BSM HIGGS SEARCHES AT CMS

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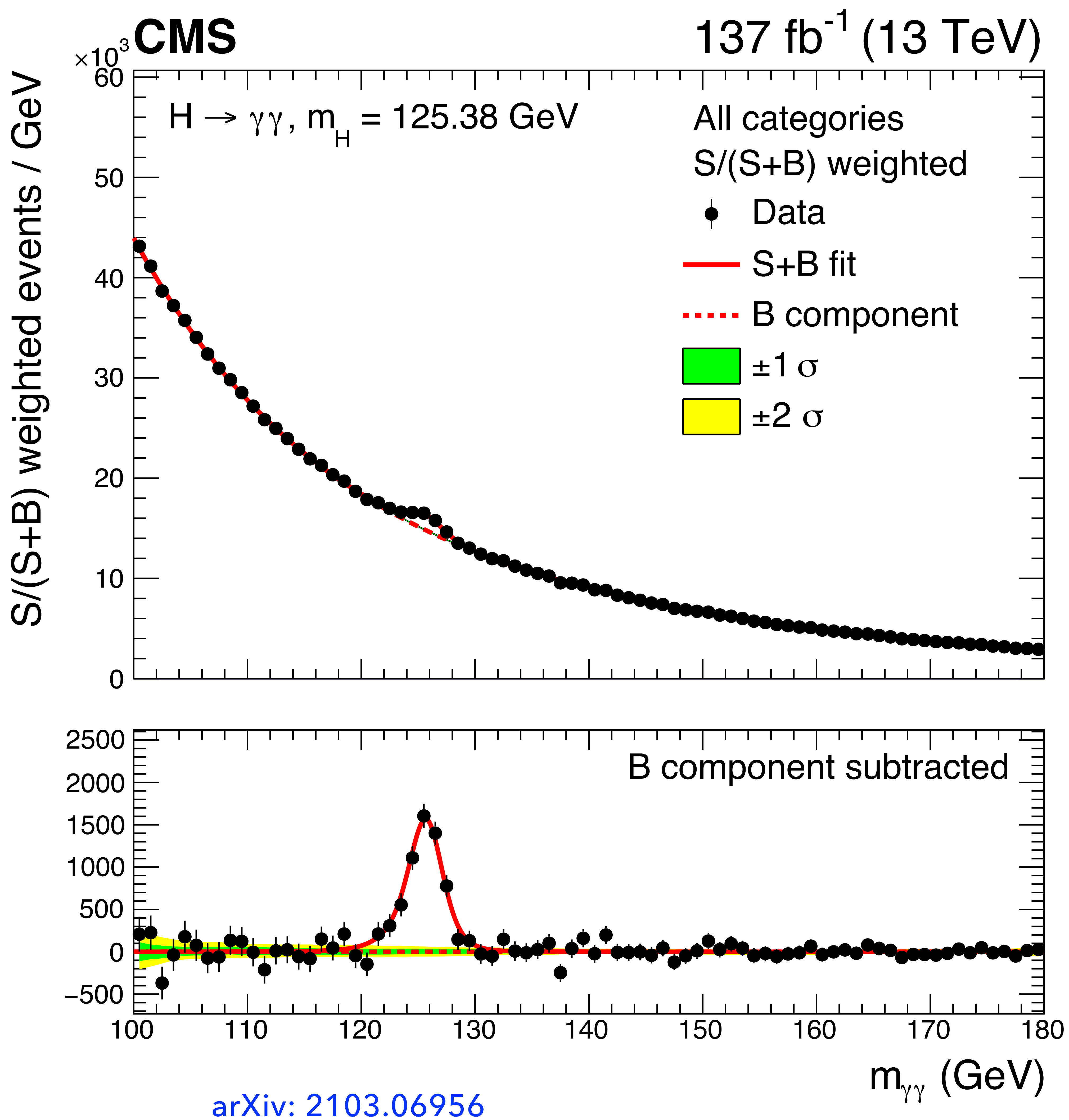
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

PHYSICS BEYOND THE STANDARD MODEL

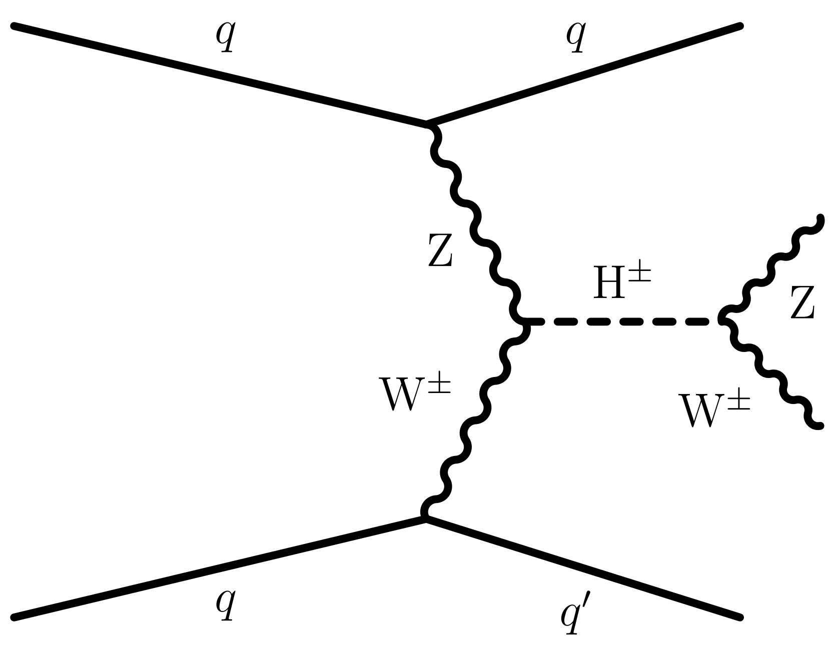
- Standard Model (SM) of particle physics remarkably successful in describing and predicting experimental results
  - Discovery of Higgs boson in 2012 completed SM
- However: strong evidence that physics beyond the SM (BSM) exist, for example:
  - Neutrino masses
  - Dark Matter
- Today: overview on recently published CMS results targeting BSM physics



