Search for additional Higgs bosons in the CMS experiment

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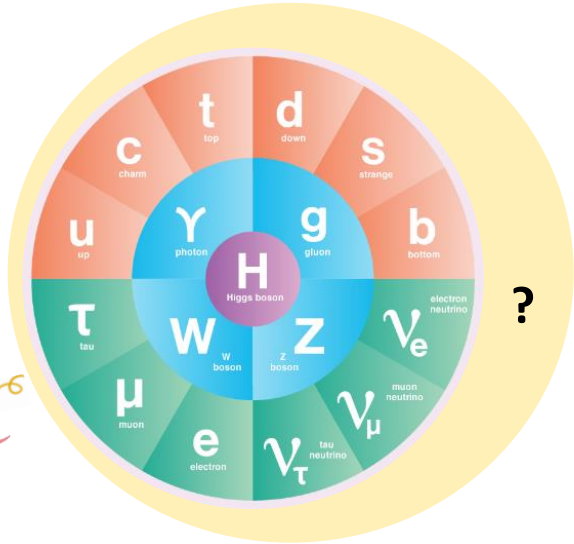
ICHEP2024

Theoretical motivation

Must the Standard Model (SM) be like this? No!

- The simplest Higgs sector
- Problems: 3 generations? Hierarchy problem? Dark matter? ...

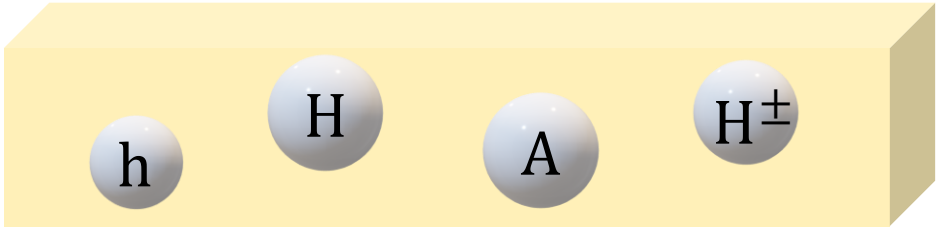


Can SM be in other forms? Yes!
Extension of the Higgs sector

Electroweak singlet model

2-Higgs-doublet model (2HDM)

Supersymmetry (SUSY)



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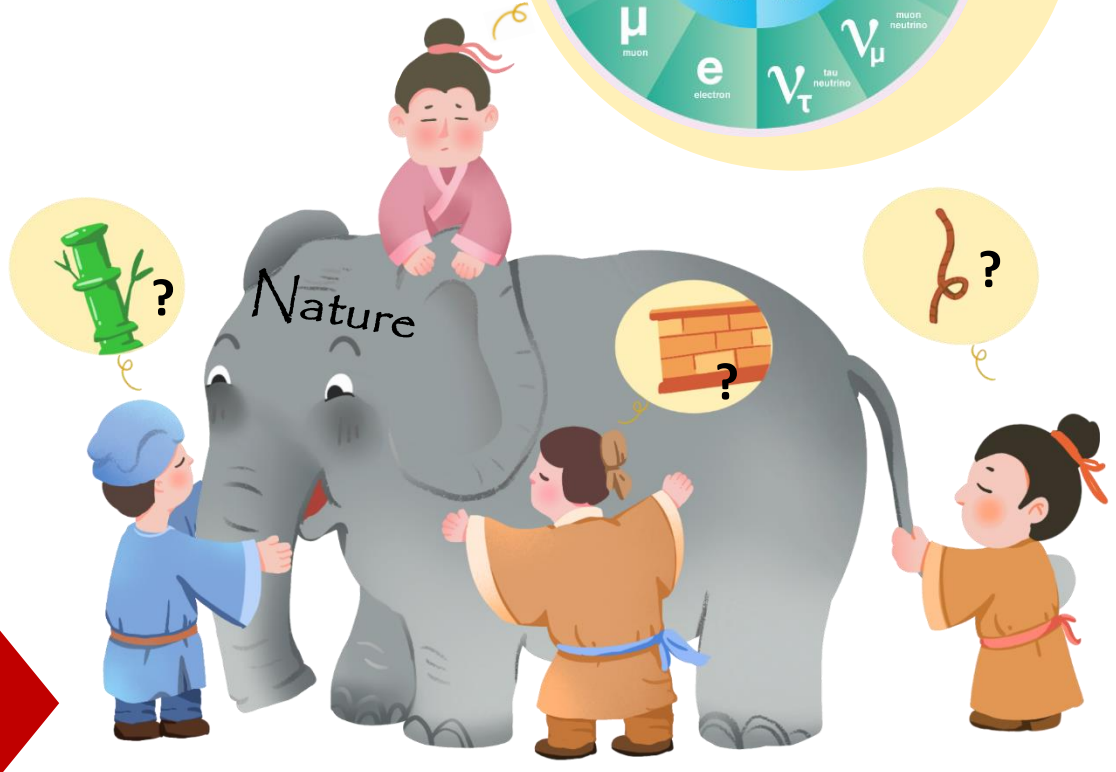

Search for additional Higgs bosons predicted by these models!

Experimental exploration in the CMS experiment

Neutral scalar Higgs boson (X)

Decay to vector bosons (V)

- ➢ X→VV→4q/b: CMS-B2G-20-009
- ➢ Light X→γγ: CMS-HIG-20-002
- ❖ Heavy X->γγ: CMS-EXO-22-024
- • X→WW→llνν: CMS-PAS-HIG-20-016
- ✓ **X→ZZ→4l: CMS-PAS-HIG-24-002**

Decay to Higgs bosons (H)

- ➢ X→HH→bbττ: CMS-HIG-20-014
- ➢ X→HH→4W/τ: CMS-HIG-21-002
- ➢ X→HH→4b: CMS-B2G-21-003
- ➢ X→HH/YH→bbγγ: CMS-HIG-21-011
- ➢ X→HH→bbWW: CMS-HIG-21-005
- ✓ **X→HH/YH→γγττ: CMS-PAS-HIG-22-012**

Other decays

- ➢ X→ττ: CMS-HIG-21-001
- ✓ **X/A→bb: CMS-PAS-SUS-24-001**

Neutral pseudoscalar Higgs boson (A/a)

Decay to ZH

- ○ A→ZH→llττ: CMS-PAS-B2G-23-006
- ✓ **A→ZH→llττ: CMS-PAS-HIG-22-004**

Decay from the Higgs boson(H)

- ➢ H→aa→4γ: CMS-HIG-21-016
- ➢ H→Za→2l2γ: CMS-HIG-22-003
- ❑ H→aa→2μ2b, 2τ2b: CMS-HIG-22-007
- ❑ H→aa→4μ: CMS-PAS-HIG-21-004

All with full Run 2 dataset!

- ➢ Previous results
- ❖ Included in the talk of J. Babbar
- ❑ Included in the talk of S. Kwan
- ○ Included in the talk of D. HundHausen
- ✓ **Published in 2024 and included in this talk !**

Charged Higgs boson (H±)

- ➢ H++(H+)→WW(WZ): CMS-HIG-20-017
- ➢ H±→WH(ττ): CMS-HIG-21-010
- ❖ H±→Wγ: CMS-EXO-21-017

Experimental exploration in the CMS experiment

Neutral scalar Higgs boson (X)

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- ✓ X→ZZ→4l: CMS-PAS-HIG-24-002

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- ➢ X→HH→bbWW: CMS-HIG-21-005
- ✓ X→HH/YH→γγττ: CMS-PAS-HIG-22-012

Other decays

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- ✓ X/A→bb: CMS-PAS-SUS-24-001

Neutral pseudoscalar Higgs boson (A/a)

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CMS-PAS-HIG-22-012

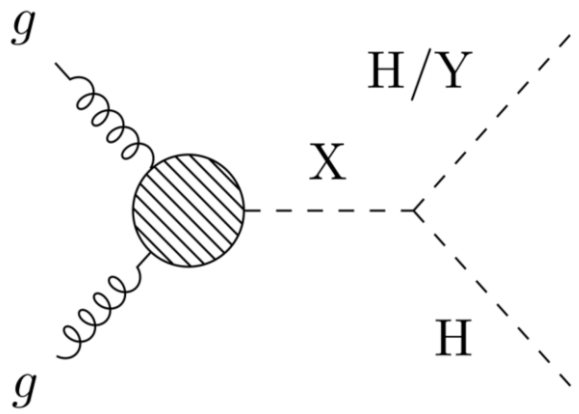
Search for scalar X→HH/YH→γγττ

X→HH/YH→γγττ: Analysis strategy

CMS-PAS-HIG-22-012

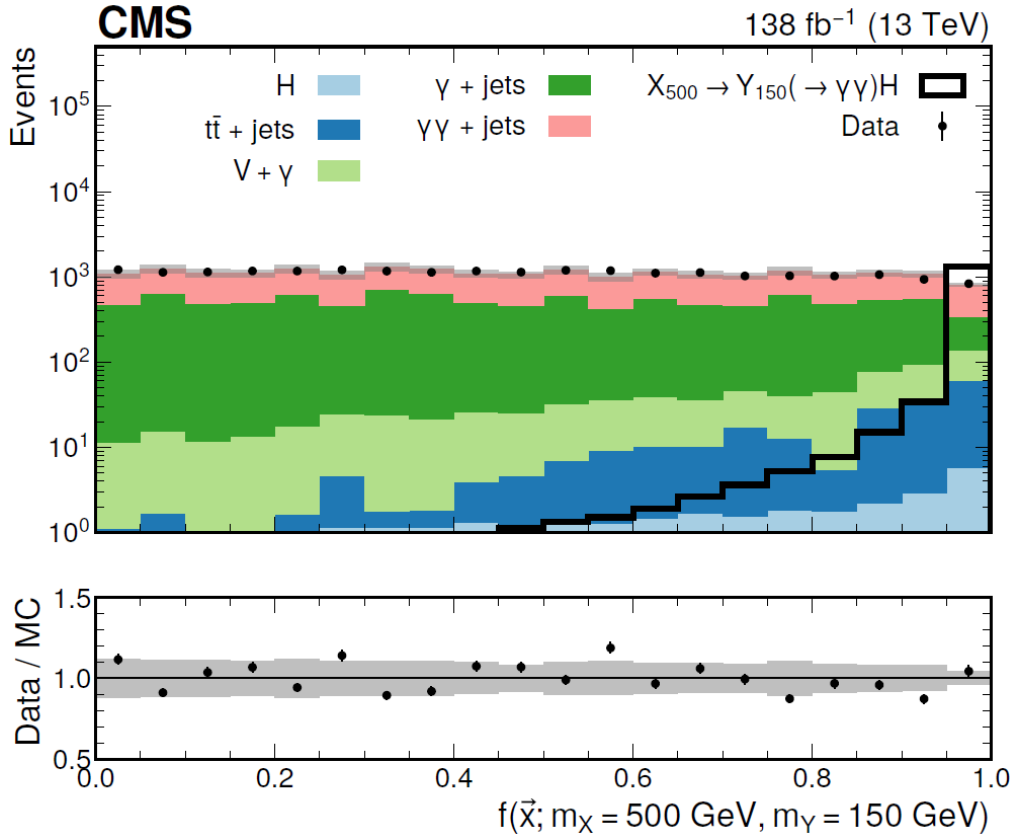
Physics

- **X→HH→γγττ:** warped extra dimension (WED) theories
  - **bulk radion** and **graviton**
- **X→YH→γγττ / ττγγ:** NMSSM
  - 2HDM + 1 complex singlet
  - 3 scalar Higgs bosons (X, Y, H)



Event selection and categorization

- Trigger on γγ
- Select 2 good photons, and ≥ 1 τ candidate (e, μ, hadronic τ, or an isolated track)
- **8 channels depending on the lepton flavor**
- **Parameterized Neural Network** (pNN) used for event categorization: $f(\vec{x}|M_X, M_Y)$



X→HH/YH→γγττ: Analysis strategy

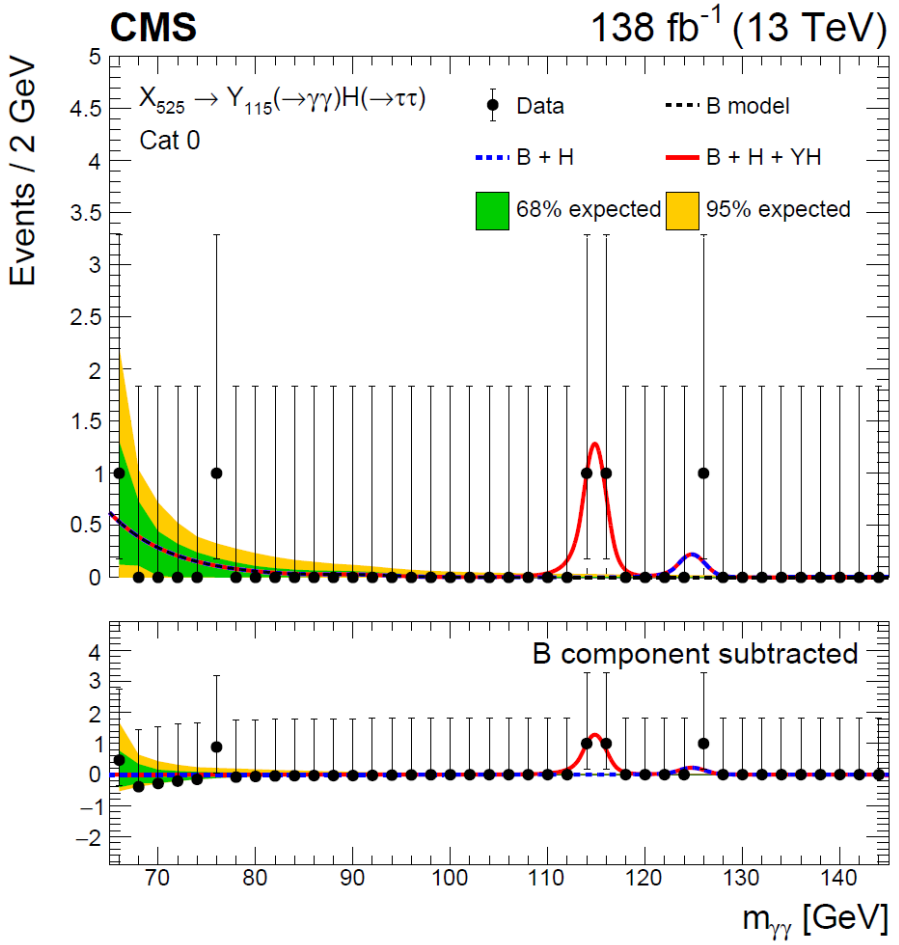
CMS-PAS-HIG-22-012

Discriminating variable: $M_{\gamma\gamma}$

Process modelling

- **Signals**: double crystal ball functions (DCB) on $M_{\gamma\gamma}$
- **Single Higgs boson**: DCB
- **Continuum backgrounds**: smooth functions
- **Drell-Yan (DY)** background: ABCD method

