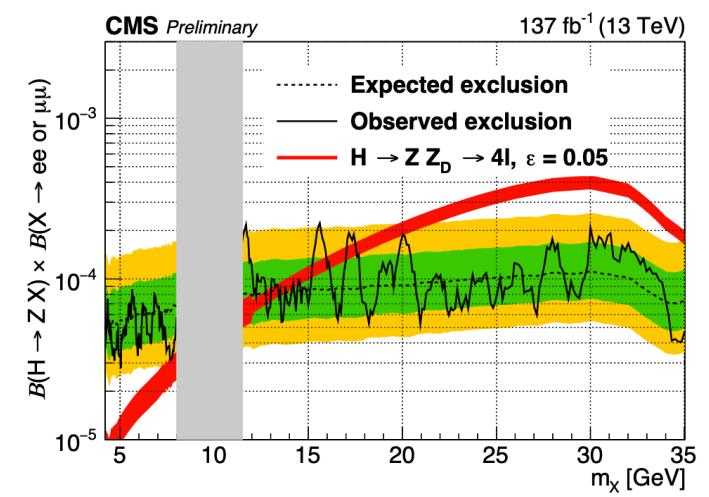
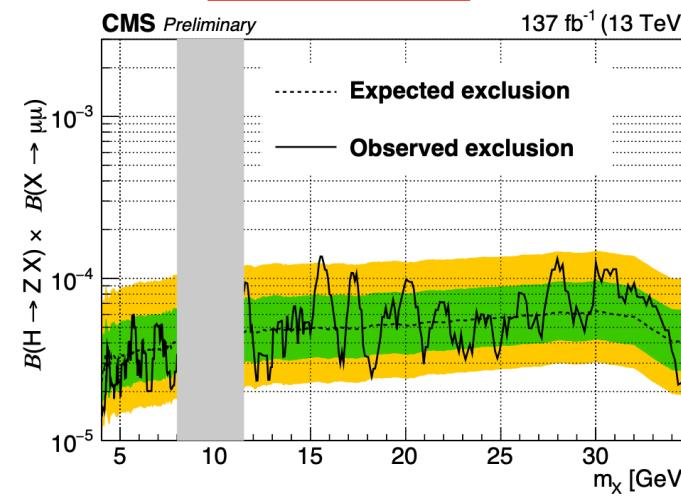
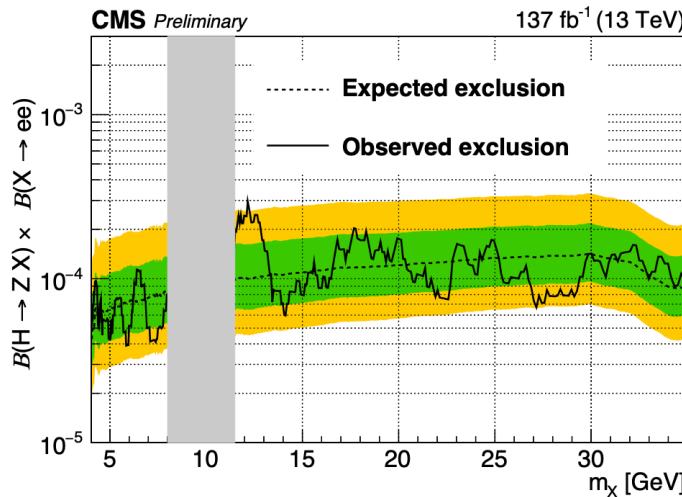


No significant deviation with respect to the SM background prediction is observed.
 For each mass hypothesis, a cut-and-count experiment is performed on the m_{Z_2} distribution.

