DYqT: version 1.0

This is a note about the DYqT program, which computes the transverse-momentum (q_T) spectrum of Drell–Yan lepton pairs with high invariant mass (M) produced, via vector boson V ($V = W^{\pm}, Z/\gamma^*$) decay, in pp or $p\bar{p}$ collisions. The DYqT calculation combines the fixed-order result at high values of q_T ($q_T \sim M$) up to $\mathcal{O}(\alpha_S^2)$ with the resummation of the logarithmically enhanced contributions at small values of q_T ($q_T \ll M$) up to next-to-next-to-leading logarithmic (NNLL) accuracy. The rapidity of the vector boson and the leptonic kinematical variables are integrated over the entire kinematical range. When referring to the program, please quote Refs. [1, 2].

Overview

The program performs the resummation of the large logarithmic contributions that appear in the region where the vector boson transverse momentum q_T is much smaller than the invariant mass M ($q_T \ll M$). The method to perform the resummation is presented in Refs. [3, 4]. The resummed result in the small-q_T region ($q_T \ll M$) is consistently matched to the fixed-order calculation that is valid at high q_T ($q_T \sim M$). The fixed-order calculation implements the analytic results of Ref. [5]. We suggest the program to be used for transverse momenta $q_T \lesssim M$. When $q_T \gtrsim M$ the use of the resummation formalism is no longer justified and one can use the standard fixed-order result.

The program can be used at NLL+LO and NNLL+NLO accuracy [1]. At NLL+LO accuracy the resummed part is evaluated at next-to-leading logarithmic (NLL) accuracy, and the fixed-order part is evaluated at the leading order (LO) (it is given by the $\mathcal{O}(\alpha_S)$ terms with 'V + 1 parton' in the final state). At NNLL+NLO accuracy the resummed part is evaluated at NNLL accuracy, and the fixed-order part is evaluated up to the next-to-leading order (NLO) (it includes all the terms with 'V + 1 parton' and 'V +2 partons' up to $\mathcal{O}(\alpha_S^2)$) at NLO (V + 1 or 2 partons). At NNLL+NLO (NLL+LO) accuracy the `DYqT` calculation exactly recovers the total cross section at NNLO (NLO) upon integration over q_T.

Input parameters

The mass and total width of the W and Z bosons are respectively $m_W = 80.385$ GeV, $\Gamma_W = 2.085$ GeV and $m_Z = 91.1876$ GeV, $\Gamma_Z = 2.4952$ GeV. As for the electroweak (EW) couplings, we use the so called G_μ scheme, where the input parameters are G_F , m_W, m_Z. The Fermi constant is set to the value $G_F = 1.16637 \times 10^{-5}$ GeV^{-2}, and we use the following (unitarity constrained) values of the CKM matrix elements: $V_{ud} = 0.97427$, $V_{us} = 0.22536$, $V_{ub} = 0.00355$, $V_{cd} = 0.22522$, $V_{cs} = 0.97343$, $V_{cb} = 0.0414$. All these values of EW parameters are taken from the PDG 2014 [9]. The EW couplings of the W and Z bosons to quarks and leptons are treated at the tree level, so that the above parameters are sufficient to fully specify the EW content of our calculation.

Compilation

The `DYqT` program can be downloaded from
`http://pcteserver.mi.infn.it/~ferrera/dyqt.html`

- To extract it type:

[1]According to this notation [1, 2] for the resummed+matched expansion, the fixed-order labels, LO and NLO, refer to the perturbative accuracy in the large-q_T region. Note, however, that the NNLL (NLL) part completely includes the perturbative contributions up to $\mathcal{O}(\alpha_S^2)$ ($\mathcal{O}(\alpha_S)$). Therefore, from the viewpoint of the perturbative accuracy in the small-q_T region ($q_T \ll M$), the NLL+LO and NNLL+NLO calculations should be denoted [6] as NLL+NLO and NNLL+NNLO, respectively.

```
tar -xzvf DYqT-v1.0.tgz
```

- To compile it simply use:
  `make`
- To run it type:
  `./dyqt < infile`

The program can be compiled with its own Parton Distribution Function (PDF) interface (set `PDFROUTINES = NATIVE` in the `Makefile`) or with the Les Houches Accord PDF interface (LHAPDF) (set `PDFROUTINES = LHAPDF` in the `Makefile`). In the latter case, the library `libLHAPDF.a` is needed (with the correct path set in the `Makefile`).

