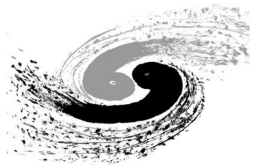
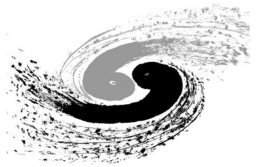


Search for low-mass dilepton resonance in Higgs boson decays to four-lepton final states at $\sqrt{s} = 13\ TeV$

China LHC Physics Workshop

Nov. 27, 2021

Zebing Wang



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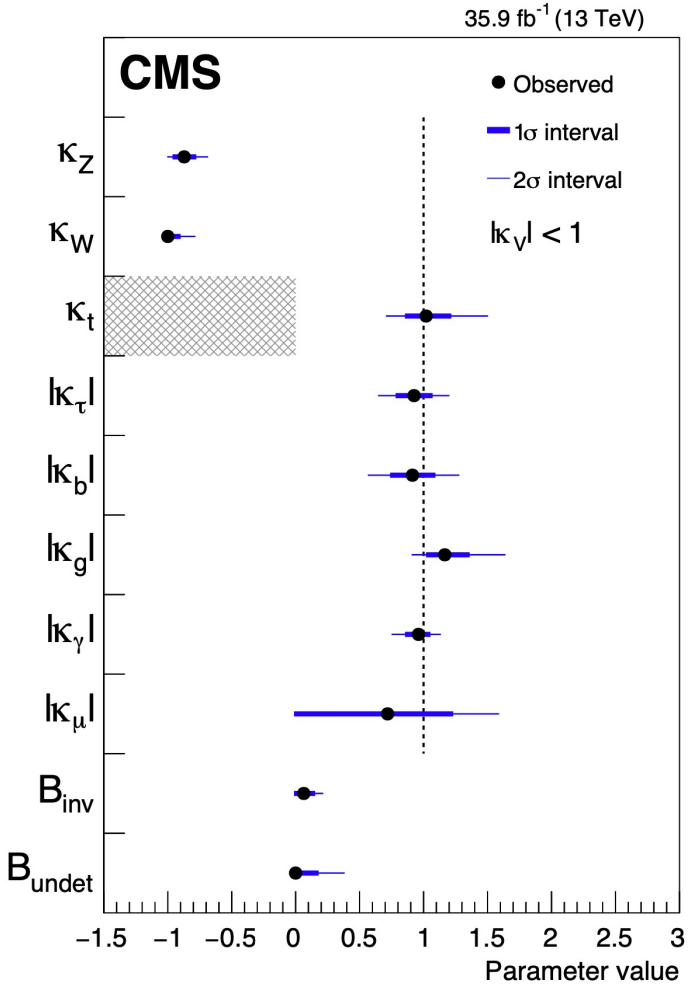
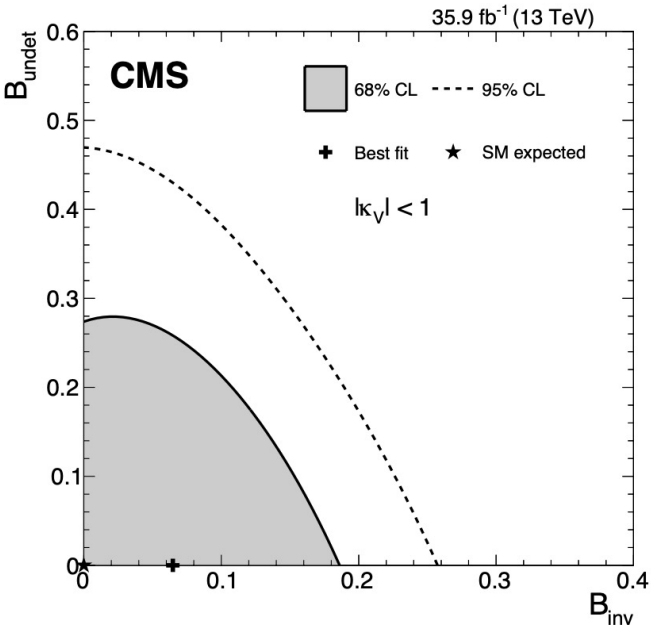
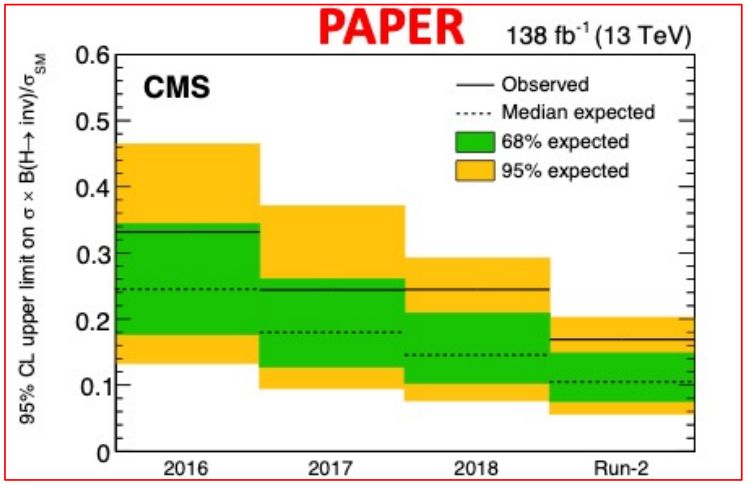
Introduction







