From nucleon to meson PDF fits

... a cooperative presentation & discussion

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Jefferson Lab, & Southern Methodist University

Thanks for substantial input
from our friends & colleagues

I: Tools for nucleon and meson PDF fits

- Nuclear Fits to Pion Fits
- Analysis Tools (xFitter, Python, Mathematica)

II: Toward Global Analyses of meson structure

- Nucleon PDFs: CTEQ-TEA, CTEQ-JLab
- Nuclear PDFs: nCTEQ (nuclear CTEQ)
- Meson PDFs in the AMBER/EIC era
- New methodology

III: Discussion

Workshop on Pion and Kaon
Structure Functions at the EIC
2-June 5, 2020
CFNS Virtual Meeting

Part I: Tools for nucleon and meson PDF fits

... xFitter with nucleons & pions ...

Special thanks to: Ivan Novikov, Alexander Glazov, Oleksandr Zenaiev

xFitter release xfitter-2.0.1

www.xFitter.org

xFitter

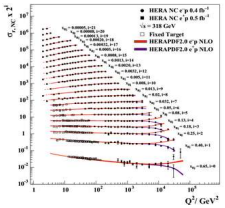
xFitter

xFitter/xFitterTalks » xFitter/../xFitterDevel.. » xFitter/../Meeting2017-.. » xFitter » xFitter/DownloadPage

Sample data files:

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

Experimental Data



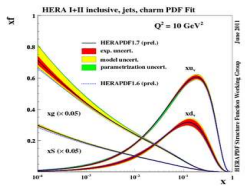
Data: HERA, Tevatron, LHC, fixed target experiments

Processes:
Inclusive DIS, Jets, Drell-Yan, Diffraction, Top production W and Z production

Theory Calculations

HQ Schemes:	MSTW, NNPDF, ABM, ACOT
Jets, W, Z:	FastNLO, ApplGrid
Top:	Hathor
Evolution:	QCDNUM, APFEL, k_T
Other:	NNPDF reweighting TMDs, Dipole Model, ...

xFitter



Parton Distribution Functions:
PDF, Updf, TMD

$\alpha_S(M_Z)$, m_c,m_b,m_t ...

Theoretical Cross Sections

Comparisons to other PDFs (LHAPDF)

extensions include nuclear PDFs

Features & Recent Updates:

Photon PDF & QED
Pole & MS-bar masses
Profiling and Re-Weighting

Heavy Quark Variable Treshold
Improvements in χ^2 and correlations
TMD PDFs (uPDFs)
… and many other

xFitter 2.0.1
Old Fashioned

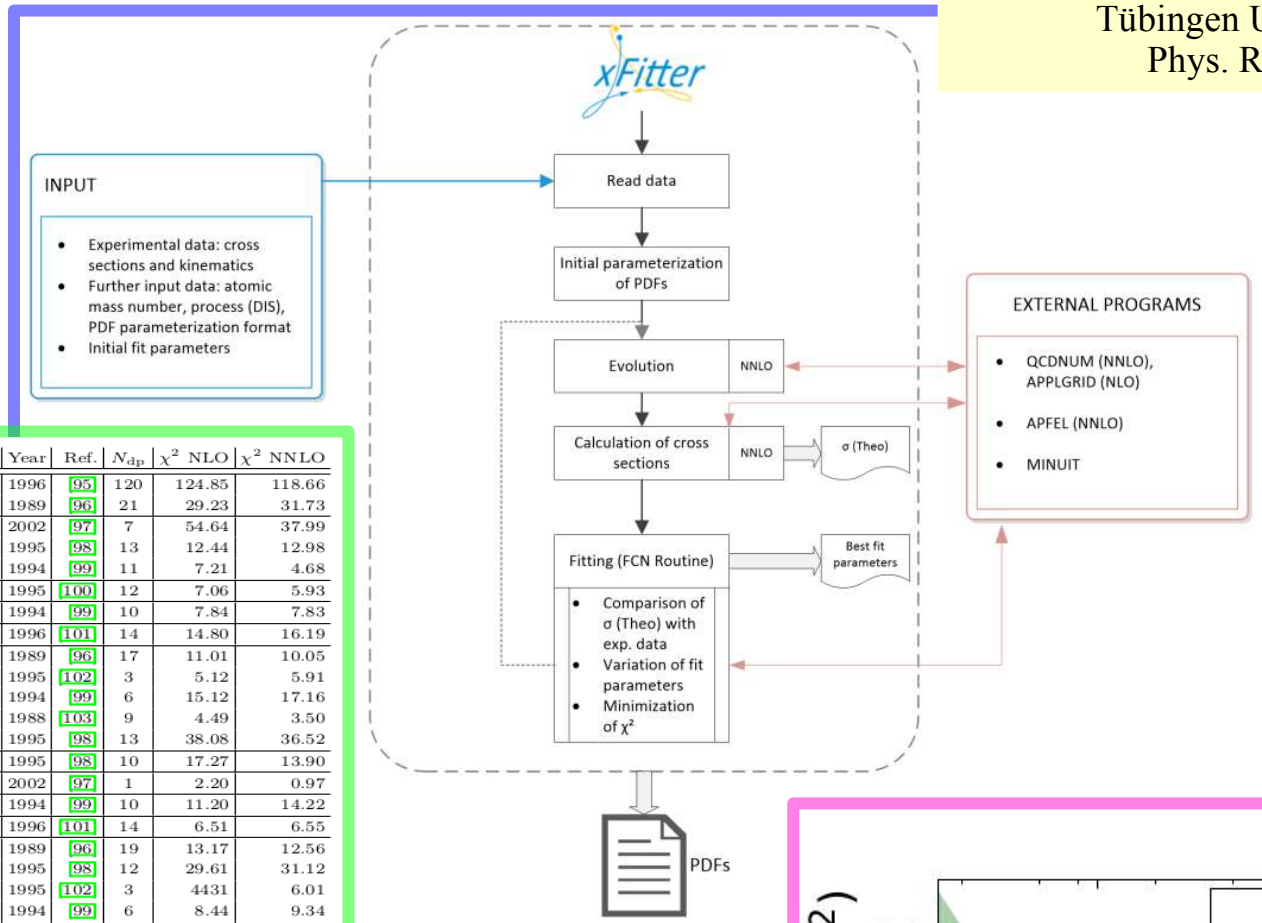
xFitter Nuclear Fit

xFitter Nuclear PDFs

Open-source QCD analysis of nuclear parton distribution functions at NLO and NNLO

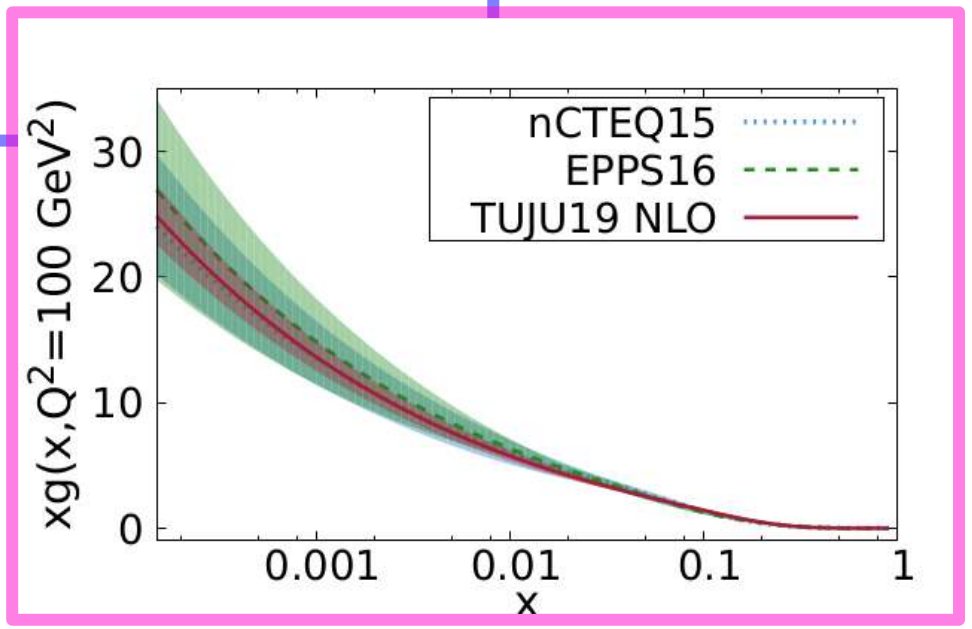
Marina Walt, Ilkka Helenius, Werner Vogelsang
Tübingen U, Jyvaskyla U (TUJU)

