OpenLoops

a one-loop generator by

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interfaced to Sherpa in collaboration with

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CERN, ATLAS-CMS MC meeting “Future challenges”
November 19, 2012

The NLO revolution

Multi-particle final states

- NLO predictions for $\mathrm{t\bar{t}b\bar{b}}$, $\mathrm{t\bar{t}}jj$, $Vjjj, \ldots$

Various new one-loop techniques

- unitarity/diagrams, OPP/tensor reduction, numerical integration, ...
- efficiency, stability, flexibility, automation

Automation and progress in MC techniques

- NLO subtraction, matching, merging

$\Rightarrow$ NLO(+PS) as default simulation accuracy

OpenLoops in a nutshell

New technique for 1-loop scattering amplitudes [Cascioli, Maierhöfer, S.P. '12]

- Feynman diagrams and tensor integrals
- numerical and recursive

Fully general and automatic

- process-definition $\Rightarrow$ numerical code in $\mathcal{O}$(sec/min)
- fully flexibile in terms of processes and models
- QCD corrections to many SM processes available and thoroughly validated

Very efficient up to (at least) 4 final-state particles

- similar **speed and stability** as algebraic NLO calculations for $\mathrm{t\bar{t}b\bar{b}}$ and $\mathrm{WWb\bar{b}}$ [Bredenstein,Denner,Dittmaier,Kallweit, S.P. '09/'11]
- no bottlenecks that hamper **large-scale applicability** (fast code generation, small executables)

Robust against numerical instabilities

- spurious poles (Gram det.) $\Rightarrow$ instabilities at exceptional points
- tensor integrals with `COLLIER`
  - **numerically stable tensor reduction** [Denner, Dittmaier '06]
  - scalar integrals with complex masses [Denner, Dittmaier '11]

One-loop + MC approach

Splitting NLO into loops & trees

- focus on loop bottlenecks ⇒ boosted NLO progress/automation
- fully automatic NLO, NLO+PS, MEPS@NLO, ...
- with various possible combinations of loop/MC tools

OpenLoops

- can be interfaced to any MC (`Sherpa`, `aMC@NLO`, `POWHEG`)
- interface to `Sherpa` available and extensively checked

(In)visibility of OpenLoops

Almost "invisible" for users

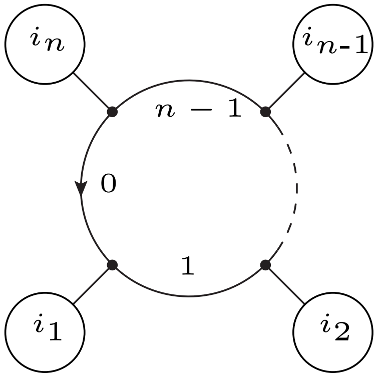
- just set `Loop_Generator = OpenLoops` in `Sherpa` runcards
- ready for experimentalists immediately after 2012 proof-of-concept paper (before official code publication)

```
##########################################################
#                  O p e n L o o p s                     #
##########################################################
#  You are using OpenLoops to evaluate loop amplitudes   #
#  Authors: F. Cascioli, P. Maierhoefer, S. Pozzorini    #
#  Please cite Phys. Rev. Lett. 108 (2012) 111601        #
#########################################################
#                    C O L L I E R                       #
##########################################################
#  You are using COLLIER to evaluate one-loop integrals #
#  Authors: A. Denner, S. Dittmaier, L. Hofer            #
#  Please cite Nucl. Phys. B844 (2011) 199               #
#              Nucl. Phys. B734 (2006) 62                #
#              Nucl. Phys. B658 (2003) 175               #
##########################################################
```

The OpenLoops algorithm

Reducing the one-loop problem to a tree-like problem

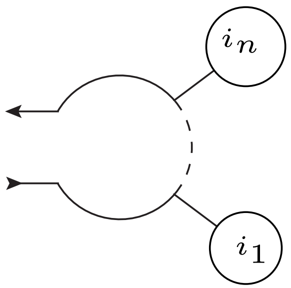
$$\int \frac{\mathrm{d}^D q\, \mathcal{N}(\mathcal{I}_n;q)}{D_0 D_1 \dots D_{n-1}} =$$



