Progress in Precision Nuclear PDFs

…

From PDFs to the underlying QCD characteristics

Fred Olness
SMU

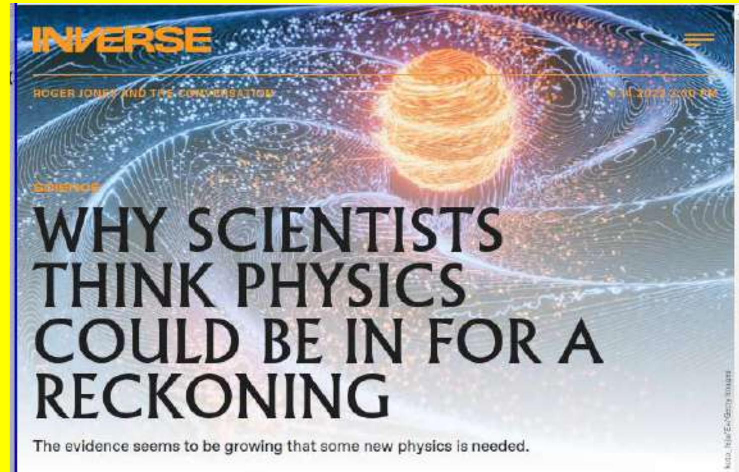
Thanks for substantial input from my friends & colleagues

nCTEQ
nuclear parton distribution functions

xFitter

C T E Q

Precision QCD
CFNS
1-5 August 2022



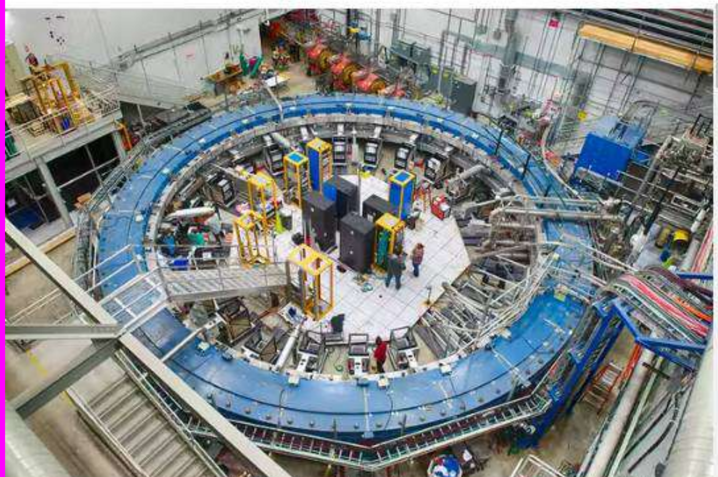
...HC) at CERN, one ...ing to find ...ide from the Higgs ...posite particles?" I ... how we have

PHYSICS TODAY

W-boson mass hints at physics beyond the standard model

Nearly a decade of coll... fundamental particle's ...

THE CONVERSATION



The storage-ring magnet for the Muon G-2 experiment at Fermilab. Reidar Hahn/wikipedia, CC BY-SA

The standard model of particle physics may be broken – an expert explains

HVP Hadronic Vacuum Polarization

Published: May 6, 2022 11.43am EDT

Roger Jones, Lancaster University

As a physicist working at the Large Hadron Collider (LHC) at Cern, one of the most frequent questions I am asked is "When are you going to find something?". Resisting the temptation to

W-Mass

g-2

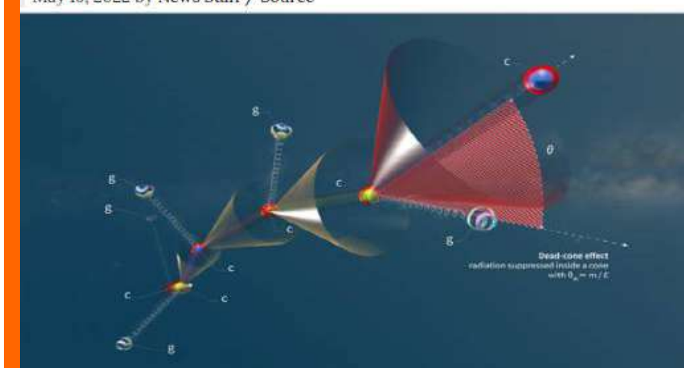
ALICE Dead-Cone

...

SCI NEWS

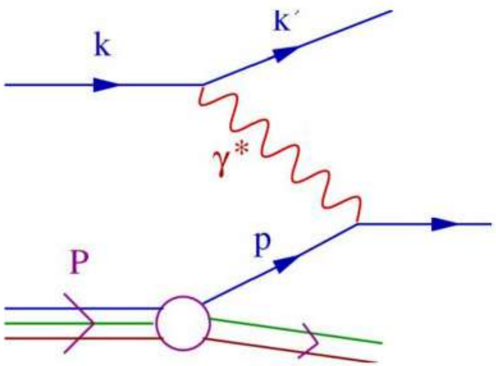
CERN Physicists Directly Observe Fundamental Phenomenon in Quantum Chromodynamics

May 19, 2022 by News Staff / Source

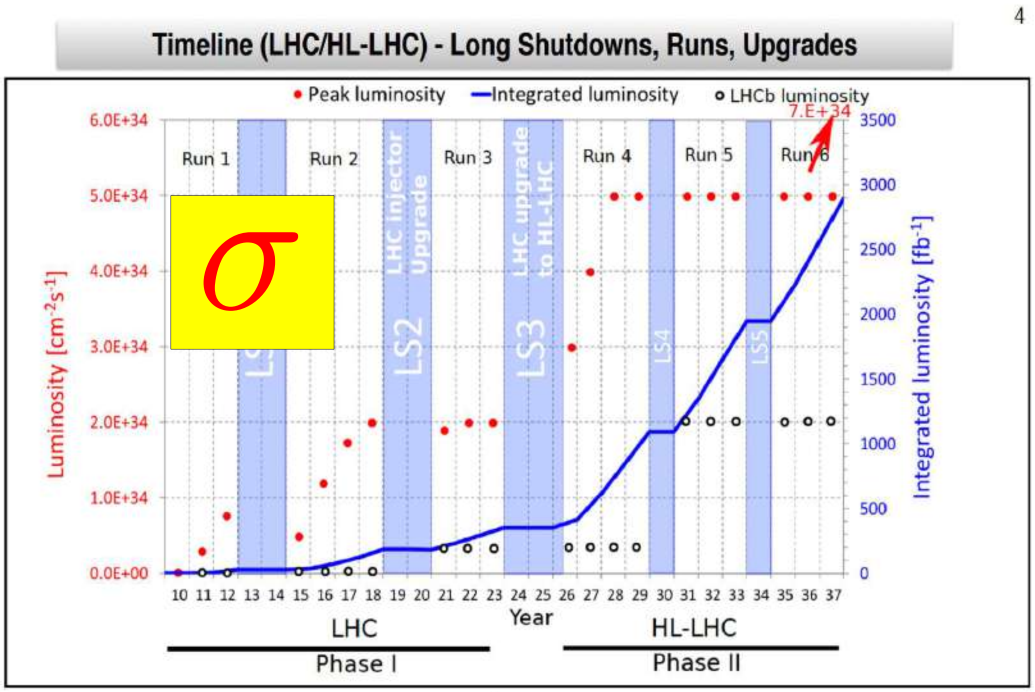


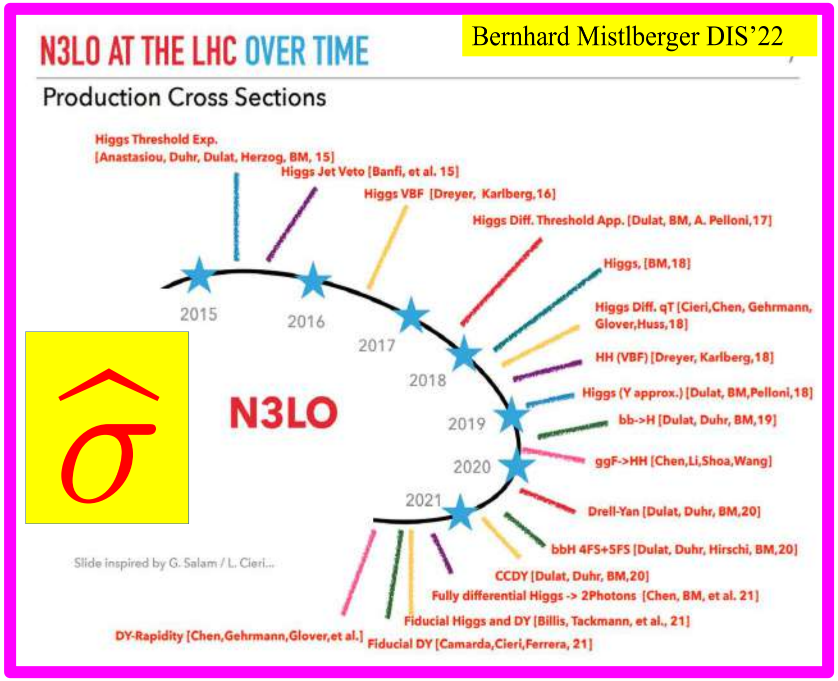
A charm quark (c) in a parton shower loses energy by emitting radiation in the form of gluons (g). The shower displays a dead cone of suppressed radiation around the quark for angles smaller than the ratio of the quark's mass (m) and energy (E). The energy decreases at each stage of the shower. Image credit: Daniel Dominguez / CERN.

We are entering the "Precision Era"

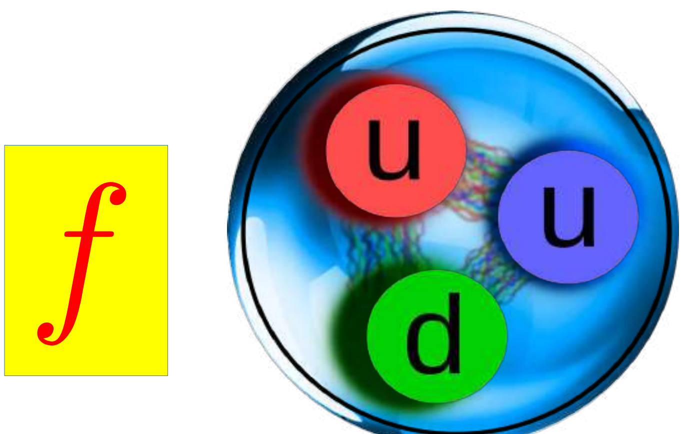


$$\sigma = f \otimes \hat{\sigma}$$





Challenge: hadronic component



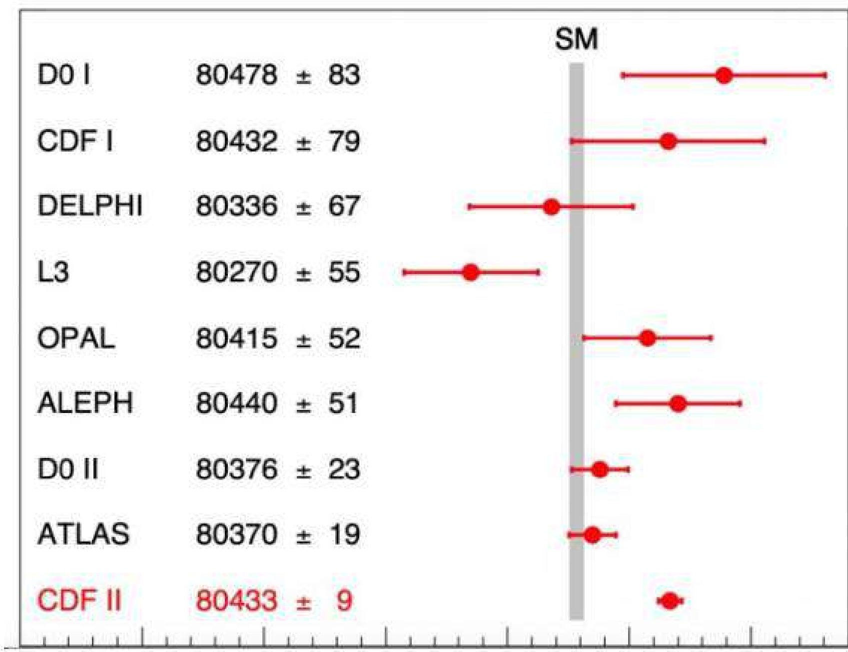
Precision Era: High Precision W Boson Mass

RESEARCH

PARTICLE PHYSICS

High-precision measurement of the *W* boson mass with the CDF II detector

CDF Collaboration†‡, T. Aaltonen[1,2], S. Amerio[3,4], D. Amidei[5], A. Anastassov[6]



1994

ICHEP'94

Table 1. Uncertainties in the W mass measurements, in MeV.

	CDF (e)	CDF (μ)	DØ(e)
Energy Scale	130	60	260
Resolution	140	120	70
Background	50	50	30
Fitting	20	20	30
PDF	100	100	70
p_T^W and und. evt.	120	145	120
Width	-	-	20
Total Sys.	250	240	307
Statistical	150	200	160
Total (Stat + Sys)	290	300	346

2022

Table 2. Uncertainties on the combined M_W result.

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

CSS Resummation

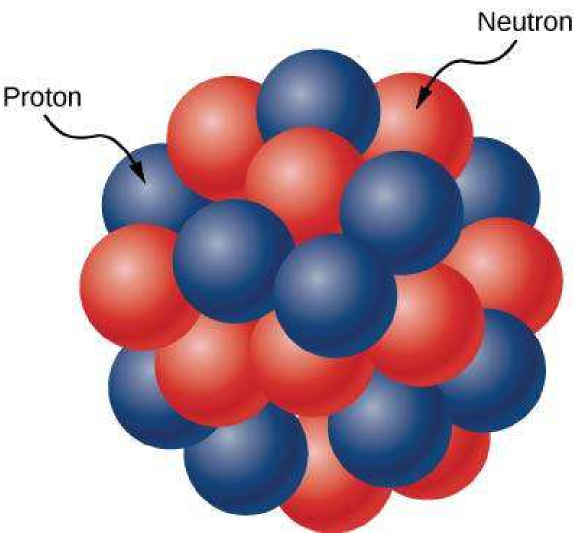
Strange PDF

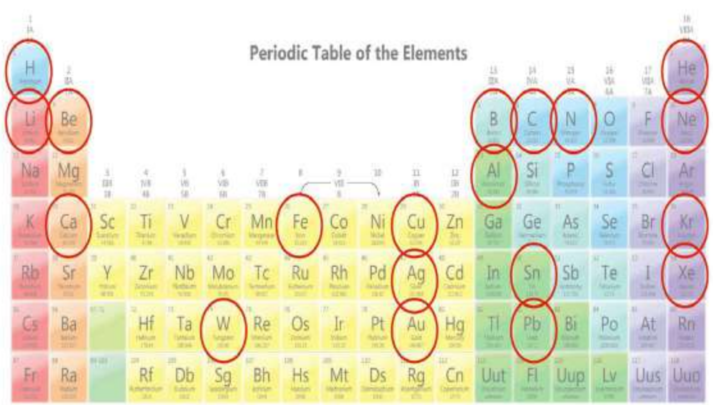
PDF Precision

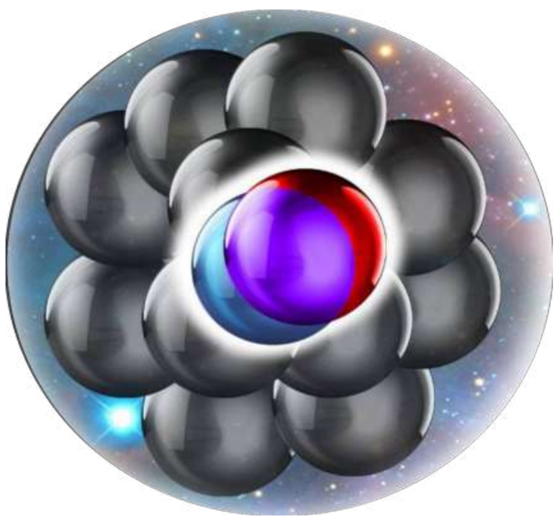
CDF Collaboration et al., Science 376, 170–176 (2022)

Nuclear PDFs

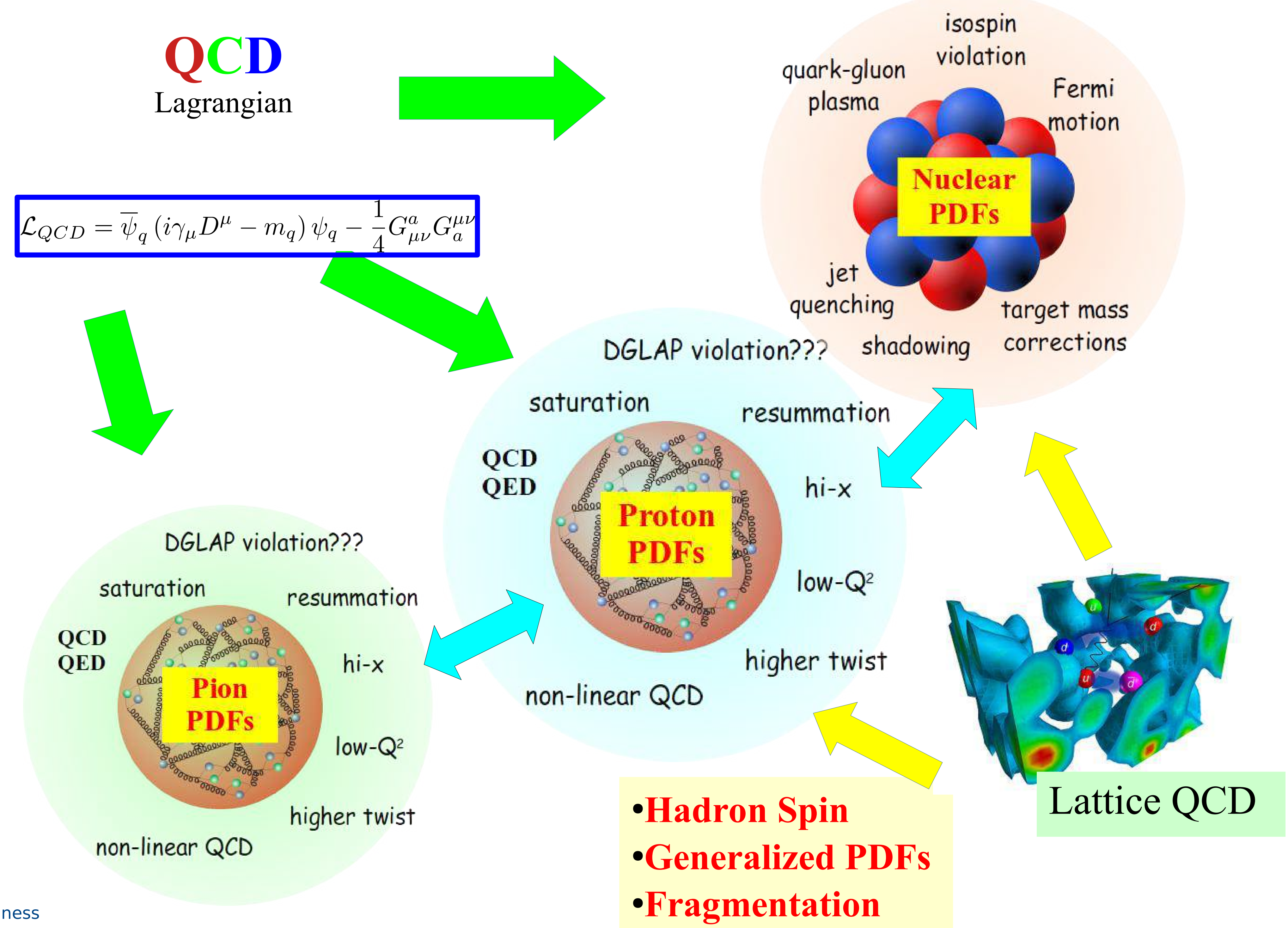
Parton Distribution Functions



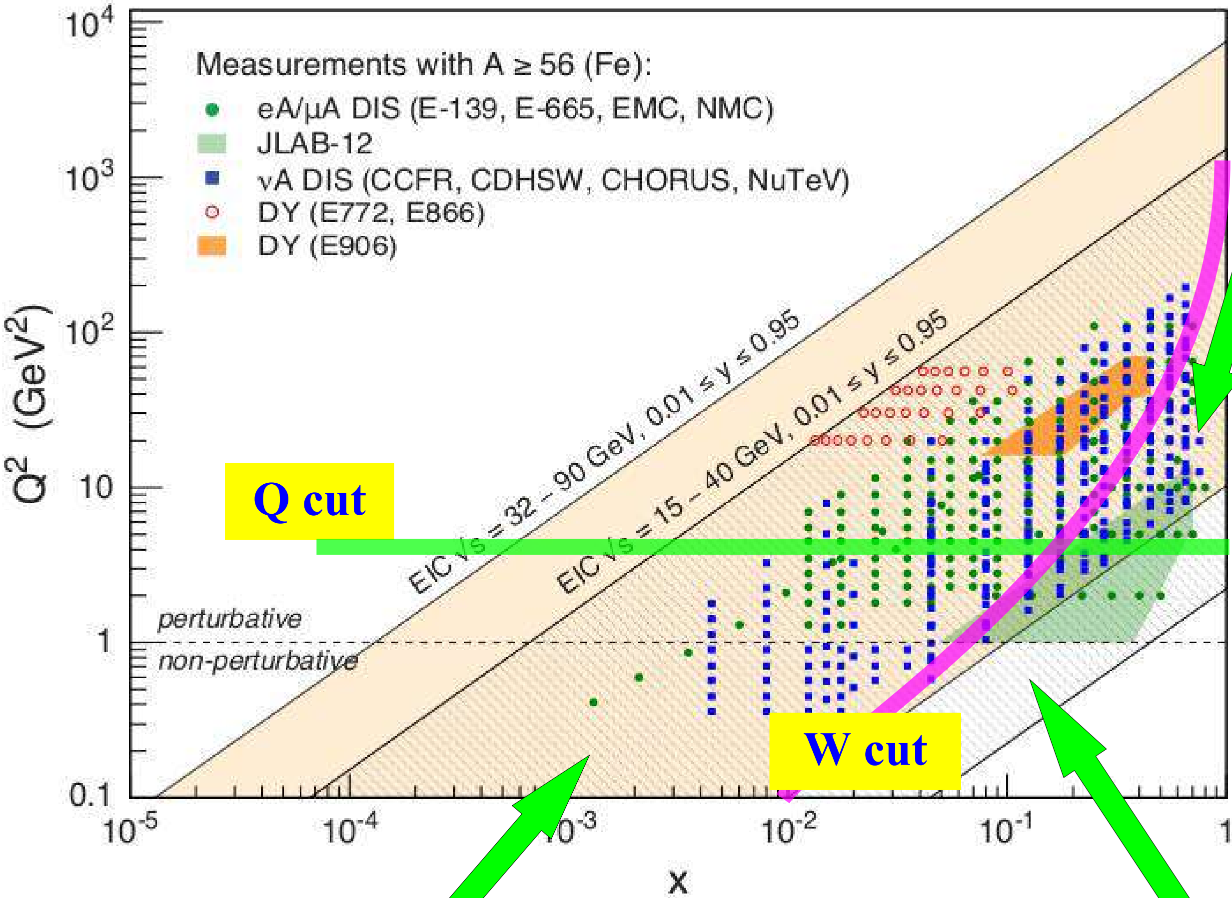




From Parameterization to a Deeper Understanding



nPDFs: Extend Kinematic Reach in {x,Q²}



High-x:

Nuclear PDFs: x>1 allowed;

impacts F_2^{Nuc}/F_2^{Iso} in Fermi region

Target Mass Corrections

pick up M^2/Q^2 higher twist

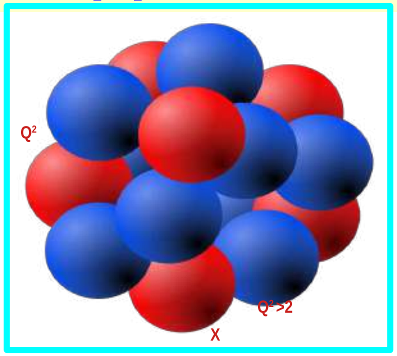
Deuteron Corrections

impacts $F_2^{Nuc}/F_2^{Deuteron}$ ratio

JLab Data @ Hi-X Low-Q²

extend nCTEQ framework for this region

& prepare for EIC



Low-x:

Shadowing

Recombination

Resummation

BFKL

Saturation

Low-Q²:

Non-Perturbative inteface

collective effects

Target Mass Corrections

pick up M^2/Q^2 higher twist

F_L at low Q^2 access to g(x)

Run at multiple energies

nPDFs: Representative Comparisons from PDG

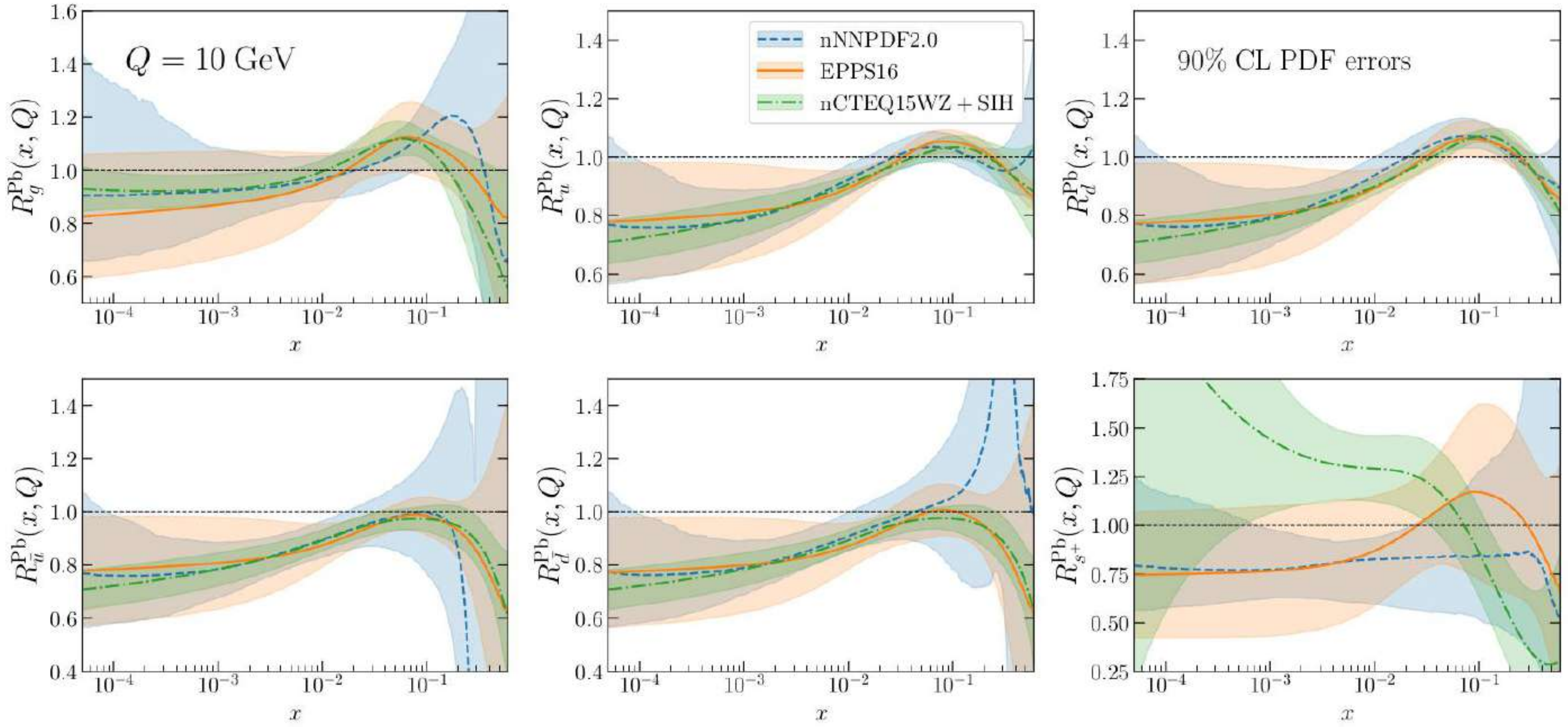


Figure 18.5: Comparison of the nNNPDF2.0, CTEQ15WZ+SIH and EPPS16 nuclear PDFs. The curves shown are ratios to the result in the limit of no nuclear corrections. Plot from NNPDF collaboration (Juan Rojo – private communication).

PDG

TUJU at NLO and NNLO

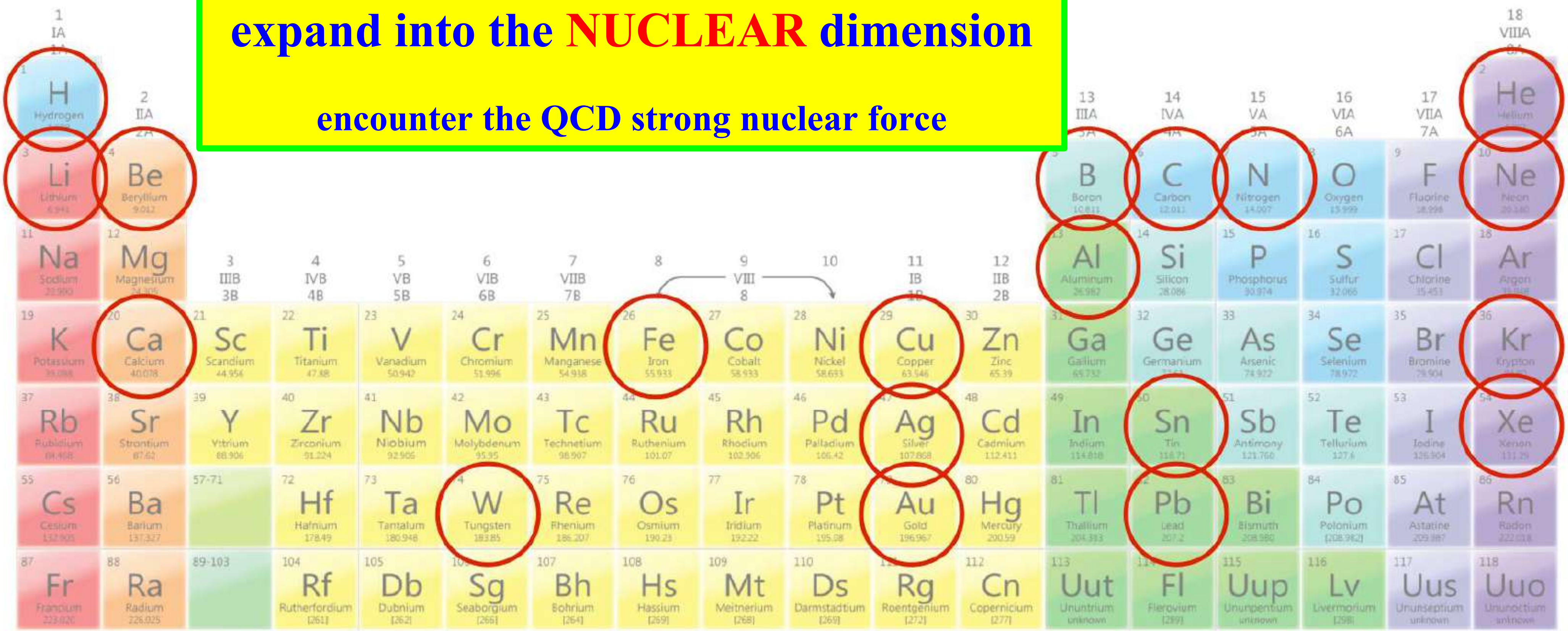
nCTEQ

nuclear parton distribution functions

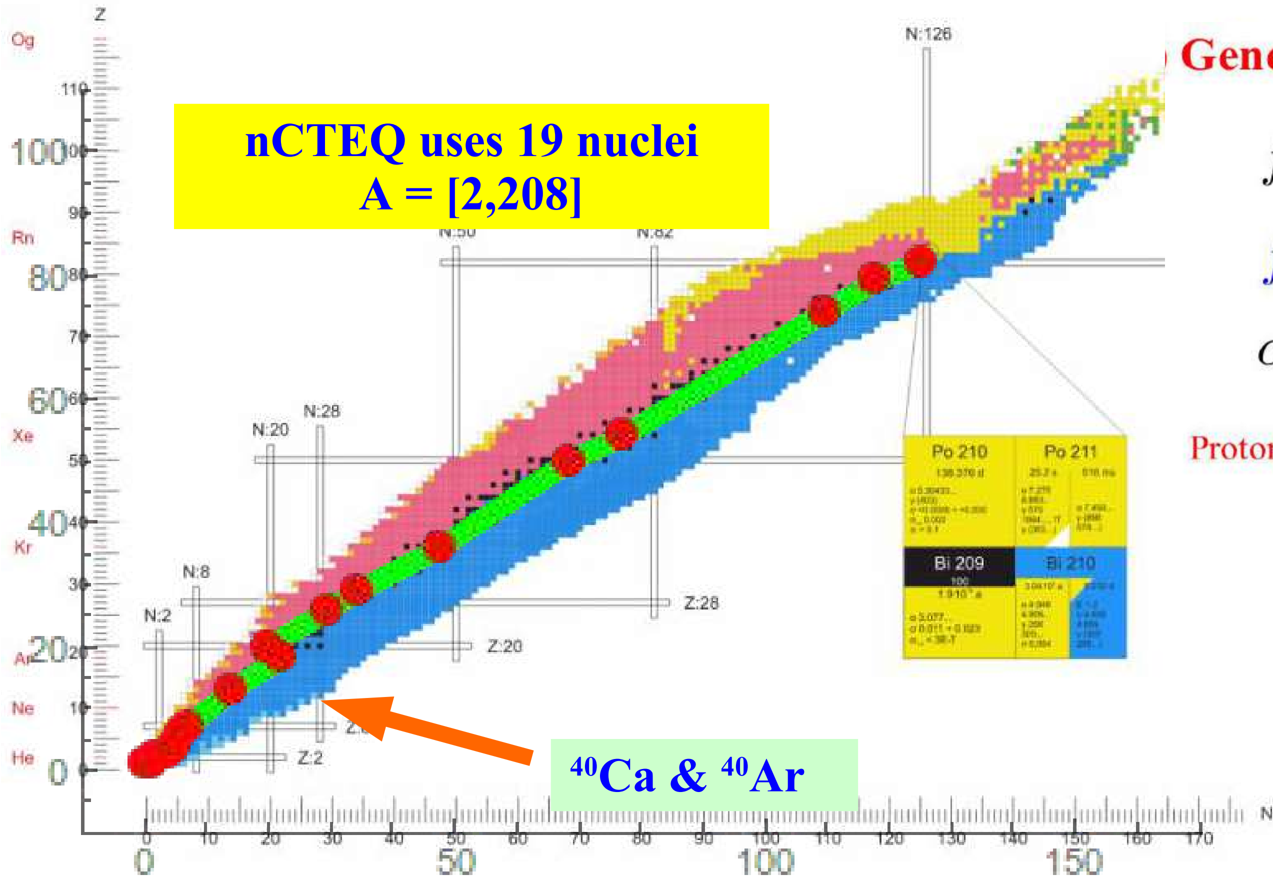
nuclear Coordinated Theoretical-Experimental Project on QCD

expand into the NUCLEAR dimension

encounter the QCD strong nuclear force



Nuclear A-Dependence



Generalized A-parameterization (nCTEQ)

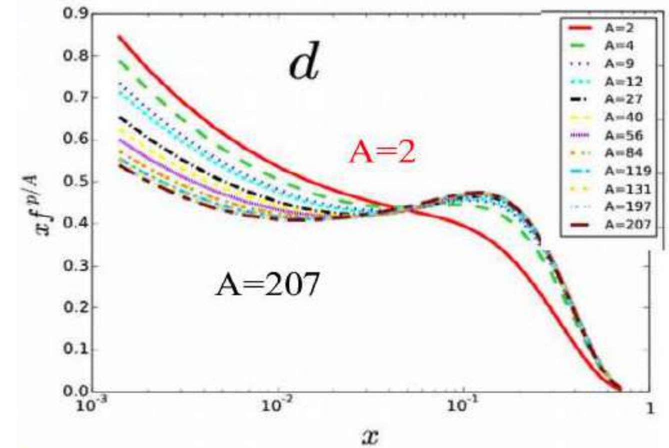
$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$

$$f \sim \ldots x^{c_1(A)}(1-x)^{c_2(A)} \ldots$$

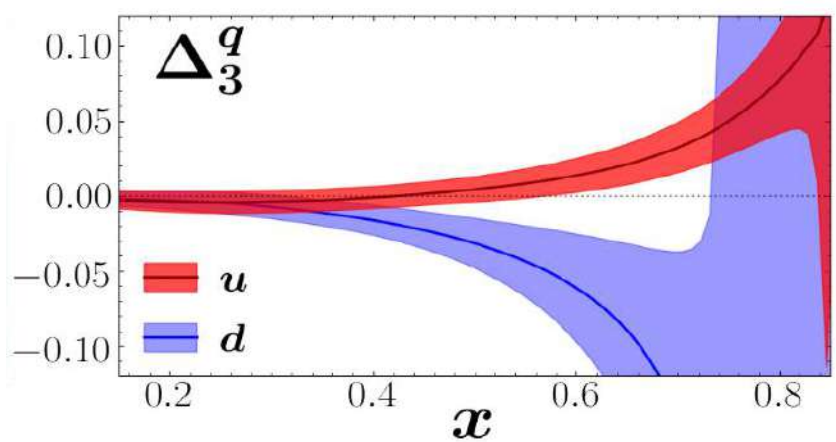
$$c_k \sim c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right)$$

Proton

Nuclear

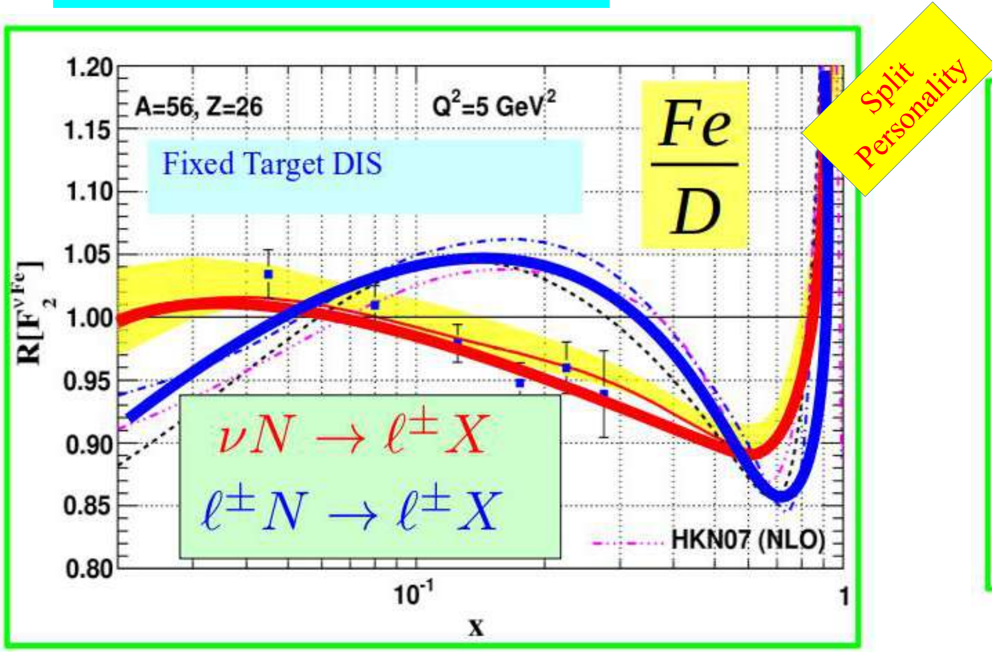


[[2, 275],
[3, 125],
[4, 66],
[6, 15],
[9, 49],
[12, 196],
[14, 101],
[27, 73],
[40, 92],
[56, 134],
[64, 61],
[84, 84],
[108, 7],
[119, 152],
[131, 4],
[184, 37],
[197, 50],
[208, 163]]



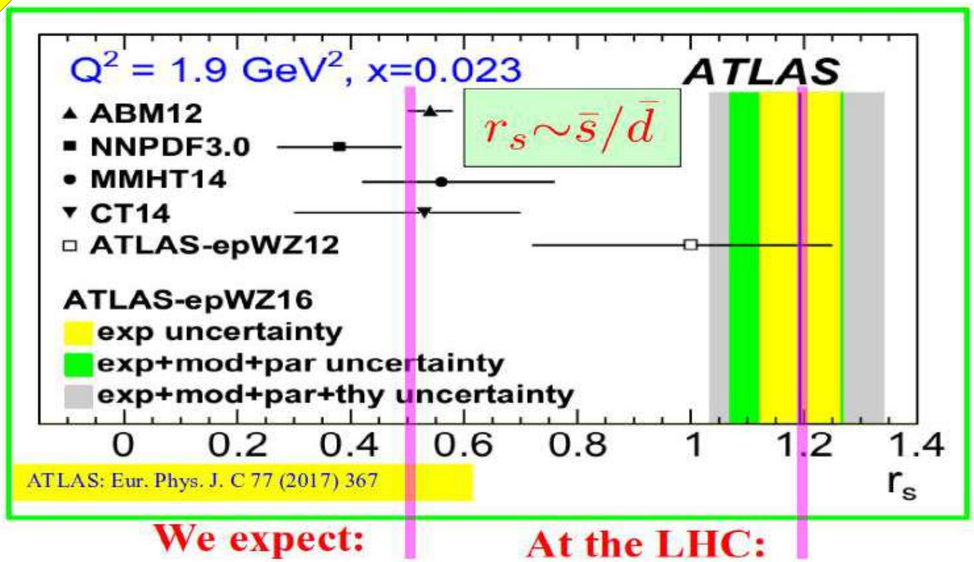
F.

nCTEQ15ν



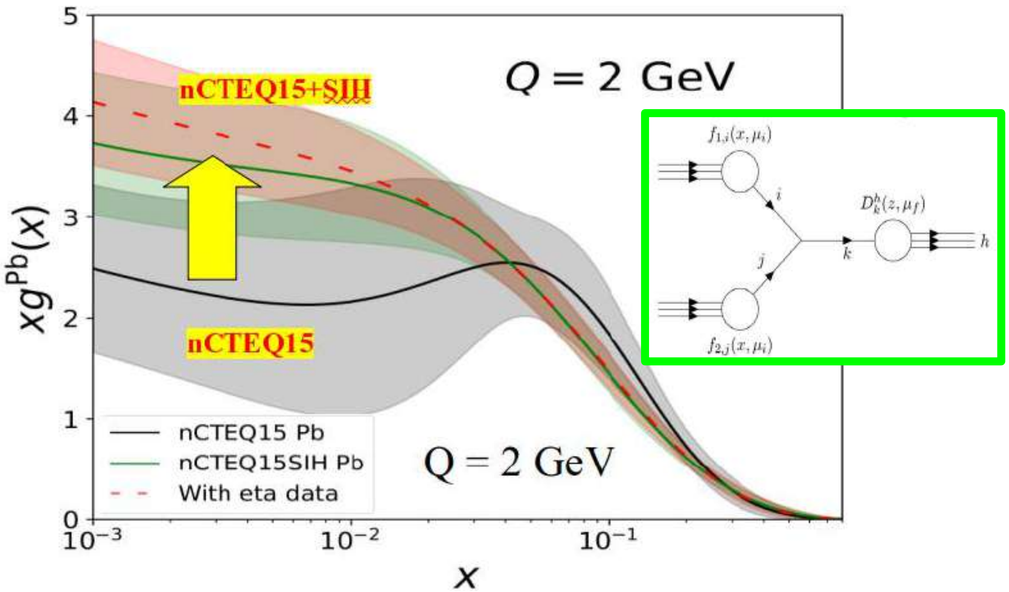
nCTEQ: arXiv: 2204.13157

nCTEQ15WZ



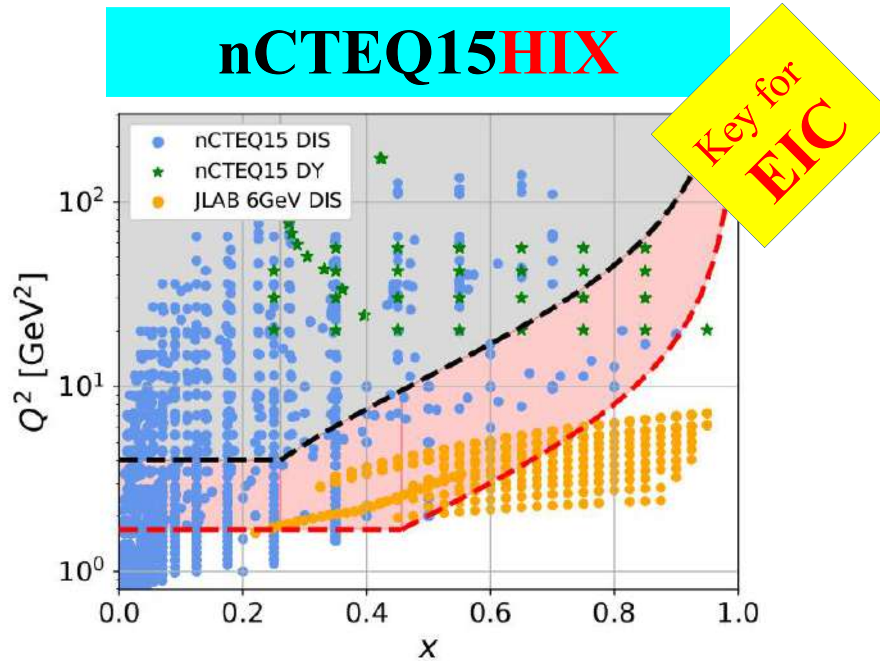
nCTEQ: Phys.Rev.D 104 (2021) 094005

nCTEQ15WZ+SIH



nCTEQ: PRD104 (2021) 094005.

