ATLAS and CMS Perspectives on MC for SM Higgs Physics

ATLAS-CMS MC Generators Workshop
3rd May 2016

David Sperka
University of Florida

On Behalf of the ATLAS and CMS Collaborations
Where We Stood Before Run 2

- The discovery of the 125 GeV Higgs boson was the triumph of LHC Run 1
- No evidence for deviations from the SM, but large uncertainties

The experiments continue to test the Higgs sector at 13 TeV
- Precise measurements of gluon fusion production, including differentially
- Approaching discovery for of sub-leading production modes
- Eventually, combined fits of couplings/cross sections using Run 2 data
Background Modeling

09:00

Perspectives on vector-boson + jets physics (ATLAS+CMS)

Also as background to higgs & searches

Speaker: Mariarosaria D’Alfonso (Massachusetts Inst. of Technology (US))

09:40

Perspectives on multi-boson + jets physics (ATLAS+CMS)

Also as background to Higgs & searches

Speakers: ATLAS, Christian Gutschow (University College London (UK))

14:45

Experimental perspectives and mis-modelling in top physics (ATLAS+CMS)

Contribution provided by the LHC TOP working group

Speakers: James Howarth (University of Manchester Unknown Unknown), James William Howarth (University of Manchester (GB))

16:30

Experimental perspectives on ttbar+X physics (ATLAS+CMS)

Speaker: Maria Moreno Llacer (CERN)

17:10

Theory perspectives on ttbar+X physics

Speaker: Laura Reina (Florida State University (US))
V+heavy flavour Background Modeling

- Modeling of V+HF critical for VH(bb) analyses, some tension observed in most recent ATLAS results
- Differences observed between aMC@NLO+Pythia8 and Sherpa, not covered by scale variations
V+heavy flavour Background Modeling

- Modeling of V+HF critical for VH(bb) analyses, some tension observed in most recent ATLAS results
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VH sub-group of LHC-HXSWG would like to start discussions on V+HF background modeling for VH(bb) analyses to benefit from more interaction between ATLAS & CMS and with the theory community.

Meeting will be called for in the near future and contributions / studies in this direction would be welcome!
γ+jet / dijet Background Modeling

- Important for MVA training in $H \to \gamma\gamma$ analysis (diphoton BDT and dijet BDT)
- Most challenging in VBF phase space to obtain sufficient statistics
- CMS currently uses Pythia8, filtered at for jets with excess of EM particles

- Interested in γ+jet aMC@NLO with FxFx matching if/when it becomes available
- Sherpa+OpenLoops also an option
Higgs Boson Production Modes

- Monte Carlo samples are normalized to best available theory calculations:

\[ \sigma(gg \rightarrow H) = 48.52 \text{ pb} \pm 3.9\% \text{ (th.) } \pm 3.2\% \text{ (pdf)} \]  
\[ (N^3\text{LO QCD} + \text{NLO EW}) \]

\[ \sigma(\text{VBF}) = 3.779 \text{ pb} \pm 0.4\% \text{ (th.) } \pm 2.1\% \text{ (pdf)} \]  
\[ (\text{NNLO QCD} + \text{NLO EW}) \]

\[ \sigma(pp \rightarrow WH) = 1.369 \text{ pb} \pm 0.7\% \text{ (th.) } \pm 1.9\% \text{ (pdf)} \]
\[ \sigma(pp \rightarrow ZH) = 0.8824 \text{ pb} \pm 3.8\% \text{ (th.) } \pm 1.9\% \text{ (pdf)} \]  
\[ (\text{NNLO QCD} + \text{NLO EW}) \]

\[ \sigma(ttH) = 0.5065 \text{ pb} \pm 5.8\% \text{ (th.) } \pm 3.6\% \text{ (pdf)} \]  
\[ (\text{NLO QCD} + \text{NLO EW}) \]
Gluon Fusion Signal Modeling

• Several generators are used in ATLAS and CMS for simulating gluon fusion production

