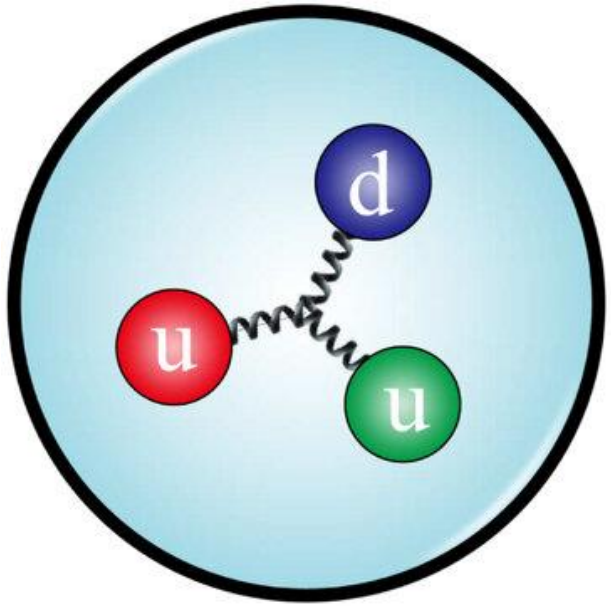
Measuring Proton Structure Functions with xFitter

Philip Antonopoulos

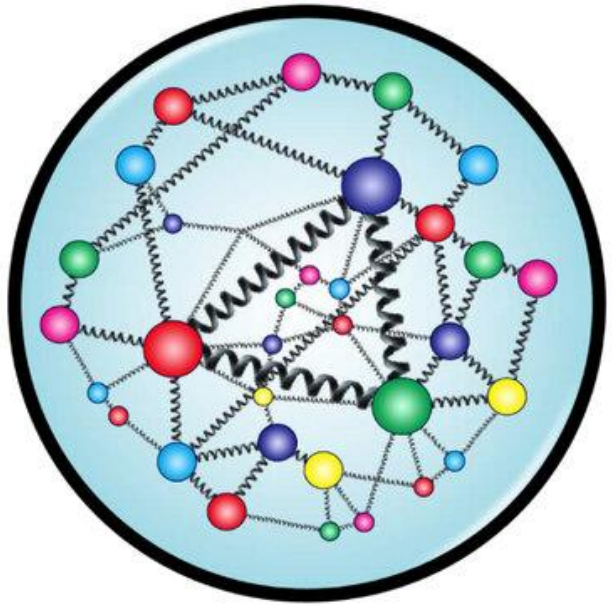
DESY Summer Student

Supervisors

Sasha Glazov & Sasha Zenaiev



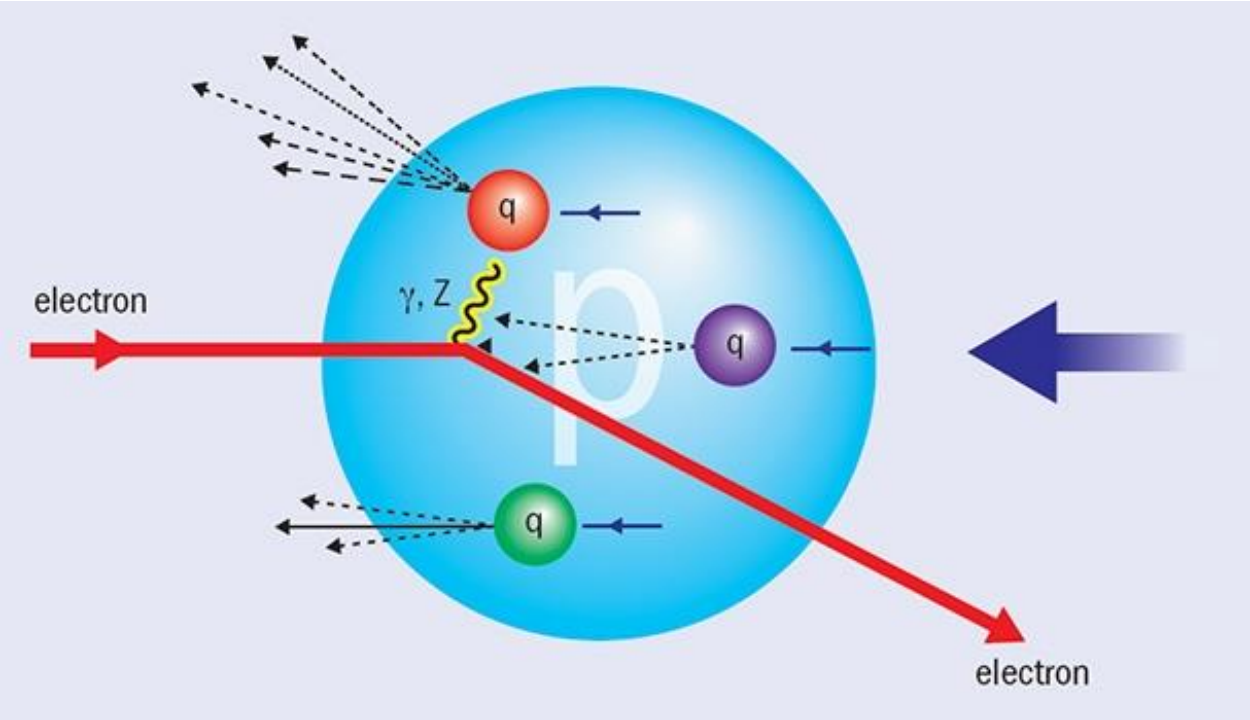
(a)



(b)

- Proton is made up of two up and one down valence quarks.
- The proton, when probed, exhibits non-trivial internal structure:
  - Valence quarks
  - Sea of quarks
  - Gluons

Chen, Hua-Xing & Chen, Wei & Liu, Xiang & Liu, Yan-Rui & Zhu, Shi-Lin. (2022). An updated review of the new hadron states. Reports on Progress in Physics. 86. 10.1088/1361-6633/aca3b6.



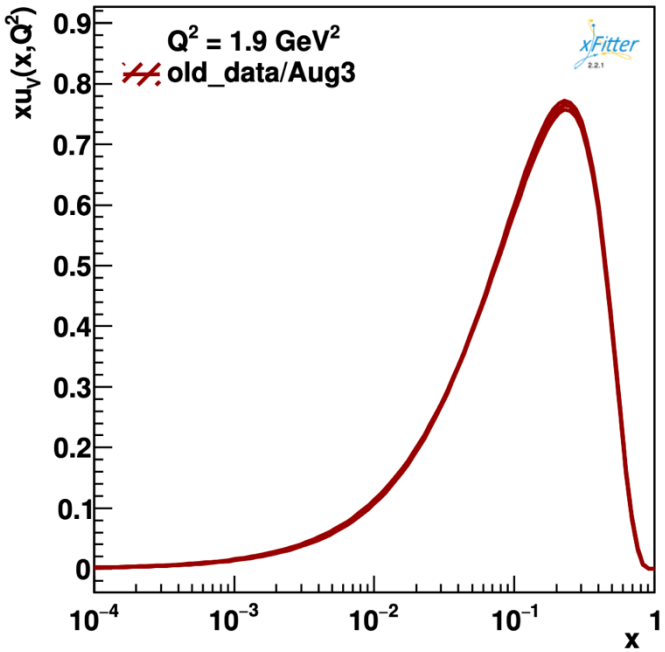
- Virtual photon interaction between the valence quark and electron:
  - q the four-momentum transfer from the photon to the proton
  - $Q^2 = -q$ resolution scale ; Higher Q^2 shorter the wavelength of the virtual photon; probing at the finer constituents of the proton.

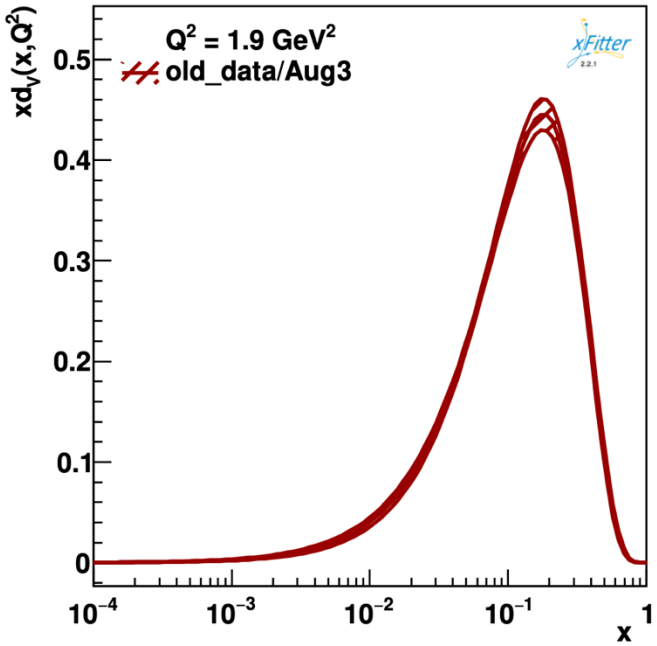
$$x = \frac{Q^2}{2p \cdot q}$$

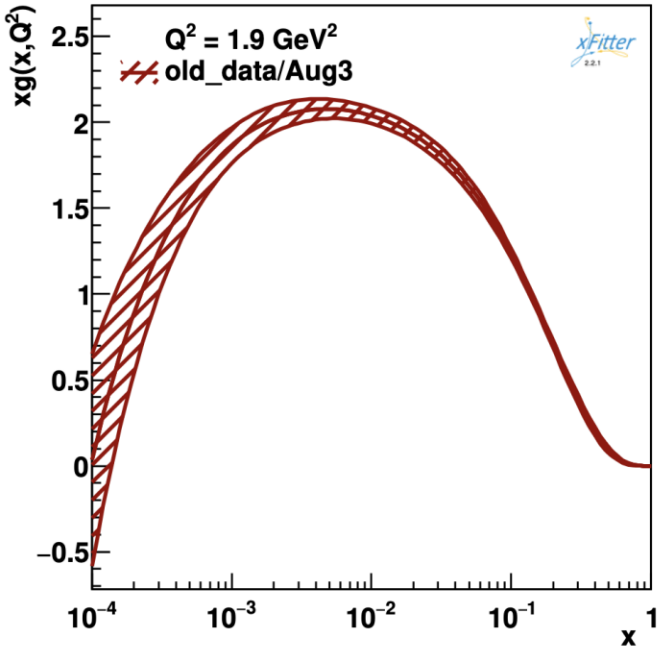
The fraction of the proton's momentum carried by the valence quark

