artemide ver.1.4

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User manual for `artemide` package, which evaluated TMDs and related cross-sections.

Manual is updating.

If you use the `artemide`, please, quote [1].
If you find mistakes, have suggestions, or have questions write to:
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Repository: https://github.com/VladimirovAlexey/artemide-public

Contents

Glossary

TMD = Transverse Momentum Dependent
PDF = Parton Distribution Function
FF = Fragmentation Function
NP = Non-perturbative
DY = Drell-Yan process
SIDIS = Semi-Inclusive Deep-Inelastic Scattering

I. GENERAL STRUCTURE AND USER INPUT OF ARTEMIDE

A. General concept

The artemide package is a set of Fortran modules for evaluation of individual TMD distributions, TMD evolution factors, and other ingredients of TMD factorization theorem. Each module produces a single function, which is a composite of integrals/products of lower-level functions. Thus, each level of operation can be used as is, in other programs. The highest-level task is the evaluation of cross-section within the TMD factorization theorem, including all needed integrations, and factors, i.e., such that it can be directly compared to the data. It also includes several tools for analysis of the obtained values, such as variation of scales, search for limiting parameters, etc. The theory structure of artemide is discussed in the next section. The dependency structure of modules is presented in fig.1.

Wide spectrum of application of artemide code makes it difficult to create a convenient interface. Moreover, at the current stage of development, I prioritize the quality of computation, to the user interface. So, the interface is changing from version to version and often is not compatible with earlier versions. It slowly converges to the (almost) perfect shape – convenient for a wider community. If you have a particular task and not sure how to operate with artemide in this case, better write an e-mail.

The main rule (implemented in ver.2.00) each part encapsulates its own theory parameters. It does not affect/change/interact with other modules, except requests for functions. It can happen that a change of a parameter in a module requires a change in another module for consistency (however, I attempt to avoid such cases). Then each parameter must be changed individually in each module. However, the module aTMDe_control does it automatically. So, I suggest to use aTMDe_control to avoid possible inconsistencies.

Historical note: In versions before ver.2.00 this rule was not implemented. I tried to make connections between modules such that they automatically control consistency. However, at some moment (after inclusion of many hadrons and different types of cross-sections, and different orders) it became practically tough to keep such a system. So, I rearrange some modules (e.g. variation of c_4 scale was in TMDs, while it related to definition of TMD it-self), removed connections between modules (no link for change of NP parameters, etc.), and introduce aTMDe_control.

B. Organization of TMD factorized cross-section and its implementation in artemide

The ultimate goal of the artemide is to evaluate the observables in the TMD factorization framework, such as cross-section, asymmetries, etc. The general structure of the TMD factorized *fully differential* cross-section is

$$\frac{d\sigma}{dX} = d\sigma(q_T) = prefactor \ \times F, \tag{1.1}$$

where $prefactor$ a process-dependent and experiment-dependent prefactor, and F is the reduced structure function. Example, for the photon induced Drell-Yan process one has for $d\sigma/dq_T$

$$\begin{aligned} prefactor &= \frac{4\pi}{9sQ^2}|C_V(Q,\mu_H)|^2\mathcal{P}(\text{cuts}), \\ F &= \int \frac{bdb}{2} J_0(bq_T)\sum_f |e_f|^2 F_f(x_A,b;\mu_H,\zeta_A)F_{\bar{f}}(x_B,b;\mu_H,\zeta_B), \end{aligned}$$

where $\mathcal{P}(\text{cuts})$ is the weighting factor for fiducial cuts. For specific expression we refer in corresponding sections of this text. The structure function F is generally defined as

$$F(q_T,x_1,x_2;\mu,\zeta_1,\zeta_2) = \int \frac{bdb}{2} b^n J_n(bq_T)\sum_{ff'} z_{ff'}F_1^f(x_1,b;\mu,\zeta_1)F_2^{f'}(x_2,b;\mu,\zeta_2), \tag{1.2}$$

where $F_{1,2}$ are TMD distributions (of any origin and polarization), $z_{ff'}$ is the process dependent flavor mixing factor. The number n is also process dependent, e.g. for unpolarized observables it is $n=0$, while for SSA's it is $n=1$. Evaluation structure functions F is performed in the module TMDF. The evaluation of cross-sections is performed in the modules TMDX. The TMD distributions are evaluated by the module TMDs and related submodules.

In this way, the computation of TMD-factorized cross-section can be naturally split into ordered parts. Each part is evaluated in corresponding module of artemide. See example, of evaluation scheme in fig.2.

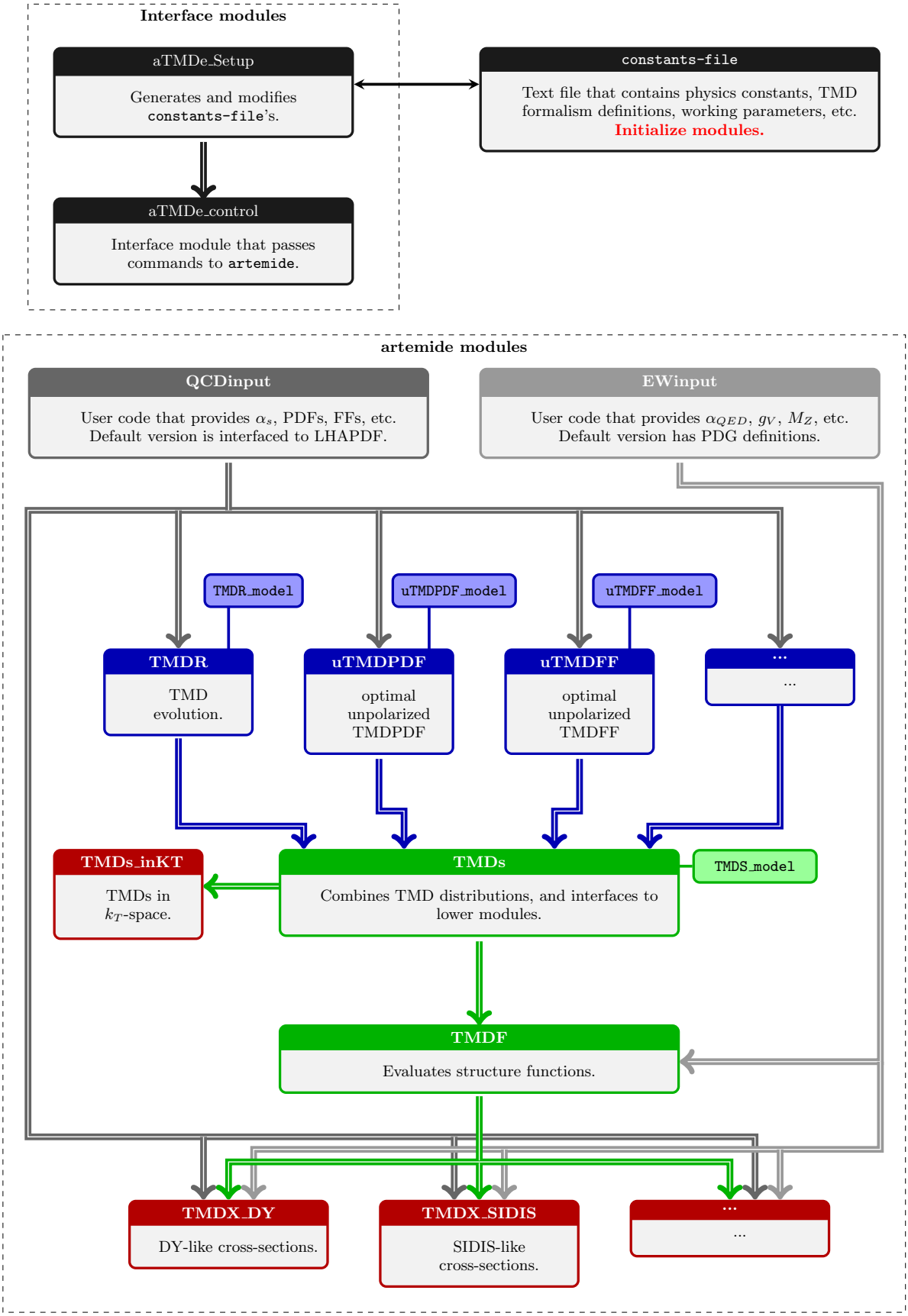

FIG. 1: Modules of `artemide`: purpose and dependencies

C. User defined functions and options

The `artemide` package has been created such that it allows to control **each aspect** of TMD factorization theorem. The TMD factorization has a large number of free, and "almost-free" parameters. It is a generally difficult task to provide a convenient interface for all these inputs. I do my best to make the interface convenient, however, some parts (e.g. setup of f_{NP}) could not be simpler (at least within FORTRAN). Also, take care that `artemide` is evolving, and I try to keep back compatibility, but it is not the main option.

Starting from ver.2.0, `artemide` uses the text initialization file, which contains all required information on static parameters for a given setup. Throughout the text I call this file `constants-file`.

The user has to provide (or **use the default values**) the set of parameters, that control various aspects of evaluation. It includes PDF sets, f_{NP}, perturbative scales, parameters of numerics, non-QCD inputs, etc. There are three input sources for statical parameters.

General parameters: These are working parameters of `artemide`, such as amount of output, tolerance of integration routines, number of NP parameters, type of used evolution, griding parameters, triggering of particular contributions, etc. There are many of them, and typically they are unchanged. These are set in `constants-file`. **Changes do not require recompilation.**

External physics input: It includes the definition of α_s, collinear PDFs, and other distributions. Twist-2 distributions are taken from LHAPDF [4], with routines defined in QCDinput module. For non-QCD parameters, e.g. α_{QED}, SM parameters, there is a module `EWinput`. These are set in `constants-file`. **Changes do not require recompilation.**

NP model: The NP model consists in NP profiles of TMD distributions, NP model for large-b evolution, selection of scales μ, etc. These parameter and functions enter nearly each low level module. The code for corresponding functions is provided by user, in appropriate files, which are collected in the subdirectory `src/Model`. The name of files are shown on diagram in colored blobs adjusted to the related module. **Changes require recompilation.**

Comments:

- **IMPORTANT:** Each module is initialized individually via `constants-file`. So, each module can be used independently on the full package, given proper section of `constants-file` and submodules (see diagram). However, unless you understand what is going on, it is recommended to use `aTMDe_setup` module for creation of `constant-file`, and `aTMDe_control` module for proper control, initialization and operations of sub-modules.
- `constants-file` can be saved and used in future to reproduce setup. I try to keep compatibility between these files.
- `constants-file` is created and modified within `aTMDe_setup` module. It could be also modified manually.
- NP functions are typically defined with a number of numeric parameters. The value of these parameters could be changed without restart (or recompilation) of the `artemide` by appropriate command. E.g. (`call TMDs_SetNPParameters(lambda)`) on the level of `TMDs` module. See sections of corresponding modules.
- The number of parameters in the model for each module is set in `constants-file`.
- The directory `/Model` together with `constants-file` are convenient to keep as they are. They contain full information about particular evaluation, and thus results can be always reproduced (at least within the same version of `artemide`). I provide results of our extraction as such directories.
- Before ver.2.0, the interface was different and chaotic.

D. Installation

Download and unpack `artemide`. The actual code is in the /src. Check the `makefile`. **You must provide options `FC` and `FOPT`, which are defined in the top of it.** `FC` is the FORTRAN compiler, `FOPT` is additional options for compiler (e.g. linking to LHAPDF library).

There is no actual installation procedure, there is just compilation. If model, inputs, etc, are set correctly (typical problem is linking to LHAPDF, be sure that it is installed correctly), then `make` compiles the library. The result are object files (`*.o`) (which are collected in `/obj`) and module files (`*.mod`) (which are collected in `/mod`).

The test of current compilation could be performed by `make test`. It compiles program `test.f90` from /Prog and run it (default test uses `NPDF31_nnlo_as_0118` set from LHAPDF, check that it is present in your LHAPDF installation). Program `test` runs some elementary code with minimum input. Output is shown later

Next, do your code, `include` appropriate modules of `artemide`, and compile it together with object-files (do not forget to add proper references to module files `-I/mod`). It should work! Linking could be done automatically if you put your code in directory /Prog, and call for `make program TARGET=...`, where ... is the name of the file with code.

```
 artemide.control: initialization done.
uTMDPDF: Grid build  (  250 x  750)  calc.time=  0.54s.
Calculating some values for cross-section one-by-one (DY around Z-boson peak, ATLAS 8TeV kinematics)
ptMin  --      ptMax           xSec
  1.0000000000000000      --   3.0000000000000000        67.129605906181411
  3.0000000000000000      --   5.0000000000000000        61.359031792423735
  5.0000000000000000      --   7.0000000000000000        47.339185816185484

Now the same by list
It must be faster since you use OPENMP
result:   67.129605906181411        61.359031792423735        47.339185816185484
-----------------------------------------------------------------------------------------------
The programm evaluation took   8.5800000000000001      sec. (CPU time)
The programm evaluation took   5.9603551737964153      sec. (wallclock time)

If you do not like so many terminal messages check the parameter outputlevel in constants file.
Not forget to cite artemide [1706.01473]
-----------------------------------------------------------------------------------------------
```

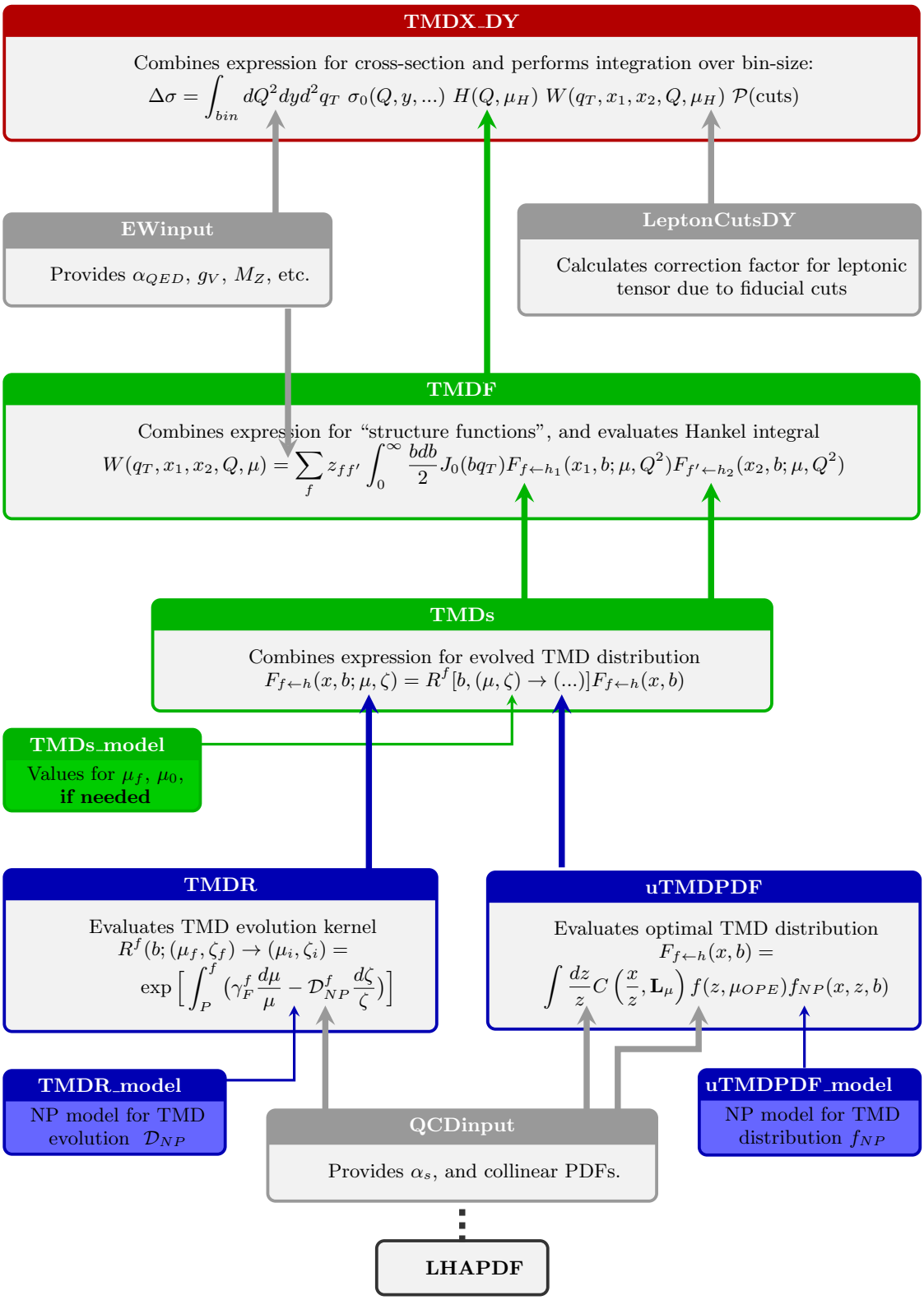

FIG. 2: Evaluation of DY cross-section by `artemide`

II. ATMDE_SETUP MODULE

The module aTMDe_setup creates and modifies the constants-file. **It is a stand-alone module, which does not require the rest modules** (however, it is called by aTMDe_control).