(n-point colour-stripped Feynman diagram)

Tree-like numerical recursion with q-dependence

$$\underbrace{\mathcal{N}^{\beta}_{\alpha}(\mathcal{I}_n;q)}_{\sum_{r=0}^{n} \mathcal{N}^{\beta}_{\mu_1\dots\mu_r;\alpha}(\mathcal{I}_n)\, q^{\mu_1}\dots q^{\mu_r}} =$$



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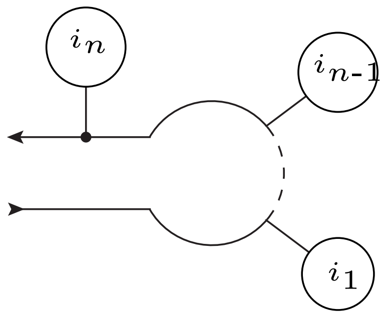
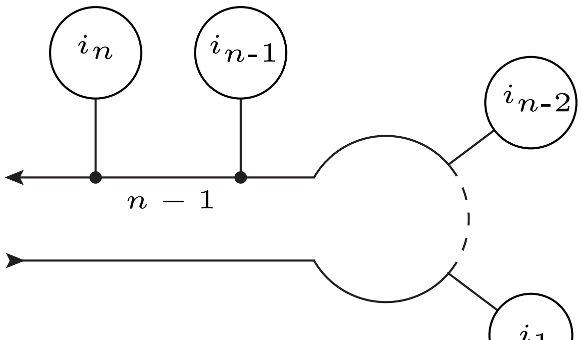


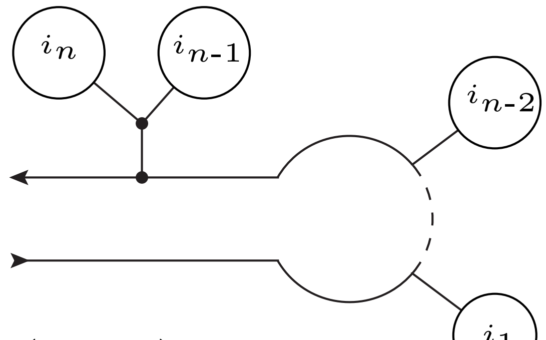
- merging lower-point open-loops and sub-trees $\Leftrightarrow \mathcal{L}_{\mathrm{int}}$ (flexible & automatic)
- much faster than conventional (fixed-q) tree algorithms $\Leftrightarrow$ tensor integrals

"Collective" construction of loops diagrams: n-point open loops from pre-computed parts of $(n-1)$-point open loops



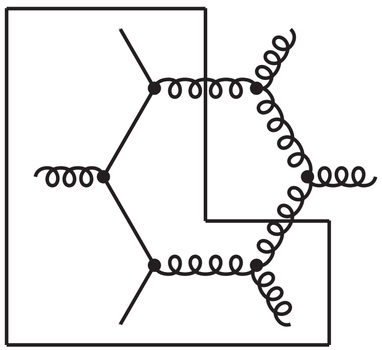
n-point parent

recycle $\mathcal{I}_{n-2}$ open loop
$\Longleftarrow$

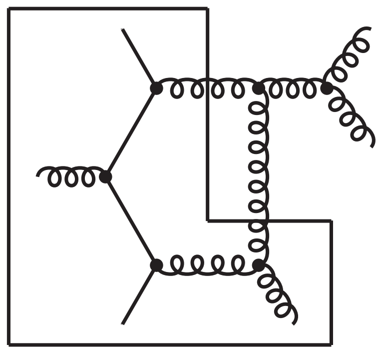


$(n-1)$-point child

Example



6-point parent



5-point child

Complicated diagrams require only "last missing piece" (always works in QCD!)