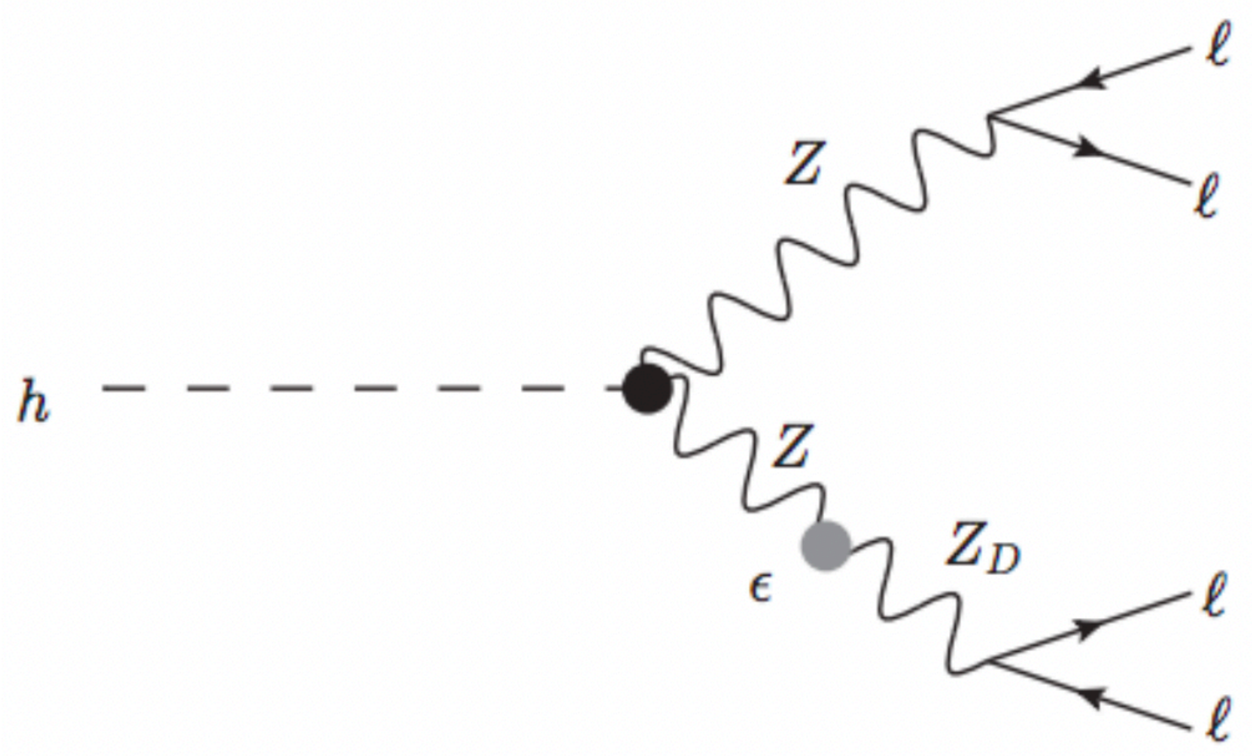
arXiv: 2103.06956

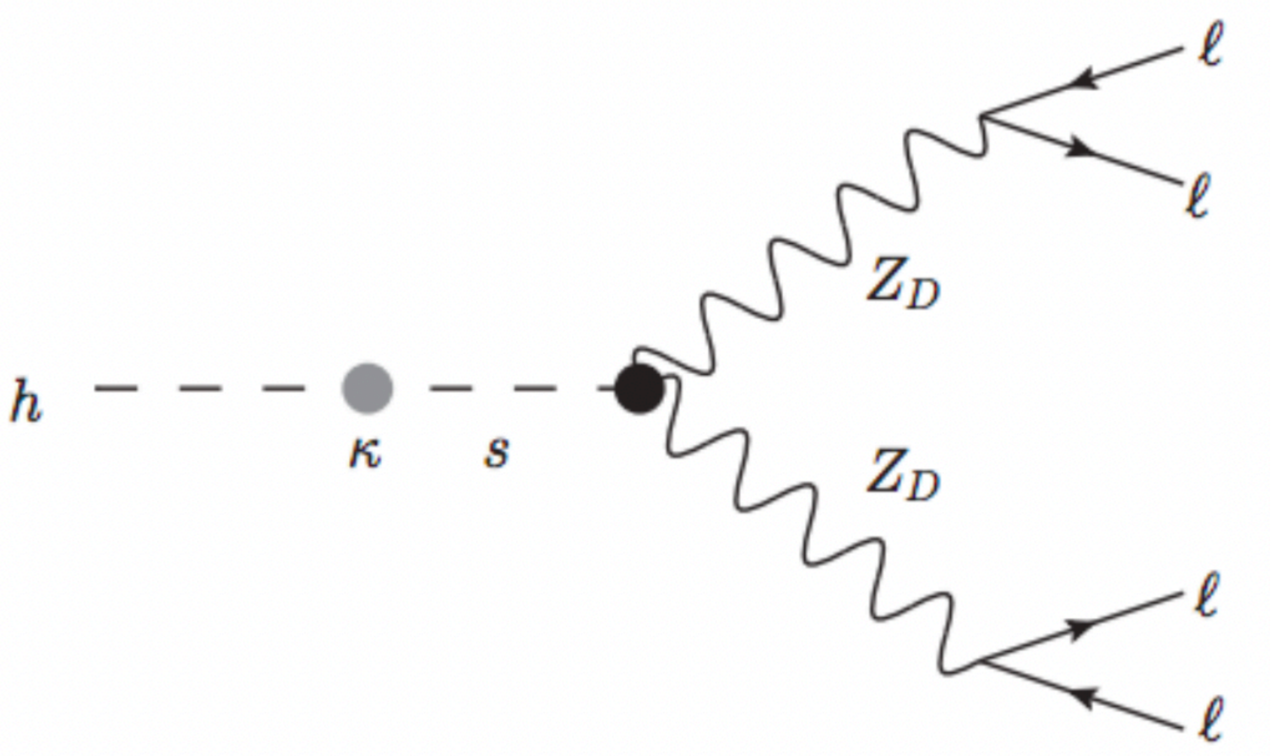
HIGGS BOSON IN BSM PHYSICS

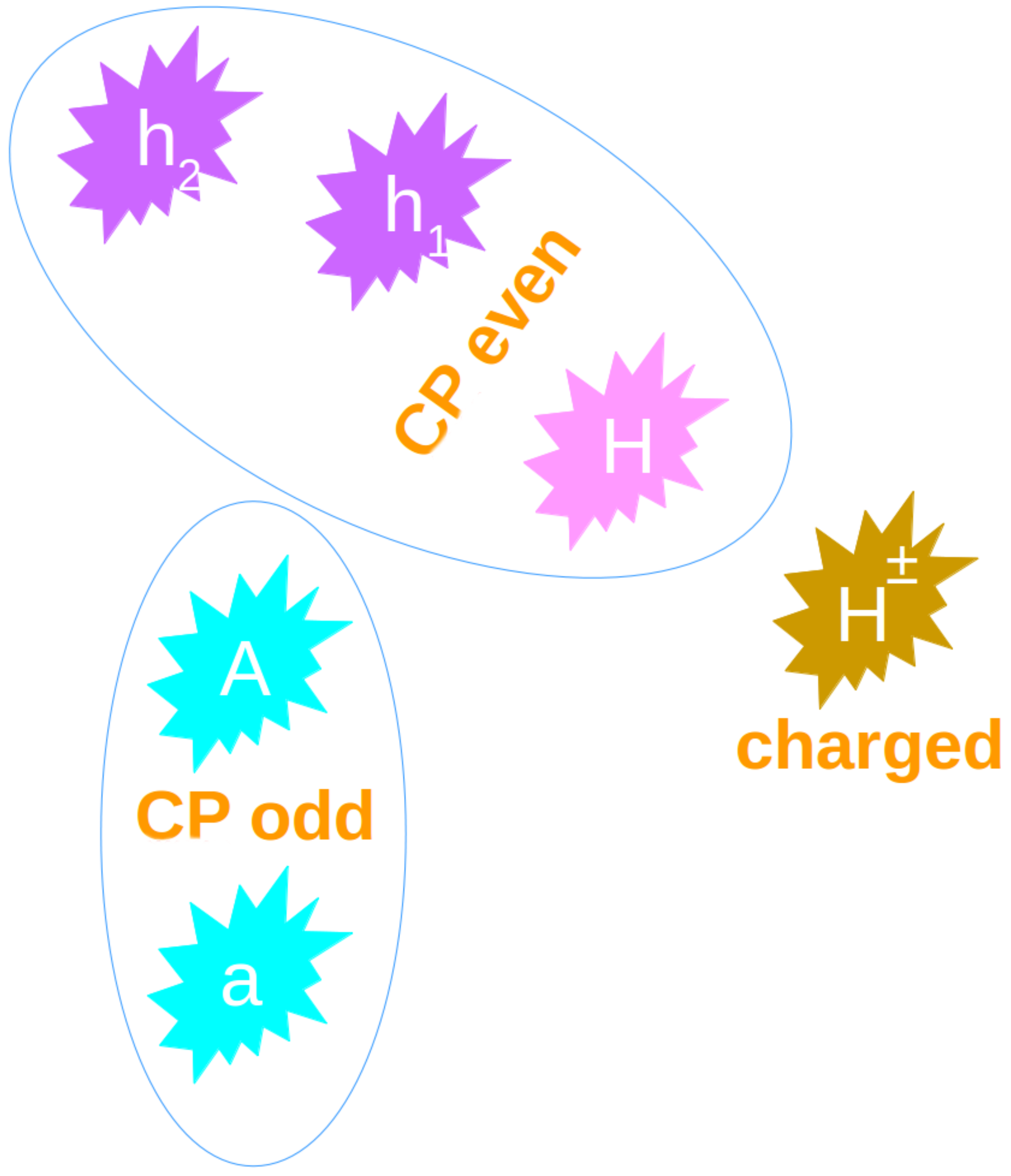
- For many BSM processes, Higgs bosons play a crucial role
  - Additional Higgs bosons in enlarged Higgs sectors
  - Exotic decays of the 125 GeV Higgs boson
  - Properties disagreeing with the SM (e.g. lepton flavor violation)



Various theoretical models investigated in analyses presented today





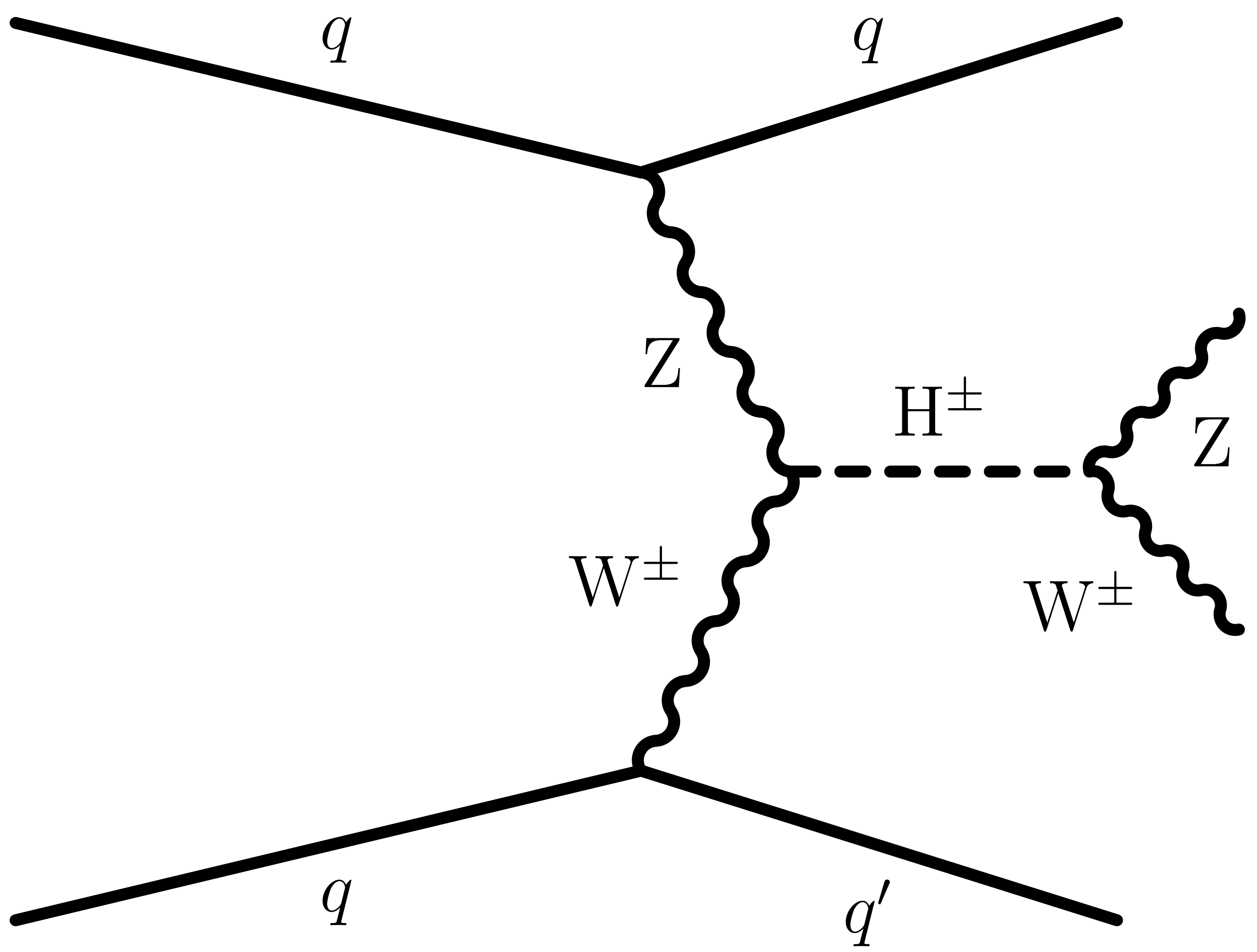


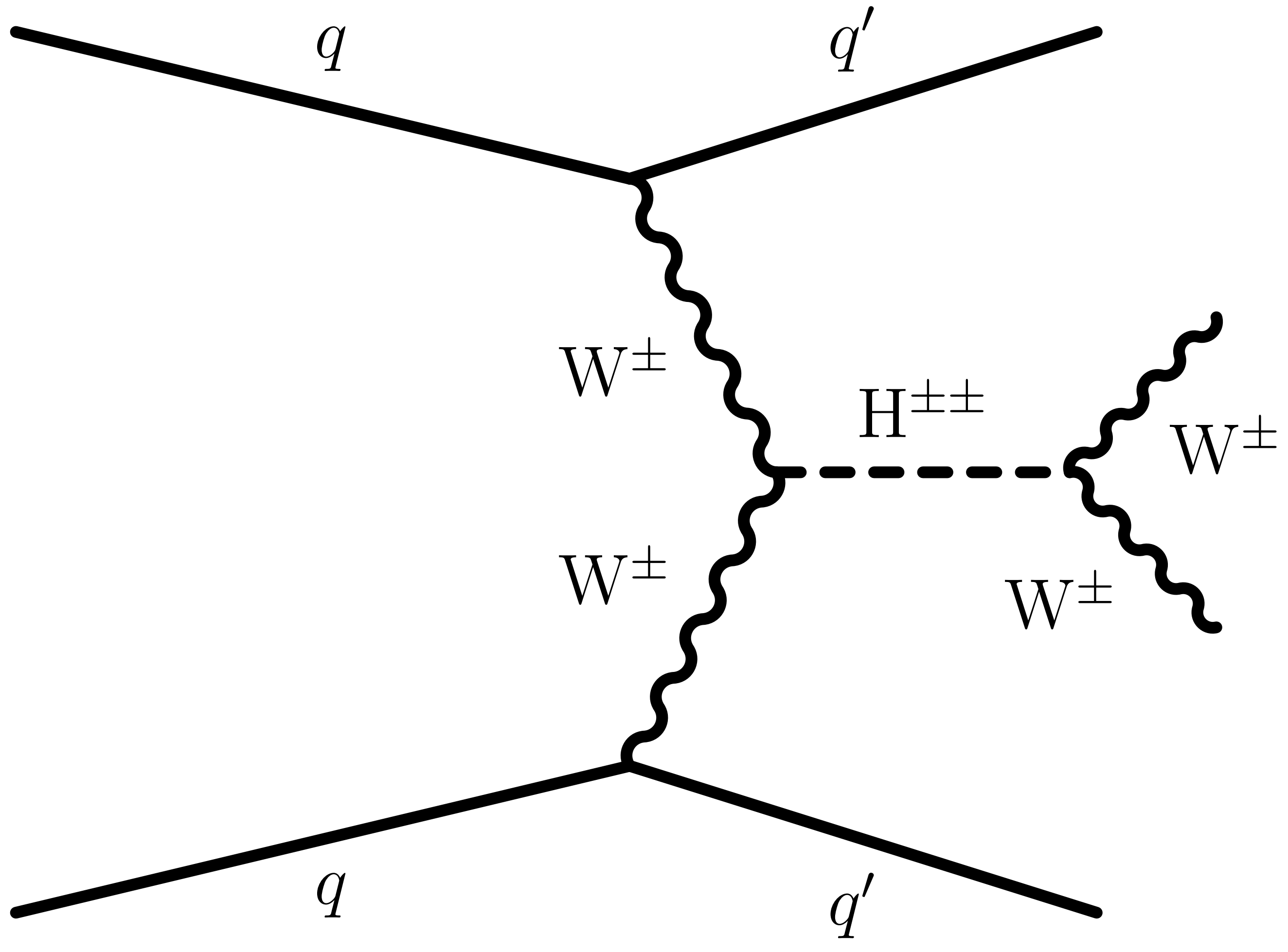
SEARCH FOR CHARGED HIGGS BOSONS IN VBF PRODUCTION

Produced in vector boson fusion and decaying into vector bosons (Full Run 2, 137 fb^{-1})

