xFitter Tutorial

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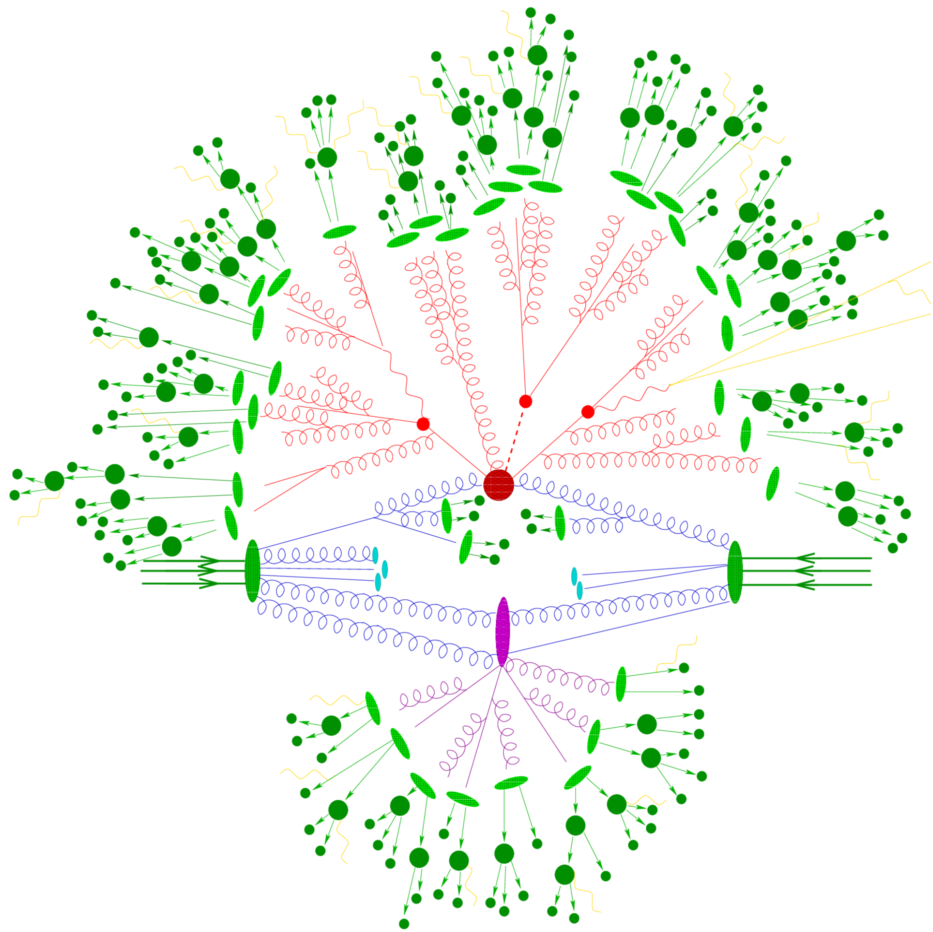
ATLAS SM workshop (Prague, Czech Republic)
14/09/2023

Motivation

- No new physics found at the LHC so far ☹
- Need for precise measurement of SM processes
- This means accurate higher order (HO) calculations…
- … but also precise knowledge of **Parton Distribution Functions (PDFs)**
- Proton-proton collision at the LHC
- For simplicity, let's consider **Deep Inelastic Scattering (DIS)** process - just one incoming parton
- pp and $p\bar{p}$ collisions will be considered in the exercises



Factorisation theorem

$$\sigma_{DIS}(x,Q^2) = \int_x^1 \frac{dz}{z} C_i\left(z,\alpha_S(Q^2)\right) f_i\left(\frac{x}{z},Q^2\right) = C_i \otimes f_i$$

Partonic cross sections:

- Process dependent
- High-scale (short-distance) objects
- Computable in perturbation theory (LO, NLO, NNLO, N^{3}LO)

PDFs:

- Universal (process independent)
- Low-scale (long-distance) objects
- Non computable in perturbation theory
- Scale dependence perturbative (DGLAP)

➢ Once PDFs have been **determined at a given scale**, the **DGLAP** evolution equations can be used to **evolve them to any other scale**

$$\mu^2 \frac{\partial}{\partial \mu^2} f_i(\mu) = P_{ij} \otimes f_j(\mu)$$

$$P_{ij}(y) = \frac{\alpha_S(\mu)}{2\pi} P_{ij}^{(0)}(y) + \left(\frac{\alpha_S(\mu)}{2\pi}\right)^2 P_{ij}^{(1)}(y) + \ldots$$

Splitting functions

How do we determine PDFs?

- Presently, the most accurate and reliable way is through **fits to data**

$f_i(x, Q_0^2)$

$x = p_i/p_p$

0 < x < 1

$Q_0 \sim 1$ GeV

(initial scale)

DGLAP →

$f_i(x, Q^2)$

Q = scale of the fitted data

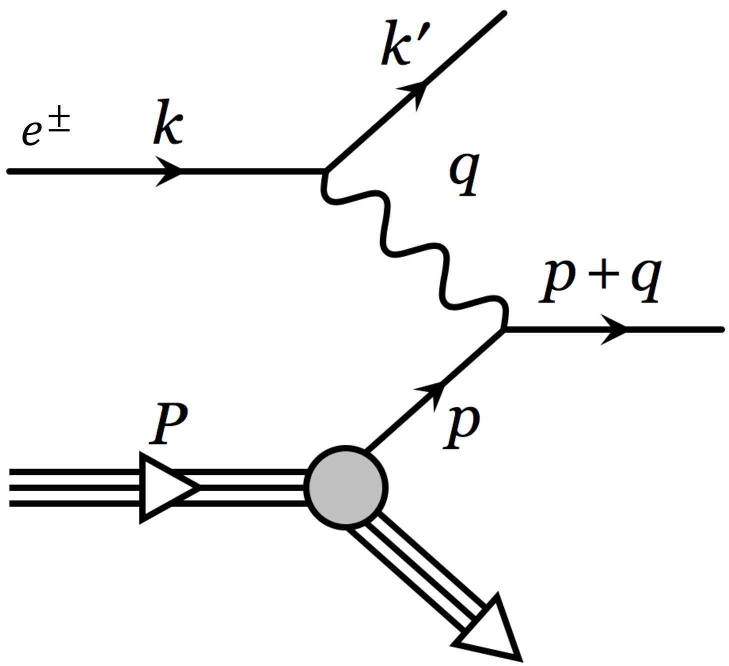
Factorisation theorem ↓

$\sigma_{DIS} = C_i \otimes f_i$

Fitting ↓

Predictions vs data

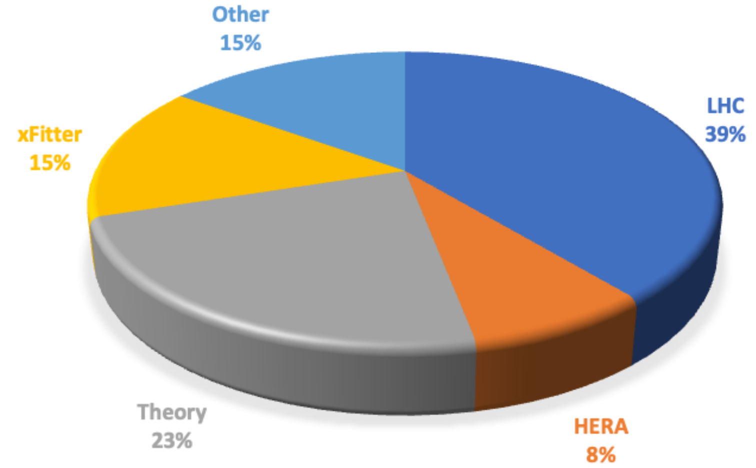
Deep Inelastic Scattering (DIS)



The xFitter Project

- The xFitter project (former HERAFitter) is a **unique open-source QCD fit framework**

- GitLab repository (open access)



- This code allows users to:
  - **extract PDFs** from a large variety of data
  - assess the **impact** of **new data on PDFs**
  - check the **consistency** of experimental data
  - test different **theoretical assumptions**

- Several active developers between experimentalists and theorists

- More than 100 publications obtained using xFitter since the beginning of the project

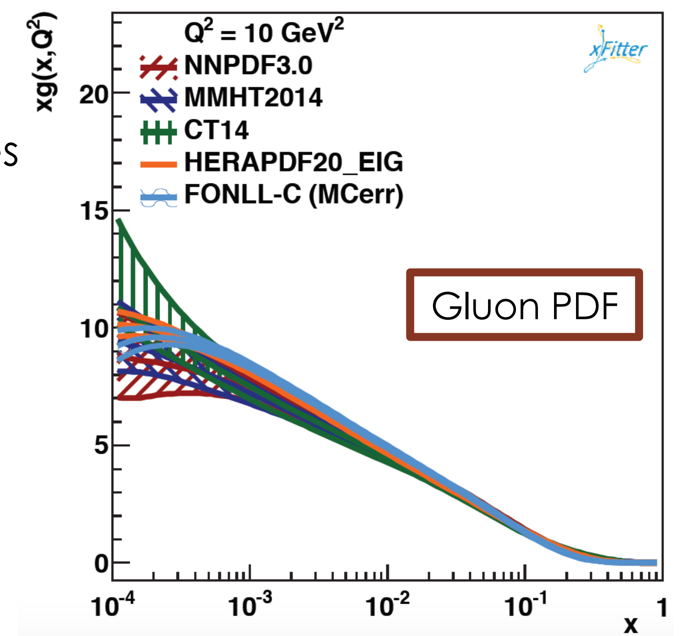
MORE IN PREPARATION!

- List of recent analyses by the xFitter Developers' Team:

Phys.Rev.D 104 (2021) 5, 056019, arXiv:2105.11306	QCD analysis of pion fragmentation functions in the xFitter framework
Phys.Rev.D 102 (2020) 1, 014040, arXiv:2002.02902	Parton Distribution Functions of the Charged Pion Within The xFitter Framework

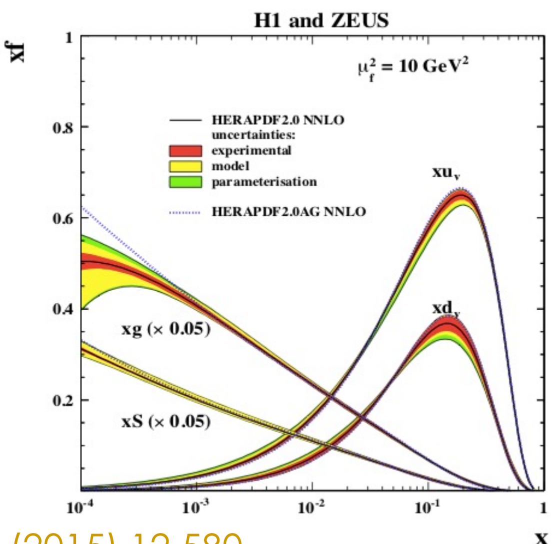
xFitter in a nutshell

- **Parametrise** PDFs at the initial scale:
  - several functional forms available
  - define PDF parameters to be minimised
- **Evolve** PDFs to the scales of the fitted data points:
  - DGLAP evolution up to NNLO in QCD and NLO QED (QCDNUM, APFEL, MELA)
  - non-DGLAP evolutions (dipole, CCFM)
- **Compute** predictions for the data points:
  - several mass schemes available in DIS (ZM-VFNS, ACOT, FONLL, TR, FFNS)
  - predictions for hadron-collider data through fast interfaces (APPLgrid, FastNLO)
- **Comparison data-predictions** via χ^2:
  - multiple definitions available
  - consistent treatment of the systematic uncertainties
- **Minimise** the χ^2 w.r.t. the fitted parameters
  - using MINUIT or by Bayesian reweighting
- **Useful drawing tools** – nice and colorful plots
- Last xFitter External meeting held in May at CERN



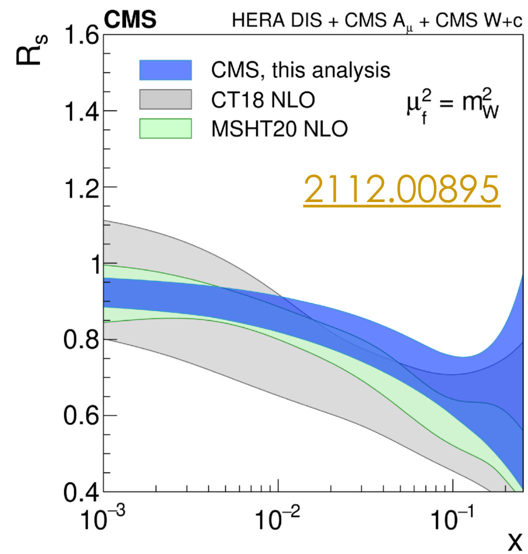
Results obtained with xFitter

DIS inclusive processes (ep)



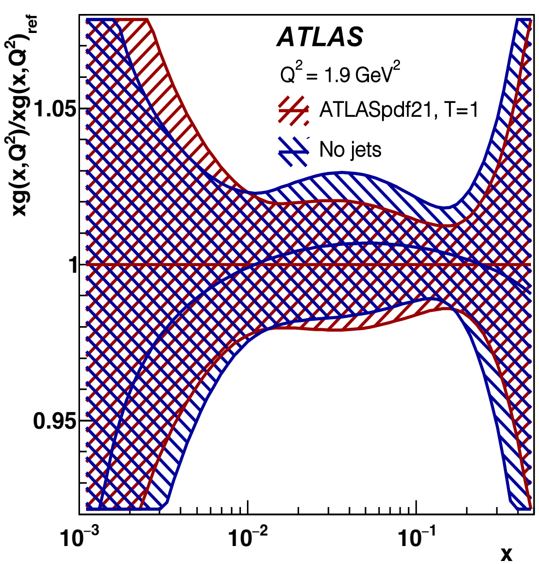
EPJC 75 (2015) 12 580

Drell-Yan processes ($pp, p\bar{p}$)

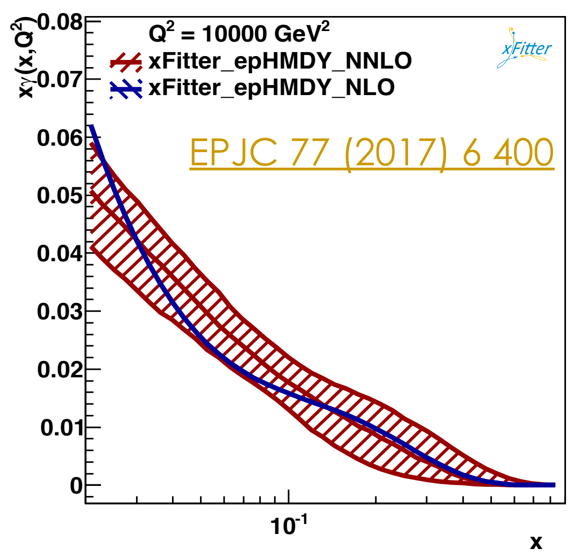


2112.00895

Jet production ($ep, pp,$) EPJC 82 (2022) 5 438



DY data sensitivity to photon PDF



EPJC 77 (2017) 6 400

xFitter release 2.2.0

xFitter

Wiki
- WikiPolicy
- RecentChanges
- FindPage
- HelpContents
- xFitter/DownloadPage

Page
- Immutable Page
- Info
- Attachments
- More Actions:

xFitter / DownloadPage

Sample data files:
LHC: ATLAS, CMS, LHCb
Tevatron: CDF, D0
HERA: H1, ZEUS, Combined
Fixed Target: …
User Supplied: …

GitLab

Releases of the xFitter QCD analysis package

- The release notes can be found in this attachment: xFitter_release_notes.pdf .
- Installation script for xFitter together with QCDNUM, APFEL, APPLGRID, LHAPDF install-xFitter-2.0.1
  - New installation script from master branch install-xfitter-master
- Data and theory files can be downloaded from gitlab gitlab data repository

Date	Version	Files	Remarks
 03/2022	2.2.0 FutureFreeze	xfitter-2.2.0.tgz	Major update of evolution and reaction interfaces
 05/2019	2.0.1 OldFashioned	xfitter-2.0.1.tgz	update/bug fix to 2.0.0 FrozenFrog
 03/2017	2.0.0 FrozenFrog	xfitter-2.0.0.tgz	stable release with decoupled data and theory files

