Search for heavy ZZ resonances in the 4ℓ and $\ell\ell\nu\nu$ final states with the ATLAS detector

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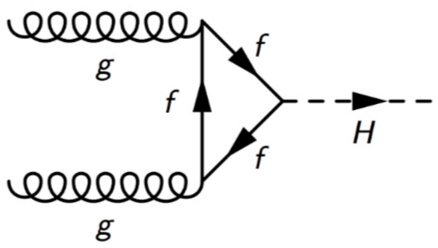
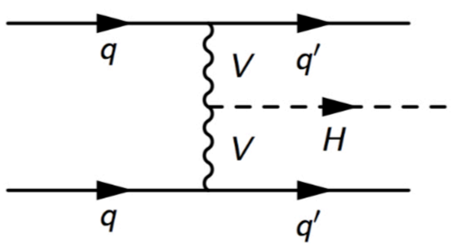
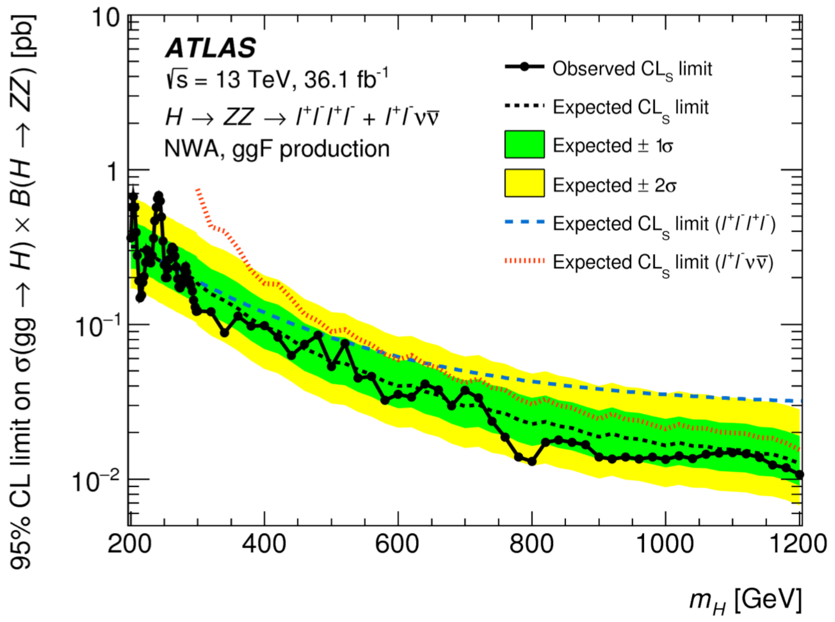
Aug. 1st, 2019

Introduction

- Benchmark models:
  - Scalars and bulk Randall-Sundrum Gravitons
- Search for heavy resonance with $X \rightarrow ZZ \rightarrow 4\ell$ / $\ell\ell\nu\nu$
  - 4ℓ: good mass resolution, high signal to background ratio
  - $\ell\ell\nu\nu$: larger branch ratio, dominates at high mass
  - Both ggF and VBF production
- 36.1 fb^{-1} data published: Eur. Phys. J. C 78 (2018) 293
- Full Run2 analysis:
  - Search for mass range from 200 – 2000 GeV





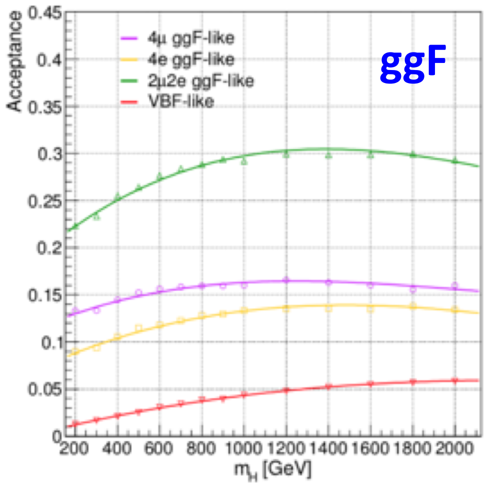


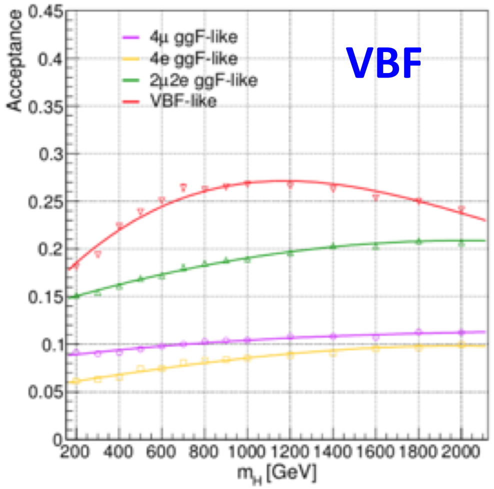
Analysis Overview

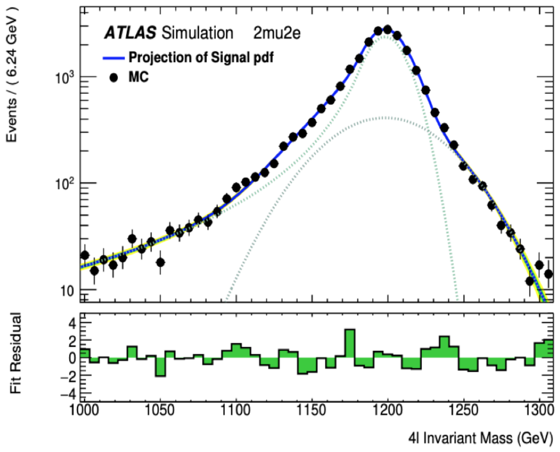
- The analysis is performed independently in $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ final states, then combine together.
- Working on full Run2 data (139 fb^{-1}): analysis is still blinded with major updates of:
  - For 4ℓ channel:
    - Optimization of VBF categorization
  - For $\ell\ell\nu\nu$ channel:
    - Bring in E_T^{miss}-significance
    - One-sideband method for $Z + jets$ estimation

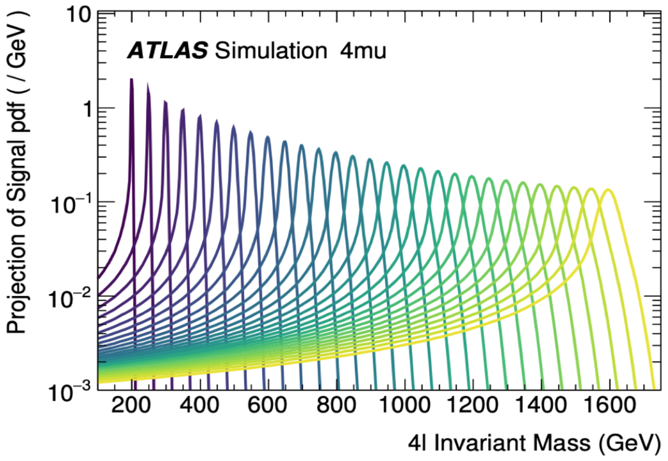
$H \rightarrow ZZ \rightarrow 4\ell$: Signal modeling

- Narrow Width Approximation
  - $\Gamma_H = 4.07$ MeV
  - Shape: sum of a Crystal Ball function and a Gaussian function
  - Fitting parameters and acceptance are interpolated between available mass points by polynomial functions
- Large Width Approximation
  - Γ_H = 1, 5, 10% of mS





