Towards automated SM NLO corrections for all colliders

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Motivation

Automated SM NLO corrections in a multi-purpose Monte-Carlo event generator for all collider processes

- SM NLO corrections: increased precision of theoretical predictions for total cross sections and kinematic distributions
  - QCD corrections mostly relevant for LHC processes
  - EW/mixed corrections relevant at the LHC/HL-LHC (large EW Sudakov factors) and highly relevant at lepton colliders, i. e. future colliders (ESU: Higgs factory!)

  $\rightarrow$ higher sensitivity to new physics
- Automation: flexibly use precise predictions for **all** collider processes
- Monte-Carlo event generator: provides exclusive simulated data!

  $\rightarrow$ Build on `WHIZARD` [Kilian, Ohl, Reuter: 0708.4233]

About WHIZARD

main reference: EPJ C71 (2011) 1742
webpage: https://whizard.hepforge.org/
support: https://launchpad.net/whizard
email contact: whizard@desy.de

WHIZARD is a multi-purpose event generator for multi-particle scattering cross sections and simulated event samples for lepton and hadron collider processes

- providing tree level MEs (O'Mega), MC phase space integrator (VAMP and VAMP2 with MPI parallelization), lepton collider beam spectra (CIRCE1/2) and a lot of interfaces to external packages (LHAPDF, FastJet, OLPs like Openloops, event formats, parton showers, etc.)
- well-established in lepton collider community
  - beam structure effects: Beamstrahlung, ISR, polarization, asymmetric beams, crossing angles, decays, ...
  - full SM samples for ILC (2012 - 2021)
  - suitable BSM studies at future colliders:
    support for a lot of BSM models and external models from UFO files

Automated NLO corrections

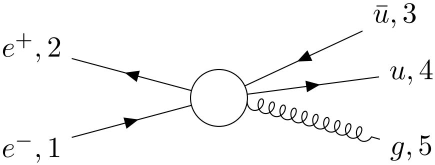
Kinoshita-Lee-Nauenberg theorem: For $2 \to n$ processes

$$\sigma_{\text{NLO}} = \int d\Phi_n \mathcal{B} + \int d\Phi_{n+1} \underbrace{\left[\mathcal{R}(\Phi_{n+1}) - d\sigma_S(\Phi_{n+1})\right]}_{\text{finite by construction}} + \underbrace{\int d\Phi_n \mathcal{V} + \int d\Phi_n d\sigma_{S,\text{int}}}_{\text{finite by KLN}}$$

$\mathcal{B}$: Born, $\mathcal{R}$: Real emission, $\mathcal{V}$: Virtual

$\to$ Due to numerical MC integration subtraction of infrared singularities must happen at the level of phase space points!

- Make use of Frixione-Kunszt-Signer (FKS) scheme [hep-ph/9512328]:
  - Partition Φ_{n+1} in regions of pairs (i, j) of external particles $i, j \leq n + 1$ that potentially induce collinear and/or soft singularities
  - Define $\mathcal{R}$ and $d\sigma_S$ in terms of (i, j)



For NLO QCD possible singular regions: $(i, j) \in \{(3, 5), (4, 5)\}$

QCD corrections for all collider processes

NLO QCD fixed order automation with extensive validation of cross sections and differential distributions for ~ 50 processes completed in 2020

by S. Braß, PB, W. Kilian, J. Reuter, V. Rothe, P. Stienemeier [Stienemeier, *et. al.*: 2104.11141]