Phys. Rev. D 100, 096015 (2019)



Nucleus	Exp.	Year	Ref.	N_{dp}	χ^2 NLO	χ^2 NNLO
D	NMC 97	1996	95	120	124.85	118.66
	EMC 90	1989	96	21	29.23	31.73
He/D	HERMES	2002	97	7	54.64	37.99
	NMC 95, re.	1995	98	13	12.44	12.98
	SLAC E139	1994	99	11	7.21	4.68
Li/D	NMC 95	1995	100	12	7.06	5.93
Be/D	SLAC E139	1994	99	10	7.84	7.83
Be/C	NMC 96	1996	101	14	14.80	16.19
C	EMC 90	1989	96	17	11.01	10.05
C/D	FNAL E665	1995	102	3	5.12	5.91
	SLAC E139	1994	99	6	15.12	17.16
	EMC 88	1988	103	9	4.49	3.50
	NMC 95, re.	1995	98	13	38.08	36.52
C/Li	NMC 95, re.	1995	98	10	17.27	13.90
N/D	HERMES	2002	97	1	2.20	0.97
Al/D	SLAC E139	1994	99	10	11.20	14.22
Al/C	NMC 96	1996	101	14	6.51	6.55
Ca	EMC 90	1989	96	19	13.17	12.56
Ca/D	NMC 95, re.	1995	98	12	29.61	31.12
	FNAL E665	1995	102	3	4431	6.01
	SLAC E139	1994	99	6	8.44	9.34
Ca/Li	NMC 95, re.	1995	98	10	7.36	5.16
Ca/C	NMC 95, re.	1995	98	10	6.47	6.70
	NMC 96	1996	101	14	7.14	6.99
Fe	SLAC E140	1993	104	2	0.05	0.05
Fe/D	SLAC E139	1994	99	14	34.08	34.18
Fe/C	NMC 96	1996	101	14	9.82	9.96
ν Fe	CDHSW	1991	105	464	347.74	365.14
$\bar{\nu}$ Fe	CDHSW	1991	105	462	423.06	398.25
Cu/D	EMC 93					
	EMC 88					
Kr/D	HERMES					
Ag/D	SLAC E13					
Sn/D	EMC 88					
Sn/C	NMC 96					
	NMC 96,					
Xe/D	FNAL E6					
Au/D	SLAC E13					
Pb/D	FNAL E6					
Pb/C	NMC 96					
ν Pb	CHORUS					
$\bar{\nu}$ Pb	CHORUS					
			In total:	2336	2072.29	2014.02

Date	Version	Files	Remarks
 02/2020	**2.0.1N Nuclear Daiquiri**	xfitter-2.0.1N.tgz	Nuclear xFitter based on OldFashioned 2.0.1



xFitter Pion Fit

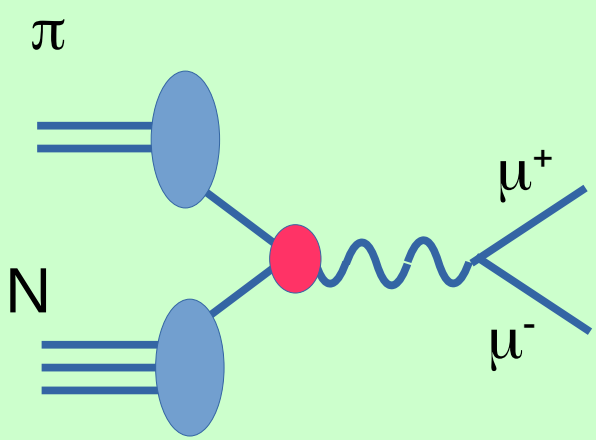
xFitter Meson PDFs

Special thanks to: Ivan Novikov, Alexander Glazov, Oleksandr Zenaiev

xFitter: open-source framework for global fits to meson PDFs

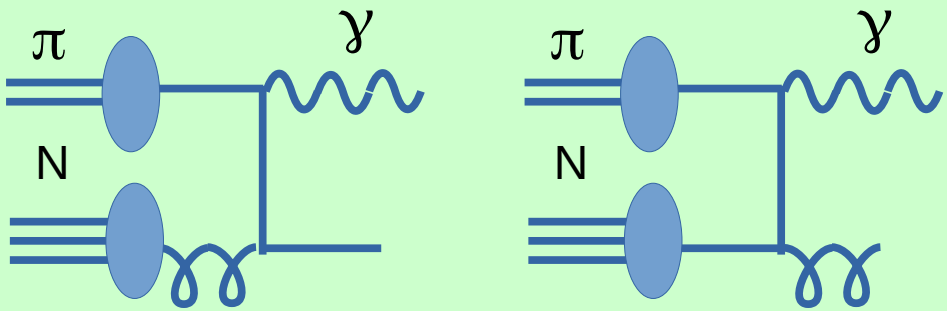
https://www.xfitter.org/

Experiment	χ^2/N_{points}
E615	206/140
NA10 (194 GeV)	107/67
NA10 (286 GeV)	95/73
WA70	64/99