nCTEQ15HIX



nCTEQ: Phys.Rev.D 103 (2021) 11, 114015

HI X

…

Hi-X at JLab

nCTEQ

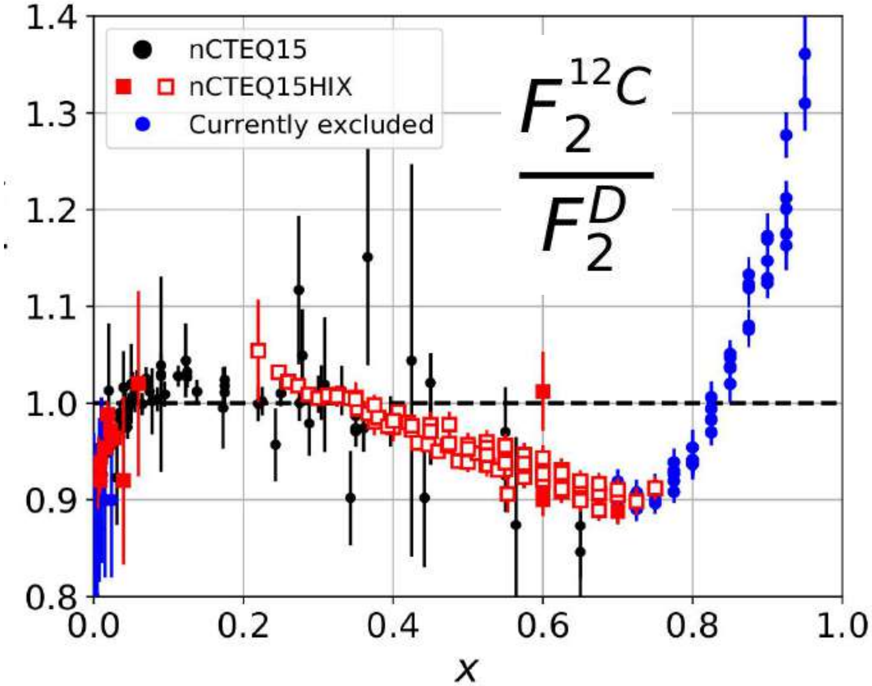
nuclear parton distribution functions

E.P. Segarra

T. Ježo

nCTEQ15HIX -- Extending nPDF Analyses into the High-x, Low Q2 Region
E.P. Segarra, T. Ježo, A. Accardi, P. Duwentäster, O. Hen, T.J. Hobbs, C. Keppel, M. Klasen, K. Kovařík, A. Kusina, J.G. Morfín, K.F. Muzakka, F.I. Olness, I. Schienbein, J.Y. Yu
PRD 103, 114015 (2021)

Challenges at Large x & Low Q^2: JLab data ⇒ EIC



Nuclear PDFs: x>1 allowed;

impacts F_2^{Nuc}/F_2^{Iso} in Fermi region

Target Mass Corrections

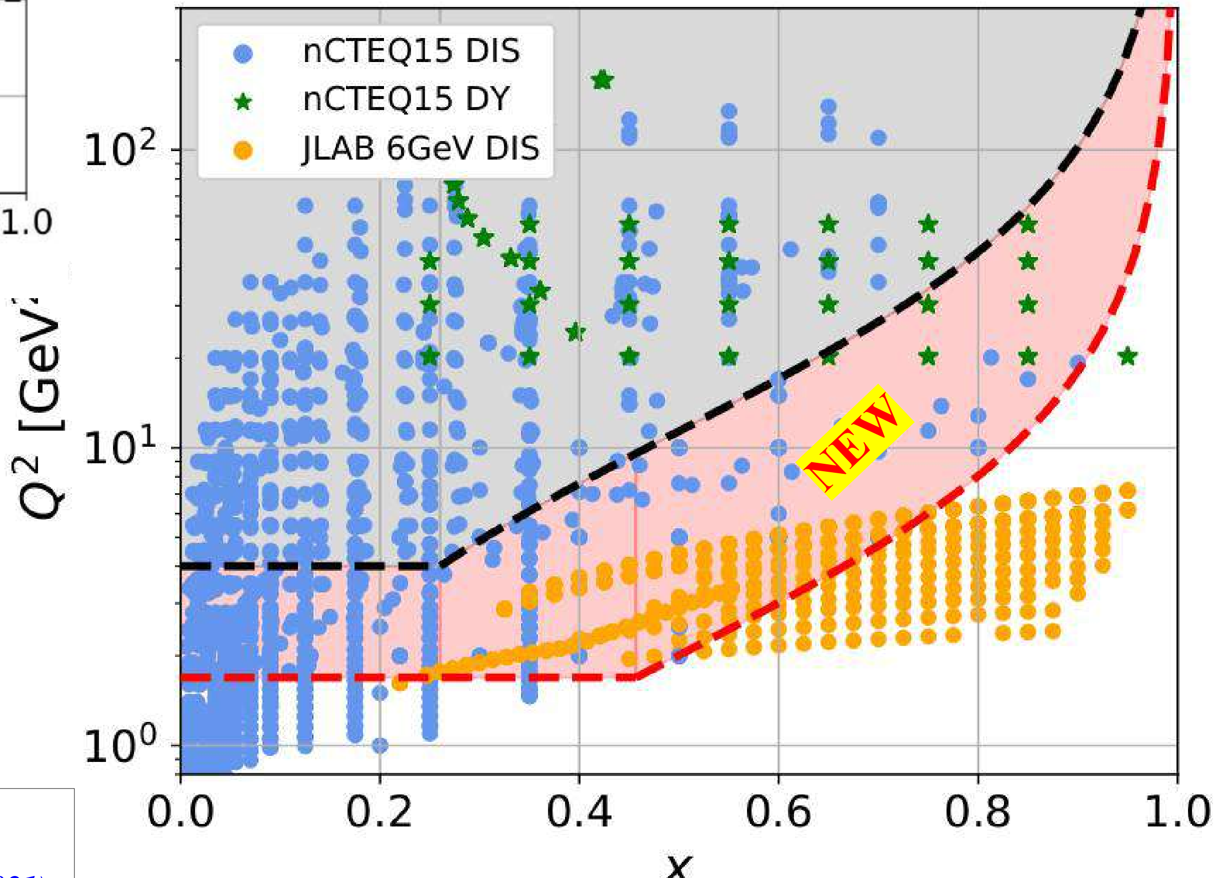
pick up M^2/Q^2 higher twist contributions

Deuteron Corrections

impacts $F_2^{Nuc}/F_2^{Deuteron}$ ratio

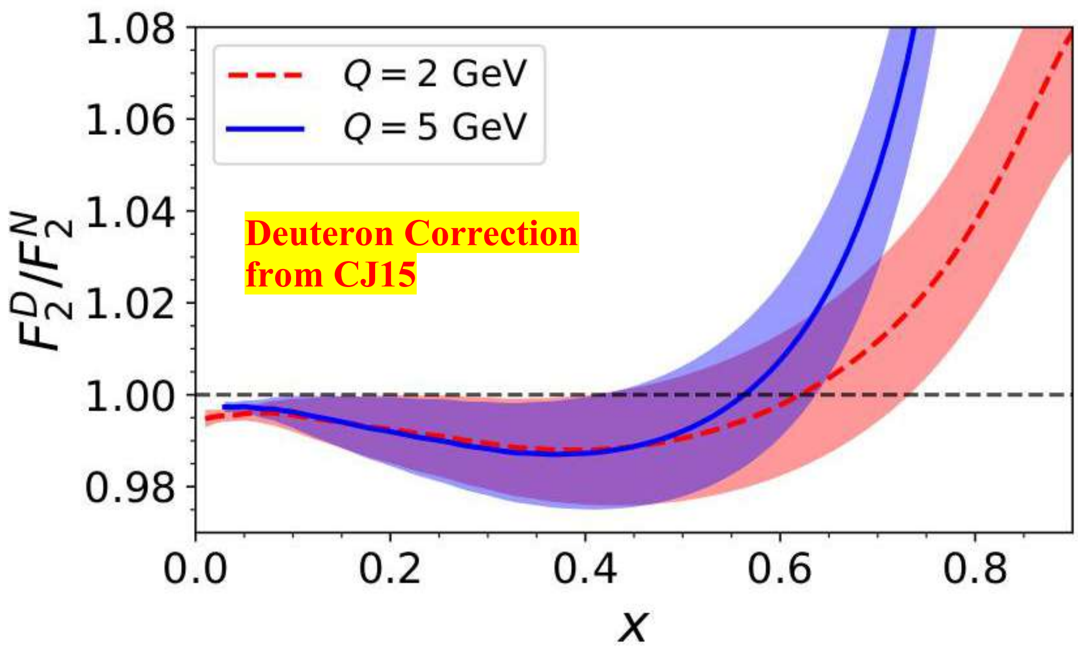
JLab Data @ Hi-X Low-Q^2

extend nCTEQ framework
to accommodate this region
& prepare for EIC



nCTEQ15HIX -- Extending nPDF Analyses into the High-x, Low Q2 Region
E.P. Segarra, T. Ježo, et al., ***PRD 103, 114015 (2021)***

nCTEQ15HIX include large x JLab data



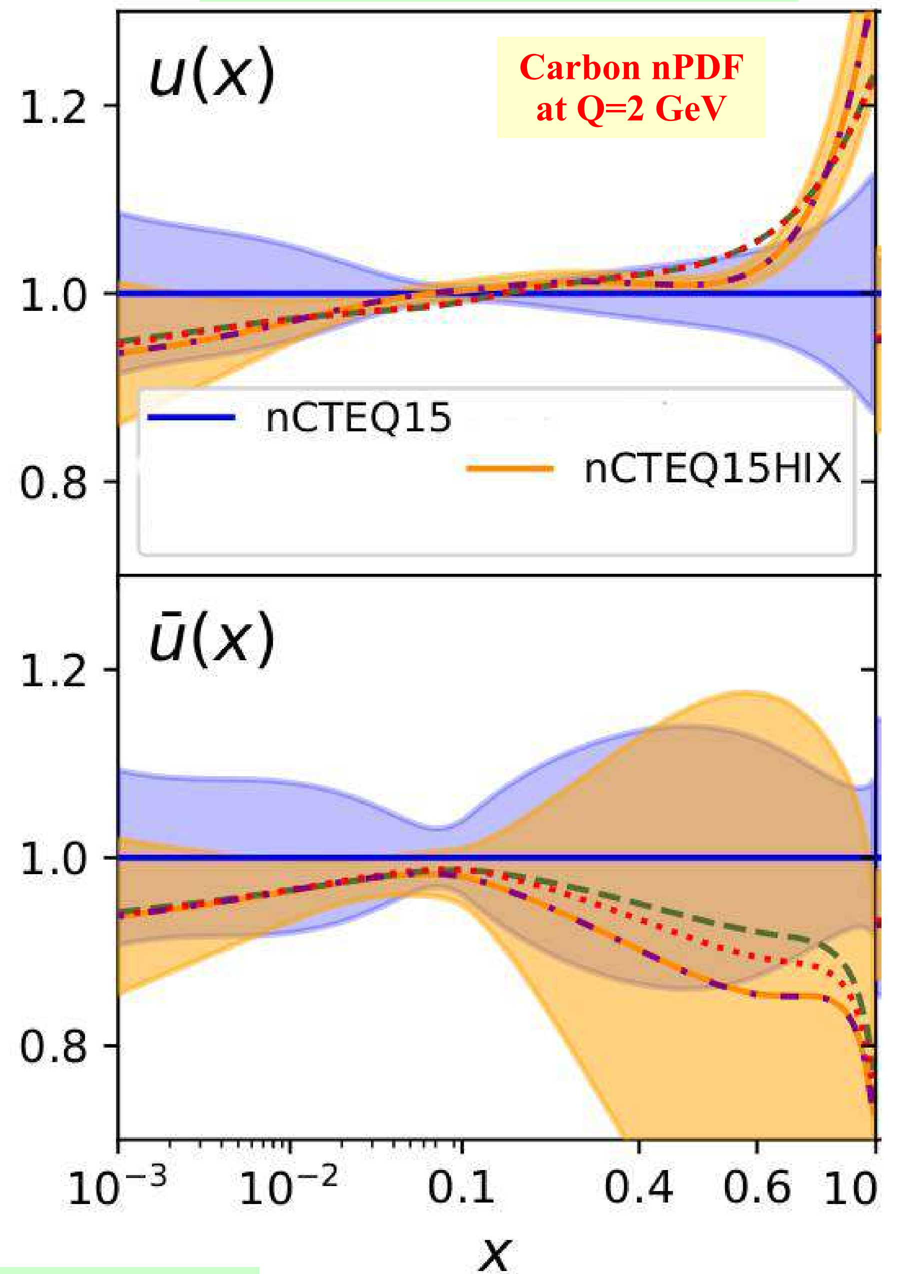
Deuteron Corrections Important!!!

Overall χ^2/N_{dof} ~0.83

Fit	χ^2	N_{data}	χ^2/N_{dof}	Q_{cut}	W_{cut}
nCTEQ15	587	740	0.81	2.0	3.5
nCTEQ15*	2664	1564	1.70	1.3	1.7
nCTEQ15HIX	1291	1564	0.83	1.3	1.7

We can extend our kinematic reach in {x,Q²}

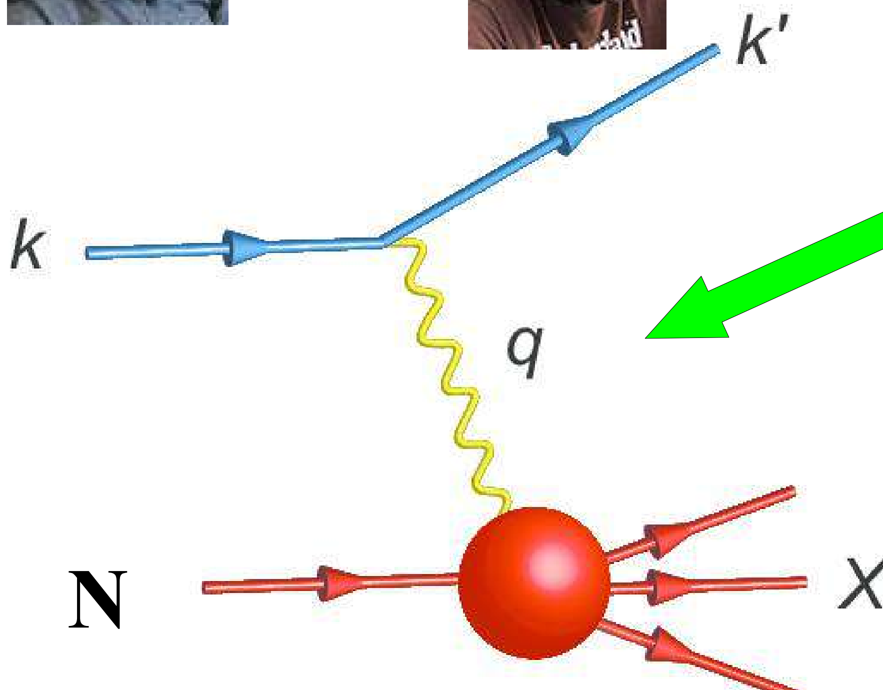
JLab data: Shifts valence PDFs from low to hi-x



what about small x region

Neutrino
Deep Inelastic Scattering (DIS)

Faiq Muzakka, Karol Kovarik, ...



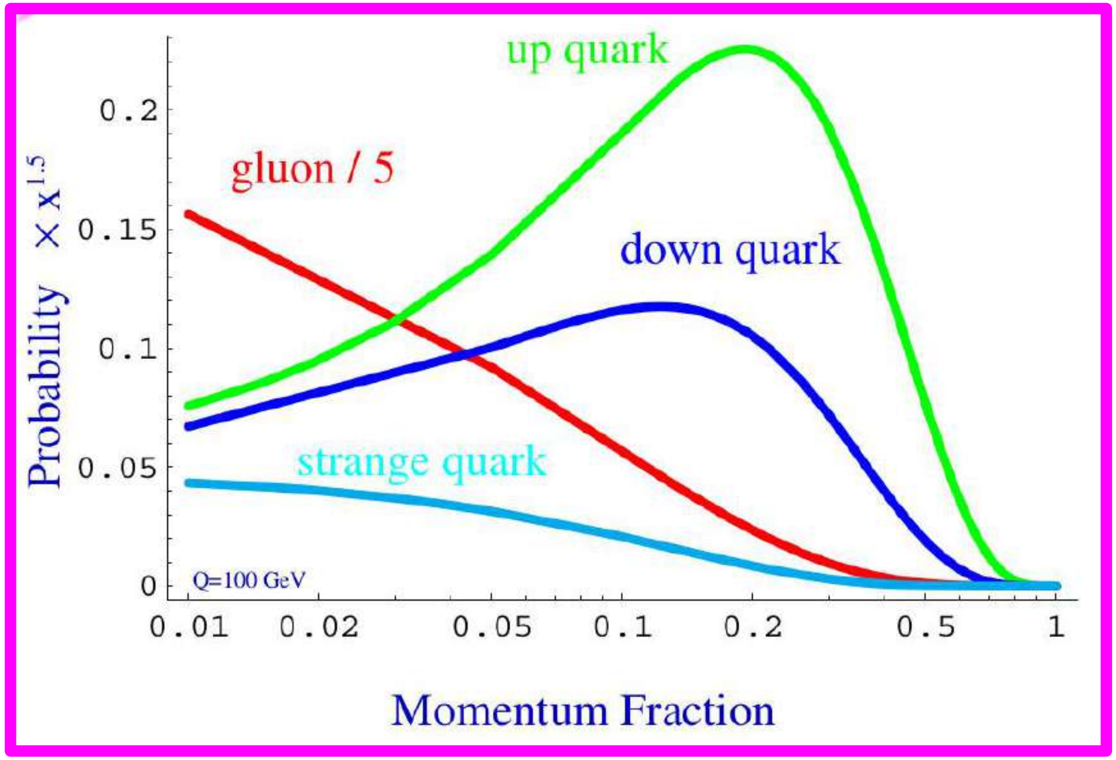
Could be:

neutral photon γ

or charged $W^{\pm}$

Strange PDF: ν Nucleon di-muon Production

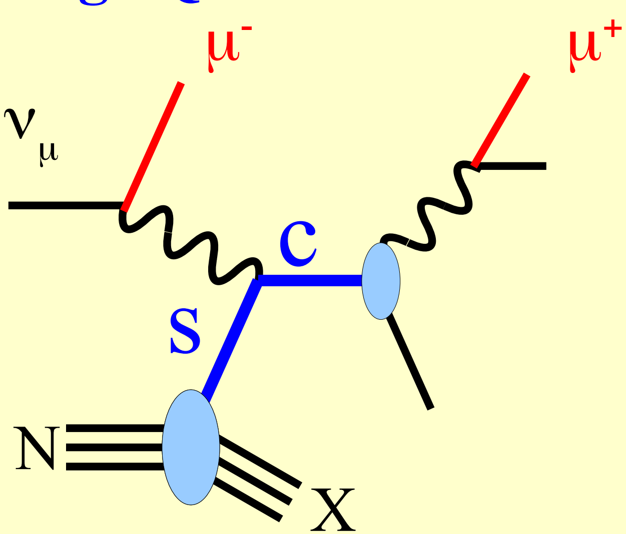
Need to "dig out" s(x) underneath d(x)