The 95% CL upper limit:

$$Br(h \to \text{undet}) < 0.38$$

$$Br(h \to inv) < 0.22$$

arXiv:1809.10733

New results about H-> inv (more details can be seen at Vukasin's talk: Search for invisible decays of a Higgs boson produced via vector boson fusion)

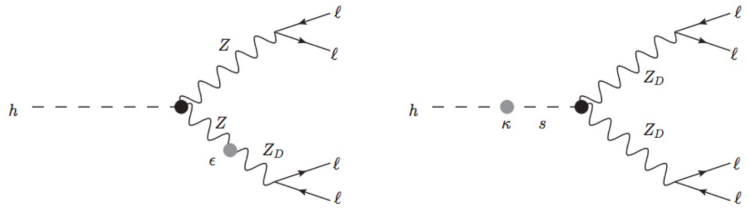
Specific BSM Models

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

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

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

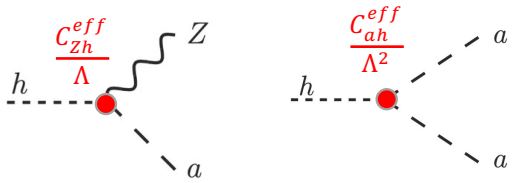
  - $h \to ZZ_d$ and $h \to Z_dZ_d$.



  - Kinematic mixing ε and the Higgs mixing κ .

$$h \to ZZ_d : \kappa = 1.0\times10^{-9}, \varepsilon = 0.02$$
$$h \to Z_dZ_d : \kappa = 1.0\times10^{-4}, \varepsilon = 0.02$$

- Axion-like particle Model (ALP)
  - Gauge-singlets pseudoscalar particles.
  - $h \to Za$ and $h \to aa$.



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

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

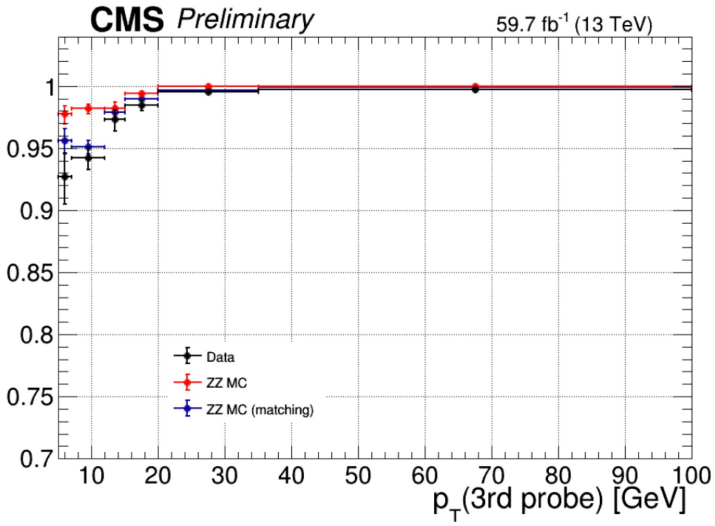
$$\Gamma(\mathrm{H} \to \mathrm{Za}) = \frac{m_h^3}{16\pi}\frac{c_{\mathrm{Zh}}^{\mathrm{eff}2}}{\Lambda^2}\lambda^{3/2}\left(\frac{m_Z^2}{m_h^2}, \frac{m_a^2}{m_h^2}\right)$$

Datasets

- Datasets: Full-Run2 (2016+2017+2018 = 137 fb^{-1})

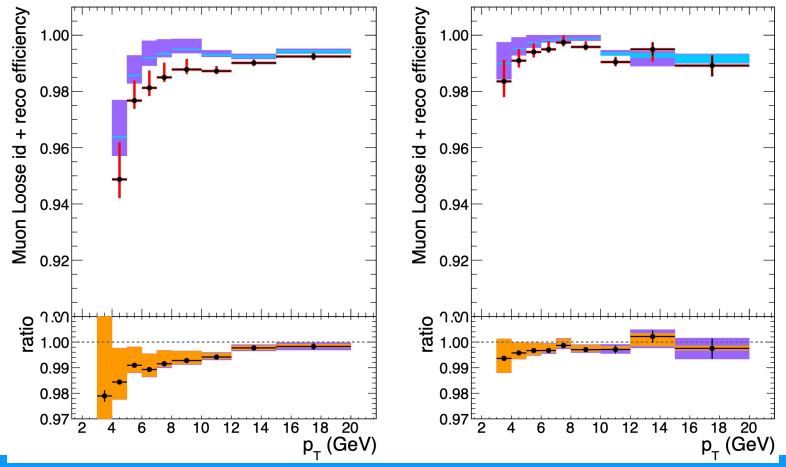
- MC Samples:
  - Signal: $h \to ZZ_d/Z_dZ_d \to 4l$ $(l = e, \mu)$ mass point: 4,7,10,15,20,25,30,35 GeV / 4,5,6,7,8,9,10,15,20,25,30,35,40,45,50,55,60 GeV (using LO MADGRAPH5, with the Hidden Abelian Higgs Model(HAHM)).
  - Backgrounds: $gg \to 4l$, $q\bar{q} \to 4l$ and SM Higgs boson processes.