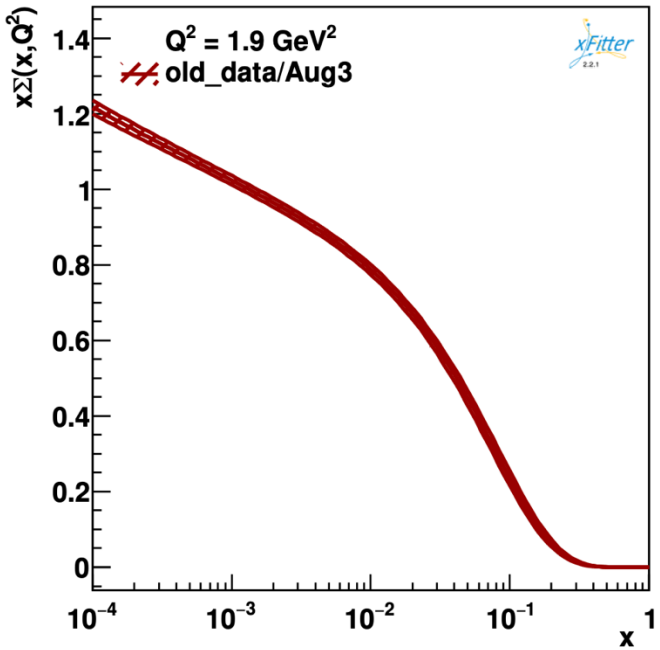
High x = valence quarks dominate; Low x = sea of quarks and gluons dominate

CERN Courier, The most precise picture of a proton, 25 Sep 2015, Electron-proton scattering neutral current