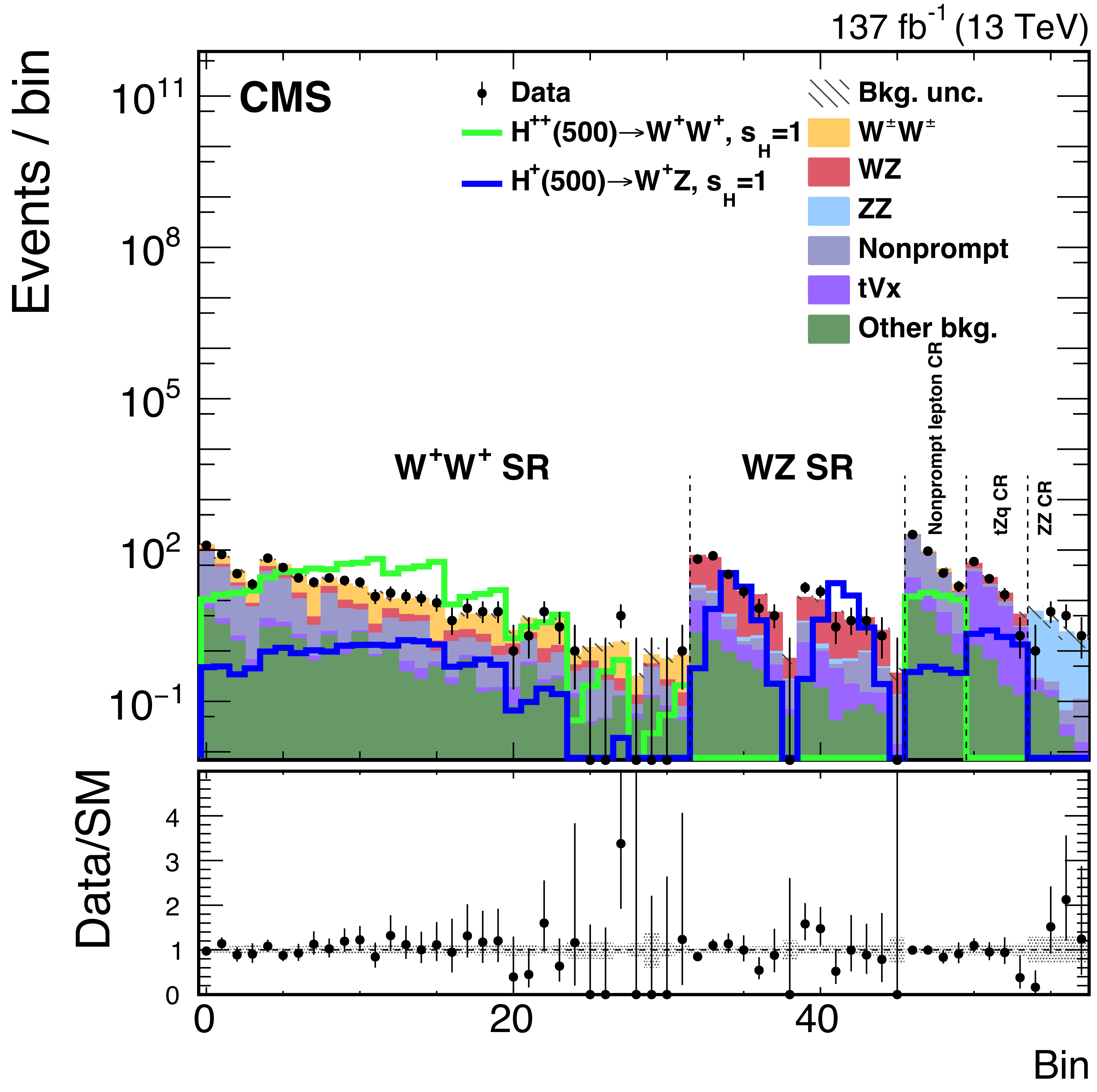
arXiv: 2104.04762

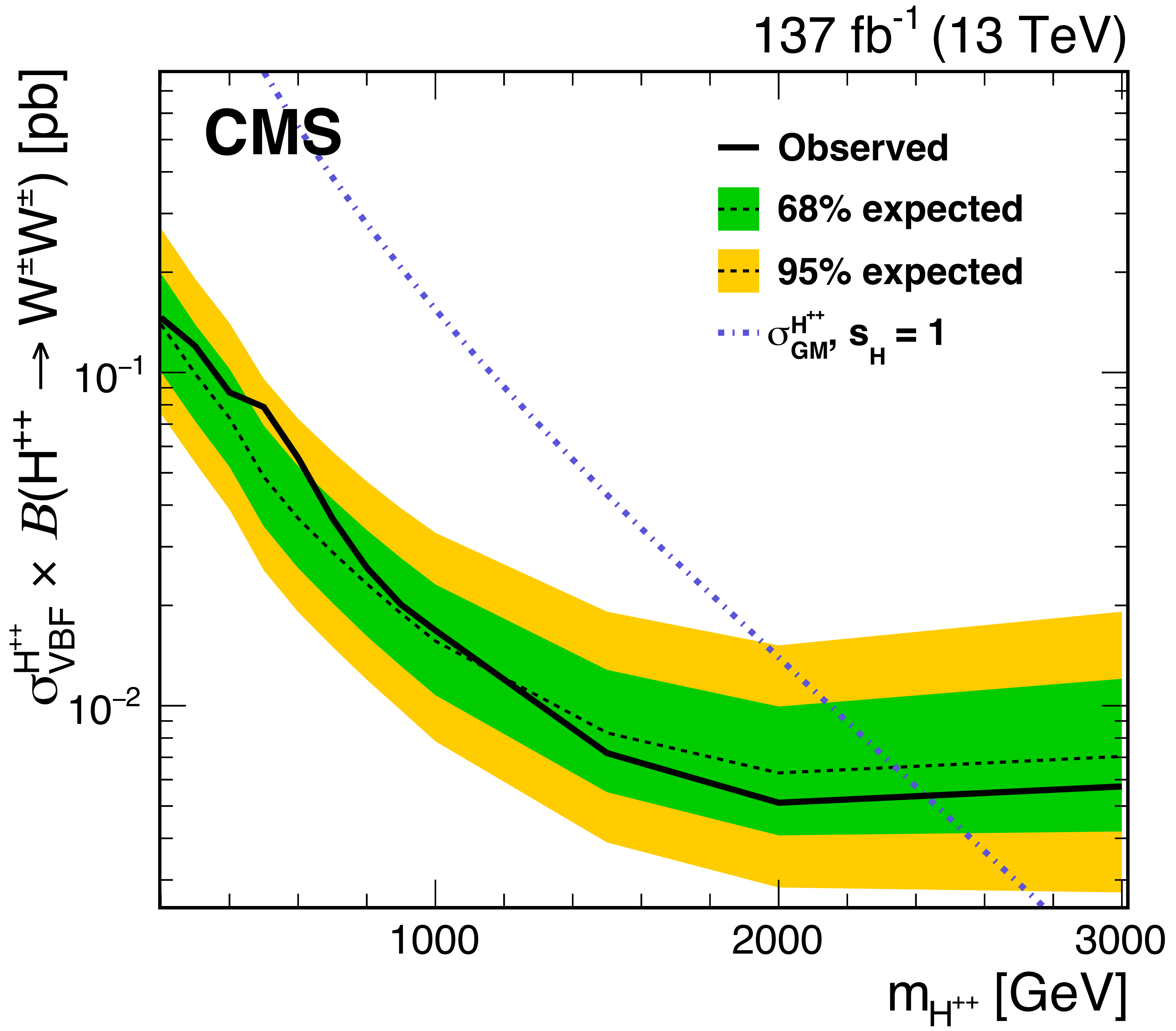
- Extended Higgs sectors with additional SU(2) doublets or triplets introduce couplings of gauge bosons to heavy Higgs bosons
- Georgi-Machacek (GM) model: global $SU(2)_L$ X $SU(2)_R$ symmetry, broken by Higgs vacuum expectation value to subgroup $SU(2)_{L+R}$
  - Ratio of masses of W and Z bosons at tree-level protected from large radiative corrections
  - Singly/Doubly charged Higgs bosons produced in vector boson fusion (VBF), decaying into vector bosons
  - $H^{\pm}$ and $H^{\pm\pm}$ degenerate in mass
  - Additional $H^{\pm}$ bosons in GM model, transforming as triplet under $SU(2)_{L+R}$, leading to fermionic couplings

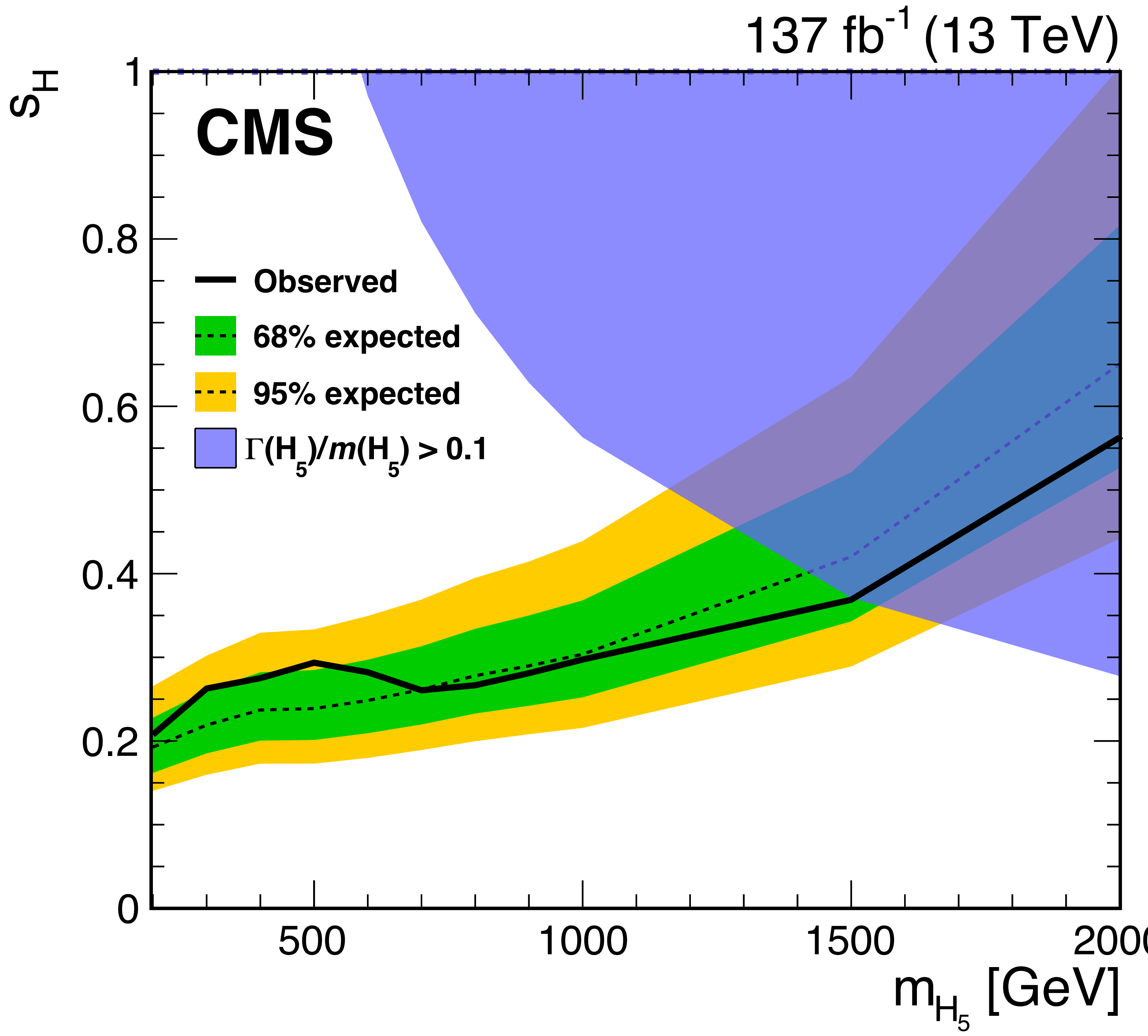




- Individual signal regions (SRs) for WZ and WW topologies, requiring or rejecting events with $|m_{ll} - m_Z| < 15$ GeV
  - Target VBF with $m_{jj} > 500$ GeV and $|\Delta\eta_{jj}| > 2.5$ for leading two jets
- Background estimated based on combination of simulation and three control regions (CRs) with reversed selection criteria in data
  - Prediction of QCD WZ background validated in CR, showing good agreement with data
- Simultaneous fit of WZ/WW SRs and CRs
  - SRs: Two-dimensional distributions (m_{jj} and m_T^{VV}); CRs: One-dimensional distribution (m_{jj})





