HO QCD and HO EW calculations for NC Drell-Yan production

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NNLO QCD and HO EW corrections - so far

ATLAS strategy since 2010 for calculations of theory predictions: a “wise” choice of the EW parameter schema may minimise the missing pure weak effects, e.g. like the $G_\mu$ schema for $W$ and $Z$ production: input $W$ and $Z$ masses and $G_\mu$

$$\frac{1}{\alpha_G} = \frac{\sqrt{2} G_\mu M_W^2}{\pi} \left( 1 - \frac{M_W^2}{M_Z^2} \right); \quad \sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

see e.g. QED FSR corrected 2010 $W$ and $Z$ data, ATLAS Phys. Rev. D85, 072004 (2012)

- apply to HO QCD predictions remaining missing HO EW corrections (pure weak, QED ISR and ISR+FSR interferences) for the differential $Z$ and $W$ distributions


- The interference effects are below 0.1% for all considered channels.

- Pure weak effects may change the predicted cross sections by about 0.5%. Shape modifications due to the pure weak corrections are calculated to be at most 10% of the quoted correction values.
NNLO QCD and HO EW corrections - now

New calculations based on FEWZ 3.1 (3.1.a3 and 3.1.b2) :
“Combining QCD and electroweak corrections to dilepton production in FEWZ”,
and
“SANC integrator in the progress: QCD and EW contributions”, D. Bardin et al.,

Aim: Combine HO QCD and HO EW corrections for precision analysis of NC and
CC DY production.

Focus : Currently ongoing high and low mass Drell-Yan analysis → crucial to
evaluate impact of EW corrections for NNLO QCD fits

Issues : Benchmarking of results obtained with FEWZ 3.1.X versions (pre-
releases used since several months in close discussion with Frank P. and Ye
Li) w.r.t. SANC
- Understand predictions for 2 different EW parameter schemata
- Understand cut and PDF sensitivity of EW corrections
- NEW since Durham workshop: estimate photon-photon induced
  contributions
EW parameter schema

- **$\alpha(0)$-scheme:** The fine-structure constant $\alpha(0)$ and all particle masses define the complete input. In this scheme, the relative corrections to the $q\bar{q} \rightarrow \gamma/Z \rightarrow l^-l^+$ cross sections sensitively depend on the light-quark masses via $\alpha \ln m_q$ terms that enter the charge renormalization.  ➔ has to be used for photon induced processes

- **$\alpha(M_Z)$-scheme:** The effective electromagnetic coupling $\alpha(M_Z)$ and all particle masses define the basic input. Tree-level couplings are derived from $\alpha(M_Z)$, and the relative corrections receive contributions from the quantity $\Delta \alpha(M_Z)$, which accounts for the running of the electromagnetic coupling from scale $Q = 0$ to $Q = M_Z$ (induced by light fermions) and cancels the corresponding $\alpha \ln m_q$ terms that appear in the corrections to the $q\bar{q}$ channels in the $\alpha(0)$-scheme.  ➔ default schema in FEWZ 2.0, 2.1, e.g. used by CMS for PAS EWK-11-007
  ➔ we use it as a cross check

- **$G_\mu$-scheme:** The Fermi constant $G_\mu$ and all particle masses define the basic input. Tree-level couplings are derived from the effective coupling $\alpha_{G_\mu} = \sqrt{2}G_\mu M_W^2 (1 - M_W^2/M_Z^2)/\pi$, and the relative corrections receive contributions from the quantity $\Delta r$ [40], which describes the radiative corrections to muon decay. Since $\Delta \alpha(M_Z)$ is contained in $\Delta r$, there is no large effect on the $q\bar{q}$ channels induced by the running of the electromagnetic coupling in the $G_\mu$-scheme either.  ➔ we used it in our $W,Z$ publication
  ➔ our nominal EW parameter schema
Scheme dependence of weak corrections

- **Full lines**: includes **leading** two-loop terms
- **Dashed lines**: include leading higher order corrections

\[
\delta_{\text{virt, weak}} \]