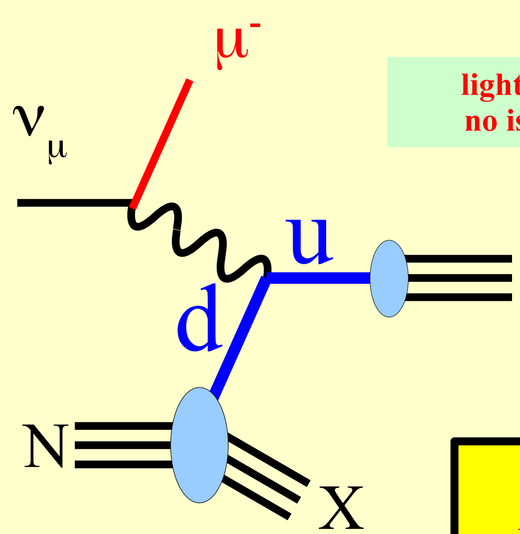
Result:

$$\bar{s}(x) \sim \frac{1}{2}\,\bar{d}(x)$$

Strange Quark



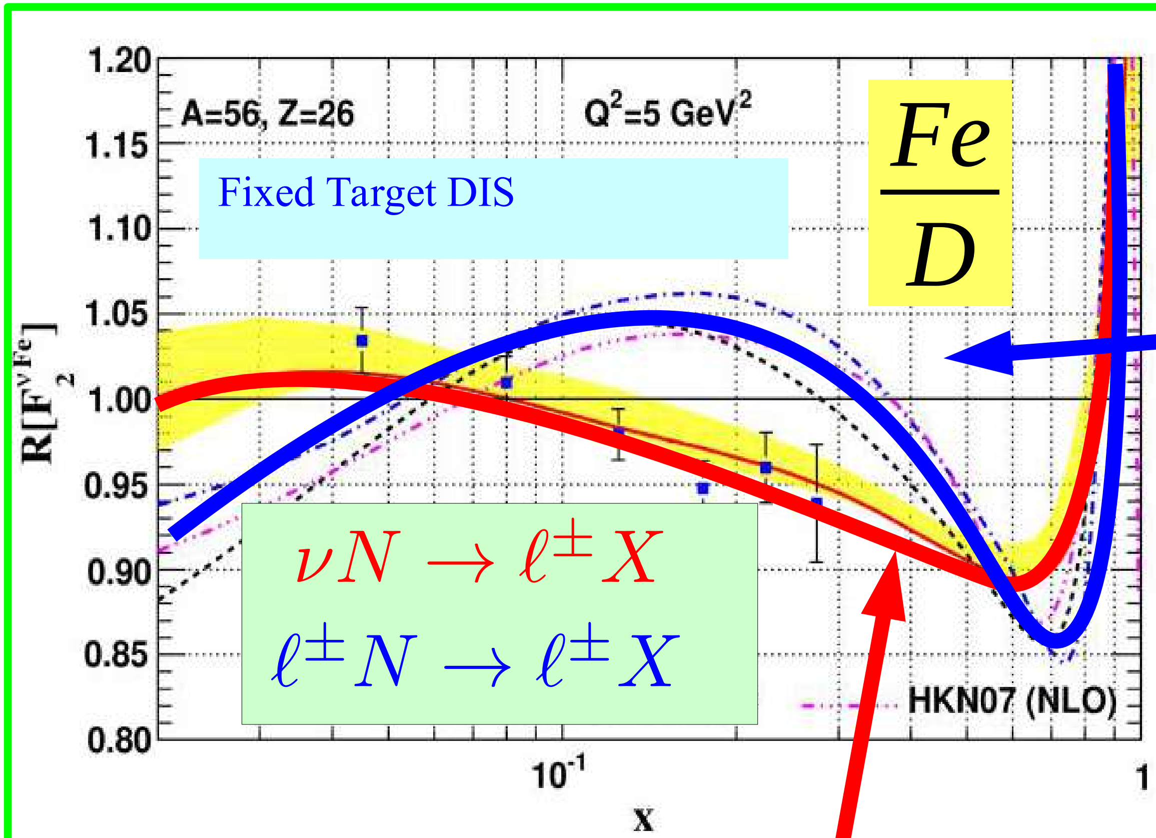
Down Quark



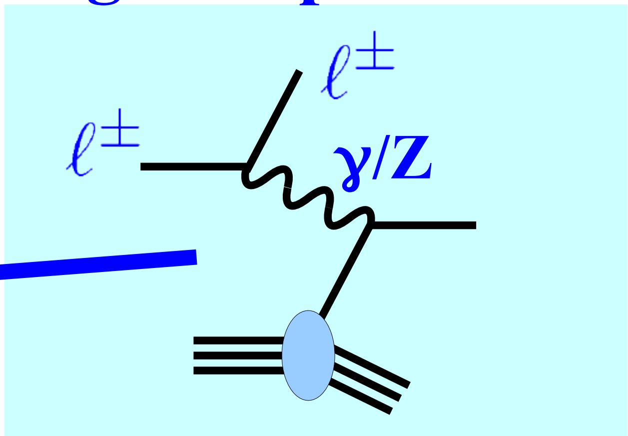
light u mass
no isolated μ

Depends on nuclear PDFs

Puzzle: Split Personality … *What is the correct Nuclear ratio*

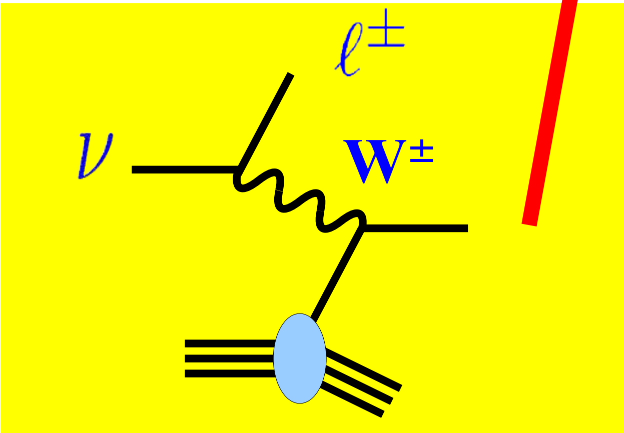


Charged Lepton DIS



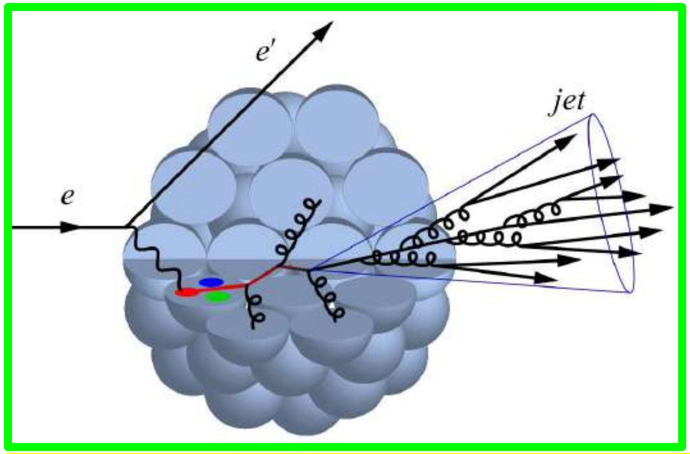
some caveats
… correlated errors

Ingo Schienbein, … (2007)
Karol Kovarik, … (2010)



Neutrino DIS

Depends on nuclear corrections

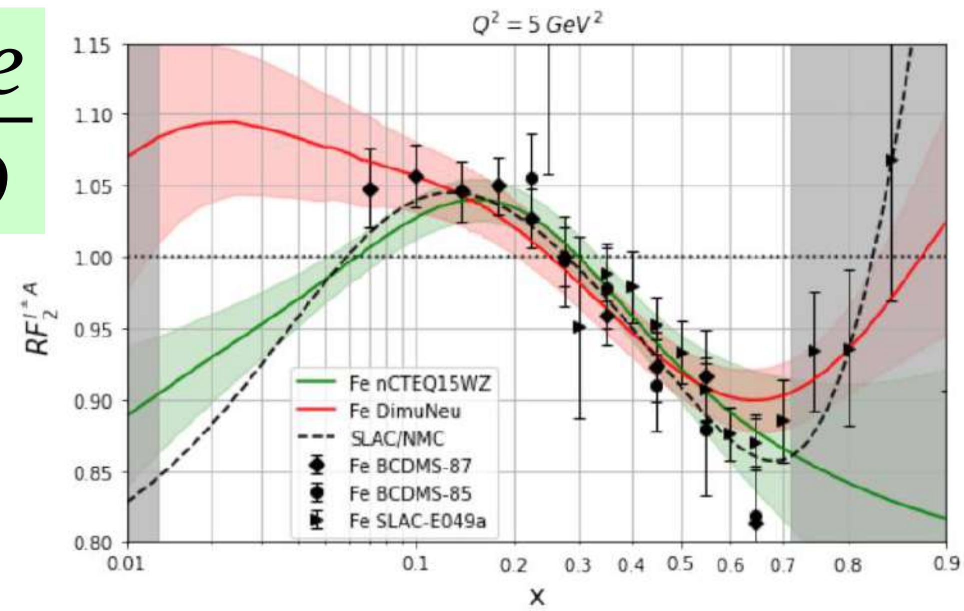


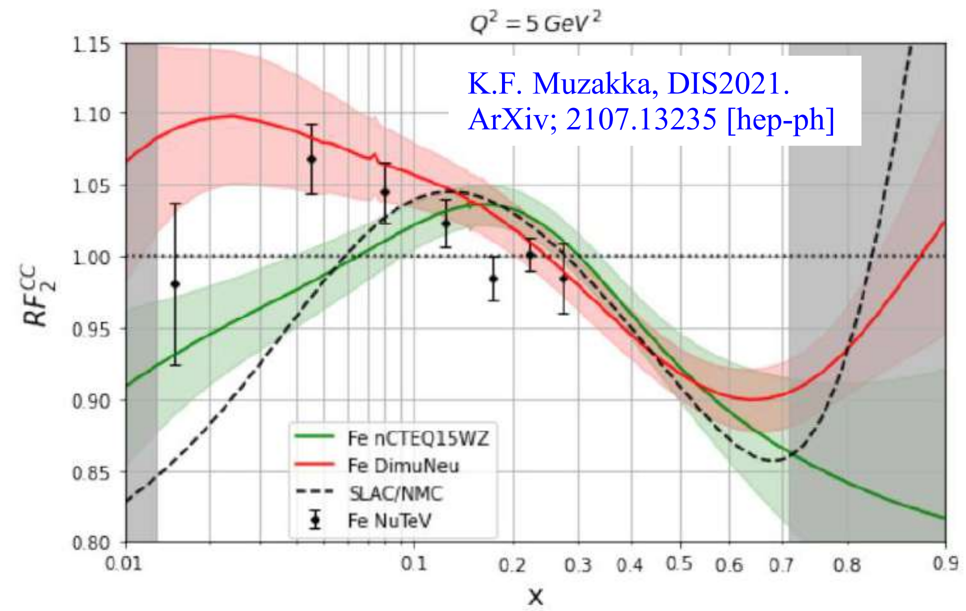
Propagation of γ/W thru nuclei

Puzzle: **Split Personality …** *What is the correct Nuclear ratio*

Faiq Muzakka, Karol Kovarik, ...

$$\frac{Fe}{D}$$





$$\frac{Iron}{(proton + neutron)}$$

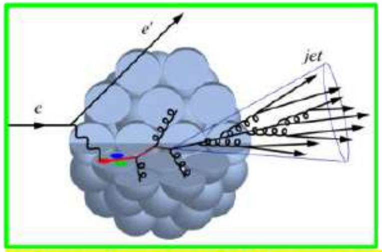
What is the correct nuclear correction ???

Are these data sets compatible???

Compatibility of neutrino DIS data and its impact on nuclear parton distribution functions

K.F. Muzakka[1,*] P. Duwentäster[1,†] T.J. Hobbs[2,3,4] T. Ježo[5,‡] M. Klasen[1,§] K. Kovařík[1,¶] A. Kusina[6,**] J.G. Morfín[7,††] F. I. Olness[2,‡‡] R. Ruiz[6] I. Schienbein[8,§§]

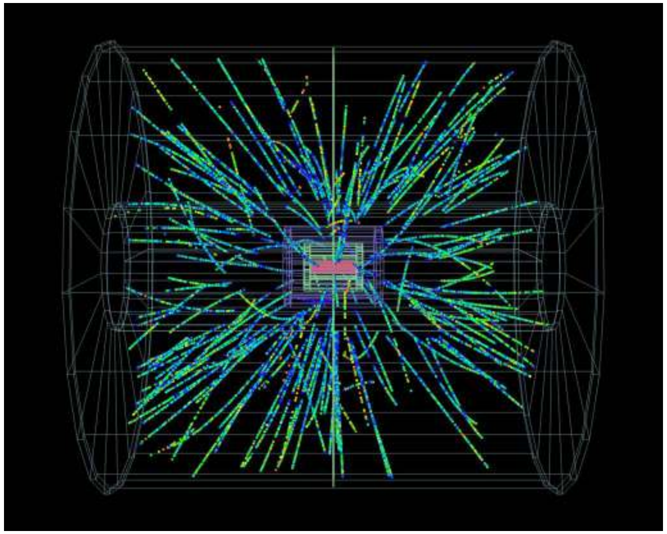
[1]*Institut für Theoretische Physik, Westfälische Wilhelms-Universität Münster,*



Propagation of γ/W thru nuclei

W and Z Boson Production at the Large Hadron Collider (LHC)

Tomas Jezo, Aleksander Kusina, Fred Olness, ...



$$p\ p \to W, Z$$
$$p\, Pb \to W, Z$$

LHC Heavy Ion

… there's another way to measure the strange quark

nCTEQ: Eur.Phys.J.C 80 (2020) 10, 968

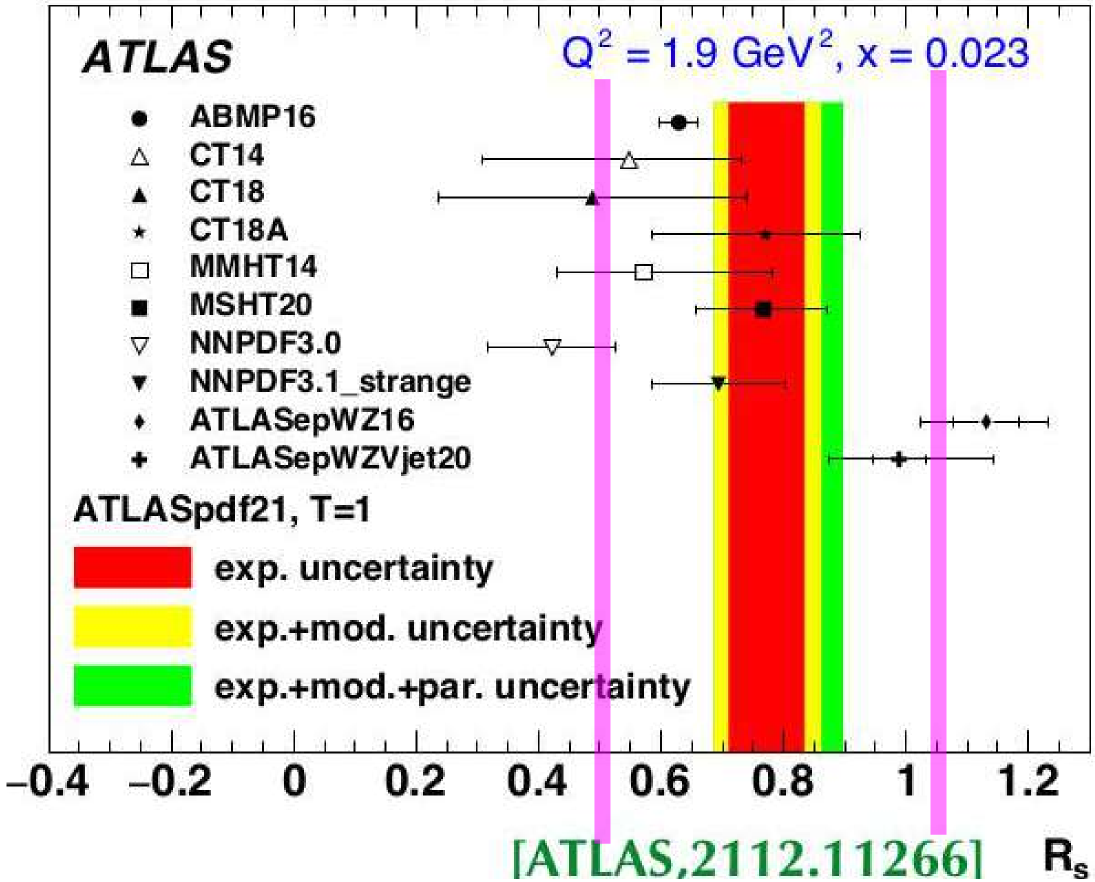
Surprise: … LHC sees more strange than expected

$$u\bar{d} + u\bar{s} + c\bar{d} + c\bar{s} \rightarrow W^+$$
$$\bar{u}d + \bar{u}s + \bar{c}d + \bar{c}s \rightarrow W^-$$
$$u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} \rightarrow Z$$

Surprise:

We expected $R_s = 1/2$

some $R_s > 1$

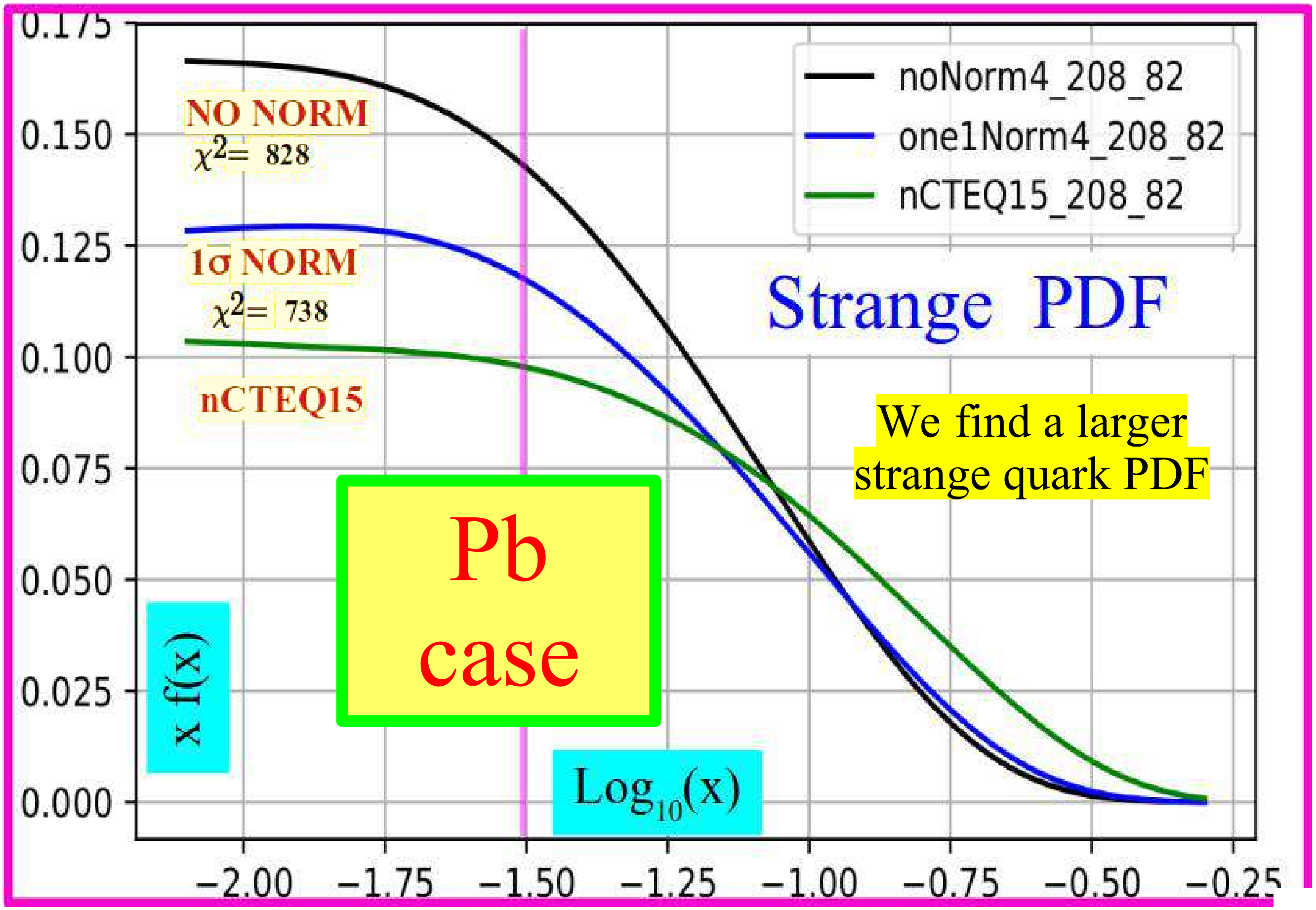


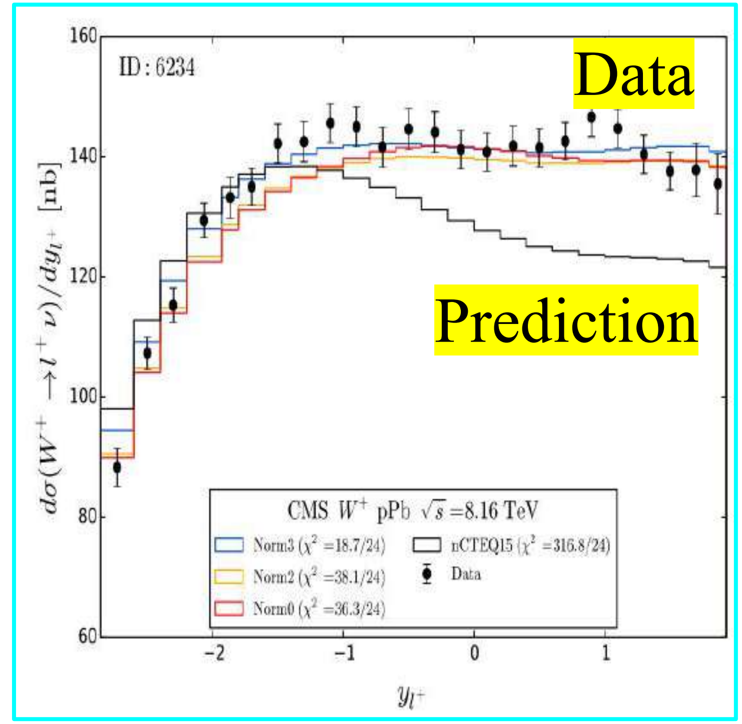
Proton case

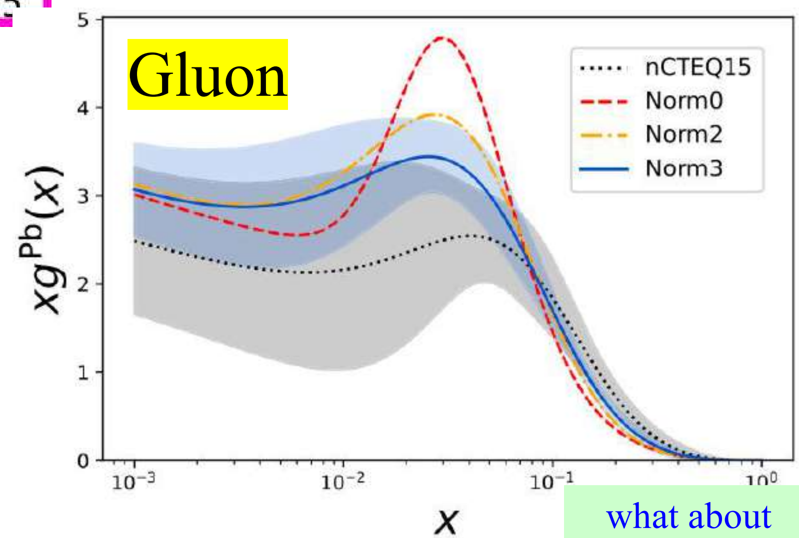
$$R_S = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$$

ATLAS: Eur. Phys. J. C 77 (2017) 367

Heavy Ion Case: … LHC STILL sees more strange than expected







Is the strange PDF driving the data ...

Or is the data driving the strange ???

what about the gluon???

EIC

...