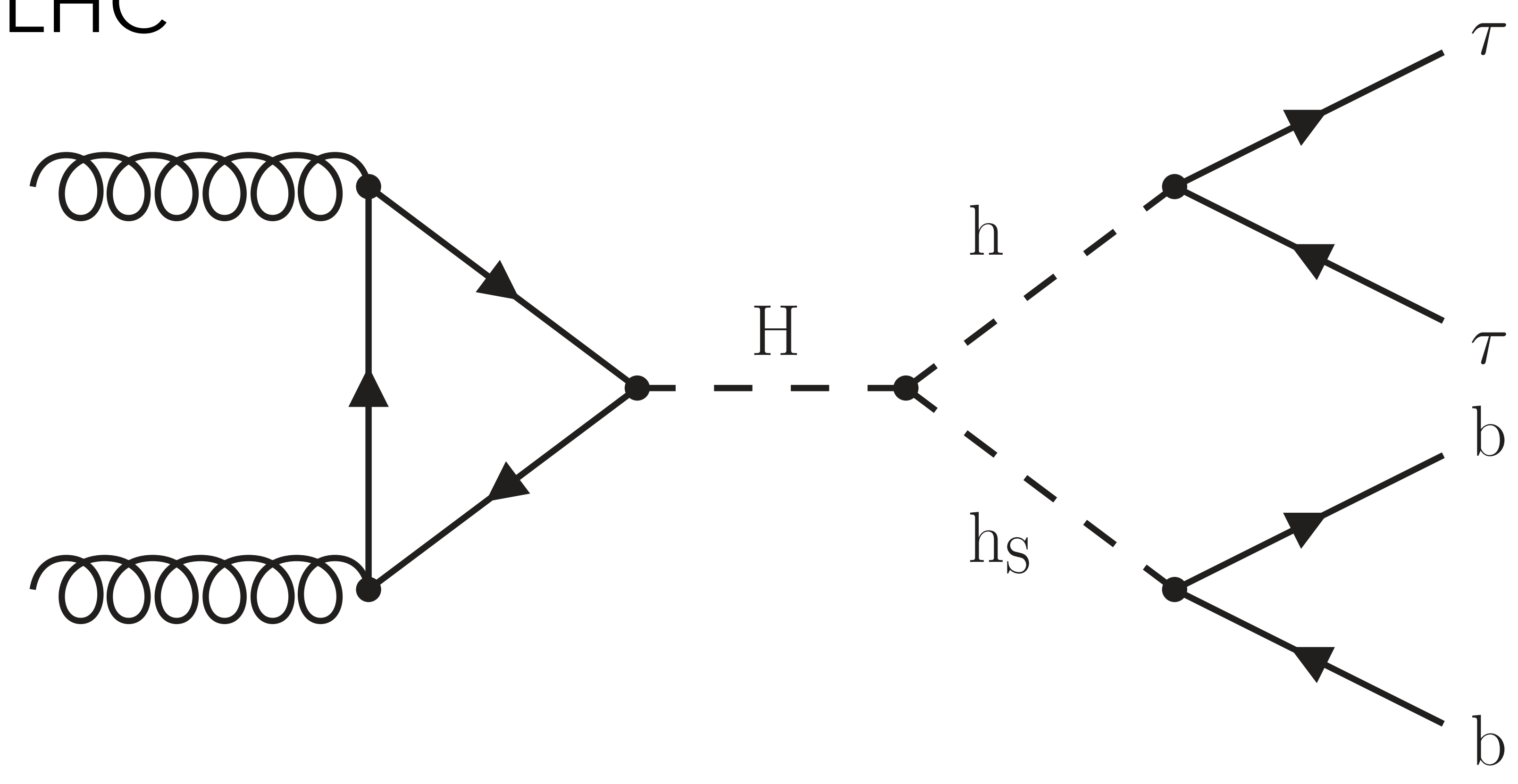


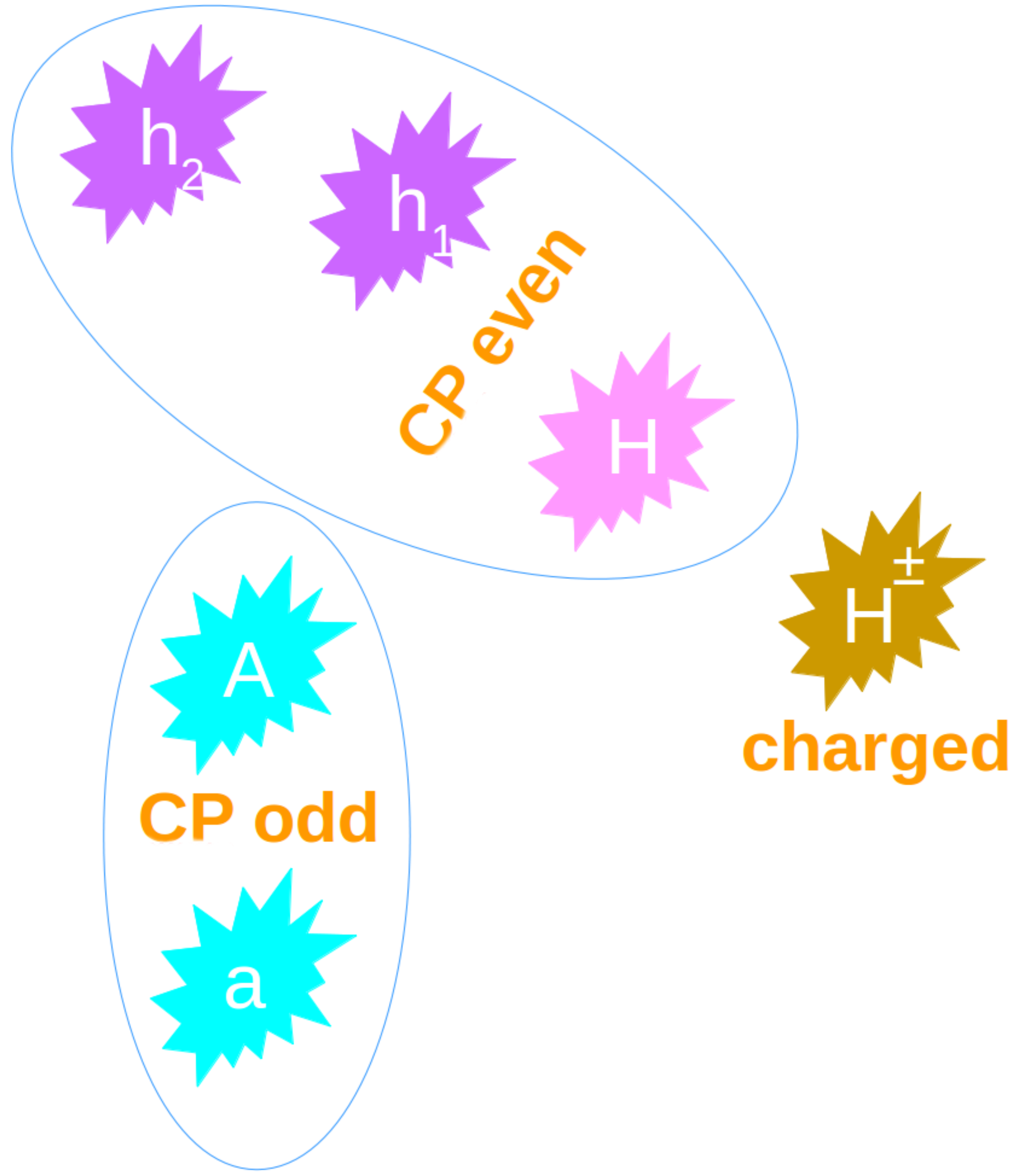
- No significant deviation from SM: limits calculated on cross-section times branching fraction of charged Higgs boson
- Interpretation in terms of m_{H5} ($m_{H\pm}$ and $m_{H\pm\pm}$) and s_H (s_H^2: fraction of W boson mass squared generated by vacuum expectation value of triplet fields)
- s_H range of 0.20 to 0.35 excluded for m_{H5} of 200 to 1500 GeV, significantly improving previous CMS results (s_H > ~0.4)

SEARCH FOR ADDITIONAL NEUTRAL HIGGS BOSONS

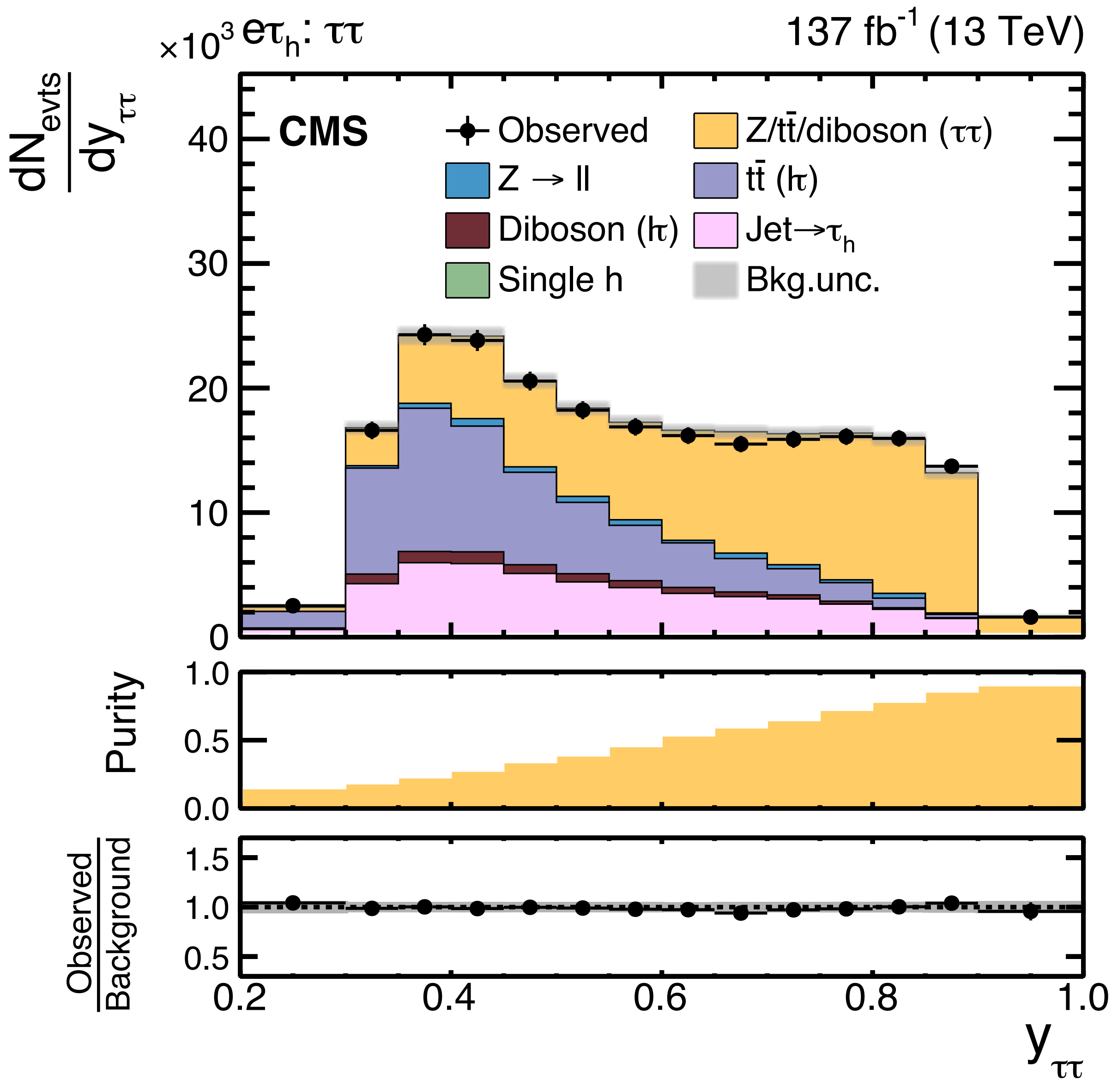
Decay of a heavy neutral Higgs boson H into a pair of lighter neutral bosons h in the bbττ final state (Full Run 2, 137 fb^{-1}) arXiv: 2106.10361

- Heavy, neutral Higgs boson H decaying into 125 GeV boson h and additional state h_S, $m_{h_S} < |m_H - m_h|$
  - Subsequent decays: $h \to bb$, $h_S \to \tau\tau$
  - Predicted for example in next-to-minimal supersymmetric standard model NMSSM
  - Additional Higgs doublet plus singlet leading to seven Higgs bosons
    - h_S assumed to have significant admixtures from singlet; thus: suppressed couplings to SM particles and preferred production in H decay
- First search of this signature at the LHC

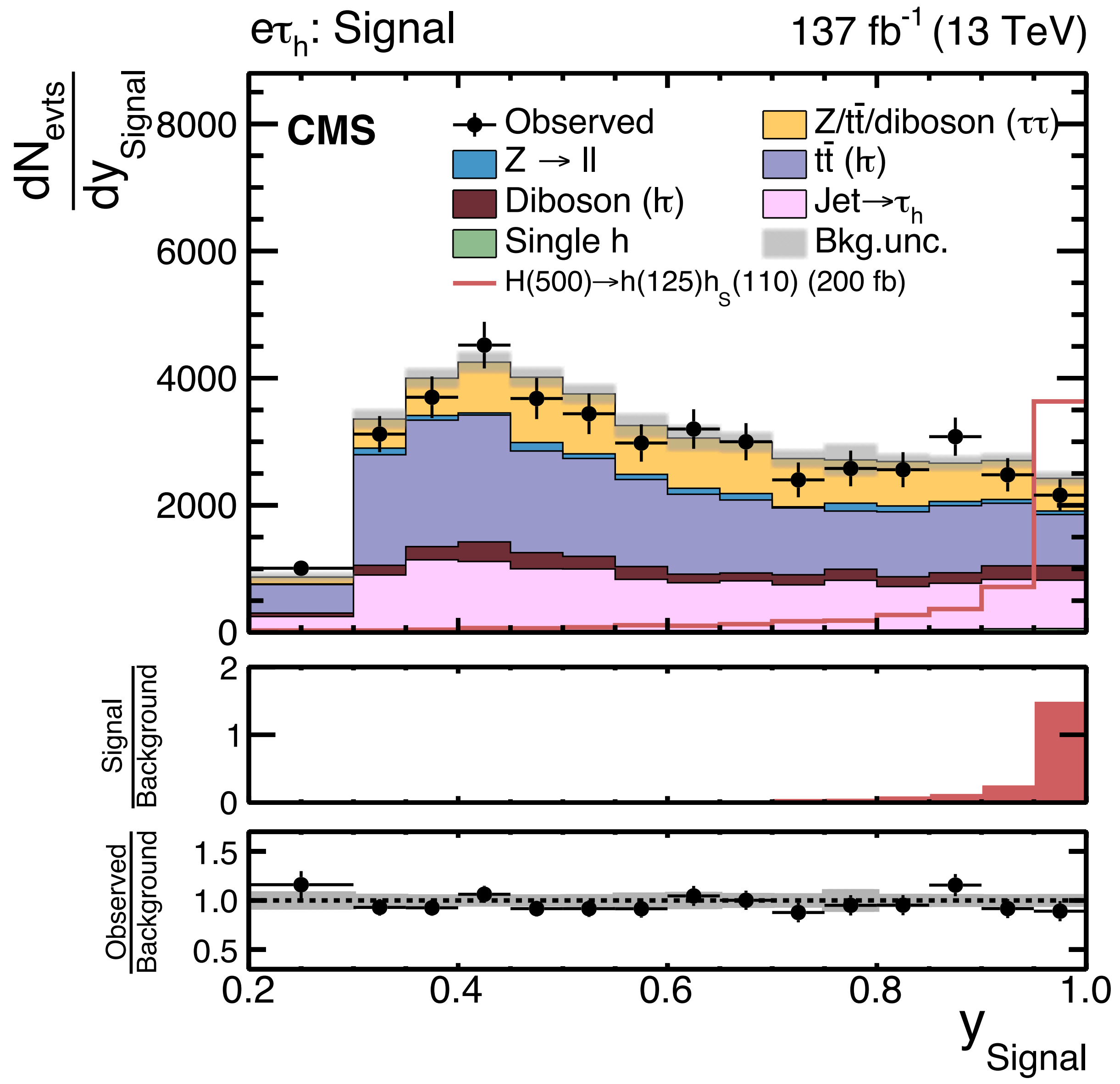




- Requiring $m_{\tau\tau}$ to be close to 125 GeV and opposite-sign τ leptons; m_{bb} ranging from 60 to 2800 GeV
  - τ final states can be $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$, $\tau_{had}\tau_{had}$, identified by DeepTau algorithm; at least one b-jet required, selected by DeepJet algorithm
- Several neural networks (NN) used to assign event to the SR or a CR for certain regions of m_H and m_{hS}
- Different background estimation procedures used depending on final state