Low mass Y (< 125 GeV)



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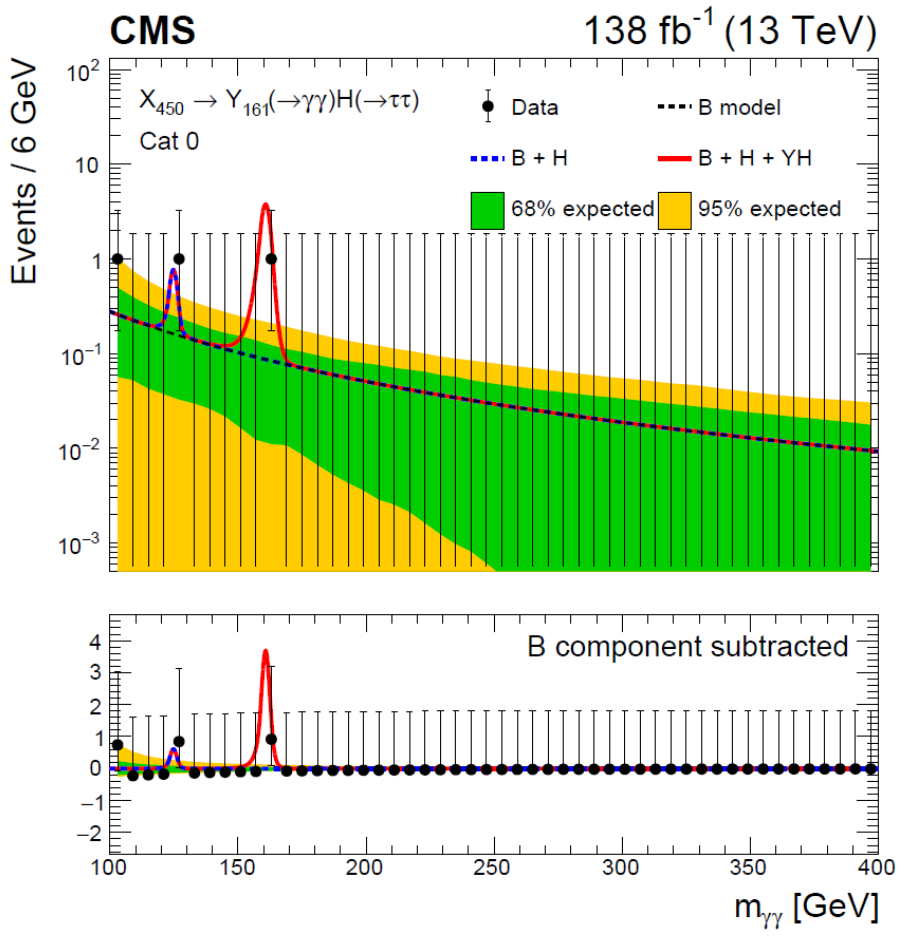


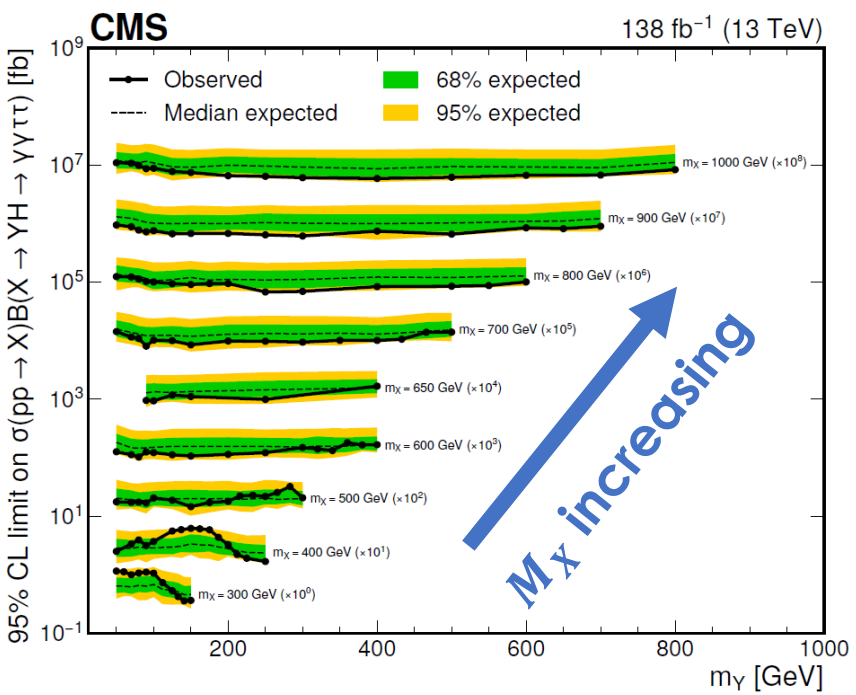
X→HH/YH→γγττ: Results

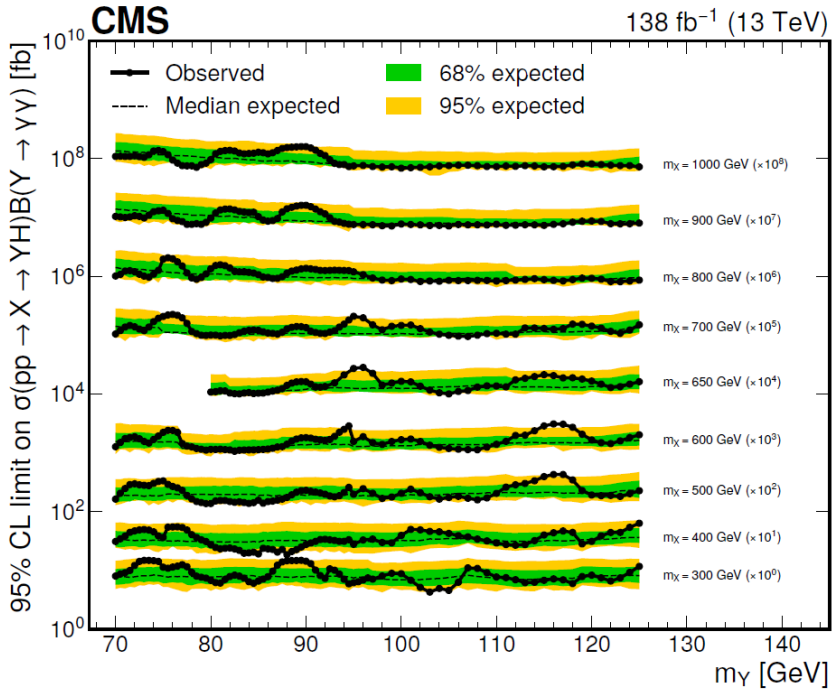
CMS-PAS-HIG-22-012

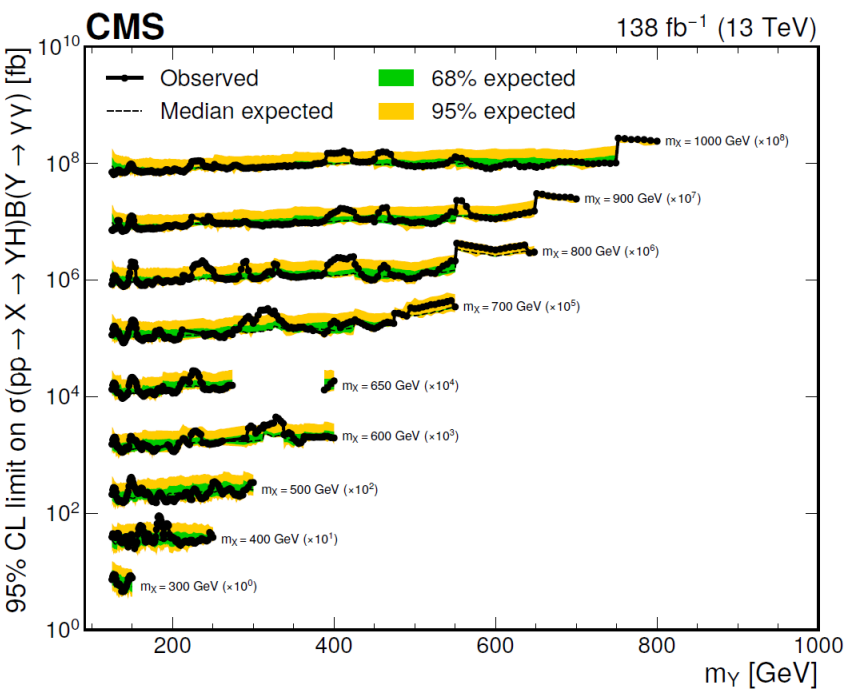
Results on NMSSM, X→YH

Different trigger efficiency and kinematics

Y(ττ)H(γγ) | **Y(γγ)H(ττ) low mass** ⟷ **Y(γγ)H(ττ) high mass**







Highest excess:
(M_X, M_Y)=(320, 60) GeV
Local 2.6 σ, global 2.2 σ

Highest excess:
(M_X, M_Y)=(525, 115) GeV
Local 3.2 σ, global 0.1 σ

Highest excess:
(M_X, M_Y)=(450, 161) GeV
Local 3.2 σ, global 0.3 σ

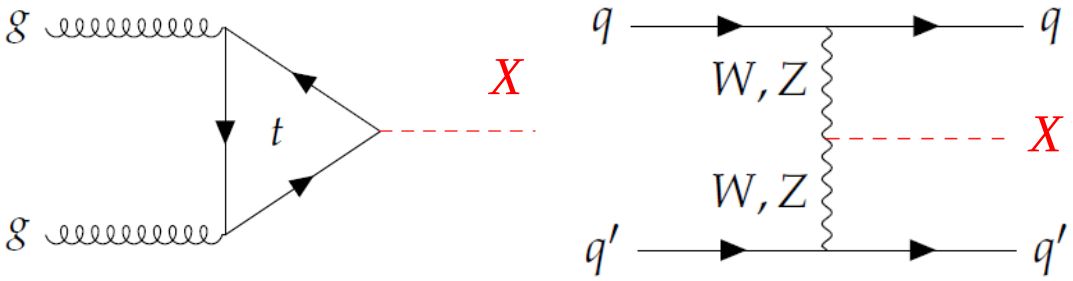
CMS-PAS-HIG-24-002
Search for scalar X→ZZ→4l

X→ZZ→4l: Analysis strategy

CMS-PAS-HIG-24-002

Physics

- X→ZZ→4l (e / μ)
- X produced with gluon fusion (**ggF**) or vector boson fusion (**VBF**)
- Model-independent search



Event selection

- Trigger on 1, 2 or 3 leptons
- Select electrons and muons
- Build Z candidates, then the ZZ candidate

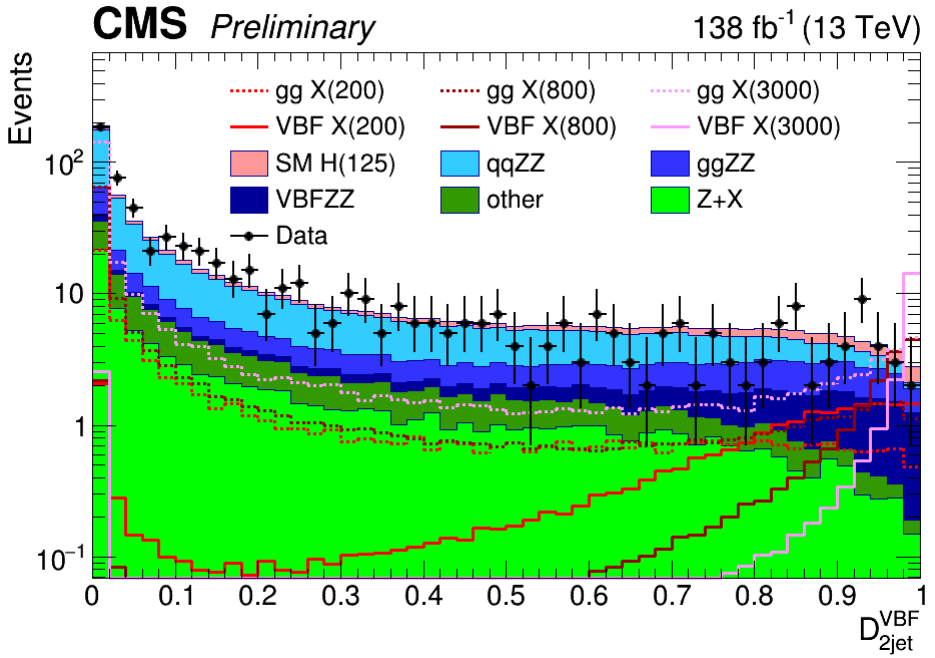
Event Categorization

- **Two categories targeting ggF and VBF** based on jet kinematics and D_{2jet}^{VBF} computed from MELA

Matrix Element Likelihood Approach (MELA)

- Compute discriminants based on matrix elements and kinematics

$$D_{2jet}^{VBF} = \left[1 + \frac{P_{ggH+jj}(\Omega^{4l+jj}|m_{4l})}{P_{VBFH}(\Omega^{4l+jj}|m_{4l})}\right]^{-1}$$

