Search for heavy resonances decaying into a pair of Z bosons in 4l and llvv final states using 139 fb^{-1} of pp collisions at 13 TeV with the ATLAS detector

*Submitted into **Eur. Phys. J. C**, e-print: arXiv:2009.14791*

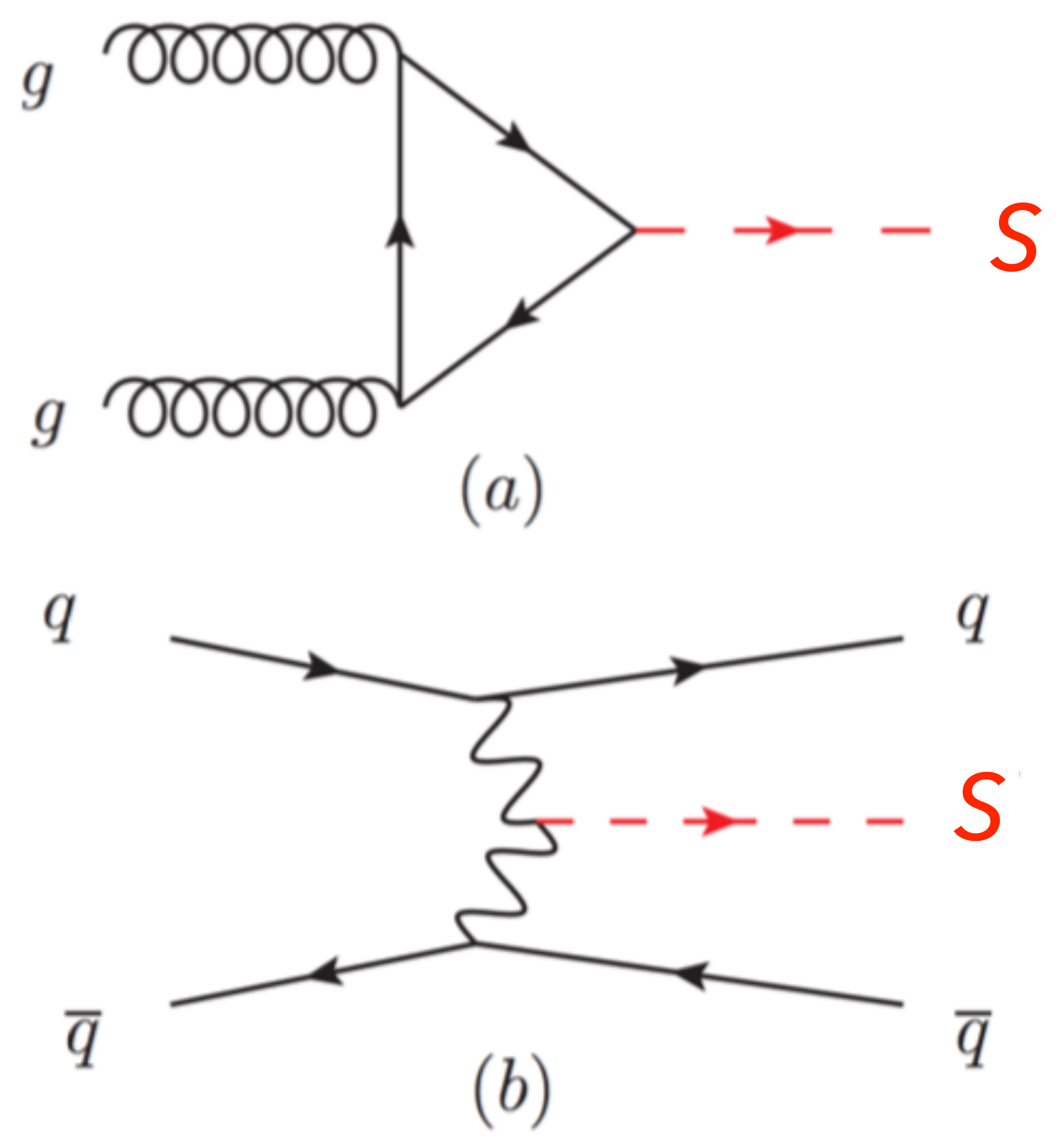
Heling Zhu (祝鹤龄)

Nov. 7th, 2020 @ CLHCP

Introduction

- Standard Model extension: not only one Higgs (125 GeV) boson responsible for electroweak symmetry breaking?
- Search for heavy resonance with S→ZZ→4l/llvv.
- Heavy resonance productions: gluon-gluon Fusion (ggF) and the Vector Boson Fusion (VBF)
- Several benchmark models:
  - Heavy spin-0 resonance of Narrow Width Approximation (NWA)
  - Heavy spin-0 resonance of Larrow Width Approximation (LWA) with widths of 1, 5, 10, 15% of signal mass
  - Two-Higgs-Doublet Model (2HDM)
  - Spin-2 graviton in Randall–Sundrum model

200 GeV to 2000 GeV



ZZ→4l Analysis

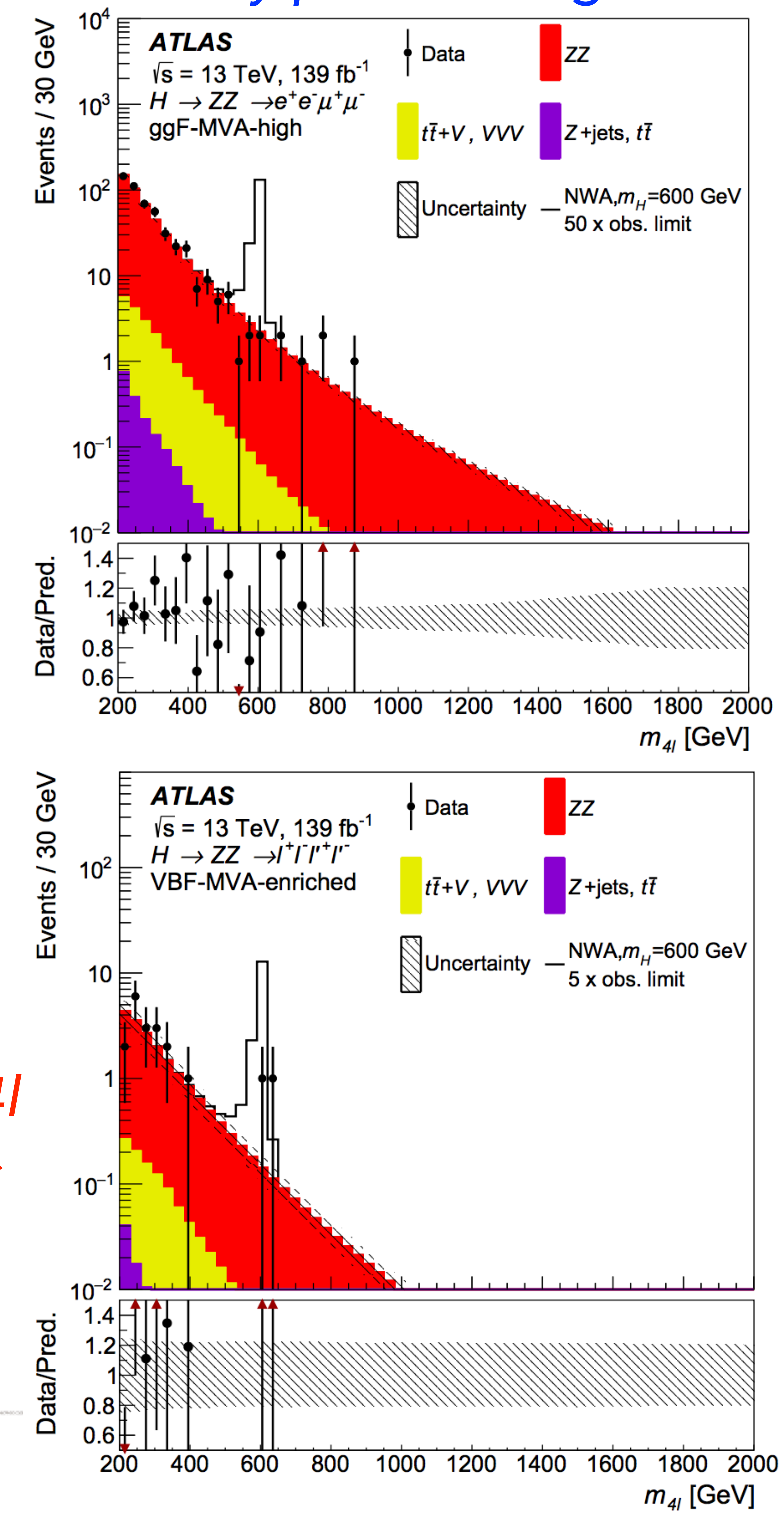
- Two opposite sign same flavor lepton (e, μ) pairs.
- The 4l **Signals** are modeled from parameterization
  - Truth width of NWA: ignored, LWA and Graviton: analytical function
  - Detector resolution:

$$P_s(m_{4\ell}) = f_C \cdot \mathcal{C}(m_{4\ell};\mu,\sigma_C,\alpha_C,n_C) + (1-f_C)\cdot \mathcal{G}(m_{4\ell};\mu,\sigma_{\mathcal{G}})$$

  - For LWA signal, the interferences between heavy Higgs and SM ggZZ process (H-b), and heavy Higgs and SM Higgs (H-h) are considered.
- Irreducible backgrounds (~97%): qq→ZZ, gg→ZZ, EW-qqZZ
  - Shapes are modeled with empirical function
  - Normalizations are constrained by data
- Reducible backgrounds: Z+jets, ttbar
  - Shapes from MC simulation
  - Normalizations from data driven method