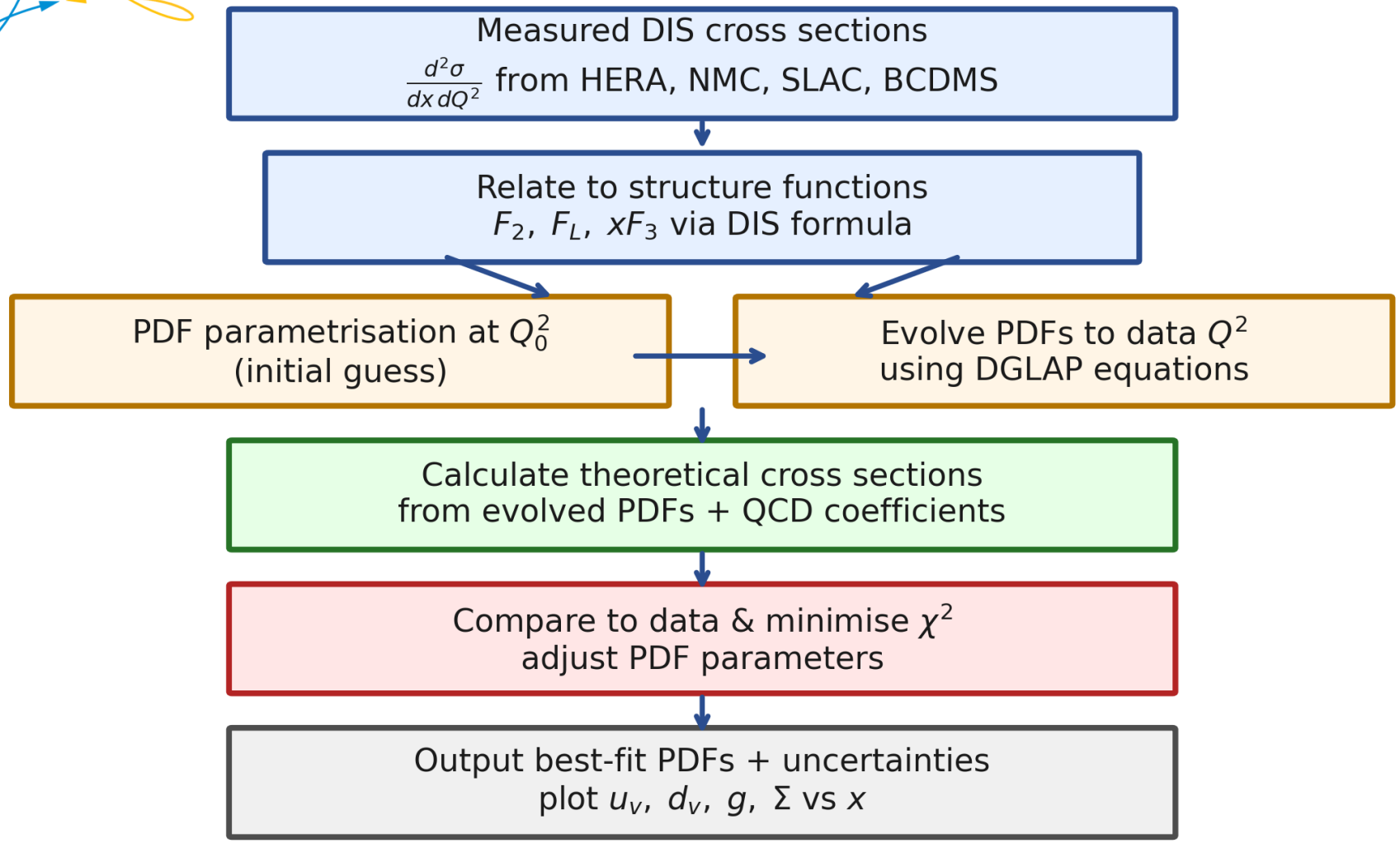


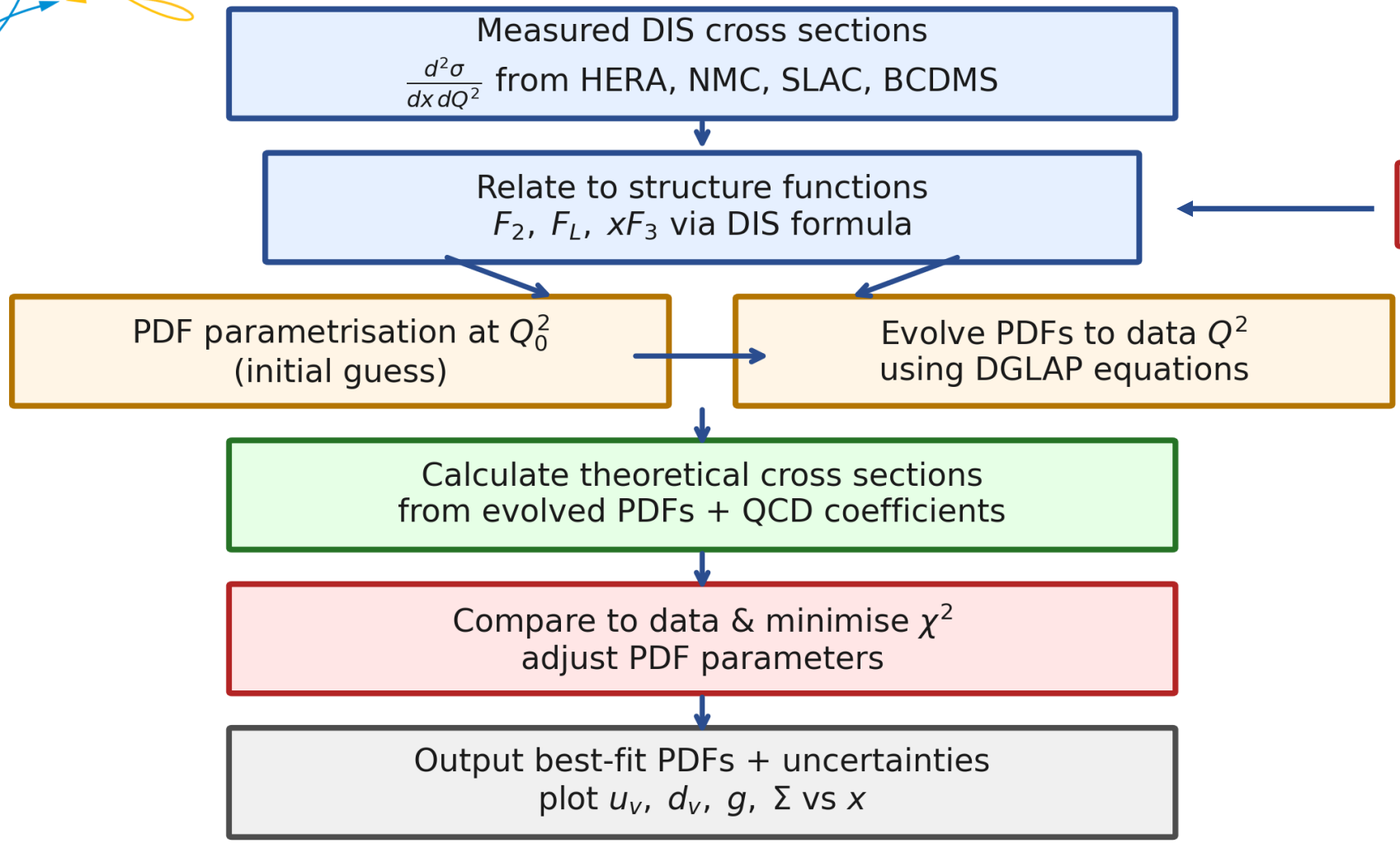




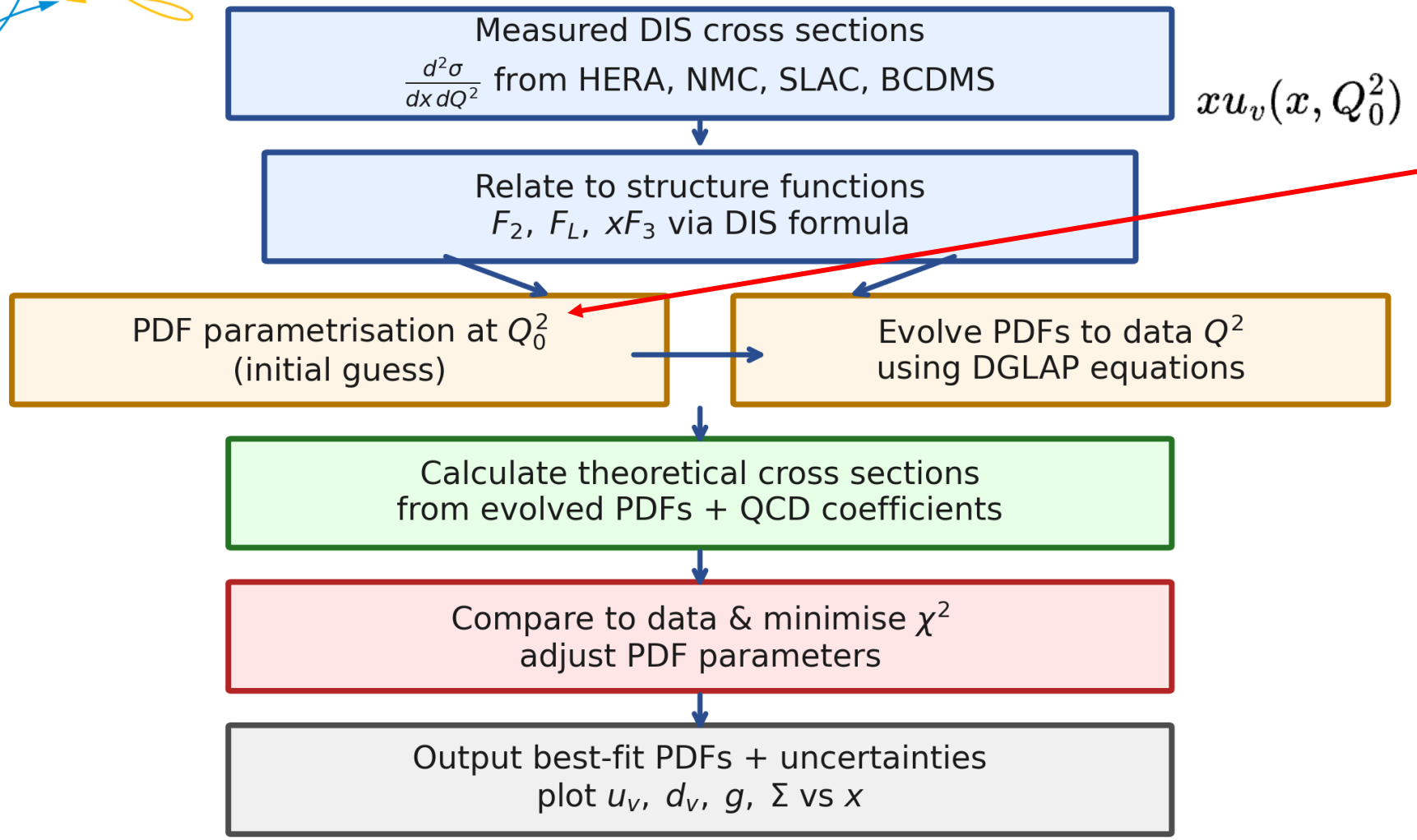
HERA electron-proton collision fits with xFitter

Showcase u-valence d-valence and gluon distributions at set energy as a function of the momentum transfer.


Measured DIS cross sections
$\frac{d^2\sigma}{dx\,dQ^2}$ from HERA, NMC, SLAC, BCDMS
Relate to structure functions
F_2, F_L, xF_3 via DIS formula
PDF parametrisation at Q_0^2
(initial guess)
Evolve PDFs to data Q^2
using DGLAP equations
Calculate theoretical cross sections
from evolved PDFs + QCD coefficients
Compare to data & minimise χ^2
adjust PDF parameters
Output best-fit PDFs + uncertainties
plot u_v, d_v, g, Σ vs x

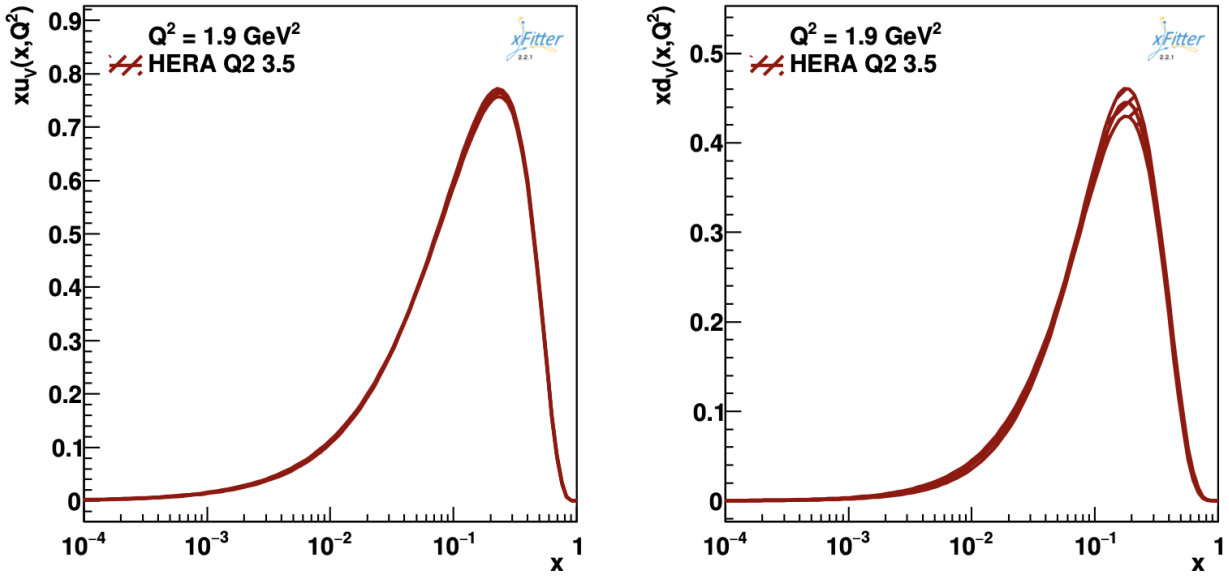


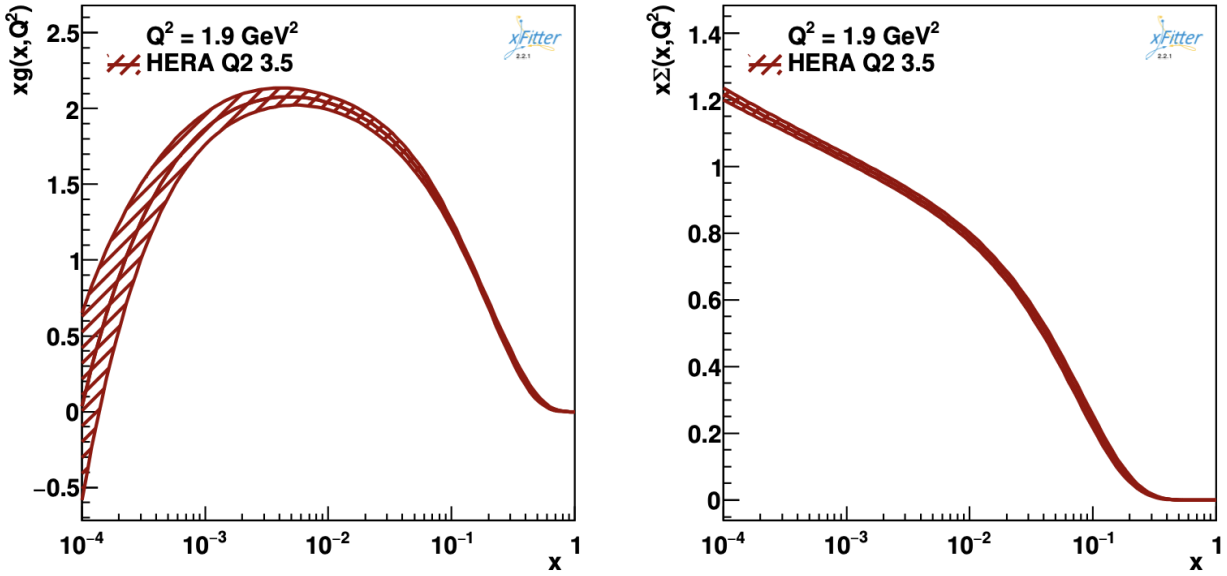
- Kinematic cuts constrain the fitting algorithm to data that are in the regime where known theory applies, i.e., asymptotic freedom and non-resonant scattering.
- All fits presented include a Q^2 cut at 3.5 GeV^2
- All fits are N3LO