Default schema
FEWZ 2.0
(w/o HO EW)
\(\rightarrow\) smaller corrections for low mass DY

\(G_{\mu}\): smallest corrections for Z exchange

“offset” = \(\frac{\alpha_S}{\alpha(m_Z)}\)^2 - 1
SANC : 5.74 %
FEWZ 3.1.a3 : 5.44%
FEWZ 2.0 : 6.9 %
\(\rightarrow\) choice of \(\alpha(m_Z)\)
Methodology

- Use FEWZ 3.1.a3 / FEWZ 3.1.b2
- Baseline: as given in the plots, e.g. NLO QCD
- default: cuts applied (not indicated), but mentioned if “no cuts” applied
- default: $G_\mu$ schema or EW schema as indicated in the plots
- scales set individually per bin, or use of dynamic scales with FEWZ 3.1.b2
  - each bin calculated separately to avoid integration bias
  - statistical precision <0.01% for LO, ~0.02% for NLO, for NNLO ~0.2% (with cuts)
- To get MISS (Weak, ISR*FSR, ISR on; FSR off): use FEWZ flag Ewflag = 1
  - to compare with QED FSR corrected Atlas data

Comparisons done to
- FEWZ 2.1.1 vs FEWZ 3.1.X
  - agreement better than 0.2% found
- NLO MCFM for all mass ranges
  - trend: MCFM lower by about -0.8% (but not a fully tuned comparison yet)
- LO QCD and MISS SANC for all mass ranges, no cuts
- NLO QCD and MISS SANC low mass with cuts
  - very new and work in progress!

Selected examples shown in the following
Kinematic requirements
• 116 GeV\(\lesssim M_{ll}\lesssim 1500\) GeV
• \(P_T^{\ell}\rangle 25\) GeV
• \(|\eta_\ell| < 2.5\)

→ focus in understanding HO EW corrections for NNLO QCD and HO EW corrections mainly for fiducial cuts

→ NLO QCD is usually used as the standard baseline: best compromise between incorporating HO QCD effects and precision of the calculation
High mass Drell Yan (2)

Observations:
- ratio of 2 EW schemata shows expected offset, but not strictly flat
- But very good convergence (max dev. 0.4% for lowest mass bin with cuts) for EW corrected predictions
- Good agreement with SANC MISS values versus FEWZ MISS values within 0.2% (no cuts) and 0.5% with cuts
- approximately rescaling for MISS corrections derived based on LO QCD to N(N)LO QCD works

\[ \sigma_{(HO\_QCD+EW)} = \sigma_{HO\_QCD} \left( 1 + \delta_{MISS} \frac{\sigma_{LO\_QCD}}{\sigma_{HO\_QCD}} \right) \]
High mass Drell Yan (3)

- NNLO QCD fiducial cross section predictions including HO EW MISS contributions

$\rightarrow$ CT10nnlo predictions lower than MSTW2008nnlo, while HERA15nnlo and ABM11 tend to be higher
Atlas extended binning:
- 12 GeV $<$ $M_{ll}$ $<$ 66 GeV
- $P_T^{1(2)}>9(6)$ GeV
- $|\eta_l|<2.4$

Checks:
- Constant offset of 5.5% between the two EW schemata at NLO (NNLO) QCD
- MISS corrected predictions agree within 0.2% for $M_{ll}>30$ GeV and QCD NNLO/NLO factors including MISS are flat
- But strong effects for lower mass bins
Atlas nominal binning:
- $26 \text{ GeV} < M_{ll} < 66 \text{ GeV}$
- $P_T^{1(2)} > 15(12) \text{ GeV}$
- $|\eta_l| < 2.4$

Checks:
- ✓ good agreement to MCFM (max. dev. -0.8%) at NLO QCD
- ✓ MISS corrected predictions agree within 0.2% for $M_{ll} > 36 \text{ GeV}$, QCD NNLO/NLO factors including MISS are flat
- ➔ strong effects for lower mass bins
Neutral Current Drell Yan processes
• $qqbar$ induced processes: sensitive to structure of the proton

