Predictions for $H \to WW^*$ background in exclusive jet bins with Sherpa+OpenLoops

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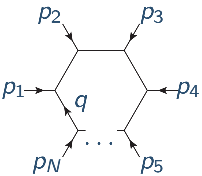
Based on
F. Cascioli, P. M., S. Pozzorini
PRL **108** (2012) 111601 [arXiv:1111.5206]
and
F. Cascioli, S. Höche, F. Krauss, P. M., S. Pozzorini, and F. Siegert
arXiv:1309.0500

Outline

1. **NLO Automation with Sherpa+OpenLoops**
   - The OpenLoops Matrix Element Generator
   - Sherpa+OpenLoops
2. **Irreducible background to $H \to WW^*$+0,1 jet**
   - p_T Distribution and Jet Veto Effects
   - Squared Loop Contributions
   - Cross Sections and Extrapolation Uncertainties
   - $W^+W^-b\bar{b}$ with massive bottom quarks

The OpenLoops Matrix Element Generator

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



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

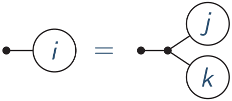
$D_i = (q + \sum_{\ell=0}^{i} p_\ell)^2 - m_i^2$

- **Algebraic colour reduction** and summation once per process.
- **Tensor integral reduction** [Melrose; Passarino, Veltman; Denner, Dittmaier; Binoth et al.; Fleischer, Riemann; & many others]
  with `Collier` [Denner, Dittmaier, Hofer]: cures numerical instabilities, e. g. by applying expansions in small Gram determinants.
- **Recursive numerical construction of the coefficients $\mathcal{N}_r^{\mu_1 \ldots \mu_r}$**
  - Avoid huge expressions & expensive algebraic simplifications.
  - 4-dimensional → rational terms R_2 are restored using tree-level Feynman rules.

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

From Tree Recursion to Open Loops

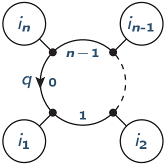
Wave functions w^α of "sub-trees" are 4-tuples (for the spinor/Lorentz index) which are built by recursivly connecting lower sub-trees with vertices $X^\beta_{\gamma\delta}$ and propagators, starting from external legs.



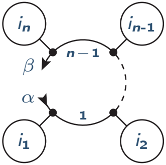
$$w^\beta(i) = \frac{X^\beta_{\gamma\delta}}{p_i^2 - m_i^2}\, w^\gamma(j)\, w^\delta(k)$$

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.

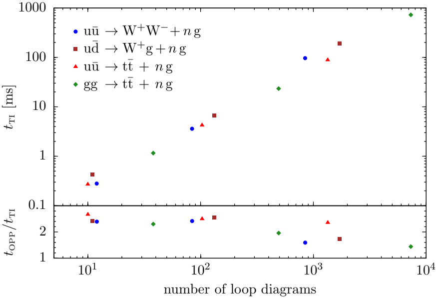
Performance and Numerical Stability

Performance

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



Numerical stability

- Numerically stable in double precision almost everywhere.
- "Suspicious" points are detected on-the-fly and rescued if possible.
- Critical kinematics: decaying particles can be aligned with the beam: in $pp \to \ell\ell\nu\nu j$ a fraction of $O(10^{-4}$-$10^{-5})$ of the points is unstable.
- In NNLO real-virtual corrections, MC integration in soft regions is stable down to $10^{-4}\sqrt{s}$ in double precision.
- **New**: on-the-fly switching to quad precision.

Sherpa+OpenLoops

Full automation of NLO simulations:
combine OpenLoops with Monte Carlo event generators.