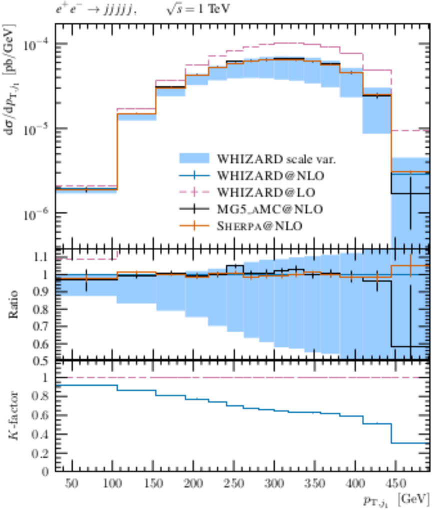
Process Vector boson (pair) plus jets	WHIZARD σ_{LO}[fb]	σ_{NLO}[fb]	K
$pp \to W^{\pm}$ *	$1.3749(8) \cdot 10^8$	$1.7696(10) \cdot 10^8$	1.29
$pp \to W^{\pm}j$ *	$2.046(3) \cdot 10^7$	$2.854(5) \cdot 10^7$	1.39
$pp \to W^{\pm}jj$	$6.856(12) \cdot 10^6$	$7.814(27) \cdot 10^6$	1.14
$pp \to W^{\pm}jjj$ †	$1.840(5) \cdot 10^6$	$1.978(7) \cdot 10^6$	1.07
$pp \to Z$	$4.2541(3) \cdot 10^7$	$5.4086(16) \cdot 10^7$	1.27
$pp \to Zj$	$7.215(4) \cdot 10^6$	$9.733(10) \cdot 10^6$	1.35
$pp \to Zjj$	$2.364(5) \cdot 10^6$	$2.676(7) \cdot 10^6$	1.13
$pp \to Zjjj$	$6.381(23) \cdot 10^5$	$6.85(3) \cdot 10^5$	1.07
$pp \to W^+W^-(4f)$	$7.352(10) \cdot 10^4$	$10.268(11) \cdot 10^4$	1.40
$pp \to W^+W^-j(4f)$	$2.853(7) \cdot 10^4$	$3.733(7) \cdot 10^4$	1.31
$pp \to W^+W^-jj(4f)$ *	$1.150(5) \cdot 10^4$	$1.372(6) \cdot 10^4$	1.19
$pp \to W^+W^+jj$ *	$1.506(5) \cdot 10^2$	$2.235(7) \cdot 10^2$	1.48
$pp \to W^-W^-jj$	$6.772(24) \cdot 10^1$	$9.982(28) \cdot 10^1$	1.47
$pp \to ZW^{\pm}$	$2.780(5) \cdot 10^4$	$4.488(4) \cdot 10^4$	1.61
$pp \to ZW^{\pm}j$	$1.609(4) \cdot 10^4$	$2.0940(28) \cdot 10^4$	1.30
$pp \to ZW^{\pm}jj$	$8.06(3) \cdot 10^3$	$9.02(4) \cdot 10^3$	1.12
$pp \to ZZ$ *	$1.0969(10) \cdot 10^4$	$1.4183(11) \cdot 10^4$	1.29
$pp \to ZZj$	$3.667(9) \cdot 10^3$	$4.807(8) \cdot 10^3$	1.31
$pp \to ZZjj$ *	$1.356(6) \cdot 10^3$	$1.684(8) \cdot 10^3$	1.24

Process Top quarks plus jets	WHIZARD σ_{LO}[fb]	σ_{NLO}[fb]	K
$e^+e^- \to jj$	622.737(8)	639.39(5)	1.03
$e^+e^- \to jjj$	340.6(5)	317.8(5)	0.93
$e^+e^- \to jjjj$	105.0(3)	104.2(4)	0.99
$e^+e^- \to jjjjj$	22.33(5)	24.57(7)	1.10
$e^+e^- \to t\bar{t}$	166.37(12)	174.55(20)	1.05
$e^+e^- \to t\bar{t}j$	48.12(5)	53.41(7)	1.11
$e^+e^- \to t\bar{t}jj$	8.592(19)	10.526(21)	1.23
$e^+e^- \to t\bar{t}jjj$	1.035(4)	1.405(5)	1.36
$e^+e^- \to t\bar{t}t\bar{t}$	$0.6388(8) \cdot 10^{-3}$	$1.1922(11) \cdot 10^{-3}$	1.87
$e^+e^- \to t\bar{t}t\bar{t}j$	$2.673(7) \cdot 10^{-5}$	$5.251(11) \cdot 10^{-5}$	1.96

Top quarks plus boso	σ_{LO}[fb]	σ_{NLO}[fb]	K
$e^+e^- \to t\bar{t}H$	2.020(3)	1.912(3)	0.95
$e^+e^- \to t\bar{t}Hj$	$2.536(4) \cdot 10^{-1}$	$2.657(4) \cdot 10^{-1}$	1.05
$e^+e^- \to t\bar{t}Hjj$	$2.646(8) \cdot 10^{-2}$	$3.123(9) \cdot 10^{-2}$	1.18
$e^+e^- \to t\bar{t}Z$	4.638(3)	4.937(3)	1.06
$e^+e^- \to t\bar{t}Zj$	$6.027(9) \cdot 10^{-1}$	$6.921(11) \cdot 10^{-1}$	1.15
$e^+e^- \to t\bar{t}Zjj$	$6.436(21) \cdot 10^{-2}$	$8.241(29) \cdot 10^{-2}$	1.28
$e^+e^- \to t\bar{t}W^{\pm}jj$	$2.387(8) \cdot 10^{-4}$	$3.716(10) \cdot 10^{-4}$	1.56
$e^+e^- \to t\bar{t}HZ$	$3.623(19) \cdot 10^{-2}$	$3.584(19) \cdot 10^{-2}$	0.99
$e^+e^- \to t\bar{t}ZZ$	$3.788(6) \cdot 10^{-2}$	$4.032(7) \cdot 10^{-2}$	1.06
$e^+e^- \to t\bar{t}HH$	$1.3650(15) \cdot 10^{-2}$	$1.2168(16) \cdot 10^{-2}$	0.89
$e^+e^- \to t\bar{t}W^+W^-$	$1.3672(21) \cdot 10^{-1}$	$1.5385(22) \cdot 10^{-1}$	1.13

