National Taiwan University

# Searches for Additional Scalar Bosons with CMS

Efe Yazgan

on behalf of the CMS Collaboration

# Are there additional Higgs-like States?

- Many extensions of the SM involve additional Higgs bosons.
  - To explain baryogenesis, dark matter, hierarchy problem, …
- Such scalar particles at mass scales < 1 TeV within the reach of the LHC.
- Many searches complemented by model-dependent interpretations
  - 2HDM/*MSSM*: 5 physical Higgs bosons ($h, A, H, H^{\pm}$)
  - Generalized 2HDM (*g2HDM*): 2HDM w/o $Z_2$ symmetry
  - 2HDM+Scalar Singlet/*NMSSM*: 7 physical Higgs bosons: $h_{1,2,3}$, $a_{1,2}$, $H^{\pm}$
  - …

**Selected recent CMS Measurements**

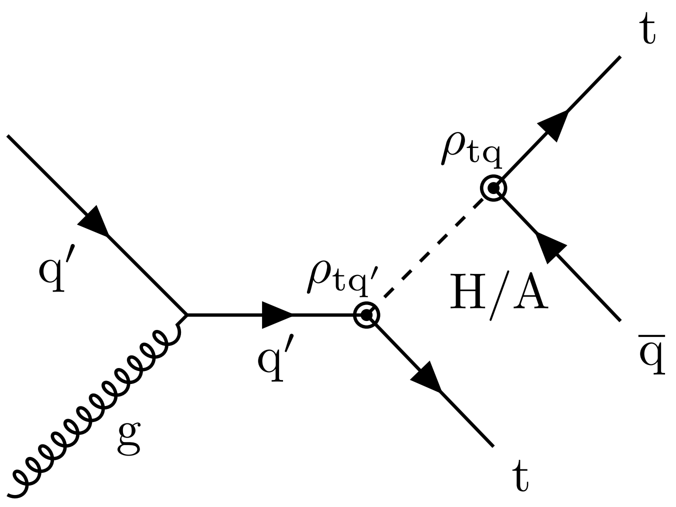
| | | |
|---|---|---|
| $tH \to tt\bar{c}, tt\bar{u}$ | [PLB850(2024)138478] | g2HDM |
| $A \to Zh_{125} \to (\ell\ell)(\tau\tau)$ | [CMS-PAS-HIG-22-004] | MSSM |
| $X \to ZZ \to 4\ell$ | [CMS-PAS-HIG-24-002] | Model-independent |
| $X \to Yh_{125} \to 4b$ | [CMS-PAS-HIG-20-012] | NMMSM |
| $A/H \to t\bar{t}$ | [CMS-PAS-HIG-22-013] | 2HDM, $t\bar{t}$ bound state |

$X \to HH/YH$ covered by
Élise Jourd'Huy
$H \to aa$ by
Chen Zhou & Lakshmi Priya Nair
$A/H \to t\bar{t}$ by
Samuel Baxter

# A/H with FCNC based on g2HDM

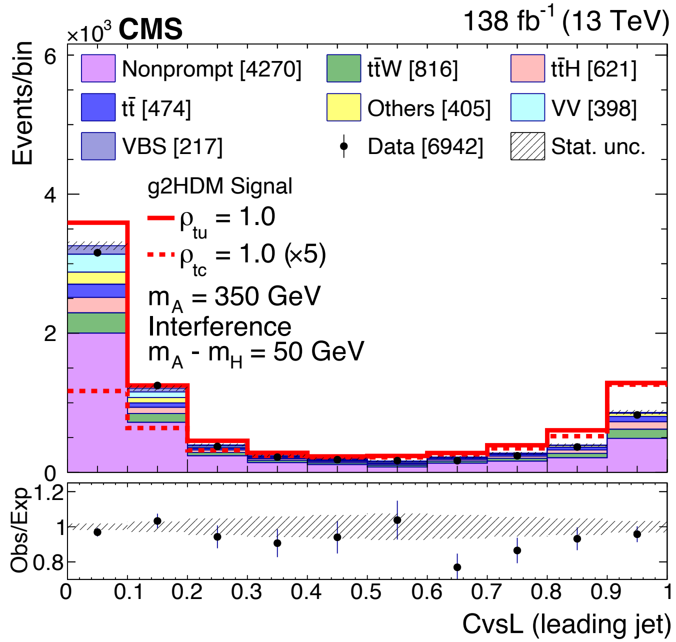
Phys. Briefing | PLB 850 (2024) 138478

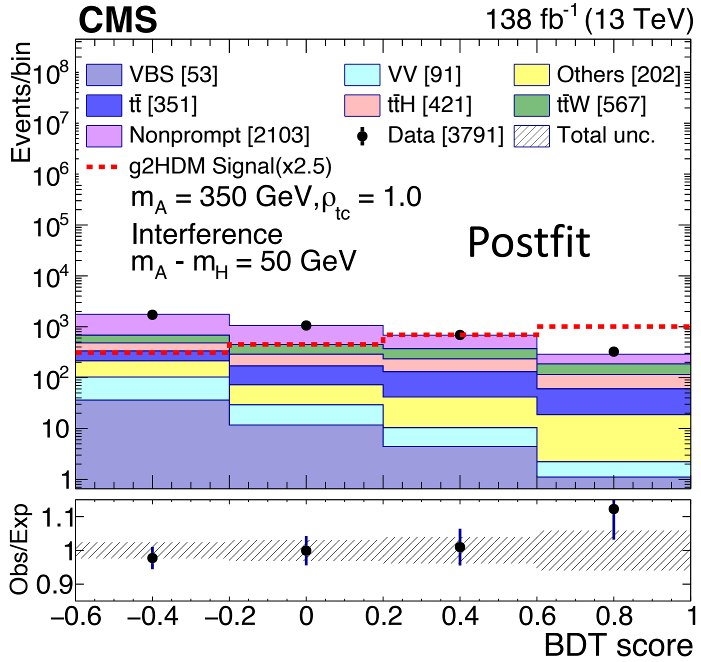
- g2HDM: 2HDM w/o $Z_2$ symmetry can drive electroweak baryogenesis w/ sub-TeV extra Higgs bosons [Hou & Kikuchi EPL 123 (2018) 11001].
  - Alignment ($h \to h_{125}$) in g2HDM if **extra Yukawa couplings** ($\rho$) are $\mathcal{O}(1)$.
  - No HVV, AVV interactions.
  - No FCNC for h but allowed for H and A.
  - Many parameters and extra processes but focus on $\rho_{tu}/\rho_{tc}$-induced **same-sign top quark** final states: $qg \to tH \to tt\bar{q} \to (\ell^+ b\nu)(\ell^+ b\nu)\bar{q}$




$\bar{q} = \bar{c}$ or $\bar{u}$

- BDTs trained independently for different data-taking periods, mass, w/ and w/o A-H interference and coupling ($\rho_{tu} = 0.4$ and $\rho_{tc} = 0.4$) hypothesis.
- 4 bins of BDT score in each decay mode simultaneously fit to extract limits for each signal mass-coupling hypothesis.

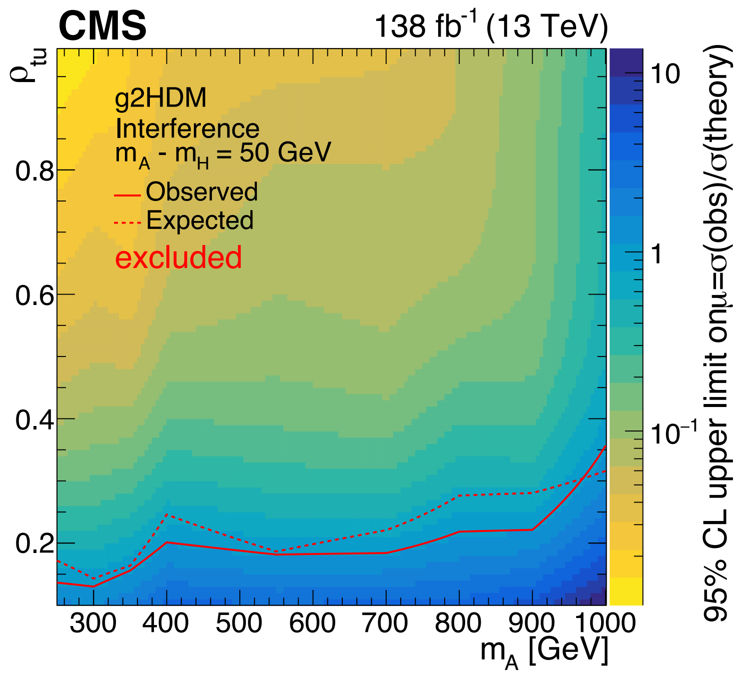


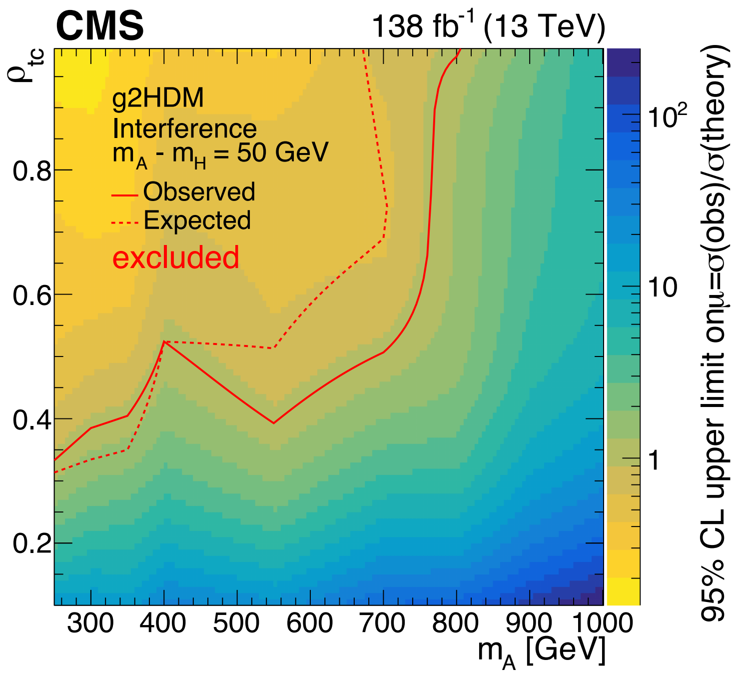



# A/H with FCNC based on g2HDM

PLB 850 (2024) 138478

Phys. Briefing




| Observed (expected) mass limit [GeV] | without interference | with interference | with interference |
|---|---|---|---|
| | $m_A$ or $m_H$ | $m_A$ | $m_H$ |
| $\rho_{tu}$ | | | |
| 0.4 | 920 (920) | 1000 (1000) | 950 (950) |
| 1.0 | 1000 (1000) | 1000 (1000) | 950 (950) |
| $\rho_{tc}$ | | | |
| 0.4 | no limit | 340 (370) | 290 (320) |
| 1.0 | 770 (680) | 810 (670) | 760 (620) |

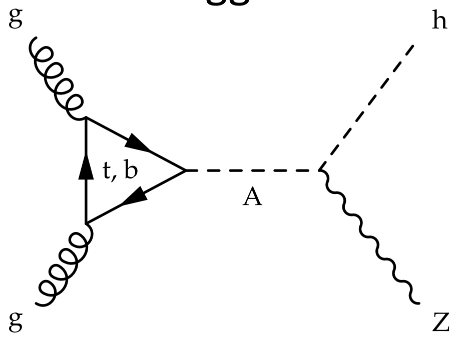
- *$\rho_{tu}$ largely excluded, but still large portion of phase space not constrained for $\rho_{tc}$.*
- *Stricter limits*
  - *for $\rho_{tu}$: higher signal cross section <— PDF effect.*
  - *w/ interference: higher signal cross section <— having A & H simultaneously.*
- Dominant uncertainties: *Flavor tagging, nonprompt lepton, $t\bar{t}W$ cross section, statistical.*
- First search based on g2HDM considering A-H interference.

