Ratios of Higgs Cross Sections at 14 TeV and 8 TeV

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work with Iain Stewart, Frank Tackmann, and Saba Zuberi - 1307.1808

with many thanks to Frank Tackmann for providing runs for this talk
Demands for Precision QCD in Higgs Cross Sections

\[ H \rightarrow WW \rightarrow 2\ell + 2\nu \]

No mass peak in this channel

“\textit{The systematic uncertainties that have the largest impact on the sensitivity of the search are the theoretical uncertainties associated with the signal.}”

from ATLAS, 1206.0756
Demands for Precision QCD in Higgs Cross Sections

**Leading systematic uncertainties**

<table>
<thead>
<tr>
<th>Source (0-jet)</th>
<th>Signal (%)</th>
<th>Bkg. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive ggF signal ren./fact. scale</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>1-jet incl. ggF signal ren./fact. scale</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>PDF model (signal only)</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>QCD scale (acceptance)</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>W+jets fake factor</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>WW theoretical model</td>
<td>-</td>
<td>5</td>
</tr>
</tbody>
</table>

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<th>Source (1-jet)</th>
<th>Signal (%)</th>
<th>Bkg. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-jet incl. ggF signal ren./fact. scale</td>
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<td>-</td>
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<tr>
<td>2-jet incl. ggF signal ren./fact. scale</td>
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<td>-</td>
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<tr>
<td>b-tagging efficiency</td>
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<td>11</td>
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<tr>
<td>PDF model (signal only)</td>
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<tr>
<td>QCD scale (acceptance)</td>
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<tr>
<td>Jet energy scale and resolution</td>
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<tr>
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<td>-</td>
<td>5</td>
</tr>
<tr>
<td>WW theoretical model</td>
<td>-</td>
<td>3</td>
</tr>
</tbody>
</table>

**dominant contribution:**

- perturbative QCD scale uncertainties
  - \( \delta \sigma_{0\text{jet}} = 16.5\% \)
  - \( \delta \sigma_{1\text{jet}} = 30\% \)

“The systematic uncertainties that have the largest impact on the sensitivity of the search are the theoretical uncertainties associated with the signal.”

from ATLAS, 1206.0756
Overview of the H + 0-jet Calculation

Make a prediction for the resummed+matched (NNLL’ + NNLO) H + 0-jet cross section:

Use a factorization theorem for the cross section:

- Global/local veto bootstrap in each function
- New calculations in SCET

Focus on uncertainty estimates on the result:

- Makes the prediction robust
- Many scales, sources of uncertainty

Jet algorithm clustering effects are theoretically interesting, phenomenologically important
H + 0-jet Cross Section

\[ \sigma(p_T^{\text{cut}}) \sim H_{gg}(\mu) \left[ B_a(p_T^{\text{cut}}, \mu, \nu) \times B_b(p_T^{\text{cut}}, \mu, \nu) \times S(p_T^{\text{cut}}, \mu, \nu) \right] + \sigma_{ns}(\mu) \]

- Logarithms known to NNLO through RGE
  - Finite log(R) dependence calculated by us (finite means \( p_T^{\text{cut}} \) independent)
  - Remaining finite terms fit via MCFM

- Fit to NNLO from MCFM
  - Fit for several R values for the MSTW PDFs
  - Would like to vary \( m_H \), PDFs

- Virtuals known to NNLO can add \( m_b \), EW corrections (sum largely cancels)

- Fully calculated to NNLO (allows for precision predictions for \( E_T \))
H + 0-jet Results

0-jet cross section resummed convergence

rates with uncertainties:

R = 0.4:

\[ p_{T}^{\text{cut}} = 25 \text{ GeV} : \sigma_0 = 12.67 \pm 1.22(9.6\%) \]
\[ p_{T}^{\text{cut}} = 30 \text{ GeV} : \sigma_0 = 14.09 \pm 0.96(6.8\%) \]

R = 0.5:

\[ p_{T}^{\text{cut}} = 25 \text{ GeV} : \sigma_0 = 12.40 \pm 1.12(9.0\%) \]
\[ p_{T}^{\text{cut}} = 30 \text{ GeV} : \sigma_0 = 13.85 \pm 0.87(6.3\%) \]

compare to 17%! 
H + 0-jet Results

0-jet cross section
resummed convergence

0-jet cross section
compared to fixed order

cross sections

uncertainties

FIG. 7: The 0-jet cross section for
"0" u c
T 0
Of Ref. [9] which seems reasonable given the above