• Powheg (0-jet @ NLO): first jet at LO, additional jets from parton shower. Imperfect modeling of jet activity and $p_T(H)$, but can be tuned using generator parameters (e.g. hfact) to try and match e.g. HRes

  → aMC@NLO (NLO merged (FxFx) 0,1,2 jets @NLO)

  → Powheg NNLOPS: (inclusive NNLO, 1j @NLO)

• In Run 1, distributions were reweighted: $p_T(H)$ to match HRes 2.3 (dynamic scale) and N(jets) to match higher order calculations

  → In Run-2 goal is to not have to apply any reweighting

• MC Generators have been compared to state of the art parton level / analytical predictions to ensure their accuracy
Gluon Fusion Signal Modeling

- Inclusive cross sections for different jet multiplicities computed by hadron level event generators compared to parton level calculations
  - NNLOPS agrees well with higher order calculations for all jet multiplicity
  - aMC@NLO prediction is low for lower jet multiplicity (only NLO)
  - Pretty good agreement for both generators when $N(\text{jets}) \geq 2$
Gluon Fusion Signal Modeling

- Higgs rapidity spectrum important for estimating experimental acceptance
- NNLOPS matches HNNLO prediction by construction, aMC@NLO has a different shape especially at large $y$, where NNLO corrections are larger
  - Only matters for extrapolation to full phase space (i.e. total cross section)
Gluon Fusion Signal Modeling: $p_T(H)$

- $p_T(H)$ spectrum also important for determining acceptance, as well as testing for presence of BSM particles in the loop
- NNLOPS agrees well with higher order calculations, even at low $p_T$ where it is not formally NNLL and at high $p_T$ where it is only NLO for H+1jet
Gluon Fusion Signal Modeling

- $p_T(H)$ spectrum also important for determining acceptance, as well as testing for presence of BSM particles in the loop
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Gluon Fusion in Exclusive Jet Bins

- Exclusive jet bin predictions and uncertainties are important for channels which categorize events based on jet multiplicity (e.g. WW, ττ)

- Predictions for higher jet multiplicities also extremely important for measurement of VBF production (ggH is an irreducible background)

**H(χχ): ATLAS-CONF-2016-067**

**H(WW): ATLAS-CONF-2016-112**

<table>
<thead>
<tr>
<th>Source</th>
<th>(\Delta \mu_{\text{VBF}}/\mu_{\text{VBF}}) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>+60 / -50</td>
</tr>
<tr>
<td>Fake factor, sample composition</td>
<td>+18 / -15</td>
</tr>
<tr>
<td>MC statistical</td>
<td>±15</td>
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<tr>
<td>VBF generator</td>
<td>+14 / -5</td>
</tr>
<tr>
<td>WW generator</td>
<td>+11 / -7</td>
</tr>
<tr>
<td>QCD scale for ggF signal for (N_{\text{jet}} \geq 3)</td>
<td>+8 / -7</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>+8 / -7</td>
</tr>
<tr>
<td>b-tagging</td>
<td>+8 / -6</td>
</tr>
<tr>
<td>Pile-up</td>
<td>+8 / -6</td>
</tr>
<tr>
<td>QCD scale for ggF signal for (N_{\text{jet}} \geq 2)</td>
<td>±6</td>
</tr>
<tr>
<td>JES flavour composition</td>
<td>+6 / -4</td>
</tr>
<tr>
<td>WW renormalisation scale</td>
<td>±5</td>
</tr>
<tr>
<td>Total systematic</td>
<td>+33 / -26</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>+70 / -50</td>
</tr>
</tbody>
</table>
Gluon Fusion in Exclusive Jet Bins

- Again, pretty good agreement with higher order calculations even for larger jet multiplicities, while aMC @NLO is a bit low for lower jet multiplicities.
- Estimation of migration uncertainties is important, e.g. using JVE or ST approaches, standard uncertainties from scale variations unreliable.
- More studies welcome on modeling of kinematic distributions in jet bins.
Discussion items on NNLOPS

- We have seen that NNLOPS agrees well with state of the art calculations, and ATLAS and CMS plan to use it as the baseline for future measurements.

