CMS

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Institute of High Energy Physics
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Searches for heavy resonances decaying to two Z bosons at the CMS detector

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on behalf of the CMS Collaboration

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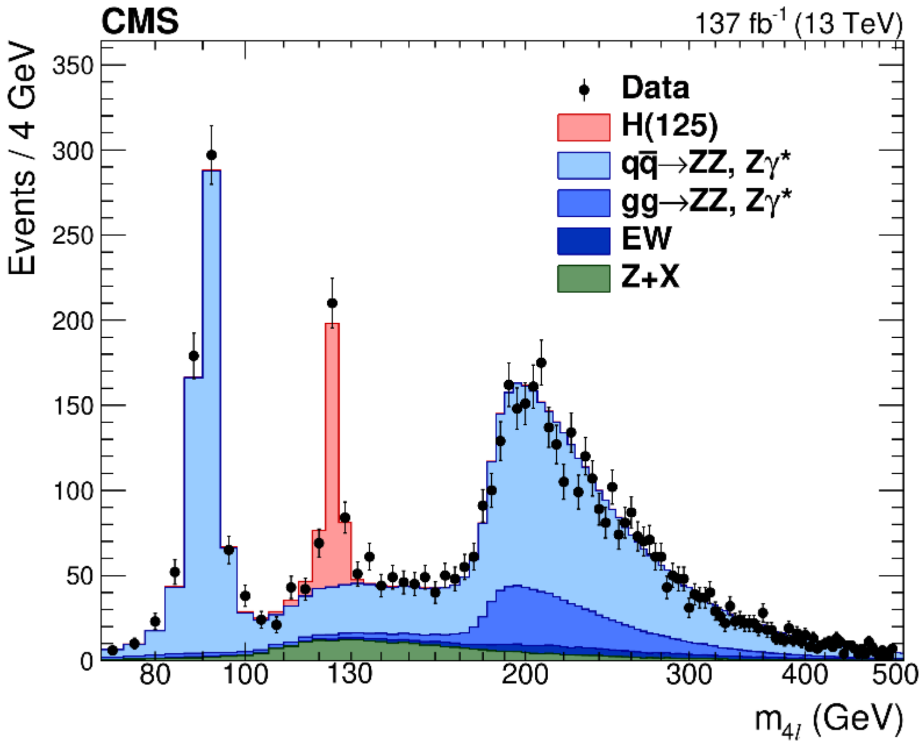
Motivation

➢ Search for heavy resonances

- Direct searches for theories beyond the Standard Model (BSM)
- **Additional Higgs bosons** from 2HDM, SUSY, etc.
- **Radion / graviton** from extra dimension theories.

➢ The ZZ decay channels

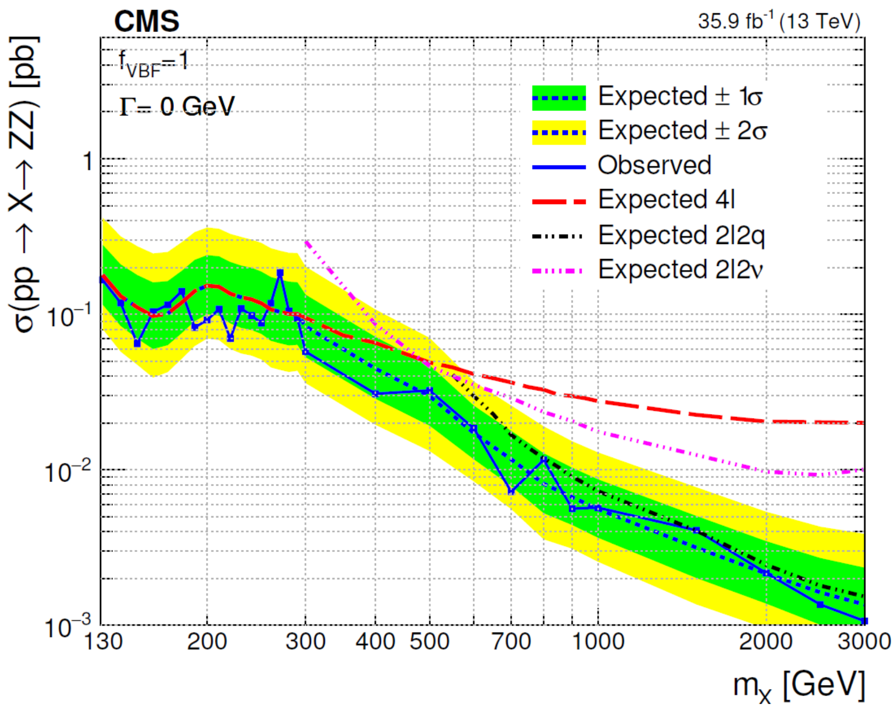
- ZZ→4l: golden channel in the SM Higgs boson search
  - Great S/B ratio
  - High efficiency and good energy resolution
  - Well-modeled backgrounds
- ZZ→2l2q/2l2ν: higher branching ratios
  - Provide better sensitivities at high masses



Overview

Previous searches

- ATLAS: EPJC 81, 332 (2021)
  - **4l+2l2v** with full Run 2 data
- CMS: JHEP 2018, 127 (2018)
  - **4l+2l2v+2l2q** with 2016 data



Studies included in this talk

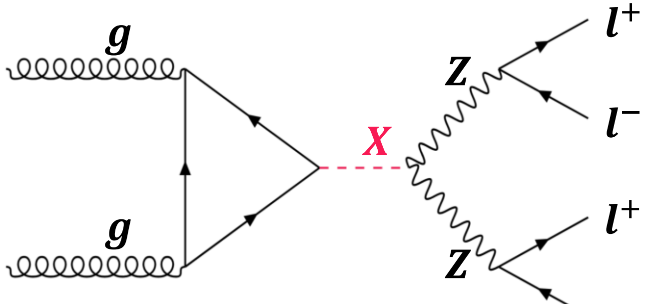
- **X→ZZ→4l** with full Run 2 data
  - CMS-PAS-HIG-24-002
- **X→ZZ→4l** projection to HL-LHC
  - CMS-NOTE-2025-003

Ongoing studies within the CMS Collaboration

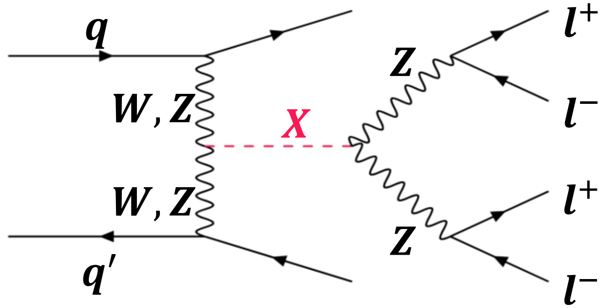
- **X→ZZ→2l2q** with full Run 2 data
- **X→ZZ→2l2v** with full Run 2 data
- **Combination** among different channels

Analysis strategy

- **Spin-0 resonances decaying to ZZ to 4l**
  - lepton being electron or muon
- **Production mechanism: ggF and VBF**
- **Mass ranges:** 130 – 3000 GeV
- **Width ranges**
  - From narrow width assumption (NWA) to large widths up to 30% of mass
- **Model-independent searches**
- **Full description of signals**
  - **Both on-shell and off-shell** production of the resonance
  - **All possible interferences** (since the width can be large)



ggF



VBF

Event selection

- **Trigger selection**
  - From single-lepton triggers to triple-lepton triggers
    Large phase space coverage

- **Lepton selection**
  - **Tight μ**: p_T > 5 GeV, |η| < 2.4, SIP < 4, |dxy| < 0.5, |dz| < 1, muon PF ID + tracker high-pT ID, iso < 0.35
  - **Tight e**: p_T > 7 GeV, |η| < 2.5, SIP < 4, |dxy| < 0.5, |dz| < 1, dedicated ID and iso for H->4l analyses
  - **FSR** recovery

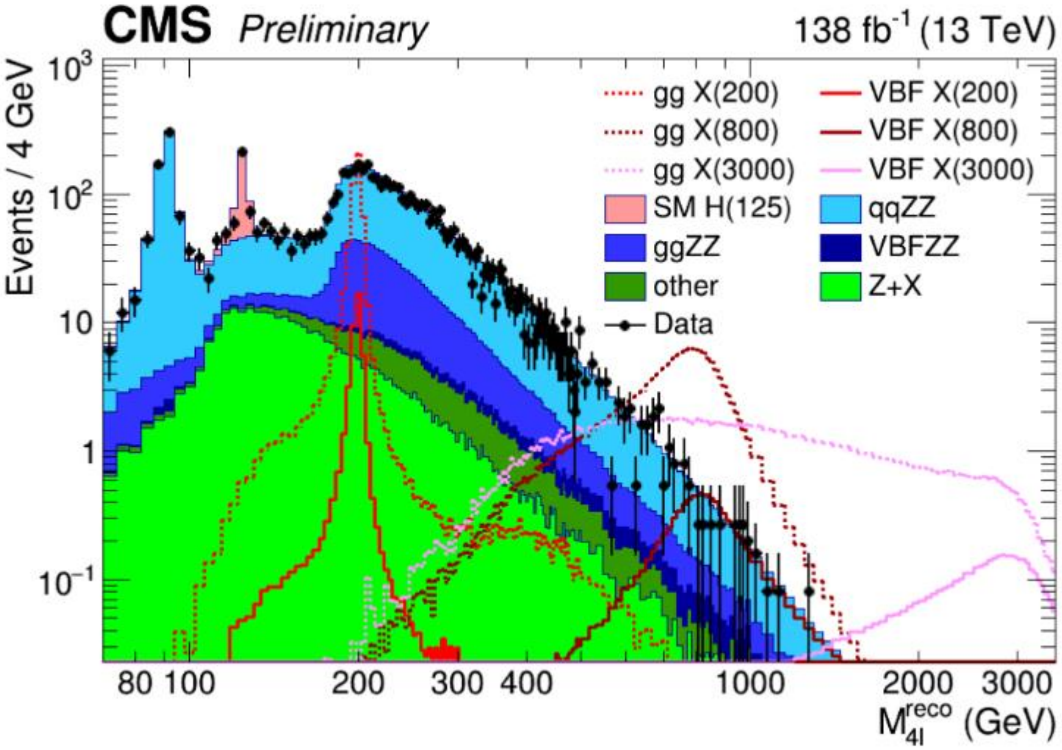
- **Z selection**
  - Opposite sign, same flavor (ee or μμ)
  - 12 GeV < M_Z < 120 GeV