Flexibility and Automation

Full automation of 1-loop QCD corrections to SM processes

- process-definition file $\Rightarrow$ `Fortran 90` tree & 1-loop matrix elements

Process	size [MB]	$t_{\rm code}$ [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
- $\mathcal{O}(10^2\text{–}10^3)$ compression in $2 \to 4$

Fast code generation/compilation

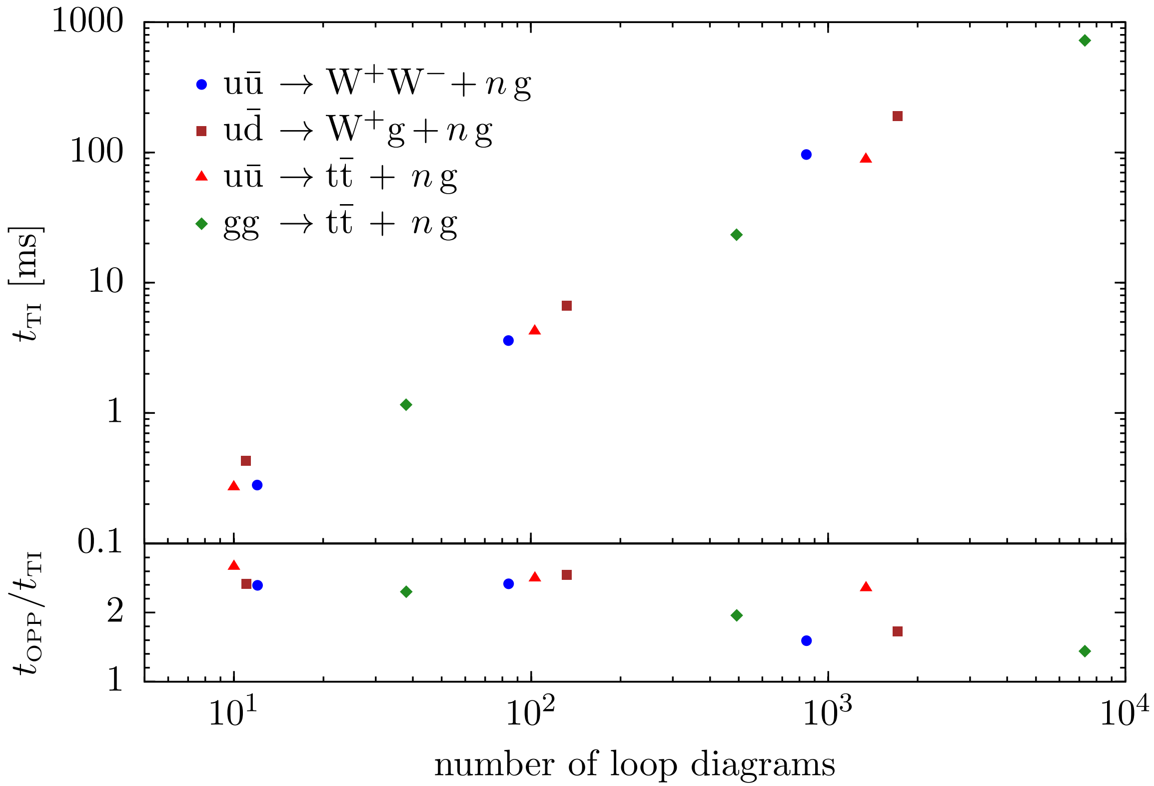
- few seconds to minutes
- $\mathcal{O}(10^3)$ speed-up in $2 \to 4$

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 (`Intel i5-750` core)



$2 \to 4$ amplitudes

- $n_{\mathrm{diag}} = \mathcal{O}(10^3–10^4)$
- $t_{2\to 4} \lesssim 0.1–1\,\mathrm{s/point}$