List of commands optional parameters are shown in blue.

Command	Sec.	Short description
artemide_Setup_Default(order)	II A	The main command which initializes variables by default values corresponded to a particular order.
artemide_Setup_fromFile(file,prefix,order)	II A	The main command which initialize variables by pre-saved values in file. prefix is path to the file. order is the order of default version of parameters (used if versions of files are incompatible).
CreateConstantsFile(file,prefix)	-	Write a new constants-file according to current modification.
artemide_include(arg1,arg2,...,arg10)	-	Include the modules into the initialization procedure. arg is (string) with the module name.
Set_outputLevel(level,numMessages)	-	Set the level of artemide-messages to (int)level. 0= only critical, 1=+warnings, 2=+module evaluation information, 3=+ details. Default=2. (integer)numMessages set number of non-critical Warnings of the same type to show (prevent spaming by same messages).
Set_uPDF(hadron,setName,replica)	IV A	Assign the hadron for uPDF with number hadron(int) a PDF set setName(string) in LHAPDF library. It will be initialized in with replica replica(int)(default =0).
Set_uFF(hadron,setName,replica)	IV A	Assign the hadron for uFF with number hadron(int) a FF set setName(string) in LHAPDF library. It will be initialized in with replica replica(int)(default =0).
Set_quarkMasses(mC,mB)	-	Set values for pole quark masses, charm and bottom (real), which determine N_f-thresholds. Default mC=1.4, mB=4.75.
Set_EWparameters(alphaInv,massZ,massW,widthZ,widthW, sin2ThetaW,UD,US,UB,CD,CS,CB)	-	Set parameters of electro-weak theory. alphaInv=inverse $\alpha_{QED}(M_Z)$. UD,US,UB,CD,CS,CB are elements of CKM matrix. Masses and widths are in GeV.
Set_TMDR_order(order)	VI B	Set the perturbative order of anomalous dimensions used for evolution. order=string(8)
Set_TMDR_evolutionType(num)	VI D	Set the type of evolution solution used to (int)num.
Set_TMDR_lengthNParray(num)	VI C	Set the length of λ_{NP} for $\mathcal{D}_{NP}$ to num(int).
Set_uTMDPDF(hadron,setName,replica)	IV A VII	Assign the hadron for uTMDPDF with number hadron(int) a PDF set setName(string) in LHAPDF library. It will be initialized in with replica replica(int)(default =0). Automatically calls for Set_uPDF.
Set_uTMDPDF_order(order)	VII A	Set the perturbative order of convolution. order=string(8)
Set_uTMDPDF_gridEvaluation (prepareGrid,includeGluon)	VII D	Set the trigger to prepare the grid, and to include the gluons in the grid (default=.false.). Both logical.
Set_uTMDPDF_lengthNParray(num)	VII B	Set the length of λ_{NP} for uTMDPDF NP model to num(int).
Set_uTMDFF(hadron,setName,replica)	IV A VIII	Assign the hadron for uTMDFF with number hadron(int) a FF set setName(string) in LHAPDF library. It will be initialized in with replica replica(int)(default =0). Automatically calls for Set_uFF.
Set_uTMDFF_order(order)	VII A	Set the perturbative order of convolution. order=string(8)
Set_uTMDFF_gridEvaluation (prepareGrid,includeGluon)	VII D	Set the trigger to prepare the grid, and to include the gluons in the grid (default=.false.). Both logical.
Set_uTMDFF_lengthNParray(num)	VII B	Set the length of λ_{NP} for uTMDFF NP model to num(int).

A. aTMDe_Setup

TO BE WRITTEN

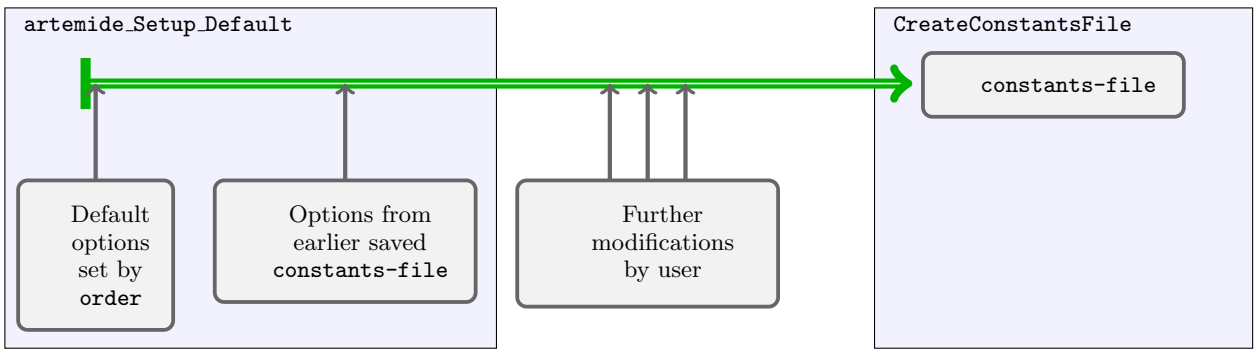

FIG. 3: Scheme of creation and modification of `constants-file` by `aTMDe_setup`.

III. ATMDE_CONTROL MODULE

The module aTMDe_setup is used to coordinate the operation of other modules. It does not bring any new features, just operates other modules in proper order. It is only for convenience.

List of commands optional parameters are shown in blue.

Command	Sec.	Short description
artemide_Initialize(file,prefix,order)	II A	The command which initialize modules according to constants-file created by artemide_Setup_fromFile(file,prefix,order) .
artemide_ShowStatistics()		Shows some information.
artemide_SetNPparameters(lambdaNP)	III A	Receive a (real*8)list of NP parameters, split it according to current setup and passes NP parameters to appropriate modules. Reset modules counters.
artemide_SetNPparameters_TMDR(lambdaNP)	III A	Reset NP parameters of TMDR-module by (real*8) list lambdaNP. Reset modules counters.
artemide_SetNPparameters_uTMDPDF(lambdaNP)	III A	Reset NP parameters of uTMDPDF-module by (real*8) list lambdaNP. Reset modules counters.
artemide_SetNPparameters_uTMDFF(lambdaNP)	III A	Reset NP parameters of uTMDFF-module by (real*8) list lambdaNP. Reset modules counters.
artemide_SetReplica_TMDR(num)	III A	Reset NP parameters of TMDR-module by values corresponding to replica (int)num. Reset modules counters.
artemide_SetReplica_uTMDPDF(num)	III A	Reset NP parameters of uTMDPDF-module by values corresponding to replica (int)num. Reset modules counters.
artemide_SetReplica_uTMDFF(num)	III A	Reset NP parameters of uTMDFF-module by values corresponding to replica (int)num. Reset modules counters.
artemide_SetScaleVariations(c1,c2,c3,c4)	-	Change the value of scale-variation constants $c_1 - c_4$.

A. Passing non-perturbative parameters

The important part of the initialization is the number of NP parameters for each TMD distributions under consideration. Each TMD-evaluating module (say, uTMDPDF, uTMDFF, etc.) requires n_i number of parameters. The numbers are specified in constants-file. The number must be greater then zero $n_i > 0$ for any used module, i.e. f_{NP} is at least 1-parametric (if it is not so, just do not use the parameter in the definition of f_{NP}, but keep $n_i > 0$). These numbers are read during the initialization procedure, and allocate the memory.

The set of particular values of these parameters can be done by several ways.

Option I: Set all values in a single call
`call artemide_SetNPParameters(lambda)`
where

$\{\lambda_i\}$ real*8(1:$\sum_i n_i$) The set of parameters which define the non-perturbative functions f_{NP} within modules. It is split into parts and send to corresponding modules. I.e. lambda(1:n_0) →uTMDR, lambda(n_0+1:n_0+n_1) →uTMDPDF, lambda(n_0+n_1+1:$n_0+n_1+n_2$) →uTMDFF (fixed order).

Option II: Set value for particular function. For it call artemide_SetNPparameters_???(lambdaNP), where ??? is module name, e.g.
`artemide_SetNPparameters_uTMDPDF(lambdaNP)`
will set parameters for unpolarized TMDPDF.

Option III: You can use presaved values of λ_{NP} for a given function. They are provided by model file (if provided). To set NP-input given by integer num, call artemide_SetReplica_???(num), where ??? is module name, e.g.

`artemide_SetReplica_uTMDPDF(num)`
will set parameters for unpolarized TMDPDF.

IV. QCDINPUT MODULE

The module QCDinput gives an interface to external function provided by the user, such as PDF, FF, values of alpha-strong. It is completely user defined. In particular, in the default version it is linked to LHAPDF library [4].

List of available commands optional parameters are shown in blue.

Command	Description
QCDinput_Initialize(file,prefix)	Subroutine to initialize anything what is needed. (string) file is the name of constants-file, which contains initialization information. (string)prefix is appended to file if provided.
QCDinput_SetPDFreplica(num)	Changes the PDF replica number.
As(Q)	Returns the (real*8) value of $\alpha_s(Q)/(4\pi)$. Q is (real*8).
xPDF(x,Q,hadron)	Returns the (real*8(-5:5)) value of $xf(x,Q)$ for given hadron. x, Q are (real*8), hadron is (integer).
xFF(x,Q,hadron)	Returns the (real*8(-5:5)) value of $xd(x,Q)$ for given hadron. x, Q are (real*8), hadron is (integer).
mCHARM	(real*8)Constant for mass of charm quark.
mBOTTOM	(real*8)Constant for mass of bottom quark.

A. Initialization

TOBE WRITTEN

V. EWINPUT MODULE

`EWinput` module contains definitions of various physical parameters of elector-weak interactions, such as masses of Z and W bosons, CKM matrix, code for evolution of α_{QED} etc.

TOBE WRITTEN

VI. TMDR MODULE

The module TMDR performs the evaluation of the TMD evolution kernel in the (μ, ζ)-plane.

List of available commands

Command	Sec.	Short description
TMDR_Initialize(file,prefix)	VI B	Initialization of module. (string) file is the name of constants-file, which c
TMDR_setNPparameter(...)	VI C	Set new NP parameters used in DNP and zetaNP.
TMDR_CurrentNPparameters(var)	VI C	Return the (real*8) array of current values of NP parameters.
TMDR_R(...)	VI D	Evolution kernel from (μ_f, ζ_f) to (μ_i, ζ_i).
TMDR_Rzeta(...)	VI D	Evolution kernel from (μ_f, ζ_f) to (μ_i, ζ_{μ_i}).
LowestQ()	VI E	Returns the values of Q (and the band) for which the evolution inverts.

List of inputs

Input	Setup by	Short description
DNP(mu,b,f)	write-in	NP-model for $\mathcal{D}_{\rm NP}$.
zetaNP(mu,b,f)	write-in	NP-model for ζ_μ. Should follow equipotential.
NPparam	TMDR_setNPparameter(input)	NP parameters used in DNP and zetaNP.
a_s	defined in QCDinput	Strong coupling. See sec.IV

A. Theory

The detailed theory is given in the article [3]. The NLO rapidity anomalous dimension has been evaluated in [7]. The NNLO rapidity anomalous dimension has been evaluated in [8, 9].
TO BE WRITTEN

B. Initialization

Prior the usage module is to be initialized (once per run prior to any other module-related command). By
`call TMDR_Initialize(order)`
This command read the input from the constants-file, and set the other parameters according to

order (string) declaration of order for the evolution kernel. Typically, one set $\Gamma_{\rm cusp}$ one order higher then the rest of anomalous dimensions. There are following set of orders

order	$\Gamma_{\rm cusp}$	γ_V	$\mathcal{D}$ *	$\mathcal{D}_{\rm resum}$	ζ_μ **
LO	a_s^1	a_s^0	a_s^0	a_s^0	a_s^0
LO+	a_s^1	a_s^1	a_s^1	a_s^0	a_s^0
NLO	a_s^2	a_s^1	a_s^1	a_s^1	a_s^1
NLO+	a_s^2	a_s^2	a_s^2	a_s^1	a_s^1
NNLO	a_s^3	a_s^2	a_s^2	a_s^2	a_s^2
NNLO+	a_s^3	a_s^3	a_s^3	a_s^2	a_s^2

* $\mathcal{D}_{\rm resum}$ starts from a_s^0, it already contains Γ_0.

** Definition of ζ_μ is correct only in the natural ordering, i.e. LO,NLO,NNLO. Proper definition in + orders would make the function too heavy. The resumed version has the same counting.

C. NP input and NP parameters

The NP parameters are used in the definition of the function $\mathcal{D}_{\rm NP}$. Their number is read from the `constants`-file, and allocated (and set = 0) during the initialization procedure. Their values are set by command

`call TMDR_setNPparameter(input)`

where `input` is real*8 list NP parameters, with the length equals to the number of NP parameters.

– `DNP` –

The important part of TMD evolution is the rapidity anomalous dimension. It has a NP part which is to be parameterized by user. It should be done in the function `DNP(mu,b,f)` in the end of the file, where `mu` is (real*8) scale, `b` is (real*8) parameter b, `f` is (integer) flavor. **This functions is used for all evolution kernels.** Specifying it, you can use build-in functions `Dpert(mu,b,f)` and `Dresum(mu,b,f)` for the perturbative expressions of $\mathcal{D}$. Also the NP parameters from the set which are given by variables `NPparam(i)`.

– `zetaNP` –

The artemide is founded on the notion of ζ-prescription, therefore, the ζ_μ line plays essential role. For $\mathcal{D} \neq \mathcal{D}_{\rm NP}$ (which is standard situation), the ζ_μ line is different from the perturbative. It should be set within the artemide. It is done by user in the function `zetaNP(mu,b,f)`, with the same arguments as for `DNP`. Note, that **it MUST approach ζ_μ perturbation in small-b regeme. Otherwise, the evolution is calculated incorrectly.** E.g. if $\mathcal{D}_{\rm NP} = \mathcal{D}_{\rm pert}(b^*) + g_K b^2$ the $\zeta_{\rm NP} = \zeta_{perp}(b^*) + ..$, where dots are power suppressed, and thus can be dropped. Defining this function you can use `zetaMUpert` and `zetaMUresum` for perturbative and resumed versions of ζ_μ, as well as, `NPparam(i)`.

In the model code user can provide the `ReplicaParameters(n)`, which returns the array of NP parameters corresponding to integer number `n`. It is convenient to specify initializing values here, or indeed, the values for fit replicas.
i

D. Evaluating TMD evolution kernel

The evolution kernel are presented in two types for the evolution from arbitrary point to arbitrary, and for th evolution from the arbitrary point to the ζ-line. Since all three types of evolution discussed here has different number of arguments, they could not be confused.

