NLO automation with OpenLoops and new results for H→WW* irreducible background

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Outline

- NLO automation
- OpenLoops algorithm
- Sherpa+OpenLoops
- Irreducible background to $H \to WW^* + 0, 1$ jets
- Conclusions

Introduction

After Higgs discovery at 8 TeV we have to measure its couplings and continue to explore BSM searches. Move to higher $\sqrt{s}$ and $\mathcal{L}$.

- High energy $\Rightarrow$ many-particles final-states.
- Large theoretical uncertainties at leading-order (LO) up to $\mathcal{O}(100\%)$.
- Need next-to-leading order (NLO) corrections to many multi-particle processes.

New techniques have allowed to compute several NLO processes with ≥ 6 particles.

$pp \to t\bar{t}\, b\bar{b}$	[Bredenstein, Denner, Dittmaier, Pozzorini '09]
	[Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09]
$pp \to t\bar{t}\, jj$	[Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '10]
$pp \to WW\, b\bar{b}$	[Denner, Dittmaier, Kallweit, Pozzorini '11]
	[Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '11]
$pp \to b\bar{b}\, b\bar{b}$	[Greiner, Guffanti, Reiter, Reuter '11]
	[Bevilacqua, Czakon, Krämer, Kubocz, Worek '13]
$pp \to WW\, jj$	[Melia, Melnikov, Rontsch, Zanderighi '10]
	[Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano '12]
$pp \to W/Z + 3j$	[Ellis, Melnikov, Zanderighi '09]
	[Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre '09–'10]
$pp \to W/Z + 4j$	[Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre '11]
$pp \to 4j$	[Bern, Diana, Dixon, Febres Cordero, Hoeche, Kosower, Ita, Maitre, Ozeren '11]
$pp \to W + 5j$	[Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre, Ozeren '13]
$pp \to W\gamma\gamma\, j$	[Campanario, Englert, Rauch, Zeppenfeld '11]
$e^+e^- \to 7j$	[Becker, Goetz, Reuschle, Schwan, Weinzierl '11]
$pp \to t\bar{t}\, t\bar{t}$	[Bevilacqua, Worek '12]
$pp \to WZ\, jj$	[Campanario, Kerner, Ninh, Zeppenfeld '13]

Introduction

Various important 6-particles LHC processes have been computed...

- 2005/2007 Les-Houches priority list: $t\bar{t}b\bar{b}$, $t\bar{t}jj$, $WWb\bar{b}$, $WWjj$, $Vjjj$, $b\bar{b}b\bar{b}$

... but plenty of things still need to be done!

- Decays of unstable particles (at NLO).
- Beyond parton-level NLO (parton shower, jet merging).
- Beyond QCD (EW corrections, large impact on BSM searches at TeV scale).
- Beyond LH wish-list ($Hjjj$, $AAjj$, $ZZjj$, $Vb\bar{b}j$, $VVVj$, $AAt\bar{t}$, $VVt\bar{t}$, $AAb\bar{b}$, $ZZb\bar{b}$, $AAWW, \dots$)

Such a program is unconceivable without automation!

Automatised tools for one-loop calculations

Technical challenges

- Speed: slow codes $> 1\,\mathrm{sec/point} \Rightarrow$ CPU-months for precise distributions.
- Automation: handle up to $\mathcal{O}(10^4)$ diagrams minimizing needed human power.
- Stability: spurious singularities can introduce serious numerical instabilities.

`BlackHat`	[Bern, Diana, Dixon, Febres Cordero, Kosower, Ita, Maitre, Ozeren]
`GoSam`	[Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano]
`HELAC-NLO`	[Bevilacqua, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau, Worek]
`MadLoop`	[Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau]
`NGluon`	[Badger, Biedermann, Uwer, Yundin]
`Recola`	[Actis, Denner, Hofer, Scharf, Uccirati]
`CutTools`	[Ossola, Papadopoulos, Pittau]
`Collier`	[Denner, Dittmaier, Hofer]

OpenLoops

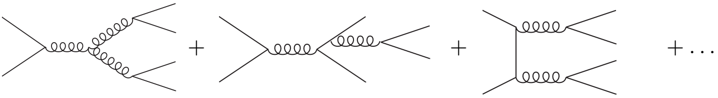
New automated algorithm that maximises both speed and flexibility. [FC, Maierhöfer, Pozzorini '12]

- Numerical and recursive diagrammatic approach.
- Tensor integrals [`Collier`] or OPP reduction [`Samurai, CutTools`].
- Fully general in terms of processes and models.
- One-loop amplitudes in terms of q-dependent tree structures (*open loops*).