Discriminant: 4l invariant mass

B-only post-fit + signal

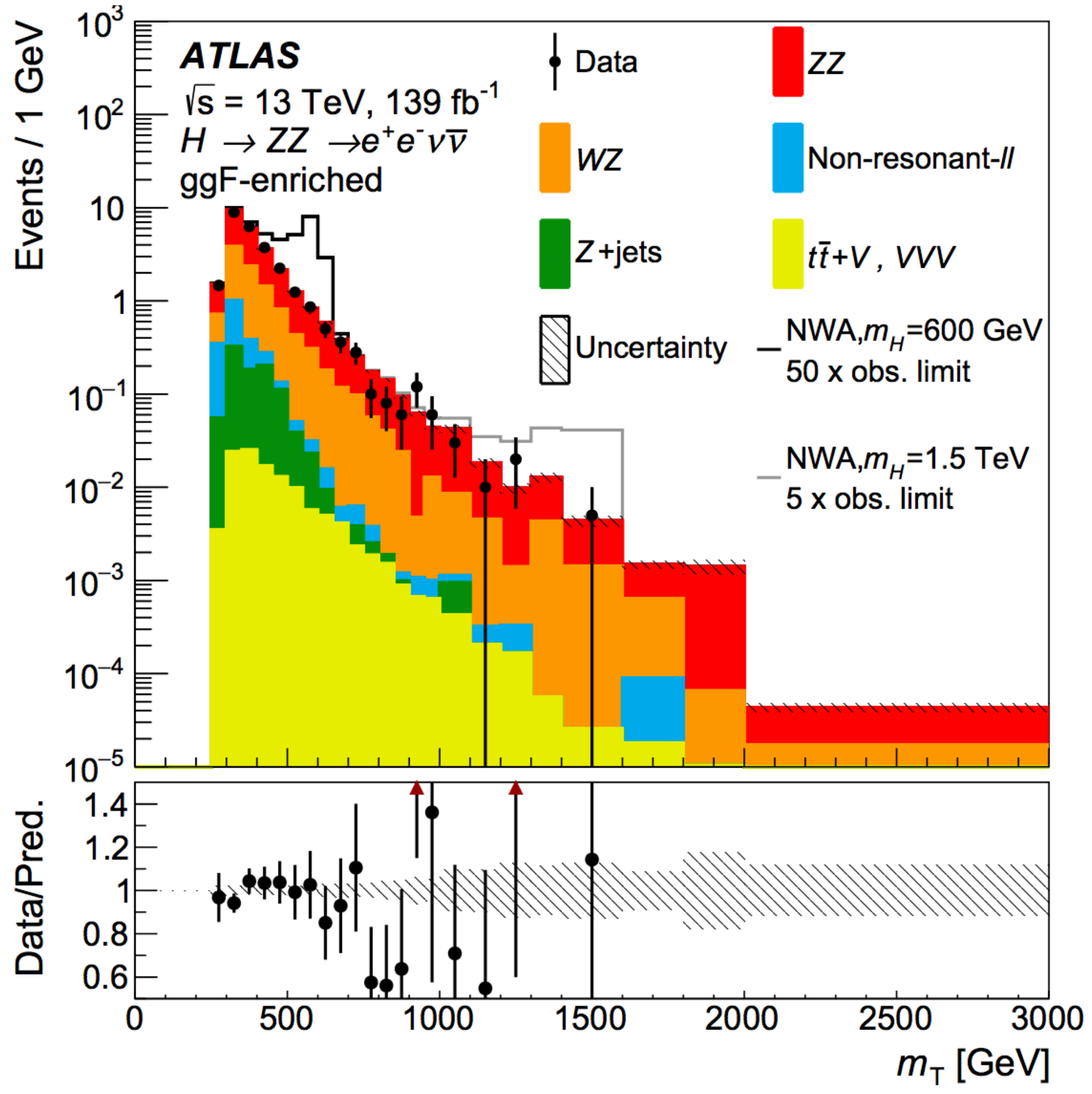


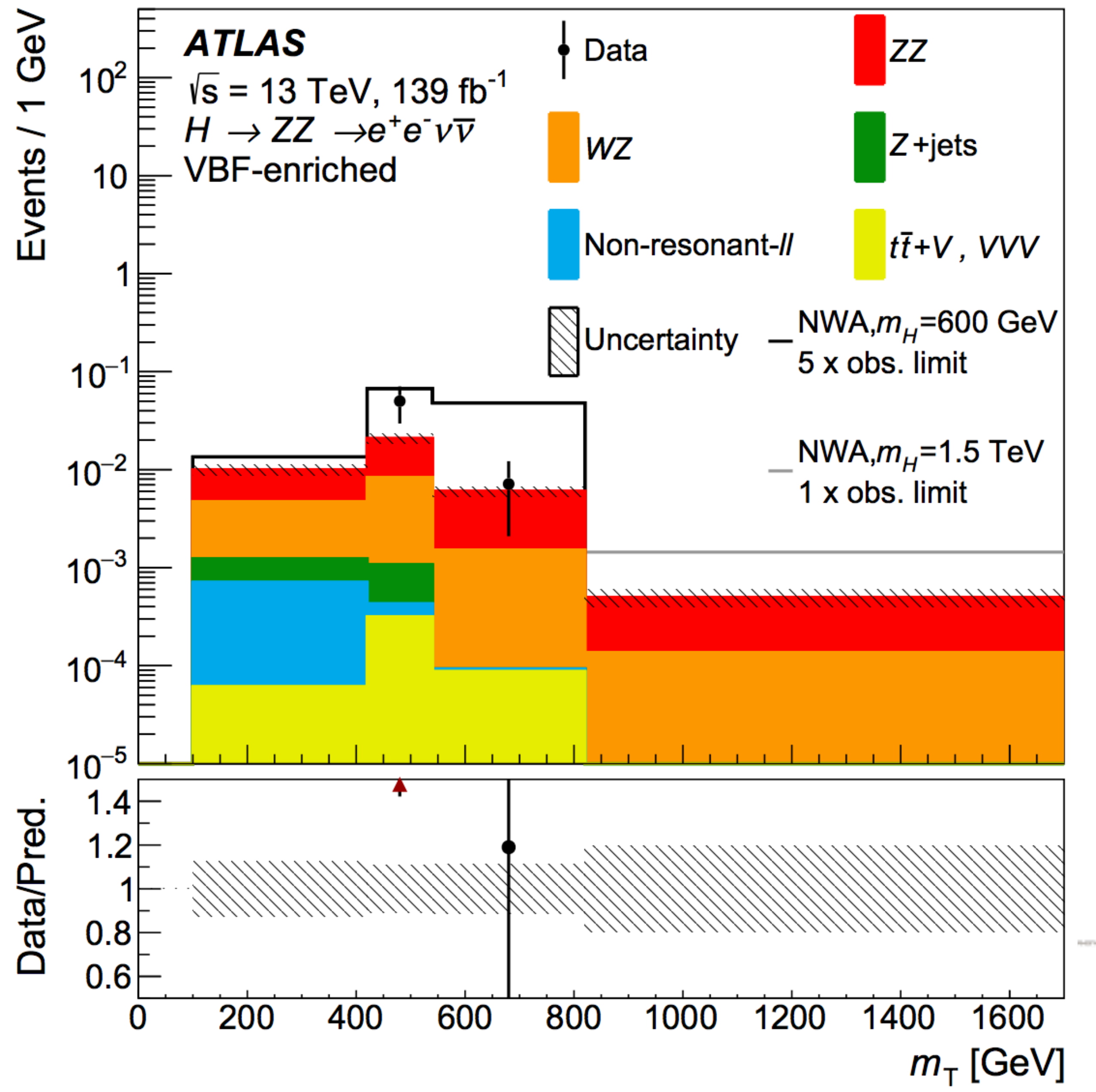
ZZ→llνν Analysis

- One opposite sign same flavor lepton (e, μ) pair + E_T^{miss} (>120 GeV).
- The llνν **Signals** are estimated from MC simulations
- ZZ backgrounds (qqZZ, ggZZ, EW-ZZjj , 60%):
  - Shapes are estimated from MC simulation
  - Normalization is obtained from data (free parameter in fit)
- WZ backgrounds (32%):
  - Shape from MC simulation
  - Yield is estimated in 3-lepton control region.
- Others: Non-resonant-ll (WW/top/Z→$\tau\tau$, 5%), Z (ee, μμ) + jets (3%):
- Fitting discriminant:

$$m_T \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_T^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_T^{miss}\right)^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{miss}\right|^2}$$

B-only post-fit + signal



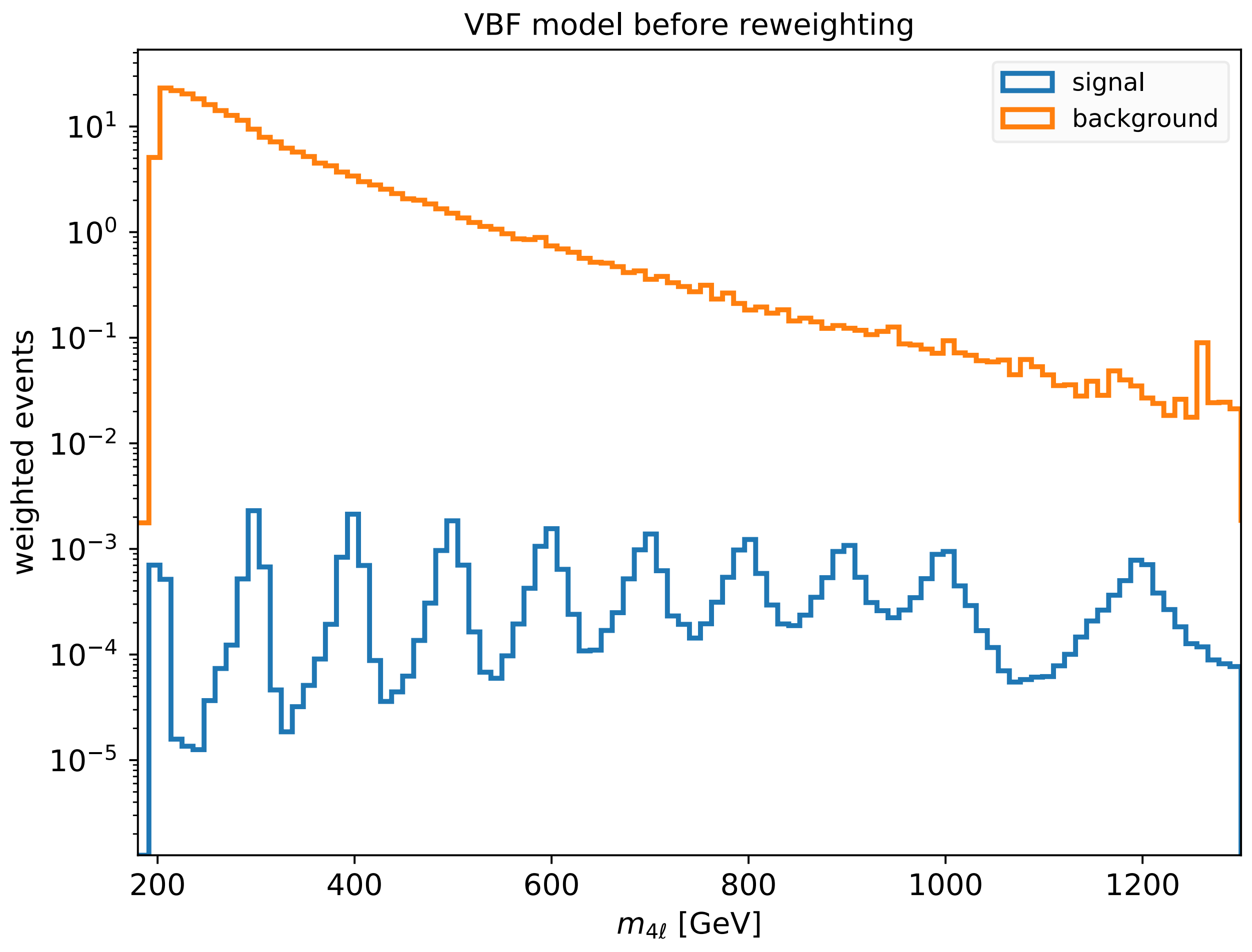


MVA Method for 4l NWA Model

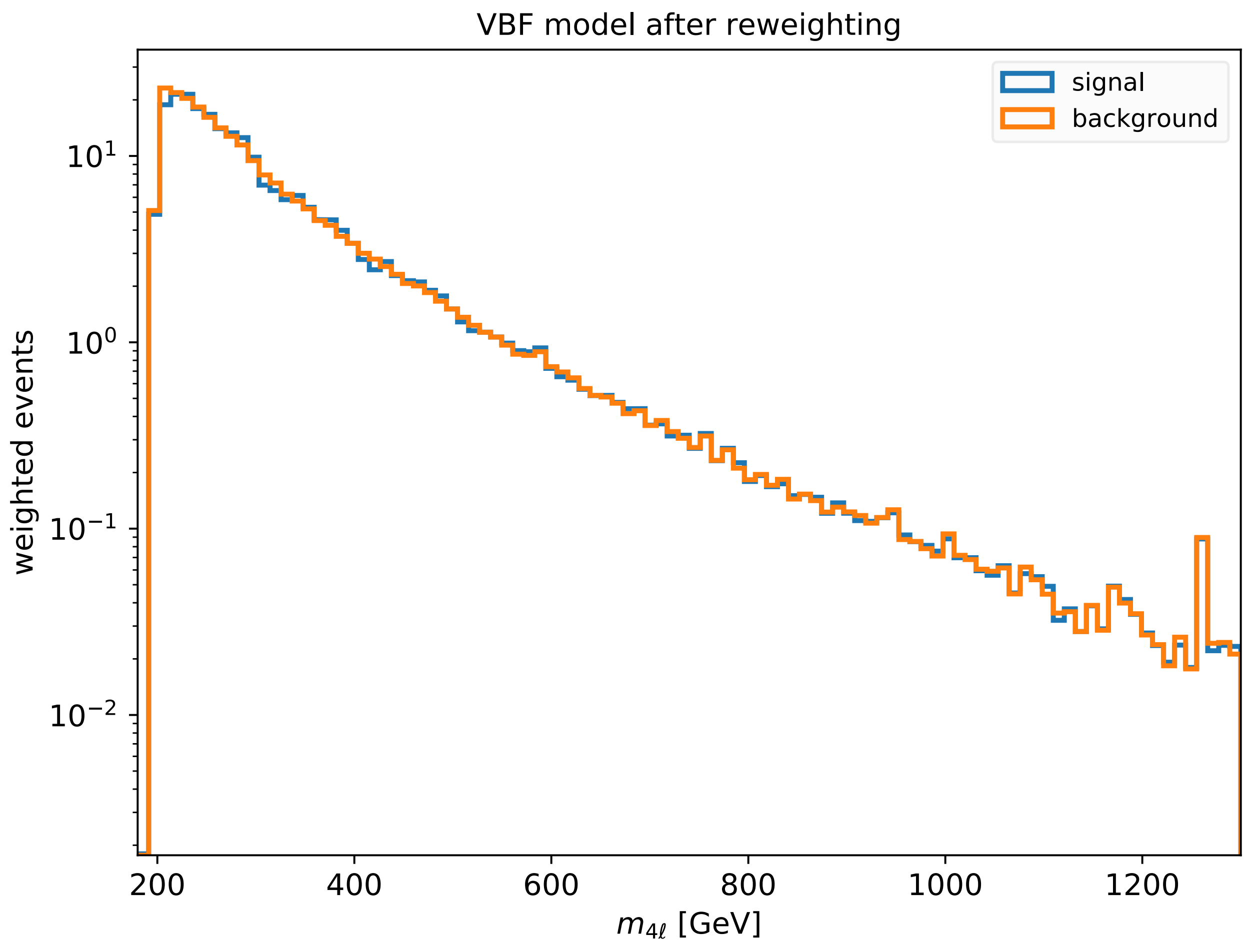
- Two classifiers based on Deep Neural Network: one VBF classifier and one ggF classifier
- The ggF and VBF models are trained **independently** under different phase spaces after all analysis selection
- Use simulated 4l NWA signal events with mH from 200 to 1400 GeV
- Background: qq→ZZ + gg→ZZ (→ 4l)
- To avoid bias, during training, re-weight signal samples to perfectly match falling background spectrum
  - Bias test: no sculpting in either signal acceptance or background distributions
- Input features are kinematics of leptons and jets

- Training of VBF:
  - Events with Njets >= 2
  - Signal: VBF signal samples
- Training of ggF:
  - Events with Njets < 2
  - Signal: ggF signal samples

