The automation of EW corrections in
MadGraph5_aMC@NLO

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NWO

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LHCP

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Road to precision: where are we?

• Higgs cross section at N³LO in QCD (ggF and VBF)
• NNLO available for all 2→2 processes, general subtraction techniques available
  see e.g Del Duca et al, arXiv:1501.07226, Caola et al, arXiv:1702.01352
• Bottleneck to go to higher multiplicities is the lack of 2-loop amplitudes
• NLO automated since a couple of years ago
• Since $\alpha \approx \alpha_s^2$, NLO EW corrections cannot be neglected and have to be included.
• EW corrections are enhanced in certain kinematics regimes (e.g. by Sudakov logarithms at large scales) or for very exclusive observables.
  Automation in a very advanced stage
Steps towards the automation of EW corrections

- IR subtraction: techniques established for QCD corrections can be extended to EW ones.
- Replace color factors with charges ($C_F \rightarrow q_i^2$, $C_A \rightarrow 0$, $T_F \rightarrow N_{C,i} q_i^2$)
- Replace color-linked Borns with charge-linked ones
- Loop amplitudes: one-loop techniques can be exploited for EW loops.
- UV/R$_2$ counterterms for the EW interactions are needed
- Higher ranks appear, integrand-reduction may lead to unstable results
  Switch to other techniques (Tensor-integral reduction, Laurent-series expansion,…)
- Use scalar-integral libraries that support complex masses
  OneLoop: van Hameren, arXiv:1007.4716
The FKS subtraction has been extended to handle mixed QCD/EW corrections.
The NLO-capable model features all $R_2/UV$ counterterms. The complex-mass scheme can be activated.
Models exist both in the $\alpha(M_Z)$ and $G_\mu$ scheme.
Collier and Ninja have been linked to MadLoop.
Formulas have been worked out to include FFs in the FKS subtraction. Still to be implemented → processes with tagged photons in the final state cannot be generated.
The code has been extensively tested against results in literature.
The process generation can be done exactly as for the QCD case:

```python
> import model loop_qed_qcd_sm_Gmu
> set complex_mass_scheme True
> generate p p > e+ e- mu+ mu- [QED] # or [QED QCD]
> output pp_4lep
> launch NLO
```
The FKS sub-processes can be activated.
The NLO-capable model features all $R_{\text{QCD}}$ and $\alpha_s(\mu)$ corrections.
Models exist both in the scheme and $\mu$.
Collier and Ninja have been linked to MadLoop.

The code has been extensively tested against results in literature
be generated
be implemented

Collier: Denner et al, arXiv:1604.06792

The overall impact of quasi-collinear enhancements on observable cross sections ultimately depends on

Formulas have been chosen so as to
be implemented
be generated

The code has been extensively tested against results in literature

The cross sections have been calculated

In detail, the definitions of the quantities
are dominated by di-boson resonant contributions (namely, di-
di

The interplay between their kinematics characteristics, the partonic matrix elements, and PDF e
than in the case of 2
occurs in 4
quasi-collinear
that give rise to 2
to the direct
e
enlarged at large momentum transfers). These appear in

it is only the former case that features diagrams with

Finally, the transverse momenta of the
two is set equal to
in the case of 2

the neutrino), and the largest of the two is set equal to

then, the transverse momenta of the

σ per bin [pb]

p_T(ll / lv) [GeV]

NLO/LO

 Automation in
MadGraph5_aMC@NLO

Frixione, Frederix, Hirschi, Pagani, Shao, MZ, 1804.10017

Hardest S.F. ll or lv trans. mom.