# $A \rightarrow Zh_{125} \rightarrow (\ell\ell)(\tau\tau)$

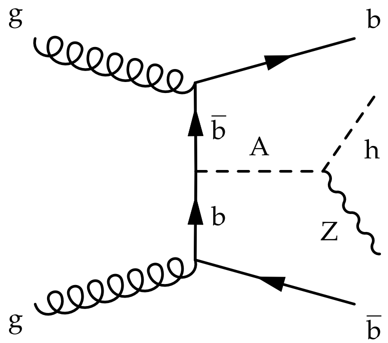
CMS-PAS-HIG-22-004

Phys. Briefing

ggF

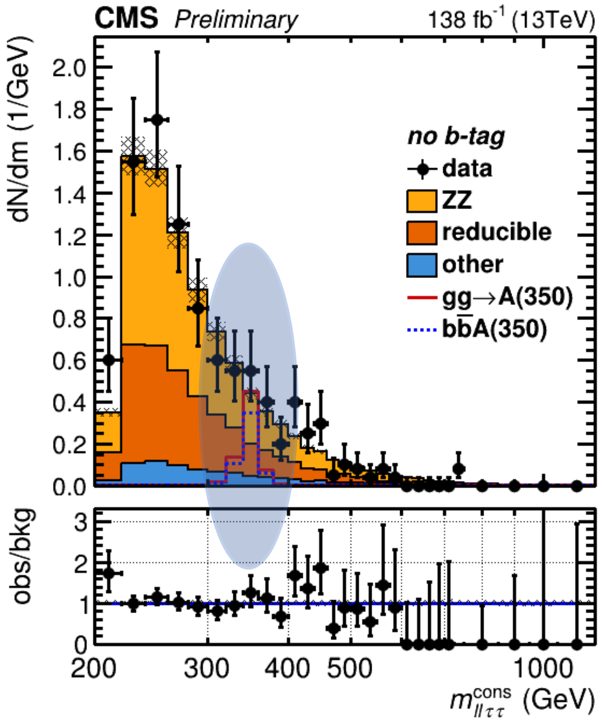


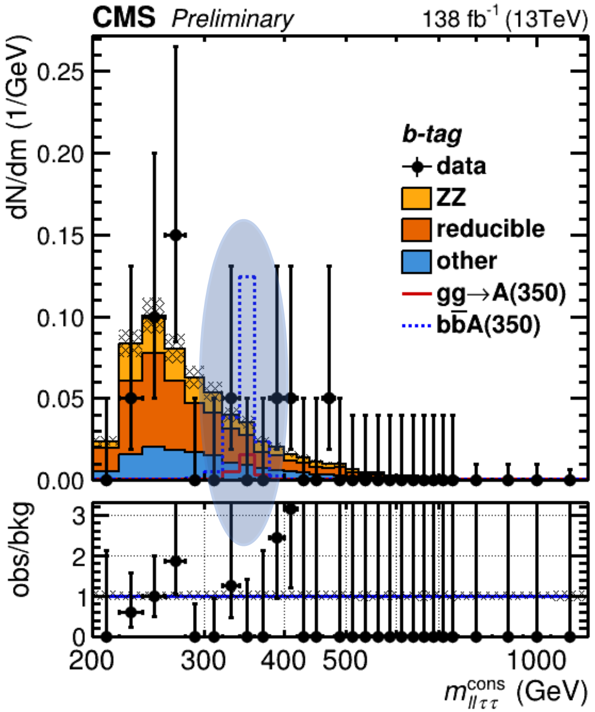

bbA




- Search range: $m_A = 225 - 800$ GeV
- 0 and ≥ 1 b-jet categories.
- Signal from maximum likelihood fit combining $m_A = m_{\ell\ell\tau\tau}^{cons}$ from each search channel.
- Matrix Element Method based $h(\tau\tau)$ reconstruction correcting the effect of neutrinos with constraint $m_{\tau\tau} = 125\ GeV$.
  - $m_{\ell\ell\tau\tau}^{cons}$ mass resolution 5-7%.
- Irreducible bkg. from simulation:
  - $ZZ/H, t\bar{t}Z/H, VVV.$
- Reducible bkg. from data:
  - jet misidentified as $\tau_{had}$ or lepton.

$h \rightarrow \tau\tau \rightarrow e\tau_h, \mu\tau_h, \tau_h\tau_h$



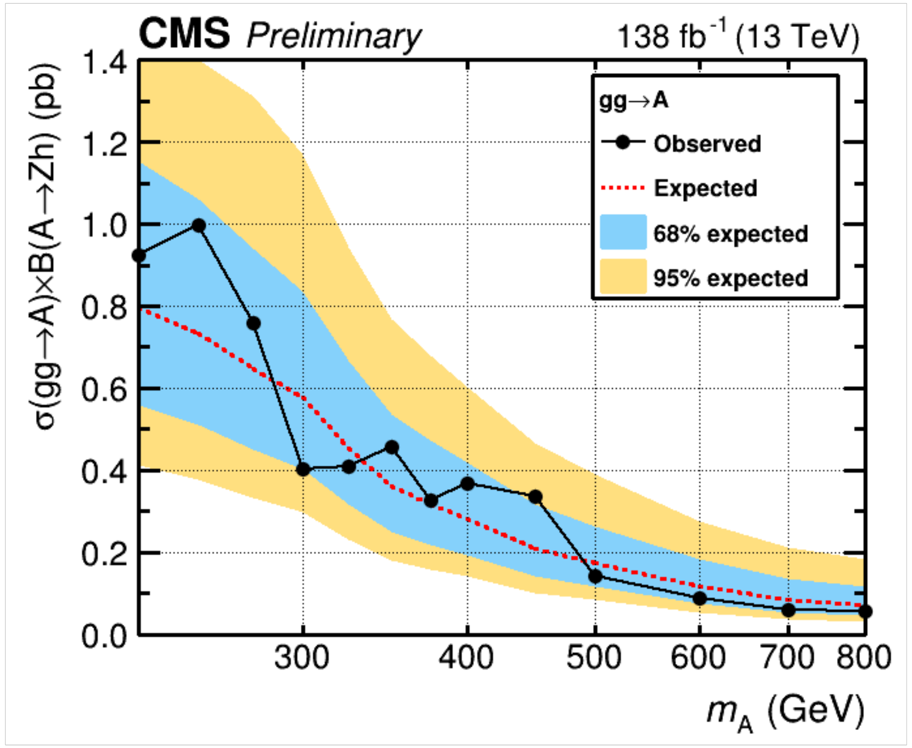



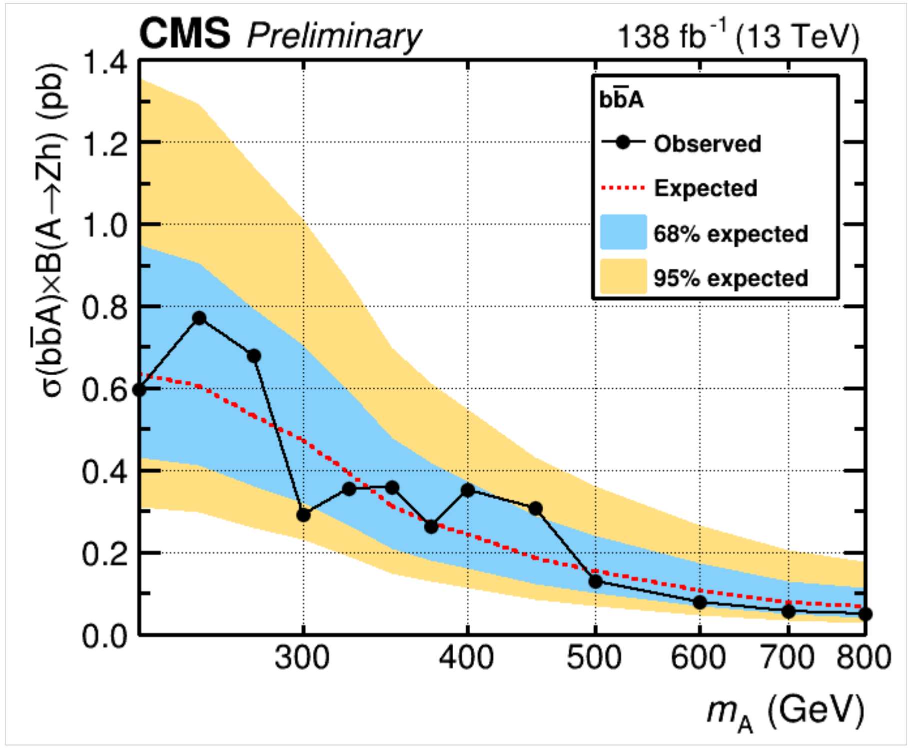
# $A \rightarrow Zh_{125} \rightarrow (\ell\ell)(\tau\tau)$