before re-weighting

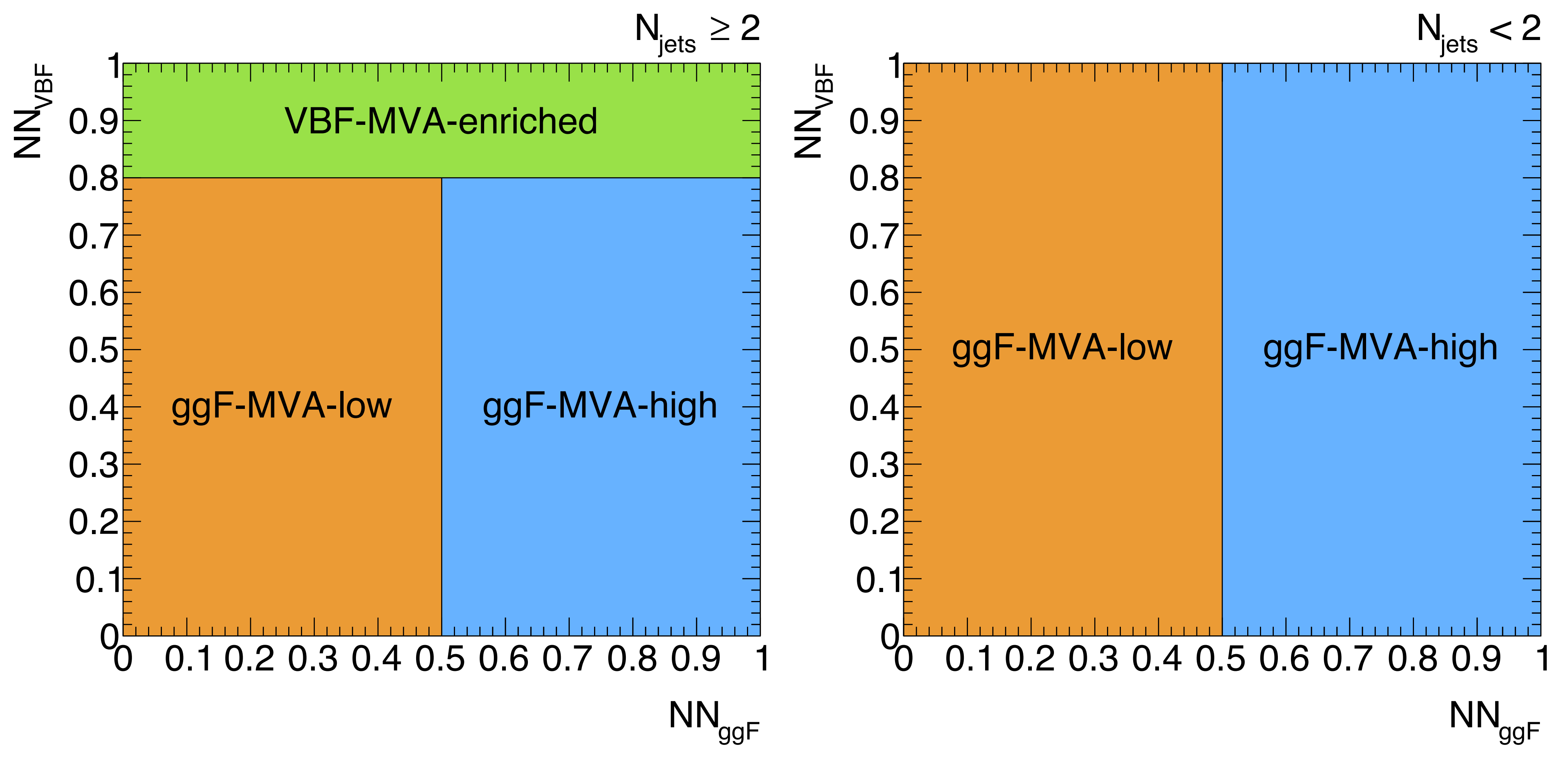


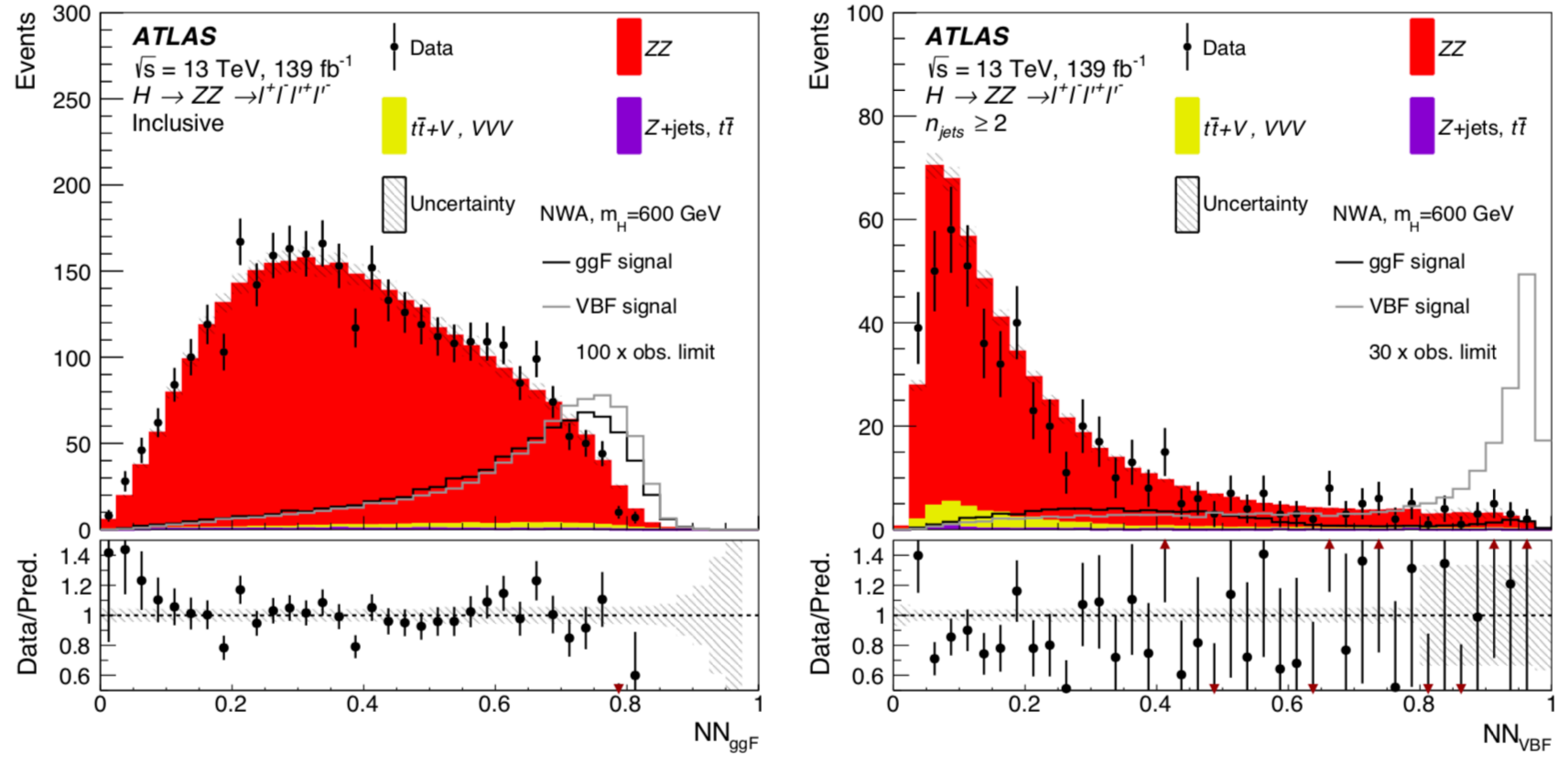
weighted m4l distribution in training



Two Event Categorizations

- Cut-based (4l & llvv):
  - **A model-independent analysis**
  - VBF-enriched: 4l (llvv) m_{jj} > 400 (500) GeV and $\Delta\eta_{jj}$ > 3.3 (4.4)
  - ggF-enriched: remaining events
- MVA-based (4l NWA signal only):
  - **Gain better signal and background separation for NWA specific model**
  - Cut at NN_{ggF} and NN_{VBF}: VBF-MVA-enriched, ggF-MVA-high, ggF-MVA-low
- For NWA signal, consider both ggF and VBF production mode 4l channel: MVA-based analysis as baseline.
- For LWA and Graviton signal, only consider ggF categories with Cut-based analysis.





Systematics

- Overall, the impacts of systematic uncertainties are small
- Experimental uncertainties: ATLAS combined performance (CP) recommendation
- Theory uncertainties:
  - QCD scale, PDF, Parton shower, EW correction
- Other shape uncertainties from background estimation: due to the ZZ backgrounds are constrained by data.

ggF production: Systematic source	Impact [%]	VBF production: Systematic source	Impact [%]
m_H = 300 GeV			
ZZ parameterisation ($\ell^+\ell^-\ell'^+\ell'^-$)	4.5	Jet flavor composition	3.0
Z + jets modelling ($\ell^+\ell^-\nu\bar{\nu}$)	2.3	$q\bar{q} \to ZZ$ QCD scale (VBF-enriched category, $\ell^+\ell^-\ell'^+\ell'^-$)	2.8
Parton showering of ggF ($\ell^+\ell^-\ell'^+\ell'^-$)	2.2	ZZ parameterisation ($\ell^+\ell^-\ell'^+\ell'^-$)	2.3
$e\mu$ statistical uncertainty $\ell^+\ell^-\nu\bar{\nu}$	2.0	Jet energy scale(*in-su* calibration)	1.8
Data stat. uncertainty	53	Data stat. uncertainty	58
Total uncertainty	55	Total uncertainty	60
m_H = 1000 GeV			
Electroweak corrections for $q\bar{q} \to ZZ$ ($\ell^+\ell^-\nu\bar{\nu}$)	9.3	Parton showering ($\ell^+\ell^-\nu\bar{\nu}$)	6.8
Parton showering ($\ell^+\ell^-\nu\bar{\nu}$)	5.2	Electroweak corrections for $q\bar{q} \to ZZ$ ($\ell^+\ell^-\nu\bar{\nu}$)	4.7
QCD scale of $q\bar{q} \to ZZ$ ($\ell^+\ell^-\nu\bar{\nu}$)	4.8	QCD scale of $q\bar{q} \to ZZ$ ($\ell^+\ell^-\nu\bar{\nu}$)	2.4
Z + jets modelling ($\ell^+\ell^-\nu\bar{\nu}$)	2.4	Jet flavor composition	2.4
Data stat. uncertainty	57	Data stat. uncertainty	58
Total uncertainty	59	Total uncertainty	59

Combination between 4l and llvv

- **Final results are obtained by combining 4l and llvv channels.**
- In both 4l and 2l2v channels, the data are consistent with the SM.
- Separate ZZ bkg normalization factors due to different selections:

ZZ normalization factors:

Analysis	Normalisation factor	Fitted value
$\ell^+\ell^-\ell'^+\ell'^-$	$\mu_{ZZ}^{\text{VBF-MVA}}$	0.9 ± 0.3
	$\mu_{ZZ}^{\text{ggF-MVA-high}}$	1.07 ± 0.05
	$\mu_{ZZ}^{\text{ggF-MVA-low}}$	1.12 ± 0.03
$\ell^+\ell^-\nu\bar{\nu}$	μ_{ZZ}	1.07 ± 0.05

Post-fit numbers from B-only hypothesis

4l

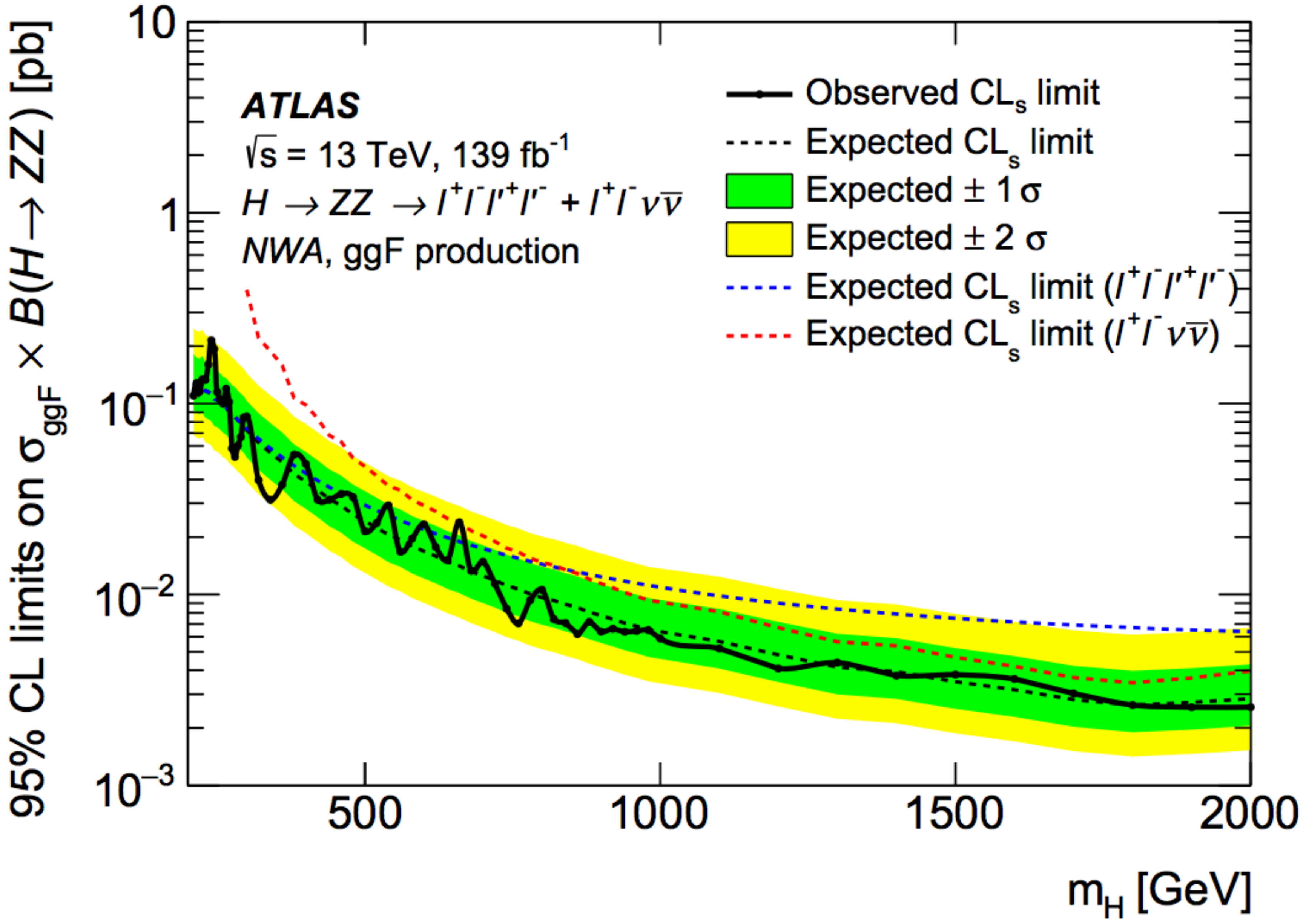
Process	VBF-enriched category	ggF-MVA-high categories: 4μ channel	ggF-MVA-high categories: $2e2\mu$ channel	ggF-MVA-high categories: $4e$ channel	ggF-MVA-low category
$q\bar{q} \to ZZ$	11 ± 4	232 ± 10	389 ± 17	154 ± 7	2008 ± 47
$gg \to ZZ$	3 ± 2	37 ± 6	64 ± 10	26 ± 4	247 ± 19
ZZ (EW)	4.1 ± 0.4	4.5 ± 0.2	7.5 ± 0.4	3 ± 0.2	14.3 ± 0.7
Z + jets,$t\bar{t}$	0.08 ± 0.02	0.6 ± 0.1	1.7 ± 0.4	0.8 ± 0.1	8.8 ± 2.1
$t\bar{t}V, VVV$	0.97 ± 0.1	9.8 ± 0.2	17.5 ± 0.4	7.8 ± 0.2	21.9 ± 0.5
Total background	19 ± 5	284 ± 12	480 ± 20	192 ± 8	2300 ± 51
Observed	19	271	493	191	2301