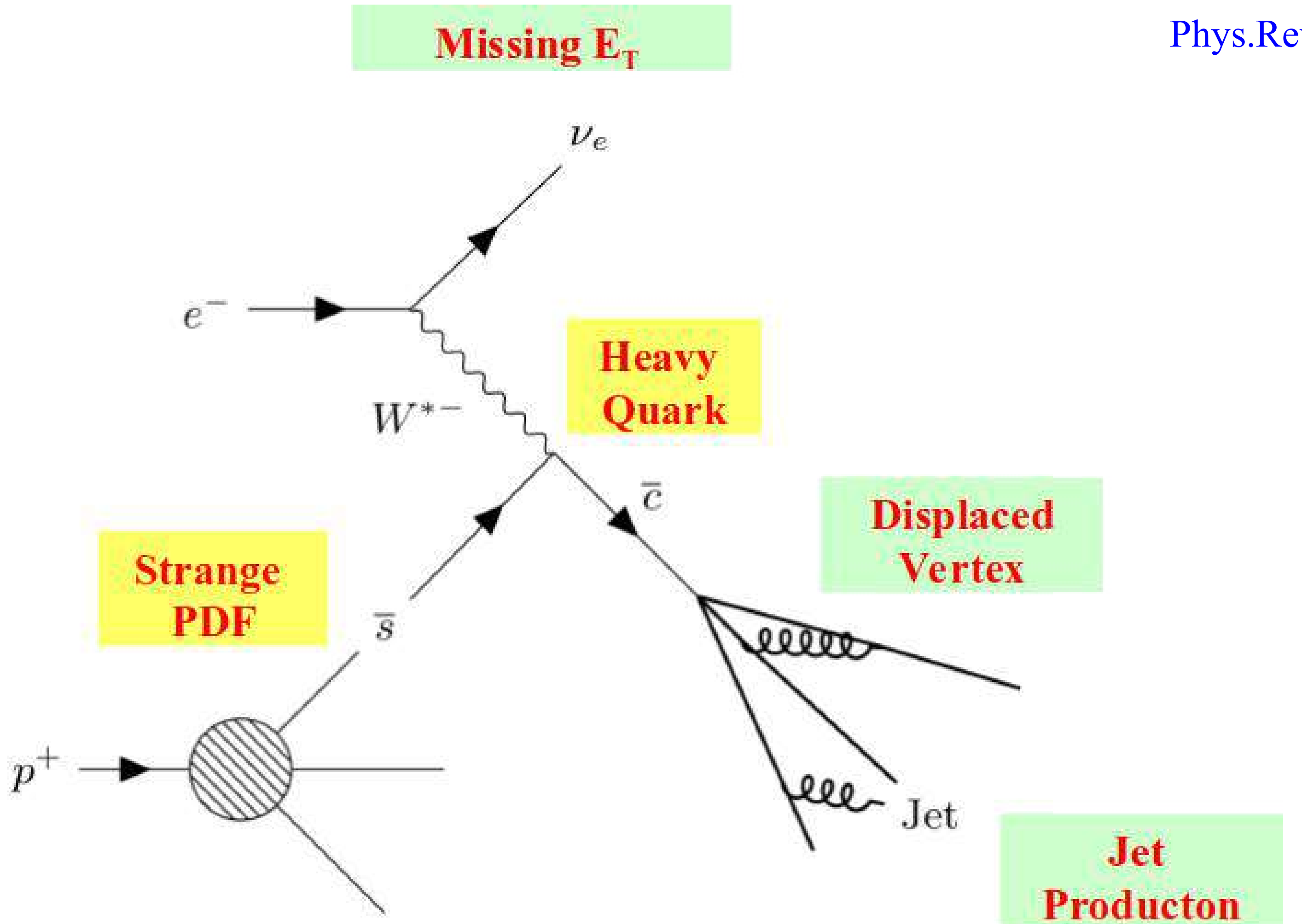
Charm Jets at the EIC

JLAB-PHY-20-3205, SMU-HEP-20-05

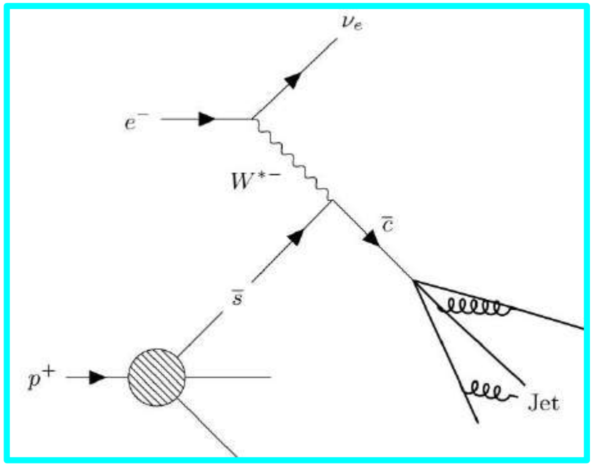
Charm jets as a probe for strangeness at the future Electron-Ion Collider

Miguel Arratia,[1,2] Yulia Furletova,[2] T. J. Hobbs,[3,4] Fredrick Olness,[3] and Stephen J. Sekula[3,*]

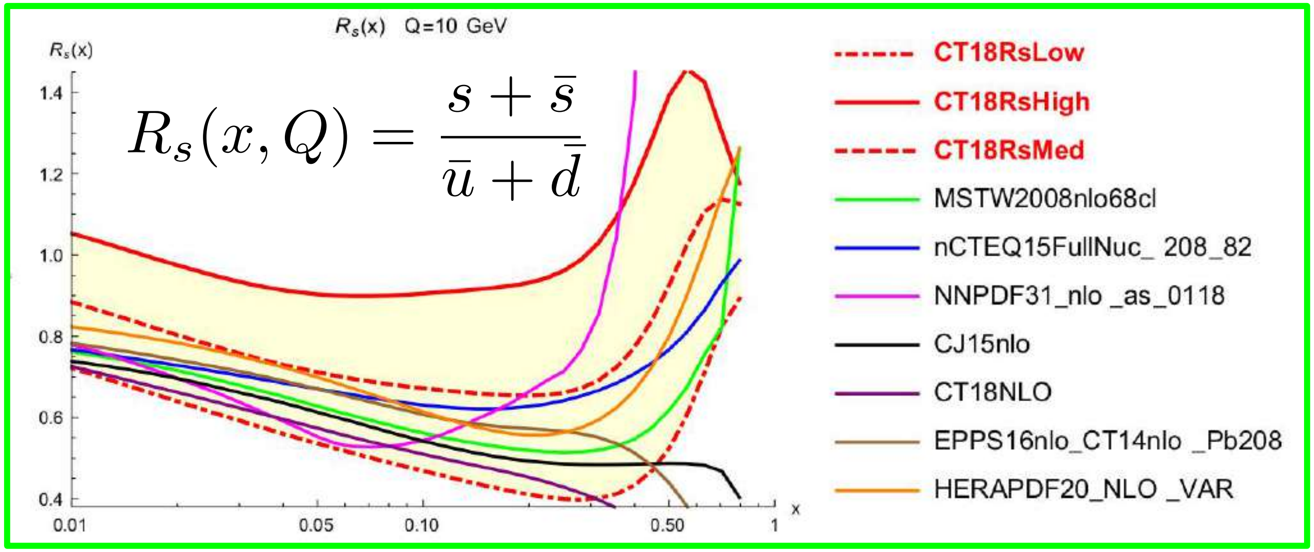
Phys.Rev.D 103 (2021) 7, 074023

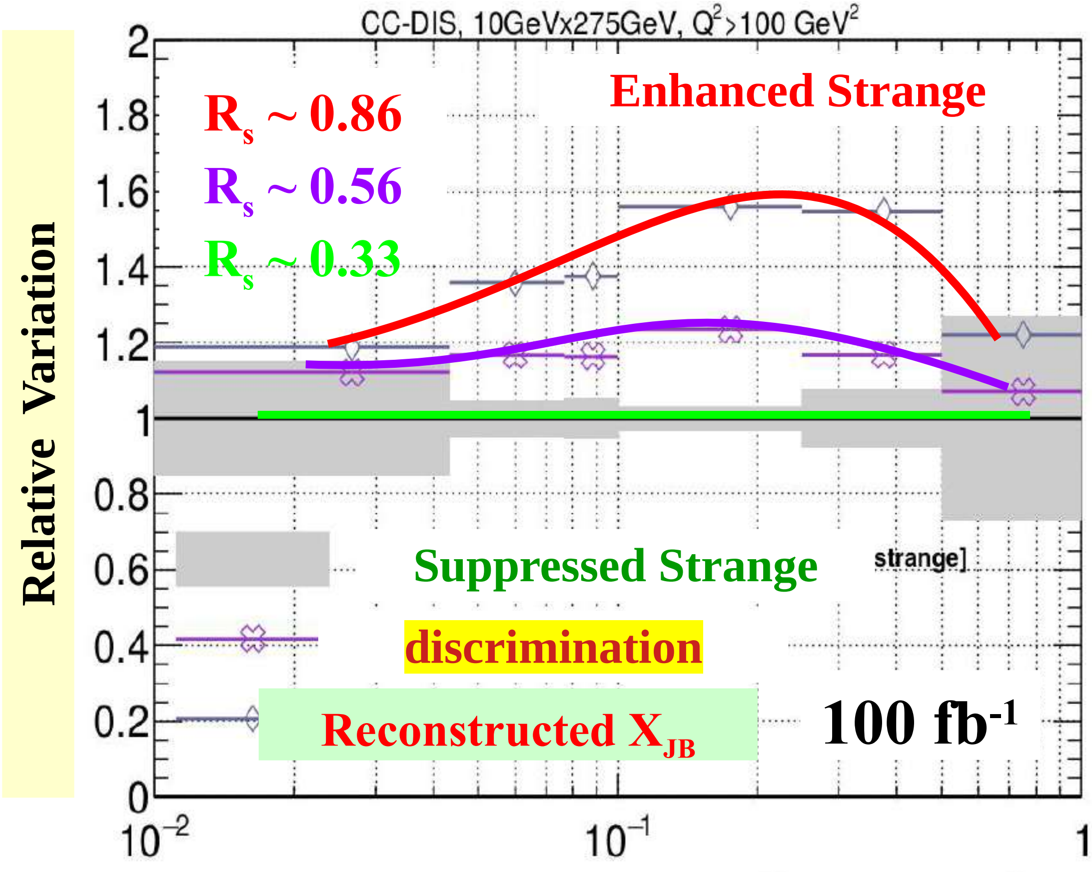


Charm Jets at the EIC ⇒ The Strange PDF



W+s → c$_{jet}$





Clear measure of Strange PDF beyond uncertainties

M. Arratia, Y. Furletova, T.J. Hobbs, F. Olness, S.J. Sekula, Phys.Rev.D 103 (2021) 7, 074023

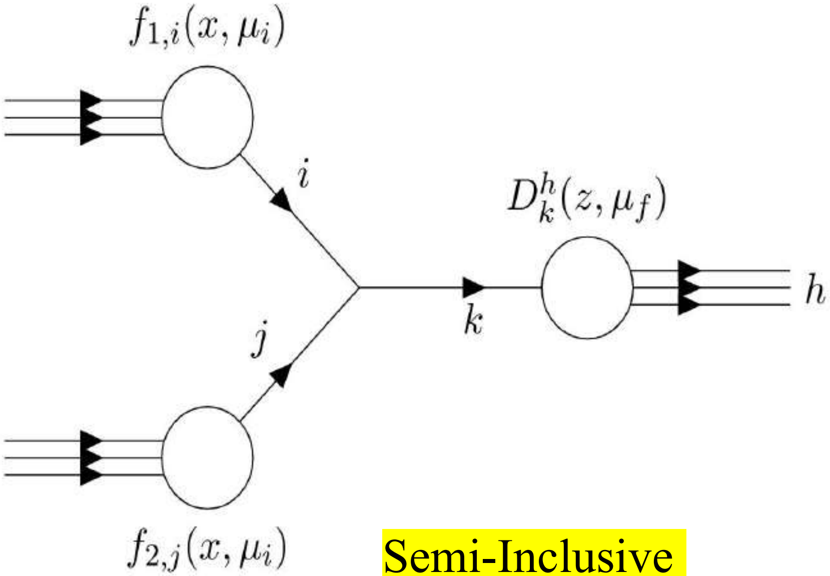
GLUON

…

Measuring the nuclear Gluon PDF

Parton Distribution Functions

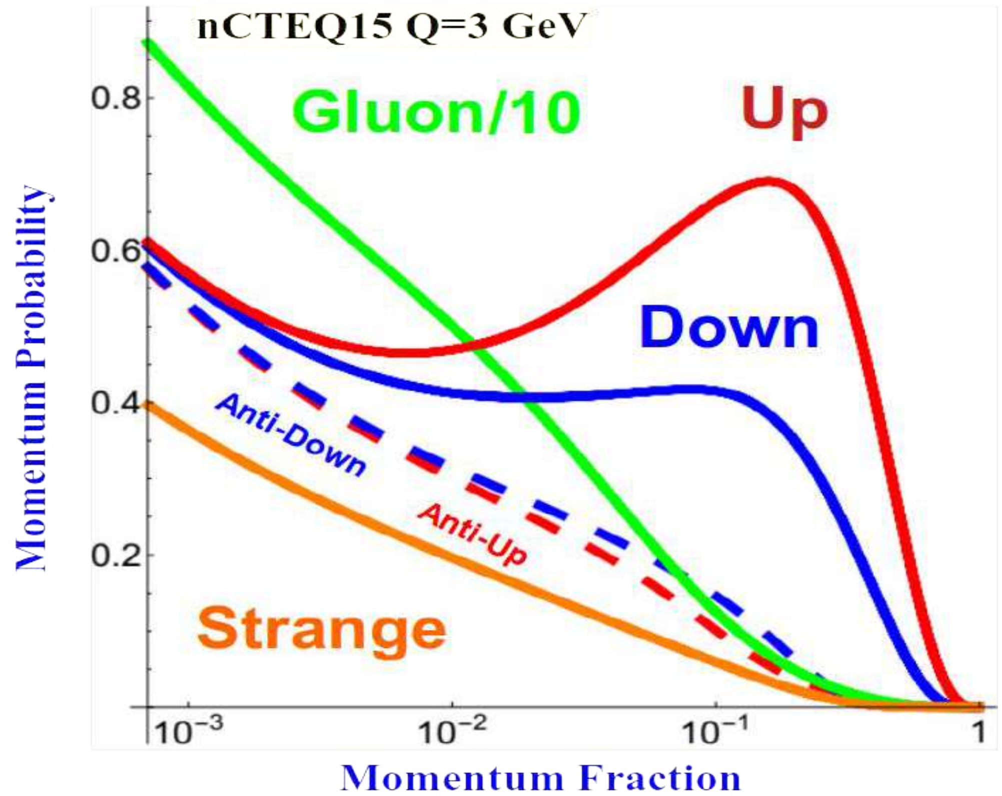
Pit Duwentaster, Michael Klasen, ...

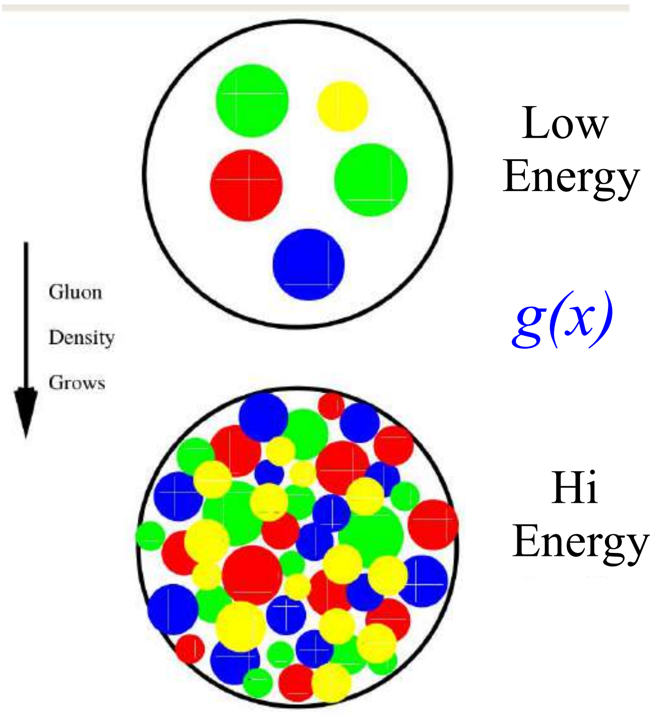


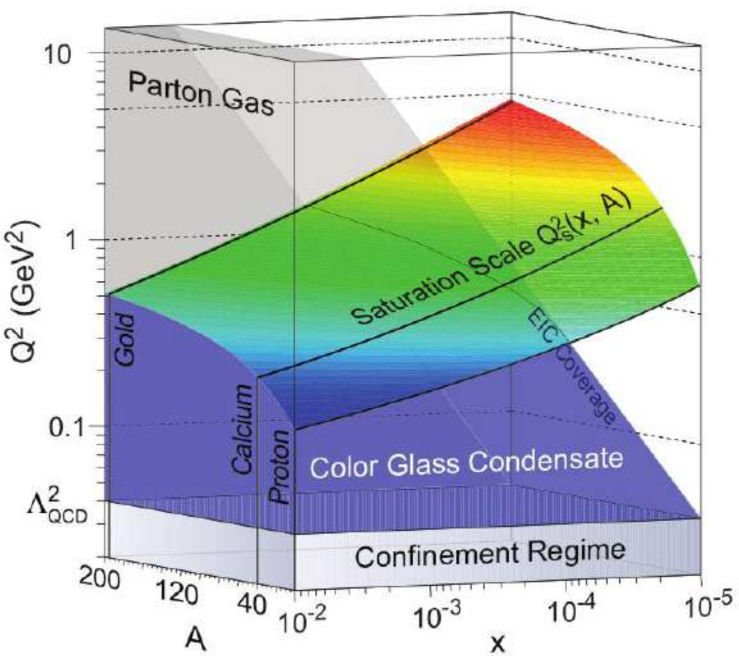
Semi-Inclusive
Hadron Production

how can we determine the gluon

Nuclear Medium Effects at small momentum fraction (x)

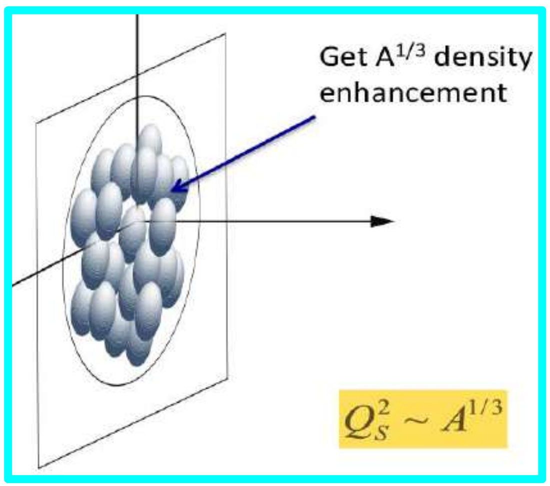






Nuclear medium effects:
- Quark Gluon Plasma
- Color Glass Condensate
- Recombination
- Saturation
- Resummation
- … *your theory here*

We gain a geometric factor of $A^{1/3}$



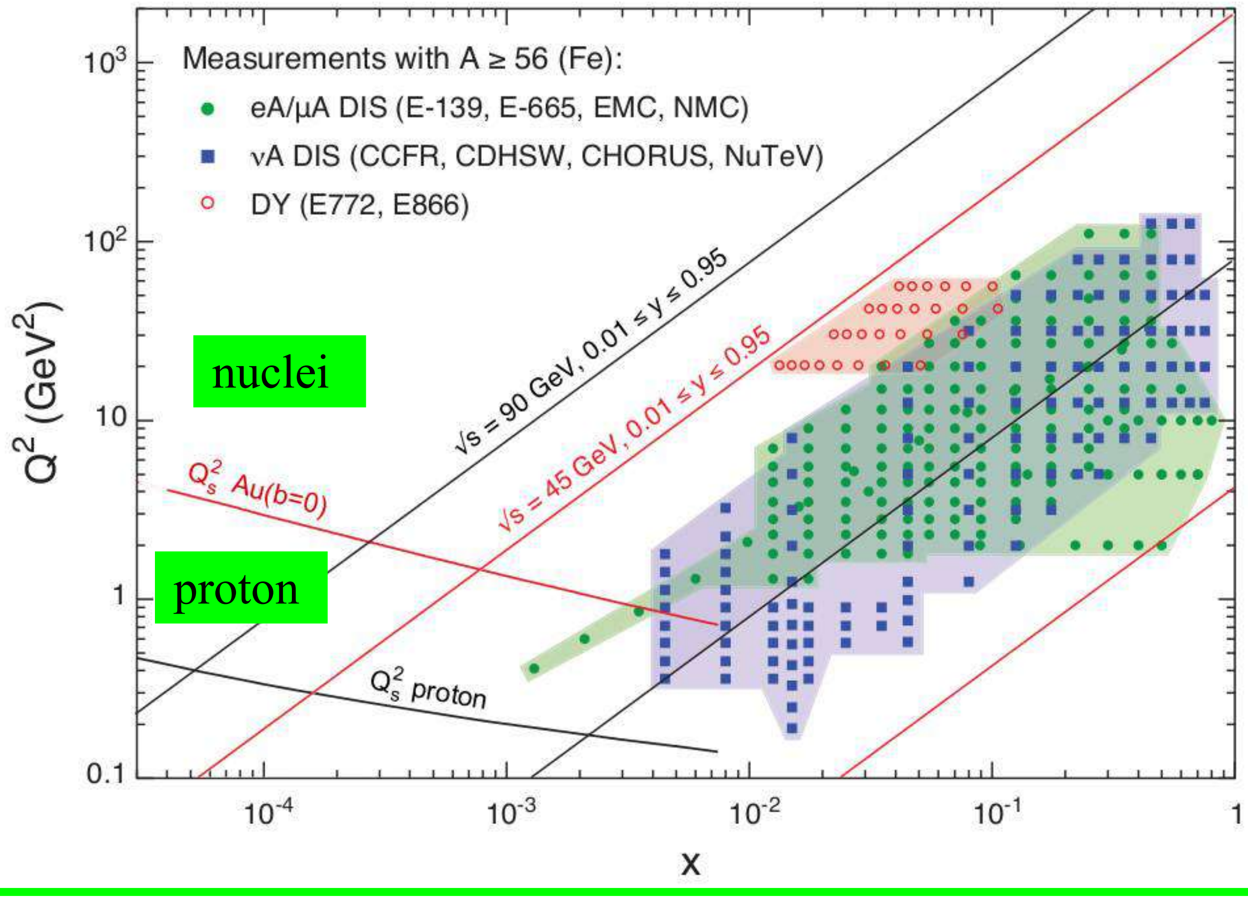
Review: Edmond Iancu & Raju Venugopalan: arXiv:0303204

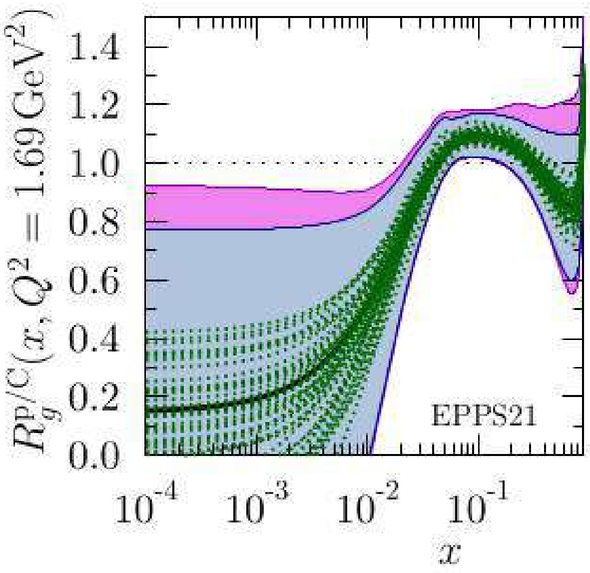
New Phenomena in Corners of Kinematic Plane

Saturation, BFKL, recombination, ...

Can Saturation be Discovered at EIC?