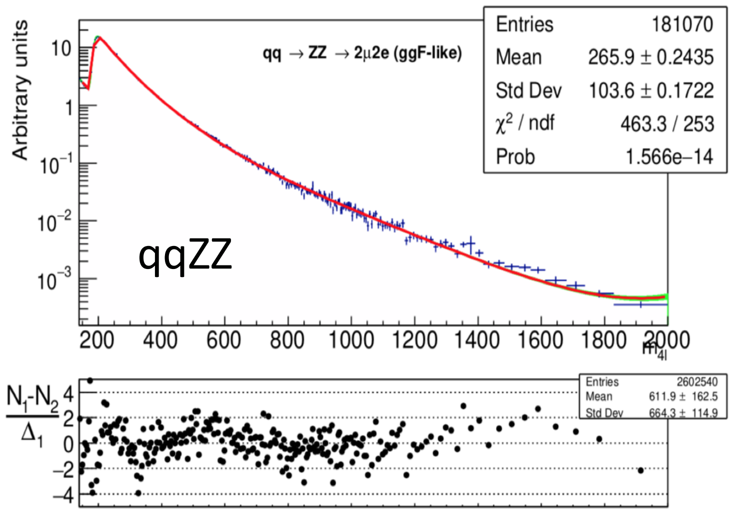




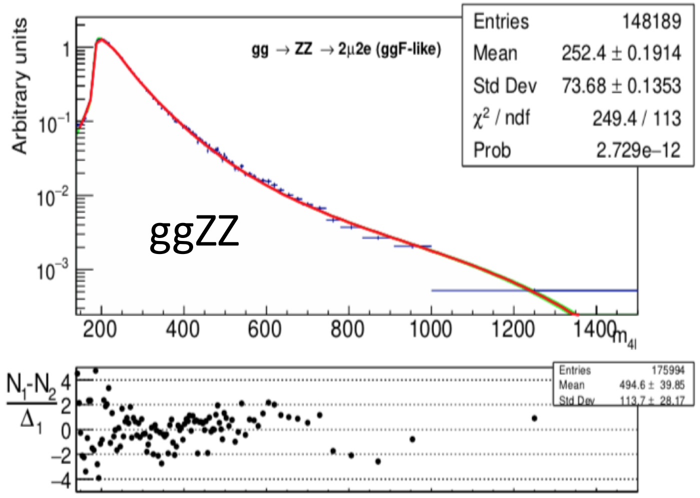
$H \to ZZ \to 4\ell$: Background

- ZZ continuum (~98%), $qq \to ZZ$ and $gg \to ZZ$
  - Shape is modeled with empirical function
  - The uncertainty of parameterization (green band) will be considered as NP
  - Fit the normalization from the data
- Reducible from data driven: $Z + jets, t\bar{t}$
- Others from MC: VVV, ttV

Signal region:
$50 < m_{12}(m_{34}) < 106(115)$ GeV
$200 < m_{4\ell} < 2000$ GeV



$2\mu 2e$



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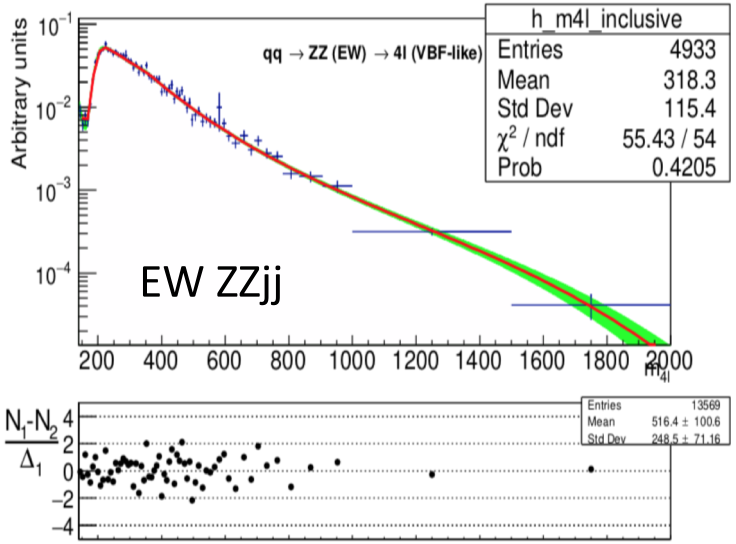
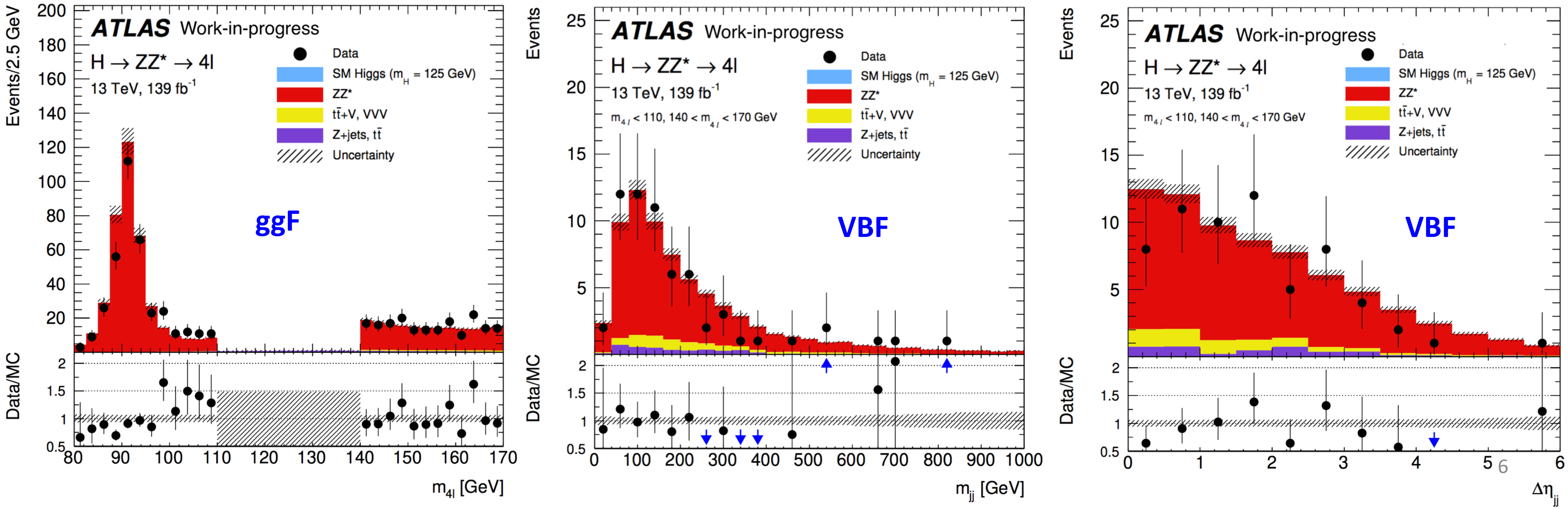


