VBF $H \rightarrow WW$ in ATLAS

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Outline

Introduction

Theory, VBF signature

Selection and background estimation

Results

Statistical treatment, $p_0$ significance, best fit signal strength
Physics context

- Second largest Higgs production mode at the LHC
- VBF production in the WW decay is particularly interesting because it is a good probe of WWH coupling
- Deviation from SM rate could be window to extended Higgs sector
- While errors are large, VBF Higgs production is statistically consistent with the SM rate
  - $H \to \gamma\gamma$  $\mu_{VBF} = 1.9^{+0.8}_{-0.5}$
  - $H \to ZZ^* \to 4l$  $\mu_{VBF} = 1.2^{+1.5}_{-0.9}$

\[
\mu = \frac{\text{observed } \sigma \cdot BR}{\text{expected } \sigma \cdot BR}
\]

at $m_H = 125$ GeV:

- $\sigma = 19.3$ pb
- $\sigma = 1.58$ pb

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VBF H → WW → ℓνℓν signature

- Two light-flavor jets with large rapidity gap
- Because there is no color flow between jets, little QCD activity in the central region
- Charged leptons are close in Φ due to spin 0 nature of Higgs and V-A nature of the weak force
Event display

Longitudinal view

Transverse view

\[
\begin{align*}
M_{jj} &= 1.5 \text{ TeV} \\
\Delta Y_{jj} &= 6.6 \\
m_{ll} &= 21 \text{ GeV} \\
m_T &= 95 \text{ GeV}
\end{align*}
\]
Event selection: VBF cuts

- Background is dominated by top after $N_{\text{jets}} > 1$
- Top suppressed with cuts that isolate VBF
  - $N_{\text{btag}} = 0$
  - $\Delta Y_{jj} > 2.8$ and $M_{jj} > 500$ GeV (highly correlated)
- Veto events with jet ($p_T > 20$ GeV) that falls in central rapidity region defined by tag jets
- Require leptons to be in the central region

![Graph showing event distribution after various selections](image-url)

**After pre-selection (MET)**

- $N_{\text{jets}} > 1$
- $M_{jj} > 500$ GeV

![Graph showing event distribution after b-jet veto and $p_{T\text{tot}}$](image-url)

**After $\Delta Y_{jj}$ cut**

- $\Delta Y_{jj} > 2.8$
Event selection: $WW \rightarrow \ell\nu\ell\nu$ cuts

- After VBF cuts, background dominated by top, $Z$/DY ($\tau\tau$), and $WW$
- Isolate the $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ topology
  - $M_{ll} < 60$ GeV (looser than other jet bins)
  - $\Delta \Phi_{ll} < 1.8$

Top estimate

- Use top rich control region to estimate top contribution in signal region
  - Instead of vetoing on btagged jets, require exactly one
  - Apply VBF cuts: DY_{jj}, M_{jj}, no central jets, leptons in central region
  - Calculate normalization factor and extrapolate to signal region

\[
\text{Top NF} = \frac{N_{data} - N_{MC}^{non-top}}{N_{MC}^{top}} \quad \text{extrapolate to signal region}
\]

\[
N_{est}^{top} = \text{Top NF} \times N_{MC}^{top}
\]

- Top NF = 0.59 ± 0.07 (stat) ± 0.09 (sys)
- Systematic on extrapolation from control to signal region is 15%

compare \(\alpha = \frac{N_{SR}^{top}}{N_{CR}^{top}}\) between MC@NLO and Alpgen
WW+2j estimate

- WW + 2j production is a large background to VBF (30% for eμ/μe, 8% for ee/μμ)
- Currently estimated with POWHEG+Pythia6 for QCD and Sherpa for EW
- Theory uncertainties on WW +2j are large

<table>
<thead>
<tr>
<th></th>
<th>QCD</th>
<th>EW</th>
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<tbody>
<tr>
<td>QCD scale</td>
<td>47%</td>
<td>-</td>
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<tr>
<td>PDF</td>
<td>4%</td>
<td>3%</td>
</tr>
<tr>
<td>EW Modelling</td>
<td>-</td>
<td>11%</td>
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**Work in progress:** Replace large theory systematic with statistical uncertainty from control region normalization factor

- **WW CR:** same as SR, but invert \( M_{ll} \) (\( M_{ll} > 60 \)) and no \( D\Phi_{ll} \) cut

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[SHERPA vs. MADGRAPH](#)