CMS-PAS-HIG-22-004

Phys. Briefing

No signal in data —> Model-independent limits assuming $h_{125} = h_{SM}$



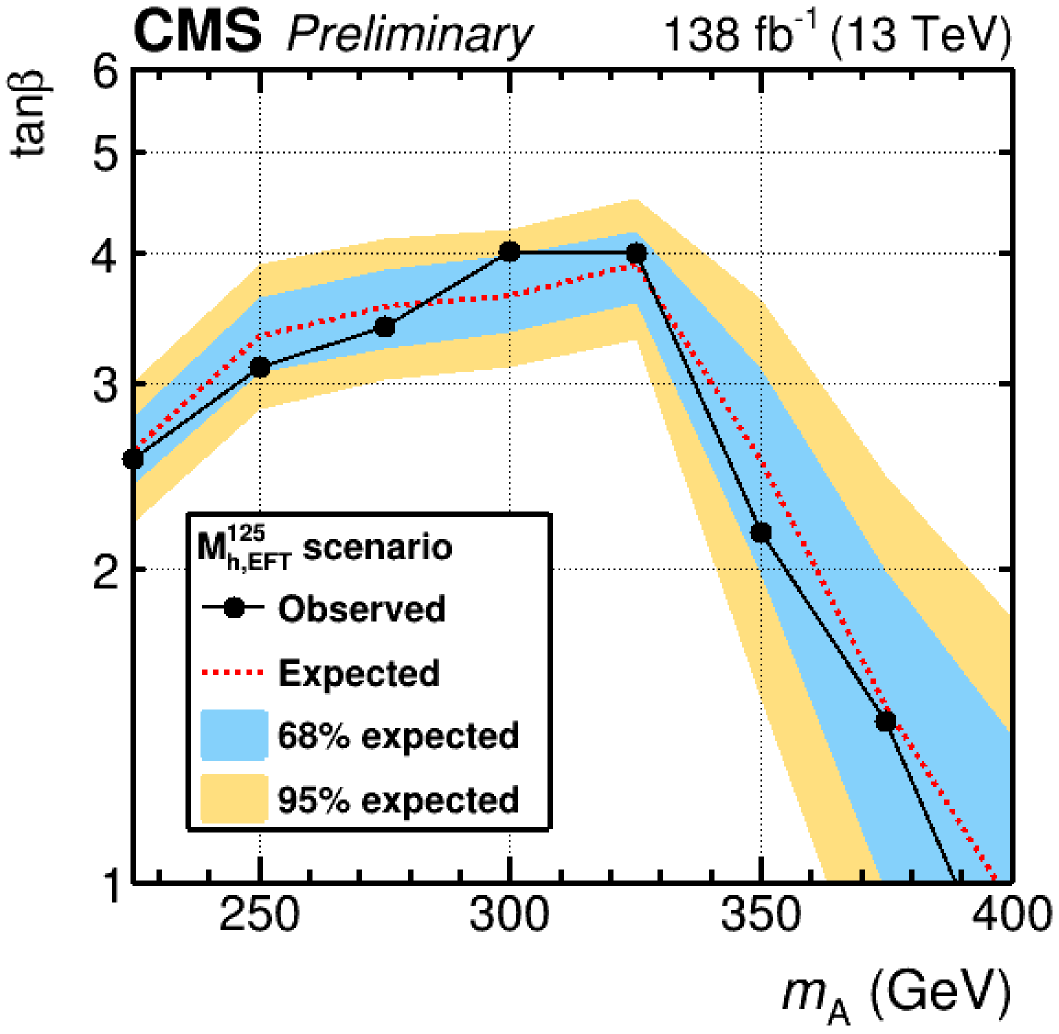




- Most stringent limits on $A \rightarrow Zh_{125} \rightarrow (\ell\ell)(\tau\tau)$ to date.
- Dominant systematics: backgrounds, signal modelling.
- w.r.t. 2016 CMS analysis: increased integrated luminosity, better hadronic $\tau$ lepton id and b jet tagger, added bbA production, and the range extended by ~2x.

# $A \to Zh_{125} \to (\ell\ell)(\tau\tau)$

CMS-PAS-HIG-22-004

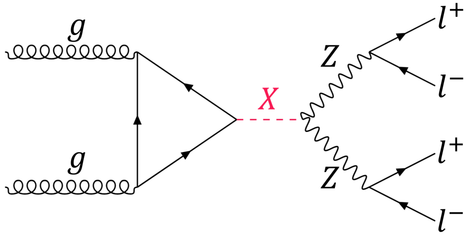
Phys. Briefing

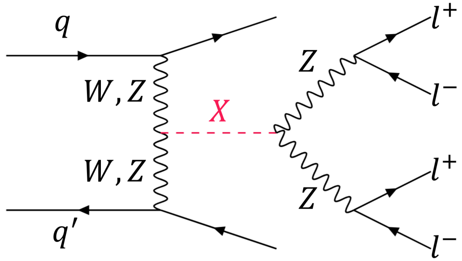



MSSM $M_{h,EFT}^{125}$ benchmark w/ $M_{SUSY} \approx 10^{16}$ GeV and model adjusted to values compatible with $m_h \approx 125$ GeV.

- $\tan\beta < 2.2$ *excluded for* $225 \leq m_A \leq 350$ *GeV.*
- *bbA probes higher* $\tan\beta$.
- *At higher* $m_A$, $A \to t\bar{t}$ *becomes allowed and suppresses* $A \to Zh_{125}$ *decay.*

# $X \to ZZ \to 4\ell$




CMS-PAS-HIG-24-002

Phys. Briefing

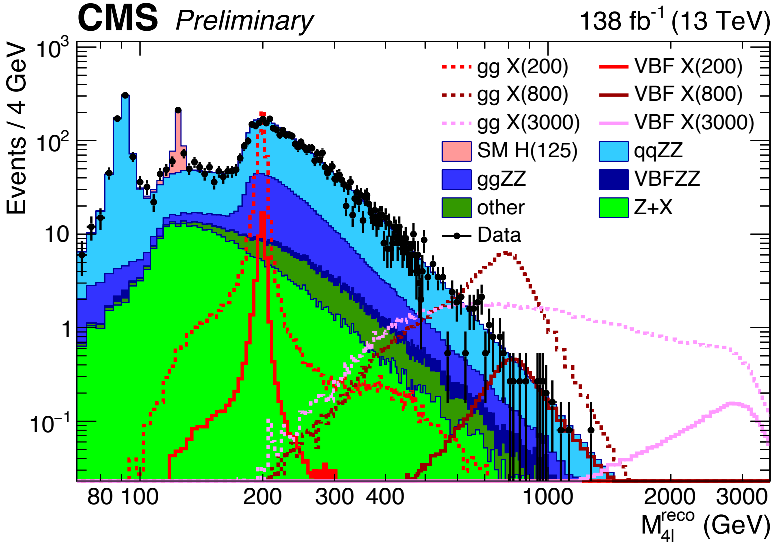
- Golden channel: High efficiency & resolution, low backgrounds.
- Model-independent search for X(spin-0) with ggF and VBF in $M_X = 130 - 3000$ GeV with $\Gamma_X/M_X = 0 - 30\,\%$ .
- Signal vs bkg. from fit to 2D templates: $M_{4\ell}^{reco}$ vs $D_{bkg}^{kin}$ .
- Matrix element (ME) approach both for likelihood parametrisation and to construct event-categorisation observables.

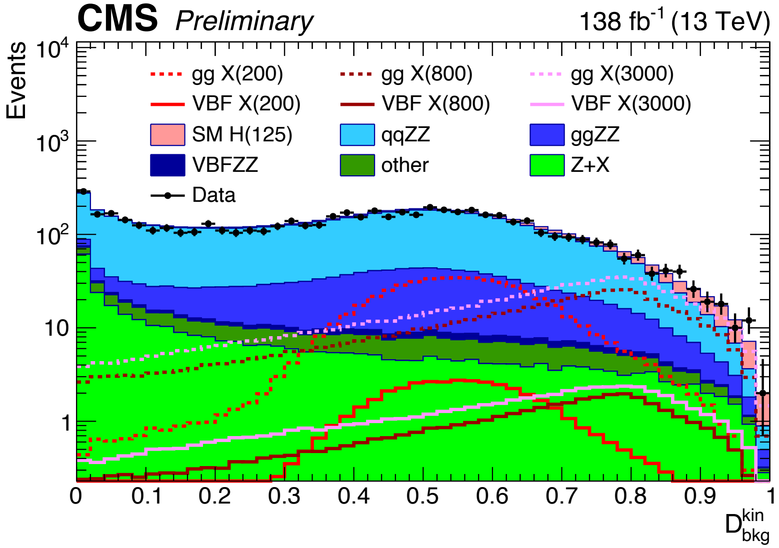
$$D_{bkg}^{kin} = \left[ 1 + \frac{\mathcal{P}_{bkg}^{q\bar{q}}(\overrightarrow{\Omega}^{H\to4\ell}\,|\,M_{4\ell}^{reco})}{\mathcal{P}_{sig}^{gg}(\overrightarrow{\Omega}^{H\to4\ell}\,|\,M_{4\ell}^{reco})} \right]^{-1}$$

*$\mathcal{P}_{bkg}^{q\bar{q}}$: Prob. of event to be $q\bar{q} \to 4\ell$-like (ME).*

*$\mathcal{P}_{sig}^{gg}$: Prob. of event to be SM H from ggF (ME).*

- Two event categories: VBF-tagged using VBF Tagging cuts & $D_{2jet}^{VBF}$> 0.46 and non-VBF (mainly ggF).



# $X \to ZZ \to 4\ell$

CMS-PAS-HIG-24-002

Phys. Briefing

- Parametric approach for signal

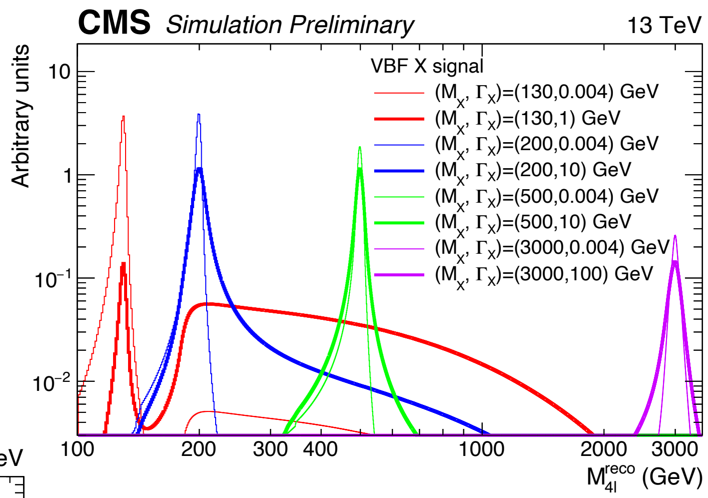
signal lineshape (Analytical) | Signal efficiency (MC) | Signal resolution (MC) | 2D templates (MC)

