A generic NLO SM framework for LHC and future collider processes

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Particle Physics Phenomenology after the Higgs Discovery

NLO SM precision in an automated tool

Why do we care?

- NLO QCD corrections
  - Dominant QCD background at hadron colliders, $\alpha_s \gg \alpha$ at $\mu \sim M_Z$
  - ...
- NLO EW corrections
  - $\mathcal{O}(\alpha \log^2 p_{ij}^2/M_W^2)$ EW Sudakov suppressions large
    - $\rightarrow$ in high-p_T regions of distributions of pp processes, $\mathcal{O}(10\%)$ at the LHC
    - $\rightarrow$ for high-energy lepton colliders, $p_{ij}^2 \sim \hat{s} \sim s$
  - $\mathcal{O}(\alpha \log s/m_l^2)$ enhancements for QED ISR at lepton colliders
  - $\mathcal{O}(\alpha \log s/E_\gamma^2)$ soft photon radiation at lepton colliders
  - ...

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What do we do?

- Apply universal principles of NLO SM corrections in the Monte-Carlo generator `WHIZARD` [EPJ C71 (2011) 1742] for both collider types and arbitrary final states

Overview

Parts:

I) Automation of NLO SM corrections in `WHIZARD`

II) Application of NLO EW corrections to multi-boson processes at a future muon collider

I) Automation of NLO SM corrections in WHIZARD

I) WHIZARD

What is WHIZARD?

Multi-purpose event generator for cross sections and differential distributions of **arbitrary processes** at HEP experiments (LHC, Belle II, ILC/CLIC/FCC/CEPC, MuCol, ...)

recent version: v3.1.2
team: **Wolfgang Kilian, Thorsten Ohl, Jürgen Reuter**
PB, Nils Kreher, Krzysztof Mękała, Tobias Striegl
webpage: https://whizard.hepforge.org/
support: https://launchpad.net/whizard
email contact: whizard@desy.de

Essential elements of WHIZARD

- physics models: SM, internal (hard-coded) BSM and UFO models
- phase-space integrator: VAMP (VEGAS AMPlified) [CPC 120 (1999) 13],
  VAMP2[EPJ C79 (2019) 4 344] incl. MPI parallelization
- matrix elements: tree-level ME generator O'Mega [LC-TOOL (2001) 040], interface to OLPs
  OpenLoops[1907.13071], RECOLA[1711.07388] and GoSam[1404.7096]
- precision methods: FKS subtr., POWHEG matching, PYTHIA-interface, lepton collider
  Beam features (QED ISR, Beamsstrahlung, polarization), ...

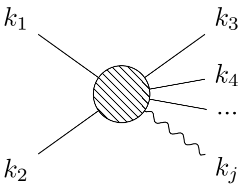
I) NLO framework in WHIZARD

(contributors: PB, B. C.-Nejad, W. Kilian, J. Reuter, V. Rothe, P. Stienemeier, C. Weiss)

$$\sigma_{\text{NLO}} = \underbrace{\int d\Phi_n \mathcal{B}}_{\text{Born}} + \underbrace{\int d\Phi_{n+1} \mathcal{R}}_{\text{div. real}} + \underbrace{\int d\Phi_n \mathcal{V}}_{\text{div. virtual}} = \text{finite}$$

Need observables **exclusive** in kinematic properties!

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



'j' radiated with several different emitters
⇒ Subtract singularities related to IR splittings systematically!

Frixione-Kunszt-Signer (FKS) subtraction

Divide phase space into disjoint regions with **at most one** soft and/or collinear singularity.
⇒ kinematical weight factors related to pairs (i, j)

I) NLO framework in WHIZARD

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FKS subtraction per α_r region

$$\mathcal{R} = \sum_{\alpha_r} \mathcal{R}_{\alpha_r} = \sum_{\alpha_r} \mathcal{S}_{\alpha_r} \mathcal{R} \qquad \text{for } \mathcal{I}_{\alpha_r} = (i,j) \in P_{\text{FKS}}(f_r)$$

works in conjunction with POWHEG matching scheme

$$d\sigma_{\text{NLO}} = \bar{\mathcal{B}}(\Phi_n) \left(\Delta(p_{T,\text{min}}) + \Delta(k_T(\Phi_{n+1})) \frac{\mathcal{R}(\Phi_{n+1})}{\mathcal{B}(\Phi_n)} d\Phi_{\text{rad}} \right) d\Phi_n$$

using a *modified* Sudakov form factor

$$\Delta(\Phi_n, p_T) = \exp\left[- \int \frac{\mathcal{R}(\Phi_{n+1})}{\mathcal{B}(\Phi_n)} \theta\left(k_T(\Phi_{n+1}) - p_T\right) d\Phi_{\text{rad}} \right]$$

$$\Delta^{f_\mathcal{B}}(\Phi_n, p_T) = \prod_{\alpha_r \in \{\alpha_r | f_\mathcal{B}\}} \Delta^{f_\mathcal{B}}_{\alpha_r}(\Phi_n, p_T)$$

I) NLO framework in WHIZARD: NLO QCD

(contributors: PB, B. C.-Nejad, W. Kilian, J. Reuter, V. Rothe, P. Stienemeier, C. Weiss)

For pp and e^+e^- colliders

- Automation of fNLO simulation of cross sections and distributions
  - $\rightarrow$ Validated for about 50 processes with MG5_aMC@NLO[1405.0301] and SHERPA[1905.09127]
- Automation of POWHEG-matched event generation for NLO QCD corrections (thanks to Pascal Stienemeier)
  - $\rightarrow$ Validated for $pp \rightarrow e^+e^-$ and $e^+e^- \rightarrow t\bar{t}j$ with POWHEG-BOX[1002.2581]

I) NLO framework in WHIZARD: NLO EW

Extension to electroweak corrections

- QED FKS subtraction terms:

$$d\sigma_{S,\text{coll}} \sim \alpha \underbrace{\hat{P}^{\mu\nu}_{E\to(i,j),\text{QED}}\mathcal{B}^{(E)}_{\mu\nu}}_{\text{pol. AP kernel}\,\times\,\text{spin-corr.}}, \; d\sigma_{S,\text{soft}} \sim \alpha \sum_{k,l=1}^{n} \underbrace{\frac{\bar{k}_k \cdot \bar{k}_l}{(\bar{k}_k \cdot \hat{k}_j)(\bar{k}_l \cdot \hat{k}_j)}\mathcal{B}_{kl}}_{\text{eikonal}\,\times\,\text{charge-corr.}}$$

- EW loop contributions (interface to OpenLoops, RECOLA, GoSam)
- EW renorm. schemes & photons entering at Born level