-mc@nlo \( \mu_r \) and \( \mu_f \) variation

- CT10 vs. MSTW2008

-SHERPA vs. MADGRAPH

**In WW control region**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Count</th>
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<tr>
<td>QCD WW</td>
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<tr>
<td>EW WW</td>
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<tr>
<td>Non WW</td>
<td>27</td>
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40% stat. uncert

## Signal region event yield summary

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<tr>
<th></th>
<th>$\mu/\mu$</th>
<th>$e/e$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>8 TeV only</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VBF Higgs</td>
<td>5.1 ± 0.1</td>
<td>3.7 ± 0.1</td>
</tr>
<tr>
<td>ggF Higgs</td>
<td>1.3 ± 0.1</td>
<td>0.7 ± 0.1</td>
</tr>
<tr>
<td>WW</td>
<td>4.1 ± 0.4</td>
<td>4.4 ± 1.1</td>
</tr>
<tr>
<td>ttbar 1-top</td>
<td>4.4 ± 0.8</td>
<td>4.0 ± 0.6</td>
</tr>
<tr>
<td>Z/γ*</td>
<td>1.9 ± 0.5</td>
<td>25.0 ± 2.0</td>
</tr>
<tr>
<td>W+jets</td>
<td>0.6 ± 0.3</td>
<td>0.1 ± 0.2</td>
</tr>
<tr>
<td><strong>Total non-VBF</strong></td>
<td>12.3 ± 1.0</td>
<td>34.2 ± 2.4</td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>23</td>
<td>42</td>
</tr>
</tbody>
</table>

- Sensitivity is significantly higher in $\mu/\mu$
- Clear excess in both channels
- Large contamination from DY with these MET cuts

\[ m_{T}^{2} = \left( \sqrt{m_{ll}^{2} + p_{Tll}^{2}} + E_{T}^{miss} \right)^{2} - \left( p_{Tll} + E_{T}^{miss} \right)^{2} \]
Statistical treatment

- Profile likelihood test statistic is used for statistical computations
- The top normalization is floating in the fit and is same for $e\mu/\mu e$ and $ee/\mu\mu$
- The $m_T$ distribution is used for fitting with bin boundaries of (30,50,120)
- Gluon fusion $H\to WW$ is considered a background with a floating normalization
- Object and theory systematics are profiled in the fit

**Dominant systematics for VBF [%]**

<table>
<thead>
<tr>
<th>Source</th>
<th>Background</th>
<th>Signal</th>
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<td>Theoretical uncertainties</td>
<td>$N_{jet} \geq 2$</td>
<td>$N_{jet} \geq 2$</td>
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<td>QCD scale for ggF signal for $N_{jet} \geq 0$</td>
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<td>-</td>
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<tr>
<td>QCD scale for ggF signal for $N_{jet} \geq 1$</td>
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<td>-</td>
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<tr>
<td>QCD scale for ggF signal for $N_{jet} \geq 2$</td>
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<td>4</td>
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<tr>
<td>QCD scale for ggF signal for $N_{jet} \geq 3$</td>
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<tr>
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<tr>
<td>$H \to WW$ branching ratio</td>
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<td>4</td>
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<tr>
<td>QCD scale (acceptance)</td>
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<tr>
<td>WW normalisation</td>
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<table>
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<td>Jet energy scale and resolution</td>
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<td>6</td>
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<td>$b$-tagging efficiency</td>
<td>2</td>
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<tr>
<td>$f_{\text{recoil}}$ efficiency</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>


- note: these numbers are averaged over all processes
At $m_H = 125$ GeV
- Observed best-fit signal strength: $1.66 \pm 0.67$ (stat) $\pm 0.28$ (sys)

Significance
- Expected: 1.6$\sigma$
- Observed: 2.5$\sigma$
Ongoing studies

- VBF $H \rightarrow WW \rightarrow l\nu l\nu$ lends itself to multivariate techniques because it is a busy final state with many correlated physics objects
- Boosted decision tree (BDT) based multivariate analysis
  - Sequence of binary cuts on a collection of discriminating variables
- Nine BDT inputs for VBF analysis:
  - $M_{jj}$, $\Delta Y_{jj}$, $p_{T\text{tot}}$, $M_{ll}$, $\Delta \Phi_{ll}$, outside lepton veto, $m_T$, sum of $M_{lj}$, $E_{T\text{miss}}$ centrality with respect to leptons
- Preliminary results without all systematics, sensitivity improvement of $\sim 30\%$

