$\mathrm{H} \to \mathrm{WW}^*$ background in exclusive jet bins using Sherpa and OpenLoops

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Outline of the talk

NLO automation with OpenLoops+Sherpa

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

NLO Revolution and Automation

NLO calculations for $2 \to 4(5,6)$ processes at the LHC

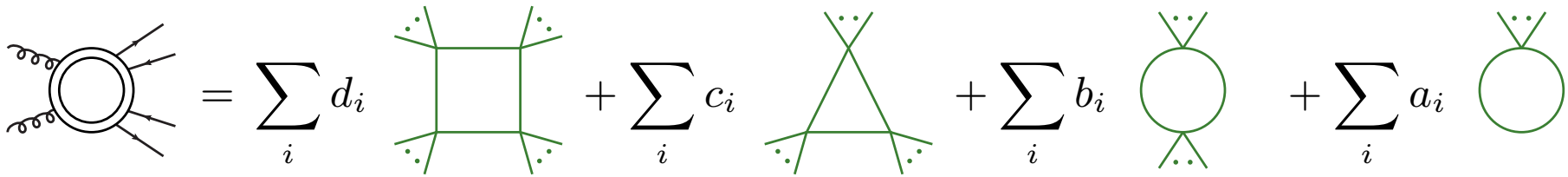
- many recent results (2009-2013): $jjjj$, $\mathrm{W}+5j$, $\mathrm{Z}+4j$, $\mathrm{WW}jj$, $\mathrm{WZ}jj$, $\mathrm{W}\gamma\gamma j$, $\mathrm{WWb\bar{b}}$, $\mathrm{b\bar{b}b\bar{b}}$, $\mathrm{t\bar{t}b\bar{b}}$, $\mathrm{t\bar{t}}jj$, $\mathrm{t\bar{t}t\bar{t}}$
- *multi-particle* processes increasingly important at high energy and luminosity

  $\Rightarrow$ more details: matching, merging, NLO decays (t,W,Z), NLO EW,...

  $\Rightarrow$ more processes: $Hjjj$, $\gamma\gamma jj$, $\mathrm{ZZ}jj$, $V\mathrm{b\bar{b}}j$, $VVVj$, $\gamma\gamma\mathrm{t\bar{t}}$, $VV\mathrm{t\bar{t}}$, $\gamma\gamma\mathrm{b\bar{b}}$, $\mathrm{ZZb\bar{b}}$, $\gamma\gamma\mathrm{WW}$, ...

NLO automation (indispensable)

- many new NLO tools: `CutTools`, `Samurai`, `FormCalc`, `HELAC-NLO`, `MadLoop`, `GoSam`, `BlackHat`, `NGluon`, `Collier`, `Recola`
- lot of MC progress (matching and merging): `aMC@NLO`, `POWHEG`, `Sherpa`



One-loop amplitudes (reduction to basis integrals)

- most serious bottlenecks (automation, flexibility, speed, stability)
- most significant conceptual progress (on-shell methods,. . .)
- maximising speed *and* flexibility still nontrivial

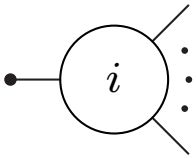
OpenLoops [Cascioli, Maierhöfer, S.P., PRL **108** (2012) 111601]

- novel, fast and fully flexible one-loop generator
- based on off-shell and "tree–loop hybrid" building blocks (open loops)
- 2-years old project now delivering first pheno results

OpenLoops algorithm

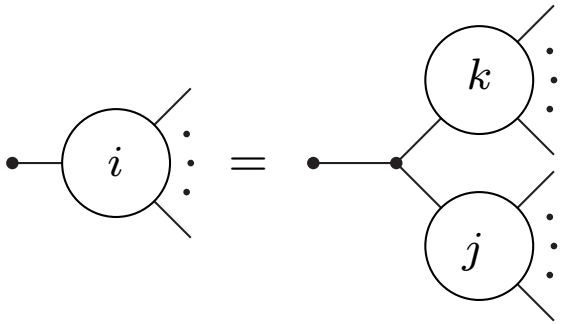
Tree generator

Colour-stripped tree **diagrams** are built **numerically** in terms of **sub-trees**

$w^\beta(i) =$ 

$\beta \leftrightarrow$ off-shell line spin

and **recursively merged** by attaching vertices and propagators

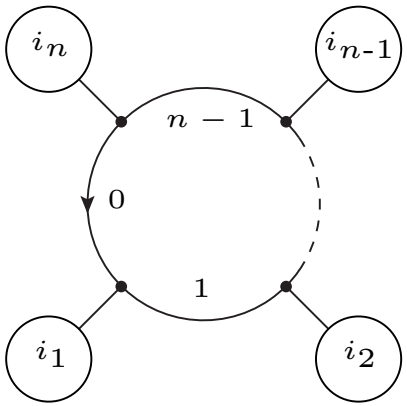


$$w^\beta(i) = \frac{X^\beta_{\gamma\delta}(i,j,k)}{p_i^2 - m_i^2}\, w^\gamma(j)\, w^\delta(k)$$

Flexible (only $\mathcal{L}_{\rm int}$ dependent), **fast** (many diagrams share *common sub-trees*)
efficient colour bookkeeping

Loop diagrams (reduction to basis integrals)

Colour-stripped **loop diagrams** are **ordered sets of sub-trees** connected by loop propagators $D_i = (q+p_i)^2 - m_i^2 + \mathrm{i}\varepsilon$,