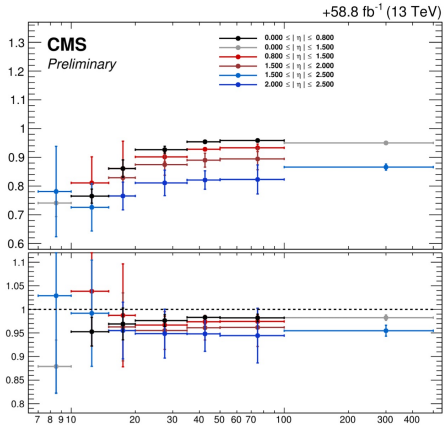
- Trigger:
  - Single lepton + di-lepton + tri-lepton trigger.
  - Trigger efficiency measured by Tag and Prob method (>99%).

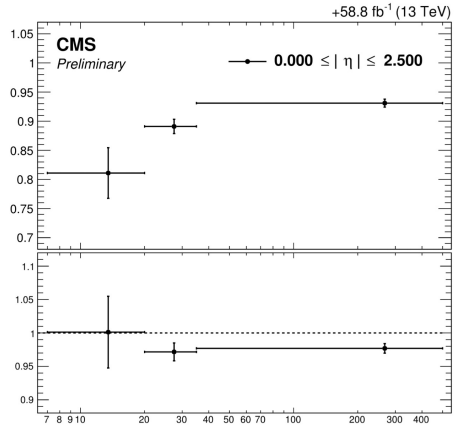


Object Selection

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

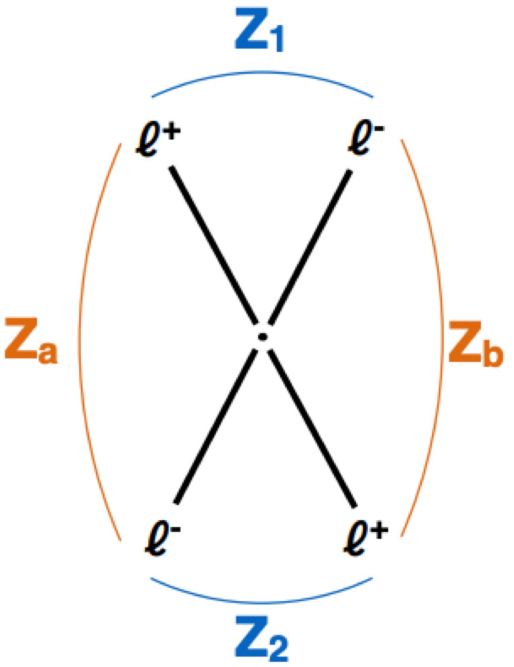






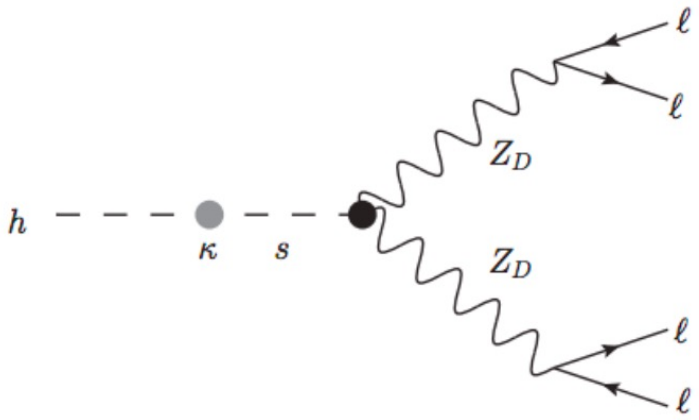
ZX Selection

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



XX Selection

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



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)

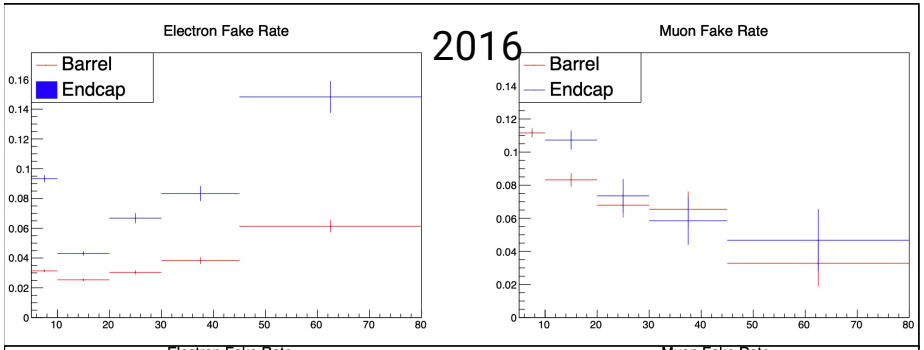
Z+X: one or more mis-identified non-prompt leptons.
Non-prompt leptons: non-isolated electrons and muons from heavy-flavour hadrons; mis-identified jets and electrons from photon conversion.