EIC has an unprecedented small-x reach for DIS on large nuclear targets, allowing to seal the discovery of saturation physics and study of its properties:

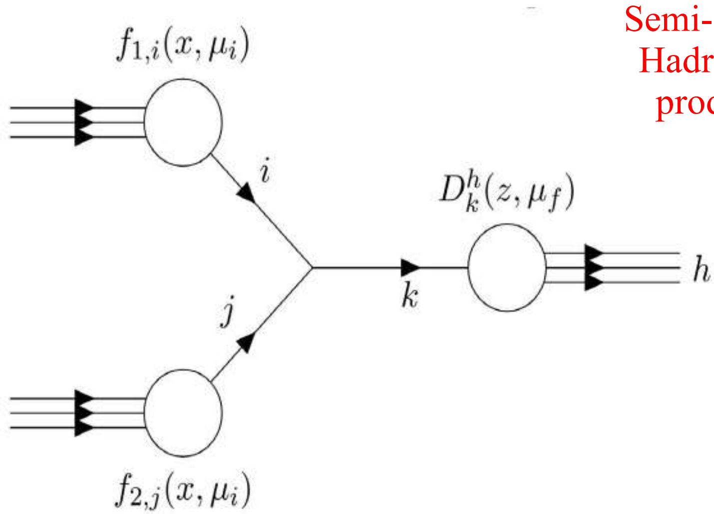




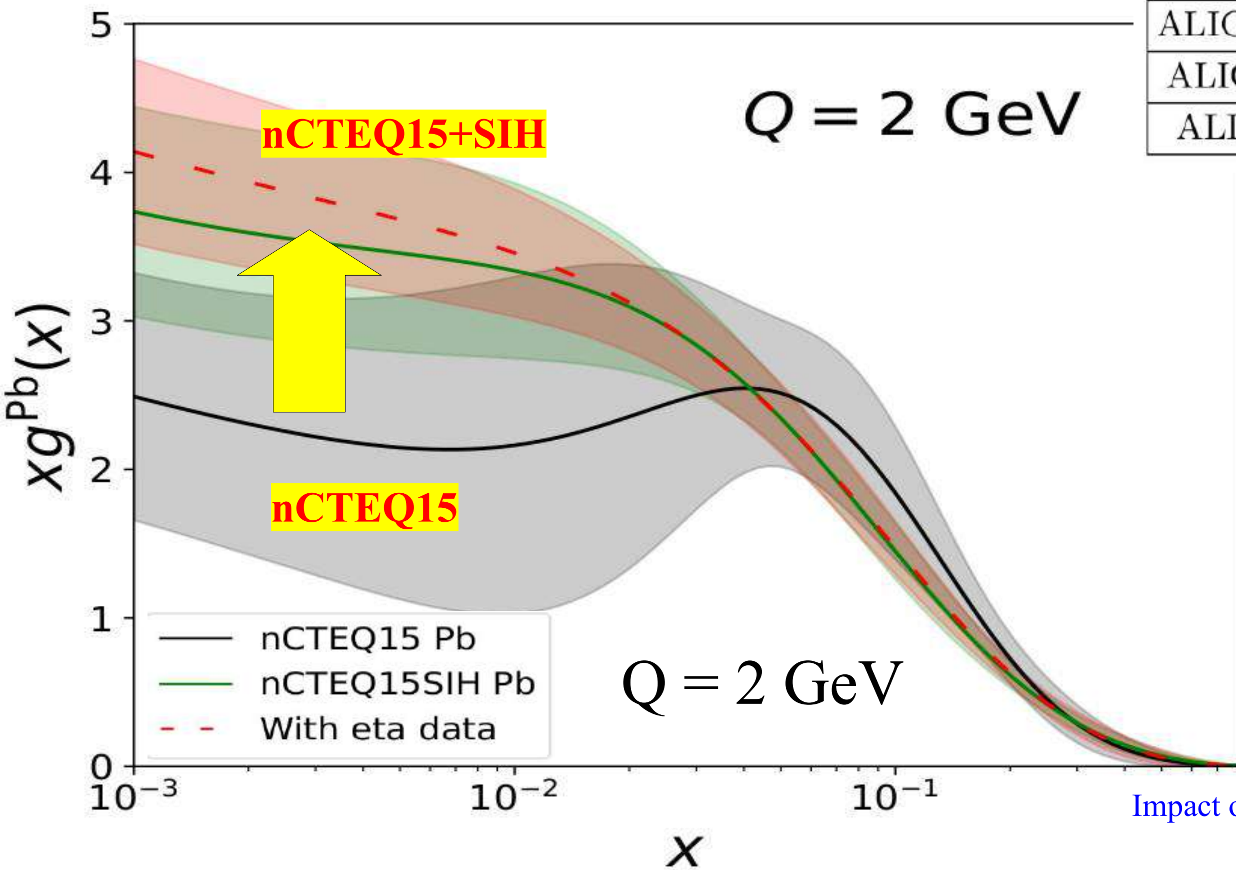
Precision Gluon can help study nuclear medium effects

Pit Duwentaster, Michael Klasen, ...

Semi-Inclusive Hadron (SIH) production



Data set	$\sqrt{s_{NN}}$ [GeV]	Observ.	No. points
PHENIX π^0	200	R_{dAu}	21
PHENIX η	200	R_{dAu}	12
PHENIX $\pi^\pm$	200	R_{dAu}	20
PHENIX $K^\pm$	200	R_{dAu}	15
STARπ^0	200	R_{dAu}	13
STAR η	200	R_{dAu}	7
STAR $\pi^\pm$	200	R_{dAu}	23
ALICE 5 TeV π^0	5020	R_{pPb}	31
ALICE 5 TeV η	5020	R_{pPb}	16
ALICE 5 TeV $\pi^\pm$	5020	R_{pPb}	58
ALICE 5 TeV $K^\pm$	5020	R_{pPb}	58
ALICE 8 TeV π^0	8160	R_{pPb}	30
ALICE 8 TeV η	8160	R_{pPb}	14

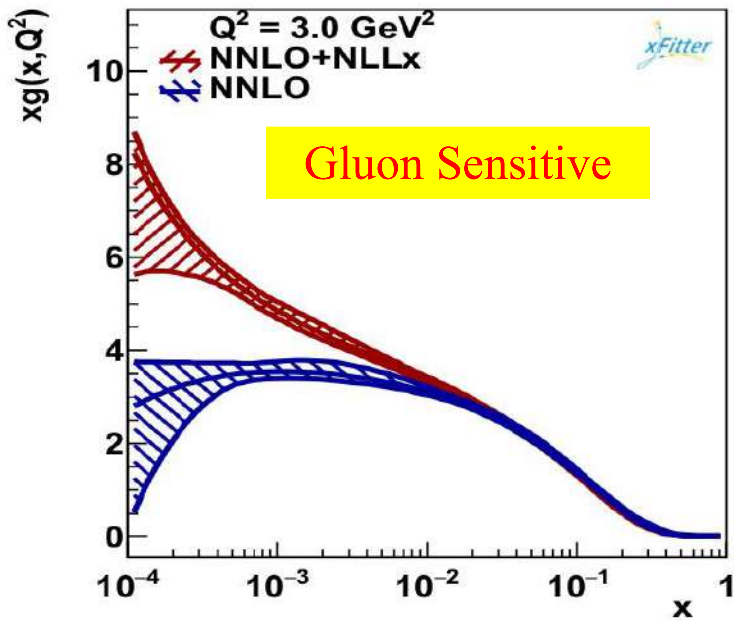


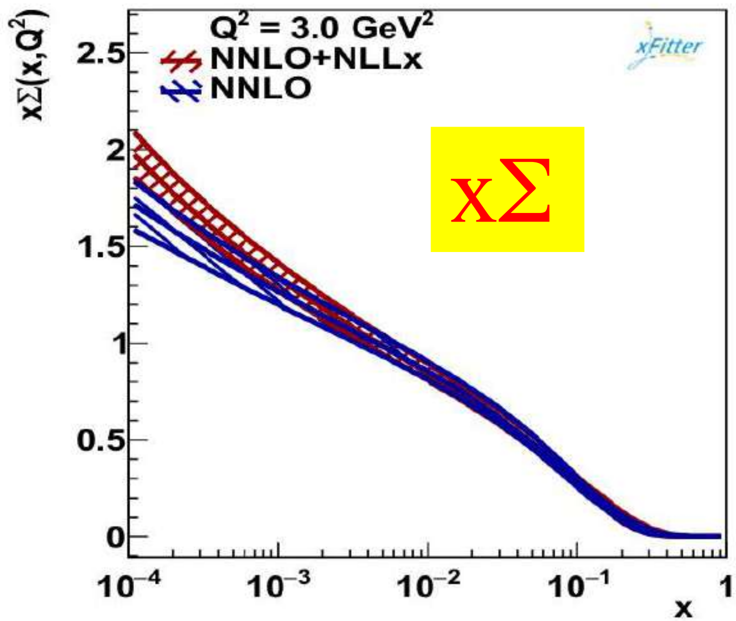
Semi-Inclusive Hadron (SIH) production

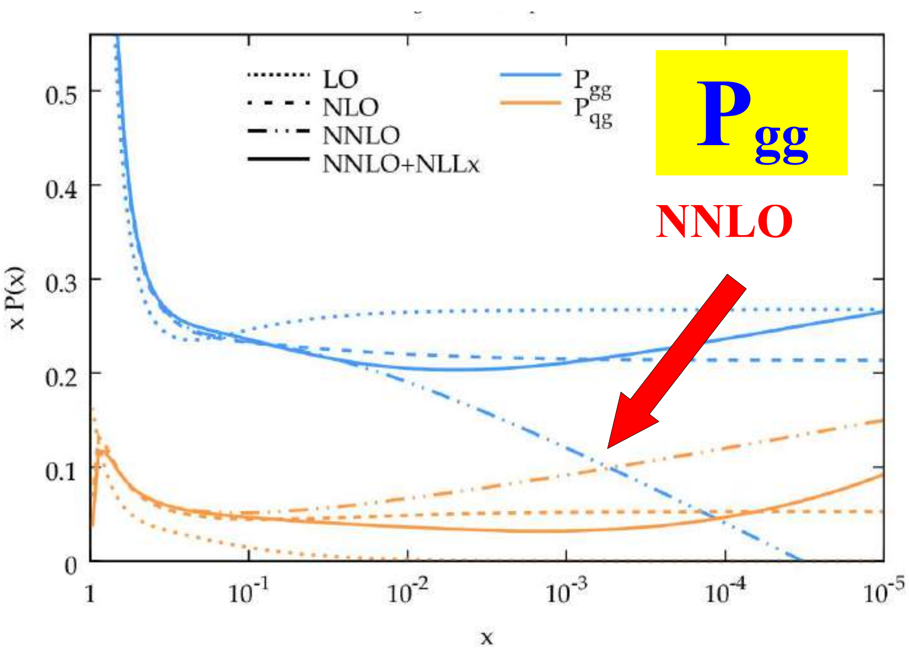
Determines gluon in small x region

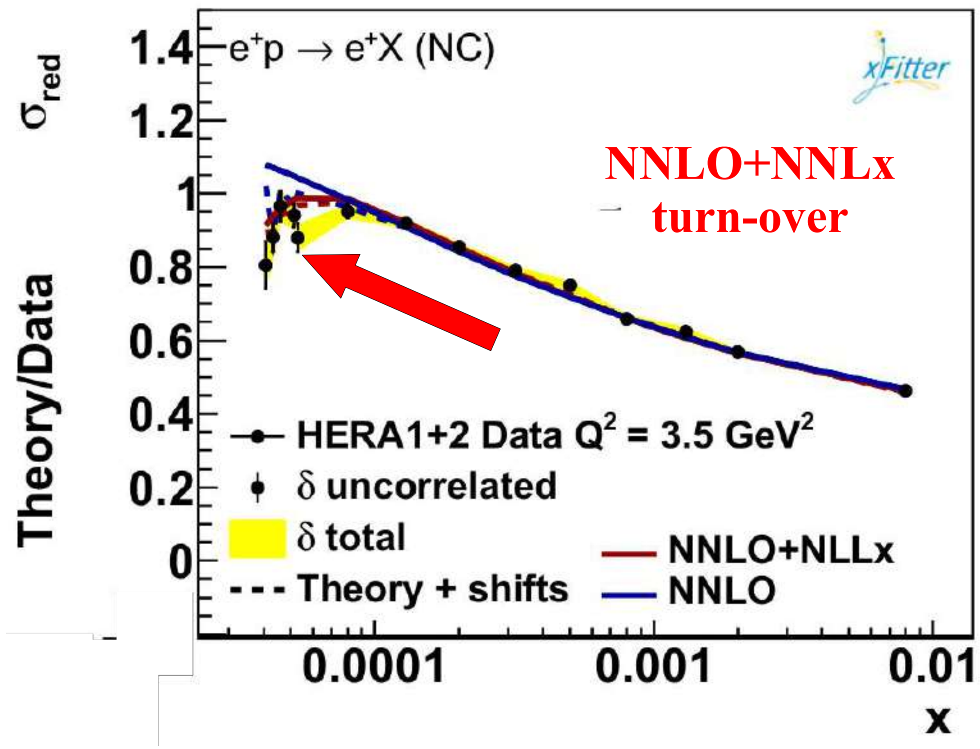
Impact of inclusive hadron production data on nuclear gluon PDFs
nCTEQ: P. Duwentäster, et al., PRD104 (2021) 094005.

xFitter Resummation Study









Impact of low-x resummation on QCD analysis of HERA data
xFitter Developers' Team: Eur.Phys.J.C 78 (2018) 8, 621

xFitter

xFitter Collaboration Meeting February 2020, DESY

www.xFitter.org

xFitter

PROTON

NUCLEON

MESON

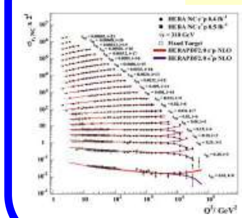
xFitter/xFitterT ... evel.. ... adPage

www.xFitter.org

Sample data files:

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

Experimental Data



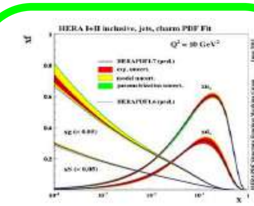
Data: HERA, Tevatron, LHC, fixed target experiments

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*

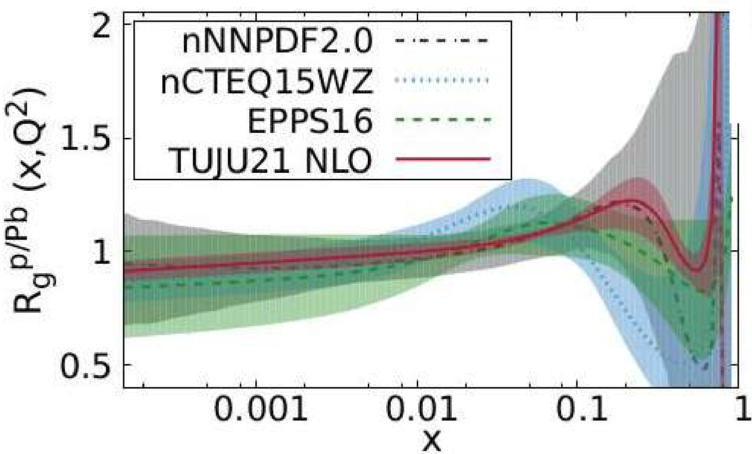
xFitter 2.2.0
Future Freeze

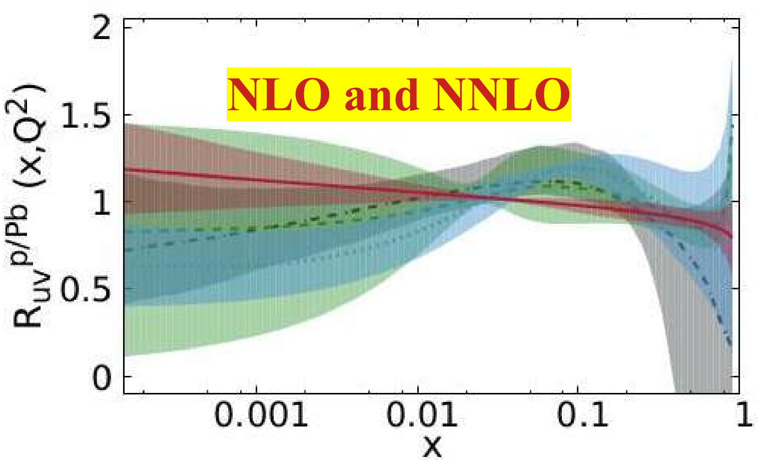
Nuclear xFitter: *(Daiquiri)*

PHYSICAL REVIEW D **100**, 096015 (2019)

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

Marina Walt,[1,*] Ilkka Helenius,[2,3,†] and Werner Vogelsang[1,‡]





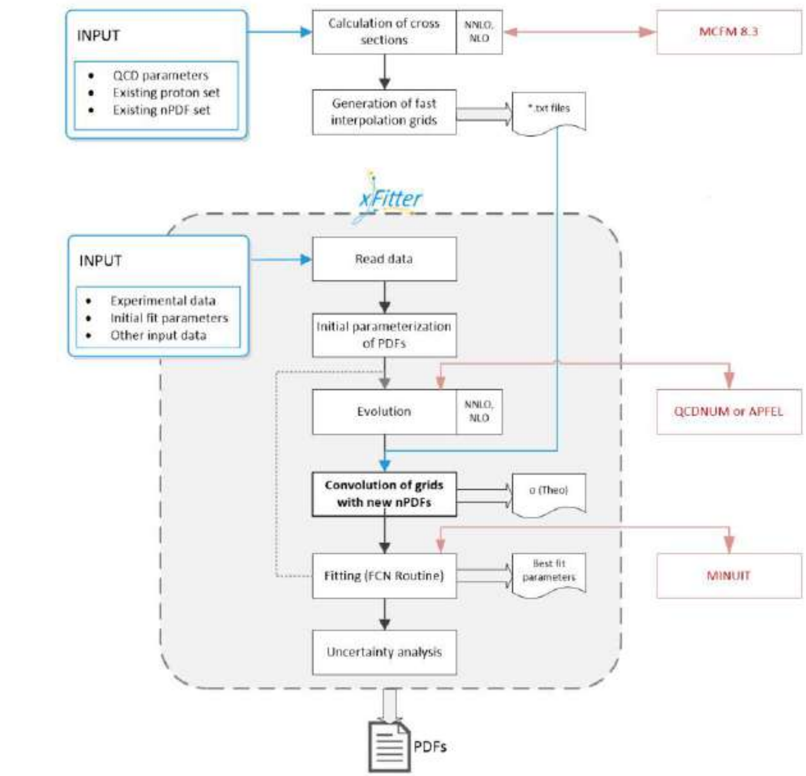


FIG. 1: Schematic view of the high-level xFITTER functionalities as relevant for Drell-Yan and $W^{\pm}$, Z boson production processes, with the newly implemented convolution routine in xFITTER as used for the nPDF fit TUJU21. xFITTER logo credited from [60].

xFitter

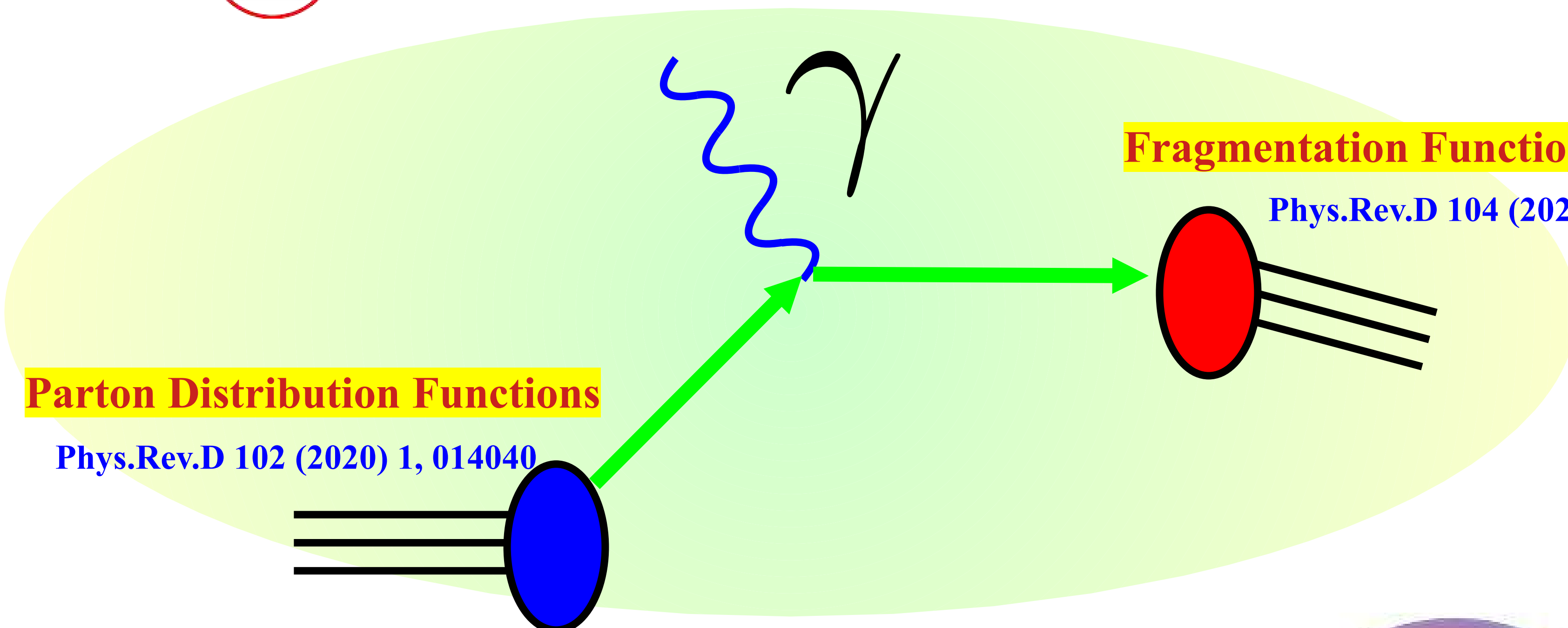
Volunteers Welcome

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

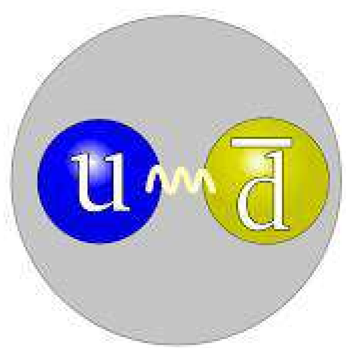
Pion PDFs & FFs

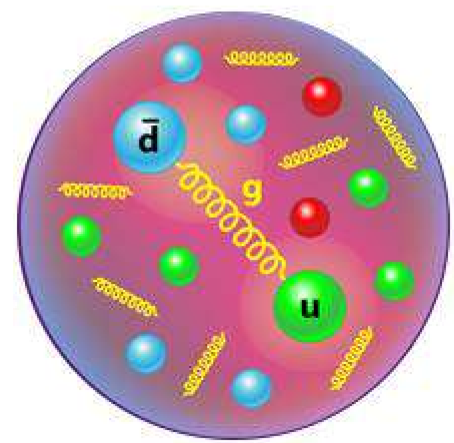
Parton Distribution Functions

Fragmentation Functions



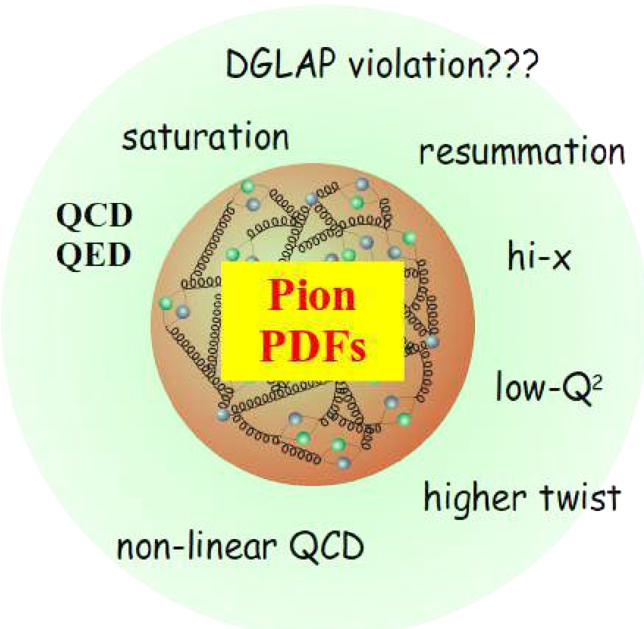
Pion $\pi^+ = u\bar{d}$





xFitter Pion Fit

Phys.Rev.D 102 (2020) 1, 014040



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

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]