Sherpa [Gleisberg et al. '09] 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

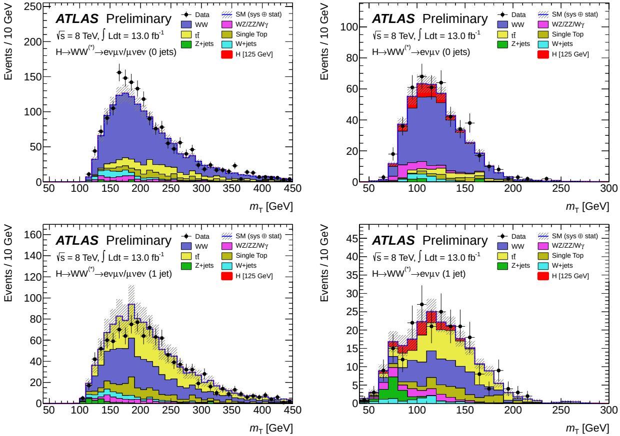
- Steered by standard Sherpa runcards,
  matrix element generation is completely transparent to the user.
- Available to ATLAS and CMS Monte Carlo working groups,
  including libraries for a wide range of processes.
- Process-by-process validated for over 100 partonic channels.

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 $pp \to e^- \bar{\nu}_e \mu^+ \nu_\mu + 0/1\,\text{jets}$

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

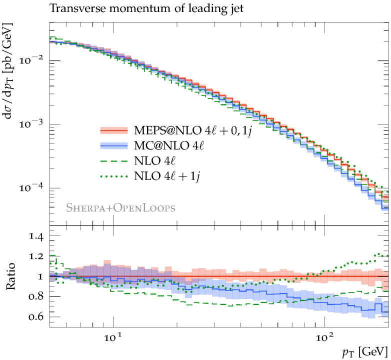
Setup of NLO simulations

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

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

- All off-shell, interference, and spin correlation effects.
- Central scale $\mu_0 = (E_T^{W^+} + E_T^{W^-})/2$, factor 2 variation of QCD scales, factor $\sqrt{2}$ variation of resummation scale.
- In MEPS@NLO, μ_0 is used in the core process, CKKW scale for jet emission.
- `Rivet` implementation of ATLAS & CMS analyses: 0-/1-jet bins, preselection, signal, control region cuts, distr. in p_T, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_T.

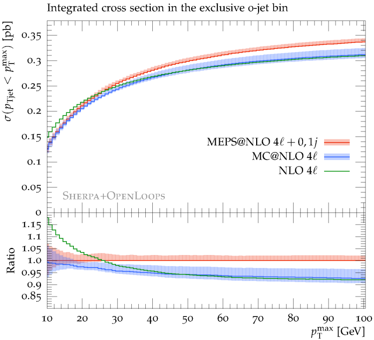
Jet p_T distribution

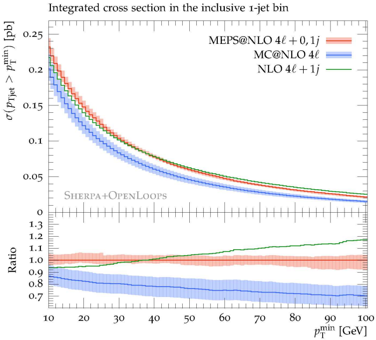


$p_T^\ell > 25$ GeV
$|\eta_\ell| < 3.5$
$\not{E}_T > 25$ GeV
anti-k_T jets
$R = 0.4$

- 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) $\rightarrow$ 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 $\rightarrow$ growing deviations wrt. MEPS@NLO for large p_T.

Jet veto effects





exclusive 0-jet bit

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

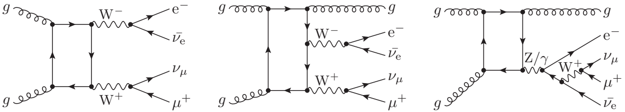
inclusive 1-jet bit

- Sizable discrepancies between the different simulations:

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

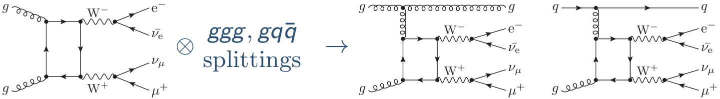
Squared loop diagram contributions

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



Can give sizable contributions due to the large gluon flux.