Z+X Background Estimation

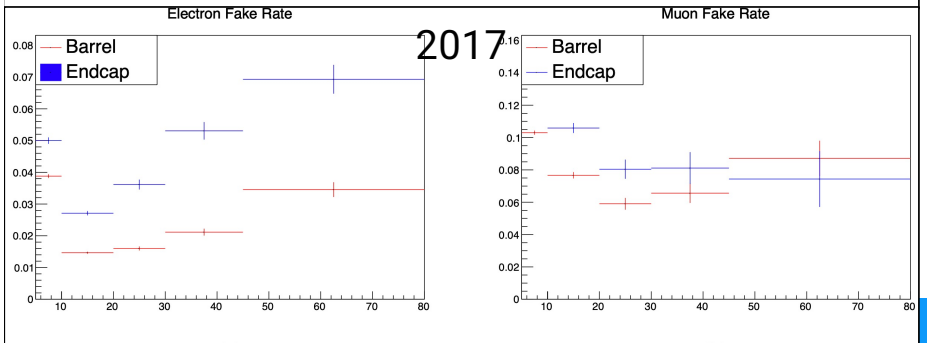
- Opposite sign method:
  - Two control region: 2P2F and 3P1F.
  - Measure lepton fake rate with tight selection in lepton Pt bines.
  - Reweight events in the 2P2F and 3P1F control region with the measured lepton fake rate.

$$N_{\mathrm{SR}}^{bkg} = (1 - \frac{N_{3P1F}^{ZZ}}{N_{3P1F}}) \sum_{j}^{N_{3P1F}} \frac{f_a^j}{1 - f_a^j} - \sum_{i}^{N_{2P2F}} \frac{f_3^i}{1 - f_3^i} \frac{f_4^i}{1 - f_4^i}$$

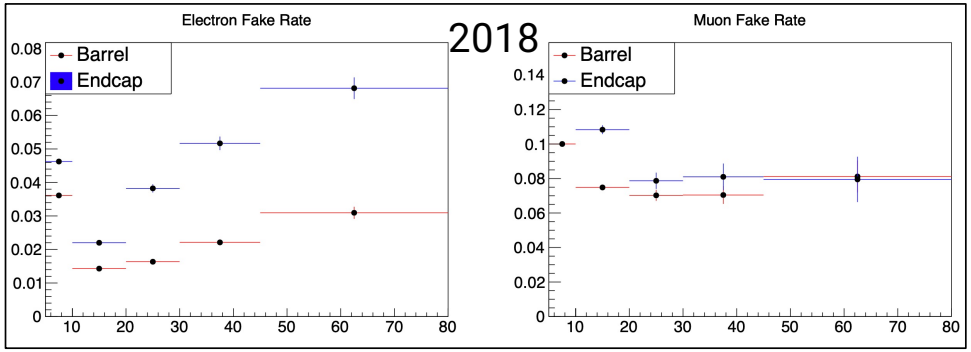
2016



2017



2018



Systematic Uncertainties

- Luminosity:
- Lepton identification and reconstruction efficiency:
- Reducible background:
- Theoretical:
  - renormalization and factorization scales
  - PDF
  - branching fractions of Higgs to four leptons via ZZ_D and Z_DZ_D

Summary of relative systematic uncertainties	
Common experimental uncertainties	
Luminosity	2.6 %
Lepton identification/reconstruction efficiencies	2.5 – 9 %
Lepton energy scale	0.1 – 12.7 %
Lepton energy resolution	0.01 – 4.7 %
Common theory related uncertainties	
Higgs branching fraction	2 %
QCD scale	0.4 – 4.2 %
PDF scale	1.6 – 3.4 %
Background related uncertainties	
Reducible background (Z+X)	53 – 79 %
$q\bar{q} \to 4\ell$ electroweak correction	0.1 %
$gg \to 4\ell$ kfactor	10.0 %
Signal related uncertainties	
Interference	2.0 %
QCD scale	0.4 – 4.2 %
PDF scale	1.6 – 3.4 %
Branching ratio	10 – 20 %

2016

Summary of relative systematic uncertainties	
Common experimental uncertainties	
Luminosity	2.3 %
Lepton identification/reconstruction efficiencies	3. – 12.5 %
Lepton energy scale	0.1 – 10.3 %
Lepton energy resolution	0.01 – 2.6 %
Common theory related uncertainties	
Higgs branching fraction	2 %
QCD scale	0.4 – 4.2 %
PDF scale	1.6 – 3.4 %
Background related uncertainties	
Reducible background (Z+X)	48 – 78 %
$q\bar{q} \to 4\ell$ electroweak correction	0.1 %
$gg \to 4\ell$ kfactor	10.0 %
Signal related uncertainties	
Interference	2.0 %
QCD scale	0.4 – 4.2 %
PDF scale	1.6 – 3.4 %
Branching ratio	10 – 20 %