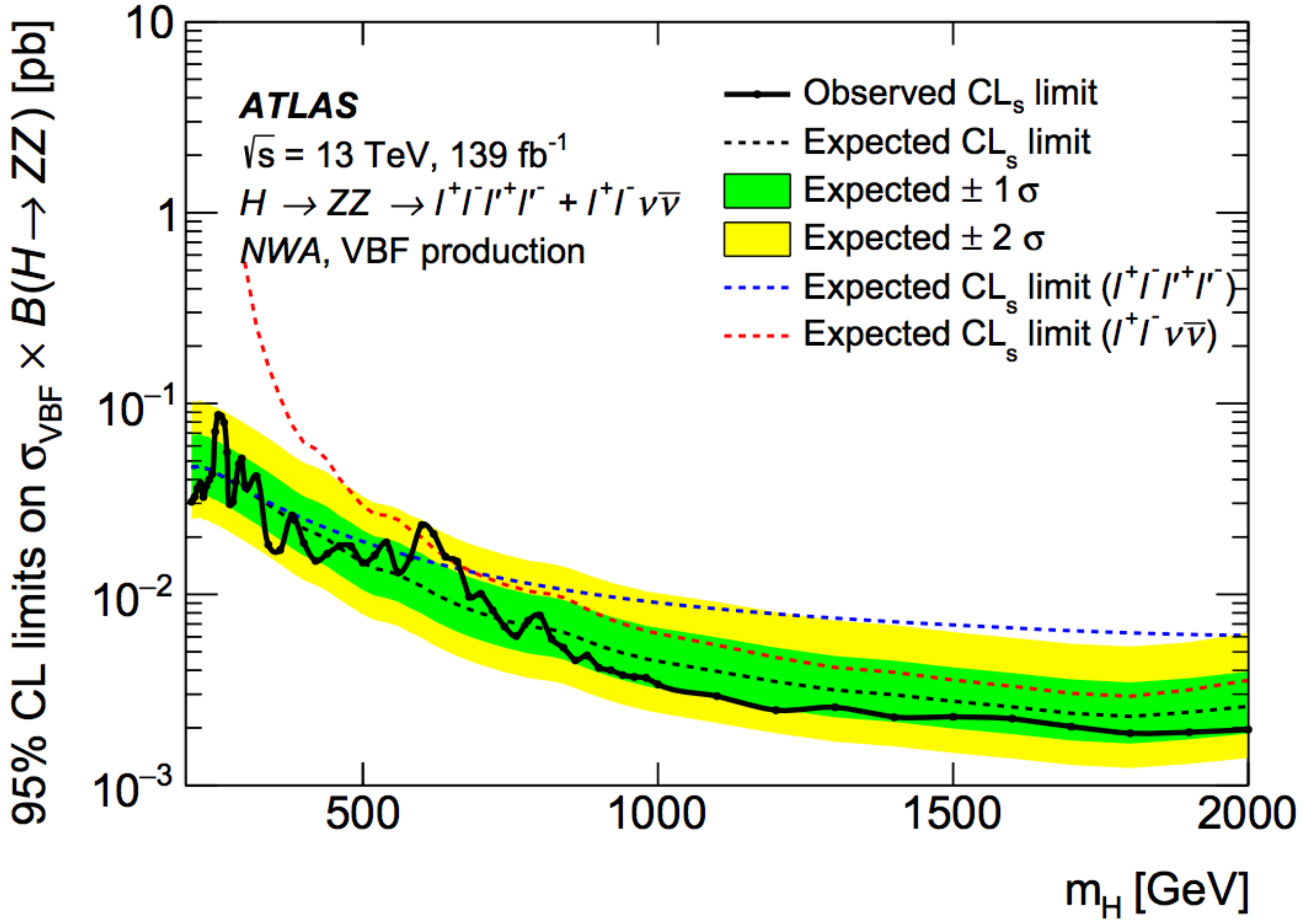
llvv

Process	ggF-enriched categories: e^+e^- channel	ggF-enriched categories: $\mu^+\mu^-$ channel	VBF-enriched categories: e^+e^- channel	VBF-enriched categories: $\mu^+\mu^-$ channel
$q\bar{q} \to ZZ$	714 ± 38	817 ± 44	2.9 ± 0.2	3.5 ± 0.2
$gg \to ZZ$	94 ± 29	105 ± 32	1 ± 0.5	1 ± 0.4
ZZ (EW)	6.6 ± 0.5	7 ± 0.5	0.8 ± 0.1	0.9 ± 0.1
WZ	412 ± 14	455 ± 12	2.5 ± 0.5	3 ± 1.5
Z + jets	43 ± 13	60 ± 22	0.3 ± 0.2	0.4 ± 0.3
Non-resonant-ll	66 ± 6	77 ± 7	0.2 ± 0.2	0.3 ± 0.2
$t\bar{t}V$,VVV	5.9 ± 0.4	5.9 ± 0.4	0.09 ± 0.02	0.04 ± 0.01
Total backgrounds	1342 ± 52	1527 ± 60	7.8 ± 0.8	9 ± 1.6
Observed	1323	1542	8	10

Interpretation: NWA model

- No significant excess is observed, therefore, the results of the search are interpreted as 95% CLs upper limits on the production cross section in the asymptotic approximation.
- For NWA model
  - During statistical fit, both ggF and VBF signals are included, and the other signal not under test is profiled
  - MVA-based analysis as baseline for NWA, Cut-based analysis is also studied



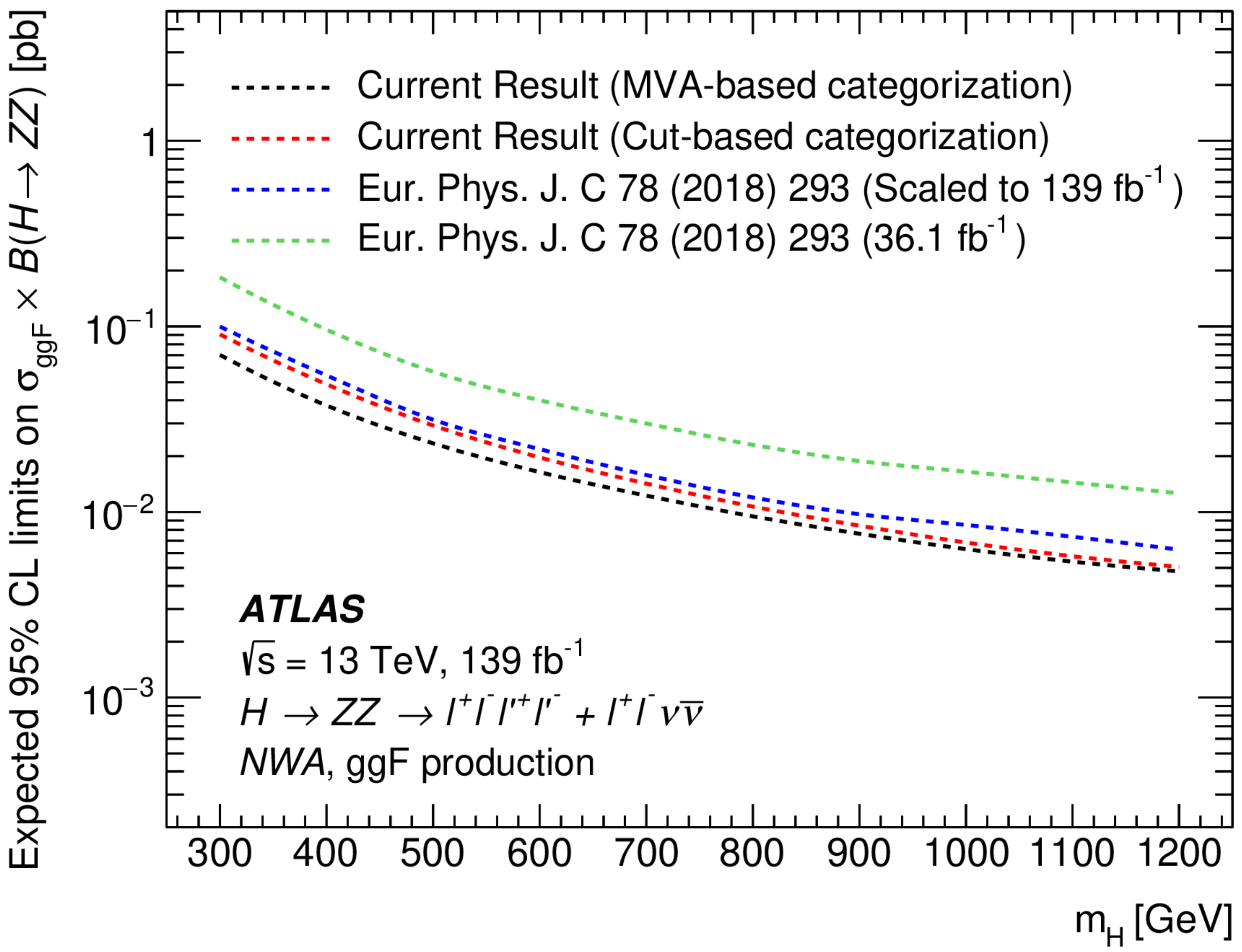


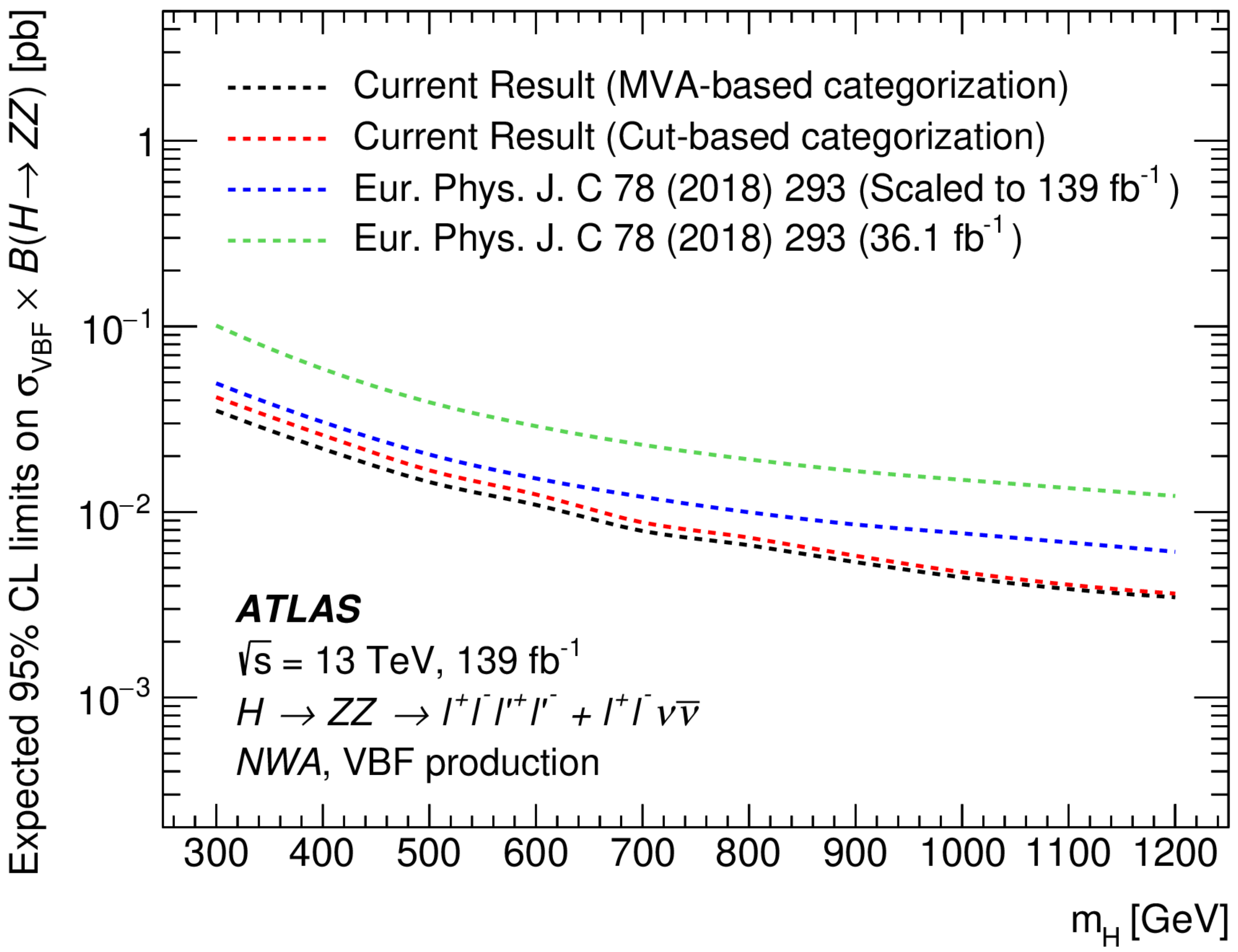
Compare to last paper

- Last paper: 2015+2016 datasets with 36.1/fb, also projected to 139/fb
- Compare with both the MVA- and Cut- based analysis in this paper
- Expected 95% CLs upper limits in the case of NWA model
  - Up to 70% reduction: ~50% reduction due to the luminosity increase

Changes:

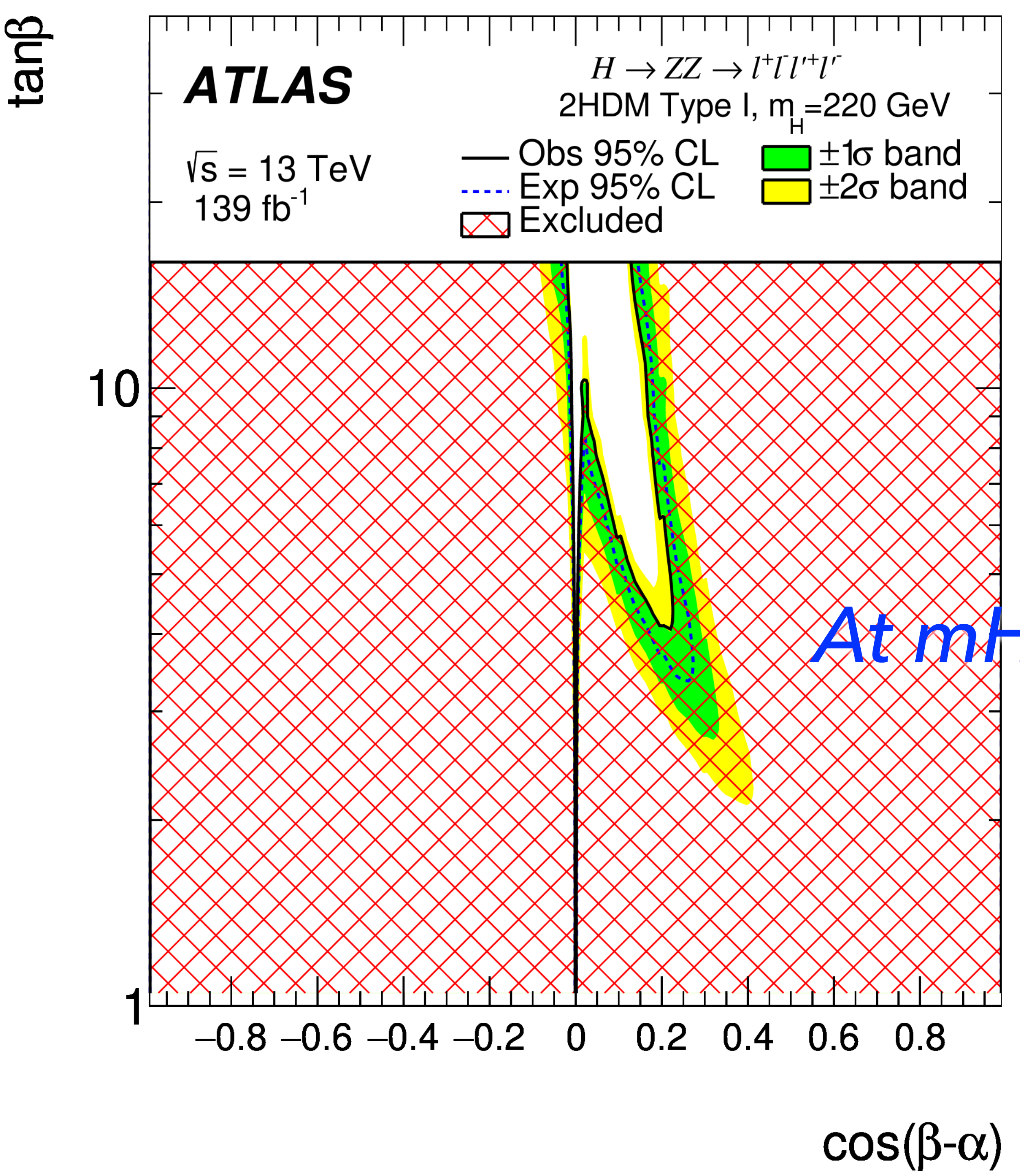
1. *Jets and lepton isolation: more robust for high pile-up condition.*
2. *ZZ bkg constrained by data: reduce uncertainties from theo.*
3. *Search range extend to 2 TeV*
4. *Selection and categorization optimizations.*