Feynman Diagrams & OpenLoops

Numerical recursion for trees

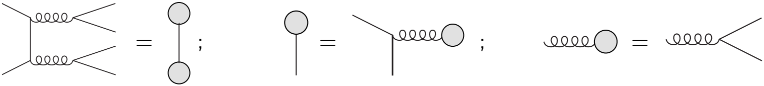
$$\mathcal{M} = \sum_d \mathcal{M}^{(d)} =$$



- Factorisation of individual diagrams in colour factors and colour-stripped amplitudes.

$$\mathcal{M}^{(d)} = \mathcal{C}^{(d)} \mathcal{A}^{(d)}$$

- Colour reduction and sums are done algebraically only once ⇒ zero CPU cost.
- Starting from external legs, connect wave functions w^α with vertices and propagators to recursively build "sub-trees". They are n-tuples of complex numbers.



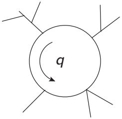
$$w^\beta = X^\beta_{\gamma\delta} w^\gamma w^\delta$$

- $X^\beta_{\gamma\delta}$ describes the interaction between particles (numerical routine).
- Feynman rules define set of *universal* vertices $X^\beta_{\gamma\delta}$ (depends only on $\mathcal{L}$).
- Diagrams are built merging sub-trees with recursive procedure (fully automatic).
- Many diagrams related by presence of common sub-trees ⇒ strong speed-up.

Computing one-loop amplitudes

A loop diagram is a set of sub-trees connected by loop propagators $D_i = (q+p_i)^2 - m_i^2 + \mathrm{i}\varepsilon$.

$$\delta\mathcal{M}^{(d)} =$$



$$= \int \mathrm{d}^D q \frac{\mathcal{N}(\mathcal{I}_n; q)}{D_0 D_1 \dots D_{n-1}}$$

The amplitude must be reduced to a combination of scalar integrals.

Tensor Reduction [Melrose '65] [Passarino, Veltman '79] [Binoth et al. '05] [Denner, Dittmaier '05]

$$\delta\mathcal{M}^{(d)} = \sum_{r=0}^{R} \mathcal{N}_{\mu_1 \dots \mu_r} \int \mathrm{d}^D q \frac{q^{\mu_1} \dots q^{\mu_r}}{D_0 D_1 \dots D_{n-1}}$$

- Recursive reduction of tensor integrals to scalar integrals.
- Avoid instabilities with Gram-determinant (and other) expansions.

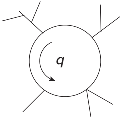
OPP Reduction [Ossola, Papadopoulos, Pittau '07]

$$\delta\mathcal{M}^{(d)} = \int d^D q \left[\sum_{i_1} \frac{a_{i_1}}{D_{i_1}} + \sum_{i_1,i_2} \frac{b_{i_1 i_2}}{D_{i_1} D_{i_2}} + \sum_{i_1,i_2,i_3} \frac{c_{i_1 i_2 i_3}}{D_{i_1} D_{i_2} D_{i_3}} + \sum_{i_1,i_2,i_3,i_4} \frac{d_{i_1 i_2 i_3 i_4}}{D_{i_1} D_{i_2} D_{i_3} D_{i_4}} \right]$$

- Direct reduction at the integrand level.
- $a_{i_1}, \dots, d_{i_1 i_2 i_3 i_4}$ from repeated evaluations of $\mathcal{N}(\mathcal{I}_n; q)$ at on-shell cuts.

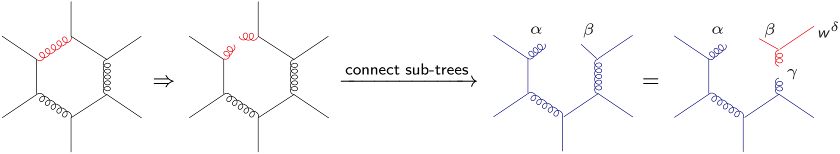
Building loops with (conventional) tree algorithms and OPP

$\delta\mathcal{M}^{(d)} =$



$= \int \mathrm{d}^D q \frac{\mathcal{N}(\mathcal{I}_n; q)}{D_0 D_1 \dots D_{n-1}}$

- The numerator contains all information about vertices and external sub-trees.
- Cut open the loop and build $\mathcal{N}$ using tree-level-like techniques.
- Recursively connect sub-trees along the loop.