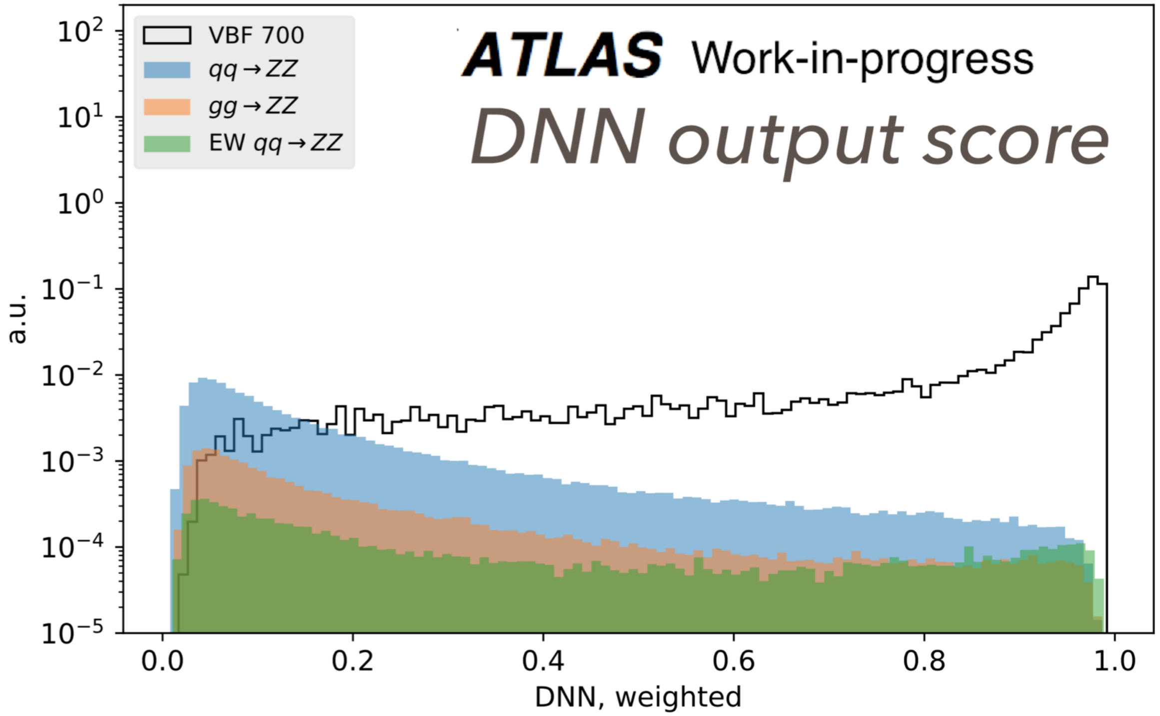
$H \to ZZ \to 4\ell$: Control region

- To check the modeling of the background in the control region:
  - m4l between [70GeV, 110GeV] and [140GeV, 200GeV]
  - Using full Run 2 datasets
- No clear shape mismodeling



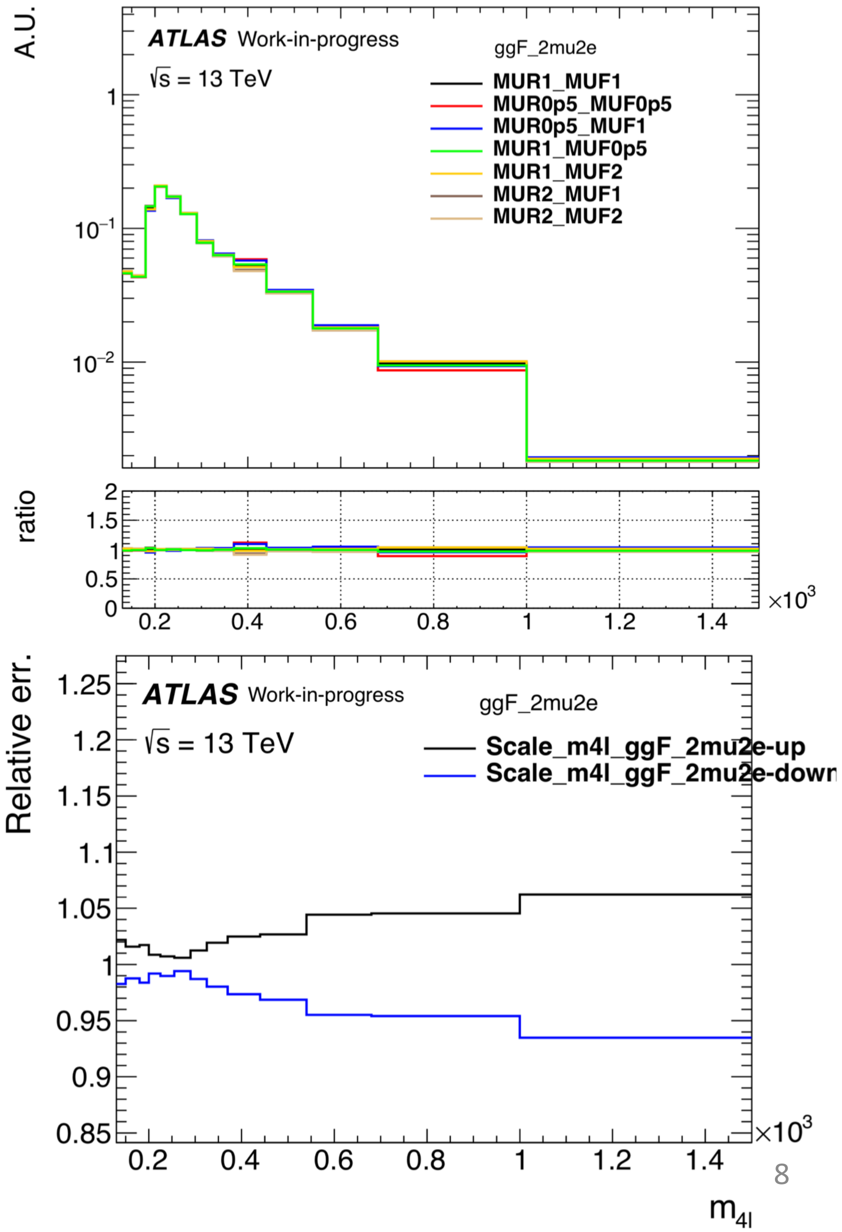
$H \to ZZ \to 4\ell$: VBF classifier for NWA

- Cut-based VBF categorization: $m_{jj} > 400$ GeV, $|\Delta\eta_{jj}| > 3.3$
  - Standard VBF cuts were also revised and found to be the most optimum in this round
- Re-optimization:
  - Deep neural network
  - Cross check with BDT
- Input variables include leptons and jets kinematics