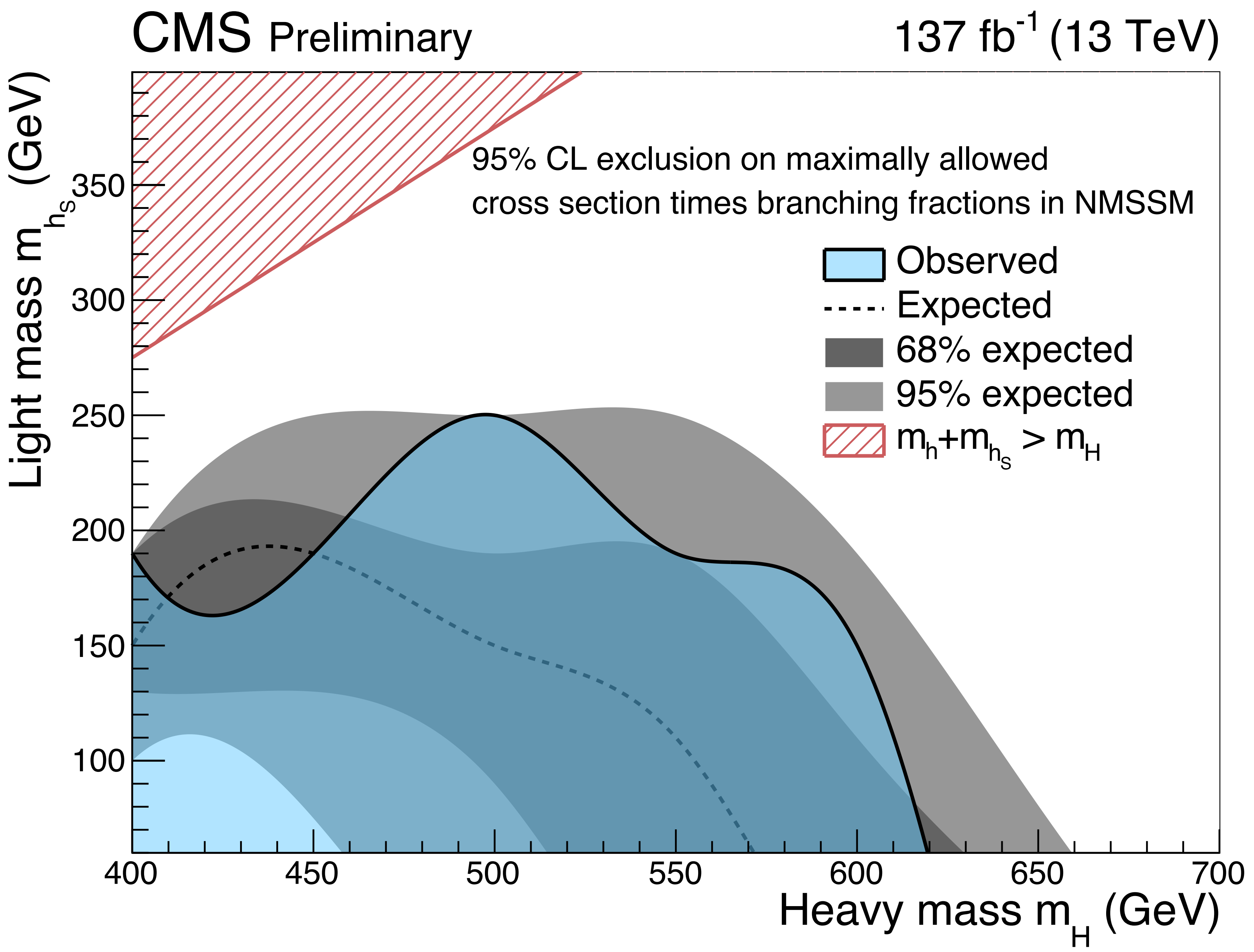
- ττ background and signal region in the $\tau_e\tau_{had}$ final state after NN classification
- m_H = 500 GeV, 100 GeV ≤ m_{hS} ≤ 150 GeV

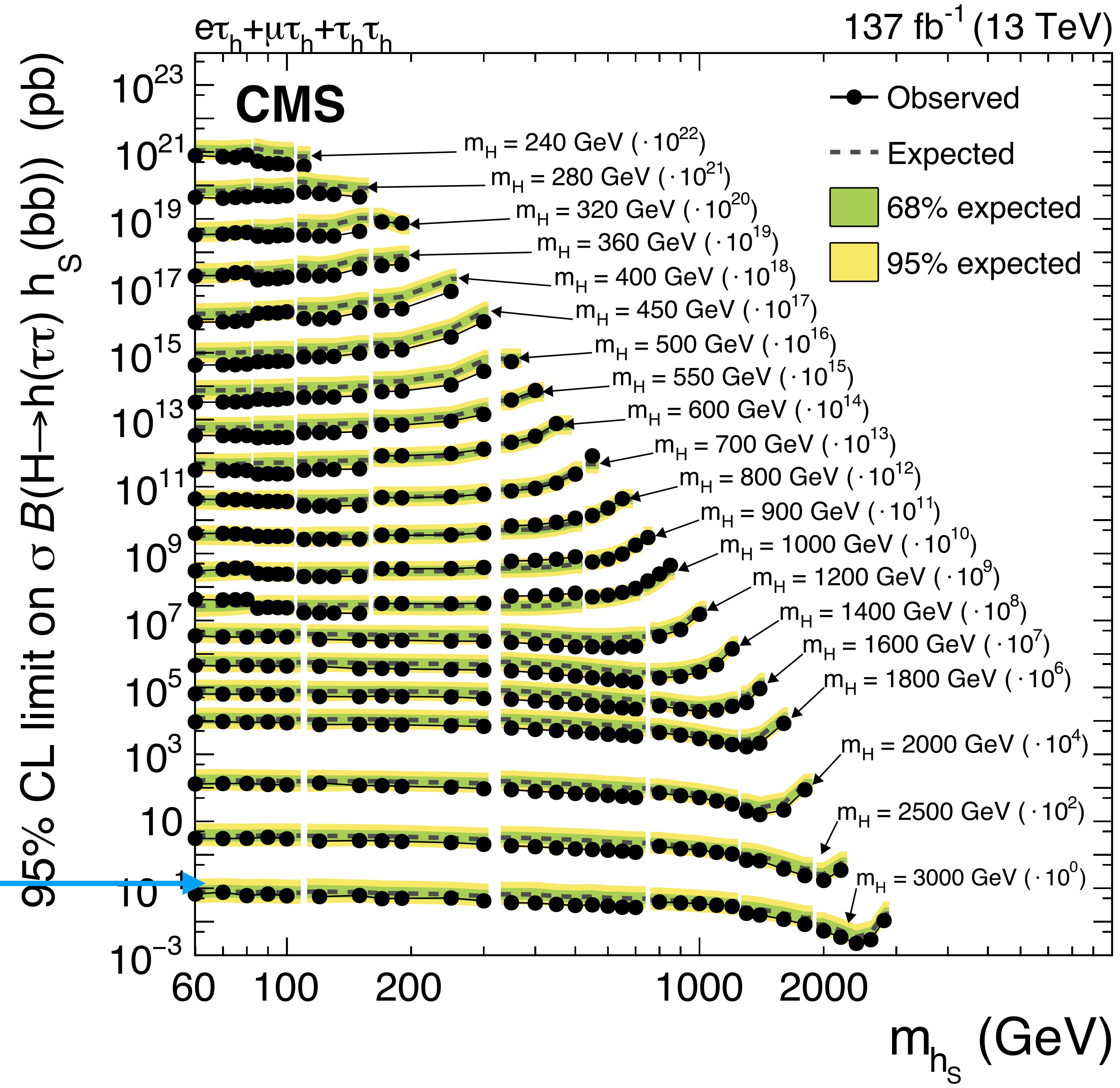


- Model independent limits from 2016, 2017, and 2018 for all final states

- 240 GeV ≤ m_H ≤ 3000 GeV

- Limits range from 125 fb (m_H = 240 GeV, m_{hS} = 85 GeV) to 2.7 fb (m_H = 1000 GeV, m_{hS} = 350 GeV)





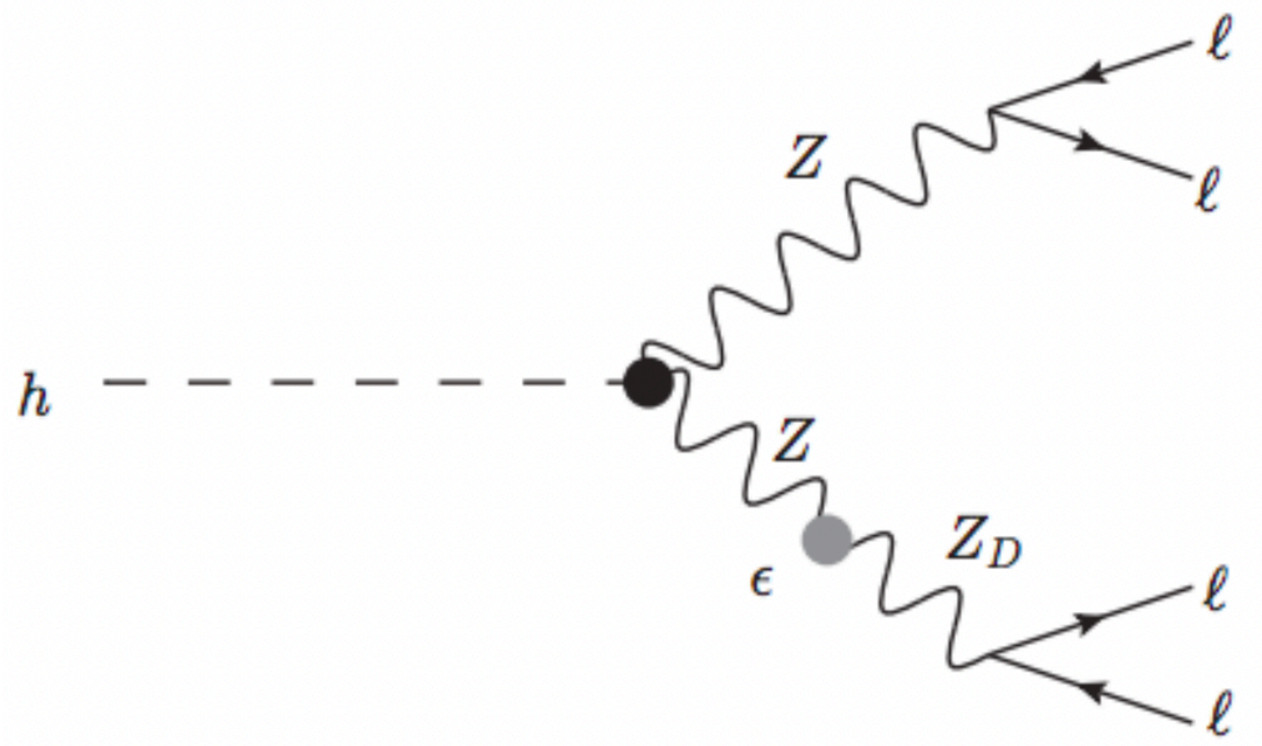
Unscaled

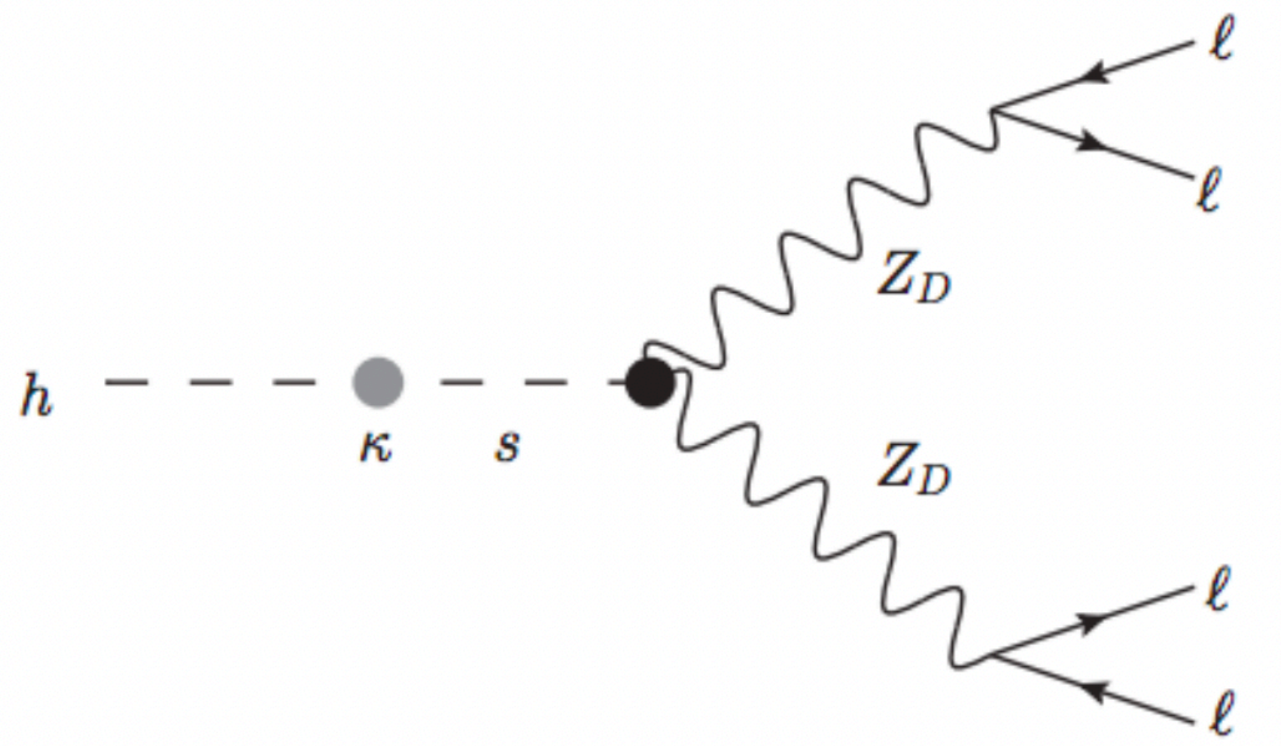
- Interpretation in terms of NMSSM:
  - Mass regions excluded based on maximally allowed cross-section times branching fraction

SEARCH FOR A LOW MASS DI-LEPTON RESONANCE

Decay of the Higgs boson into exotic particles; four-lepton final state (Full Run 2, 137 fb^{-1}) HIG-19-007

