Resummation effects in colour-singlet production processes at the LHC

P. F. Monni
Rudolf Peierls Centre for Theoretical Physics
University of Oxford

Royal Holloway, University of London (RHUL) - 11 March 2015
The vast majority of processes at the LHC involves QCD jets. This massive activity often makes the signal/background discrimination very cumbersome for a variety of processes. Signal and background rates are often measured in fiducial/control volumes defined in such a way as to optimise the experimental sensitivity.

Owing the overwhelming background, the definition of fiducial volumes (e.g. for EW of H boson production) often involves heavy constraint on the accompanying QCD activity, which may lead to technical issues in the theory prediction.

Among several phase space cuts on the kinematics of decay products, a categorisation of events into exclusive jet bins with different jet multiplicities is used in several LHC analysis (e.g. H, WW, VBF, ...).

This talk will focus on this issue and its phenomenological impact in some relevant colour-singlet production reactions at the LHC.
One relevant example is Higgs boson production in association with jets.

Different jet bins have different background compositions (different experimental analyses for different jet multiplicities).

Major problem is the massive $t\bar{t}$ background (100 times as large as the signal) which mimics the signal when jets are made out of initial state radiation.

The same background affects direct WW production, which to some extent constitutes a background for the Higgs itself (i.e. one W produced off-shell).

* Is not even possible to define a top-free WW cross section if one works in the 5FS.
One relevant example is Higgs boson production in association with jets.

Different jet bins have different background compositions (different experimental analyses for different jet multiplicities).

Major problem is the massive $t\bar{t}$ background (100 times as large as the signal) which mimics the signal when jets are made out of initial state radiation.

$t\bar{t}$ cross section is dramatically suppressed if one vetoes events containing jets with $p_t > p_{t,\text{veto}} = 25 - 30$ GeV.

Why jet vetoes?

![Graph showing the suppression of the Higgs signal with jet veto.](image)

\[ \text{events} = 8 \text{ TeV}, \int \text{L}dt = 20.7 \text{ fb}^{-1} \]

$H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$.
High energy (strongly interacting) processes are well described by a perturbative expansion in the strong coupling constant.

Each emission is associated to a power of the coupling constant evaluated at some characteristic scale of the order of the emission’s transverse momentum.

In a fixed-order computation, all couplings are evaluated at some common (hard) scale of the process - this ensures the coupling to be small and the expansion to be meaningful.

When the transverse momentum of the real radiation is constrained to be small the actual coupling becomes large and an arbitrary amount of QCD emissions become equally important.

The large coupling manifests itself in terms of large single logarithms in the perturbative expansion.

\[
\alpha_s(k_t^2) \sim \frac{\alpha_s(Q^2)}{1 - \alpha_s(Q^2)\beta_0 \ln \frac{Q^2}{k_t^2}}
\]
Additional double logarithms arise from the kinematic constraint on the radiation’s phase space, as a leftover of the cancellation between real and virtual infrared/collinear singularities.

- Real emissions forced to be soft and/or collinear to the emitter
- Virtual corrections unaffected

\[
\frac{dk_t}{k_t} d\eta \alpha_s(k_t^2)
\]

\[
- \frac{dk_t}{k_t} d\eta \alpha_s(k_t^2)
\]

\[
P(k_t < p_{t,veto}) \sim 1 - \frac{4\alpha_s}{2\pi} C_F \ln^2 \frac{Q}{p_{t,veto}}
\]
In the perturbative regime these logarithms can get as large as (non-perturbative regime below this limit)

\[ L \sim \frac{1}{\alpha_s} \]

This makes “higher-order” corrections as large as leading-order ones

\[(\alpha_s L)^n L \sim \alpha_s L^2\]

In this limit the perturbative series breaks down and the fixed-order prediction suffers from a (double) logarithmic divergence instead of being exponentially suppressed.

An all-order treatment (i.e. resummation) of these enhanced terms is necessary in order to restore the correct (physical) suppression and to rescue the predictive power of the perturbative theory.
Issues with fixed-order uncertainties

- In the large logarithms regime one expects huge theory uncertainties associated with the unreliable (diverging) fixed-order prediction.
- On the contrary, often large (positive) K factors compensate large (negative) logarithms when the renormalisation scale is varied.
- Scale variation is not a reliable estimate of the uncertainty any longer.

**e.g. 0-jets cross section**

\[ \sigma_{0\text{jet}}(p_{t,veto}) = \sigma_{\text{tot}} - \sigma_{\geq 1\text{jet}}(p_{t,veto}) \]

**Dramatic cancellation for veto scales used in experimental analyses at ATLAS & CMS**
Need for alternative ways to assess the theory uncertainty

A good prescription should apply to different jet multiplicities and allow for combination of different predictions (e.g. resummed and fixed-order). Also used to compute bin-bin correlations

A few methods available

**Combination of uncorrelated inclusive jet-bin uncertainties**

\[
\sigma_{0\text{jet}}(p_t, \text{veto}) = \sigma_{\text{tot}} - \sigma_{\geq 1\text{jet}}(p_t, \text{veto}) \quad \quad \delta\sigma_{0\text{jet}}^2 = \delta\sigma_{\text{tot}}^2 + \delta\sigma_{\geq 1\text{jet}}^2
\]

**Treat uncertainties in exclusive jet rates and total cross section as uncorrelated**

\[
\begin{align*}
\sigma_{0\text{-jet}} &= \epsilon_0 \sigma_{\text{tot}}, \\
\sigma_{1\text{-jet}} &= \epsilon_1 (1 - \epsilon_0) \sigma_{\text{tot}}, \\
\sigma_{2\text{-jet}} &= \epsilon_2 (1 - \epsilon_1) (1 - \epsilon_0) \sigma_{\text{tot}}, \\
&\quad \vdots \\
\sigma_{n\text{-jet}} &= \epsilon_n (1 - \epsilon_{n-1}) \cdots (1 - \epsilon_0) \sigma_{\text{tot}},
\end{align*}
\]

**Combination of migration and yield uncertainties**

- [Banfi, Salam, Zanderighi 1203.5773, + PM 1206.4998]
- [Stewart, Tackmann 1107.2117]
- [Boughezal, Liu, Petriello, Tackmann, Walsh 1312.4535]
Resummation of large logarithms

Resummation offers a solution to both the spoiled convergence of the fixed-order series and the uncertainty problem.