E615 & NA10

Pions on Tungsten



WA70

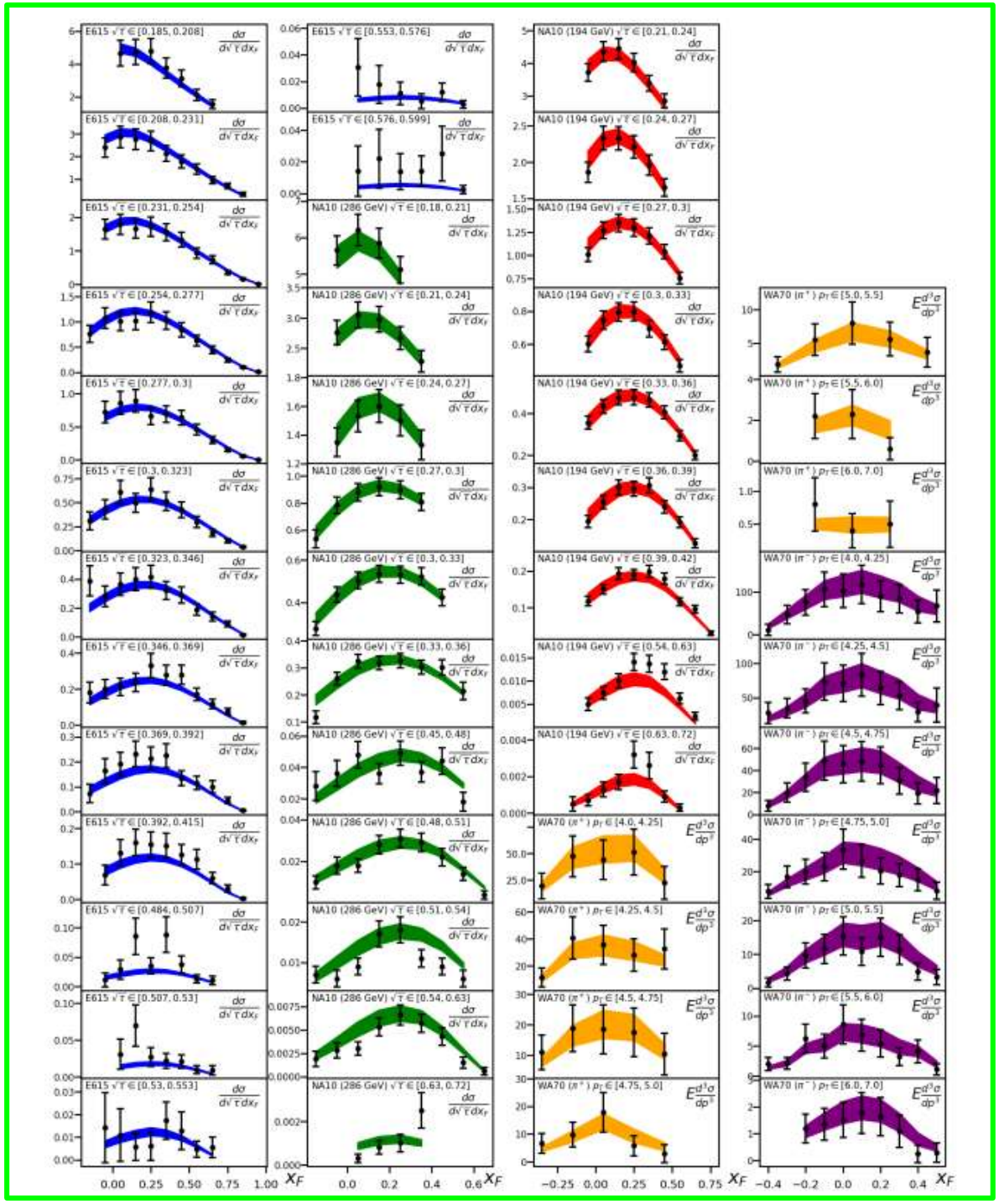
Pions on Proton

Parton Distribution Functions of the Charged Pion Within The xFitter Framework

xFitter Developers' team: Ivan Novikov,[1,2,*] Hamed Abdolmaleki,[3] Daniel Britzger,[4] Amanda Cooper-Sarkar,[5] Francesco Giuli,[6] Alexander Glazov,[2,†] Aleksander Kusina,[7] Agnieszka Luszczak,[8] Fred Olness,[9] Pavel Starovoitov,[10] Mark Sutton,[11] and Oleksandr Zenaiev[12]

e-Print: 2002.02902 [hep-ph]

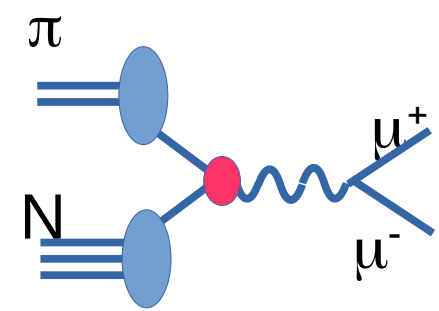
Pion Data:



Pions (π^-) on Tungsten

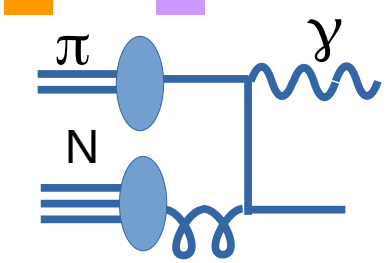
E615 E_π = **252 GeV**

NA10 E_π = **194 GeV** & **286 GeV**



Pions ($\pi^\pm$) on Proton

WA70 π^+ π^-



NLO computation with MCFM / APPLGRID

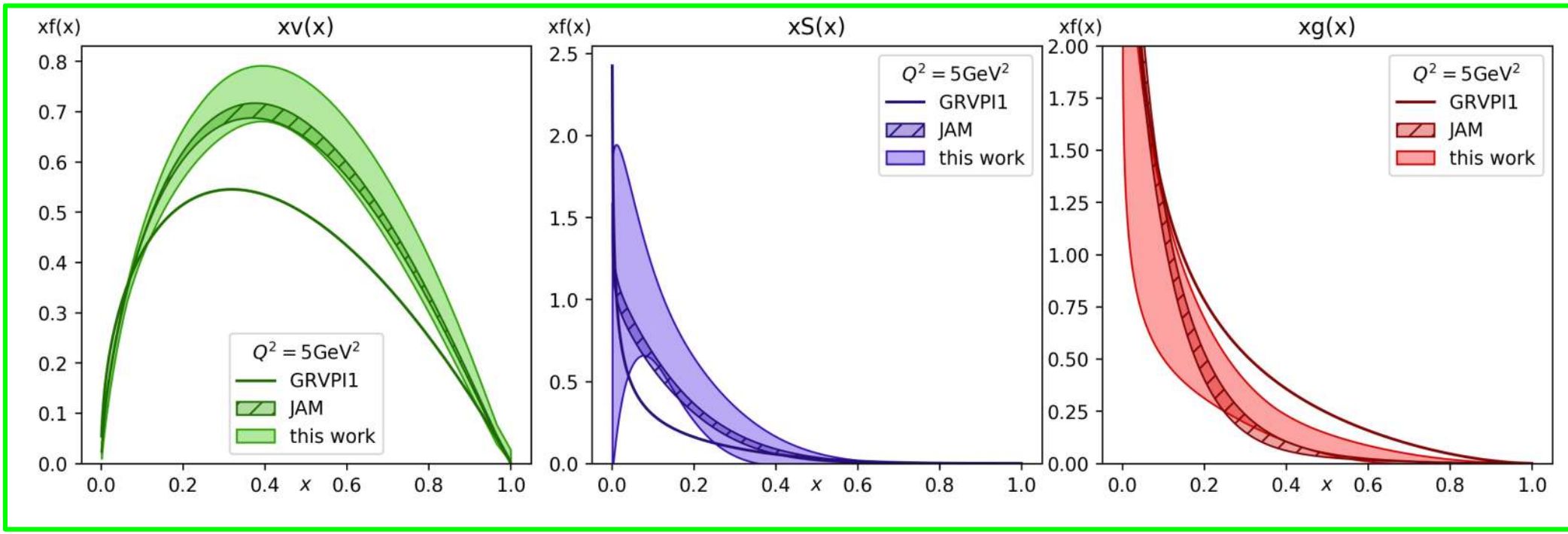
- theory errors from α_S, and nPDF uncert
- uncertainties include scale variations.
- for factorization scale variation modify APPLGRID for two PDFs

xFitter Pion PDFs

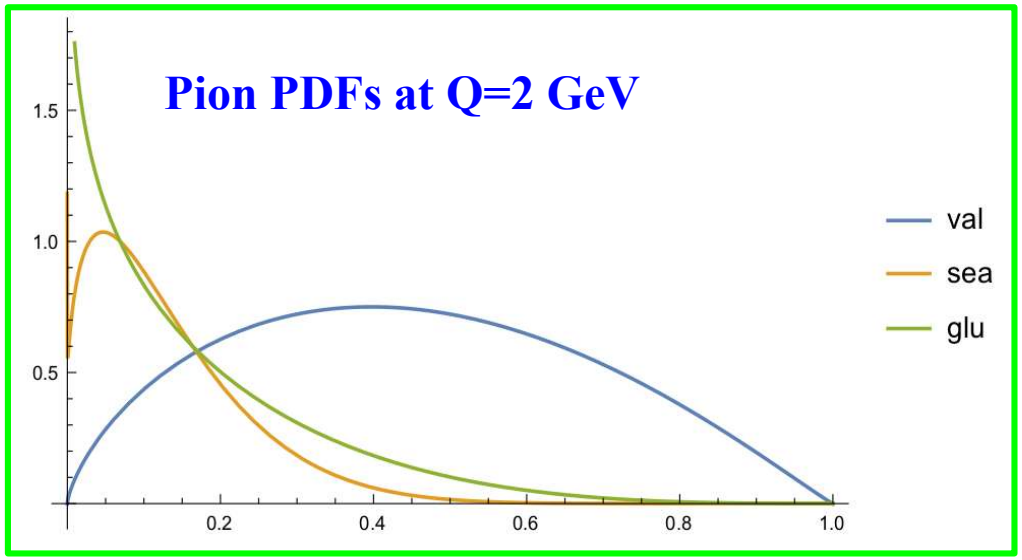
Experiment	Normalization uncertainty	χ^2/N_{points}
E615	15 %	206/140
NA10 (194 GeV)	6.4%	107/67
NA10 (286 GeV)	6.4%	95/73
WA70	32%	64/99

