Nuclear xFitter: Towards performing a global analysis of nuclear PDFs using the xFitter

Muhammad Goharipour
In collaboration with S. Rostami and
A. Aleedaneshvar

School of Particles and Accelerators
Institute for Research in Fundamental Sciences (IPM)

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Introduction

Various nPDF parameterizations

Available nPDF parametrizations in 2018

	EPS09	DSSZ12	KA15	NCTEQ15	EPPS16
Order in α_s	NLO	NLO	NNLO	NLO	NLO
DIS in ℓ^-+A	✓	✓	✓	✓	✓
Drell-Yan in p+A	✓	✓	✓	✓	✓
RHIC pions d+Au	✓	✓		✓	✓
Neutrino-nucleus DIS		✓			✓
Drell-Yan in π+A					✓
LHC p+Pb dijets					✓
LHC p+Pb W, Z					✓
Q cut in DIS	1.3 GeV	1 GeV	1 GeV	2 GeV	1.3 GeV
datapoints	929	1579	1479	708	1811
free parameters	15	25	16	16	20
error analysis	Hessian	Hessian	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	50	30	N.N	35	52
proton baseline PDFs	CTEQ6.1	MSTW2008	JR09	CTEQ6M-like	CT14NLO
Heavy-quark effects		✓		✓	✓
Flavour separation				partial	full
Reference	JHEP 0904 065	PR D85 074028	PR D93, 014026	PR D93 085037	EPJ C77 163

Nuclear modification of PDFs

EPPS16 [1612.05741]

$$f_i^{p/A}(x,Q^2) = R_i^A(x,Q^2) f_i^p(x,Q^2)$$

$$R_i^A(x,Q_0^2) = \begin{cases} a_0 + a_1(x-x_a)^2 & x \le x_a \\ b_0 + b_1 x^\alpha + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1, \end{cases}$$

nCTEQ15 [1509.00792]

$$x f_i^{p/A}(x,Q_0) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5},$$
$$\text{for} \quad i = u_v, d_v, g, \bar{u}+\bar{d}, s+\bar{s}, s-\bar{s},$$

$$\frac{\bar{d}(x,Q_0)}{\bar{u}(x,Q_0)} = c_0 x^{c_1}(1-x)^{c_2} + (1+c_3 x)(1-x)^{c_4}.$$

$$c_k \to c_k(A) \equiv c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right), \quad k = \{1,\ldots,5\}.$$