An all order treatment of the large logarithms restores the expected suppression at small transverse momentum as well as allows one to estimate separately the size of (uncertainty) higher-order missing logarithms (thus avoid cancellation with the K factor effects).

Since double logarithms are known to exponentiate for this observable, we can define the following new perturbative logarithmic ordering:

\[ \Sigma(v) = \int_0^v \frac{1}{\sigma_{\text{Born}}} \frac{d\sigma}{dv'} dv' \sim e^{\alpha_s^n L^{n+1}} + \alpha_s^n L^n + \alpha_s^n L^{n-1} + ... \]

In the region where \( L \sim 1/\alpha_s \), LL are enhanced w.r.t. the Born, NLL are as large as the Born itself, NNLL count as NLO and so on.
Resummation commonly performed with fully exclusive Parton Shower (PS) Monte Carlo Generators which are formally almost NLL (NLL for NLO generators) accurate for this type of observable.

So far the uncertainty associated with a PS is hard to assess, even harder is to separate the effect of K factor from the effect of missing large logarithms in this context.

Moreover, NNLL corrections are necessary to obtain a reliable prediction once the resummation is matched to NNLO fixed order calculations (NNLL provides the full logarithmic structure at NNLO).

Therefore, PS generators should be validated against exact resumptions in a more inclusive region of phase space in which the full resummation can be carried out.

In recent years, a lot of theory work was devoted to the zero-jet bin where NNLL+NNLO predictions for H production are available, while only partial NLL results have been obtained for the 1-jet bin (more cumbersome logarithmic structure).

[Banfi et al. 1206.4998; Becher et al. 1307.0025; Stewart et al. 1307.1808; Liu et al. 1210.1906]
Jet Veto Resummation

At NLL, the all-order logarithmic structure is entirely described (up to virtuals and running coupling effects) by an independent-soft/collinear-emissions model where emissions are very far in rapidity from each other \cite{Banfi:2012jw}.

For jet veto, resummation structure turns out to be unexpectedly simple. Consider as an example the known Higgs transverse momentum case ($p_{t,H}$ and $p_{t,\text{veto}}$ are identical at NLO, though, all-order pattern very different beyond LL)

for $p_{t,H}$: bind inclusive sum of initial state radiation transverse momenta - factorisation and exponentiation non-trivial (usually performed in Fourier space)

$$\Sigma(p_{t,H}) \sim \sigma_0 \sum_{n=0}^{\infty} \frac{1}{n!} \left( \prod_{i=1}^{i=n} \int [dk_i] |M(k_i)|^2 \right) \left( \Theta(p_{t,H} - \sum_{i=1}^{n} k_{ti}) - 1 \right)$$

for $p_{t,\text{veto}}$: bind transverse momentum of the hardest jet - if each jet contains a single parton (NLL approximation) then factorization and exponentiation take place in momentum space

$$\Sigma(p_{t,\text{veto}}) \sim \sigma_0 \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=1}^{i=n} \int [dk_i] |M(k_i)|^2 (\Theta(p_{t,\text{veto}} - k_{ti}) - 1)$$

$$= \sigma_0 \exp \left[ - \int [dk_i] |M(k_i)|^2 \Theta(k_{ti} - p_{t,\text{veto}}) \right]$$
Jet Veto Resummation

The structure remains remarkably simple at NNLL

\[ \Sigma(p_{t,veto}) = \mathcal{L}(p_{t,veto})|\mathcal{M}_B|^2 \times e^{-R(p_{t,veto})} \mathcal{F}(p_{t,veto}) \]

- Process dependent Born, virtual corrections and parton luminosities.
- Easy to extend to any colour-singlet production process (jet radius dependence at NNLL and same for any \( k_t \)-like algorithm)
- Result is analytic and general for any colour-singlet production process (jet radius dependence at NNLL and same for any \( k_t \)-like algorithm)

\[ \mathcal{F}(p_{t,veto}) = 1 + \mathcal{O}(\text{NNLL}) \]

Same results obtained also in a SCET framework

[Becher, Neubert, Rothen 1307.0025]
[Stewart, Tackmann, Walsh, Zuberi 1307.1808]
Exclusive Higgs cross section and efficiency

\[ \text{gg} \rightarrow H, \ m_H = 125 \text{ GeV} \]

\[ \text{pp, 8 TeV} \]

\[ m_t / 4 < m_{H,F}, Q < m_H, \text{ schemes a,b,c} \]

\[ \text{MSTW2008 NNLO PDFs, anti-} k_t, R = 0.5 \]

\[ \text{Pythia partons, Perugia 2011 tune} \]

- \text{NNLO}
- \text{NLL+NNLO}
- \text{HNLL+NNLO}
- \text{HqT-rescaled POWHEG + Pythia}

\[ \epsilon(p_{t,veto}) \]

\[ \epsilon(p_{t,veto}) / \epsilon(\text{central}(p_{t,veto})) \]

\[ p_{t,veto} [\text{GeV}] \]

\[ \sigma_0(\text{jet}, p_{t,veto}) [\text{pb}] \]

\[ p_{t,veto} [\text{GeV}] \]

\[ \sigma_0(\text{jet}, p_{t,veto}) = 25 \text{ GeV} \]

\[ \delta \sigma_{0-\text{jet}} \sim 10\% \] \text{[NNLL+NNLO]}

\[ \delta \sigma_{0-\text{jet}} \sim 13.8\% \] \text{[NNLL+NNLO + JVE method w } \sigma_{\text{tot}}^{\text{NNLO}} \text{]}\]

\[ \delta \sigma_{0-\text{jet}} \sim 12.8\% \] \text{[NNLL+NNLO + JVE method w } \sigma_{\text{tot}}^{\text{HXSWG}} \text{]}

Public code at: http://jetvheto.hepforge.org

[Banfi, PM, Salam, Zanderighi 1206.4998]
Comparison to ATLAS data

Results used in experimental analyses, will play a role in precise determinations of the Higgs boson couplings.

