DYRes: version 1.0

This is a note about the DYRes program, which computes the cross section for vector boson production in pp or $p\bar{p}$ collisions. DYRes combines the calculation of the cross section up to next-to-next-to-leading order (NNLO) with the resummation of the logarithmically-enhanced contributions at small values of the transverse momentum (q_T) up to next-to-next-to-leading accuracy (NNLL) in QCD perturbation theory. The program includes $Z-\gamma^*$ interference, finite-width effects and the leptonic decay of the vector boson with the corresponding spin correlations. The calculation retains the full kinematics of the vector boson and of its decay products, allowing the user to apply arbitrary cuts on these final-state kinematical variables, and to plot the corresponding distributions in the form of bin histograms. The decay modes included are $W \to l\bar{\nu}_l$ and $Z/\gamma^* \to l\bar{l}$. When referring to this program, please quote Refs. [1, 2].

1 Introduction

The DYRes program computes the cross section of Drell–Yan lepton pairs with high invariant mass M ($M \gg \Lambda_{QCD}$) produced, via vector boson V ($V = W^{\pm}, Z/\gamma^*$) decay, in hadronic collisions. 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 that is used to perform the resummation is presented in Refs. [3, 4].

The calculation includes the leptonic decay of the vector boson with the corresponding spin correlations, retaining the full dependence on the final-state lepton(s) kinematics, the $Z-\gamma^*$ interference and the finite-width effects. We implement the leptonic decays $W \to l\bar{\nu}_l$ and $Z/\gamma^* \to l\bar{l}$.

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 ($q_T \sim M$) up to $\mathcal{O}(\alpha_S^2)$. The fixed-order calculation is performed by using the dipole formalism [5] as implemented in the MCFM program [6]. Since the fixed-order cross section is divergent when the transverse momentum q_T of the vector boson becomes small, a suitable counterterm must be subtracted to make the result finite as $q_T \to 0$. The counterterm is evaluated through an appropriate modification of the DYNNLO program [7].

In the resummed part of the calculation, the Born-level angular distribution of the lepton pair is generated according to the q_T-recoil procedure that is described in Ref. [1]. The default q_T-recoil prescription [1] corresponds to the computation of the Born-level angular distribution in the Collins–Soper rest frame [8] of the vector boson. In the large-q_T region ($q_T \sim M$), the DYRes calculation uses a smooth switching procedure (see Ref. [1]) to recover the customary fixed-order result at high values of q_T ($q_T \gg M$).

The program can be used at NLL+NLO and NNLL+NNLO accuracy. At NLL+NLO accuracy, the resummed part is evaluated up to next-to-leading logarithmic (NLL) accuracy and the fixed-order result is included up to $\mathcal{O}(\alpha_S)$. At NNLL+NNLO accuracy, the resummed part is evaluated up to NNLL accuracy and the fixed-order result is included up to $\mathcal{O}(\alpha_S^2)$. The NNLL+NNLO (NLL+NLO) calculation thus embodies the complete next-to-next-to-leading order (next-to-leading order) accuracy in the small-q_T region.

The `DYRes` program can be downloaded from

`http://pcteserver.mi.infn.it/~ferrera/dyres.html`

To extract it, simply use

```
tar -xzvf DYRes-v1.0.tar.gz
```

and the `DYRes-v1.0` directory will be created. The structure of the directory is

- `bin`: The directory containing the executable `dyres` and the input and output files.
- `doc`: The directory containing this note.
- `obj`: The directory containing the object files.
- `src`: The directory containing the source of the code.

2 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.

3 Implementation of cuts

Before compiling the program, the user can choose the cuts to be applied on the kinematical variables of the final-state leptons. This is done through the `cuts` subroutine.

The default version of the subroutine `cuts` contains some selection cuts that are typically used in the experimental analyses. In the default version, the lines of the code that implement the various cuts are all commented; in order to activate the various cuts the user must uncomment the corresponding lines in `cuts.f`.