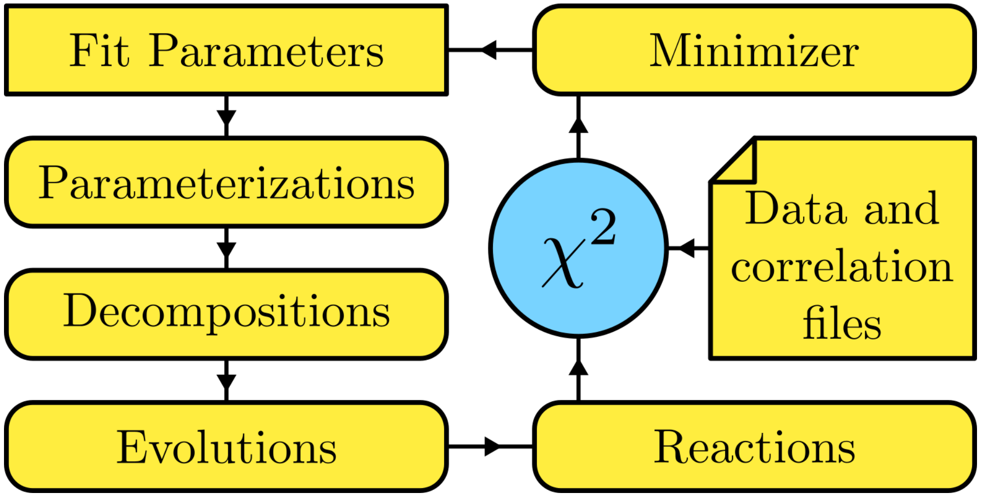
2.2.0
Future Freeze

https://www.xfitter.org/xFitter/xFitter/DownloadPage

- **Release 2.2.0 released!** (major update of evolution and reaction interfaces)
- Script to install xFitter and all its dependencies: install-xFitter

Talking about the new release…

- **Significant changes** in the internal structure
- **Re-written interfaces** to minimizers, PDF parameterisation, decomposition, evolution and theory reactions
- **Large changes in the user interface**
- Data handling, format and chi2 calculation remain largely the same (but there are changes)
- Nicely summarized in this talk by S. Glazov
- Picture taken from Ivan Novikov's talk



xFitter usage in the HEP comunity

- xFitter is the **tool of choice for PDF/QCD analyses by the LHC Collaborations**

- **ATLAS**:
  - PDF fit from diverse ATLAS data at $\sqrt{s}$ = 7, 8 and 13 TeV - EPJC 82 (2022) 5 438

- **Drell-Yan phenomenology:**
  - PDF impact of A_{FB} in NC Drell-Yan events - JHEP 10 (2019) 176
  - PDF sensitivity of the longitudinal Z-boson polarisation - Phys.Lett.B 821 (2021) 136613
  - PDF sensitivity to A_{FB} and A_W in Drell-Yan for Precision EW Measurements and New Physics Searches - Nucl.Phys.B 968 (2021) 115444
  - Enhancing the LHC sensitivity to broad W'/Z' resonances of new gauge sectors - JHEP 02 (2022) 179, PLB 841 (2023) 137915

- Important contribution in **several ongoing activities of the LHC EW WG**:
  - **Correlations between different PDFs** trough pseudo-data fits
  - ATLAS/CMS/LHCb $\sin^2\theta^l_{eff}$ **pseudo data** and combination exercise
  - Tevatron/ATLAS (and in future LHCb and CMS) m_W **combination**

- α_S **extraction** from Z boson transverse momentum distribution - 2203.05394, ATLAS-CONF-2023-015

List of exercises

- **Exercise 1:** PDF fit
  - learn the basic settings of a QCD analysis, based on HERA data only
- **Exercise 2:** α_S extraction
  - learn the basic of an α_S extraction using ATLAS Z p_T data
- **Exercise 3:** LHAPDF analysis
  - how to estimate impact of a new data without fitting
  - basis on profiling and reweighting techniques

Other useful/interesting exercise you might want to have a look at in backup:

- **Exercise 4:** Including small-x resummation correction in a PDF fit
- **Exercise 5:** Adding your preferred PDF parametrization
- **Exercise 6:** Fit to final combined HERAI+II data and ATLAS W,Z data at 7 TeV
  - strange-quark density: fixed vs free r_s
  - unsuppressed strange at low-x
- **Exercise 7:** Charged pion PDF
- **Exercise 8:** Charged pion Fragmentation Functions (FFs)
- **Bonus:** how to generate fixed-order predictions (key ingredient of a PDF fit)

$$r_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

Overview

- Each exercise in a separate directory: `~/xFitterTutorial/`
  - `exercise1`
  - `exercise2`
  - `exercise3`
  - `exercise4`
  - `exercise5`
  - `exercise6`
  - `exercise7`
  - `exercise8`
- You can find the xFitter manual and this tutorial in `~/xFitterTutorial/DOC`
  - `DOC/xFitter_Manual.pdf`
  - `DOC/xFitter_Tutorial.pdf`
- All these exercises (with many more examples) can be found here
- Updated Wiki to help users, with also the list of existing JIRAs
- If you cannot find an answer to your question, **create a new JIRA ticket**, with issue type "Question"

Input files for a xFitter run

- Each time we run xFitter, we need to care about three configuration files:
  - `parameters.yaml`:
    - Minimisers – MINUIT or CERES
    - Settings and commands for MINUIT
    - Define parameters of the PDF parameterization
    - Running mode: PDF fit or LHAPDF analysis
    - QCD order (NLO or NNLO)
    - Heavy flavor scheme (TR, ACOT, FONLL, etc.)

```
Minimizer: MINUIT # CERES
CERES:
  offset: 2
  tolerance: 1e-5
  strategy: 0
  covariance: 1
```

(CERES instructions since the tutorial uses MINUIT)

  - `steering.txt`:
    - List of data sets
    - χ^2 settings
  - `constants.yaml`:
    - EW and SM input parameters e.g. couplings, quark masses etc.

General structure of the exercise

- Each exercise has all the necessary inputs and datafiles for running xFitter
- The results will be saved in the '`output`' directory for further manipulation
- Before every exercise, in order to set up environmental variables, do
  `$> source ~/Software/setup.sh`
- To run xFitter, in the exercise folder type **`$> xfitter`**
- To draw graphical visualisation of the results: **`$> xfitter-draw output`**
  - Many drawing options! Type **`$> xfitter-draw --help`** to see all of them
- Post-fit and pre-fit manipulation of the LHAPDF files: **`$> xfitter-process`** (needed for exercise3 in backup)
  - Many modules available! Type **`$> xfitter-process --help`** to see all of them
    - `profile` – to be used with Hessian PDF eigenvectors error sets
    - `reweight` – to be used with NNPDF-style PDF sets (MC replicas)
    - `scale90to68` – scale PDF error bands from 90% CL to 68% CL
    - `rotate` – obtain a PDF set which members are sorted according to their sensitivity to particular data
    - `symmetrize` – produces symmetric bands out of hessian PDF set

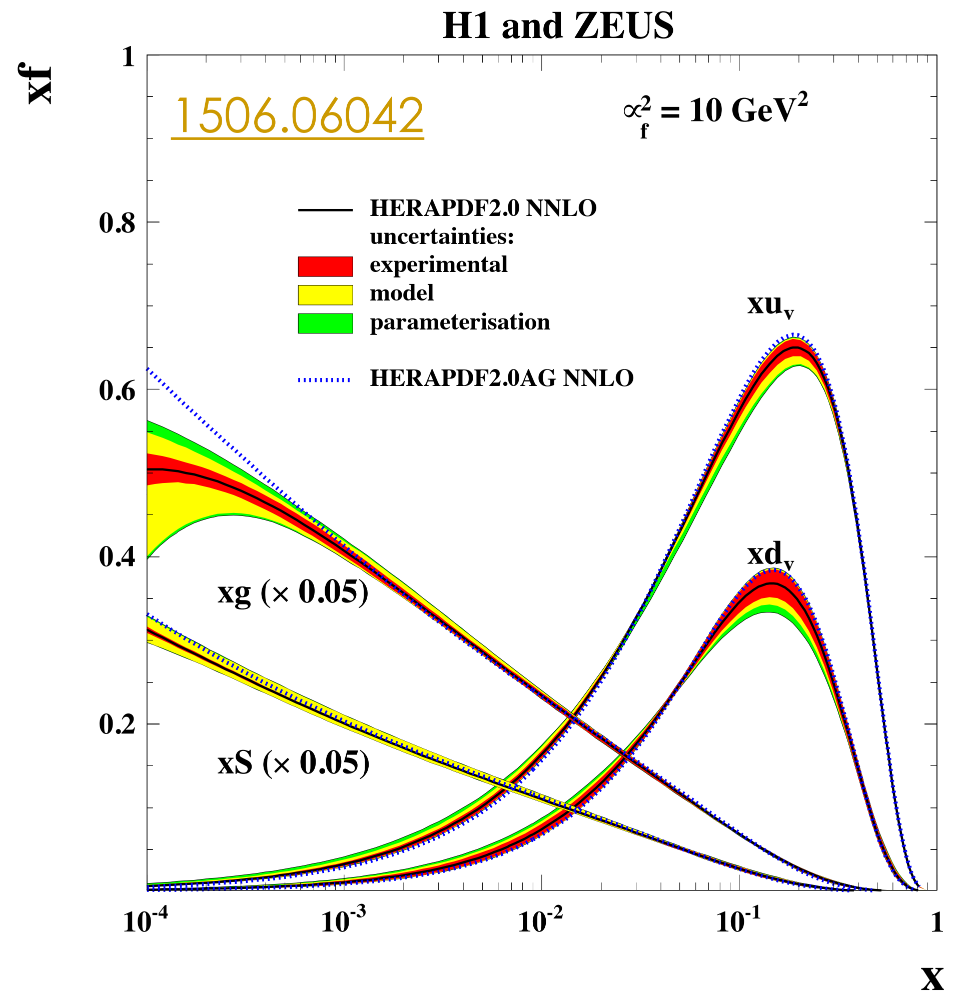
EXERCISE 1

PDF fit

Exercise 1

- **Purpose:** Learn the basic settings of a QCD analysis and reproduce the results of the HERAPDF2.0 fit
- **Data set:** Final combined HERAI+II DIS data
- **QCD order:** NNLO

This data set is very important! **Backbone of all modern PDF fits**



Exercise 1 - settings

- `$> cd ~/xFitterTutorial/exercise1`

- Final combined HERAI+II DIS data in `steering.txt`

```
&InFiles
  ! Number of intput files
    NInputFiles = 7

  ! Input files:

     InputFileNames =
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCep_920-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCep_820-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCep_575-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCep_460-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCem-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_CCep-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_CCem-thexp.dat',

&End
```

- FYI you can add as many data sets as you want! The fit will take longer ☺ have a look at this example

The structure of a xFitter datafile - DIS

```
&Data
  Name = "HERA1+2 NCep 460"
  IndexDataset = 106
  Reaction = "NC e+-p"

  TermName = 'R'
  TermSource = 'use:hf_scheme_DISNC'
  TermInfo = 'type=sigred:flav=incl:echarge=1:epolarity=0' ! in CInfo there was also "YSWIMEXP" = 1.0
  TheorExpr = 'R'

  NData =   210
  NColumn =   176
  ColumnType = 3*"Bin","Sigma", 172*"Error"
  ColumnName = "Q2","x","y","Sigma", "stat", "uncor","sysHZComb1001","sysHZComb1002","sysHZComb1003","sysHZComb1004","sysHZComb1005",
  Percent = 172*true
&End
```

- ‘`Name`’ provides the name of the data set
- ‘`IndexDataset`’ is an internal index of the data set (provide unique numbers to get extra χ^2 info)
- ‘`Reaction`’ indicates the reaction type of the data set (used to trigger the corresponding theory calculation)
- ‘`NData`’ specifies the number of data points in the file
- ‘`NColumn`’ is the number of columns in the data table
- ‘`ColumnType`’ defines layout of the data table: *Bin, Sigma, Error and Ignored*
- ’`ColumnName`’ defines names of the columns (e.g. x, Q^2 and y are required for DIS NC xsec)
  - If `ColumnType = Sigma`, it provides a label for the observable
  - If `ColumnType = Error`, the following names have special meaning: *stat, uncor and total*
    - Other names specify columns of correlated systematic uncertainties (e.g. each column of the correlated uncertainty must have unique name)
- ‘`Percent`’ tells if an uncertainty is given in absolute (false) or in percent (true)

The structure of a xFitter datafile - LHC

Gitlab repository

```
TermName = 'A','K'
TermSource = 'APPLgrid','KFactor'
TermInfo = 'GridName=datafiles/lhc/atlas/wzProduction/1612.03016/grid-40-6-15-3-Z0_zypeak_cc.root',
           'FileName=datafiles/lhc/atlas/wzProduction/1612.03016/kf.zypeak_cc.txt:FileColumn=3'
TheorExpr = 'K*A/1000'
```

- '**`TermName`**' gives names of terms used in the theory expression
- '**`TermSource`**' might be:
  - `KFactor` → term which denotes an array of K-factors corresponding to the data bins
  - `APPLgrid, FastNLO, …` → this term tells the parser to initialize the correct theory reaction for the cross section evaluation
  - `VirtGrid` → it can be used if the fit is performed using multidimensional measurements (here, each row denotes a single bin of the cross section and, the APPLGRID file location and number of bins in it)

```
# y1    y2    applgrid                                       n_grid_bins
0.0     0.3   theoryfiles/atlas/Jets2010-vg/R04/eta1.root    17
0.3     0.8   theoryfiles/atlas/Jets2010-vg/R04/eta2.root    17
0.8     1.2   theoryfiles/atlas/Jets2010-vg/R04/eta3.root    17
1.2     2.1   theoryfiles/atlas/Jets2010-vg/R04/eta4.root    16
2.1     2.8   theoryfiles/atlas/Jets2010-vg/R04/eta5.root    13
```

- '**`TermInfo`**' gives paths from where the term numerical values should be taken
- '**`TheorExpr`**' is the theory expression in simple algebraic form

The structure of a xFitter datafile - Plot

```
&PlotDesc
        PlotN = 1
        PlotDefColumn = 'y_max'
        PlotDefValue = 0., 5.
        PlotOptions(1)  = 'Experiment:ATLAS@ExtraLabel:pp #rightarrow Z; #sqrt{s} = 7 TeV; #int L = 4.7 fb^{-1}@Title: 66 < M_{Z} < 116
&End                                                                                     @XTitle: y @YTitle: d#sigma/dy [pb] '
```

- ‘**`PlotN`**’ tells us the number of of distributions to be plotted
- ‘**`PlotDefColumn`**’ is the variable name you want to plot
- ‘**`PlotDefValue`**’ specifies the x-axis range of the variable you’re plotting
- ‘**`PlotOptions`**’ are several plotting options to have some graphical improvement and labels on the standard xFitter plots in output

Exercise 1 - settings

- The PDF parametrisation is set in parameters.yaml

```
Parameterisations:
  par_uv:
    class: HERAPDF
    parameters: [Auv,Buv,Cuv,Duv,Euv]
  par_dv:
    class: HERAPDF
    parameters: [Adv,Bdv,Cdv]
  par_ubar:
    class: HERAPDF
    parameters: [Adbar,Bdbar,Cubar,Dubar]
  par_dbar:
    class: HERAPDF
    parameters: [Adbar,Bdbar,Cdbar]
  par_s: # s=fs/(1-fs) * Dbar
    class: Factor
    factor: DbarToS #name of parameter
    input: par_dbar
  par_g:
    class: NegativeGluon
    parameters: [Ag,Bg,Cg,ZERO,ZERO,Agp,Bgp,Cgp]
```

```
DefaultDecomposition: proton
Decompositions:
  proton:
    class: UvDvUbarDbarS
    xuv: par_uv
    xdv: par_dv
    xubar: par_ubar
    xdbar: par_dbar
    xs: par_s
    xg: par_g
```

equivalent to…

```
#par_s:
  #class: Expression
  #expression: "Adbar*fs/(1-fs)*(x^Bdbar*(1-x)^Cdbar)"
# Another example for Expression parameterisation
#par_g:
  #class: Expression
  #expression: "Ag*(x^Bg*(1-x)^Cg-Agp*x^Bgp*(1-x)^Cgp)"
```

- HERAPDF-like PDF parametrisation:

$$Ax^{B}(1-x)^{C}(1+Dx+Ex^{2}) - \underbrace{A'x^{B'}(1-x)^{C'}}$$

  - Sum rules
  - Asymptotic behaviour
  - To better model the high-x region

Just for the gluon PDF ($C'_g = 25$) to suppress negative contributions at high-x

Exercise 1 - settings

- The starting values of the parameters are set in parameters.yaml

```
Parameters:
  Ag    :  DEPENDENT
  Bg    : [ -0.061953, 0.27  ]
  Cg    : [  5.562367, 0.32  ]
  Agp   : [  0.166092, 0.01  ]  # negative gluon ....
  Bgp   : [ -0.383100, 0.01  ]
  Cgp   : [ 25.0,      0.    ]  # fix C of negative gluon
  Auv   :  DEPENDENT
  Buv   : [  0.810476, 0.016 ]
  Cuv   : [  4.823512, 0.06  ]
  Euv   : [  9.921366, 0.8   ]
  Adv   :  DEPENDENT
  Bdv   : [  1.029995, 0.06  ]
  Cdv   : [  4.846279, 0.3   ]
  CUbar: [  7.059694, 0.8   ]
  DUbar: [  1.548098, 1.0   ]
  ADbar: [  0.26883,  0.01  ]
  BDbar: [ -0.1273,   0.004 ]
  CDbar: # another example of providing value, step etc.
    value: 9.586246
    step: 1.2345
    #min
    #max
    #pr_mean
    #pr_sigma
  ZERO : [ 0. ]          # zero
  fs   : [ 0.4, 0.0 ]
  fd   : "=1-fs"
  AUbar: "=(1-fs)*ADbar"
```

- The first number is the starting value, the second number the step size in the minimisation (if set to 0, the parameter is fixed)
- You can also define parameters as a function of other parameters i.e. AUBar

Another possible way to provide values, step, etc.