BDT schematic


BDT score in signal region

more background-like events

more VBF-like events

ATLAS work-in-progress
Conclusion

- VBF production in the H->WW channel is an important probe of the WWH coupling

- We have observed an excess of events with respect to the Standard Model background that is consistent with the Standard Model rate for VBF, corresponding to a signal strength of $1.66 \pm 0.67 \text{ (stat)} \pm 0.28 \text{ (sys)}$

- We are currently studying the possibility of using a multivariate approach in this channel with promising results
Acknowledgements

Thanks to my ATLAS colleagues in the H->WW group and VBF subgroup

References

BONUS MATERIAL
Missing transverse momentum distributions for events after pre-selection for (a) $E_{T,\text{rel}}^{\text{miss}}$ for $N_{\text{jet}} \leq 1$, (b) $p_{T,\text{rel}}^{\text{miss}}$ for $N_{\text{jet}} \leq 1$, and (c) $E_{T,\text{STVF}}^{\text{miss}}$ for $N_{\text{jet}} \geq 2$ modes. The plot in (b) is made after the requirement on $E_{T,\text{rel}}^{\text{miss}}$ and the one in (c) after the requirement on $E_{T}^{\text{miss}}$. The plot in (d) shows the $f_{\text{recoil}}$ distribution in $ee+\mu\mu$ events passing the $N_{\text{jet}} = 0$ selection after $m_{ll} < 50$ GeV for simulated DY, non-DY and signal processes. The shaded area (too small to be visible in these figures) represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources. The signal is overlaid as a red curve in (a) and (b); in (c), the ggF signal is stacked at the bottom while the VBF signal is overlaid as a thick black line. Selections are listed in Table 2. Details are given in Section 3.3.1.
Jet multiplicity for events in 8 TeV data. The plots are shown for the (a) eμ; +μe and (b) ee+μμ; channels after pre-selection and E_{T,rel}^{miss} > 25 GeV and > 45 GeV, respectively. The signal is too small to be seen. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.
Distribution of the transverse mass, $m_{T}$, for 8 TeV data. The plots are shown for the $e\mu;+\mu\mu;e$ (left) and $ee;+\mu\mu;\mu$ (right) channels in $N_{\text{jet}} = 0$ (top), $N_{\text{jet}} = 1$ (middle), and $N_{\text{jet}} \geq 2$ modes (bottom). The distributions are shown prior to splitting the samples into two $m_{ll}$ regions for the $e\mu;+\mu\mu;e$ channel in the $N_{\text{jet}} \geq 2$ and $= 1$ modes, as described in Table 2. The visible signal is stacked at the top of the background. For the $N_{\text{jet}} \geq 2$ mode, the signal is plotted separately for the ggF and VBF production processes. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.
Distributions of $m_T$ in (a) $N_{\text{jet}} = 1$ and (b) $N_{\text{jet}} \geq 2$ top background control regions. The distributions are normalised to the data. The right-most bin in (b) represents the overflow. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.
Background-subtracted $m_T$ distribution for $N_{\text{jet}} \leq 1$ in 7 and 8 TeV data. The signal is overlaid. The error bars represent the statistical uncertainties of the data and the subtracted background; it does not include the systematic uncertainties of the latter.

Results for (a) $p_0$ and (b) 95% CL upper limit using combined 7 TeV and 8 TeV data. The $p_0$ is the given probability for the background-only scenario as a function of $m_H$. The expected 95% CL upper limit is computed in the absence of a signal. The upper limit is on the cross section normalised to the SM cross section. For both figures, the smaller green bands represent ±1σ uncertainties on the expected values, and the larger yellow bands represent ±2σ uncertainties.
Signal strength parameter $\mu$ vs. $m_H$: (a) fitted $\mu$ value for the given $m_H$ and (b) two-dimensional likelihood contours of $-2\ln\lambda(\mu,m_H)$ in the best-fit signal strength.

VBF results for (a) $p_0$ and (b) 95% CL upper limit using 8 TeV data considering VBF as signal and ggF as part of the background. Details are given in the caption of Fig. 10.
VBF results for (a) $p_{t0}$ and (b) 95% CL upper limit using 8 TeV data considering VBF as signal and ggF as part of the background. Details are given in the caption of Fig. 10.

VBF signal strength parameter $\mu$. The observed (solid black line with shaded cyan band) and the expected result (solid red line with dashed band) are shown.
Likelihood contours for separate ggF and VBF signal strength parameters (a) and the likelihood curves for the ratio of the ggF/VBF strength parameters (b). hWW^{(*)} \rightarrow l\nu l\nu; analysis uses the combined 7 and 8 TeV data.

