Status of OpenLoops and simulation of $H \rightarrow WW$ backgrounds with Sherpa+OpenLoops

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Based on
F. Cascioli, S. Höche, F. Krauss, P. M., S. Pozzorini, and F. Siegert
arXiv:1309.0500
Outline

1. **The OpenLoops Algorithm**
   - Loop Amplitudes and Tensor Integrals
   - Open Loops Recursion
   - Performance and Numerical Stability

2. **Sherpa+OpenLoops**
   - Interfacing Sherpa with OpenLoops
   - Process libraries for ATLAS and CMS

3. **Irreducible background to** $H \rightarrow WW^* + 0,1\text{ jet}$
   - $p_T$ Distribution and Jet Veto Effects
   - Squared Loop Contributions
   - ATLAS and CMS Analyses
Tensor integral representation of loop amplitudes

Decompose Feynman diagrams into **colour factors**, tensor coefficients, and tensor integrals.

\[
p_1 \rightarrow p_2 p_3 p_4 \rightarrow q \rightarrow \ldots \rightarrow p_N \rightarrow p_5
\]

\[
\begin{align*}
&= C \cdot \sum_{r=0}^{R} \mathcal{N}_{r}^{\mu_{1}...\mu_{r}} \cdot \int d^{d}q \frac{q_{\mu_{1}} \cdots q_{\mu_{r}}}{D_{0} D_{1} \cdots D_{N-1}} \\
&D_{i}=(q+\sum_{\ell=0}^{i} p_{\ell})^{2} - m_{i}^{2}
\end{align*}
\]

- **Algebraic colour reduction** and summation once per process.
- **Recursive numerical construction of the coefficients**
  
  [van Hameren ‘09: Dyson-Schwinger recursion for multi-gluon amplitudes]

  → avoid huge expressions & expensive algebraic simplifications.

- **Tensor integral reduction** [Melrose; Passarino, Veltman; Denner, Dittmaier; Binoth et al.; Fleischer, Riemann; ...]
  
  with **Collier** [Denner, Dittmaier, Hofer]: Denner-Dittmaier reduction cures numerical instabilities, e.g. by applying expansions in small Gram determinants.

- Alternatively **OPP reduction** [Ossola, Papadopoulos, Pittau]
  
  with **CutTools** or **Samurai** [Mastrolia, Ossola, Reiter, Tramontano].
Wave functions $w^\alpha$ of “sub-trees” are 4-tuples (for the spinor/Lorentz index) which are built by recursively connecting lower sub-trees with vertices $X_{\gamma\delta}^\beta$ and propagators, starting from external legs.

$$w^\beta(i) = \frac{X_{\gamma\delta}^\beta}{p_i^2 - m_i^2} w^\gamma(j) w^\delta(k)$$

A one-loop diagram is an ordered set of sub-trees $I_n = \{i_1, \ldots, i_n\}$

$$\mathcal{N}(I_n; q) = \frac{X_{\gamma\delta}^\beta}{p_0^2 - m_0^2} \mathcal{N}_\alpha^\beta(I_{n-1}; q) w^\delta(i_n)$$
Open Loops Recursion

Start from $\mathcal{N}_\alpha^\beta(\mathcal{I}_n; q) = X_\gamma^\beta(q) \mathcal{N}_\alpha^\gamma(\mathcal{I}_{n-1}; q) w_\delta^\beta(i_n)$

and disentangle the loop momentum $q$ from the coefficients

$$\mathcal{N}_\alpha^\beta(\mathcal{I}_n; q) = \sum_{r=0}^{n} \mathcal{N}_{\mu_1...\mu_r;\alpha}(\mathcal{I}_n) q^{\mu_1} ... q^{\mu_r}, \quad X_\gamma^\beta = Y_\gamma^\beta + q^\nu Z_\nu^\beta;_\gamma^\delta$$

Leads to the recursion formula for “open loops” polynomials $\mathcal{N}_{\mu_1...\mu_r;\alpha}$:

$$\mathcal{N}_{\mu_1...\mu_r;\alpha}(\mathcal{I}_n) = \left[ Y_\gamma^\beta \mathcal{N}_{\mu_1...\mu_r;\alpha}(\mathcal{I}_{n-1}) + Z_{\mu_1;\gamma}^\beta \mathcal{N}_{\mu_2...\mu_r;\alpha}(\mathcal{I}_{n-1}) \right] w_\delta^\beta(i_n)$$

- $\mathcal{N}_{\mu_1...\mu_r;\alpha}$ are the coefficients of the tensor integrals.
- Open loops encode the functional dependence of the numerator of the amplitude on the loop momentum.
- Numerical implementation requires only universal building blocks, derived from the Feynman rules of the theory.
Implementation and performance

Input: process definition file

- **FeynArts** [Hahn] generates Feynman diagrams.
- Mathematica organises recursion, reduces colour factors, and generates Fortran 90 code.
- QCD corrections to Standard Model processes implemented.
- Rational terms $R_2$ are restored using tree-level Feynman rules.