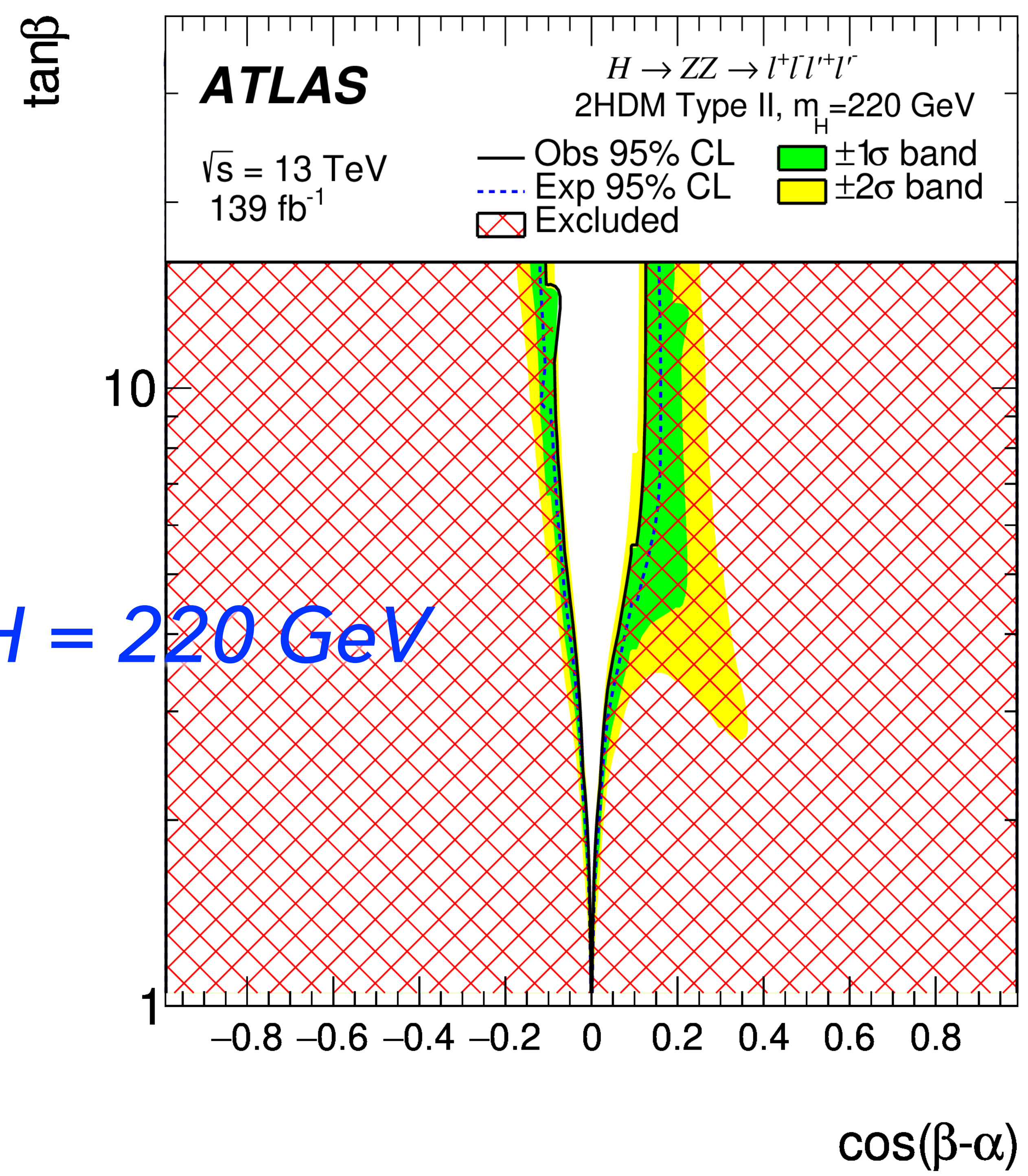


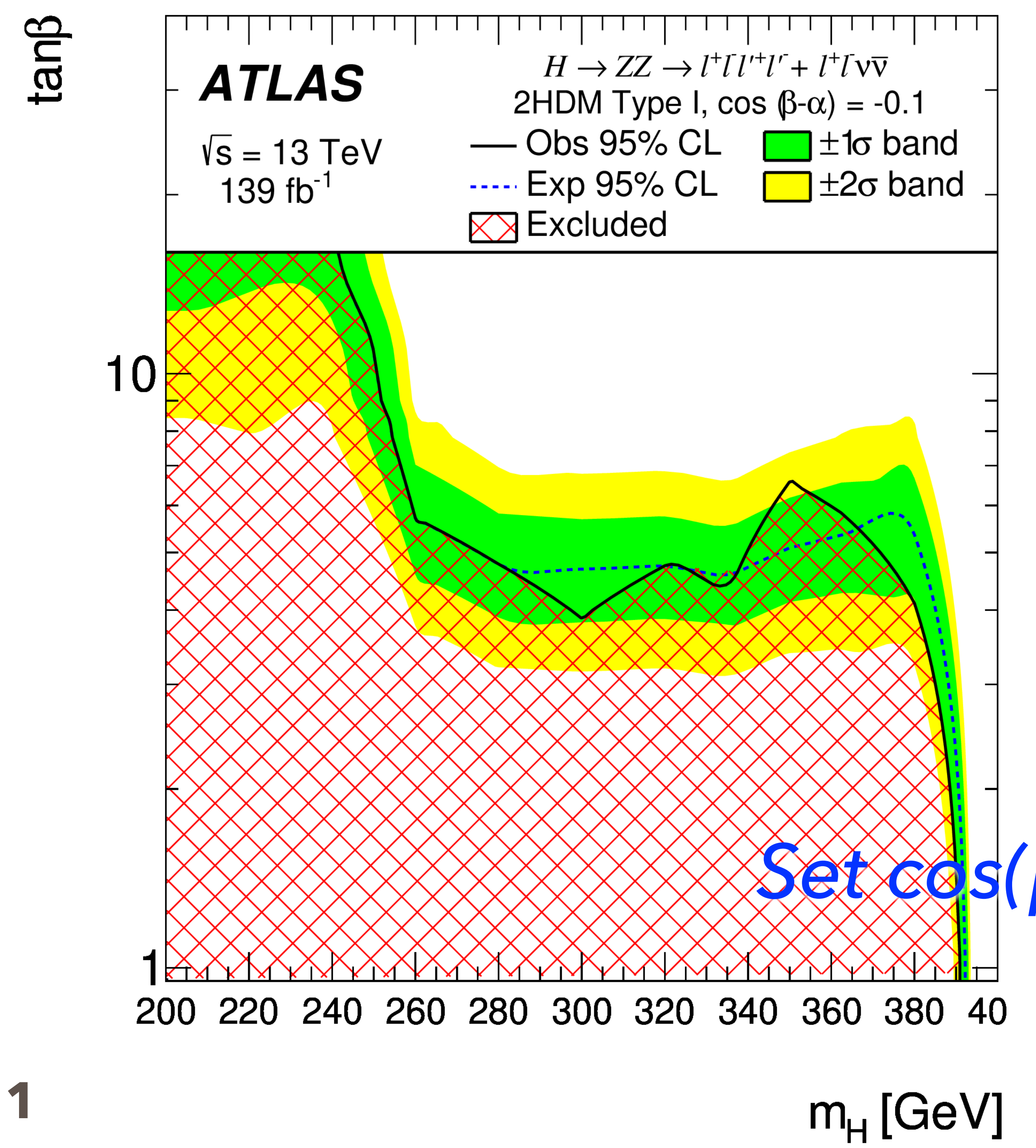


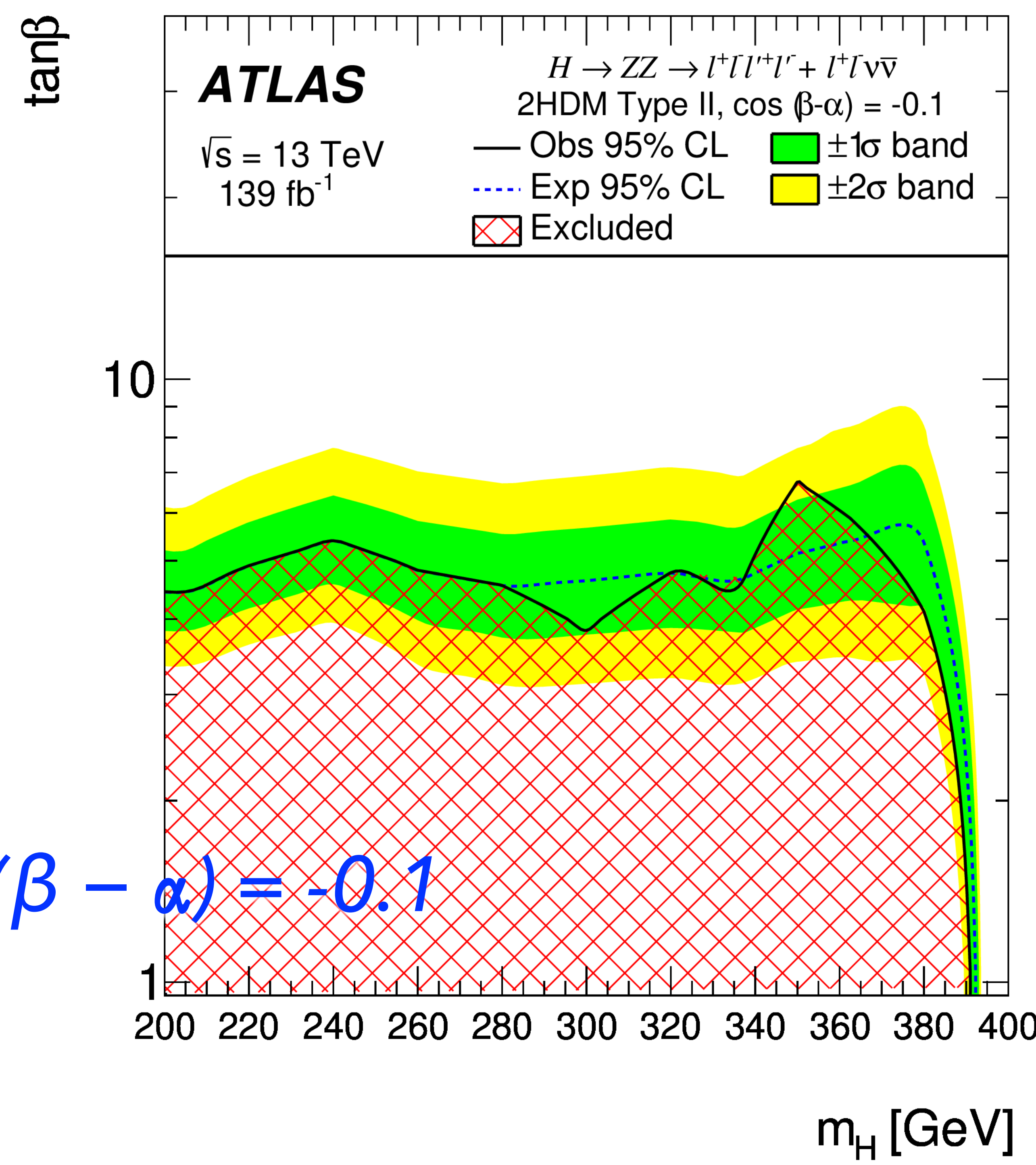
Interpretation: 2HDM

- 2HDM exclusion contours under the assumption of NWA signal
  - Type-I: All quarks and leptons couple only to second Higgs doublet (Φ_2)
  - Type-II: Φ_1 couples to down-type quarks and leptons and Φ_2 couples to up-type quarks
- $tan\beta$: the ratio of Higgs doublets' vacuum expectation values
- Coupling of the heavier Higgs (H) is proportional to $cos(\beta\text{-}\alpha)$