Further improvements involve the ongoing calculations of the N3LO total cross section and the H+1jet cross section at NNLO which will lead to a NNLL+N3LO prediction.

[Boughezal et al. 1302.6216]  [Bonvini et al. 1303.3590 - 1404.3204]
[Chen et al. 1408.5325]        [Anastasiou et al. 1403.4616]
[de Florian et al. 1408.6277]
Constraining the Higgs width

- Enhancement in total cross section in off-shell production of $H \rightarrow VV$ allows for a precise measurement of $\Gamma_H$ [Kauer, Passarino ’12, Caola, Melnikov ’13, Campbell, Ellis, Williams ’13]
- Latest measurements $\Gamma_H/\Gamma_{SM} < 5.4$ (CMS), $4.5 - 7.5$ (ATLAS) in $H \rightarrow ZZ$ [CMS 1405.5534; ATLAS 1503.01060]
- Approach also extended to $H \rightarrow W^+W^-$ [Campbell, Ellis, Williams ’13]
- Conclusions change if a jet veto is applied ($H \rightarrow W^+W^-$) [Moult, Stewart ’14]

A veto on extra jets suppresses both signal and signal-background interference in the off-shell region

Sudakov suppression weakens the bounds on the Higgs width by about a factor of two

$ZZ$ channel not affected
Another case: WW production at the LHC

Relevance of WW production at the LHC

probe/test non-abelian structure of EW Standard Model

Direct sensitivity to Triple Gauge Couplings (TGCs)

Deviations in total cross section and kinematic distributions can be due to anomalous TGCs or new states decaying into leptons + missing energy

Important irreducible background for Higgs boson production (off-shell production)
ATLAS & CMS analyses

ATLAS & CMS performed analyses on both 7 and 8 TeV data.

<table>
<thead>
<tr>
<th>√s [TeV]</th>
<th>ATLAS</th>
<th>CMS</th>
<th>Theory (MCFM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ [pb]</td>
<td>σ [pb]</td>
<td>σ [pb]</td>
</tr>
<tr>
<td>7 TeV</td>
<td>51.9$^{+2.0+3.9+2.0}_{-2.0-3.9-2.0}$ [13]</td>
<td>52.4$^{+2.0+4.5+1.2}_{-2.0-4.5-1.2}$ [14]</td>
<td>47.04$^{+2.02+0.90}_{-1.51-0.66}$</td>
</tr>
<tr>
<td>8 TeV</td>
<td>71.4$^{+1.2+5.0+2.2}_{-1.2-4.4-2.1}$ [15]</td>
<td>69.9$^{+2.8+5.6+3.1}_{-2.8-5.6-3.1}$ [16]</td>
<td>57.25$^{+2.35+1.09}_{-1.60-0.80}$</td>
</tr>
</tbody>
</table>

* includes formally NNLO gg → WW and gg → H → WW

Systematic discrepancy of about 2.1 σ with the NLO prediction found by both experiments.

The tension seems to increase with the collider energy.

Tension not present for other di-boson channels (e.g. WZ, ZZ, Zγ, Wγ).

No significant tension observed in differential distributions.
What can possibly explain the excess?

Sizeable perturbative effects have been neglected in the theory prediction:
- for the signal process
- for the background reactions

Deviations are signal for new physics beyond the Standard Model
- SUSY, Anomalous TGCs
- ....
Explanations for the excess

What can possibly explain the excess?

- Sizeable perturbative effects have been neglected in the theory prediction:
  - for the signal process
  - for the background reactions

- Deviations are signal for new physics beyond the Standard Model
  - SUSY, Anomalous TGCs
  - ....
Signal and fiducial region

- Signal events are required to have two opposite-charged leptons with high transverse momentum, accompanied by a large fraction of missing transverse energy.

- Analyses are carried out in the three lepton channels $e\mu$, $\mu\mu$, $ee$ separately, and then combined via a Bayesian log-likelihood approach.

- Measurements are carried out in a fiducial region, defined in an experiment-dependent way in order to optimise sensitivity.

### 8 TeV fiducial region

<table>
<thead>
<tr>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_t &gt; 25(20)$ GeV for the leading (subleading) lepton and charged leptons separated by $\Delta R &gt; 0.1$</td>
</tr>
<tr>
<td>Muon pseudorapidity $</td>
</tr>
<tr>
<td>No jets (anti-$k_t$ [10], $R = 0.4$) with $p_t &gt; 25$ GeV and $</td>
</tr>
<tr>
<td>$m_{ll'} &gt; 15, 15, 10$ GeV and $</td>
</tr>
<tr>
<td>$p_{t,\text{Rel}}^{\nu+\bar{\nu}} &gt; 45, 45, 15$ GeV and $p_t^{\nu+\bar{\nu}} &gt; 45, 45, 20$ GeV for $ee, \mu\mu$, and $e\mu$, respectively</td>
</tr>
</tbody>
</table>

[ATLAS 8 TeV analysis: ATLAS-CONF-2014-033]
The signal is then extrapolated to the inclusive phase space by means of MC event generators. The above extrapolation requires a full control of the theory prediction and a robust assessment of the uncertainties associated with the MC generators in the fiducial region. Do we really understand so well the used tools?

The comparison with theory should be first carried out in the fiducial region, and claims of discrepancies should be made at this level.

Extrapolation to the total volume

\[
\sigma(pp \rightarrow WW) = \frac{N_{\text{data}} - N_{\text{bg}}}{A_{WW} \\times C_{WW} \times \mathcal{L} \times \text{Br}}
\]

Kinematic and geometrical acceptance for the extrapolation from the fiducial to the total volume, i.e. efficiency of phase space cuts, simulated by MC generators.

Detector and trigger acceptances and efficiencies, lepton reconstruction, missing phase space regions in the detector geometry, non-prompt leptons...