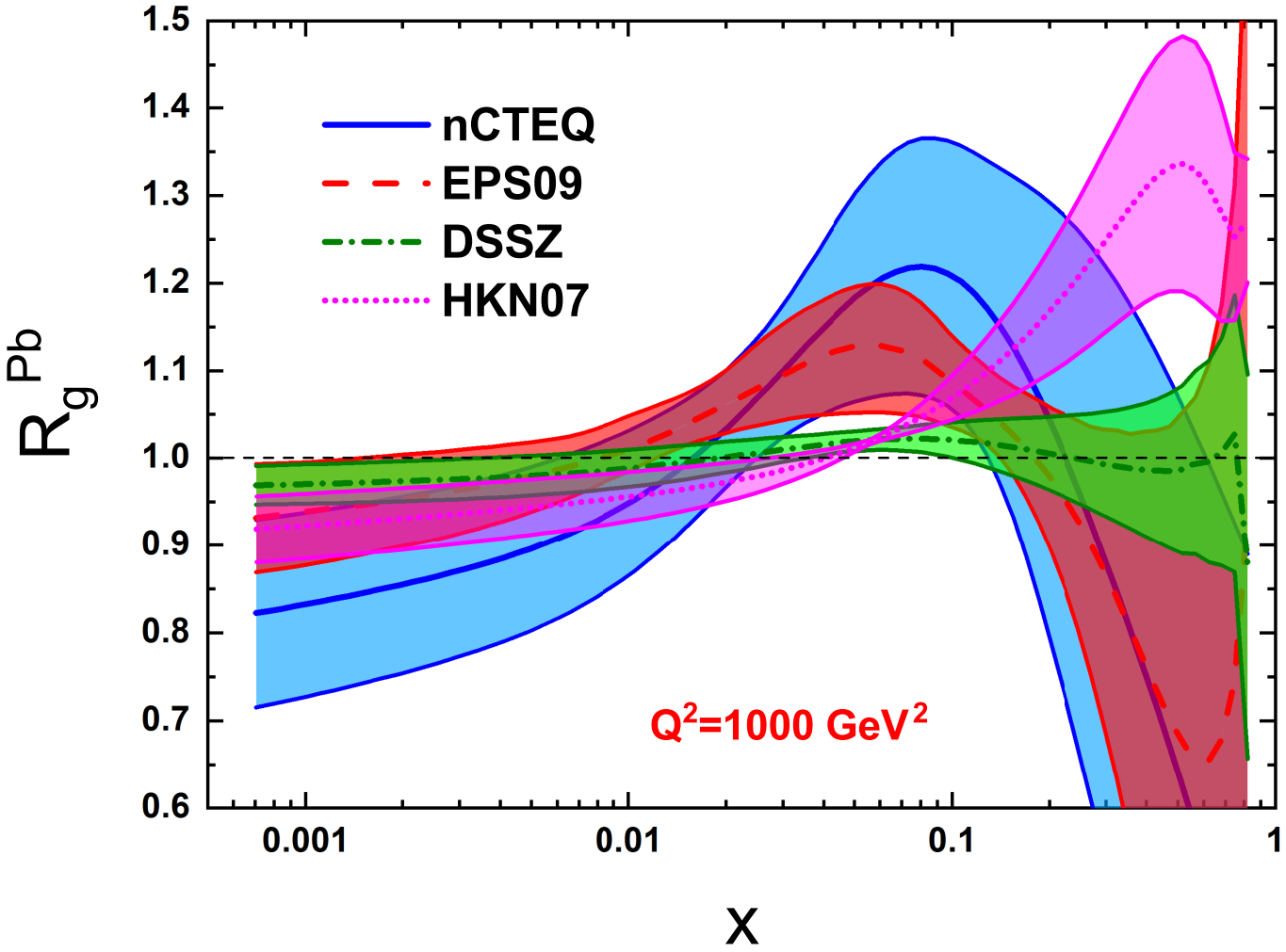
Taken from the talk of Rabah Abdul Khalek in Hard Probes 2018 conference

For quark PDFs in a nucleus with mass number A and Z protons:

$$f_i^{(A,Z)}(x,Q^2) = \frac{Z}{A} f_i^{p/A} + \frac{A-Z}{A} f_i^{n/A}.$$

bound neutron PDFs, $f_i^{n/A}$, are constructed assuming iso-spin symmetry.

Gluon nuclear modifications



Nuclear xFitter

What should we do?

- Adding all available nuclear experimental data to xFitter.
- Developing xFitter to include the related theoretical calculations of the experimental data included.
- Including various parameterizations and different approaches.
- Generating the results of NPDFs automatically for various nuclei.
- Plotting both nuclear modifications and parton densities inside a bound proton automatically in addition to NPDFs themselves.