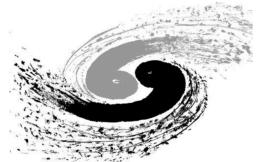


Effective Branch Fraction

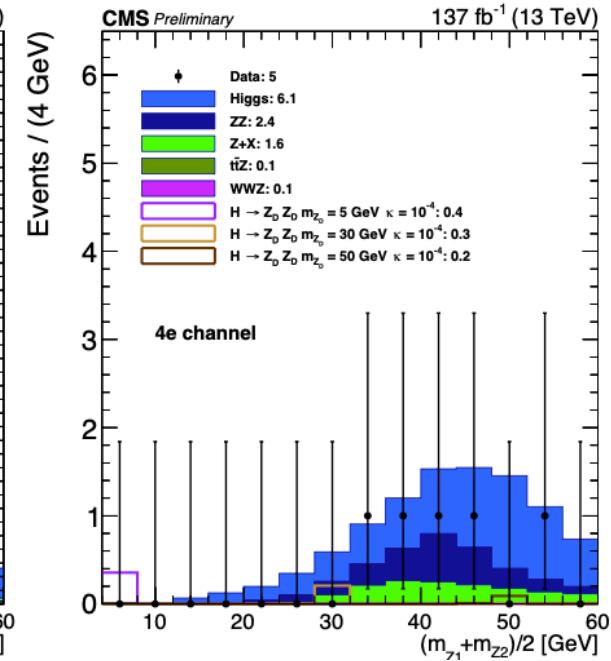
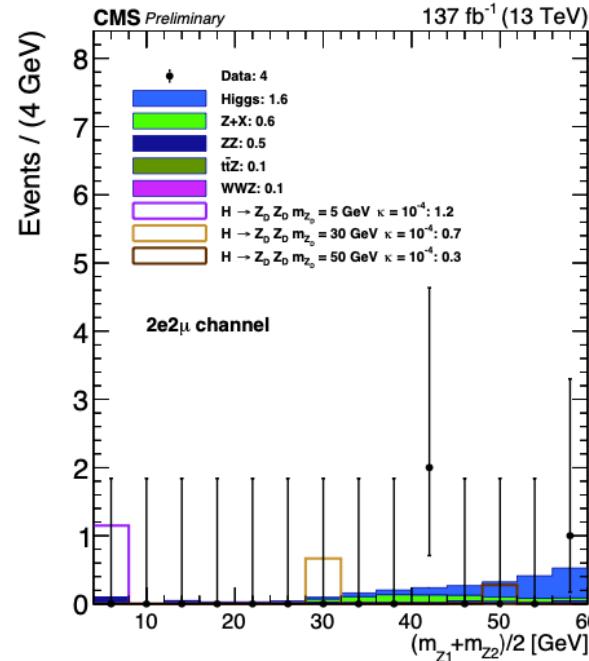
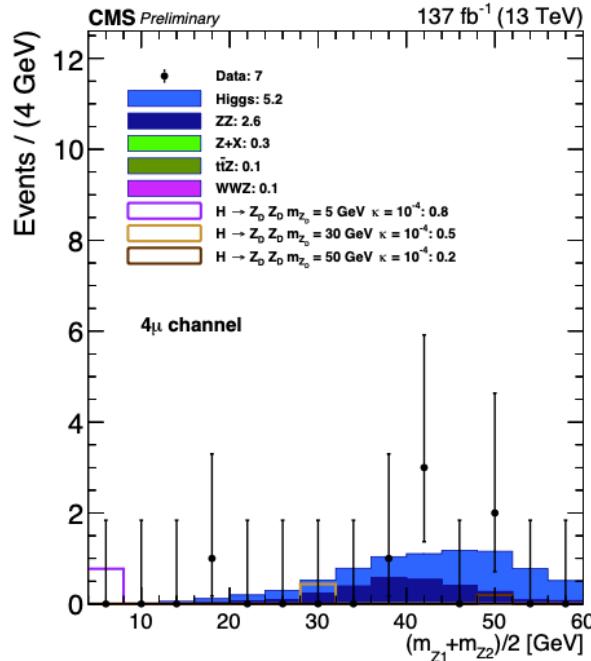
ZZ_D channel



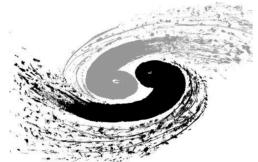
The largest local observed significance is 3.0σ at 15.6 GeV with the flavor-symmetric scenario.