2017

Summary of relative systematic uncertainties	
Common experimental uncertainties	
Luminosity	2.5 %
Lepton identification/reconstruction efficiencies	3. – 12.5 %
Lepton energy scale	0.0 – 11.0 %
Lepton energy resolution	0.01 – 2.4 %
Common theory related uncertainties	
Higgs branching fraction	2 %
QCD scale	0.4 – 4.2 %
PDF scale	1.6 – 3.4 %
Background related uncertainties	
Reducible background (Z+X)	48 – 78 %
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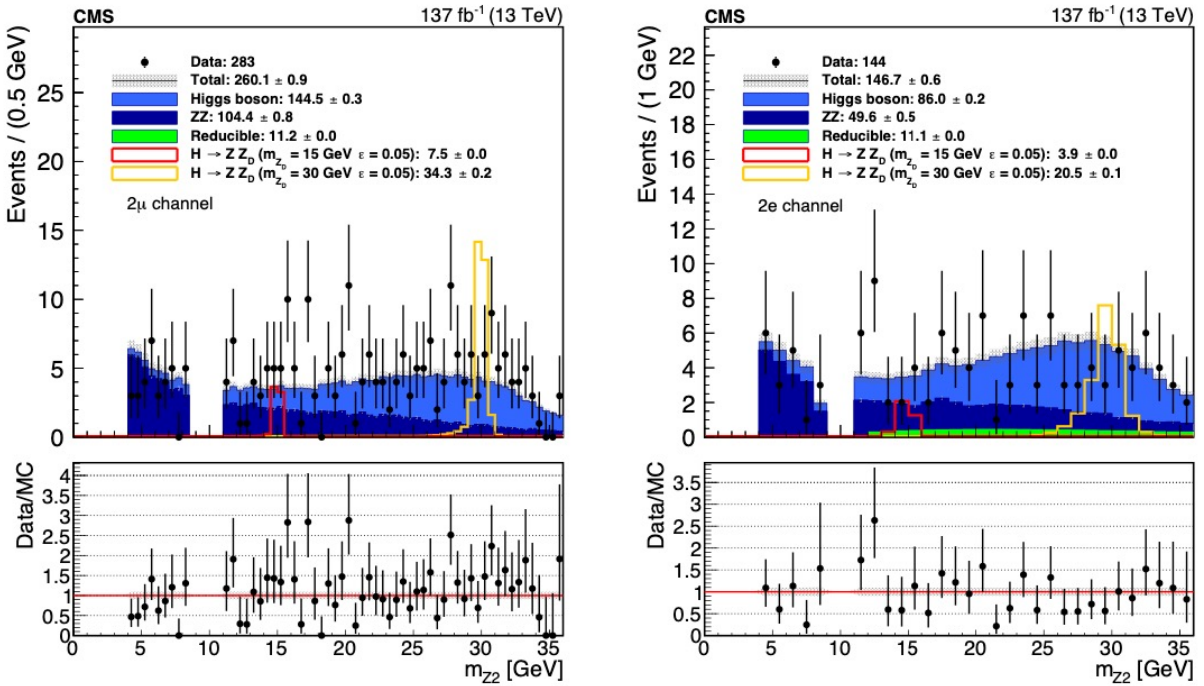
Branching ratio	10 – 20 %

2018

Discrimination Distribution

ZZ_D channel

Paper

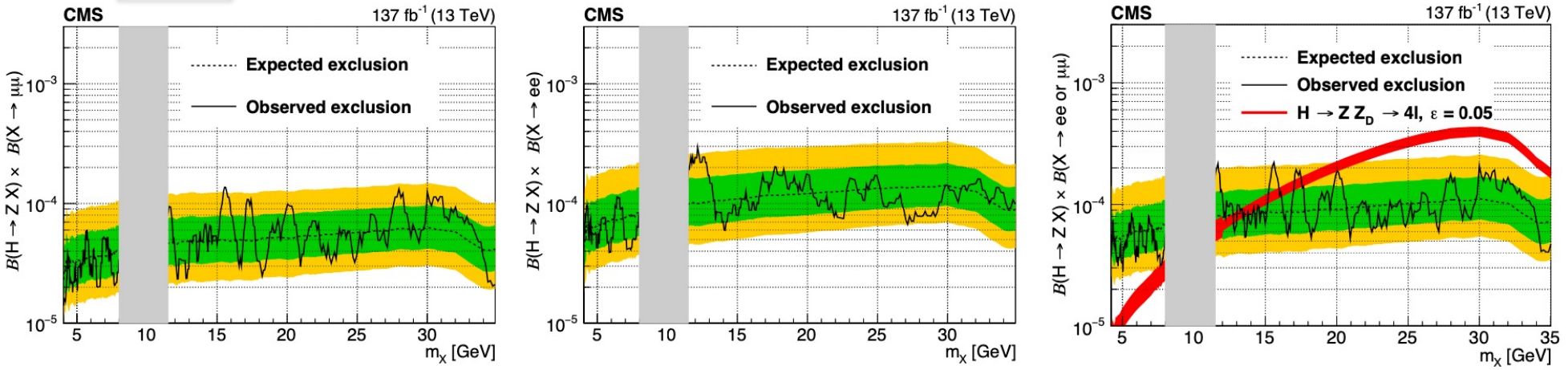


No significant deviation with respect to the SM background prediction is observed.
For each mass hypothesis, a cut-and-count experiment is performed on the m_{Z_2} distribution.