xFitter: Phys.Rev.D 102 (2020) 1, 014040

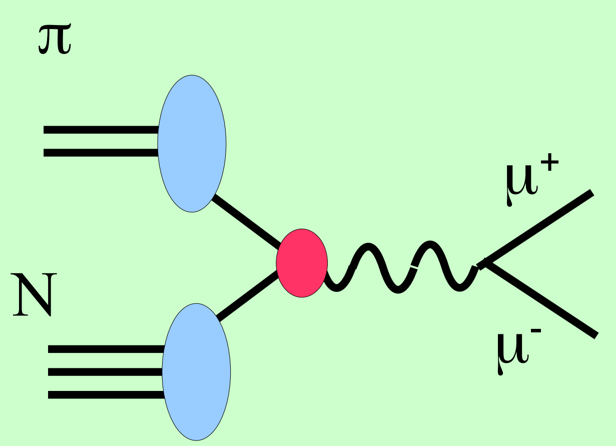
xFitter Meson PDFs

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

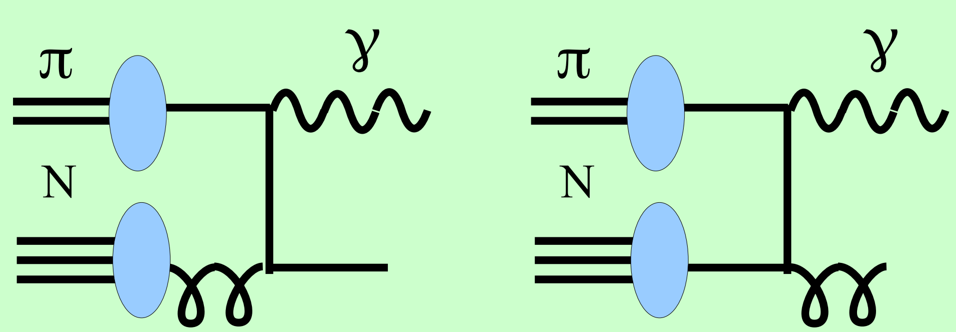
https://www.xfitter.org/

xFitter

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]

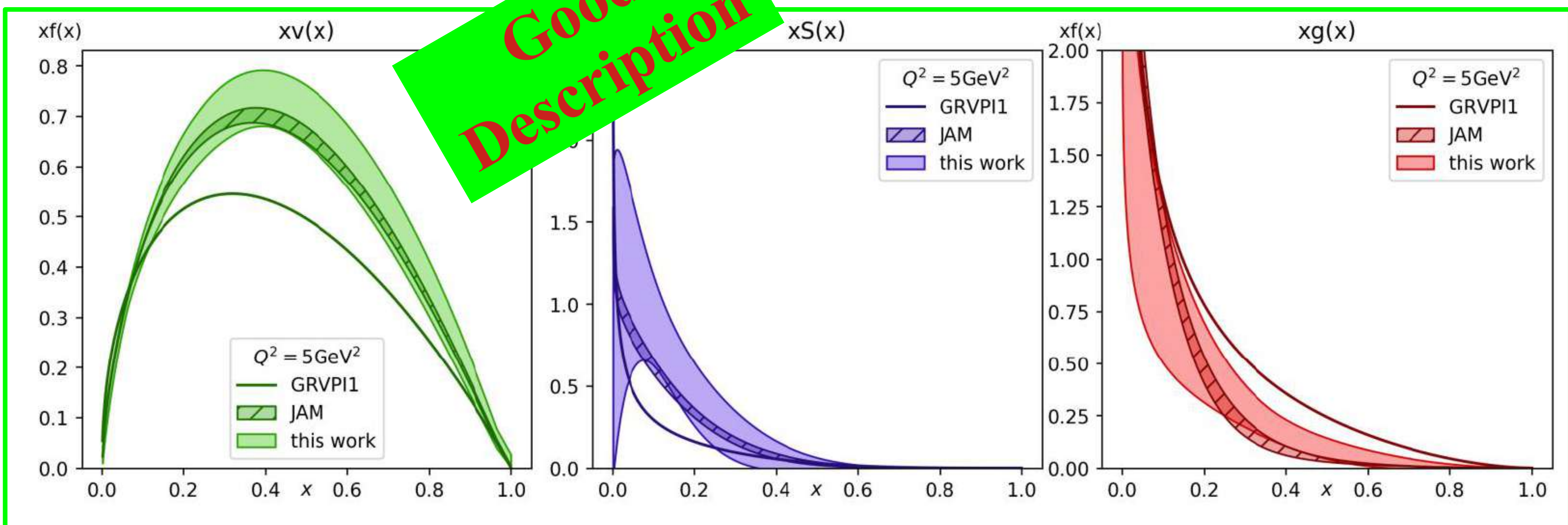
xFitter Pion PDFs

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

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

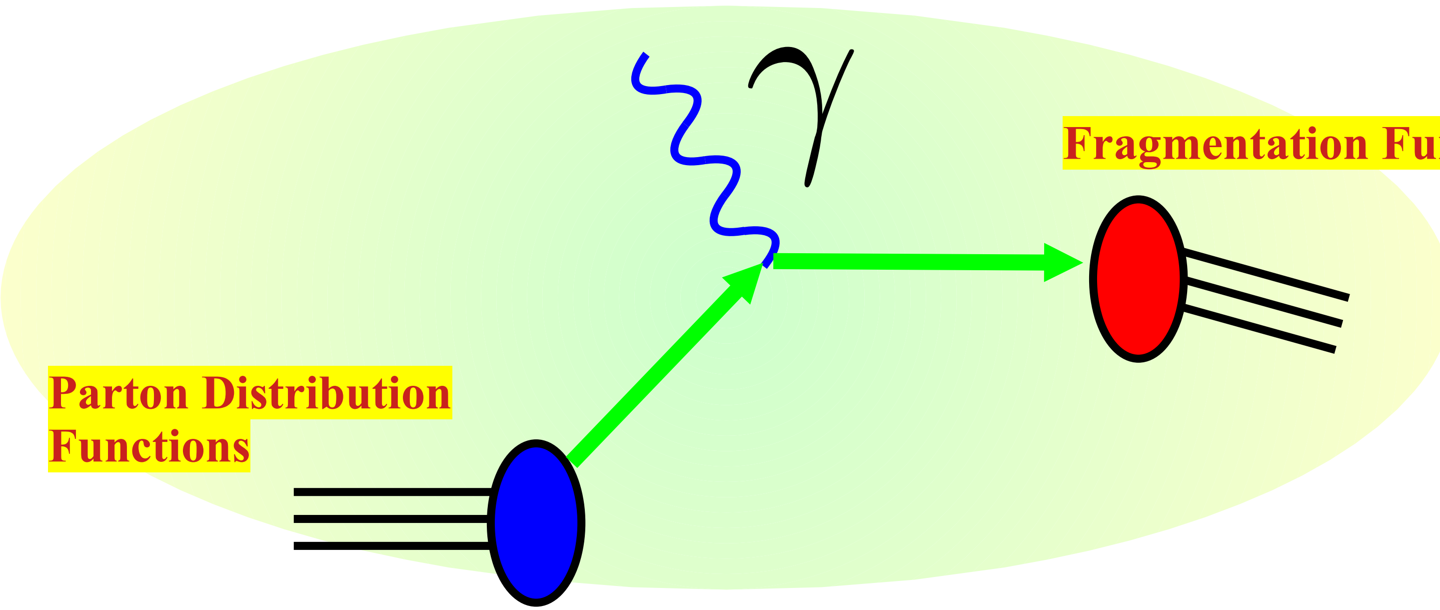
	$\langle xv \rangle$	$\langle xS \rangle$	$\langle xg \rangle$	Q^2 (GeV^2)
JAM [31]	0.54 ± 0.01	0.16 ± 0.02	0.30 ± 0.02	1.69
JAM (DY)	0.60 ± 0.01	0.30 ± 0.05	0.10 ± 0.05	1.69
this work	0.55 ± 0.06	0.26 ± 0.15	0.19 ± 0.16	1.69
Lattice-3 [18]	0.428 ± 0.030			4
SMRS [25]	0.47			4
Han et al. [44]	0.51 ± 0.03			4
GRVPI1 [27]	0.39	0.11	0.51	4
Ding et al. [11]	0.48 ± 0.03	0.11 ± 0.02	0.41 ± 0.02	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 [16]	0.558 ± 0.166			5.76
Lattice-2 [17]	0.48 ± 0.04			5.76
this work	0.48 ± 0.05	0.25 ± 0.12	0.27 ± 0.13	5.76
WRH [26]	0.434 ± 0.022			27
ChQM-1 [13]	0.428			27
ChQM-2 [15]	0.46			27
this work	0.42 ± 0.04	0.25 ± 0.10	0.32 ± 0.10	27
SMRS [25]	0.49 ± 0.02			49
this work	0.41 ± 0.04	0.25 ± 0.09	0.34 ± 0.09	49

Good Description



Pion Fragmentation Functions

Phys.Rev.D 104 (2021) 5, 056019



xFitter

Hamed Abdolmaleki, Maryam Soleymaninia, Hamzeh Khanpour

PHYSICAL REVIEW D **104,** 056019 (2021)

QCD analysis of pion fragmentation functions in the xFitter framework

Hamed Abdolmaleki,[1,*] Maryam Soleymaninia,[1,†] Hamzeh Khanpour,[1,2,3,‡] Simone Amoroso,[4,§] Francesco Giuli,[5,∥] Alexander Glazov,[4,¶] Agnieszka Luszczak,[6,**] Fredrick Olness,[7,††] and Oleksandr Zenaiev[8,‡‡]

(xFITTER Developers' Team:)

xFitter: Multiple fits with a vast array of data sets

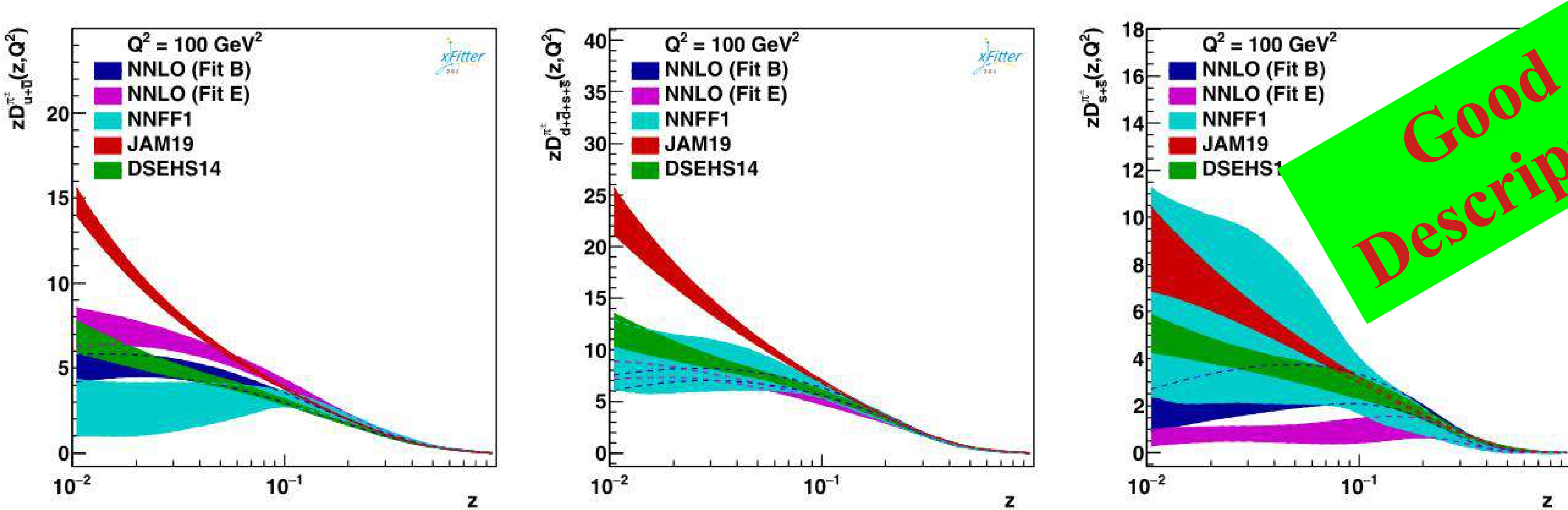
HAMED ABDOLMALEKI *et al.* PHYS. REV. D **104,** 056019 (2021)

TABLE I. The Single Inclusive electron-positron Annihilation (SIA) datasets used in the pion FFs analysis. The values of χ^2 per N data points for the individual SIA experiments are shown. The z range for each experiment is displayed in Fig. 8. The measured observable is also listed where $\sqrt{s}$ is the total CMS energy, $\beta = p_h/E_h$, and $z = 2E_h/\sqrt{s}$.

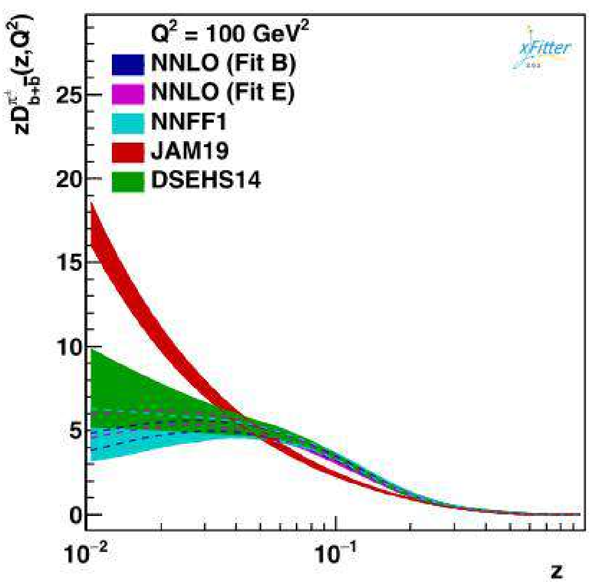
			χ^2/number of points					
Observable	Experiment	$\sqrt{s}$ [GeV]	Fit A (NLO)	Fit A (NNLO)	Fit B (NNLO)	Fit C (NNLO)	Fit D (NNLO)	Fit E (NNLO)
$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^h}{dz}$	SLD	91.20	57/34	41/34	41/34	48/34	39/34	45/34
$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^h}{dz}\|_{\rm uds}$	$\mathrm{SLD_{uds}}$	91.20	66/34	52/34	56/34	44/34	43/34	45/34
$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^h}{dz}\|_c$	$\mathrm{SLD_c}$	91.20	35/34	33/34	32/34	32/34	32/34	32/34
$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^h}{dz}\|_b$	$\mathrm{SLD_b}$	91.20	25/34	24/34	24/34	24/34	23/34	24/34
$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^h}{dp_h}$	OPAL	91.20	42/24	41/24	41/24	39/24	39/24	39/24
$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^h}{dp_h}$	DELPHI	91.20	37/21	41/21	41/21	44/21	44/21	43/21
$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^h}{dp_h}\|_{\rm uds}$	$\mathrm{DELPH_{uds}}$	91.20	25/21	27/21	26/21	30/21	31/21	30/21
$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^h}{dp_h}\|_b$	$\mathrm{DELPH_b}$	91.20	20/21	20/21	21/21	19/21	20/21	19/21
$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^h}{dz}$	ALEPH	91.20	21/23	14/23	14/23	11/23	11/23	12/23
$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^h}{dz}$	TASSO44	44.00	15/6	17/6	15/6	18/6	16/6	18/6
$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^h}{dz}$	TASSO34	34.00	6.8/9	8.0/9	6.8/9	9.3/9	7.3/9	8.3/9
$\frac{1}{\beta\sigma_{\rm tot}}\frac{d\sigma^h}{dz}$	TPC	29.00	6.3/13	11/13	11/13	11/13	7.1/13	9.2/13
$\frac{s}{\beta}\frac{d\sigma^h}{dz}$	TASSO22	22.00	5.7/8	5.5/8	5.6/8	6.1/8	5.9/8	5.8/8
$\frac{s}{\beta}\frac{d\sigma^h}{dz}$	TASSO14	14.00	11/9	11/9	11/9	9.9/9	11/9	9.8/9
$\frac{s}{\beta}\frac{d\sigma^h}{dz}$	TASSO12	12.00	1.4/4	1.4/4	1.3/4	0.96/4	1.4/4	1.1/4
$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^h}{dp_h}$	*BABAR*	10.52	71/40	53/40	77/40	...	...	33/37
$\frac{d\sigma^h}{dz}$	BELLE13	10.54	21/70	14/70	...	...	...	...
$\frac{d\sigma^h}{dz}$	BELLE20	10.58	...	...	82/32	32/32	9.2/28	17/28
Correlated χ^2			11	9.4	8.4	16	9.4	12
Log penalty χ^2			+4.2	+3.0	+4.2	+7.7	+5.6	+6.8
Total χ^2/dof			480/386	427/386	518/348	404/308	357/304	410/341

xFitter: Comparisons: … good overall … *more work needed*

HAMED ABDOLMALEKI *et al.* PHYS. REV. D **104,** 056019 (2021)



Good Description



Good description of the data in general

Deviations in the low-z region

BELLE and BaBar data pull in opposite directions

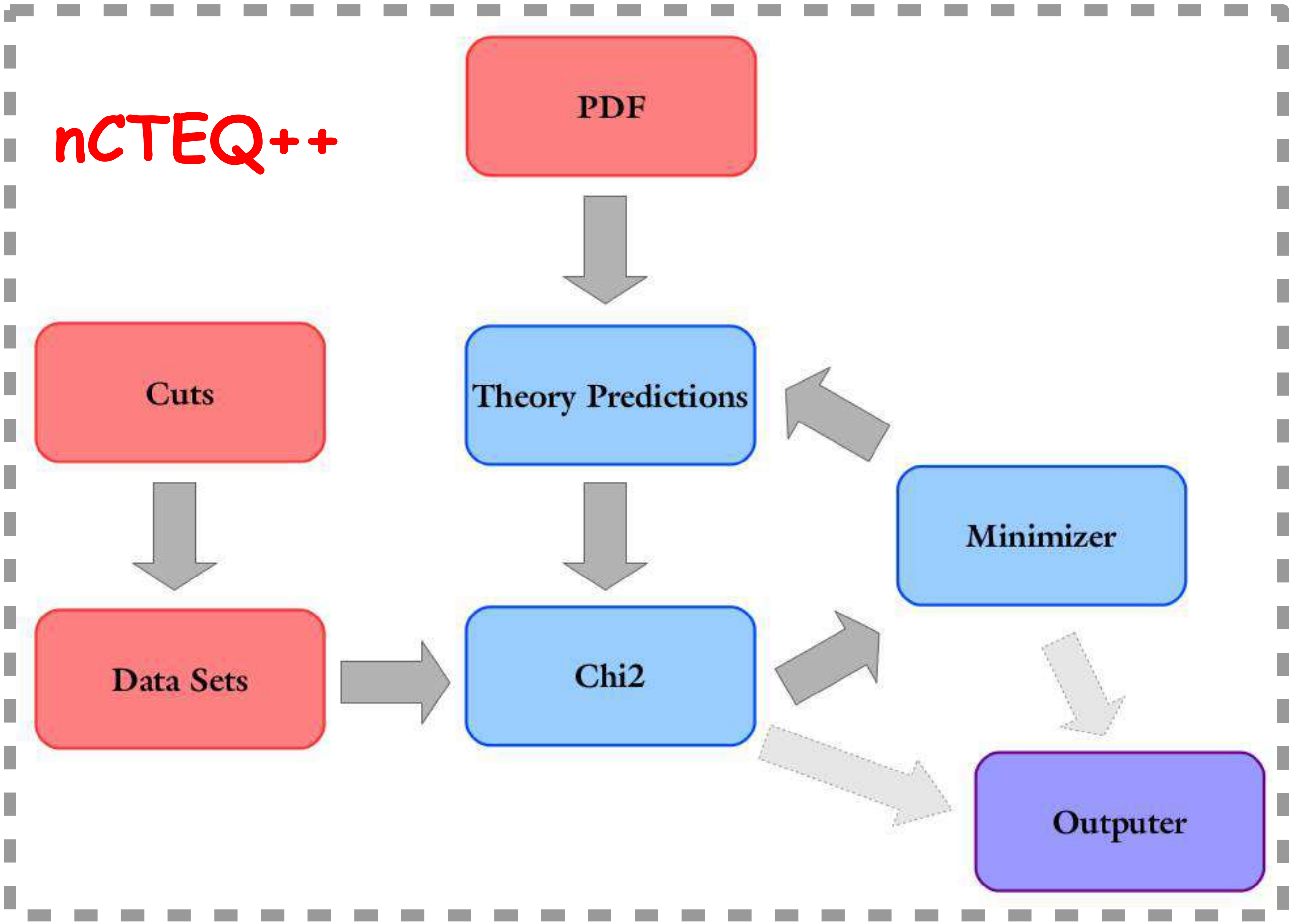
Clearly further investigation is warranted

nCTEQ++

a modern, modular code base

nCTEQ++ … a complete rewrite in C++

Top level C++, modular structure, output to YAML & Python scripts



Use external programs
- Minuit
- HOPPET
- MCFM
- APPLgrid

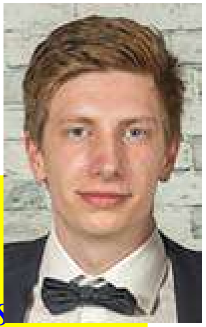
Pre-Computed Grids

Tremendous speed-up for higher order calculation

… for example …

High order DIS processes (Peter Risse)

Special thanks to:
Tomas Jezo
Eric Godat
Florian Lyonnet
Aleksander Kusina



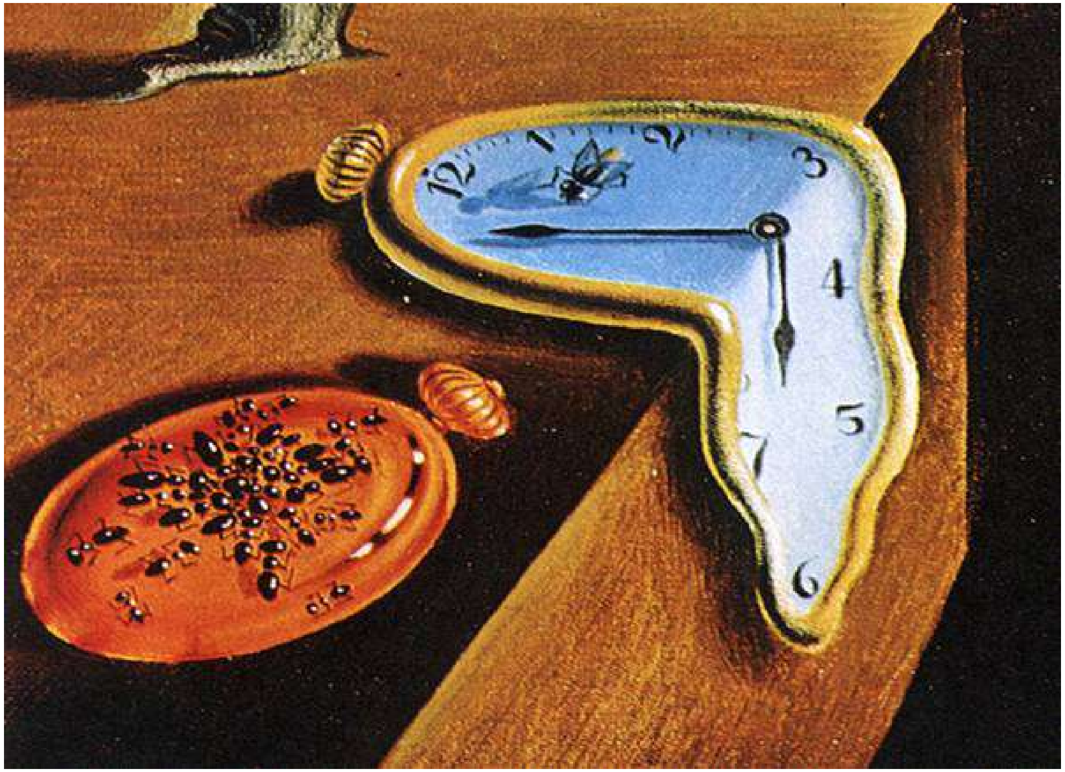
Code benchmark timings:

Original Fortran Code

contains multiple levels of integrals

New C++ Code

using modern grid techniques



Typical fits current run a few days to a week.
This will be reduced to a few hours.