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

with photon virtuality Q^2_γ

$\to$ α coupling constant, renormalization factors

I) NLO framework in WHIZARD: NLO EW

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

process $pp \to$	MUNICH$_{(CS)}$ +OpenLoops σ^{tot}_{NLO} [fb]	WHIZARD +OpenLoops σ^{tot}_{NLO} [fb]	δ [%]	dev [%]	σ^{sig}
ZZ	$1.05729(1) \cdot 10^4$	$1.05729(11) \cdot 10^4$	-4.20	0.0001	0.01
W^+Z	$1.71505(2) \cdot 10^4$	$1.71507(2) \cdot 10^4$	-0.15	0.001	0.88
W^-Z	$1.08576(1) \cdot 10^4$	$1.08574(1) \cdot 10^4$	$+0.07$	0.001	0.90
W^+W^-	$7.93106(7) \cdot 10^4$	$7.93087(21) \cdot 10^4$	$+4.55$	0.002	0.89
ZH	$6.18523(6) \cdot 10^2$	$6.18533(6) \cdot 10^2$	-5.29	0.002	1.17
W^+H	$7.18070(7) \cdot 10^2$	$7.18072(9) \cdot 10^2$	-2.31	0.0003	0.18
W^-H	$4.59289(4) \cdot 10^2$	$4.59299(5) \cdot 10^2$	-2.15	0.002	1.62
ZZZ	$9.7429(2) \cdot 10^0$	$9.7417(11) \cdot 10^0$	-9.47	0.012	1.01
W^+W^-Z	$1.08288(2) \cdot 10^2$	$1.08293(10) \cdot 10^2$	$+7.67$	0.004	0.45
W^+ZZ	$2.0188(4) \cdot 10^1$	$2.0188(23) \cdot 10^1$	$+1.58$	0.0001	0.01
W^-ZZ	$1.09844(2) \cdot 10^1$	$1.09838(12) \cdot 10^1$	$+3.09$	0.006	0.51
$W^+W^-W^+$	$8.7979(2) \cdot 10^1$	$8.7991(15) \cdot 10^1$	$+6.18$	0.014	0.79
$W^+W^-W^-$	$4.9447(1) \cdot 10^1$	$4.9441(2) \cdot 10^1$	$+7.13$	0.013	2.52
ZZH	$1.91607(2) \cdot 10^0$	$1.91614(18) \cdot 10^0$	-8.78	0.004	0.39
W^+ZH	$2.48068(2) \cdot 10^0$	$2.48095(28) \cdot 10^0$	$+1.64$	0.011	0.96
W^-ZH	$1.34001(1) \cdot 10^0$	$1.34016(15) \cdot 10^0$	$+2.51$	0.011	1.02
W^+W^-H	$9.7012(2) \cdot 10^0$	$9.700(2) \cdot 10^0$	$+9.83$	0.014	0.75
ZHH	$2.39350(2) \cdot 10^{-1}$	$2.39337(32) \cdot 10^{-1}$	-11.06	0.005	0.41
W^+HH	$2.44794(2) \cdot 10^{-1}$	$2.44776(24) \cdot 10^{-1}$	-12.04	0.007	0.74
W^-HH	$1.33525(1) \cdot 10^{-1}$	$1.33471(19) \cdot 10^{-1}$	-11.53	0.041	2.80

LHC setup (Run II), $\delta \equiv (\sigma^{tot}_{NLO} - \sigma^{tot}_{LO})/\sigma^{tot}_{LO}$, dev $\equiv |\sigma^{tot}_{WHIZARD} - \sigma^{tot}_{MUNICH}|/\sigma^{tot}_{WHIZARD}$

I) NLO framework in WHIZARD: NLO EW

Pure electroweak pp processes with off-shell vector bosons

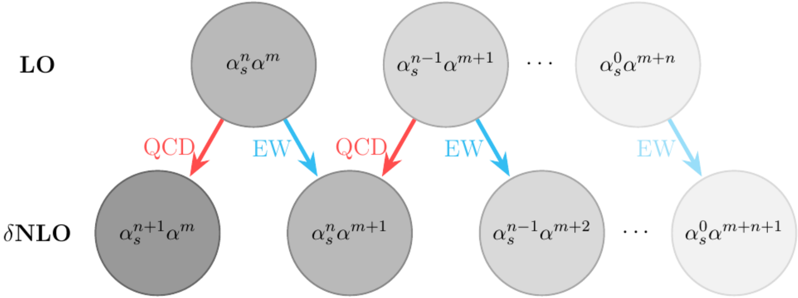
process $pp \to$	α^m	MG5_aMC@NLO[1804.10017] $\sigma^{\text{tot}}_{\text{NLO}}$ [pb]	WHIZARD+OpenLoops $\sigma^{\text{tot}}_{\text{NLO}}$ [pb]	δ [%]	$\sigma^{\text{sig}}_{\text{NLO}}$
$e^+\nu_e$	α^2	$5.2005(8)\cdot 10^3$	$5.1994(4)\cdot 10^3$	-0.73	1.24
e^+e^-	α^2	$7.498(1)\cdot 10^2$	$7.498(1)\cdot 10^2$	-0.50	0.004
$e^+\nu_e\mu^-\bar{\nu}_\mu$	α^4	$5.2794(9)\cdot 10^{-1}$	$5.2816(9)\cdot 10^{-1}$	$+3.69$	1.69
$e^+e^-\mu^+\mu^-$	α^4	$1.2083(3)\cdot 10^{-2}$	$1.2078(3)\cdot 10^{-2}$	-5.25	1.26
$He^+\nu_e$	α^3	$6.4740(17)\cdot 10^{-2}$	$6.4763(6)\cdot 10^{-2}$	-4.04	1.24
He^+e^-	α^3	$1.3699(2)\cdot 10^{-2}$	$1.3699(1)\cdot 10^{-2}$	-5.86	0.32
Hjj	α^3	$2.7058(4)\cdot 10^0$	$2.7056(6)\cdot 10^0$	-4.23	0.27
tj	α^2	$1.0540(1)\cdot 10^2$	$1.0538(1)\cdot 10^2$	-0.72	0.74

LHC setup (Run II): $\sqrt{s} = 13$ TeV $\quad \mu_R = \mu_F = \frac{1}{2}\sum_i \sqrt{p_{T,i}^2 + m_i^2}$ EW scheme: G_μ CMS

PDF set: `LUXqed_plus_PDF4LHC15_nnlo_100` cuts from ref. [1804.10017]

I) NLO framework in WHIZARD: NLO EW and mixed

Interfering correction types (NLO QCD×EW): for processes with $\mathcal{O}(\alpha_s^n)$ contributions with $n \geq 1$:



Example: $pp \to Zj$ at $\mathcal{O}(\alpha\alpha_s)$:
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 $\mathcal{O}(\alpha\alpha_s)$] × [QED splitting]
and [$\mathcal{B}(q\bar{q} \to Z\gamma)$ at $\mathcal{O}(\alpha^2)$] × [QCD splitting]

I) NLO framework in WHIZARD: NLO EW and mixed

Cross-validation with MUNICH/MATRIX using OpenLoops for $pp \to t\bar{t}$ and $pp \to t\bar{t} + W^{\pm}/Z/H$ with complete NLO SM corrections, e. g.

$pp \to t\bar{t}W^+$	$\alpha_s^n \alpha^m$	σ^{tot} [fb] MUNICH$_{(\text{CS})}$	σ^{tot} [fb] WHIZARD	σ^{sig} / *dev* MUNICH$_{(\text{CS})}$-WHIZARD
LO_{21}	$\alpha_s^2\alpha$	$2.411403(1) \cdot 10^2$	$2.4114(1) \cdot 10^2$	0.72 / 0.003%
LO_{12}	$\alpha_s\alpha^2$	0.000	0.000	0.00 / 0.000%
LO_{03}	α^3	$2.31909(1) \cdot 10^0$	$2.3193(1) \cdot 10^0$	1.76 / 0.009%
δNLO_{31}	$\alpha_s^3\alpha$	$1.18993(2) \cdot 10^2$	$1.1905(5) \cdot 10^2$	1.06 / 0.048%
δNLO_{22}	$\alpha_s^2\alpha^2$	$-1.09511(9) \cdot 10^1$	$-1.0947(3) \cdot 10^1$	1.13 / 0.035%
δNLO_{13}	$\alpha_s\alpha^3$	$2.93251(3) \cdot 10^1$	$2.9334(8) \cdot 10^1$	1.14 / 0.030%
δNLO_{04}	α^4	$5.759(3) \cdot 10^{-2}$	$5.756(4) \cdot 10^{-2}$	0.58 / 0.049%

Non-negligible and even enhanced EW effects for α_s subleading contributions at NLO!