- **ZZ selection**
  - M_{ZZ} > 70 GeV, as well as other kinematic requirements
  - Select the ZZ pair with highest $\mathrm{D}_\mathrm{bkg}^\mathrm{kin}$ (defined later)
  - Three final states: 4μ, 4e, 2e2μ

Discriminating variables

Invariant mass of the 4-lepton final state:

$$M_{4l}^{reco} = \left(p_{l_1} + p_{l_2} + p_{l_3} + p_{l_4}\right)^2$$

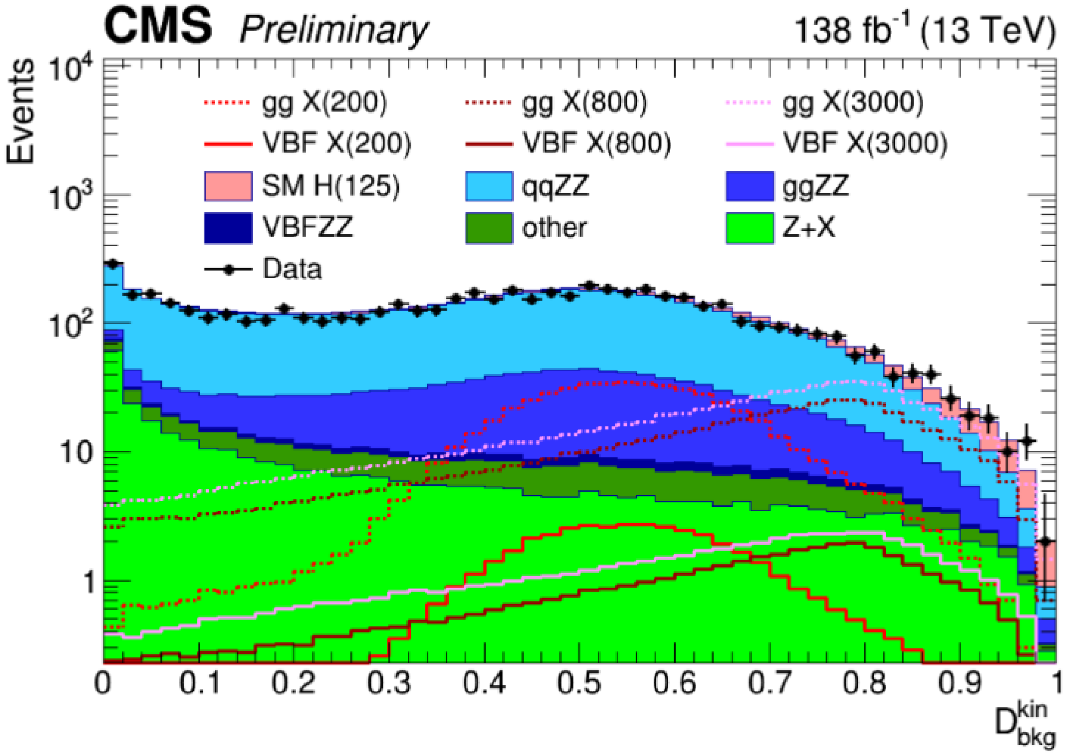


The discriminant built from

Matrix Element Likelihood Approach (MELA):

likelihood constructed based on matrix elements and kinematics

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



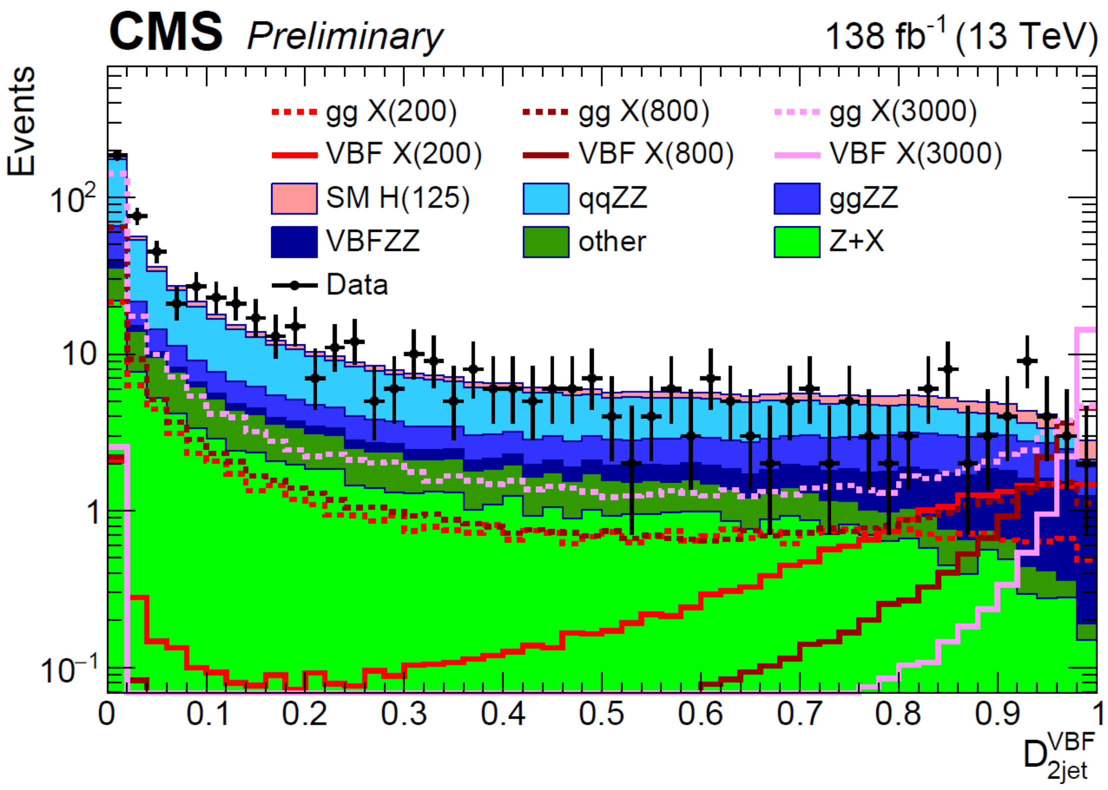
Event categorization

Two categories: VBF tagged and untagged

- **VBF tagged**: no extra lepton && [(Njet=2 or 3 && Nbjet<=1) || (Njet>=4 && Nbjet=0)] && $D_{2jets}^{VBF} > 0.46$
- **ggF tagged**: remaining events

D_{2jet}^{VBF}: a discriminant built from **MELA** to distinguish ggF and VBF signals

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



Signal model

Parametric statistical model

- Avoid bin-by-bin MC statistical uncertainties
- Flexible to test different mass and width hypotheses

$$\mathbf{P}\left(\mathbf{m}_{\mathbf{X}}^{\mathbf{reco}}, \mathbf{D}_{\mathbf{bkg}}^{\mathbf{kin}}\right) = \left\{\left[\mathbf{P}\left(\mathbf{m}_{\mathbf{X}}^{\mathbf{gen}} \middle| \mathbf{m}_{\mathbf{X}}^{\mathbf{pole}}, \boldsymbol{\Gamma}_{\mathbf{X}}\right) \times \mathbf{eff}\left(\mathbf{m}_{\mathbf{X}}^{\mathbf{gen}}\right)\right] \otimes \mathbf{R}\left(\mathbf{m}_{\mathbf{X}}^{\mathbf{reco}} \middle| \mathbf{m}_{\mathbf{X}}^{\mathbf{gen}}\right)\right\} \cdot \mathbf{P}\left(\mathbf{D}_{\mathbf{bkg}}^{\mathbf{kin}} \middle| \mathbf{m}_{\mathbf{X}}^{\mathbf{reco}}\right)$$