Irreducible background
• $\gamma\gamma$ ($\gamma q$) induced processes: sensitive to QED and structure of the photon
  ➔ non-resonant; suppressed due to the smallness of the photon PDF
## LO predictions

**MRST2004QED**

G\(_{\mu}\) schema;

All scales set to M\(_{Z}\)

'Benchmark' FEWZ 3.1.b2

\(\Rightarrow\) I could reproduce exactly those (blue and red) numbers within 0.2% for photon-induced and weak contributions (c.f. also FEWZ 3.1 paper).

\(\Rightarrow\) Perform calculations for Atlas cuts and bins

### Table 1

<table>
<thead>
<tr>
<th>(M_{ll}/\text{GeV})</th>
<th>50–∞</th>
<th>100–∞</th>
<th>200–∞</th>
<th>500–∞</th>
<th>1000–∞</th>
<th>2000–∞</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_{0}/\text{pb})</td>
<td>738.733(6)</td>
<td>32.7236(3)</td>
<td>1.48479(1)</td>
<td>0.0809420(6)</td>
<td>0.00679953(3)</td>
<td>0.000303744(1)</td>
</tr>
<tr>
<td>(\sigma_{0}</td>
<td>_{\text{FS/PS}}/\text{pb})</td>
<td>738.773(6)</td>
<td>32.7268(3)</td>
<td>1.48492(1)</td>
<td>0.0809489(6)</td>
<td>0.00680008(3)</td>
</tr>
<tr>
<td>(\delta_{\gamma,\gamma,0}/%)</td>
<td>0.17</td>
<td>1.15</td>
<td>4.30</td>
<td>4.92</td>
<td>5.21</td>
<td>6.17</td>
</tr>
<tr>
<td>(\delta_{\text{rec, phot}}/%)</td>
<td>-1.81</td>
<td>-4.71</td>
<td>-2.92</td>
<td>-3.36</td>
<td>-4.24</td>
<td>-5.66</td>
</tr>
<tr>
<td>(\delta_{\mu^{+}\mu^{-}, phot}/%)</td>
<td>-3.34</td>
<td>-8.85</td>
<td>-5.72</td>
<td>-7.05</td>
<td>-9.02</td>
<td>-12.08</td>
</tr>
<tr>
<td>(\delta_{\mu^{+}\mu^{-}, multi-\gamma}/%)</td>
<td>0.073(^{+0.027}_{-0.024})</td>
<td>0.49(^{+0.18}_{-0.15})</td>
<td>0.17(^{+0.06}_{-0.05})</td>
<td>0.23(^{+0.07}_{-0.06})</td>
<td>0.33(^{+0.09}_{-0.08})</td>
<td>0.54(^{+0.13}_{-0.12})</td>
</tr>
<tr>
<td>(\delta_{q_{t}, weak}/%)</td>
<td>-0.71</td>
<td>-1.02</td>
<td>-0.14</td>
<td>-2.38</td>
<td>-5.87</td>
<td>-11.12</td>
</tr>
<tr>
<td>(\delta_{\text{h.o., weak}}/%)</td>
<td>0.030</td>
<td>0.012</td>
<td>-0.23</td>
<td>-0.29</td>
<td>-0.31</td>
<td>-0.32</td>
</tr>
<tr>
<td>(\delta_{\text{Sudakov}}^{(2)}/%)</td>
<td>-0.00046</td>
<td>-0.0067</td>
<td>-0.035</td>
<td>0.23</td>
<td>1.14</td>
<td>3.38</td>
</tr>
<tr>
<td>(\delta_{q_{t}, g_{t}, phot}/%)</td>
<td>-0.11</td>
<td>-0.21</td>
<td>0.38</td>
<td>1.53</td>
<td>1.91</td>
<td>2.34</td>
</tr>
<tr>
<td>(\delta_{\gamma,\gamma, phot}/%)</td>
<td>-0.0060</td>
<td>-0.032</td>
<td>-0.11</td>
<td>-0.14</td>
<td>-0.16</td>
<td>-0.23</td>
</tr>
<tr>
<td>(\delta_{\gamma,\gamma, phot}/%)</td>
<td>-0.011</td>
<td>-0.058</td>
<td>-0.22</td>
<td>-0.30</td>
<td>-0.39</td>
<td>-0.59</td>
</tr>
<tr>
<td>(\delta_{\gamma,\gamma, weak}/%)</td>
<td>0.000045</td>
<td>0.00056</td>
<td>-0.025</td>
<td>-0.14</td>
<td>-0.31</td>
<td>-0.64</td>
</tr>
<tr>
<td>(\delta_{QCD}/%)</td>
<td>4.0(1)</td>
<td>13.90(6)</td>
<td>26.10(3)</td>
<td>21.29(2)</td>
<td>8.65(1)</td>
<td>-11.93(1)</td>
</tr>
</tbody>
</table>