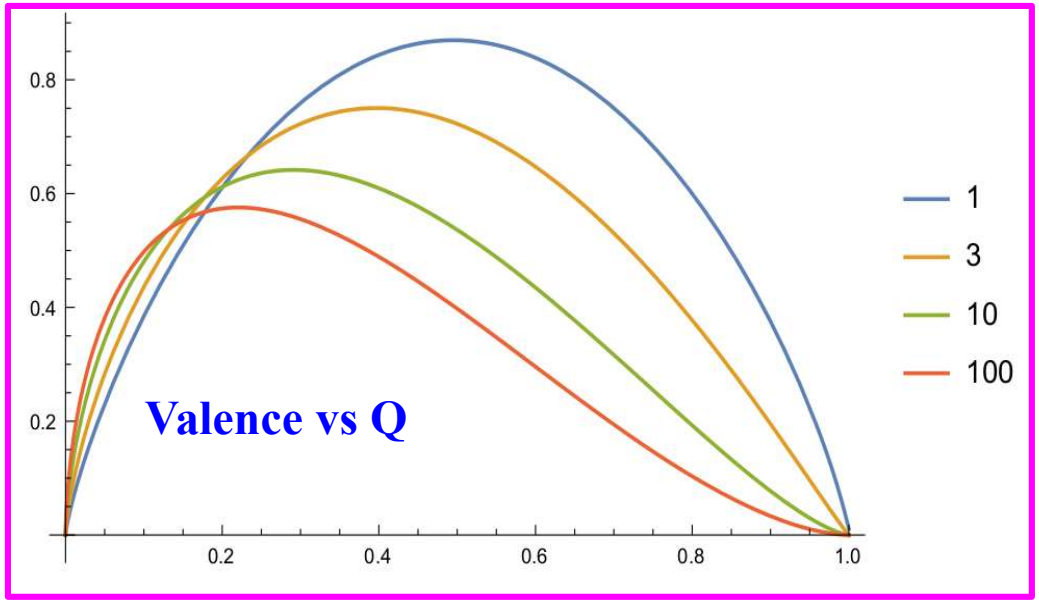
$$xv(x) = A_v x^{B_v}(1-x)^{C_v}(1+D_v x^{\alpha}),$$
$$xS(x) = A_S x^{B_S}(1-x)^{C_S}/\mathcal{B}(B_S+1, C_S+1),$$
$$xg(x) = A_g(C_g+1)(1-x)^{C_g},$$

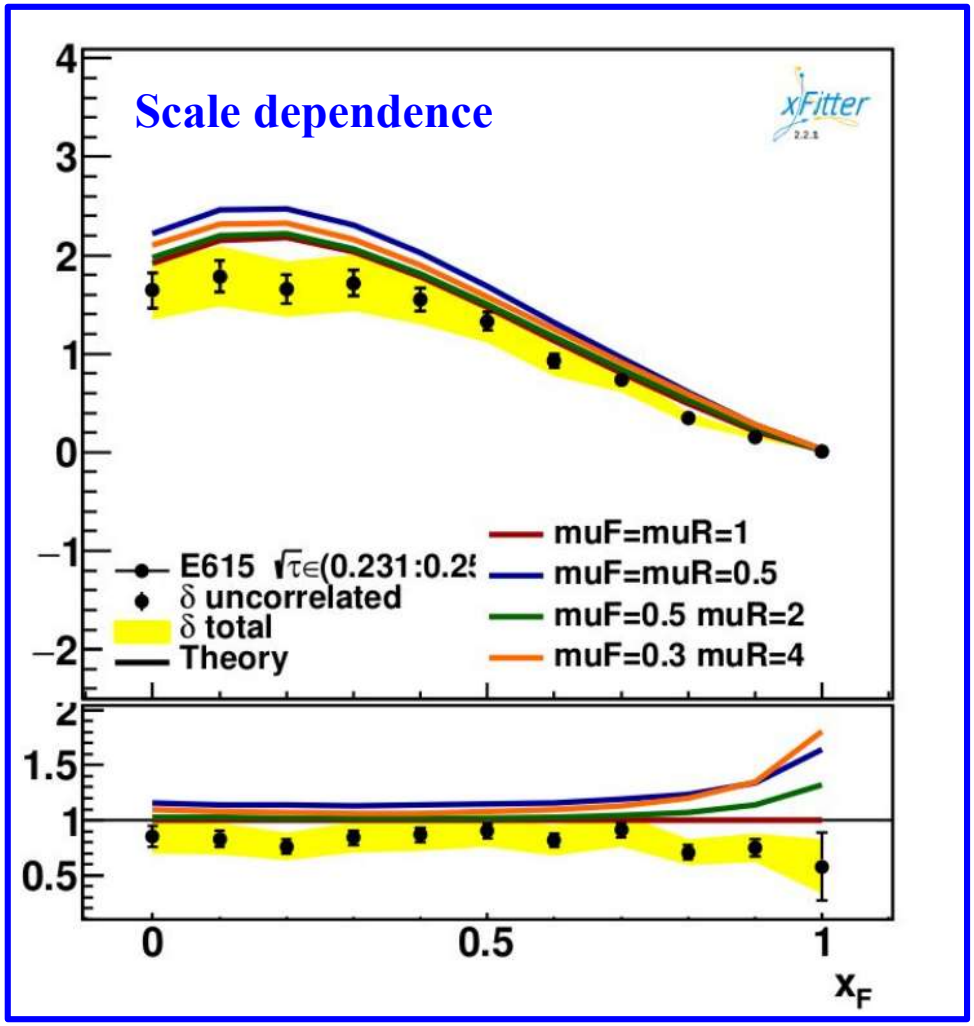
	$\langle xv\rangle$	$\langle xS\rangle$	$\langle xg\rangle$	Q^2 (GeV^2)
JAM [26]	0.54 ± 0.01	0.16 ± 0.02	0.30 ± 0.02	1.69
JAM (DY)	0.60 ± 0.01	0.30 ± 0.05	0.10 ± 0.05	1.69
this work	0.55 ± 0.06	0.26 ± 0.15	0.19 ± 0.16	1.69
Lattice-3 [16]	0.428 ± 0.030			4
SMRS [20]	0.40 ± 0.02			4
Han et al. [42]	0.428 ± 0.03			4
DSE [7]	0.52			4
this work	0.50 ± 0.05	0.25 ± 0.13	0.25 ± 0.13	4
JAM	0.48 ± 0.01	0.17 ± 0.01	0.35 ± 0.02	5
this work	0.49 ± 0.05	0.25 ± 0.12	0.26 ± 0.13	5
Lattice-1 [14]	0.558 ± 0.166			5.76
Lattice-2 [15]	0.48 ± 0.04			5.76
this work	0.48 ± 0.05	0.25 ± 0.12	0.27 ± 0.13	5.76
WRH [21]	0.434 ± 0.022			27
ChQM-1 [11]	0.428			27
ChQM-2 [13]	0.46			27
this work	0.42 ± 0.04	0.25 ± 0.10	0.32 ± 0.10	27
SMRS [20]	0.49 ± 0.02			49
this work	0.41 ± 0.04	0.25 ± 0.09	0.34 ± 0.09	49