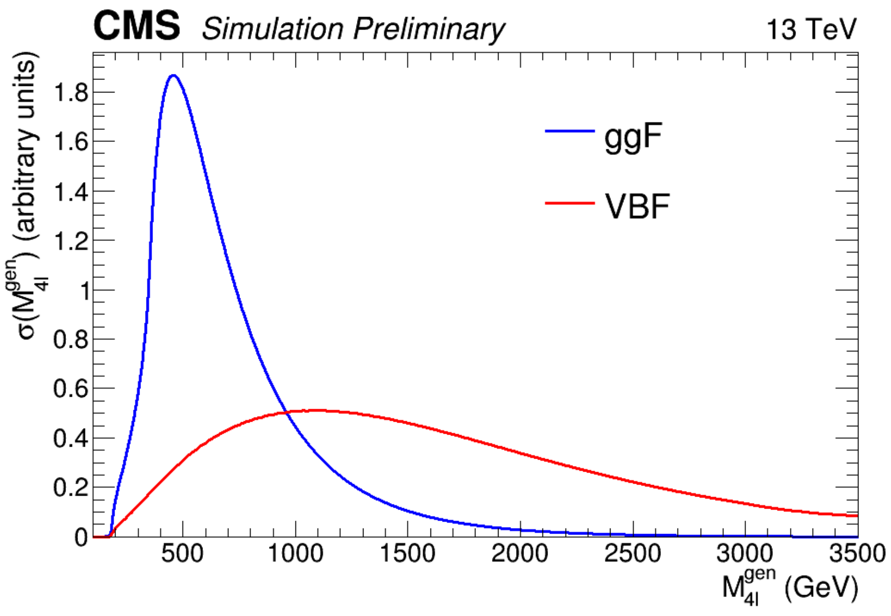
Signal model

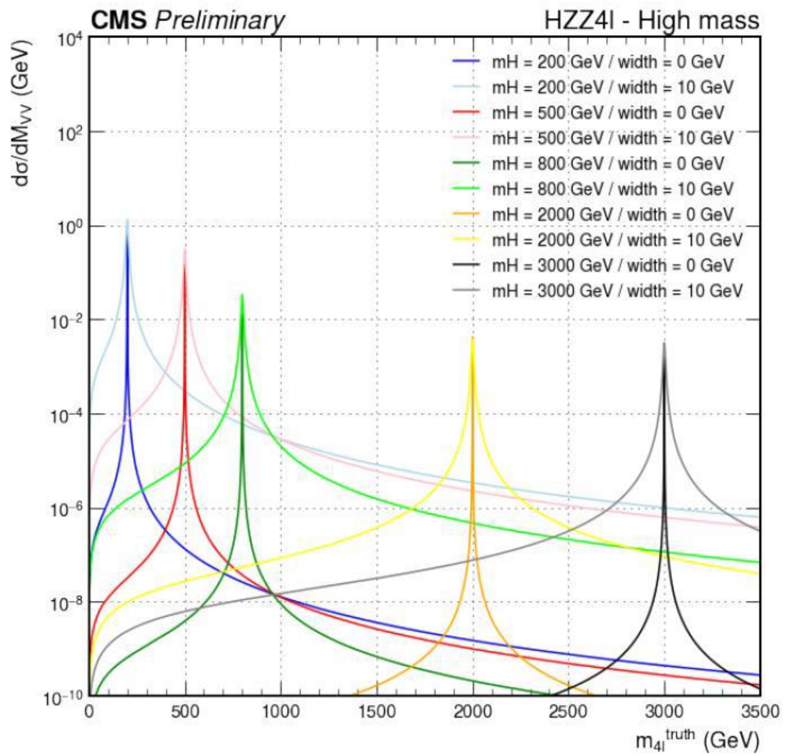
$$P(m_X^{reco}, D_{bkg}^{kin}) = \{[P(m_X^{gen} | m_X^{pole}, \Gamma_X) \times eff(m_X^{gen})] \otimes R(m_X^{reco} | m_X^{gen})\} \cdot P(D_{bkg}^{kin} | m_X^{reco})$$

1. **Signal analytic lineshape:** $P(M_X^{gen} | M_X, \Gamma_X) = \sigma(M_X^{gen}) \cdot \frac{2M_X^{gen} M_X}{\left[(M_X^{gen})^2 - M_X^2\right]^2 + (M_X \Gamma_X)^2}$

Take into account parton distribution functions, matrix elements, phase space, etc.

Relativistic Breit-Wigner function for the propagator.

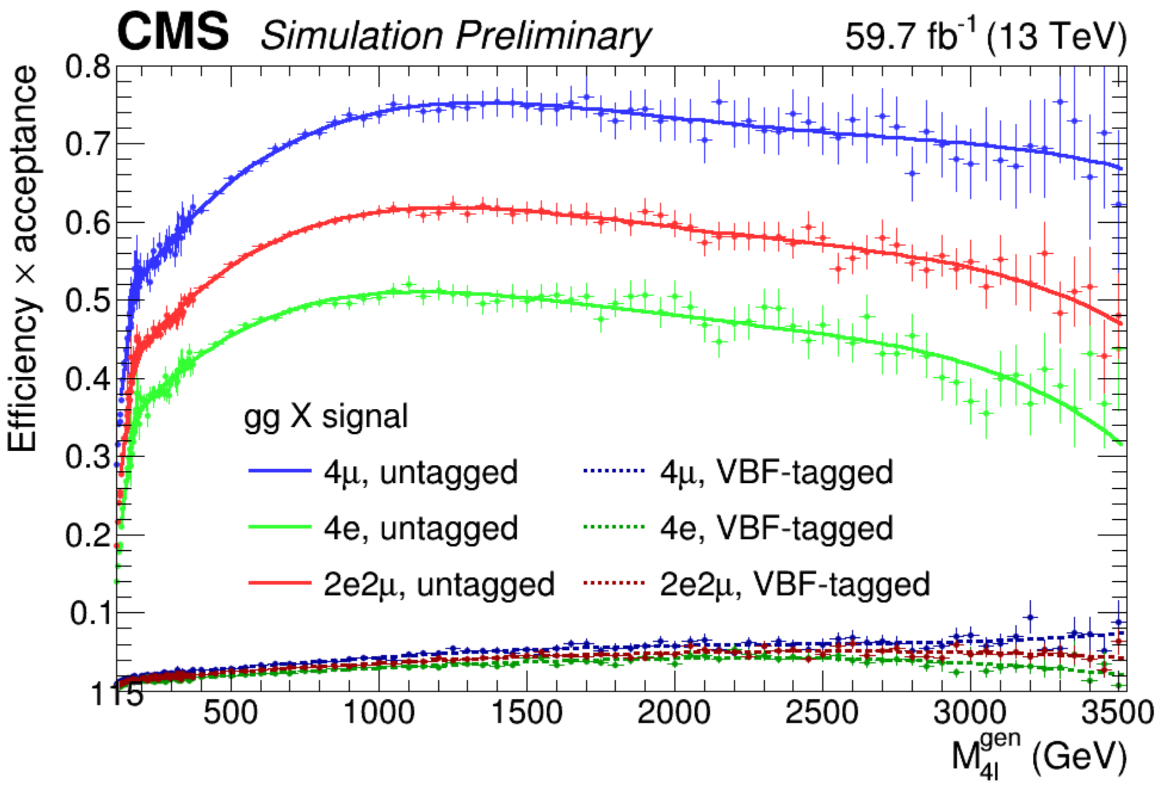


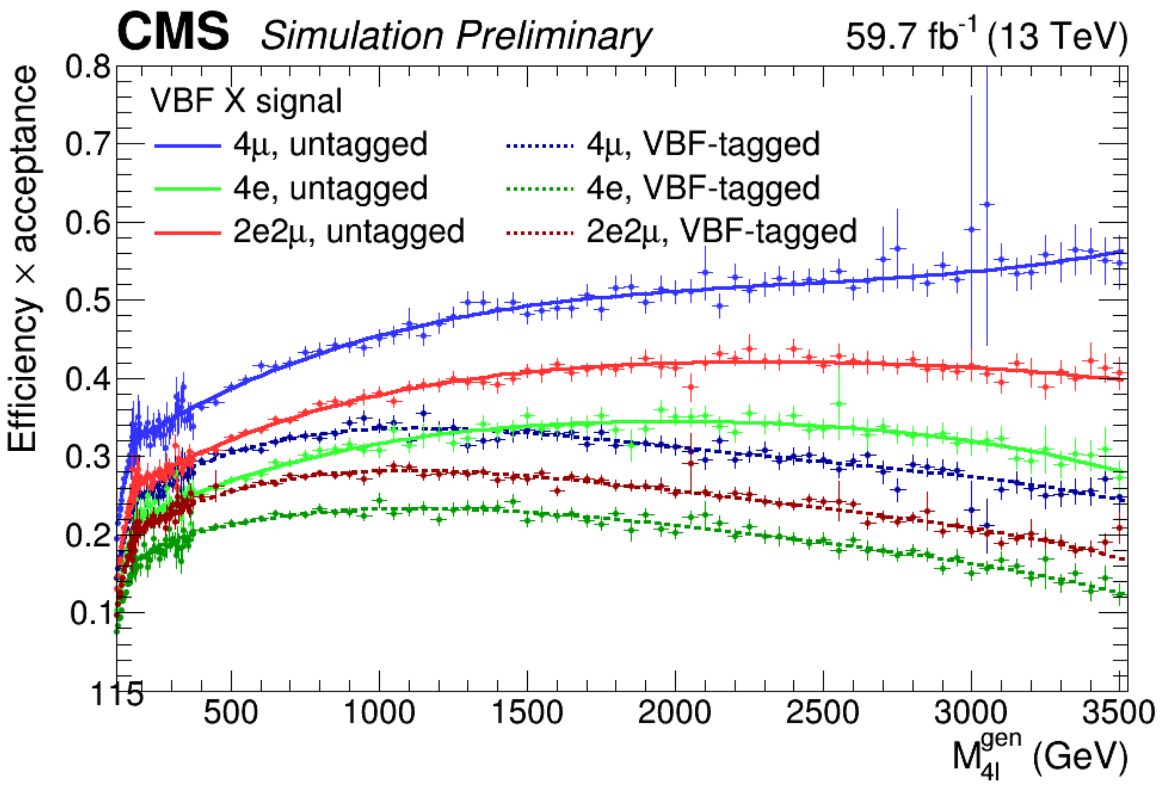


Signal model

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

2. **Signal efficiency:** $\mathrm{eff}^{\mathrm{production}}(M_X^{gen} | \mathrm{final\ state, category}) = \dfrac{N_{\mathrm{selected}}^{\mathrm{production}}(M_X^{gen} | \mathrm{final\ state, category})}{N_{\mathrm{generated}}^{\mathrm{production}}(M_X^{gen} | \mathrm{final\ state})}$