Exercise 1 - settings

- Settings for PDFs as output of the fit in `steering.txt`

```
&Output
  ! -- Q2 values at which the pdfs & errors are done (up to 20)
  Q2VAL = 1.9, 3.0, 4.0, 5., 10., 100., 6464, 8317
!  Q2VAL = 1.9, 4., 10., 100., 6464, 8317

  ! How many x points to write (standard = 101)
  OUTNX = 101

  ! x-range of output (standard = 1E-4 1.0)
  OUTXRANGE = 1E-4, 0.9999

  ! Write out LHAPDF5 output
  ! WriteLHAPDF5 = false
&End
```

There's also a 'binFlag' in the datafiles:

0 → bin not included in the fit

1 → bin included in the fit

- Process dependent cuts in `steering.txt`

```
!--------------------- CC ep -----------------

 ProcessName(3)      = 'CC e+-p'
 Variable(3)         = 'Q2'
 CutValueMin(3)      = 3.5
 CutValueMax(3)      = 1000000.0

 ProcessName(4)      = 'CC e+-p'
 Variable(4)         = 'x'
 CutValueMin(4)      = 0.000001
 CutValueMax(4)      = 1.0
```

← Should be identical to 'Name' in the datafile (ProcessName)

← Should be one of the variable name ('ColumName') in the datafile (Variable)

Exercise 1 - settings

- We want to perform a PDF fit…
- … So we will use the option '`DefaultEvolution: proton-QCDNUM`' in `parameters.yaml`

```
DefaultEvolution: proton-QCDNUM

Evolutions:
  proton-QCDNUM:
    ? !include evolutions/QCDNUM.yaml
    decomposition: proton #this could be omitted, as the default decomposition is set
```

- The QCD perturbative order is set in `parameters.yaml` as well:

```
# QCD parameters
Order: NNLO
NFlavour: 5
isFFNS: 0
Q0 : 1.378404875209 # Initial scale =sqrt(1.9)
alphas : 0.118

? !include constants.yaml
```

Q_0 is the starting scale where we parametrize PDFs

- Here you can see other parameters as well i.e. number of flavours, Q_0, α_S value etc. – this will overwrite what you have in constants.yaml (leaving everything else unchanged)

Exercise 1 - settings

- The Heavy Flavour scheme is set in `parameters.yaml`

```
# Specify HF scheme used for DIS NC processes:
hf_scheme_DISNC :
  defaultValue : 'RT_DISNC'        # global specification
#  defaultValue : 'BaseDISNC'       # global specification
#  defaultValue : 'FONLL_DISNC'     # global specification
#  defaultValue : 'FFABM_DISNC'
#  'HERA1+2 NCep 920' : 'BaseDISNC' # datafile specific (based on name)
#  1 : BaseDISNC
#  'HERA1+2 NCep 920' : 'Fractal_DISNC'  # Fractal model. Add parameters file if you want to try it (see above)

# Specify HF scheme used for DIS CC processes:
hf_scheme_DISCC :
  defaultValue : 'BaseDISCC'       # global specification
#  defaultValue : 'FONLL_DISCC'     # global specification
#  defaultValue : 'FFABM_DISCC'     # global specification
```

- Several mass schemes available in DIS:
  - ZM-VFNS
  - ACOT
  - FONLL
  - TR
  - FFNS

Exercise 1 - settings

- To do a real fit with proper MINUIT minimisation:

```
MINUIT:
  Commands: |
   call fcn 1
   set str 2
   call fcn 3
   migrad
   hesse
   call fcn 3
```

minimisation (migrad, hesse)

- To run just 3 iterations:

```
MINUIT:
  Commands: |
    set str 2
    call fcn 3
```

PDF errors – 3 options:

- Pumplin – Eq. 43 of hep-ph/0611148 (asymmetric)
- Hesse – symmetric version of Pumplin
- None – no error bands evaluation

Regulated by `doErros: ###`

- To obtain datafiles: `$> ln -s ~/Software/xfitter-master/datafiles .`
- To run xFitter: `$> xfitter`
- To draw your results: `$> xfitter-draw output`
- To see the full list of plotting options: `$> xfitter-draw --help`

The output folder

- You can modify the folder name by changing `OutputDirectory: "output"`
- '`Status.out`' tells us if the fit has converged (OK) or not (Failed)
- '`minuit.out.txt`' contains the information about the MINUIT output of the fit
- '`Results.txt`' shows the global and partial χ^2, as well as the pulls of each systematic uncertainty present in the fit
- '`parsout_0`' contains the ouput fit parameters (and their associated errors) in MINUIT format
- '`fittedresults.txt`' shows the comparison between data and fit predictions for each data point
- The '**proton**' contains the output PDFs in LHAPDF format
  - You can modify the name in `parameters.yaml`

```
WriteLHAPDF6:
  name: "proton"
  description: "..."
  authors: "..."
  reference: "..."
```

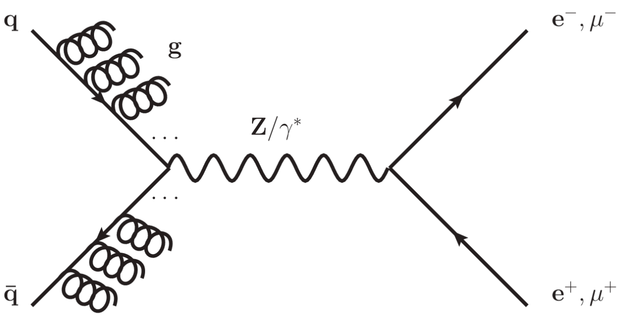
- '`pdfs_q2val_0*.txt`' are .txt files with the PDF values at different Bjorken x ('01' represents the starting scale, and then you have one file for each scale defined in the steering card → Q2VAL)

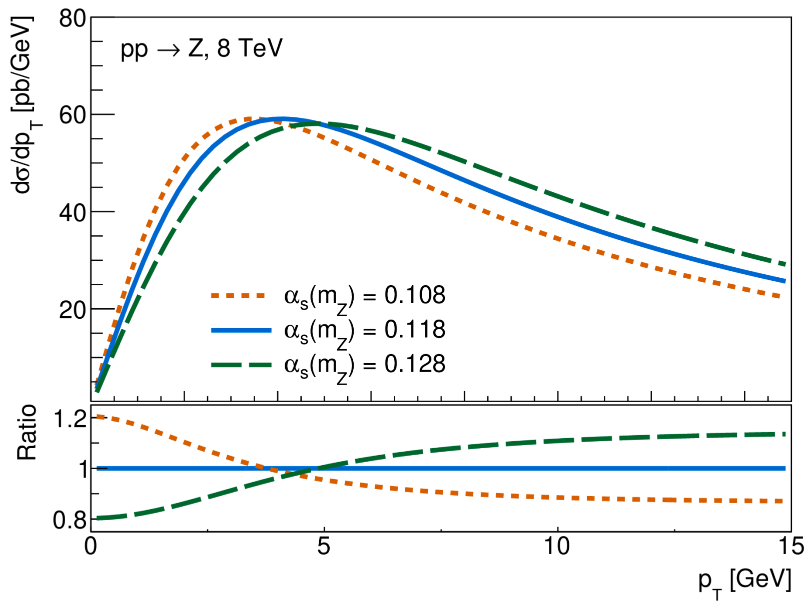
EXERCISE 2

α_S extraction from ATLAS Z p_T data

Exercise 2

- **Purpose:** Learn the basics of an α_S extraction
- **Data set:** Final combined HERAI+II DIS data + ATLAS 8 TeV Z p_T data (ATLAS-CONF-2023-013) – see backup for more details
- **QCD order:** $N^3LL + N^3LO$ (through DYTurbo predictions)
- Strong coupling constant $\boldsymbol{\alpha_S}$ is the **least well known in nature**
- **Dominant uncertainties** to precision measurements of **Higgs coupling** at LHC or **EW precision observables** at e^+e^- colliders
- Non-zero value of Z p_T arises from initial state radiations from incoming partons due to momentum conservation
- The **peak position of Z p_T** and above is **sensitive to $\boldsymbol{\alpha_S(m_Z)}$**





Exercise 2 - settings

- `$> cd ~/xFitterTutorial/exercise2/`

- We added the ATLAS 8 TeV Z p_T data on top of the final combined HERAI+II DIS data in `steering.txt`

```
'datafiles/lhc/atlas/zptfull8tev/zpt_y00_bwi.dat',
'datafiles/lhc/atlas/zptfull8tev/zpt_y01_bwi.dat',
'datafiles/lhc/atlas/zptfull8tev/zpt_y02_bwi.dat',
'datafiles/lhc/atlas/zptfull8tev/zpt_y03_bwi.dat',
'datafiles/lhc/atlas/zptfull8tev/zpt_y04_bwi.dat',
'datafiles/lhc/atlas/zptfull8tev/zpt_y05_bwi.dat',
'datafiles/lhc/atlas/zptfull8tev/zpt_y06_bwi.dat',
'datafiles/lhc/atlas/zptfull8tev/zpt_y07_bwi.dat',
```

- Additional datasets which have sensitivity to α_S (i.e. CDF Z p_T data) can be downloaded using the **`./tool/xfitter_getdata.sh`** script

- Very easy to use! `./tool/xfitter_getdata.sh arXiv_number`

- To see available data sets: `./tool/xfitter-getdata.sh --print`

Exercise 2 – Z p_T datafiles

- Open e.g. `./datafiles/lhc/atlas/zptfull8tev/zpt_y00_bwi.dat`

```
Reaction =    'NC pp'
TheoryType     = 'expression'
TermName = 'A1','K','C'
TermSource = 'DYTurbo','KFactor','KFactor'
TermInfo = 'FileName=datafiles/lhc/atlas/zptfull8tev/dyturbo/z-8tev-y00-n3ll.in',
       'FileName=datafiles/lhc/atlas/zptfull8tev/qedisr/qedisr_zpt_y00.txt:FileColumn=3',
       'FileName=datafiles/lhc/atlas/zptfull8tev/mcfm/afactor/n3lo-afactor-y00.txt:FileColumn=3'
TheorExpr= '(2*A1+C)*K*0.996/1000'
```

- Note the kind of reaction → ‘`NC pp`’ (Neutral Current production in pp collisions)
- ‘`TermSource = DYTurbo`’ thanks to a direct interface to xFitter
- The first file is literally a DYTurbo input file
- Additional k_F to take into account e.g. ISR QED corrections or missing N^3LO QCD contributions

Exercise 2 - settings

- We add the statistical correlation matrices in `steering.txt`

```
&InCorr
  ! Number of correlation (statistical, systematical or full) files
    NCorrFiles = 36

  ! Correlation files:
    CorrFileNames(1) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y0_y0.corr',
    CorrFileNames(2) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y0_y1.corr',
    CorrFileNames(3) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y0_y2.corr',
    CorrFileNames(4) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y0_y3.corr',
    CorrFileNames(5) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y0_y4.corr',
    CorrFileNames(6) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y0_y5.corr',
    CorrFileNames(7) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y0_y6.corr',
    CorrFileNames(8) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y0_y7.corr',
    CorrFileNames(9) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y1_y1.corr',
    CorrFileNames(10) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y1_y2.corr',
    CorrFileNames(11) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y1_y3.corr',
    CorrFileNames(12) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y1_y4.corr',
    CorrFileNames(13) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y1_y5.corr',
    CorrFileNames(14) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y1_y6.corr',
    CorrFileNames(15) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y1_y7.corr',
    CorrFileNames(16) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y2_y2.corr',
    CorrFileNames(17) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y2_y3.corr',
    CorrFileNames(18) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y2_y4.corr',
    CorrFileNames(19) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y2_y5.corr',
    CorrFileNames(20) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y2_y6.corr',
    CorrFileNames(21) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y2_y7.corr',
    CorrFileNames(22) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y3_y3.corr',
    CorrFileNames(23) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y3_y4.corr',
    CorrFileNames(24) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y3_y5.corr',
    CorrFileNames(25) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y3_y6.corr',
    CorrFileNames(26) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y3_y7.corr',
    CorrFileNames(27) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y4_y4.corr',
    CorrFileNames(28) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y4_y5.corr',
    CorrFileNames(29) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y4_y6.corr',
    CorrFileNames(30) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y4_y7.corr',
    CorrFileNames(31) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y5_y5.corr',
    CorrFileNames(32) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y5_y6.corr',
    CorrFileNames(33) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y5_y7.corr',
    CorrFileNames(34) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y6_y6.corr',
    CorrFileNames(35) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y6_y7.corr',
    CorrFileNames(36) = 'datafiles/lhc/atlas/zptfull8tev/corr/zpt_y7_y7.corr',
&End
```

- The general format of correlation matrices
  - `'Name1,Name2'` are the dataset name(s)
  - `'IdColumns'` are the variables i.e. p_T, m_{ll}, etc.
  - `'NBins'` are the number of bins for each variables
  - You need to specify the kind of correlation (i.e. you ca also have `'Full covariance matrix'`)
  - The input format is very easy to understand!

```
&StatCorr
Name1 = 'ATLAS 1D ttbar vs ptavt 13 TeV'
Name2 = 'ATLAS 1D ttbar vs mtt 13 TeV'

NIdColumns1 = 2
NIdColumns2 = 2

IdColumns1 = 'ptlow','pthigh'
IdColumns2 = 'mtt1','mtt2'

NBins1 = 2
NBins2 = 3

MatrixFormatIsTable = true

MatrixType = 'Statistical correlations'
&End
0      0     325    400    480
0      0     400    480    580
0     50     0.5    0.2   -0.07
50   100     0.5    0.4    0.07
```

Exercise 2 - settings

- Let's also have a look at the DYTurbo part in `parameters.yaml`

```
DYTurbo:
  #? !include reactions/DYTurbo.yaml
   order: 3    # Perturbative order in QCD: 0 for LL, 1 for NLL+NLO, 2 for NNLL+NNLO, 3 for NNNLL+NNLO
   muR: 1.     # Renormalization scale
   muF: 1.     # Factorization scale
   muRes: 1.   # Resummation scale
   g1: 0.66       # Universal Gaussian non-perturbative form factor
   g2: 0       # Q-dependent Gaussian non-perturbative form factor
   g3: 0       # x-dependent Gaussian non-perturbative form factor
   q: 0.1      # quartic term
   debug: 0
```

- g_1, g_2 and g_3 regulates a non-perturbative form factor which affects the region of Z $p_T < 5$ GeV

- q regulates the quartic term

- **g_1 and q are free parameters of the fit!** Constrained by data

```
DYTurbo/g1: [    0.488881,     0.0434729   ]
DYTurbo/q:  [   -0.187143,     0.0296958   ]
```

$$S_{\rm NP}(b) = \exp\left[-g_j(b) - g_K(b)\log\frac{m_{\ell\ell}^2}{Q_0^2}\right]$$

$$g_j(b) = \frac{g\,b^2}{\sqrt{1+\lambda\,b^2}} + \mathrm{sign}(q)\left(1-\exp\left[-|q|\,b^4\right]\right)$$

$$g_K(b) = g_0\left(1-\exp\left[-\frac{C_F\alpha_s(b_0/b_*)b^2}{\pi g_0\,b_{\rm lim}^2}\right]\right)$$

Exercise 2 - settings

- We have to free the $\alpha_s(m_Z)$ parameter in `parameters.yaml`

```
alphas: [    0.117178,    0.000417857    ]
```

- We want to do a real MINUIT minimisation fit, so:

```
MINUIT:
  Commands: |
   call fcn 1
   set str 2
   call fcn 3
   migrad
   hesse
   call fcn 3

  doErrors : Hesse # None
```

EPJ Plus (2019) 134, 531

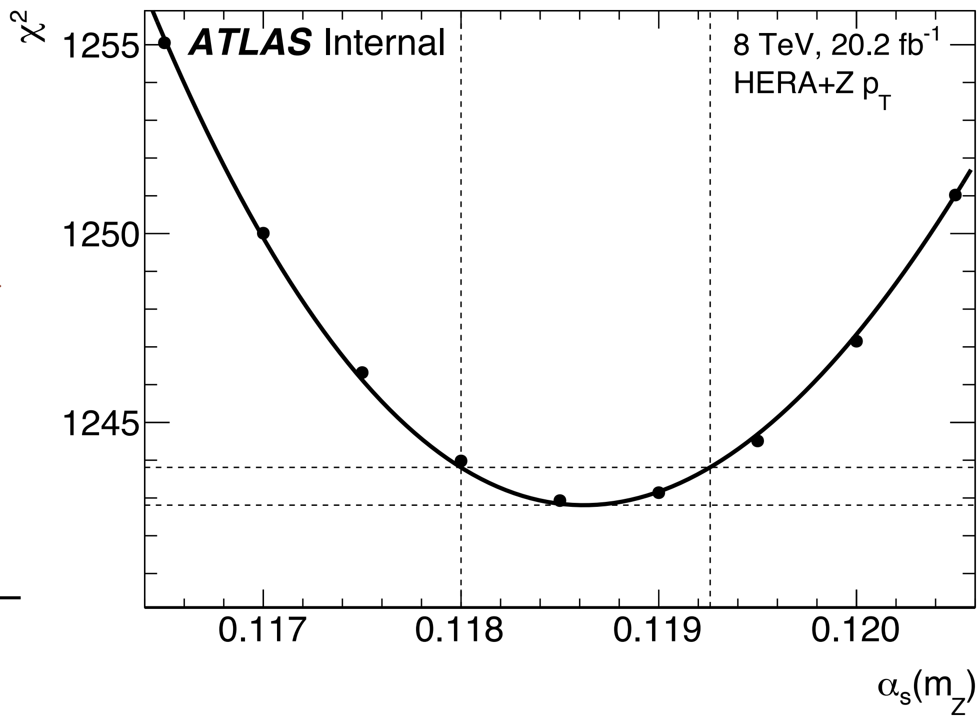
> As regards the PDF parametrisation, we adopt one with more flexibility at low x - see Exserice 5 in backup!