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

- Build *n*-point cut loops by merging lower-point cut loops and sub-trees.
- High automation and flexibility.
- OPP reduction requires CPU expensive evaluations at multiple *q*-values.

Loop amplitudes require loop-momentum *q functional* dependence (integral over *q*).

Building loops with OpenLoops algorithm

Handle building blocks of recursion as *polynomials* in the loop momentum, separating q-monomials from coefficients, in what we call the *open loops* representation

$$\mathcal{N}^{\beta}_{\alpha}(\mathcal{I}_n; q) = \sum_{r=0}^{R} \mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_n)\; q^{\mu_1}\ldots q^{\mu_r}$$

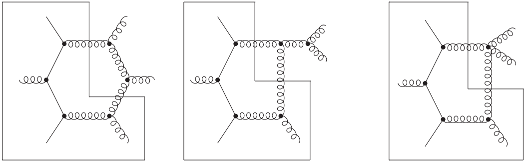
$$X^{\beta}_{\gamma\delta}(q) = Y^{\beta}_{\gamma\delta} + q^{\nu} Z^{\beta}_{\mu_1;\gamma\delta}$$

which leads to the *open loops* recursion

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

OpenLoops

- Simple concept but entirely new generator (fully general and automatic).
- Combines in an optimal way tree-recursion and tensor-integrals language.
- Recursive approach also allows to recycle open loops in different diagrams.



Implementation

Full automation of 1-loop QCD corrections to Standard Model processes

User input: process-definition file

- Generate Feynman diagrams [`FeynArts`].
- Skeleton of recursion, colour algebra, code generation [`Mathematica`].
- `Fortran` 90 code to compute matrix elements.

No user interaction required: process-file ⇒ code within seconds/minutes

Validation

- Automatised consistency checks.
- Numerical stability checks.
- Explicit checks of matrix elements for many processes.

Technical studies

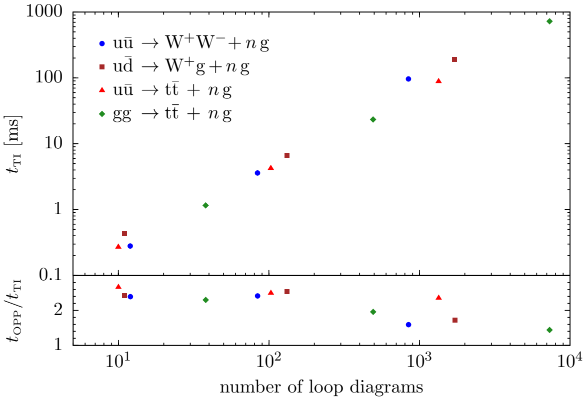
Performance

- Four families of $2 \to 2, 3, 4$ reactions with $n = 0, 1, 2$ gluons.
- Assess automation and flexibility of the generator.
- Investigate speed for non-trivial LHC processes.
- Assess numerical stability.

$$
\begin{aligned}
&u\bar{u} \to W^+ W^- + n\, g \\
&u\bar{d} \to W^+ g + n\, g \\
&u\bar{u} \to t\bar{t} + n\, g \\
&g\, g \to t\bar{t} + n\, g
\end{aligned}
$$

Speed studies

Runtime of col/hel summed matrix elements per phase space point

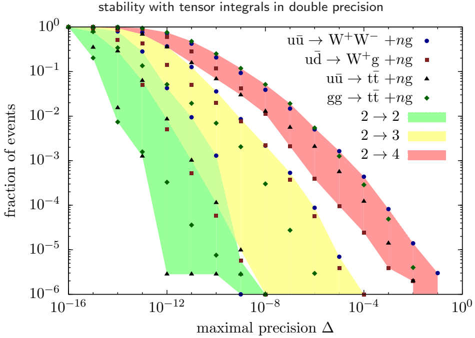


- Four orders of magnitude in complexity.
- CPU cost scales almost linearly.
- $2 \to 5$ and $\mathcal{O}(10^5)$ diagrams feasible.
- $t_{OPP} \simeq t_{TI}$ with open loops.