Experimental data included

We have included all available DIS data for nuclear structure function ratios.

```
&InFiles
  ! Number of intput files
    NInputFiles = 43

  ! Input files:

    InputFileNames(1) = 'datafiles/Nuclear/E139/He-D_E139.dat'
    InputFileNames(2) = 'datafiles/Nuclear/NMC95re/He-D_NMC95re.dat'
    InputFileNames(3) = 'datafiles/Nuclear/HERMES/He-D_HERMES.dat'
    InputFileNames(4) = 'datafiles/Nuclear/NMC95/Li-D_NMC95.dat'
    InputFileNames(5) = 'datafiles/Nuclear/E139/Be-D_E139.dat'
    InputFileNames(6) = 'datafiles/Nuclear/E139/C-D_E139.dat'
    InputFileNames(7) = 'datafiles/Nuclear/NMC95/C-D_NMC95.dat'
    InputFileNames(8) = 'datafiles/Nuclear/NMC95re/C-D_NMC95re.dat'
    InputFileNames(9) = 'datafiles/Nuclear/EMC88/C-D_EMC88.dat'
    InputFileNames(10) = 'datafiles/Nuclear/EMC90/C-D_EMC90.dat'
    InputFileNames(11) = 'datafiles/Nuclear/E665-95/C-D_E665-95.dat'
    InputFileNames(12) = 'datafiles/Nuclear/BCDMS85/N-D_BCDMS85.dat'
    InputFileNames(13) = 'datafiles/Nuclear/HERMES/N-D_HERMES.dat'
    InputFileNames(14) = 'datafiles/Nuclear/E049/Al-D_E049.dat'
    InputFileNames(15) = 'datafiles/Nuclear/E139/Al-D_E139.dat'
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    InputFileNames(17) = 'datafiles/Nuclear/NMC95re/Ca-D_NMC95re.dat'
    InputFileNames(18) = 'datafiles/Nuclear/EMC90/Ca-D_EMC90.dat'
    InputFileNames(19) = 'datafiles/Nuclear/E665-95/Ca-D_E665-95.dat'
    InputFileNames(20) = 'datafiles/Nuclear/E087/Fe-D_E087.dat'
    InputFileNames(21) = 'datafiles/Nuclear/E139/Fe-D_E139.dat'
    InputFileNames(22) = 'datafiles/Nuclear/E140/Fe-D_E140.dat'
    InputFileNames(23) = 'datafiles/Nuclear/BCDMS87/Fe-D_BCDMS87.dat'
    InputFileNames(24) = 'datafiles/Nuclear/BCDMS85/Fe-D_BCDMS85.dat'
    InputFileNames(25) = 'datafiles/Nuclear/EMC93/Cu-D_EMC93.dat'
    InputFileNames(26) = 'datafiles/Nuclear/EMC93/Cu-D_EMC93(chariot).dat'
    InputFileNames(27) = 'datafiles/Nuclear/EMC88/Cu-D_EMC88.dat'
    InputFileNames(28) = 'datafiles/Nuclear/HERMES/Kr-D_HERMES.dat'
    InputFileNames(29) = 'datafiles/Nuclear/E139/Ag-D_E139.dat'
    InputFileNames(30) = 'datafiles/Nuclear/EMC88/Sn-D_EMC88.dat'
    InputFileNames(31) = 'datafiles/Nuclear/E665-92/Xe-D_E665-92.dat'
    InputFileNames(32) = 'datafiles/Nuclear/E139/Au-D_E139.dat'
    InputFileNames(33) = 'datafiles/Nuclear/E140/Au-D_E140.dat'
    InputFileNames(34) = 'datafiles/Nuclear/E665-95/Pb-D_E665-95.dat'

    InputFileNames(35) = 'datafiles/Nuclear/NMC96/Be-C_NMC96.dat'
    InputFileNames(36) = 'datafiles/Nuclear/NMC96/Al-C_NMC96.dat'
    InputFileNames(37) = 'datafiles/Nuclear/NMC96/Ca-C_NMC96.dat'
    InputFileNames(38) = 'datafiles/Nuclear/NMC95re/Ca-C_NMC95re.dat'
    InputFileNames(39) = 'datafiles/Nuclear/NMC96/Fe-C_NMC96.dat'
    InputFileNames(40) = 'datafiles/Nuclear/NMC96/Sn-C_NMC96.dat'
    InputFileNames(41) = 'datafiles/Nuclear/NMC96/Pb-C_NMC96.dat'
    InputFileNames(42) = 'datafiles/Nuclear/NMC95re/C-Li_NMC95re.dat'
    InputFileNames(43) = 'datafiles/Nuclear/NMC95re/Ca-Li_NMC95re.dat'
```

Experimental data included

We have added a new reaction type, namely "Ratio F2A".

```
* info from hepdata:
*EXPeriment      = CERN-NA-037
*REACtion        = muon C --> muon X
*Plab            = 200.0 GeV
*Collaboration   = NMC
*Author          = Arneodo et al
*REFerence       = Nucl. Phys. B441 (1995) 12
*Additional info: easurement of the structure function ratio in deep inelastic
*                 muon Carbon scattering to Deuterium at incident moun energy of
*                 200 GeV in the kinematic x range 0.0001 to 0.7 and Q**2 0.01
*                 to 70 GeV**2. Data merged with previous NMC data from Amaudruz
*                 et al 1995 Nucl.Phys. B441 3. Additional normalization error
*                 of 0.004 not included.
*
*
*
&Data
          Name = 'C-D_NMC95'

          Reaction = 'Ratio F2A'

          NDATA = 24

          NColumn = 11
          ColumnType = 6*'Bin','Sigma',4*'Error'
          ColumnName = 'x','Q2','Anum2','Znum2','Anum1','Znum1','Ratio
F2A','stat','sysNMC95','ignore','ignore'

          Percent  = 4*true
```