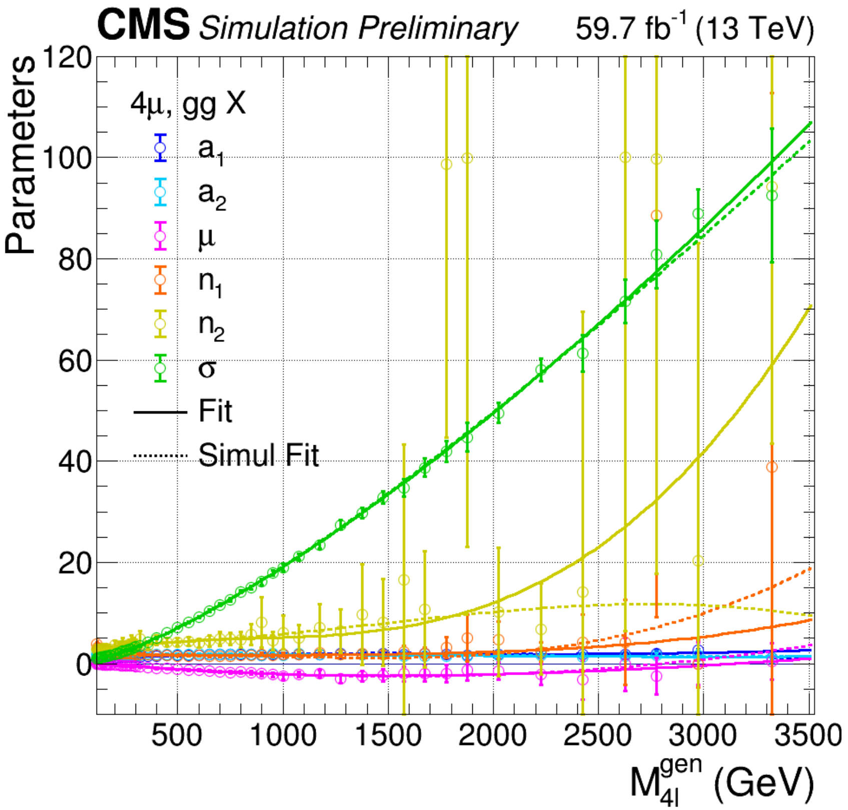


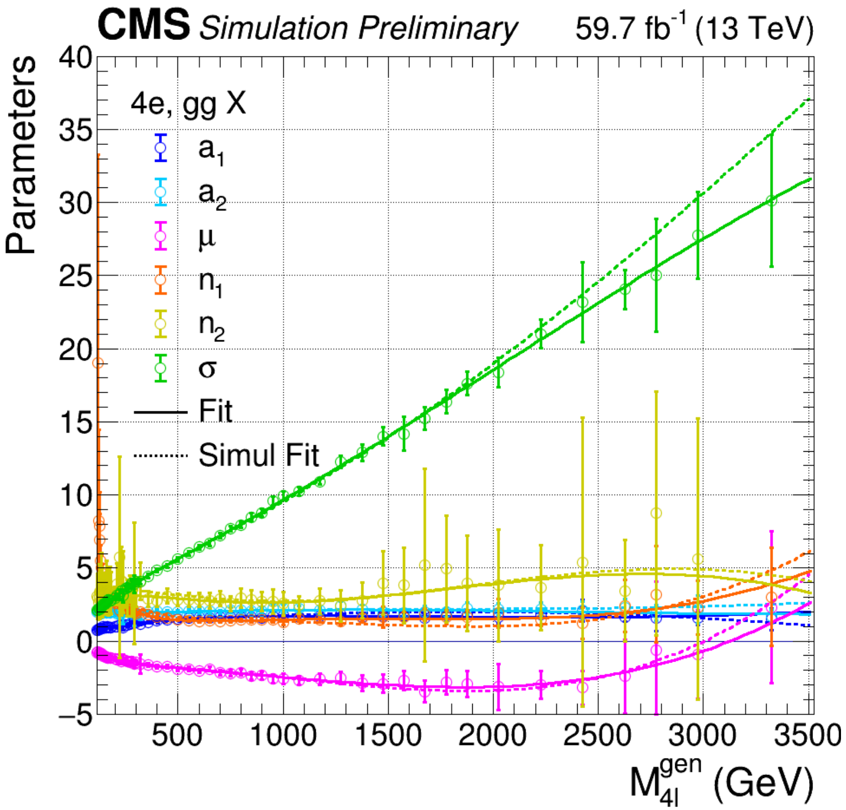


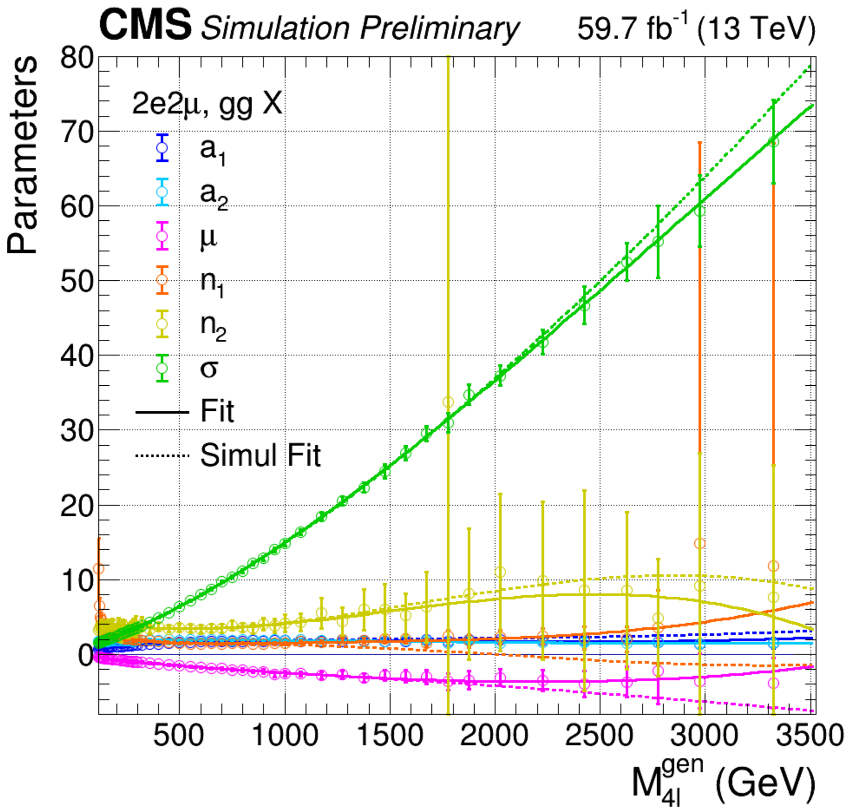
Signal model

$$P\left(m_X^{reco}, D_{bkg}^{kin}\right) = \left\{\left[P\left(m_X^{gen}\middle|m_X^{pole}, \Gamma_X\right) \times eff\left(m_X^{gen}\right)\right] \otimes R\left(m_X^{reco}\middle|m_X^{gen}\right)\right\} \cdot P\left(D_{bkg}^{kin}\middle|m_X^{reco}\right)$$

3. **Mass resolution:** $R\left(M_X^{reco}\middle|M_X^{gen}\right) = \mathrm{DoubleCB}\left(M_X^{reco} - M_X^{gen}\middle|\, \mu, \sigma, \alpha_1, n_1, \alpha_2, n_2\right)$
   - All parameters are functions of M_X^{gen}



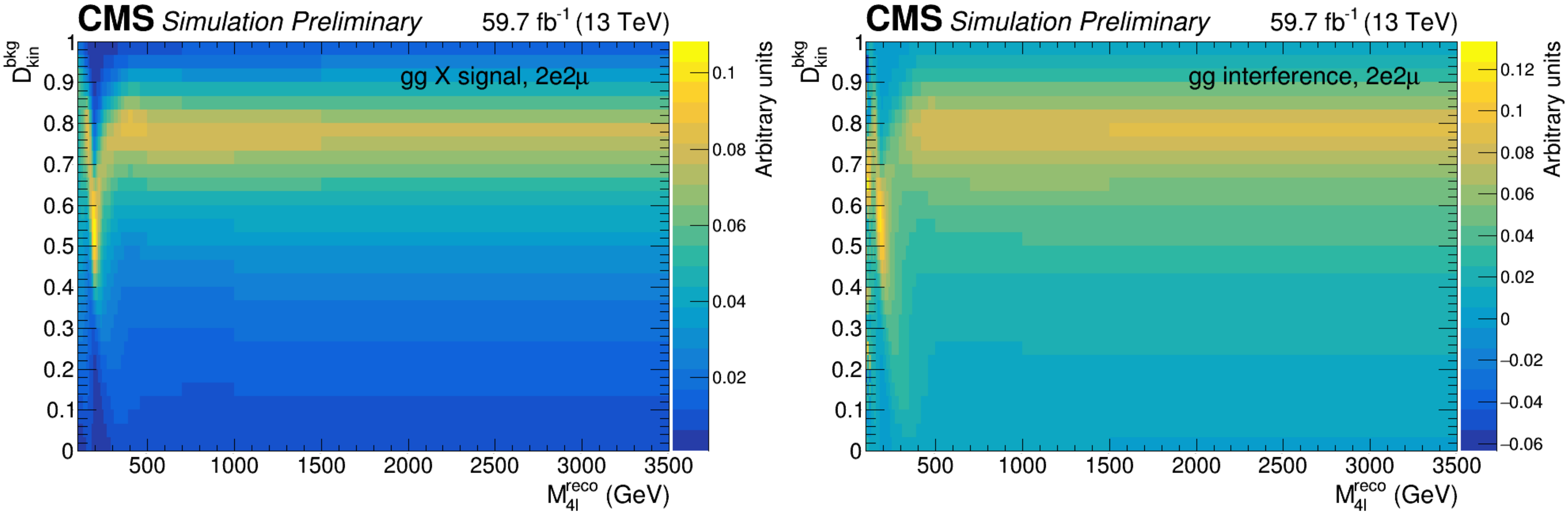




Signal model

$$\mathrm{P}\left(\mathrm{m_X^{reco}}, \mathrm{D_{bkg}^{kin}}\right) = \left\{\left[\mathrm{P}\left(\mathrm{m_X^{gen}} \middle| \mathrm{m_X^{pole}}, \Gamma_\mathrm{X}\right) \times \mathrm{eff}\left(\mathrm{m_X^{gen}}\right)\right] \otimes \mathrm{R}\left(\mathrm{m_X^{reco}} \middle| \mathrm{m_X^{gen}}\right)\right\} \cdot \mathbf{P}\left(\mathbf{D_{bkg}^{kin}} \middle| \mathbf{m_X^{reco}}\right)$$