Function	solution	Evol.type	Comments
Evolution from (μ_f, ζ_f) to (μ_i, ζ_i)			
`TMDR_R(b,muf,zetaf,mui,zetai,mu0,f)`	improved $\mathcal{D}$	1	
`TMDR_R(b,muf,zetaf,mui,zetai,f)`	improved γ	2	
Evolution from (μ_f, ζ_f) to (μ_i, ζ_{μ_i})			
`TMDR_Rzeta(b,muf,zetaf,mui,mu0,f)`	improved $\mathcal{D}$	1	
`TMDR_Rzeta(b,muf,zetaf,mui,f)`	improved γ	2	
`TMDR_Rzeta(b,muf,zetaf,f)`	fixed μ	3	Evolution along ζ. Absolutely fastest.

where

`b` (real*8) Transverse distance ($b > 0$) in GeV

`zetaf,muf` (real*8) hard-factorization scales (ζ_f, μ_f) in GeV. Typically, $=(Q^2, Q)$

`zetai,mui` (real*8) low-factorization scales (ζ_i, μ_i) in GeV.

`mu0` (real*8) The scale of perturbative definition of rapidity anomalous dimension $\mathcal{D}$ μ_0 in GeV.

`f` (integer) parton flavor. 0 for gluon, $\neq 0$ for quarks.

The parameter evolution type is set in `constants`-file and is used by `TMDs` to call particular version of evolution. Within only the `TMDR`-module it is not needed.

E. Inverted evolution and the lowest available Q

At small values of parameter $Q = Q_0$ the point (Q, Q^2) crosses the ζ-lines. The value of Q_0 dependents on b. The dangerous situation is then hard scale of the process Q is smaller then Q_0 at large $b = b_\infty$. In this case the evolution kernel $R[b_\infty, (Q, Q^2) \to \zeta_\mu] > 1$, which is generally implies that it grows to infinity. However, it happens only at small values of Q. E.g. at NNLO the typical value of Q_0 is ~ 1.5GeV. That should be taken into account during consideration of low-energy experiment and especially their error-band, since the point $(c_2 Q, Q^2)$ could cross the point at larger values of Q.

The function `LowestQ()` returns the values (real*8(1:3)) $\{Q_{-1}, Q_0, Q_{+1}\}$, which are solution of equation $Q^2 = \zeta_{cQ}(b)$, for (fixed bu) large values of b. Q_{-1} corresponds to $c = 0.5$, Q_0 corresponds to $c = 1$ and Q_{+1} corresponds to $c = 2$.

VII. uTMDPDF MODULE

The module uTMDPDF performs the evaluation of the unpolarized TMD PDF at low scale μ_i in ζ-prescription. It is given by the following integral

$$F_f(x,b) = \int_x^1 \frac{dz}{z} C_{f\leftarrow f'}(z, b^*, c_4\mu_{\rm OPE}) f_{f'}(\frac{z}{x}, c_4\mu_{\rm OPE}) f^f_{NP}(x,z,b,\{\lambda\}), \tag{7.1}$$

where $f_f(x,\mu)$ is PDF of flavor f, C is the coefficient function in ζ-prescription, f_{NP} is the non-perturbative function. The variable c_4 is used to test the scale variation sensitivity of the TMD PDF. The NNLO coefficient functions used in the module were evaluated in [5] (please, cite it if use).

List of available commands optional parameters are shown in blue.

Command	Type	Sec.	Short description
uTMDPDF_Initialize(file,prefix)	subrout.	VII A	Initialization of module. (string) file is the name of constants-file, which contains initialization information. (string)prefix is appended to file if provided.
uTMDPDF_SetLambdaNP(lambda, buildGrid, gluonRequared) uTMDPDF_SetLambdaNP(num, buildGrid, gluonRequared)	subrout	VII B	Set new NP parameters used in FNP and bSTAR. The option with (real*8 array)lambda set the parameters directly. The option with (int)num set the parameters according to ReplicaParameters defined in model. Optional (logical) parameter buildGrid, gluonRequared override the options for grid contraction.
uTMDPDF_CurrentNPparameters(var)	subrout.	VII B	Return the (real*8) array of current values of λ_{NP}.
uTMDPDF_lowScale5(x,b,h)	(real*8(-5:5))	VII C	Returns unpolarized TMD PDF at x, b and hadron h. Gluon flavour undefined.
uTMDPDF_lowScale50(x,b,h)	(real*8(-5:5))	VII C	Returns unpolarized TMD PDF at x, b and hadron h.
uTMDPDF_SetScaleVariation(c4))	subrout		Set new value of c_4 (default value $c_4 = 1$).
uTMDPDF_resetGrid(bG,g)	subrout	VII D	Force reset or deconstruct the grid.
uTMDPDF_SetPDFreplica(num)	subrout	–	Call QCDinput to change the PDF replica number, deconstructs grid.

List of functions which must be provided by a model code

Input	Short description
ModelInitialization()	Necessary predefinitions by user. E.g. some precalculations for FNP. Can be black.
FNP(x,z,b,hadron)	NP-model for $f_{NP}(x,z,b,\{\lambda\})$ depends on the hadron. See sec.VII B
mu_OPE(x,bt)	The value of $\mu_{\rm OPE}$.
bSTAR(bT,lambdaNP)	The value of b^*, can be just bSTAR=bT.
ReplicaParameters(rep)	Returns a presaved array of λ_{NP} corresponding to integer rep. Can be black.

A. Initialization

Prior the usage module is to be initialized (once per run). By
call uTMDPDF_Initialize(file)
In constants-file the order of the perturbative input is defined by

$$\texttt{LO,LO+} = a_s^0, \qquad \texttt{NLO,NLO+} = a_s^1, \qquad \texttt{NNLO,NNLO+} = a_s^2.$$

B. Definition of TMD model, f_{NP} and parameters

The model for TMD is given by f_{NP}, b^*, and in smaller amount by μ_{OPE}. The definitions of these functions is provided by user in the file `uTMDPDF_model.f90`, which is located in the `scr/model` directory.

- The function `FNP` is dependent on x, z, b and λ (and the hadron flavor). It is an array for all flavors (-5:5). It uses the parameters $\lambda_{1,2....}$ which are passed to it by main module. The total number of NP parameters `LambdaNPLength`, is declared in the `constants`-file.
- User provides the value of $\mu_{\rm OPE}$ (or use the default one) in the function `mu_OPE(x,b)`. This scale is used inside the convolution $F(x,b) = C(x,b;\mu_{\rm OPE}) \otimes q(x,\mu_{\rm OPE})$. The function could depend on x (the one which enter $f(x)$ in the convolution).
- User provides the value of b^* (or use the default one) in the function `bSTAR(b,lambdaNP)`. This function is used withing the coefficient function $C(x,b^*;\mu)$. Generally, the (twist-2) coefficient function depends only on logarithms $\ln(\mu_{OPE}b^*)$. The function could depend on λ.
- Together with the model user can provide the function `ReplicaParameters(n)`, which returns NP parameters in accordance to input integer number n. These parameters will be set as be current $\lambda_{1,2..}$, upon the call `uTMDPDF_SetLambdaNP(n)`, where `n` is integer number of the replica. It is convenient to specify initializing values here, or indeed, the values for fit replicas.

To set the values for array `lambdaNP` use the subroutine
`call uTMDPDF_SetLambdaNP((/`λ_1, λ_2`,.../))`
Optional: There exist the overloaded version of `uTMDPDF_SetLambdaNP`, with two additional boolean parameters
`call uTMDPDF_SetLambdaNP((/`λ_1, λ_2`,.../),makeGrid,includeGluons)`
If parameter `makeGrid=.true.` then for *this* run of non-perturbative parameters the grid for TMD will be evaluated. Then until new NP parameters set the TMDs are reconstructed from the grid, see sec.VII D.
If parameter `includeGluons=.true.`, the grid is calculated with gluons. If parameter `includeGluons=.false.`, the grid is calculated without gluons (but the mixture of quark with gluon is taken into account. The difference is the same as, e.g. between `uTMDPDF_lowScale5` and `uTMDPDF_lowScale50` functions (see next section).
Default version has `makeGrid=.false.`,`includeGluons=.false.`. Note, that this command compare new values of parameters to the old one. If they coincides, the grid is not renewed.
Optional: There exist the overloaded version of `uTMDPDF_SetLambdaNP(n)`, with `n` being an integer. It attempt to load user defined set of NP parameters associated with number n.

C. Evaluating unpolarized TMD PDFs

The expression for unpolarized TMD PDFs is given by the function
`uTMDPDF_lowScale??(x,b,h)`
where

- `x` (real*8) Bjorken-x ($0 < x < 1$)
- `b` (real*8) Transverse distance ($b > 0$) in GeV
- `h` (integer) The number that indicates the hadron. Since coefficient function is hadron independent, this number influence the PDF that used, and `FNP`.

The questions marks stand for a flavor content of TMD-vector. The functions evaluate the TMD PDFs of different flavours simultaneously.

`uTMDPDF_lowScale5(x,b,h)` returns (real*8) array(-5:5) for $\bar{b}, \bar{c}, \bar{s}, \bar{u}, \bar{d}, ?, d, u, s, c, b$. Gluon contribution is undefined, but taken into account in the mixing contribution.

`uTMDPDF_lowScale50(x,b,h)` returns (real*8) array(-5:5) for $\bar{b}, \bar{c}, \bar{s}, \bar{u}, \bar{d}, g, d, u, s, c, b$. This procedure is slower ($\sim 10-50\%$ depending on parameters, mainly on x) in comparison to the previous command. The slowdown is presented since the gluon coefficient function has $1/x$ behavior, and requires more iteration to reach the demanded precision. If gluons are not needed use previous.

Important note: there is no arguments μ and ζ, because the `artemide` uses the ζ-prescription, where a TMD distribution is scaleless. The scale of matching procedure $\mu_{\rm OPE}$ is set in the function `mu_OPE` (see previous subsection). Note, that the TMD at different then ζ-prescription point can be evaluated within `TMDs` package (which uses `uTMDPDF` in turn).

Additional points:

- In order to avoid possible problems at $b = 0$, at $b < 10^{-6}$ the value of b is set to $b = 10^{-6}$. This region is numerically non-important, since in any cross-section it is suppressed by b^n ($n \geqslant 1$) within the Fourier integral.
- The convolution procedure $C \otimes f$ is the most costly procedure in the package. Its timing seriously increases from NLO to NNLO coefficient function (about 10 times). In the current version we implement the Gauss-Kronrod adaptive algorithm, with estimation of accuracy as $|(G7 - K15)/(f(x)f_{NP}(1))| < \epsilon$, where the default value of ϵ is 10^{-3}. According to our checks default estimation guaranties the 4-digit precision of the evaluation. If integrand does not converge fast enough at $z \to 1$ (e.g. for gluon contribution at NNLO, where $\ln^3 \bar{z}$ is presented), the integral at $(x_0, 1)$ is replaced by exact integral with constant $f(x)f_{NP}$. The value of x_0 is determined by $f'(x_0) < \epsilon$ and $x_0 > 1 - \epsilon$. This additional procedure is needed to ensure convergence of the integral. However, in our experience (which uses only quark TMDs), this extra procedure is not used at all.

D. Grid construction

For fitting procedure one often needs to evaluate TMDs multiple times. For example, for fit performed in [1] the evaluation of singe χ^2 entry requires $\sim 16 \times 10^6$ calls of `uTMDPDF_...` I recall that a TMD is given by the expression

$$F(x, \boldsymbol{b}) \simeq \int dy C(x/y, \ln(\boldsymbol{b}^2)) f(y) f_{NP}(x, y, \boldsymbol{b}, \lambda). \tag{7.2}$$

So, every call of `uTMDPDF_..` at NNLO order, requires ~ 200 calls of pdfs, depending on x, b and λ's, in order to evaluate the integral over y. In such situations, it is much faster to make a grid of TMD distributions for a given set of non-pertrubative parameters (i.e. the grid is in x and b), and then use this grid for the interpolation of TMD values. The calculation of a grid is not a very fast procedure, nonetheless, for large computation (number of TMD calls $> 10^4 - 10^5$) is more efficient.

The griding is turned on by the call of overloaded version of `uTMDPDF_SetLambdaNP(lambda,makeGrid,includeGluons)` with `makeGrid=.true.` (see also sec.VII B). After this call the grid will be built (the corresponding massage will be shown on the screen, if output level is > 1). This grid is used for the interpolation of TMD distribution until the next call of `uTMDPDF_SetLambdaNP`, which resets/cancels grid. To speed up the multiple changes of parameters, the packages checks the function $f_{NP}(x, y)$ onto the y-dependence, and b^* on λ-dependence. If any of them is observed, it implies that the convolution integral depends on λ. If convolution integral does not depend on λ, then the grid is not renewed (unless it is forcibly reseted) but reweighted with new f_{NP}.

The interpolation is cubic. The grid is build for the finite domain of $x \in (x_{\rm min}, 1)$ and $b \in (0, b_M)$. For $x < x_{\rm min}$ the program will be terminated (with an error). In the default set we have

$$x_{\rm min} = 10^{-5}, \qquad b_M = 100.$$

The default grid is 250×750 (the grid is logarithmic in both x and b, small x and $b \to 0$), we have found that it gives in average 5-6 digit precision. All this parameter can be changed in `constants` file in the section 3.D. These parameters have been used to fit a large domain of energies and q_T. However, we recommend, to check the obtained result by exact evaluation without a grid to ensure the precision in particular cases.

For $b > b_M$ we use the following approximate formula

$$\text{for } b > b_M: \quad F(x, b) = f_{NP}(x, x, b) \frac{F(x, b_M)}{f_{NP}(x, x, b_M)}. \tag{7.3}$$

This formula is an approximation which is exact only in the case: b(in convolution) freezes at large values, and f_{NP} is y-independent. For the overwhelming part of models it is the case. Otherwise, there is a numerical error. However, I have checked this error is typically not large (for smooth models) $\sim 0.1 - 10\%$ at $b = 1.5 b_M$ (at $b_M = 100$). Numerically, such error is absolutely negligible, since typical values at $b_M = 100$ of F is 10^{-50}, and thus it gives unobserved correction to the Fourier integral. This approximation has been interoduced in ver.1.5, in previous versions

an interpolation procedure has been used, which produced seriously higher error, that actually affected small-q_T bins in small but visible amount $\sim 0.1\%$.

The subroutine `uTMDPDF_resetGrid(makeGrid,includeGluons)` changes the current behaviour (for the meaning of arguments see `uTMDPDF_SetLambdaNP`). If `makeGrid=.true.` the grid will be recalculated.

E. Theoretical uncertainties

`uTMDPDF_SetScaleVariation(c4)` changes the scale multiplicative factor c_4 (see [1], eqn.(2.46)).

F. Technical note

The convolution integral reads

$$I(x) = \int_x^1 \frac{dz}{z} C(z) f\left(\frac{x}{z}\right) f_{NP}(x,z), \tag{7.4}$$

where the function $C(z)$ has a general form

$$C(z) = C_0 \delta(1-z) + (C_1(z))_+ + C_2(z). \tag{7.5}$$

Here the plus-distribution is undestood in the usual way

$$(C_1(z))_+ = C_1(z) - \delta(1-z) \int_0^1 dy C_1(y) dy. \tag{7.6}$$

In NNLO coefficient function there are only possible two $(..)_+$ terms, $1/(1-z)$ and $\ln(1-z)/(1-z)$.