Likelihood contours for separate ggF and VBF signal strength parameters (a) and the likelihood curves for the ratio of the ggF/VBF strength parameters (b). hWW^{(*)} \rightarrow l\nu l\nu; analysis uses the combined 7 and 8 TeV data.
A candidate event for $H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu + 2$ jets produced via VBF, $qq \rightarrow Hqq$. The event variables are: $m_{jj} = 1.5$ TeV, $|\Delta y_{jj}| = 6.6$, $m_{ll} = 21$ GeV, and $m_{T} = 95$ GeV. For the figure on the left (starting from the top left going clockwise): $p_T$ of the electron is 51 GeV (thick green line), the muon is 15 GeV (orange line), the jet (right blue cone) is 68 GeV, the $E_T^{miss}$ (thin dotted red line on the left) is 33 GeV, and the jet (left cyan cone) is 42 GeV. A view transverse to the beam direction is given on the right; previous descriptions of various objects apply except for $E_T^{miss}$, which is represented as a thick dotted line.
Rapidity distributions of the leading and sub-leading tagging jets. The distribution is shown at the 2 jets requirement, the signal is magnified by a factor 2000 to show the peculiar forward distribution of jets from the VBF process. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.
The $|\Delta y_{jj}|$ and $m_{jj}$ distributions after the $p_{T}^{\text{tot}} < 45$ GeV cut. $p_{T}^{\text{tot}}$ is defined as the total transverse momentum of all leptons, jets and missing $E_T$ passing the selection. The $m_{jj}$ distribution is shown after the $|\Delta y_{jj}| > 2.8$ cut. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.

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The $|\Delta y_{jj}|$ and $m_{jj}$ distributions after the $p_T^{\text{tot}} < 45$ GeV cut. $p_T^{\text{tot}}$ is defined as the total transverse momentum of all leptons, jets and missing $E_T$ passing the selection. The $m_{jj}$ distribution is shown after the $|\Delta y_{jj}| > 2.8$ cut. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.
The $|\Delta \phi_{ll}|$, $m_T$ and $m_{ll}$ distributions after the $p_T^{\text{tot}} < 45$ GeV cut in the top CR, defined by the requirement of one and only one $b$ tagged jet. $p_T^{\text{tot}}$ is defined as the total transverse momentum of all leptons, jets and missing $E_T$ passing the selection. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.
The $|\Delta \phi_{ll}|$, $m_T$ and $m_{ll}$ distributions after the $p_T^{tot} < 45$ GeV cut in the top CR, defined by the requirement of one and only one b tagged jet. $p_T^{tot}$ is defined as the total transverse momentum of all leptons, jets and missing $E_T$ passing the selection. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.

The $m_{ll}$ and the $|\Delta \phi_{ll}|$ distributions after the outside lepton veto cut, accepting events with leptons between the two tagging jets. $|\Delta \phi_{ll}|$ is shown after the $m_{ll} < 60$ GeV cut. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.
The $m_{ll}$ and $|\Delta \phi_{ll}|$ distributions after the outside lepton veto cut, accepting events with leptons between the two tagging jets. $|\Delta \phi_{ll}|$ is shown after the $m_{ll} < 60$ GeV cut. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.

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The $m_{ll}$ and $|\Delta\phi_{ll}|$ distributions after the outside lepton veto cut, accepting events with leptons between the two tagging jets. $|\Delta\phi_{ll}|$ is shown after the $m_{ll} < 60$ GeV cut. The shaded area represents the uncertainty on the signal and background yields from statistical, experimental, and theoretical sources.
ATLAS Preliminary

$H \rightarrow WW^{(*)} \rightarrow ll\nu\nu$ VBF

$\sqrt{s} = 7$ TeV: $\int L dt = 4.6$ fb$^{-1}$

$\sqrt{s} = 8$ TeV: $\int L dt = 20.7$ fb$^{-1}$

- Obs.
- Exp.

$\pm 1 \sigma$
$\pm 2 \sigma$

95% CL limit on $\mu$. 