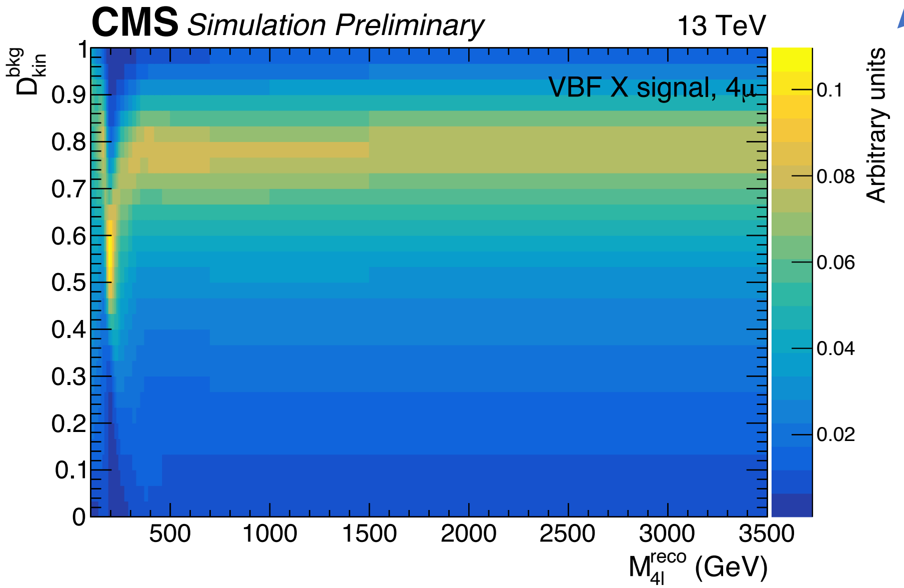
$$\mathscr{P}_{sig}(M_{4\ell}^{reco}, D_{bkg^{kin}} \mid M_X, \Gamma_X) = \{[\mathscr{P}_{sig}(M_{4\ell}^{reco} \mid M_X, \Gamma_X) \times \epsilon(M_{4\ell}^{gen})] \otimes \mathscr{R}(M_{4\ell}^{reco} \mid M_{4\ell}^{gen})\} \times \mathscr{P}(D_{bkg}^{kin} \mid M_{4\ell}^{reco})$$

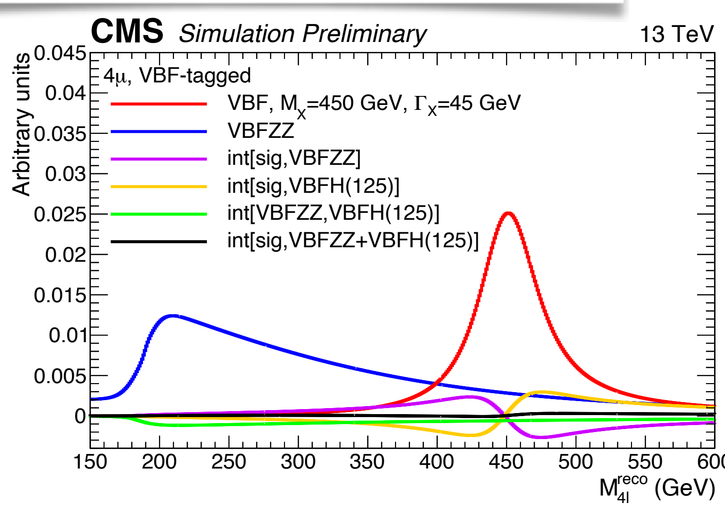
- and irreducible background modelling ($q\bar{q} \to ZZ$, $gg \to ZZ$, VBFZZ, WZZ, WWZ, $t\bar{t}Z$, $t\bar{t}ZZ$, $t\bar{t}WW$).

$$\mathscr{P}_{bkg}(M_{4\ell}^{reco}, D_{bkg}^{kin})$$

$$= \mathscr{P}(M_{4\ell}^{reco}) \times \mathscr{P}(D_{bkg}^{kin} \mid M_{4\ell}^{reco})$$



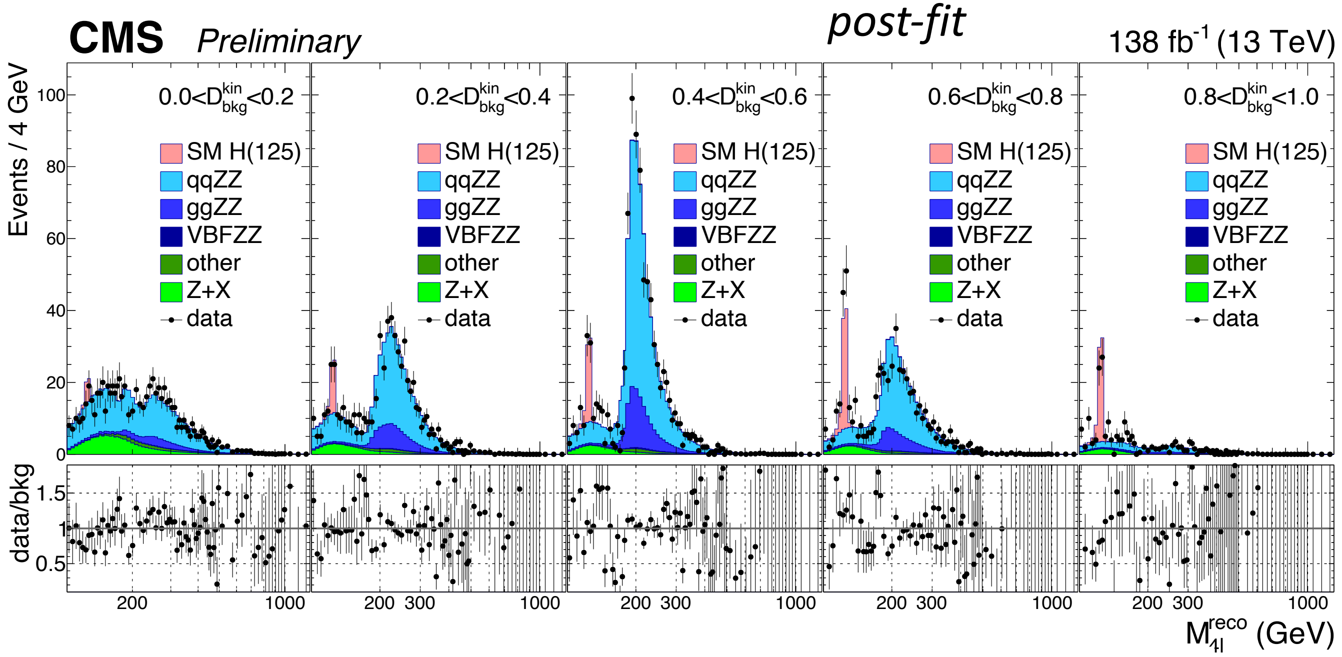

$$\mathscr{P}_{int} = [\mathscr{P}_{int}(M_{4\ell}^{gen} \mid \mathscr{P}_{sig}(M_{4\ell}^{gen}), \mathscr{P}_{bkg}(M_{4\ell}^{gen}), phases) \otimes \mathscr{R}(M_{4\ell}^{reco} \mid M_{4\ell}^{gen})] \times \mathscr{P}(D_{bkg}^{kin} \mid M_{4\ell}^{reco})$$

- and interference modelling:
  - Amplitudes from lineshapes of signals, SM Higgs boson and interfering backgrounds.
  - Phases from generators and kinematics.

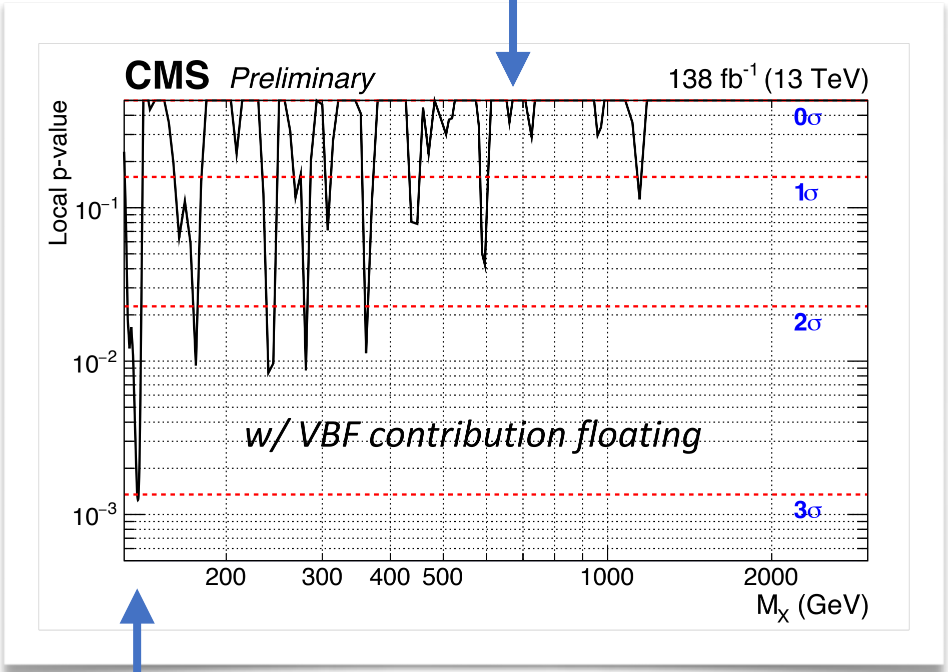
# $X \to ZZ \to 4\ell$

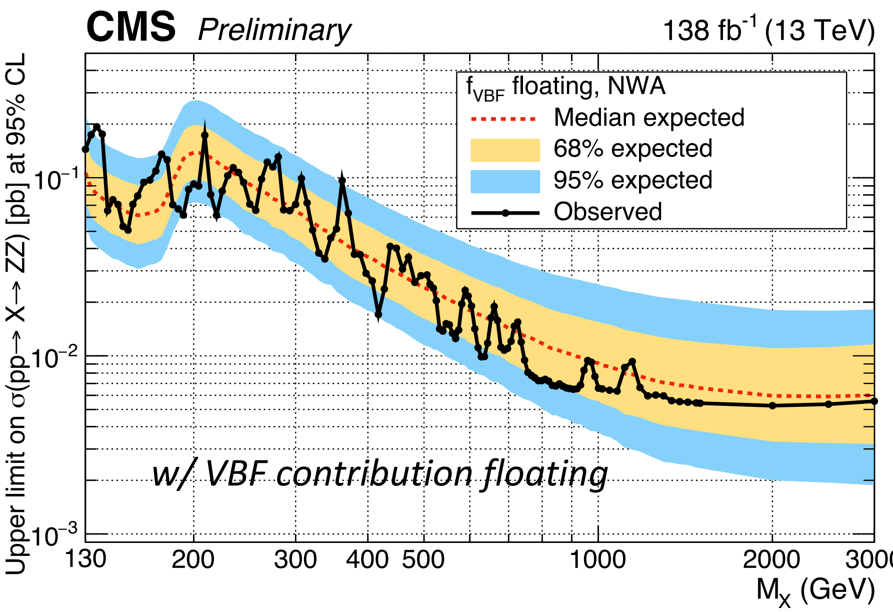
CMS-PAS-HIG-24-002

Phys. Briefing




No significant excess (None at the 680 GeV [ATLAS] either).