Integrated luminosity and branching ratios.
Overview of results for ATLAS & CMS

Fiducial signal efficiency simulated with different generators for the (dominant) $q\bar{q} \to WW$ channel*

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>ATLAS (fiducials below) $\sigma$ [pb]</th>
<th>CMS (no fiducials) $\sigma$ [pb]</th>
<th>Theory (MCFW) $\sigma$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>$51.9^{+2.0+3.9+2.0}_{-2.0-3.9-2.0}$ [13]</td>
<td>$52.4^{+2.0+4.5+1.2}_{-2.0-4.5-1.2}$ [14]</td>
<td>$47.04^{+2.02+0.90}_{-1.51-0.66}$</td>
</tr>
<tr>
<td>8 TeV</td>
<td>$71.4^{+1.2+5.0+2.2}_{-1.2-4.4-2.1}$ [15]</td>
<td>$69.9^{+2.8+5.6+3.0}_{-2.8-5.6-3.1}$ [16]</td>
<td>$57.25^{+2.35+1.09}_{-1.60-0.80}$</td>
</tr>
</tbody>
</table>

ATLAS @ 7 TeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>Measured $\sigma_{WW}^{fid}$ (fb)</th>
<th>Predicted $\sigma_{WW}^{fid}$ (fb)</th>
<th>Measured $\sigma_{WW}$ (pb)</th>
<th>Predicted $\sigma_{WW}$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee$</td>
<td>$56.4 \pm 6.8 \pm 9.8 \pm 2.2$</td>
<td>$54.6 \pm 3.7$</td>
<td>$46.9 \pm 5.7 \pm 8.2 \pm 1.8$</td>
<td>$44.7^{+4.1}_{-1.9}$</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>$73.9 \pm 5.9 \pm 6.9 \pm 2.9$</td>
<td>$58.9 \pm 4.0$</td>
<td>$56.7 \pm 4.5 \pm 5.5 \pm 2.2$</td>
<td>$44.7^{+2.1}_{-1.9}$</td>
</tr>
<tr>
<td>$e\mu$</td>
<td>$262.3 \pm 12.3 \pm 20.7 \pm 10.2$</td>
<td>$231.4 \pm 15.7$</td>
<td>$51.1 \pm 2.4 \pm 4.2 \pm 2.0$</td>
<td>$44.7^{+2.1}_{-1.9}$</td>
</tr>
<tr>
<td>Combined</td>
<td>...</td>
<td>...</td>
<td>$51.9 \pm 2.0 \pm 3.9 \pm 2.0$</td>
<td>$44.7^{+2.1}_{-1.9}$</td>
</tr>
</tbody>
</table>

ATLAS @ 8 TeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>Measured $\sigma_{WW}^{fid}$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\mu$</td>
<td>$377.8^{+6.9}<em>{-6.8}$ (stat) $^{+25.1}</em>{-22.2}$ (syst) $^{+11.4}_{-10.7}$ (lumi)</td>
</tr>
<tr>
<td>$ee$</td>
<td>$68.5^{+4.2}<em>{-4.1}$ (stat) $^{+7.7}</em>{-6.6}$ (syst) $^{+2.1}_{-2.0}$ (lumi)</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>$74.4^{+3.3}<em>{-3.2}$ (stat) $^{+7.0}</em>{-6.0}$ (syst) $^{+2.3}_{-2.1}$ (lumi)</td>
</tr>
</tbody>
</table>

Mixed channel dominant in the recombination

<table>
<thead>
<tr>
<th>Channel</th>
<th>Measured $\sigma_{WW}^{total}$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\mu$</td>
<td>$71.4^{+1.3}<em>{-1.3}$ (stat) $^{+5.0}</em>{-4.4}$ (syst) $^{+2.1}_{-2.0}$ (lumi)</td>
</tr>
<tr>
<td>$ee$</td>
<td>$68.6^{+4.2}<em>{-4.1}$ (stat) $^{+7.8}</em>{-6.7}$ (syst) $^{+2.1}_{-2.0}$ (lumi)</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>$68.6^{+3.1}<em>{-3.0}$ (stat) $^{+6.6}</em>{-5.6}$ (syst) $^{+2.1}_{-2.0}$ (lumi)</td>
</tr>
<tr>
<td>Combined</td>
<td>$71.4^{+1.2}<em>{-1.2}$ (stat) $^{+5.0}</em>{-4.4}$ (syst) $^{+2.2}_{-2.1}$ (lumi)</td>
</tr>
</tbody>
</table>

* $gg2WW$ everywhere for the $gg \to (H \to)WW$ channels  

[13] ATLAS @ 7 TeV: MC@NLO + Herwig ++  
[14] CMS @ 7 TeV: MadGraph + Pythia  
[15] ATLAS @ 8 TeV: POWHEG + Pythia  
[16] CMS @ 8 TeV: MadGraph + Pythia
Overview of results for ATLAS & CMS

Fiducial signal efficiency simulated with different generators for the (dominant) $q\bar{q} \rightarrow WW$ channel*

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>ATLAS (fiducials below)</th>
<th>CMS (no fiducials)</th>
<th>Theory (MCFM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma$ [pb]</td>
<td>$\sigma$ [pb]</td>
<td>$\sigma$ [pb]</td>
</tr>
<tr>
<td>7 TeV</td>
<td>$51.9_{-2.0}^{+2.0}+3.9+2.0$ [13]</td>
<td>$52.4_{-4.5}^{+4.5}+1.2$ [14]</td>
<td>$47.04_{-1.51}^{+2.02}+0.90$</td>
</tr>
<tr>
<td>8 TeV</td>
<td>$71.4_{-4.4}^{+1.2}+5.0+2.2$ [15]</td>
<td>$69.9_{-5.8}^{+2.8}+3.1$ [16]</td>
<td>$57.25_{-1.60}^{+2.35}+1.09$</td>
</tr>
</tbody>
</table>