Stability studies

During reduction to scalar integrals one has to invert systems of algebraic equations. Appearance of determinants that become singular in particular kinematic configurations.

Numerical instabilities can give completely wrong numbers!



- we study twelve processes
- high statistics: 2×10^6 events/process
- probability of having less than 5 digits of precision $\simeq$ 1 permille in the worst 2 → 4 case

- Very good stability in double precision for $n_{\mathrm{part}} \leq 6$.
- Instabilities cured by `Collier` with Gram-determinant expansions. [Denner, Dittmaier '05]

Validation

One-loop amplitudes carefully checked before pheno applications.

Self-consistency checks

- UV/IR pole cancellations.
- Ward identities.
- OpenLoops vs standard trees.

Precision check against independent calculation

- We use an in-house computer-algebra generator (CAG) developed for $t\bar{t}b\bar{b}$ and $WWb\bar{b}$.
  [Bredenstein, Denner, Dittmaier, Kallweit, Pozzorini '09-'11]

Process	OpenLoops	CAG	agreement
$\bar{u}d \to e^-\bar{\nu}_e$	$1.75911512013164631 \cdot 10^{-5}$	$1.75911512013164970 \cdot 10^{-5}$	$2 \cdot 10^{-15}$
$\bar{u}d \to e^-\bar{\nu}_e\, g$	$1.44264278623861696 \cdot 10^{-6}$	$1.44264278623860193 \cdot 10^{-6}$	$1 \cdot 10^{-14}$
$\bar{u}d \to e^-\bar{\nu}_e\, gg$	$1.46590850889200081 \cdot 10^{-9}$	$1.46590850889179753 \cdot 10^{-9}$	$1 \cdot 10^{-13}$
$u\bar{u} \to e^-e^+$	$3.39939790956756674 \cdot 10^{-5}$	$3.39939790956757419 \cdot 10^{-5}$	$2 \cdot 10^{-15}$
$u\bar{u} \to e^-e^+\, g$	$7.00209271987758522 \cdot 10^{-7}$	$7.00209271987766145 \cdot 10^{-7}$	$1 \cdot 10^{-14}$
$u\bar{u} \to e^-e^+\, gg$	$6.93325400698801091 \cdot 10^{-9}$	$6.93325400699020542 \cdot 10^{-9}$	$3 \cdot 10^{-13}$

Similar agreement for more than 100 partonic processes!

Sherpa+OpenLoops

Monte Carlo event generators

- Event generators allow to simulate real-life scattering events. They are essential for the experimental analysis.
- OpenLoops (1-loop virtuals) can be interfaced with any tool that handles complementary tasks (real-emission, IR-subtraction, PS-integration).
- `Sherpa` is a multi-purpose generator including NLO+PS matching and MEPS@NLO merging. [Gleisberg et al. '09] [Höeche, Krauss, Schönherr, Siegert '13]

Dedicated interface of OpenLoops with Sherpa

- Full NLO automation (NLO calculations controlled via Sherpa Runcards).
- Extensive technical tests and validation already performed.
- Ready to produce phenomenological results with `Collier` as default reduction library.

Sherpa+OpenLoops

We provide ATLAS and CMS collaborations with a process library for NLO simulations.

Process library for ATLAS & CMS

- Careful process-by-process validation.
- Full set of 1-loop QCD diagrams, full colour.
- Off-shell leptonic W/Z decays: interferences, complex masses.