($pp \to b\bar{b}X$ in validation progress)

I) NLO framework in WHIZARD: NLO EW and mixed

Comparison with MG5_aMC@NLO for $pp \to e^+ \nu_e j$ and $pp \to e^+ e^- j$ at NLO EW

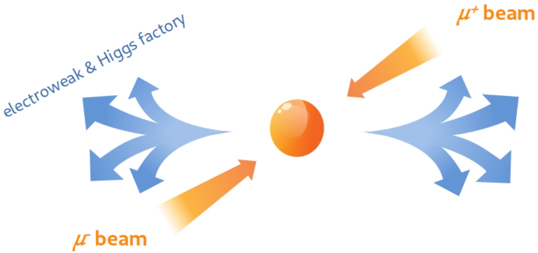
process	$\alpha_s^n \alpha^m$	MG5_aMC@NLO		WHIZARD+OpenLoops			σ^{sig}
$pp \to Xj$		$\sigma_{\text{LO}}^{\text{tot}}$ [pb]	$\sigma_{\text{NLO}}^{\text{tot}}$ [pb]	$\sigma_{\text{LO}}^{\text{tot}}$ [pb]	$\sigma_{\text{NLO}}^{\text{tot}}$ [pb]	δ [%]	LO/NLO
$e^+ \nu_e j$	$\alpha_s \alpha^2$	914.81(6)	904.75(8)	914.74(7)	904.59(7)	-1.11	0.8/1.5
$e^+ e^- j$	$\alpha_s \alpha^2$	150.59(1)	149.09(2)	150.59(1)	149.08(2)	-1.00	0.05/0.4

LHC-setup (Run II), cuts with photon recombination **and** jet clustering

II) Application of NLO EW corrections to multi-boson processes at a future muon collider

II) Multi-boson processes at a muon collider at NLO EW

[PB, W. Kilian, J. Reuter, P. Stienemeier; JHEP 12 (2022)]



large IS mass:

- large scales (multi-TeV)

→ high new physics discovery potential: Scanning for BSM theories related to $(g-2)_\mu$

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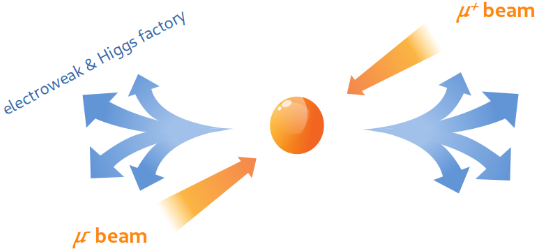

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→ fixed $\mathcal{O}(\alpha)$ expansion viable

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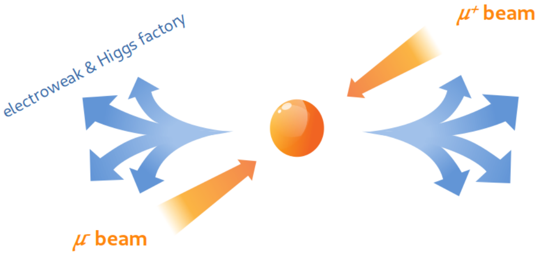

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⇒ Fixed-order massive approximation for $\mu^+\mu^- \to V^n H^m$ with $V \in \{W^\pm Z\}$ and $n + m \leq 4$ at NLO EW

II) Multi-boson processes at a muon collider at NLO EW

[PB, W. Kilian, J. Reuter, P. Stienemeier; JHEP 12 (2022)]

WHIZARD+RECOLA, G_μ scheme, $m_\mu = 0.1056...$ GeV

$\mu^+\mu^- \to X, \sqrt{s} = 3$ TeV	$\sigma_{\text{LO}}^{\text{incl}}$ [fb]	δ_{EW} [%]	δ_{ISR} [%]
W^+W^-	$4.6591(2) \cdot 10^2$	$+4.0(2)$	$+13.82(4)$
ZZ	$2.5988(1) \cdot 10^1$	$+2.19(6)$	$+15.71(4)$
HZ	$1.3719(1) \cdot 10^0$	$-1.51(4)$	$+30.24(3)$
W^+W^-Z	$3.330(2) \cdot 10^1$	$-22.9(2)$	$+2.90(9)$
W^+W^-H	$1.1253(5) \cdot 10^0$	$-20.5(2)$	$+7.10(8)$
ZZZ	$3.598(2) \cdot 10^{-1}$	$-25.5(3)$	$+5.24(8)$
HZZ	$8.199(4) \cdot 10^{-2}$	$-19.6(3)$	$+8.39(8)$
HHZ	$3.277(1) \cdot 10^{-2}$	$-25.2(1)$	$+7.58(7)$
$W^+W^-W^+W^-$	$1.484(1) \cdot 10^0$	$-33.1(4)$	$-1.3(1)$
W^+W^-ZZ	$1.209(1) \cdot 10^0$	$-42.2(6)$	$-1.8(1)$
W^+W^-HZ	$8.754(8) \cdot 10^{-2}$	$-30.9(5)$	$-0.1(1)$
W^+W^-HH	$1.058(1) \cdot 10^{-2}$	$-38.1(4)$	$+1.7(1)$
$ZZZZ$	$3.114(2) \cdot 10^{-3}$	$-42.2(2)$	$+0.8(1)$
$HZZZ$	$2.693(2) \cdot 10^{-3}$	$-34.4(2)$	$+1.4(1)$
$HHZZ$	$9.828(7) \cdot 10^{-4}$	$-36.5(2)$	$+2.2(1)$
$HHHZ$	$1.568(1) \cdot 10^{-4}$	$-25.7(2)$	$+5.7(1)$

with $\delta_{\text{EW}} = \sigma_{\text{NLO}}^{\text{incl}}/\sigma_{\text{LO}}^{\text{incl}} - 1$ and $\delta_{\text{ISR}} = \sigma_{\text{LO,LL-ISR}}^{\text{incl}}/\sigma_{\text{LO}}^{\text{incl}} - 1$

II) Multi-boson processes at a muon collider at NLO EW

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$$\Lambda_{\text{EW,Sud}} \sim -\frac{\alpha}{8\pi} \sum_{k,l\neq k} \sum_{a=\gamma,Z,W} I^a(k) I^{\bar{a}}(l) \log^2 \frac{(p_k+p_l)^2}{M_W^2} \Rightarrow \text{virtual } \mathcal{V}$$

$\mu^+\mu^- \to X, \sqrt{s} = 3$ TeV	$\sigma^{\text{incl}}_{\text{LO}}$ [fb]	δ_{EW} [%]	δ_{ISR} [%]
W^+W^-	$4.6591(2)\cdot 10^2$	$+4.0(2)$	$+13.82(4)$
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II) Multi-boson processes at a muon collider at NLO EW

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W^+W^-HH	$1.058(1) \cdot 10^{-2}$		
$ZZZZ$	$3.114(2) \cdot 10^{-3}$		
$HZZZ$	$2.693(2) \cdot 10^{-3}$	$-34.4(2)$	$+1.4(1)$
$HHZZ$	$9.828(7) \cdot 10^{-4}$	$-36.5(2)$	$+2.2(1)$
$HHHZ$	$1.568(1) \cdot 10^{-4}$	$-25.7(2)$	$+5.7(1)$

$$\Lambda_{\text{EW,Sud}} \sim -\frac{\alpha}{8\pi} \sum_{k,l\neq k} \sum_{a=\gamma,Z,W} I^a(k) I^{\bar{a}}(l) \log^2 \frac{(p_k+p_l)^2}{M_W^2} \Rightarrow \text{virtual } \mathcal{V}$$

$$\text{LL PDF } \Gamma^{\text{LL}(1)}_{\mu/\mu} \sim \frac{\alpha}{2\pi} \log \frac{s}{m_\mu^2} \Rightarrow \text{real } \mathcal{R}$$

with $\delta_{\text{EW}} = \sigma^{\text{incl}}_{\text{NLO}}/\sigma^{\text{incl}}_{\text{LO}} - 1$ and $\delta_{\text{ISR}} = \sigma^{\text{incl}}_{\text{LO,LL-ISR}}/\sigma^{\text{incl}}_{\text{LO}} - 1$

II) Multi-boson processes at a muon collider at NLO EW

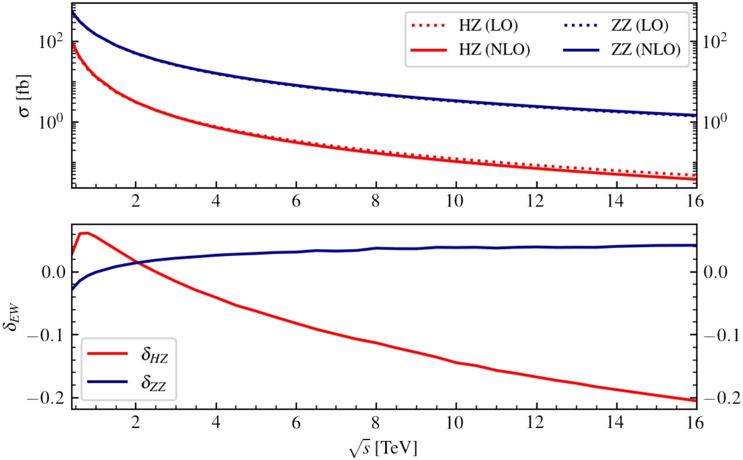
[PB, W. Kilian, J. Reuter, P. Stienemeier; JHEP 12 (2022)]