Effective Branch Fraction

ZZ_D channel

Paper

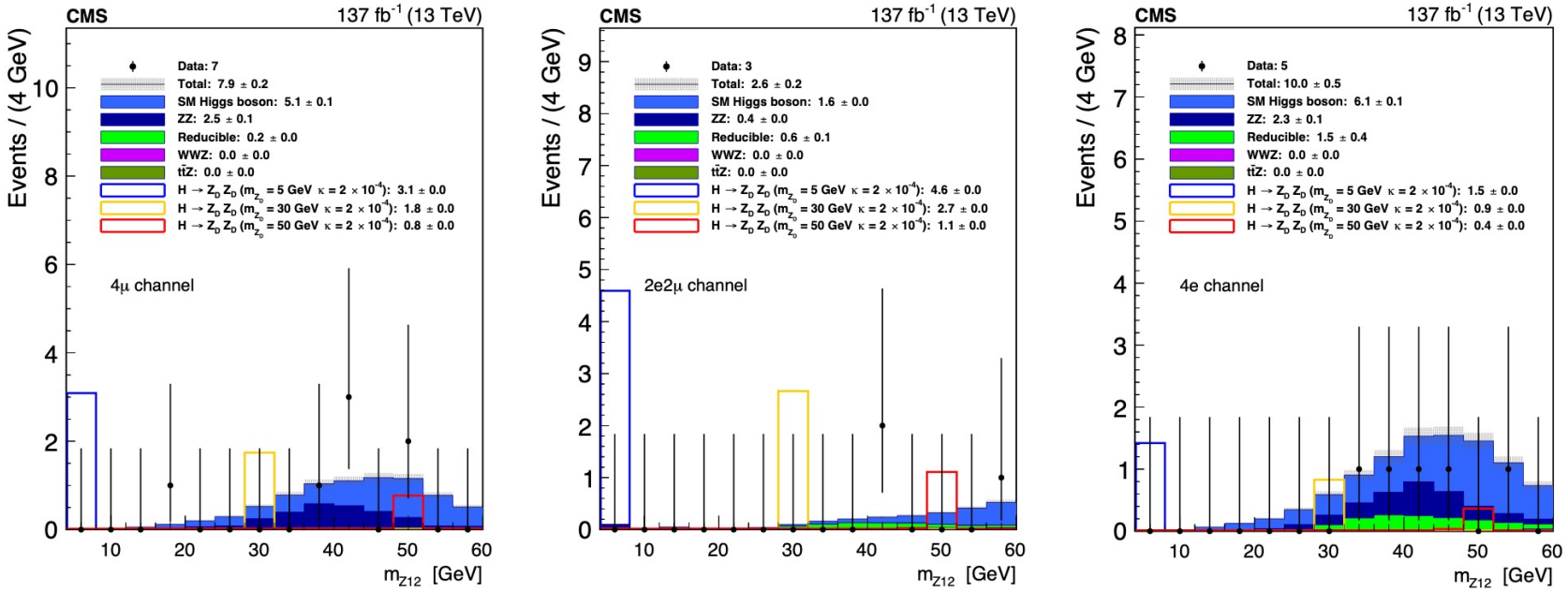


Expected and observed 95% CL limits on $\mathcal{B}(H \to ZX)\mathcal{B}(X \to \mu\mu)$ assuming X decays to dimuons only, $\mathcal{B}(H \to ZX)\mathcal{B}(X \to ee)$ assuming X decays to dielectrons only, and $\mathcal{B}(H \to ZX)\mathcal{B}(X \to \mu\mu \; or \; ee)$ assuming a flavor symmetric decay of X to dimuons and dielectrons.

Discrimination Distribution

Paper

$Z_D Z_D$ channel



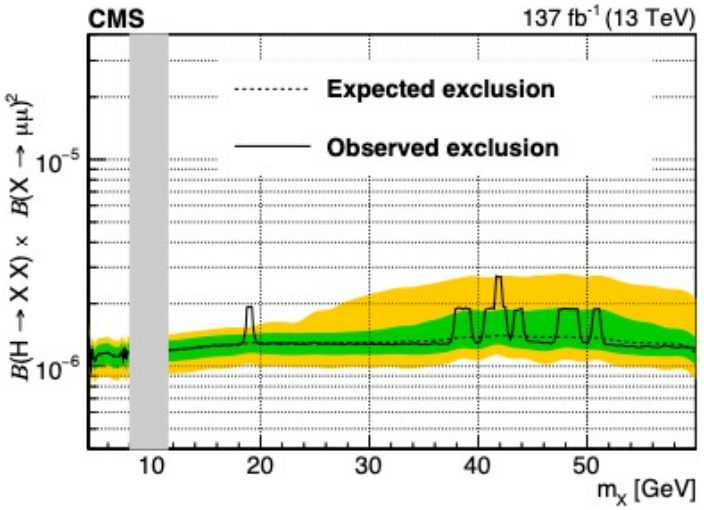
No significant deviation with respect to the SM background prediction is observed.