The input file

This is a typical example of input file:

```
-1  !  Collider:  pp (1), ppbar (-1)
3   !  Vector boson:  photon (1),W+ and W- (2),W+ (21),W- (22),Z (3),Z/photon (5)
1   !  Narrow Width Approximation (NWA), only for W and Z prod.:  false (0), true
(1)
0   !  Remove Branching Ratio (only within the NWA): false (0), true (1)
91.1876d0   !  Lepton pair invariant mass [GeV] (dummy within the NWA)
2           !  Order of calculation:  NLL+LO (1), NNLL+NLO (2)
test.dat    !  Output file name
92 3        !  PDF number, loop for alpha_S (for native PDFs)
'MSTW2008nnlo68cl.LHgrid' 0   !  PDF name, member (for LHAPDF)
1.96d3                        !  Centre--of--mass energy [GeV]
91.1876d0 91.1876d0 91.1876d0 !  Renormaliz., Factoriz., Resummation scales [GeV]
0.0d0          !  Non-perturbative smearing (g parameter)
0d0 20d0 2d0   !  qtmin qtmax qtbin
```

- `ic`: Integer variable setting the type of hadronic collisions: pp (`ic=1`), $p\bar{p}$ (`ic=-1`).
- `prodflag`: Integer variable setting the type of vector boson produced:
  γ^* (`prodflag=1`), W^+ and W^- (`prodflag=2`), W^+ (`prodflag=21`),
  W^- (`prodflag=22`), Z (`prodflag=3`), Z/γ^* (`prodflag=5`),
- `fnwa`: Integer variable setting the use of the narrow width approximation (NWA). If `fnwa=0` the code computes the differential cross section $M^2 d\sigma^V/dM^2/dq_T$ [pb/GeV], if `fnwa=1` the code computes the differential cross section $d\sigma^V/dq_T$ [pb/GeV] within the NWA. The NWA is valid only for W and Z production (`prodflag=2,21,22,3`) and it consists in the substitution $1/((M^2-m_V^2)^2+m_V^2\Gamma_V^2) \to \pi/(m_V\Gamma_V)\,\delta(M^2-m_V^2)$ in the corresponding cross section (m_V and Γ_V are respectively the vector boson mass and total width).

- `brflag`: Integer variable setting the W and Z leptonic branching ratios: $\mathrm{BR}(V \to l_1 l_2) = \Gamma_{V\to l_1 l_2}/\Gamma_V$, where $\Gamma_{V\to l_1 l_2}$ is the W or Z partial width due to the leptonic decays $W \to l\bar{\nu}_l$ and $Z \to l\bar{l}$. If `brflag=0` $\mathrm{BR}(V \to l_1 l_2)$ is equal to the Standard Model value at tree level, if `brflag=1` then $\mathrm{BR}(V \to l_1 l_2) = 1$. This flag is valid only if `fnwa=1`.

- `amv`: Double precision variable that sets the mass of the lepton pair invariant mass M [GeV]. If `fnwa=1` this is a dummy variable since $M = m_V$.

- `flag1`: Integer variable fixing the order of the calculation: NLL+LO (`flag1=1`) or NNLL+NLO (`flag1=2`).

- `runstring`: Character string which sets the output file name.

- `isetproton, nloop`: Integer variables for PDF choice (`isetproton`) and order of α_S (`nloop`). These variables are valid with the native PDF interface. A list of available PDFs is given below. The number of loops to which α_S should be evaluated has to be chosen accordingly.

