Mixed QCD-EW two-loop amplitudes for neutral current Drell-Yan production

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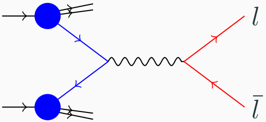
December 2, 2021

Drell-Yan



- ✓ **One of the standard candle processes**
  - Large cross section and clean experimental signature - important for detector calibration and constraining parton distribution functions
- ✓ **Precise predictions for electroweak parameter**
  - W boson mass (m_W), Weak mixing angle ($\sin^2\theta_{\mathrm{W}}$) ...
- ✓ **New physics potential**
  - Many BSM scenarios with same final states

Chronicles of the inclusive Drell-Yan

NLO

Politzer (1977)

Sachrajda (1978)

Altarelli, Ellis, Martinelli (1979)

Humpert, van Neerven (1979)

Baur, Brein, Hollik, Schappacher, Wackeroth (2002)

Carloni Calame, Montagna, Nicrosini, Vicini (2007)

Arbuzov, Bardin, Bondarenko, Christova, Kalinovskaya, Nanava, Sadykov (2008)

Dittmaier, Huber (2010)

NNLO

Altarelli, Ellis, Martinelli (1979)

Hamberg, Matsuura, van Neerven (1991)

Harlander, Kilgore (2002)

N^3LO

Duhr, Dulat, Mistlberger (2020)

Progress in obtaining the NNLO QCDxEW corrections

On-shell Z/W production - first step towards full Drell-Yan

- Pole approximation : Dittmaier, Huss, Schwinn;
- Analytic QCDxQED corrections : de Florian, Der, Fabre;
- p_T^Z distribution in QCDxQED including p_T resummation : Cieri, Ferrera, Sborlini;
- Differential on-shell Z production including QCDxQED : Delto, Jaquier, Melnikov, Roentsch;
- Total QCDxEW corrections to Z production (fully analytic):

Bonciani, Buccioni, NR, Triscari, Vicini; Bonciani, Buccioni, NR, Vicini;

- Differential on-shell Z/W production including QCDxEW :

Behring, Buccioni, Caola, Delto, Jaquier, Melnikov, Roentsch;

Complete Drell-Yan

- neutrino pair production in QCDxQED : Cieri, de Florian, Der, Mazzitelli;
- $pp \to l\nu_l + X$ in QCDxEW : Buonocore, Grazzini, Kallweit, Savoini, Tramontano;
- two-loop amplitudes: Heller, von Manteuffel, Schabinger;
- Complete NNLO QCDxEW corrections to neutral current Drell-Yan:

Bonciani, Buonocore, Grazzini, Kallweit, NR, Tramontano, Vicini; $\Longleftarrow$ This Talk

Perturbative expansion

Parton model

$$\sigma_{tot}(z) = \sum_{i,j \in q,\bar{q},g,\gamma} \int \mathrm{d}x_1 \mathrm{d}x_2 \; f_i(x_1,\mu_F) f_j(x_2,\mu_F) \sigma_{ij}(z,\varepsilon,\mu_F)$$

In the full QCD-EW SM, we have a double series expansion of the partonic cross sections in the electromagnetic and strong coupling constants, α and α_s, respectively:

$$\begin{aligned}
\sigma_{ij}(z) &= \sigma_{ij}^{(0)} \sum_{m,n=0}^{\infty} \alpha_s^m \alpha^n \; \sigma_{ij}^{(m,n)}(z) \\
&= \sigma_{ij}^{(0)} \Big[\sigma_{ij}^{(0,0)}(z) \\
&\quad + \alpha_s \sigma_{ij}^{(1,0)}(z) + \alpha \sigma_{ij}^{(0,1)}(z) \\
&\quad + \alpha_s^2 \sigma_{ij}^{(2,0)}(z) + \alpha \alpha_s \sigma_{ij}^{(1,1)}(z) + \alpha^2 \sigma_{ij}^{(0,2)}(z) \\
&\quad + \alpha_s^3 \sigma_{ij}^{(3,0)}(z) + \alpha \alpha_s^2 \sigma_{ij}^{(2,1)}(z) + \alpha^2 \alpha_s \sigma_{ij}^{(1,2)}(z) + \cdots \Big]
\end{aligned}$$

Why $\sigma_{ij}^{(1,1)}(z)$ is important?