**ATLAS @ 7 TeV**

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma_{WW}^{fiducial}$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee$</td>
<td>$56.4 \pm 6.8 \pm 9.8 \pm 2.2$</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>$73.9 \pm 5.9 \pm 6.9 \pm 2.9$</td>
</tr>
<tr>
<td>$e\mu$</td>
<td>$262.3 \pm 12.3 \pm 20.7 \pm 10.2$</td>
</tr>
<tr>
<td>Combined</td>
<td>$\ldots$</td>
</tr>
</tbody>
</table>

**ATLAS @ 8 TeV**

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma_{WW}^{total}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee$</td>
<td>$46.9 \pm 5.7 \pm 8.2 \pm 1.8$</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>$56.7 \pm 4.5 \pm 5.5 \pm 2.2$</td>
</tr>
<tr>
<td>$e\mu$</td>
<td>$51.1 \pm 2.4 \pm 4.2 \pm 2.0$</td>
</tr>
<tr>
<td>Combined</td>
<td>$51.9 \pm 2.0 \pm 3.9 \pm 2.0$</td>
</tr>
</tbody>
</table>

Larger discrepancy with NLO.
Let's focus on this for a while...

Mixed channel dominant in the recombination

*gg2WW everywhere for the $gg \rightarrow (H \rightarrow) WW$ channels

[13] ATLAS @ 7 TeV: MC@NLO + Herwig ++
[14] CMS @ 7 TeV: MadGraph + Pythia
[15] ATLAS @ 8 TeV: POWHEG + Pythia
[16] CMS @ 8 TeV: MadGraph + Pythia

[Kauer, Passarino 1206.4803; Kauer 1310.7011]
Similar extrapolation methods from a fiducial to the total volume are used in other di-boson \((WZ, ZZ, Z\gamma, W\gamma)\) measurements, whose results are all consistent with the corresponding Standard Model predictions.

What's special in the WW channel?

Unlike for other di-boson analyses, the WW fiducial volume requires a veto on extra jet activity, i.e. neglect events containing at least a jet with \(p_{t,j} > p_{t,\text{veto}}\).

A jet veto is a necessary evil to suppress the large background due to top-pair production, leading to a sizeable loss of signal events.

### Possible theoretical issues

<table>
<thead>
<tr>
<th>Channels</th>
<th>(e\mu)</th>
<th>(ee)</th>
<th>(\mu\mu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_\text{ll} &gt; 10/15/15) GeV</td>
<td>83042</td>
<td>4918726</td>
<td>8357583</td>
</tr>
<tr>
<td>(</td>
<td>m_\text{ll} - m_Z</td>
<td>&gt; 0/15/15) GeV</td>
<td>83042</td>
</tr>
<tr>
<td>(E_{T,\text{rel}} &gt; 15/45/45) GeV</td>
<td>52142</td>
<td>11594</td>
<td>19887</td>
</tr>
<tr>
<td>(p_{T,\text{miss}} &gt; 20/45/45) GeV</td>
<td>43718</td>
<td>5762</td>
<td>9152</td>
</tr>
<tr>
<td>(\Delta\phi(E_{T,\text{miss}}, p_{T,\text{miss}}) &lt; 0.6/0.3/0.3)</td>
<td>27591</td>
<td>2613</td>
<td>4291</td>
</tr>
<tr>
<td>Jet-veto requirement</td>
<td>5067</td>
<td>594</td>
<td>975</td>
</tr>
</tbody>
</table>

[ATLAS-CONF-2014-033]
Jet veto treatment in experimental analyses

- The effect of the jet veto is simulated by computing a jet veto efficiency $\epsilon_{WW}^{MC}$ with a number of tools (POWHEG + Pythia, MC@NLO + Herwig/Pythia, MadGraph + Pythia), and rescaling it with the ratio of data to MC jet veto efficiency for $Z/\gamma^* \rightarrow \ell\ell$ with fiducial lepton selection criteria

$$\epsilon_{\text{pred}} = \frac{\epsilon_{Z/\gamma^*}^{\text{data}}}{\epsilon_{Z/\gamma^*}^{MC}} \frac{\epsilon_{WW}^{MC}}{\epsilon_{WW}^{MC}}$$

- Jet veto efficiency is a problematic quantity, a misestimate could affect the extrapolation

- Is the MC jet veto efficiency fully reliable?
The effect of the jet veto is simulated by computing a jet veto efficiency $\epsilon_{WW}^{MC}$ with a number of tools (POWHEG + Pythia, MC@NLO + Herwig/Pythia, MadGraph + Pythia), and rescaling it with the ratio of data to MC jet veto efficiency for $Z/\gamma^* \rightarrow \ell\ell$ with fiducial lepton selection criteria.

Jet veto efficiency is a problematic quantity, a misestimate could affect the extrapolation.

Is the MC jet veto efficiency fully reliable?
The effect of the jet veto is simulated by computing a jet veto efficiency $\epsilon_{WW}^{MC}$ with a number of tools (POWHEG + Pythia, MC@NLO + Herwig/Pythia, MadGraph + Pythia), and rescaling it with the ratio of data to MC jet veto efficiency for $Z/\gamma* \rightarrow \ell\ell$ with fiducial lepton selection criteria.

$$\epsilon_{WW}^{pred} = \frac{\epsilon_{data}^{Z/\gamma*}}{\epsilon_{MC}^{Z/\gamma*}} \times \epsilon_{WW}^{MC}$$

The correction factor reduces the experimental uncertainties due to Jet Energy Scale/Resolution (assumed to be one in the following).

However, uncertainty in Z production are smaller, making the final uncertainty on WW efficiency even larger.

Jet veto efficiency is a problematic quantity, a misestimate could affect the extrapolation.

Is the MC jet veto efficiency fully reliable?
At the fiducial level, a comparison to the NLO (MCFM) prediction does not show any significant excess.