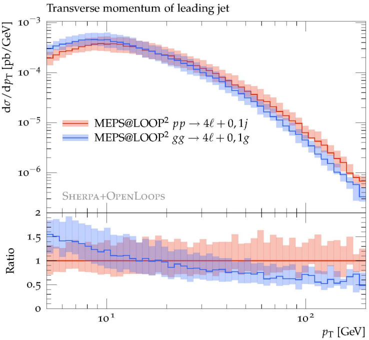
- First result of loop^2 $gg \to 4\ell + 0, 1$ jets ME+PS merging.
- Finite matrix elements → apply tree-level merging techniques
- Parton shower introduces qg, $\bar{q}g$, $q\bar{q}$ channels via $g \to q\bar{q}$ splittings.
  Corresponding matrix elements must be included for consistency.

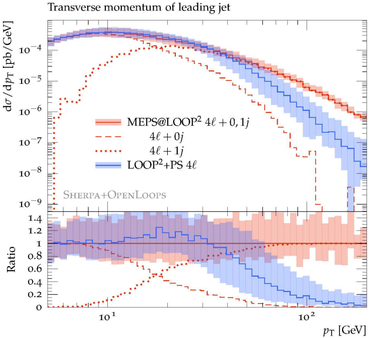


Squared loop jet-p_T distribution

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_{cut} = 20 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.

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.
- Loop^2 effects up to 6% in the signal region (larger in distributions).

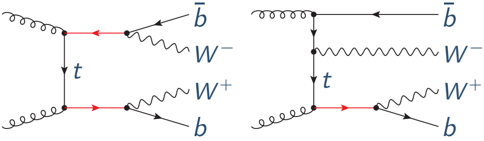
σ_S/σ_C	NLO	MC@NLO	MEPS@NLO	MEPS@NLO+LOOP^2	$\delta_{S/C}$
0-jets	0.615 $^{-0.1\%}_{-0.1\%}$	0.622 $^{-0.7\%}_{+0.1\%}{}^{+0.2\%}_{-0.4\%}$	0.624 $^{+0\%}_{-0.3\%}{}^{+0.5\%}_{-0\%}$	0.632 $^{-0.3\%}_{+0.5\%}{}^{+0.2\%}_{+0.3\%}$	1.3%
1-jet	0.339 $^{+1.4\%}_{-3.4\%}$	0.326 $^{-2.3\%}_{-0.1\%}{}^{+1.2\%}_{+0.1\%}$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

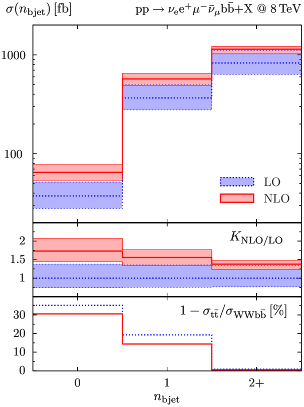
$W^+W^-b\bar{b}$ with massive bottom quarks

NLO QCD $W^+W^-b\bar{b}$ with $m_b > 0$

[Cascioli, Kallweit, PM, Pozzorini arXiv:1312.0546]



- Consistent unified description of $t\bar{t}$, Wt, and $W^+W^-b\bar{b}$ (double-, single-, non-resonant) production with interferences at NLO.
- Full b quark phase space.
- Contribution to $H \to WW$ in 0- and 1-jet bins accessible.



similar study presented recently: [Frederix '13] | with massless b quarks: [Denner, Dittmaier, Kallweit, Pozzorini '11; Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '11]

Summary

OpenLoops

- Diagrammatic recursion for loop momentum polynomials
  + tensor integral reduction to calculate one-loop amplitudes.
- Automatic, fast, numerically stable.
- **Sherpa+OpenLoops**: fully automated interface,
  NLO matching with parton shower, jet merging, ...

$H \to WW^*$ background in exclusive jet bins

- NLO, MC@NLO, and MEPS@NLO simulations.
  NLO+PS accuracy in 0- and 1-jet bins.
- Detailed studies of various observables for ATLAS & CMS analyses.
- Small and more reliably estimated theoretical uncertainties,
  especially in the presence of jet vetos.
- $W^+W^-b\bar{b}$ with massive bottom quarks & contributions to jet bins