In order to simplify the integration we rewrite

$$I(x) = \frac{1}{x} \int_x^1 dz C(z) \tilde{f}\left(\frac{x}{z}\right) f_{NP}(x,z), \qquad \tilde{f}(z) = z f(z). \tag{7.7}$$

Then the integral is split as

$$I(x) = \frac{1}{x} \Big\{ I_2(x) + C_0 \tilde{f}(x) f_{NP}(x,1) + \tilde{f}(x) f_{NP}(x,1) \int_0^x dz C_1(z) \Big\}, \tag{7.8}$$

where

$$I_2(x) = \int_x^1 dz \Big[C_1(z) \left(\tilde{f}\left(\frac{x}{z}\right) f_{NP}(x,z) - \tilde{f}(x) f_{NP}(x,1) \right) + C_1(z) \tilde{f}\left(\frac{x}{z}\right) f_{NP}(x,z) \Big] \tag{7.9}$$

Presumably, the term $\sim C_0$ give the dominant contribution w, since it is ~ 1 whereas the other terms $\sim a_s$. Therefore, it serves as the estimation of the integral value, with respect to which the integration convergence is calculated. The convolution integral is evaluated by the G7K15 rule adaptively with given tolerance with respect to w.

The integral I is calculated in the procedure `Common_lowScale50` and `Common_lowScale5`, which is common for all twist-2 terms. The integral I_2 is calculated in the iterative procedures `MellinConvolutionVectorPart50` and `MellinConvolutionVectorPart5`, which is common for all twist-2 terms.

In the case of TMDFF we have the coefficient function with the structure $C(z)/z^2$ (plus-distribution, δ, etc, are multiplied by $1/z^2$), and collinear function $f(z)/z^2$. In this case it is convenient to rewrite

$$I(x) = \int_x^1 \frac{dz}{z} \frac{C(z)}{z^2} \frac{f\left(\frac{x}{z}\right)}{(x/z)^2} f_{NP}(x,z) = \frac{1}{x^3} \int_x^1 dz C(z) \hat{f}\left(\frac{x}{z}\right) f_{NP}(x,z), \qquad \hat{f}(z) = z f(z). \tag{7.10}$$

Since the common-code calculates the integral PDF-like convolution, I divide by factor $1/x^2$ all output of the common-code.

VIII. `UTMDFF` MODULE

The TMDFF functions structurally repeats the TMDPDF functions. Therefore, the module is practically the same as `uTMDFF`. Command are the same as for `uTMDPDF` with replacement `uTMDPDF_...` to `uTMDFF_...`. The NNLO coefficient functions used in the module were evaluated in [5, 6] (please, cite it if use).

IX. TMDS MODULE

The module TMDs joins the lower modules and performs the evaluation of various TMD distributions in the ζ-prescription. Generally a TMD distribution is given by the expression

$$F_f(x,b;\mu,\zeta) = R_f[b,(\mu,\zeta)\to(\mu_i,\zeta_{\mu_i})]\tilde{F}_f(x,b), \tag{9.1}$$

where R is the TMD evolution kernel, $\tilde{F}$ is a TMD distribution at low scale. The scale μ_i is dependent on the evolution type, and could be out of use. Note, that TMDs initializes the lower modules automatically. Therefore, no special initializations should be done.

List of available commands

Command	Type	Sec.	Short description
TMDs_Initialize(file,prefix)	subrout.	-	Initialization of module. (string) file is the name of constants-file, which contains initialization information. (string)prefix is appended to file if provided.
TMDs_SetScaleVariations(c1,c3)	subrout.	IX D	Set new values for the scale-variation constants.
uTMDPDF_5(x,b,mu,zeta,h)	(real*8(-5:5))	IX B	Unpolarized TMD PDF (gluon term undefined)
uTMDPDF_50(x,b,mu,zeta,h)	(real*8(-5:5))	IX B	Unpolarized TMD PDF (gluon term defined)
uTMDFF_5(x,b,mu,zeta,h)	(real*8(-5:5))	IX B	Unpolarized TMD FF (gluon term undefined)
uTMDFF_50(x,b,mu,zeta,h)	(real*8(-5:5))	IX B	Unpolarized TMD FF (gluon term defined)
uTMDPDF_5(x,b,h)	(real*8(-5:5))	IX B	Unpolarized TMD PDF at optimal line (gluon term undefined)
uTMDPDF_50(x,b,,h)	(real*8(-5:5))	IX B	Unpolarized TMD PDF at optimal line (gluon term defined)
uTMDFF_5(x,b,h)	(real*8(-5:5))	IX B	Unpolarized TMD FF at optimal line(gluon term undefined)
uTMDFF_50(x,b,h)	(real*8(-5:5))	IX B	Unpolarized TMD FF at optimal line (gluon term defined)
uPDF_uPDF(x1,x2,b,mu,zeta,h1,h2)	(real*8(-5:5))	IX C	Product of Unpolarized TMD PDF $f_{q\leftarrow h_1}(x_1)f_{\bar{q}\leftarrow h_1}$ at the same scale (gluon term undefined)
uPDF_anti_uPDF(x1,x2,b,mu,zeta,h1,h2)	(real*8(-5:5))	IX C	Product of Unpolarized TMD PDF $f_{q\leftarrow h_1}(x_1)f_{q\leftarrow h_1}$ at the same scale (gluon term undefined)

List of functions which must be provided by a model code

Input	Short description
mu_LOW(b)	The value of μ_i used in the evolutions of type 1 and 2 (improved $\mathcal{D}$ and γ). See [3].
mu0(b)	The value of μ_0 used in the evolution of type 1 (improved $\mathcal{D}$). See [3].

A. Definition of low-scales

The low scales μ_i and μ_0 are defined in the functions mu_LOW(bt) and mu0(bt) which can be found in the end of TMDs.f90 code. Modify it if needed.

B. Evaluating TMDs

The expression for unpolarized TMD PDF is obtained by the functions

(real*8(-5:5))`uTMDPDF_5(x,b,mu,zeta,h)`
where

`x` (real*8) Bjorken-x ($0 < x < 1$)

`b` (real*8) Transverse distance ($b > 0$) in GeV

`mu` (real*8) The scale μ_f in GeV. Typically, $\mu_f = Q$.

`zeta` (real*8) The scale ζ_f in GeV^2. Typically, $\zeta_f = Q^2$.

`h` (integer) The hadron type.

This function return the vector real*8(-5:5) for $\bar{b}, \bar{c}, \bar{s}, \bar{u}, \bar{d}, ?, d, u, s, c, b$.

- Gluon contribution in `uTMDPDF_5` is undefined, but taken into account in the mixing contribution. The point is that evaluation of gluons slow down the procedure approximately by 40%, and often is not needed. To calculate the full flavor vector with the gluon TMD, call `uTMDPDF_50(x,b,mu,zeta,h)`, where all arguments defined in the same way.
- The other TMDs, such as unpolarized TMDFF, transversity, etc. are obtained by similar function see the table in the beginning of the section.
- Each function has version without parameters `mu` and `zeta`. It corresponds to the evaluation of a TMS at optimal line [3]. Practically, it just transfers the outcome of corresponding TMD module, e.g.module `uTMDPDF`, see sec.VII.

C. Products of TMDs

The the evaluation of majority of cross-sections one needs the product of two TMDs at the same scale. There are set of functions which return these products. They are slightly faster then just evaluation and multiplication, due to the flavor blindness of the TMD evolution. The function have common interface
(real*8(-5:5)) `uPDF_uPDF(x1,x2,b,mu,zeta,h1,h2)`
where

`x1,x2` (real*8) Bjorken-x's ($0 < x < 1$)

`b` (real*8) Transverse distance ($b > 0$) in GeV

`mu` (real*8) The scale μ_f in GeV. Typically, $\mu_f = Q$.

`zeta` (real*8) The scale ζ_f in GeV^2. Typically, $\zeta_f = Q^2$.

`h1,h2` (integer) The hadron's types.

The function return a product ofthe form $F_{f_1 \leftarrow h_1}(x_1, b; \mu, \zeta) F_{f_2 \leftarrow h_2}(x_2, b; \mu, \zeta)$, where $f_{1,2}$ and the type of TMDs depend on the function.

D. Theoretical uncertainties

`TMDs_SetScaleVariations(c1,c3,c4)` changes the scale multiplicative factors c_i (see [3], sec.6). The default set of arguments is (1,1,1), i.e. the scales as they given in corresponding functions. This subroutine changes $c1$ and $c3$ constants and call corresponding subroutines for variation of $c4$ in TMD defining packages. Note, that in some types of evolution particular variations absent.

X. TMDF MODULE

This module evaluates the structure functions, that are universally defined as

$$F(Q^2, q_T, x_1, x_2, \mu, \zeta_1, \zeta_2) = \int_0^\infty \frac{bdb}{2} b^n J_n(bq_T) \sum_{ff'} z_{ff'}(Q^2) F_1^f(x_1, b; \mu, \zeta_1) F_2^{f'}(x_2, b; \mu, \zeta_2), \tag{10.1}$$

where

- Q^2 is hard scale.
- q_T is transverse momentum in the factorization frame. It coincides with measured q_T in center-mass frame for DY, but $q_T \sim p_T/z$ for SIDIS.
- x_1 and x_2 are parts of collinear parton momenta. I.e. for DY $x_{1,2} \simeq Qe^{\pm y}/\sqrt{s}$, while for SIDIS $x_2 \sim z$. It can also obtain power correction, ala Nachmann variables.
- μ is the hard factorization scale $\mu \sim Q$
- $\zeta_{1,2}$ are rapidity factorization scales. In the standard factorization scheme $\zeta_1\zeta_2 = Q^4$.
- f, f' are parton flavors.
- $z_{ff'}$ is the process related function. E.g. for photon DY on $p + \bar{p}$, $z_{ff'} = \delta_{ff'}|e_f|^2$.
- n The order of Bessel transformation is defined by structure function. E.g. for unpolarized DY $n = 1$. For SSA's $n = 1$. In general for angular modulation $\sim \cos(n\theta)$.
- $F_{1,2}^f$ TMD distribution (PDF or FF) of necessary polarization and flavor.

The module has simple structure since it evaluates only this integral and does not require any exra input.

List of available commands

Command	Type	Sec.	Short description
`TMDF_Initialize(file,prefix)`	subrout.	X A	Initialization of module. (string) `file` is the name of `constants-file`, which contains initialization information. (string)`prefix` is appended to `file` if provided.
`TMDF_ShowStatistic())`	subrout.	–	Print current statistic on the number of calls.
`TMDF_ResetCounters()`	subrout.	–	Reset intrinsic counters. E.g.release convergenceIS-lost state.
`TMDF_F(Q2,qT,x1,x2,mu,zeta1,zeta2,N)`	(real*8)	X B	Evaluates the structure function

A. Initialization

Prior the usage module is to be initialized (once per run) by
`call TMDF_Initialize(file)`
It reads `constants-file` and initialize it-self accordingly.

B. Evaluating Structure functions

The value of the structure function is obtained by
(real*8)`TMDF_F(Q2,qT,x1,x2,mu,zeta1,zeta2,N)`
where

`Q2` (real*8) hard scale in GeV^2.

`qT` (real*8) modulus of transverse momentum in the factorization frame in GeV, $q_T > 0$

`x1` (real*8) x passed to the first TMD distribution ($0 < x1 < 1$)

`x2` (real*8) x passed to the first TMD distribution ($0 < x2 < 1$)

`mu` (real*8) The hard scale μ in GeV. Typically, $\mu = Q$.

`zeta1` (real*8) The scale ζ_f in GeV^2 for the first TMD distribution. Typically, $\zeta_f = Q^2$.

`zeta2` (real*8) The scale ζ_f in GeV^2 for the second TMD distribution. Typically, $\zeta_f = Q^2$.

`N` (integer) The number of process.

The function returns the value of

$$F^N(Q^2, q_T, x_1, x_2, \mu, \zeta_1, \zeta_2) = \int_0^\infty \frac{bdb}{2} b^n J_n(bq_T) \sum_{ff'} z^N_{ff'}(Q^2) F_1^f(x_1, b; \mu, \zeta_1) F_2^{f'}(x_2, b; \mu, \zeta_2). \tag{10.2}$$

The parameter n depends on the argument `N` and uniformly defined as

$n = 0$	for `N` < 10000
$n = 1$	for `N` $\in [10000, 20000]$
$n = 2$	for `N` $\in [20000, 30000]$
$n = 3$	for `N` > 30000

The particular values of $z_{ff'}$ and $F_{1,2}$ are given in the following table. User function can be implemented by code modification.

Notes on the integral evaluation:

- The integral is uniformly set to 0 for $q_T < 10^{-7}$.
- The integrand is uniformly set to 0 for $b > 10^3$.
- If for any element of evaluation (including TMD evolution factors and convolution integrals, and the integral of the structure function it-self) obtained divergent value. The trigger is set to ON. In this case, the integral returns uniformly large value 10^{100} for all integrals without evaluation. The trigger is reset by new values of NP parameters. It is done in order to cut the improper values of NP parameters in the fastest possible way, which speed up fitting procedures.
- The Fourier is made by Ogata quadrature, which is double exponential quadrature. I.e.

$$\int_0^\infty \frac{bdb}{2} b^n I(b) J_n(q_T b) \simeq \frac{1}{q_T^{n+2}} \sum_{k=1}^{\infty} \tilde{\omega}_{nk} b_{nk}^{n+1} I\left(\frac{b_{nk}}{q_T}\right), \tag{10.3}$$

  where

$$b_{nk} = \frac{\psi(\tilde{h}\tilde{\xi}_{nk})}{\tilde{h}} = \tilde{\xi}_{nk} \tanh(\frac{\pi}{2} \sinh(\tilde{h}\tilde{\xi}_{nk}))$$

$$\tilde{\omega}_{nk} = \frac{J_n(\tilde{b}_{nk})}{\tilde{\xi}_{nk} J_{n+1}^2(\tilde{\xi}_{nk})} \psi'(\tilde{h}\tilde{\xi}_{nk})$$

  Here, $\tilde{\xi}_{nk}$ is k'th zero of $J_n(x)$ function. Note, that $\tilde{h} = h/\pi$ in the original Ogata's notation.
- For $q_T < 1$ the integrand is narrower, and precision of the integration is not covered by given h. For this region we use tables with $h = 0.05h$. Typically, it is enough to have reasonable precision at $q_T \sim 0.01$.
- The sum over k is restricted by $N_{\max}$ where $N_{\max}$ is hard coded number, $N_{\max} = 200$.
- The sum over k is evaluated until the sum of absolute values of last four terms is less then *tolerance*. If $M > N_{\max}$ the integral declared divergent, and the trigger is set to ON.

WARNING!
The error for Ogata quadrature is defined by parameters h and M(number of terms in the sum over k). In the parameter M quadrature is double-exponential, i.e. converges fast as M approaches $N_{\max}$. And the convergence of the sum can be simply checked. In the parameter h the quadrature is quadratic (the convergence is rather poor). The convergence to the true value of integral is very expensive especially at large q_T (it requires the complete reevaluation of integral at all nodes). Unfortunately, $N_{\max} \sim h^{-1}$, and has to find the balance value for h. In principle, TMD functions decays rather fast, and suggested default value $h = 0.005$ is trustful. **Nonetheless, we suggest to test other values (*/2) of h to validate the obtained values in your model.**
The adaptive check of convergence will implemented in the future versions.