xFitter Pion PDFs







The Tools

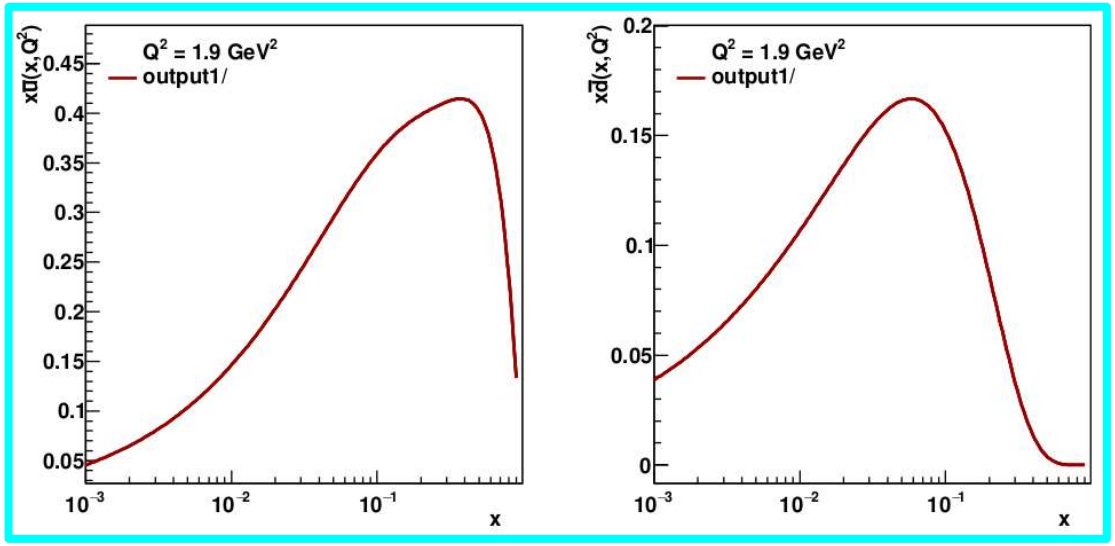
xFitter-draw

Python Jupyter

Mathematica: ManeParse

xFitter Tools:

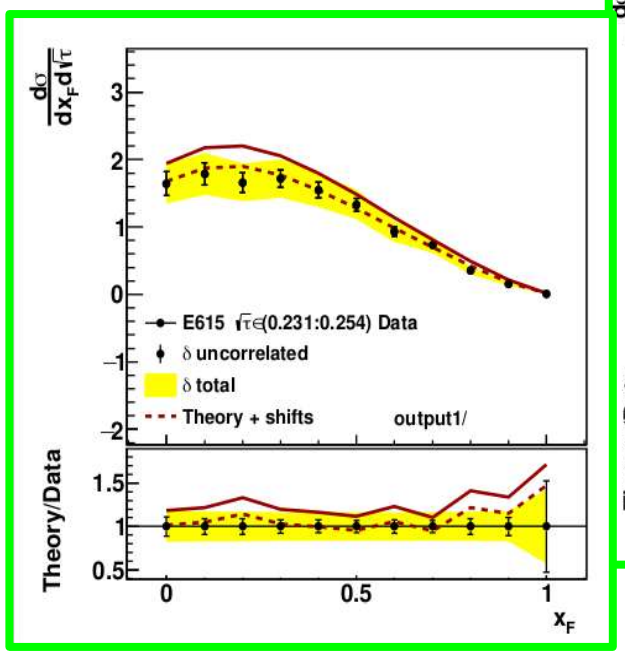
xfitter-draw
xfitter-process

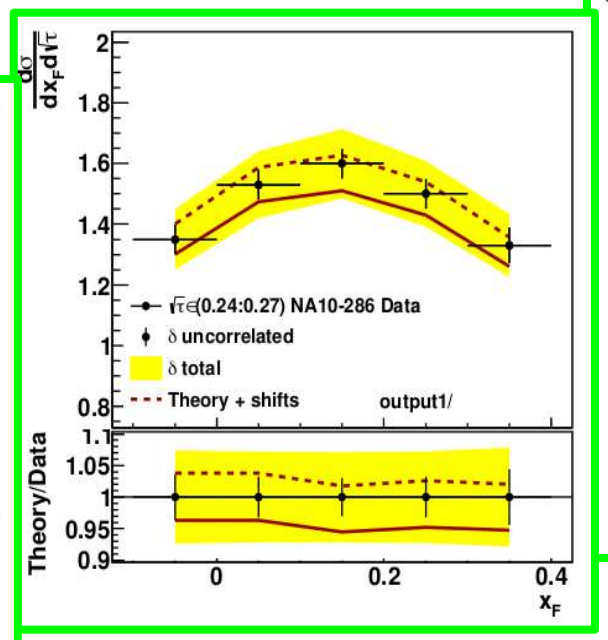


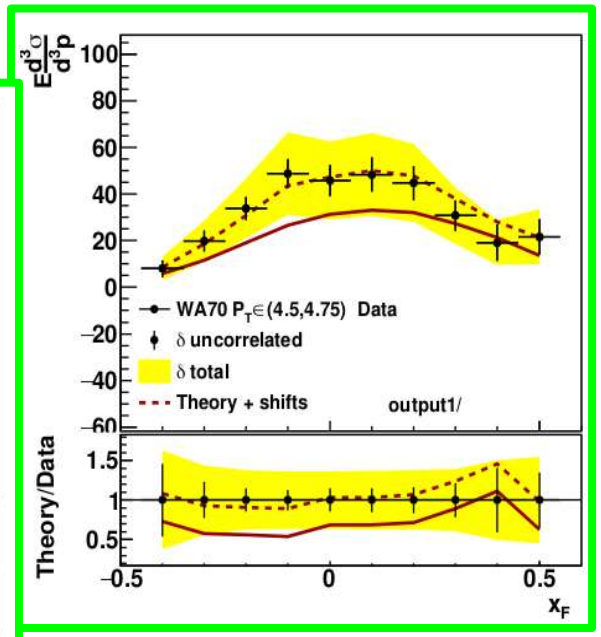
PDF Plots

Chi2 Tables

Dataset	output1
E615-0	13 / 7
E615-1	9.5 / 10
E615-2	13 / 11
E615-3	15 / 12
E615-4	8.9 / 11
E615-5	9.7 / 11
E615-6	12 / 11
E615-7	16 / 11
E615-8	16 / 11
E615-9	18 / 10
E615-13	32 / 8
E615-14	18 / 7
E615-15	3.5 / 8
E615-16	8.0 / 6
E615-17	16 / 6
NA10-194-0	8.8 / 6
NA10-194-1	6.5 / 6
NA10-194-2	8.3 / 7
NA10-194-3	5.1 / 7
NA10-194-4	2.7 / 8
NA10-194-5	6.0 / 8
NA10-194-6	21 / 9
NA10-194-7	40 / 8
NA10-194-8	9.8 / 8
NA10-286-0	10 / 4
NA10-286-1	1.7 / 5
NA10-286-2	3.6 / 5
NA10-286-3	1.5 / 6
NA10-286-4	4.7 / 7
NA10-286-5	15 / 8
NA10-286-6	10 / 8
NA10-286-7	5.9 / 9
NA10-286-8	20 / 8
NA10-286-9	13 / 9
NA10-286-10	13 / 4
WA70plus-0	1.1 / 5
WA70plus-1	4.9 / 5
WA70plus-2	2.3 / 5
WA70plus-3	4.5 / 5
WA70plus-4	1.7 / 5
WA70plus-5	2.2 / 3
WA70plus-6	3.5 / 3
WA70-0	3.8 / 10
WA70-1	5.4 / 10
WA70-2	4.0 / 10
WA70-3	8.8 / 10
WA70-4	8.9 / 10
WA70-5	9.5 / 10
WA70-6	3.0 / 8
Correlated χ^2	3.5
Log penalty χ^2	-36.91
Total χ^2 / dof	445 / 373
χ^2 p-value	0.01