$$xu_v(x,Q_0^2) = A_{u_v}x^{B_{u_v}}(1-x)^{C_{u_v}}(1+E_{u_v}x^2)$$

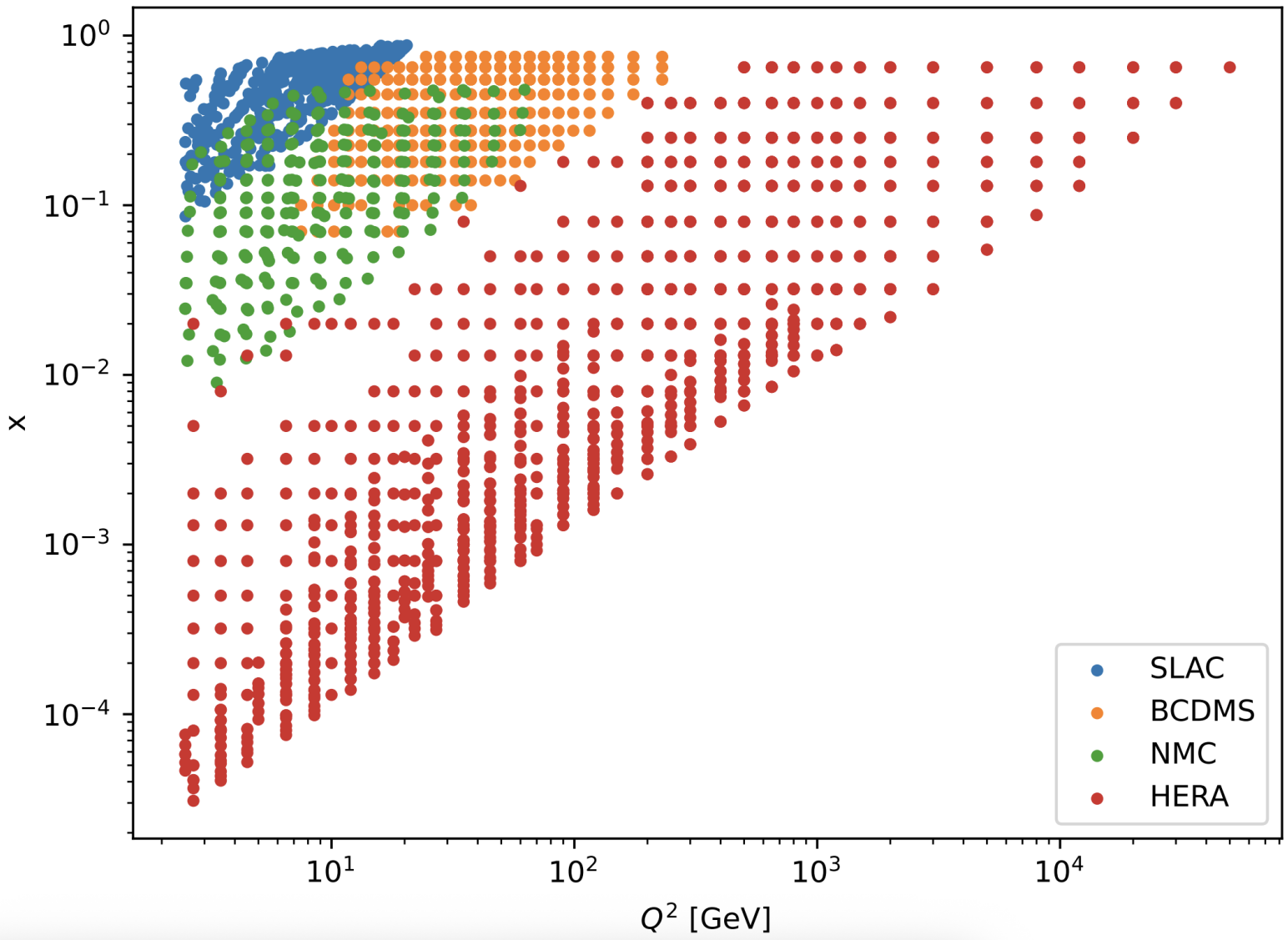
Revisiting HERA





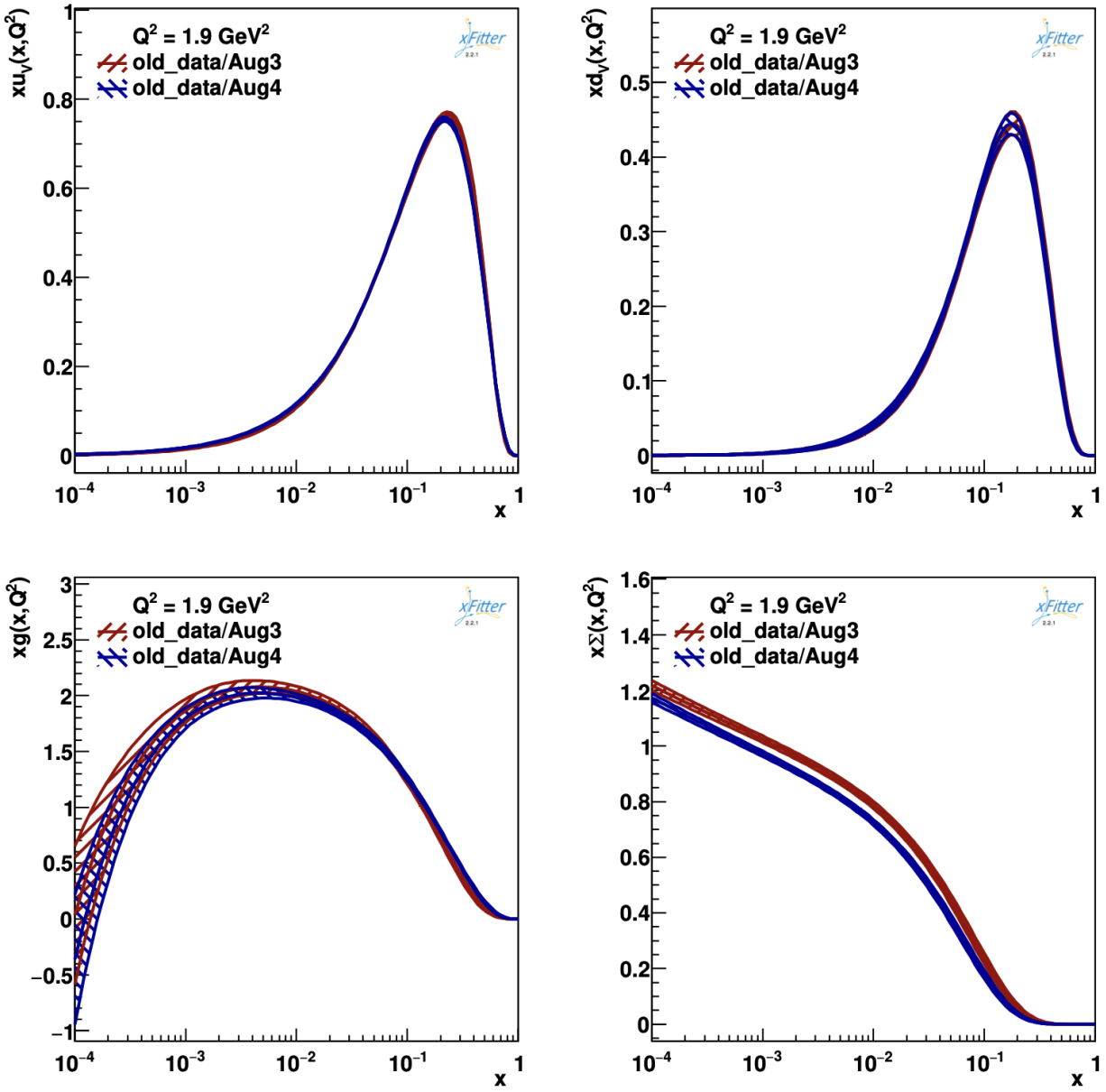
- HERA data have been studied before
- Using these to establish a control dataset to compare new data with
- HERA χ^2
  - 1826 / 1205 : 1.27

Need for more data



- HERA has already been studied but focuses on lower x and lower Q^2
- Introducing new fixed target data allows testing the predictions for higher x and higher Q^2

HERA & Fixed Target Data



- Blue data: HERA & Fixed Target
- Red data: HERA only

- New χ^2
  - 2412 / 1815 : 1.33

- This fit has a higher χ^2 and a lot of the PDF plots deviate from HERA by more than 2σ

- High χ^2 values from the new datasets fits hint at tension between the datasets

By adding the total normalisation of the new datasets as a fit parameter, χ^2 shows a slight improvement, so it will be kept for future studies

- 2386 / 1815 : 1.31

Steering.txt changes

```
*  Namelist to control input data
*

&InFiles
  ! Number of intput files
    !NInputFiles = 9

  ! 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',
     'datafiles/hera/h1zeusCombined/charmbeautyProduction/1804.01019/H1ZEUS_Charm_combined-thexp.dat',
     'datafiles/hera/h1zeusCombined/charmbeautyProduction/1804.01019/H1ZEUS_Beauty_combined-thexp.dat',
     'datafiles/fixedTarget/bcdms/inclusiveDis/cern-ep-89-06/BCDMS_F2p.100gev-thexp.dat',
     'datafiles/fixedTarget/bcdms/inclusiveDis/cern-ep-89-06/BCDMS_F2p.120gev-thexp.dat',
     'datafiles/fixedTarget/bcdms/inclusiveDis/cern-ep-89-06/BCDMS_F2p.200gev-thexp.dat',
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     'datafiles/fixedTarget/nmc/inclusiveDis/NPB_483_1997_3/nmc-90gev.dat',
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     'datafiles/fixedTarget/nmc/inclusiveDis/NPB_483_1997_3/nmc-200gev.dat',
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     'datafiles/fixedTarget/slac/inclusiveDis/SLAC-REPORT-357/slac-49b.dat',
     'datafiles/fixedTarget/slac/inclusiveDis/SLAC-REPORT-357/slac-87.dat',
     'datafiles/fixedTarget/slac/inclusiveDis/SLAC-REPORT-357/slac-89b.dat'
```

Steering.txt changes

```
*  Namelist to control input data
*

&InFiles
  ! Number of intput files
    !NInputFiles = 9

  ! 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',
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     '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',
     'datafiles/hera/h1zeusCombined/charmbeautyProduction/1804.01019/H1ZEUS_Charm_combined-thexp.dat',
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     datafiles/fixedTarget/bcdms/inclusiveDis/cern-ep-89-06/BCDMS_F2p.100gev-thexp.dat',
     datafiles/fixedTarget/bcdms/inclusiveDis/cern-ep-89-06/BCDMS_F2p.120gev-thexp.dat',
     datafiles/fixedTarget/bcdms/inclusiveDis/cern-ep-89-06/BCDMS_F2p.200gev-thexp.dat',
     datafiles/fixedTarget/bcdms/inclusiveDis/cern-ep-89-06/BCDMS_F2p.280gev-thexp.dat',
     datafiles/fixedTarget/nmc/inclusiveDis/NPB_483_1997_3/nmc-90gev.dat',
     datafiles/fixedTarget/nmc/inclusiveDis/NPB_483_1997_3/nmc-120gev.dat',
     datafiles/fixedTarget/nmc/inclusiveDis/NPB_483_1997_3/nmc-200gev.dat',
     datafiles/fixedTarget/nmc/inclusiveDis/NPB_483_1997_3/nmc-280gev.dat',
     datafiles/fixedTarget/slac/inclusiveDis/SLAC-REPORT-357/slac-49a.dat',
     datafiles/fixedTarget/slac/inclusiveDis/SLAC-REPORT-357/slac-49b.dat',
     datafiles/fixedTarget/slac/inclusiveDis/SLAC-REPORT-357/slac-87.dat',
     datafiles/fixedTarget/slac/inclusiveDis/SLAC-REPORT-357/slac-89b.dat'
```

Parameters.yaml

```
Minimizer: MINUIT
MINUIT:
  Commands: |
    set str 2
    MIGRAD 20000
    HESSE
    call fcn 3

  doErrors: Pumplin
  threads: 20
```

```
Parameters:
  Adbar : [ 0.21729894, 0.00596153 ]
  Adv : [ 1.00000000, 0.00000000 ]
  Ag : [ 1.00000000, 0.00000000 ]
  Agp : [ 0.06116521, 0.04085875 ]
  Auv : [ 1.00000000, 0.00000000 ]
  Bdbar : [ -0.07669832, 0.00379618 ]
  Bdv : [ 1.18174075, 0.06832448 ]
  Bg : [ -0.14441817, 0.04632487 ]
  Bgp : [ -0.48321435, 0.04931820 ]
  Buv : [ 0.82332140, 0.01248925 ]
  Cdbar : [ 14.65042635, 2.17686357 ]
  Cdv : [ 5.52795978, 0.32504327 ]
  Cg : [ 3.23168719, 0.25974569 ]
  Cgp : [ 25.00000000, 0.00000000 ]
  Cubar : [ 13.35201436, 1.65139685 ]
  Cuv : [ 2.61122356, 0.08321544 ]
  DATANORM_NMC120 : [ 1.00000000, 0.1000000 ]
  DATANORM_NMC200 : [ 1.00000000, 0.1000000 ]
  DATANORM_NMC280 : [ 1.00000000, 0.1000000 ]
  DATANORM_NMC90 : [ 1.00000000, 0.1000000 ]
  DATANORM_SLAC49a : [ 1.00000000, 0.10000000 ]
  DATANORM_SLAC49b : [ 1.00000000, 0.10000000 ]
  DATANORM_SLAC87 : [ 1.00000000, 0.00000000 ]
  DATANORM_SLAC89b : [ 1.00000000, 0.10000000 ]
  Dubar : [ 3.70239580, 2.47561356 ]
  Duv : [ 0.00000000, 0.00000000 ]
  Euv : [ -1.00048890, 0.06650143 ]
  ZERO : [ 0.00000000, 0.00000000 ]
  fs : [ 0.40000000, 0.00000000 ]
```

