Automation of NLO electroweak calculations

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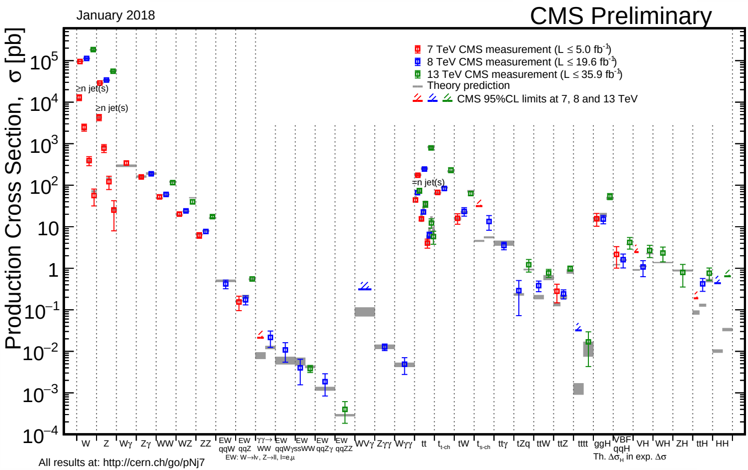
Blois
5.6.2018


January 2018
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
13 TeV CMS measurement (L ≤ 35.9 fb⁻¹)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
≥n jet(s)
=n jet(s)
W
Z
Wγ
Zγ
WW
WZ
ZZ
EW qqW
EW qqZ
γγ→WW
EW qqWγ
EW ssWW
EW qqZγ
EW qqZZ
WVγ
Zγγ
Wγγ
tt
t-ch
tW
s-ch
ttγ
tZq
ttW
ttZ
tttt
ggH
VBF qqH
VH
WH
ZH
ttH
HH
EW: W→lν, Z→ll, l=e,μ
Th. ΔσH in exp. Δσ
All results at: http://cern.ch/go/pNj7

Why electroweak corrections?

- New Physics effects are expected at the order of electroweak corrections.

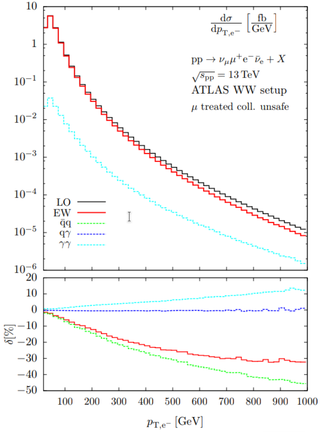
- They are typically small compared to QCD corrections.

- Known to be large only in certain phase-space regions (high energy, high p_{T} tails).

- Origin attributed to so-called Sudakov logarithms

$$-\frac{\alpha}{4\pi}\log^2\frac{s_{ij}^2}{M_{\mathrm{W}}^2}$$

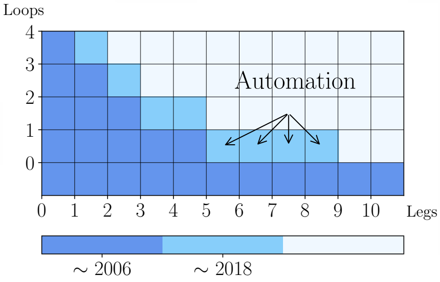
$\mathrm{pp} \to \mathrm{W}^+\mathrm{W}^-$, 1605.03419



Automation of EW corrections

Automation is a very efficient long-term approach:

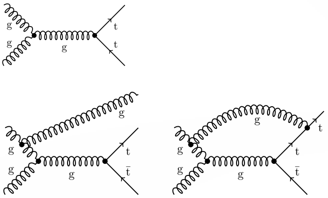
- Solve entire process classes in one step.
- Repeat predictions with new theories.
- Push limits to new extreme cases:



- Propagation of tools to experimental collaboration.

One-loop provider (OLP)

- Compute tree and one-loop matrix elements:



- Off-shell corrections:

Monte-Carlo Integrator (MC)

- Subtraction:

$$\sigma^{\mathrm{NLO}} = \int_{m+1} \mathrm{d}\sigma^{\mathrm{R}} + \int_{m} \mathrm{d}\sigma^{\mathrm{V}}$$

$$= \int_{m+1} (\mathrm{d}\sigma^{\mathrm{R}} - \mathrm{d}\sigma^{\mathrm{A}}) + \int_{m} (\mathrm{d}\sigma^{\mathrm{V}} + \int_{1} \mathrm{d}\sigma^{\mathrm{A}})$$

- Resummation/Parton showers:

One-loop provider (OLP)

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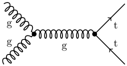
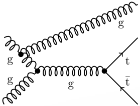
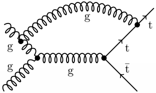
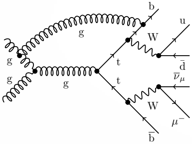






- Off-shell corrections:



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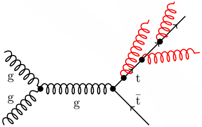
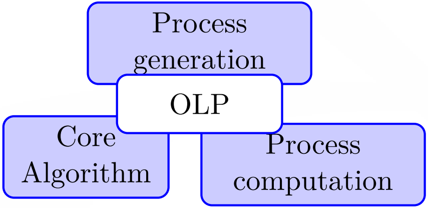
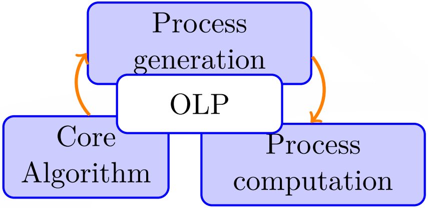
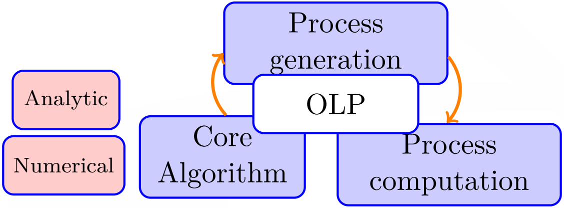
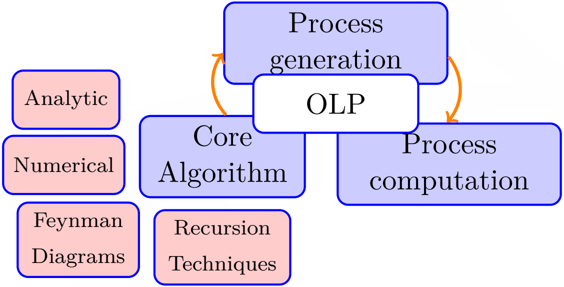


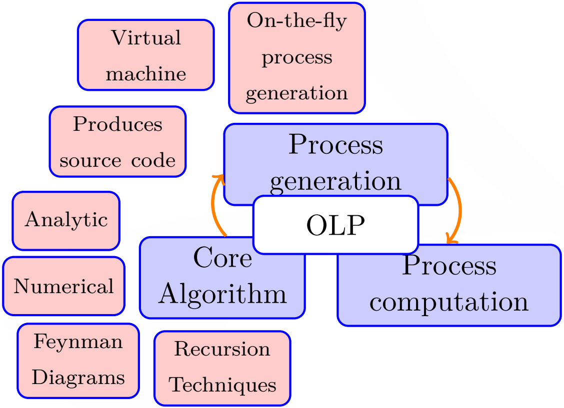

Process generation
OLP
Core Algorithm
Process computation

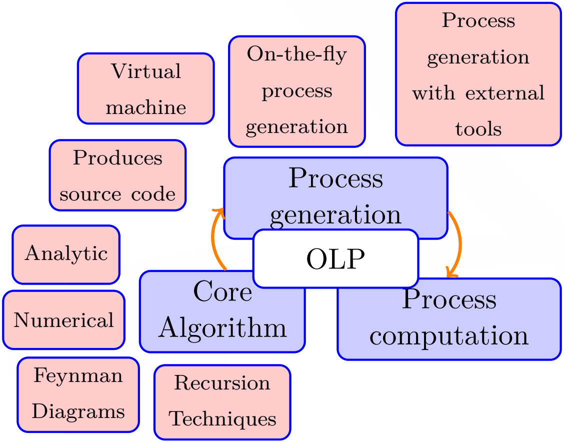
One-Loop Technology Landscape




Analytic
Numerical
Core Algorithm
Process generation
OLP
Process computation


Analytic
Numerical
Feynman Diagrams
Core Algorithm
Recursion Techniques
Process generation
OLP
Process computation


Virtual machine
On-the-fly process generation
Produces source code
Process generation
Analytic
OLP
Core Algorithm
Process computation
Numerical
Feynman Diagrams
Recursion Techniques