Discrimination Distribution

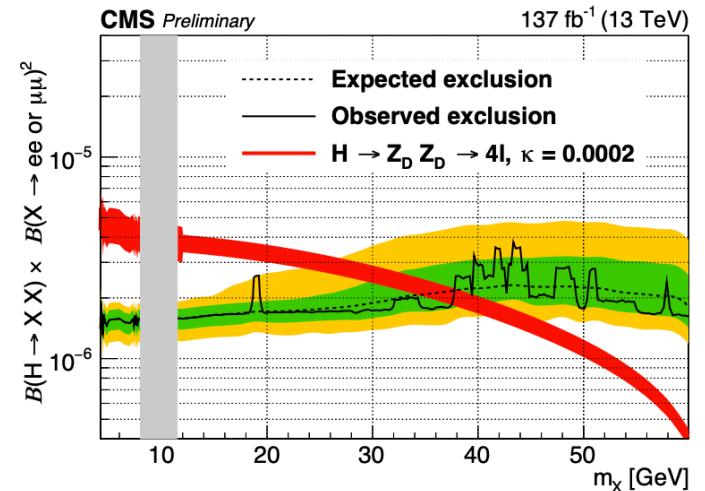
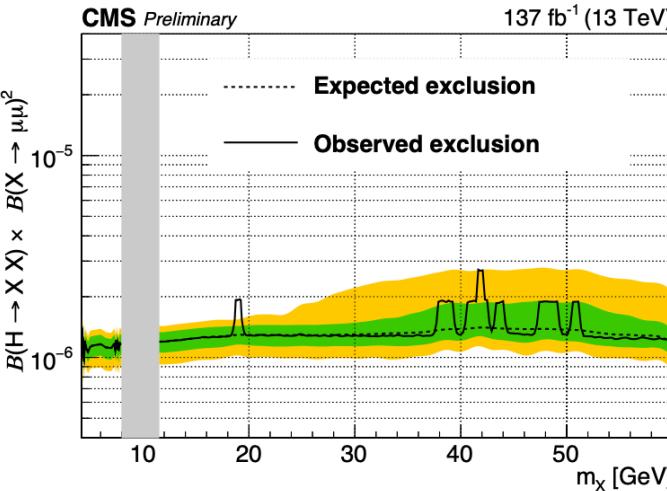
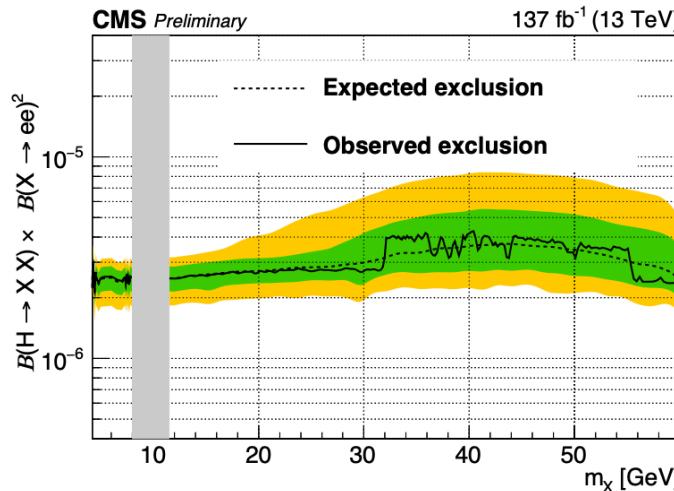


No significant deviation with respect to the SM background prediction is observed.