$H \to ZZ \to 4\ell$: Systematics

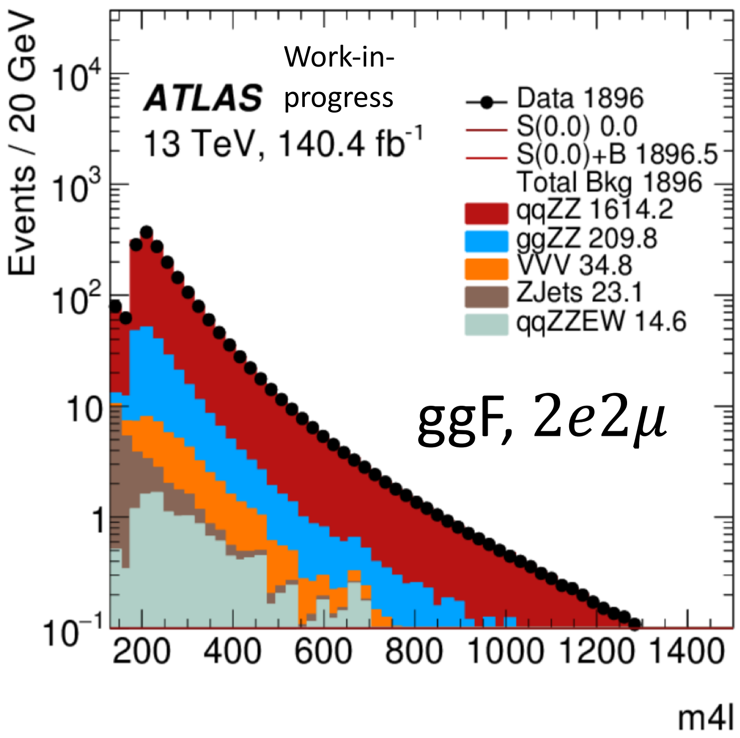
- Experimental uncertainties:
  - Minitrees ready with all CP systematics included
- Theoretical uncertainties:
  - $qqZZ, ggZZ$ background modeling:
    - Normalization taken from data
    - Shape systematics from MC by varying QCD scale/PDF/shower
    - Consider acceptance uncertainties for $qqZZ, ggZZ$
  - Signal acceptance uncertainties: QCD scale/PDF/shower
    - 2% for ggF signals, 10% for VBF signals

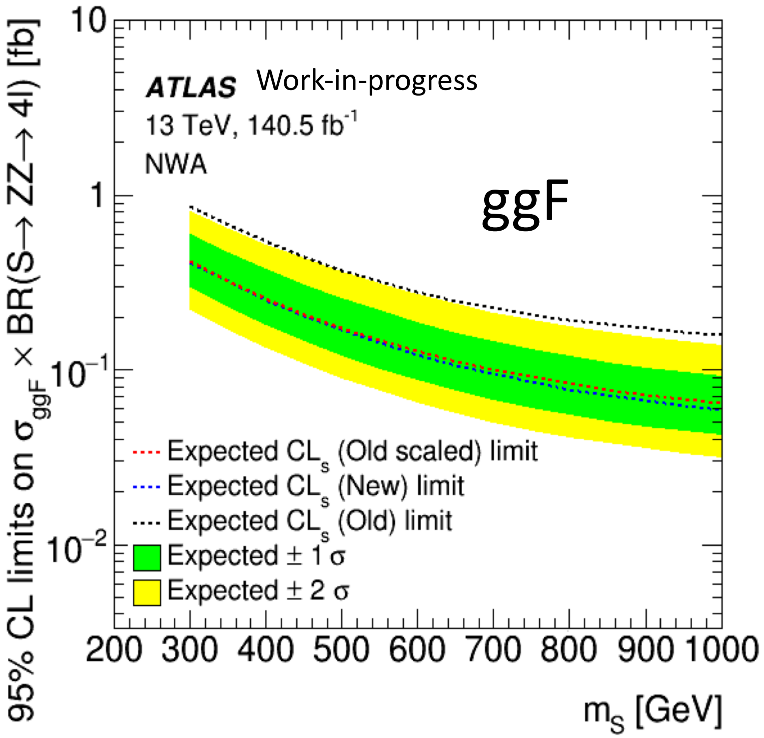


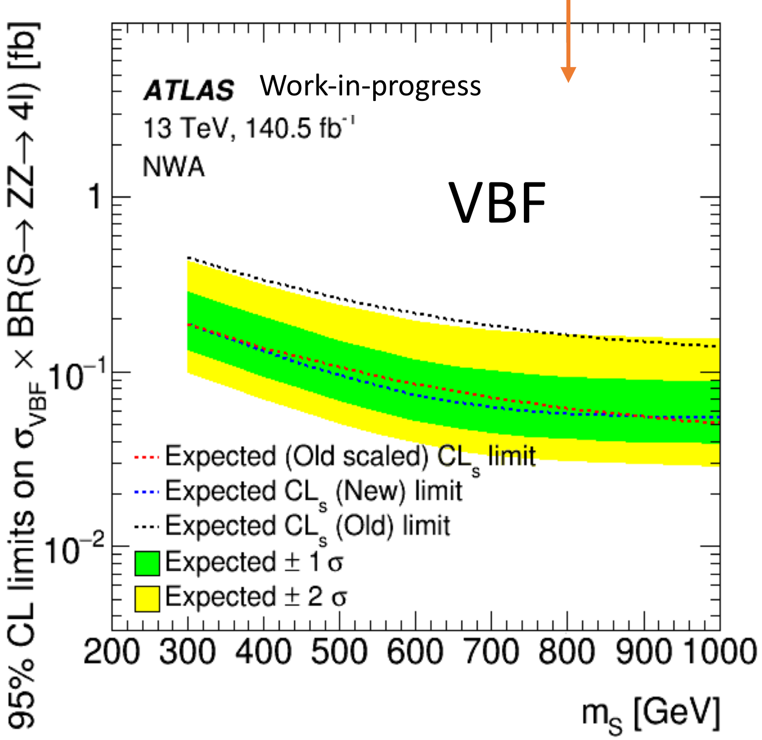
$H \to ZZ \to 4\ell$: Expected sensitivity

Old: 36.1 fb^{-1} results (mc15)
Old scaled: scaled to 140 fb^{-1}
New: 140 fb^{-1}, mc16

- Fit to $m_{4\ell}$ distribution
- Fit to 4 categories simultaneously: $ggF_{2e2\mu}, ggF_{4e}, ggF_{4\mu}, VBF_{inclusive}$





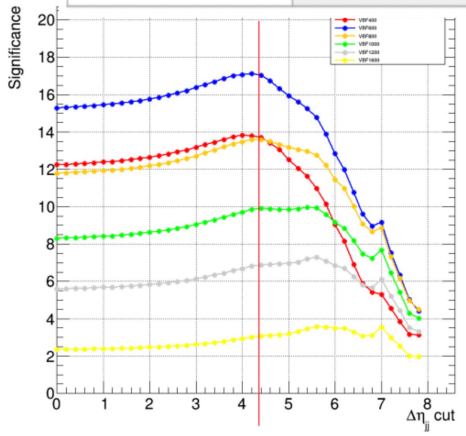


$H \to ZZ \to \ell\ell\nu\nu$: Cut optimization

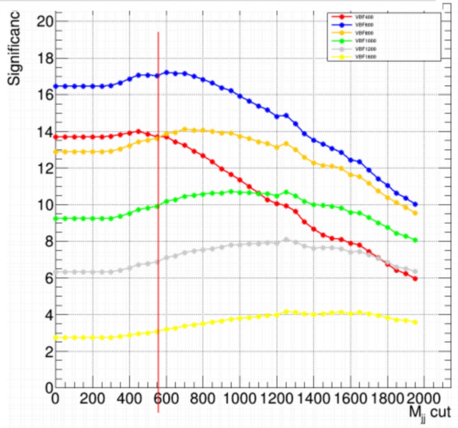
- Compared to last round, some optimizations have been made.
- E_T^{miss}-significance is new variable in this round and replace E_T^{miss}/HT.
- Optimization has been done with two variables: E_T^{miss}-significance and $\Delta\phi(Z, E_T^{miss})$
- Additionally, for VBF categorization:
  - Apply selections on additional two leading jets
  - m_{jj} and $|\Delta\eta_{jj}|$