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

lower jet multiplicities implicitly understood

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

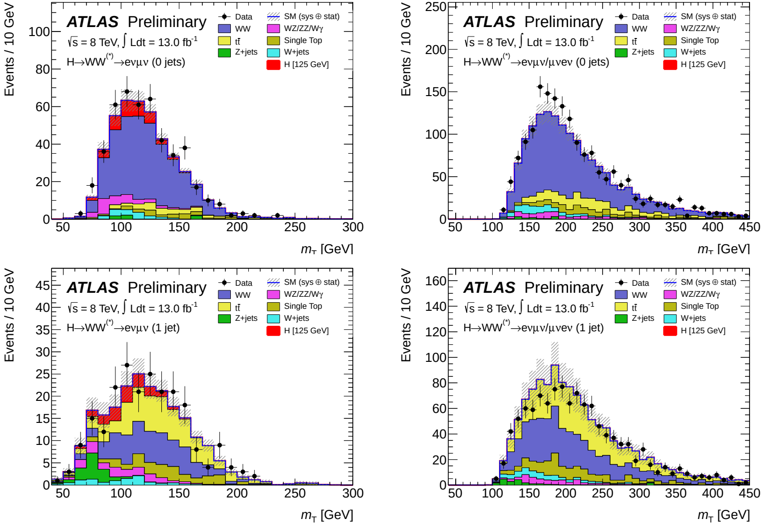
Irreducible background to $H \to WW^* \to e^- \bar{\nu}_e \mu^+ \nu_\mu$ in exclusive 0,1 jet bins

- Two opposite sign leptons + E_T^{miss}.
- Binned in jet multiplicities (different background and signal composition).
- Main WW bkg normalised to data in Control Region and *extrapolated* to Signal Region.

Signal Region **Control Region**

0-jets

1-jet



Irreducible background to $H \to WW^* \to e^- \bar{\nu}_e \mu^+ \nu_\mu +$ jets

Theory predictions for $pp \to e^- \bar{\nu}_e \mu^+ \nu_\mu +$jets

	NLO	**gg-induced**	**NLO+PS**
0 jets	[Campbell,Ellis,Williams '11]	[Binoth et al. '05] [Campbell,Ellis,Williams '11]	[Melia et al. '11] [Frederix et al. '11]
1 jet	[Dittmaier,Kallweit,Uwer '07] [Campbell,Ellis,Zanderighi '07]	[Melia et al. '12] [Agrawal,Shivaji '12]	
2 jets	[Jäger,Oleari,Zeppenfeld '06] [Melia et al. '12] [GoSam '12]		[Jäger,Zanderighi '13]

Sherpa+OpenLoops **(preliminary results)**

- NLO for $ll\nu\nu$+0,1 jets
- All off-shell, interference and spin-correlation effects.
- $gg \to ll\nu\nu$+0,1 jets in progress.
- Parton shower and jet merging.

Irreducible background to $H \to WW^* \to e^- \bar{\nu}_e \mu^+ \nu_\mu +$ jets

We compare predictions with **NLO**, MC@NLO and MEPS@NLO accuracy.

- **NLO** for $ll\nu\nu$+0,1 jets ⇒ no resummation.
- MC@NLO for $ll\nu\nu$ ⇒ LO in 1-jet bins.
- MEPS@NLO for $ll\nu\nu$+0,1 jets ⇒ NLO+LL in 0- and 1-jet bins.
- Detailed studies of ATLAS and CMS experimental analysis.

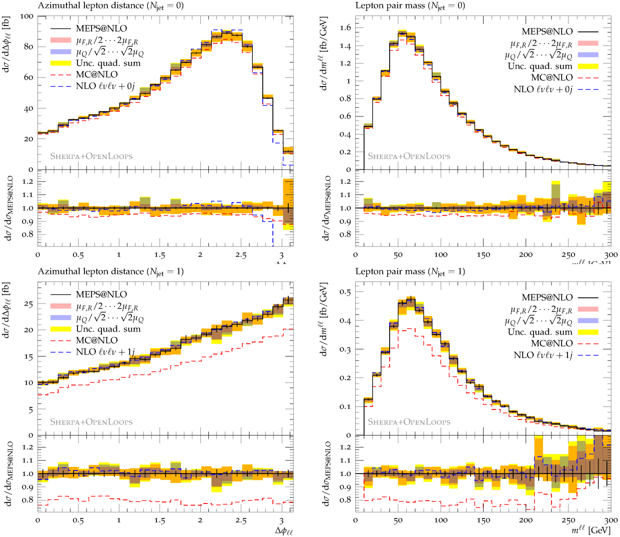
- Theoretical uncertainties estimated varying QCD scales μ_R, μ_F and resummation scale μ_Q.
- This allows to take into account $\ln(p_T^{\text{veto}})$ and to give realistic error estimates in jet bins.