Effective Branch Fraction

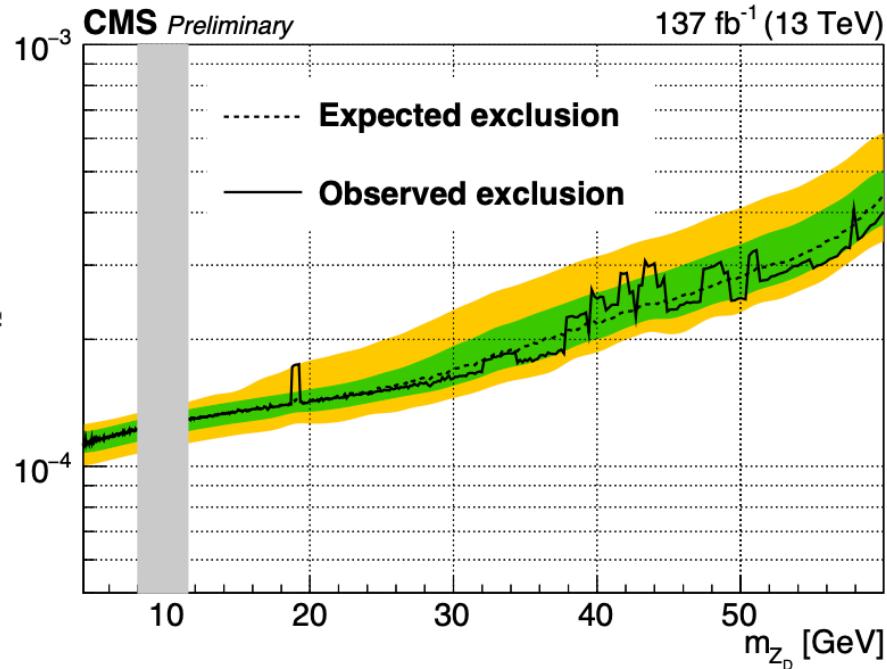
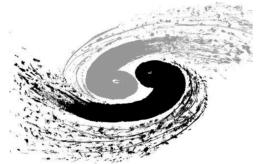
$Z_D Z_D$ channel



The largest local observed significance is 2.9σ at 18.8 GeV with the muon channel.



Dark Photon Interpretation

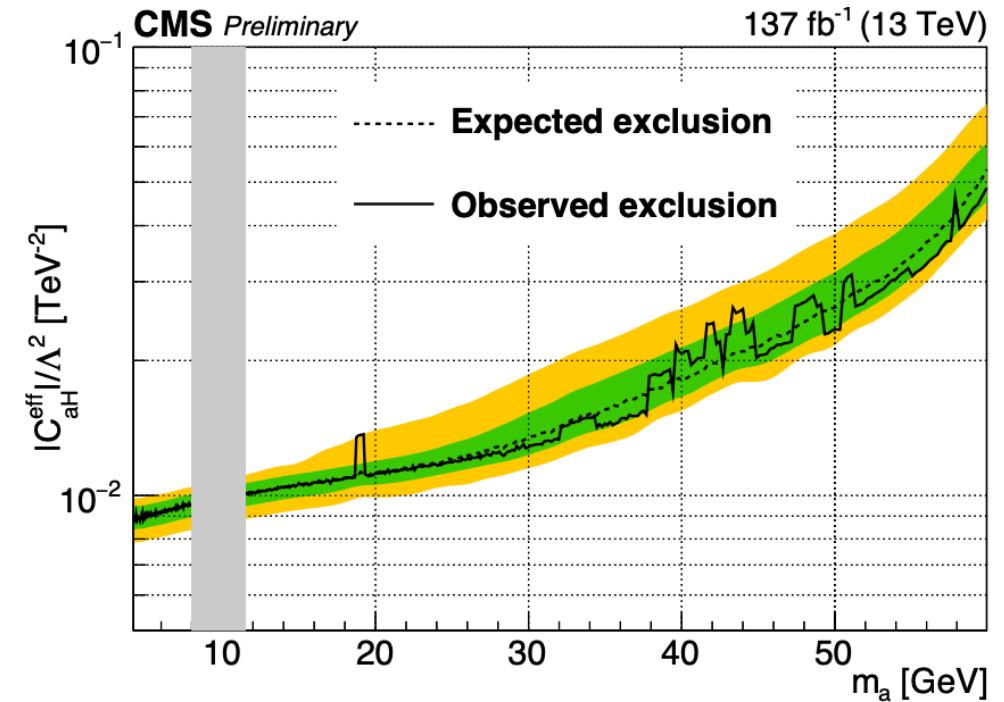
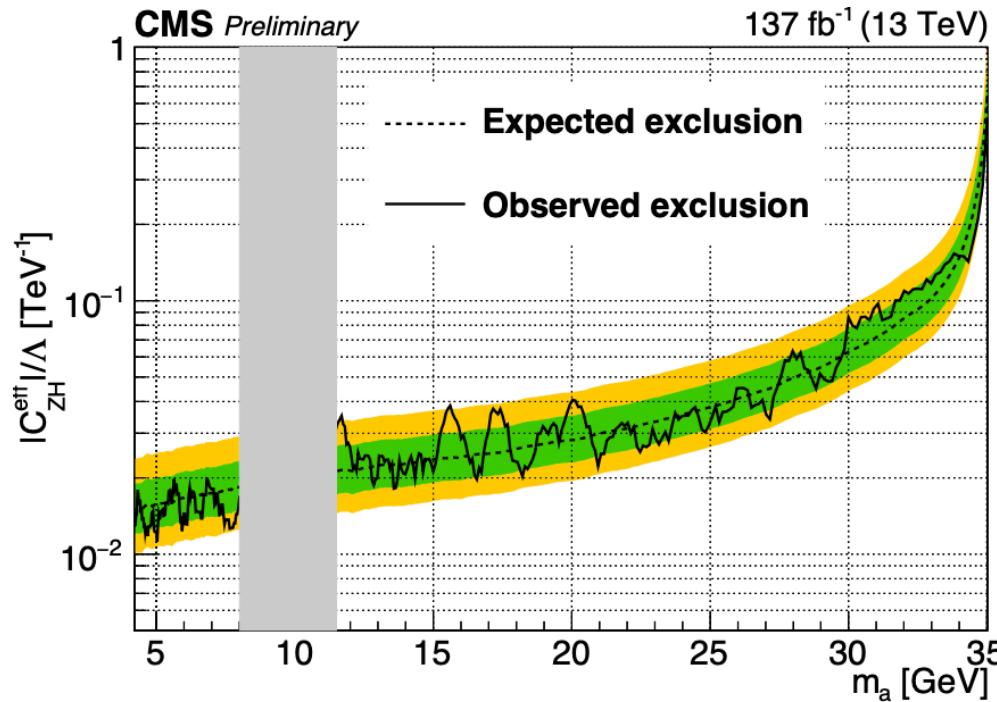
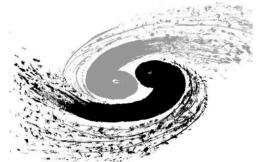