Virtual machine
On-the-fly process generation
Process generation with external tools
Produces source code
Process generation
Analytic
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Core Algorithm
Process computation
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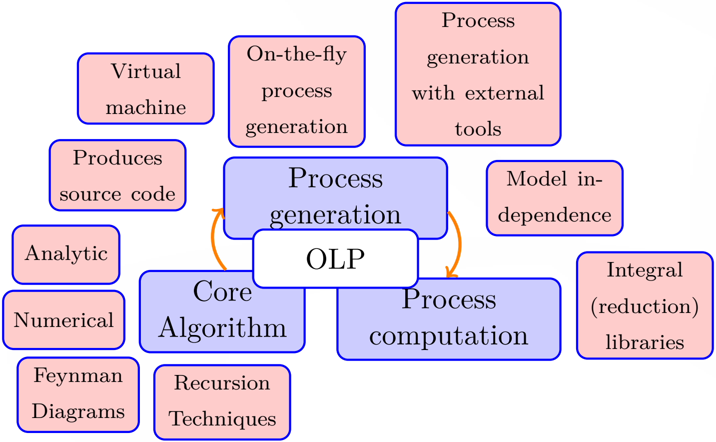
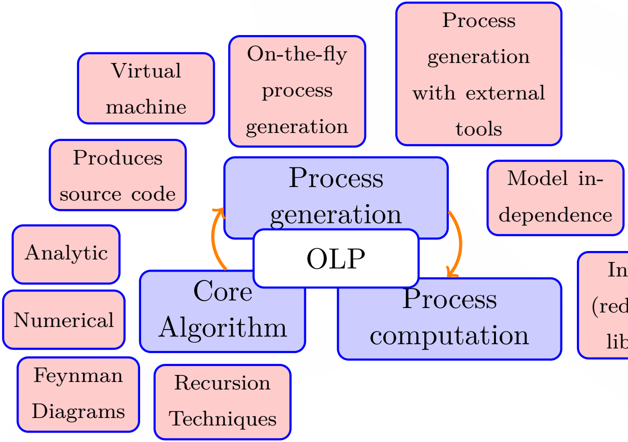
Recursion Techniques

One-Loop Technology Landscape



One-Loop Technology Landscape



Automated OLPs for EW corrections:

- GoSam[1]
- MadLoop[2]
- OpenLoops[3]
- Recola[4]
- NLOX
- ...

[1] `gosam.hepforge.org`
[2] `launchpad.net/mg5amcnlo`
[3] `openloops.hepforge.org`
[4] `recola.hepforge.org`

Automation of SM EW corrections is quite advanced:

- $\mathcal{O}(5)$ OLPs *are able* to compute EW corrections in *automated fashion*.
- Progress in Monte-Carlo programs to compute EW corrections.
  - Completion requires solid interfaces to Monte-Carlo programs (Sherpa, POWHEG, Herwig, Whizard, ...).
- EW dipole subtraction ready:
  - Sherpa: 1712.07975.
    RECOLA + Sherpa: 1704.05783
    EW interfaces to other OLPs (GOSAM, OPENLOOPS) functional (see e.g. 1803.07977).
  - MADGRAPH5_AMC@NLO: 1804.10017

Implementation of NLO EW corrections in MC

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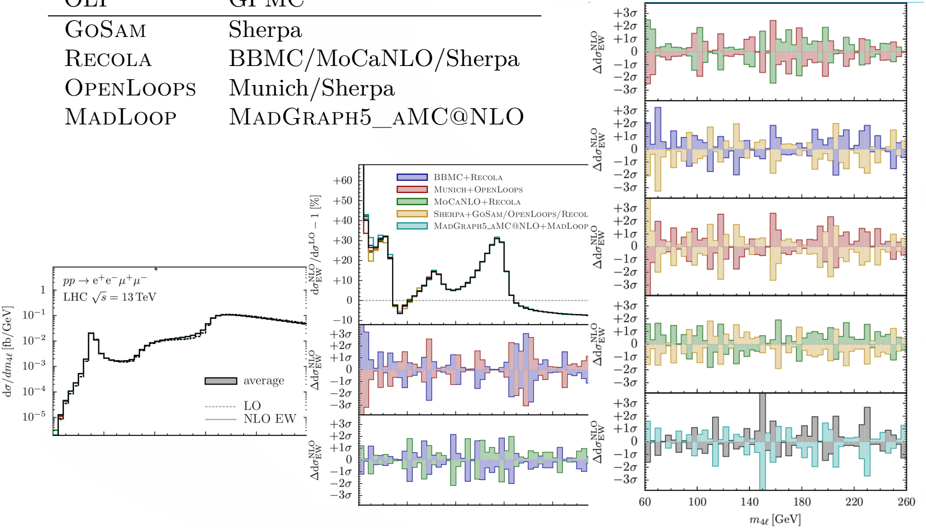
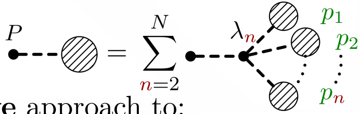
  - MADGRAPH5_aMC@NLO: 1804.10017