$\alpha_s(m_Z) \simeq 0.118$	$\alpha(m_Z) \simeq 0.0078$	$\frac{\alpha_s(m_Z)}{\alpha(m_Z)} \simeq 15.1$	$\frac{\alpha_s^2(m_Z)}{\alpha(m_Z)} \simeq 1.8$

1. From naive argument of coupling strength, N^{3}LO QCD $\sim$ mixed NNLO QCD$\otimes$EW.
2. However, in specific phase-space points, fixed order EW corrections can become very large because of logarithmic (weak and QED Sudakov type) enhancement. These effects are large for W mass measurements. On the other hand, these corrections suffer from large uncertainties coming from unphysical scales.
3. N^{3}LO QCD corrections control the uncertainties arising from the unphysical scales, but they lack the large EW effects.
4. The appearance of photon induced processes $\Rightarrow$ photon PDFs.

The NNLO mixed QCD-EW corrections

- have similar magnitude as N^{3}LO QCD,
- contain the large EW effects,
- reduce the theoretical uncertainties.

NNLO QCD$\otimes$EW corrections extremely important for high ($\mathcal{O}(10^{-4})$) precision pheno.

Another motivation : Electroweak scheme dependence

The Lagrangian has 3 inputs (g, g', v). More observables (like $G_\mu, \alpha, m_W, m_Z, \sin\theta_W$) are experimentally measured and can be considered as input parameters in different schemes. Such two schemes are

1. G_μ-scheme : where (G_μ, m_W, m_Z) are considered as input
2. $\alpha(0)$-scheme : where (α, m_W, m_Z) are considered as input

The relation between G_μ and α gets EW and mixed QCD⊗EW corrections.

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha}{2\sin^2\theta_W \cos^2\theta_W m_Z^2}(1 + \Delta r)$$

At LO, $\alpha(G_\mu)$ and $\alpha(0)$ differs by 3.53%. For onshell Z production

order	G_μ-scheme	$\alpha(0)$-scheme	$\delta_{G_\mu-\alpha(0)}$ (%)
LO	48882	47215	3.53
NLO QCD (LO + Δ_{10})	55732	53831	3.53
NNLO QCD (LO + Δ_{10} + Δ_{20})	55651	53753	3.53
NLO EW (LO + Δ_{01})	48732	48477	0.53
LO + Δ_{10} + Δ_{01}	55582	55093	0.89

NNLO contributions to neutral current Drell-Yan

Pure Virtual

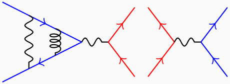
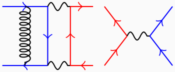
Real-Virtual

Double Real

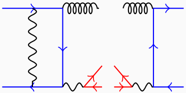
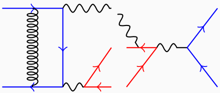
Each individual contribution is divergent : $\frac{1}{\epsilon}$ in dimensional regularization

NNLO contributions to neutral current Drell-Yan

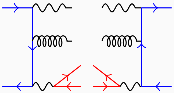
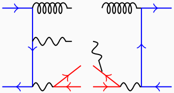
Pure Virtual

 $+\cdots+$  $- \; S^{(1,1)}$

Real-Virtual

 $+\cdots+$ 

Double Real

 $+\cdots+$ 

$\Big\} + d\sigma_{CT}^{(1,1)}$

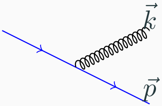
Subtraction : $S^{(1,1)} \sim \int d\sigma_{CT}^{(1,1)} \quad \Rightarrow$ The two sets are separately finite!

NNLO contributions to neutral current Drell-Yan

Pure Virtual

The two-loop virtual amplitudes contain divergences of two types

(a) **Ultraviolet divergences** : UV renormalization of fields and couplings
(b) **Infrared divergences** : Soft (soft gluons & photons) & collinear (collinear partons)



$$\frac{1}{(k+p)^2} = \frac{1}{2k.p} = \frac{1}{2k^0 p^0 (1-\cos\theta)}$$

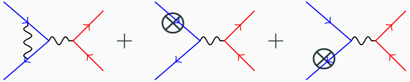
$k^0 \to 0$ Soft divergence
$\theta \to 0$ Collinear divergence

The infrared structure of scattering amplitudes is universal!

Ultraviolet renormalization

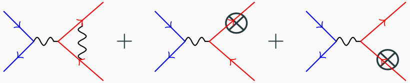
⊛ The Born contribution is zeroth order in α_s, hence no α_s renormalization is needed.