QCD corrections for all collider processes

Including up to 5-jet distributions and new result for 6-jet cross section at NLO QCD [Rothe, Dissertation, 2021]



Process	WHIZARD σ_{LO} [fb]	WHIZARD σ_{NLO} [fb]
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$e^+e^- \to jjjjj$	22.33(5)	24.57(7)
$e^+e^- \to jjjjjj$	3.583(17)	4.46(4)

Pure electroweak corrections for pp processes

New elements for EW corrections:

- coupling, group-factors, color vs. charge correlations, etc.
- compatibility of photon characteristics, i. e. on-shell vs. off-shell, with renormalization, EW-input and subtraction scheme
- photon recombination with fermions

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Validation of `WHIZARD+OpenLoops` cross sections of $\mathcal{O}(\alpha_s^0)$ processes at NLO EW with `MadGraph5_aMC@NLO`, setup from [1804.10017]:

process $pp \to$	α^n	`MG5_aMC@NLO` $\sigma_{\text{NLO}}^{\text{tot}}$ [pb] [1804.10017]	`WHIZARD` $\sigma_{\text{NLO}}^{\text{tot}}$ [pb]	δ [%]	$\sigma_{\text{LO}}^{\text{sig}}$	$\sigma_{\text{NLO}}^{\text{sig}}$
$e^+\nu_e$	α^2	5200.5(8)	5199.4(4)	–0.73	0.81	1.24
e^+e^-	α^2	749.8(1)	749.8(1)	–0.50	0.082	0.004
$e^+\nu_e\mu^-\bar{\nu}_\mu$	α^4	0.52794(9)	0.52816(9)	+3.69	1.27	1.69
$e^+e^-\mu^+\mu^-$	α^4	0.012083(3)	0.012078(3)	–5.25	0.68	1.26
$He^+\nu_e$	α^3	0.064740(17)	0.064763(6)	–4.04	0.06	1.24
He^+e^-	α^3	0.013699(2)	0.013699(1)	–5.86	0.03	0.32
Hjj	α^3	2.7058(4)	2.7056(6)	–4.23	0.67	0.27
tj	α^2	105.40(1)	105.38(1)	–0.72	0.20	0.74

$$\delta \equiv \frac{\sigma_{\text{NLO}}^{\text{tot}} - \sigma_{\text{LO}}^{\text{tot}}}{\sigma_{\text{LO}}^{\text{tot}}} \qquad \sigma^{\text{sig}} \equiv \frac{\left|\sigma_{\texttt{WHIZARD}}^{\text{tot}} - \sigma_{\texttt{MG5}}^{\text{tot}}\right|}{\sqrt{\Delta_{\text{err},\texttt{WHIZARD}}^2 + \Delta_{\text{err},\texttt{MG5}}^2}}$$

pp processes with on-shell heavy particles at NLO EW

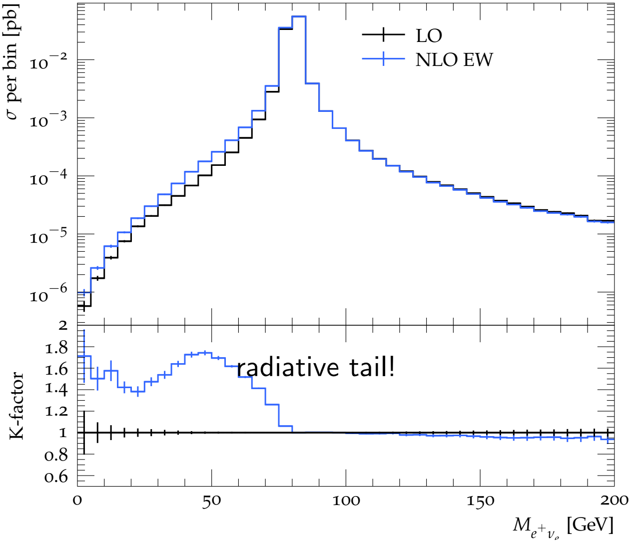
Cross-validation of `WHIZARD` and `MATRIX` orig. ref. [1711.06631]