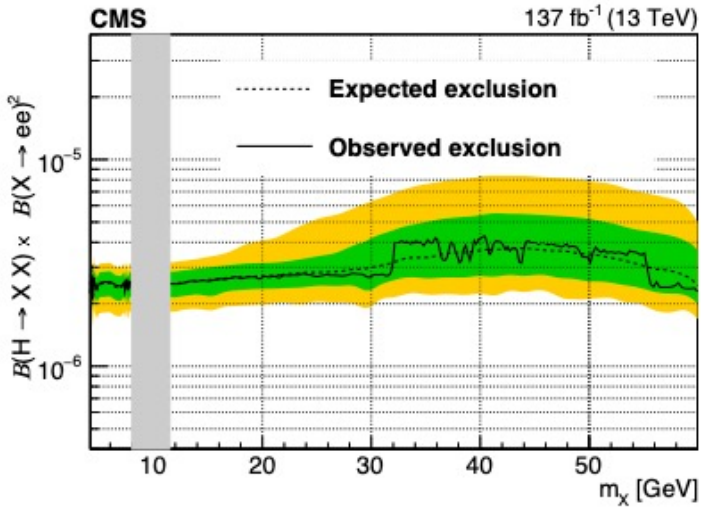
Result

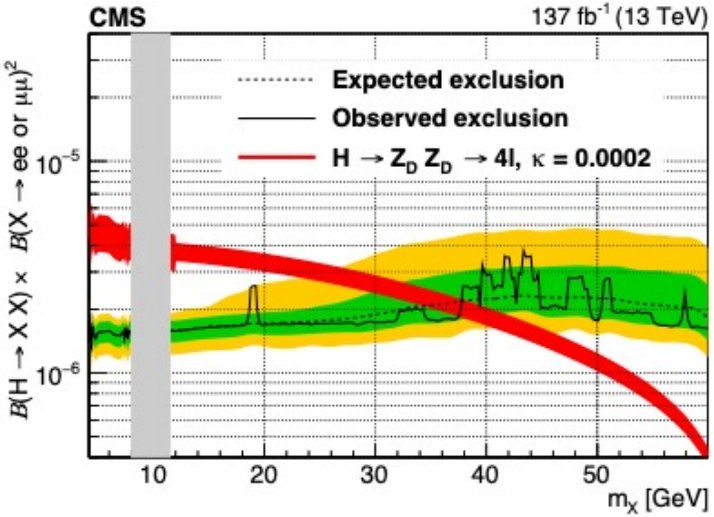
Effective Branch Fraction

Paper

$Z_D Z_D$ channel



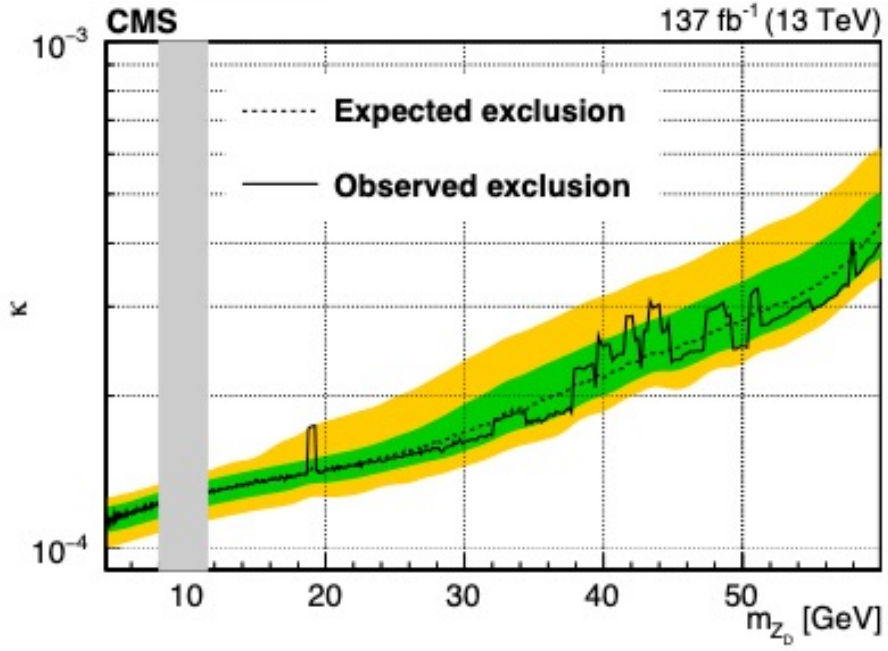




Expected and observed 95% CL limits on $\mathcal{B}(H \to XX)\mathcal{B}(X \to \mu\mu)^2$ assuming X decays to dimuons only, $\mathcal{B}(H \to XX)\mathcal{B}(X \to ee)^2$assuming X decays to dielectrons only, and $\mathcal{B}(H \to XX)\mathcal{B}(X \to \mu\mu \; or \; ee)^2$assuming a flavor symmetric decay of X to dimuons and dielectrons.