[Draggiotis, Garzelli, Malamos, Papadopoulos, Pittau ‘09, ‘10; Shao, Zhang, Chao ‘11]

Time to generate code: seconds to minutes

Compiled library size: 100 kB to a few MB

Runtime per phase space point: <1 s for a $2 \rightarrow 4$ process (i7-750 single core, ifort 10.1)
Numerical Stability

\[ \sqrt{s} = 1 \text{ TeV}, \ p_T > 50 \text{ GeV}, \ \Delta R_{ij} > 0.5, \ 10^6 \text{ points/process} \]

- Numerical precision, measured by a scale test using tensor integrals, in double precision;
- 11-15 digits on average, 1 permille with <5 digits in the worst 2 → 4 case for well separated particles.

- “Suspicious” points are detected on-the-fly and rescued if possible.
- In practice, e.g. decaying particles can be aligned with the beam: in \( \text{pp} \rightarrow \ell\ell\nu\nu j \) a fraction of \( O(10^{-4}-10^{-5}) \) of the points is unstable.
- In NNLO real emission, MC integration in soft regions is stable down to \( 10^{-4}Q \) (double precision). See talk by Dirk Rathlev.
- Quad precision support is available and can be used on-the-fly for even more challenging applications and reliable stability studies.
Sherpa+OpenLoops

Loop matrix elements are one building block of NLO simulations.

The Sherpa [Gleisberg et al. ‘09] Monte Carlo event generator provides

- IR subtraction, real emission, phase space integration
- parton shower and MC@NLO matching [Höche, Krauss, Schönherr, Siegert ‘12]
- MEPS@NLO multi-jet merging [Höche, Krauss, Schönherr, Siegert ‘13]
- ...

Sherpa+OpenLoops

- Seamless integration via dynamic library loader.
- Steered by standard Sherpa runcards, matrix element generation is completely transparent to the user.

Fully automated NLO calculations
Process libraries for ATLAS and CMS

Libraries for a wide range of processes are available to the ATLAS and CMS Monte Carlo groups.

<table>
<thead>
<tr>
<th>W/Z</th>
<th>jets</th>
<th>HQ pairs</th>
<th>single-top</th>
<th>Higgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>V + 3j</td>
<td>γ+3j</td>
<td>t\bar{t} + 1j</td>
<td>t + 1(2)j</td>
<td>(H + 2j)</td>
</tr>
<tr>
<td>VV + 2j</td>
<td>γγ+1(2)j</td>
<td>t\bar{t}V + 0(1)j</td>
<td>tW + 0(1)j</td>
<td>VH + 1j</td>
</tr>
<tr>
<td>gg → VV + 1j</td>
<td>Vγ+2j</td>
<td>\bar{b}bV + 0(1)j</td>
<td></td>
<td>t\bar{t}H</td>
</tr>
<tr>
<td>VVV + 0(1)j</td>
<td></td>
<td></td>
<td></td>
<td>qq → Hqq + 0(1)j</td>
</tr>
</tbody>
</table>

(including lower jet multiplicities)

- Validated process-by-process (> 100 partonic channels).
- Automatic regression tests (Python bindings).
- All contributing 1-loop diagrams, full colour.
- Off-shell leptonic W/Z decays (complex masses).
- First step towards a public OpenLoops release.
Irreducible background to $H \rightarrow WW^* + 0,1$ jet

Signal: two opposite sign leptons + $E_T^{\text{miss}}$, binned in jet multiplicities.

Data driven analysis: normalise background (from MC simulation) to data in control region (left) and extrapolate to signal region (right). Percent level theory extrapolation uncertainty required.
The OpenLoops Algorithm

Irreducible background to $H \rightarrow WW^* + 0,1$ jet

$H \rightarrow WW^* \rightarrow e^- \nu_e \mu^+ \nu_\mu$ in exclusive 0-/1-jet bins

Previously available predictions for $pp \rightarrow e^- \nu_e \mu^+ \nu_\mu + 0/1$ jets

<table>
<thead>
<tr>
<th>jets</th>
<th>NLO</th>
<th>gg induced</th>
<th>NLO+PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>[Campbell, Ellis, Williams ‘11]</td>
<td>[Binoth et al. ‘05]  [Campbell, Ellis, Williams ‘11]</td>
<td>[Melia et al. ‘11] [Frederix et al. ‘11]</td>
</tr>
<tr>
<td>1</td>
<td>[Dittmaier, Kallweit, Uwer ‘07] [Campbell, Ellis, Zanderighi ‘07]</td>
<td>[Melia et al. ‘12] [Agrawal, Shivaji ‘12]</td>
<td></td>
</tr>
</tbody>
</table>

Requirements go beyond fixed order NLO

- Exclusive jet bins → disentangle production modes ($ggH$, VBF), and background sources ($WW$, $t\bar{t}$).
- Jet vetoes to suppress $t\bar{t}$ background ($\ln p_T^{\text{veto}} +$ uncertainties).
- Exclusive observables → parton shower / Sudakov resummation.
- Squared quark loop contributions.
- NLO accuracy in jet bins → MEPS@NLO jet merging.
Setup of NLO simulations

We compare simulations with different accuracy levels to study the impact of parton shower, loop\(^2\), and jet merging effects.