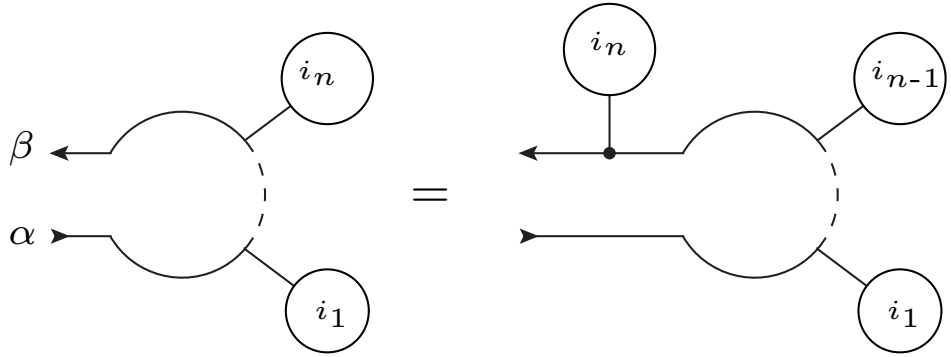


$$= \int \frac{\mathrm{d}^D q\, \mathcal{N}(\mathcal{I}_n; q)}{D_0 D_1 \ldots D_{n-1}} = \sum_{r=0}^{R} \mathcal{N}_{\mu_1 \ldots \mu_r}(\mathcal{I}_n) \underbrace{\int \frac{\mathrm{d}^D q\, q^{\mu_1} \ldots q^{\mu_r}}{D_0 D_1 \ldots D_{n-1}}}_{\text{tensor integral}}$$

We compute $\mathcal{N}_{\mu_1 \ldots \mu_r}(\mathcal{I}_n)$ (see later) and apply two alternative reductions:

(A) **Tensor-integral reduction** [Denner/Dittmaier '05] **avoids instabilities** (Gram-determinant expansions)

(B) **OPP reduction** [Ossola, Papadopolous, Pittau '07] is based on numerical $\mathcal{N}(\mathcal{I}_n; q)$ evaluations at multiple q-values: **huge speed-up exploiting** $\mathcal{N}_{\mu_1 \ldots \mu_r}(\mathcal{I}_n)$!



Tree generators for "usual" OPP-input $\mathcal{N}(\mathcal{I}_n; q)$

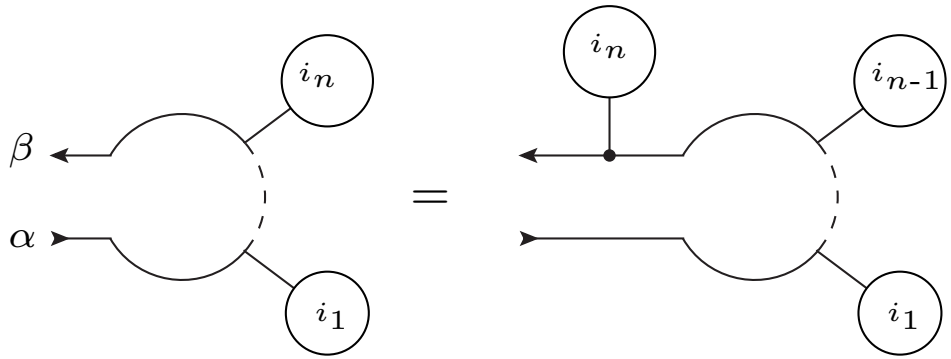
Cut-open loops can be built by recursively attaching external sub-trees

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

like in **conventional tree generators**

- one-loop automation in `Helac-NLO` (off-shell recursion) and `MadLoop` (diagrams)
- CPU expensive OPP reduction (multiple-q evaluations) since *tree algorithms conceived for fixed momenta*

Nature of loop amplitudes requires loop-momentum *functional* dependence!



OpenLoops recursion for $\mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_n)$

Handle building blocks of recursion as *polynomials* in the loop momentum q

$$\underbrace{\mathcal{N}^{\beta}_{\alpha}(\mathcal{I}_n;q)}_{\sum_{r=0}^{n}\mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_n)\,q^{\mu_1}\ldots q^{\mu_r}} = \underbrace{X^{\beta}_{\gamma\delta}(\mathcal{I}_n,i_n,\mathcal{I}_{n-1})}_{Y^{\beta}_{\gamma\delta}+q^{\nu}\,Z^{\beta}_{\nu;\gamma\delta}}\ \underbrace{\mathcal{N}^{\gamma}_{\alpha}(\mathcal{I}_{n-1};q)}_{\sum_{r=0}^{n-1}\mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_{n-1})\,q^{\mu_1}\ldots q^{\mu_r}}\ w^{\delta}(i_n)$$

and construct polynomial coefficients ("open loops") with

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

- **conceptually simple** (*tree recursion + tensor formalism*) but **entirely new** generator
- **fully flexible, automatic, and fast** (pinch identities, fast helicity/colour sums)

Implementation and technical performance

OpenLoops Implementation

One-loop QCD corrections to SM processes fully automated

- process-definition file $\Rightarrow$ `Fortran 90` libraries for matrix elements

Validation

- precision checks on more than 100 partonic reactions

Performance studies on 4 families of $2 \to 2, 3, 4$ reactions

- $\mathrm{u\bar{d}} \to \mathrm{W+} \leq 3\ \mathrm{g}$
- $\mathrm{u\bar{u}} \to \mathrm{WW+} \leq 2\ \mathrm{g}$
- $\mathrm{u\bar{u}} \to \mathrm{t\bar{t}+} \leq 2\ \mathrm{g}$
- $\mathrm{gg} \to \mathrm{t\bar{t}+} \leq 2\ \mathrm{g}$