nPDF parameterizations

At this stage, for the nPDF parameterizations we have implemented the HKN (HKN04 and HKN07) parameterizations, according to Hirai *et al.* papers Phys. Rev. C70 (2004) 044905 and Phys .Rev. C76 (2007) 065207.

```
 ! PDF type. Possible types are currently available:
 ! 'proton'  -- default (fitting proton data)
 ! 'lead'    -- fitting ONLY lead data (can't be used in combination with proton
data)
 ! 'NUCLPDF'    -- fitting nuclear data to determine nuclear PDFs

 PDFType = 'NUCLPDF'

 ! PDF parameterisation style. Possible styles are currently available:
 !  'HERAPDF' -- HERAPDF-like with uval, dval, Ubar, Dbar, glu evolved pdfs
 !  'CTEQ'        -- CTEQ-like parameterisation
 !  'CTEQHERA'    -- Hybrid: valence like CTEQ, rest like HERAPDF
 !  'CHEB'        -- CHEBYSHEV parameterisation based on glu,sea, uval,dval
evolved pdfs
 !  'LHAPDFQ0'    -- use lhapdf library to define pdfs at starting scale and
evolve with local qcdnum parameters
 !  'LHAPDF'      -- use lhapdf library to define pdfs at all scales
 !  'LHAPDFNATIVE'-- use lhapdf library to access pdfs and alphas
 !  'DDIS'        -- use Diffractive DIS
 !  'BiLog'       -- bi-lognormal parametrisation

  PDFStyle = 'HERAPDF'

 ! NPDF parameterisation style. It can be used if PDFType = 'NUCLPDF'.
 ! Possible styles are currently available:
 !  'HKN04'     -- exact HKN04 weight function for nuclear uval, dval, flavor
asymmetric antiquark and glu distributions with LHAPDFSET free
 !                 proton PDFs
 !  'HKN07'     -- exact HKN07 weight function for nuclear uval, dval, flavor
asymmetric antiquark and glu distributions with LHAPDFSET free
 !                 proton PDFs

  NPDFStyle = 'HKN04'
```

HKN parameterizations

In the HKN framework, the nuclear parton densities are written as follows

$$u_v^A(x,Q_0^2) = w_{u_v}(x,A,Z)\frac{Zu_v(x,Q_0^2)+Nd_v(x,Q_0^2)}{A},$$
$$d_v^A(x,Q_0^2) = w_{d_v}(x,A,Z)\frac{Zd_v(x,Q_0^2)+Nu_v(x,Q_0^2)}{A},$$
$$\bar{u}^A(x,Q_0^2) = w_{\bar{q}}(x,A,Z)\frac{Z\bar{u}(x,Q_0^2)+N\bar{d}(x,Q_0^2)}{A},$$
$$\bar{d}^A(x,Q_0^2) = w_{\bar{q}}(x,A,Z)\frac{Z\bar{d}(x,Q_0^2)+N\bar{u}(x,Q_0^2)}{A},$$
$$\bar{s}^A(x,Q_0^2) = w_{\bar{q}}(x,A,Z)\bar{s}(x,Q_0^2),$$
$$g^A(x,Q_0^2) = w_g(x,A,Z)g(x,Q_0^2),$$

The nuclear modification is assumed to have the following functional form:

$$w_i(x,A,Z) = 1+\left(1-\frac{1}{A^\alpha}\right)\frac{a_i+b_ix+c_ix^2+d_ix^3}{(1-x)^{\beta_i}},$$

HKN04 VS HKN07

The 'HKN07' parameterization includes some improvements both in x and A dependence of the nuclear modification.