4. **2D templates to extend the mass-dimension PDF to the 2D PDF: $\mathbf{D_{bkg}^{kin}}$ on condition of $\mathbf{m_X^{reco}}$**



Background model

SM Higgs boson: the same as signals, with $\mathrm{M_H}$ = 125 GeV and Γ_H = 4.1 MeV

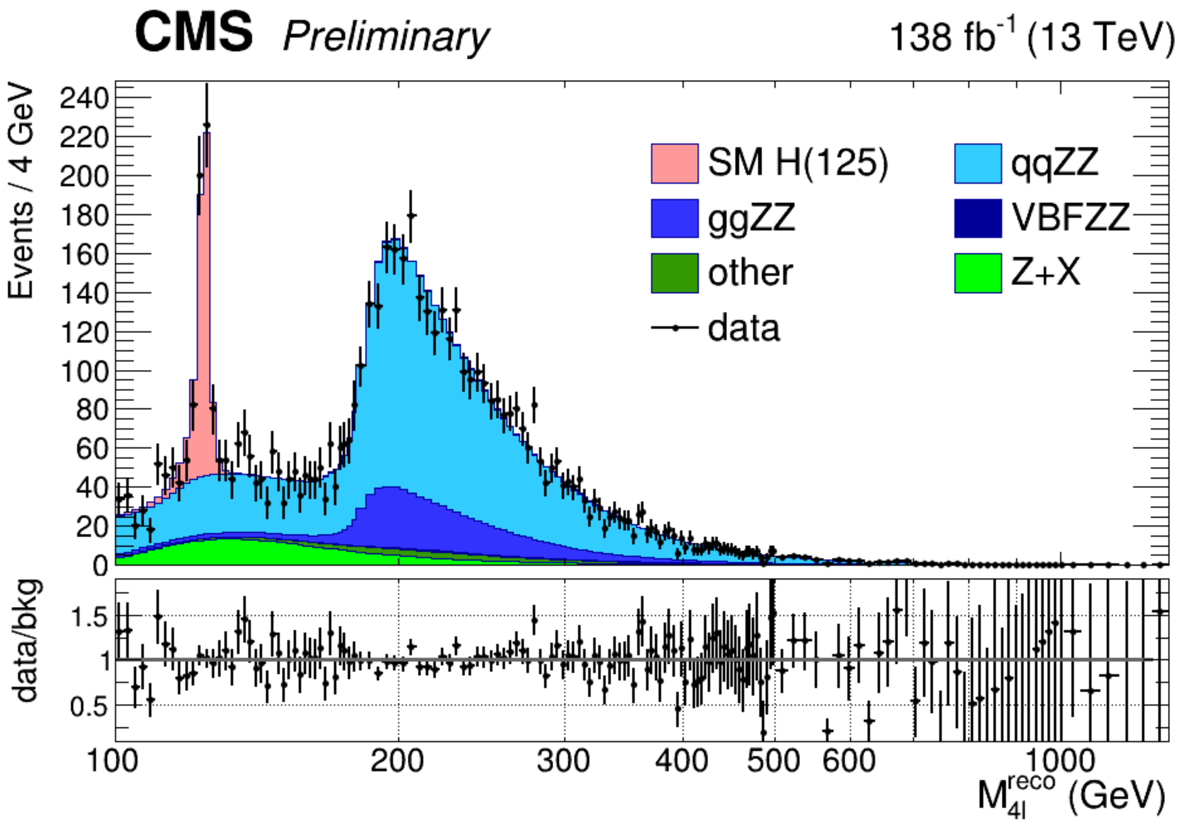
qqZZ (dominating): by MC (NLO in QCD, with NNLO QCD k-factor and NLO EW k-factor)

ggZZ: by MC (LO, with NNLO k-factor)

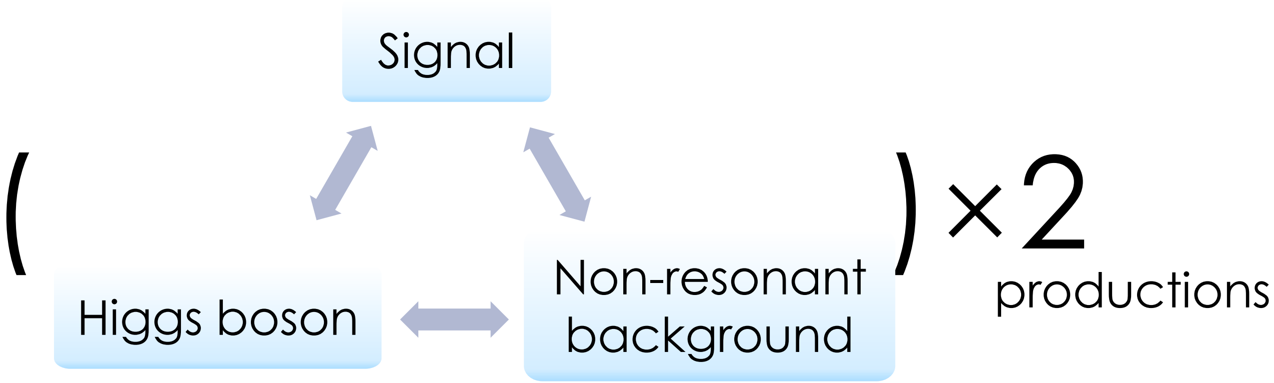
Triboson and tops+bosons, VBFZZ: by MC

Z+X: estimated from control region data using a data-driven method

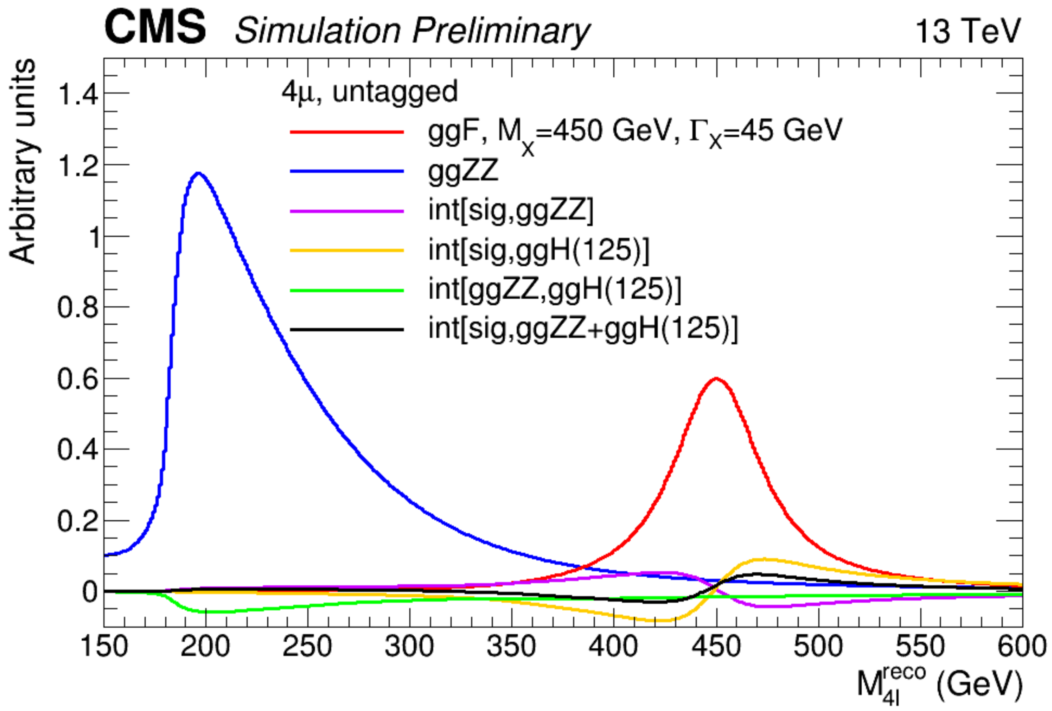
$\mathbf{M_{4l}^{reco}}$ is parameterized with empirical functions

