Towards automated SM NLO corrections for all colliders

Pia Mareen Bredt

DESY Hamburg

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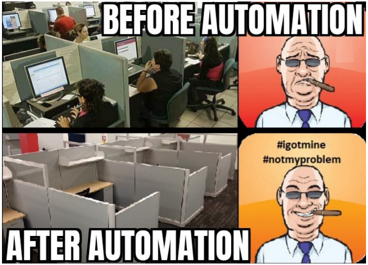
Motivation

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

- **Monte-Carlo event generator:** provides exclusive simulated data!
  - → Build on WHIZARD [Kilian, Ohl, Reuter: 0708.4233]
- **SM NLO corrections:** increased precision of theoretical predictions ⇒ 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



About WHIZARD

recent version: v3.0.2 (released today)

team: **Wolfgang Kilian, Thorsten Ohl, Jürgen Reuter**
Pia Bredt, Nils Kreher, Pascal Stienemeier, Tobias Striegl

webpage: https://whizard.hepforge.org/

support: https://launchpad.net/whizard

email contact: whizard@desy.de

WHIZARD [EPJ C71 (2011) 1742] 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 [LC-TOOL (2001) 040]
- phase space evaluation with VAMP2 [EPJ C79 (2019) 4 344]:
  - twofold self-adaptive multi-channel parametrization
  - OpenMP and MPI for parallelization ⇒ speedup of factor $\mathcal{O}(100)$
- lepton collisions in WHIZARD

beamstrahlung	CIRCE1/CIRCE2 [CPC 101 (1997) 269]
bremsstrahlung	LL resummation via ISR and EPA functions
beam polarization	inclusion for a user-defineable setup

- interfaces to LHAPDF, OLPs, parton showers, event formats, ...

Automated NLO corrections

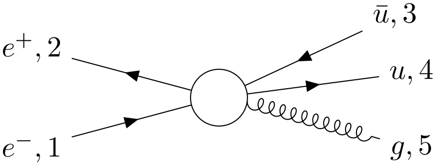
Kinoshita-Lee-Nauenberg theorem: For $2 \to n$ processes

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

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

→ 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: $(i, j) \in \{(3, 5), (4, 5)\}$

Full SM NLO automation in WHIZARD

- FKS scheme implemented
- One-loop provision by `OpenLoops` [1907.13071] as standard
- Matching to parton showers by POWHEG scheme
  (for e^+e^- processes in validation, for pp processes work in progress)
- Validation with several other Monte-Carlo event generators:
  `MG5_aMC@NLO`, `Sherpa`, `MUNICH`, `POWHEG-BOX`, ...

- NLO QCD automation completed ☑
- NLO EW automation for LHC processes (nearly) completed ☑
  - pure EW corrections ☑
  - QCD-EW mixed corrections (in validation) ☑
- next step: NLO EW for e^+e^- collisions □
  (technical results for massive IS)

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

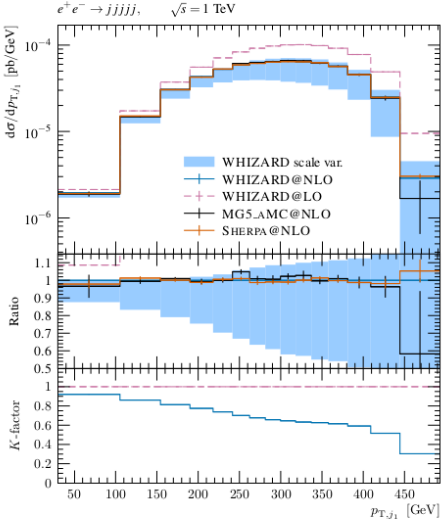
by S. Braß, PB, W. Kilian, J. Reuter, V. Rothe, P. Stienemeier [Stienemeier, *et. al.*: 2104.11141]