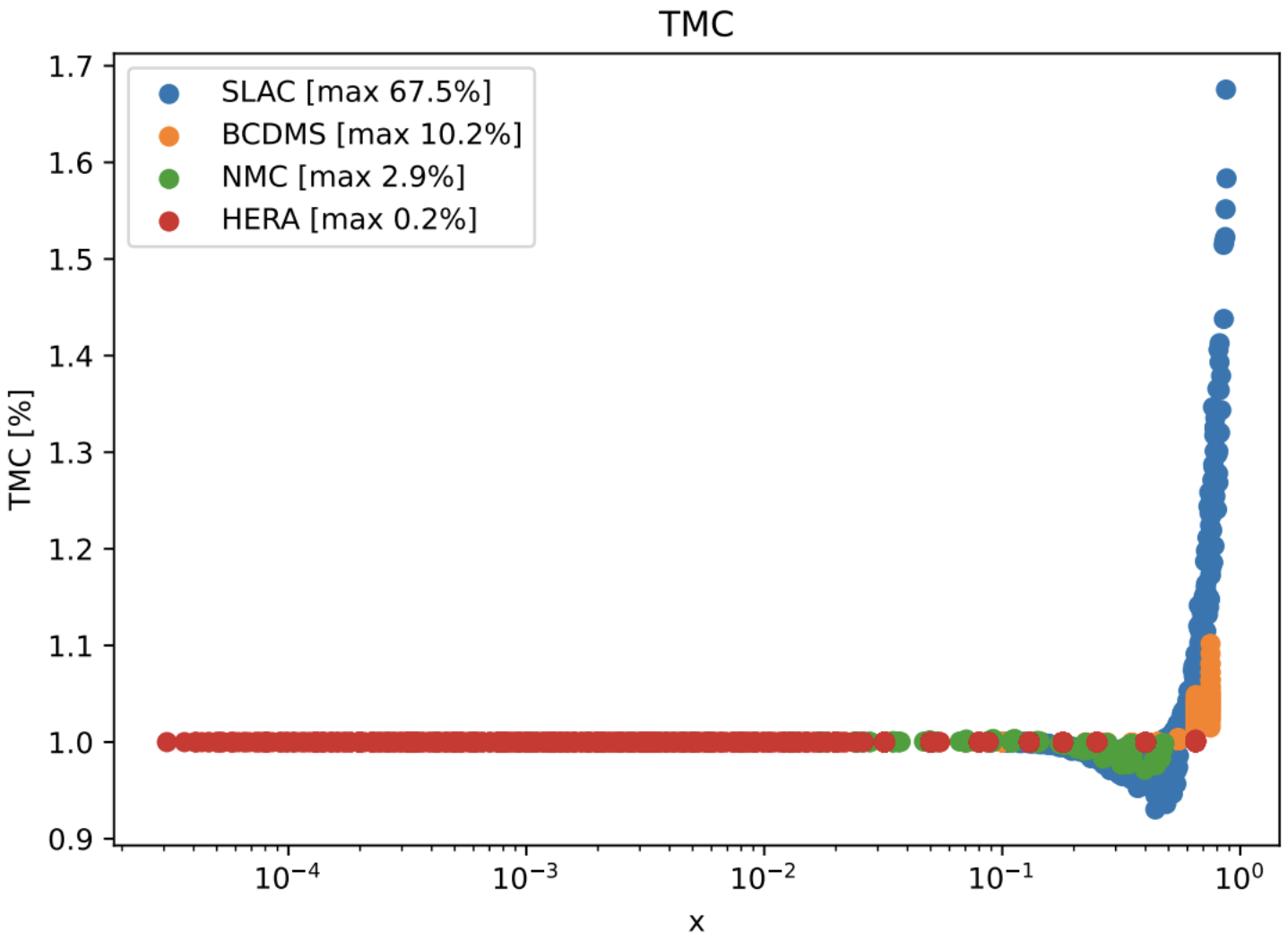
Parameters.yaml

```
Minimizer: MINUIT
MINUIT:
  Commands: |
    set str 2
    MIGRAD 20000
    HESSE
    call fcn 3

  doErrors: Pumplin
  threads: 20
```

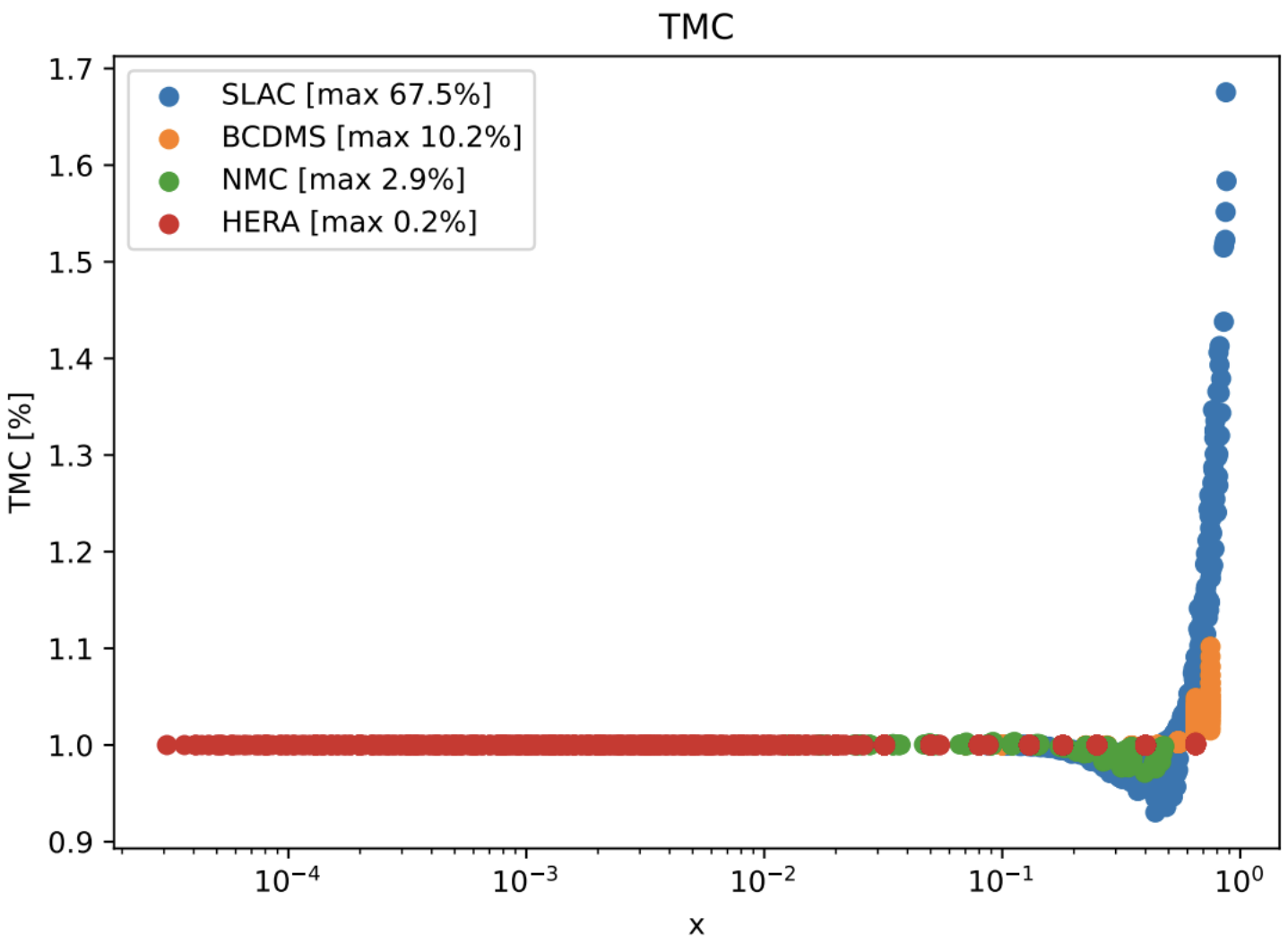
```
Parameters:
  Adbar : [ 0.21729894, 0.00596153 ]
  Adv : [ 1.00000000, 0.00000000 ]
  Ag : [ 1.00000000, 0.00000000 ]
  Agp : [ 0.06116521, 0.04085875 ]
  Auv : [ 1.00000000, 0.00000000 ]
  Bdbar : [ -0.07669832, 0.00379618 ]
  Bdv : [ 1.18174075, 0.06832448 ]
  Bg : [ -0.14441817, 0.04632487 ]
  Bgp : [ -0.48321435, 0.04931820 ]
  Buv : [ 0.82332140, 0.01248925 ]
  Cdbar : [ 14.65042635, 2.17686357 ]
  Cdv : [ 5.52795978, 0.32504327 ]
  Cg : [ 3.23168719, 0.25974569 ]
  Cgp : [ 25.00000000, 0.00000000 ]
  Cubar : [ 13.35201436, 1.65139685 ]
  Cuv : [ 2.61122356, 0.08321544 ]
  DATANORM_NMC120 : [ 1.00000000, 0.1000000 ]
  DATANORM_NMC200 : [ 1.00000000, 0.1000000 ]
  DATANORM_NMC280 : [ 1.00000000, 0.1000000 ]
  DATANORM_NMC90 : [ 1.00000000, 0.1000000 ]
  DATANORM_SLAC49a : [ 1.00000000, 0.10000000 ]
  DATANORM_SLAC49b : [ 1.00000000, 0.10000000 ]
  DATANORM_SLAC87 : [ 1.00000000, 0.00000000 ]
  DATANORM_SLAC89b : [ 1.00000000, 0.10000000 ]
  Dubar : [ 3.70239580, 2.47561356 ]
  Duv : [ 0.00000000, 0.00000000 ]
  Euv : [ -1.00048890, 0.06650143 ]
  ZERO : [ 0.00000000, 0.00000000 ]
  fs : [ 0.40000000, 0.00000000 ]
```