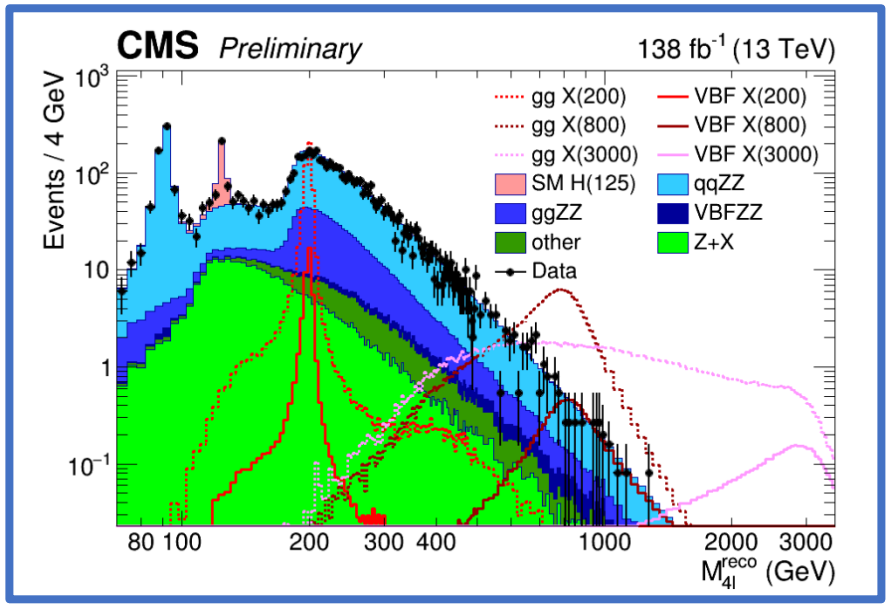


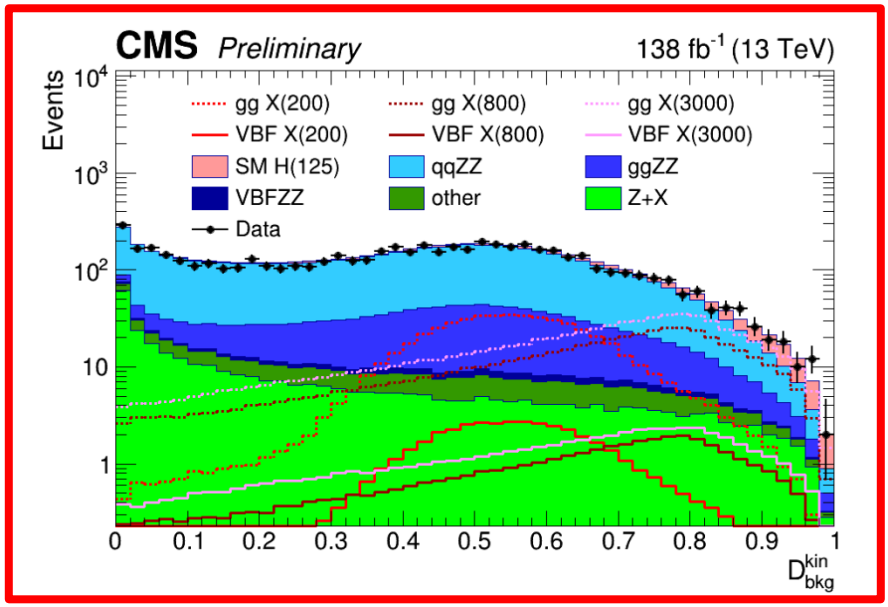
X→ZZ→4l: Analysis strategy

CMS-PAS-HIG-24-002

Two-dimensional discriminating variables:

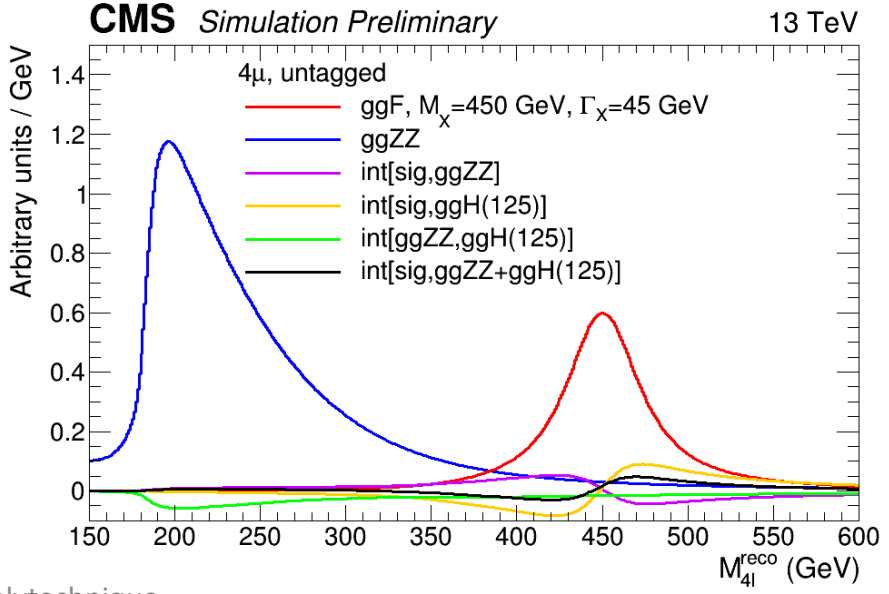
- M_{4l}^{reco}
- $D_{bkg}^{kin} = \left[1 + \frac{P_{bkg}^{qqZZ}(\Omega^{4l}|m_{4l})}{P_{sig}^{ggH}(\Omega^{4l}|m_{4l})}\right]^{-1}$





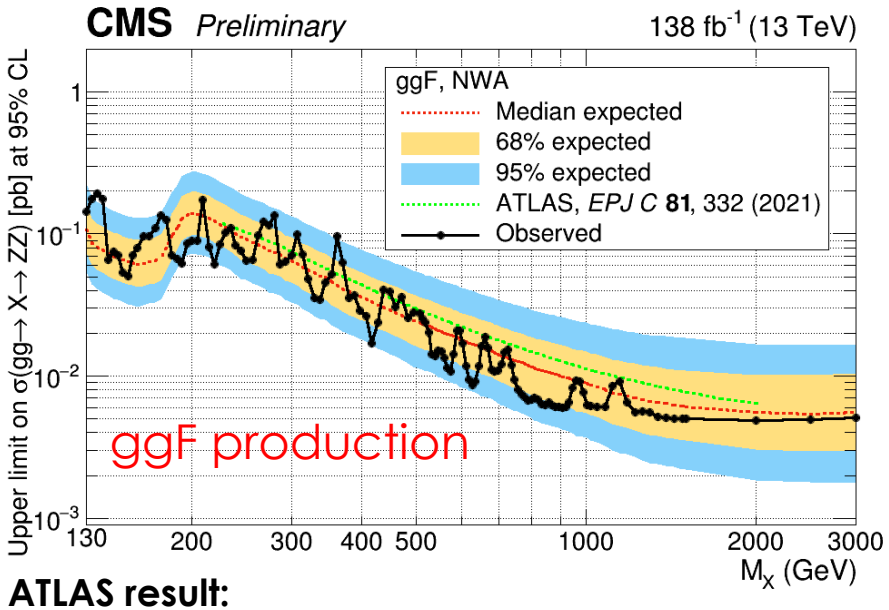
Parametric process modeling

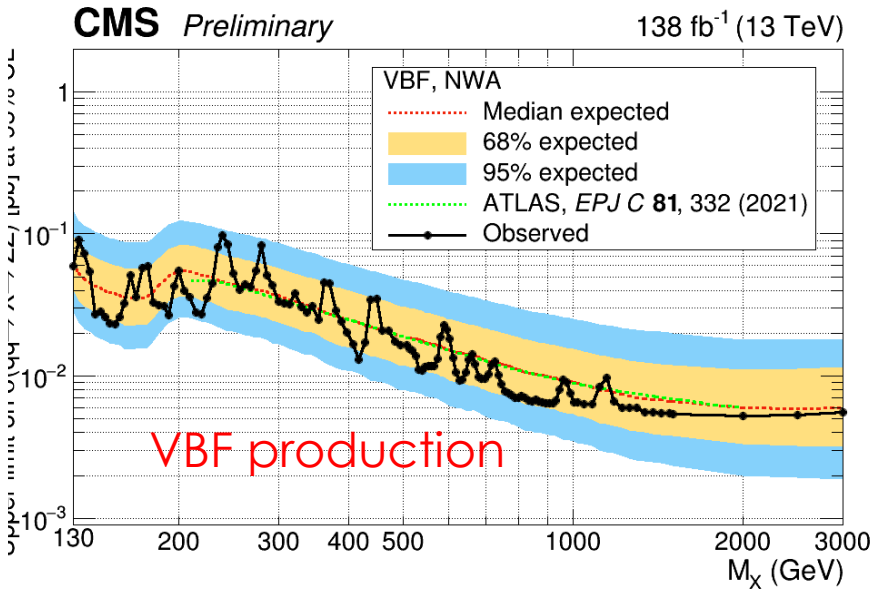
- **Signals**: by MC, with M_{4l}^{reco} **parameterized** as (analytic lineshape × signal efficiency) ⊗ mass resolution
- **Irreducible backgrounds**: by MC, with M_{4l}^{reco} **parameterized**
- **Reducible backgrounds**: data-driven method
- **Interferences**: amplitudes from signal, backgrounds; phases from generators and kinematics



X→ZZ→4l: narrow width assumption

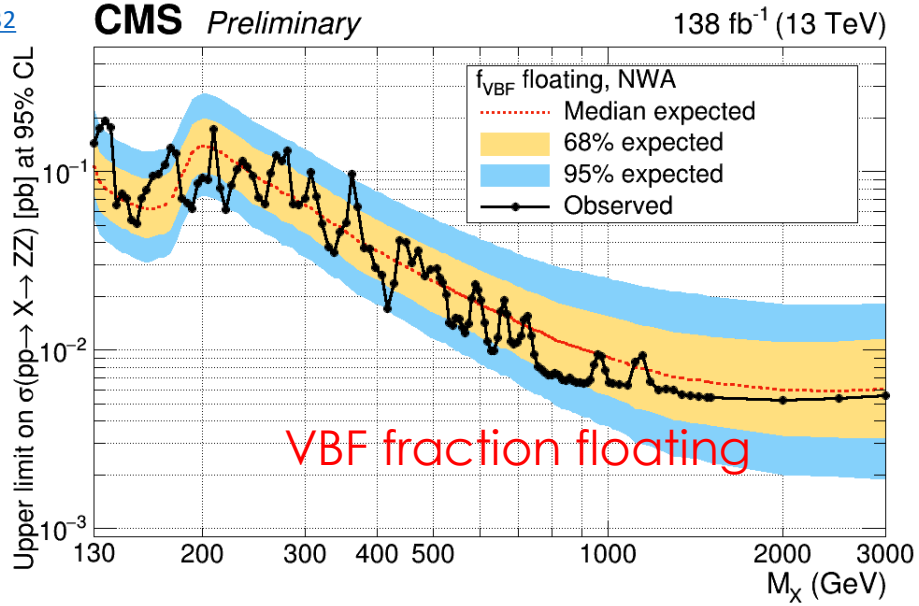
CMS-PAS-HIG-24-002





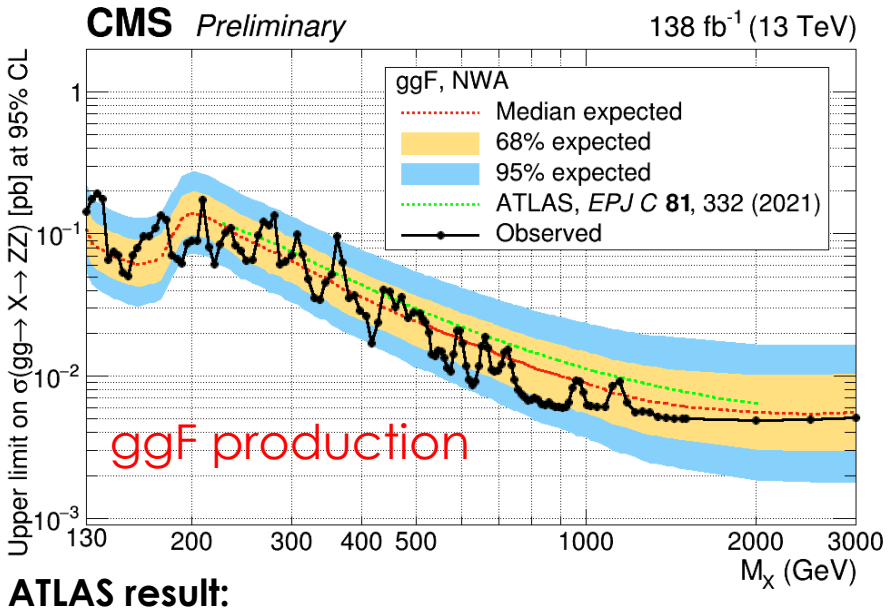
ATLAS result:

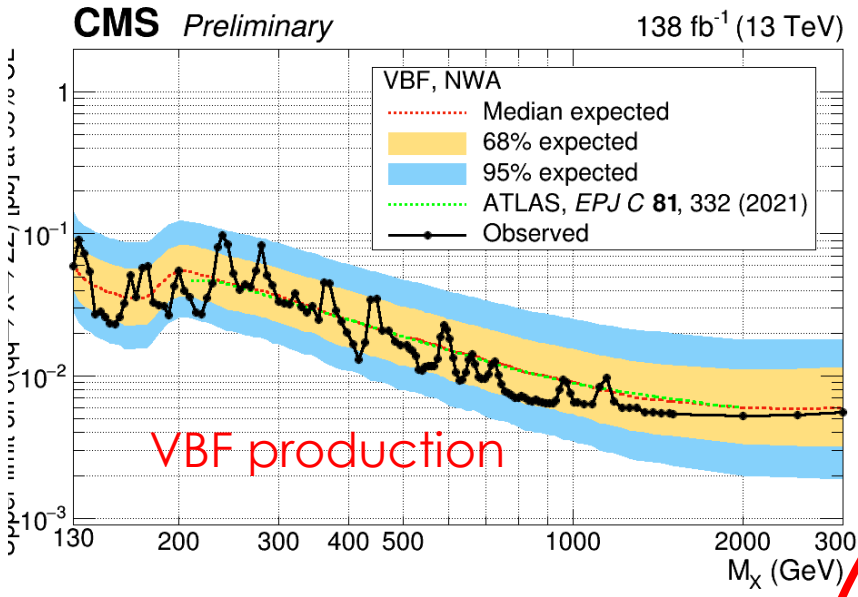
Eur. Phys. J. C 81 (2021) 332



X→ZZ→4l: narrow width assumption

CMS-PAS-HIG-24-002





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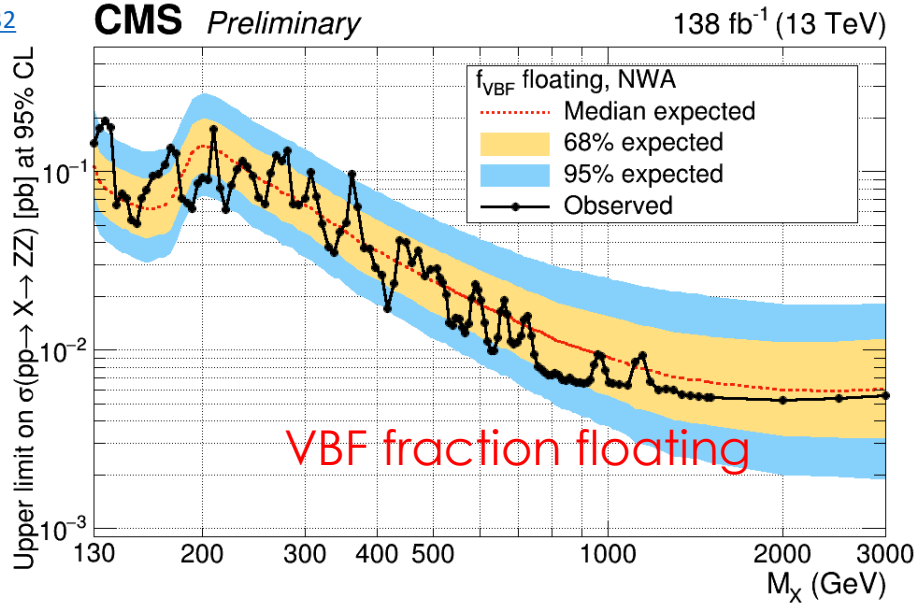
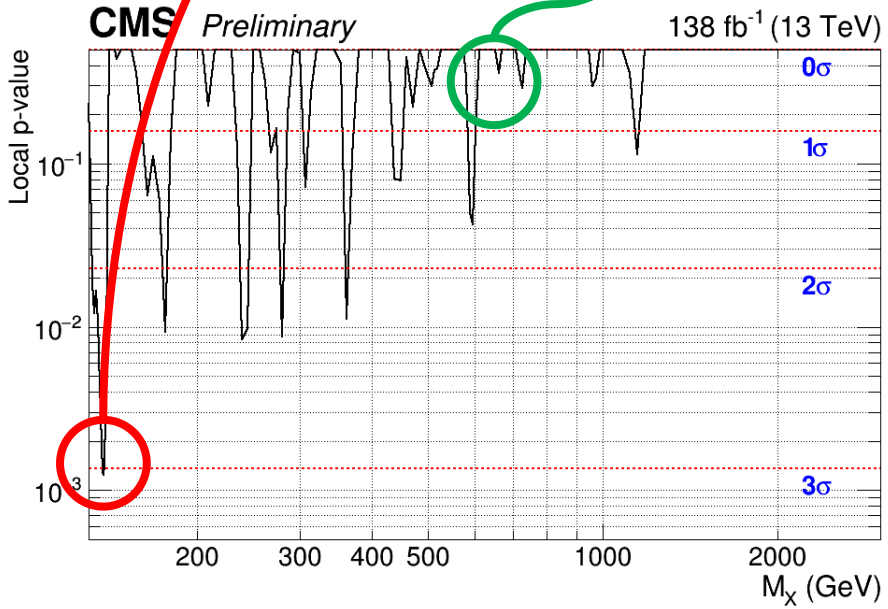


p-value scan

Highest significance reached at 137.8 GeV
Local 3.02 σ, global 1.85 σ

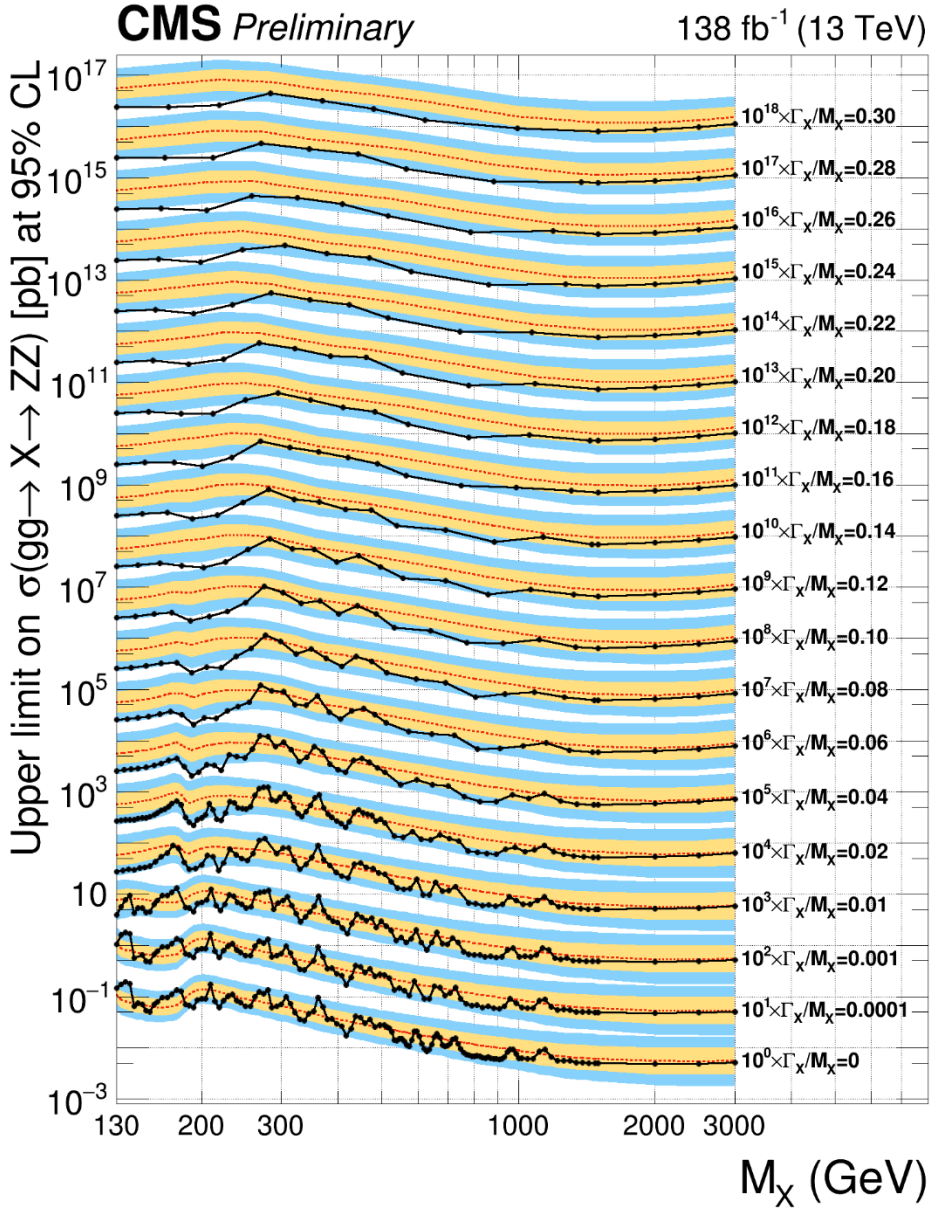
No excess at around 650 GeV



X→ZZ→4l: various width assumption

CMS-PAS-HIG-24-002

This is **ggF production**; **VBF production** shown in backup



ggF

Median expected

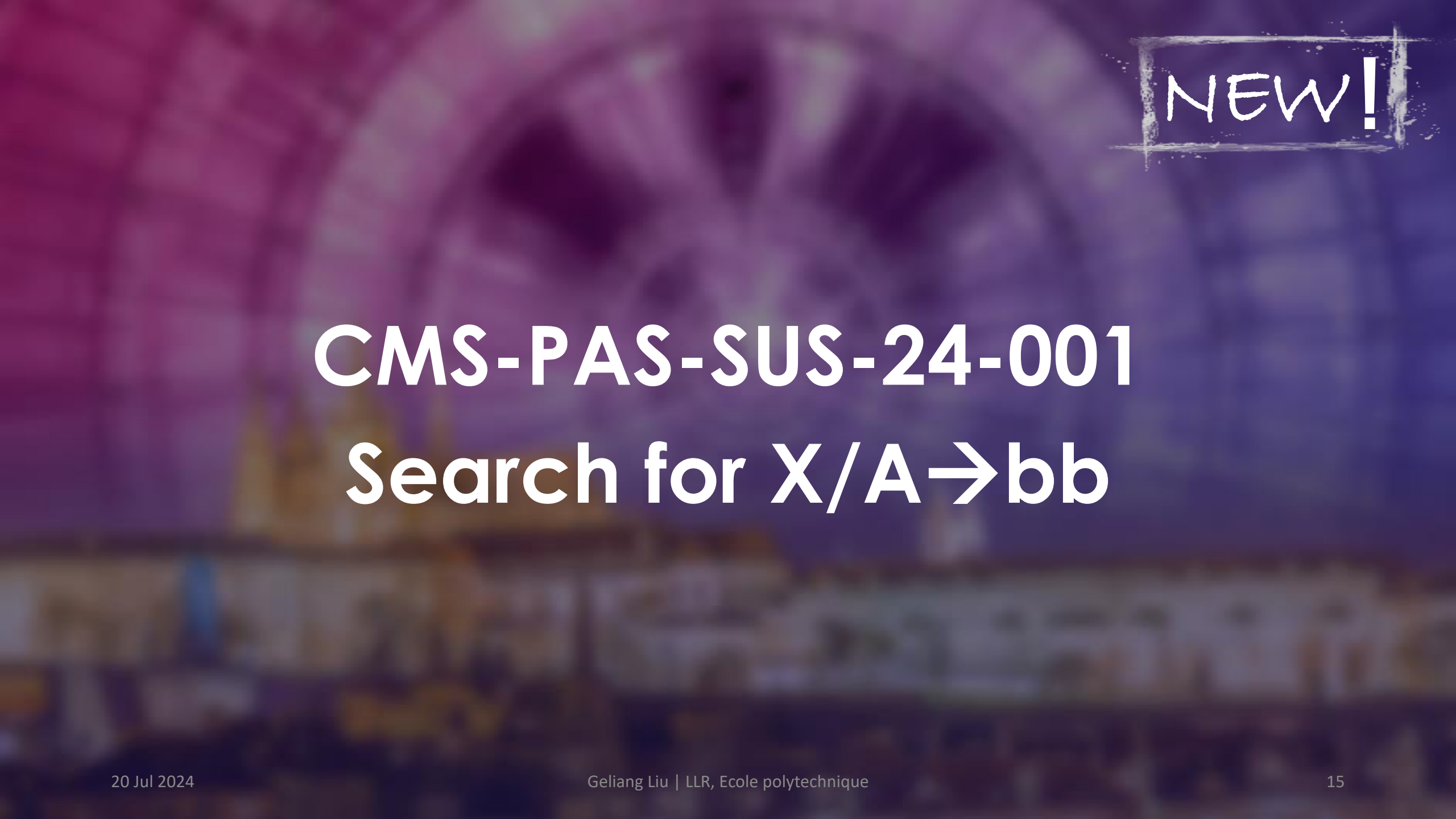
68% expected

95% expected

Observed

$\frac{\Gamma_X}{M_X}$ increasing

No other excess observed



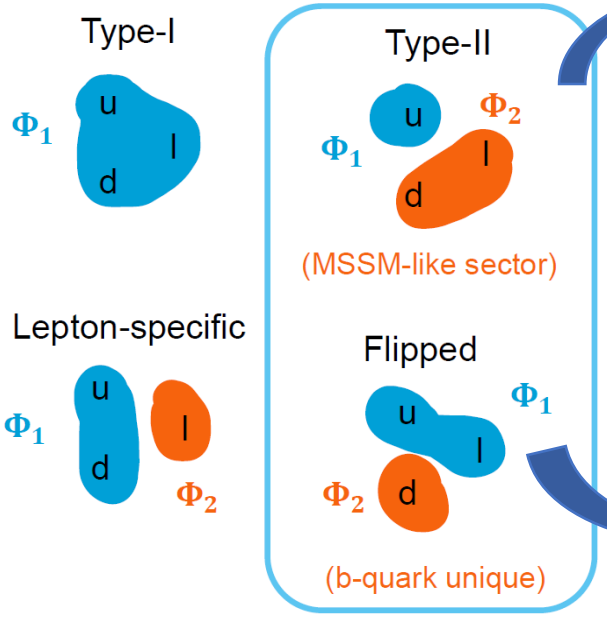
CMS-PAS-SUS-24-001
Search for X/A→bb

ϕ(H,h,A)→bb: Analysis strategy

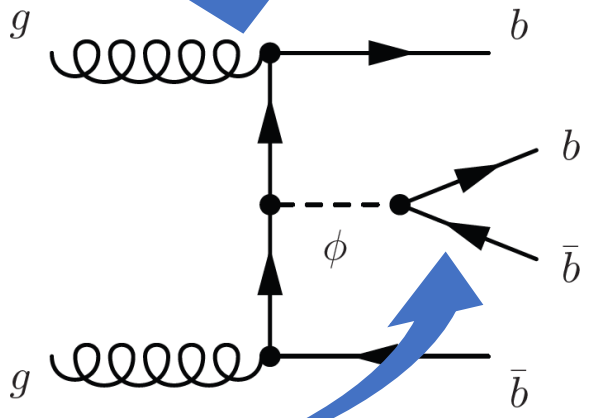
CMS-PAS-SUS-24-001

Physics

➢ 2HDM & MSSM

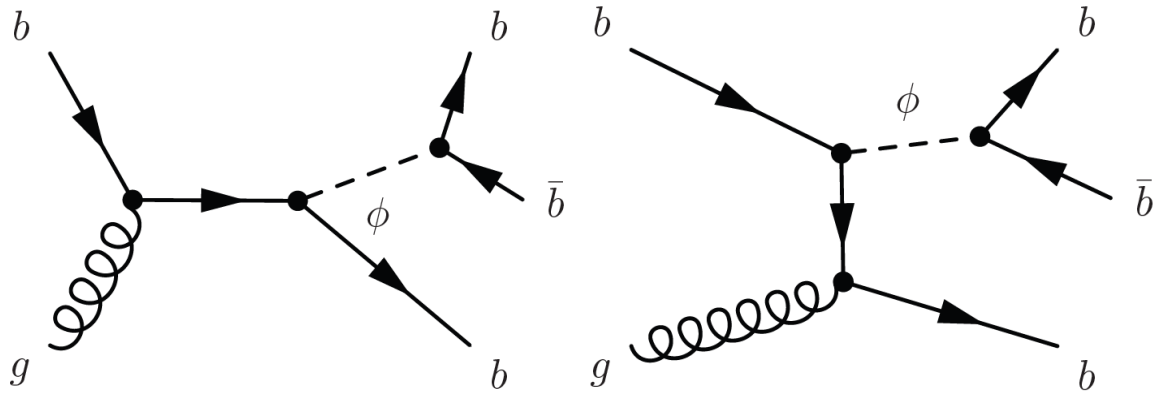


Enhance by 2(tanβ)^2



High BR(ϕ→bb)