It is interesting to compare our results and uncertain-

ties between the di
and finally we use a factorization based approach to un-

Comparison is the inclusion of the

because

adding

and the uncertainties follow a pattern similar to the case

same direction, decreasing the uncertainty relative to the

improves the convergence of our results and decreases our

comparison is the inclusion of the

resummation (see Ta-

resummation were turned o

only,

...
Inclusive 1-jet Cross Section, 0-jet Efficiency

resummed convergence

Inclusive 1-jet Cross Section, 0-jet Efficiency

resummed vs. fixed order

inclusive 1-jet cross section

0-jet efficiency
Recent Work on $(p_T)$ Jet Vetoes

H + 0 jets
- Banfi, Monni, Salam, Zanderighi - 1203.5773, 1206.4996, 1308.4634 (also Z + 0 jets)
- Becher, Neubert, Rothen - 1205.3806, 1307.0025
- Stewart, Tackmann, Walsh, Zuberi - 1206.4312, 1307.1808

H + 1 jet
- Liu, Petriello - 1210.1906, 1303.4405
- Liu, Petriello, Tackmann, Walsh (H + 0/1-jet combination) - ongoing

H + 2 jets
- Gangal, Tackmann (fixed order uncertainties) - 1302.5437

VH + 0 jets
- Li, Li, Shao - 1309.5015

clustering effects
- Alioli, Walsh - ongoing
Jet Veto Thresholds

$$H \rightarrow WW \rightarrow 2\ell + 2\nu$$

thresholds governed by two considerations:

- poorly measured jets at low $p_T$
- $p_T$ cut < poor background discrimination

**Figure 1:** Multiplicity of jets within the acceptance description. The hashed area indicates the region of interest, while the darker outer bands show the total uncertainty from the data. The plots show the distribution of jets for different lepton flavours and the expected signal for a SM Higgs boson. The $\ell\ell$ invariant mass, for events satisfying the pre-selection criteria, is shown for the different lepton channels. This improves the rejection of the Drell-Yan background.

**Figure 2:** The 0-jet cross section for $gg \rightarrow H$ (8 TeV) at NNLL+NNLO results presented earlier, compared to the NNLL prediction of Ref. [9] which seems reasonable given the above comparison is the inclusion of the $t\bar{t}$ background source. Only the small background contribution from diboson processes other than $WW$ and $ZZ$ is shown. The top quark and heavy flavour decays in jets are fully estimated.

The impact parameter significance and secondary vertex tagging rate of approximately 6% [56]. The total contribution from diboson processes is shown in Table 2. Figure 2 shows the distribution of jets for different lepton flavours combined. No distribution is shown for the right we compare our best prediction at NNLL+NNLO results presented earlier.

The transverse momentum, $p_T$, is defined as:

$$p_T = \sqrt{E_T^2 - m^2}$$

where $m$ is the mass of the Higgs boson. The $p_T$ threshold is chosen to be at least 500 GeV. This variable is defined as:

$$\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$$

where $\eta$ and $\phi$ are the rapidity and azimuthal angle, respectively. The $\Delta R$ threshold is chosen to be at least 500 GeV. This variable is defined as:

$$\Delta \eta = \Delta \phi$$

The $\Delta \eta$ threshold is chosen to be at least 500 GeV. This variable is defined as:

$$\delta m$$

where $m$ is the mass of the Higgs boson. The $\delta m$ threshold is chosen to be at least 500 GeV. This variable is defined as:

$$\delta m = m_{H} - m_{H}^{\text{true}}$$

where $m_{H}^{\text{true}}$ is the true mass of the Higgs boson.
Jet Veto Thresholds

Thresholds governed by two considerations:

- Poorly measured jets at low $p_T$:
  - $p_T$ cut

- Poor background discrimination

Figure 0: Jet $p_T$ distribution and jet $\eta$ distribution for all jets having a $p_T > 0$, GeV for the full 0570 dataset.