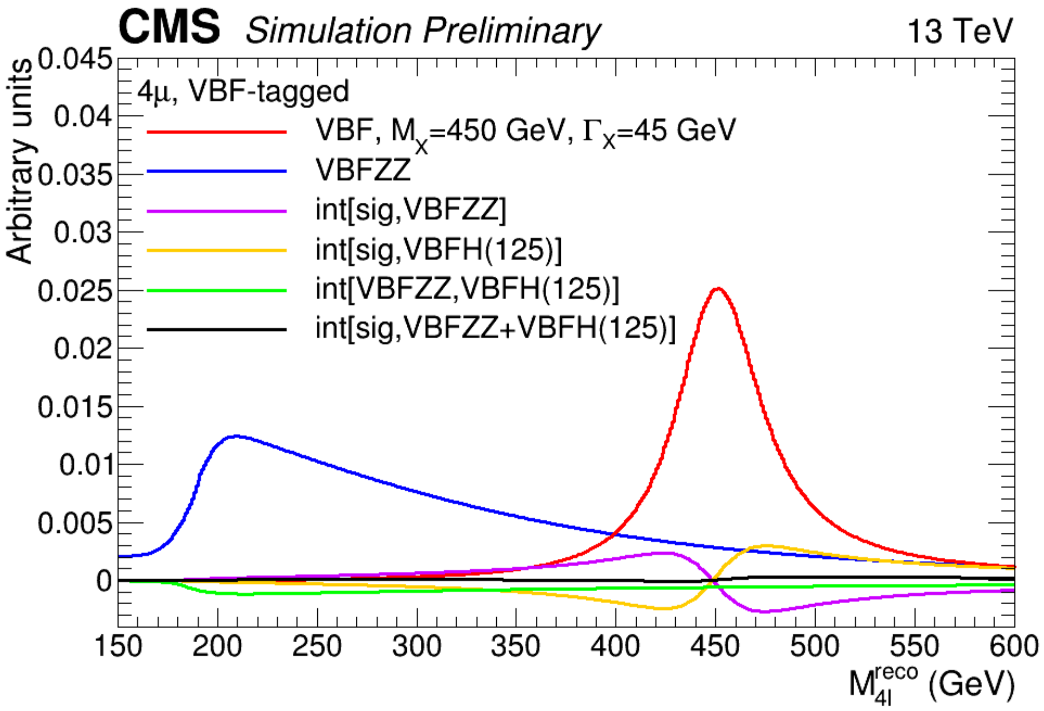


Interference model

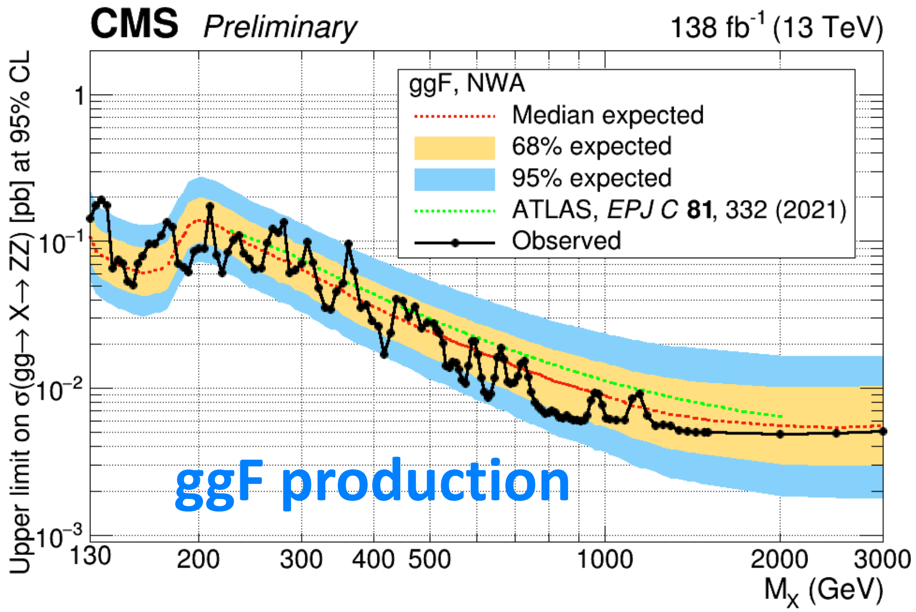


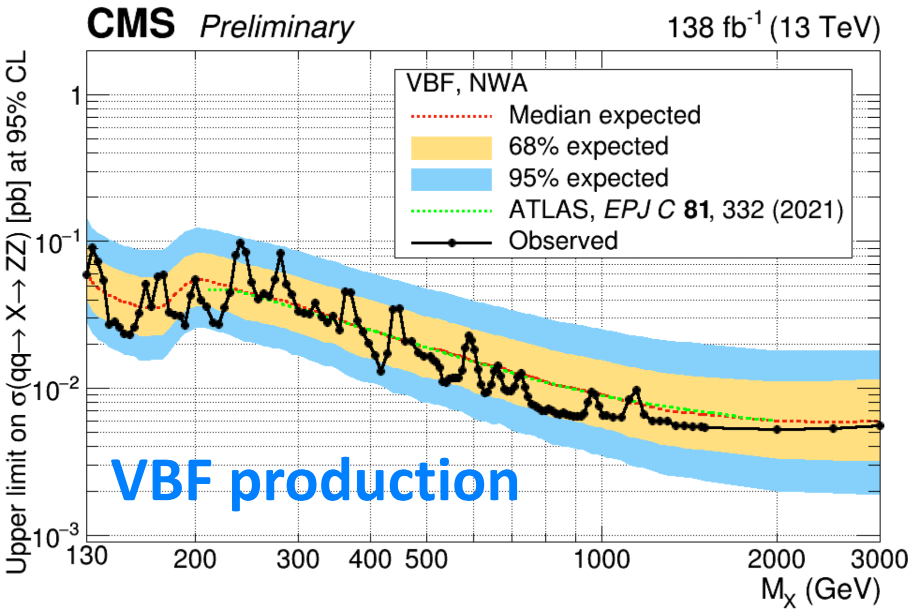
- **Inputs**
  - Lineshapes of signals and backgrounds
  - Phase inputs from MCFM generators
  - MELA techniques to build the 2D templates