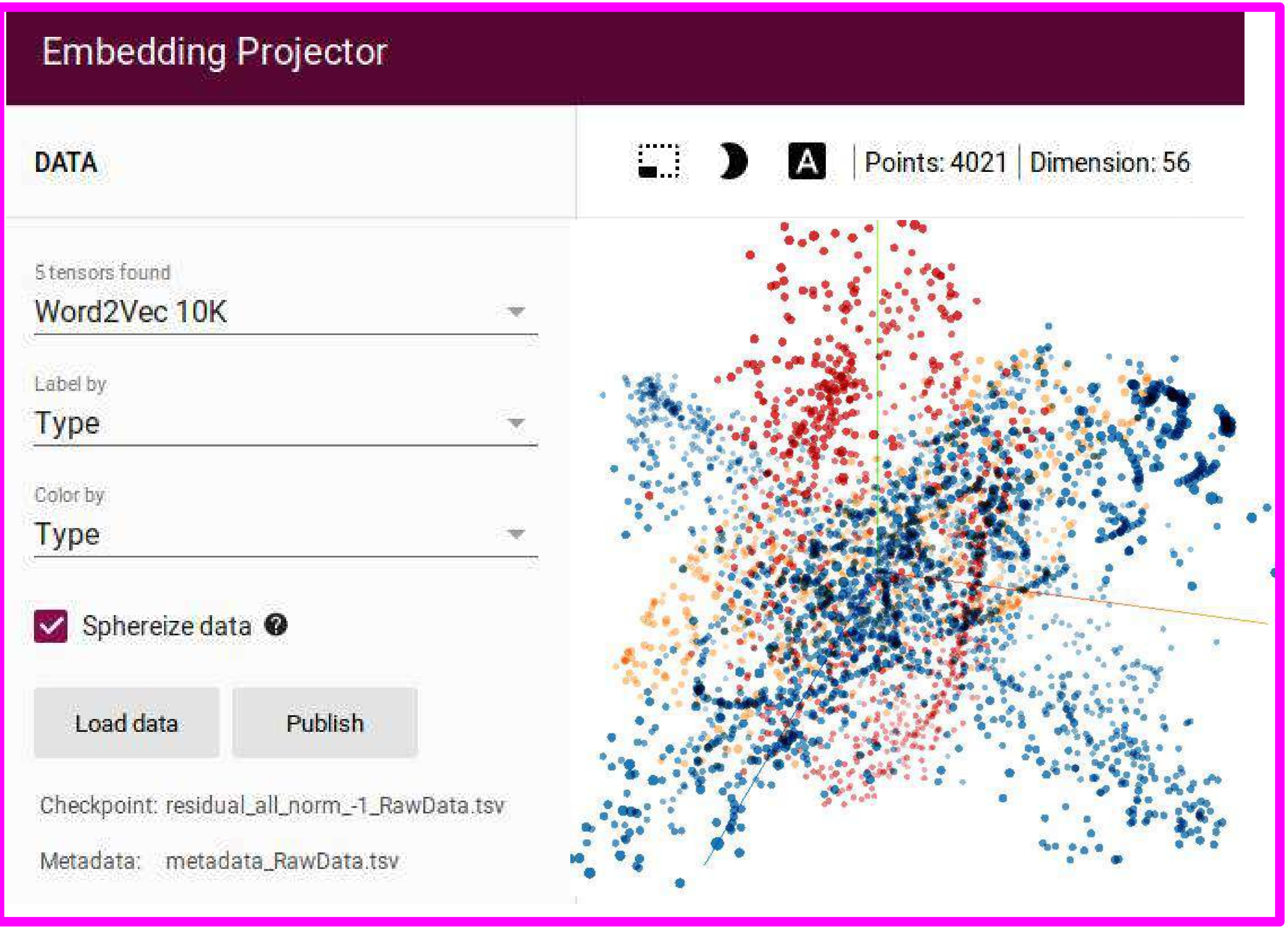
High order DIS processes
(Peter Risse)

New Tools

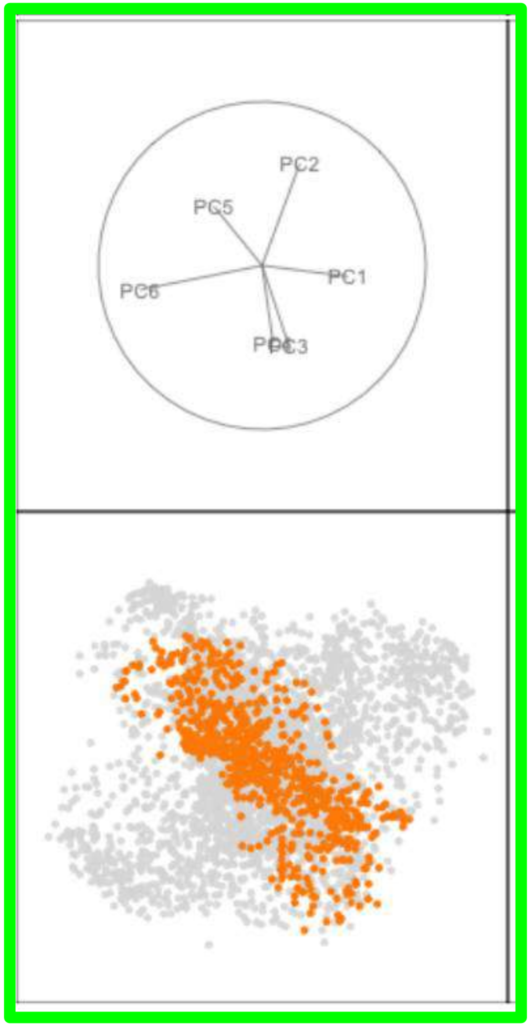
PDFSense
&
… borrowing from AI

Applications of PDFSense:

Artificial Intelligence Tools: Projector tool of Google TensorFlow



Pavel Nadolsky et al.

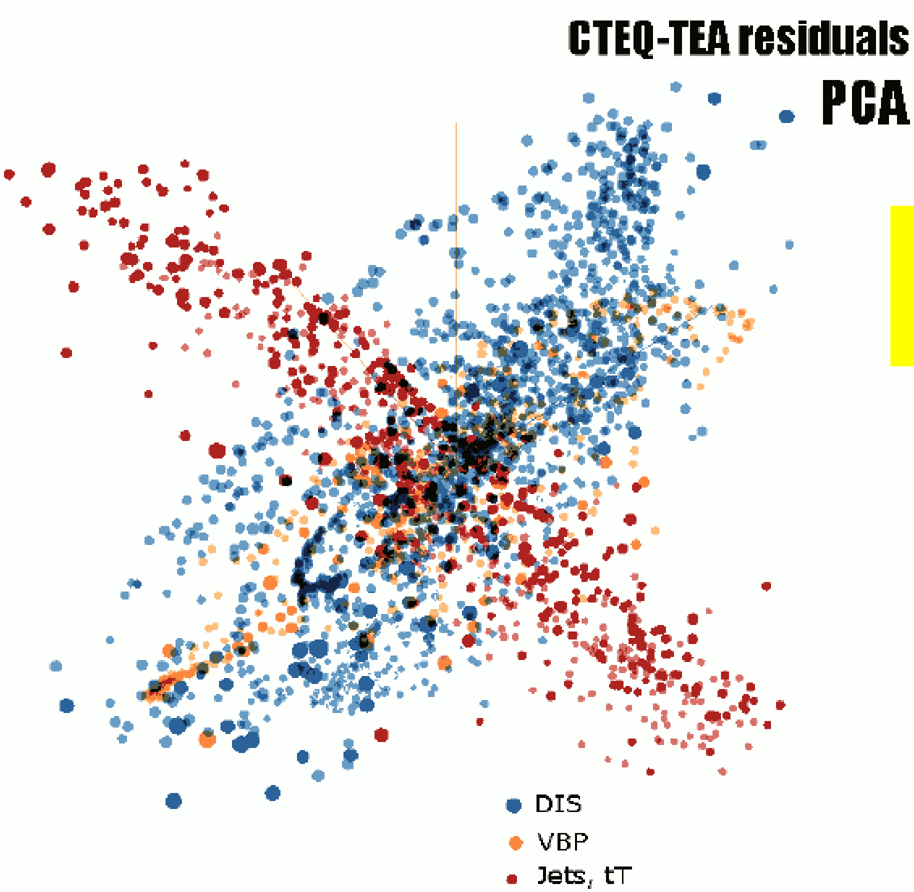


Dynamical projections for the visualization of PDFSense data

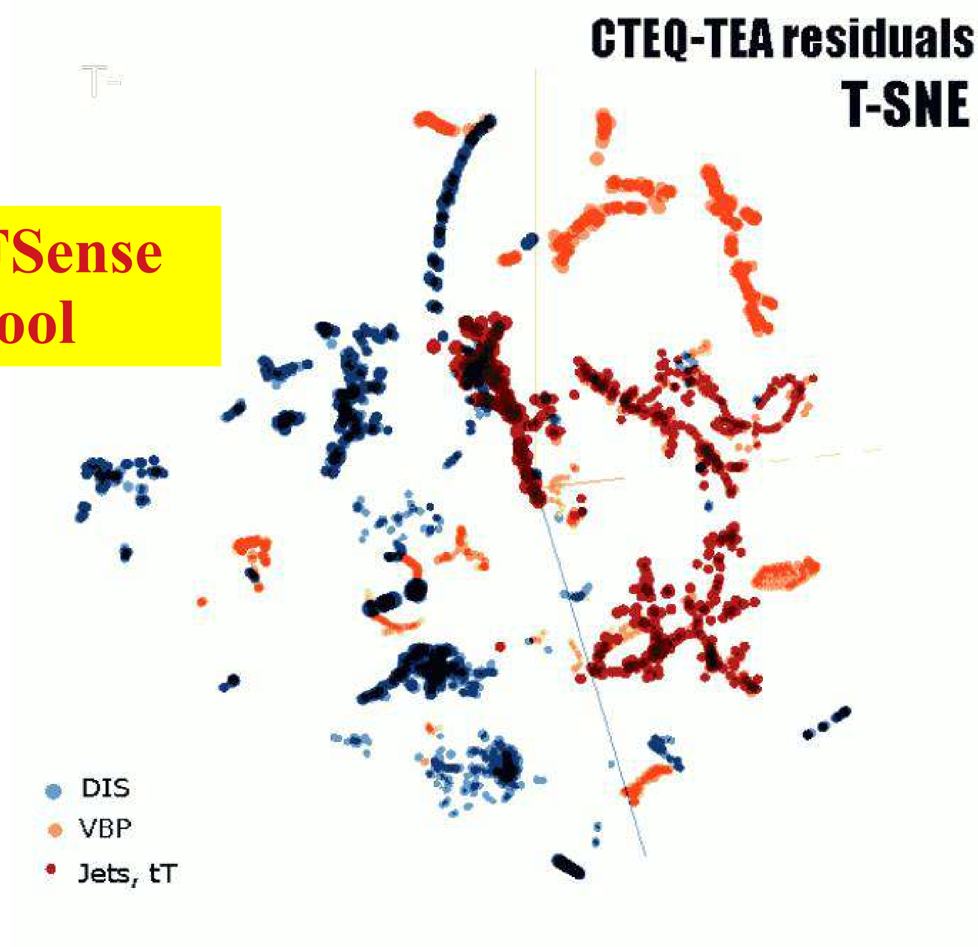
Dianne Cook, Ursula Laa, German Valencia arXiv:1806.09742

TensorFlow Embedding Projector

https://metapdf.hepforge.org/PDFSense/



PDFSense tool



Principal Component Analysis (PCA) visualizes the 56-dim. manifold by reducing it to 10 dimensions (à la META PDFs)

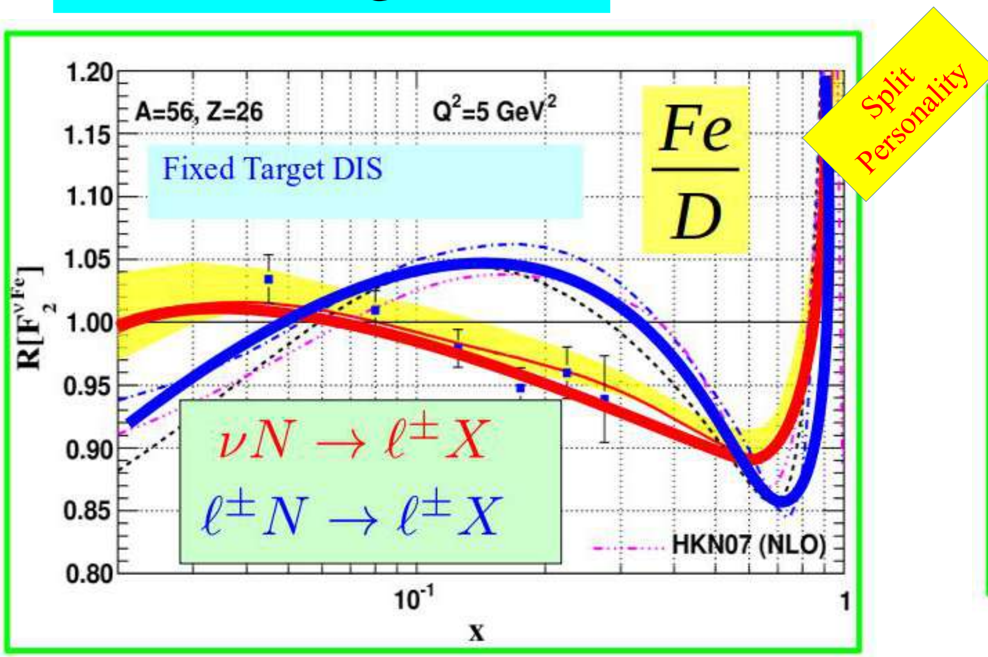
t-distributed stochastic neighbor embedding (**t-SNE**) sorts vectors according to their similarity

$$r_i(\vec{a}) = \frac{1}{s_i}\left(T_i(\vec{a}) - D_{i,sh}(\vec{a})\right),$$

http://projector.tensorflow.org

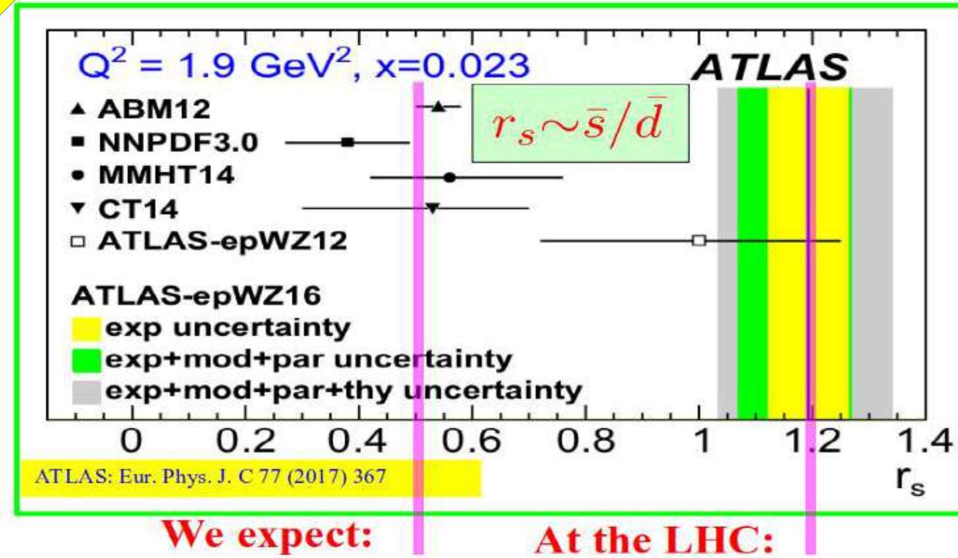
CONCLUSIONS

nCTEQ15ν



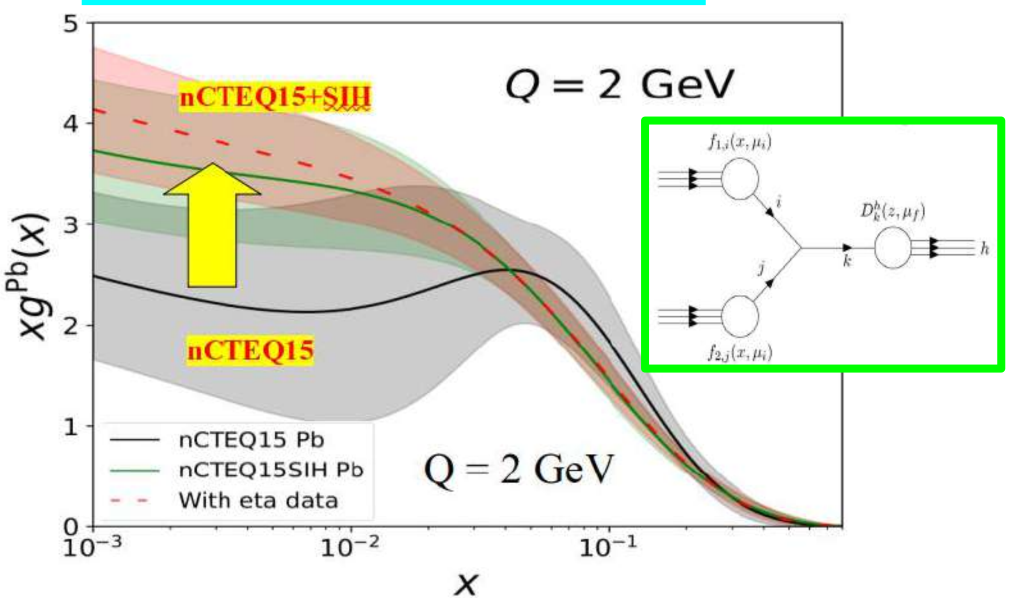
nCTEQ: arXiv: 2204.13157

nCTEQ15WZ



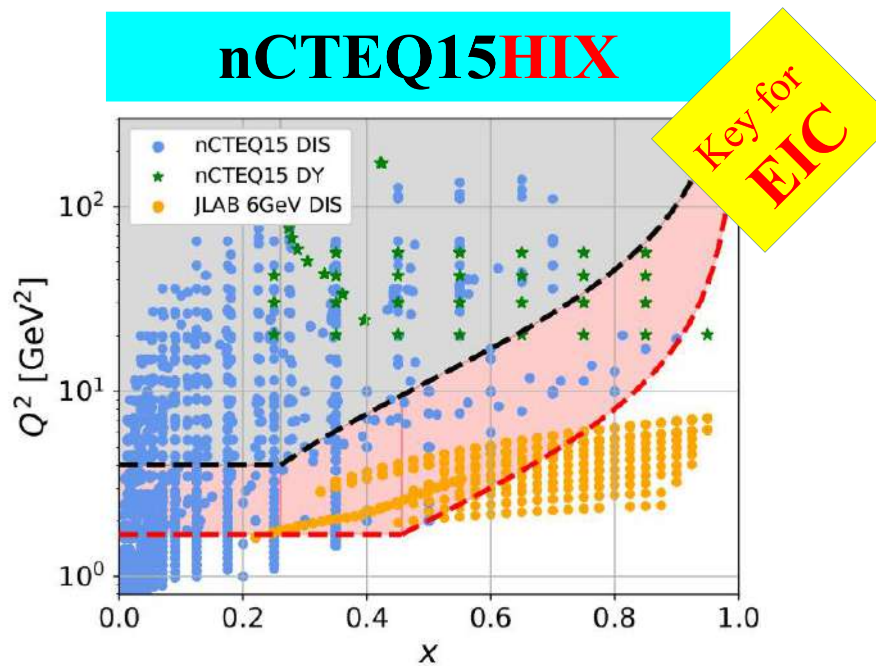
nCTEQ: Phys.Rev.D 104 (2021) 094005

nCTEQ15WZ+SIH



nCTEQ: PRD104 (2021) 094005.

nCTEQ15HIX



nCTEQ: Phys.Rev.D 103 (2021) 11, 114015

From Parameterization to a Deeper Understanding