Flexibility and Automation

Process	size [MB]	t_{code} [s]
$u\bar{u} \to t\bar{t}$	0.1	2.2
$u\bar{u} \to W^+W^-$	0.1	7.2
$u\bar{d} \to W^+g$	0.1	4.2
$gg \to t\bar{t}$	0.2	5.4
$u\bar{u} \to t\bar{t}g$	0.4	12.8
$u\bar{u} \to W^+W^-g$	0.4	39.8
$u\bar{d} \to W^+gg$	0.5	22.9
$gg \to t\bar{t}g$	1.2	52.9
$u\bar{u} \to t\bar{t}gg$	3.6 (200)*	236 ($\sim 10^6$)*
$u\bar{u} \to W^+W^-gg$	2.5 (1000)*	381.7 ($\sim 10^6$)*
$u\bar{d} \to W^+ggg$	4.2	366.2
$gg \to t\bar{t}gg$	16.0	3005

Compact code

- 100 kB to few MB object files
- $\mathcal{O}(10^2$–$10^3)$ compression in $2 \to 4$

Fast code generation/compilation

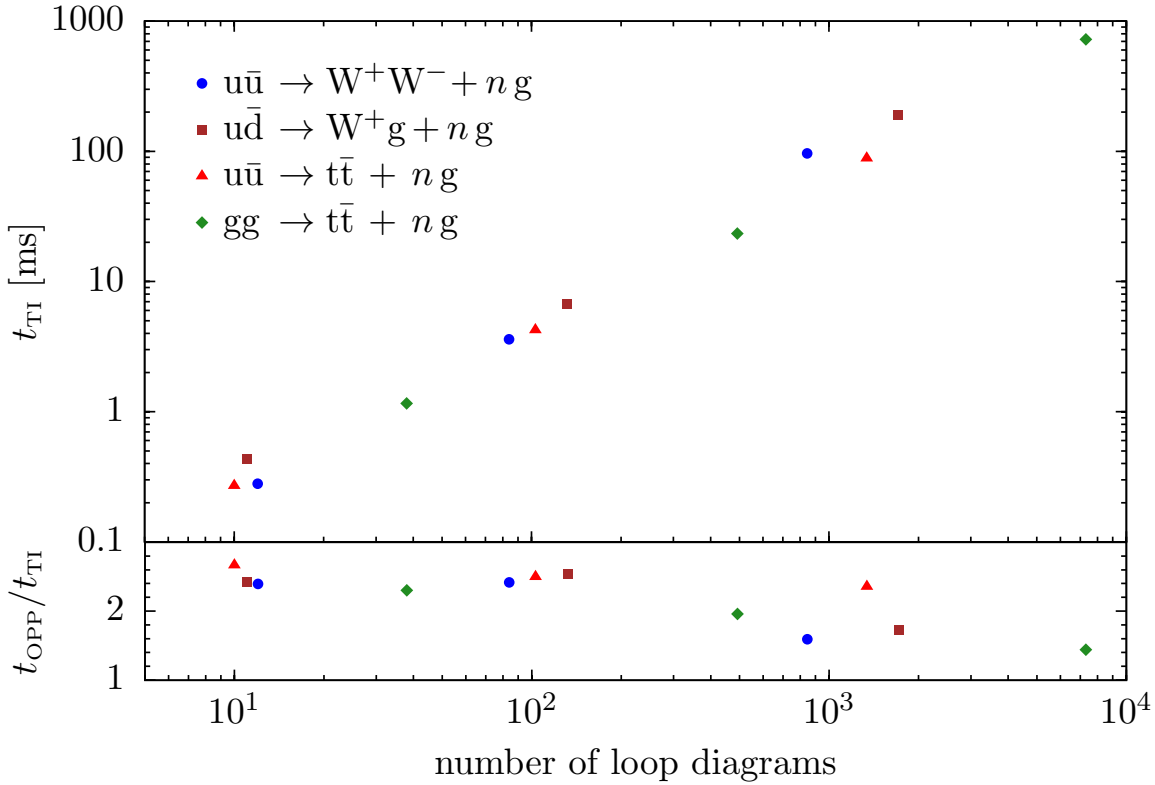
- few seconds to minutes
- $\mathcal{O}(10^3)$ speed-up in $2 \to 4$

Large-scale applicability!

*$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ & $\mathrm{WWb\bar{b}}$ (Bredenstein, Denner, Dittmaier, Kallweit and S.P. '09–'11)

High CPU efficiency for multi-particle LHC processes

Timings including col/hel sums (`single Intel i5-750` core)



$2 \to 4$ amplitudes

- $n_{\rm diag} = \mathcal{O}(10^3\text{–}10^4)$
- competitive with fastest codes