$\phi = H, h, A$



➢ Search for **ϕ (H,h,A)→bb associated with ≥ 1 b**

Online and offline selection

➢ **Full hadronic (FH):** double-b-jet triggers, with high pT thresholds

➢ **Semi leptonic (SL):** one of the two leading jets contains a muon from the b hadron decay

➢ **Three off-line b-tagged jets**, with different kinematic requirements

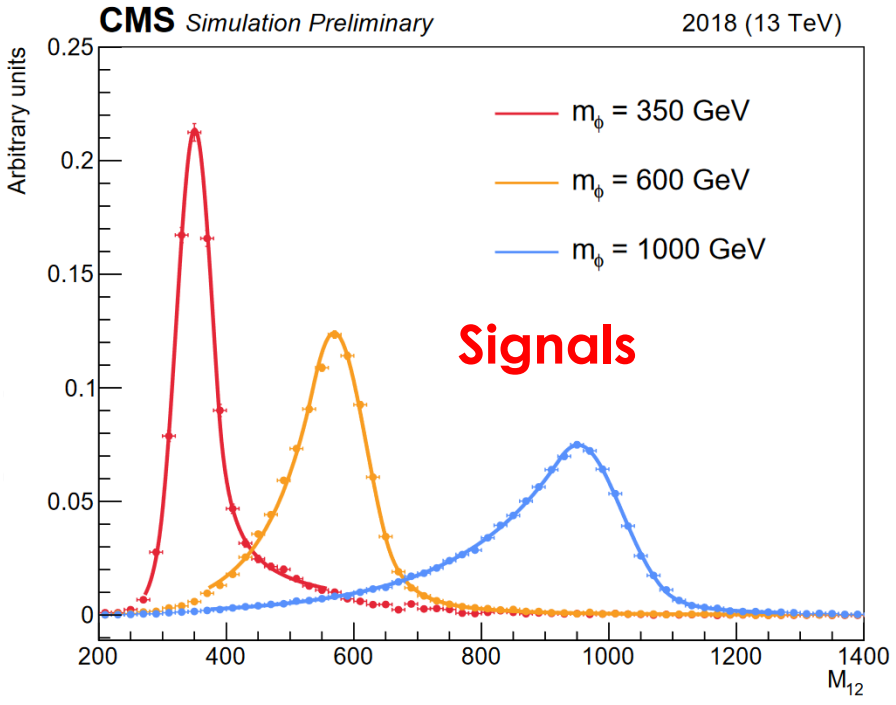
ϕ(H,h,A)→bb: Analysis strategy

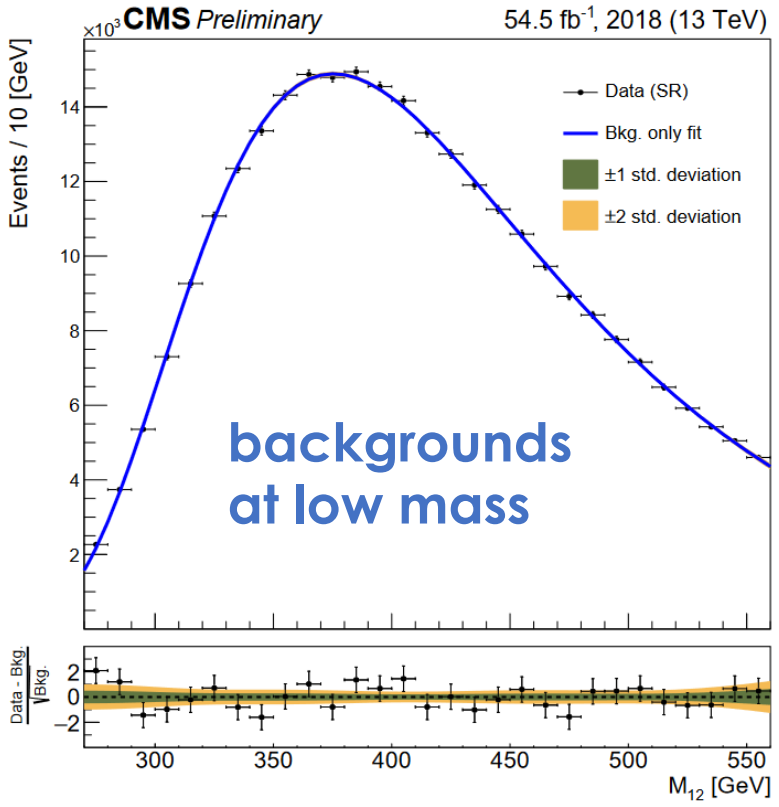
CMS-PAS-SUS-24-001

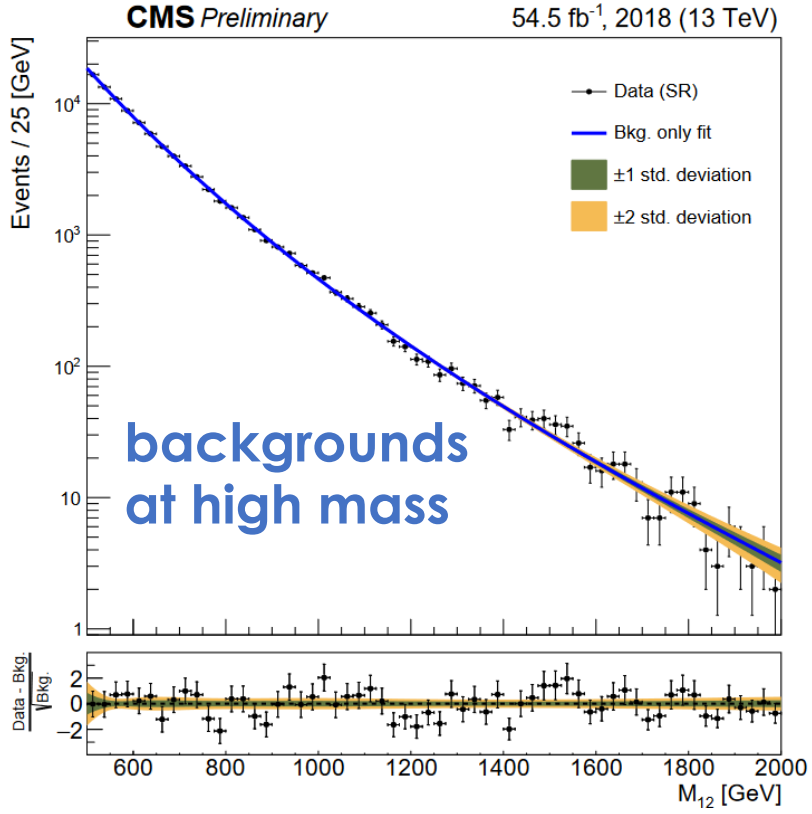
Discriminating variable: $\mathbf{M_{j_1 j_2}}$ (jet ordered by pT)

Process modeling

- **Signals**: from MC, fitted with the **DCB function**. Predicted to be narrow.
- **Backgrounds** (QCD multijet): **smooth functions** fitted from control regions (defined that j_3 not b-tagged), corrected with **transfer functions** from MC



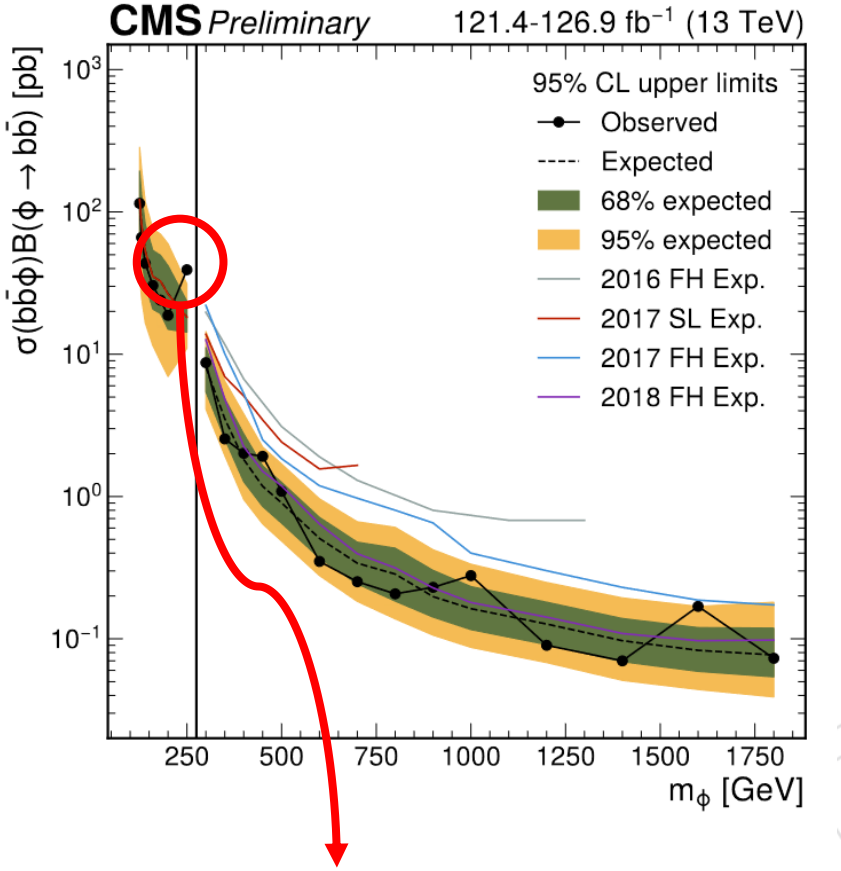




ϕ(H,h,A)→bb: results

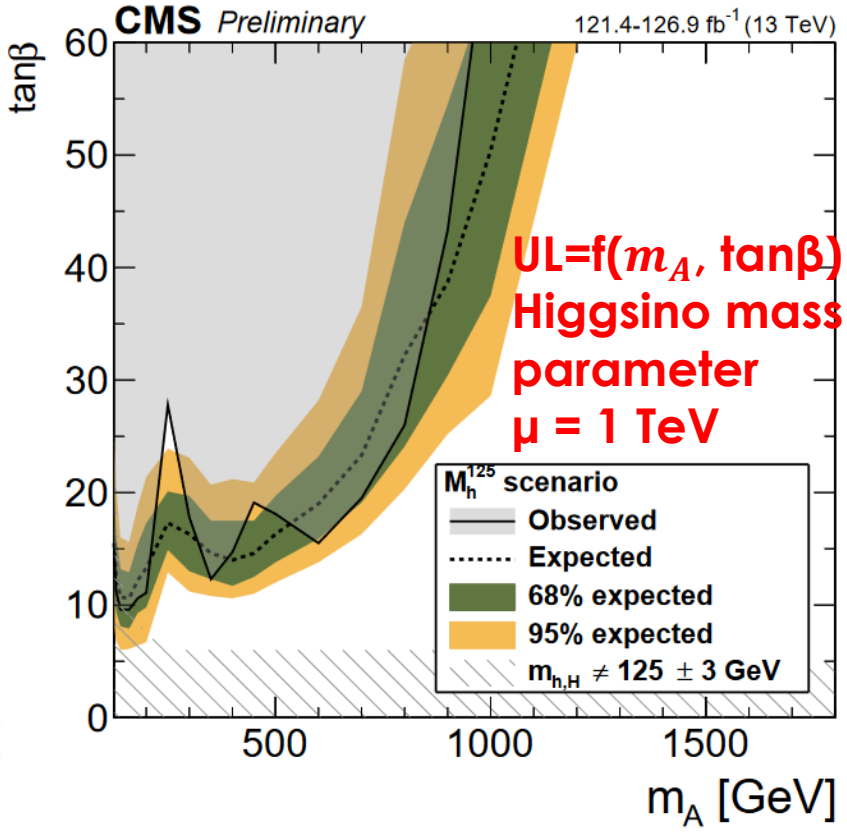
CMS-PAS-SUS-24-001

Model-independent search



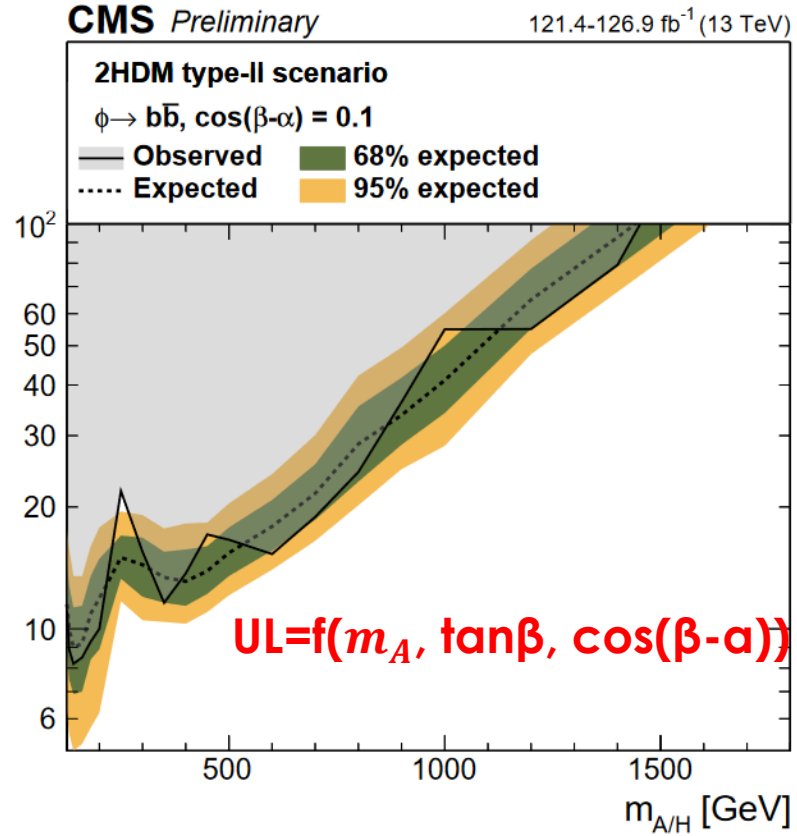
At 250 GeV, local (global) 3.2 (2.8) σ from the 2017 SL dataset

