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

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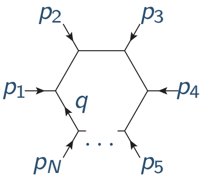
Based on
F. Cascioli, S. Höche, F. Krauss, P. M., S. Pozzorini, and F. Siegert
arXiv:1309.0500

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 $H \to WW^*$+0,1 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.



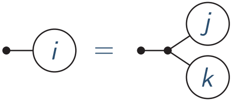
$$= \mathcal{C} \cdot \sum_{r=0}^{R} \mathcal{N}_r^{\mu_1\ldots\mu_r} \cdot \int d^d q \, \frac{q_{\mu_1}\ldots q_{\mu_r}}{D_0 \; D_1 \; \ldots \; D_{N-1}}$$

$$D_i=(q+\textstyle\sum_{\ell=0}^{i} p_\ell)^2-m_i^2$$

- **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].

From Tree Recursion to Open Loops

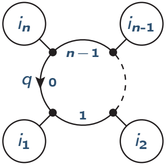
Wave functions w^α of "sub-trees" are 4-tuples (for the spinor/Lorentz index) which are built by recursivly connecting lower sub-trees with vertices $X^\beta_{\gamma\delta}$ and propagators, starting from external legs.



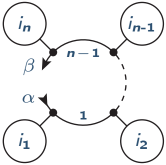
$$w^\beta(i) = \frac{X^\beta_{\gamma\delta}}{p_i^2 - m_i^2}\, w^\gamma(j)\, w^\delta(k)$$

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

$\mathcal{N}(\mathcal{I}_n; q) =$



$\xrightarrow{\text{cut } D_0}$ $\mathcal{N}^\beta_\alpha(\mathcal{I}_n; q) =$



Connect sub-trees along the loop to build the numerator $\mathcal{N} = \mathcal{N}^\alpha_\alpha$

$$\mathcal{N}^\beta_\alpha(\mathcal{I}_n; q) = X^\beta_{\gamma\delta}(q)\, \mathcal{N}^\gamma_\alpha(\mathcal{I}_{n-1}; q)\, w^\delta(i_n)$$

Open Loops Recursion

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

and disentangle the loop momentum q from the coefficients

$$\mathcal{N}^{\beta}_{\alpha}(\mathcal{I}_n; q) = \sum_{r=0}^{n} \mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_n)\, q^{\mu_1}\ldots q^{\mu_r}, \quad X^{\beta}_{\gamma\delta} = Y^{\beta}_{\gamma\delta} + q^{\nu} Z^{\beta}_{\nu;\gamma\delta}$$

Leads to the recursion formula for "open loops" polynomials $\mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}$:

$$\mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_n) = \left[Y^{\beta}_{\gamma\delta}\, \mathcal{N}^{\gamma}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_{n-1}) + Z^{\beta}_{\mu_1;\gamma\delta}\, \mathcal{N}^{\gamma}_{\mu_2\ldots\mu_r;\alpha}(\mathcal{I}_{n-1}) \right] w^{\delta}(i_n)$$

- $\mathcal{N}^{\alpha}_{\mu_1\ldots\mu_r;\alpha}$ 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

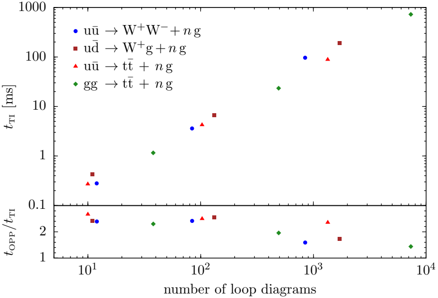
Input: process definition file

- 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 $2 \to 4$ process
(i7-750 single core, ifort 10.1)

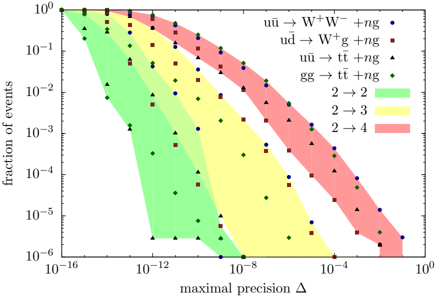


Numerical Stability

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 $2 \to 4$ case
for well separated particles

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



- "Suspicious" points are **detected on-the-fly** and **rescued** if possible.
- In practice, e. g. decaying particles can be aligned with the beam: in $pp \to \ell\ell\nu\nu j$ a fraction of $O(10^{-4}\text{-}10^{-5})$ 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.