MET sig > (value)	mH = 300 GeV	mH = 600 GeV	mH = 1000 GeV
11	606.14	42.07	13.87
10	580.1	42.15	13.85
9	593.23	42.28	13.84
8	594.01	42.47	13.84
7	636.92	42.66	13.8

dPhi > (value)	mH = 300 GeV	mH = 600 GeV	mH = 1000 GeV
2.5	542.57	40.94	13.57
2.7	606.14	42.07	13.87



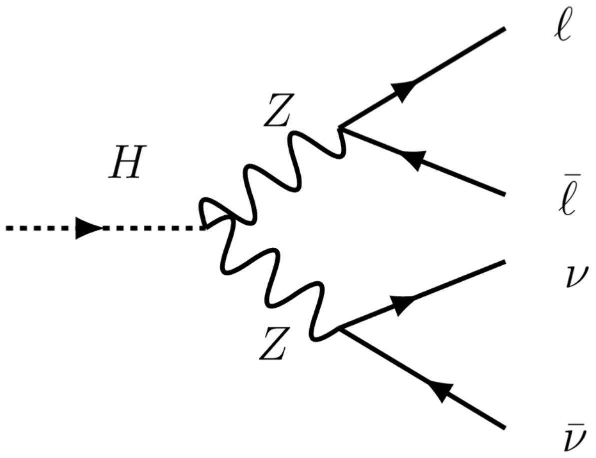
Fix Mjj > 550



Fix Detajj > 4.4

Using overall significance $Z = \sqrt{2\left((S+B)\log\left(1+\frac{S}{B}\right) - S\right)}$

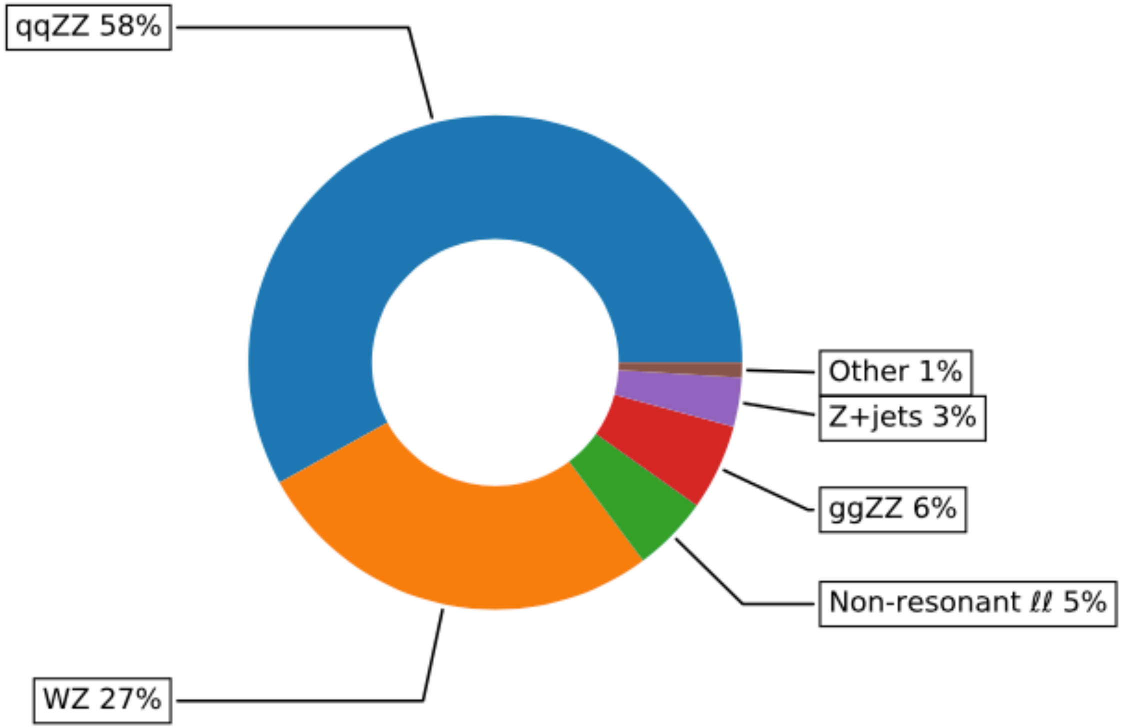
$H \to ZZ \to \ell\ell\nu\nu$: Backgrounds



- 2 same flavor opposite sign leptons
- $76 < m_{\ell\ell} < 106$ GeV
- $\Delta R_{\ell\ell} < 1.8$

- E_T^{miss}-significance > 10.0
- $E_T^{miss} > 120$ GeV

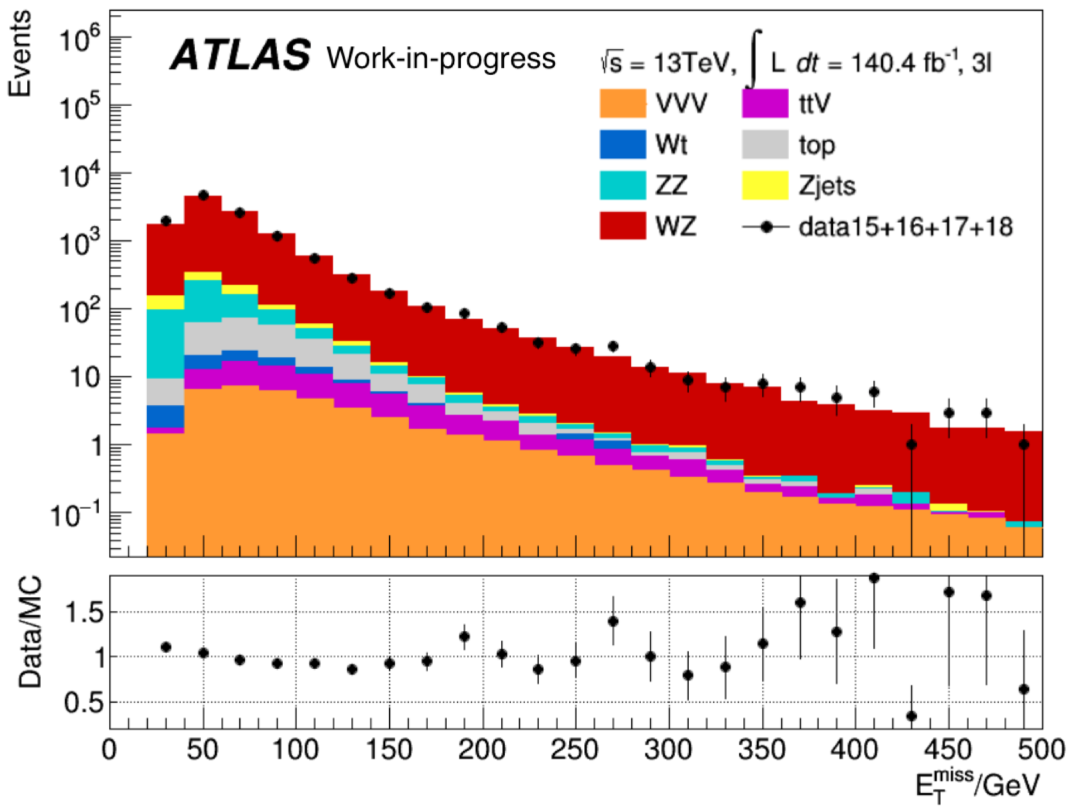
- $\Delta\phi(jet_{p_T>100\ GeV}, E_T^{miss}) > 0.4$
- $\Delta\phi(Z, E_T^{miss}) > 2.5$
- No B-jets