- To obtain datafiles: `$> ln -s ~/Software/xfitter-master/datafiles .`
- To run xFitter: `$> xfitter`
- To draw your results: `$> xfitter-draw output_PDF_aS`
- Bonus: you can also run separate fits with fixed values of α_s (see next slide)
  - In this way we can check the correlation between α_s and the gluon PDF

Exercise 2 - results

ATL-COM-PHYS-2023-076

- $\alpha_s(m_Z) = 0.118616 \pm 0.000757$
- Now we can compare the results with what has been found in the:
  - N³LO+N³LL scan
  - $\alpha_s(m_Z)$ determination based on aN⁴LL+N³LO predictions



Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088

$$\alpha_s(m_Z) = 0.11828^{+0.00084}_{-0.00088}$$

$$\alpha_s(m_Z) = 0.11866 \pm 0.00064$$

(from the $\Delta\chi^2 = 1$ criterion)

All the three approaches give consistent results!

EXERCISE 3

LHAPDF analysis

Exercise 3

- **Purpose:** Learn how to include a new dataset into an existing PDF set, without redoing a PDF fit (profiling/reweighting) – a very simple exercise which can be nicely put in a paper

- **Data set:** Tevatron W-boson charge asymmetry

- **QCD order:** NLO

- PDF sets from LHAPDF stored in `~/Software/deps/lhapdf/share/LHAPDF/`

- LHAPDF is a convenient library for the generic interpolation of PDFs as functions of x and Q^2

- PDFs are saved in tables of PDF values at fixed points in x and Q^2, and fast interpolation functions allow to access the PDFs at any other value

- To download from PDF sets in LHAPDF format:

```
$> cd ~/Software/deps/lhapdf/share/LHAPDF/
$> lhapdf --pdfdir=./install HERAPDF20_NNLO_EIG (VAR)
$> export LHAPATH=‘pwd’/:$LHAPATH
```

Exercise 3 - settings

- Settings for running a LHAPDF Analysis in `parameters.yaml`
- We need to specify that we want to use LHAPDF evolution

```
DefaultEvolution: proton-QCDNUM

Evolutions:
  proton-QCDNUM:
    ? !include evolutions/QCDNUM.yaml
    decomposition: proton #this could be omitted, as the default decomposition is set
    # The following allows QCDNUM to read PDFs from other evolutions:
    EvolutionCopy: "proton-LHAPDF"
  proton-LHAPDF:
    class: LHAPDF
    set: "HERAPDF20_NNLO_EIG"
    member: 0
```

Here you specify the LHAPDF set you want to use

Profiling methodology

- The inclusion of new data into an existing PDF set can be done with a Hessian profiling technique
- We define a χ^2 with theory uncertainties (β_{th} represent the PDF uncertainties)

$$\chi^2(\beta_{exp}, \beta_{th}) = \chi^2_{exp} + \boldsymbol{\chi^2_{th}}$$
$$= \sum_{i=1}^{N_{data}} \frac{\left(\sigma_i^{exp} + \sum_j \Gamma_{ij}^{exp} \beta_{j,exp} - \sigma_i^{th} - \sum_k \Gamma_{ik}^{th} \beta_{k,th}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,exp}^2 + \sum_k \boldsymbol{\beta_{k,th}^2}$$

- Find the $\beta_{k,th}$ which minimised the χ^2 on the new data
- The fit is done by solving a system of liner equations
- Reinterpret the $\beta_{k,th}^2$ shifts as optimisation of the PDFs

Exercise 3 - settings

- `$> cd ~/xFitterTutorial/exercise3/`

- The Tevatron W asymmetry data sets and correlations files are set in `steering.txt`

```
&InFiles
  ! Number of intput files
    NInputFiles = 2

  ! Input files:

    InputFileNames =
    'datafiles/tevatron/cdf/wzProduction/0901.2169/CDF_W_asymmetry-thexp.dat',
    'datafiles/tevatron/d0/wzProduction/1312.2895/D0_W_asymmetry-thexp.dat',
&End

&InCorr
  ! Number of correlation (statistical, systematical or full) files
    NCorrFiles = 1

  ! Correlation files:
    CorrFileNames(1) = 'datafiles/tevatron/d0/wzProduction/1312.2895/D0_W_asymmetry.corr'
&End
```

- We also include a correlation matrix to take statistical correlation into account (see Exercise 2 for more details)

Exercise 3 - settings

- We follow the instructions described in the xFitter twiki

```
Profiler:
  Evolutions:
    proton-LHAPDF:
      sets: [HERAPDF20_NNLO_EIG, HERAPDF20_NNLO_VAR, HERAPDF20_NNLO_VAR]
      members: [,[0,1,10],[0,11,13]] # when omitted, default members is [0,1,end]
      error_type_override: [None,hessian,symmhessian] # treat parametrisation variations (members 11-13
  Status: "On"                 # "Off" to turn off profiler
  WriteTheo: "Asymmetric"      # Can be "Off", "On" or "Asymmetric" (to store asymmetric variations)
  getChi2: "On"                # determine and report chi2 for each variation
```

- Remember to set `enableExternalProfiler:"On”` (it creates of additional files, needed for `xfitter-draw` command)

- PDFs are taken from LHAPDF, so there is no need to specify a parametrisation in parameters.yaml file

- We also enable the treatment of asymmetric PDF uncertainties with ‘`WriteTheo`’ and we get the χ^2 at every single iteration (‘`getChi2`’)

Exercise 3 – produce a new PDF set

- To produce a new PDF set in LHAPDF format

```
$> xfitter-process profile output/pdf_shifts.dat output/pdf_rotate.pdf
output/HERAPDF20nnlo/ HERAPDF20nnlo-TevatronW
```

- Save the new PDF set into our LHAPDF collection

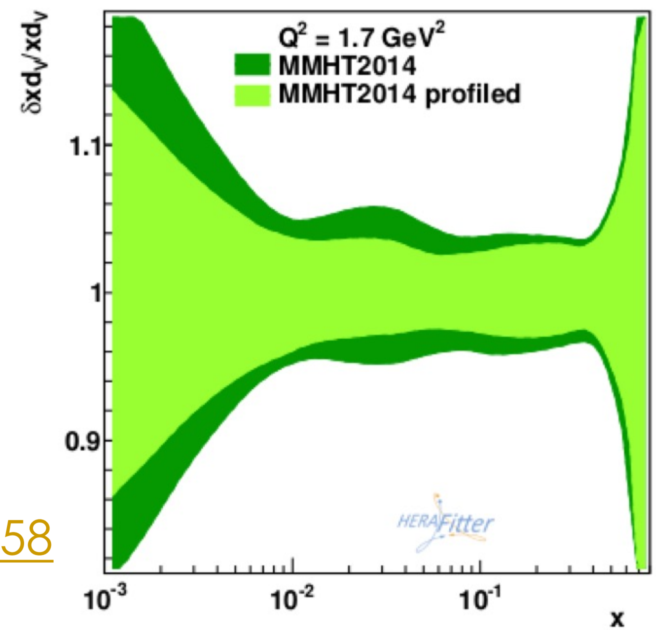
```
$> mv HERAPDF20nnlo-TevatronW ~/Sofyware/deps/lhapdf/share/LHAPDF/
```

- Run a new LHAPDF analysis specifying the new PDF set in `parameters.yaml` file

```
proton-LHAPDF:
  sets: [HERAPDF20nnlo-TevatronW]
```

- To run xFitter: `$> xfitter`

- To draw your results: `$> xfitter-draw HERAPDF20nnlo HERAPDF20nnlo-TevatronW`

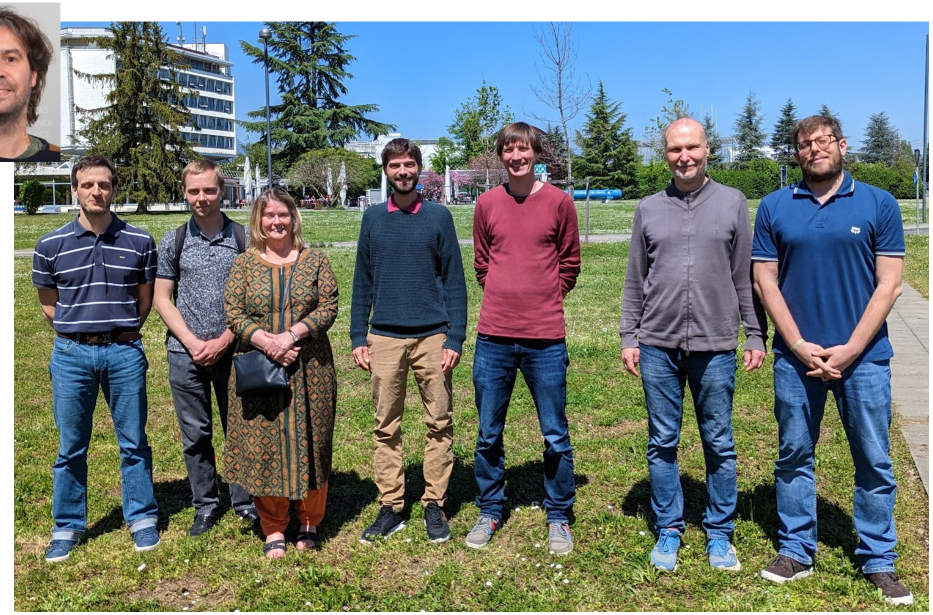


EPJC 75 (2015) 458

Summary

- xFitter is **open-source QCD fit framework!** The program has many settings to address very different problems
- Big efforts have been made to keep the user interface accessible for simple and basic usage
- **Release 2.2.0** now out! (major update of evolution and reaction interfaces)
  - Modular and flexible! More examples in the 'examples' folder
- The PDF world is amazing, fantastic and marvellous! ☺

We are nice people! You should really consider the possibility to join and work with us! ☺



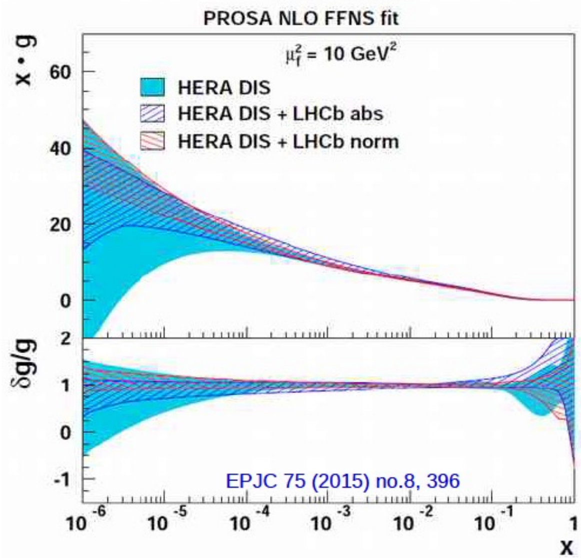
Backup Slides

xFitter usage in the HEP comunity

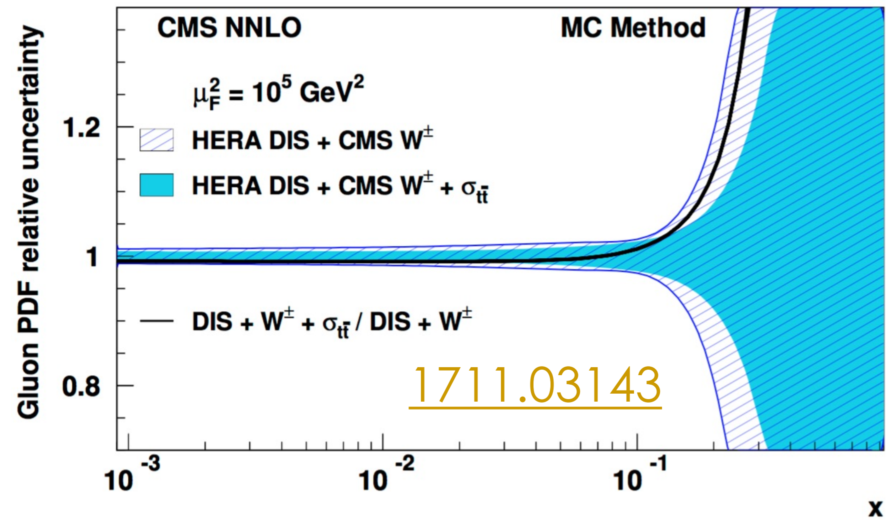
- **CMS**:
  - Multi-differential $t\bar{t}$ cross sections at 13 TeV - EPJC 80 (2020) 7 658
  - Extraction of PDFs, α_S and contact-interactions from new inclusive jet cross section measurement at 13 TeV - JHEP 02 (2022) 142 (more in this talk)
  - W+charm analysis at 8 TeV - 2112.00895
- Strange quark PDF analysis with DIS HERA2 data, ATLAS W,Z cross-sections and ATLAS, CMS W+charm cross-sections - PRD 104 (2021) 7 076004
- NLO analysis of heavy-quark production cross-sections using **different mass renormalisation schemes** - JHEP 04 (2021) 043
- **TMD parton densities** and corresponding parton showers: the advantage of four- and five-flavour schemes - 2106.09791
- Implementation of **target mass corrections and higher-twist effects** in the xFitter framework - PRD 101 (2020) 7 074015
- NNLO PDFs with EW boson data from the LHC (**nuclear PDFs**) - 2112.11904

Results obtained with xFitter: Examples (2)

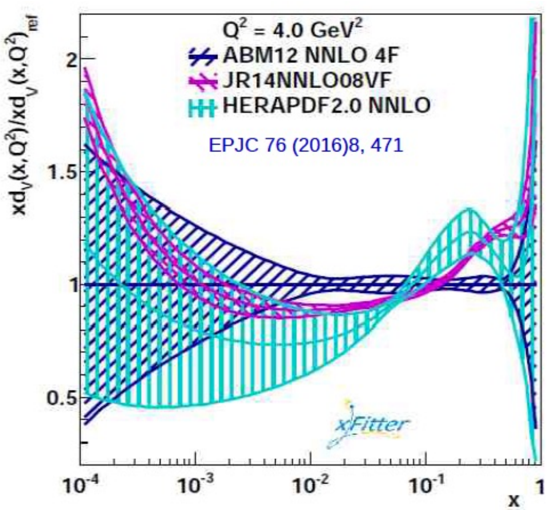
Heavy quark production($ep, pp, p\overline{p}$)