$m_H$ [GeV] 

120 130 140 150 160 170 180 190 200
Z/DY estimate

**eμ/μe channel**
- Z -> ττ is a non-negligible background in the signal region: 1.7 out of 9.7 background events
- Large MET tails in Z -> ττ -> eμ + neutrinos
- Z + jets is corrected in orthogonal Z rich region
  - ΔΦ|| < 1.8 in SR --> ΔΦ|| > 2.8 in Z control region
  \[
  \frac{N_{data} - N_{MC}^{non-DY}}{N_{MC}^{DY}} \sim 0.93 \pm 0.11 \text{(stat)}
  \]
- Additionally, VBF cut efficiencies are corrected in ee/μμ Z peak

**ee/μμ channel**
- With the MET > 45 GeV and MET_STVF > 35 GeV, DY remains a large contribution in signal region: 20.3 out of 26.6 background events
- MET mismodeling in DY is corrected with ABCD method:
  \[
  N_{data}^{A} = N_{data}^{C} \cdot f_{MC} \cdot \frac{N_{data}^{B}}{N_{data}^{D}}
  \]
- Assumes small correlation between MET and M||. Correlation captured by \( f_{MC} \), defined by
  \[
  N_{MC}^{A} = N_{MC}^{C} \cdot f_{MC} \cdot \frac{N_{MC}^{B}}{N_{MC}^{D}}
  \]
  \[f_{MC} = 1.03 \pm 0.10\]
  Correction factor: \( NF_{ABCD} = 0.81 \pm 0.06 \)
Top estimate

- Use top rich control region to estimate top contribution in signal region
- Top CR: instead of vetoing on btagged jets, require exactly 1

\[ \text{Top NF} = \frac{N_{\text{data}} - N_{\text{MC\,non-top}}}{N_{\text{MC\,top}}} \]

extrapolate to signal region

\[ N_{\text{est\,top}} = \text{Top NF} \times N_{\text{MC\,top}} \]

Top CR selection | Top NF
--- | ---
\( N_{\text{Jet}} \geq 2 \) | 1.02
\( N_{\text{BJet}} = 1 \) | 1.02
\( P_T^{\text{total}} < 45 \) | 1.02
\( |M_{\tau\tau} - M_Z| > 25 \) | 1.02
\( \Delta Y_{JJ} > 2.8 \) | 0.89
\( M_{JJ} > 500 \) | 0.71
No jets > 20 GeV in central region | 0.58
Leptons in central region | 0.58

mT distribution in top CR

mismodeling in MC@NLO in this corner of phase space

Systematic on extrapolation from CR to SR

compare \( \alpha = \frac{N_{\text{SR\,top}}}{N_{\text{CR\,top}}} \) between MC@NLO and Alpgen

Event selection summary

- Preselection: two oppositely charged leptons, leading lepton $> 25$ GeV, subleading $> 15$ GeV
- $\mu e/\mu e$: MET $> 20$ GeV
- $ee/\mu \mu$: cuts to suppress Drell Yan: $| M_{ll} - M_Z | > 15$, MET $> 45$, MET_{STVF} $> 35$

<table>
<thead>
<tr>
<th>$N_{Jet}$ $\geq 2$</th>
<th>VBF + VH</th>
<th>Bkg + ggF</th>
</tr>
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<tbody>
<tr>
<td>$N_{BJet} = 0$</td>
<td>43</td>
<td>48k</td>
</tr>
<tr>
<td>$P_T^{total} &lt; 45$</td>
<td>31</td>
<td>5.7k</td>
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<tr>
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<td>&gt; 25$</td>
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<td>$\Delta Y_{JJ} &gt; 2.8$</td>
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<td>$M_{JJ} &gt; 500$</td>
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1-to-1000

1-to-200

1-to-200

1-to-200

1-to-50

1-to-20

1-to-10

1-to-10

1-to-3

1-to-3

1-to-2

numbers from 21 fb$^{-1}$ $\mu e/\mu e$
Z/DY estimate

**eμ/μe channel**

- Z -> ττ is a non-negligible background in the signal region: 1.7 out of 9.7 background events
- Large MET tails in Z -> ττ -> eμ + neutrinos
- Use data to correct MET cut efficiency in Z rich region
  - $\Delta \Phi_{ll} < 1.8$ in SR $\rightarrow$ $\Delta \Phi_{ll} > 2.8$
  
  $$\frac{N_{data} - N_{non-DY}^{MC}}{N_{DY}^{MC}} \sim 0.93 \pm 0.11 \text{(stat)}$$

- Additionally, VBF cut efficiencies are corrected in ee/μμ Z peak

**ee/μμ channel**

- With the $E_{T}^{miss}$ cuts, DY remains a large contribution in signal region: 20.3 out of 26.6 background events
- Correct efficiency of MET cuts in the Z peak and extrapolate to low $M_{ll}$ region

  MET Correction factor: $0.81 \pm 0.06$

- VBF topological cuts efficiencies are corrected in low MET CR