Automated NLO SM corrections for all colliders

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Motivation

- **Monte-Carlo event generator:** provides exclusive simulated data!
- **SM NLO corrections:** increased precision of theoretical predictions
  $\Rightarrow$ higher sensitivity to new physics
  - QCD corrections most relevant for hadron collider processes
  - Even though $\alpha \sim \alpha_s^2$, EW corrections relevant at hadron colliders (e. g. large EW Sudakov factors) and highly relevant at lepton colliders
- **Automation:** flexibly use precise predictions for all collider processes

Overview: Automated NLO corrections in WHIZARD

`https://whizard.hepforge.org`

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- `WHIZARD` [1] is a **multi-purpose event generator** for multi-particle scattering cross sections and simulated event samples for **lepton and hadron collider** processes covering **SM** and **BSM** physics
- tree level matrix elements - `O'Mega`[2], phase space evaluation - `VAMP2`[3]
- NLO matrix elements from one-loop providers: `OpenLoops`[4], `RECOLA`[5], ...
- Regularisation of infrared singularities based on **FKS subtraction** scheme
  $\Rightarrow$ NLO QCD, EW and mixed corrections
- Matching to parton showers with **POWHEG** scheme
  $\Rightarrow$ QCD corrections

NLO EW corrections to cross sections of LHC processes

`WHIZARD+OpenLoops` NLO EW cross sections of pp processes with

- ... on-shell bosons VV, VH, VVV and VVH validated with `MUNICH+OpenLoops`[6]
- ... off-shell vector bosons (+ associated Higgs) validated with `MG5_aMC@NLO`[7]:
  $\sqrt{s} = 13$ TeV $\quad \mu_R = \mu_F = \frac{H_T}{2} = \frac{1}{2}\sum_i \sqrt{p_{T,i}^2 + m_i^2} \quad$ α input scheme: G_μ CMS

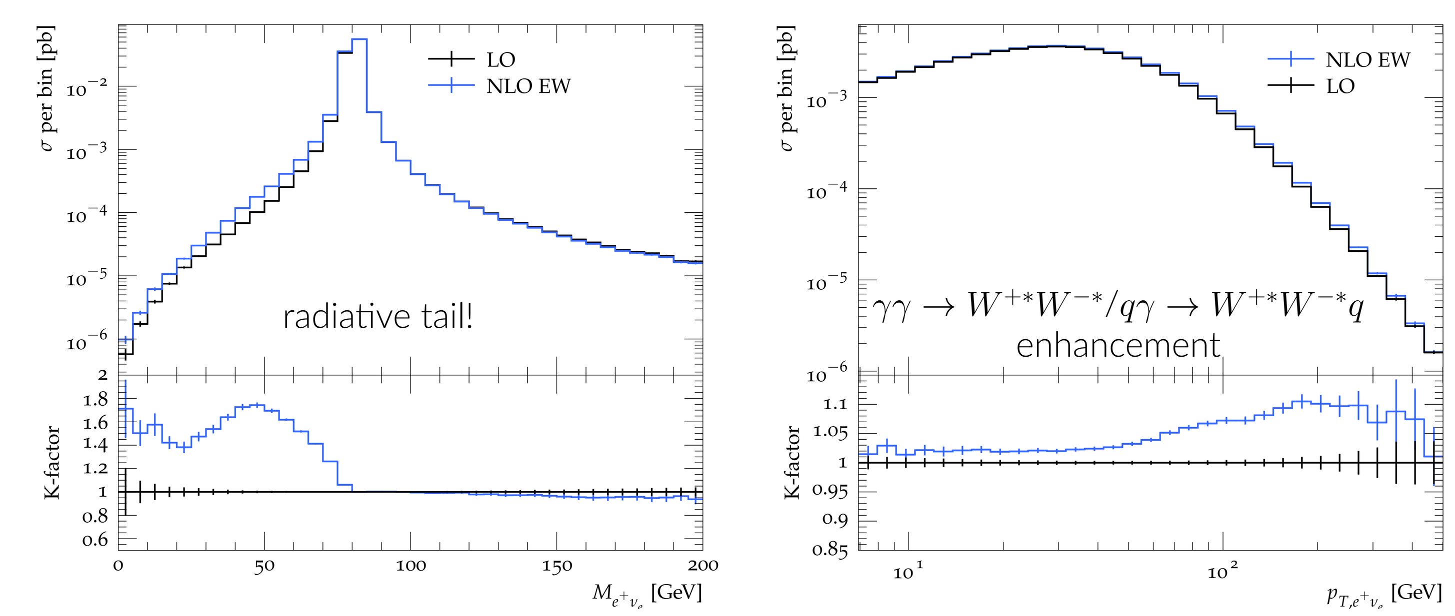
process $pp \to$	α^n	`MG5_aMC@NLO` $\sigma^{\text{tot}}_{\text{NLO}}$ [pb]	`WHIZARD+OpenLoops` $\sigma^{\text{tot}}_{\text{NLO}}$ [pb]	δ [%]	$\sigma^{\text{sig}}_{\text{LO}}$	$\sigma^{\text{sig}}_{\text{NLO}}$
$e^+\nu_e$	α^2	5200.5(8)	5199.4(4)	−0.73	0.81	1.24
e^+e^-	α^2	749.8(1)	749.8(1)	−0.50	0.08	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