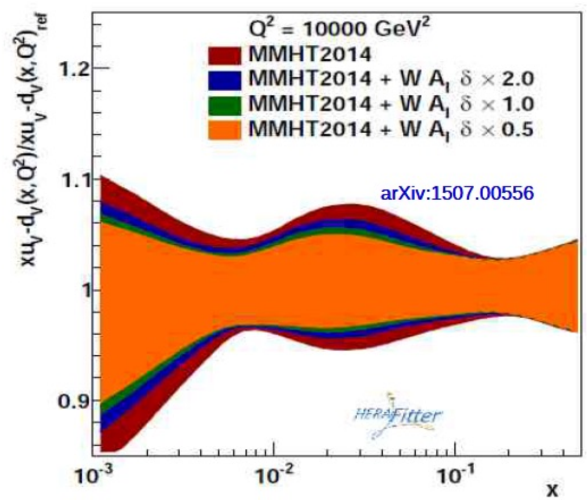
Top-quark production ($pp, p\overline{p}$)



Evolution of moder PDFs (benchmarking)

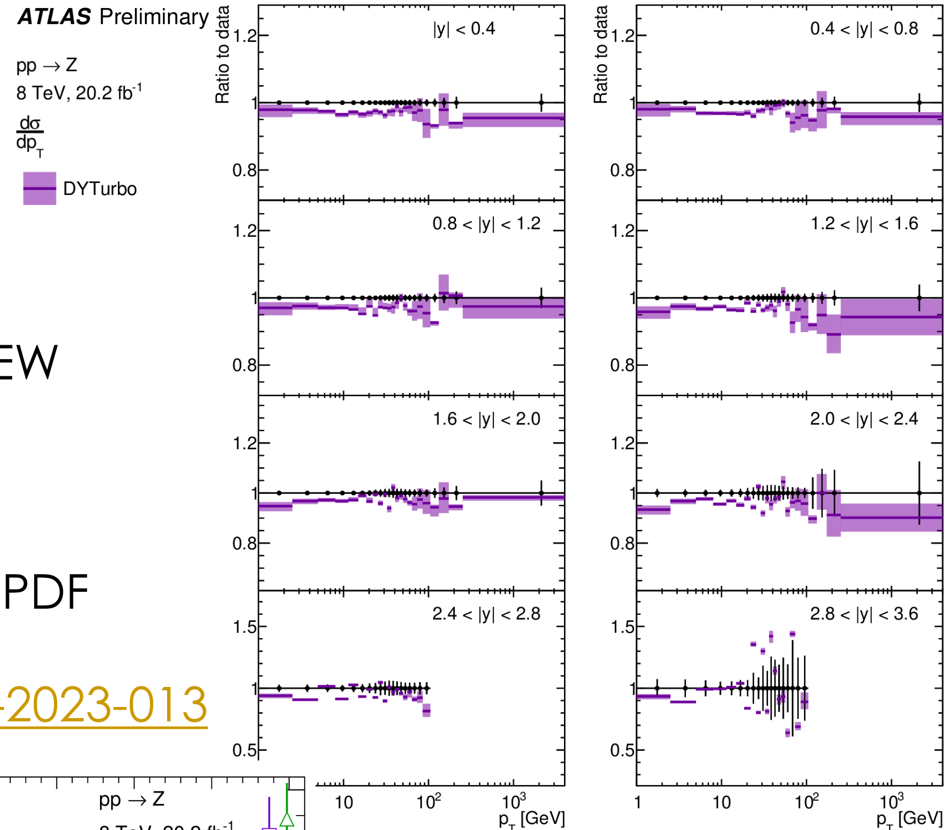


PDF4LHC report (benchmarking)

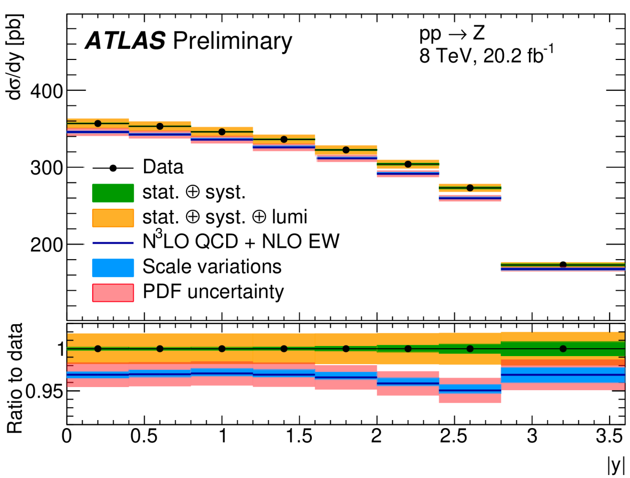


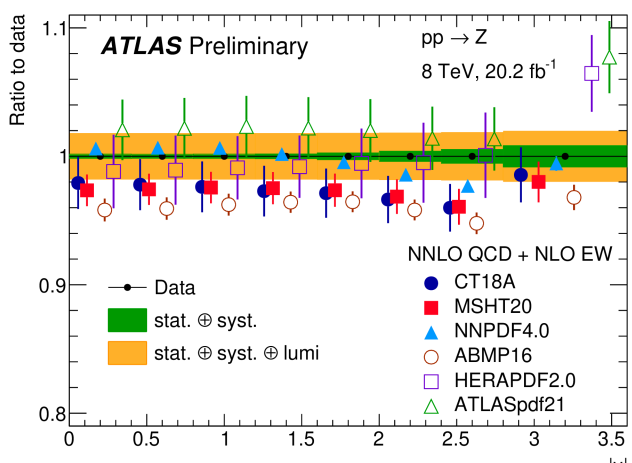
Z p_T and rapidity at 8 TeV

- Per mille level precision in the central region
- Sub-percent precision up to |y| < 3.6
- First comparison to N³LO QCD + NLO EW predictions (DYTurbo + ReneSANCe)
- Allow precise PDF interpretations with QCD scale uncertainties smaller than PDF uncertainties



ATLAS-CONF-2023-013





Good agreement with several high-order qT-resummed predictions

α_S extraction from Z p_T at 8 TeV

- Evaluate $\chi^2(\alpha_S)$ with α_S variations in LHAPDF
  - Include experimental ($\beta_{j,exp}$) and PDF uncertainties ($\beta_{k,th}$) in the $\chi^2(\alpha_S)$ definition
  - For each value of α_S, $\beta_{k,th}$ terms explore the PDF space to find the best fit to Z p_T data
  - aN^{3}LO MSHT20 PDF set is used for the α_S extraction

$$\chi^2(\beta_{\rm exp},\beta_{\rm th}) = \sum_{i=1}^{N_{\rm data}} \frac{\left(\sigma_i^{\rm exp} + \sum_j \Gamma_{ij}^{\rm exp}\beta_{j,{\rm exp}} - \sigma_i^{\rm th} - \sum_k \Gamma_{ik}^{\rm th}\beta_{k,{\rm th}}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,{\rm exp}}^2 + \sum_k \beta_{k,{\rm th}}^2 .$$

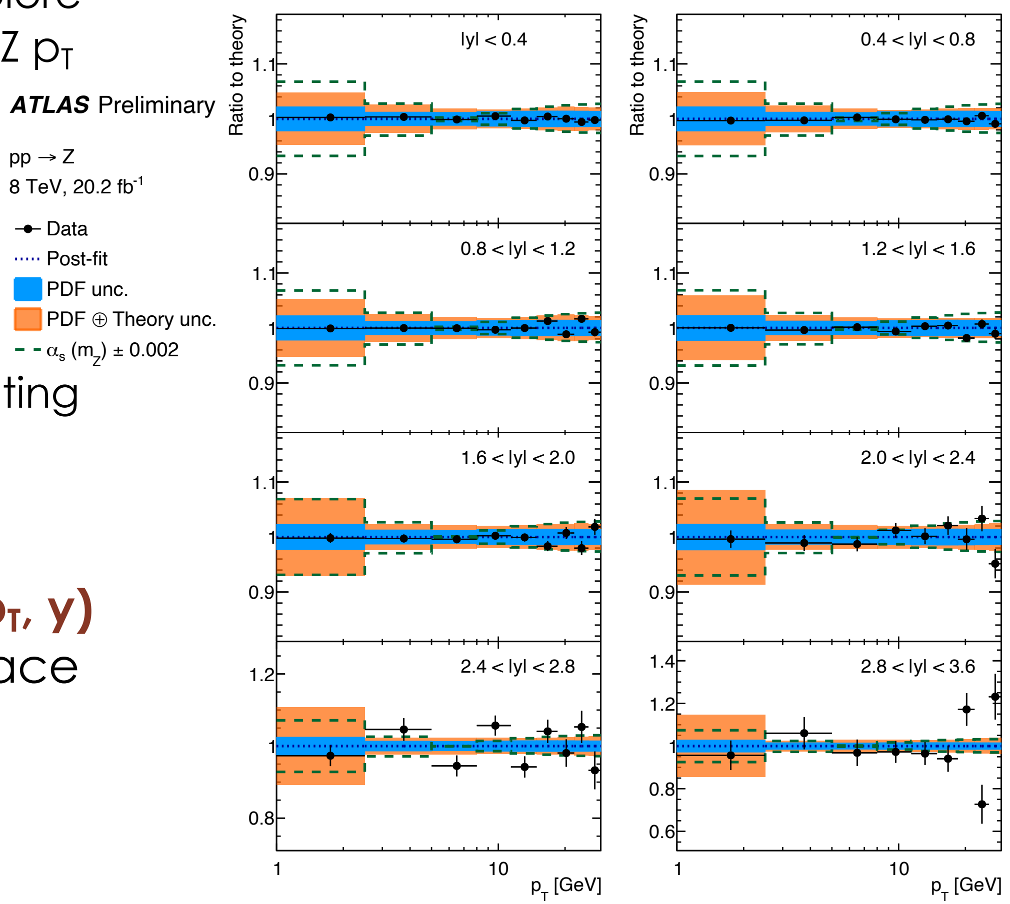
correlated systematic uncertainties

uncorrelated systematic uncertainties

- Fit **Z p_T < 29 GeV region**
  - Non-perturbative form factor (affecting Z p_T < 5 GeV) is added with unconstrained nuisance parameter

- $\alpha_S(m_Z)$ extracted by fitting the **2D (p_T, y) cross section** in full lepton phase space

- **χ^2/ndf = 82/72**

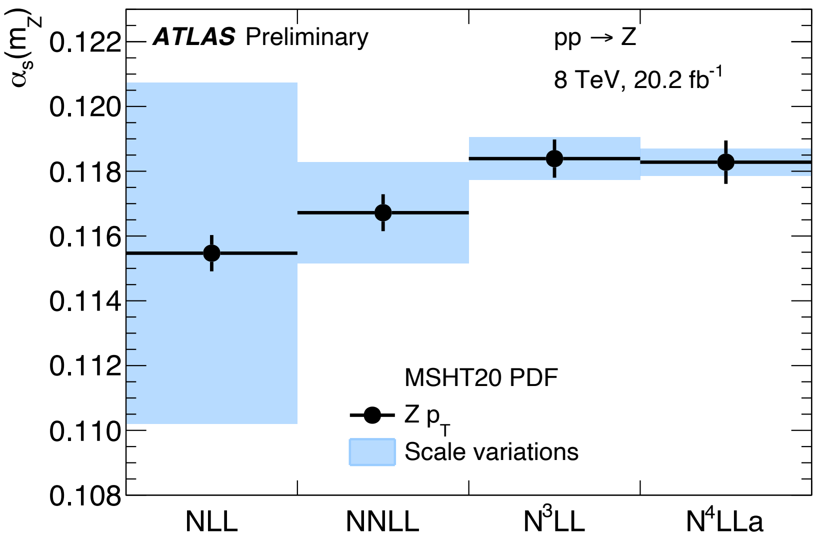


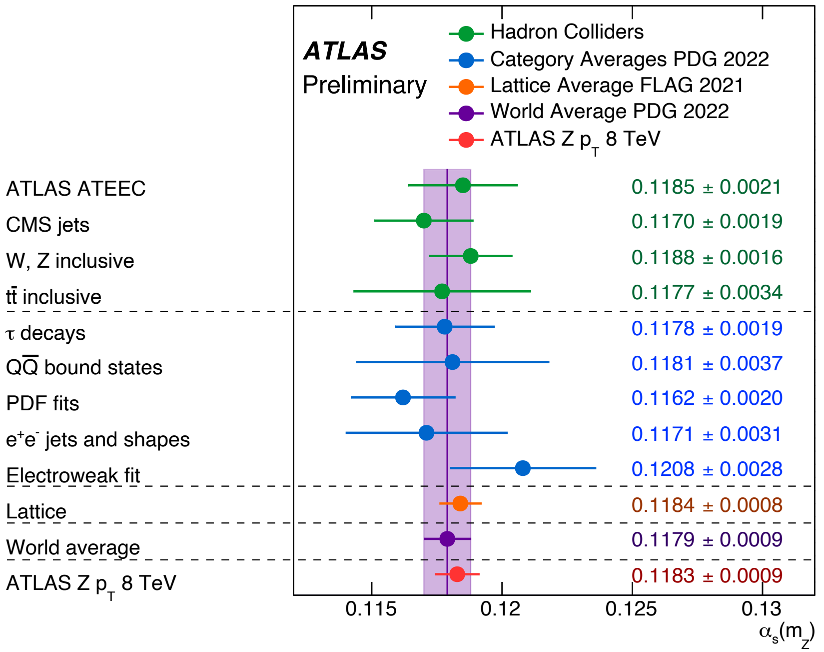
Exercise 2 - results

- **First $\alpha_S(m_Z)$ determination based on aN⁴LL+N³LO predictions**
- $\alpha_S(m_Z)$ determined at lower orders → good perturbative series convergence
- **Most precise experimental determination** of $\alpha_S(m_Z)$
- ATLAS-CONF-2023-015

Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088

$$\alpha_s(m_Z) = 0.11828^{+0.00084}_{-0.00088}$$



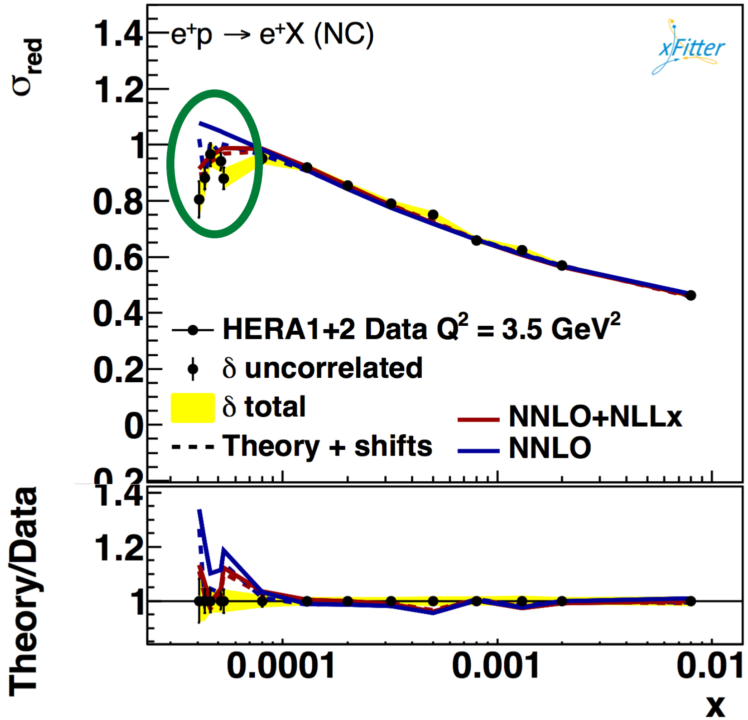


EXERCISE 4

Including small-x resummation corrections

Exercise 4

- **Purpose:** Test the impact of small-x resummation corrections on PDFs
- **Data set:** Final combined HERAI+II DIS data
- **QCD order:** NNLO (+ NLLx)
- Small-x resummation formalism based on **k_T-factorization** and **BFKL**
- Developed in the 90s-00s
- Recent developments: 1607.02153, 1708.07510
  - Resummation matched to NNLO, allowing NNLO+NLLx phenomenology
  - Public code: HELL
  - Installed automatically with the provided install-xFitter script



Small-x logarithmic enhancement

$$\sigma_{DIS} = C_i \otimes f_i \qquad \mu^2 \frac{\partial}{\partial \mu^2} f_i(\mu) = P_{ij} \otimes f_j(\mu)$$

LO	$\frac{1}{x} \alpha_S^0 [\quad 1 \quad]$
NLO	$\frac{1}{x} \alpha_S [\# \log\left(\frac{1}{x}\right) + 1]$
NNLO	$\frac{1}{x} \alpha_S^2 [\# \log^2\left(\frac{1}{x}\right) + \# \log\left(\frac{1}{x}\right) + 1]$
N³LO	$\frac{1}{x} \alpha_S^3 [\# \log^3\left(\frac{1}{x}\right) + \# \log^2\left(\frac{1}{x}\right) + \# \log\left(\frac{1}{x}\right) + 1]$
	LL **NLL** **NNLL**

If $\alpha_S \log\left(\frac{1}{x}\right) \sim 1$ → all such terms in the perturbative series are equally important

Reorganisation of the expansion:

$$\frac{1}{x}\left[1 + \#\, \alpha_S \log\left(\frac{1}{x}\right) + \#\, \alpha_S^2 \log^2\left(\frac{1}{x}\right) + \#\, \alpha_S^3 \log^3\left(\frac{1}{x}\right) + \ldots\right] \quad \textbf{(LL)}$$

$$\frac{\alpha_S}{x}\left[1 + \#\, \alpha_S \log\left(\frac{1}{x}\right) + \#\, \alpha_S^2 \log^2\left(\frac{1}{x}\right) + \#\, \alpha_S^3 \log^3\left(\frac{1}{x}\right) + \ldots\right] \quad \textbf{(NLL)}$$

All-order resummation

Exercise 4 - settings

- `$> cd ~/xFitterTutorial/exercise4`

- Final combined HERAI+II DIS data in `steering.txt`

```
&InFiles
  ! Number of intput files
    NInputFiles = 7

  ! Input files:

     InputFileNames =
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCep_920-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCep_820-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCep_575-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCep_460-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCem-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_CCep-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_CCem-thexp.dat',

&End
```

- Bonus: you can repeat this exercise with more data sets which are probing the low-x region ☺ i.e. low mass or very forward DY, J/ψ or Υ production etc.