Process	WHIZARD+OpenLoops $\sigma_{\rm LO}$[fb]	WHIZARD+OpenLoops $\sigma_{\rm NLO}$[fb]	K
$pp \to jj$	$1.162(4) \cdot 10^9$	$1.601(5) \cdot 10^9$	1.38
$pp \to jjj$	$9.01(4) \cdot 10^7$	$7.46(9) \cdot 10^7$	0.83
$pp \to t\bar{t}$	$4.589(9) \cdot 10^5$	$6.740(10) \cdot 10^5$	1.47
$pp \to t\bar{t}j$	$3.123(6) \cdot 10^5$	$4.087(9) \cdot 10^5$	1.31
$pp \to t\bar{t}jj$	$1.360(4) \cdot 10^5$	$1.775(7) \cdot 10^5$	1.31
$pp \to t\bar{t}t\bar{t}$	$4.485(6)$	$9.070(9)$	2.02
$pp \to W^\pm$	$1.3749(8) \cdot 10^8$	$1.7696(10) \cdot 10^8$	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
$pp \to W^+W^+jj$	$1.506(5) \cdot 10^2$	$2.235(7) \cdot 10^2$	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	WHIZARD+OpenLoops $\sigma_{\rm LO}$[fb]	WHIZARD+OpenLoops $\sigma_{\rm NLO}$[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
$e^+e^- \to t\bar{t}H$	$2.020(3)$	$1.912(3)$	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

Jet production at a lepton collider at NLO QCD

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



Integrated results with MC-errors for e^+e^- to n-jet production processes

Process	WHIZARD+OpenLoops σ_{LO} [fb]	WHIZARD+OpenLoops σ_{NLO} [fb]
$e^+e^- \to jj$	622.737(8)	639.39(5)
$e^+e^- \to jjj$	340.6(5)	317.8(5)
$e^+e^- \to jjjj$	105.0(3)	104.2(4)
$e^+e^- \to jjjjj$	22.33(5)	24.57(7)
$e^+e^- \to jjjjjj$	3.583(17)	4.46(4)

NLO electroweak corrections

Requirements for pure electroweak pp processes at NLO EW (supported since `WHIZARD v3.0.1`):

- application of FKS scheme to QED IR subtraction + EW virtual loop contributions
- QED IR-safety requirements → photon recombination with fermions
- consistent treatment of photons nature, i. e. on-shell or off-shell, throughout all schemes

$Q_\gamma^2 \to 0$	$Q_\gamma^2 \sim$ EW scale
on-shell photons no γ splittings	*off-shell* photons $\gamma^* \to f\bar{f}$
$\alpha(0)$	$\alpha\|_{G_\mu}$, $\alpha\left(M_Z\right)$
$\left[\frac{\delta\alpha(0)}{\alpha(0)} + \delta Z_{AA}\right]_{\text{light}} = 0$	$\left[\frac{\delta\alpha(M_Z)}{\alpha(M_Z)} + \delta Z_{AA}\right]_{\text{light}} + \delta Z_{\gamma,\text{PDF}}$ → finite overall photon factor $\neq 0$

⇒ Have to be treated consistently in IR subtraction (FKS), EW input and renormalization scheme (at 1-loop)!

pp processes with off-shell vector bosons at NLO EW

Validation of cross sections of pure electroweak pp processes at NLO EW with MadGraph5_aMC@NLO, setup from [1804.10017]:

process $pp \to$	α^n	MG5_aMC@NLO $\sigma^{\text{tot}}_{\text{NLO}}$ [pb] [1804.10017]	WHIZARD $\sigma^{\text{tot}}_{\text{NLO}}$ [pb] +OpenLoops	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

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

pp processes with on-shell heavy bosons at NLO EW

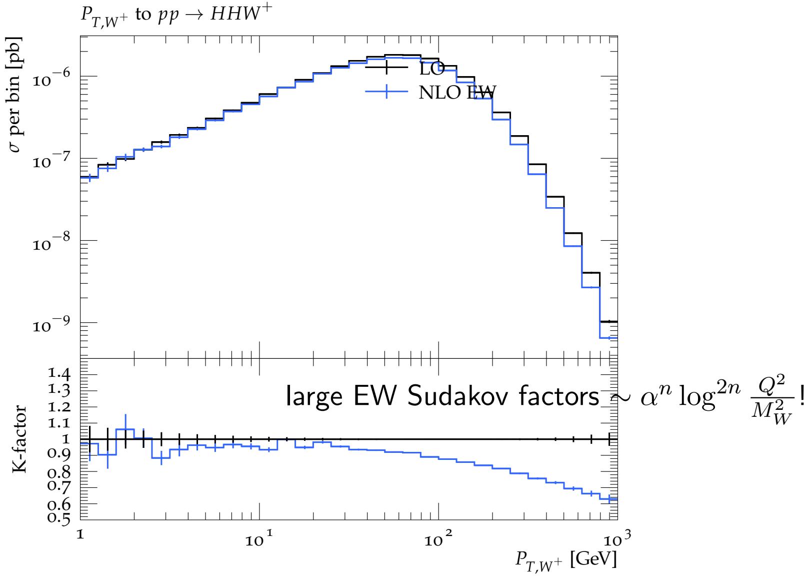
Cross-validation of WHIZARD and MUNICH orig. ref. [Kallweit *et. al.*: 1412.5157]