- Exotic decay signatures of the 125 GeV Higgs boson, H → ZX or H → XX; final states: 4e, 4μ, 2e2μ
  - X: possible new, neutral particle decaying into a pair of same-flavor leptons, m_X < 35 GeV (m_X < m_H/2 ≈ 62.5 GeV) in H → ZX (H → XX) allowed for on-shell decays
  - 4l channel clean, large signal-to-background ratio, allowing for full reconstruction of event kinematics
- Two specific models considered:
  - Dark photon (Z_D) model with X = Z_D; interaction of dark sector with SM via kinematic or Higgs mixing
  - Axion-like particles (ALPs), X = gauge singlet pseudo scalar (a); first search for H → Za

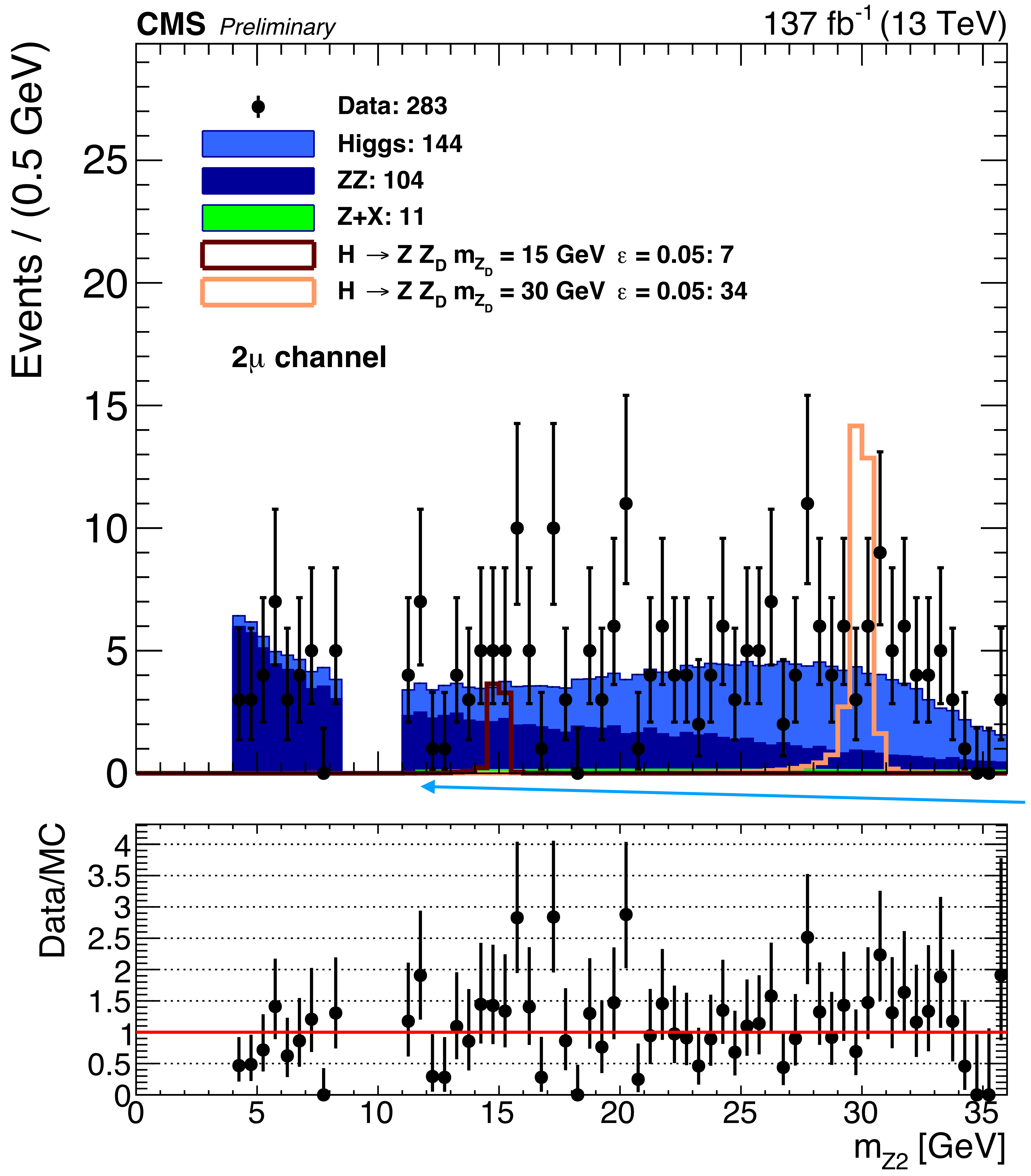




SEARCH FOR A LOW MASS DI-LEPTON RESONANCE

Event selection and background estimation

- Leptons must be isolated, 118 GeV ≤ m_{4l} ≤ 130 GeV, and m_{l+l-} > 4 GeV (regardless of lepton flavor) to reduce background from jet fragmentation
  - Several combinations of leptons and assignment to decay products (Z and X) considered
- Main irreducible background from SM Higgs and ZZ production
- Reducible backgrounds mainly from Z + jets production, estimated by use of two control regions, inverting identification criteria for one/two leptons from signal selection
  - Predict background in SR by reweighting events in CRs by lepton misidentification probabilities
  - Observation in all channels agrees well with prediction within uncertainties



ε: Z ↔ Z_D mixing

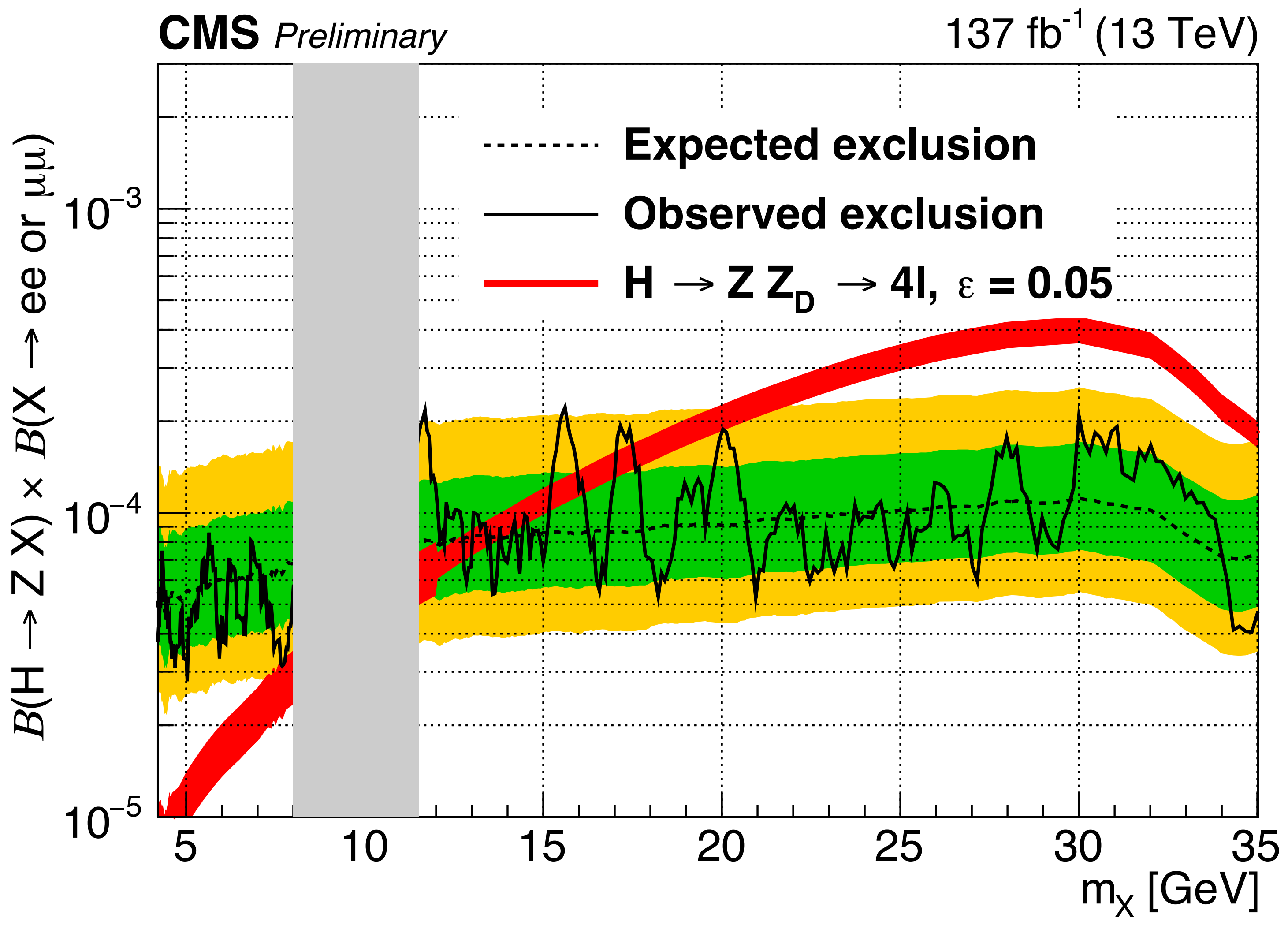
Excluded mass window accounts for Υ meson