Higgs boson transverse momentum

ll [GeV]

Higgs transverse momentum in the processes of

ll or lv [GeV]

\begin{align*}
\text{e}^+\text{e}^-\mu^+\mu^- \text{ NLO (x10)} \\
\text{LO (x10)} \\
\text{e}^+\nu_e\bar{\nu}_\mu \text{ NLO} \\
\text{LO}
\end{align*}
Beyond EW-corrections: complete-NLO accuracy

- In general a process proceeds through different coupling combinations at LO.
- Such a structure induces a similar one at NLO.
- Usually the contribution with the largest power of $s$ is considered as ‘LO’ and contributions with larger powers of $s$ are expected to be subleading by power counting.
- This is the case e.g. for di-jet, or top pair production.
- But…
A particular case: \( W^+W^+ \) production

- \( W^+W^+jj \) has three coupling combinations at LO, four at NLO:

\[
\begin{align*}
\text{QCD-induced} & : \alpha^4\alpha_s^2 \\
\text{interference} & : \alpha^5\alpha_s \\
\text{VBS} & : \alpha^6
\end{align*}
\]

- The vector-boson scattering (VBS) contribution is typically considered the signal, while the QCD-induced is a background.

- At LO, even before applying cuts to enhance VBS, the size of VBS and of the QCD background is comparable. 

Kulesza, Stirling, hep-ph/9912232

The coupling hierarchy is not respected at LO
A particular case: \( W^+W^+ \) production

- \( W^+W^+jj \) has three coupling combinations at LO, four at NLO:

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The coupling hierarchy is not respected at LO.

What happens at NLO?

Kulesza, Stirling, hep-ph/9912232
Complete NLO corrections to W⁺W⁺ scattering

Biedermann, Denner, Pellen, arXiv:1708.00268

- The complete-NLO corrections for this 2→6 process have been computed with Recola+Collier, including all contributions (non/single/double-resonant diagrams, s/t/u-channel diagrams, …) and employing the complex-mass scheme.
- When VBS cuts are imposed, the coupling hierarchy is flipped!

VBS cuts

| p_{T,\ell} > 20 \text{ GeV}, |y_\ell| < 2.5, \Delta R_{\ell\ell} > 0.3. | E_{T,\text{miss}} = p_{T,\text{miss}} > 40 \text{ GeV} |
| m_{jj} > 500 \text{ GeV}, |\Delta y_{jj}| > 2.5. |

VBS (86%) | Int. (3%) | QCD (11%)

| Order | \mathcal{O}(\alpha_s^6) | \mathcal{O}(\alpha_s^2\alpha_s^4) | \mathcal{O}(\alpha_s^2\alpha_s^6) | Sum |
| \sigma_{LO} [fb] | 1.4178(2) | 0.04815(2) | 0.17229(5) | 1.6383(2) |

\delta\sigma_{NLO} [fb] | -0.2169(3) | -0.0568(5) | -0.00032(13) | -0.00063(4) |

\delta\sigma_{NLO}/\sigma_{LO} [%] | -13.2 | -3.5 | 0.0 | -0.4 |


Marco Zaro, 08-06-2018
Complete-NLO corrections for 4-top (and ttW)

Frederix, Pagani, MZ, arXiv:1711.02116

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- Increasing the energy to 100 TeV reduces the relative effects both at LO and NLO

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The 4-top invariant mass at the LHC

• At the differential level, the behaviour is similar to at the inclusive one.
The 4-top invariant mass at the LHC

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- At threshold, NLO$_4\to4$ are all quite large (>30% of LO$_1$) because of the Sommerfeld enhancement.

![Graph showing the 4-top invariant mass at the LHC with various NLO contributions.]
The 4-top invariant mass at the LHC

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- Away from threshold, NLO_2 and NLO_3 almost completely cancel each other. They both display a large scale dependence, which disappears in the sum. BSM effects may spoil such a cancelation.
- This makes the complete-NLO correction remarkably close to the NLO QCD one, except for at threshold.
The $p_T$ of the hardest top at the FCC

$$\alpha_s^4 \alpha_s a^2 a_s^2 a^3 a_s a^4 a_s \alpha^4 \alpha s^5$$

$t\bar{t}t\bar{t}$, 100 TeV

Ratios over LO$_1$, $\mu=H_T/4$
The $p_T$ of the hardest top at the FCC

- No threshold enhancement is present for this observable
- At large $p_T$, NLO$_2$ shows the typical effect of the Sudakov logarithms of EW origin
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Conclusions and outlook