process $pp \to$	α^n	`MATRIX` $\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	`WHIZARD` $\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	δ [%]	dev [%]	$\sigma^{\text{sig}}_{\text{NLO}}$
ZZ	α^2	$1.05729(1) \cdot 10^4$	$1.05729(11) \cdot 10^4$	-4.20	0.0001	0.01
W^+Z	α^2	$1.71505(2) \cdot 10^4$	$1.71507(2) \cdot 10^4$	-0.15	0.001	0.88
W^-Z	α^2	$1.08576(1) \cdot 10^4$	$1.08574(1) \cdot 10^4$	$+0.07$	0.001	0.90
W^+W^-	α^2	$7.93106(7) \cdot 10^4$	$7.93087(21) \cdot 10^4$	$+4.55$	0.002	0.89
ZH	α^2	$6.18523(6) \cdot 10^2$	$6.18533(6) \cdot 10^2$	-5.29	0.002	1.17
W^+H	α^2	$7.18070(7) \cdot 10^2$	$7.18072(9) \cdot 10^2$	-2.31	0.0003	0.18
W^-H	α^2	$4.59289(4) \cdot 10^2$	$4.59299(5) \cdot 10^2$	-2.15	0.002	1.62
ZZZ	α^3	$9.7429(2) \cdot 10^0$	$9.7417(11) \cdot 10^0$	-9.47	0.012	1.01
W^+W^-Z	α^3	$1.08288(2) \cdot 10^2$	$1.08313(25) \cdot 10^2$	$+7.67$	0.022	0.96
W^+ZZ	α^3	$2.0188(4) \cdot 10^1$	$2.0188(23) \cdot 10^1$	$+1.58$	0.0001	0.01
W^-ZZ	α^3	$1.09844(2) \cdot 10^1$	$1.09838(12) \cdot 10^1$	$+3.09$	0.006	0.51
$W^+W^-W^+$	α^3	$8.7979(2) \cdot 10^1$	$8.7991(15) \cdot 10^1$	$+6.18$	0.014	0.79
$W^+W^-W^-$	α^3	$4.9447(1) \cdot 10^1$	$4.9441(2) \cdot 10^1$	$+7.13$	0.013	2.52
ZZH	α^3	$1.91607(2) \cdot 10^0$	$1.91614(18) \cdot 10^0$	-8.78	0.004	0.39
W^+ZH	α^3	$2.48068(2) \cdot 10^0$	$2.48095(28) \cdot 10^0$	$+1.64$	0.011	0.96
W^-ZH	α^3	$1.34001(1) \cdot 10^0$	$1.34016(15) \cdot 10^0$	$+2.51$	0.011	1.02
ZHH	α^3	$2.39350(2) \cdot 10^{-1}$	$2.39337(32) \cdot 10^{-1}$	-11.06	0.005	0.41
W^+HH	α^3	$2.44794(2) \cdot 10^{-1}$	$2.44776(24) \cdot 10^{-1}$	-12.04	0.007	0.74
W^-HH	α^3	$1.33525(1) \cdot 10^{-1}$	$1.33471(19) \cdot 10^{-1}$	-11.53	0.041	2.80

$$\delta \equiv \frac{\sigma^{\text{tot}}_{\text{NLO}} - \sigma^{\text{tot}}_{\text{LO}}}{\sigma^{\text{tot}}_{\text{LO}}} \qquad \text{dev} \equiv \frac{|\sigma^{\text{tot}}_{\texttt{WHIZARD}} - \sigma^{\text{tot}}_{\texttt{MATRIX}}|}{\sigma^{\text{tot}}_{\texttt{WHIZARD}}} \qquad \sigma^{\text{sig}} \equiv \frac{|\sigma^{\text{tot}}_{\texttt{WHIZARD}} - \sigma^{\text{tot}}_{\texttt{MATRIX}}|}{\sqrt{\Delta^2_{\text{err},\texttt{WHIZARD}} + \Delta^2_{\text{err},\texttt{MATRIX}}}}$$