OLP	GPMC
GoSam	Sherpa
Recola	BBMC/MoCaNLO/Sherpa
OpenLoops	Munich/Sherpa
MadLoop	MadGraph5_aMC@NLO



RECOLA as compared to other OLPs:

- **No Feynman diagrams** at any stage
  [Berends Giele '88][Van Hameren '09]



  Fully recursive approach to:
  - process generation
  - process computation
  - treatment of colourflow and helicity conservation
- **On-the-fly process-generation** as "byte-code". No (compilation of) source files. Usage as simple as:

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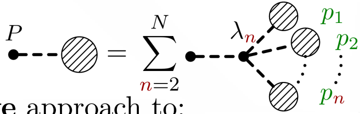

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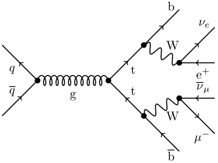
- **On-the-fly process-generation** as "byte-code". No (compilation of) source files. Usage as simple as:

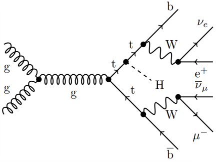
```
from pyrecola import *
define_process_rcl(1,'u u~ -> e+ e- mu+ mu-','NLO')
define_process_rcl(2,'u u~ -> Z (e+ e-) Z (mu+ mu-)','NLO')
generate_processes_rcl()
compute_process(1, p, 'NLO')
compute_process(2, p, 'NLO')
```

[Denner et al.;1506.07448,1607.05571,1612.07138,1711.10359]

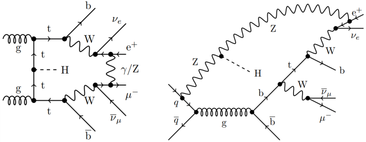
tt/tth

$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu \mathrm{b}\bar{\mathrm{b}}(h)$$
$$pp \to \mu^-\bar{\nu}_\mu \mathrm{b}\bar{\mathrm{b}}\mathrm{jj}$$



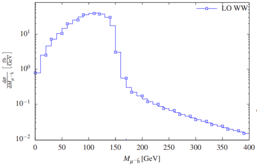


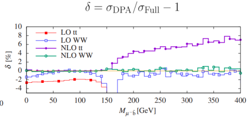
- Major technical achievement involving up to 9-point functions



using COLLIER.
[Denner, Dittmaier, Hofer '16]

- Tests on reliability of double pole approximations

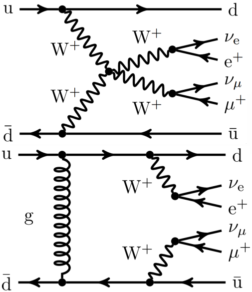




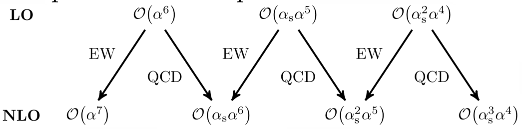
[Biedermann et al.;1611.02951,1708.00268]

VBS

$(pp \to \mu^+\nu_\mu e^+\nu_e \mathrm{jj})$



- Computation of complete NLO:



- Validation via several approximations.

- Unexpectedly large EW corrections:

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{\mathrm{NLO}}$ [fb]	−0.2169(3)	−0.0568(5)	−0.00032(13)	−0.0063(4)	−0.2804(7)
$\delta\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$ [%]	−13.2	−3.5	0.0	−0.4	−17.1

No significant signs for BSM. Approaches to parametrize deviations:

- Formulate the SM in the language of EFT.
  Challenge: Vertices including higher powers in momenta. Purely technical challenge.

- Study concrete UV complete models.
  Challenge: EW renormalization is non-trivial, but theoretically very interesting. (e.g. δt_β)

Recola2

REcursive Computation of One Loop Amplitudes 2

[Denner, Lang, Uccirati, '17]

- Recola2 is a *tree* and *one-loop* amplitude provider for **BSM/SM EFT**
- **Model independent** approach via *model files*.
- **General power-counting** for EFT and new (gauge-) couplings:
- **All features** of Recola, **same performance**.
- Powerful computations and crosschecks with the **Background-Field Method**.

Release version 2.1.1:

`https://recola.hepforge.org/`

[Denner, Chiesa, JNL, Uccirati]

1705.06053: Complete NLO corrections in *Extended Higgs Sectors*.