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

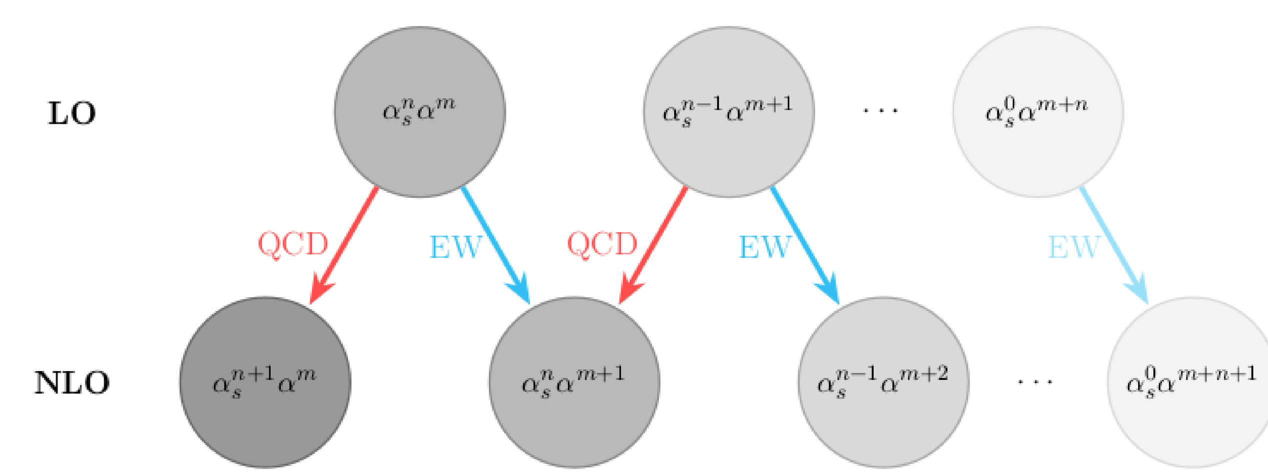
NLO EW corrections to differential distributions of LHC processes

Electroweak effects observable in differential distributions as

- ... for $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$ at NLO EW:



NLO SM mixed corrections at the LHC



- Except for the leading α_s and α NLO contributions, subtraction of both, QCD and QED IR singularities in one NLO contribution at fixed couplings
- Validation of all leading and subleading NLO contributions of $pp \to t\bar{t}(H/Z/W^\pm)$ with `MUNICH`, e. g.

$pp \to t\bar{t}H$	$\alpha_s^m\alpha^n$	σ^{tot} [fb] `MUNICH+OpenLoops`	σ^{tot} [fb] `WHIZARD+OpenLoops`	σ^{sig}	*rel. deviation*
LO_{21}	$\alpha_s^2\alpha$	$3.44865(1) \cdot 10^2$	$3.4487(1) \cdot 10^2$	0.76	0.003%
LO_{12}	$\alpha_s\alpha^2$	$1.40208(2) \cdot 10^0$	$1.4022(1) \cdot 10^0$	1.44	0.011%
LO_{03}	α^3	$2.42709(1) \cdot 10^0$	$2.4274(2) \cdot 10^0$	2.07	0.011%
NLO_{31}	$\alpha_s^3\alpha$	$9.9656(4) \cdot 10^1$	$9.968(4) \cdot 10^1$	0.62	0.023%
NLO_{22}	$\alpha_s^2\alpha^2$	$6.209(1) \cdot 10^0$	$6.208(2) \cdot 10^0$	0.20	0.009%
NLO_{13}	$\alpha_s\alpha^3$	$1.7238(2) \cdot 10^0$	$1.7232(5) \cdot 10^0$	1.24	0.040%
NLO_{04}	α^4	$1.5053(3) \cdot 10^{-1}$	$1.5060(7) \cdot 10^{-1}$	1.00	0.048%

- Non-trivial cut evaluation including photon recombination and jet clustering for processes with jets and leptons in the FS, e. g. $pp \to e^+\nu_e j, e^+e^-j$:

process $pp \to$	$\alpha_s^m\alpha^n$	`MG5_aMC@NLO` $\sigma^{\text{tot}}_{\text{NLO}}$ [pb]	`WHIZARD+OpenLoops` $\sigma^{\text{tot}}_{\text{NLO}}$ [pb]	δ [%]	$\sigma^{\text{sig}}_{\text{LO}}$	$\sigma^{\text{sig}}_{\text{NLO}}$
$e^+\nu_e j$	$\alpha_s\alpha^2$	$9.0475(8) \cdot 10^5$	$9.0459(7) \cdot 10^5$	−1.11	0.8	1.5
e^+e^-j	$\alpha_s\alpha^2$	$1.4909(2) \cdot 10^5$	$1.4908(2) \cdot 10^5$	−1.00	0.05	0.4

Lepton collider processes at NLO EW

Fixed order computations with massive initial state

- FKS phase space construction with on-shell projection
- Checks on $e^+e^- \to HZ$ cross sections at NLO EW for ILC setup:

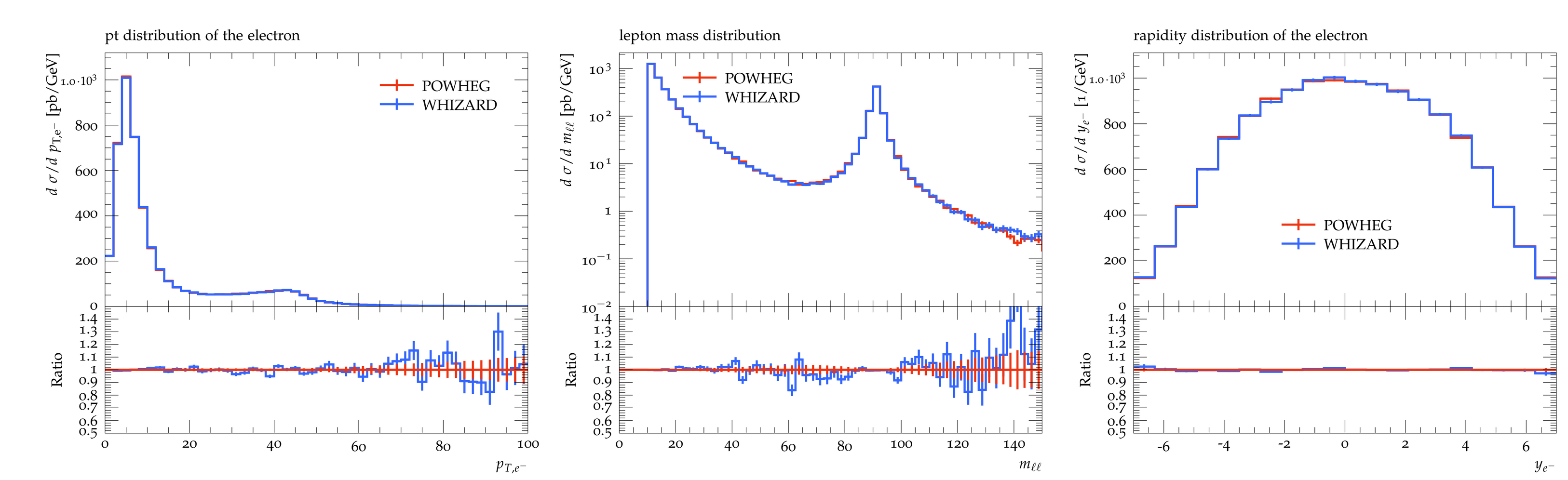
$\sqrt{s}$ [GeV]	`MCSANCee`[8] $\sigma^{\text{tot}}_{\text{LO}}$ [fb]	`MCSANCee`[8] $\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	`WHIZARD+RECOLA` $\sigma^{\text{tot}}_{\text{LO}}$ [fb]	`WHIZARD+RECOLA` $\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	`WHIZARD+RECOLA` δ_{EW} [%]	σ^{sig} (LO/NLO)
250	225.59(1)	206.77(1)	225.60(1)	207.0(1)	−8.25	0.4/2.1
500	53.74(1)	62.42(1)	53.74(3)	62.41(2)	+16.14	0.2/0.3
1000	12.05(1)	14.56(1)	12.0549(6)	14.57(1)	+20.84	0.5/0.5

Approximation of the massless initial state

- Collinear factorization and resummation of large logarithms in the form of LL and NLL electron PDFs - implemented and validated
- Embedding into FKS scheme - work in progress

POWHEG-matched and showered NLO event generation

- POWHEG matching for Drell-Yan and similar processes validated
- Comparison of p_{T,e^-}, $m_{e^+e^-}$ and y_{e^-} distributions for $pp \to e^+e^-$ with matched events from `WHIZARD` and `POWHEG-BOX`[9] and showered with `PYTHIA`[10]:



References

[1] W. Kilian, T. Ohl, and J. Reuter *Eur. Phys. J.*, vol. C71, p. 1742, 2011.
[2] M. Moretti, T. Ohl, and J. Reuter pp. 1981--2009, 2 2001.
[3] S. Brass, W. Kilian, and J. Reuter *Eur. Phys. J. C*, vol. 79, no. 4, p. 344, 2019.
[4] F. Buccioni et. al. *Eur. Phys. J. C*, vol. 79, no. 10, p. 866, 2019.
[5] S. Actis, A. Denner, L. Hofer, A. Scharf, and S. Uccirati *JHEP*, vol. 04, p. 037, 2013.
[6] S. Kallweit et. al. *JHEP*, vol. 04, p. 012, 2015.
[7] R. Frederixi et. al. *JHEP*, vol. 07, p. 185, 2018.
[8] R. R. Sadykov et. al. *J. Phys. Conf. Ser.*, vol. 1525, no. 1, p. 012012, 2020.
[9] S. Alioli et. al. *JHEP*, vol. 07, p. 060, 2008.
[10] T. Sjöstrand et. al. *Comput. Phys. Commun.*, vol. 191, pp. 159--177, 2015.