W/Z	γ	jets	HQ pairs	single-top	Higgs
$V+3j$ $VV+2j$ $gg \to VV+1j$ $VVV+0(1)j$	γ+$3j$ $\gamma\gamma$+$1(2)j$ $V\gamma$+$2j$	$3(4)j$	$t\bar{t}+1j$ $t\bar{t}V+0(1)j$ $b\bar{b}V+0(1)j$	$tb+1j$ $t+1(2)j$ $tW+0(1)j$	$(H+2j)$ $VH+1j$ $t\bar{t}H$ $qq \to Hqq+0(1)j$

(including lower jet multiplicities)

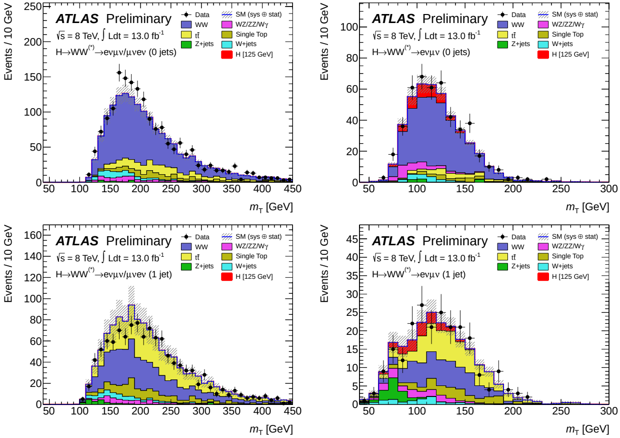
- Validated process-by-process ($>$ 100 partonic channels).
- Automatic regression tests (Python bindings).
- All contributing 1-loop diagrams, full colour.
- Off-shell leptonic W/Z decays (complex masses).
- First step towards a public OpenLoops release.

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

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

0-jets
75% WW

1-jet
40% WW



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.

$H \to WW^* \to e^-\bar{\nu}_e\mu^+\nu_\mu$ in exclusive 0-/1-jet bins

Previously available predictions for $pp \to e^-\bar{\nu}_e\mu^+\nu_\mu + 0/1\,\mathrm{jets}$

jets	NLO	gg induced	NLO+PS
0	[Campbell, Ellis, Williams '11]	[Binoth et al. '05] [Campbell, Ellis, Williams '11]	[Melia et al. '11] [Frederix et al. '11]
1	[Dittmaier, Kallweit, Uwer '07] [Campbell, Ellis, Zanderighi '07]	[Melia et al. '12] [Agrawal, Shivaji '12]	

Requirements go beyond fixed order NLO

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

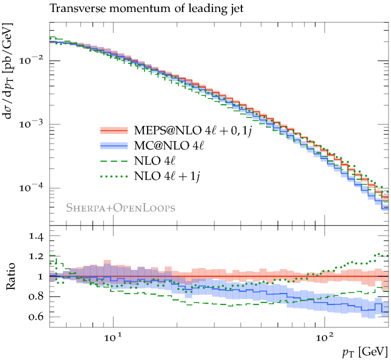
Setup of NLO simulations

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

simulation	0-jet	1-jet	2-jet
NLO 4ℓ	NLO	LO	-
NLO $4\ell + 1j$	-	NLO	LO
MC@NLO 4ℓ	NLO+PS	LO+PS	PS
MC@NLO $4\ell + 1j$	-	NLO+PS	LO+PS
MEPS@NLO $4\ell + 0, 1j$	NLO+PS	NLO+PS	LO+PS
LOOP² 4ℓ	LO	-	-
LOOP² $4\ell + 1j$	-	LO	-
LOOP²+PS 4ℓ	LO+PS	PS	PS
LOOP²+PS $4\ell + 1j$	-	LO+PS	PS
MEPS@LOOP² $4\ell + 0, 1j$	LO+PS	LO+PS	PS

- $\sqrt{s} = 8\,\text{TeV}$, 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, μ_0 is used in the core process, and a CKKW scale for jet emission $\alpha_s(bk_T)$.