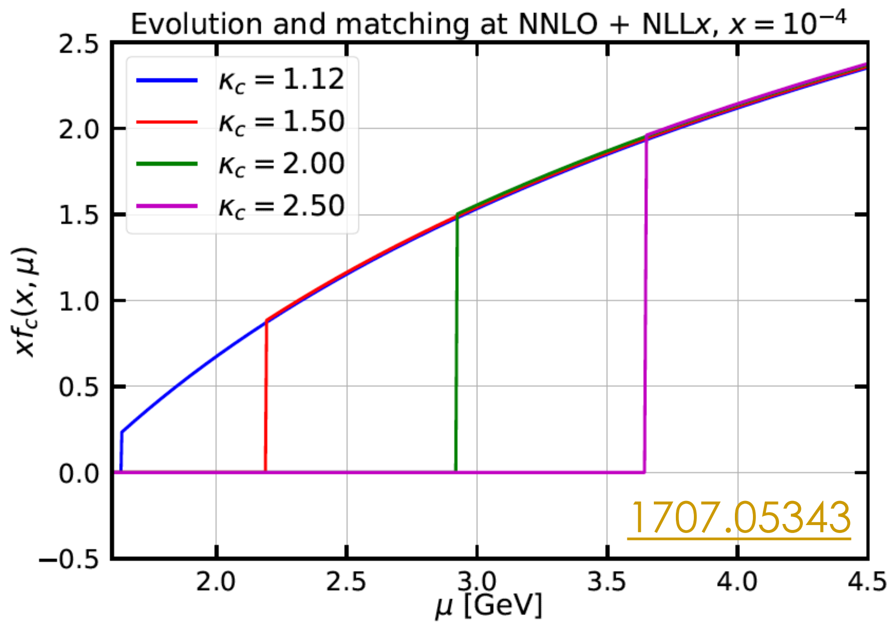
Exercise 4 - settings

- First, we change the program to evolve PDFs: from QCDNUM to APFEL
- Then:
  - We raise the charm matching scale $\mu_c = \kappa_c \cdot m_c$ (with m_c = 1.43 GeV), so it can be generated perturbatively
  - We switch on the small-x resummation

```
DefaultEvolution: proton-APFELff

Evolutions:
  proton-APFELff:
    ? !include evolutions/APFEL.yaml
    decomposition: proton
    kmc : 1.2 # ratio between charm quark threshold and mass
    nllxResummation : "On"
```

- We change HF scheme

```
byReaction:
  # FONLL scheme settings:
  FONLL_DISNC:
    ? !include reactions/FONLL_DISNC.yaml
  FONLL_DISCC:
    ? !include reactions/FONLL_DISCC.yaml

# Specify HF scheme used for DIS NC processes:
hf_scheme_DISNC :
  defaultValue : 'FONLL_DISNC'      # global specification

# Specify HF scheme used for DIS CC processes:
hf_scheme_DISCC :
  defaultValue : 'FONLL_DISCC'      # global specification
```



	NNLO	NNLO+NLLx
Total χ^2/d.o.f	1388/1131	1316/1131

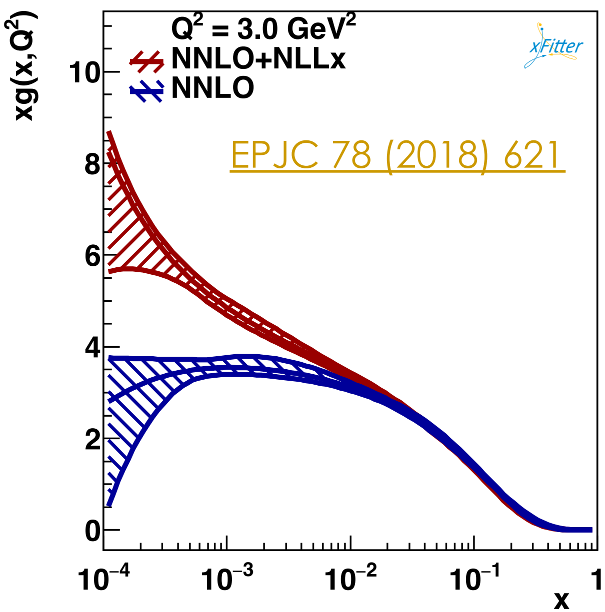
Gain in χ^2 of 72 units

Exercise 4 - results

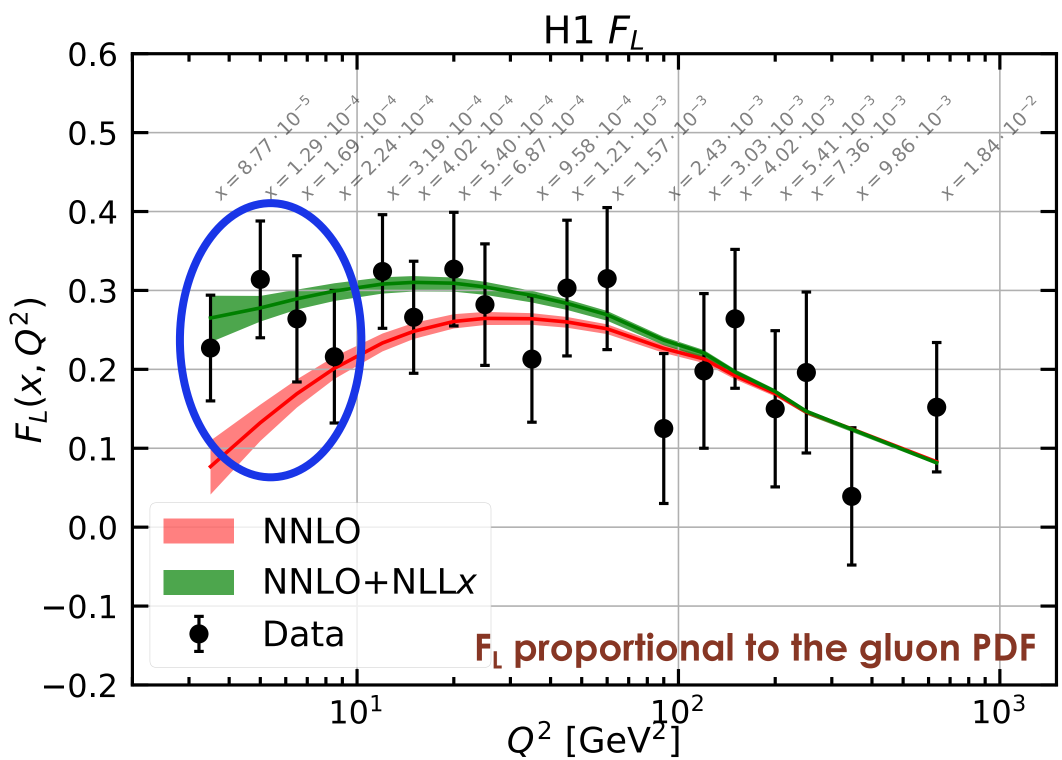
- To obtain datafiles: `$> ln -s ~/Software/xfitter-master/datafiles .`
- To run xFitter: `$> xfitter`
- To draw your results: `$> xfitter-draw output`
- You need to compare these PDFs with HERAPDF2.0 NNLO

$$\sigma_{\text{red}} = F_2 - \frac{y^2}{Y_+} F_L$$

$$Y_+ = (1 + (1-y)^2)$$
$$y = Q^2/(sx)$$



Other PDFs unaffected



EXERCISE 5

Add your preferred PDF parametrisation

Exercise 5

- **Purpose:** Test alternative PDF parametrisation
- **Data set:** Final combined HERAI+II DIS data
- **QCD order:** NNLO (+ NLLx)
- To model small-x region we proposed polynomial in $\log(x)$

$$(1 + F\log(x) + G\log^2(x) + H\log^3(x) + \cdots)$$

- Considered both a multiplicative and an additive option, and we chose the latter:

EPJ Plus (2019) 134, 531

$$xf(x, \mu_0^2) = Ax^B(1-x)^C[1 + Dx + Ex^2 + F\log(x) + G\log^2(x) + H\log^3(x)]$$

- Public code: HELL
- Installed automatically with the provided install-xFitter script
- FYI this is just one possible alternative parametrisation → many more to test! Bernstein or Chebyshev polynomials etc.

Exercise 5 - settings

- `$> cd ~/xFitterTutorial/exercise5`
- Final combined HERAI+II DIS data in `steering.txt`

```
&InFiles
  ! Number of intput files
    NInputFiles = 7

  ! Input files:

     InputFileNames =
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCep_920-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCep_820-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCep_575-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCep_460-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_NCem-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_CCep-thexp.dat',
     'datafiles/hera/h1zeusCombined/inclusiveDis/1506.06042/HERA1+2_CCem-thexp.dat',

&End
```

Exercise 5 - settings

- We need to modify the parametrization in `parameters.yaml`
- You can define as many parameters as you want
- You provide your preferred parametrization here

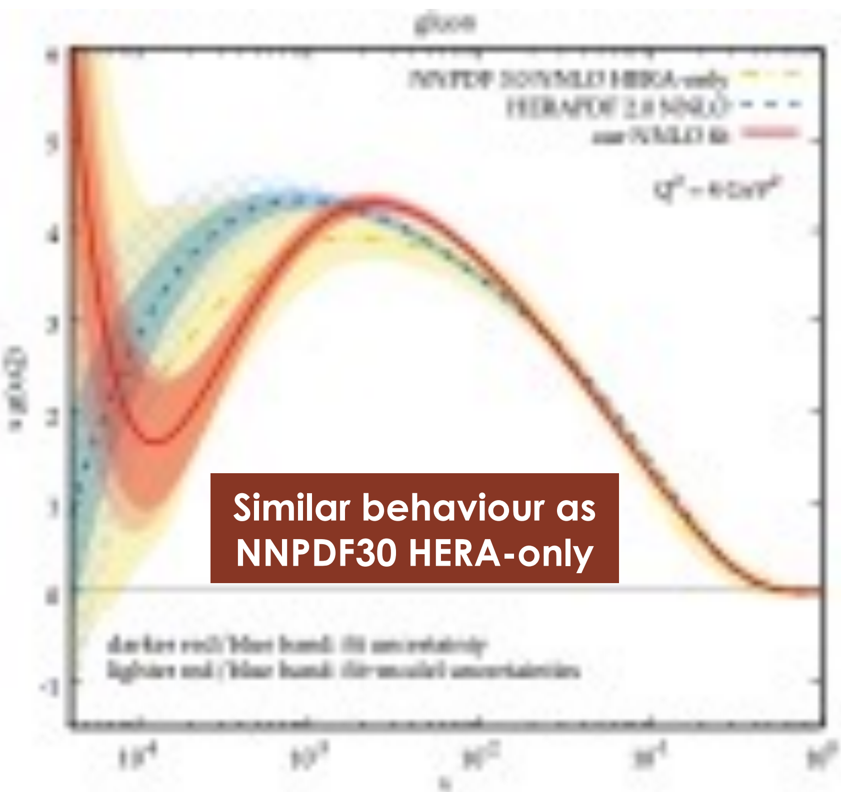
```
Parameterisations:
  par_uv:
    class: Expression
    expression: "Auv*(x^Buv*(1-x)^Cuv)*(1+Euv*x^2+Fuv*ln(x)+Guv*ln(x)^2)"
  par_dv:
    class: Expression
    expression: "Adv*(x^Bdv*(1-x)^Cdv)"
  par_ubar:
    class: Expression
    expression: "Adbar*(x^Bdbar*(1-x)^Cubar)*(1+Dubar*x+Fdbar*ln(x))"
  par_dbar:
    class: Expression
    expression: "Adbar*(x^Bdbar*(1-x)^Cdbar)*(1+Ddbar*x+Fdbar*ln(x))"
  par_s:
    class: Expression
    expression: "Adbar*fs/(1-fs)*(x^Bdbar*(1-x)^Cdbar)*(1+Ddbar*x+Fdbar*ln(x))"
  par_g:
    class: Expression
    expression: "Ag*(x^Bg*(1-x)^Cg)*(1+Fg*ln(x)+Gg*ln(x)^2)"
```

- You can also switch on small-x resummation (see Exercise 4) to check if any improvement in χ^2

```
Parameters:
  Ag    :  DEPENDENT
  Bg    : [ -0.5009,   0.0060 ]
  Cg    : [  4.4885,   0.1944 ]
  Fg    : [  0.2156,   0.0005 ]
  Gg    : [  0.0119,   0.0010 ]
  Auv   :  DEPENDENT
  Buv   : [  0.7392,   0.0021 ]
  Cuv   : [  4.5845,   0.0170 ]
  Euv   : [  2.7839,   0.0633 ]
  Fuv   : [  0.3416,   0.0027 ]
  Guv   : [  0.0470,   0.0040 ]
  Adv   :  DEPENDENT
  Bdv   : [  0.9882,   0.0108 ]
  Cdv   : [  4.6983,   0.0742 ]
  Cubar: [ 10.9607,   0.2749 ]
  Dubar: [ 17.2935,   0.2808 ]
  Adbar: [  0.0854,   0.0241 ]
  Bdbar: [ -0.3354,   0.0031 ]
  Cdbar: [ 23.8266,   0.9917 ]
  Ddbar: [ 35.0368,   4.5302 ]
  Fdbar: [  0.0744,   0.0011 ]
  ZERO : 0
  fs : [ 0.4, 0.0 ]
```

Exercise 5 - results

- To obtain datafiles: `$> ln -s ~/Software/xfitter-master/datafiles .`
- To run xFitter: `$> xfitter`
- To draw your results: `$> xfitter-draw output`
- You need to compare these PDFs with HERAPDF2.0 NNLO



Contribution to χ^2	HERAPDF2.0	Our fit (new parametrization)
subset NC e^+ 920 $\tilde{\chi}^2$/n.d.p.	444/377	403/377
subset NC e^+ 820 $\tilde{\chi}^2$/n.d.p.	66/70	74/70
subset NC e^+ 575 $\tilde{\chi}^2$/n.d.p.	219/254	221/254
subset NC e^+ 460 $\tilde{\chi}^2$/n.d.p.	217/204	222/204
subset NC e^- $\tilde{\chi}^2$/n.d.p.	219/159	220/159
subset CC e^+ $\tilde{\chi}^2$/n.d.p.	45/39	38/39
subset CC e^- $\tilde{\chi}^2$/n.d.p.	56/42	50/42
correlation term + log term	91 + 5	75 − 3
Total χ^2/d.o.f.	**1363/1131**	**1301/1127**

- If small-x resummation included, further gain of 28 units in χ^2
- **The addition of small-x resummation is thus very important**

EXERCISE 6

ATLASepWZ16: fixed vs free r_s

Exercise 6

- **Purpose:** Reproduce the ATLASepWZ16 fit results and χ^2 comparison for two different cases → fixed VS free r_s

- **Data set:** Final combined HERAI+II DIS data and ATLAS W,Z precise measurement at 7 TeV

- Below the datasets we need to add to the steering.txt file:

```
'datafiles/lhc/atlas/wzProduction/1612.03016/wminus-thexp.dat',
'datafiles/lhc/atlas/wzProduction/1612.03016/wplus-thexp.dat',
'datafiles/lhc/atlas/wzProduction/1612.03016/zyhigh_cc-thexp.dat',
'datafiles/lhc/atlas/wzProduction/1612.03016/zyhigh_cf-thexp.dat',
'datafiles/lhc/atlas/wzProduction/1612.03016/zypeak_cc-thexp.dat',
'datafiles/lhc/atlas/wzProduction/1612.03016/zypeak_cf-thexp.dat',
```

- We also need to apply a cut on the minimum Q^2 of the data to enter the fit to be greater than 10 GeV – so we are not sensitive to non-perturbative effects i.e. higher-twist, small-x logarithmic enhancement, etc.