Since the resummation procedure is necessarily inclusive over the QCD radiation that recoils against the vector boson, cuts on jets or isolation cuts on final state leptons can*not* be implemented.

The file `cuts.f` can be found in the `src/User` directory and the source file `setup-RES.f` can be found in the `src/Need` directory.

4 Compilation

The program is self-contained and it has been successfully tested on Linux and Mac-OS X environments. It supports different `FORTRAN` compilers, and it allows the user to choose between built in (native) Parton Distribution Functions (PDFs) or PDFs supplied through the LHAPDF interface [10].

To compile the code, edit the `makefile` to choose compilation options and PDF implementation (by commenting and uncommenting the corresponding lines) and insert the correct path to the LHAPDF libraries in case the LHAPDF interface is used. Then go in the `DYRes-v1.0` directory and type

- `make`

To run the program go in the `bin` directory and type:

- `./dyres < infile`

5 The input file

This is a typical example of input file:

```
7d3                              !  Centre--of--mass energy:  sroot
1 1                              !  Collision type:  ih1 ih2
3                                !  Vector boson:  W+ (1), W- (2), Z/gamma* (3)
91.1876d0 91.1876d0 91.1876d0    !  Ren., fact. and res. scales
0.0d0                            !  Non-perturbative smearing (g parameter)
2                                !  Perturbative order
'tota'                           !  Part
.false.                          !  Narrow Width Approximation
66d0 116d0                       !  Dilepton invariant mass range
20 20000000                      !  itmx1, ncall1
30 20000000                      !  itmx2, ncall2
1089                             !  Random number seed:  rseed
92 0                             !  For native PDFs only:  iset, nset
'NNPDF30_nnlo_as_0118.LHgrid' 0  !  For LHAPDF only:  'name', 'mem'
'test'                           !  Output file name:  runstring
```

- `sroot`: Double precision variable for centre–of–mass energy $\sqrt{s}$ [GeV].
- `ih1, ih2`: Integers identifying the beam (proton=1, antiproton=-1).
- `nproc`: Integer variable setting the type of vector boson produced.
  W^+ (`nproc=1`), W^- (`nproc=2`), Z/γ^* (`nproc=3`).
- `scale, facscale, resscale`: Renormalization, factorization and resummation scale [GeV]. These are double precision variables that can be different among one another

but they should always be set of the order of the vector boson (lepton pair) invariant mass.

- `g_param`: 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.

- `order`: Integer setting the order of the calculation. NLL+NLO (`order=1`), NNLL+NNLO (`order=2`).

- `part`: String identifying the part of the calculation to be performed: `part=virt` for resummed contribution, `part=real` for finite contribution, `part=tota` for the complete calculation.

- `zerowidth`: Logical variable setting the use of the narrow width approximation. To take into account finite width effect the logical variable `zerowidth` should be set to `false`*.

- `mwmin, mwmax`: Lower and higher limit on the vector boson (lepton pair) invariant mass.

- `itmx1, ncall1`: Number of iterations and calls to `Vegas` for setting the grid, respectively of the order ~ 15 or 20 and ~ 1000000 or 20000000.

- `itmx2, ncall2`: Number of iterations and calls to `Vegas` for the main run, respectively of the order ~ 20 or 30 and ~ 1000000 or 20000000.

- `rseed`: Random number seed (integer).

- `iset, nset`: Only in case of native PDFs (in case LHAPDF is used they are dummy). Integers identifying the PDF set chosen and the eigenvector for computing PDF errors (for MSTW2008 only). A list of available PDFs is given below.

- `name, mem`: Only in case of LHAPDF (in case of native PDFs they are dummy). The specific PDFset name and the individual PDF member.

- `runstring`: String for grid and output files.

6 Output

At the end of the run, the program returns the cross section and its error. The program also writes an output file in the topdrawer [11] format containing the required histograms with an estimate of the corresponding statistical errors. During the run, the user can control the intermediate results. The plots are defined in the `plotter.f` subroutine. The user can easily modify this subroutine according to his/her needs.