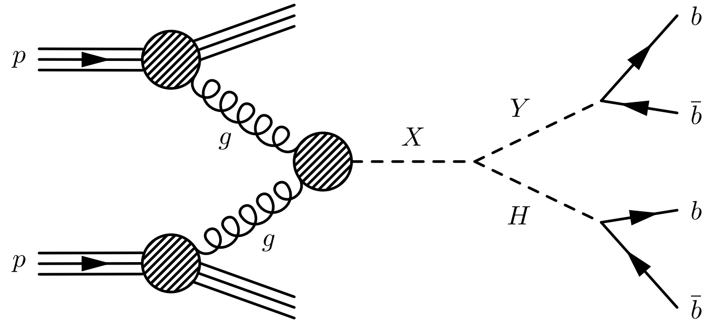


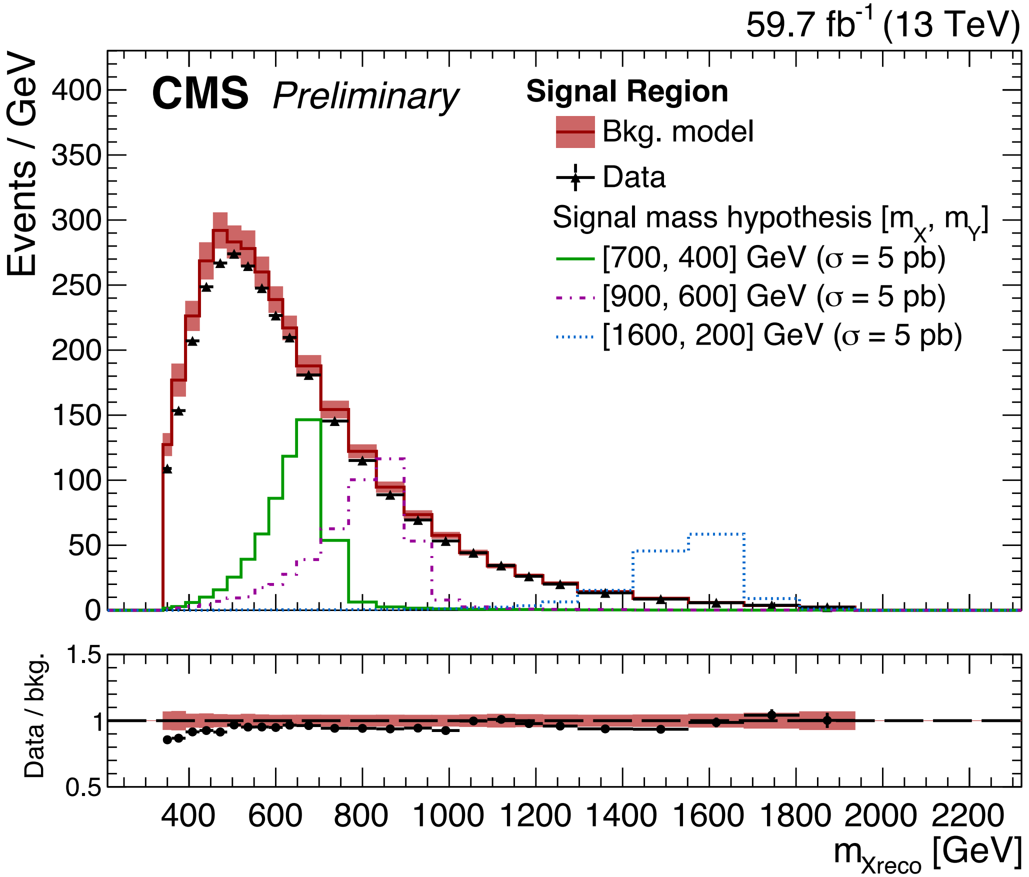

Largest significance ~3$\sigma$ (local) and ~2$\sigma$ (global) at ~138 GeV.

NEW

# $X \to Yh_{125} \to 4b$




- Search range:
  $m_X = 400$ GeV – $1.6$ TeV, $m_Y = 60$ GeV – $1.4$ TeV
- Signal extracted from a 2D fit in $m_X - m_Y$ parameter space.
- Signal simulated w/o a specific model with X, Y widths = 1 MeV.
- 4 jets w/ highest DeepJet b-tag scores.
  - $m_h^{reco}$ and $m_Y^{reco}$ from pairing jets.
  - $m_h^{reco}$ used to define signal, CR, and VRs.
  - $m_h^{reco} = 125$ GeV and momentum adjusted.
- Minimize impact of mismodeling of trigger and jet reconstruction:
  - exclude $m_X^{reco} - m_Y^{reco} < 120$ GeV
- Analysis not optimised for highly boosted Y decays:
  - exclude regions with high $m_X^{reco}$ and low $m_Y^{reco}$.

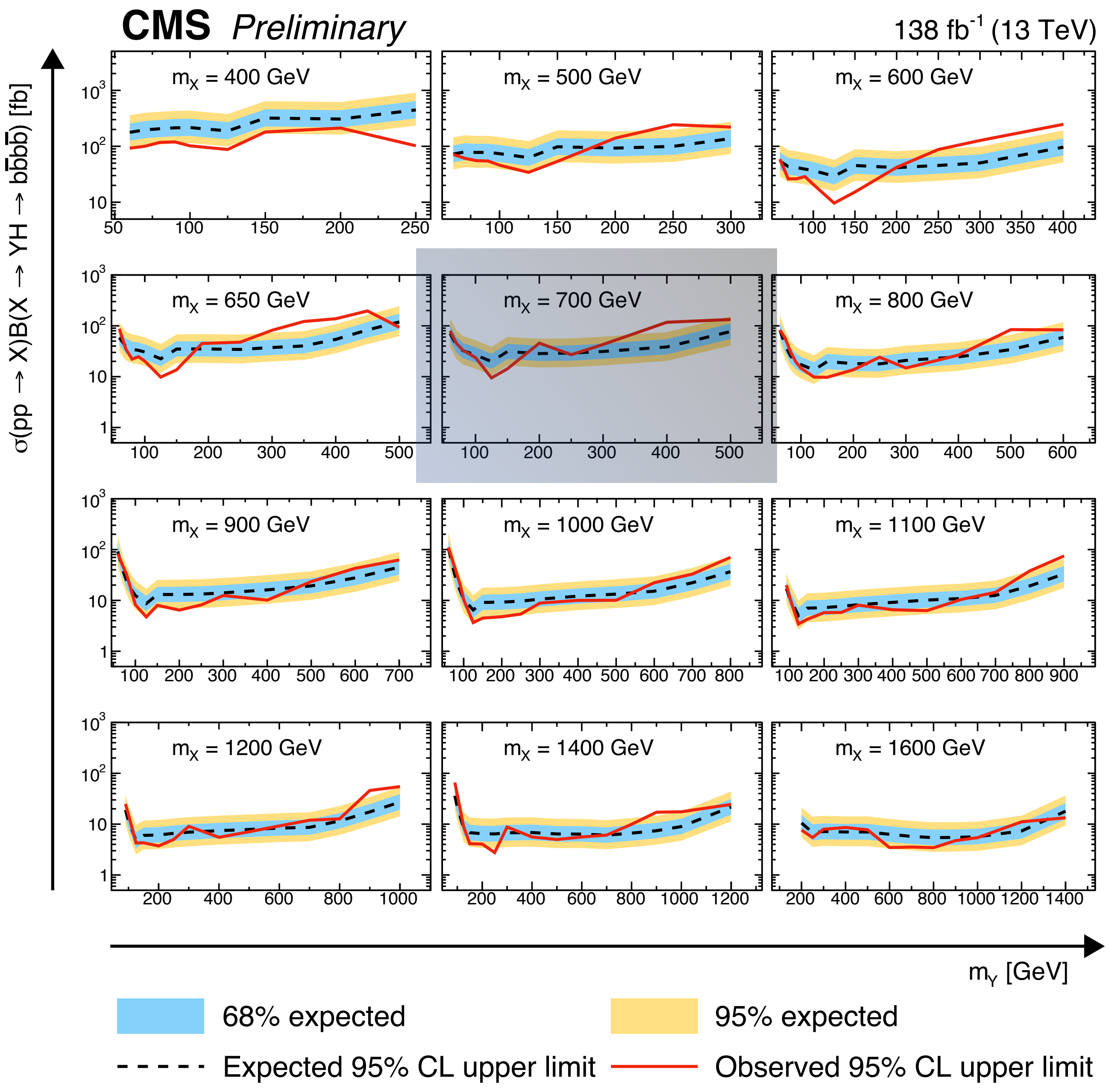


# $X \to Yh_{125} \to 4b$

CMS-PAS-HIG-20-012

NEW

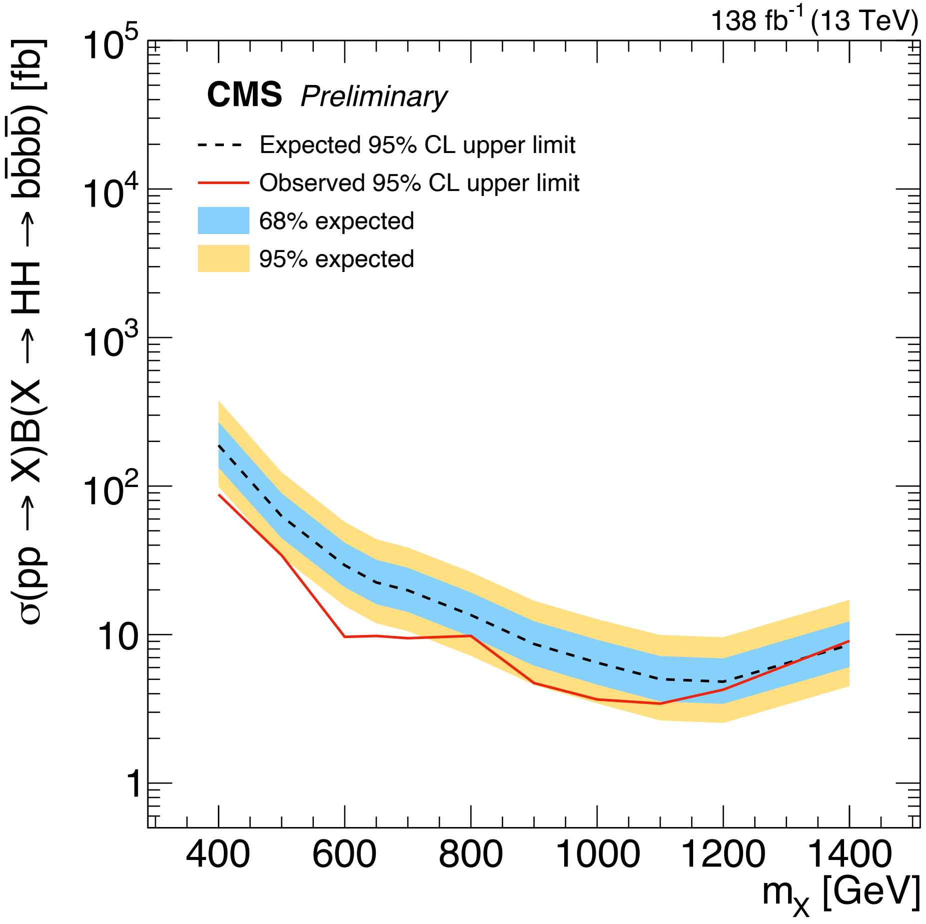
- Largest excess at $m_X^{reco} = 700$ GeV, $m_Y^{reco} = 400$ GeV with $4.1(2.5)\sigma$ local(global).
  - Local significance is highly reduced by the look-elsewhere-effect because of high number of mass points.