A parton shower matched to NLO is used to resum the relevant logarithms. Competing effects tend to lower the fiducial cross section (i.e. average number of jets increases, out-of-jet radiation and MPI affect the leading jet’s transverse momentum).

e.g. ATLAS 8 TeV fiducial setup - no gg contribution
POWHEG + Pythia 6.4.28 - Perugia tune 350

Fiducial cross section reduced by 9-11 %
Resummation effects

Too much suppression for a quark-initiated process with no extra QCD jets at tree level. This can be due to a number of effects (e.g. shower tune dependence, uncontrolled sizeable higher order logarithmic effects)

Need to validate this prediction against exact resummations in a more inclusive phase space region

Resummation effects can be estimated by looking at processes with similar radiation patterns
e.g. for the jet veto efficiency in the $q\bar{q} \rightarrow WW$ channel, we can extract resummation effects from the $Z$ production analysis

same initial state colour structure at Born level (quark initiated)

at sufficiently small $p_{t,\text{veto}}$ Sudakov effects dominate the efficiency, and hard physics effects (virtual corrections, parton luminosities, EW parameters) largely cancel in the efficiency

In this phase space region, the leading difference is the hard scale in the logs

Similarly, effects in the efficiency for $gg \rightarrow WW$ can be estimated from Higgs production
First observe that the scale which appears in the large logarithms \( \ln \left( \frac{M}{p_{t,\text{veto}}} \right) \) is the invariant mass of the colourless final state system (in general off-shell). The invariant mass spectrum is peaked at \( M \sim 2M_W \) and steeply falls for higher values.

We assume that the cross section is dominated by \( M \sim 2M_W \) - same applies to \( Z \) production with \( M \sim M_Z \). More appropriate to take the median/mean \[ \text{median/mean} \]

The dynamics in the low \( p_{t,\text{veto}} \) region is ruled by the large logarithms, so we can extract information from \( Z/H \) production via a simple rescaling.

\[ p_{t,\text{veto}}^{WW} = 25 - 30 \text{ GeV} \quad p_{t,\text{veto}}^{Z} = \frac{M_Z}{2M_W} p_{t,\text{veto}}^{WW} \sim 15 \text{ GeV} \]

Logarithms are dominant in this region.

\[ \text{pp} \rightarrow WW, E_{\text{cm}} = 8 \text{ TeV} \]
Technically, the correct relationship in the large-logarithms regime is obtained by replacing the invariant mass of the DY pair (and renorm/fact scales accordingly) with the WW’s one (or its median/mean value).

This differs from the above rescaling procedure in running coupling effects (very moderate) and differences in parton luminosities (different final-state invariant mass and factorisation scale).

These effects are very moderate if one considers the ratio to the NLO efficiency (what we want to estimate). The above approximation still valid.

Ratio of the WW to the DY efficiency
setting $M_Z$ to the median
of the WW invariant mass spectrum (222 GeV)

[Becher, Frederix, Neubert, Rothen 1412.8408]

[PM, Zanderighi 1410.4745 - v2]
An estimate of higher orders (NNLL+NNLO) corrections to the efficiency can be extracted from Z and H production.

Where, for the three contributing channels:

\[ p_{t,veto}^{Z} = \frac{M_{Z}}{2M_{W}} p_{t,veto}^{WW} \sim 15 \text{ GeV} \]

\[ p_{t,veto}^{H} = \frac{M_{H}}{2M_{W}} p_{t,veto}^{WW} \sim 19.5 \text{ GeV} \]

\[ p_{t,veto}^{H} = 25 \text{ GeV} \]
An estimate of higher orders (NNLL+NNLO) corrections to the efficiency can be extracted from Z and H production.

Where, for the three contributing channels:

\[ p_{t,veto}^Z = \frac{M_Z}{2M_W} p_{t,veto}^{WW} \sim 15 \text{ GeV} \]

\[ p_{t,veto}^H = \frac{M_H}{2M_W} p_{t,veto}^{WW} \sim 19.5 \text{ GeV} \]

\[ p_{t,veto}^H = 25 \text{ GeV} \]
An estimate of higher orders (NNLL+NNLO) corrections to the efficiency can be extracted from $Z$ and $H$ production.

Where, for the three contributing channels:

- $q\bar{q} \rightarrow WW$
  \[ p_{t,veto}^{Z} = \frac{M_{Z}}{2M_{W}} p_{t,veto}^{WW} \sim 15 \text{ GeV} \]

- $gg \rightarrow WW$
  \[ p_{t,veto}^{H} = \frac{M_{H}}{2M_{W}} p_{t,veto}^{WW} \sim 19.5 \text{ GeV} \]

- $gg \rightarrow H \rightarrow WW$
  \[ p_{t,veto}^{H} = 25 \text{ GeV} \]
An estimate of higher orders (NNLL+NNLO) corrections to the efficiency can be extracted from Z and H production.

Where, for the three contributing channels:

- $q\bar{q} \to WW$
  \[ p_{t,\text{veto}}^Z = \frac{M_Z}{2M_W} p_{t,\text{veto}}^{WW} \sim 15 \text{ GeV} \]

- $gg \to WW$
  \[ p_{t,\text{veto}}^H = \frac{M_H}{2M_W} p_{t,\text{veto}}^{WW} \sim 19.5 \text{ GeV} \]

- $gg \to H \to WW$
  \[ p_{t,\text{veto}}^H = 25 \text{ GeV} \]
The enhancement due to the NNLO K factor is balanced by the Sudakov suppression in the efficiency. The combined effect amounts to a moderate enhancement with respect to the NLO predictions.