⊛ Renormalization of quark wave function receives one-loop EW and two-loop mixed QCD⊗EW contributions in the on-shell scheme.



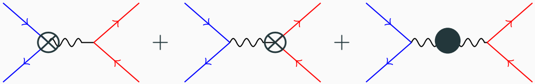
$\Rightarrow$ UV finite

⊛ Renormalization of lepton wave function receives one-loop EW contributions.



$\Rightarrow$ UV finite

⊛ The neutral current vertex is renormalized using background field gauge, with the advantage that the vertex and propagator contributions are separately UV finite.



$\Rightarrow$ UV finite

The infrared divergences and lepton mass

The infrared structure of scattering amplitudes is universal!

$$\mathcal{M}_{\text{fin}}^{(1,1)} = \mathcal{M}^{(1,1)} - \mathcal{I}^{(1,1)}\mathcal{M}^{(0)} - \mathcal{I}^{(0,1)}\mathcal{M}_{\text{fin}}^{(1,0)} - \mathcal{I}^{(1,0)}\mathcal{M}_{\text{fin}}^{(0,1)}$$

The q_T subtraction requires the leptons to be massive!

The full computation with lepton mass is extremely difficult!

Divergence regulator massless lepton : $\frac{1}{\epsilon}$ massive lepton : $\log m_l$

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(c) Hence, the collinear singularities from leptons ($\log m_l$) come from only the QED-type corrections to the lepton vertex corrections, which we compute with full lepton mass dependence.

The generic procedure

$\boxed{d = 4 - 2\epsilon}$

- Diagrammatic approach -> `QGRAF` to generate Feynman diagrams
- In-house `FORM` routines for algebraic manipulation :

  Lorentz, Dirac and Color algebra
- Decomposition of the dot products to obtain scalar integrals

$$\frac{2l.p}{l^2(l-p)^2} = \frac{l^2-(l-p)^2+p^2}{l^2(l-p)^2} = \frac{1}{(l-p)^2} - \frac{1}{l^2} + \frac{p^2}{l^2(l-p)^2}$$

- Identity relations among scalar integrals : IBPs, LIs & SRs
- Algebraic linear system of equations relating the integrals

$$\Downarrow$$

Master integrals (MIs)

- Computation of MIs : Method of differential equation & semi-analytic approach
- Ultraviolet renormalization
- Subtraction of the universal infrared poles ($S^{(1,1)}$).
- Numerical evaluation of the hard function to prepare the grid.

The method of differential equations

A Feynman integral is a function of spacetime dimension d and kinematic invariant $z = m^2/q^2$.

$$J_i \sim \int \frac{d^d l_1}{(2\pi)^d} \, \frac{d^d l_2}{(2\pi)^d} \, \frac{1}{l_1^2 l_2^2 ((l_1 - l_2)^2 - m^2)(l_1 - q)^2 (l_2 - q)^2} \equiv f(d,\, z)$$

The idea is to obtain a differential eqn. for the integral $w.r.t.$ z and solve it.

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$$\begin{aligned} \frac{d}{dz} J_i &= \text{some combinations of integrals} \\ &\quad \Downarrow \ \text{IBP identities/reduction} \\ &= \sum_j c_{ij} J_j \end{aligned}$$

c_{ij}'s are rational function of d and z.

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$$d_z \begin{pmatrix} J_1 \\ J_2 \\ J_3 \\ J_4 \\ \vdots \\ J_n \end{pmatrix} = \begin{bmatrix} \bullet & \bullet & \bullet & \bullet & \cdots & \bullet \\ \bullet & \bullet & \bullet & \bullet & \cdots & \bullet \\ \bullet & \bullet & \bullet & \bullet & \cdots & \bullet \\ \bullet & \bullet & \bullet & \bullet & \cdots & \bullet \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \bullet & \bullet & \bullet & \bullet & \cdots & \bullet \end{bmatrix} \begin{pmatrix} J_1 \\ J_2 \\ J_3 \\ J_4 \\ \vdots \\ J_n \end{pmatrix}$$

$$d_z \mathbb{J} = \mathbb{A}(d, z)\mathbb{J}$$

The black dots ($\bullet$) denote rational functions in d and z.

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To solve such a system, we need to perform series expansion in ϵ and to organize the matrix in each order of ϵ in such a way that it diagonalizes, or at least it takes a block-triangular form. Now, it can be solved using bottom-up approach.