• Accurate predictions are becoming of utmost importance for the LHC programme
• Focusing on QCD corrections is not enough: EW effects can be large
• The automation of EW corrections has become an hot topic in the recent years
• Within MadGraph5_aMC@NLO, the automation has been achieved, and the code is public (as MG5_aMC v3)! https://launchpad.net/mg5amcnlo
• The code has some limitations (no EW corrections in processes with tagged photons), which will be lifted in the future
• A by-product of the automation is the possibility to compute the complete NLO corrections for arbitrary processes
• Despite the coupling suppression, they can be important for some processes (e.g. VBS, ttW and 4-top)
• In particular for 4-top production, subheading contributions show important cancelations which may be spoiled by BSM effects
Backup
EW renormalisation schemes in a nutshell

The renormalisation of $\alpha$ can be performed in different schemes:

- $\alpha(0)$: $\alpha$ is measured in the Thompson scattering, in the zero-momentum limit. Terms $\sim \log(Q/m_f)$ appear in the cross section, except for external photons. Fermion masses must be retained.

- $\alpha(M_Z)$: $\alpha$ is measured at the $Z$ peak (e.g. at LEP). It removes the dependence on the fermion masses, which can be set to zero.

- $G_\mu$ scheme: the Fermi constant is measured from the muon lifetime, then $\alpha$ is extracted. W.r.t. the $\alpha(M_Z)$ scheme, also contributions of weak origin ($\Delta \rho$) are resummed.

The $G_\mu$ scheme is generally preferred for processes without final-state photons at the LO.
Final-state photons

At variance with the QCD case, when EW corrections are turned on, short-distance photons are not IR safe. They can split into a (collinear) pair of massless fermions.

Two solutions can be adopted

- **Use the** $\alpha(0)$ **scheme, for the vertices where photons are emitted**
  
  see e.g. Les Houches 2013, arXiv:1405.1067, Sect.2

- This assumes finite fermion masses, even if they are discarded elsewhere in the computation. $\gamma \rightarrow f\bar{f}$ splittings are not included

- Not sure that this works in general, when complete-NLO corrections are considered

- **Use fragmentation functions. Physical photons are those which come after fragmentation.**

  - IR-subtraction scheme must be extended to include FFs
  - FFs can be used also for other particles. E.g. for leptons, where $\log(Q/m_f)$ can be resumed as for heavy quarks Mele, Nason, Nucl.Phys.B361
Other results: Setup

- $G_\mu$ scheme, complex-mass scheme, $G_\mu=1.6639 \cdot 10^{-5}$ GeV$^{-2}$
- On-shell masses and widths:
  - $M_W = 80.385$ GeV, $\Gamma_W = 2.0897$ GeV, $M_Z = 91.1876$ GeV, $\Gamma_Z = 2.4955$ GeV,
  - $M_t = 173.34$ GeV, $\Gamma_t = 1.369$ GeV, $M_H = 125$ GeV, $\Gamma_H = 4.07$ MeV
- LUXqed_plus_PDF4LHC_nnlo_100 PDF set, $\mu_r/\mu_f = H_T/2$
- Photons and charged fermions are combined if $R_{\gamma f} < 0.1$ dressed fermions
- Leptons must have $p_T(l) > 10$ GeV, $|\eta(l)| < 2.5$. OSSF pairs must satisfy $\Delta R_{ll} > 0.4$, $M_{ll} > 30$ GeV
- Quarks, gluon and non-recombined photons are clustered into anti-$k_T$ jets, $\Delta R = 0.4$, $p_T(j) > 30$ GeV, $|\eta(j)| < 4.5$
- Only NLO EW corrections will be shown (except for the complete-NLO results)
Results:
\( W(\rightarrow e^+\nu_e) + \text{jets} \)

- With 0 extra jets, \( H_T > M_W \) is populated only by off-shell configurations at LO; large K-factor come from real emissions
- With 1 jet, giant K-factors appear at large scale. Dominant topology is dijet+soft/collinear W
- With 2 jets EW corrections display the expected Sudakov suppression at large \( H_T \)
Results: single-top and 3-jet production