Assuming that lepton efficiencies are not significantly affected by higher order corrections

\[
\sigma_{\text{fid.}}^{\text{th.}} = \sum_{c \in \text{channel}} \sigma_{\text{fid.}}^{(c),NLO} \sigma_{\text{incl.}}^{(c),NLO} \frac{\epsilon_c^{(c),\text{NNLL}+\text{NNLO}}(p_t,veto)}{\epsilon_c^{(c),\text{NLO}}(p_t,veto)}
\]

(MCFM)

(assume NNLO does not change lepton acceptances)

[PM, Zanderighi 1410.4745]

<table>
<thead>
<tr>
<th>decay mode</th>
<th>(\sigma_{\text{fid.}}^{\text{exp.}}) [fb]</th>
<th>(\sigma_{\text{fid.}}^{\text{th.}}) [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e^+\mu^- + e^-\mu^+)</td>
<td>377.8 +/− 6.9(stat.) +/− 6.8(syst.) +/− 22.2(lumi.)</td>
<td>353.5 +/− 15.5</td>
</tr>
<tr>
<td>(e^+e^-)</td>
<td>68.5 +/− 4.2(stat.) +/− 7.7</td>
<td>68.1 +/− 2.9</td>
</tr>
<tr>
<td>(\mu^+\mu^-)</td>
<td>74.4 +/− 3.3(stat.) +/− 7.0(lumi.)</td>
<td>74.1 +/− 3.2</td>
</tr>
</tbody>
</table>

Agreement improves at the fiducial level. More careful assessment of uncertainties required (e.g. JVE, ST methods).

Uncertainties in EW parameters also have a sizeable impact \(\sigma_{WW} \sim 1/(\Gamma_W M_W)^2\)

Uncertainties combined in quadrature

Numbers just indicative, full NNLL+NNLO analysis needed!
As expected, over-all resummation effects are small when compared to the NNLO prediction. Still relevant for the uncertainty.

The suppression in the efficiency is cancelled by the inclusive NNLO K factor

**Bottom line**: higher-order effects do not change sensibly the agreement observed at NLO - also confirmed by the pure NNLO calculation below.
POWHEG + Pythia’s jet veto efficiency (no lepton cuts) is 7-8% smaller than NLO (different results with different shower tunes).

NNLL + NLO efficiency is reduced by 3-4% with respect to the NLO one.

NNLL + NNLO efficiency is reduced by 7-8% with respect to the NLO one.

At current values of the jet veto cut, POWHEG + Pythia accidentally mimics the NNLL + NNLO result for the jet veto efficiency - the resulting extrapolation to the inclusive phase space will be in better agreement with the NNLO total cross section.

Additional cuts on final state leptons lead to further 3% reduction at the fiducial level. The latter effect is formally due to higher-order (unphysical ?) corrections at the LHA event level in the NLO + PS matching procedure (systematic uncertainty).
Exact NNLL+NLO resummation performed recently for the qq channel - results in agreement with what presented here.

Matching to NNLO (now possible) necessary to have robust predictions.

Comparisons to MC results show that some NLO+PS systematically leads to lower efficiencies, hence larger total cross sections in the extrapolation.

Similar conclusions also found by reweighting the differential distributions with the NNLL-resummed WW transverse momentum spectrum.
For an extrapolation from fiducial to total cross section to be performed, theory predictions (and relative uncertainties) in the fiducial volume should be well under control.

General analyses show that MC generators can often underestimate the jet veto efficiency (larger difference observed for the POWHEG+Pythia combination) - uncertainties underestimated.

Comparison with theory should be carried out preferably at the fiducial level and MC-dependent effects in the extrapolation should be avoided.

As a cross check of the measurement, experiments could extrapolate their fiducial cross sections to each other’s fiducial phase space.

Small extrapolations (not orders of magnitude) imply less MC dependent effects.

Similar effects could be hiding in some data-driven background extrapolations to the fiducial volume.
Conclusions

- Higher order matching (i.e. NNLL+NNLO) is often necessary to have a good prediction and a reliable assessment of theory uncertainty when phase space cuts give rise to large logarithms.

- Fully exclusive NLO+PS generators should be validated against exact resummations (if available) in more inclusive phase space regions in order to determine accuracy and systematic uncertainties.

- Predictions for the exclusive Higgs cross section and relative uncertainties under control - further improvement will come soon with the inclusions of (yet) higher (fixed)-order contributions. Progress desirable for higher jet multiplicities.

- The excess in the WW cross section is an artefact of the extrapolation process. Full NNLL+NNLO can now be performed and taken into account in the analysis prior to extrapolation. Some care required with the th. uncertainty.

- In general, extrapolations of several orders of magnitude should be avoided since they might hide MC-dependent effects which propagate dramatically into the final measurement.
Extra material
Need to disentangle Sudakov large logarithms from K factor due to hard physics in order to avoid cancellations.

Express the exclusive cross sections as products of jet veto efficiencies (JVE) and the total cross section:

\[
\begin{align*}
\sigma_{0-\text{jet}} & = \epsilon_0 \sigma_{\text{tot}}, \\
\sigma_{1-\text{jet}} & = \epsilon_1 (1 - \epsilon_0) \sigma_{\text{tot}}, \\
\sigma_{2-\text{jet}} & = \epsilon_2 (1 - \epsilon_1)(1 - \epsilon_0) \sigma_{\text{tot}}, \\
& \vdots \\
\sigma_{n-\text{jet}} & = \epsilon_n (1 - \epsilon_{n-1}) \cdots (1 - \epsilon_0) \sigma_{\text{tot}}, \\
\sigma_{>n-\text{jet}} & = (1 - \epsilon_n) (1 - \epsilon_{n-1}) \cdots (1 - \epsilon_0) \sigma_{\text{tot}}
\end{align*}
\]

Observe that at small transverse momentum the effects due to hard physics cancel in the efficiencies, and contribute as a global K factor in the total cross section.

In this phase space region JVEs are dominated by large Sudakov logarithms, and their uncertainty can be considered as uncorrelated from the one in the total cross section (and uncorrelated with each other jet bin’s uncertainty).
Scale variation uncertainty in the total cross section due to inclusive K factor effects

Scale uncertainty in the JVE is mainly associated with miss higher order large logarithms

Moreover, the spread between central values relative to all possible definitions for the JVE at a given perturbative order is considered as an additional systematic.