Extrapolating linear scaling

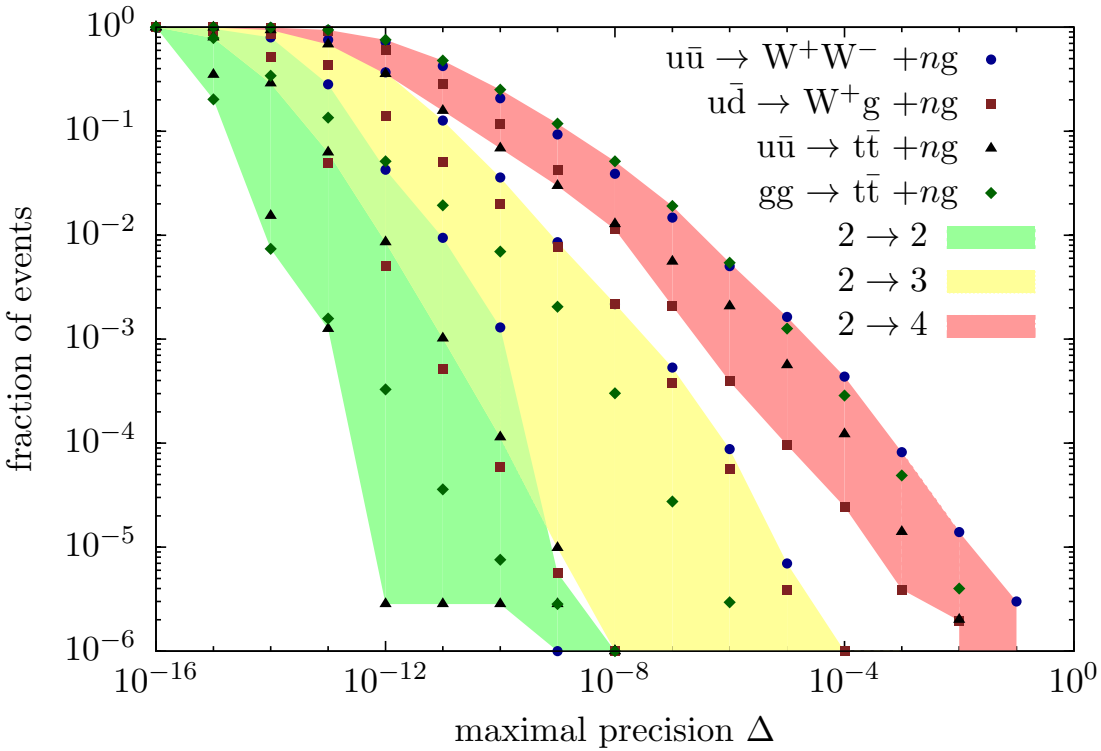
- $n_{\rm diag} = \mathcal{O}(10^5)$ and $2 \to 5$ feasible

$t_{\rm OPP} \simeq t_{\rm TI}$ with open loops!

Numerical stability with **tensor integrals** in double precision

Stability Δ_S in samples of 10^6 points ($\sqrt{\hat{s}} = 1\,\mathrm{TeV}$, $p_T > 50\,\mathrm{GeV}$, $\Delta R_{ij} > 0.5$)

$$\{p_i, m_j, \mu\} \to \{\xi p_i, \xi m_j, \xi\mu\}\,, \qquad \delta\mathcal{W} \to \delta\mathcal{W}' = \xi^K \delta\mathcal{W}, \qquad \Delta_S = \frac{\xi^{-K}\delta\mathcal{W}' - \delta\mathcal{W}}{\delta\mathcal{W}}$$



Average number of digits

- 11-15

Cross section accuracy

- depends on tails
- stability issues grow with n_{part}

$2 \to 4$ processes very stable

- $\lesssim 0.01\%$ prob. that $\Delta_S < 10^{-3}$

High stability thanks to Gram-determinant expansions in `COLLIER`

OpenLoops+Sherpa

Using OpenLoops with Sherpa2.0

- dedicated interface fully automates NLO (from process definition to event analysis)
- tensor reduction and scalar integrals with COLLIER [Denner/Dittmaier/Hofer]
- automated matching (MC@NLO) and merging of jet multiplicities (MEPS@NLO)

OpenLoops process library for MC working groups of ATLAS/CMS

- wide range of $2 \to 2, 3, 4$ processes
- public version in 2013

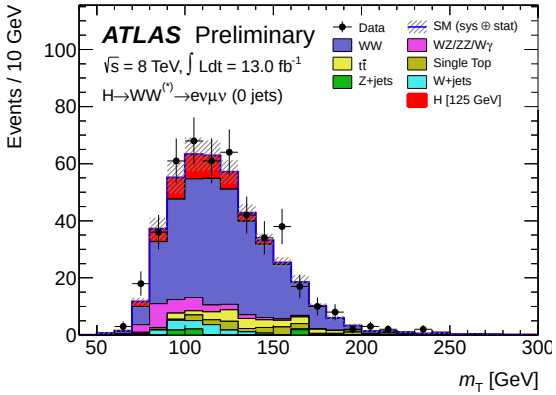
W/Z	γ	jets	HQ pairs	single-top	Higgs
V+3j	γ+3j	3(4)j	t$\bar{\text{t}}$+1j	tb+1j	(H+2j)
VV+2j	$\gamma\gamma$+1(2)j		t$\bar{\text{t}}V$+0(1)j	t+1(2)j	VH+1j
gg $\to VV$+1j	$V\gamma$+2j		b$\bar{\text{b}}V$+0(1)j	tW+0(1)j	t$\bar{\text{t}}$H
VVV+0(1)j					$qq \to$ Hqq+0(1)j

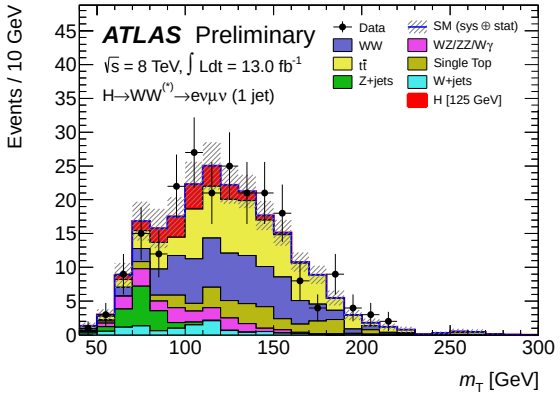
lower jet multiplicities implicitly understood