- Do you remember how to do it?
  - Hint: look inside `steering.txt` ☺

Exercise 6

- Two different folders:

```
$> cd ~/xFitterTutorial/exercise6/rsFixed
$> cd ~/xFitterTutorial/exercise6/rsFree
```

$$r_s = \frac{f_s}{1 - f_s}$$

$$f_s = \frac{r_s}{1 + r_s}$$

- Then, we have to freeze/free r_s parameter in the `parameters.yaml` file

- ATLASepWZ16 → $r_s \sim 1.19$ so $f_s \sim 0.54$

```
Parameters:
  rs    : [  1.1007,   0.1785 ]
```

Proposed range to scan:
$0.91 < r_s < 1.21$

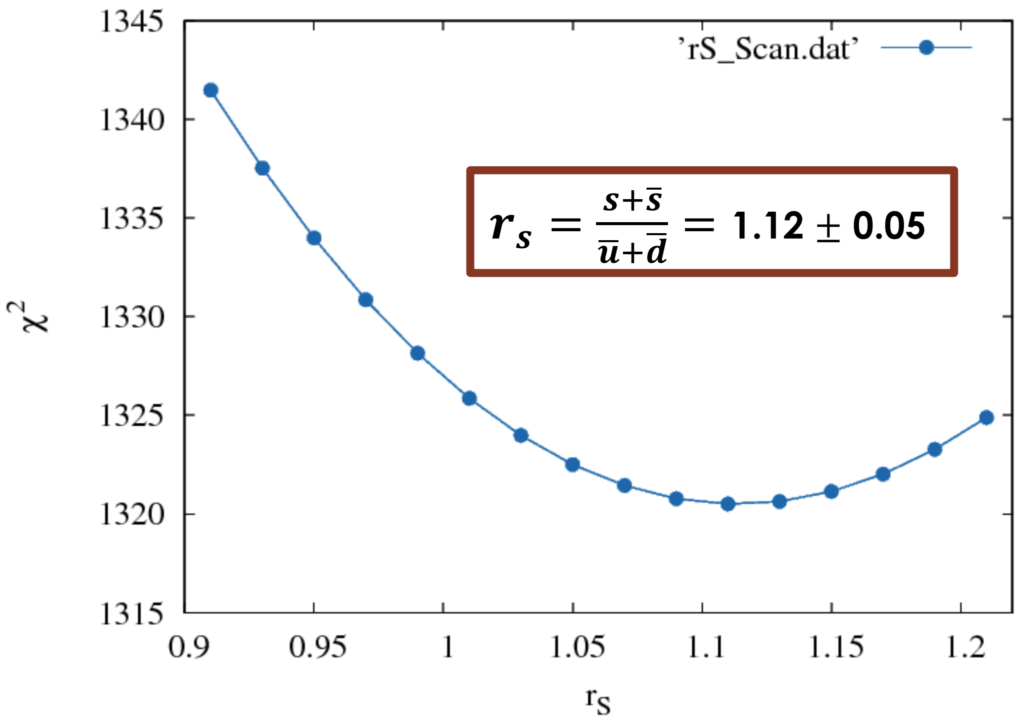
- FYI in HERAI+II → $f_s = 0.4$ (fixed) so $r_s \sim 0.667$

- To obtain datafiles: `$> ln -s ~/Software/xfitter-master/datafiles .`

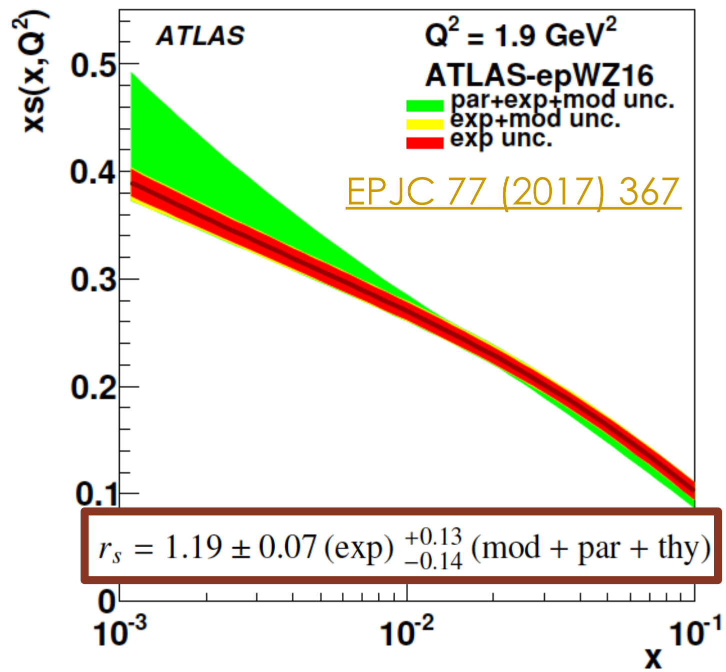
- To run xFitter: `$> xfitter`

- To draw your results: `$> xfitter-draw rsFixed rsFree`

Exercise 6 - Results

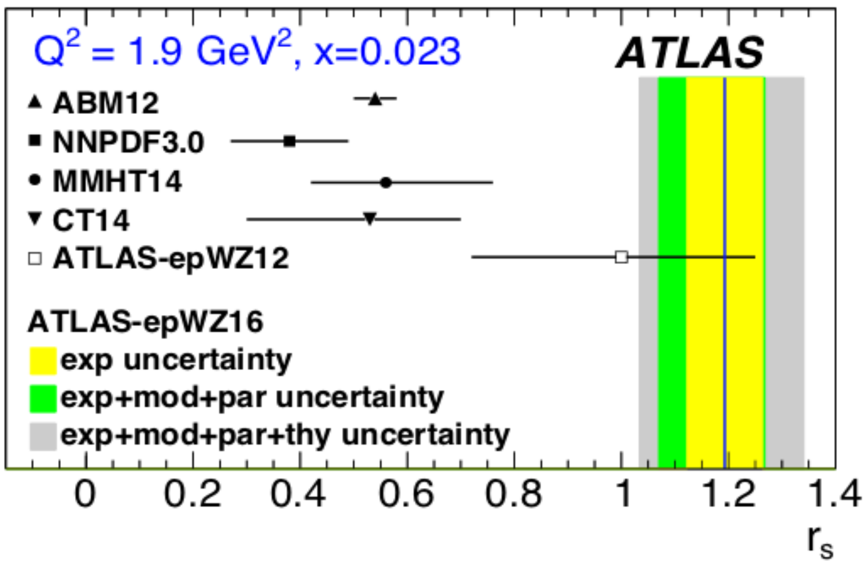


$$r_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}} = 1.12 \pm 0.05$$



EPJC 77 (2017) 367

$$r_s = 1.19 \pm 0.07\,(\text{exp})\,^{+0.13}_{-0.14}\,(\text{mod} + \text{par} + \text{thy})$$

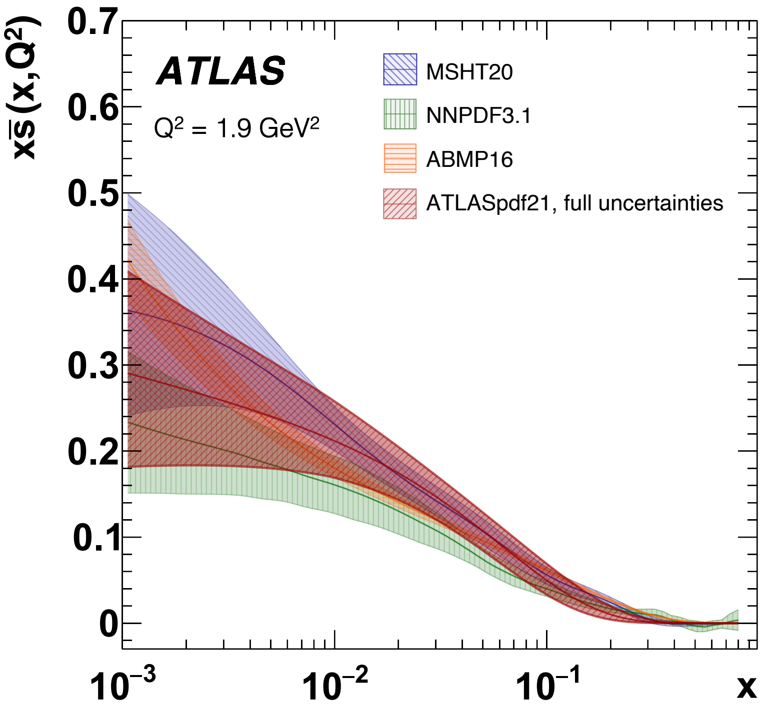


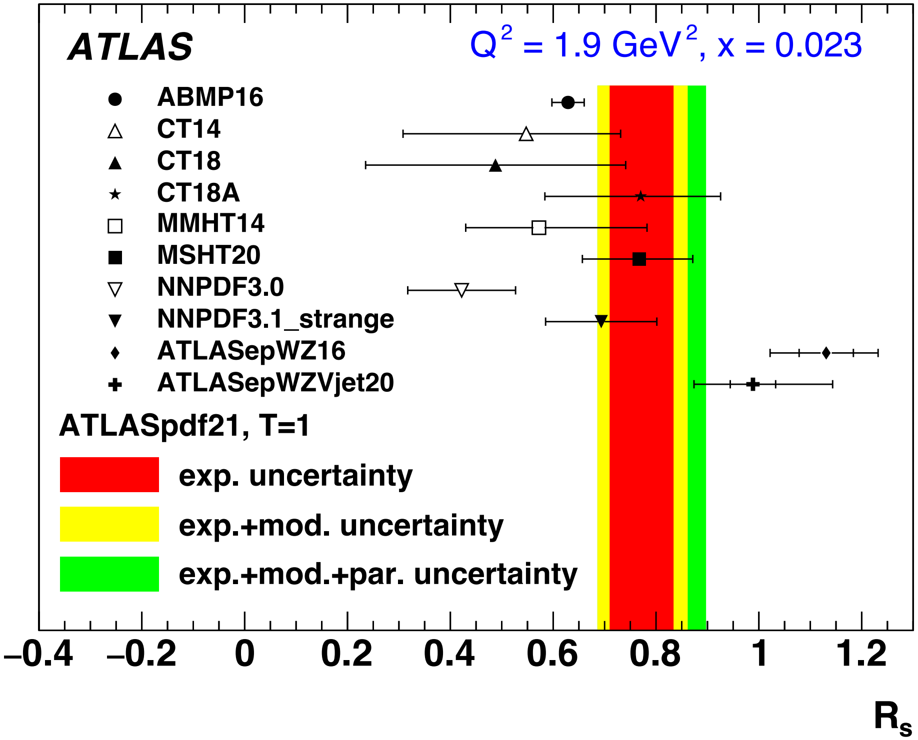
Enhanced r_s confirmed!

The two approaches give compatible results

Exercise 6 - bonus

- What happens if you start adding more and more ATLAS data?
- **ATLASpdf21** is a PDF fit to **multiple ATLAS data sets** - EPJC 82 (2022) 5, 438
  - Fit example + data files (to reproduce published results)
- **ATLAS r_s** has come **DOWN** from ~1.2 to 0.8
- **MSHT, CT** and **NNPDF r_s** have come **UP** from ~0.5 to 0.8 when including W,Z 7 TeV ATLAS data



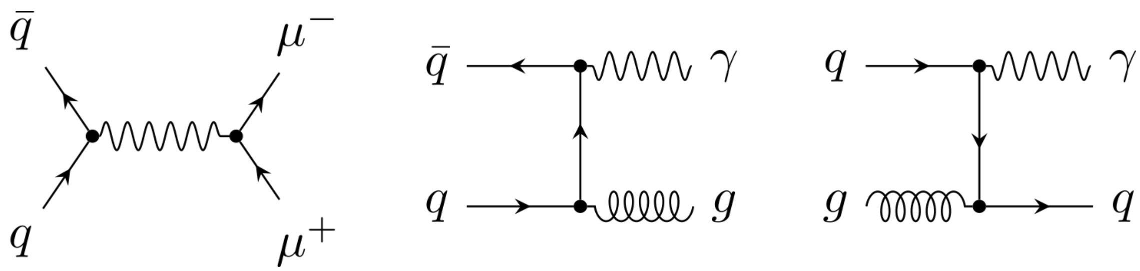


EXERCISE 7

Charged pion PDF

Exercise 7

- **Purpose:** Extract the charged pion PDF (poorly studied experimentally)
- **Data set:** Data from **E615**, **NA10** and **WA70** experiments (di-muon and direct photon production)



- Charge symmetry $d = \bar{u}$ and SU(3)-symmetric sea $u = \bar{d} = s = \bar{s}$ at the initial scale $Q_0^2 = 1.9$ GeV^2

$$v := (d - \bar{d}) - (u - \bar{u}), \qquad xv(x) = A_v x^{B_v}(1-x)^{C_v}(1 + D_v x^{\frac{5}{2}}),$$
$$S := 2u + 2\bar{d} + s + \bar{s} = 6u, \qquad xs(x) = A_S x^{B_S}(1-x)^{C_S},$$
$$g := g, \qquad xg(x) = A_g x^{B_g}(1-x)^{C_g}.$$

- The A_v and A_g parameters are determined by the sum rules:

$$\int_0^1 v(x)\mathrm{d}x = 2, \qquad \int_0^1 x(v(x) + S(x) + g(x))\mathrm{d}x = 1$$

Exercise 7 - settings

- `$> cd ~/xFitterTutorial/exercise7`
- We need to add data from **E615**, **NA10** and **WA70** experiments in the `steering.txt` file

```
InputFileNames =
'datafiles/fixedTarget/NA10/thexp-0.dat',
'datafiles/fixedTarget/NA10/thexp-1.dat',
'datafiles/fixedTarget/NA10/thexp-2.dat',
'datafiles/fixedTarget/NA10/thexp-3.dat',
'datafiles/fixedTarget/NA10/thexp-4.dat',
'datafiles/fixedTarget/NA10/thexp-5.dat',
'datafiles/fixedTarget/NA10/thexp-6.dat',
'datafiles/fixedTarget/NA10/thexp-7.dat',
'datafiles/fixedTarget/NA10/thexp-8.dat',
'datafiles/fixedTarget/WA70/thexp-0.dat',
'datafiles/fixedTarget/WA70/thexp-1.dat',
'datafiles/fixedTarget/WA70/thexp-2.dat',
'datafiles/fixedTarget/WA70/thexp-3.dat',
'datafiles/fixedTarget/WA70/thexp-4.dat',
'datafiles/fixedTarget/WA70/thexp-5.dat',
'datafiles/fixedTarget/WA70/thexp-6.dat',
'datafiles/fixedTarget/WA70positive/thexp-0.dat',
'datafiles/fixedTarget/WA70positive/thexp-1.dat',
'datafiles/fixedTarget/WA70positive/thexp-2.dat',
'datafiles/fixedTarget/WA70positive/thexp-3.dat',
'datafiles/fixedTarget/WA70positive/thexp-4.dat',
'datafiles/fixedTarget/WA70positive/thexp-5.dat',
'datafiles/fixedTarget/WA70positive/thexp-6.dat',
'datafiles/fixedTarget/NA10-286/thexp-0.dat',
'datafiles/fixedTarget/NA10-286/thexp-1.dat',
'datafiles/fixedTarget/NA10-286/thexp-2.dat',
'datafiles/fixedTarget/NA10-286/thexp-3.dat',
'datafiles/fixedTarget/NA10-286/thexp-4.dat',
'datafiles/fixedTarget/NA10-286/thexp-5.dat',
'datafiles/fixedTarget/NA10-286/thexp-6.dat',
'datafiles/fixedTarget/NA10-286/thexp-7.dat',
'datafiles/fixedTarget/NA10-286/thexp-8.dat',
'datafiles/fixedTarget/NA10-286/thexp-9.dat',
'datafiles/fixedTarget/NA10-286/thexp-10.dat',
'datafiles/fixedTarget/E615/thexp-0.dat',
'datafiles/fixedTarget/E615/thexp-1.dat',
'datafiles/fixedTarget/E615/thexp-2.dat',
'datafiles/fixedTarget/E615/thexp-3.dat',
'datafiles/fixedTarget/E615/thexp-4.dat',
'datafiles/fixedTarget/E615/thexp-5.dat',
'datafiles/fixedTarget/E615/thexp-6.dat',
'datafiles/fixedTarget/E615/thexp-7.dat',
'datafiles/fixedTarget/E615/thexp-8.dat',
'datafiles/fixedTarget/E615/thexp-9.dat',
'datafiles/fixedTarget/E615/thexp-13.dat',
'datafiles/fixedTarget/E615/thexp-14.dat',
'datafiles/fixedTarget/E615/thexp-15.dat',
'datafiles/fixedTarget/E615/thexp-16.dat',
'datafiles/fixedTarget/E615/thexp-17.dat',
```