$\mu^+\mu^- \to X$	$\sqrt{s} = 10$ TeV		$\sqrt{s} = 14$ TeV	
	$\sigma^{\text{incl}}_{\text{LO}}$ [fb]	δ_{EW} [%]	$\sigma^{\text{incl}}_{\text{LO}}$ [fb]	δ_{EW} [%]
W^+W^-	$5.8820(2) \cdot 10^1$	$+3.9(2)$	$3.2423(1) \cdot 10^1$	$+3.6(2)$
ZZ	$3.2730(4) \cdot 10^0$	$+3.9(1)$	$1.80357(9) \cdot 10^0$	$+3.8(2)$
HZ	$1.22929(8) \cdot 10^{-1}$	$-14.12(7)$	$6.2702(4) \cdot 10^{-2}$	$-18.7(1)$
W^+W^-Z	$9.609(5) \cdot 10^0$	$-39.0(2)$	$6.369(3) \cdot 10^0$	$-45.0(4)$
W^+W^-H	$2.1263(9) \cdot 10^{-1}$	$-38.4(5)$	$1.2846(6) \cdot 10^{-1}$	$-43.3(9)$
ZZZ	$8.565(4) \cdot 10^{-2}$	$-38.5(9)$	$5.475(3) \cdot 10^{-2}$	$-44.2(6)$
HZZ	$1.4631(6) \cdot 10^{-2}$	$-34.9(4)$	$8.754(4) \cdot 10^{-3}$	$-39.7(4)$
HHZ	$6.083(2) \cdot 10^{-3}$	$-51.6(5)$	$3.668(1) \cdot 10^{-3}$	$-59.4(3)$

Suppression due to EW Sudakov logarithms at high energies pronounced for **(di-)Higgsstrahlung!**

II) Multi-boson processes at a muon collider at NLO EW

[PB, W. Kilian, J. Reuter, P. Stienemeier; JHEP 12 (2022)]



Suppression due to
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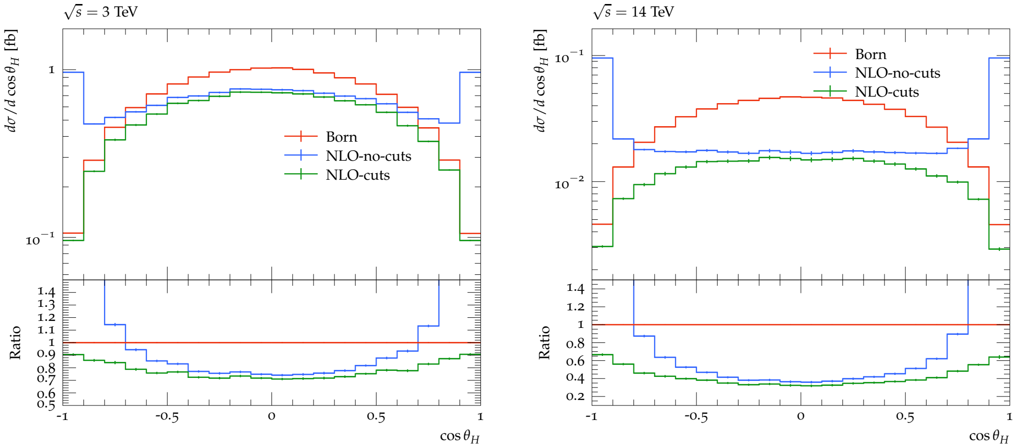
II) Multi-boson processes at a muon collider at NLO EW

[PB, W. Kilian, J. Reuter, P. Stienemeier; JHEP 12 (2022)]

Fixed order differential distributions: $d\sigma(\mu^+\mu^- \to HZ)/d\cos\theta_H$



'NLO-cuts': phase-space cut on hard photons occuring at NLO: $E_\gamma < 0.7\sqrt{s}$

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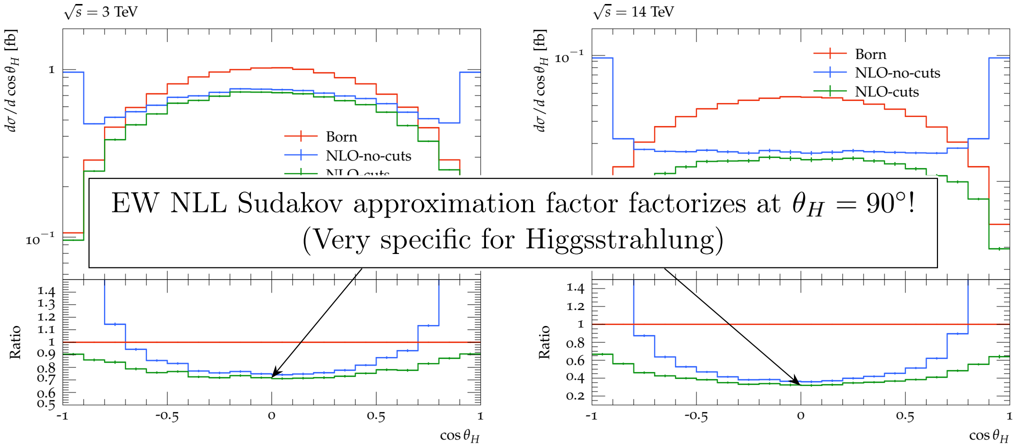


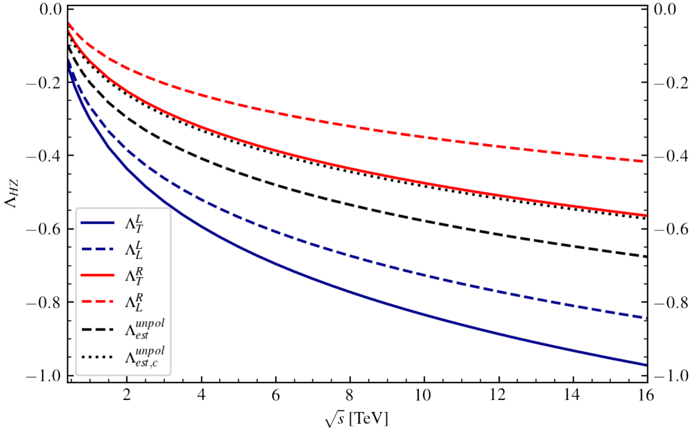
EW NLL Sudakov approximation factor factorizes at $\theta_H = 90°$!
(Very specific for Higgsstrahlung)

'NLO-cuts': phase-space cut on hard photons occuring at NLO: $E_\gamma < 0.7\sqrt{s}$

II) Multi-boson processes at a muon collider at NLO EW

[PB, W. Kilian, J. Reuter, P. Stienemeier; JHEP 12 (2022)]

NLL EW $\mu^+\mu^- \to HZ$ Sudakov factor: $\to \Lambda_{\text{est}}^{\text{unpol}}(\theta_H = 90°)$ (black dashed line)



- Λ_λ^κ: Sudakov factors for muon chiralities $\kappa = L, R$ and Z polarisations $\lambda = T, L$
- $\Lambda_{\text{est}}^{\text{unpol}}$: estimated unpolarised correction factor at $\theta_H = 90°$
- $\Lambda_{\text{est,c}}^{\text{unpol}}$: $\Lambda_{\text{est}}^{\text{unpol}}$ without angular dependent terms

Summary

I) Automated computation of NLO SM corrections in `WHIZARD`
   → POWHEG-matching automated for QCD corrections
   → At the LHC precision frontier for EW corrections
   → Automated fixed-order EW corrections to lepton collider processes