process $pp \to$	α^n	MUNICH +OpenLoops $\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	WHIZARD +OpenLoops $\sigma^{\text{tot}}_{\text{NLO}}$ [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	$1.08288(2) \cdot 10^2$	$1.08293(10) \cdot 10^2$	$+7.67$	0.004	0.45
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

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

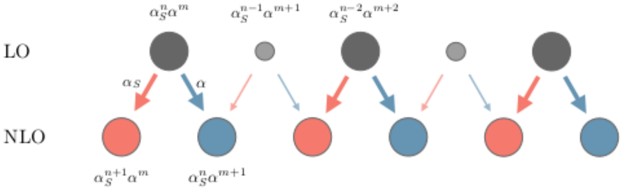
pp processes with on-shell heavy particles at NLO EW

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



Interfering correction types (QCD$\times$EW)

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



[1907.13071]

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

Difficulties:

- Bookkeeping of amplitudes complicated (esp. with interferences, e.g. $q\bar{q} \to q\bar{q}$ at $\mathcal{O}(\alpha\alpha_s)$)
- Non-singular real contributions possible, e.g. $q\bar{q} \to Zq\bar{q}$ at $\mathcal{O}(\alpha^2\alpha_s)$ for $pp \to Zj$
- Overlapping NLO QCDxEW virtual loop contributions, e. g. $b\bar{b} \to t\bar{t}$ at $\mathcal{O}(\alpha\alpha_s^2)$

Interfering correction types (QCD×EW)

QCD×EW mixed corrections in WHIZARDs recent v3.0.2:
Necessary SINDARIN commands for NLO $\mathcal{O}(\alpha^{n+1}\alpha_s^m)$ contributions

```
alpha_power = <n>
alphas_power = <m>
$nlo_correction_type = "EW"
```

Validation for pp processes at NLO EW:

process $pp \to$	$\alpha^n \alpha_s^m$	MG5_aMC@NLO $\sigma^{\text{tot}}_{\text{NLO}}$ [pb] [1804.10017]	WHIZARD $\sigma^{\text{tot}}_{\text{NLO}}$ [pb]	δ [%]	dev [%]	$\sigma^{\text{sig}}_{\text{NLO}}$
W^+j	$\alpha\alpha_s$	11552.(4)	11545.(4)	−0.37	0.07	1.26
Zj	$\alpha\alpha_s$	7062.(1)	7064.(3)	−0.80	0.03	0.77
$t\bar{t}$	α_s^2	432.90(6)	432.99(5)	−1.15	0.02	1.16
$t\bar{t}W^+$	$\alpha\alpha_s^2$	0.23025(3)	0.23017(5)	−4.53	0.03	1.28
$t\bar{t}Z$	$\alpha\alpha_s^2$	0.50033(7)	0.50041(10)	−0.84	0.02	0.67

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

EW/mixed corrections for lepton collider processes

Lepton collision processes with **massless** IS:
require **NLO QED PDFs** which factorize collinear IS singularities
$\rightarrow$ perturbatively calculable
Solutions for unpolarized NLO QED PDFs in e^+e^- collisions:

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

$\Rightarrow$ Implementation and embedding into FKS scheme in `WHIZARD` work in progress

Lepton collision processes with **massive** IS:
Only soft singularities to be cancelled for the IS
$\Rightarrow$ Technically possible in `WHIZARD`

Summary

SM NLO corrections for all collider processes 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:

- equip e^+e^- processes at NLO EW with beamstrahlung
- match EW NLO fixed order corrections to QED parton showers
- EW corrections with resummation of exclusive photons via YFS

Thanks! :)

Questions?