MSSM interpretation:

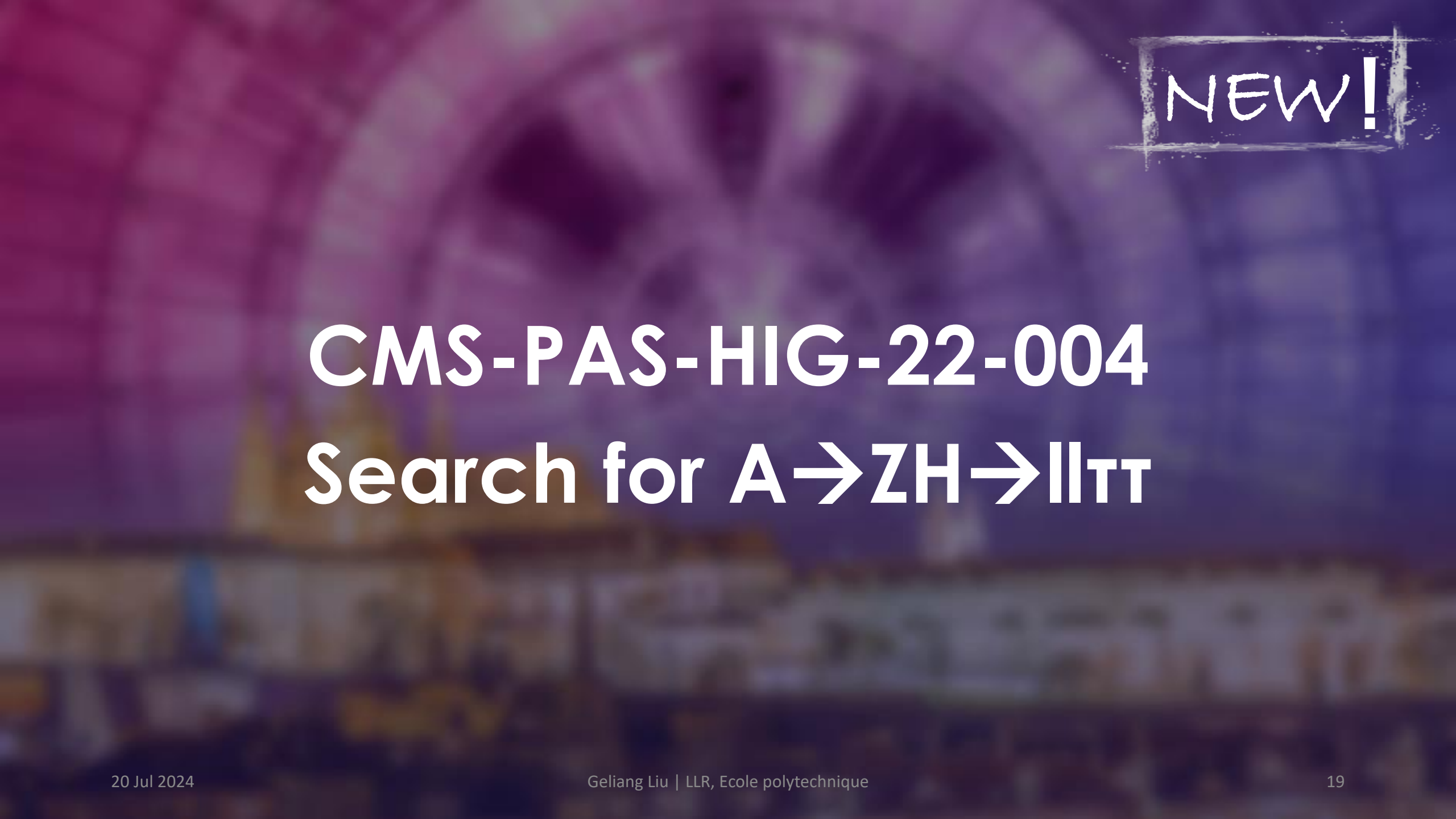


M_h^{mod+} and hMSSM scenarios also tested

2HDM interpretation:



Flipped scenario also tested



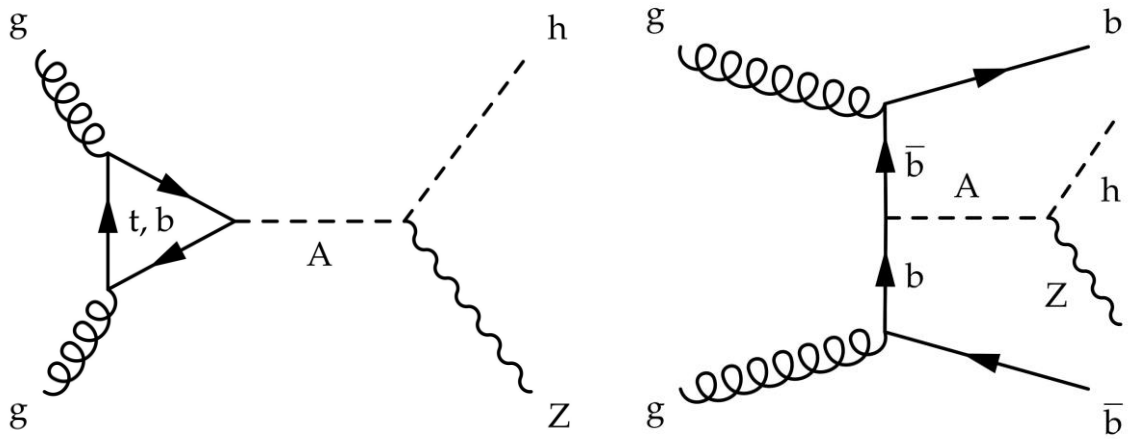
CMS-PAS-HIG-22-004
Search for A→ZH→llττ

A→ZH→llττ: Analysis strategy

CMS-PAS-HIG-22-004

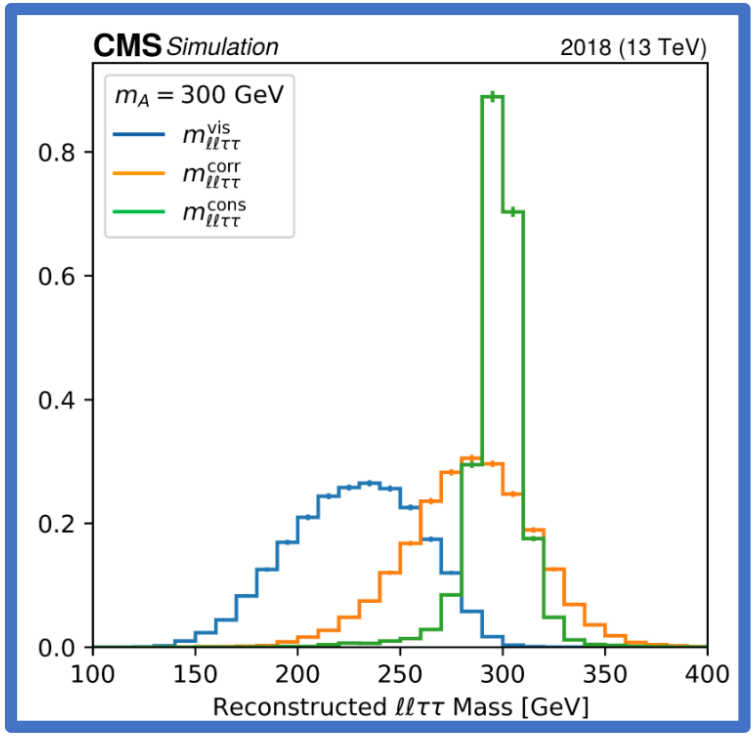
Physics

- A pseudoscalar Higgs boson predicted from MSSM, decaying to **Z(ll)H(ττ)**
- Two production mechanisms: **ggF** and **bbA**, predicted to be the dominating ones in certain scenarios



Event selection and categorization

- Single e/μ triggers on Z→ll (l=e/μ)
- Select leptons (e, μ, hadronic τ)
- Build the Z and H candidate
- Categorize based on the number of b jet tagged with DeepJet: **0 b jet** and **≥ 1 b jet** category.
- FastMTT algorithm to construct H(ττ), with $M_{\tau\tau}$ fixed at the Higgs boson mass

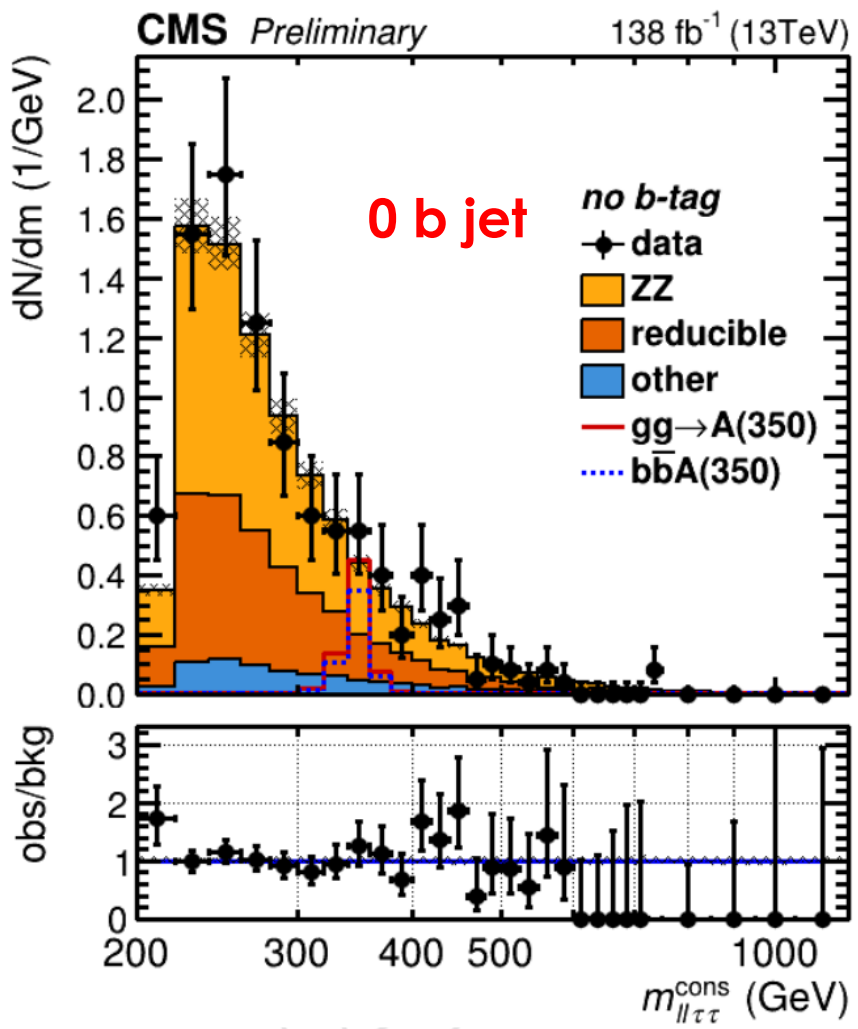


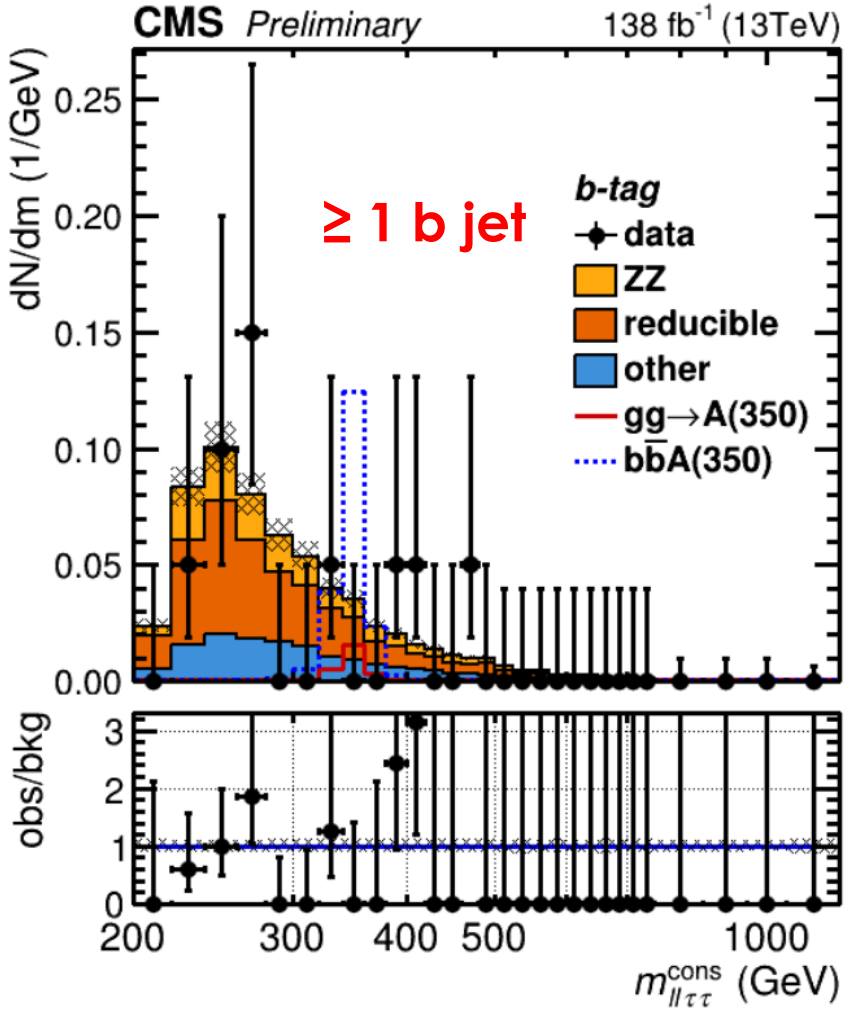
A→ZH→llττ: Analysis strategy

CMS-PAS-HIG-22-004

Discriminating variable:
$M_{ll\tau\tau}$

Process modeling
- **Signals**: by MC
- **Irreducible backgrounds**: by MC
- **Reducible backgrounds**: by a data-driven method