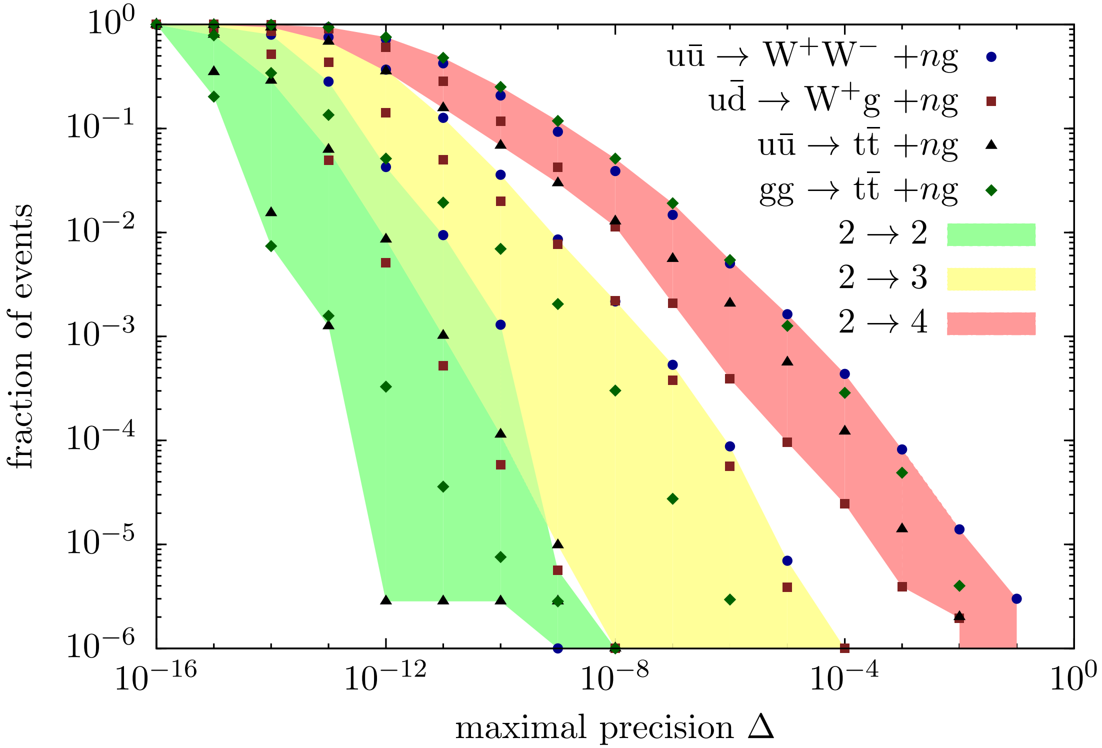
$\Rightarrow$ σ_{NLO} w.o. big cluster!

Extrapolating linear scaling

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

Numerical accuracy in double precision

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



Average number of digits

- 11-15

Cross section accuracy

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

$2 \to 4$ processes very stable

- $\lesssim 0.1‰$ prob. that $\Delta < 10^{-3}$

High stability thanks to Gram-determinant (and other) expansions in `COLLIER`

Process-by-process validation

Before delivering one-loop amplitudes to MC/experimental community

(1) Self-consistency checks (necessary but insufficient!)

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

(2) Precision check against independent calculation

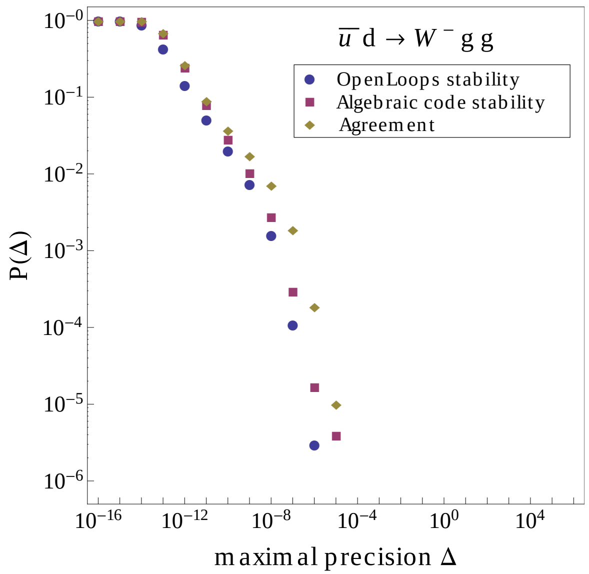
Process	OpenLoops	CAG	agreement
$\bar{u}d \to \mathrm{e}^-\bar{\nu}_\mathrm{e}$	$1.7591151201316463 1\cdot 10^{-5}$	$1.75911512013164970\cdot 10^{-5}$	$2\cdot 10^{-15}$
$\bar{u}d \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\, g$	$1.44264278623861696\cdot 10^{-6}$	$1.44264278623860193\cdot 10^{-6}$	$1\cdot 10^{-14}$
$\bar{u}d \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\, gg$	$1.46590850889200081\cdot 10^{-9}$	$1.46590850889179753\cdot 10^{-9}$	$1\cdot 10^{-13}$
$u\bar{u} \to \mathrm{e}^+\mathrm{e}^-$	$3.39939790956756674\cdot 10^{-5}$	$3.39939790956757419\cdot 10^{-5}$	$2\cdot 10^{-15}$
$u\bar{u} \to \mathrm{e}^+\mathrm{e}^-\mathrm{g}$	$7.00209271987758522\cdot 10^{-7}$	$7.00209271987766145\cdot 10^{-7}$	$1\cdot 10^{-14}$
$u\bar{u} \to \mathrm{e}^+\mathrm{e}^-\mathrm{gg}$	$6.93325400698801091\cdot 10^{-9}$	$6.93325400699020542\cdot 10^{-9}$	$3\cdot 10^{-13}$