Difference between schemes increases for slowly converging PT series

e.g. H+0-jets @ NNLO

\[ \epsilon^{(a)}(p_{t,veto}) = \frac{\sigma_{0-\text{jet}}^{\text{NNLO}}}{\sigma_{\text{tot}}^{\text{NNLO}}} \]

\[ \epsilon^{(b)}(p_{t,veto}) = 1 - \frac{\sigma_{\geq 1-\text{jet}}^{\text{NLO}}}{\sigma_{\text{tot}}^{\text{NLO}}} \]

\[ \epsilon^{(c)}(p_{t,veto}) = \text{strict fixed order expansion} \]

spread depends on inclusive K(\text{NNLO}/\text{NLO})

spread depends on inclusive K(\text{NLO}/\text{LO})
Resummation effects

These effects are moderate if one considers the ratio to the NLO efficiency.

At most 1% difference in the ratios to NLO. Same situation in the gg channel.
Background processes are often normalised to data in a Control Region, and then extrapolated to the fiducial region by means of acceptances computed with Monte Carlo (MC) generators.

Obtained with a number of tools e.g. ALPGEN, MadGraph, MC@NLO, POWHEG,...
Kinematic distributions

Higher statistics for $e\mu$ channel

Slight shape difference - no significant discrepancy in distributions

Unfolded lepton transverse momentum distribution sets bounds on anomalous couplings
Reweight MC prediction for the WW transverse momentum with the rescaling factor

\[ F[p_T] = \frac{\text{Resummed bin}[p_T]}{\text{MC bin}[p_T]} \]

[e.g. 8 TeV]

[Meade, Ramani, Zeng 1407.4481]
Reweighting of fiducial differential distributions

- The largest discrepancy compared to MC comes from POWHEG + Pythia
- Reweighting has a sizeable impact on MC prediction

\[
\text{percentage difference} = \frac{(\text{events}_{\text{res}} - \text{events}_{\text{MC}}) \cdot 100}{\text{events}_{\text{MC}}}
\]

- Most important correction due to jet veto effects

**ATLAS fiducial 8 TeV, POWHEG + Pythia**

<table>
<thead>
<tr>
<th>Cut</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exactly two oppositely-sign leptons, ( p_T &gt; 20 \text{ GeV} ), ( p_{T,\text{leading}} &gt; 25 \text{ GeV} )</td>
<td>1.36</td>
</tr>
<tr>
<td>( m_{\ell\ell} ) cuts</td>
<td>1.16</td>
</tr>
<tr>
<td>( \not{E}<em>T,</em>{\text{Rel}} )</td>
<td>0.83</td>
</tr>
<tr>
<td>Jet Veto</td>
<td>9.72</td>
</tr>
<tr>
<td>( p_{T\ell} )</td>
<td>10.75</td>
</tr>
</tbody>
</table>

- Overall effect is to increase the fiducial by 3-7% with respect to NLO, improving the agreement with data
NNLL+NLO vs. event generators

NLO generators underestimate the actual jet veto efficiency in comparison to NNLL+NLO, leading to a larger extrapolated total cross section

\[ \epsilon_{\text{veto}} = \frac{\sigma_{q\bar{q}}^{\text{veto}} + \sigma_{gg}}{\sigma_{q\bar{q}} + \sigma_{gg}} = \frac{\epsilon_{q\bar{q}}^{\text{veto}} \sigma_{q\bar{q}} + \sigma_{gg}}{\sigma_{q\bar{q}} + \sigma_{gg}} \]

[Jaiswal, Okui 1407.4537]
NNLL+NLO prediction improves the agreement with data at the $\sim 1\sigma$ level or better.

Enhancement due to the NNLO K factor will lead to further improvement (effect partly mimicked by $\pi^2$ resummation here).

Proper treatment of the $gg \rightarrow WW$ channel still desirable.

ATLAS/CMS vetoed cross sections obtained by undoing the quoted total cross section using MC

\begin{table}
\centering
\begin{tabular}{|c|c|c|}
\hline
 & $R = 0.4$ & $R = 0.5$ \\
$\sqrt{s} = 7$ TeV & $p_T^{\text{veto}} = 25$ GeV & $p_T^{\text{veto}} = 30$ GeV \\
\hline
ATLAS & $37.9^{+3.8\%+5.0\%+3.8\%}_{-3.8\%-5.0%-3.8\%}$ & $-$ \\
$\sigma_{WW}^\text{veto}$ [pb] & & \\
\hline
CMS & $-3.8\%-7.2%-2.3\%$ & $41.5^{+3.8\%+7.2\%+2.3\%}_{-3.8\%-7.2%-2.3\%}$ \\
$\sigma_{WW}^\text{veto}$ [pb] & & \\
\hline
Theory & $37.6^{+4.2\%-3.4\%}$ & $39.1^{+2.8\%-2.5\%}$ \\
$\sigma_{WW}^\text{veto}$ [pb] & & \\
\hline
Theory & $2.1^{+13.5\%-11.4\%}$ & $2.3^{+11.5\%-10.6\%}$ \\
$\sigma_{h\rightarrow WW}$ [pb] & & \\
\hline
\end{tabular}
\end{table}

\begin{table}
\centering
\begin{tabular}{|c|c|c|}
\hline
 & $R = 0.4$ & $R = 0.5$ \\
$\sqrt{s} = 8$ TeV & $p_T^{\text{veto}} = 25$ GeV & $p_T^{\text{veto}} = 30$ GeV \\
\hline
ATLAS & $48.1^{+1.7\%+6.2\%+3.1\%}_{-1.7%-5.2%-2.9\%}$ & $-$ \\
$\sigma_{WW}^\text{veto}$ [pb] & & \\
\hline
CMS & $-1.7%-6.5%-4.4\%$ & $54.2^{+4.0\%+6.5\%+4.4\%}_{-4.0%-6.5%-4.4\%}$ \\
$\sigma_{WW}^\text{veto}$ [pb] & & \\
\hline
Theory & $44.9^{+3.8\%-3.1\%}$ & $46.8^{+2.5\%-2.3\%}$ \\
$\sigma_{WW}^\text{veto}$ [pb] & & \\
\hline
Theory & $2.6^{+13.3\%-11.7\%}$ & $2.9^{+11.5\%-11.5\%}$ \\
$\sigma_{h\rightarrow WW}$ [pb] & & \\
\hline
\end{tabular}
\end{table}

[Jaiswal, Okui 1407.4537]