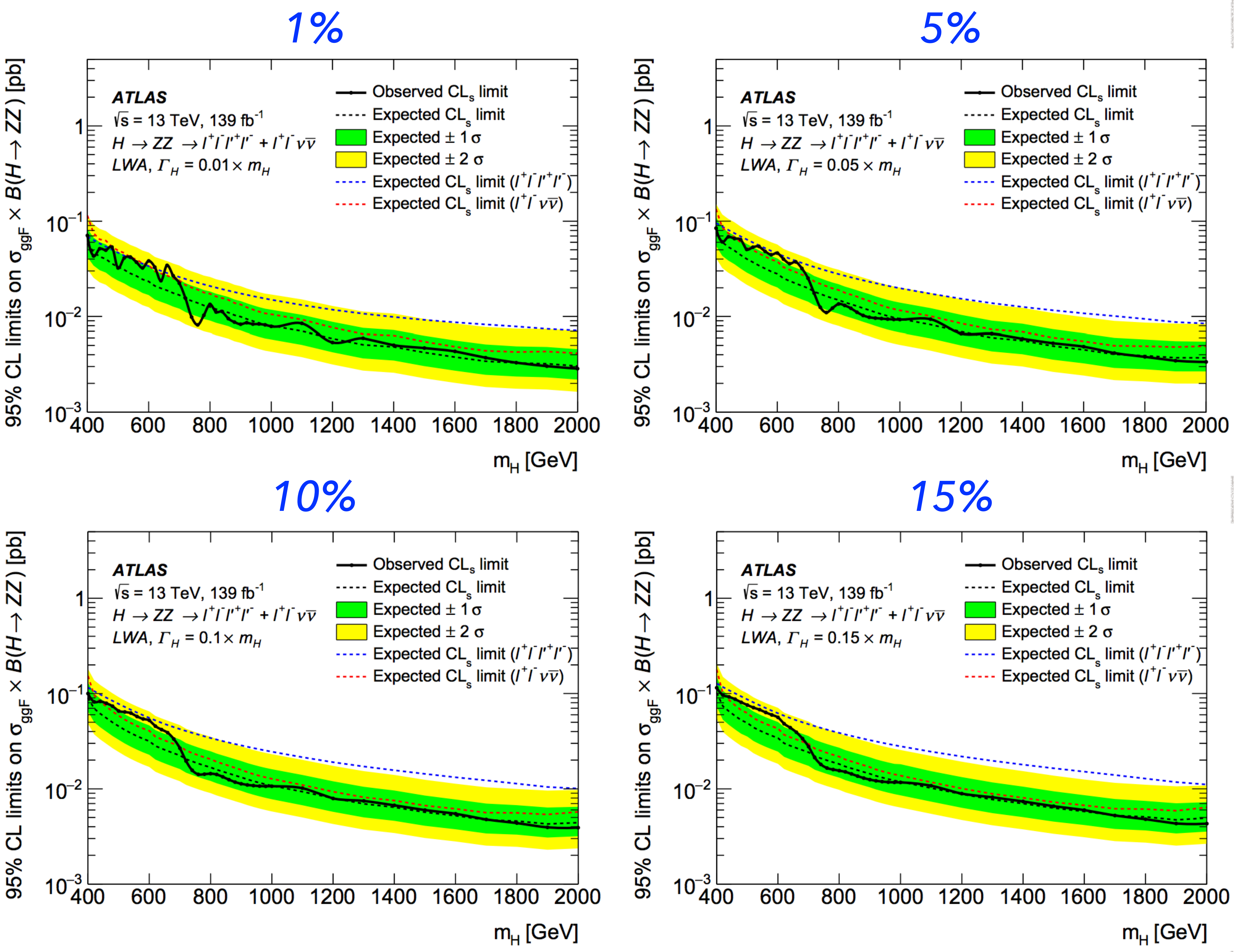






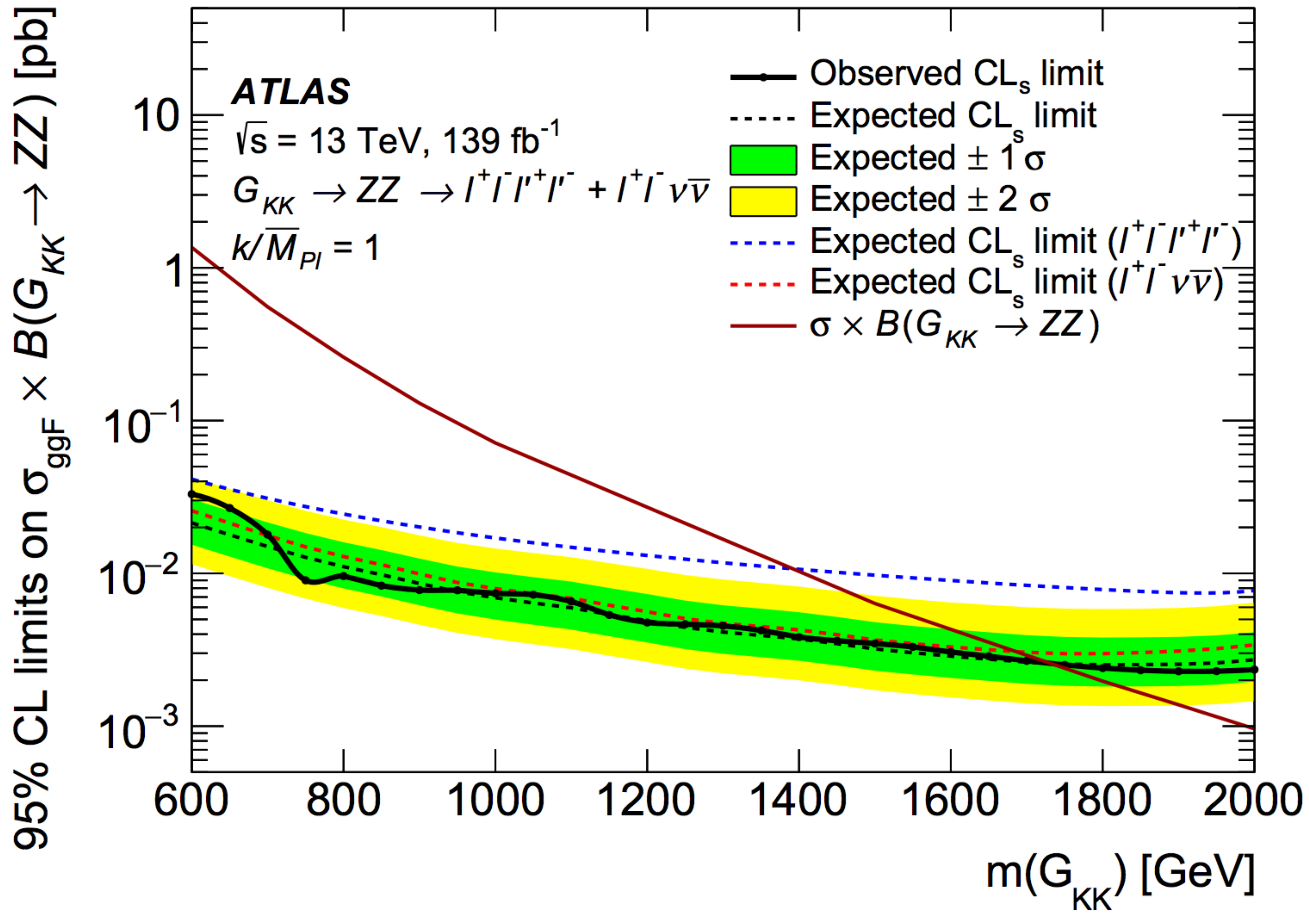
Interpretation: LWA model

- For LWA model, study only ggF production
- Search range from 400 GeV to 2000 GeV
- Interpretation at 4 widths: 1, 5, 10, 15% of signal masses
- Interference of H-b and H-h are all taken into account



Interpretation: RS Graviton

- Graviton excitation in the context of the bulk RS model (G_{KK})
- Coupling strength depends on $k/\overline{M}_{pl}$, where k is the curvature of the extra dimension and $\overline{M}_{pl}$ is the reduced plank mass (2.4×10^{18} GeV)
- Set coupling $k/\overline{M}_{pl}$ to 1, mass of G_{KK} is the only free parameter in this simplified model
- Comparing to the theoretical prediction, mass below 1750 GeV is excluded.



Conclusion

- Search for heavy resonances decaying into a pair of Z bosons in 4l and llvv channels is presented with 139 fb^{-1} 13 TeV data collected by ATLAS detector.
  - Submitted into **Eur. Phys. J. C**, e-print: arXiv:2009.14791
- Several models are studied:
  - Narrow-width spin-0 resonance
  - Large-width spin-0 resonance with widths of 1, 5, 10, 15% of signal mass
  - Parameters in two-Higgs-Doublet Model (2HDM)
  - A Graviton excitation spin-2 resonance in the context of the Randall–Sundrum model.
- Search range: 200 GeV to 2000 GeV.
- No significant excess is observed.
- The results of the search are interpreted as upper limits on the production cross section.

Backup

ZZ→4l analysis: Event selection

- Four leptons final state, 2 opposite sign same flavor pairs.
  - Discriminant: 4-lepton invariant mass, **m4l**
- Use **Particle-flow (PFlow)** jets & lepton isolation: robust for high pile-up condition

Quadruplet Selection	- Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-charge leptons fulfilling the following requirements: - p_T thresholds for three leading leptons in the quadruplet: 20, 15 and 10 GeV - Maximum one calo-tagged or stand-alone muon or silicon-associated forward per quadruplet - Leading di-lepton mass requirement: $50 < m_{12} < 106$ GeV - Sub-leading di-lepton mass requirement: $50 < m_{34} < 115$ GeV - $\Delta R(\ell, \ell') > 0.10$ for all leptons in the quadruplet - Remove quadruplet if alternative same-flavour opposite-charge di-lepton gives $m_{\ell\ell} < 5$ GeV - Keep all quadruplets passing the above selection
Isolation	- Contribution from the other leptons of the quadruplet is subtracted - FixedCutPFlowLoose WP for all leptons
Impact Parameter Significance	- Apply impact parameter significance cut to all leptons of the quadruplet - For electrons: $d_0/\sigma_{d_0} < 5$ - For muons: $d_0/\sigma_{d_0} < 3$
Best Quadruplet	- If more than one quadruplet has been selected, choose the quadruplet with highest Higgs decay ME according to channel: 4μ, $2e2\mu$, $2\mu2e$ and $4e$
Vertex Selection	- Require a common vertex for the leptons: - χ^2/ndof < 5 for 4μ and < 9 for others decay channels

Input features for DNN

Table 15 & 16 in paper draft (Auxiliary material)

For VBF classifier

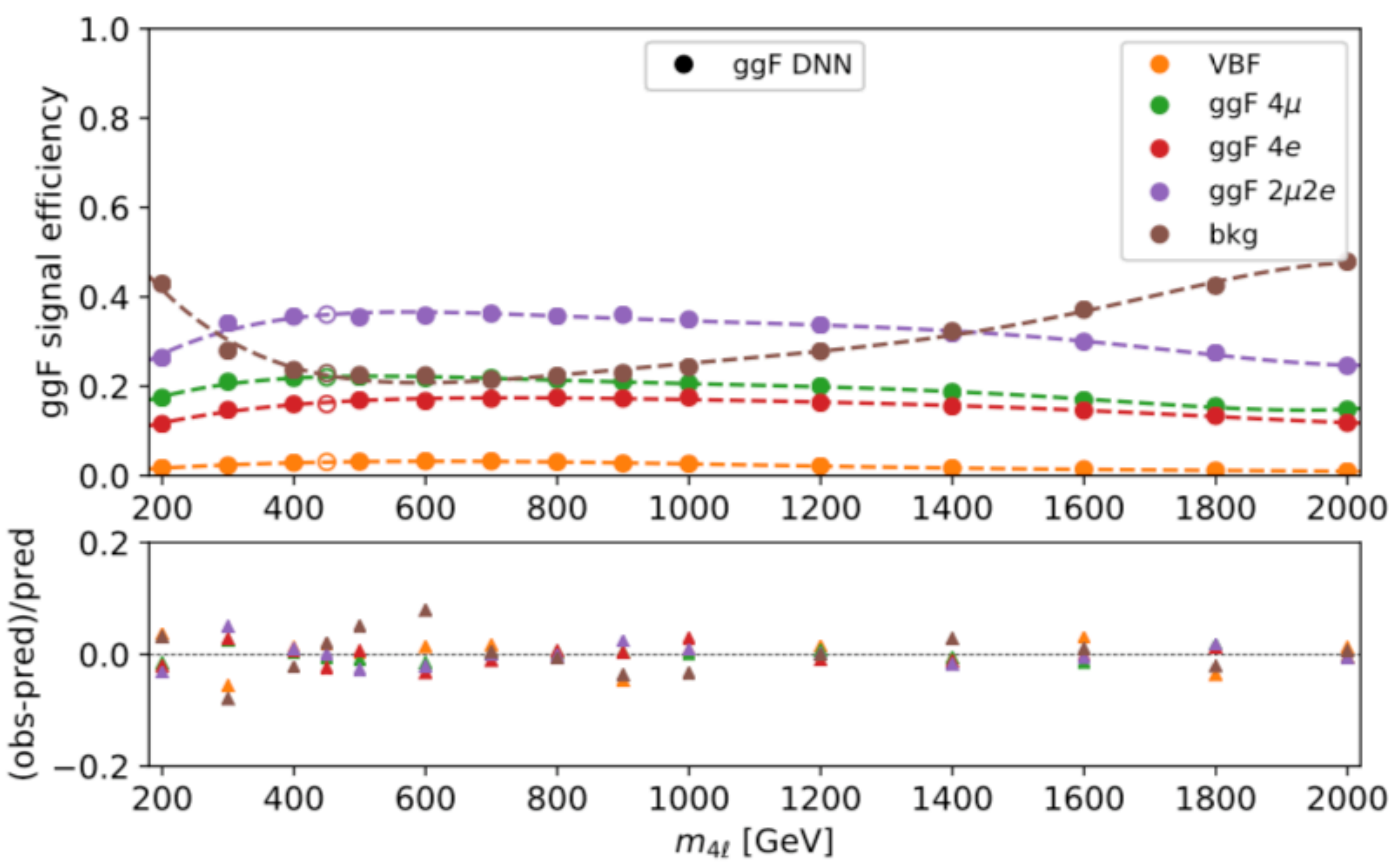
Model	Inputs	Description
rNN	$p_T^{j0,j1}$	transverse momenta of the two leading jets
	$\eta^{j0,j1}$	pseudorapidity of the two leading jets
	$p_T^{\ell 0,\ell 1,\ell 2,\ell 3}$	transverse momenta of the four leptons
	$\eta^{\ell 0,\ell 1,\ell 2,\ell 3}$	pseudorapidity of the four leptons
MLP	$m_{4\ell}$	invariant mass of the four lepton system
	m_{jj}	invariant mass of the two leading jet system
	p_T^{jj}	transverse momentum of the two leading jet system
	$\Delta\eta_{H,j}$	difference in pseudorapidity between the four lepton system and the leading jet
	$\min\Delta R_{jZ}$	minimum distance between one of the two lepton pairs and a jet