- `name, mem`: Character string (`name`) which sets the PDF group and integer variable (`mem`) which sets the PDF member. These variables are valid with the LHAPDF interface.

- `sroot`: Double precision variable for centre–of–mass energy $\sqrt{s}$ [GeV].

- `mur, muf, muq`: Double precision variables that set the renormalization, factorization and resummation scales [GeV]: they can be different from one another but they should always be set of the order of M.

- `g`: Double precision variable for non perturbative smearing. The smearing is applied as an additional factor $\exp\{-gb^2\}$ in the resummed part, where b is the impact parameter variable that is Fourier conjugated to q_T. The choice `g=0` means that no smearing is applied to the perturbative result.

- `qtmin, qtmax, qtbin`: Double precision variables setting minimum, maximum and step [GeV] in loop over the transverse momenta of the vector boson.

Output

At the beginning, the code will perform a fit of the chosen PDFs at the given factorization scale and obtain the necessary Mellin moments. Then the program computes the cross section for the given values of q_T. The results are printed in the standard output and written in a file whose name is set in the input file. An example of output corresponding to a calculation at NNLL+NLO accuracy is shown below. The transverse momentum, the purely resummed result, asymptotic and fixed-order results are displayed in the first four columns, respectively. The last column displays the final matched result. The results are given in pb/GeV. Running on a AMD Athlon 64-bit 2.6 GHz CPU, it takes about 50 minutes to obtain this output. The same calculation at NLL+LO accuracy takes instead about 5 minutes.

```
(
( PROGRAM DYqT (v1.0) Date:  28/03/2011 Time:  00:00:37
(
( Z Production
( BR(Z)= 0.0336386054
( alphas(mZ^2)= 0.117069888 alphas(1 GeV^2)= 0.387710006
(
( input file:
( ic= -1
( V= 3
( NWA= 1
( removeBR= 0
( q= 91.1876
( order= 2
( filename=test.dat
( PDF,loops= 92 3
( LHAPDF name,mem=MSTW2008nnlo68cl.LHgrid 0
( sqrt(s)= 1960.
( muR,muF,muQ= 91.1876 91.1876 91.1876
( NP g-par= 0.
( qtmin,qtmax,qtbin= 0.  20.  2.
(
(------------------------------------------------------------------------
(      qt           resum           asym          fixed          matched
(------------------------------------------------------------------------
(
 1.0000000E+00  1.6687015E+01  8.2387225E+01  8.2536101E+01  1.6835892E+01
 3.0000000E+00  2.3222481E+01  3.8746025E+01  3.8872153E+01  2.3348609E+01
 5.0000000E+00  1.8255223E+01  2.1748443E+01  2.1840246E+01  1.8347025E+01
 7.0000000E+00  1.3658863E+01  1.3999289E+01  1.4091829E+01  1.3751402E+01
 9.0000000E+00  1.0315014E+01  9.7373869E+00  9.8436618E+00  1.0421289E+01
 1.1000000E+01  7.9230646E+00  7.1133317E+00  7.2375642E+00  8.0472970E+00
 1.3000000E+01  6.1840501E+00  5.3728592E+00  5.5169394E+00  6.3281303E+00
 1.5000000E+01  4.8924724E+00  4.1560807E+00  4.3192093E+00  5.0556010E+00
 1.7000000E+01  3.9134823E+00  3.2715204E+00  3.4520544E+00  4.0940164E+00
 1.9000000E+01  3.1579074E+00  2.6088257E+00  2.8049882E+00  3.3540700E+00
```