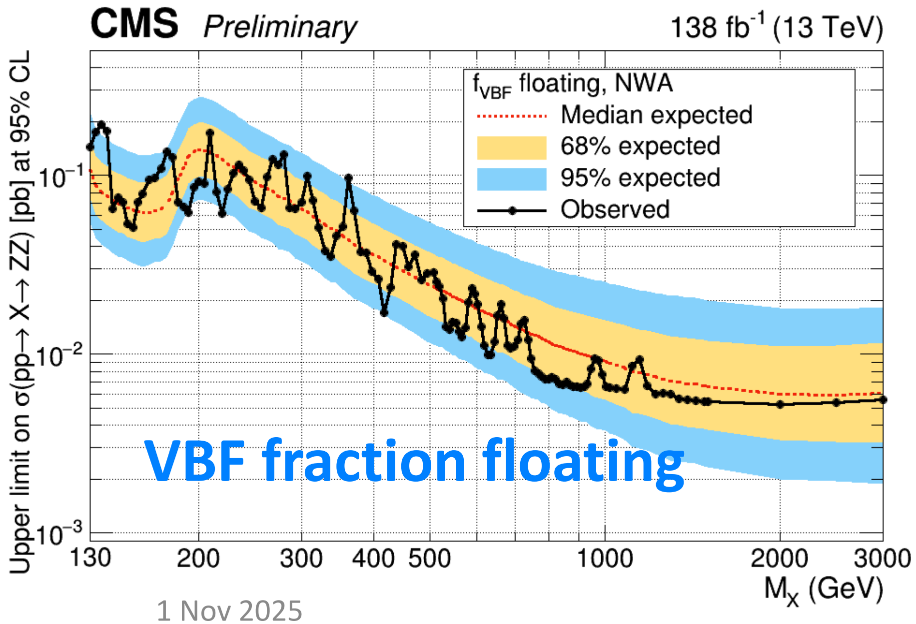




Results: narrow width assumption







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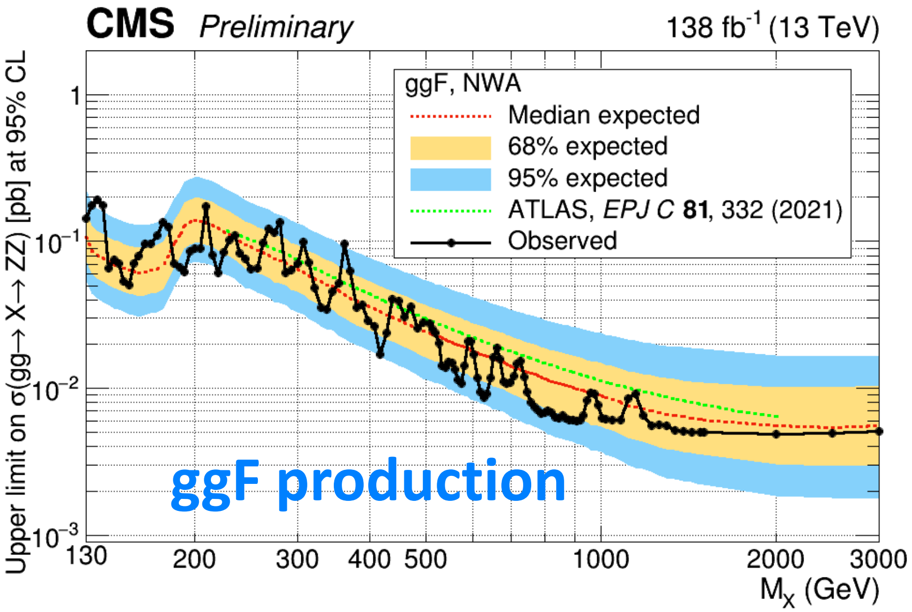
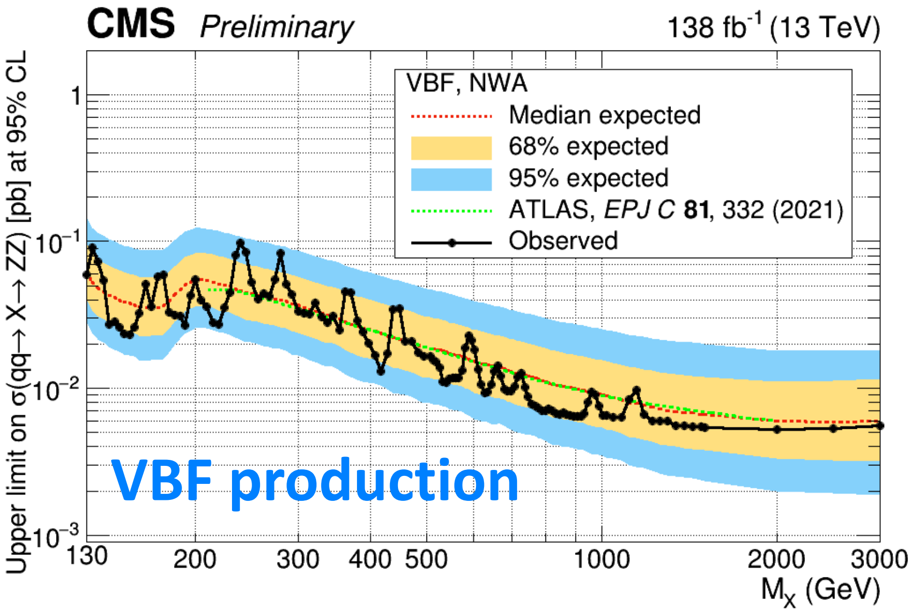
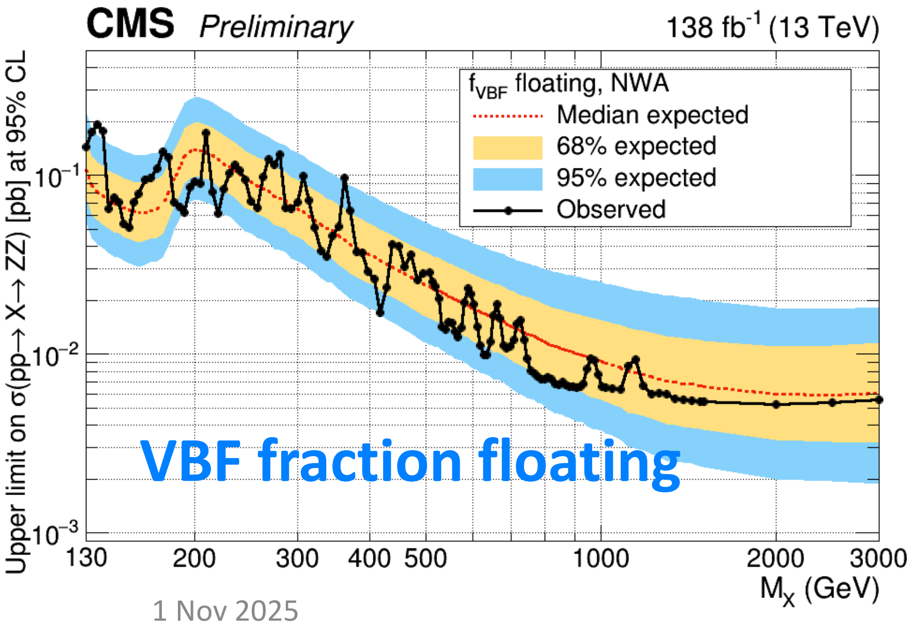
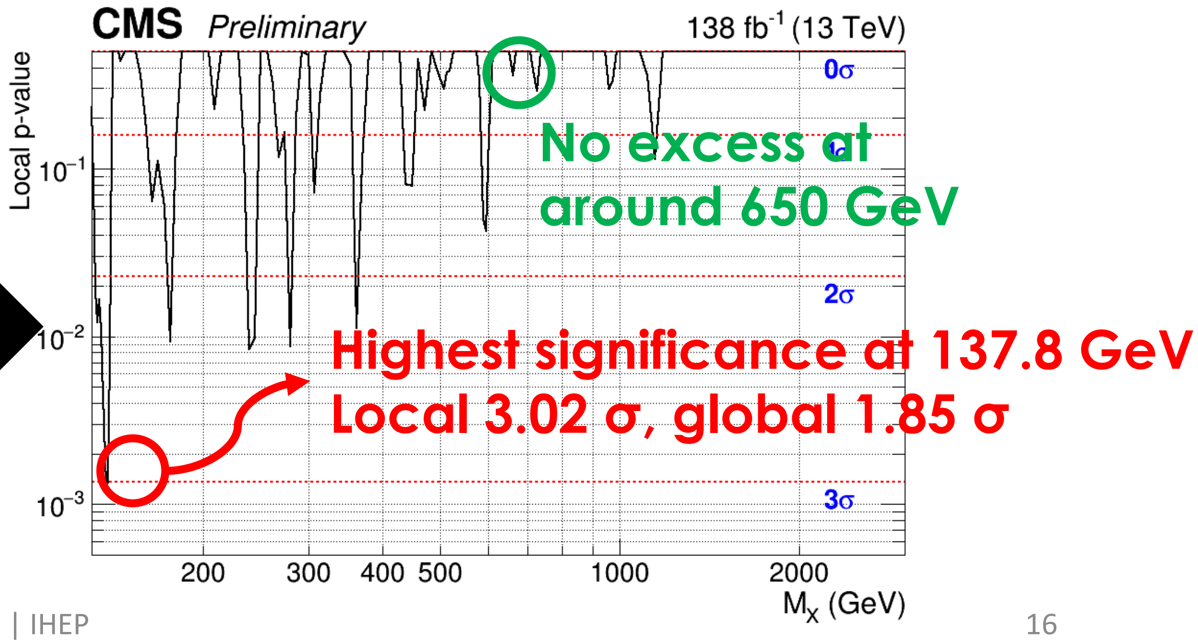
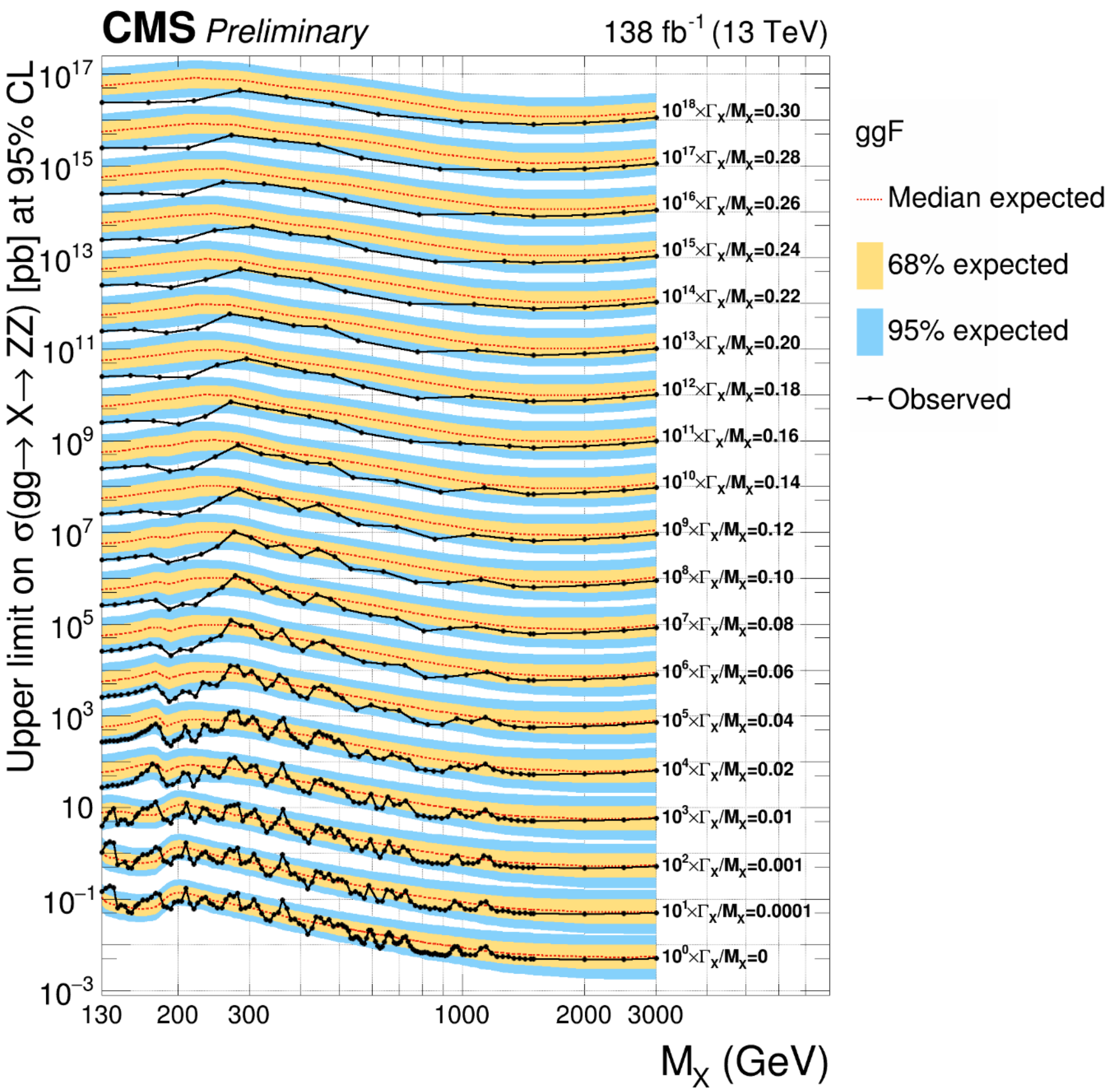