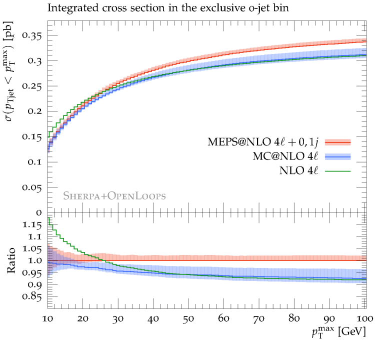
Jet p_T distribution

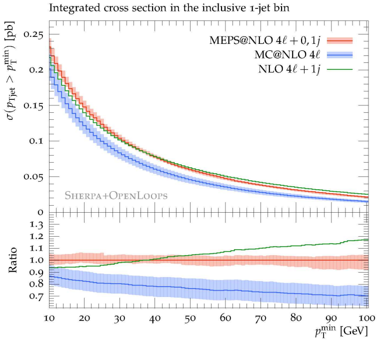


$p_T^\ell > 25$ GeV
$|\eta_\ell| < 3.5$
$\not{E}_T > 25$ GeV
anti-k_T jets
$R = 0.4$

- Inclusive NLO and MC@NLO predictions underestimate hard jet emission (LO accuracy).
- IR singularity of NLO 4ℓ: enhancement in low p_T region (20%@5 GeV) $\to$ Sudakov logs are important, but no dramatic effects.
- In NLO $4\ell + j$ the α_s scale is not adapted to the jet p_T $\to$ 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 4ℓ at $p_T = 30$ GeV.
- Percent level uncertainties (subleading logs and higher order effects).

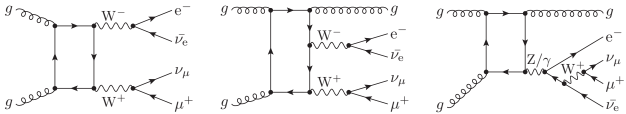
inclusive 1-jet bin

- Sizable discrepancies between the different simulations:

  20-30% deficit of MC@NLO, up to 20% excess of NLO $4\ell + j$ in the tail.

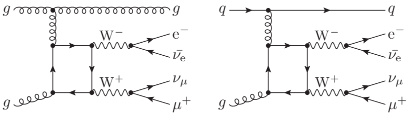
Squared loop diagram contributions

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



Can give sizable contributions due to the large gluon flux.

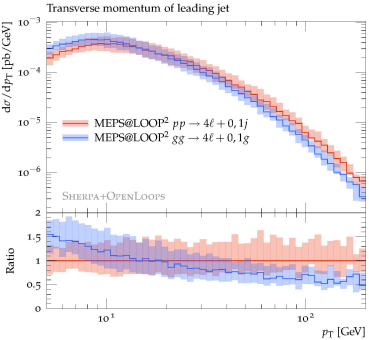
- First result of loop^2 $gg \to 4\ell + 0, 1$ jets ME+PS merging.
- Finite matrix elements $\to$ apply LO merging techniques
  [Höche, Krauss, Schumann, Siegert '09]
- Parton shower introduces qg, $\bar{q}g$, $q\bar{q}$ channels via $g \to q\bar{q}$ splittings. Corresponding matrix elements must be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

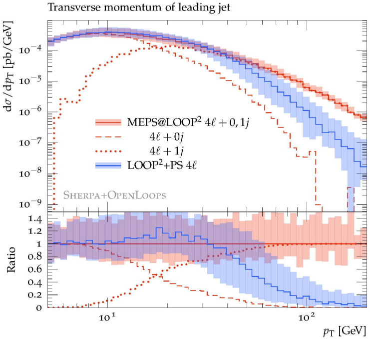


Squared loop jet-p_T distribution

gg-only vs. all channels

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



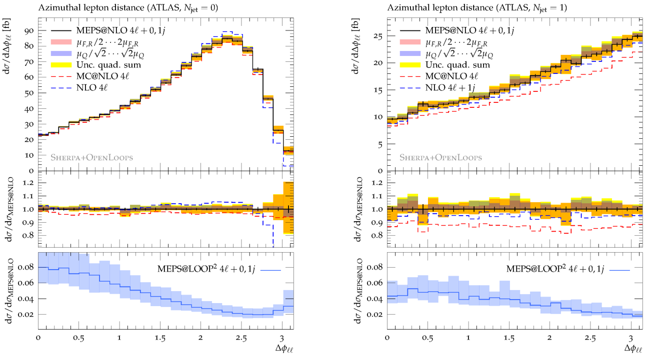


Merging effects ($Q_{\text{cut}} = 20\,\text{GeV}$)