The parametrization of x dependence is modified as

$$b_i = 3d_i x_{0i}^{+} x_{0i}^{-}, \quad c_i = -\frac{3d_i}{2}(x_{0i}^{+} + x_{0i}^{-}).$$

In order to make some improvements in A dependence, one can consider some of parameters to be A dependent.

$$\eta = \eta^{(1)}\left(1 - \frac{1}{A^{\eta^{(2)}}}\right), \quad \eta = d_v, \quad a_{\bar{q}}, \quad d_{\bar{q}}, \quad d_g.$$

Sum rules

There are three constraints for the parameters by the nuclear charge Z, baryon number A, and momentum conservation

$$Z = \int dx \frac{A}{3}\left[2u_v^A(x, Q_0^2) - d_v^A(x, Q_0^2)\right],$$

$$A = \int dx \frac{A}{3}\left[u_v^A(x, Q_0^2) + d_v^A(x, Q_0^2)\right],$$

$$A = \int dx Ax\left[u_v^A(x, Q_0^2) + d_v^A(x, Q_0^2) + 2\{\bar{u}^A(x, Q_0^2) + \bar{d}^A(x, Q_0^2) + \bar{s}^A(x, Q_0^2)\} + g^A(x, Q_0^2)\right].$$

Sum rules

We choose parameters a_i for valence and gluon nuclear modifications to be constrained with sum rules.

$$a_{u_v}(A,Z) = -\frac{ZI_1(A) + (A-Z)I_2(A)}{ZI_3 + (A-Z)I_4}, \tag{A3}$$

$$a_{d_v}(A,Z) = -\frac{ZI_2(A) + (A-Z)I_1(A)}{ZI_4 + (A-Z)I_3}, \tag{A4}$$

$$a_g(A,Z) = -\frac{1}{I_8}\left\{a_{u_v}(A,Z)\left[\frac{Z}{A}I_5 + \left(1-\frac{Z}{A}\right)I_6\right] + a_{d_v}(A,Z)\left[\frac{Z}{A}I_6 + \left(1-\frac{Z}{A}\right)I_5\right] + I_7(A)\right\}. \tag{A5}$$

We have modified the file "`sumrules.f`" to include these relations and constrain three parameters properly.

All modifications

All modifications we have made in xFitter package have been implemented in the following files:

dis_sigma.f
evolution.f
fcn.f
init_theory.f
read_steer.f
steering.inc
sumrules.f
theory_dispatcher.f

Preliminary Results

Phenomenological framework

- We choose the HKN04 parameterization with no any A dependence for the parameters.
- We fix the parameters α_i and β_i as $\alpha_i = 1/3$ and $\beta_i = 0.1$.
- The analysis is performed at next-to-leading order (NLO) using ZM-VFNS.
- We choose CT14nlo as free proton set.
- We apply the kinematics cut $Q^2 > 1.0$ GeV^2 on data.