Native Parton Distribution Functions

A list of available parton densities for the native PDF interface is given below. A similar list is reported in the file `pdf_nat.f`. New PDFs can be easily added in that code by the user. Alternatively the user can set the use of the LHAPDF interface in the `Makefile`.

```
C
C Iset distribution
c
c 0 CTEQ4M NLO (MS)
c 1 --------------
c 2 CTEQ4L LO
c 3 grv-98 NLO (MS)
c 4 MRST ft08a-98 NLO
c 5 MRST ft09a-98 NLO
c 6 MRST ft11a-98 NLO
c 7 MRST ft24a-98 NLO
c 8 MRST ft23a-98 NLO
c 9 MRST lo05a-98 LO
c 10 MRST lo09a-98 LO
c 11 MRST lo10a-98 LO
c 12 MRST lo01a-98 LO
c 13 MRST lo07a-98 LO
C 14 CTEQ5M Standard MSbar scheme
C 15 CTEQ5D Standard DIS scheme
C 16 CTEQ5L Leading Order
C 17 CTEQ5HJ Large-x gluon enhanced
C 18 CTEQ5HQ Heavy Quark
C 19 CTEQ5F3 Nf=3 FixedFlavorNumber
C 20 CTEQ5F4 Nf=4 FixedFlavorNumber
C 21 CTEQ5M1 Improved CTEQ5M
C 22 CTEQ5HQ1 Improved CTEQ5HQ
c 24 HMRS b
c 25 MRS S0
C 30 MRST 99 default (MS)

C MRST2000 set:

C 31 VNV000 new NLO (g-up)
C 32 VNV001 NNLO average
C 33 VNV002 NNLO AA
C 34 VNV003 NNLO BB
C 35 VNV004 NNLO AB
C 36 VNV005 NNLO BA
```

```
C 37 VNV006 LO

C MRST2001 NLO set

C 41 alf119 central gluon
C 42 alf117 lower a_s
C 43 alf121 higher a_s
C 44 j121 better fit to jet data

C MRST2001 NNLO set

C 45 vnvalf1155 ‘average’ evolution
C 46 vnvalf1155a ‘fast’ evolution
C 47 vnvalf1155b ’slow’ evolution
C 48 vnvalf1180j better fit to jet data

C MRST2002 new LO set

C 49 lo2002

C CTEQ6

C 50 cteq6l
C 51 cteq6m

C CTEQ6.6

C 55 cteq6.6m

C MRST2002 new updated set

c 61 mrst2002 NLO
c 62 mrst2002 NNLO

C MRST2004 set

c 71 mrst2004 NLO
c 72 mrst2004 NNLO

C MSTW2008 set

c 90 mstw2008 LO
c 91 mstw2008 NLO
c 92 mstw2008 NNLO
```

References

[1] G. Bozzi, S. Catani, G. Ferrera, D. de Florian, M. Grazzini, Nucl. Phys. **B815** (2009) 174-197 [arXiv:0812.2862 [hep-ph]].

[2] G. Bozzi, S. Catani, G. Ferrera, D. de Florian, M. Grazzini, Phys. Lett. **B696** (2011) 207-213 [arXiv:1007.2351 [hep-ph]].

[3] S. Catani, D. de Florian and M. Grazzini, Nucl. Phys. B **596** (2001) 299 [hep-ph/0008184].

[4] G. Bozzi, S. Catani, D. de Florian and M. Grazzini, Nucl. Phys. **B737** (2006) 73-120 [hep-ph/0508068], Nucl. Phys. B **791** (2008) 1 [arXiv:0705.3887 [hep-ph]].

[5] R. J. Gonsalves, J. Pawlowski, C. -F. Wai, Phys. Rev. **D40** (1989) 2245.

[6] S. Catani, D. de Florian, G. Ferrera and M. Grazzini, arXiv:1507.06937 [hep-ph].

[7] R. Hamberg, W. L. van Neerven, T. Matsuura, Nucl. Phys. **B359** (1991) 343-405.

[8] R. V. Harlander, W. B. Kilgore, Phys. Rev. Lett. **88** (2002) 201801 [hep-ph/0201206].

[9] K. A. Olive *et al.* [Particle Data Group Collaboration], Chin. Phys. C **38** (2014) 090001.