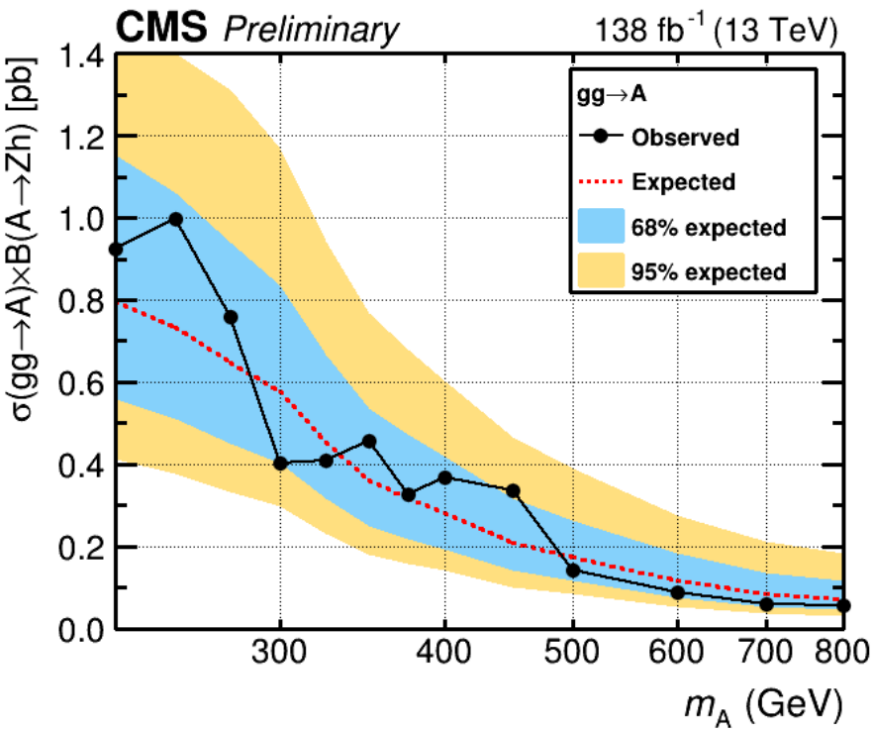




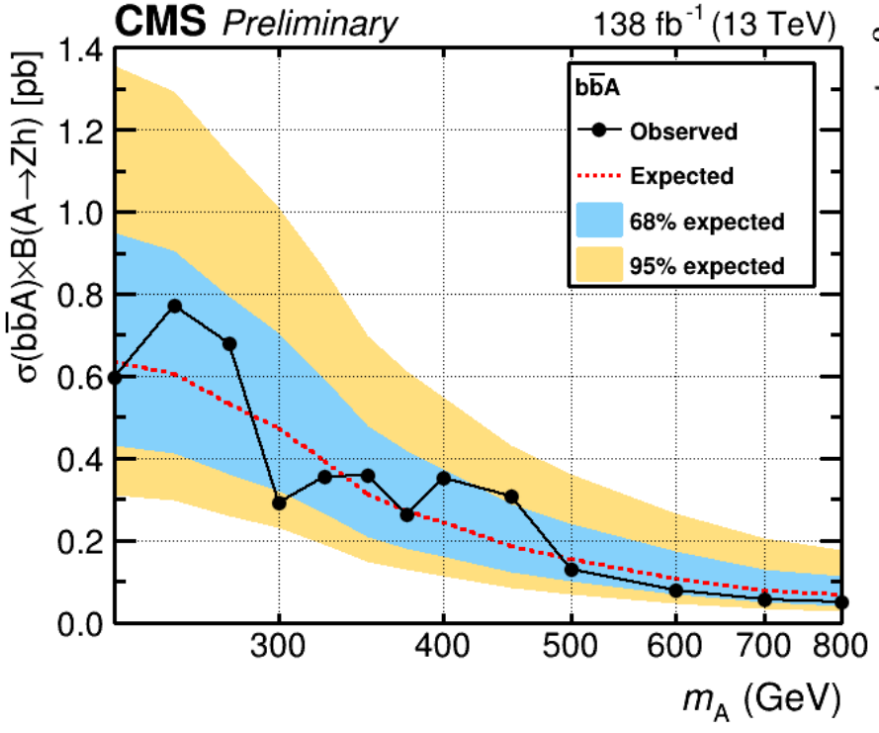
A→ZH→llττ: results

CMS-PAS-HIG-22-004

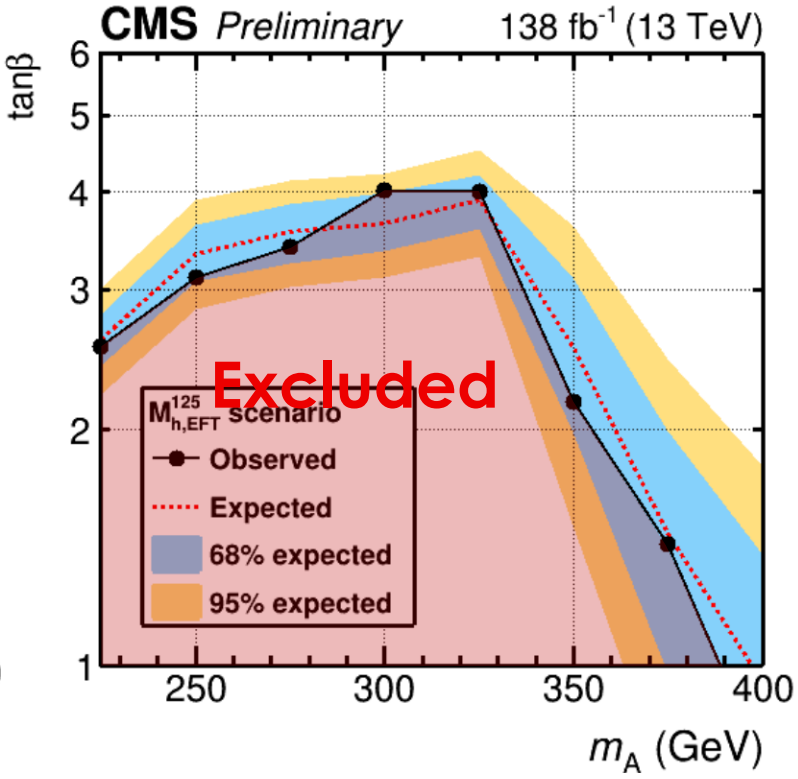
Model-independent search: pure ggF



Model-independent search: pure bbA



MSSM: M_{h125}^{EFT} scenario



No excess observed

Conclusion

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Four results published in 2024 on searches for additional Higgs bosons are shown.

- scalar X→YH→γγττ/ττγγ
- scalar X→ZZ→4l produced via ggF/VBF
- scalar/pseudoscalar ϕ→bb associated with b jets
- pseudoscalar A→ZH→llττ produced via ggF/bbA

No Significant excess observed.

- Still blinded from new physics

More exploration are needed!

- With Run 3 data to further constrain more phase space and to check potential hints
- New ideas to search for new physics are welcome

Conclusion

Four results published in 2024 on searches for additional Higgs bosons are shown.

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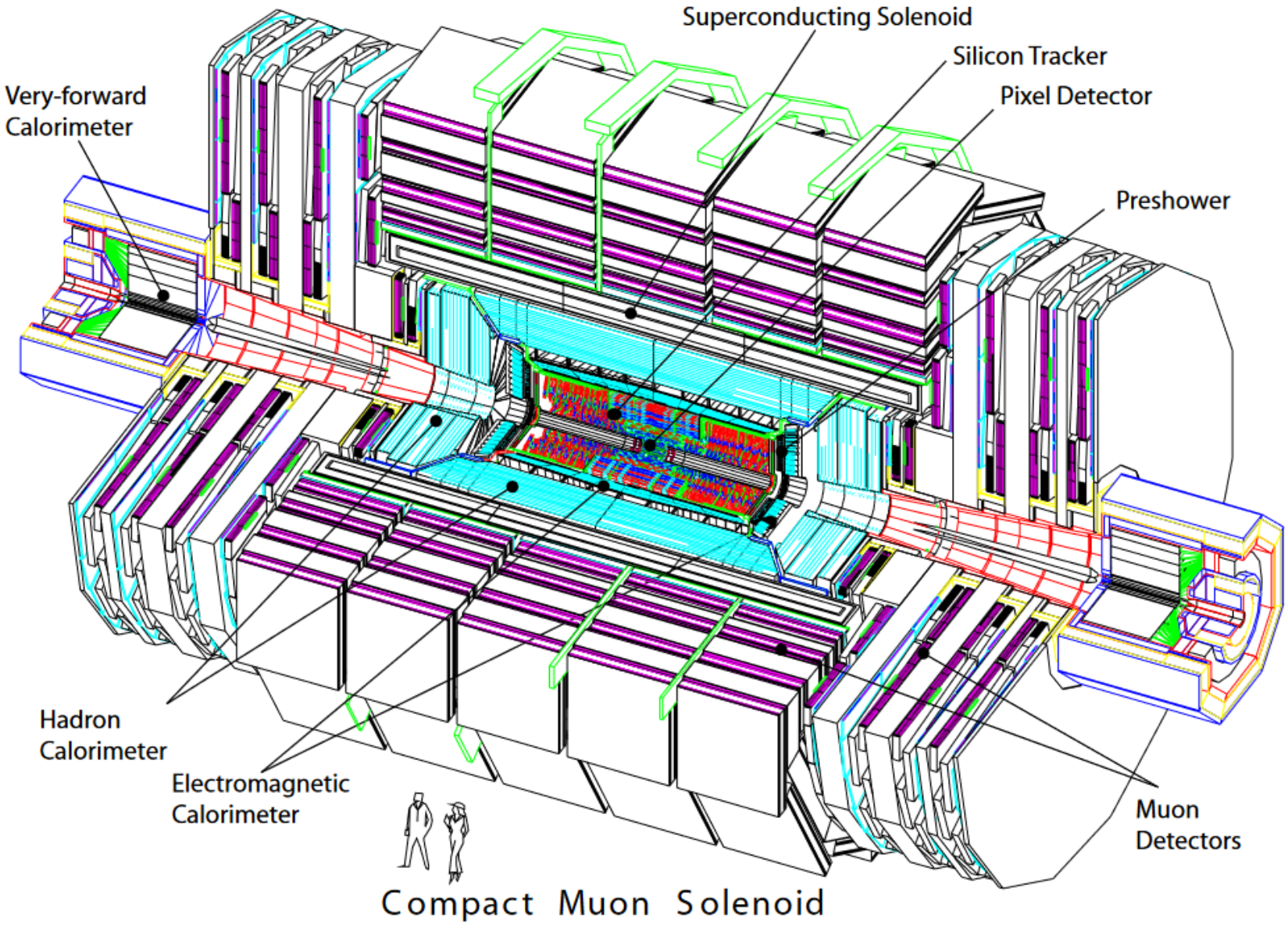
Thanks for your attention!

Backup

The CMS detector

2008 *JINST* **3** S08004 2017 *JINST* **12** P01020



- Raw: 40 MHz
- Level-1 trigger: 100 kHz
- High level trigger: 1 kHZ

X→HH/YH→γγττ: pNN training

CMS-PAS-HIG-22-012

Input features

Object Group	Features
τ_h, e, μ, IsoTrack	p_T, η, multiplicity
Photon	$p_T/m_{\gamma\gamma}, \eta$, pixel veto
Diphoton	$p_T/m_{\gamma\gamma}, \eta, \Delta\phi(\gamma^1, \gamma^2), \Delta R(\gamma^1, \gamma^2)$
Jet	p_T, η, b−tag multiplicity, b-jet multiplicity
MET	p_T
Composite	$m_{\tau\tau}^{SVFit}, \Delta R(\gamma\gamma, \tau\tau^{SVFit}), \Delta\phi(\text{MET}, \gamma\gamma), m_X$ …
Other	Channel (τ_h, $\tau_h\tau_h$, $\tau_h\mu$, …)

$+ M_{\gamma\gamma\tau\tau}$

Categorization optimization

- From the highest pNN score, add up 10 background events every time until the limit won't increase by > 1% to decide one category. Keep on doing so until all events are assigned.