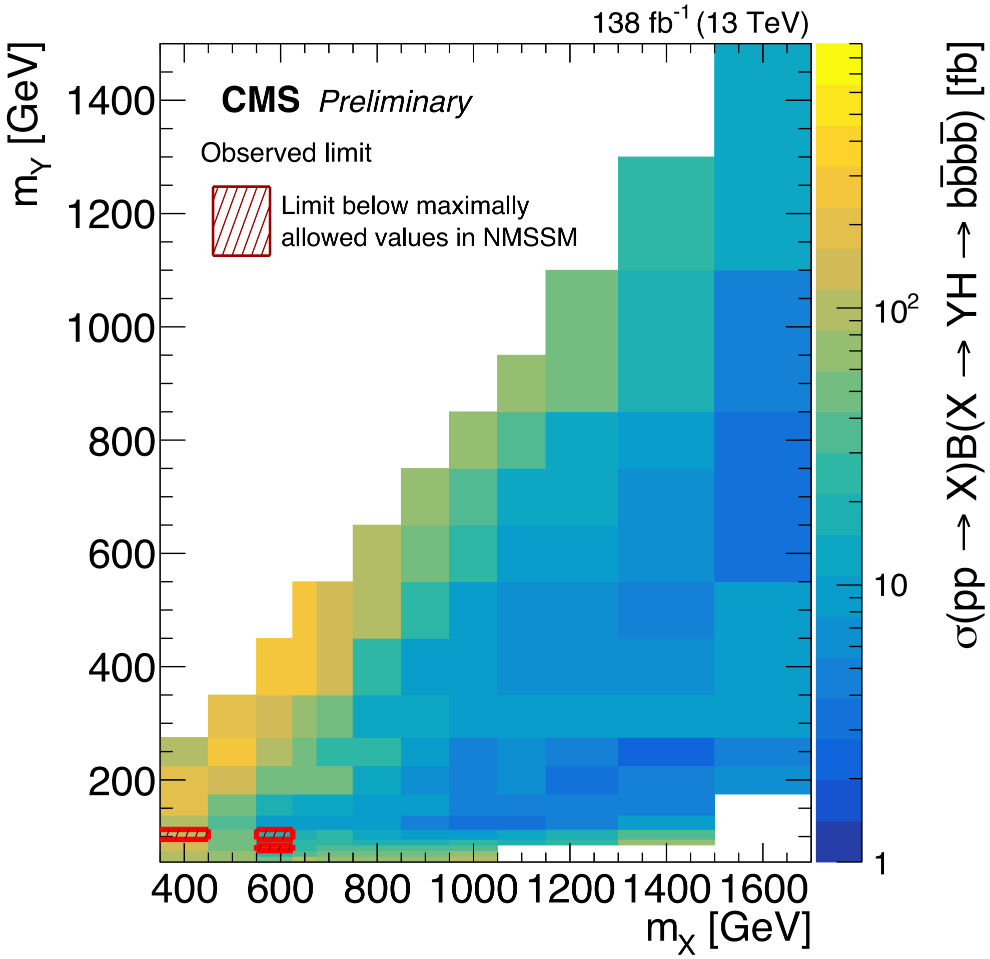
# $X \to Y h_{125} \to 4b$

CMS-PAS-HIG-20-012 NEW

$X \to HH$ limits

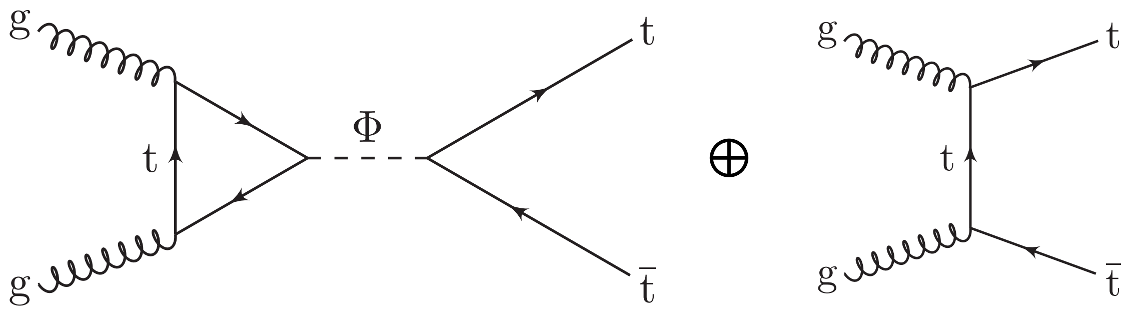


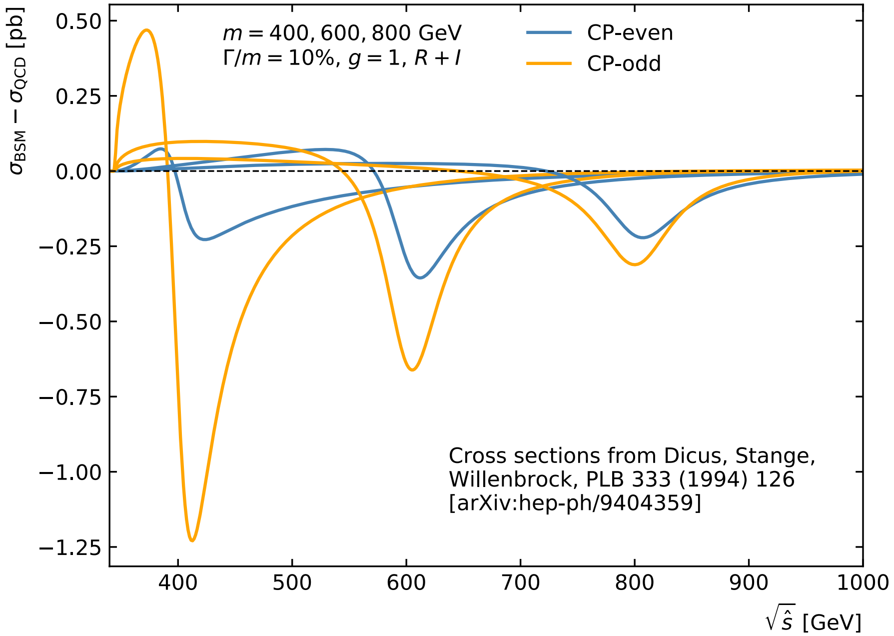

*Observed upper limits*



NEW

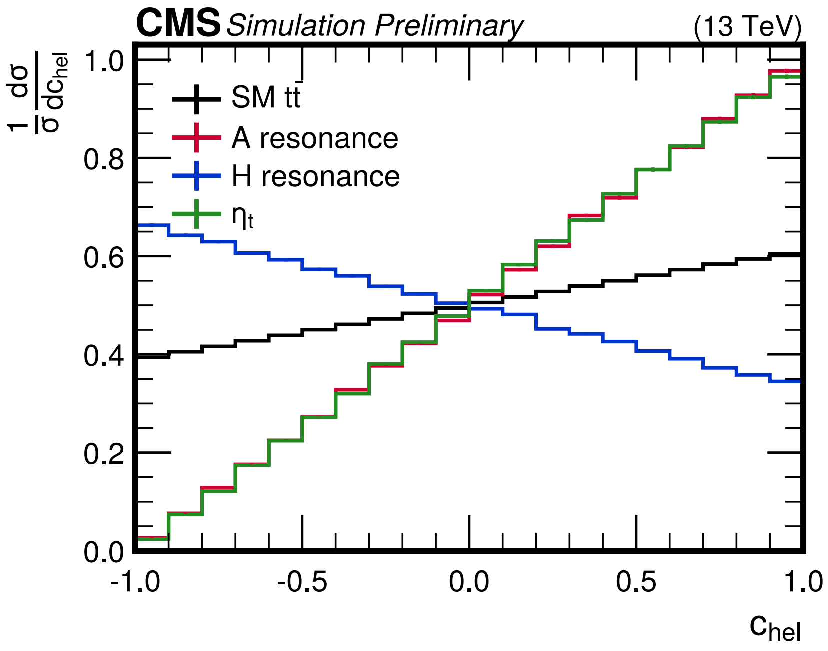
# $A/H \to t\bar{t}$




https://cds.cern.ch/record/2684750

- Signal extraction using $m_{t\bar{t}}$ and spin correlation observables in dilepton and lepton+jets channels.
- Interpretations with
  - Pseudoscalar color-singlet $t\bar{t}$ bound state ($\eta_t$) from a simplified model of non relativistic QCD (NRQCD) [Fuks et al. arXiv:2102.11281].
  - A and/or H including interference with SM $t\bar{t}$ production w/ & w/o $\eta_t$ background.
    - No interference between A and H.