Probable Cause : Target Mass Correction



- At large Bjorken x the fact that the proton cannot be treated as a point-like particle produces systematic errors
- SLAC data exhibit a high mass correction at large x
- TMC also present to a lesser extent in BCDMS and NMC

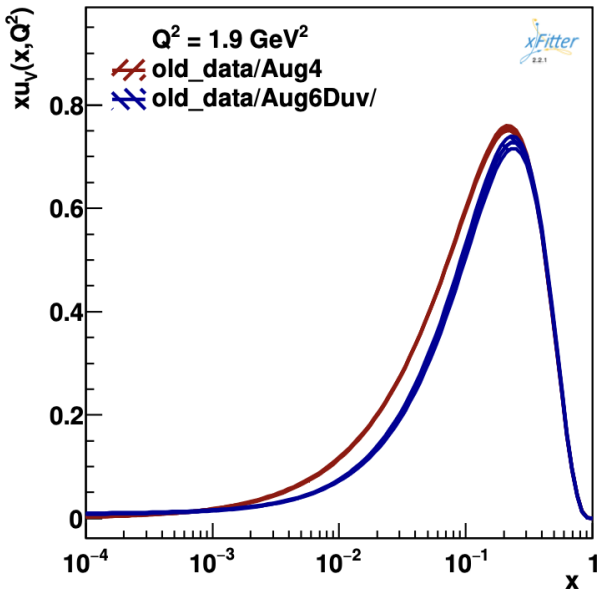
Proposed Modifications : Target Mass Correction

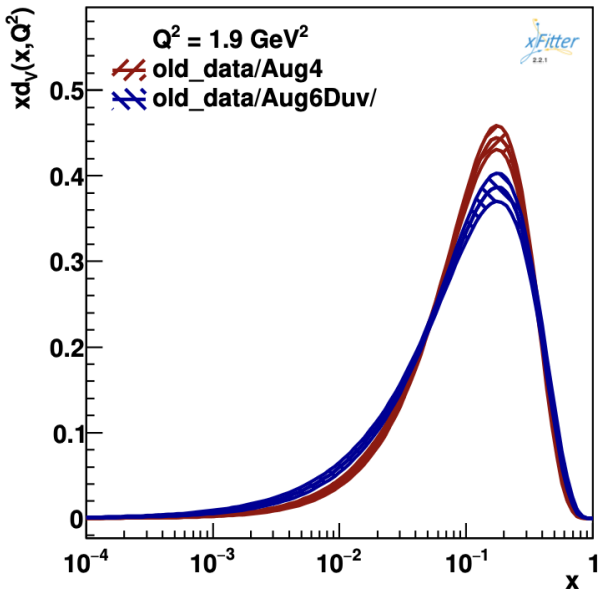


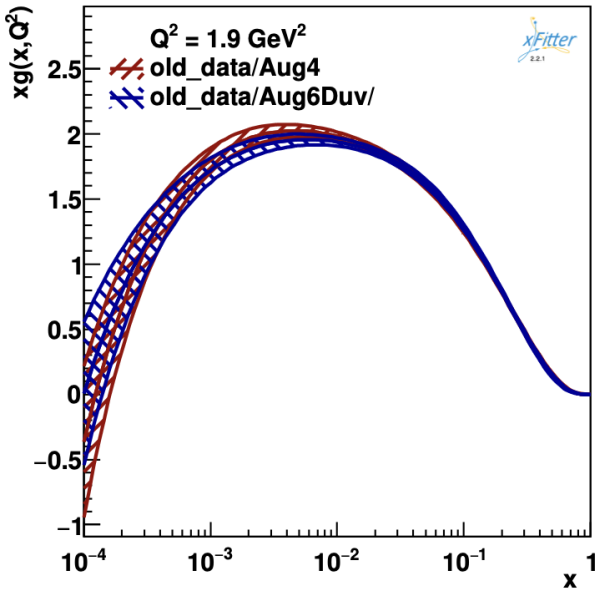
Two main solutions:

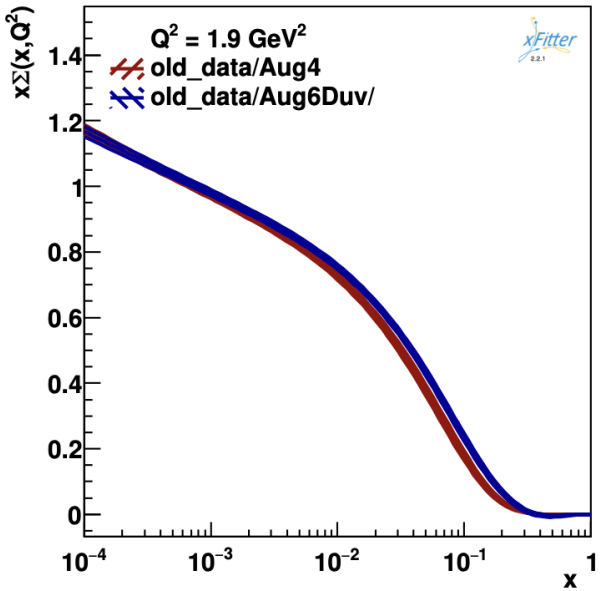
- Add additional polynomial terms to the fit, retaining all data points
- Introduce new cuts to the data to eliminate data points that are in the non-ideal regime

Adding additional polynomial terms









- Produces inexplainable shifts and reductions in the peaks of the u and d valence PDFs compared to the all data fit(in red)

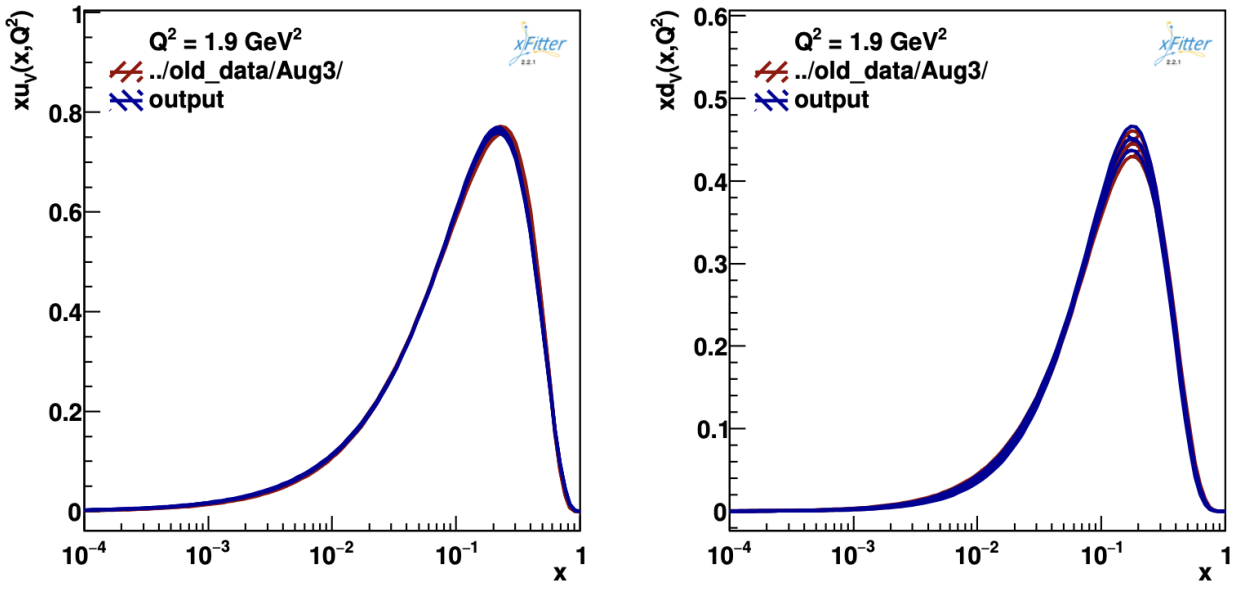
- New parameter unphysically high, indicating possible convergence at local minimum.

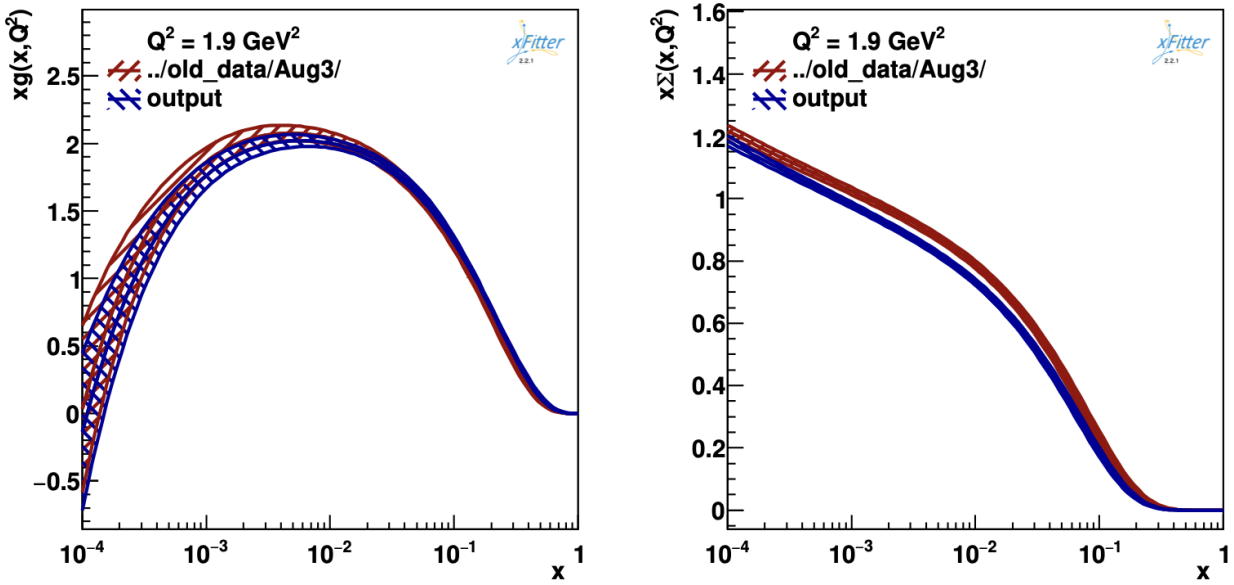
$$xu_v(x,Q_0^2) = A_{u_v}x^{B_{u_v}}(1-x)^{C_{u_v}}(1+D_{u_v}x+E_{u_v}x^2)$$

'Dubar'	$-2.75^{+0.28}_{-0.32}$
'Duv'	673^{+100}_{-136}
'Euv'	362^{+102}_{-93}

Tests could be conducted with higher order terms, but would be very time-intensive as fitting code converges in ~7h

Introducing new cuts to remove TMC signature : Bjorken x





- The plots of HERA(red) overlayed by the new fit with a cut at 0.2 for x(blue) show better convergence with HERA
- Still some data points show more than 2 sigma deviations from HERA but the χ^2 gets better
  - 2368 / 1782 : 1.33

This cut doesn't produce the necessary improvement.