- Parton shower describes low p_T jet emission up to Q_{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

σ [fb]	NLO	MC@NLO	MEPS@NLO	MEPS@LOOP^2
σ_S (0j)	$34.28(9)\,^{+2.1\%}_{-1.6\%}$	$32.52(8)\,^{+2.1\%}_{-0.8\%}\,^{+1.2\%}_{-0.7\%}$	$33.81(12)\,^{+1.4\%}_{-2.2\%}\,^{+2.0\%}_{-0.4\%}$	$1.98(2)\,^{+23\%}_{-16.5\%}\,^{+27\%}_{-20\%}$
σ_C (0j)	$55.76(9)\,^{+2.0\%}_{-1.7\%}$	$52.28(9)\,^{+1.4\%}_{-0.7\%}\,^{+1.4\%}_{-1.1\%}$	$54.18(15)\,^{+1.4\%}_{-1.9\%}\,^{+2.5\%}_{-0.4\%}$	$2.41(2)\,^{+22\%}_{-17\%}\,^{+27\%}_{-18\%}$
σ_S (1j)	$8.99(4)\,^{+4.9\%}_{-9.5\%}$	$8.02(4)\,^{+8.5\%}_{-6.4\%}\,^{+0\%}_{-3.1\%}$	$9.37(9)\,^{+2.6\%}_{-2.7\%}\,^{+2.5\%}_{-0.0\%}$	$0.46(1)\,^{+40\%}_{-18\%}\,^{+2.2\%}_{-6.3\%}$
σ_C (1j)	$26.50(8)\,^{+6.4\%}_{-12.5\%}$	$24.58(8)\,^{+6.1\%}_{-6.5\%}\,^{+1.2\%}_{-3.0\%}$	$28.32(13)\,^{+3.1\%}_{-4.7\%}\,^{+4.1\%}_{-0.0\%}$	$0.79(1)\,^{+33\%}_{-20\%}\,^{+15\%}_{-7\%}$

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

σ_S/σ_C	NLO	MC@NLO	MEPS@NLO	MEPS@NLO+LOOP^2	$\delta_{S/C}$
0-jets	$0.615\,^{-0.1\%}_{-0.1\%}$	$0.622\,^{-0.7\%}_{+0.1\%}\,^{+0.2\%}_{-0.4\%}$	$0.624\,^{+0\%}_{-0.3\%}\,^{+0.5\%}_{-0\%}$	$0.632\,^{-0.3\%}_{+0.5\%}\,^{+0.2\%}_{+0.3\%}$	1.3%
1-jet	$0.339\,^{+1.4\%}_{-3.4\%}$	$0.326\,^{-2.3\%}_{-0.1\%}\,^{+1.2\%}_{+0.1\%}$	$0.331\,^{+0.5\%}_{-2.1\%}\,^{+1.5\%}_{-0\%}$	$0.338\,^{-0.4\%}_{-1.8\%}\,^{+1.8\%}_{+0.1\%}$	2.1%

- Correlated scale variations yield unrealistically small errors.
- loop^2 gives insight into kinematic effects beyond NLO
  $\to O(2\%)$ 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.

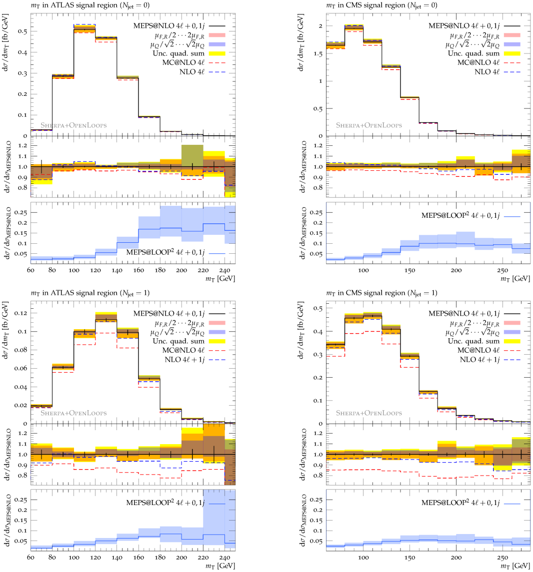
Predictions for $H \to WW^*$ background in 0/1-jet bins

- 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.

Backup

Backup Slides

M_T in Signal Region



$M_{\ell\ell}$ in Signal Region