<table>
<thead>
<tr>
<th>simulation</th>
<th>0-jet</th>
<th>1-jet</th>
<th>2-jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLO 4(\ell)</td>
<td>NLO</td>
<td>LO</td>
<td>-</td>
</tr>
<tr>
<td>NLO 4(\ell)+1(j)</td>
<td>-</td>
<td>NLO</td>
<td>LO</td>
</tr>
<tr>
<td>MC@NLO 4(\ell)</td>
<td>NLO+PS</td>
<td>LO+PS</td>
<td>PS</td>
</tr>
<tr>
<td>MC@NLO 4(\ell)+1(j)</td>
<td>-</td>
<td>NLO+PS</td>
<td>LO+PS</td>
</tr>
<tr>
<td>MEPS@NLO 4(\ell)+0,1(j)</td>
<td>NLO+PS</td>
<td>NLO+PS</td>
<td>LO+PS</td>
</tr>
<tr>
<td>LOOP(^2) 4(\ell)</td>
<td>LO</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LOOP(^2) 4(\ell)+1(j)</td>
<td>-</td>
<td>LO</td>
<td>-</td>
</tr>
<tr>
<td>LOOP(^2)+PS 4(\ell)</td>
<td>LO+PS</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>LOOP(^2)+PS 4(\ell)+1(j)</td>
<td>-</td>
<td>LO+PS</td>
<td>PS</td>
</tr>
<tr>
<td>MEPS@LOOP(^2) 4(\ell)+0,1(j)</td>
<td>LO+PS</td>
<td>LO+PS</td>
<td>PS</td>
</tr>
</tbody>
</table>

- \(\sqrt{s} = 8\) TeV, CT10NLO PDFs.
- All off-shell, interference, and spin correlation effects.
- Central scale \(\mu_0 = (E_T^{W^+} + E_T^{W^-})/2\), factor 2 variations of QCD scales, factor \(\sqrt{2}\) variation of resummation scale.
- In MEPS@NLO, \(\mu_0\) is used in the core process, and a CKKW scale for jet emission \(\alpha_s(bk_T)\).
Jet $p_T$ distribution

- Inclusive NLO and MC@NLO predictions underestimate hard jet emission (LO accuracy).
- IR singularity of NLO $4\ell$: enhancement in low $p_T$ region (20%@5 GeV) → Sudakov logs are important, but no dramatic effects.
- In NLO $4\ell + j$ the $\alpha_s$ scale is not adapted to the jet $p_T$ → growing deviations wrt. MEPS@NLO for large $p_T$.
Jet veto effects

exclusive 0-jet bin

- Moderate Sudakov effects beyond NLO: 5% deviation of NLO $4\ell$ at $p_T = 30$ GeV.
- Percent level uncertainties (subleading logs and higher order effects).

inclusive 1-jet bin

- Sizable discrepancies between the different simulations:
  20-30% deficit of MC@NLO, up to 20% excess of NLO $4\ell + j$ in the tail.
Squared loop diagram contributions

At loop\(^2\)-level the gluon fusion channel \(gg \rightarrow 4\ell(\pm j)\) opens, a finite and gauge invariant subset of NNLO contributions.

Can give sizable contributions due to the large gluon flux.

- First result of loop\(^2\) \(gg \rightarrow 4\ell + 0,1\) jets ME+PS merging.
- Finite matrix elements → apply LO merging techniques
  
  [Höche, Krauss, Schumann, Siegert '09]
- Parton shower introduces \(qg, \bar{q}g, q\bar{q}\) channels via \(g \rightarrow q\bar{q}\) splittings. Corresponding matrix elements must be included for consistency.
Squared loop jet-\(p_T\) distribution

**gg-only vs. all channels**

- Quark channels enhance hard jet emission, Sudakov suppression at low \(p_T\).
- Shape distortion of \(\pm 50\%\).