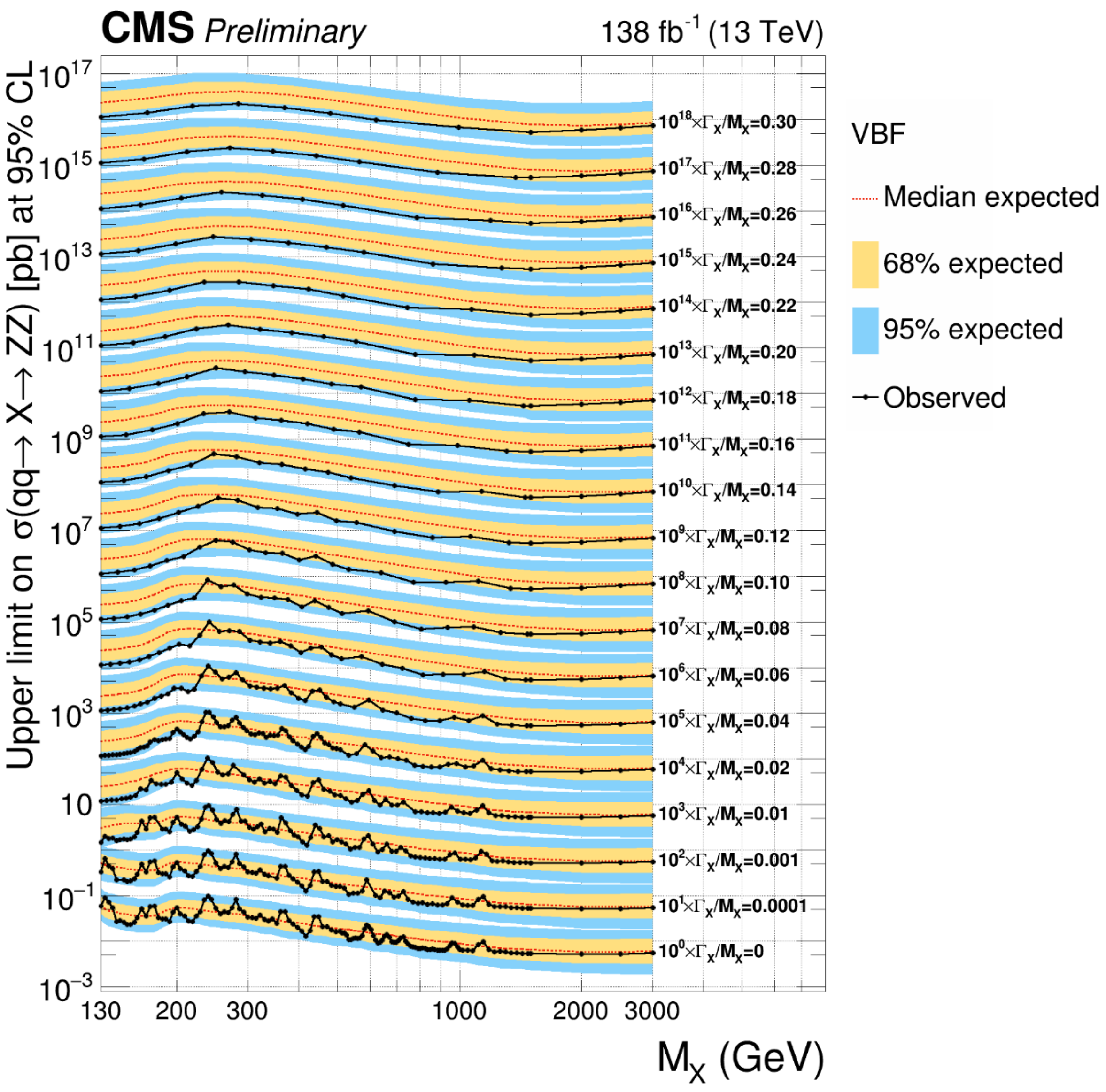






Results: scan both mass and width





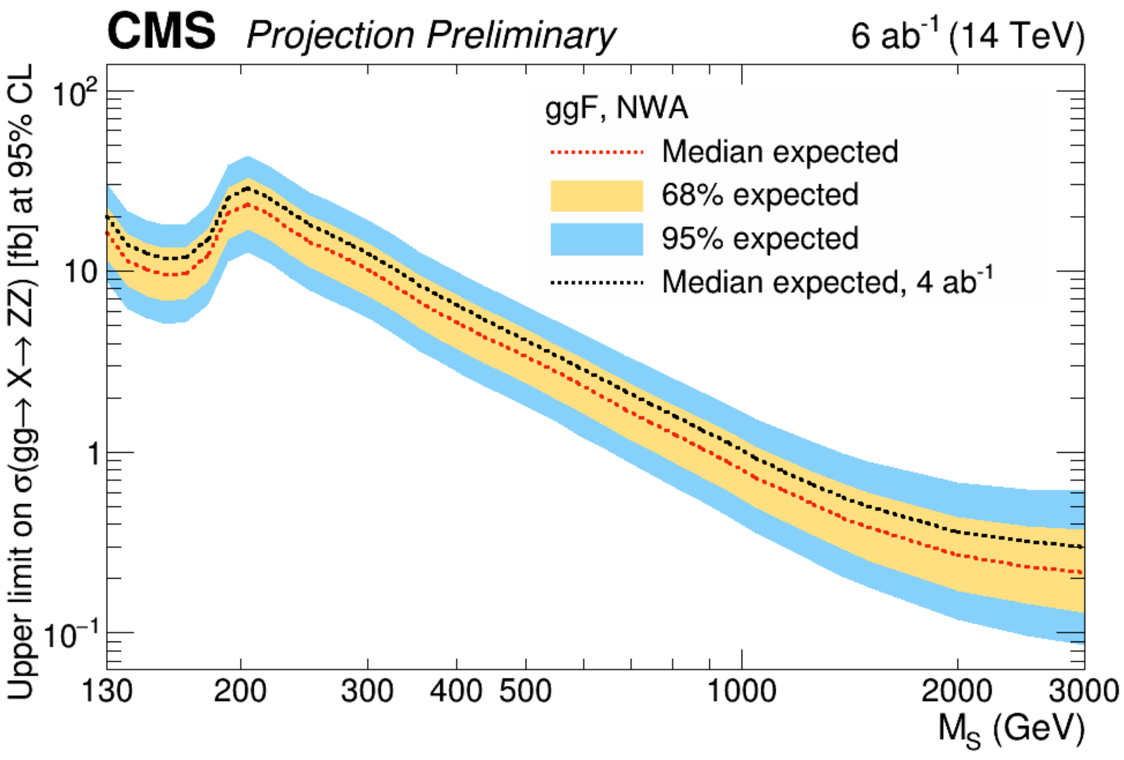
Projections to HL-LHC

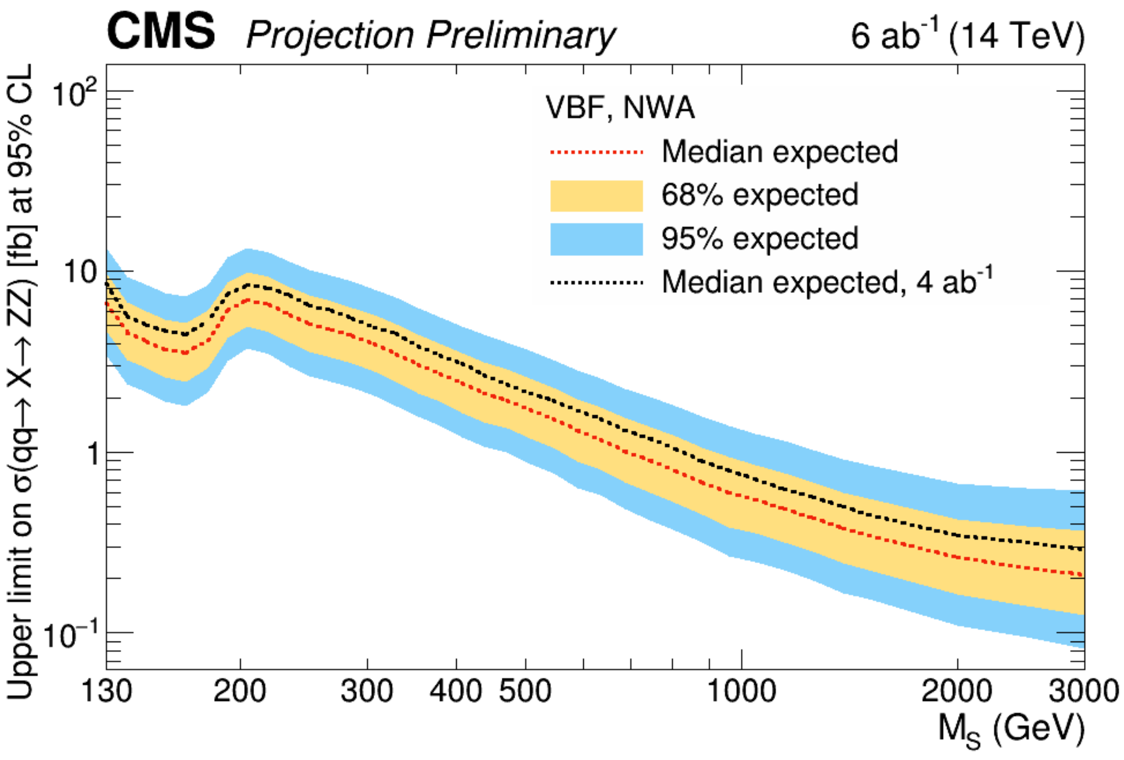
- Estimation of sensitivities and phase space exclusion to be reached at HL-LHC

<table>
<tr><th></th><th>Assumption</th><th>Reality</th></tr>
<tr><td>Luminosity</td><td colspan="2">Scale yields to 4 ab-1 or 6 ab-1
2 ab-1 or 3 ab-1 from both CMS and ATLAS experiments</td></tr>
<tr><td>Efficiency and Resolution</td><td>Same as Run 2</td><td>Improved through detector upgrades</td></tr>
<tr><td>Background yields</td><td colspan="2">Scaled by their cross sections at 14 TeV / at 13 TeV</td></tr>
<tr><td>Shapes</td><td>Same as Run 2</td><td>Change from 13 to 14 TeV: small effects</td></tr>
<tr><td>Systematic uncertainties</td><td>Same as Run 2</td><td>More popular scenario:
• Theoretical uncertainties reduced by half
• Experimental ones reduced by square root of luminosity
Little effects since the analysis is statistical dominant</td></tr>
</table>

- In general conservative estimation

Projections to HL-LHC: results





- Published as **CMS note**, together with X->tt projections: CMS-NOTE-2025-003
- Contribution to **ATLAS+CMS Inputs to EPPSU**: 2504.00672

Conclusion and plans

Heavy resonance searches in ZZ→4l final states

- A model-independent search for heavy scalar resonances decaying into 4 leptons are performed with the Run 2 data collected from the CMS detector.
- **PAS publication** in 2024 (CMS-PAS-HIG-24-002).
- **Paper draft review** ongoing, expected to be published as a paper soon.
- Projections to HL-LHC, and contributions to **EPPSU 2026.**

More results are coming up

- Searches in 2l2q final states expected to be public in 2 months.
- A combination of 4l, 2l2q and 2l2v final states will come later.

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Thanks for your attention!

Backup

X→ZZ→4l: signal model

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