# $A/H \to t\bar{t}$

NEW

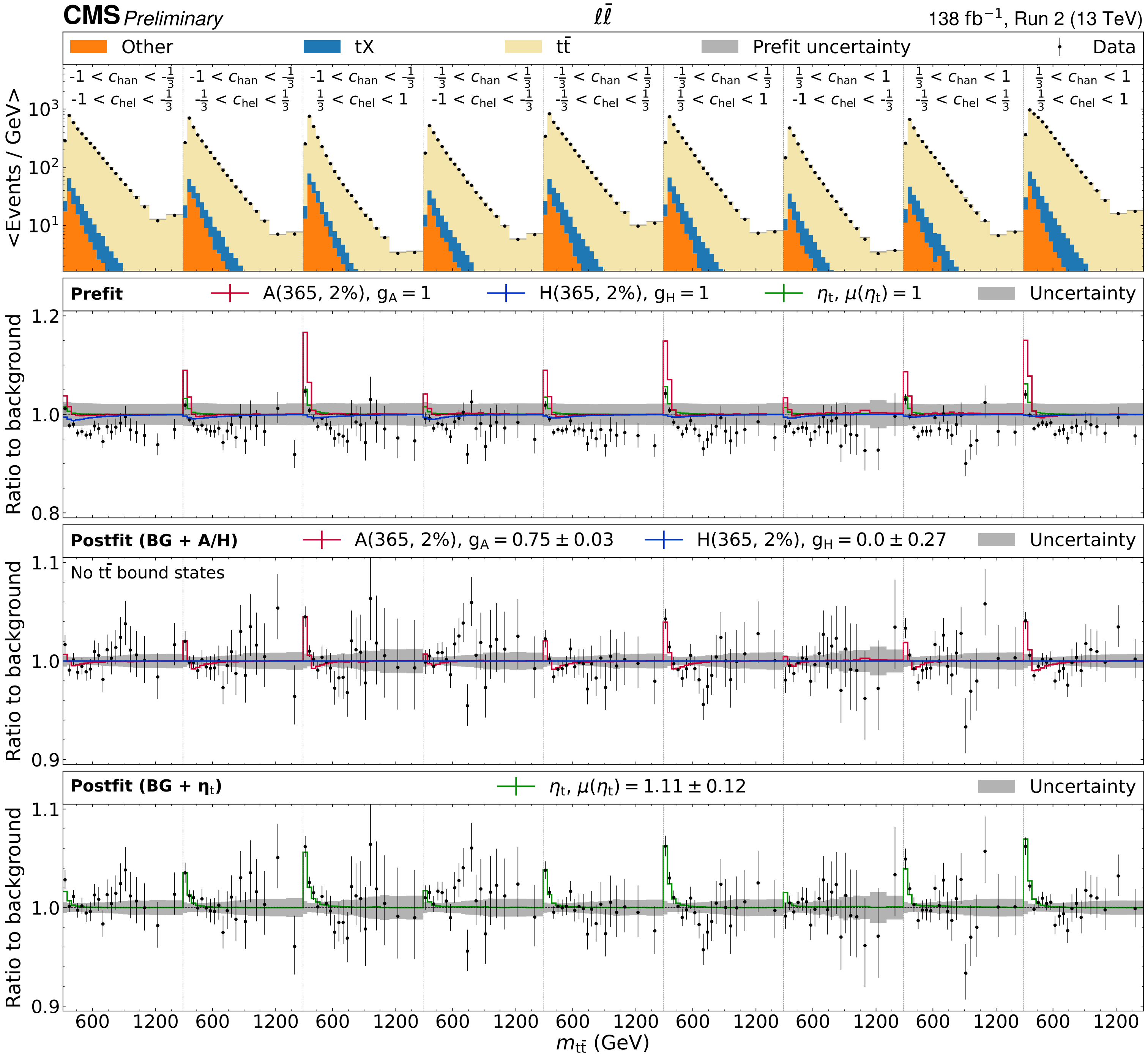
CMS-PAS-HIG-22-013

$> 5\sigma$ deviation.
More pronounced for A

**Pseudoscalar $^1S_0^{[1]}$ $t\bar{t}$ bound state:**
—> Consistent with the simplified model prediction in arXiv:2102.11281.
—> $\sigma(\eta_t)^{CMS} = 7.1$ pb ($\delta \sim 11\%$) assuming a bkg. model of resonant $t\bar{t}$ production at NLO pQCD.

*Including $\eta_t$, stringent constraints on A, H, and A+H covering $m_{A/H}$ = 365-1000 GeV and rel. widths 0.5-25% excluding coupling values as low as 0.4 (0.6) for A and H.*

More details in Samuel Baxter's talk.



# Are there additional Higgs-like States?

- Still no sign of additional Higgs-like states from many CMS measurements: https://cms-results-search.web.cern.ch/
- Improving measurements with machine learning for object reconstruction and signal extraction
- Extending phase space of searches.
- Effects of Higgs width and different interference effects being studied (between signal and backgrounds, between different Higgs bosons, …)
- Improving constraints
  - with models incorporating inputs from LHC and others.
  - Effects of $t\bar{t}$ bound state started to be studied.
  - Starting to limit possible BSM contributions to di-Higgs production.
- Significant improvements expected with LHC Run 3 and HL-LHC with increased statistics, improved analysis techniques, and modelling.

# Additional Slides

# A/H with FCNC based on g2HDM

PLB 850 (2024) 138478

Phys. Briefing

Summary of systematic uncertainties for $\rho_{tc} = 0.4$ and $m_A = 350$ GeV with A-H interference assuming $m_A - m_H = 50$ GeV. The first column indicates the source of uncertainty. The second column specifies whether the shape of the fit discriminant is affected by the nuisance parameter (✓) or not (dash). The impact in percent of these nuisance parameters on the pre-fit expected event yields is displayed in the third column. This column is subdivided into three event categories representing the analysis channels. The percentage impacts are given as a range of values representing the minimum and maximum differences obtained in the different bins of the BDT distribution through the four data-taking periods. The numbers for the normalization component of the nonprompt lepton background represent the uncertainties used for each data-taking period. Whether or not a nuisance parameter is taken correlated across years and categories is specified in the last two columns. The luminosity and jet flavor identification nuisances are only partially correlated across years.

| Uncertainty source | Shape | Category | | | Correlated across | |
|---|---|---|---|---|---|---|
| | | $e^\pm e^\pm$ | $\mu^\pm \mu^\pm$ | $e^\pm \mu^\pm$ | Years | Categories |
| Experimental | | | | | | |
| Luminosity | — | 1.2–2.5 | 1.2–2.5 | 1.2–2.5 | ✓ | ✓ |
| Pileup | ✓ | <0.1–2.8 | <0.1–1.8 | <0.1–2.3 | ✓ | ✓ |
| Trigger efficiency | ✓ | 0.4–2.6 | 0.2–1.1 | 0.3–1.2 | — | — |
| L1 trigger inefficiency | ✓ | 0.1–0.8 | 0.1–0.3 | 0.1–0.4 | ✓ | ✓ |
| Lepton identification | ✓ | 0.1–1.7 | <0.1–0.4 | <0.1–0.6 | — | ✓ |
| Lepton energy scale | ✓ | — | <0.1–0.2 | <0.1–0.2 | — | ✓ |
| Charge misid. | ✓ | 1.2–13.1 | — | — | — | — |
| Jet energy scale | ✓ | <0.1–4.5 | <0.1–1.7 | <0.1–1.5 | ✓ | ✓ |
| Jet energy resolution | ✓ | <0.1–2.6 | <0.1–1.8 | <0.1–1.6 | — | ✓ |
| Unclustered energy | ✓ | <0.1–2.6 | <0.1–0.5 | <0.1–0.8 | — | ✓ |
| Jet flavor identification | ✓ | <0.1–12.1 | <0.1–8.8 | <0.1–11.6 | ✓ | ✓ |
| Nonprompt lepton BG statistical component | ✓ | <0.1–27.2 | 1.9–16.2 | 3.0–13.2 | — | ✓ |
| Nonprompt lepton BG | — | 27,15,11,10 | 27,15,11,10 | 27,15,11,10 | — | ✓ |
| Theoretical | | | | | | |
| Signal QCD scales | ✓ | 10.3–10.5 | 10.0–10.2 | 9.9–10.0 | ✓ | ✓ |
| Signal PDF | ✓ | 0.7 | 0.6–0.7 | 0.5–0.6 | ✓ | ✓ |
| Signal parton shower | ✓ | 3.6–4.3 | 4.0–4.3 | 6.3–7.3 | ✓ | ✓ |
| $t\bar{t}$ | — | 6.1 | 6.1 | 6.1 | ✓ | ✓ |
| VV | — | 4.5 | 4.5 | 4.5 | ✓ | ✓ |
| VBS | — | 10.4 | 10.4 | 10.4 | ✓ | ✓ |
| $t\bar{t}H$ | — | 7.8 | 7.8 | 7.8 | ✓ | ✓ |
| $t\bar{t}W$ | — | 10.7 | 10.7 | 10.7 | ✓ | ✓ |
| Other backgrounds | — | 5.4 | 5.4 | 5.4 | ✓ | ✓ |

# $A \to Zh_{125} \to (\ell\ell)(\tau\tau)$

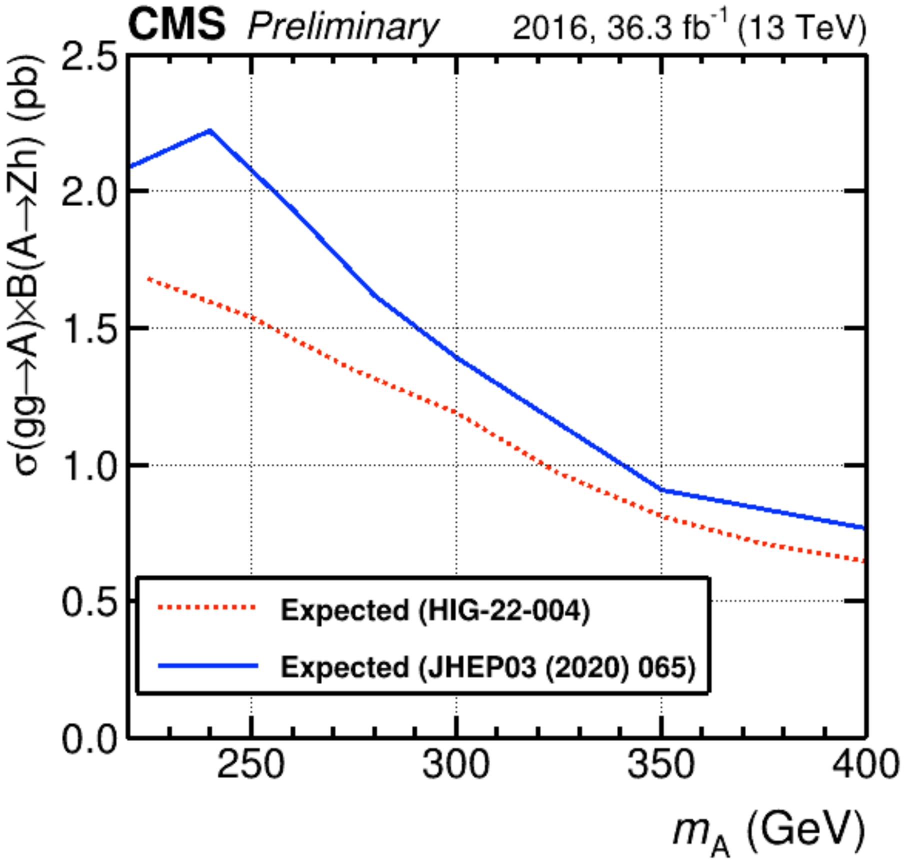
HIG-22-004

Phys. Briefing

| Source of uncertainty | Magnitude | Process |
|---|---|---|
| | Experimental uncertainties | |
| $\tau_h$ id. | 2–4% | All simulations |
| $\tau_h$ energy scale$^\dagger$ | 0.5–1.5% | All simulations |
| electron energy scale$^\dagger$ | 1–2% | All simulations |
| e id. & isolation | 1.5–4.5% | All simulations |
| e trigger | 2% | All simulations |
| $\mu$ id. & isolation | 1.5–4.5% | All simulations |
| $\mu$ trigger | 2% | All simulations |
| *b-tag* uncertainties | 1–4% (heavy flavor) 5–10% (light flavour) | All simulations |
| $\vec{p}_T^{miss}$ unclustered energy scale$^\dagger$ | 2–4% | All simulations |
| Jet energy scale$^\dagger$ | 1–3% | All simulations |
| Jet energy resolution$^\dagger$ | $< 1\%$ | All simulations |
| Limited statistics of MC events | bin-by-bin unc. | All simulations |
| Integrated luminosity | $< 2\%$ | All simulations |
| | Uncertainties in reducible background estimate | |
| | | misidentified $\tau$ leptons (data-driven estimate) |
| statisicts in AR | $20-40\%$ | (*b-tag* category) |
| | $10-20\%$ | (*no b-tag* category) |
| nonclosure of method | 30% | $e\tau_h$ channel |
| | 20% | $\mu\tau_h$ channel |
| | 20% | $\tau_h\tau_h$ channel |
| | Theoretical uncertainties in background estimate | |
| qq $\to$ ZZ cross section | 5% | qq $\to$ ZZ |
| gg $\to$ ZZ cross section | 10% | gg $\to$ ZZ |
| gg $\to$ ZZ NNLO $K$ factor estimate | 10% | gg $\to$ ZZ |
| $t\bar{t}Z$ cross section | 25% | $t\bar{t}Z$ |
| triboson cross section | 25% | triboson |
| Theoretical uncertainty in $\mathcal{B}(h \to \tau\tau)$ | $<2\%$ | gg $\to$ A, $b\bar{b}A$, Higgs bkg. |
| PDFs | $1.3-3.6\%$ | Higgs bkg. |
| $\mu_F$ and $\mu_R$ scales | $1-8\%$ | Higgs bkg. |
| | Theoretical uncertainties in signal estimate (applied in MSSM interpretation) | |
| signal cross section ($\mu_F$, $\mu_R$ scale, PDFs, $\alpha_S$) | $5-20\%$ ($10-25\%$) | gg $\to$ A ($b\bar{b}A$) |