Lepton observables in 0-jets and 1-jet bins: ATLAS preselection cuts

$\Delta\phi_{ll}$ m_{ll}

0-jets

1-jet



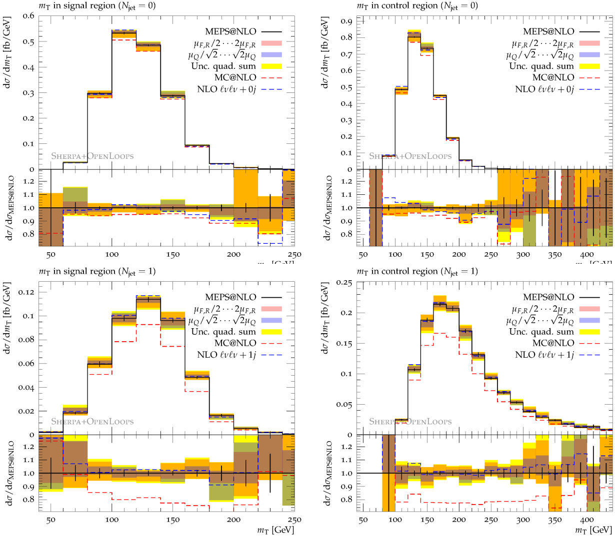
- Few-% agreement in 0-jets bin.
- 20% discrepancies between MC@NLO and MEPS@NLO in 1-jet bin.
- Small shape distortions.

Transverse WW mass in signal and control regions: ATLAS @ 8 TeV

Signal region **Control region**

0-jets

1-jet



- Few-% agreement in 0-jets bin.
- 20% discrepancies between MC@NLO and MEPS@NLO in 1-jet bin.
- Small shape distortions.

Exclusive 0/1-jet XS in Signal (S) and Control (C) regions

ATLAS analysis at 8 TeV

0-jets bin	**NLO** $\pm\Delta_{QCD}$	MC@NLO	MEPS@NLO $\pm\Delta_{QCD}$ $\pm\Delta_{res}$
σ_S [fb]	$35.08(9)\ ^{+2.0\%}_{-1.9\%}$	33.33(8)	$35.21(15)\ ^{+1.8\%}_{-3.3\%}\ ^{+1.7\%}_{-0.6\%}$
σ_C [fb]	$57.05(9)\ ^{+2.1\%}_{-2.0\%}$	53.76(9)	$56.76(17)\ ^{+2.3\%}_{-3.6\%}\ ^{+1.9\%}_{-0.3\%}$
σ_S/σ_C	0.615	0.620	0.620

1-jet bin	**NLO** $\pm\Delta_{QCD}$	MC@NLO	MEPS@NLO $\pm\Delta_{QCD}$ $\pm\Delta_{res}$
σ_S [fb]	$9.43(3)\ ^{+1.8\%}_{-4.7\%}$	7.43(4)	$9.23(9)\ ^{+3.5\%}_{-1.9\%}\ ^{+0.9\%}_{-0\%}$
σ_C [fb]	$29.14(6)\ ^{+1.6\%}_{-4.7\%}$	22.59(7)	$28.80(86)\ ^{+3.1\%}_{-2.5\%}\ ^{+1.4\%}_{-1.7\%}$
σ_S/σ_C	0.324	0.329	0.320

- **NLO**$\simeq$MEPS@NLO at $\mathcal{O}(1\%)$ level ⇒ small Sudakov logs.
- Confirmed by small Δ_{res} uncertainties.
- MC@NLO up to 22% smaller in 1-jet bin (LO accuracy).
- Small MEPS@NLO scale uncertainty.
- Good theoretical control of absolute XS and uncertainty in exclusive jet bins.

Conclusions

OpenLoops

- Numerical, recursive, diagrammatic algorithm.
- Implemented for QCD corrections to Standard Model processes.

Sherpa+OpenLoops

- Fully automated interface for NLO, MC@NLO, MEPS@NLO calculations.
- Library with lots of SM processes for ATLAS&CMS.

$H \to WW^*$ irreducible background

- New MEPS@NLO predictions with NLO+LL accuracy in 0- *and* 1-jet bins.
- Small theoretical uncertainties in exclusive jet bins.
- Todo: gg-channels, theo unct. in ratios (extrapolation from CR to SR), effects of hadronization and underlying event.