Pileup jet identification relies on two distinct classes of variables:

- Vertexing related variables
- Shape related variables

Charged PF candidates with tracks contribute to roughly half of the total pileup. Two thirds of the pileup in the tracker volume is charged; the other half of the pileup originates from either neutral candidates from charged particles which are outside of the tracker volume or true neutral candidates where no track is linked. Inside or near the tracker volume, a distinct enhancement in the ability to discriminate against pileup is possible by exploiting the compatibility of the jet tracks to come from the PV. Outside the tracker volume, this use of vertexing is not possible, thus jet shower shapes are the only handle to distinguish pileup jets. Since characteristically overlapping pileup jets tend to result in wider jets, shape related variables are precisely designed to target the diffuseness of a jet.

To perform the identification of pileup jets, twelve distinct variables, four of which relate to the charged tracking information, are combined in a boosted decision tree (BDT) yielding a single discriminator which can be cut on to give jets of varying pileup contamination. This is known as the Pileup Jet multivariate analysis (MVA).

The training of the BDT and optimization of the jet id working points are done separately in four regions corresponding to the four different regions of the calorimeters: the tracker volume ($|\eta| < 0.2$), the tracker-endcap transition region ($0.2 < |\eta| < 2$), the endcap region ($2 < |\eta| < 2.5$), and the HF region ($2.5 < |\eta| < 2.5$). The tracker volume corresponds to the region where tracks are reconstructed. The transition region corresponds to the region where part of the jet is typically within the tracker volume and thus tracking variables can still be used, however, their behavior is different to those within the tracker volume. The endcap region corresponds to the region where the HCAL and ECAL endcap are still present. The HF region corresponds to the region where the central jet axis lies in HF.

The training is done on the Z$\rightarrow$\(\mu\mu\) MC sample with target good jets and pileup jets given by the definitions in Sec. 2.2.

The BDT based pileup jet id represents a baseline for usage by the CMS collaboration. Pileup corrections essential for precision measurements in vetoed rates.
Bin Migration Effects from Pileup: Uncertainties

The uncertainties in other observables follow by standard and we can easily read for total cross section and probe the nonlogarithmic contri-

Here, consistent with the fact that in this limit migration ef-

An additional advantage is that the uncertainties are de-

With these identifications, the full covariance matrix corres-


covariance matrices resummed and fixed order parts

\[
C(\{\sigma_{\geq 0}, \sigma_0, \sigma_{\geq 1}\}) = C_{\mu} + C_{\text{resum}},
\]

\[
C_{\mu} = \begin{pmatrix}
\Delta_{\text{tot}}^2 & \Delta_{\text{tot}} \Delta_{\mu 0} & \Delta_{\text{tot}} \Delta_{\mu \geq 1} \\
\Delta_{\text{tot}} \Delta_{\mu 0} & \Delta_{\mu 0}^2 & \Delta_{\mu 0} \Delta_{\mu \geq 1} \\
\Delta_{\text{tot}} \Delta_{\mu \geq 1} & \Delta_{\mu 0} \Delta_{\mu \geq 1} & \Delta_{\mu \geq 1}^2
\end{pmatrix}
\]

\[
C_{\text{resum}} = \begin{pmatrix}
0 & 0 & 0 \\
0 & \Delta_{\text{resum}}^2 & -\Delta_{\text{resum}}^2 \\
0 & -\Delta_{\text{resum}}^2 & \Delta_{\text{resum}}^2
\end{pmatrix}
\]

allows for control over correlations between jet bins

pileup corrections are:

1. purely uncorrelated
2. anti-correlated between jet bins

\[
C_{\text{pileup}}(\sigma_0, \sigma_{\geq 1}) = \begin{pmatrix}
\Delta_{\text{pu}}^2 & -\Delta_{\text{pu}}^2 \\
-\Delta_{\text{pu}}^2 & \Delta_{\text{pu}}^2
\end{pmatrix}
\]

threshold and pileup jet effects have separate kinematic dependence, e.g.: on veto scale, steepness of 0-jet rate

would be interesting to see the size of these terms at LHC8, LHC14, hi lumi LHC can be estimated from MC (for theorists)
Can we probe veto threshold effects more sensitively with ratios of rates?