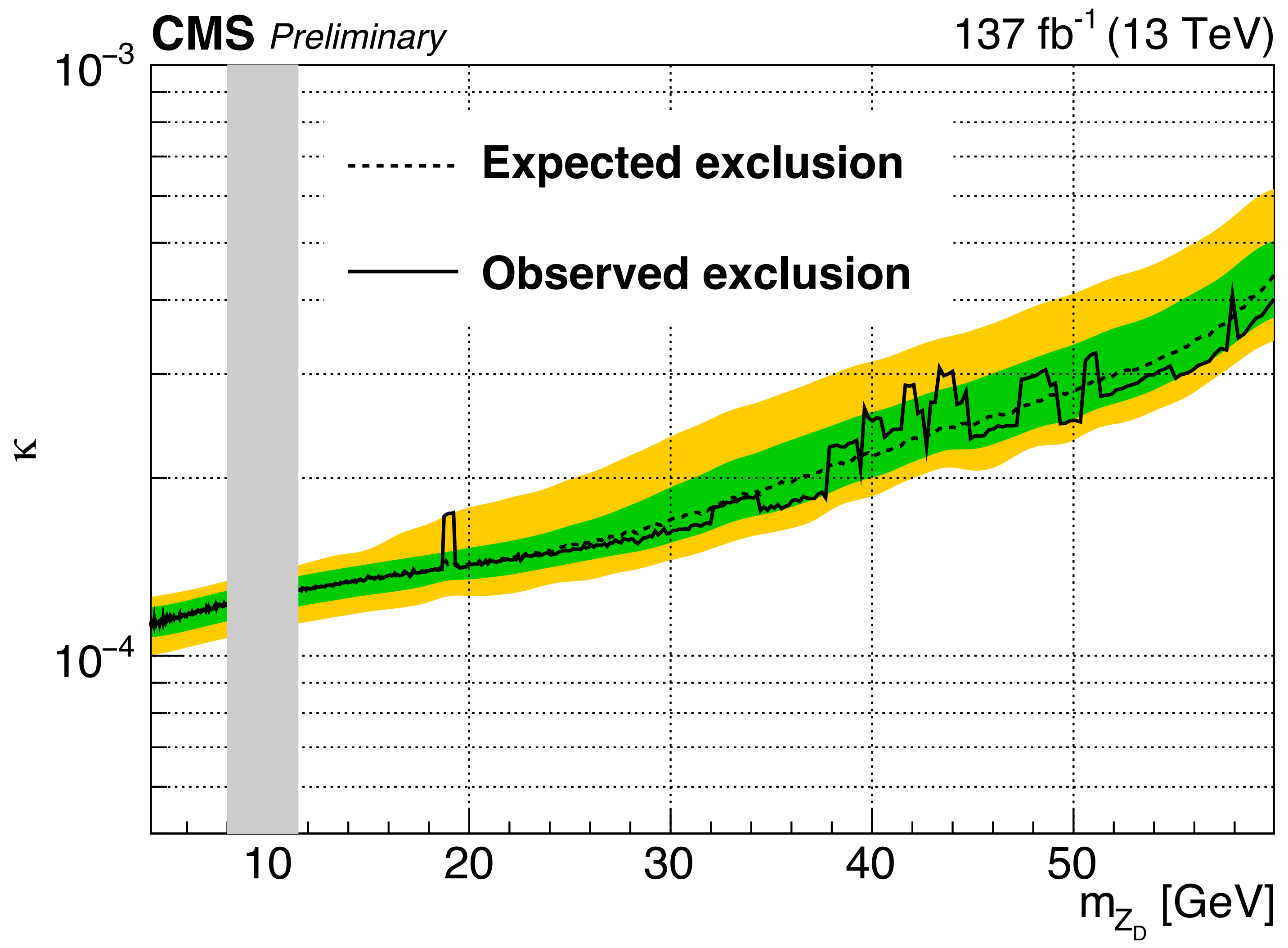
Z_2: lighter di-lepton candidate

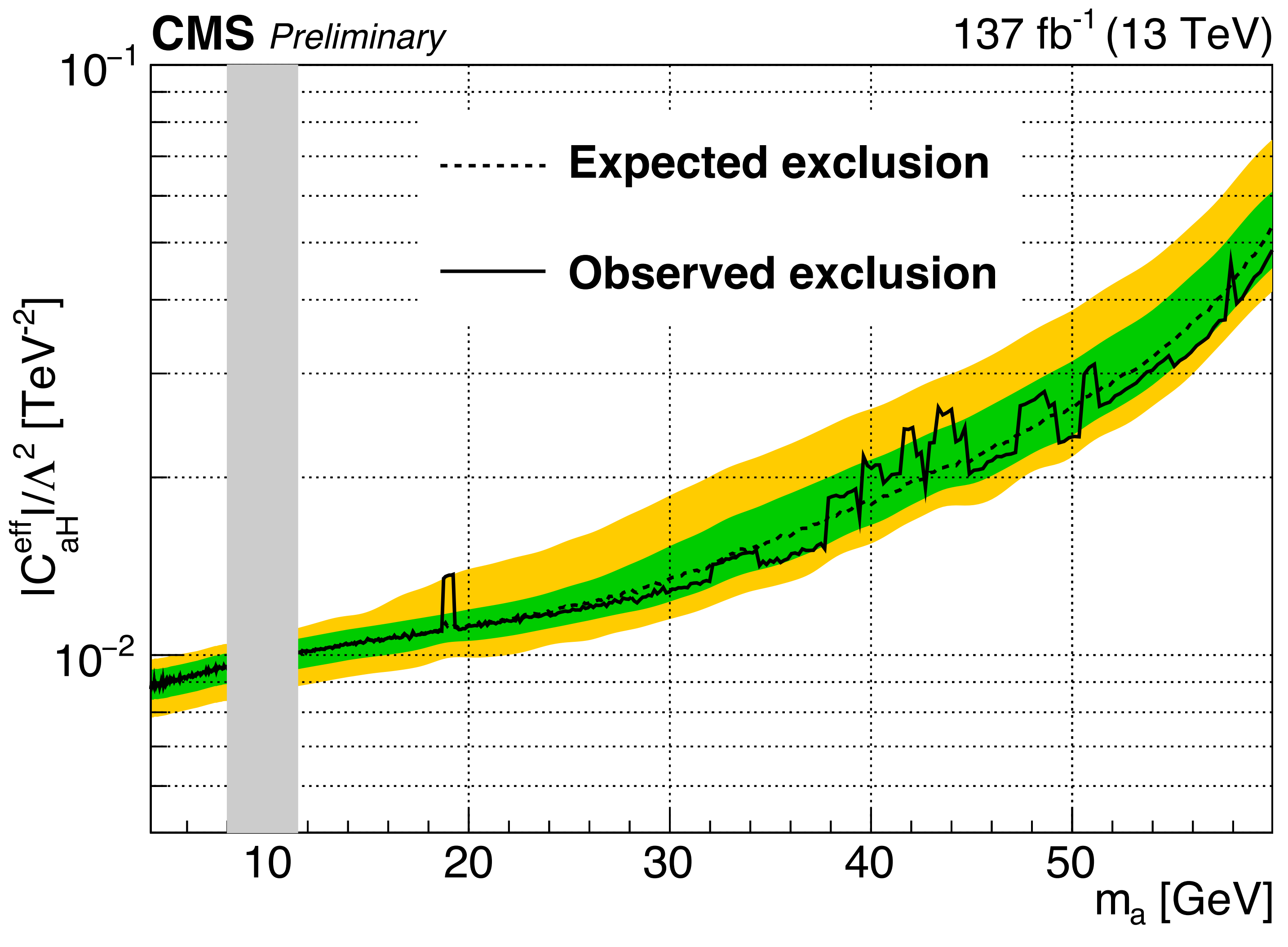
SEARCH FOR A LOW MASS DI-LEPTON RESONANCE

Results

HIG-19-007







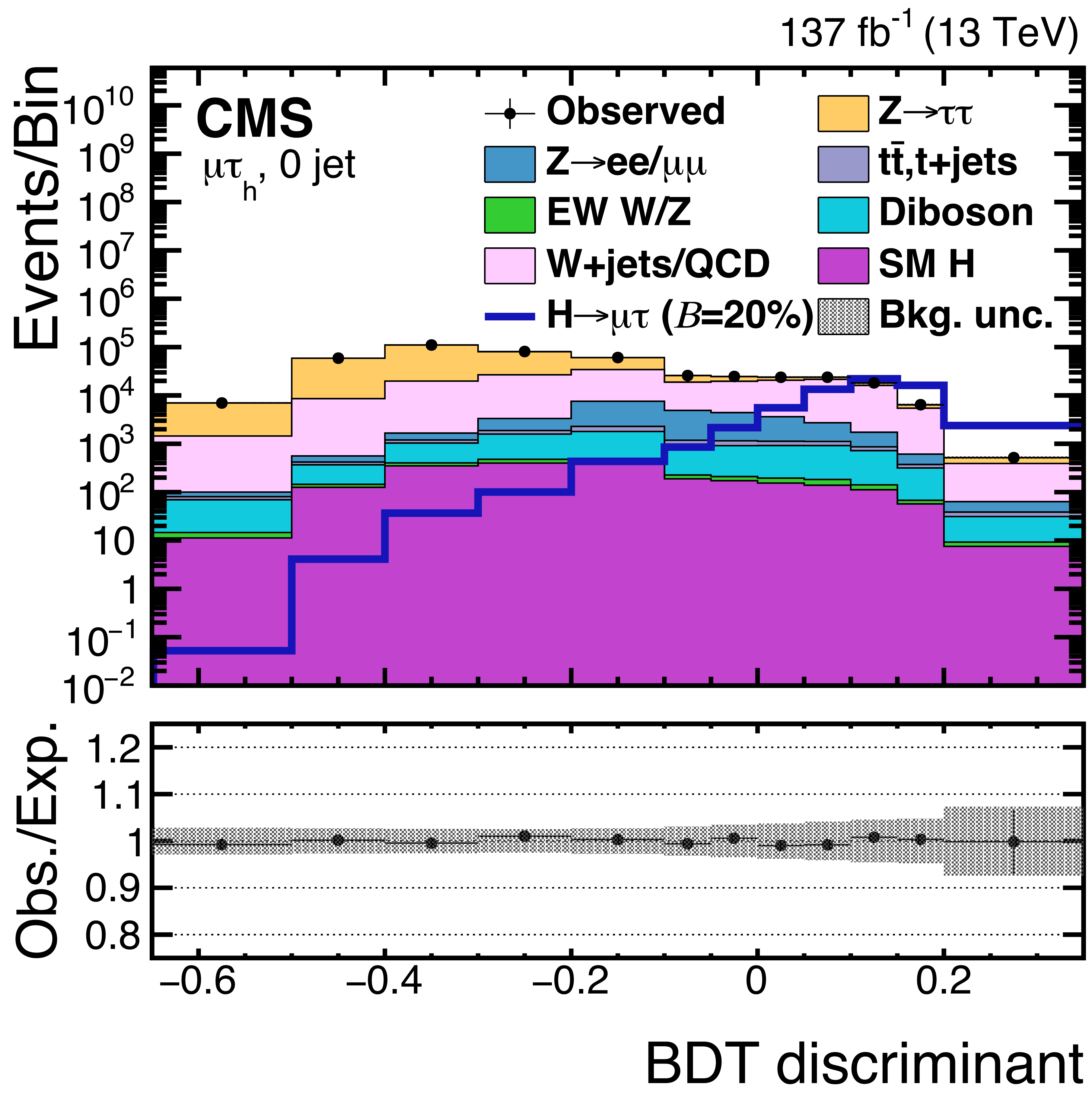
Model independent;
ZX selection

κ: Higgs mixing parameter
(Dark-photon model)

C_{aH}^{eff}: effective coupling of
Higgs boson and ALP;
Λ: new physics scale

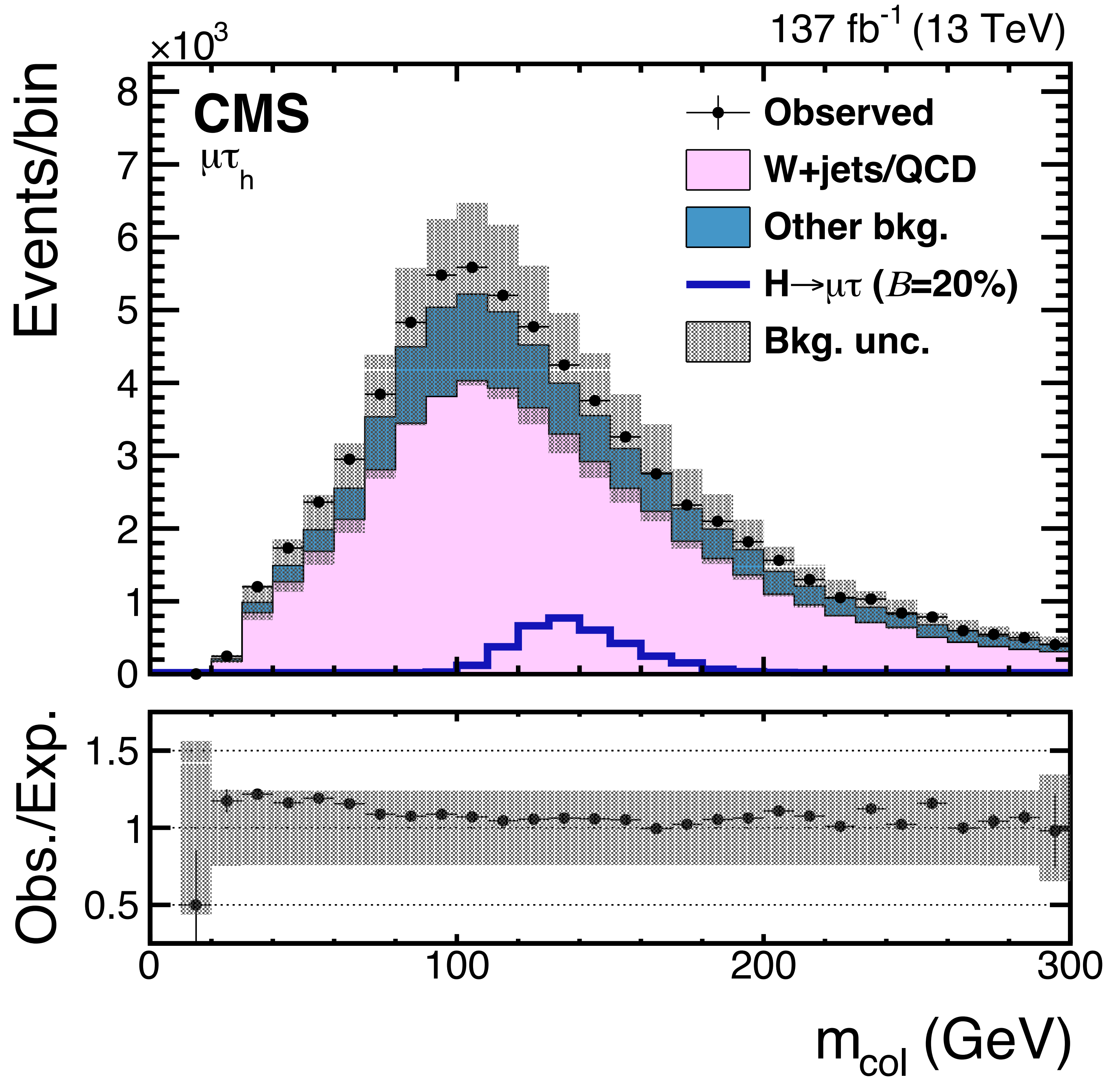
- No significant deviation from SM observed → strong limits set
- Several hundred mass hypotheses considered for both XX and ZX final states; excesses with largest local significance: 2.9 and 3.0σ at m_X of 18.8 and 15.6 GeV, respectively
- Limits on production cross-section times branching fraction interpreted in terms of dark-photon and ALP models

- Lepton-flavor violating (LFV) decays of Higgs boson forbidden in SM, would indicate new physics
  - Predicted in certain 2HDM, SUSY, extra-dimension, and composite-Higgs models
  - Search in eτ and μτ channels (results on μ → eγ strongly constrain $\mathscr{B}$(H → eμ) to < 10^{-8})
    - Exclude $e\tau_e$ and $\mu\tau_\mu$ modes and require prompt lepton to suppress Z and H → ττ backgrounds
- Distinguishing between signal and background using BDT
  - Separating production modes by number of jets