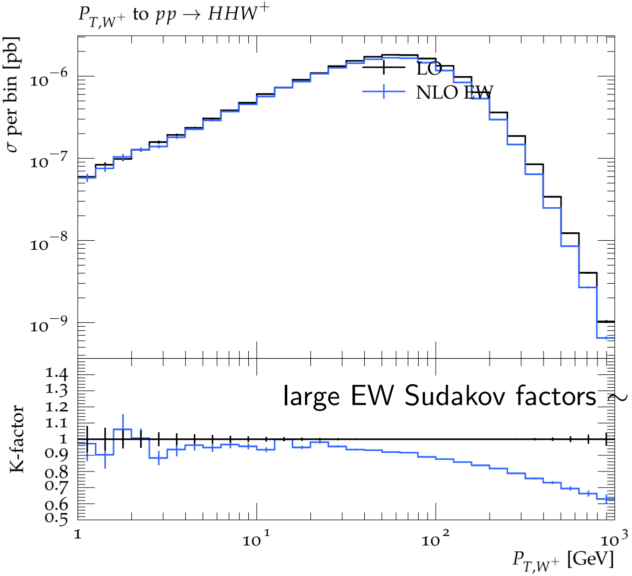
pp processes with off-shell bosons at NLO EW

Fixed order differential distributions for $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$ at NLO EW



pp processes with on-shell heavy particles at NLO EW

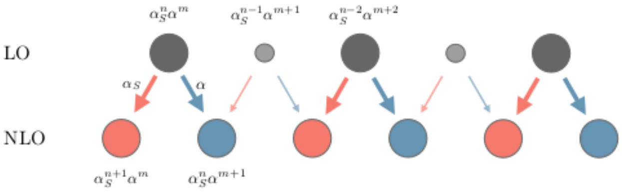
Fixed order differential distributions for $pp \to HHW^+$ at NLO EW



large EW Sudakov factors $\sim \alpha^n \log^{2n} \frac{Q^2}{M_W^2}$!

EW/mixed corrections for pp processes

Treat gluons and photons in jets/protons on democratic basis
$\rightarrow$ for EW corrections of processes at $\mathcal{O}(\alpha_s)$ and higher:
QCD counterterms needed!



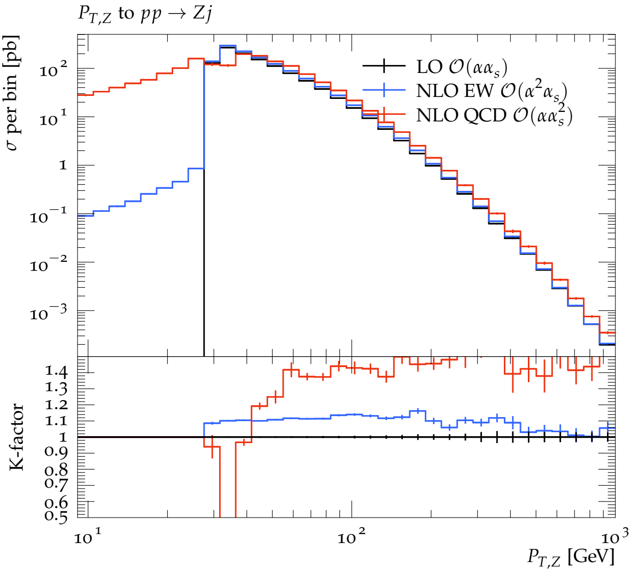
[1907.13071]

Example: $pp \rightarrow Zj$ at $\mathcal{O}(\alpha\alpha_s)$:
At NLO EW contributions from $q\bar{q} \rightarrow Zg\gamma$ at $\mathcal{O}(\alpha^2\alpha_s)$
$\Rightarrow$ Needs cancellations from $[\mathcal{B}(q\bar{q} \rightarrow Zg)$ at $\mathcal{O}(\alpha\alpha_s)] \times$ [QED splitting]
and $[\mathcal{B}(q\bar{q} \rightarrow Z\gamma)$ at $\mathcal{O}(\alpha^2)] \times$ [QCD splitting]
Which coupling power contributions at NLO (and LO)?

$\Rightarrow$ **Broad and active research field!**

EW/mixed corrections for pp processes

Fixed order differential distributions for $pp \to Zj$ at NLO EW/QCD



$P_{T,j} > 30$ GeV

$|\eta_j| < 4.5$

EW/mixed corrections for lepton collider processes

EW corrections require NLO QED PDFs for lepton collision processes which factorize collinear IS singularities
$\rightarrow$ perturbatively calculable:

- NLO initial conditions of electron and photon PDFs [1909.03886]
- NLL resummation [1911.12040]

$\Rightarrow$ Automation in `WHIZARD`: Implementation and embedding into FKS scheme

Summary

SM NLO corrections for all colliders in `WHIZARD`:

- full automation of NLO QCD corrections for all collider processes and pure EW corrections for pp processes
- first results for NLO QCD-EW mixed corrections for pp processes
- automation of NLO EW corrections for lepton collider processes started

Outlook:

- matching of EW NLO fixed order corrections to QED parton showers
- EW corrections with resummation of exclusive photons via YFS

Thanks! :)