$H \to ZZ \to \ell\ell\nu\nu$: 3ℓCR

- One $ee/\mu\mu$ pair + one additional lepton
- Veto any other lepton
- $|m_{\ell\ell} - m_Z| < 15$ GeV
- $m_T^W > 60$ GeV and E_T^{miss}-significance > 3 to suppress non-WZ processes
- Purity of WZ sample: $\sim 92\%$
- Use scale factor to constrain the normalization of WZ in signal region

$$SF = \frac{data \ - nonWZ}{WZ}$$



$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$: $e\mu$CR

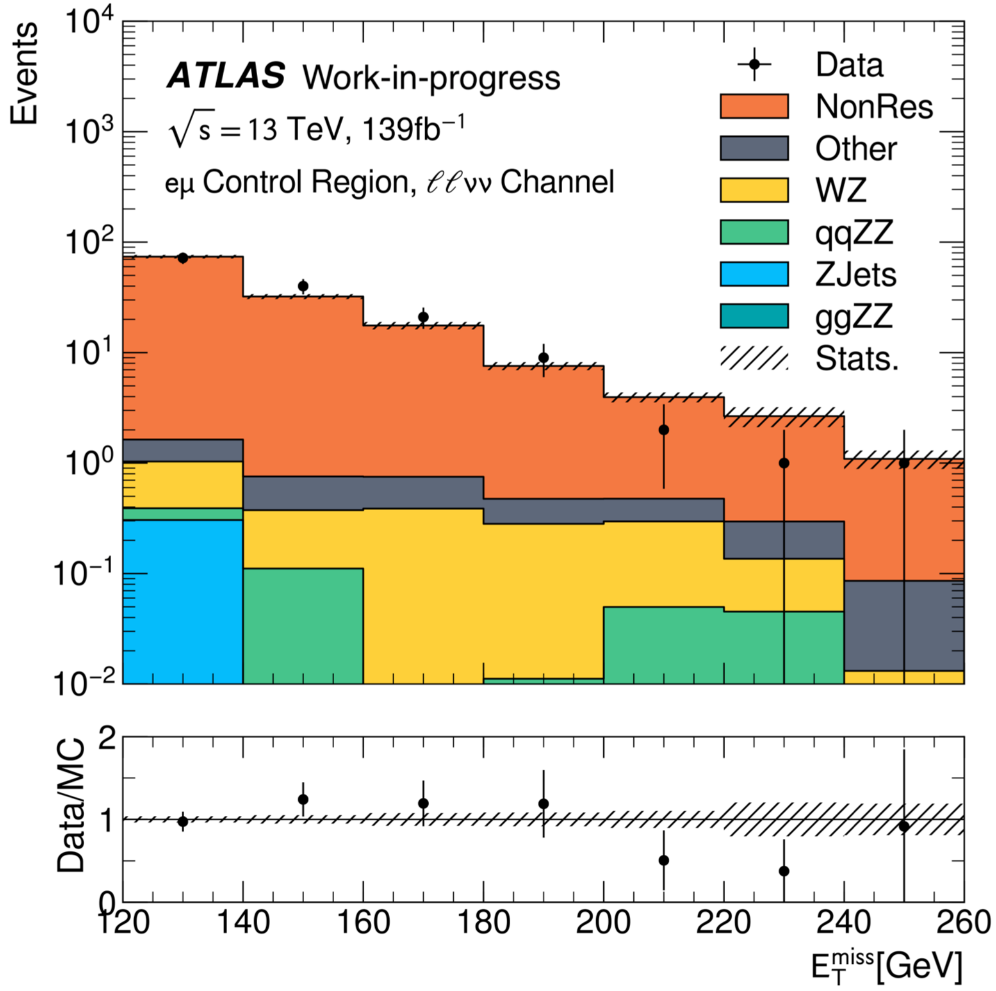
- Non-resonant $\ell\ell$ backgrounds: $t\bar{t}, WW, Wt, Z \rightarrow \tau\tau$
- ϵ-factor represents the reconstruction efficiency difference between electrons and muons:

$$\epsilon = \sqrt{\frac{N_{ee}}{N_{\mu\mu}}}$$

- Apply ϵ-factor on $e\mu$ Data events:

$$N_{SRee}^{estimation} = \frac{1}{2} \times \epsilon \times N_{e\mu}^{data,sub}$$

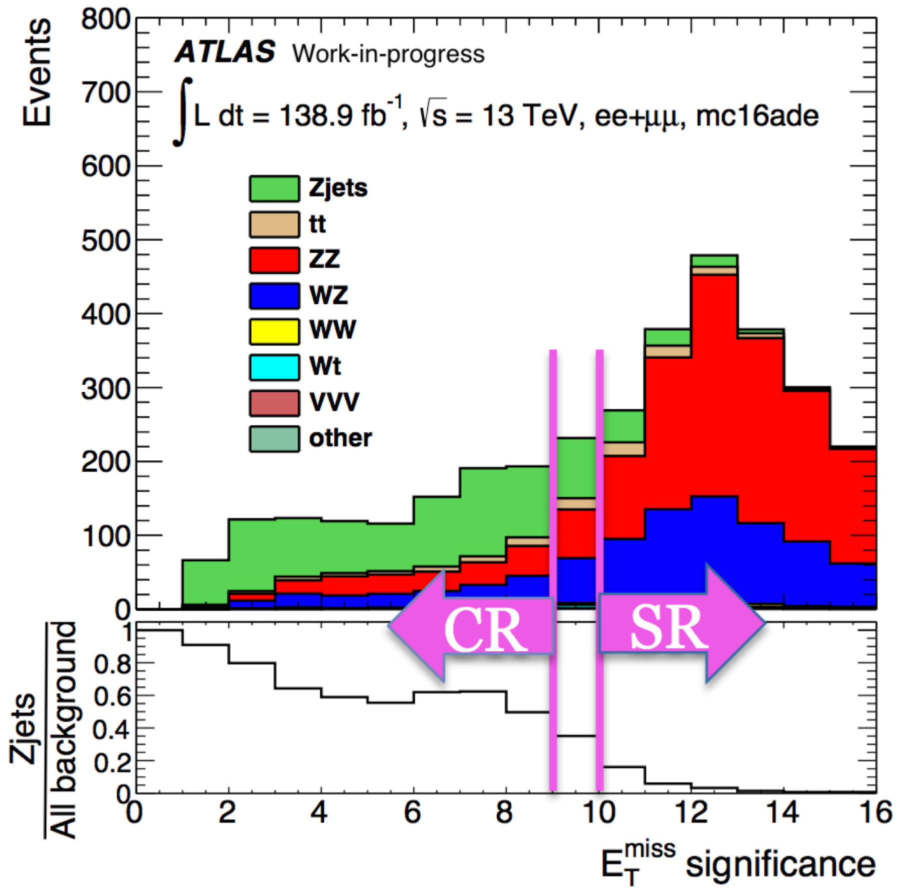
$$N_{SR\mu\mu}^{estimation} = \frac{1}{2} \times \frac{1}{\epsilon} \times N_{e\mu}^{data,sub}$$



$H \to ZZ \to \ell\ell\nu\nu$: $Z + jets$

- 1D sideband method for $Z \to ee, Z \to \mu\mu$ backgrounds
- Control region: E_T^{miss}-significance < 9
- Control region purity: 79%
- Extrapolate to the signal region:

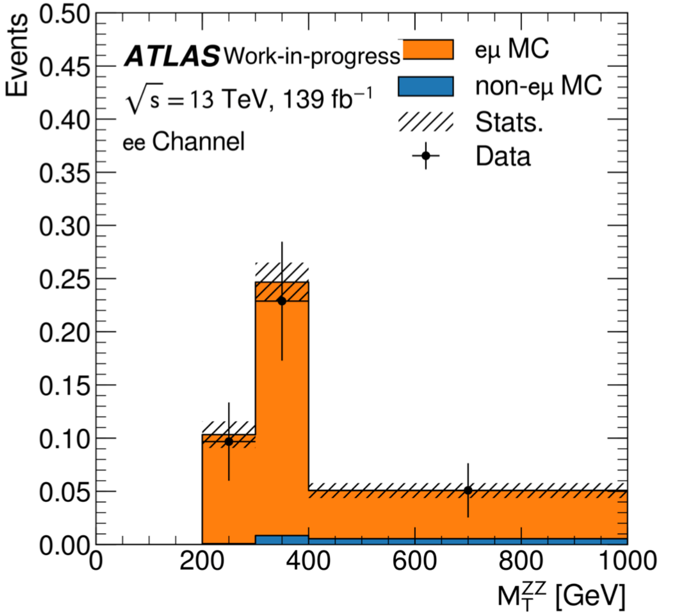
$$N_{SR}^{estimation} = N_{CR}^{data,sub} \times \frac{N_{SR}^{MC}}{N_{CR}^{MC}}$$

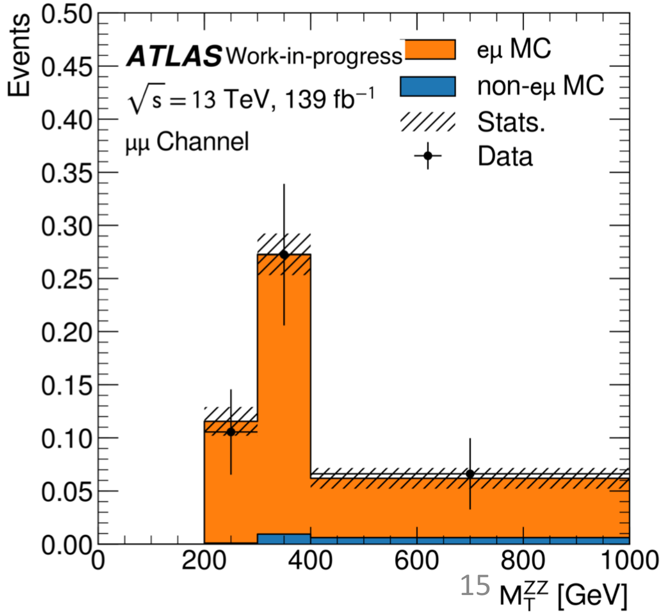


$H \to ZZ \to \ell\ell\nu\nu$: VBF backgrounds

- WZ
  - Based on the inclusive 3ℓCR, require additional two jets
  - Purity $\sim 90\%$, apply scale factor = 0.84 on the signal region contribution
- Non-resonant $\ell\ell$
  - Require additional two jets, propagate into the VBF signal region:

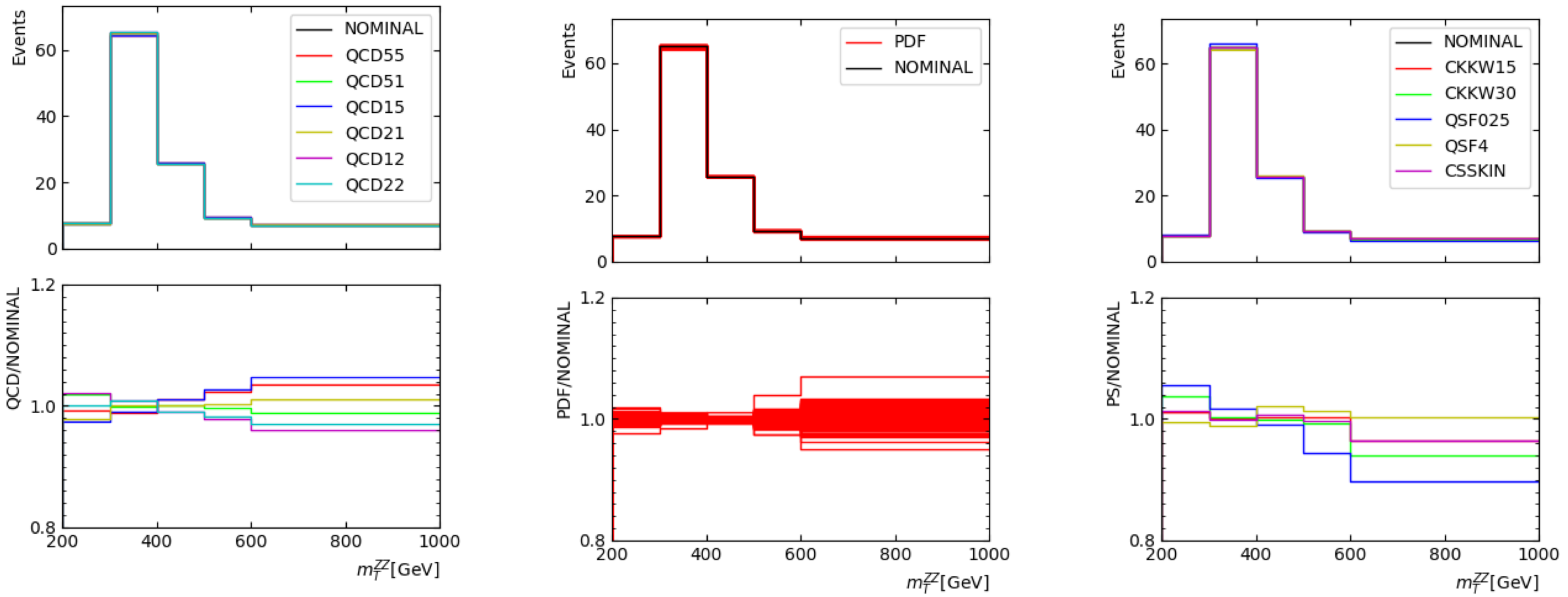
$$DataDriven(n_j \geq 2) \times \frac{MC(n_j \geq 2; m_{jj} > 550; \Delta\eta_{jj} > 4.4)}{MC(n_j \geq 2)}$$





$H \to ZZ \to \ell\ell\nu\nu$: Systematics

- (ongoing) Experimental uncertainties
- Theoretical uncertainties:
  - $qqZZ, ggZZ$ background modeling:
    - Same as 4l: normalization taken from data
    - Shape systematics from MC and acceptance difference between $qqZZ$ and $ggZZ$