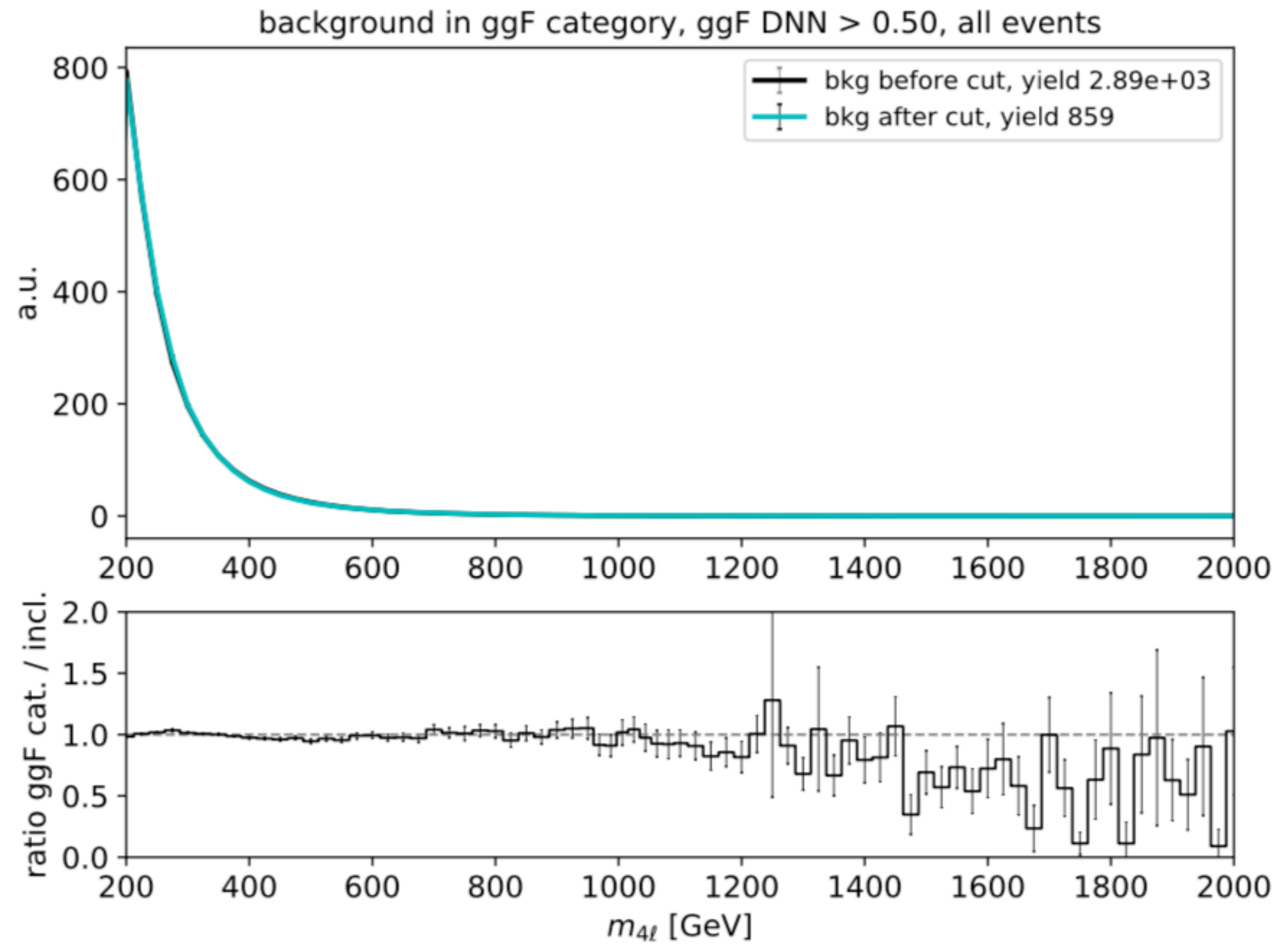
For ggF classifier

Model	Inputs	Description
rNN	$p_T^{\ell 0,\ell 1,\ell 2,\ell 3}$	transverse momenta of the four leptons
	$\eta^{\ell 0,\ell 1,\ell 2,\ell 3}$	pseudorapidity of the four leptons
MLP	$m_{4\ell}$	invariant mass of the four lepton system
	$p_T^{4\ell}$	transverse momentum of the four lepton system
	$\eta^{4\ell}$	pseudorapidity of the four lepton system
	$\cos\theta^*$	production angle of the leading Z defined in the four lepton rest frame
	$\cos\theta_1$	angle beteween the negative final state lepton and the direction of flight of leading Z in the Z rest frame
	$\cos\theta_2$	angle beteween the negative final state lepton and the direction of flight of sub-leading Z in the Z rest frame
	Φ	angle between the decay planes of the four final state leptons expressed in the four lepton rest frame
	p_T^{j0}	transverse momentum of the leading jet
	η^{j0}	pseudorapidity of the leading jet

DNN classifier bias test

- Evaluate the ggF classifier on a newly generated ggF signal mass point at 450 GeV which has not seen during training (right figure)
- No background sculpting comparing the background shape before and after DNN cut (left)





$ZZ \to llvv$ *analysis*: Event selection and categorization

- Final state with 2 opposite sign same flavour leptons plus E_T^{miss}
  - Events are not fully reconstructable, discriminant: transverse mass, **mT**

$$m_{\mathrm{T}} \equiv \sqrt{\left[\sqrt{m_Z^2 + (p_{\mathrm{T}}^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_{\mathrm{T}}^{\mathrm{miss}})^2}\right]^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$

- Sensitive at mass range > 300 GeV
- Large branching ratio, dominant in higher mass region.

- Use Cut-based categorization (4 categories):
  - Obtained from 2D significance scan
  - VBF: m_{jj} > 550 GeV and $\Delta\eta_{jj}$ > 4.4
  - ggF: remaining events passing analysis selection
  - Both are separated in ee$\nu\nu$ and $\mu\mu\nu\nu$ channel

Criterion	Mainly suppresses
$E_{\mathrm{T}}^{\mathrm{miss}}$ >120 GeV	Z+jets
$\Delta R_{\ell,\ell} < 1.8$	Z+jets, WW,top,$Z \to \tau\tau$
$\Delta\phi(Z, E_T^{\mathrm{miss}}) > 2.5$	Z+jets, WW,top,$Z \to \tau\tau$
$\Delta\phi(\mathrm{jet}_{p_{\mathrm{T}}>100\,\mathrm{GeV}}, E_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$	Z+jets
$E_{\mathrm{T}}^{\mathrm{miss}}$-significance > 10.0	Z+jets
$n_{\text{b-jets}} = 0$, (jet $p_{\mathrm{T}} > 20$ GeV, b-tagging MV2c10 WP 85%)	Top quarks

LWA Signal Modeling

Cross section:

$$\sigma_{pp\to H\to ZZ}(m_{4\ell}) = 2\cdot m_{4\ell}\cdot \mathcal{L}_{gg}\cdot \frac{1}{\left|s-s_H\right|^2}\cdot \Gamma_{H\to gg}(m_{4\ell}^2)\cdot \Gamma_{H\to ZZ}(m_{4\ell}^2)$$

Higgs propagator

$$\frac{1}{s-s_H} = \frac{1+i\cdot \overline{\Gamma}_H/\overline{m}_H}{s-\overline{m}_H^2+i\cdot s\cdot \overline{\Gamma}_H/\overline{m}_H}$$

$$\overline{m}_H = \sqrt{\Gamma_H^2+m_H^2}$$

$$\overline{\Gamma}_H = \overline{m}_H\cdot \frac{\Gamma_H}{m_H}$$

H→ZZ width

$$\Gamma_{H\to ZZ}(s) = C\cdot s^{\frac{3}{2}}\cdot \left[1-\frac{4m_Z^2}{s}+\frac{3}{4}\left(\frac{4m_Z^2}{s}\right)^2\right]\cdot \left[1-\frac{4m_Z^2}{s}\right]^{\frac{1}{2}}$$

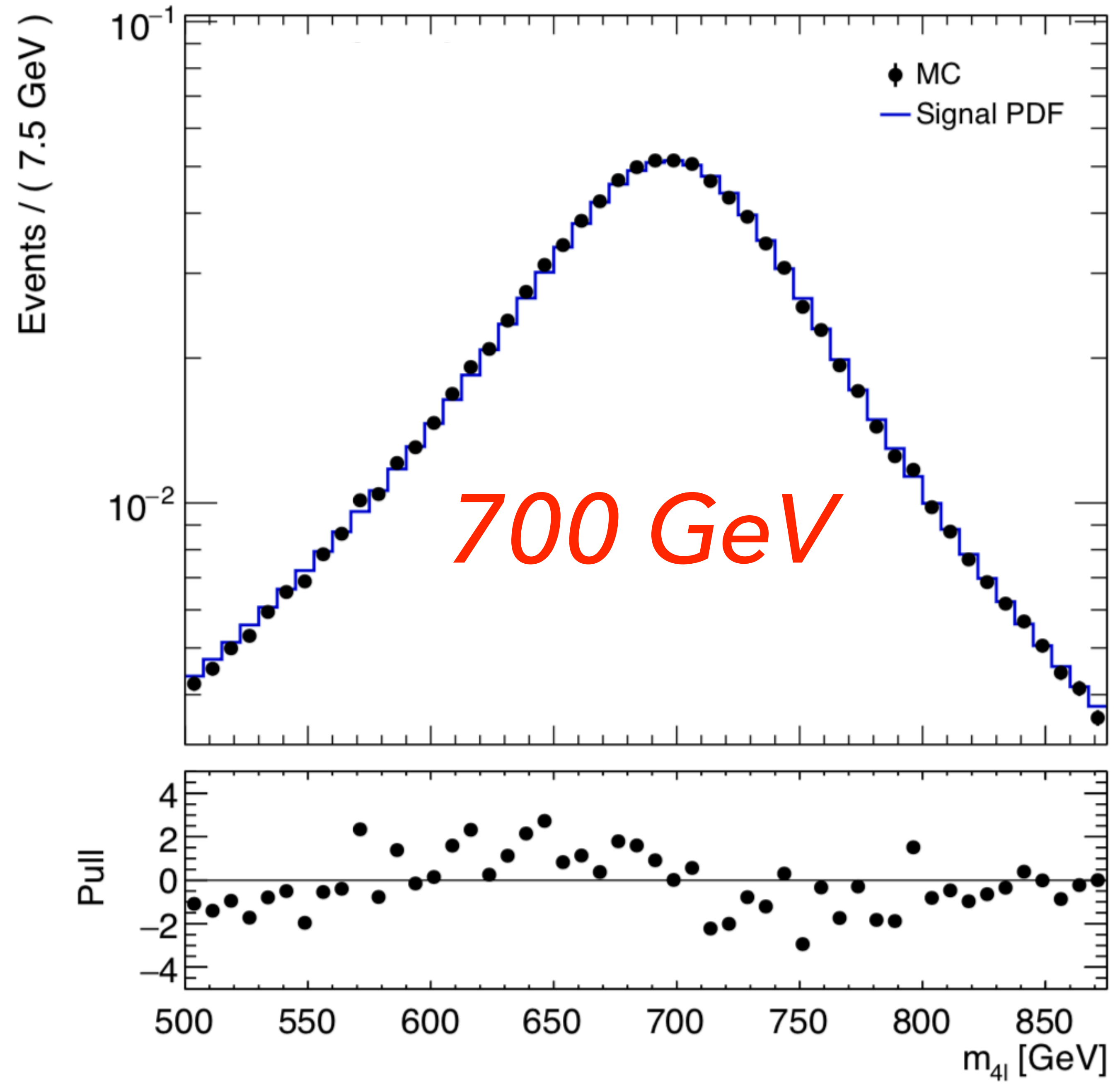
gg→H width (via t or b-quark)

$$\Gamma_{H\to gg}(s) = C\cdot s^{\frac{3}{2}}\cdot \left|A_t(\tau_t)\right|^2$$

$$A_t(\tau) = 2\frac{\tau+(\tau-1)f(\tau)}{\tau^2}$$

$$\tau_t = \frac{s}{4m_t^2}$$

$$f(\tau) = \begin{cases} \arcsin^2(\sqrt{\tau}), & \tau \leqslant 1 \\ -\frac{1}{4}\left[\log\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}}-i\pi\right]^2, & \tau > 1 \end{cases}$$