C. Enumeration of structure functions

List of enumeration of structures functions
N<10000

N	$z_{ff'}$	F_1	F_2	Short description	Gluon req.
0	–	–	–	Test case	no
1	$\delta_{\bar{f}f'}\lvert e_f\rvert^2$	f_1	f_1	(unpol.)$p+p\to\gamma$	no
2	$\delta_{ff'}\lvert e_f\rvert^2$	f_1	f_1	(unpol.)$p+\bar{p}\to\gamma$	no
3	$\delta_{\bar{f}f'}\frac{(1-2\lvert ef\rvert s_w^2)^2-4e_f^2s_w^4}{8s_w^2c_w^2}$	f_1	f_1	(unpol.)$p+p\to Z$	no
4	$\delta_{ff'}\frac{(1-2\lvert ef\rvert s_w^2)^2-4e_f^2s_w^4}{8s_w^2c_w^2}$	f_1	f_1	(unpol.)$p+\bar{p}\to Z$	no
5	$\delta_{\bar{f}f'}\frac{z_{ll'}z_{ff'}}{\alpha_{\rm em}^2}$ given in (2.8) of [1]	f_1	f_1	(unpol.)$p+p\to Z+\gamma$	no
6	$\delta_{ff'}\frac{z_{ll'}z_{ff'}}{\alpha_{\rm em}^2}$ given in (2.8) of [1]	f_1	f_1	(unpol.)$p+\bar{p}\to Z+\gamma$	no
7	$\frac{1}{4s_w^2}\frac{\lvert V_{ff'}\rvert^2}{4s_w^2}\frac{Q^4}{(Q^2-M_W^2)^2+\Gamma_W^2M_W^2}$	f_1	f_1	(unpol.)$p+p\to W^+$	no
8	$\frac{1}{4s_w^2}\frac{\lvert V_{ff'}\rvert^2}{4s_w^2}\frac{Q^4}{(Q^2-M_W^2)^2+\Gamma_W^2M_W^2}$	f_1	f_1	(unpol.)$p+p\to W^-$	no
9	$\frac{1}{4s_w^2}\frac{\lvert V_{ff'}\rvert^2}{4s_w^2}\frac{Q^4}{(Q^2-M_W^2)^2+\Gamma_W^2M_W^2}$	f_1	f_1	(unpol.)$p+p\to W^++W^-$	no
10	$\frac{1}{4s_w^2}\frac{\lvert V_{ff'}\rvert^2}{4s_w^2}\frac{Q^4}{(Q^2-M_W^2)^2+\Gamma_W^2M_W^2}$	f_1	f_1	(unpol.)$p+\bar{p}\to W^+$	no
11	$\frac{1}{4s_w^2}\frac{\lvert V_{ff'}\rvert^2}{4s_w^2}\frac{Q^4}{(Q^2-M_W^2)^2+\Gamma_W^2M_W^2}$	f_1	f_1	(unpol.)$p+\bar{p}\to W^-$	no
12	$\frac{1}{4s_w^2}\frac{\lvert V_{ff'}\rvert^2}{4s_w^2}\frac{Q^4}{(Q^2-M_W^2)^2+\Gamma_W^2M_W^2}$	f_1	f_1	(unpol.)$p+\bar{p}\to W^++W^-$	no
13	$\frac{\lvert V_{ff'}\rvert^2}{4s_w^2}$	f_1	f_1	(unpol.)$p+p\to W^+$ (for narrow-width approx.)	no
14	$\frac{\lvert V_{ff'}\rvert^2}{4s_w^2}$	f_1	f_1	(unpol.)$p+p\to W^-$ (for narrow-width approx.)	no

15	$\frac{\lvert V_{ff'}\rvert^2}{4s_w^2}$	f_1	f_1	(unpol.)$p + p \to W^+ + W^-$ (for narrow-width approx.)	no
16	$\frac{\lvert V_{ff'}\rvert^2}{4s_w^2}$	f_1	f_1	(unpol.)$p + \bar{p} \to W^+$ (for narrow-width approx.)	no
17	$\frac{\lvert V_{ff'}\rvert^2}{4s_w^2}$	f_1	f_1	(unpol.)$p + \bar{p} \to W^-$ (for narrow-width approx.)	no
18	$\frac{\lvert V_{ff'}\rvert^2}{4s_w^2}$	f_1	f_1	(unpol.)$p + \bar{p} \to W^+ + W^-$ (for narrow-width approx.)	no
1001	$R^{Cu}_{ff'}e_f e_{f'}$ see (3.1) of [1]	f_1	f_1^{Cu}	(unpol.)$p + Cu \to \gamma$ (roughly simulates isostructure of Cu, used to describe E288 experiment in [1])	no
1002	$R^{^2H}_{ff'}e_f e_{f'}$ see (3.1) of [1] with $Z = 1$ and $A = 2$	f_1	$f_1^{^2H}$	(unpol.)$p +^2 H \to \gamma$ (roughly simulates isostructure of ^2H, used to describe E772 experiment)	no
1003	$R^{W}_{ff'}e_f e_{f'}$ see (3.1) of [1] with $Z = 74$ and $A = 183$	f_1	f_1^W	(unpol.)$\bar{p} + W \to \gamma$ (roughly simulates isostructure of W(tungsten), used to describe E537 experiment)	no
2001	$\delta_{ff'}\lvert e_f\rvert^2$	f_1^H	$d_1^{h_1}$	(unpol)$H + \gamma \to h_1$	no
200N	$\delta_{ff'}\lvert e_f\rvert^2$	f_1^H	$d_1^{h_N}$	(unpol)$H + \gamma \to h_N$, for $N = \{1, ..., 9\}$ (including case 2001)	no

10000⩽N<20000

N	$z_{ff'}$	F_1	F_2	Short description	Gluon req.
10000	–	–	–	Test case	no

20000⩽N<30000

N	$z_{ff'}$	F_1	F_2	Short description	Gluon req.
20000	–	–	–	Test case	no

30000⩽N

N	$z_{ff'}$	F_1	F_2	Short description	Gluon req.
30000	–	–	–	Test case	no

Notes on parameters and notation:
s_w^2, M_Z, Γ_Z, etc. are defined in `constants`
f_1-unpolarized TMDPDF
d_1-unpolarized TMDFF

XI. TMDX_DY MODULE

This module evaluates cross-sections with the Drell-Yan-like kinematics. I.e. it expects the following kinematic input, (s, Q, y) which defines the variables x's, etc.

The general structure of the cross-section is

$$\frac{d\sigma}{dX} = d\sigma(q_T) = prefactor1 \int [bin]\ prefactor2\ \times F, \tag{11.1}$$

where

$$dX = dQ^2 dy dq_T^2.$$

Prefactor1 is related to the definition of the phase-space, while *prefactor2* is about process and cross-section. Generally, the *prefactor2* $\times F$ is

$$prefactor2 \times F = (\text{cuts for lepton pair}) \times H(Q, \mu_H) F(Q, q_T, x_1, x_2, \mu, \zeta_1, \zeta_)), \tag{11.2}$$

where F is defined in (10.1). There are following feature of current implementation

- In the current version the scaling variables are set as

  $$\mu^2 = \zeta_1 = \zeta_2 = Q^2. \tag{11.3}$$

  Currently, it is hard coded and could not be easily modified. However, there is a possibility to vary the value of μ as $\mu = c_2 Q$, where c_2 is variation parameter (see sec.XI F).

- For the definition of *(cuts for lepton pair)*-function see [1]. It is evaluated within module `LeptonCutsDY.f90`. The presence of cuts, and their parameters are set by the `SetCuts` subroutine.

- The expression for the hard factor H is taken from [10]. It is the function of $\ln(Q/\mu_H)$ and $a_s(\mu_H)$). Since in the current realization $\mu_H = Q$, the logarithm is replaced by $\ln(c_2)$, where c_2 is the variation constant.

This section is to be updated by definition of kinematics

List of available commands

Command	Type	Sec.	Short description
`TMDX_DY_Initialize(order)`	subrout.	XI A	Initialization of module.
`TMDX_DY_ShowStatistic()`	subrout.	–	Print current statistic on the number of calls.
`TMDX_DY_ResetCounters()`	subrout.	–	Reset intrinsic counters of the module.
`TMDX_DY_SetProcess(p)`	subrout.	XI B	Set the process
`TMDX_DY_SetCuts(inc,pT,eta1,eta2)`	subrout.	XI B	Set the current evaluation of cut for lepton pair.
`TMDX_DY_XSetup(s,Q,y)`	subrout.	XI B	Set the kinematic variables
`TMDX_DY_SetScaleVariation(c2)`	subrout.	–	Set new value for the scale-variation constant c_2.
`CalcXsec_DY...`	subrout.	XI C	Evaluates cross-section. Many overloaded versions see sec.XI C.
`xSec_DY(X,proc,s,qT,Q,y,iC,CutP,Num)`	subrout.	XI C	Evaluates cross-section completely integrated over the bin. Can be called without preliminary `...Set...`'s.
`xSec_DY_List(X,proc,s,qT,Q,y,iC,CutP,Num)`	subrout.	XI C	Evaluates cross-section completely integrated over the bin over the list. Can be called without preliminary `...Set...`'s.

A. Initialization

Prior the usage module is to be initialized (once per run) by
`call TMDX_DY_Initialize(file)`
The order of used coefficient function is set in `constant-file` by `'LO'`, `'LO+'`, `'NLO'`, `'NLO+'`,`'NNLO'` or `'NNLO+'`, that corresponds to a_s^0, a_s^0, a_s^1, a_s^1, a_s^2, or a_s^2.

B. Setting up the parameters of cross-section

Prior to evaluation of cross-section one must declare which process is considered and to set up the kinematics. The declaration of the process is made by
`call TMDX_DY_SetProcess(p1,p2,p3)`
`call TMDX_DY_SetProcess(p0)`
where `p0=(/p1,p2,p3/)` and

`p1` (integer) Defines the $prefactor1$ that contains the phase space elements.

`p2` (integer) Defines the $prefactor2$ that contains the universal part of factorization formula.

`p3` (integer) Defines the structure function F. See sec.X C.

Alternatively, process can be declared by a shorthand version (not updated any more, too many options)
`call TMDX_DY_SetProcess(p)`

where p(integer) corresponds to particular combinations of p1,p2,p3. See table XI H.

The kinematic of the process is declared by

`call TMDX_DY_XSetup(s,Q,y)`

where s is the Mandelshtam variable s, Q is hard virtuality Q, y is the rapidity parameter y. Note, that these values will be used for the evaluation of the cross-section. In the case, the integration over the bin is made these values are overridden. Also in the case of the parallel computation these variables are overridden. So, often there is little sense in this command, nonetheless it set initial values.

All non-perturbative parameters are defined in the lower-level modules, and could be set via `artemide_control` or directly in the module.

Finally, one must specify the fiducial cuts on the lepton pair. It is made by calling

`call SetCuts(inc,pT,eta1,eta2)`

where parameter inc is (logical). If `inc=.true.` the evaluation of cuts will be done, otherwise it will be ignored. The cuts are defined as

$$|l_T|, |l'_T| < \texttt{pT}, \qquad \texttt{eta1} < \eta, \eta', \texttt{eta2}, \tag{11.4}$$

where l and l' are the momenta of produced leptons, with l_T's being their transverse components and η's being their rapidities. For accurate definition of the cut-function see sec.2.6 of [1] (particularly equations (2.40)-(2.42)). For asymmetric cuts use `call SetCuts(inc,pT1,pT2,eta1,eta2)`.

C. Cross-section evaluation

After the parameters of cross-section are set up, the values of the cross-section at different q_T can be obtained by

`call CalcXsec_DY(X,qt)`

where X is real*8 variable where cross-section will be stored, qt is real*8 is the list of values of q_T's at which the X is to be calculated. There exists an overloaded version with X (real*8)(1:N) and qT(real*8)(1:N), which evaluates the array of crossections over array of q_T.

Typically, one needs to integrate over bin. There is a whole set of subroutines which evaluate various integrals over bin they are

Subroutine	integral	Comment
`CalcXsec_DY_Yint(X,qt)`	$\int_{-y_0}^{y_0} dyd\sigma(q_T)$	y_0 is maximum allowed y by kinematics, $y_0 = \ln(s/Q^2)/2$.
`CalcXsec_DY_Yint(X,qt,yMin,yMax)`	$\int_{y_{\min}}^{y_{\max}} dyd\sigma(q_T)$	$\lvert y_{\max/\min}\rvert < y_0$
`CalcXsec_DY_Qint (X,qt,Qmin,Qmax)`	$\int_{Q_{\min}}^{Q_{\max}} 2QdQd\sigma(q_T)$	
`CalcXsec_DY_Qint_Yint (X,qt,Qmin,Qmax)`	$\int_{Q_{\min}}^{Q_{\max}} 2QdQ \int_{-y_0}^{y_0} dyd\sigma(q_T)$	
`CalcXsec_DY_Qint_Yint (X,qt,Qmin,Qmax,yMin,yMax)`	$\int_{Q_{\min}}^{Q_{\max}} 2QdQ \int_{y_{\min}}^{y_{\max}} dyd\sigma(q_T)$	
`CalcXsec_DY_PTint_Qint_Yint (X,qtmin,qtmax,Qmin,Qmax)`	$\int_{q_T\,\min}^{q_T\,\max} 2q_T dq_T \int_{Q_{\min}}^{Q_{\max}} 2QdQ \int_{-y_0}^{y_0} dyd\sigma(q_T)$	Integration over q_T is Simpsons by default number of sections.
`CalcXsec_DY_PTint_Qint_Yint (X,qtmin,qtmax,Qmin,Qmax,yMin,yMax)`	$\int_{q_T\,\min}^{q_T\,\max} 2q_T dq_T \int_{Q_{\min}}^{Q_{\max}} 2QdQ \int_{y_{\min}}^{y_{\max}} dyd\sigma(q_T)$	Integration over q_T is Simpsons by default number of sections.
`CalcXsec_DY_PTint_Qint_Yint (X,qtmin,qtmax,Qmin,Qmax,N)`	$\int_{q_T\,\min}^{q_T\,\max} 2q_T dq_T \int_{Q_{\min}}^{Q_{\max}} 2QdQ \int_{-y_0}^{y_0} dyd\sigma(q_T)$	Integration over q_T is Simpsons by N-section.
`CalcXsec_DY_PTint_Qint_Yint (X,qtmin,qtmax,Qmin,Qmax,yMin,yMax,N)`	$\int_{q_T\,\min}^{q_T\,\max} 2q_T dq_T \int_{Q_{\min}}^{Q_{\max}} 2QdQ \int_{y_{\min}}^{y_{\max}} dyd\sigma(q_T)$	Integration over q_T is Simpsons by N-section.
More to be added		

Note 1: Each command has overloaded version with arrays for X and qt.
Note 2: Cross-section integrated over q_T bins have overloaded versions with `X`, `qtmin` and `qtmax` being arrays. Then the integral is done for `X`(i) from `qtmin(i)` to `qtmax(i)`.
Note 2+: There exists an overloaded version for `CalcXsec_DY_PTint_Qint_Yint` with `X`, `qtmin` and `qtmax`, `yMin`, `yMax` being arrays. Then the integral is done for `X`(i) from `qtmin(i)` to `qtmax(i)`, `yMin(i)` to `yMax(i)`.
Note 3: There exist special overloaded case for integrated over q_T-bins, with successive bins. I.e. for bins that adjust to each other. In this case only one argument `qtlist` is required (instead of `qtmin`,`qtmax`). E.g. `CalcXsec_DY_PTint_Qint_Yint (X,qtList,Qmin,Qmax)`. The length of `qtlist` must be larger then the length of `X` by one. The integration for `X(i)` is done from `qtlist(i)` till `qtlist(i+1)`. This function saves boundary values and therefore somewhat faster than the usual evaluation. (Improvement takes a place is only for unparallel calculation).
Note 4: Integration over p_T is numerically problematic at $p_T \to 0$. Thus, the integration over $p_T < 0.1$MeV is cut out. Anyway, contribution of this region is negligible, due to prefactor p_T.

Take care that every next function is heavier to evaluate then the previous one. The integrations over Q and y are adaptive Simpsons. We have found that it is the fastest (adaptive) method for typical cross-sections with tolerance $10^{-3} - 10^{-4}$. Naturally, it is not suitable for higher precision, which however is not typically required. The integration over p_T is not adaptive, since typically p_T-bins are rather smooth and integral is already accurate if approximated by 4-8 points (default minimal value is set in `constants`, which is automatically increased for larger bins). For

unexceptionally large q_T-bins, or very rapid behavior we suggest to use overloaded versions with manual set of N (number of integral sections).