$$\Gamma(h \rightarrow Z_D Z_D) = \kappa'^2 \frac{1}{32\pi} \frac{v^2}{m_h} \sqrt{1 - \frac{4m_{Z_D}^2}{m_h^2}} \frac{(m_h^2 + 2m_{Z_D}^2)^2 - 8(m_h^2 - m_{Z_D}^2)m_{Z_D}^2}{m_h^4}$$

$$\kappa' = \kappa \frac{m_h^2}{|m_h^2 - m_s^2|}$$

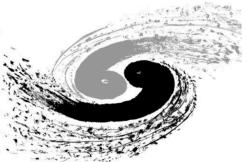


ALP Interpretation



$$\Gamma(H \rightarrow Za) = \frac{m_h^3}{16\pi} \frac{c_{Zh}^{\text{eff2}}}{\Lambda^2} \lambda^{3/2} \left(\frac{m_Z^2}{m_h^2}, \frac{m_a^2}{m_h^2} \right)$$

$$\Gamma(H \rightarrow aa) = \frac{v^2 m_h^3}{32\pi} \frac{c_{ah}^{\text{eff2}}}{\lambda^4} \left(1 - \frac{2m_a^2}{m_h^2} \right)^2 \sqrt{1 - \frac{4m_a^2}{m_h^2}}$$



Summary

- A generic search for a dilepton resonance in Higgs boson decays to the four-lepton final state has been presented.
- This search includes two decay topologies: $pp \rightarrow H \rightarrow ZX$ and $pp \rightarrow H \rightarrow XX$.
- No significant deviations from SM is observed.
- Constraints on dark photon model and ALP model are presented.



Thanks