\[M_{ll} > 50 \text{ GeV}, \quad p_{T,l^\pm} > 25 \text{ GeV}, \quad |y_{l^\pm}| < 2.5, \quad \text{arXiv:0911.2329v2}\]
Results

[work in progress ]

- MRST2004qed
- NLO QCD
- Fiducial cuts: $\eta < 2.4$ (2.5)

$\delta$ calculation:
- Denominator: NLO QCD w/o photon
- Numerator: MISS=triangles (green)
  LO $\gamma$ induced=open (red)
  with $\sim 50\%$ error bar
  QED FSR=triangles (blue)
  MISS including $\gamma$ induced =full (black)

$\Rightarrow$ LO photon-photon induced contributions are as sizeable as the PW+ISR+IFI effects (MISS) and the PDF uncertainties

Low mass, extended bins, pt1 $(2) > 9$ (6) GeV

Low mass, nominal bins, pt1 $(2) > 15$ (12) GeV

High mass
Tools: FEWZ 3.1.a3 and FEWZ 3.1.b2 (pre-releases) and SANC

Baseline 1: LO QCD, CT10, $G_\mu$ schema, no cuts
Goal: Calculate HO EW MISS (pure weak, ISR, ISR+FSR interference)
✓ benchmark LO QCD cross sections
✓ MISS corrections between FEWZ and SANC within 0.2-0.5%

Baseline 2: (N)NLO QCD, various PDFs, $G_\mu$ and Mz schema, with and w/o cuts
Goal: Calculate HO EW MISS (pure weak, ISR, ISR+FSR interference)
✓ benchmark NLO MCFM versus FEWZ ($G_\mu$ – perhaps remaining small parameter mismatch which may cause a ~0.5-1% offset), started to benchmark NLO SANC versus FEWZ
✓ Confirm the expected constant offset between the 2 schemata w/o HO EW for high mass DY, but non-convergence for lowest DY bin for fiducial cross sections! offset remains also at NNLO QCD!
✓ Pdf sensitivity for MISS: found to be small (<0.5%)
✓ Cut sensitivity for MISS: small for high mass and low mass bins well above cuts
✓ NNLO/NLO k-factors for QCD fits using HERA15NNLO, but those k-factors are not flat anymore for the lowest and highest mass regions
A working list

✧ Assign uncertainty for applying HO EW corrections (cut dependence, non-convergence between EW schemata etc.)

✧ Issue 1 : LO photon induced contribution based on NLO QCD calculated effects as large as PDF sensitivity observed

✧ Issue 2 : NLO photon induced contributions have to be added as well

✧ Issue 3 : Estimate remaining NNLO QCD scale uncertainties (CPU time)

✧ Issue 4 : Do we miss further EW corrections?
   ➔ EW corrections have to be matched with experimental procedures, e.g. we correct for QED FSR, we subtract diboson background with MC ...
   ➔ MC modelling of photon induced contributions would be highly welcome

ToDo : final combination of ALL effects and estimate uncertainties relevant for PDF fits
Mandatory : high precision calculations are crucial...