There is a subroutine that evaluate cross-section without preliminary call of SetCuts,TMDX_DY_SetProcess,TMDX_DY_XSetup**.** It is called `xSec_DY` and it have the following interface:

```
xSec_DY(X,process,s,qT,Q,y,includeCuts,CutParameters,Num)
```

where

- `X` is (real*8) value of cross-section.
- `process` is integer `p`, or (integer)array `(p1,p2,p3)`.
- `s` is Mandelshtam variable s
- `qT` is (real*8)array `(qtmin,qtmax)`
- `Q` is (real*8)array `(Qmin,Qmax)`
- `y` is (real*8)array `(ymin,ymax)`
- `includeCuts` is logical
- `CutParameters` is (real*8) array `(k1,k2,eta1,eta2)` **OPTIONAL**
- `Num` is even integer that determine number of section in q_T integral **OPTIONAL**

Note, that optional variables could be omit during the call.

IMPORTANT: Practically, the call of this function coincides with `X` evaluated by the following set of commands

```
call TMDX_DY_SetProcess(process)
call TMDX_DY_XSetup(s,any,any)
call SetCuts(includeCuts,k1,k2,eta1,eta2)
call CalcXsec_DY_PTint_Qint_Yint (X,qtmin,qtmax,Qmin,Qmax,yMin,yMax,Num)
```

However, there is an important difference: the values of `s, process, cutParameters` which are set by routines `..Set..`, are global. For that reason such approach could not be used in a parallel computation. Contrary, in the function `xSec_DY` these variables are set locally and thus this function can be used in parallel computations.

?**BUG?:** Take care that some Fortran compilers, do not understand the usage of arrays directly within function with optional arguments. E.g. `xSec_DY(p,s,(/q1,q2/),Q,y,iC,CutParameters=cc)`. Although it compiles without problems but lead to a freeze during the calculation. In this case, it helps to define: `qT=(/q1,q2/)` and call `xSec_DY(p,s,qT,Q,y,iC,CutParameters=cc)`. The same problem can appear if `xSec_DY` is used as argument of another function. I guess there is some problem with memory references.

There is also analogous subroutine that evaluate cross-section by list. It is called `xSec_DY_List` and it have the following interface:

```
xSec_DY_List(X,process,s,qT,Q,y,includeCuts,CutParameters,Num)
```

All variables are analogues to those of `xSec_DY`, but should come in lists, i.e. `X` is (1:n), `process` is (1:n,1:3), `s` is (1:n), `qT`,`Q`,`y` are (1:n,1:2), `includeCuts` is (1:n), `CutParameters` is (1:n,1:4), and `Num` is (1:n). **Only the `Num` argument is OPTIONAL arguments. The argument `CutParameters` must be presented**. This command compiled by OPENMP, so runs in parallel on multi-core computers.

D. Parallel computation

Currently, the parallel evaluation is used within the commands `CalcXsec_DY_...` with array variable `qt` (see **Note 1** in sec.TMDX:xsec). Basically, in this case, individual values for the list of cross-sections are evaluated in parallel. Unfortunately the parallel scaling-rate is not very high, on 8 processors it is about 400%-500% only.

The parallelization is made with OPENMP library. To make the parallel computation possible, add `-fopenmp` option in the compilation instructions. The maximum number of allowed threads is set `constants-file`.

WARNING: the parallel operation is possible only together with grid option, otherwise it will cause a running condition in TMD modules (which typically results into the program crush). There is no check for grid option trigger, check it manually.

E. LeptonCutsDY

The calculation of cut prefactor is made in `LeptonCutsDY.f90`. It has two public procedures: `SetCutParameters`, and `CutFactor`.

- The subroutine `SetCutParameters(kT,eta1,eta2)` set a default version of cut parameters: $p_{1,2} < k_T$ and $\eta_1 < \eta < \eta_2$.
- The overloaded version of the subroutine `SetCutParameters(k1,k2,eta1,eta2)` set a default version of asymmetric cut parameters. $p_1 < k_1$,$p_2 < k_2$ and $\eta_1 < \eta < \eta_2$.
- Function `CutFactor(qT,Q_in,y_in, CutParameters)` calculates the cut prefactor at the point q_T, Q, y. The argument `CutParameters` is **optional**. If it is not present, cut parameters are taken from default values (which are set by `SetCutParameters`). `CutParameters` is array `(/ k1,k2,eta1,eta2/)`. The usage of global definition for `CutParameters` is not recommended, since it can result into running condition during parallel computation. This is interface is left fro compatibility with earlier version of `artemide`.

F. Variation of scale

TO BE WRITTEN

G. Power corrections

There are many sources of power corrections. For a moment there is no systematic studies of power corrections for TMD factorization. Nonetheless I include some options in `artemide`, and plan to make more systematic treatment in the future.

Exact values of $x_{1,2}$ for DY: The TMD distributions enter the cross-section with x_1 and x_2 equal to

$$\begin{aligned} x_1 &= \frac{q^+}{p_1^+} = \frac{Q}{\sqrt{s}} e^{y} \sqrt{1+\frac{\boldsymbol{q}_T^2}{Q^2}} \simeq \frac{Q}{\sqrt{s}} e^{y}, \\ x_1 &= \frac{q^+}{p_1^+} = \frac{Q}{\sqrt{s}} e^{-y} \sqrt{1+\frac{\boldsymbol{q}_T^2}{Q^2}} \simeq \frac{Q}{\sqrt{s}} e^{-y}. \end{aligned} \tag{11.5}$$

Traditionally, the corrections $\sim q_T/Q$ are dropped, since they are power corrections. Nonetheless, they could be included since they have different sources in comparison to power corrections to the factorized cross-section. Usage of one or another version of $x_{1,2}$ is switched in `constants-file`.

H. Enumeration of processes

List of enumeration for $prefactor1$

`p1`

p1	$prefactor1$	Short description
1	1	$dX = dydQ^2dq_T^2$.
2	$\frac{2\sqrt{Q^2+\boldsymbol{q}_T^2}}{\sqrt{s}}\cosh y$	$dX = dx_F dQ^2 dq_T^2$ where $x_F = \frac{2\sqrt{Q^2+\boldsymbol{q}_T^2}}{\sqrt{s}}\sinh y$ is Feynman x. **Important:** In this case the integration y is preplaced by the integration over x_F. I.e. `..._Yint`$(..., a, b, ..)$ which usually evaluates $\int_a^b dy$ evaluates $\int_a^b dx_F$.

List of enumeration for $prefactor2$
p2

p2	$prefactor2$	Short description
1	$\frac{4\pi}{9}\frac{\alpha_{\rm em}^2(Q)}{sQ^2}\lvert C_V^{DY}(c_2Q)\rvert^2 R \times \mathrm{cut}(q_T)$	DY-cross-section $\frac{d\sigma}{dQ^2dyd(q_T^2)}$. $\mathrm{cut}(q_T)$ is the weight for the lepton tensor with fiducial cuts (see sec.2.6 in [1]). Corresponds to DY-cross-section $\frac{d\sigma}{dQ^2dyd(q_T^2)}$. **Process declared $y \leftrightarrow -y$ symmetric.** The result is in pb/GeV^2
2	$\frac{4\pi}{9}\frac{\alpha_{\rm em}^2(Q)}{sQ^2}\lvert C_V^{DY}(c_2Q)\rvert^2 R \times \mathrm{cut}(q_T)$	DY-cross-section $\frac{d\sigma}{dQ^2dyd(q_T^2)}$. $\mathrm{cut}(q_T)$ is the weight for the lepton tensor with fiducial cuts (see sec.2.6 in [1]). **Process declared $y \leftrightarrow -y$ non-symmetric.** The result is in pb/GeV^2
3	$\frac{4\pi^2}{3}\frac{\alpha_{\rm em}(Q)}{s}Br_Z\lvert C_V^{DY}(c_2Q)\rvert^2 R \times \mathrm{cut}(q_T)$	DY-cross-section $\frac{d\sigma}{dQ^2dyd(q_T^2)}$ for the Z-boson production in the narrow width approximation. $Br_Z = 0.03645$ is Z-boson branching ration to leptons. $\mathrm{cut}(q_T)$ is the weight for the lepton tensor with fiducial cuts (see sec.2.6 in [1]). **Process declared $y \leftrightarrow -y$ symmetric.** The result is in pb/GeV^2
4	$\frac{4\pi^2}{3}\frac{\alpha_{\rm em}(Q)}{s}Br_W\lvert C_V^{DY}(c_2Q)\rvert^2 R \times \mathrm{cut}(q_T)$	DY-cross-section $\frac{d\sigma}{dQ^2dyd(q_T^2)}$ for the W-boson production in the narrow width approximation. $Br_W = 0.1086$ is W-boson branching ration to leptons. $\mathrm{cut}(q_T)$ is the weight for the lepton tensor with fiducial cuts (see sec.2.6 in [1]). Use together with p3=13,...,18. In this case, Q is be M_Z. The result is in pb/GeV^2

Here $R = 0.3893379 \cdot 10^9$ the transformation factor from GeV to pb.

List of shorthand enumeration for processes

p	p1	p2	p3	Description
1	1	1	5	$p + p \to Z + \gamma^* \to ll$. Standard DY process measured in the vicinity of the Z-peak. E.g. for LHC measurements.
2	1	1	6	$p + \bar{p} \to Z + \gamma^* \to ll$. Standard DY process measured in the vicinity of the Z-peak. E.g. for Tevatron measurements.

XII. TMDX_SIDIS MODULE

This module evaluates cross-sections with the SIDIS-like kinematics. I.e. it expects the following kinematic input, (Q, x, z) or (Q, y, z) or (x, y, z), that are equivalent.

The general structure of the cross-section is

$$\frac{d\sigma}{dX} = d\sigma(q_T) = prefactor1 \int [bin]\ prefactor2\ \times F, \tag{12.1}$$

where $dX \sim dl'$, with l' momentum of scattered lepton. For better definition of parameters see sec.XII F.

List of available commands

Command	Type	Sec.	Short description
`TMDX_SIDIS_Initialize(file,prefix)`	subrout.	XI A	* Initialization of module.
`TMDX_SIDIS_ResetCounters()`	subrout.	–	* Reset intrinsic counters of module.
`TMDX_SIDIS_ShowStatistic()`	subrout.	–	* Print current statistic on the number of calls.
`TMDX_SIDIS_SetProcess(p)`	subrout.	XII A	Set the process
`TMDX_SIDIS_XSetup(s,z,x,Q,mTARGET,mPRODUCT)`	subrout.	XII A	Set the kinematic variables (`mTARGET` and `mPRODUCT` are optional variables)
`TMDX_SIDIS_SetCuts(inc,yMin,yMax,W2)`	subrout.	XII C	Set global values of cuts
`TMDX_SIDIS_SetScaleVariation(c2)`	subrout.	–	* Set new values for the scale-variation constants.
`CalcXsec_SIDIS...`	subrout.	XII B	Evaluates cross-section. Many overloaded versions see sec.XII B.
`xSec_SIDIS(X,process,s,pT,z,x,Q)`	subrout.	XII B	Evaluates cross-section completely integrated over the bin. Can be called without preliminary `...Set...`'s.
`xSec_SIDIS_List(X,process,s,pT,z,x,Q)`	subrout.	XII B	Evaluates cross-section completely integrated over the bin over the list. Can be called without preliminary `...Set...`'s.

*)The structure of the module repeats the structure of `TMDX_DY` module, with the main change in the kinematic definition. Most part of routines has the same input and output with only replacement `_DY`→`_SIDIS`. We do not comment such commands. They marked by $*$ in the following table.

A. Setting up the parameters of cross-section

Prior to evaluation of cross-section one must declare which process is considered and to set up the kinematics.

The declaration of the process is made by
`call TMDX_SIDIS_SetProcess(p1,p2,p3)`
`call TMDX_SIDIS_SetProcess(p0)`
where `p0=(/p1,p2,p3/)` and

`p1` (integer) Defines the $prefactor1$ that contains the phase space elements, and generally experimental dependent. Could be set outside of bin-integration.

`p2` (integer) Defines the $prefactor2$ that contains the universal part of factorization formula. Participate in the bin-integration

`p3` (integer) Defines the structure function F. See sec.X C.

Alternatively, process can be declared by shorthand version
`call TMDX_SIDIS_SetProcess(p)`
where `p`(integer) corresponds to particular combinations of `p1,p2,p3`. See table.

The kinematic of the process is declared by variables (s, Q, x, z)
`call TMDX_SIDIS_XSetup(s,Q,x,z)`
where `s` is Mandelshtam variable s, `Q` is hard virtuality Q, and (x,z) are standard SIDIS variables. Additionally one can declare masses of target and produced hadrons, by using optional variables
`call TMDX_SIDIS_XSetup(s,Q,x,z,mTARGET,mPRODUCT)`
where corresponding masses are given in GeV. Note, that during initialization procedure the target and produced masses are set from `constants`-file. These values are used or not used according to triggers for 'mass corrections' set in `constants`-file.

All non-perturbative parameters are defined in the `TMDs` and lower-level modules. For user convenience there is a subroutine, which passes the values of parameters to `TMDs`. It is
`call TMDX_SIDIS_SetNPParameters(lambda/)`
where `lambda` is real*8(1:number of parameters)/ or `n` is the number of replica. See also IX B.

B. Cross-section evaluation

After the parameters of cross-section are set up, the values of the cross-section at different q_T can be obtained by
`call CalcXsec_DY(X,qt)`
where `X` is real*8 variable where cross-section will be stored, `qt` is real*8 is the list of values of q_T's at which the `X` is to be calculated. There exists an overloaded version with `X` (real*8)(1:N) and `qT`(real*8)(1:N), which evaluates the array of crossections over array of q_T.
Typically, one needs to integrate over bin. There is a whole set of subroutines which evaluate various integrals over bin they are

Subroutine	integral	Comment
`CalcXsec_SIDIS(X,pt)`	single-point cross-section at given p_T	
`CalcXsec_SIDIS_Zint_Xint_Qint (X,pt,zMin,zMax,xMin,xMax,Qmin,Qmax)`	$\int_{z_{\min}}^{z_{\max}} dz \int_{x_{\min}}^{x_{\max}} dx \int_{Q_{\min}}^{Q_{\max}} 2QdQd\sigma(p_T)$	$0 < z_{\min} < z_{\max} < 1$ $0 < x_{\min} < x_{\max} < 1$ $0 < Q_{\min} < Q_{\max}$
`CalcXsec_SIDIS_PTint_Zint_Xint_Qint (X,ptMin,ptMax,zMin,zMax,xMin,xMax,Qmin,Qmax)`	$\int_{z_{\min}}^{z_{\max}} dz \int_{x_{\min}}^{x_{\max}} dx \int_{Q_{\min}}^{Q_{\max}} 2QdQ \int_{pT_{\min}}^{pT_{\max}} 2p_T dp_T d\sigma(p_T)$	$0 < z_{\min} < z_{\max} < 1$ $0 < x_{\min} < x_{\max} < 1$ $0 < Q_{\min} < Q_{\max}$
More to be added		

Note 1: The point $p_T = 0$ is somewhat problematic, since it leads to flat Hankel integral. Thus for $p_T < 1$MeV it is set to 1MeV.
Note 2: Each command has overloaded version with arrays for X and qt.
Note 3: Cross-section integrated over p_T bins have overloaded versions with `X`, `qtmin` and `qtmax` being arrays. Then the integral is done for `X`(i) from `ptmin(i)` to `ptmax(i)`.
Note 4: There exist special overloaded case for integrated over p_T-bins, with successive bins. I.e. for bins that adjust to each other. In this case only one argument `ptlist` is required (instead of `qtmin`,`qtmax`). The integration for `X(i)` is done from `ptlist(i)` till `ptlist(i+1)`.

Take care that every next function is heavier to evaluate then the previous one. The integrations over Q and y are adaptive Simpsons. We have found that it is the fastest (adaptive) method for typical cross-sections with tolerance $10^{-3} - 10^{-4}$. Naturally, it is not suitable for higher precision, which however is not typically required. The integration over pt is not adaptive, since typically p_T-bins are rather smooth and integral is already accurate if approximated by 5-7 points (default value is set in `constants`). For larger p_T-bins we suggest to use overloaded versions with manual set of N (number of integral sections).