Irreducible Background to $\mathrm{H} \to \mathrm{WW}^* \to \mathrm{e}^- \bar{\nu}_\mathrm{e} \mu^+ \nu_\mu + 0, 1$ jets

0-jets 1-jet

SIGNAL





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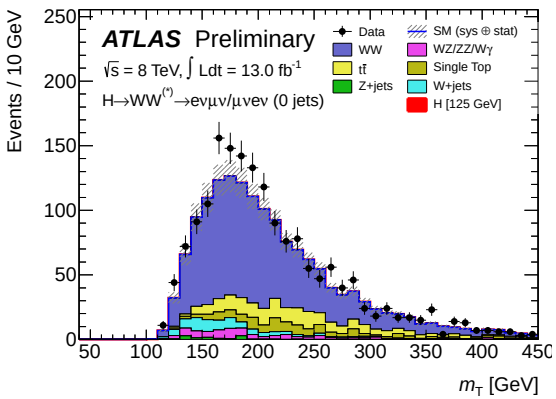
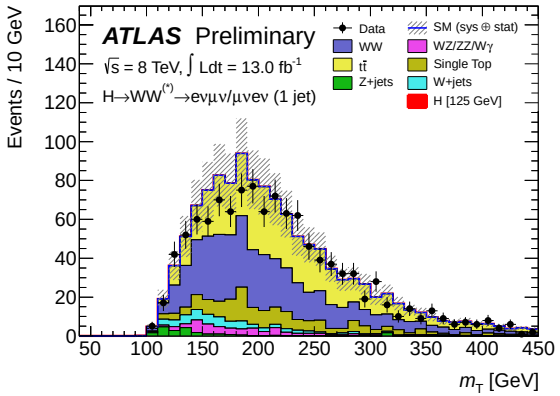




Nontrivial analysis

- large WW+tt backgrounds
- exclusive jet bins
- data driven WW+tt estimates (using MC simulations!)

Uncertainties small and crucial

- $\Delta\mu_\mathrm{H} = 20$–$30\%$ (assuming WW theory uncertainties $\sim 1\%$!)

Precise WW simulation requires:

- $\alpha_\mathrm{S}^n \ln^{2n}(p_\mathrm{T}^\mathrm{veto}/\mu_Q)$ in jet bins

$\Rightarrow$ NLO+PS with μ_Q-uncertainty

- loop-induced $gg \to ll\nu\nu + 0, 1$jets

Existing predictions for $\mathrm{pp} \to \mathrm{e}^- \bar{\nu}_\mathrm{e} \mu^+ \nu_\mu$+jets

	NLO	$gg \to ll\nu\nu$+jets	NLO+PS
0-jets	Campbell '11	Binoth et al. '05 Campbell '11	Melia et al. '11 (POWHEG) Frederix et al. '11 (MC@NLO)
1-jet	Dittmaier et al. '07 (OS) Campbell et al. '07 (OS)	Melia et al. '12 Agrawal,Shivaji '12	

Sherpa+OpenLoops predictions for $ll\nu\nu + 0, 1$ jets (see HXSWG YR3)

- MEPS@NLO [Höche,Krauss,Schönherr,Siegert '12] = merged 0/1-jets MC@NLO simulations
- loop-induced $gg \to ll\nu\nu + 0, 1$ jets (still in preparation)

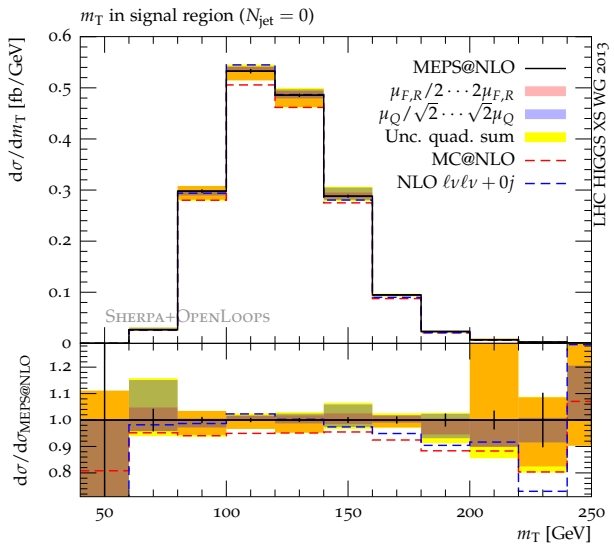
Features

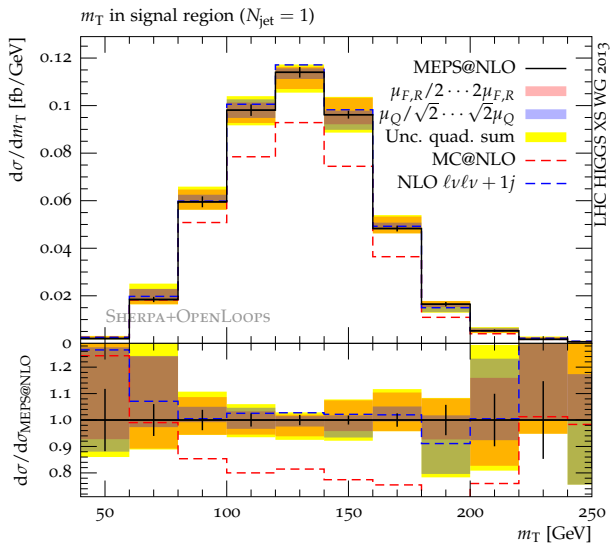
- more accurate (NLO+LL for 0/1 jets, gg channel open in 0/1 jet bins, ...)
- more realistic uncertainty with QCD ($\mu_{\mathrm{R,F}}$) *and* resummation (μ_Q) scale variations!
- all off-shell, interference and spin-correlation effects
- ATLAS and CMS analysis setup