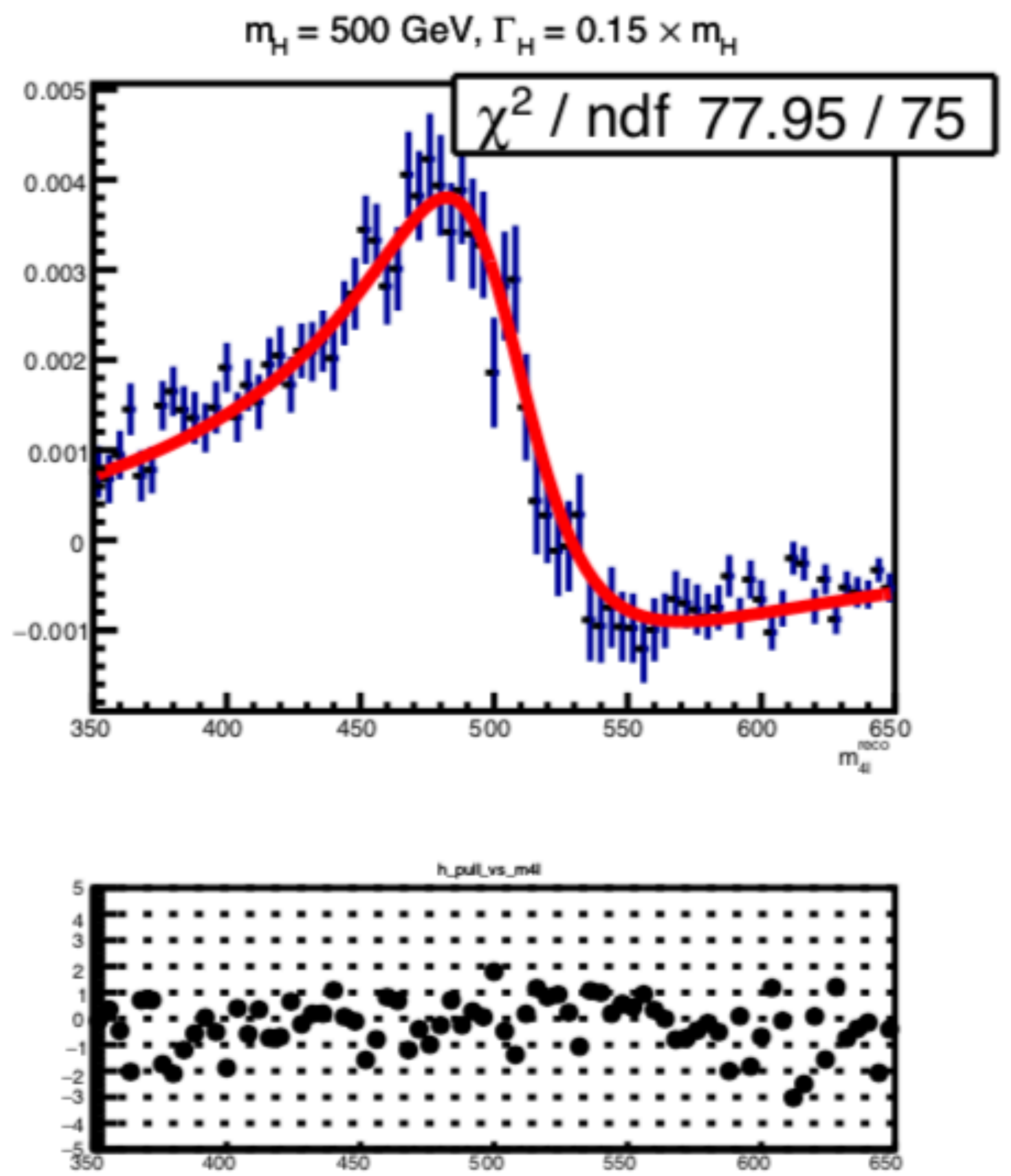
Truth convolute with NWA reco

MC with 15% width

where $s = m_{4l}^2$, L_{gg}: gluon-gluon luminosity

Interference Modeling

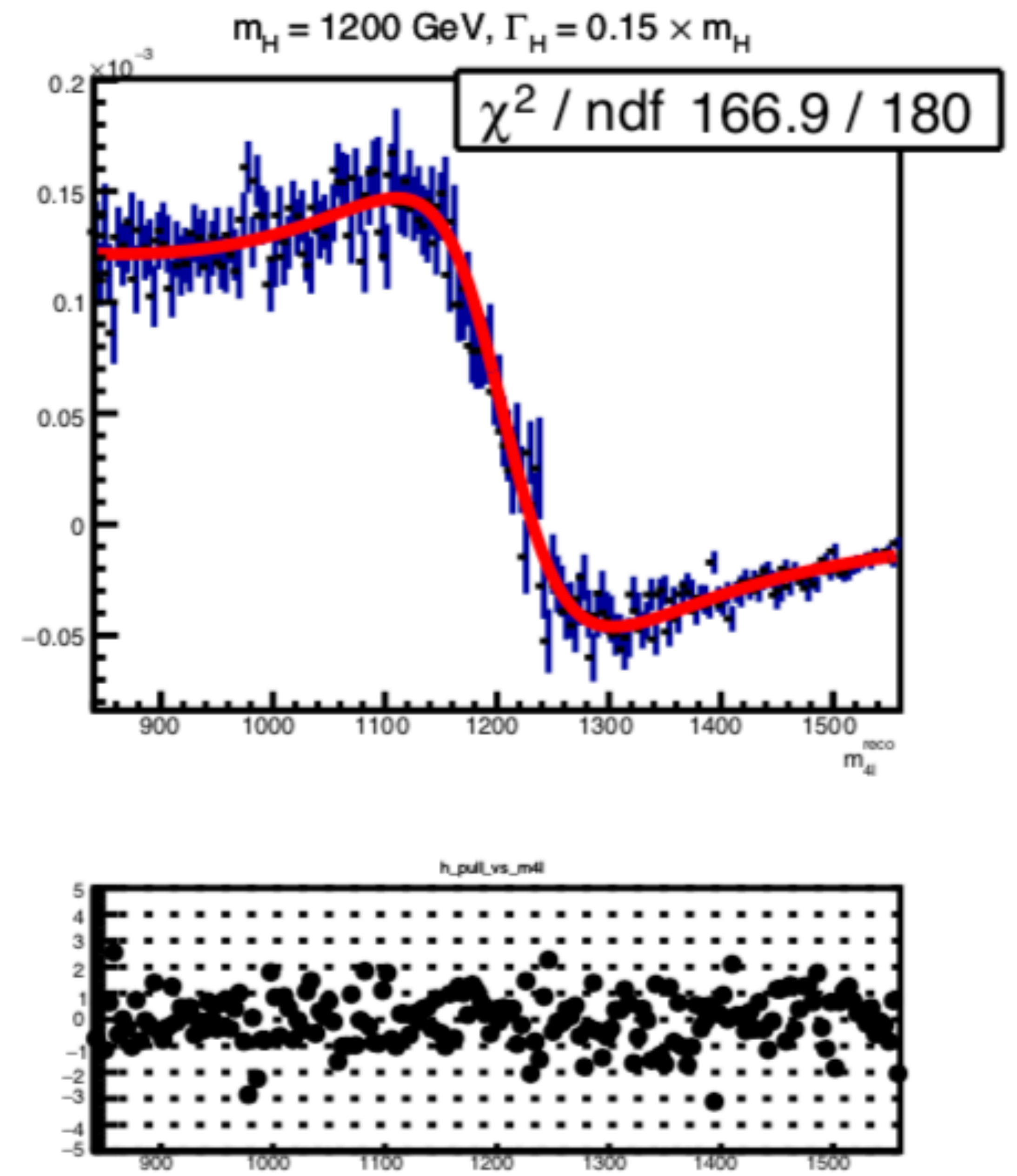
- Interference between heavy Higgs and $gg \to ZZ$ continuum
  - Fit to truth-level MC



$$\sigma_{pp}(m_{4\ell}) = \mathcal{L}_{gg} \cdot \frac{1}{m_{4\ell}} \cdot \mathrm{Re}\left[\frac{1}{s - s_H} \cdot \left((a_0 + a_1 \cdot m_{4\ell} + \dots) + i \cdot (b_0 + b_1 \cdot m_{4\ell} + \dots)\right)\right]$$

- Interference between heavy Higgs and SM Higgs
  - Calculate from analytical function directly (like LWA)

$$\sigma_{pp}(m_{4\ell}) = 4 \cdot m_{4\ell} \cdot \mathcal{L}_{gg} \cdot \mathrm{Re}\left[\frac{1}{s - s_H} \cdot \frac{1}{(s - s_h)^*}\right] \cdot \Gamma_{H \to gg}(m_{4\ell}) \cdot \Gamma_{H \to ZZ}(m_{4\ell})$$



ZZ background parameterization

- Empirical function:

$$f(m_{4\ell}) = C_0 H(m_0 - m_{4\ell}) f_1(m_{4\ell}) + H(m_{4\ell} - m_0) f_2(m_{4\ell}),$$

$$f_1(x) = \left(\frac{x - a_4}{a_3}\right)^{a_1 - 1} \left(1 + \frac{x - a_4}{a_3}\right)^{-a_1 - a_2},$$

$$f_2(x) = \exp\left[b_0 \left(\frac{x - b_4}{b_3}\right)^{b_1 - 1} \left(1 + \frac{x - b_4}{b_3}\right)^{-b_1 - b_2}\right],$$

$$C_0 = \frac{f_2(m_0)}{f_1(m_0)}.$$

  - f1: covers low mass region
  - f2: describes high mass tail
  - Transition point: m_0, m_0 = 260 GeV for qqZZ background, and 350 GeV for ggZZ and EW-ZZjj backgrounds.

Parameterization's error

- P.d.f with visualized 1-sigma error band: VisualizeError() in RooFit
- Linear propagation of the covariance matrix

```
error(x) = Z* F_a(x) * Corr(a,a') F_a'(x)
where    F_a(x) = [ f(x,a+da) - f(x,a-da) ] / 2,
         with f(x) = the plotted curve
              'da' = error taken from the fit result
         Corr(a,a') = the correlation matrix from the fit result
         Z = requested significance 'Z sigma band', we use Z = 1
```

Fast but may not be accurate in the presence of strong correlations (~>0.9)

Reducible Background Estimation

- llee: from Z boson with light-flavor jets (Z+LF)
  - Fit to the number of hits in the innermost ID layer in 3l + X CR, second lepton pair should be same sign.
- llμμ: Z boson with heavy-flavor jets (Z+HF) or top-quark
  - Fit to M_{Z1} in dedicate CRs: inverted d_0CR, $e\mu$ + $\mu\mu$ CR, inverted isolationCR, Same-signCR
- The normalizations from fit are then propagated to SR, by applying transfer factors to account for the difference of **selection efficiencies** between SR and CRs

Experimental Uncertainties

- Electron:
  - Reconstruction & Identification: EL_EFF_Reco_TOTAL_1NPCOR_PLUS_UNCOR, EL_EFF_ID_CorrUncertaintyNP[0-15]
  - Energy scale & Resolution: EG_SCALE_ALLCORR,
    arise from detector components: EG_SCALE_E4SCINTILLATOR, EG_SCALE_LARTEMPERATURE_EXTRA2016PRE, EG_RESOLUTION_ALL
- Muon:
  - Reconstruction & identification: MUON_EFF_RECO_STAT(_LOWPT), MUON_EFF_RECO_SYS(_LOWPT)
  - Momentum scale & resolution: tracking properties are different in the different tracking systems: MUON_ID, MUON_MS, MUON_SAGITTA_RESBIAS, MUON_SAGITTA_RHO
  - Track-to-vertex-association (TTVA): performance of matching a muon track to a vertex: MUON_EFF_TTVA_STAT, MUON_EFF_TTVA_SYS
- Jet energy scale and resolution: JET_JER_DataVsMC, JET_JER_EffectiveNP[1-7]
- Pile-up: rescale <μ> according to data vs MC comparisons: PRW_DATASF

Statistic Procedure

- Binned likelihood function: $L = \prod_i^{cat} \prod_j^{bins} Pois(n_{ij}|\mathrm{Yield}_{ij}(\vec{\sigma}, \vec{\theta})) \prod_k^{\bar{var}} G(\theta_k|0,1)$
  - where **n** = (n_1, …, n_N) is histogram (eg. m4l distribution)
  - θ nuisance parameters (eg. exp. and theo. uncertainties) constrained by Gaussian
- Under the case we have two (ggF, VBF signal) in this analysis:

$$\mathrm{Yield}_{\text{cat i, bin j}} = S_{ggF} f_{\mathrm{ggF}}(x_{ij}) + S_{VBF} f_{\mathrm{VBF}}(x_{ij}) + B f_{\mathrm{B}}(x_{ij})$$

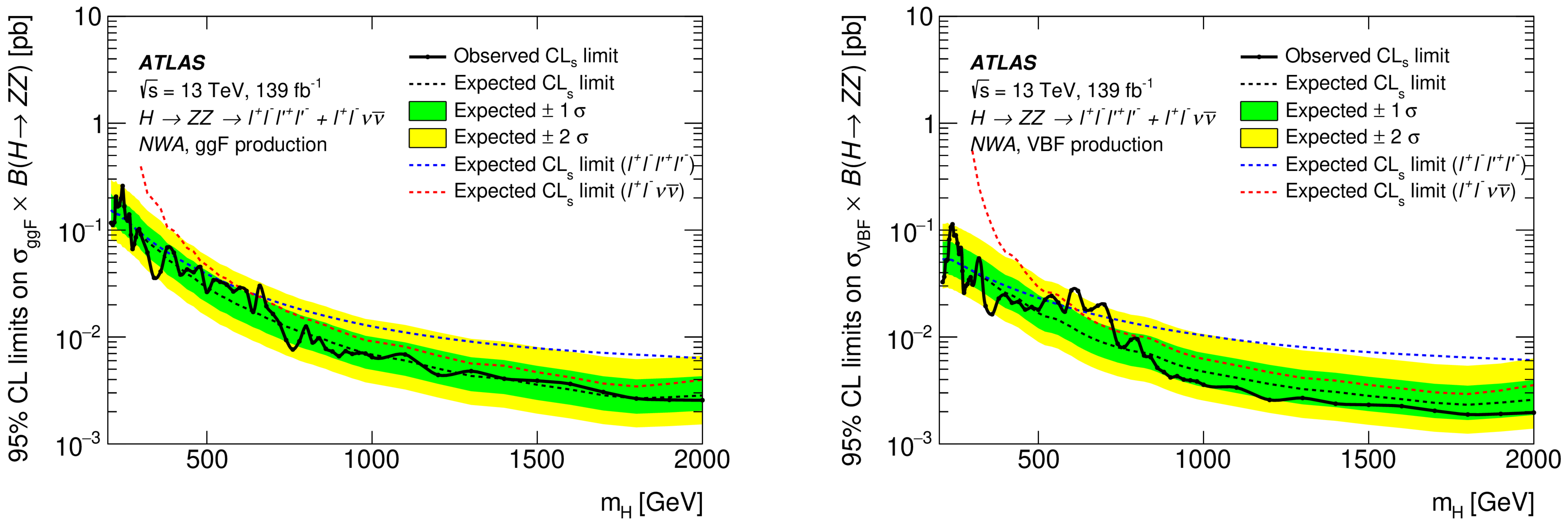
  - where $f_{ggF/VBF}$, f_B are the P.D.F.s of ggF/VBF signal and background follow modeling
  - $S_{ggF/VBF}$, B are the normalization for signal and background, and background normalization can either modeled by MC simulation or constrained by data:

$$S_{\mathrm{ggF(VBF)}} = \sigma_{\mathrm{ggF(VBF)}} \times B(S \to ZZ) \times A \times C \times \int \mathcal{L}$$

- To test the hypothesized value of σ, define the profile likelihood ratio: $\lambda(\sigma) = \dfrac{\mathcal{L}(\sigma, \hat{\hat{\boldsymbol{\theta}}})}{\mathcal{L}(\hat{\sigma}, \hat{\boldsymbol{\theta}})}$
- Define the test statistic and minimize t_σ: $t_\sigma = -2ln\lambda(\sigma)$

NWA upper limits: Cut-based

- Up to 20% worse than DNN-based analysis (for mass < 1500 GeV)
- 95% CLs upper limits are set in the asymptotic approximation



Two-Higgs-Doublets Model

- Through electroweak symmetry breaking, there are five physical Higgs bosons: two CP-even (h, H), one CP-odd (A), and two charged ones ($H^{\pm}$).
- $tan\beta$: the ratio of Higgs doublets' vacuum expectation values
- α: the two neutral CP-even Higgs bosons mixing angle
- Couplings of neural Higgs boson to vector bosons (W/Z):
  - The coupling of the lighter Higgs (h) equals to the SM coupling times $sin(\beta - \alpha)$
  - The coupling of the heavier Higgs(H) equals to the SM coupling times $cos(\alpha - \beta)$
  - The coupling of the pseudoscalar (A) to vector bosons is zero
- Couplings to fermions (different types of models):
  - Type-I : all quarks and leptons couple only to Φ_2
  - Type-II : down-type quarks and leptons couple to Φ_1, and up-type quarks couple to Φ_2
  - Type-III : leptons couple to Φ_1, while all quarks couple to Φ_2
  - Type-IIII: down-type quarks couple to Φ_1, while up-type quarks and leptons couple to Φ_2