Exercise 7 - settings

- We need to modify the parametrization in `parameters.yaml`, as well as decomposition

```
Parameters:
  Av:  SUMRULE
  Bv: [ 0.75,0.03]
  Cv: [ 0.95,0.04, 0,10]
  As: [ 0.21,0.1]
  Bs: [ 0.5 ,0.1,-1,10]
  Cs: [ 8,3]
  Ag:  SUMRULE
  Bg:   0
  Cg: [ 3,1]
```

```
Parameterisations:
  v:
    class: HERAPDF
    parameters: [Av,Bv,Cv]
  S:
    class: Normalized
    parameters: [As,Bs,Cs]
  g:
    class: Normalized
    parameters: [Ag,Bg,Cg]
```

```
Decompositions:
  pion:
    class: SU3_Pion
    valence: v
    sea: S
    gluon: g
```

- We also need to change evolution, and define it for both π^+ and π^-

```
Evolutions:
  negative_pion:
    ? !include evolutions/QCDNUM.yaml
    decomposition: pion
  positive_pion:
    class: FlipCharge
    input: negative_pion
  tungsten_target:
    class: LHAPDF
    set:    nCTEQ15FullNuc_184_74
    member: 0
  proton:
    class: LHAPDF
    set:    nCTEQ15FullNuc_1_1
    member: 0
DefaultEvolution: negative_pion
```

Nice feature! In this way you have the same evolution used for π^-, just with inverted charged

We have to define a nuclear PDF set for both the incoming proton and the target (tungsten in this case)

Exercise 7 - results

- To obtain datafiles: `$> ln -s ~/Software/xfitter-master/datafiles .`
- To run xFitter: `$> xfitter`
- To draw your results: `$> xfitter-draw output`
- You need to compare these PDFs with i.e. JAM or GRVPI1
- Valence and gluon distributions in good agreement with JAM and both disagree with the early GRV analysis

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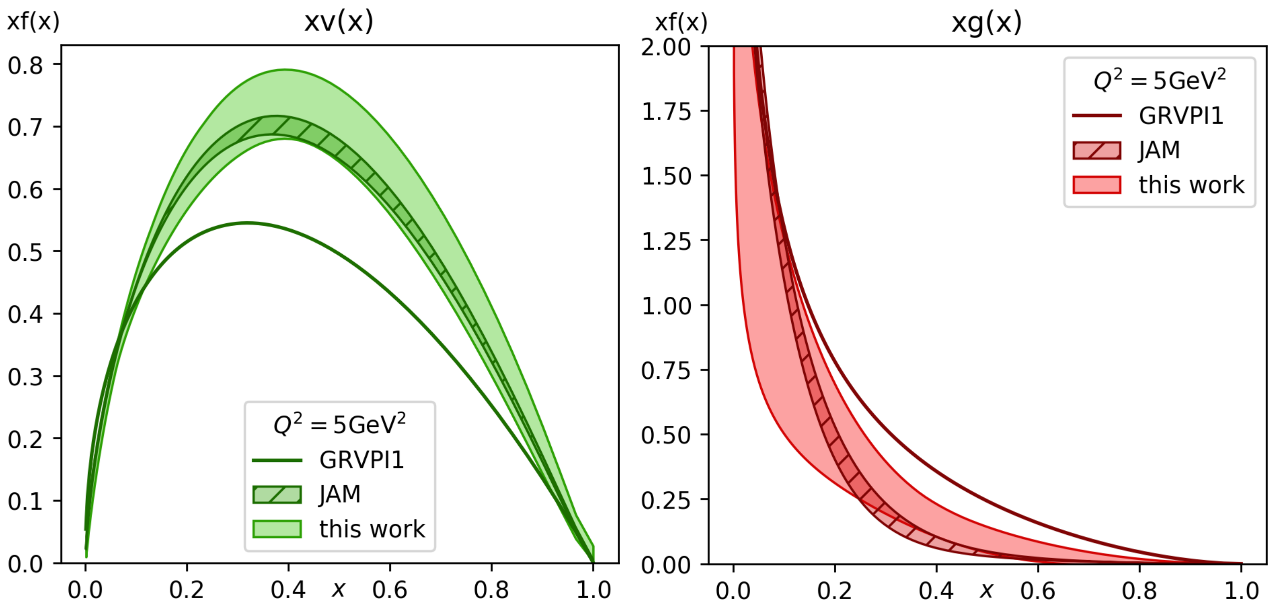

Experiment	χ^2/N_{points}
E615	194/140
NA10 (194 GeV)	98/67
NA10 (286 GeV)	92/73
WA70	74/99

EXERCISE 8

Charged pion Fragmentation Functions

Exercise 8

- **Purpose:** Extract the charged pion **fragmentation functions** (FFs)
- **Data set:** Single inclusive electron-positron annihilation (SIA) + BELLE13/20 data
- **Parametrization form**: $D_i^{\pi^\pm}(z, Q_0) = \dfrac{\mathcal{N}_i z^{\alpha_i}(1-z)^{\beta_i}[1+\gamma_i(1-z)^{\delta_i}]}{B[2+\alpha_i, \beta_i+1]+\gamma_i B[2+\alpha_i, \beta_i+\delta_i+1]}$
- We assume isospin symmetry $D_u^{\pi^+} = D_{\bar{d}}^{\pi^-}$ and $D_{\bar{u}}^{\pi^+} = D_d^{\pi^-}$
- We assume the charge conjugate $D_i^{\pi^+} = D_i^{\pi^-}$ for all the flavour component
- We fit the flavour combinations $i = u^+, d^+, s^+, c^+, b^+$ and g
- We parametrise FFs at a starting scale of $Q_0^2 = 5\ \mathrm{GeV}^2$
- **19 free parameters in total**
- Fitted distributions: $\dfrac{d\sigma^h}{dz}$, $\dfrac{1}{\sigma_{\rm tot}}\dfrac{d\sigma^h}{dp_h}$, $\dfrac{s}{\beta}\dfrac{d\sigma^h}{dz}$, $\dfrac{1}{\beta\sigma_{\rm tot}}\dfrac{d\sigma^h}{dz}$, ... ($z = 2E_h/\sqrt{s}$)

Exercise 8 - settings

- `$> cd ~/xFitterTutorial/exercise8`
- We need to add SIA and BELLE13/20 data in the `steering.txt` file

```
    NInputFiles = 17
     InputFileNames =
  ! Input files:
!   4 active flavour
            'datafiles/NC_SIA/BABAR/inclusive/BABAR_inclusive_pi_o.dat',
            'datafiles/NC_SIA/BELLE20/BELLE20_inclusive_pi_1.dat'




!    Inclusive
            'datafiles/NC_SIA/ALEPH/inclusive/ALEPH_inclusive_pi_h.dat',
            'datafiles/NC_SIA/DELPHI/inclusive/DELPHI_inclusive_pi.dat',
            'datafiles/NC_SIA/OPAL/inclusive/OPAL_inclusive_pi.dat',
            'datafiles/NC_SIA/SLD/inclusive/SLD_inclusive_pi.dat',
            'datafiles/NC_SIA/TASSO/inclusive/TASSO_12_inclusive_pi.dat',
            'datafiles/NC_SIA/TASSO/inclusive/TASSO_14_inclusive_pi.dat',
            'datafiles/NC_SIA/TASSO/inclusive/TASSO_22_inclusive_pi.dat',
            'datafiles/NC_SIA/TASSO/inclusive/TASSO_34_inclusive_pi.dat',
            'datafiles/NC_SIA/TASSO/inclusive/TASSO_44_inclusive_pi.dat',
            'datafiles/NC_SIA/TPC/TPC_inclusive_pi.dat',

!   b tag
            'datafiles/NC_SIA/DELPHI/b_tag/DELPHI_b_tag_pi.dat',
            'datafiles/NC_SIA/SLD/b_tag/SLD_b_tag_pi.dat',
!   c tag
            'datafiles/NC_SIA/SLD/c_tag/SLD_c_tag_pi.dat',
!   light tag
            'datafiles/NC_SIA/DELPHI/light_tag/DELPHI_light_tag_pi_o.dat',
            'datafiles/NC_SIA/SLD/light_tag/SLD_light_tag_pi.dat',
```

Exercise 8 - settings

- We need to modify the parametrization in `parameters.yaml`, as well as decomposition

```
Parameters:
  ABp : [ 1.0199, 0.01618693 ]
  ACp : [ 1.1305, 0.01827819 ]
  ASp : [ 0.7049, 0.09370628 ]
  Ag :  [ 2.0073, 0.03766856 ]
  Aup : [ 1.4261, 0.04923525 ]
  BBp : [ -0.4543, 0.04601485 ]
  BCp : [ -1.0443, 0.04583320 ]
  BSp : [ -0.5754, 0.55702822 ]
  Bg : [   3.3722, 0.37066418 ]
  Bup : [ -0.7829, 0.04777496 ]
  CBp : [ 3.9881, 0.22672656 ]
  CCp : [ 4.6312, 0.16315390 ]
  CSp : [ 8.7524, 1.01469245 ]
  Cg : [  58.3529, 3.15872362 ]
  Cup : [ 1.6871, 0.02898839 ]
  DBp : [ 17.0749, 1.31370713 ]
  DCp : [ 0.00000000, 0.00000000 ]
  DSp : [ 0.00000000, 0.00000000 ]
  Dg : [ 0.00000000, 0.00000000 ]
  Dup : [ 5.1060, 0.61927213 ]
  EBp : [ 9.0314, 0.68378218 ]
  ECp : [ 0.00000000, 0.00000000 ]
  ESp : [ 0.00000000, 0.00000000 ]
  Eg : [ 0.00000000, 0.00000000 ]
  Eup : [ 4.0594, 0.32218262 ]
  ZERO : [ 0.00000000, 0.00000000 ]
```

```
Parameterisations:
  par_up:
    class: Pion_FF
    parameters: [Aup,Bup,Cup,Dup,Eup]
  par_cp:
    class: Pion_FF
    parameters: [ACp,BCp,CCp,DCp,ECp]
  par_bp:
    class: Pion_FF
    parameters: [ABp,BBp,CBp, DBp, EBp]
  par_sp: # s=fs/(1-fs) * Dbar
    class: Pion_FF
    parameters: [ASp,BSp,CSp,DSp,ESp]
  par_g:
    class: Pion_FF
    parameters: [Ag,Bg,Cg,Dg,Eg]
```

```
DefaultDecomposition: Pion_FF_B_C
Decompositions:
  Pion_FF_B_C: #proton:
    class: Pion_FF_BC
    xup: par_up
    xcp: par_cp
    xbp: par_bp
    xsp: par_sp
    xg: par_g
```

- We also need to change evolution – to study antiproton, we used the same trick used for π^+ in Exercise 7 (FlipCharge)

```
DefaultEvolution: proton-APFELff
Evolutions:
  proton-APFELff:
    ? !include evolutions/APFEL.yaml
    fragmentation : "on"
    decomposition: Pion_FF_B_C #proton
  proton-LHAPDF:
    class: LHAPDF
    set: "NNPDF30_nlo_as_0118"
    #set: "CT10nlo"
    member: 0
  antiproton:
    class: FlipCharge
    #input: proton-QCDNUM
    input: proton-LHAPDF
```

Exercise 8 - results

- To obtain datafiles: `$> ln -s ~/Software/xfitter-master/datafiles .`
- To run xFitter: `$> xfitter`
- To draw your results: `$> xfitter-draw output`
- You can compare these PDFs with NNLO NNFF1 and NLO JAM19 and DSEHS14
- **Generally compatible with NNFF1 and DSEHS14 at larger z**, but they differ at low-z (more pronounced for Fit E)

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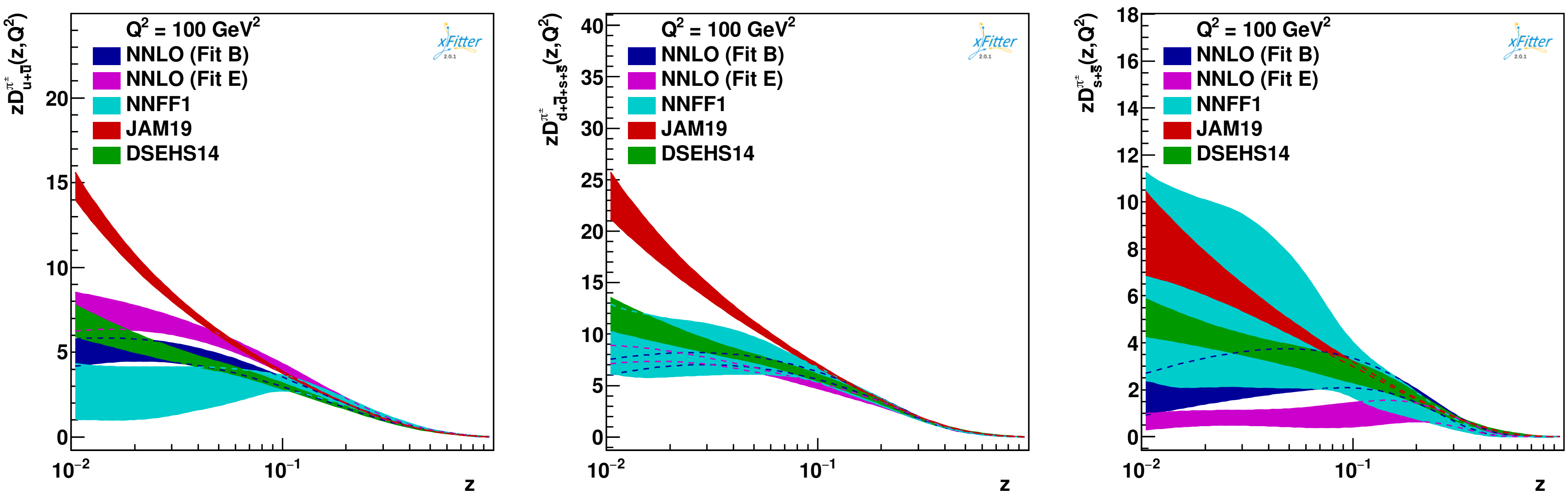

How to generate fixed order predictions

- First of all, you need to download APPLgrid from here
  - You can download the latest version available 1.6.32
- Then you need to download aMC@NLO from here
  - I would recommend you to download version 2.9.X/3.5.X (standard in ATLAS)
- After having installed aMC@NLO you need to generate the process you want to simulate, so e.g. p p > l vl. An example set of commands might be:

```
import model loop_sm-no_b_mass
define p = p b b~
define j = p
define l = e+ e- mu+ mu-
define vl = ve ve~ vm vm~
generate p p > l vl [NLO]
output run_Wlnu
```

> If you have doubts, please follow the instructions on any MG5_aMC@NLO tutorial to produce this process

- Then download aMCfast and follow the instructions described here
- At this stage, you need to write your analysis file (I would suggest the top-drawer format). You have lots of examples in the FOAnalysis folder, please have a look there
  - It is in fortran, but it should be pretty straightforward to understand how to define new distribution

How to generate fixed order predictions

- Then you have to run first a preparatory run
- To perform this preparatory run, we set in the run card

```
1 = iappl ! aMCfast switch (0=OFF, 1=prepare APPLgrids, 2=fill grids)
```

- Since at this stage the interpolation grids are not filled up, there is no need of a high accuracy, thus setting something like `0.01 = req_acc_FO` in the run card is enough
- If the run finishes successfully, the code will have created the starting grid that now need to be filled up. So we have to run again the code giving: `launch -o` ("-o" ensures that the code restarts the run from the grids generated in the previous run)
- Now for this second run, we only need to edit the run card and to set:

```
2 = iappl ! aMCfast switch (0=OFF, 1=prepare APPLgrids, 2=fill grids)
```

- In addition, we might want to increase the accuracy of the integration by setting, for example: `0.001 = req_acc_FO`
- Requiring an higher accuracy should get rid of the statistical fluctuation