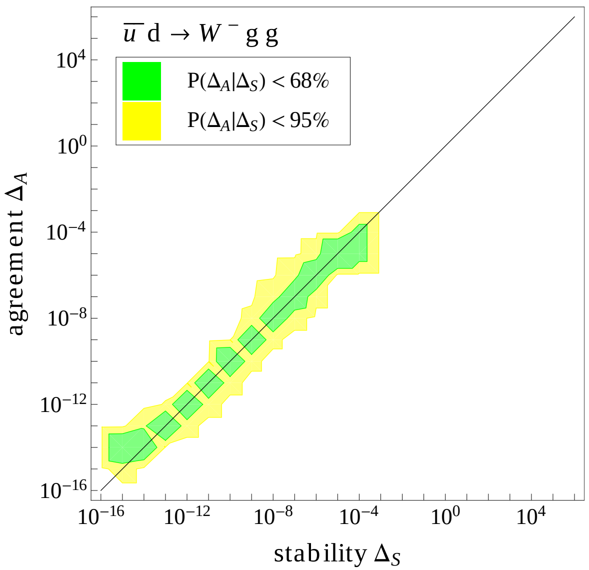
(CAG = computer-algebra generator developed for $\mathrm{t\bar{t}b\bar{b}}$ & $\mathrm{WWb\bar{b}}$)

similar agreement for more than 80 partonic reactions!

(3) Stability studies with large phase-space samples

`OpenLoops` vs CAG agreement (Δ_A) and intrinsic stability (Δ_S) well consistent (1-2 digit correlation at 95% CL)





(4) Stability monitor at runtime

- 20% of points with largest K-factor recomputed with 2^{nd} tensor reduction
- wild instabilities with $K \gg 1$ extremely rare ($P < 10^{-4}$ in highly nontrivial processes) $\Rightarrow$ set $K \to 1$

Status and perspectives

OpenLoops process library (plan for Sherpa 2.0 release)

- careful process-by-process validation (many processes ready)
- full set of NLO QCD diagrams, full colour
- off-shell leptonic W/Z decays: interferences, complex masses
- on-shell top quarks

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

lower jet multiplicities implicitly understood

Todo list

- loop-induced processes ($gg \rightarrow 4l$)
- effective ($m_{\mathrm{t}} \rightarrow \infty$) Higg-gluons interactions
- BLHA interface
- full NLO precision in production $\times$ decay of top quarks
- same for hadronic W/Z decays
- coloured matrix elements
- EW corrections
- ...

Conclusions

OpenLoops is a brand new one-loop generator

- **flexibility, speed and stability** are its main strengths
- **several SM processes at NLO QCD** extensively validated
- interfaced to Sherpa and ready for 2012-13 data analysis

We are looking forward to fruitful interactions with experimentalists

- give us feedback to improve and extend OpenLoops
- keep in mind NLO pitfalls when using automatic NLO tools
- compare different combinations of one-loop & MC tools
- ask for theoretical advice when deadling with nontrivial processes