Steering.txt changes

```
&Cuts

  !--------------------- NC ep  -------------------------

  ! Rule #1: Q2 cuts
   ProcessName(1)     = 'NC e+-p'
   Variable(1)        = 'Q2'
   CutValueMin(1)     = 3.5
   CutValueMax(1)     = 1000000.0

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

   ProcessName(2)     = 'CC e+-p'
   Variable(2)        = 'Q2'
   CutValueMin(2)     = 3.5
   CutValueMax(2)     = 1000000.0


  !------------------- Charm
   ProcessName(3)     = 'NC e+-p charm'
   Variable(3)        = 'Q2'
   CutValueMin(3)     = 3.5
   CutValueMax(3)     = 1000000.0

  !------------------- Beauty
   ProcessName(4)     = 'NC e+-p beauty'
   Variable(4)        = 'Q2'
   CutValueMin(4)     = 3.5
   CutValueMax(4)     = 1000000.0
   ProcessName(5)     = 'muon p'
   Variable(5)        = 'Q2'
   CutValueMin(5)     = 3.5
   CutValueMax(5)     = 1000000.0
   ProcessName(6)     = 'NC e+-p slac'
   Variable(6)        = 'x'
   CutValueMin(6)     = 0
   CutValueMax(6)     = 0.2
   ProcessName(7)     = 'NC e+-p slac'
   Variable(7)        = 'Q2'
   CutValueMin(7)     = 3.5
   CutValueMax(7)     = 1000000
```

Steering.txt changes

```
&Cuts

  !-------------------- NC ep  -------------------------

  ! Rule #1: Q2 cuts
   ProcessName(1)     = 'NC e+-p'
   Variable(1)        = 'Q2'
   CutValueMin(1)     = 3.5
   CutValueMax(1)     = 1000000.0

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

   ProcessName(2)     = 'CC e+-p'
   Variable(2)        = 'Q2'
   CutValueMin(2)     = 3.5
   CutValueMax(2)     = 1000000.0


  !------------------- Charm
   ProcessName(3)     = 'NC e+-p charm'
   Variable(3)        = 'Q2'
   CutValueMin(3)     = 3.5
   CutValueMax(3)     = 1000000.0

  !------------------- Beauty
   ProcessName(4)     = 'NC e+-p beauty'
   Variable(4)        = 'Q2'
   CutValueMin(4)     = 3.5
   CutValueMax(4)     = 1000000.0
   ProcessName(5)     = 'muon p'
   Variable(5)        = 'Q2'
   CutValueMin(5)     = 3.5
   CutValueMax(5)     = 1000000.0
   ProcessName(6)     = 'NC e+-p slac'
   Variable(6)        = 'x'
   CutValueMin(6)     = 0
   CutValueMax(6)     = 0.2
   Variable(7)        = 'Q2'
   CutValueMin(7)     = 3.5
   CutValueMax(7)     = 1000000
```

Introducing new cuts to remove TMC signature : W2

```
* info from hepdata:
*EXPeriment     = CERN-NA-4
*REACtion       = muon P --> muon X
*Plab           = 100 GeV
*Collaboration  = BCDMS
*Author         = Benvenuti et al
*REFerence      = Phys. Lett. 223B (1989) 485
*Additional info: The combined energy proton structure function as measured
*                 by the BCDMS Collaboration in muon-proton deep inelastic
*                 scattering.
*
* additional info:
*REFerence      = Cern-ep-89-170.pdf, Cern-ep-89-06.pdf
*Data measured at 100 GeV beam energy
*The columns are: x, Q^2, inelastisity Y, reduced c.s.=F_2*(1-Y....,
*uncorrelated error, the number of syst. errors, correlated errors (all
*errors in percent):
*  due to the beam momentum calibration, due to the spectrometer magnetic
*field calibration, uncertainty in the spectrometer resolution,
*uncertainty in the detector and trigger inefficiencies, uncertainty in
*the relative normalization of data from external and internal targets,
*the absolute normalization of the data taken at the beam energy of 200
*GeV, the relative normalization of the data taken at other energies
*(100, 120, and 280 GeV).
* the last column corresponds to 1.3sigma systematic shift due to the
*beam energy or spectrometer resolution.
*and was not included in the original table
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        Reaction = 'muon p'
        NDATA = 97
        NColumn = 18
        ColumnType = 4*'Bin','Sigma','Error','Dummy',11*'Error'
        ColumnName = 'x','Q2','y','W2','reduced x-section','stat','ignore','bcdms_b
        Percent  = 11*true
        NInfo    = 3
        DataInfo =     -1.,        1.,        0.
        CInfo    = 'e charge', 'reduced', 'e polarity'
        IndexDataset = 90
```

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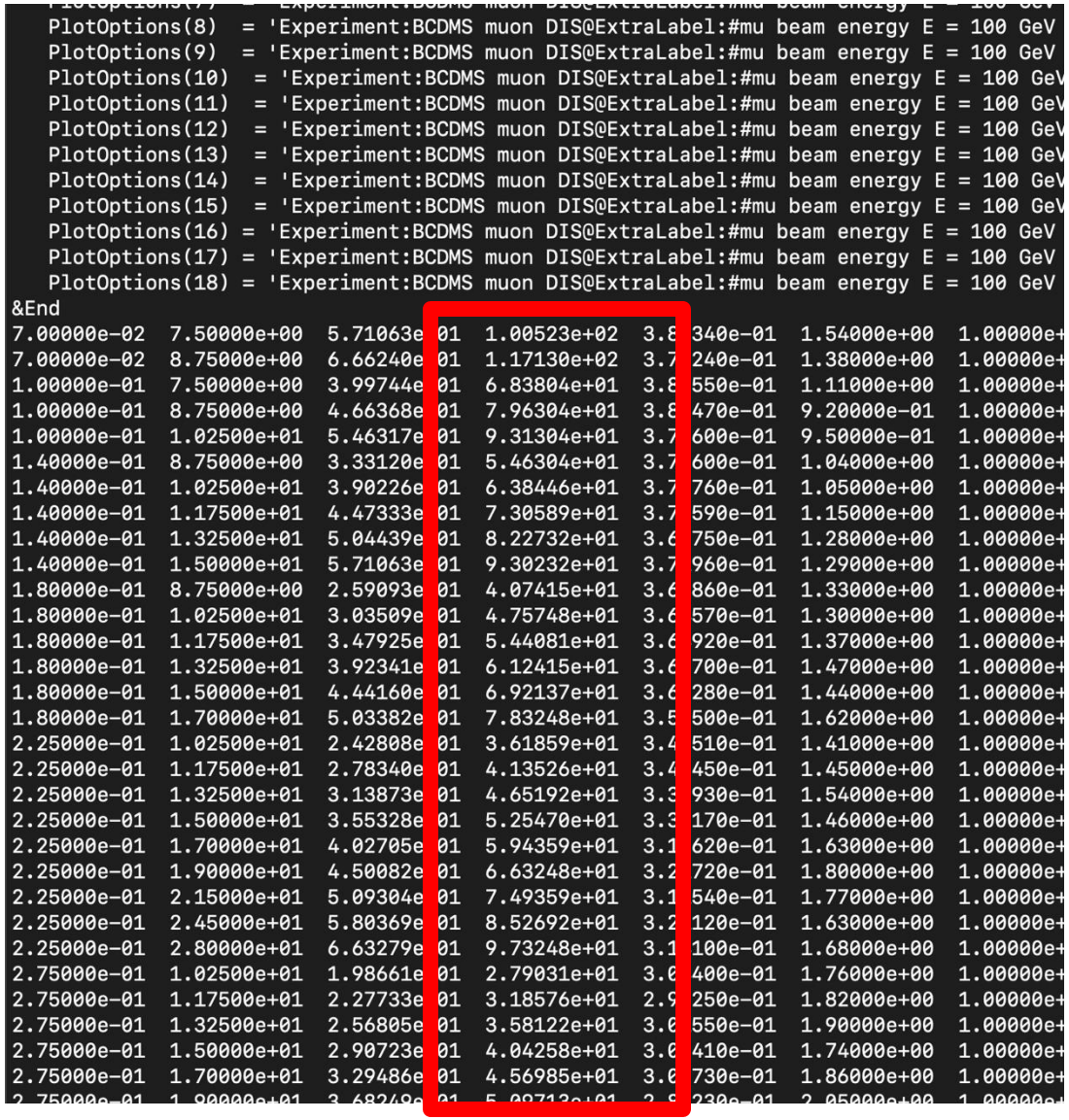
Introducing new cuts to remove TMC signature : W2



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   PlotOptions(10)  = 'Experiment:BCDMS muon DIS@ExtraLabel:#mu beam energy E = 100 GeV
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   PlotOptions(12)  = 'Experiment:BCDMS muon DIS@ExtraLabel:#mu beam energy E = 100 GeV
   PlotOptions(13)  = 'Experiment:BCDMS muon DIS@ExtraLabel:#mu beam energy E = 100 GeV
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   PlotOptions(17) = 'Experiment:BCDMS muon DIS@ExtraLabel:#mu beam energy E = 100 GeV
   PlotOptions(18) = 'Experiment:BCDMS muon DIS@ExtraLabel:#mu beam energy E = 100 GeV
&End
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7.00000e-02  8.75000e+00  6.66240e 01  1.17130e+02  3.7 240e-01  1.38000e+00  1.00000e+
1.00000e-01  7.50000e+00  3.99744e 01  6.83804e+01  3.8 550e-01  1.11000e+00  1.00000e+
1.00000e-01  8.75000e+00  4.66368e 01  7.96304e+01  3.8 470e-01  9.20000e-01  1.00000e+
1.00000e-01  1.02500e+01  5.46317e 01  9.31304e+01  3.7 600e-01  9.50000e-01  1.00000e+
1.40000e-01  8.75000e+00  3.33120e 01  5.46304e+01  3.7 600e-01  1.04000e+00  1.00000e+
1.40000e-01  1.02500e+01  3.90226e 01  6.38446e+01  3.7 760e-01  1.05000e+00  1.00000e+
1.40000e-01  1.17500e+01  4.47333e 01  7.30589e+01  3.7 590e-01  1.15000e+00  1.00000e+
1.40000e-01  1.32500e+01  5.04439e 01  8.22732e+01  3.6 750e-01  1.28000e+00  1.00000e+
1.40000e-01  1.50000e+01  5.71063e 01  9.30232e+01  3.7 960e-01  1.29000e+00  1.00000e+
1.80000e-01  8.75000e+00  2.59093e 01  4.07415e+01  3.6 860e-01  1.33000e+00  1.00000e+
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2.75000e-01  1.70000e+01  3.29486e 01  4.56985e+01  3.0 730e-01  1.86000e+00  1.00000e+
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$$W^2 = M_p^2 + \frac{Q^2(1-x)}{x}$$