II) Application of this framework to muon collider physics
   → EW corrections highly significant for multi-TeV scales and high boson multiplicities

Outlook:

- NLO EW cross sections with QED NLL PDFs for lepton collisions
- SMEFT@NLO with `WHIZARD+GoSam` (in collab. with G. Heinrich and M. Höfer)

Back-Up

1. FKS subtraction scheme
2. Applied LHC phase-space cuts
3. Coupling power counting algorithm
4. Fixed-order masive approximation for lepton collisions at NLO EW
5. Electron/photon PDFs for lepton collisions
6. Complex-mass scheme at NLO
7. NLL EW $\mu^+\mu^- \to HZ$ Sudakov factor
8. `WHIZARD` features

Back-Up: FKS subtraction scheme

FKS parametrisation:

For $2 \to n$ processes: integrands parametrised by

Φ_n for $\mathcal{B}$, $\mathcal{V}$, $d\sigma_{S,\text{int}}$ and $\Phi_{n+1} = (\Phi_n, \Phi_{\text{rad}})$ for $\mathcal{R}$, $d\sigma_S$

$$\text{FKS variables:} \quad \Phi_{\text{rad}} \to \{\xi, y, \phi\}$$

$$d\Phi_{n+1} = d\Phi_{\text{rad}} d\Phi_n = \underbrace{\mathcal{J}(\xi, y, \phi)}_{\text{Jacobian}} d\xi dy d\phi d\Phi_n$$

with $\xi \equiv 2E_{\text{rad}}/\sqrt{s}$, $y \equiv \cos\theta_{ij}$ and ϕ: angle difference in transversal plane

$$\text{collinear limit:} \quad y \to 1$$

$$\text{soft limit:} \quad \xi \to 0$$

Back-Up: FKS subtraction scheme

IR cancellation:

- Define:

$$\mathcal{R}_{(i,j)} = \mathcal{S}_{(i,j)}\mathcal{R}$$

  with $\mathcal{S}_{(i,j)}$ depending on the kinematics of (i,j), $\sum_{i,j}\mathcal{S}_{(i,j)} = 1$ and $\lim_{y\to 1}\mathcal{S}_{(i,j)} = 1$, $\lim_{\xi\to 0}\mathcal{S}_{(i,j)} = \mathcal{S}^{\text{soft}}_{(i,j)}$
  Subtraction:

$$\tilde{\mathcal{R}}(\xi,y) \equiv (1-y)\xi^2\mathcal{R}(\xi,y)$$

$$\frac{\hat{\tilde{\mathcal{R}}}_{(i,j)}(\xi,y)}{\xi^2(1-y)} = \frac{1}{\xi^2(1-y)}\left(\tilde{\mathcal{R}}_{(i,j)}(\xi,y) - \underbrace{\tilde{\mathcal{R}}_{(i,j)}(0,y)}_{\text{soft}} - \underbrace{\tilde{\mathcal{R}}_{(i,j)}(\xi,1)}_{\text{collinear}} + \underbrace{\tilde{\mathcal{R}}_{(i,j)}(0,1)}_{\text{soft-collinear}}\right)$$

- Subtraction "events" get Born phase-space configuration
  $\Rightarrow$ Mind IR-safe observables for event generation!

$$\lim_{p_i \| p_j} O_{n+1}(p_1,\ldots,p_i,\ldots,p_j,\ldots,p_{n+1}) = O_n(p_1,\ldots,p_{ij},\ldots,p_n)$$

$$\lim_{p_i\to 0} O_{n+1}(p_1,\ldots,p_j,\ldots,p_{n+1}) = O_n(p_1,\ldots,p_{j-1},p_{j+1},\ldots,p_n)$$

Back-Up: FKS subtraction scheme

Subtraction terms: For split. partons $\bar{\mathcal{I}}_i \to \mathcal{I}_i \mathcal{I}_j$ and $k_i^2 = 0$ for emitting parton $\mathcal{I}_i$ after splitting

- collinear limit: unreg. polarised splitting functions × spin-correlated ME^2

$$\lim_{y\to 1} \tilde{\mathcal{R}}_{(i,j)}(\xi, y) \simeq \tilde{\mathcal{R}}_{(i,j)}(\xi, 1) = \lim_{y\to 1} \frac{8\pi\alpha_s(1-y)\xi^2}{\bar{k}_i^2} \hat{P}^{\mu\nu}_{\bar{\mathcal{I}}_i \to \mathcal{I}_i\mathcal{I}_j, \mathrm{QCD}}(z, k_\perp)\mathcal{B}^{(i)}_{\mu\nu}$$

$$\text{For } \bar{\mathcal{I}}_i = g, \quad \mathcal{B}^{(i)}_{\mu\nu} = N_B \sum_{\{m\}, s_i, s_i'} \mathcal{M}_n(\{m\}, s_i)\mathcal{M}_n^\dagger(\{m\}, s_i')(\epsilon_{s_i})^*_\mu(\epsilon_{s_i'})_\nu$$

  with $\{m\}$ colour, spins of Born conf. and s_i the spin of emitting gluon

- soft limit: eikonal × color- or charge-correlated Born ME^2

$$\lim_{\xi\to 0} \tilde{\mathcal{R}}_{(i,j)}(\xi, y) \simeq \tilde{\mathcal{R}}_{(i,j)}(0, y) = 4\pi\alpha_s(1-y) \sum_{k,l=1}^{n} \frac{\bar{k}_k \cdot \bar{k}_l}{(\bar{k}_k \cdot \hat{k}_j)(\bar{k}_l \cdot \hat{k}_j)} \mathcal{B}_{kl}$$

$$\mathcal{B}_{kl} = -|\mathcal{M}^n_{kl}|^2 = \langle \mathcal{M}^n | \mathbf{T}_k \cdot \mathbf{T}_l | \mathcal{M}^n \rangle$$

  with $\mathcal{I}_j = g$ the radiated parton and $\mathbf{T}_k$ the colour charge operator

QCD → QED: $\{g, \alpha_s, \hat{P}^{\mu\nu}_{\bar{\mathcal{I}}_i \to \mathcal{I}_i\mathcal{I}_j, \mathrm{QCD}}, \mathbf{T}_k\} \longrightarrow \{\gamma, \alpha, \hat{P}^{\mu\nu}_{\bar{\mathcal{I}}_i \to \mathcal{I}_i\mathcal{I}_j, \mathrm{QED}}, \mathbf{Q}_k\}$

Back-Up: FKS subtraction scheme

Regularisation by integrated subtraction terms:

From dimensional regularisation with $d = 4 - 2\varepsilon$ and expansions in ε

$\xi^{-1-2\varepsilon} = -\frac{1}{2\varepsilon}\delta(\xi) + \left(\frac{1}{\xi}\right)_+ - 2\varepsilon\left(\frac{\log\xi}{\xi}\right)_+ = -\frac{1}{2\varepsilon}\delta(\xi) + \mathcal{P}_+(\xi)$ and

$(1-y)^{-1-\varepsilon} = -\frac{2^{-\varepsilon}}{\varepsilon}\delta(1-y) + \left(\frac{1}{1-y}\right)_+ - \varepsilon\left(\frac{\log(1-y)}{1-y}\right)_+$ we get

$$\begin{aligned}
\int d\Phi_{\text{rad}}\mathcal{R} &= \int d\Phi_{\text{rad}}(\xi,y)\frac{\tilde{\mathcal{R}}(\xi,y)}{\xi^2(1-y)} \\
&= \frac{s^{1-\varepsilon}}{(4\pi)^{3-2\varepsilon}}\int d\Omega^{(2-2\varepsilon)}\int_{-1}^{1} dy(1-y)^{-1-\varepsilon}\int_0^{\xi_{\max}} d\xi\xi^{-1-2\varepsilon}\tilde{\mathcal{R}}(\xi,y) \\
&= \underbrace{\frac{I^{(2)}_{\text{soft-coll}}}{\varepsilon^2} + \frac{I^{(1)}_{\text{soft}}}{\varepsilon} + + I^{(0)}_{\text{soft}}}_{①} + \underbrace{\frac{I^{(1)}_{\text{coll}}}{\varepsilon} + I^{(0)}_{\text{coll}}}_{②} + \int \underbrace{d\Phi_{\text{rad}}\hat{\mathcal{R}}}_{③} + \mathcal{O}(\varepsilon)
\end{aligned}$$

with plus-distributions $\int_{-1}^{1} dy\left(\frac{g(y)}{1-y}\right)_+ f(y) = \int_{-1}^{1} dy g(y)\frac{f(y)-f(1)}{1-y}$