Transverse WW mass in exclusive jet bins (ATLAS analysis)

0-jets | 1-jet

SIGNAL





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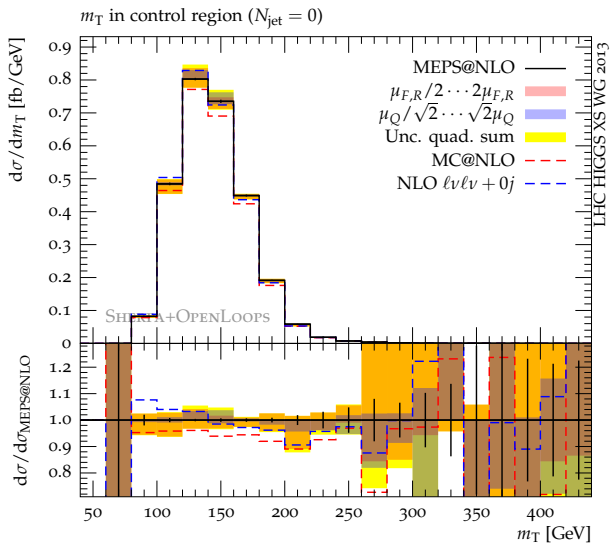
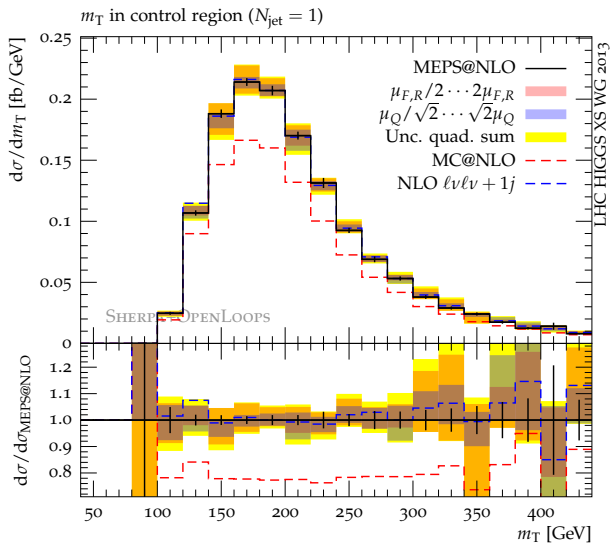


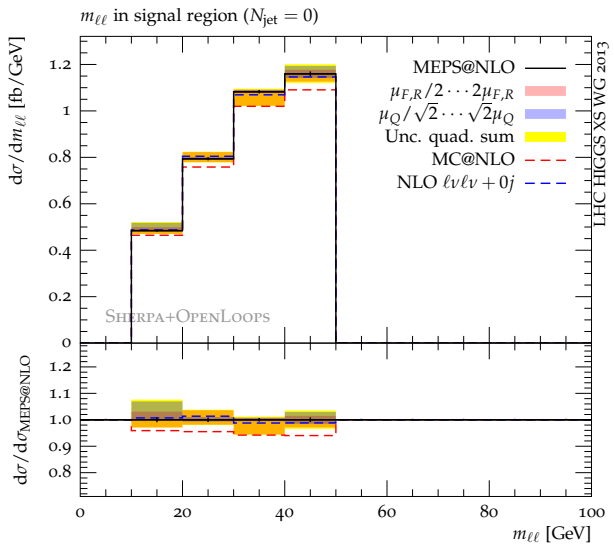


- **NLO** (no LLs) vs **MC@NLO** (LO for 1-jet) and **MEPS@NLO** (best) predictions
- $\mu_{R,F}$ and μ_Q colour-additive **MEPS@NLO variation bands** (percent precision!)

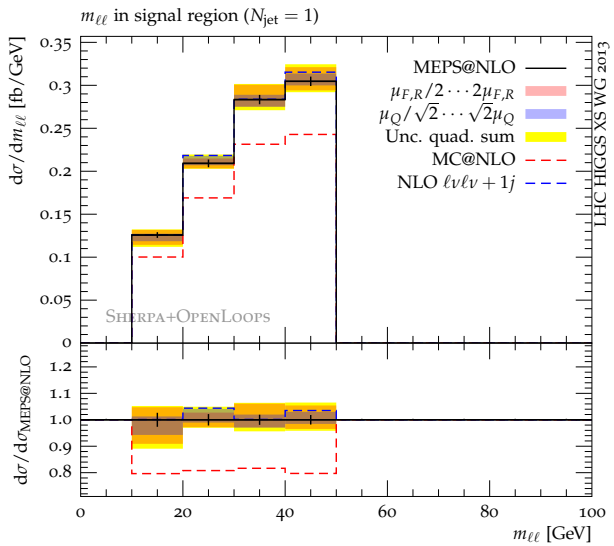
Dilepton mass in exlusive jet bins (ATLAS analysis)