There is a subroutine that evaluate cross-section without preliminary call of SetCuts,TMDX_SIDIS_SetProcess,TMDX_SIDIS_XSetup**.** It is called `xSec_SIDIS` and it have the following interface:

```
xSec_SIDIS(X,process,s,pT,z,x,Q,incC,cuts,masses)
```

where

- `X` is (real*8) value of cross-section.
- `process` is (integer)array `(p1,p2,p3)`.
- `s` is (real*8)Mandelshtam variable s
- `pT` is (real*8)array `(qtmin,qtmax)`
- `z` is (real*8)array `(zmin,zmax)`
- `x` is (real*8)array `(xmin,xmax)`
- `Q` is (real*8)array `(Qmin,Qmax)`
- `incC` is (logical) flag to include cuts.
- `cuts` is (real*8) array `(ymin,ymax,W0)` that parameterizes kinematic cuts.
- `masses` is (real*8) array `(mt,mp)` which is $(M_{target}, m_{produced})$ in GeV OPTIONAL.

IMPORTANT: Practically, the call of this function coincides with `X` evaluated by the following set of commands

```
call TMDX_SIDIS_SetProcess(process)
call TMDX_SIDIS_XSetup(s,any,any,any)
call TMDX_SIDIS_SetCuts(incC,ymin,ymax,W0)
call CalcXsec_SIDIS_PTint_Zint_Xint_Qint (X,ptMin,ptMax,zMin,zMax,xMin,xMax,Qmin,Qmax)
```

However, there is an important difference: the values of `s, process` which are set by routines `..Set..`, are global. For that reason such approach could not be used in a parallel computation. Contrary, in the function `xSec_SIDIS` these variables are set locally and thus this function can be used in parallel computations.

There is also analogous subroutine that evaluate cross-section by list. It is called `xSec_SIDIS_List` and it have the following interface:

```
xSec_SIDIS_List(X,process,s,pT,z,x,Q,incC,cuts,masses)
```

All variables are analogues to those of `xSec_SIDIS`, but should come in lists, i.e. `X` is (1:n), `process` is (1:n,1:3), `s` is (1:n), `pT`,`x`,`Q`,`z` are (1:n,1:2). This command compiled by OPENMP, so runs in parallel on multi-core computers.

C. Kinematic cuts

Some experiments put extra constraints on the measurement. Typically, such constraint has the form

$$y_{\min} < y < y_{\max}, \qquad W^2 > W_0^2. \tag{12.2}$$

In this case the integration over x and Q^2 has additional restrictions. Say, if one integrates over a bin: $x_{\min} < x < x_{\max}$ and $Q_{\min} < Q < Q_{\max}$ the boundaries of the bin should be modified as

$$\max\{x_{\min}, \frac{Q^2}{y_{\max}(s-M^2)}\} < x < \min\{x_{\max}, \frac{Q^2}{y_{\min}(s-M^2)}, \frac{Q^2}{Q^2-M^2-W_0^2}\}, \tag{12.3}$$

$$\max\{Q^2_{\min}, x_{\min}y_{\min}(s-M^2), \frac{x_{\min}(W_0^2-M^2)}{1-x_{\min}}\} < Q^2 < \min\{Q^2_{\max}, x_{\max}y_{\max}(s-M^2)\}. \tag{12.4}$$

D. Power corrections

There are many sources of power corrections. For a moment there is no systematic studies of of effect of power corrections for TMD factorization. Nonetheless we include some options in `artemide`, and plan to make systematic treatment in the future.

Kinematic corrections to the variables/phas space. There are three sources of kinematic corrections to the variables

$$\frac{p_\perp}{Q}, \qquad \frac{M}{Q}, \qquad \frac{m}{Q},$$

where M is the target mass, m is the mass of the fragmented hadron. These terms appear in many places of the SIDIS expression (see sec.XII F, for some minimal details), even without accounting for power-suppressed terms in the factorization formula. The nice feature of these correction is that they could be accounted exactly. The majority of these terms appears during of the Lorentz transformation of factorization frame (where the factorization is performed) to the laboratory frame (where the measurement is made).

The accounting of these corrections is switched on/off in `constants`. For a moment (v1.41) the values of masses M and m are set universally for all processes.

E. Enumeration of processes

List of enumeration for $prefactor1$

`p1`

p1	$prefactor1$	Short description
1	1	No comments.
2	$\frac{Q^2}{y}$	The cross-section $\frac{d\sigma}{dxdydzd(p_\perp^2)}$, in this case integration over Q^2 is replaced by integration over y.
3	$\frac{x}{y}$	The cross-section $\frac{d\sigma}{dydQ^2dzd(p_\perp^2)}$, in this case integration over x is replaced by integration over y.

List of enumeration for $prefactor2$
p2

p2	$prefactor2$	Short description
1	$\frac{2\pi\alpha_{\rm em}^2(Q)}{Q^4}\frac{y^2}{1-\varepsilon}\lvert C_V^{SIDIS}(c_2Q)\rvert^2 c_0^{(un)} R$	(unpol.) SIDIS-cross-section $\frac{d\sigma}{dxdQ^2dzd(p_\perp^2)}$. [pb/GeV^2].
2	$\frac{x}{\pi}\frac{c_0^{(un)}}{\left(1+\frac{\gamma^2}{2x}\right)}\lvert C_V^{SIDIS}(c_2Q)\rvert^2$	Prefactor for $F_{UU,T}$ according to the tabulated definition (2.7) of [11].

Here $R = 0.3893379 \times 10^9$ the transformation factor from GeV to pb.

$$c_0^{(un)} = \frac{1+\left(\varepsilon-\frac{\gamma^2}{2}\right)\frac{\boldsymbol{\rho}_\perp^2-\rho^2}{1-\gamma^2\rho^2}}{\sqrt{1+\gamma^2\boldsymbol{\rho}_\perp^2}}.$$

F. SIDIS theory

In many aspects the theory for SIDIS is more complicated then for Drell-Yan. Here I collect the main definition which were used in the artemide. For a more detailed description see ref.[11]. Note, that some parts of definition were derived by me, since I have not found them in the literature.

1. Kinematics

The process is

$$H(P) + l(l) \to l(l') + h(p_h) + X, \tag{12.5}$$

with

$$P^2 = M^2, l^2 = l'^2 = m_l^2 \simeq 0, \qquad p_h^2 = m^2. \tag{12.6}$$

The standard variables used for the description of SIDIS are

$$q = l - l' \qquad \Rightarrow \qquad Q^2 = -q^2, \qquad x = \frac{Q^2}{2(Pq)}, \qquad y = \frac{(Pq)}{(Pl)}, \qquad z = \frac{(Pp_h)}{(Pq)}. \tag{12.7}$$

There are is also a set of power variables used to define power-corrections

$$\gamma = \frac{2Mx}{Q}, \qquad \rho = \frac{m}{zQ}, \qquad \boldsymbol{\rho}_\perp^2 = \frac{m^2+\boldsymbol{p}_\perp^2}{z^2Q^2}. \tag{12.8}$$

The variables x, y and Q^2 are dependent: $xy(s-M^2) = Q^2$. The phase-volume $dxdQ^2$ can be expressed via $dxdy$ or $dydQ^2$:

$$dxdQ^2 = \frac{Q^2}{y}dxdy = \frac{x}{y}dydQ^2. \tag{12.9}$$

A phase space point is totally characterized by the following numbers:

$$\{s, x, Q^2, z, \boldsymbol{p}_T^2\}. \tag{12.10}$$

Alternatively, one can replace x or Q^2 by y.

2. Cross-section

The cross-section for SIDIS has the general form

$$\frac{d\sigma}{dxdQ^2dzd\psi d\phi_h d\boldsymbol{p}_{h\perp}^2} = \frac{\alpha_{\rm em}^2(Q)}{Q^6}\frac{y^2}{8z}\frac{L_{\mu\nu}W^{\mu\nu}}{\sqrt{1+\boldsymbol{\rho}_\perp^2\gamma^2}}, \tag{12.11}$$

where $L_{\mu\nu}$ is the lepton tensor, and $W_{\mu\nu}$ is the hadron tensor. The hadron tensor contains many term accompanied by polarization angles.

The TMD factorization is performed in the factorization frame with respect to $\boldsymbol{q}_T^2 \ll Q^2$. In the factorization frame, the unpolarized part of the hadron tensor

$$W^{\mu\nu} = \frac{-zg_T^{\mu\nu}}{\pi}\int |\boldsymbol{b}|d|\boldsymbol{b}|J_0(|\boldsymbol{b}||\boldsymbol{q}_T|)\sum_f e_f^2|C_V(-Q^2,\mu^2)|^2F_1^f(x_1,\boldsymbol{b})D_1^f(z_1,\boldsymbol{b}) + \dots\,, \tag{12.12}$$

where dots denote, polarized terms, and power corrections. The variables x_1 and z_1 are

$$x_1 = -\frac{2x}{\gamma^2}\left(1-\sqrt{1+\gamma^2\left(1-\frac{\boldsymbol{q}_T^2}{Q^2}\right)}\right), \tag{12.13}$$

$$z_1 = -z\frac{1-\sqrt{1+\left(1-\frac{\boldsymbol{q}_T^2}{Q^2}\right)\gamma^2}}{\gamma^2}\frac{1+\sqrt{1-\rho^2\gamma^2}}{1-\frac{\boldsymbol{q}_T^2}{Q^2}}. \tag{12.14}$$

The factorization variable $|\boldsymbol{q}_T|$ is related to the measured variable $\boldsymbol{p}_{h\perp}$ as

$$|\boldsymbol{q}_T| = \frac{|\boldsymbol{p}_{h\perp}|}{z}\sqrt{\frac{1+\gamma^2}{1-\gamma^2\rho^2}}, \qquad \Leftrightarrow \qquad |\boldsymbol{p}_{h\perp}| = z|\boldsymbol{q}_T|\sqrt{\frac{1-\gamma^2\rho^2}{1+\gamma^2}}. \tag{12.15}$$

Making the convolution with unpolarized leptonic tensor, we get the following expression for the cross-section

$$\begin{aligned}\frac{d\sigma}{dxdQ^2dzd\boldsymbol{p}_{h\perp}^2} &= 2\pi\frac{\alpha_{\rm em}^2}{Q^4}\frac{1}{\sqrt{1+\boldsymbol{\rho}_\perp^2\gamma^2}}\frac{y^2}{2(1-\varepsilon)}\left\{1+\left(\varepsilon-\frac{\gamma^2}{2}\right)\frac{\boldsymbol{\rho}_\perp^2-\rho^2}{1-\gamma^2\rho^2}\right\} \\ &\int |\boldsymbol{b}|d|\boldsymbol{b}|J_0\left(\frac{|\boldsymbol{b}||\boldsymbol{p}_{h\perp}|}{z}\sqrt{\frac{1+\gamma^2}{1-\gamma^2\rho^2}}\right)\sum_f e_f^2|C_V(-Q^2,\mu^2)|^2F_1^f(x_1,\boldsymbol{b})D_1^f(z_1,\boldsymbol{b}),\end{aligned} \tag{12.16}$$

where

$$\varepsilon = \frac{1-y-\frac{\gamma^2y^2}{4}}{1-y+\frac{y^2}{2}+\frac{y^2\gamma^2}{4}}. \tag{12.17}$$

XIII. TMDS_INKT MODULE

The module TMDs_inKT is derivative of the module TMDs that provides the TMD in the transverse momentum space. We define

$$F(x, \boldsymbol{k}_T; \mu, \zeta) = \int \frac{d^2\boldsymbol{b}}{(2\pi)^2} F(x, \boldsymbol{b}; \mu, \zeta) e^{-i(\boldsymbol{k}_T \boldsymbol{b})}. \tag{13.1}$$

Since all evaluated TMDs depends only on the modulus of $\boldsymbol{b}$, within the module we evaluate

$$F(x, |\boldsymbol{k}_T|; \mu, \zeta) = \int \frac{d|\boldsymbol{b}|}{2\pi} |\boldsymbol{b}| J_0(|\boldsymbol{b}||\boldsymbol{k}_T|) F(x, |\boldsymbol{b}|; \mu, \zeta). \tag{13.2}$$

The module TMDs_inKT uses all functions from the module TMDs. In fact, all technical commands (like Initialize) just transfer the request to TMDs. Thus, the information on these commands can be found in the section IX. For the evaluation of Hankel integral we use the Ogata quadrature see X B (the parameters for it are set in corresponding section of constants.

List of available commands

Command	Type	Sec.	Short description
TMDs_inKT_Initialize(order)	subrout.	??	Initialization of module.
TMDs_inKT_ResetCounters()	subrout.	-	Reset intrinsic counters of modules
TMDs_inKT_ShowStatistic	subrout.	-	Print current statistic on the number of calls.
uTMDPDF_kT_5(x,kT,h)	(real*8(-5:5))	IX B	Unpolarized TMD PDF at the optimal line (gluon term undefined)
uTMDPDF_kT_50(x,kT,h)	(real*8(-5:5))	IX B	Unpolarized TMD PDF at the optimal line (gluon term defined)
uTMDPDF_kT_5(x,kT,mu,zeta,h)	(real*8(-5:5))	IX B	Unpolarized TMD PDF (gluon term undefined)
uTMDPDF_kT_50(x,kT,mu,zeta,h)	(real*8(-5:5))	IX B	Unpolarized TMD PDF (gluon term defined)
uTMDFF_kT_5(x,kT,h)	(real*8(-5:5))	IX B	Unpolarized TMD FF at the optimal line (gluon term undefined)
uTMDFF_kT_50(x,kT,h)	(real*8(-5:5))	IX B	Unpolarized TMD FF at the optimal line (gluon term defined)
uTMDFF_kT_5(x,kT,mu,zeta,h)	(real*8(-5:5))	IX B	Unpolarized TMD FF (gluon term undefined)
uTMDFF_kT_50(x,kT,mu,zeta,h)	(real*8(-5:5))	IX B	Unpolarized TMD FF (gluon term defined)

Comments:

- The value of k_T is expected bigger 1MeV for smaller values the function evaluates at 1MeV.
- For gluonless TMDs (_5) the gluon term is identically 0.
- The convergence of the integral is checked by convergence of $|u| + |d| + |g|$ combination.

XIV. SUPPLEMENTARY CODES

In the `artemide` archive you can find some example codes. They are located in `Prog/` and can be compiled by `make program TARGET=name`

`test.f90`	Makes some elementary computation. Can be run by `make test`
`DY_example_v14.f90`	Commented example of the code for computation of DY cross-section for `artemide` ver.1.4
`DY_example_v2.f90`	Commented example of the code for computation of DY cross-section for `artemide` ver.2.00.
`DY_for_RHIC.f90`	Example computation of Z-boson production in RHIC kinematics with error-estimation by replicas.
`DY_for_CMS.f90`	Example computation of Z-boson production in CMS kinematics with error-estimation by scale-variations.

XV. HARPY

The `harpy` (from combination of Hybrid ARtemide+PYthon)) is an interface to `artemide` to the python.

It is directly possible to interfacing the `artemide` to python since `artemide` is made on fortran95. It uses some of it features, such as interfaces, and indirect list declarations, which are alien to python. Also I have not found any convenient way to include several dependent Fortran modules in f2py (if you have suggestion just tell me). Therefore, I made a wrap module `harpy.f90` that call some useful functions from `artemide` with simple declarations. So, it could be linked to python by f2py library.

So, in the current realization I create the signature file that declare python module artemide, which has an wrap module harpy. In python it looks like

>>> import artemide

>>> artemide.harpy.initialize("NNLO")

>>> print artemide.harpy.utmdpdf_5_optimal(0.1,1.,1)

Ugly, but it works.