- ① soft (and soft-collinear) limit: $\sim -\frac{1}{2\varepsilon}\int dy(1-y)^{-1-\varepsilon}\int d\xi\delta(\xi)\tilde{\mathcal{R}}(\xi,y)$
- ② collinear limit: $\sim -\frac{2^{-\varepsilon}}{\varepsilon}\int d\xi\mathcal{P}_+(\xi)\int dy\delta(1-y)\tilde{\mathcal{R}}(\xi,y)$
- ③ subtracted Real: $d\phi dy d\xi\frac{\mathcal{J}(\xi,y,\phi)}{\xi}\left(\frac{1}{\xi}\right)_+\left(\frac{1}{1-y}\right)_+\tilde{\mathcal{R}}(\xi,y)$

Applied LHC phase-space cuts

$$\Delta R_{ij} = \sqrt{(\Delta\phi_{ij})^2 + (\Delta\eta_{ij})^2}$$

Photons appearing at NLO EW are recombined with charged massless fermions if they fulfil

$$\Delta R_{f^\pm\gamma} \leq R_0$$

Here $R_0 = 0.1$ is used.
For processes with jets the anti-k_T clustering algorithm with jet radius $R = 0.4$ is applied.
Phase-space cut expressions acting on dressed fermions and clustered jets follow the conditions

- $p_{T,l^\pm} > 10$ GeV and $|\eta_{l^\pm}| < 2.5$ on charged dressed leptons
- $\Delta R_{l^+l^-} > 0.4$ and $M_{l^+l^-} > 30$ GeV on pairs of charged dressed leptons with same flavour and opposite charge
- $p_{T,j} > 30$ GeV and $|\eta_j| < 4.5$ on clustered jets

Back-Up: Coupling power counting algorithm

For any $2 \to n$ tree-level process: total number of coupling powers of either α_s or α

$$n_{\text{tot}} \equiv p_s + p_e = n_{\text{legs}} - 2 = n \tag{1}$$

with p_s for α_s and p_e for α demanded as user input.
$\Rightarrow$ Complete set for powers l_s of α_s and l_e of α, i. e.

$$\{l_s, l_e\} = \{n-k, k\}, \qquad 0 \leq k \leq n \tag{2}$$

$\Rightarrow$ Constraints by the flavour structure of a sub-process

$$n_W + \frac{n_l}{2} \leq k \leq n - n_g \tag{3}$$

with numbers of external particles n_W for EW bosons $\gamma/W/Z/H$, n_l for leptons and n_g for gluons.

Back-Up: Coupling power counting algorithm

Additionally, for quark external states constraints by

- exactly one $q\bar{q}$ pair and only gluons

$$k = 0 \tag{4}$$

- exactly one $q\bar{q}$ pair and only EW bosons or leptons

$$k = n \tag{5}$$

- If quarks as external states are all of different flavours (pure EW couplings to $W^{\pm}$ of the quarks)

$$k = n - n_g = n_W + \frac{n_l}{2} + \frac{n_q}{2} \quad . \tag{6}$$

With range or definite value k vetoing of flavour structures which not contribute to coupling powers p_s and p_e.

Back-Up: Lepton collisions at NLO EW

Fixed-order massive approximation for NLO cross sections:

- IS leptons considered as massive ⇒ no collinear counterterms needed
- lepton mass dependencies kept explicit in matrix elements
- NLO phase-space construction with on-shell projection: radiated momentum according to FKS parametrisation; IS momenta fixed; boost of Born FS into recoiling system

Checks with `MCSANCee`, e. g.

$e^+e^- \to HZ$	MCSANCee[Sadykov,2020]		WHIZARD+RECOLA			σ^{sig}
$\sqrt{s}$ [GeV]	$\sigma^{\text{tot}}_{\text{LO}}$ [fb]	$\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	$\sigma^{\text{tot}}_{\text{LO}}$ [fb]	$\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	δ_{EW} [%]	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

$e^+e^- \to \mu^+\mu^-$	MCSANCee[2206.09469]		WHIZARD+RECOLA			σ^{sig}
$\sqrt{s}$ [GeV]	$\sigma^{\text{tot}}_{\text{LO}}$ [pb]	$\sigma^{\text{tot}}_{\text{NLO}}$ [pb]	$\sigma^{\text{tot}}_{\text{LO}}$ [pb]	$\sigma^{\text{tot}}_{\text{NLO}}$ [pb]	δ_{EW} [%]	LO/NLO
5	2978.6(1)	3434.2(1)	2978.7(1)	3433.5(3)	+15.27	0.3/2.2
7	1519.6(1)	1773.8(1)	1519.605(4)	1773.1(2)	+16.68	0.05/3.0

$\alpha(0)$ scheme, $m_e = 0.5109...$ MeV

Back-Up: Electron/photon PDFs for lepton collisions

- LL resummation[Cacciari, Deandrea, Montagna, Nicrosini, 1992; Skrypek, Jadach, 1991]:
  Non-singlet evolution equation

$$\Gamma_e(x,\mu^2) = \delta(1-x) + \int_{m^2}^{\mu^2} \frac{dq^2}{q^2} \frac{\alpha(q^2)}{2\pi} \int_x^1 dz P_{ee}(z) \Gamma_e\left(\frac{x}{z}, q^2\right)$$

One-loop accurate regularised (unpolarised) Altarelli-Parisi kernels

$$P_{ee}(z) = \langle \hat{P}_{ee}\rangle(z) - \delta(1-z)\int_0^1 dt \langle \hat{P}_{ee}\rangle(t), \qquad \langle \hat{P}_{ee}\rangle(z) = \frac{1+z^2}{1-z}$$

Recursive approach via auxiliary function $G(x,\mu^2)$

$$G(x,\mu^2) = \int_x^1 dt \Gamma_e(t,\mu^2) \qquad \Gamma_e(x,\mu^2) = -\frac{\partial}{\partial x} G(x,\mu^2)$$

Solution in asymptotic $x \simeq 1$ limit

$$\Gamma_e(x,\mu^2) = \frac{e^{\eta(\frac{3}{4}-\gamma_E)}}{\Gamma(1+\eta)} \eta (1-x)^{\eta-1} \qquad \eta = \frac{\alpha}{\pi} \log \frac{\mu^2}{m^2}$$

Back-Up: Electron/photon PDFs for lepton collisions

Alternative approach: Identically, transforming the integro-differential evolution equations into Mellin space by

$$M[f] \equiv f_N = \int_0^1 dz z^{N-1} f(z) \qquad\qquad M[g \star h] = M[g]M[h] \quad .$$

⇒ using the asymptotic limit $N \to \infty$ analogously to $z \to 1$ in z-space
⇒ analytical Mellin inversion of the resulting solution
'All x' solution:
$G(x, \mu^2)$ and $\Gamma_e(x, \mu^2)$ can be written as a perturbative series expressed as

$$G(x, \mu^2) = \sum_{n=0}^{\infty} \frac{\eta^n}{2^n n!} I_n(x), \qquad\qquad \Gamma_e(x, \mu^2) = \sum_{n=0}^{\infty} \frac{\eta^n}{2^n n!} \frac{\partial I_n(x)}{\partial x}$$

Find recurrence relation

$$I_n(x) = \int_x^1 dz P(z) I_{n-1}\left(\frac{x}{z}\right)$$

Boundary conditions $G^{(0)}(x, \mu^2) = G(x, m^2) = 1$ implicating $I_0(x) = 1$ and $I_1(x) = \int_x^1 dz P(z)$