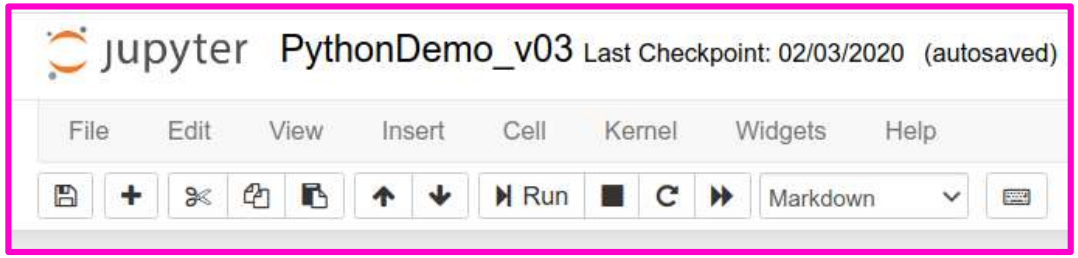


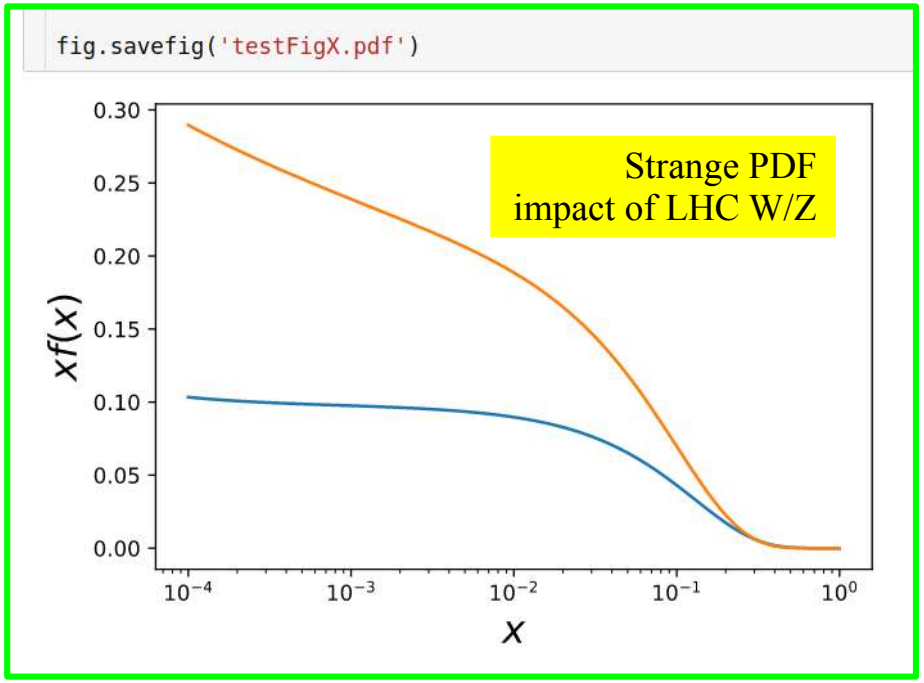


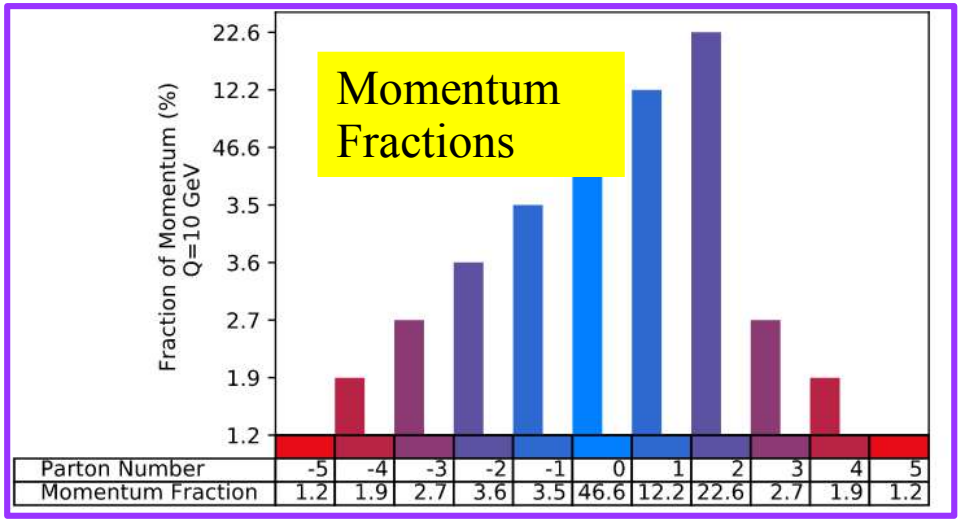
Data vs. Theory

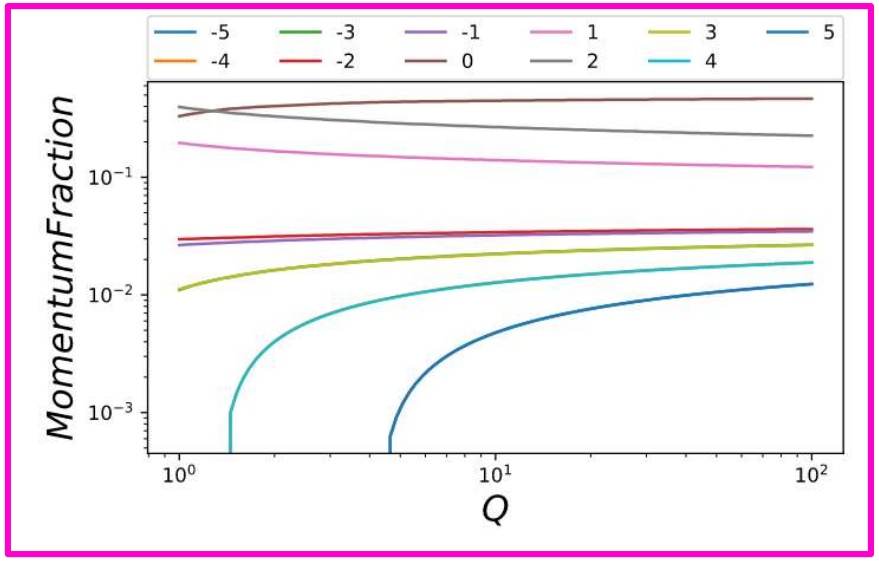
Python Jupyter Notebook

Python Jupyter Notebook









Momentum Fractions vs. Q

Mathematica

ManeParse

Mathematica: ManeParse

http://www.ncteq.org

nCTEQ

nuclear parton distribution functions

ManeParse: A Mathematica Interface to the PDFs

ManeParse is a modular Mathematica package that provides access to PDFs for hadronic calculations. It allows

ManeParse Publication:

Download the publication here:

- **ManeParse : A Mathematica reader for Parton Distribution Functions**
  D.B. Clark, E. Godat, F.I. Olness.
  Comput.Phys.Commun. 216 (2017) 126-137.
  or: arXiv:1605.08012 [hep-ph] .

ManeParse version 3.0, Mathematica package:

An SIMPLE example using LHAPDF Tables for PDFs:

This is an self-contained example that reads PDF tables in LHAPDF format.