The homogeneous solutions are in general $\log$ or Li_2. Because of the ϵ expansion, the non-homogeneous solutions are recursive integral over the homogeneous solutions.

The results are obtained in terms of iterated integrals (GPLs).

Iterated integrals

From Feynman integrals to iterated integrals : What do we gain?

Parametric Feynman integrals are multi-dimensional. The numerical evaluation is tedious, unstable and not so precise.

Iterated integrals

From Feynman integrals to iterated integrals : What do we gain?

Iterated integrals are one-dimensional. They can be computed with great precision in a short amount of time. Besides, they have the following properties:

(a) **Shuffle algebra** : Allows to obtain a basis for a set of iterated integrals. Reduction to such a basis is extremely effective to reduce the computation time by few times.

(b) **Scaling invariance** : Allows to convert the limit of these integrals from kinematical variables (z) to constants (1). This makes the integration really precise.

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- Form factor type MIs : Aglietti, Bonciani; Bonciani, Buccioni, NR, Vicini;
- Box type ($\gamma\gamma$ with massive lepton) : Bonciani, Ferroglia, Gehrmann, Maitre, Studerus;
- Box type (γZ & ZZ with massless lepton) :

Bonciani, Di Vita, Mastrolia, Schubert; Heller, von Manteuffel, Schabinger

Five among the 36 two-mass MIs of Bonciani *et al.* contain Chen iterated integrals!

The 36 two-mass master integrals

Fully analytic

- Most MIs are solved in GPLs.
- Five MIs are solved in terms of Chen's iterated integrals! Numerical evaluation possible only in the non-physical region.

Fully numerical

- Evaluation of the MIs in physical region is demanding! (using Fiesta/pySecDec)
- Specially for those five MIs, achieving a single digit precision in the physical region is extremely challenging!

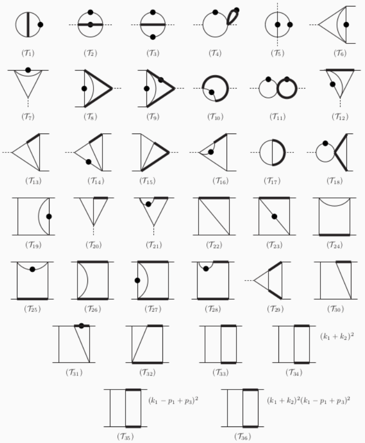


Fig from Roberto et al.

Can we find a mixed approach?

Our semi-analytic approach

What do we need for the two-loop virtual amplitudes?

Our semi-analytic approach

What do we need for the two-loop virtual amplitudes?

(a) An analytic formula for the singular part, to perform the infrared subtraction.

(b) A formula for the finite part which should be numerically stable and precise.

(i) The universal subtraction operator indicates that the singular part of the amplitude contains only simple GPLs.

(ii) We find certain internal combinations of the MIs (at the lowest order in ϵ) which can be solved in terms of simple GPLs.

So, only simple GPLs in the singular part! SOLVED!

Our semi-analytic approach

What do we need for the two-loop virtual amplitudes?

(a) An analytic formula for the singular part, to perform the infrared subtraction.

(b) **A formula for the finite part which should be numerically stable & precise.**

Most of the MIs are known in terms of GPLs. Few MIs (32-36), which contain Chen iterated integrals, we solve them using series expansion through `DiffExp`.

(i) We consider the system of differential equations for all the 36 MIs. Given a boundary point, the system can be solved using series expansion for a nearby point.
(ii) The solution in this new point can now be considered as boundary and thus we can go forward along a path to obtain solution in any phase space point.
(iii) As 31 MIs are known in closed form, they provide crucial checks for the series solution.

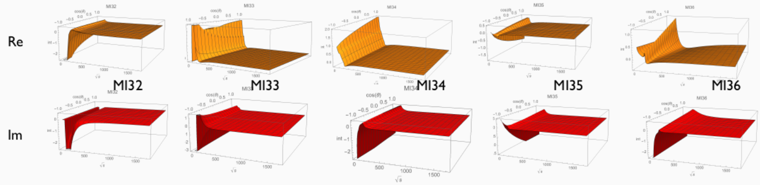
Our semi-analytic approach

What do we need for the two-loop virtual amplitudes?

(a) An analytic formula for the singular part, to perform the infrared subtraction.