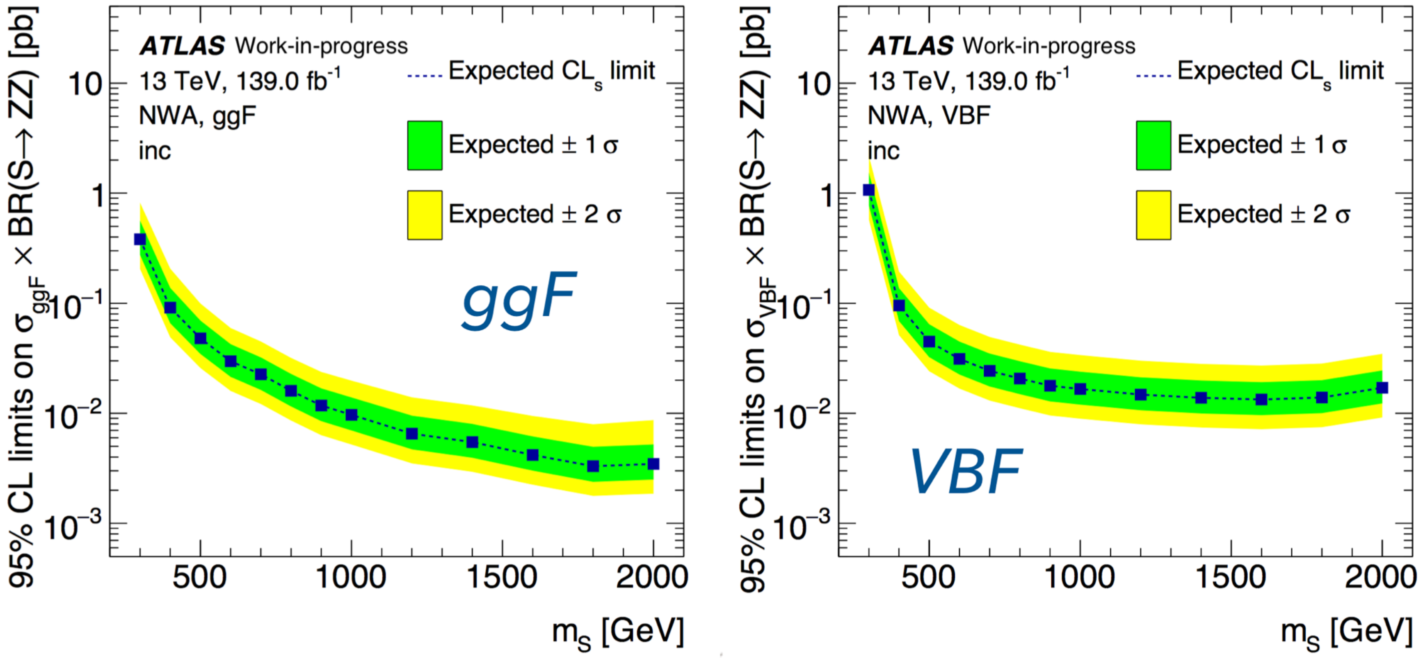


$H \to ZZ \to \ell\ell\nu\nu$: Expected sensitivity

- Discriminant for the limit setting: m_T

$$m_T^2 = \left[\sqrt{m_Z^2 + \left|\vec{p}_T^{\,\ell\ell}\right|^2} + \sqrt{m_Z^2 + \left|\vec{p}_T^{\,miss}\right|^2}\right]^2 - \left[\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,miss}\right]^2$$

- Fit to 4 categories simultaneously: $ggF_{ee}, ggF_{\mu\mu}, VBF_{ee}, VBF_{\mu\mu}$
- NWA model
- Statistic uncertainty only



Summary and outlook

- The overall status of high mass heavy resonance search in ZZ decay is presented.
- The analysis is in good shape now.
- Ongoing:
  - To finalize the systematic studies for both channels.
  - Combination of two channels for further results.

backup

$$f^{ggZZ,qqZZ,qqZZEW}(m_{4\ell}) = (f_1(m_{4\ell})+f_2(m_{4\ell}))\times H(m_0-m_{4\ell})\times C_0+f_3^{ggZZ,qqZZ,qqZZEW}(m_{4\ell})\times H(m_{4\ell}-m_0),$$

where:

$$f_1(m_{4\ell}) = \exp(a_1 + a_2 \cdot m_{4\ell} + a_3 \cdot m_{4\ell}^2),$$

$$f_2(m_{4\ell}) = \left\{\frac{1}{2} + \frac{1}{2}\,\mathrm{erf}\left(\frac{m_{4\ell} - b_1}{b_2}\right)\right\} \times \frac{1}{1 + \exp\left(\frac{m_{4\ell}-b_1}{b_3}\right)},$$

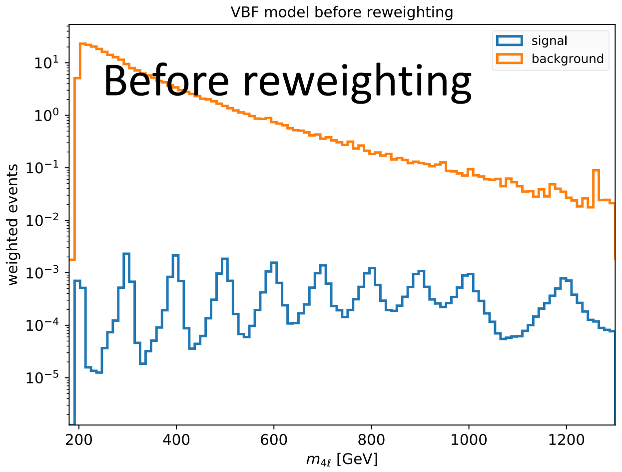
$$f_3^{qqZZEW}(m_{4\ell}) = \exp\left(c_1 + c_2 \cdot m_{4\ell} + c_3 \cdot m_{4\ell}^2 + c_4 \cdot m_{4\ell}^{2.7}\right),$$

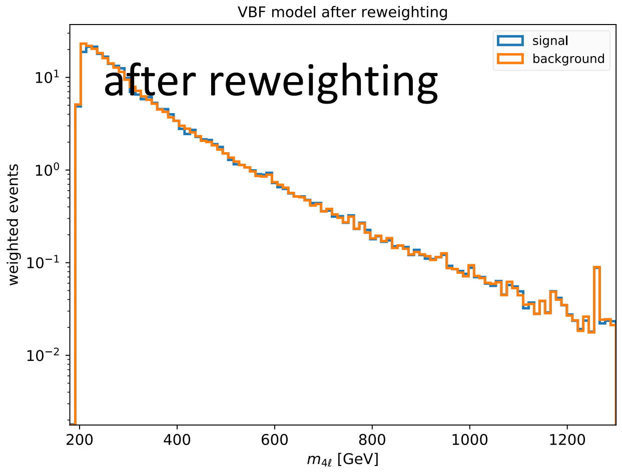
$$f_3^{qqZZ,ggZZ}(m_{4\ell}) = \exp\left(c_1 + c_2 \cdot m_{4\ell} + c_3 \cdot m_{4\ell}^2 + c_4 \cdot m_{4\ell}^3 + c_5 \cdot m_{4\ell}^4 + c_6 \cdot m_{4\ell}^5\right),$$

$$C_0 = \frac{f_3(m_0)}{f_1(m_0) + f_2(m_0)}.$$

$H \to ZZ \to 4\ell$: DNN

- Background events use MC weights that normalize to the same luminosity
- Re-weight signal samples to perfectly match falling background spectrum in training
- Significance and expected limit scan for several DNN cut, and >0.6 was chosen to be the best one





	mH = 300GeV		mH = 700GeV		mH = 1400GeV	
	XS_ggF	XS_VBF	XS_ggF	XS_VBF	XS_ggF	XS_VBF
Cut-based	0.5159	0.2088	0.09836	0.06842	0.03856	0.03453
DNN>0.6	0.4990	0.1669	0.09643	0.06021	0.03838	0.03295
Diff (%)	3.3%	20.1%	2.0%	12.0%	0.5%	4.6%