# $A \rightarrow Zh_{125} \rightarrow (\ell\ell)(\tau\tau)$

HIG-22-004




- Expected upper limits at 95% CL from the previous CMS analysis (2016) vs the new result from the present analysis based on the same dataset.

# $X \to ZZ \to 4\ell$

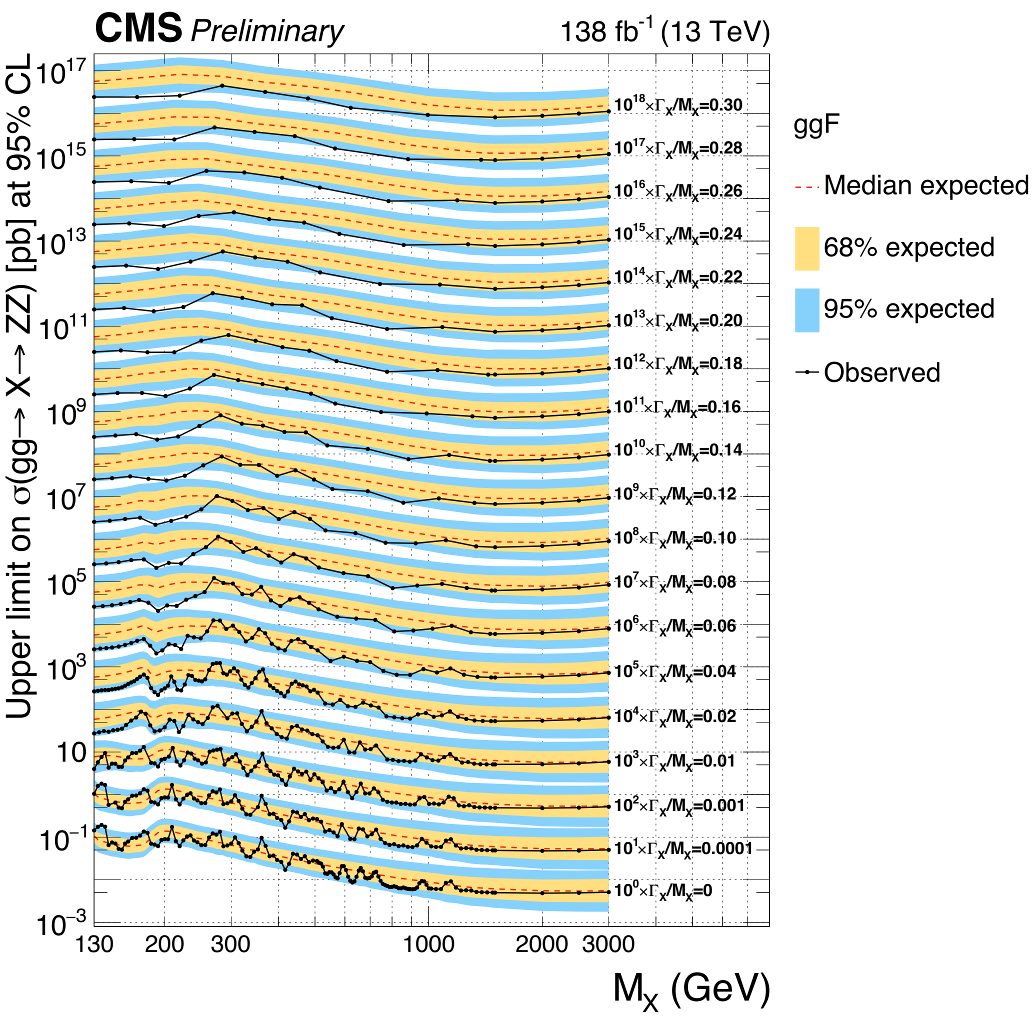
HIG-24-002

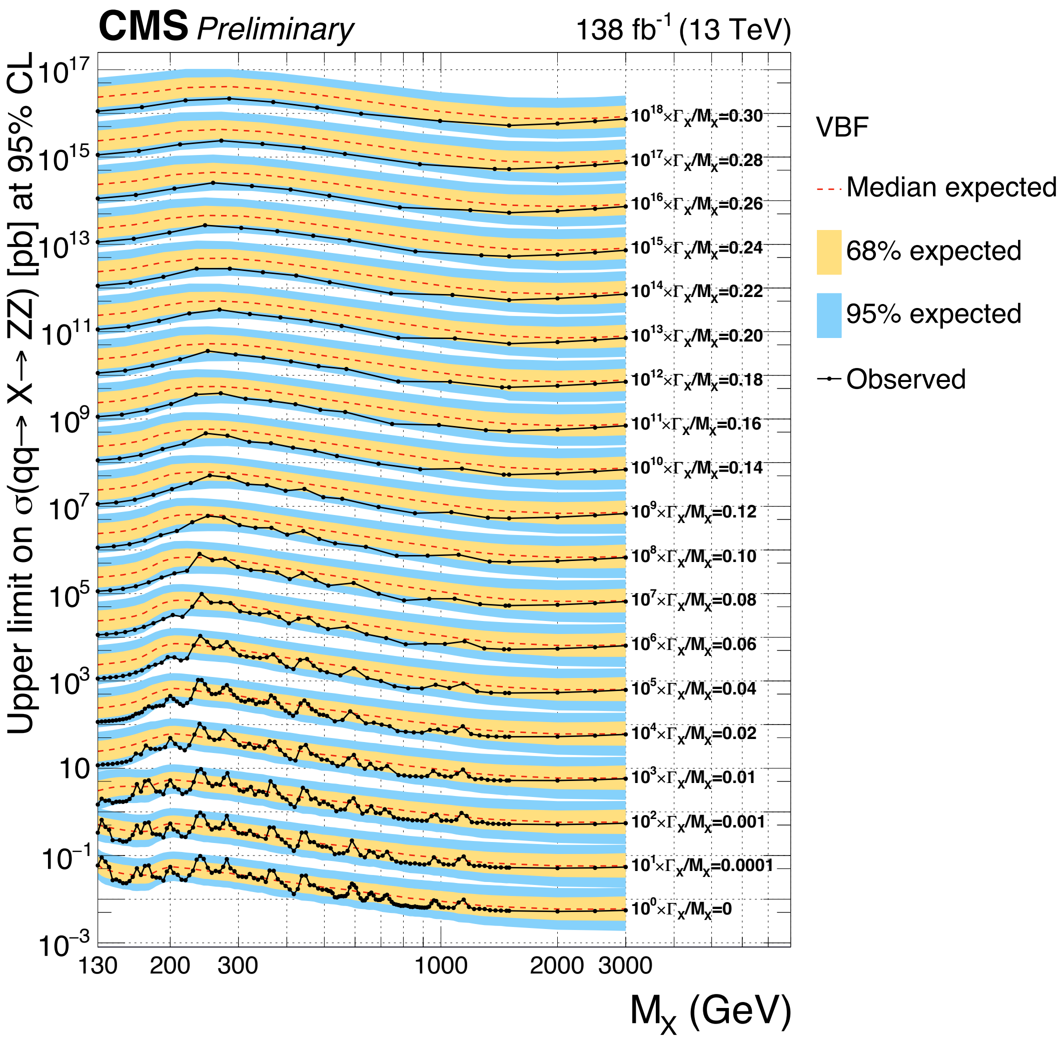
Phys. Briefing

| Experimental uncertainties | | | | | |
|---|---|---|---|---|---|
| Year | 2016 | 2017 | 2018 | Effects | Affected processes |
| Luminosity | 1.2% | 2.3% | 2.5% | norm | all except Z +X |
| e efficiency | 3-10% | 3-9% | 3-9% | norm | all except Z +X |
| $\mu$ efficiency | 1-2% | 1-2% | 1-2% | norm | all except Z +X |
| e($\mu$) energy scale | 0.15(0.03)% | | | shape | all with energy convolution |
| e($\mu$) energy resolution | 10(3)% | | | shape | all with energy convolution |
| jet energy scale | $\approx$ 1% | | | norm | all except Z +X |
| jet energy resolution | $\approx$ 1% | | | norm | all except Z +X |
| jet b-tagging efficiency | 0.1% | | | norm | all except Z +X |
| ggF interference | 9-11% | | | norm | interferences |
| VBF interference | 13-18% | | | norm | interferences |
| Z + X ($4\mu$) | 30% | 30% | 30% | norm | Z +X |
| Z + X (4e) | 31% | 31% | 30% | norm | Z +X |
| Z + X ($2e2\mu$) | 31% | 30% | 30% | norm | Z +X |
| **Theoretical uncertainties** | | | | | |
| BR($X \to ZZ$) | 2% | | | norm | signals |
| QCD scale | 1-15% | | | shape: qqZZ<br>norm: others | all except Z +X |
| PDF | 0.1-7% | | | shape: qqZZ<br>norm: others | all except Z +X |
| $\alpha_S$ | 0.1-7% | | | norm | all except Z +X |
| pythia scale | 0.4-10% | | | norm | all except Z +X |
| qqZZ $K$ factor | 0.1-30% | | | shape | qqZZ |
| ggZZ $K$ factor | 10% | | | norm | ggZZ |

# $X \to ZZ \to 4\ell$

- $\Gamma_X / M_X = 0 - 30\,\%$



# $A/H \rightarrow t\bar{t}$

CMS-PAS-HIG-22-013