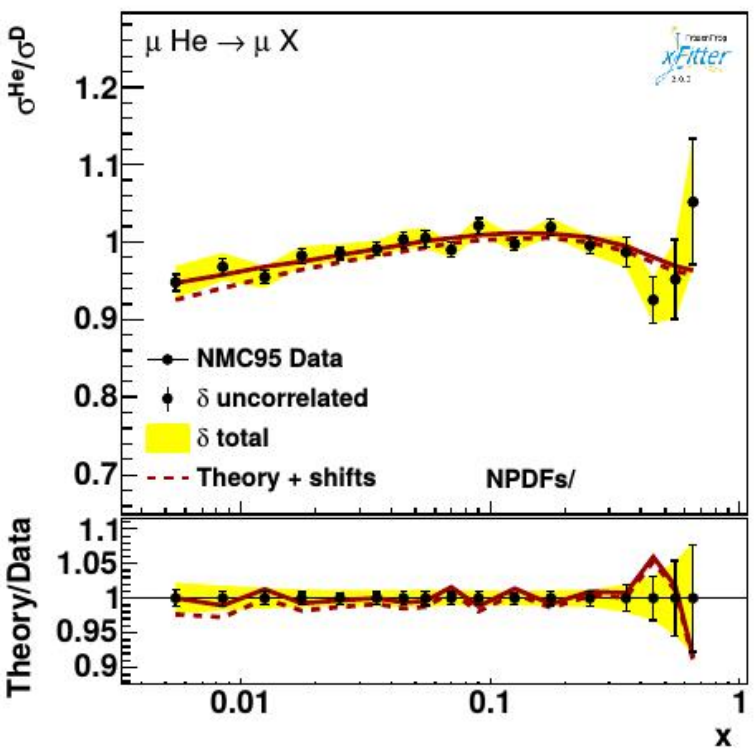
χ^2 values

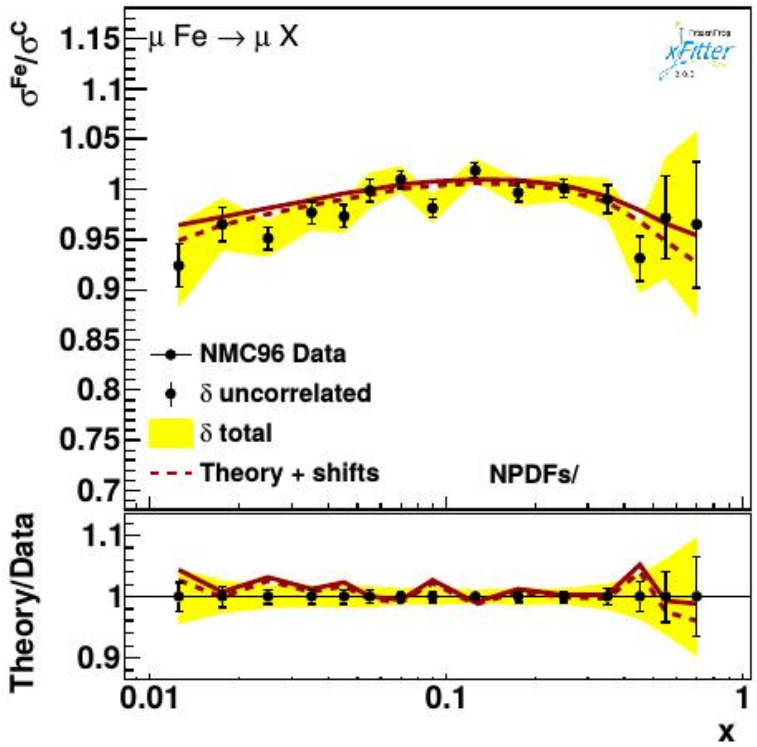
Dataset	NPDFs
He/D E139	15 / 18
He/D NMC95re	32 / 17
He/D HERMES	154 / 154
Li/D NMC95	55 / 17
Be/D E139	20 / 17
C/D E139	12 / 7
C/D NMC95	26 / 17
C/D NMC95re	41 / 17
C/D EMC88	5.5 / 9
C/D EMC90	4.5 / 5
C/D E665-95	16 / 5
N/D BCDMS85	8.8 / 9
N/D HERMES	123 / 153
Al/D E049	32 / 18
Al/D E139	12 / 17
Ca/D E139	11 / 7
Ca/D NMC95re	24 / 16
Ca/D EMC90	28 / 12
Ca/D E665-95	7.7 / 5
Fe/D E087	6.6 / 14
Fe/D E139	36 / 23
Fe/D E140	33 / 10
Fe/D BCDMS87	30 / 10
Fe/D BCDMS85	4.6 / 6
Cu/D EMC93	10 / 10
Cu/D EMC93(chariot)	8.6 / 9
Cu/D EMC88	8.3 / 9
Kr/D HERMES	151 / 144
Ag/D E139	5.4 / 7
Sn/D EMC88	13 / 8
Xe/D E665-92	4.0 / 5
Au/D E139	23 / 18
Au/D E140	3.3 / 1
Pb/D E665-95	3.9 / 5
Be/C NMC96	33 / 15
Al/C NMC96	14 / 15
Ca/C NMC96	23 / 15
Ca/C NMC95re	28 / 24
Fe/C NMC96	24 / 15
Sn/C NMC96	47 / 15
Pb/C NMC96	14 / 15
C/Li NMC95re	37 / 24
Ca/Li NMC95re	51 / 24
Correlated χ^2	24
Log penalty χ^2	+9.4
Total χ^2 / dof	1273 / 952

Optimum Parameters

Parameter	NPDFs
'bg'	2.73 ± 0.83
'dg'	-9.4 ± 4.0
'alphag'	0.3333
'betag'	0.1000
'buv'	-1.87 ± 0.18
'cuv'	-5.30 ± 0.34
'duv'	8.51 ± 0.31
'alphauv'	0.3333
'betauv'	0.1000
'asea'	-0.495 ± 0.017
'bsea'	12.73 ± 0.58
'csea'	-69.2 ± 4.8
'dsea'	416 ± 18
'alphasea'	0.3333
'betasea'	0.1000
'alphas'	0.1180
Fit status	converged
Uncertainties	migrad-hesse