- Comparison between the experiments have achieved good synchronization.

Stage-1 subprocess cross sections from NNLOPS (pb). Uncertainties are statistical uncertainties only.

<table>
<thead>
<tr>
<th>Subprocess</th>
<th>CMS</th>
<th>CMS+ATLAS PS Tune</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWDH</td>
<td>4.27 ± 0.056</td>
<td>4.27 ± 0.057</td>
<td>4.27 ± 0.01</td>
</tr>
<tr>
<td>VBF_J3V</td>
<td>0.23 ± 0.01</td>
<td>0.27 ± 0.011</td>
<td>0.27 ± 0.00</td>
</tr>
<tr>
<td>VBF_J3</td>
<td>0.41 ± 0.013</td>
<td>0.37 ± 0.012</td>
<td>0.36 ± 0.00</td>
</tr>
<tr>
<td>0J</td>
<td>26.85 ± 0.134</td>
<td>26.95 ± 0.133</td>
<td>27.25 ± 0.03</td>
</tr>
<tr>
<td>1J_0-60</td>
<td>6.58 ± 0.059</td>
<td>6.61 ± 0.059</td>
<td>6.49 ± 0.01</td>
</tr>
<tr>
<td>1J_60-120</td>
<td>4.54 ± 0.046</td>
<td>4.58 ± 0.046</td>
<td>4.50 ± 0.01</td>
</tr>
<tr>
<td>1J_120-200</td>
<td>0.75 ± 0.017</td>
<td>0.75 ± 0.017</td>
<td>0.74 ± 0.00</td>
</tr>
<tr>
<td>1J_200</td>
<td>0.14 ± 0.007</td>
<td>0.17 ± 0.008</td>
<td>0.15 ± 0.00</td>
</tr>
<tr>
<td>2J_0-60</td>
<td>1.29 ± 0.025</td>
<td>1.24 ± 0.024</td>
<td>1.22 ± 0.01</td>
</tr>
<tr>
<td>2J_60-20</td>
<td>1.97 ± 0.029</td>
<td>1.89 ± 0.029</td>
<td>1.86 ± 0.01</td>
</tr>
<tr>
<td>2J_120-200</td>
<td>1.08 ± 0.02</td>
<td>1.0 ± 0.02</td>
<td>0.99 ± 0.00</td>
</tr>
<tr>
<td>2J_200</td>
<td>0.43 ± 0.012</td>
<td>0.43 ± 0.012</td>
<td>0.42 ± 0.00</td>
</tr>
</tbody>
</table>

- Parton shower tune differences lead to significant differences in VBF phase space, should be investigated further.

- Technical point: good agreement only when generating large number of events per job, a challenge for production of high statistics samples.
Fiducial Cross Section Measurements

- Measurements of model independent fiducial cross sections, fiducial volume closely matching experimental acceptance
  - Not sensitive to production mechanism, but expected to be dominated by gluon fusion
  - Decouple uncertainties on the signal cross section from the measurement uncs.
Differential Cross Sections

- We have seen new results on differential cross section measurements at 13 TeV in ZZ (CMS) and γγ (CMS and ATLAS).
- Comparisons to Powheg and aMC@NLO (CMS) and NNLOPS (ATLAS) show no significant deviations so far.
- Combinations between the channels and experiments are possible assuming acceptance factors from theoretical calculations.
Differential Cross Sections

- ATLAS has also measured differential cross sections vs $y(H)$ and $\cos\theta^*$
  - Sensitive to the parton distribution functions of the colliding protons, production mechanism, and anomalous couplings of the Higgs
- No significant deviations observed so far
Differential Cross Sections