SIGNAL

0-jets



1-jet



General observations (also for CMS analysis – see backup slides)

- 0-jet bin: various approximations agree at few-percent level
- 1-jet bin: 20% deficit of MC@NLO in 1-jet bin well understood (LO accuracy)
- small shape distortions might be relevant for precision of $H \to WW^*$ analysis

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

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

1-jet bin	**NLO** $\pm\Delta_{\rm QCD}$	**MC@NLO**	**MEPS@NLO** $\pm\Delta_{\rm QCD} \pm \Delta_{\rm res}$
$\sigma_{\rm S}$ [fb]	$9.43(3)\ ^{+1.8\%}_{-4.7\%}$	7.43(4)	$9.23(9)\ ^{+3.5\%}_{-1.9\%}\ ^{+0.9\%}_{-0\%}$
$\sigma_{\rm C}$ [fb]	$29.14(6)\ ^{+1.6\%}_{-4.7\%}$	22.59(7)	$28.80(21)\ ^{+3.1\%}_{-2.5\%}\ ^{+1.4\%}_{-1.7\%}$
$\sigma_{\rm S}/\sigma_{\rm C}$	0.324	0.329	0.320

Comparing predictions for absolute $\sigma_{\rm S,C}$ in 0(1)-jets bins

- small **NLO** vs **MEPS@NLO** differences: 0.5%(1–3%)
- more important **MC@NLO** vs **MEPS@NLO** differences: 5–8%(20–22%)

Scale uncertainty of MEPS@NLO for absolute $\sigma_{\rm S,C}$

- **more realistic** (Sudakov logs) and **surprisingly low**

$\Rightarrow$ theory-driven (instead of data-driven) WW estimate?

Summary

OpenLoops

- new one-loop generator: highly automated, stable and CPU efficient
- NLO QCD for SM processes with up to 6 (and maybe more) particles

Sherpa+OpenLoops

- fully automated NLO, MC@NLO, MEPS@NLO generation
- library with many SM processes for ATLAS/CMS
- widely applicable, first pheno studies ongoing

MEPS@NLO for irred. $\mathrm{H} \to \mathrm{WW}^*$ background in 0,1 jet bins

- NLO accuracy and LL Sudakov resummation for various jet multiplicities
- more realiable predictions *and* uncertainty estimates in jet bins
- next: loop-induced $gg \to ll\nu\nu + 0, 1$ jets

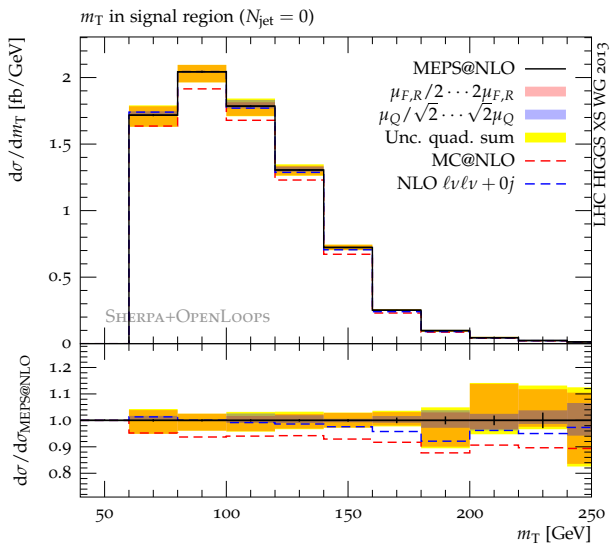
RESULTS FOR CMS ANALYSIS

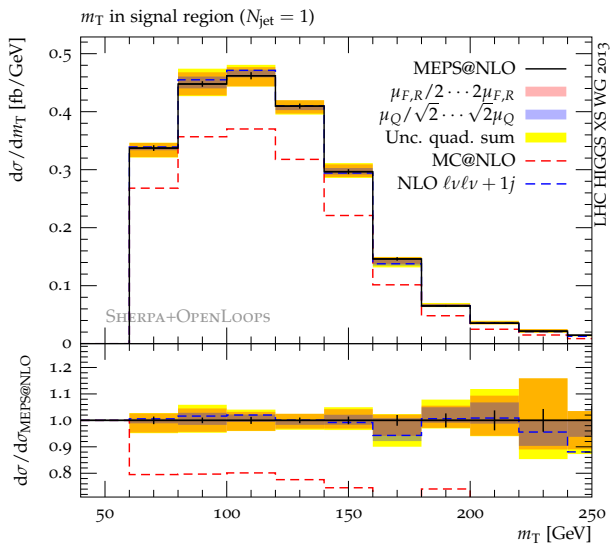
Transverse WW mass (CMS analysis)