PDF_DEMO_v01.zip

(850Kb, Version May 2020).
Includes PDF Grid files needed for demo.

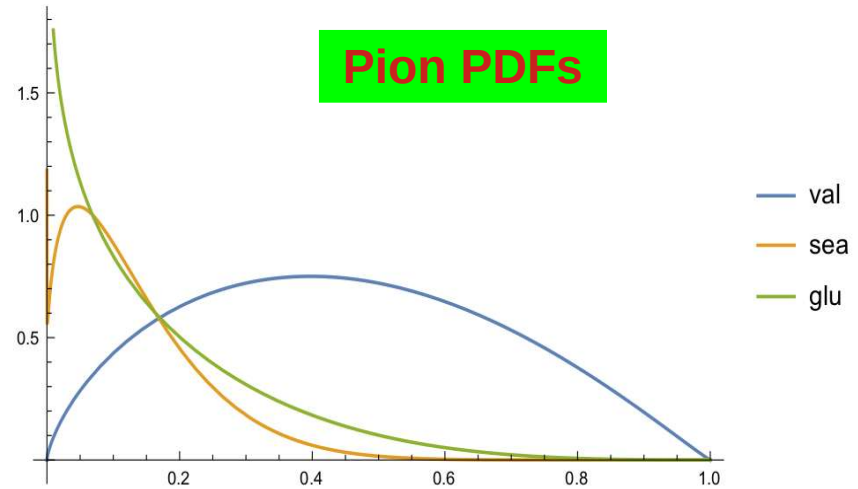
A SIMPLE example using Structure Function Tables:

This is an self-contained example that reads Structure Function tables in LHAPDF format.

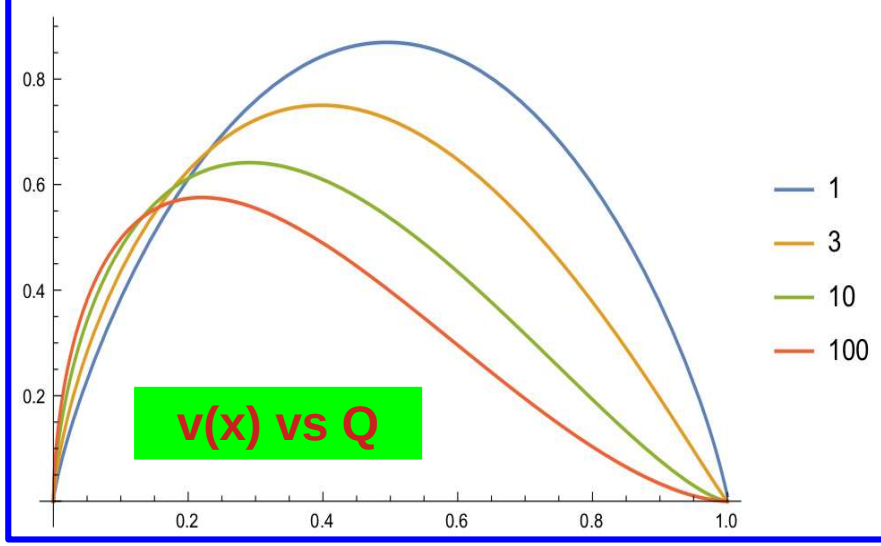
SF_DEMO_v01.zip

(460Kb, Version May 2020).
Includes Structure Function Grid files needed for demo.
Thanks to Tim Hobbs for supplying the sample tables.

```
q0 = 2.0 ;
iset0 = 1;
Plot[x {val[iset0, x, q0], sea[iset0, x, q0], glu[iset0, x, q0]}
 {x, 0.0, 1}, PlotLegends → {"val", "sea", "glu"}]
```



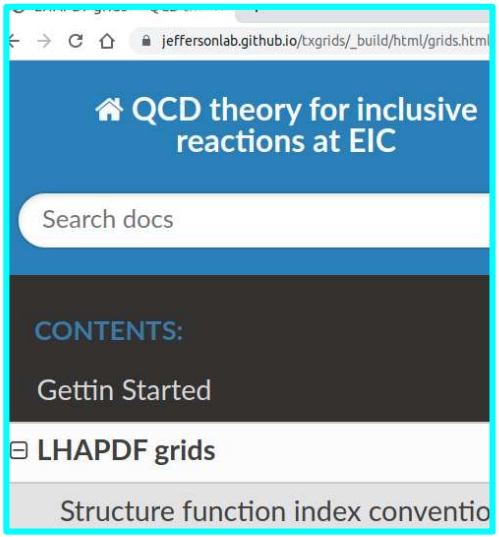

```
Plot[x {val[1, x, 1], val[1, x, 2], val[1, x, 10], val[1, x, 100]}
 {x, 0.0, 1}, PlotLegends → {"1", "3", "10", "100"}]
```



Mathematica: ManeParse

F_{123} Structure Functions

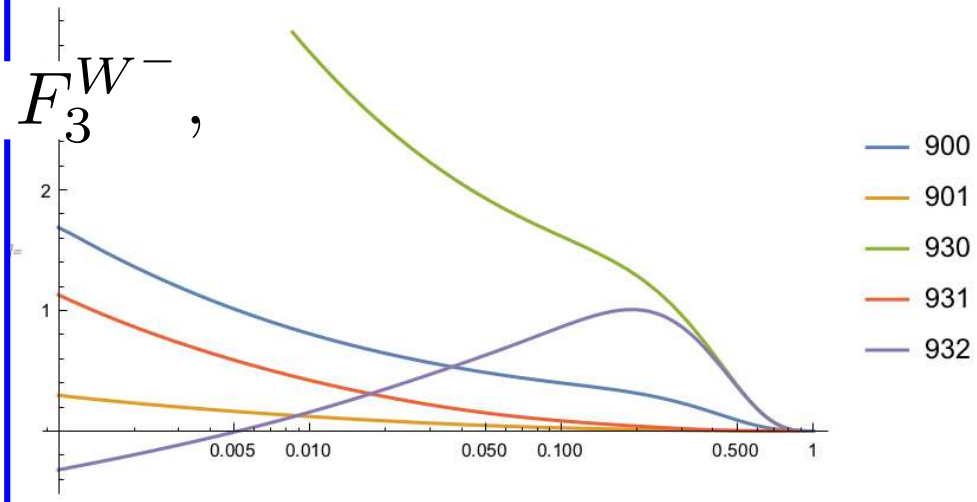
https://jeffersonlab.github.io/txgrids/_build/html/grids.html



$$F_2^\gamma, F_L^\gamma$$

$$F_2^{W^-}, F_L^{W^-}, F_3^{W^-},$$

```
q0 = 10. ;
LogLinearPlot[x pdf[1, flavors, x, q0] // Evaluate, {x, 10^-3, 1},
```