- Exclusive jet cross sections measured by both ATLAS and CMS, ATLAS also measured inclusive cross sections for different jet multiplicity requirements.
- ATLAS observes slight deficit in 0-jet bin (still compatible with SM prediction), not seen by CMS.
- Experimental uncertainties surpassing NLO theoretical unc., especially for 0-jet bin → NNLO needed.
Differential Cross Sections

- ATLAS and CMS also measure the differential cross section vs. $p_T$ of the leading jet, sensitive to higher order QCD effects, potential BSM
- No significant deviations observed so far
ATLAS and CMS Perpectives on MC For HIG  

David Sperka, on behalf of CMS and ATLAS

Differential Cross Sections

- ATLAS has also measured differential cross sections in H+2 jet phase space for $m_{jj}$ and azimuthal difference between the two jets $\Delta \Phi_{jj}$
  - SM cross section starts to be dominated by VBF at high $m_{jj}$
- Some difference in shapes, but compatible within current uncertainty
Interference Effects in Gluon Fusion

- The Higgs boson production cross section has a significant off-shell component in the diboson decay channels
- Furthermore there is interference with the $gg \rightarrow ZZ$ continuum background, which provides sensitivity to the Higgs boson width
- Interference effects are simulated at $\alpha_S^2$, lower than signal only
  - Large K-factors applied to background and interference terms

![Graph showing interference effects in gluon fusion](image)
The Higgs width has been remeasured at 13 TeV by CMS using the 12.9 fb$^{-1}$ in the ZZ → 4\ell decay channel using combination of on-shell and off-shell tail.

Best fit of width slightly broader than expected, opposite to Run 1 result.
VBF Signal Modeling

- Both ATLAS and CMS use Powheg+Pythia8 (aMC@NLO for cross checks)
- VBF in H(WW) ATLAS ICHEP results:

<table>
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<th>Source</th>
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- VBF modeling uncertainty rather important for $H \rightarrow WW$ systematic model:
  - Mainly coming from “ME” uncertainty - estimated from generator comparison (Powheg vs aMC@NLO, matched to the same parton-shower)

- Full understanding of this source of uncertainties not trivial (different effects encoded in the comparison): not trivial treatment of 2-point systematics

- From Run-1 analyses ($H \rightarrow \tau \tau$, $H \rightarrow WW$) we also know that PS systematics play an important role in VBF selections
VBF NNLO Corrections

- Experiments would like to profit from computations of fully differential NNLO QCD + NLO EWK cross sections, likely via 1D reweighting of NLO samples.
- Discussions ongoing to determine the appropriate variable and phase space.
VBF Measurements at 13 TeV

**VBF-2jet-tagged category**

$$\mu_{\text{VBF}} = 0.06^{+1.03}_{-0.06}$$

**CMS HIG-16-041**

**CMS**

**Preliminary**

35.9 fb\(^{-1}\) (13 TeV)

**Events / 4 GeV**

<table>
<thead>
<tr>
<th>Category</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>2.5</td>
</tr>
<tr>
<td>H(125), VBF</td>
<td>3.0</td>
</tr>
<tr>
<td>H(125), other</td>
<td>1.5</td>
</tr>
<tr>
<td>qq → ZZ, Zγ*</td>
<td>0.5</td>
</tr>
<tr>
<td>gg → ZZ, Zγ*</td>
<td>0.5</td>
</tr>
<tr>
<td>Z+X</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**12.9 fb\(^{-1}\) (13 TeV)**

<table>
<thead>
<tr>
<th>Category</th>
<th>Events / GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>12.6</td>
</tr>
<tr>
<td>S+B fit</td>
<td>12.0</td>
</tr>
<tr>
<td>±1 σ</td>
<td>11.8</td>
</tr>
<tr>
<td>±2 σ</td>
<td>11.6</td>
</tr>
</tbody>
</table>

**ATLAS**

**Preliminary**

13 TeV, 14.8 fb\(^{-1}\)

**Events / 2 VBF-enriched**

H → ZZ → 4l

$$\sigma_{\text{VBF}} \cdot B(H \rightarrow ZZ^*) = 0.37^{+0.28}_{-0.21} \text{ pb}$$

$$\sigma_{\text{SM, VBF}} \cdot B(H \rightarrow ZZ^*) = 0.100 \pm 0.003 \text{ pb}$$