0 jet category: mainly gluon-gluon fusion

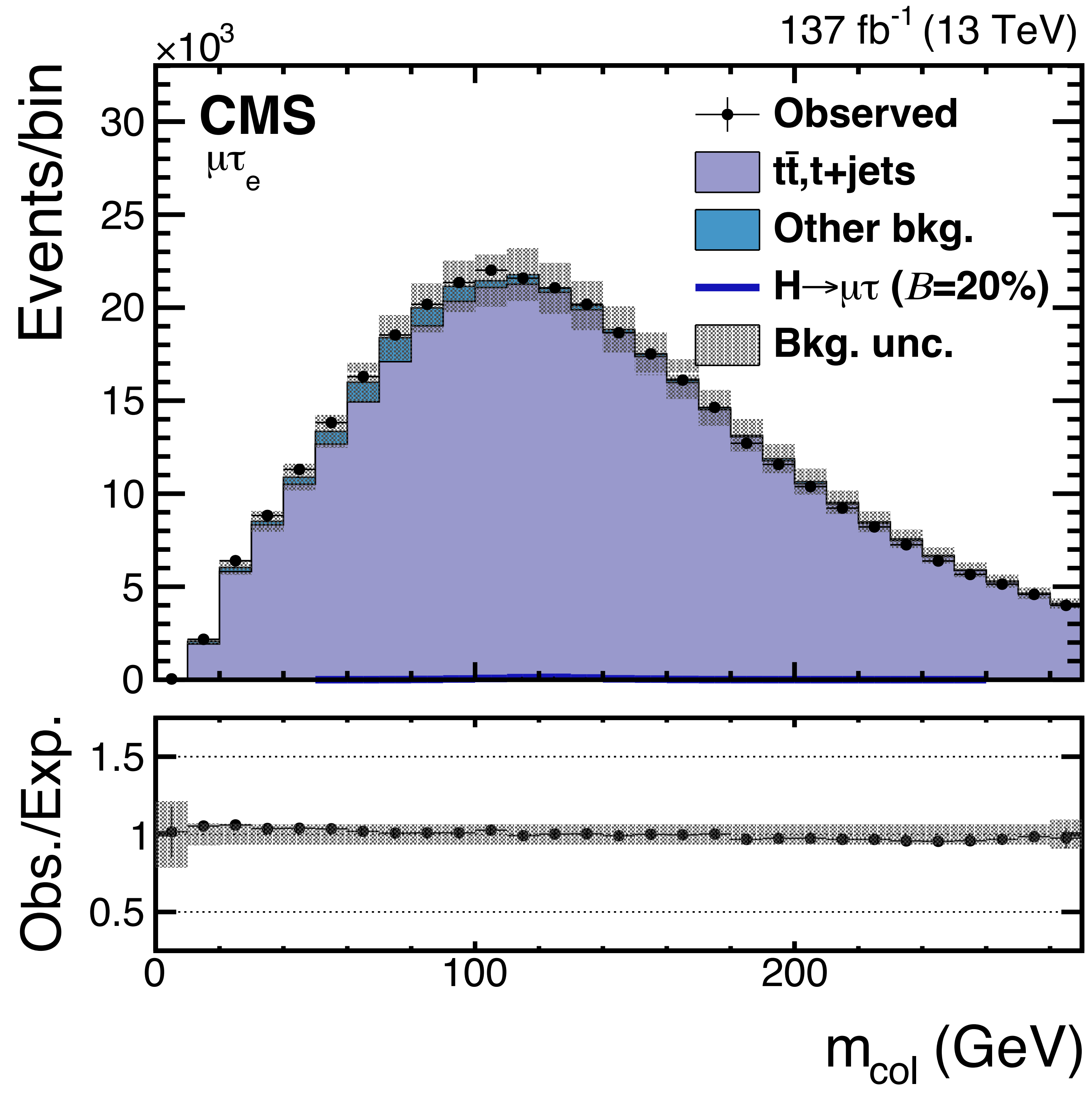
- $Z \to \tau\tau$ background estimated from embedded events, where muon in $Z \to \mu\mu$ is replaced by simulated τ
  - CRs used to estimate W+jets, QCD multi jet, and other backgrounds (e.g. $t\bar{t}$); validated in different CR
  - Background in CRs well described by estimate from independent CRs



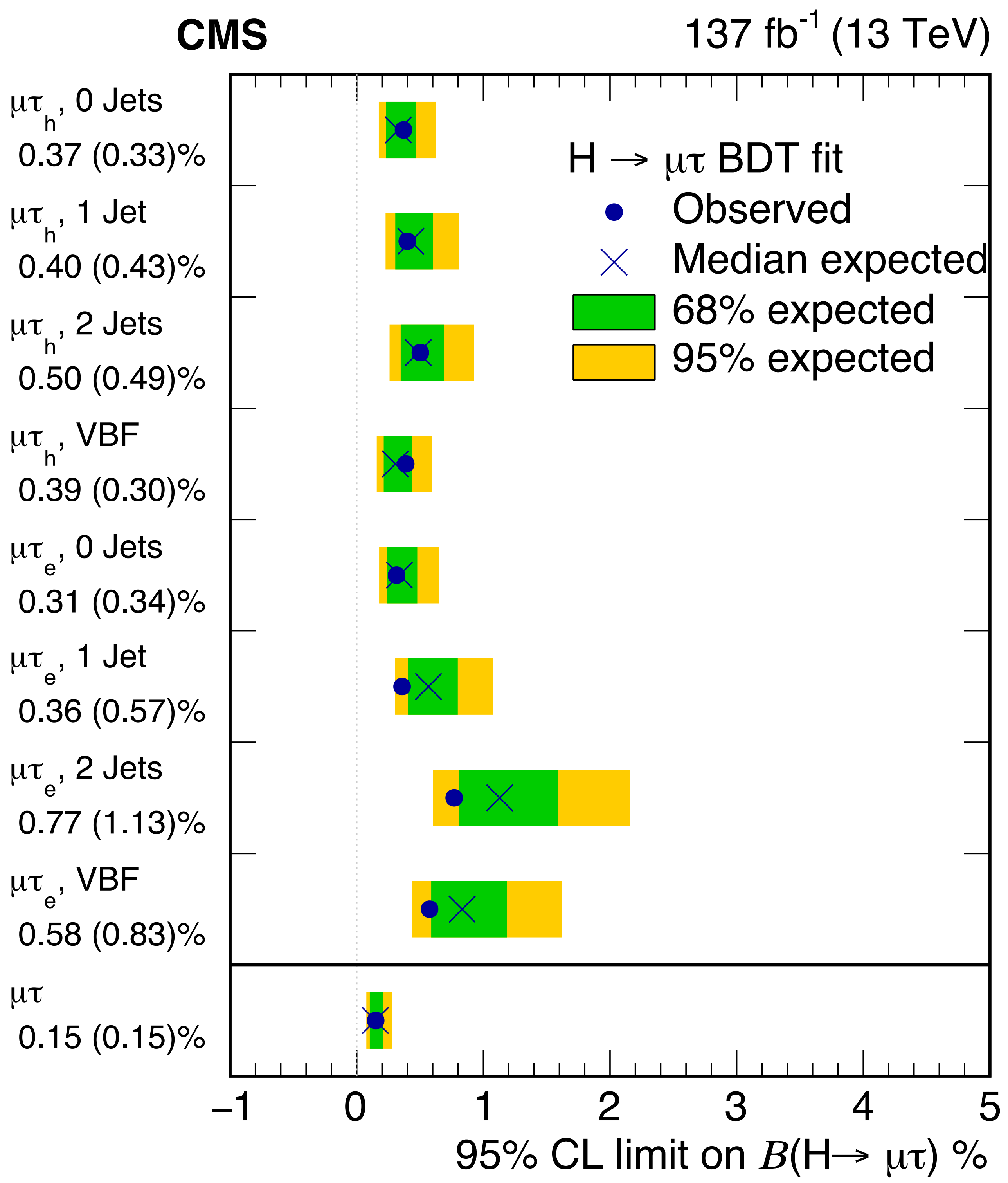
W + jets CR

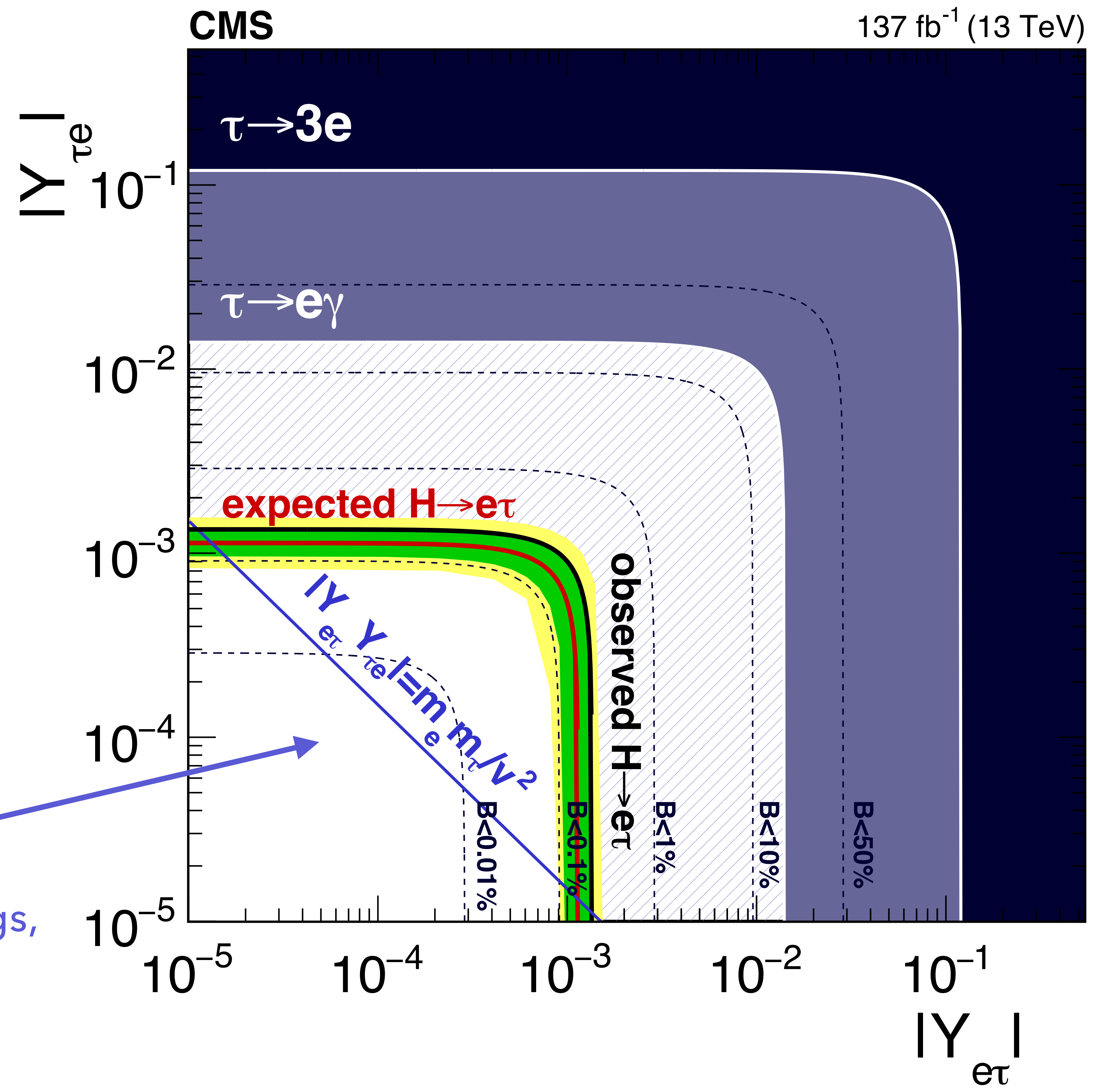
m_{col}: collinear mass, estimating m_H
→ since $m_H \gg m_\tau$, τ decay products boosted
m_{col} CR used to cross-check BDT-based CR

$t\bar{t}$ CR



- No significant deviation from SM predictions observed
  - Limits calculated on branching fraction and translated to constraints on LFV Yukawa couplings Y
  - Assumption: Only one LFV decay additionally contributes to Γ_H as well as LFV Yukawa couplings





Flavor diagonal Yukawa couplings, based on SM values

SUMMARY

- Presented various searches for Higgs physics beyond the Standard Model
- No significant deviations from SM observed yet
- Additional exciting analyses to be published, lots of Run 2 BSM results still to come
  - Significant improvement in statistical precision to come with LHC Run 3 and HL-LHC

Thank you very much for your attention

BACKUP

Structure of Higgs Sector (Search for Singly/Doubly Charged Higgs Bosons in VBF)

arXiv: 2104.04762

- Doublet field Φ, with hyper charge $Y = 1/2$, triplet field with complex part χ ($Y = 1$) and real part ξ ($Y = 0$)
- Triplet vacuum expectation value of few GeV with appropriate Yukawa couplings can contribute to m_ν
- Couplings between triplet field and leptons lead to lepton-number violating processes, perhaps lepton-flavor violating
- Mass degeneracy within each multiplet
- In quintuplet representation, $H^{\pm\pm}$ is present (these are targeted by the analysis)
- Mixing of doublet and triplet → 125 GeV h can couple stronger to vector bosons than predicted in SM
- Physical states: $H_5 = (H_5^{\pm\pm}, H_5^{\pm}, H_5^0)$, $H_3 = (H_3^{\pm}, H_3^0)$, plus two singlets with one mass eigenstate each of which one is associated with the 125 GeV boson; charged particles of a multiplet degenerate in mass

- Neural networks used to assign events to SR and CRs
  - CRs used to constrain systematic uncertainties in final fit
  - Five output nodes reflect one event category each: $\tau\tau$, jet → τ_h, $t\bar{t}$, misc, SR
  - Kinematic properties strongly depended on combination of Higgs-boson masses → 68 NNs per final state used, differing only in kinematic properties of the signal used for training
    - Adjacent sets of mass points combined
  - After training: very good separation between non-peaking background and signal events achieved, purity of correct assignment to analysis category >80%

- $\tau\tau$ background estimated from τ embedding method
  - Target events with Z/W boson decays yielding genuine τ leptons
  - Take respective events with muons and replace them with simulated τ to mask signal contributions
- Background induced from jets misidentified as τ_h estimated using F_F method
  - Mainly QCD multijet events
  - Extrapolation factors determined in CRs used to estimate background in SR using application region
    - $N_{SR} = F_F N_{AR}$, F_F from CR (one CR each for QCD, W+jets and $t\bar{t}$)
- Other backgrounds from simulation
  - In $\tau_h\tau_h$ final state: ~95% of background from previous two methods, in $e\tau_h$ and $\mu\tau_h$ only about 42%
  - Remaining background processes (e.g. Z, $t\bar{t}$, di boson production) and signal modeled in simulation

- Depending on τ decay: events split into leptonic and hadronic categories
- No events with more than 2 jets considered
  - In leptonic and hadronic channel: 0- (ggH), 1- (ggH + ISR), and 2-jet categories for different production processes
    - 2-jet further split based on m_{jj} >/< 500 (550) GeV for eτ (μτ) channel → >: VBF, <: ggH
- One BDT per channel to distinguish signal and background, trained with ggH and VBF induced simulated events
- CRs also used for training, defined based on inverted isolation requirements for each lepton