(b) **A formula for the finite part which should be numerically stable & precise.**

The MIs (32-36) are computed with an arbitrary number of significant digits (50) in the physical region, but not in closed form ⇒ semi-analytical



Finally

We obtain the two-loop virtual amplitude:
(a) The singular part is analytic and contains GPLs. This allows us to successfully check with the universal infrared behaviour of the scattering amplitudes.

(b) The finite part after performing the infrared subtraction contains GPLs and few MIs 'symbolically' which have been computed using our semi-analytic approach.

Finally

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Next?

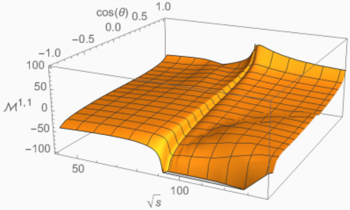
We need to evaluate the subtracted finite part numerically for few thousand phase-space points. Although evaluation of a single GPL is fast, there are ~ 11000 GPLs in the full expression. Also the expression is extremely large.

Numerical evaluation and the grid

To obtain a fast compilation and successful numerical evaluation, we divide the contributions from various Feynman diagrams in a gauge invariant way by the presence of different EW vector bosons (γ, Z, W).

Each such subset, again, can have contributions from Feynman diagrams of different topologies, like two-loop corrections to initial quark vertex, the Box contributions etc.

These subdivisions allow us to parallelize the computation. With a 3000 core cluster, it takes around **2-3 hrs** to obtain the full grid of 3250 phase-space points.



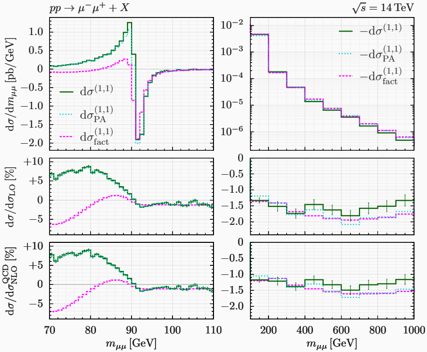
Results!

σ [pb]	σ_{LO}	$\sigma^{(1,0)}$	$\sigma^{(0,1)}$	$\sigma^{(2,0)}$	$\sigma^{(1,1)}$
$q\bar{q}$	809.56	191.85	-33.76	49.9	-4.8
qg	—	-158.08	—	-74.8	8.6
$q(g)\gamma$	—	—	-0.839	—	0.084
$q(\bar{q})q'$	—	—	—	6.3	0.19
gg	—	—	—	18.1	—
$\gamma\gamma$	1.42	—	-0.0117	—	—
total	810.98	33.77	-34.61	-0.5	4.0

$\frac{\sigma^{(i,j)}}{\sigma_{LO}}$ $+4.2\%$ -4.3% $\sim 0\%$ $+0.5\%$

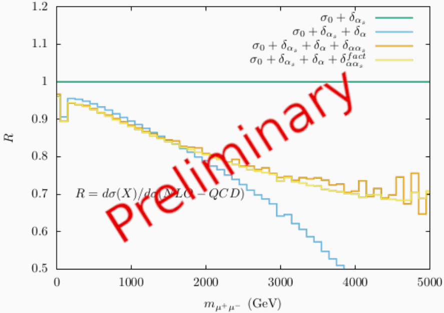
* The size of the NNLO QCD corrections depends on the chosen setup!

Results!



Complete $\mathcal{O}(\alpha_s\alpha)$ correction to the differential cross section $d\sigma^{(1,1)}$ in the anti-muon p_T. The top panels show the absolute predictions, while the central (bottom) panels display the $\mathcal{O}(\alpha_s\alpha)$ correction normalized to the LO (NLO QCD) result.

Results in the high invariant mass



In very high invariant mass region, QCD-EW effects are large and positive!

At 3 TeV, the corrections are $\mathcal{O}(10\%)$, comparable with the statistical uncertainty at the end of HL-LHC.

More statistics needed for precise comment on the effect of non-factorizable corrections!

Assuming a perfect proton PDF $\Rightarrow$ constraint on new physics
Assuming the SM validity $\Rightarrow$ constraint in the PDF fit

Summarizing

- The NNLO QCD-EW contributions to Drell-Yan production are much sought for.
- One of the bottleneck is the computation of two-loop virtual amplitudes.
- Our semi-analytic approach allows us to achieve analytic cancellation of the universal subtraction term, as well as fast and stable numerical evaluation of the finite hard function.
- The phenomenological impact of mixed QCD-EW corrections is crucial.

Thank you for your attention!