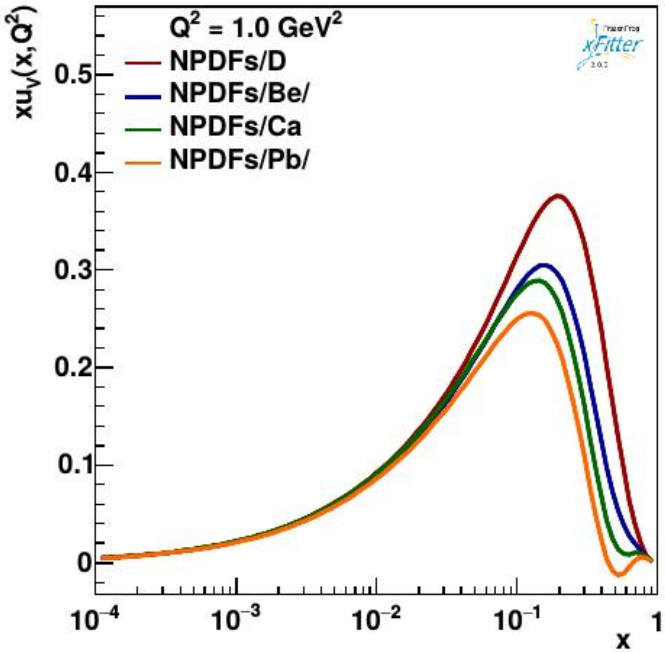
Comparison to data

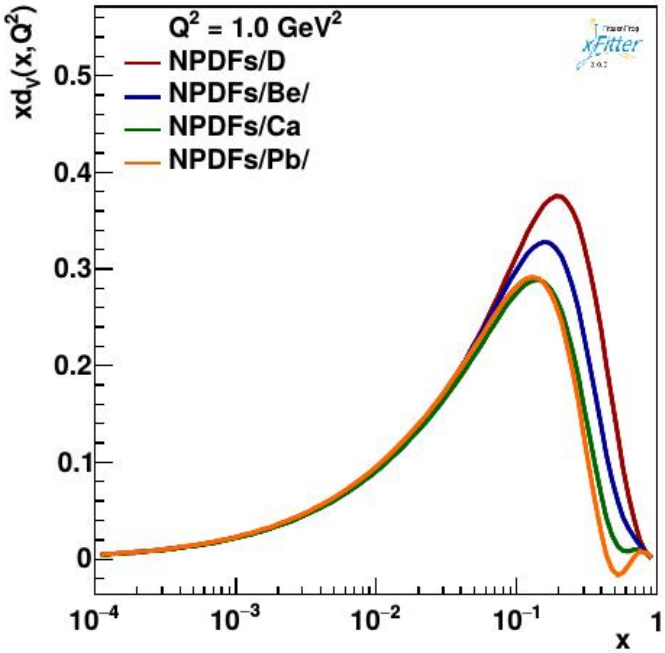




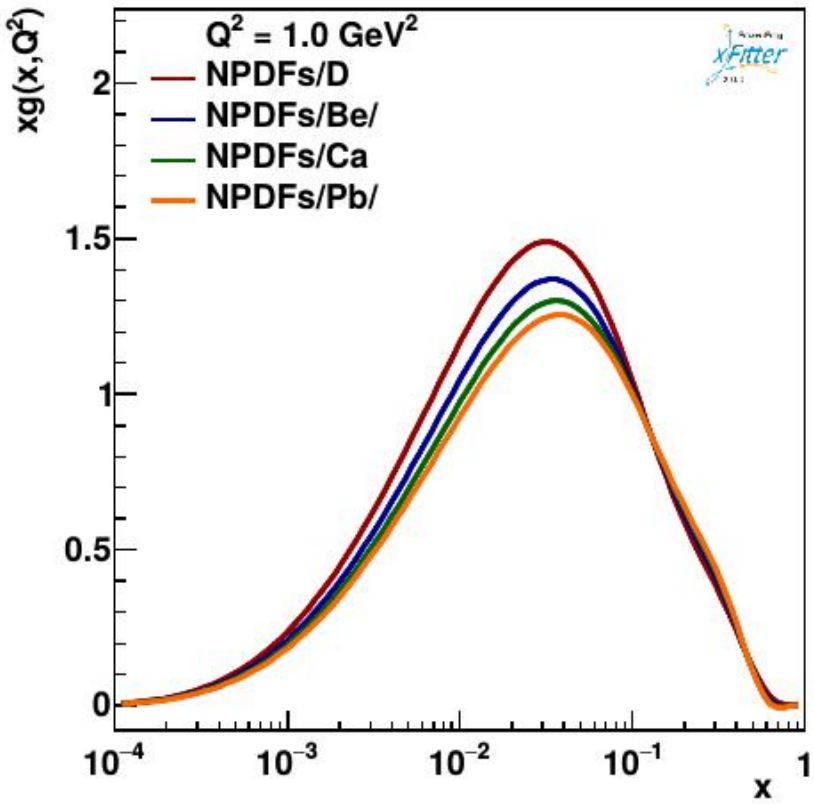
Nuclear PDFs

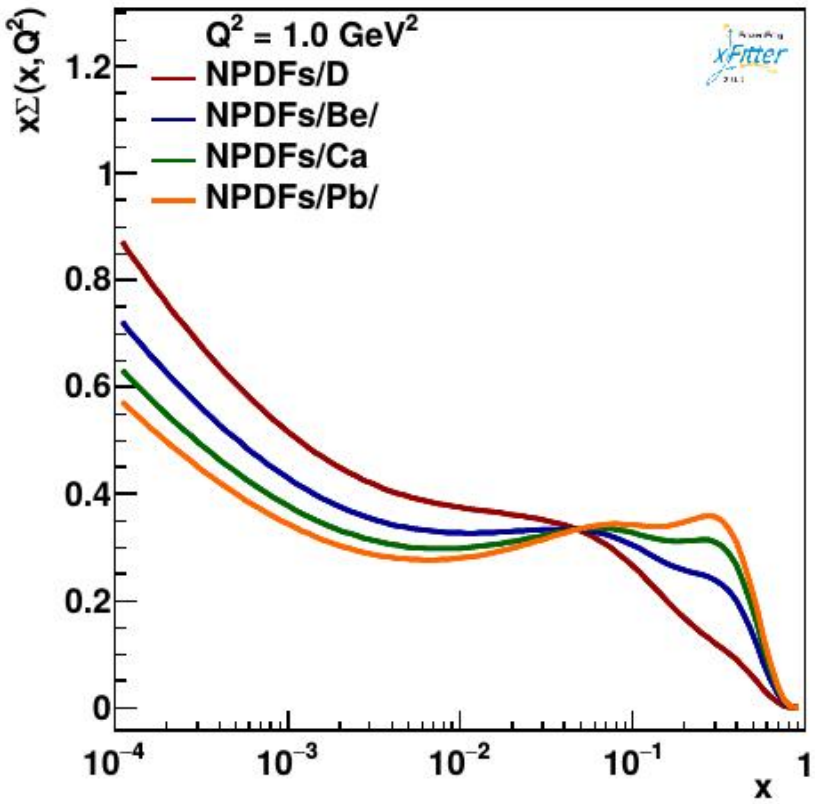
We have modified the xFitter so that the results of NPDFs are automatically generated for 17 nuclei, from Deuterium to Lead, and user can compare NPDFs of different nuclei as usual using 'xfitter-draw' command.





Nuclear PDFs





Summary and Conclusions

We have worked on xFitter to prefer it for performing nuclear PDFs analysis in a user-friendly way.

- The user can easily turn on nPDFs analysis and switch between different parametrizations in the "steering.txt" file.
- We have included all available DIS data for nuclear structure function ratios by adding a new reaction type, namely "Ratio F2A".
- At the present, we have implemented "HKN04" and "HKN07" parametrizations.
- The results of NPDFs are automatically generated for 17 nuclei, from Deuterium to Lead.
- It is possible to have a nuclear xFitter in the near future.

Outlook

- Adding other parametrizations from different groups like EPS, nCTEQ and so on.
- Including the Drell-Yan and collider data by adding related theoretical calculations.
- Modifying `xFitter` for plotting both nuclear modifications and parton densities inside a bound proton automatically, in addition to NPDFs.


THANK YOU