**Merging effects \((Q_{\text{cut}} = 20 \text{ GeV})\)**

- Parton shower describes low \(p_T\) jet emission up to \(Q_{\text{cut}}\), but shows a sizable deficit at large \(p_T\).
- 1-jet matrix elements dominate in large \(p_T\) region.
Lepton Distance Distributions

Rivet implementation of ATLAS & CMS analyses: exclusive 0-/1-jet bins, preselection, signal, control region cuts, distributions in $p_T$, $m_{\ell\ell}$, $\Delta \phi_{\ell\ell}$, $m_T$.

- Few % agreement in 0-jet bin, 10-15% deficit of MC@NLO in 1-jet bin.
- Loop$^2$ effects: up to 8%, largest in the signal region + different kinematical dependence.
- Few % scale uncertainties (QCD + resummation) in MEPS@NLO.
Cross sections in 0-jet and 1-jet bins

Cross sections in the signal and control regions for ATLAS @ 8 TeV

<table>
<thead>
<tr>
<th>( \sigma ) [fb]</th>
<th>NLO</th>
<th>MC@NLO</th>
<th>MEPS@NLO</th>
<th>MEPS@LOOP(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_S ) (0j)</td>
<td>34.28(9) +2.1% -1.6%</td>
<td>32.52(8) +2.1% +1.2% -0.8% -0.7%</td>
<td>33.81(12) +1.4% +2.0% -2.2% -0.4%</td>
<td>1.98(2) +23% -16.5% -20%</td>
</tr>
<tr>
<td>( \sigma_C ) (0j)</td>
<td>55.76(9) +2.0% -1.7%</td>
<td>52.28(9) +1.4% +1.4% -0.7% -1.1%</td>
<td>54.18(15) +1.4% +2.5% -1.9% -0.4%</td>
<td>2.41(2) +22% +27% -17% -18%</td>
</tr>
<tr>
<td>( \sigma_S ) (1j)</td>
<td>8.99(4) +4.9% -9.5%</td>
<td>8.02(4) +8.5% +0% -6.4% -3.1%</td>
<td>9.37(9) +2.6% +2.5% -2.7% -0.0%</td>
<td>0.46(1) +40% +2.2% -18% -6.3%</td>
</tr>
<tr>
<td>( \sigma_C ) (1j)</td>
<td>26.50(8) +6.4% -12.5%</td>
<td>24.58(8) +6.1% +1.2% -6.5% -3.0%</td>
<td>28.32(13) +3.1% +4.1% -4.7% -0.0%</td>
<td>0.79(1) +33% +15% -20% -7%</td>
</tr>
</tbody>
</table>

- Error estimation from QCD scales and resummation scale.
- Squared-loop effects up to 6\% in the signal region.

<table>
<thead>
<tr>
<th>( \sigma_S / \sigma_C )</th>
<th>NLO</th>
<th>MC@NLO</th>
<th>MEPS@NLO</th>
<th>MEPS@NLO+LOOP(^2)</th>
<th>( \delta_S / C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-jets</td>
<td>0.615 -0.1% -0.1%</td>
<td>0.622 -0.7% +0.2% +0.1% -0.4%</td>
<td>0.624 +0% +0.5% -0.3% -0%</td>
<td>0.632 -0.3% +0.2% +0.5% +0.3%</td>
<td>1.3%</td>
</tr>
<tr>
<td>1-jet</td>
<td>0.339 +1.4% -3.4%</td>
<td>0.326 -2.3% +1.2% -0.1% +0.1%</td>
<td>0.331 +0.5% +1.5% -2.1% -0%</td>
<td>0.338 -0.4% +1.8% -1.8% +0.1%</td>
<td>2.1%</td>
</tr>
</tbody>
</table>

- Correlated scale variations yield unrealistically small errors.
- loop\(^2\) gives insight into kinematic effects beyond NLO \( \rightarrow O(2\%) \) errors (experimental analysis assumes 1\%).
Summary

**OpenLoops**
- Diagrammatic, tree-like recursion for loop momentum polynomials to calculate one-loop amplitudes.
- Automatic, fast code generation, compact libraries.
- Fast and numerically stable evaluation of matrix elements.

**Sherpa+OpenLoops**
- Fully automated interface, NLO matching with parton shower and jet merging.
- Process libraries available to ATLAS and CMS.

**Predictions for** $H \rightarrow WW^*$ **background in 0/1-jet bins**
- NLO, MC@NLO, and MEPS@NLO simulations.
  - NLO accuracy and LL Sudakov resummation in individual jet bins.
- Detailed studies of various observables for ATLAS & CMS analyses.
- Small and more reliably estimated theoretical uncertainties.
$M_T$ in Signal Region

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$M_{ll}$ in Signal Region

$M_{ll}$ in ATLAS signal region ($N_{jets} = 0$)

$M_{ll}$ in CMS signal region ($N_{jets} = 0$)

$M_{ll}$ in ATLAS signal region ($N_{jets} = 1$)

$M_{ll}$ in CMS signal region ($N_{jets} = 1$)