⇒ 'all x' solution for G and Γ_e up to $\mathcal{O}(\alpha^3)$ by iterations up to I_3

Back-Up: Electron/photon PDFs for lepton collisions

- NLO initial conditions of electron and photon PDFs [Frixione, 1909.03886]:
  Approach:

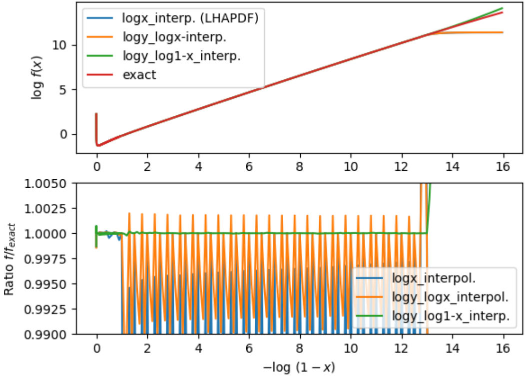
$$d\bar{\sigma}_{e^+e^-}(p_{e^+}, p_{e^-}, m^2) = \sum_{ij=e^\pm,\gamma} \int dz_+ dz_- \Gamma_{i/e^+}(z_+, \mu^2, m^2)\Gamma_{i/e^-}(z_-, \mu^2, m^2) \times d\hat{\sigma}_{ij}(z_+ p_{e^+}, z_- p_{e^-}, \mu^2) \quad (7)$$

  - explicit short-distance cross section computation for specific but arbitrary process $e^+e^- \to u\bar{u}(\gamma)$
  - parton-level cross section $d\hat{\sigma}_{ij}$ computed with massless electrons
  - particle-level cross section $d\bar{\sigma}_{kl} = d\sigma_{kl} + \mathcal{O}\left(\left(\frac{m^2}{s}\right)^p\right)$, $p \geq 1$

  $\to$ (7) solved for PDFs Γ_{i/e^-},Γ_{i/e^+}
- NLL resummation [Bertone, Cacciari, Frixione, Stagnitto, 1911.12040]:
  Recursive solutions valid for all z values computed up to $\mathcal{O}(\alpha^3)$ matched to the asymptotic large z solution (valid for $z \simeq 1$) retaining all orders in α

Back-Up: Electron PDFs for lepton collisions

MC integration methods: Interpolation between grid points



NLL electron PDF $f(x)$ (displayed as $\log_{10} f(x)$) as a function of $-\log_{10}(1-x)$

Back-Up: Electron PDFs for lepton collisions

At LO-LL:

Parametrisation of beam energy fractions in mapping variables $p_1, p_2 \in [0,1]$

$$x_1 = p_1^{p2} \qquad\qquad x_2 = p_1^{1-p2}$$

For random numbers $r_1, r_2 \in [0,1]$

$$p_1 = 1 - (1-r_1)^{1/\epsilon} = 1 - \bar{r}_1^{1/\epsilon}$$

$$p_2 = \begin{cases} 1 - (2r_2)^{1/\epsilon}/2, & u > 0 \\ (2r_2)^{1/\epsilon}/2, & u < 0 \\ 1/2, & u = 0 \end{cases} \qquad\qquad u = 2r_2 - 1.$$

$\Rightarrow$ for small ϵ mapping enhanced at the endpoints $p_1 \to 1$, $p_2 \to 1$ and $p_2 \to 0$

$\Rightarrow$ Jacobian factors '$(1-r_1)^{1/\epsilon - 1} \log p_1$' which **flattens** the integrand in the region $p_1 \to 1$, i. e. $x \to 1$ (where $\lim_{x\to 1} \Gamma_e(x) \to \infty$)

At NLO-NLL:

Rescaling of the PDF arguments for real-emission and collinear subtraction terms (and ISR remnant of collinear subtraction) – beam energy fraction differs before and after radiation
FKS phase-space construction: From Born to real configurations
Ratio of the rescaled over the unrescaled PDFs:

$$\lim_{x'\to 1} \frac{\Gamma(x')}{\Gamma(x)} = \lim_{x\to 1-\delta x} \frac{\Gamma(x+\delta x)}{\Gamma(x)} \to \infty \qquad \Rightarrow \text{ additional mapping for } \delta x$$

Back-Up: Electron PDFs for lepton collisions

Remnant of the subtraction of collinear ISR singularities in integrated form (DGLAP remnant):
The momentum dependence of the PDFs rescales as

$$\Gamma(x_j, \mu) \longrightarrow \Gamma(x_j/z_j, \mu)$$

with $x_j \leq x_j/z_j < 1$ and emitter $j \in \{1, 2\}$
Mapping of the random variable $r_z \in [0, 1]$ defining

$$p_z = 1 - (1 - r_z)^{1/\epsilon}$$

Condition $[0, 1] \longmapsto [x_j, 1]$ mapping $p_z \longrightarrow z_j$ we can find the parametrisation

$$z_j = 1 - p_z(1 - \log p_z)(1 - x_j)$$

Overall Jacobian per emitter

$$f_{\mathrm{DGLAP,j}} = f_{p_z} f_{z_j} = \frac{1}{\epsilon}(1 - r_z)^{1/\epsilon - 1}(1 - x_j)\log p_z$$

Back-Up: Electron PDFs for lepton collisions

For the real component the momentum dependencies of the PDFs rescale as

$$\Gamma(x_1,\mu) \longrightarrow \Gamma(x_1',\mu) = \Gamma\left(\frac{x_1}{\sqrt{1-\xi}}\sqrt{\frac{2-\xi(1-y)}{2-\xi(1+y)}}\right)$$

$$\Gamma(x_2,\mu) \longrightarrow \Gamma(x_2',\mu) = \Gamma\left(\frac{x_2}{\sqrt{1-\xi}}\sqrt{\frac{2-\xi(1+y)}{2-\xi(1-y)}}\right)$$

Mapping for $\{x_1, x_2, x_1', x_2'\}$ instead of $\{x_1, x_2, \xi, y\}$!

Conditions

$$x_1 \leq x_1' < 1 \qquad\qquad x_2 \leq x_2' < 1$$

Construct $\hat{p}_j \in [0,1]$ from random numbers $\hat{r}_j \in [0,1]$ as

$$\hat{p}_j = 1 - (1 - \hat{r}_j)^{1/\epsilon}$$

Define rescaled variables with mapping

$$x_j' = 1 - \hat{p}_j(1 - \log \hat{p}_j)(1 - x_j) \qquad\qquad j = 1, 2$$

leads to Jacobians

$$f_{x',j} = \frac{1}{\epsilon}(1 - \hat{r}_j)^{1/\epsilon - 1}(1 - x_j) \log \hat{p}_j$$

Back-Up: Electron PDFs for lepton collisions

Define auxiliary quantities

$$A \equiv \frac{x_1 x_2'}{x_2 x_1'} = \frac{2-\xi(1+y)}{2-\xi(1-y)} \qquad B \equiv \frac{x_1 x_2}{x_1' x_2'} = 1-\xi$$

such that ξ and y can be derived, yielding

$$\xi = 1 - B \qquad y = \left(\frac{1+B}{1-B}\right)\left(\frac{1-A}{1+A}\right) \quad .$$

Considering

$$d\xi dy = \mathcal{J}_1(A,B)\ dAdB = \mathcal{J}_1(A,B)\mathcal{J}_2(x_1',x_2')\ dx_1'dx_1'$$

with

$$\mathcal{J}_1(A,B) = 2\left(\frac{1+B}{1-B}\right)\frac{1}{(1+A)^2} \qquad \mathcal{J}_2(x_1',x_2') = 2\frac{x_1^2}{x_1'^3 x_2'}$$

we get the final Jacobian factor for ξ and y parametrised in random numbers $\hat{r}_{1/2}$,

$$f_{\mathrm{real},j} = \mathcal{J}_1(A,B)\mathcal{J}_2(x_1',x_2')f_{x',1}f_{x',2} \quad .$$

Back-Up: Complex-mass scheme at NLO

Renormalised self-energy:

$$\hat{\Sigma}^i(p^2) = \Sigma^i(p^2) - \delta M_i^2$$

Complex location of the pole $p^2 = \mu_i^2$ of propagator: $\mu_i^2 - M_{0,i}^2 + \Sigma(\mu_i^2) = 0 \quad \Rightarrow \hat{\Sigma}^i(\mu_i^2)$ vanishes

$\Rightarrow$ renormalised masses $M_i^2 = M_{0,i}^2 - \delta M_i^2$ fixed at this pole due to OS condition $\delta M_i^2 = \Sigma(p^2)|_{p^2=\mu_i^2}$

Complex-mass scheme requires calculating self-energies for complex squared momenta!