- In three-jet production, EW corrections appear to be totally negligible (also for $p_T(j_2/j_3)$)
- For single-top (both s- and t-channel), EW corrections display the typical suppression at large scales.
- EW corrections for three-jet production have never been computed in the literature

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\end{figure}
Results:
triple vector-boson production

- Unlike for $ZZZ$, $ZZW$ and $WWW$ can have contributions where photons in the initial state couples directly to the vector boson.
- This makes EW corrections for $ZZW$ and $WWW$ positive at large $p_T$.
- Vector bosons are treated as stable ($\Gamma_V=0$).
Results:
complete-NLO corrections to $\bar{t}tZ$ and $\bar{t}tH$

- Unlike $\bar{t}tW$ (Davide’s talk), for $\bar{t}tH$ and $\bar{t}tZ$ subleading contributions are well suppressed, mostly because the gg-initial state is already accessible at LO
Other published results

• NLO EW and QCD corrections for $t\bar{t}H$, $t\bar{t}W$ and $t\bar{t}Z$
  Frederix, Hirshi, Pagani, Shao, MZ, arXiv:1504.03446

• Complete-NLO corrections for di-jet
  Frederix, Frixione, Hirshi, Pagani, Shao, MZ, arXiv:1612.06548

• NLO EW and complete-NLO corrections for $t\bar{t}$
  + NNLO QCD combination
  Pagani, Tsinikos, MZ, arXiv:1606.01915,
  +Czakon, Heymes, Mitov, arXiv:1705.04105, 1711.03945,
  1712.04842

• Complete-NLO corrections for $t\bar{t}W$
  and four tops
  Frederix, Pagani, MZ, arXiv:1711.02116, Davide’s talk
What is happening in VBS?

- Already without VBS cuts, VBS is comparable to the QCD background despite the coupling powers. This is due to the larger number of diagrams in VBS [Kulesza, Stirling, hep-ph/9912232]

- VBS cuts are designed to enhance VBS over QCD background, further reducing also the VBS-QCD interference. De facto, VBS and the QCD background are two different processes.

- EW corrections are dominated by corrections in the $WW \rightarrow WW$ scattering process, which probes large scales ($m_{4\ell} \sim 400$ GeV). The bulk of the EW corrections is due to Sudakov logarithms. Details can be found in Biedermann et al, arXiv:1611.02951

$$\sigma_{LL} = \sigma_{LO} \left[ 1 - \frac{\alpha}{4\pi} 4C_{\text{ew}} \log^2 \left( \frac{Q^2}{M_W^2} \right) + \frac{\alpha}{4\pi} 2b_{\text{ew}} \log \left( \frac{Q^2}{M_W^2} \right) \right]$$

$$C_{\text{ew}} = \frac{2}{s_W^2}$$

$$b_{\text{ew}} = \frac{19}{68s_W^2}$$

- QCD corrections only affect the quark lines
Complete-NLO corrections for $tt\bar{W}$

Frederix, Pagani, MZ, arXiv:1711.02116

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$\bar{q}q$

$tt\bar{W}$

QCD

$\alpha_s^3$ $\alpha^2$ $\alpha^3$ $\alpha^4$

LO

NLO

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Complete-NLO corrections for $t\bar{t}W$

Frederix, Pagani, MZ, arXiv:1711.02116

- Subleading contributions to $t\bar{t}W$ (and $t\bar{t}Z$) exist beyond NLO QCD and EW. An estimate based on coupling-constants suggest them to be negligible.

- This is not the case:

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- At 100 TeV, NLO$_3$/LO$_1$~60% $\rightarrow$ almost as large as NLO$_1$ with the jet veto
\( p_T(\bar{t}t) \) and the effect of the jet veto

- QCD corrections to \( t\bar{t}W \) are dominated by real emissions recoiling against the \( \bar{t}t \) pair, with the \( W \) collinear to the emission or soft.
- This leads to giant K-factors for the \( p_T(\bar{t}t) \) distribution, which are greatly reduced with a jet veto.

The NLO QCD+EW uncertainty band barely overlap.
\( p_T(\bar{t}t) \) and the effect of the jet veto

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The effect of \( t-W \) scattering grows huge at 100 TeV