- No process restriction.
- Non-trivial renormalization conditions possible.
- Publicly available: 2HDM, HSESM

1804.01477: Diboson production at NLO QCD including Dim 6 and 8 Operators :

$$\mathcal{O}_{WWW} = \frac{g_{\mathrm{w}}^3}{4}\epsilon_{ijk}[W^i_{\mu\nu}W^{\nu\rho\,j}W^{\mu\,k}_{\rho}],$$

$$\mathcal{O}_{W} = \mathrm{i}g_{\mathrm{w}}(D_\mu\Phi)^\dagger\frac{\tau_k}{2}W^{\mu\nu\,k}(D_\nu\Phi),$$

$$\mathcal{O}_{B} = -\mathrm{i}\frac{g_1}{2}(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi),$$

$$\mathcal{O}_{\tilde{W}WW} = -\frac{g_{\mathrm{w}}^3}{4}\epsilon_{ijk}[\tilde{W}^i_{\mu\nu}W^{\nu\rho\,j}W^{\mu\,k}_{\rho}],$$

$$\mathcal{O}_{\tilde{W}} = -\mathrm{i}g_{\mathrm{w}}(D_\mu\Phi)^\dagger\frac{\tau_k}{2}\tilde{W}^{\mu\nu\,k}(D_\nu\Phi),$$

$$\mathcal{O}_{BW} = -\mathrm{i}\,\Phi^\dagger B_{\mu\nu}\frac{\tau_i}{2}W^{\mu\rho\,i}\,\{D_\rho, D^\nu\}\,\Phi + \mathrm{h.c.},$$

$$\mathcal{O}_{WW} = \mathrm{i}\,\Phi^\dagger\frac{\tau_i}{2}\frac{\tau_j}{2}W^i_{\mu\nu}W^{\mu\rho\,j}\,\{D_\rho, D^\nu\}\,\Phi + \mathrm{h.c.},$$

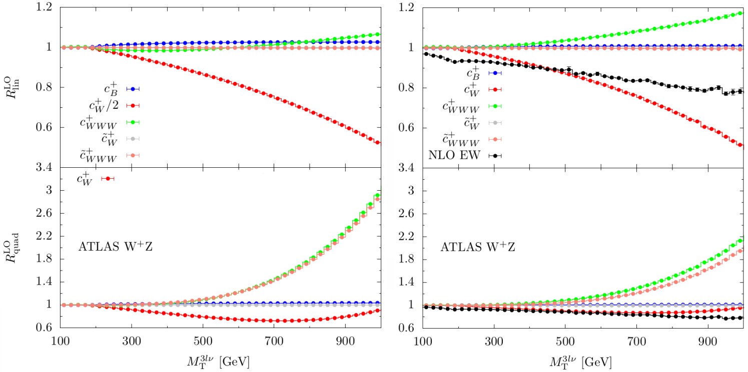
$$\mathcal{O}_{BB} = \mathrm{i}\,\Phi^\dagger B_{\mu\nu}B^{\mu\rho}\,\{D_\rho, D^\nu\}\,\Phi + \mathrm{h.c.},$$

$$\mathcal{O}_{\widetilde{B}W} = -\mathrm{i}\,\Phi^\dagger\widetilde{B}_{\mu\nu}\frac{\tau_i}{2}W^{\mu\rho\,i}\,\{D_\rho, D^\nu\}\,\Phi + \mathrm{h.c.},$$

(see e.g. 1309.7890)

BSM applications using RECOLA2

[Denner, Chiesa, JNL, Uccirati]



$$R_{\mathrm{lin}} = 1 + \frac{\mathrm{d}\sigma_{\mathrm{SM}\times\mathrm{EFT6}}\mathrm{d}X}{\mathrm{d}\sigma_{\mathrm{SM}\times\mathrm{EFT6}}\mathrm{d}X} \quad R_{\mathrm{quad}} = 1 + \frac{\mathrm{d}\sigma_{\mathrm{SM}\times\mathrm{EFT6}^2}\mathrm{d}X}{\mathrm{d}\sigma_{\mathrm{SM}\times\mathrm{EFT6}^2}\mathrm{d}X}$$

Conclusion:

Automated SM EW corrections is very far advanced:

- SM predictions can now be compared with different OLPs and subtraction methods allowing for powerful crosschecks.

- Some fine tuning is required to make usage smooth for 3rd party users.

- OLPs are (getting) ready for EW corrections in BSM.

- Missing tasks: Construction of complete one-loop renormalized model files.