0-jets

1-jet

SIGNAL





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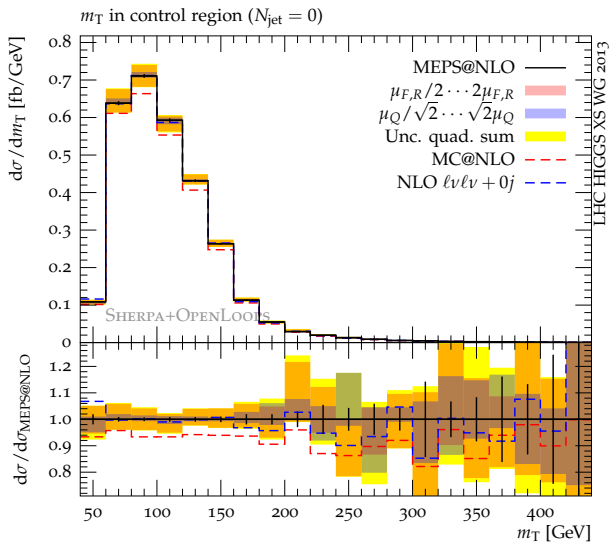
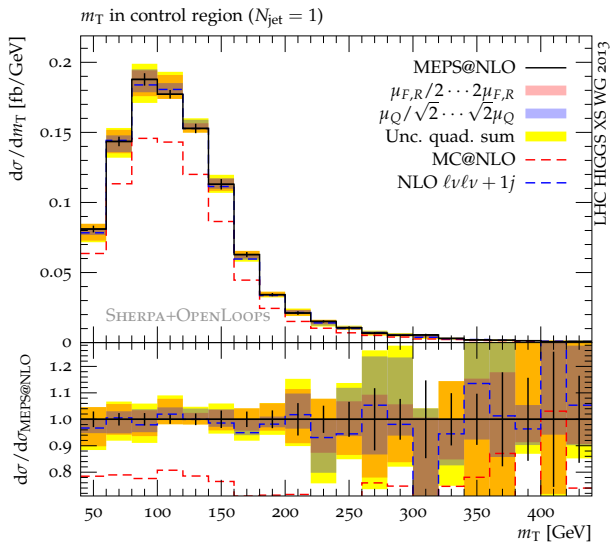
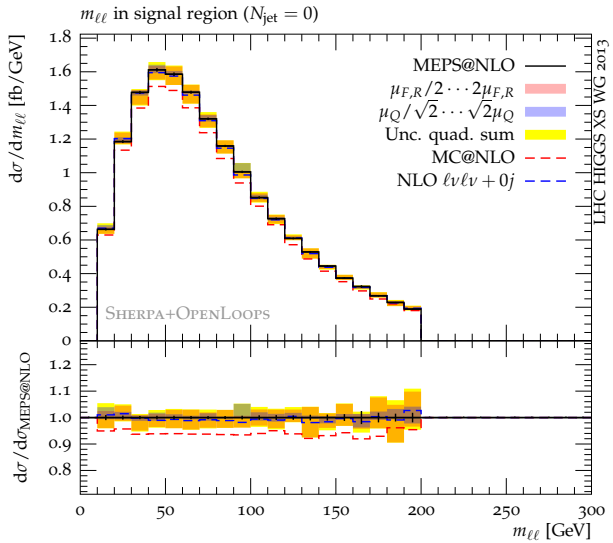




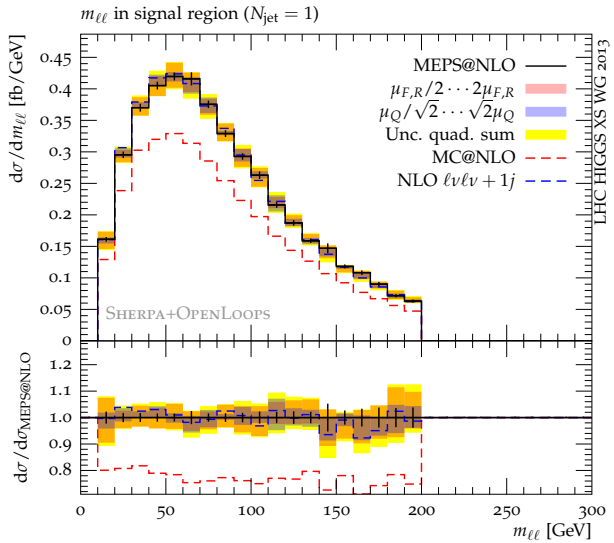
Dilepton invariant mass (CMS analysis)

SIGNAL

0-jets



1-jet



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

0-jets bin	**NLO** $\pm\Delta_{\rm QCD}$	**MC@NLO**	**MEPS@NLO** $\pm\Delta_{\rm QCD} \pm \Delta_{\rm res}$
$\sigma_{\rm S}$ [fb]	$159.34(18)\,^{+1.8\%}_{-1.7\%}$	150.6(2)	$160.3(3)\,^{+2.6\%}_{-3.8\%}\,^{+1.4\%}_{-0.5\%}$
$\sigma_{\rm C}$ [fb]	$60.08(15)\,^{+1.5\%}_{-1.4\%}$	56.60(11)	$60.31(22)\,^{+3.6\%}_{-3.5\%}\,^{+0.7\%}_{-0.2\%}$
$\sigma_{\rm S}/\sigma_{\rm C}$	2.65	2.66	2.66

1-jet bin	**NLO** $\pm\Delta_{\rm QCD}$	**MC@NLO**	**MEPS@NLO** $\pm\Delta_{\rm QCD} \pm \Delta_{\rm res}$
$\sigma_{\rm S}$ [fb]	$45.01(7)\,^{+1.3\%}_{-2.6\%}$	34.75(9)	$44.88(23)\,^{+3.0\%}_{-2.7\%}\,^{+0.1\%}_{-0.3\%}$
$\sigma_{\rm C}$ [fb]	$22.09(5)\,^{+1.2\%}_{-3.2\%}$	17.41(7)	$22.30(18)\,^{+3.0\%}_{-2.7\%}\,^{+0.5\%}_{-0.4\%}$
$\sigma_{\rm S}/\sigma_{\rm C}$	2.04	2.00	2.01