Introducing new cuts to remove TMC signature : W2

```
!---------------------- NC ep  -------------------------

! Rule #1: Q2 cuts
 ProcessName(1)     = 'NC e+-p'
 Variable(1)        = 'Q2'
 CutValueMin(1)     = 3.5
 CutValueMax(1)     = 1000000.0

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

 ProcessName(2)     = 'CC e+-p'
 Variable(2)        = 'Q2'
 CutValueMin(2)     = 3.5
 CutValueMax(2)     = 1000000.0


!-------------------- Charm
 ProcessName(3)     = 'NC e+-p charm'
 Variable(3)        = 'Q2'
 CutValueMin(3)     = 3.5
 CutValueMax(3)     = 1000000.0

!-------------------- Beauty
 ProcessName(4)     = 'NC e+-p beauty'
 Variable(4)        = 'Q2'
 CutValueMin(4)     = 3.5
 CutValueMax(4)     = 1000000.0
 ProcessName(5)     = 'muon p'
 Variable(5)        = 'Q2'
 CutValueMin(5)     = 3.5
 CutValueMax(5)     = 1000000.0
 ProcessName(6)     = 'muon p'
 Variable(6)        = 'W2'
 CutValueMin(6)     = 15
 CutValueMax(6)     = 100000
 ProcessName(7)     = 'NC e+-p slac'
 Variable(7)        = 'W2'
 CutValueMin(7)     = 15
 CutValueMax(7)     = 100000
 ProcessName(8)     = 'NC e+-p slac'
 Variable(8)        = 'Q2'
 CutValueMin(8)     = 3.5
 CutValueMax(8)     = 1000000
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 CutValueMax(2)      = 1000000.0


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 Variable(3)         = 'Q2'
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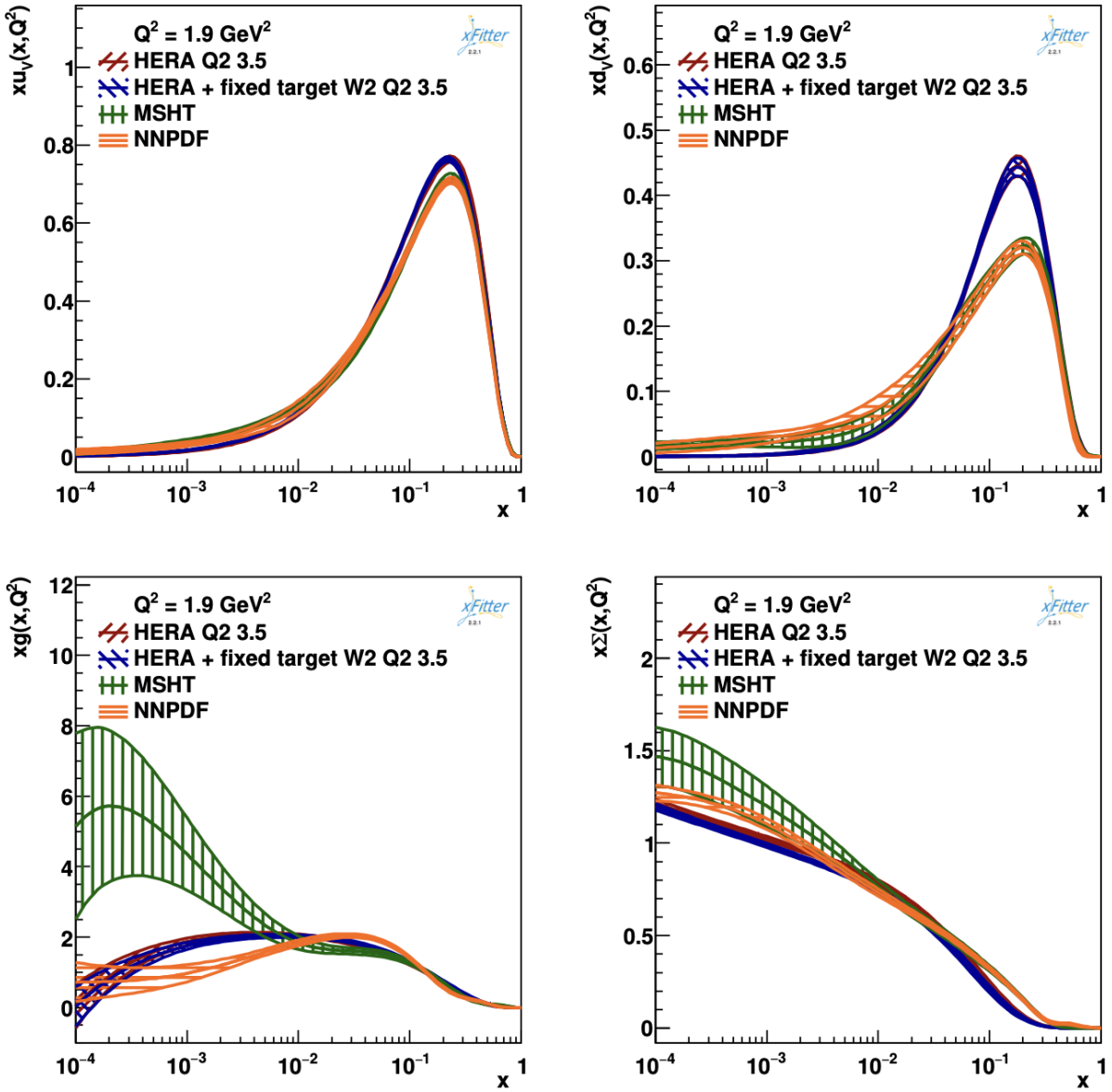

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- This fit has an improved χ^2 :
  - 2321 / 1781 : 1.30
- Some PDFs seem converge with HERA and other collaborations
- Still retain yet unexplained discrepancy in the u and d valence PDFs

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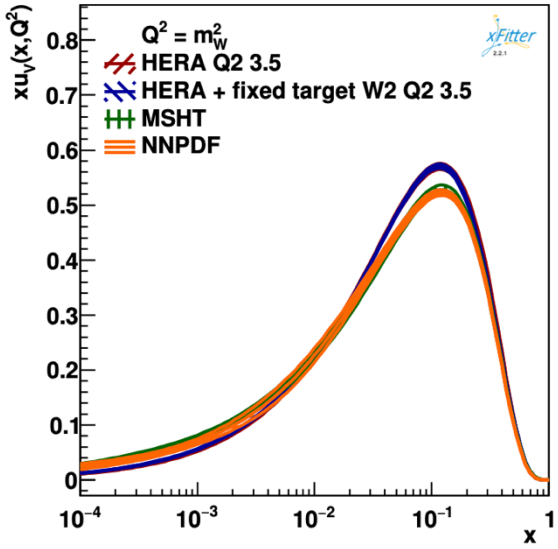

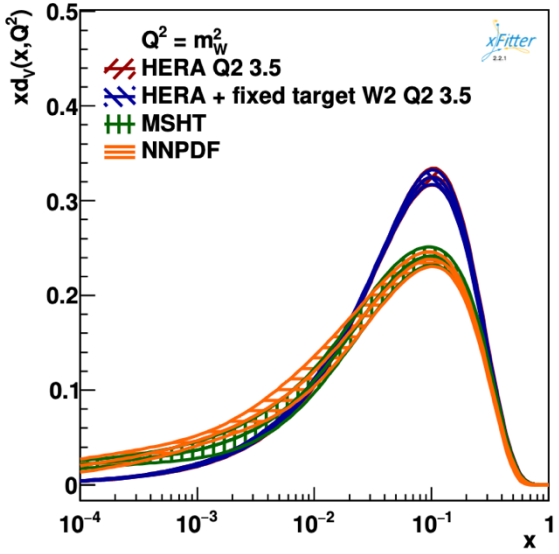

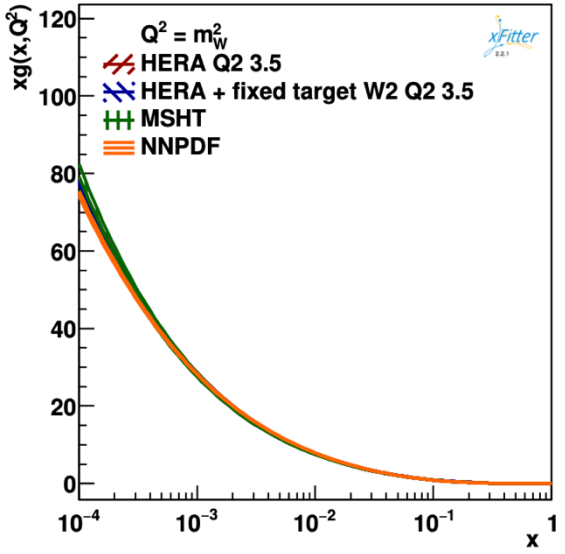

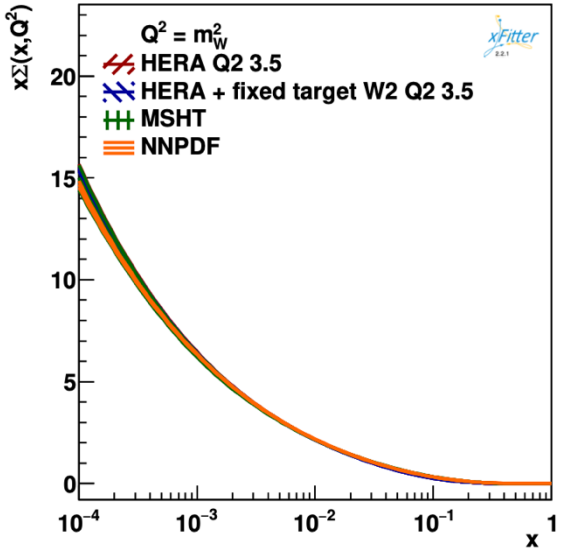

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Next steps

- Vary the Q2 cut to determine whether this deviation is dependent on the quality factor
- Plot pull as a function of Bjorken x to study the impact of individual datasets and whether there are specific problematic data points
- Conduct more tests to figure out whether the deviation in the valence quark PDFs is a new result or an artefact of the fit.