pileup, luminosities, higher order corrections
Ratios of Cross Sections

Can we probe veto threshold effects more sensitively with ratios of rates?

pileup, luminosities, higher order corrections

\[
\frac{\sigma_0^{[14]}(30 \text{ GeV})}{\sigma_0^{[8]}(30 \text{ GeV})} = 0.953^{+0.034}_{-0.024}
\]
Ratios of Cross Sections

\[ \sigma_0(p_T^{\text{cut}}) = H(m_H) \sum_{i,j} \int dx_a dx_b [C_{ij} \otimes f_i \otimes f_j] (x_a, x_b, p_T^{\text{cut}}) U_0(p_T^{\text{cut}}) + \sigma_{ns}(p_T^{\text{cut}}) \]

ratio of 14/8 TeV probes
fixed-order variations more strongly probed

higher order corrections probe the PDFs in different ways, e.g.:

\[ \int_x^1 \frac{dz}{z} P_{gg} \left( \frac{x}{z} \right) f_g(z) \]

we are not close to probing the full PS, so the luminosity dependence is the only connection to \( E_{\text{cm}} \)

blue: resummation uncertainties
light red: fixed-order uncertainties
red: total uncertainties
VBF Contamination from gg Fusion

gg fusion contaminates the VBF analysis

kinematically severe selection cuts
induces large scale uncertainties

MVA analysis to separate gg/VBF with selection cuts

Campbell, Ellis, Williams
1001.4495

MCFM paper

YR3
fig. 69
VBF Contamination from gg Fusion

$$\sigma_{\text{obs}}(\{v_i\}) = \epsilon_{\text{VBF}}(\{v_i\})\sigma_{\text{VBF}}(q\bar{q}) + \epsilon_{gg}(\{v_i\})\sigma_{gg}(gg)$$

gg fusion contaminates the VBF analysis

Kinematically severe selection cuts induces large scale uncertainties

$$\frac{\sigma_{\text{obs}}^{[14]}(\{v_i\})}{\sigma_{\text{obs}}^{[8]}(\{v_i\})} = \frac{\epsilon_{\text{VBF}}^{[14]}(\{v_i\})\sigma_{\text{VBF}}^{[14]}(q\bar{q}) + \epsilon_{gg}^{[14]}(\{v_i\})\sigma_{gg}^{[14]}(gg)}{\epsilon_{\text{VBF}}^{[8]}(\{v_i\})\sigma_{\text{VBF}}^{[8]}(q\bar{q}) + \epsilon_{gg}^{[8]}(\{v_i\})\sigma_{gg}^{[8]}(gg)}$$

can we use this ratio to lower the uncertainty on the gg contamination?
VBF Contamination from gg Fusion

\[ \sigma_{\text{obs}}(\{v_i\}) = \epsilon_{\text{VBF}}(\{v_i\})\sigma_{\text{VBF}}(q\bar{q}) + \epsilon_{\text{gg}}(\{v_i\})\sigma_{\text{gg}}(gg) \]

kinematically severe selection cuts induces large scale uncertainties

gg fusion contaminates the VBF analysis

can we use this ratio to lower the uncertainty on the gg contamination?

\[ \frac{\sigma^{[14]}_{\text{obs}}(\{v_i\})}{\sigma^{[8]}_{\text{obs}}(\{v_i\})} = \frac{\epsilon^{[14]}_{\text{VBF}}(\{v_i\})\sigma^{[14]}_{\text{VBF}}(q\bar{q}) + \epsilon^{[14]}_{\text{gg}}(\{v_i\})\sigma^{[14]}_{\text{gg}}(gg)}{\epsilon^{[8]}_{\text{VBF}}(\{v_i\})\sigma^{[8]}_{\text{VBF}}(q\bar{q}) + \epsilon^{[8]}_{\text{gg}}(\{v_i\})\sigma^{[8]}_{\text{gg}}(gg)} \]
Conclusions

• Higgs measurements at LHC14 expand the precision program

• Veto thresholds, pileup dependence are interesting issues
  • Can integrate uncertainties with theory predictions
  • Drell-Yan a good testing ground for some of these effects, although higher order corrections much smaller

• Can we understand gg fusion contamination of VBF analysis by comparing 14, 8 TeV measurements?