**ATLAS-CONF-2016-079**

**ATLAS**

**Preliminary**

13 TeV, 5.8 fb\(^{-1}\)

H → WW → eμ+μe

$$\mu_{\text{VBF}} = 1.7^{+1.1}_{-0.9}$$

**ATLAS-CONF-2016-112**
Vjj Measurements at 13 TeV

- LO Madgraph generation of EW Zjj
  - ~5% agreement with VBFNLO
- Suppression of additional jet activity in the signal enhanced region observed
  - Additional jets provided by the Parton Shower

**CMS SMP-16-018**
Both ATLAS and CMS use Powheg(MiNLO)+Pythia8

- VH modeling unc. smaller than experimental unc., but interesting to note:
  - EWK corrections not simulated in the MC, applied by reweighting
  - $gg \rightarrow ZH$ has a large uncertainty, improvement would be nice
  - Parton-shower modeling already has sizable impact on signal uncertainties

### VH(bb): ATLAS-CONF-2016-091

<table>
<thead>
<tr>
<th>Signal</th>
<th>0.7% ($q\bar{q}$), 27% ($gg$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section (scale)</td>
<td>0.7% ($q\bar{q}$), 27% ($gg$)</td>
</tr>
<tr>
<td>Cross section (PDF)</td>
<td>1.9% ($q\bar{q} \rightarrow WH$), 1.6% ($q\bar{q} \rightarrow ZH$), 5% ($gg$)</td>
</tr>
<tr>
<td>Branching ratio</td>
<td>1.7%</td>
</tr>
<tr>
<td>Acceptance (scale)</td>
<td>1.4%–5%</td>
</tr>
<tr>
<td>3-jet acceptance (scale)</td>
<td>1.4%–4.7%</td>
</tr>
<tr>
<td>$p_T^V$ shape (scale)</td>
<td>S</td>
</tr>
<tr>
<td>Acceptance (PDF)</td>
<td>0.3%–0.7%</td>
</tr>
<tr>
<td>$p_T^V$ shape (NLO EW correction)</td>
<td>S</td>
</tr>
<tr>
<td>Acceptance (parton shower)</td>
<td>4%–7.5%</td>
</tr>
</tbody>
</table>

- Dealing with this source of uncertainty is not trivial:
  - Variations in dedicated experimental tune parameters
  - 2-point comparison among PS (e.g. Pythia vs Herwig)
  - New possibility: internal weights for PS parameter variations 1605.08352
- Discussion: How to accurately determine these uncs./properly use new tools?
VH Signal Modeling

- NNLOPS simulation of VH also available, not yet used by the experiments
  - Some difference in shapes of relevant distributions, smaller uncertainties

\[ \text{CUT: } 0 < p_{T,W} < 150 \text{ GeV} + \text{jets} \]
ttH Signal Modeling

- ATLAS uses aMC@NLO+Pythia8, CMS uses aMC@NLO and Powheg + Pythia8, depending on the channel.
- Currently background modeling dominates, but signal modeling is also important:
  
  \[
  \text{ttH(combination): ATLAS-CONF-2016-088}
  \]

- MC studies (ATLAS-CONF-2016-005 and YR4) show that PS variations have a sizable effects on the shape of relevant ttH variables.
  - Difference between Pythia8 and Herwig++ larger than tune variations.
Conclusions

- **MC Tools used by ATLAS and CMS have progressed greatly since Run 1**
  - NLO generators for all production modes
  - NNLO generation for gluon fusion

- **Experimental accuracy for differential cross sections approaching theoretical uncertainty**
  - Dominated by gluon fusion
  - Subleading production modes are next

- **Previously sub-dominant uncertainties may soon become dominant (e.g. PS variations)**

- **Experiments are always interested in more accurate predictions!**