Note, that not all functions of `artemide` are available in `harpy`. I have added only the most useful, however, you can add them by our-self, or write me an e-mail. Here, list the functions from `artemide` and their synonym in `harpy`

artemide		harpy.f90
module	function	
aTMDe_control	artemide_Initialize(file)	Initialize(file)
	artemide_SetScaleVariations(c1,c2,c3,c4)	SetScaleVariations(c1,c2,c3,c4)
	artemide_SetNPparameters(lambda)	SetLambda_Main(lambda)
	artemide_SetNPparameters_TMDR(lambda)	SetLambda_TMDR(lambda)
	artemide_SetNPparameters_uTMDPDF(lambda)	SetLambda_uTMDPDF(lambda)
	artemide_SetNPparameters_uTMDFF(lambda)	SetLambda_uTMDFF(lambda)
	artemide_SetReplica_TMDR(lambda)	SetReplica_TMDR(lambda)
	artemide_SetReplica_uTMDPDF(lambda)	SetReplica_uTMDPDF(lambda)
	artemide_SetReplica_uTMDFF(lambda)	SetReplica_uTMDFF(lambda)
TMDX_DY	TMDX_DY_SetNPParameters(array)	SetLambda(array)
	TMDX_DY_SetNPParameters(integer)	SetLambda_ByReplica(integer)
	TMDX_DY_SetScaleVariations(c1,c2,c3,c4)	SetScaleVariation(c1,c2,c3,c4)
TMDs	uTMDPDF_5(x,bt,muf,zetaf,h)	uTMDPDF_5_Evolved(x,bt,muf,zetaf,h)
	uTMDPDF_50(x,bt,muf,zetaf,h)	uTMDPDF_50_Evolved(x,bt,muf,zetaf,h)
	uTMDPDF_5(x,bt,h)	uTMDPDF_5_Optimal(x,bt,h)
	uTMDPDF_50(x,bt,h)	uTMDPDF_50_Optimal(x,bt,h)
	TMDs_SetPDFreplica(n)	SetPDFreplica(n)
TMDs_inKT	uTMDPDF_kT_5(x,kt,muf,zetaf,h)	uTMDPDF_kT_5_Evolved(x,kt,muf,zetaf,h)
	uTMDPDF_kT_50(x,kt,muf,zetaf,h)	uTMDPDF_kT_50_Evolved(x,kt,muf,zetaf,h)
	uTMDPDF_kT_5(x,kt,h)	uTMDPDF_kT_5_Optimal(x,kt,h)
	uTMDPDF_kT_50(x,kt,h)	uTMDPDF_kT_50_Optimal(x,kt,h)

(continuation of table)

artemide		harpy.f90
TMDX_DY	xSec_DY(X,proc,s,qT,Q,y,iC,cuts)	X=DY_xSec_Single(proc,s,qT,Q,y,iC,cuts)
	xSec_DY_List(X,proc,s,qT,Q,y,iC,cuts)	X=DY_xSec_List(proc,s,qT,Q,y,iC,cuts,L)
TMDX_SIDIS	xSec_SIDIS(X,proc,s,pT,z,x,Q,iC,cuts)	X=SIDIS_xSec_Single(proc,s,pT,z,x,Q,iC,cuts)
	xSec_SIDIS(X,proc,s,pT,z,x,Q,iC,cuts,masses)	X=SIDIS_xSec_Single_withMasses(proc,s,pT,z,x,Q,iC,cuts
	xSec_SIDIS_List(X,proc,s,pT,z,x,Q,iC,cuts)	X=SIDIS_xSec_List(proc,s,qT,z,x,Q,iC,cuts,L)
	xSec_SIDIS_List(X,proc,s,pT,z,x,Q,iC,cuts,masses)	X=SIDIS_xSec_List_withMasses(proc,s,qT,z,x,Q,iC,cuts,m

L is the length of the input/output lists.

NOTE: there is no **OPTIONAL** parameters. All parameters should be defined (it is necessary for f2py).

For convenience I have also created a more user-friendly interface, written on python. It is called harpy.py and located in /harpy, and can be imported as is.

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XVI. VERSION HISTORY

Ver.2.0

- **TMDX_DY**: fixed a memory leak in adaptive integration. It could cause to possible source of Segmentation fault error.
- **TMDX_DY**: Added cut for very-small p_T.
- **uTMDPDF**&**uTMDFF**: Changed priority of grid-calculation during scale-variation.
- **TMD-models**&**Twist2Convolution**: Added b^* parameter. **Model files are not compatible with earlier versions.**
- **Twist2Grid**: The routine for large-b is changed. Now it is faster and more accurate.
- **aTMDe_control**&**aTMDe_setup**: Implemented.
- **ALL MODULES**: Total change of initialization routines, and interface subroutines.

Ver.1.41

- **TMDR**&**TMDs**&**TMDF**: fixed issues that arise with some older Fortran compilers (thanks to Wen-Chen Chang).
- **TMDX_SIDIS**: Totally rewritten: processes redefined, interface redefined, integration routines rewritten, masses correction, parallelization, etc.
- **TMDX_DY**: Added extra checks.
- **uTMDFF**: The factor z^2 added as an external, see sec.VII F. It should improve the convergence of "common"-convolution at small z.
- **TMDF**: Added Ogata tables for $\tilde{h} = h0.05$. They are used for integrations at smaller q_T.
- **TMDF**: Fixed potential bug in the initialization order.
- **TMDF**& higher: Fixed misprint in the name of function `TMDF_F`.
- **TMDF**: Added processes 2002-2009.
- **TMDF**&**TMDX_DY**: Added processes [?,4,2013-2018]. W-boson in the narrow width approximation.
- **TMDs**: Fixed error with the passing to NO parameters in the case of multiple distributions.

Ver.1.4

- **constants**: The format of EW input is changed. **Not compatible with older constants-file.**
- **TMDF**: Added processes 7-12. Fixed a mistake in processes 1,2,2001 (thanks to L.Zoppi & D.Gutierrez-Reyes)
- **TMDs**, **uTMDPDF** & **QCDinput**: Added `_SetPDFreplica` routine.
- **HARPY**: Implemented.
- **TMDs and sub-modules**: Added function `SetReplica`.
- **TMDs**: Added interface to optimal TMDs
- **TMDs**: Added check for length of incoming λ_{NP}
- **TMDs**: Fixed bug with incorrect gluon TMDs in functions `_50`.
- **TMDs_inKT**: Implemented.
- **TMDX_DY**: Added `xSec_DY` subroutines.
- **TMDX_DY**: Encapsulated process, and cut-parameter variables.
- **TMDX_DY**: Defined `p1`=2, which corresponds to integration over x_F. Removed old functions for x_F integrations.
- **TMDX_DY**: Fixed a bug with variation of c_2 (introduced in ver.1.3).
- **TMDX_DY**: Fixed a (potential) bug with y-symmetric processes.
- **LeptonCutsDY** : Old version of function removed, cut-parameters encapsulated into single array variable.
- **LeptonCutsDY** : asymmetric cuts in p_T are introduced.
- **LeptonCutsDY** : New function `CutFactor4`, which is analogous to `CutFactor3` but with one integral integrated analytically. Thus, it is more accurate, and faster by 5-20%
- **LeptonCutsDY** : some rearrangement of variables that makes `CutFactor4` and `CutFactor3` faster by 20%.

– **uTMDPDF** & **uTMDFF** : F_{NP} is now function of (x, z, b, h, λ). For that reason **this version incompatible with earlier versions.**

– **uTMDPDF** & **uTMDFF**: The common block of the code is extracted into a separate files. It include calculation of Mellin convolution and Grid construction.

Ver.1.32

– **TMDX_DY**: Added the routine with lists of y-bins, in addition to the lists of pt-bins.

– **TMDX_DY**: The implementation of parallel computation over the list of cross-sections.

– **LeptonCutsDY**: The kinematic variables are encapsulated.

– **TMDX_DY**: The kinematic variables are encapsulated (by the cost of small reduction of performance).

– **uTMDR**: Changed behavior at extremely small-b. Now values of b freeze at $b = 10^{-6}$.

– **uTMDPDF** & **uTMDFF**: Changed behavior at extremely small-b. Now values of b freeze at $b = 10^{-6}$.

– **TMDR**: Added NNNLO evolution (only for quarks, Γ_3 is from 1808.08981). Not tested.

– **TMDs**: Functions `RuPDFuPDF` and `antiRuPDFuPDF` are added.

Ver.1.31

– **Global**: The module `TMDF` is split out from `TMDX_..` modules.

– **Global**: Constant tables are moved to the folder \tables.

– **TMDX_..**: Change the structure of process definition.

– **TMDF**: Fixed bug with throwing exception for failed check of convergence of Ogata quadrature.

– **TMDF**: Added possibility to vary the Ogata quadrature parameters.

– **TMDX_DY**: The structure of interface to integrated cross-section simplified.

– **TMDX_DY**: Added trigger for exact power-corrected values of $x_{1,2}$.

– **uTMDPDF** & **uTMDFF**: Fixed rare error for exceptional restoration of TMD distribution from grid, then f_{NP} evaluated to zero.

Ver.1.3

– **Global**: Complete change of interface. Interface update for all modules.

– **uTMDPDF**: Added hadron dependence. `FNP` is now flavour and hadron dependent.

– **uTMDPDF**: Renormalon correction is removed. As not used.

– **TMDR**: The grid (and pre-grid) option is removed. Since it was incompatible with new interface. Also the new evolution (type 3) is faster any previous (with grids).

Ver.1.2(unpub.)

– `TMDR`: Older version is changed to `uTMDR1`. New evolution routine implemented.

– `uTMDFF`: Implemented.

– `uTMDPDF`: Fixed bug in evaluation of gluon TMDs, within the evaluation of $(..)_+$ part.

– **Global**: Removed functions for the evaluation of only 3-flavours TMDs. As outdated and not used.

– **Global**: Number of non-pertrubative parameters is now read from 'constants'-file. Module `TMDs` initialize sub-modules with accordance to this set.

– **Global**: Module `TMDX` is renamed into `TMDX_DY`, also many functions in it renamed.

– `uTMDX_SIDIS`: Implemented.

– `TMDs`: As an temporary solution introduced a rigid cut for TMD($\mu < m_q$).

– `TMDX`: Update of Ogata quadrature, with more accurate estimation of convergence.

Ver.1.1 hotfix Bugs in `uTMDPDF` and TMDR related to the evaluation of gluon TMDs fixed (thanks to Valerio Bertone).

Ver.1.1

– **Global:** The physical, numerical and option constant are moved to the file `constants`, where they are read during the initialization stage.

– `MakeGridsForTMDR`: Update of integration procedures to adaptive. Default grids accordingly updated (no significant effect).

– `uTMDPDF`: Update of the integration procedure in `uTMDPDF`, to adaptive Gauss-Kronrod (G7-K15). with special treatment of the $x \to 1$ singularity.

– `uTMDPDF`: The procedure for evaluation of TMD for individual flavour (`uTMDPDF_lowScale(f,x,b,mu)`) is removed, as outdated.

- `uTMDPDF`: Removed argument μ, from `uTMDPDF_...(x,b)`. Added function `mu_OPE(b)`, which is used as μ-definition for TMDs.
- `uTMDPDF`: Optional griding of TMDs is added. See sec.**??**
- `TMDR`: fixed potential error in the "close-to-Landau-pole" exception.
- `TMDs`: fixed potential error in the evaluation of the gluon evolution factor.
- `TMDX`: the name convention of subroutines `CalculateXsection_...`, changed to `CalculateXsec_...`, to shorten the name length.
- `TMDX`: added functions `CalculateXsec_PTint_Qint_YintComplete(X,qtMin,qtMax,QMin,QMax)` and `CalculateXsec_Qint_YintComplete(X,qtMin,qtMax,QMin,QMax)`.
- `TMDX`&`TMDs`&`uTMDPDF`: the independent variation constant c_4 is added (in the ver.1 variation of c_3 and c_4 was simultaneous). The corresponding routines are updated.

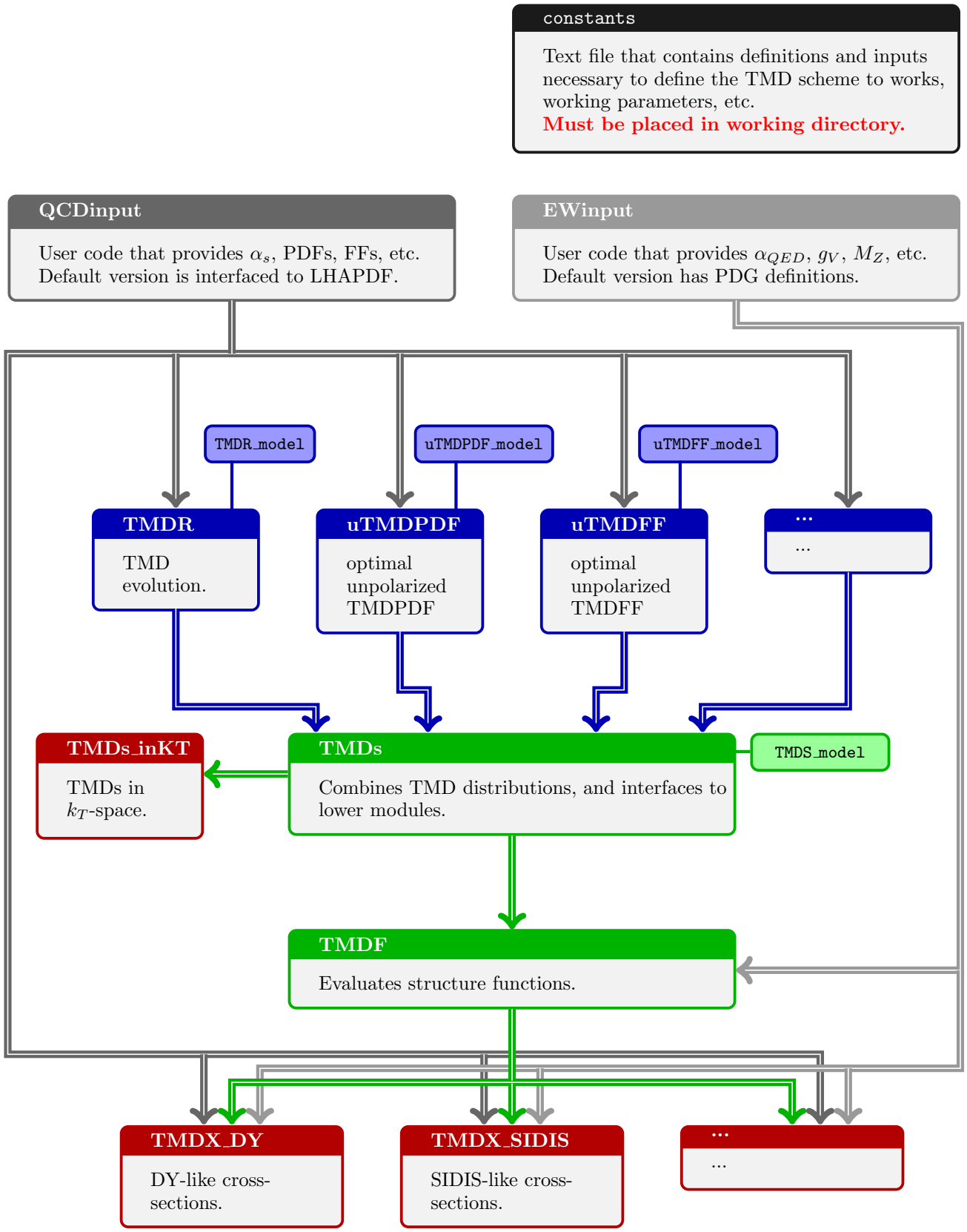
Ver.1 Release: `uTMDPDF`, `TMDR`, `TMDs` and `TMDX` modules. Only Drell-Yan-like cross-sections.

XVII. BACKUP

TO DO LIST

- Add possibility for non-perturbative definition of ζ-line.
- Fix over-computation issue in bin-integration routines for extremely small bins.

A. artemide structure before v2.00



B. artemide structure before v1.3