Category	0	1	2	3	4	5	6
$X^{(0)} \to HH$	10	10	10	10	20	80	-
$X^{(2)} \to HH$	10	10	10	10	20	80	-
$X \to Y(\tau\tau)H(\gamma\gamma)$	10	10	10	10	20	80	320
Low-Mass $X \to Y(\gamma\gamma)H(\tau\tau)$ $Y \to \gamma\gamma$	10	10	10	10	20	80	320
High-Mass $X \to Y(\gamma\gamma)H(\tau\tau)$	10	10	10	10	20	80	320

X→ZZ→4l: signal modeling

CMS-PAS-HIG-24-002

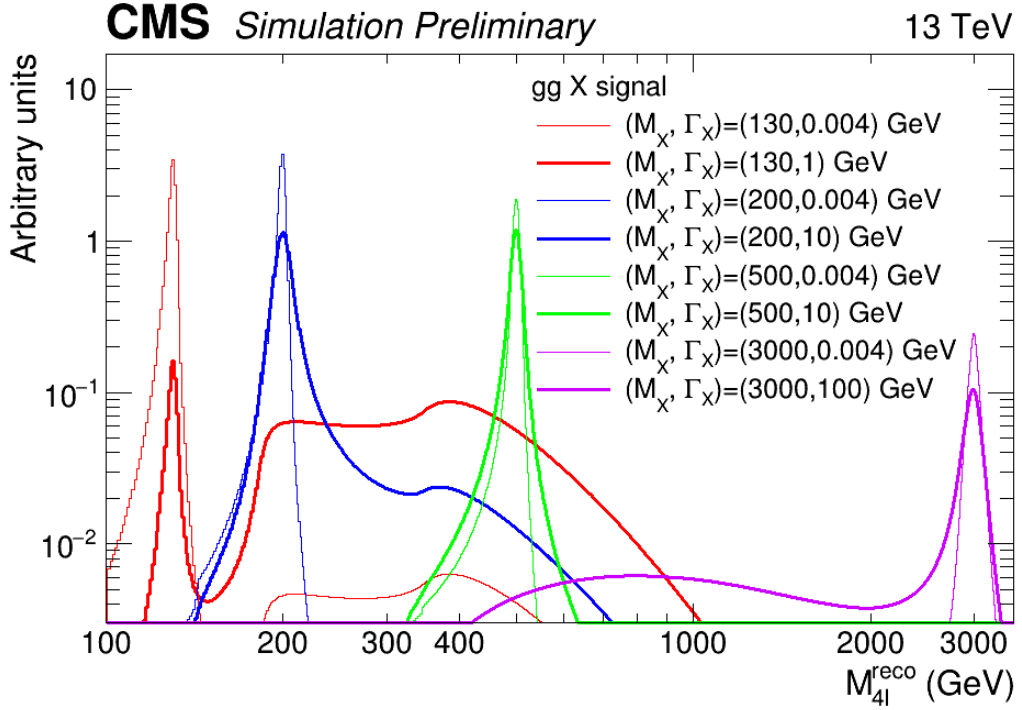
$$P(m_H^{reco}, D_{bkg}^{kin}) = \{[P(m_H^{gen}|m_H^{pole}, \Gamma_H) \times eff(m_H^{gen})] \otimes R(m_H^{reco}|m_H^{gen})\} \cdot P(D_{bkg}^{kin}|m_H^{reco})$$

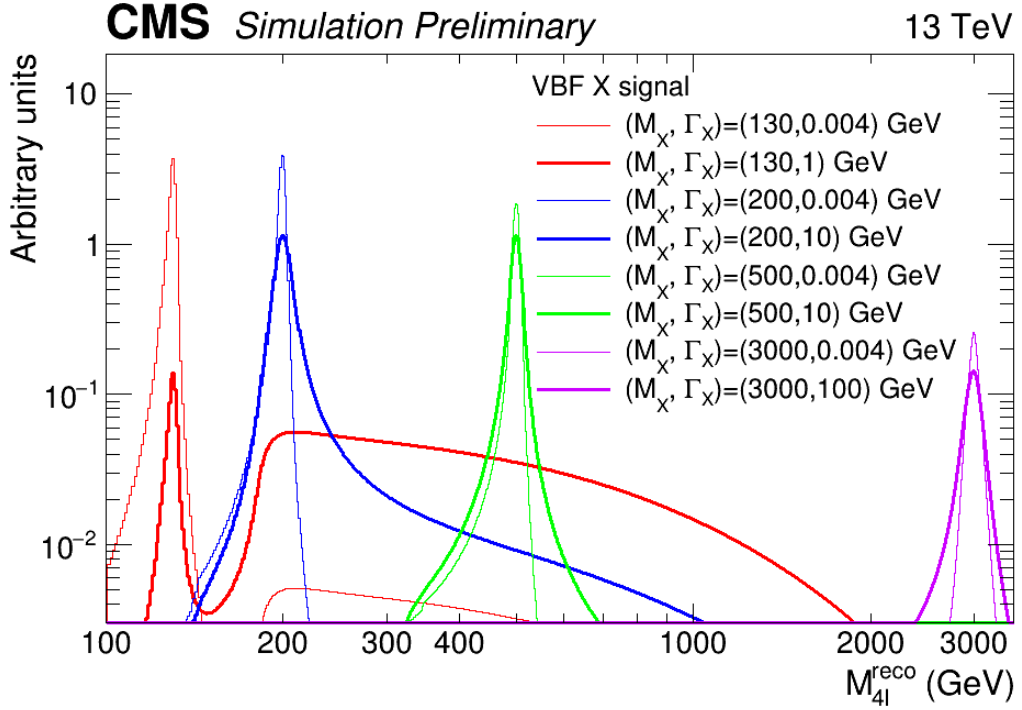
Lineshape: $P(m_H^{gen}|m_H^{pole}, \Gamma_H) = \sigma(m_H^{gen}) \cdot \frac{2m_{4l}^{gen} m_H^{pole}}{\left[(m_{4l}^{gen})^2 - (m_H^{pole})^2\right]^2 + (m_H^{pole}\Gamma_H)^2}$

Signal efficiency: $eff(m_H^{gen})$ **from MC**

Signal resolution **from MC** : $R(m_H^{reco}|m_H^{gen}) = \mathrm{DCB}(m_H^{reco} - m_H^{gen}|\, \mu, \sigma, \alpha_1, n_1, \alpha_2, n_2)$

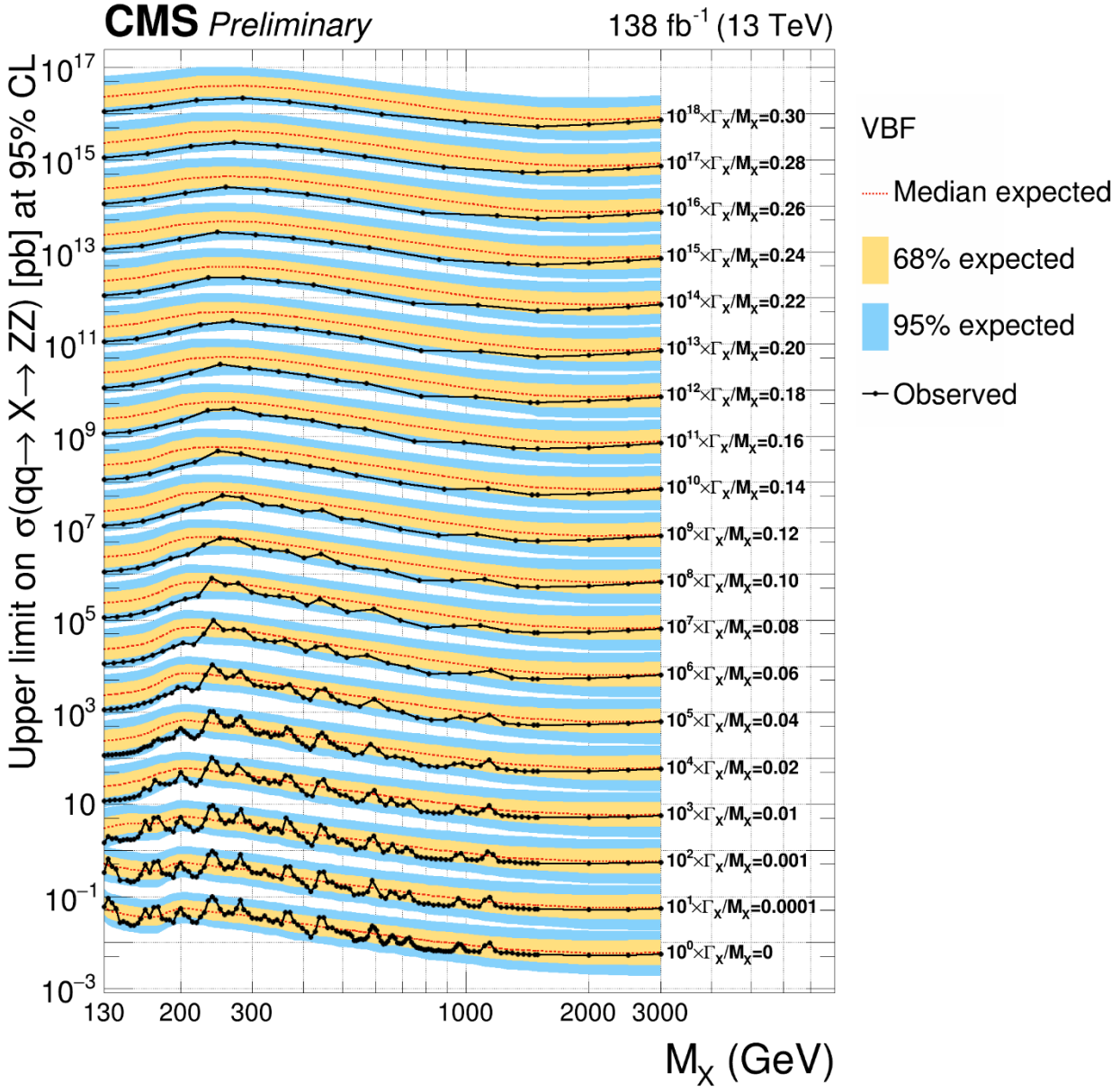
2D templates: $P(D_{bkg}^{kin}|m_H^{reco})$ **from MC** as the 2D histograms





X→ZZ→4l: various width assumption

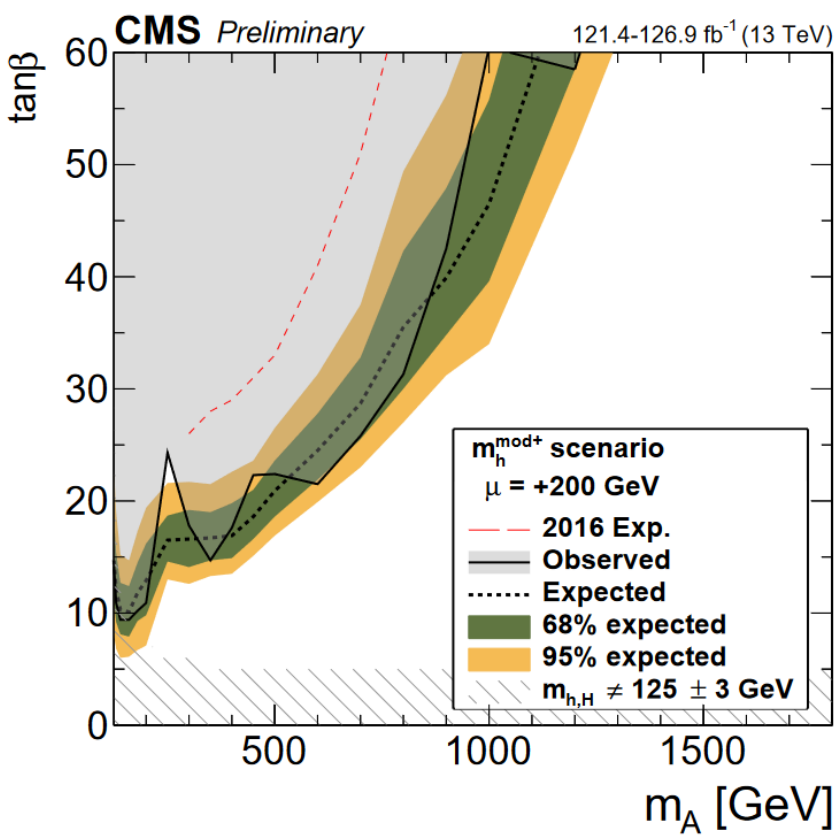
CMS-PAS-HIG-24-002



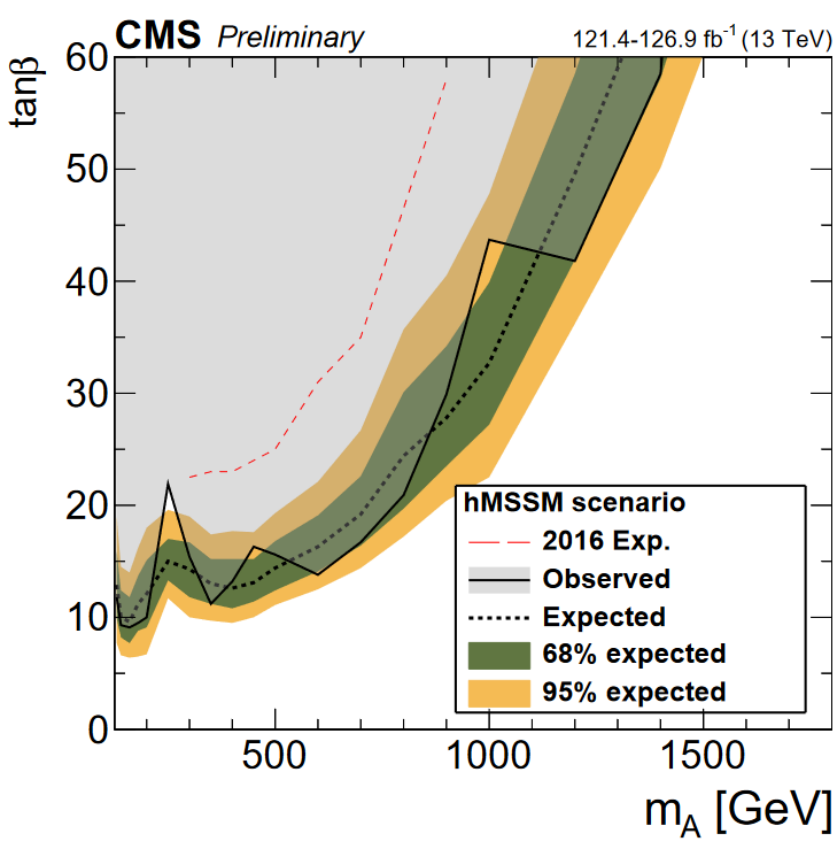
ϕ(H,h,A)→bb: results

CMS-PAS-SUS-24-001

MSSM interpretation M_h^{mod+} scenario



MSSM interpretation hMSSM scenario



2HDM interpretation Flipped scenario