Dark Photon Interpretation

Paper

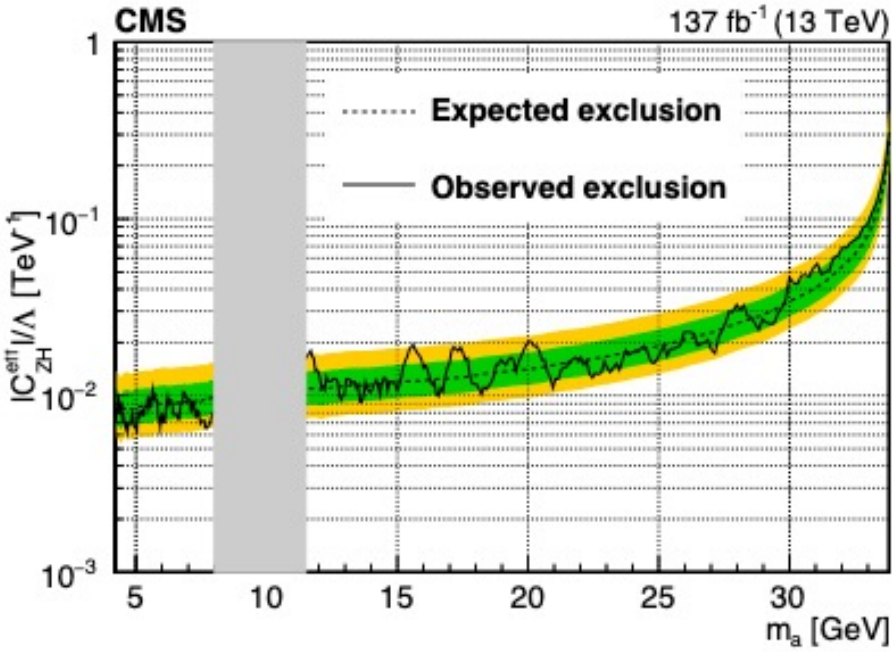


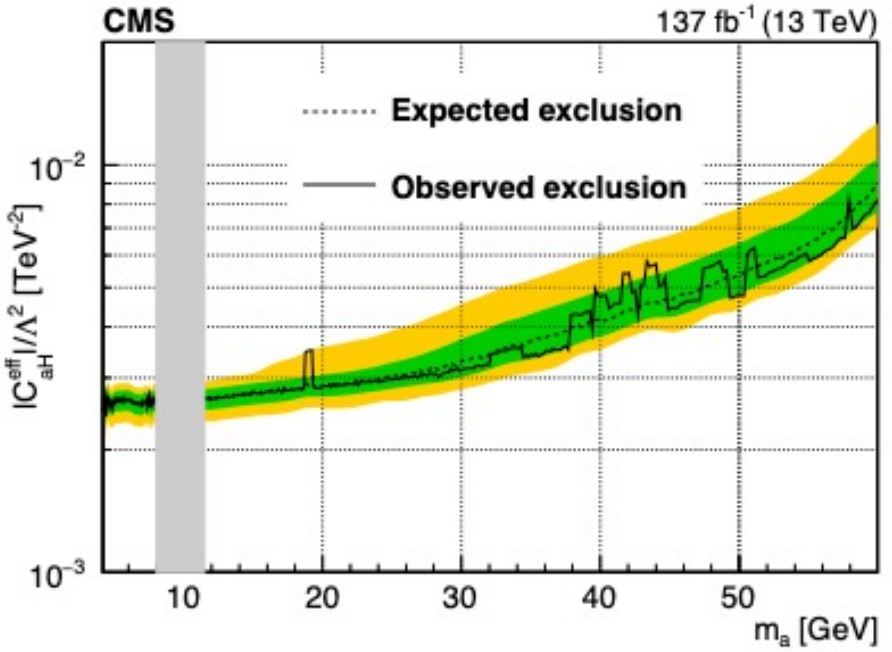
$$\Gamma(h \to Z_D Z_D) = \kappa'^2 \frac{1}{32\pi} \frac{v^2}{m_h} \sqrt{1 - \frac{4m_{Z_D}^2}{m_h^2}} \frac{(m_h^2 + 2m_{Z_D}^2)^2 - 8(m_h^2 - m_{Z_D}^2)m_{Z_D}^2}{m_h^4}$$

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

ALP Interpretation

Paper

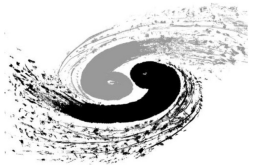




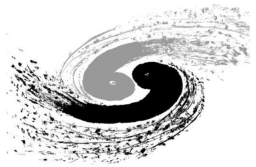
$$\Gamma(\mathrm{H} \to \mathrm{Za}) = \frac{m_h^3}{16\pi} \frac{c_{\mathrm{Zh}}^{\mathrm{eff}\,2}}{\Lambda^2} \lambda^{3/2} \left(\frac{m_Z^2}{m_h^2}, \frac{m_a^2}{m_h^2} \right)$$

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

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: $pp \to H \to ZX$ and $pp \to H \to XX$.
- No significant deviations from SM is observed.
- Constrains on dark photon model and ALP model are presented.



Thanks