Solutions:

- analytic continuation of the self-energies in the complex momentum variable to the unphysical Riemann sheet (`MadLoop`)[Frederix *et. al.*, 1804.10017]
- expansion of self-energies around real arguments such that one-loop accuracy is retained (`OpenLoops`, `Recola`) [Denner *et. al.*, 0505042]
  - 2-point integrals with $p^2 = \mu_i^2 = M_i^2 - i\Gamma_i M_i$ can be obtained through first-order expansion in Γ_i/M_i around $p^2 = M_i^2$

Back-Up: NLL EW $\mu^+\mu^- \to HZ$ Sudakov factor

Using the abbreviations for double and single logarithmic factors

$$L(s, M_W^2) = \frac{\alpha}{4\pi} \log^2 \frac{s}{M_W^2} \qquad l(s, M_W^2) = \frac{\alpha}{4\pi} \log \frac{s}{M_W^2}$$

For $s \gg M_W$, leading logarithmic, angular-independent, terms (from exchange of soft-collinear gauge bosons between pairs of external legs)

$$\Lambda_{l,\lambda}^{\kappa} = A_{\lambda}^{\kappa}\, L(s, M_W^2) + B_{\lambda}^{\kappa}\, \log \frac{M_Z^2}{M_W^2} l(s, M_W^2) + C_{\lambda}$$

with $\lambda = T, L$ the transverse and longitudinal polarisation of the Z boson, and $\kappa = L, R$ the muon initial state chirality

$$\begin{aligned} A_T^{\kappa} &= -\frac{1}{2}\left[2C_{\mu^{\kappa}}^{\mathrm{EW}} + C_{\Phi}^{\mathrm{EW}} + C_{ZZ}^{\mathrm{EW}}\right] & A_L^{\kappa} &= -\left[C_{\mu^{\kappa}}^{\mathrm{EW}} + C_{\Phi}^{\mathrm{EW}}\right] \\ B_T^{\kappa} &= 2(I_{\mu_{\kappa}}^{Z})^2 + (I_H^Z)^2 & B_L^{\kappa} &= 2\left[(I_{\mu_{\kappa}}^{Z})^2 + (I_H^Z)^2\right] \\ C_T &= \delta_H^{LSC,h} & C_L &= \delta_H^{LSC,h} + \delta_{\chi}^{LSC,h} \end{aligned} .$$

Back-Up: NLL EW $\mu^+\mu^- \to HZ$ Sudakov factor

Subleading, angular-dependent, terms due to $W^\pm$ boson exchange between initial- and final-state legs

$$\Lambda^{\kappa}_{\theta,\lambda} = -\delta_{\kappa L} \frac{D_\lambda}{I^Z_{\mu_\kappa}}\, l(s, M_W^2) \left[\log \frac{|t|}{s} + \log \frac{|u|}{s}\right]$$

Mandelstam variables t and u approximated in the high-energy limit

$$t = \ (p_{\mu^+} - p_H)^2 \sim -\frac{s}{2}(1 - \cos\theta_H) \qquad u = \ (p_{\mu^+} - p_Z)^2 \sim -\frac{s}{2}(1 + \cos\theta_H)$$

Back-Up: NLL EW $\mu^+\mu^- \to HZ$ Sudakov factor

Estimation for the unpolarised approximation factor:

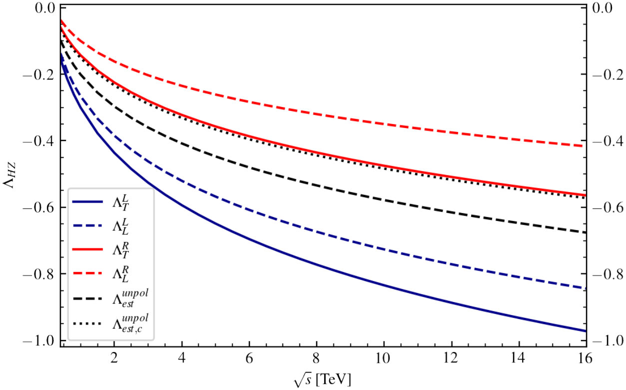
- Born amplitudes for transverse polarized Z bosons are suppressed by M_Z^2/s

$$\Lambda_\lambda^\kappa \mathcal{M}_0^{\mu_\kappa^+\mu_\kappa^- \to HZ_\lambda} \xrightarrow{s \gg M_W^2} \delta_{\lambda L} \Lambda_\lambda^\kappa \mathcal{M}_0^{\mu_\kappa^+\mu_\kappa^- \to HZ_\lambda} \tag{8}$$

- Chirality and helicity of the muon coincide in the ultrarelativistic limit (two helicity configurations $(+,-)$ and $(-,+)$ remaining, equivalent to chiralities $\kappa = L, R$). Spin-averaging yields

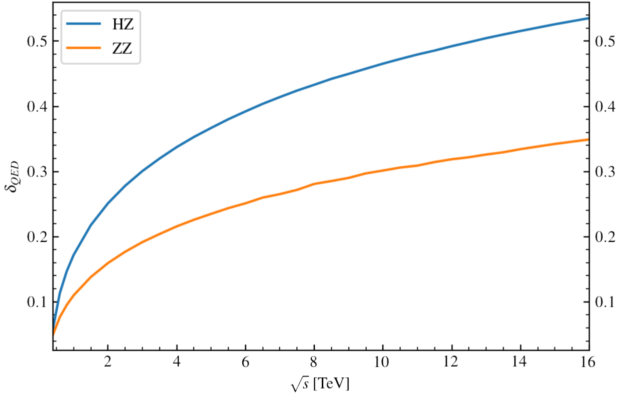
$$\Lambda_{\text{est}}^{\text{unpol}} = \frac{\sum_\kappa \Lambda_L^\kappa |\mathcal{M}_0^{\mu_\kappa^+\mu_\kappa^- \to HZ_L}|^2}{|\mathcal{M}_0^{\mu^+\mu^- \to HZ_L}|^2} \tag{9}$$

Back-Up: NLL EW $\mu^+\mu^- \to HZ$ Sudakov factor



- Λ_λ^κ: Sudakov factors for muon chiralities $\kappa = L, R$ and Z polarisations $\lambda = T, L$
- $\Lambda_{\text{est}}^{\text{unpol}}$: estimated unpolarised correction factor at $\theta_H = 90°$
- $\Lambda_{\text{est,c}}^{\text{unpol}}$: $\Lambda_{\text{est}}^{\text{unpol}}$ without angular dependent terms

Back-Up: NLO QED corrections to $\mu^+\mu^- \rightarrow HZ/ZZ$



Relative QED corrections $\delta_{QED} = \sigma^{\text{incl}}_{\text{NLO,QED}}/\sigma^{\text{incl}}_{\text{LO}} - 1$ to HZ and ZZ production at the muon collider as a function of the collider energy, $\sqrt{s}$

Back-Up: WHIZARD features

WHIZARD provides

- phase space evaluation with VAMP2 [Braß *et. al.*: 1811.09711]:
  - twofold self-adaptive multi-channel parametrization
  - OpenMP and MPI for parallelization $\Rightarrow$ speedup of factor $\mathcal{O}(100)$
- matching to parton showers: POWHEG scheme
- showering and hadronization: PYTHIA6 shipped with WHIZARD, interface between WHIZARD and PYTHIA8
- event formats: LHE, HepMC2/3, Stdhep, LCIO, ...
- special support for lepton collider processes:

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