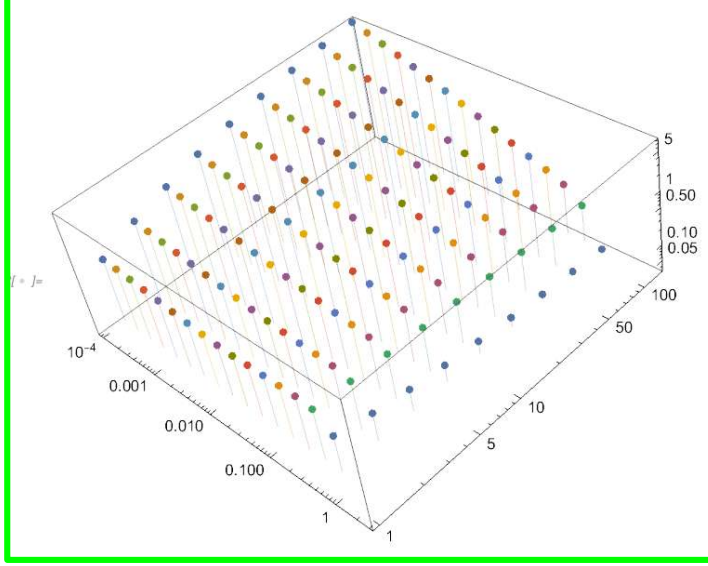
LHAPDF grids

Structure function index convention

$(T = p, n, d, \ldots, A)$

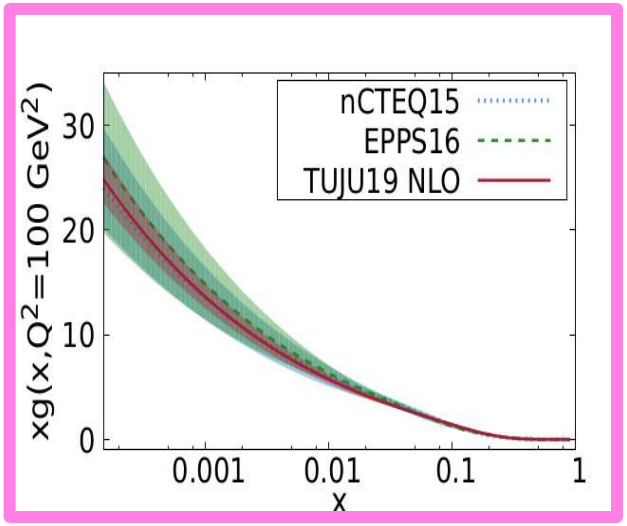
Reaction	Structure Functions	Index
$e^\pm + T \to e^\pm + X$	$F_2^\gamma,\ F_L^\gamma$	900, 901
	$F_2^{\gamma Z},\ F_L^{\gamma Z},\ F_3^{\gamma Z}$	902, 903, 904
	$F_2^Z,\ F_L^Z,\ F_3^Z$	905, 906, 907
	$F_2^{\mathrm{NC}},\ F_L^{\mathrm{NC}},\ F_3^{\mathrm{NC}}$	908, 909, 910
	$F_{2c}^\gamma,\ F_{Lc}^\gamma$	911, 912, 913
	$F_{2c}^{\mathrm{NC}},\ F_{Lc}^{\mathrm{NC}},\ F_{3c}^{\mathrm{NC}}$	914, 915, 916
	$F_{2b}^\gamma,\ F_{Lb}^\gamma$	917, 918, 919
	$F_{2b}^{\mathrm{NC}},\ F_{Lb}^{\mathrm{NC}},\ F_{3b}^{\mathrm{NC}}$	920, 921, 922

```
ListPointPlot3D[data, ScalingFunctions → {"Log", "Log", "Log"},
  Filling → Bottom]
```

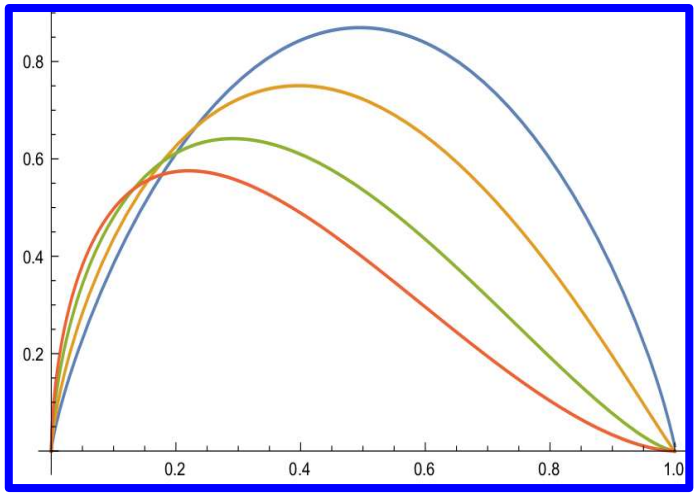


Conclusion

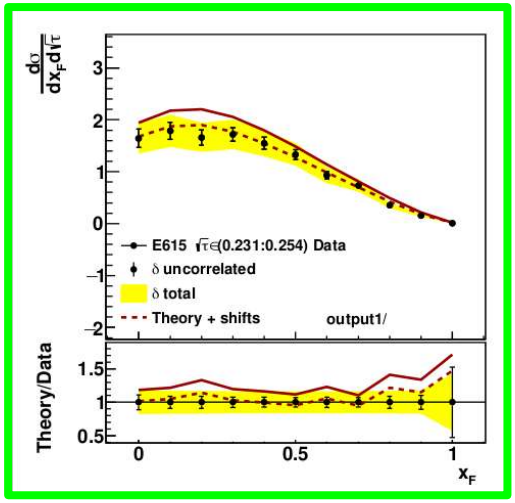
New Theoretical Tools for Global Meson PDFs



Nuclear PDFs



Pion PDFs



xFitter-draw tools

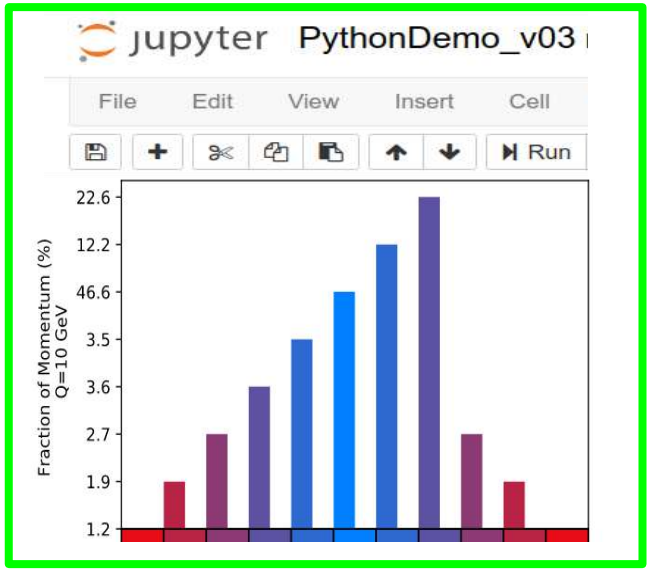
LHAPDF grids

Structure function index convention

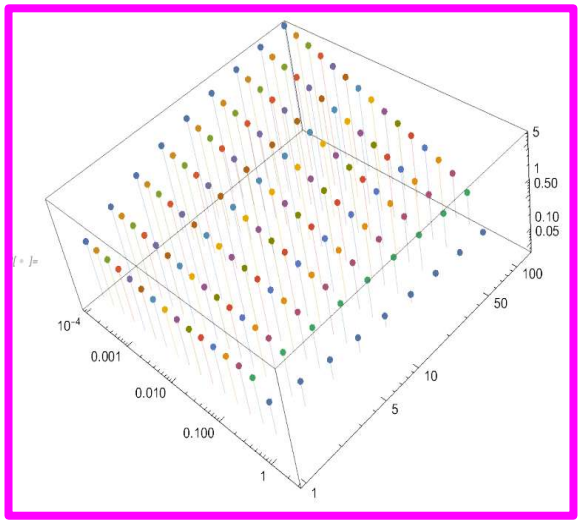
$(T = p, n, d, \ldots, A)$

Reaction	Structure Functions	Index
$e^{\pm} + T \to e^{\pm} + X$	F_2^{γ}, F_L^{γ}	900, 901
	$F_2^{\gamma Z}$, $F_L^{\gamma Z}$, $F_3^{\gamma Z}$	902, 903, 904
	F_2^{Z}, F_L^{Z}, F_3^{Z}	905, 906, 907

LHAPDF Structure Function Grids



Python Jupyter



LHAPDF to Mathematica ManeParse

… join the effort