*Note that with `zerowidth=.false.` a hard scale must be set, to have a cross section that is computable in QCD perturbation theory. The hard scale is set by applying cuts on the leptons. These cuts must necessarily enforce a lower limit on the invariant mass of the vector boson (lepton pair), and the mass scale of this lower limit must be in the perturbative region.

7 Native Parton Distribution Functions

In order to run the `DYRes` program, a parton distribution set has to be chosen. We point out that the value of $\alpha_S(m_Z)$ is not adjustable; it is hard-wired with the value of $\alpha_S(m_Z)$ in the parton distributions. Moreover, the choice of the parton distributions also specifies the number of loops that should be used in the running of α_S. A list of available parton distributions is given in Table 1. When MSTW2008 partons are used, the `nset` variable selects one of the possible 40 grids used to compute the uncertainties at 90% CL. The default choice is `nset=0`, corresponding to the central set. The variable `nset` is dummy when other sets are used.

References

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[8] J. C. Collins and D. E. Soper, Phys. Rev. D **16** (1977) 2219.

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

[10] `http://lhapdf.hepforge.org/`

[11] `http://www.slac.stanford.edu/grp/ara/groups/BIG/codes/topdrawer/td_manual.htm`

`iset`	PDF set	$\alpha_{\rm S}(m_Z)$
1	CTEQ4 LO	0.132
2	CTEQ4 Standard NLO	0.116
11	MRST98 NLO central gluon	0.1175
12	MRST98 NLO higher gluon	0.1175
13	MRST98 NLO lower gluon	0.1175
14	MRST98 NLO lower $\alpha_{\rm S}$	0.1125
15	MRST98 NLO higher $\alpha_{\rm S}$	0.1225
16	MRST98 LO	0.125
21	CTEQ5M NLO Standard Msbar	0.118
22	CTEQ5D NLO DIS	0.118
23	CTEQ5L LO	0.127
24	CTEQ5HJ NLO Large-x gluon enhanced	0.118
25	CTEQ5HQ NLO Heavy Quark	0.118
28	CTEQ5M1 NLO Improved	0.118
29	CTEQ5HQ1 NLO Improved	0.118
30	MRST99 NLO	0.1175
31	MRST99 higher gluon	0.1175
32	MRST99 lower gluon	0.1175
33	MRST99 lower $\alpha_{\rm S}$	0.1125
34	MRST99 higher $\alpha_{\rm S}$	0.1225
41	MRST2001 NLO central gluon	0.119
42	MRST2001 NLO lower $\alpha_{\rm S}$	0.117
43	MRST2001 NLO higher $\alpha_{\rm S}$	0.121
44	MRST2001 NLO better fit to jet data	0.121
45	MRST2001 NNLO	0.1155
46	MRST2001 NNLO fast evolution	0.1155
47	MRST2001 NNLO slow evolution	0.1155
48	MRST2001 NNLO better fit to jet data	0.1180
51	CTEQ6L LO	0.118
52	CTEQ6L1 LO	0.130
53	CTEQ6M NLO	0.118
49	MRST2002 LO	0.130
61	MRST2002 NLO	0.1197
62	MRST2002 NNLO	0.1154
65	GJR08VF LO	0.1263
66	GJR08VF NLO	0.1145
67	JR09VF NNLO	0.1124
71	MRST2004 NLO	0.1205
72	MRST2004 NNLO	0.1167
75	A06 NNLO	0.1128
80	NNPDF2.0_100 NLO	0.1190
85	ABKM09 NNLO	0.1129
90	MSTW2008 LO	0.13939
91	MSTW2008 NLO	0.12018
92	MSTW2008 NNLO	0.11707

Table 1: Available PDF sets and their corresponding `iset` and values of $\alpha_S(m_Z)$.