Progress in 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

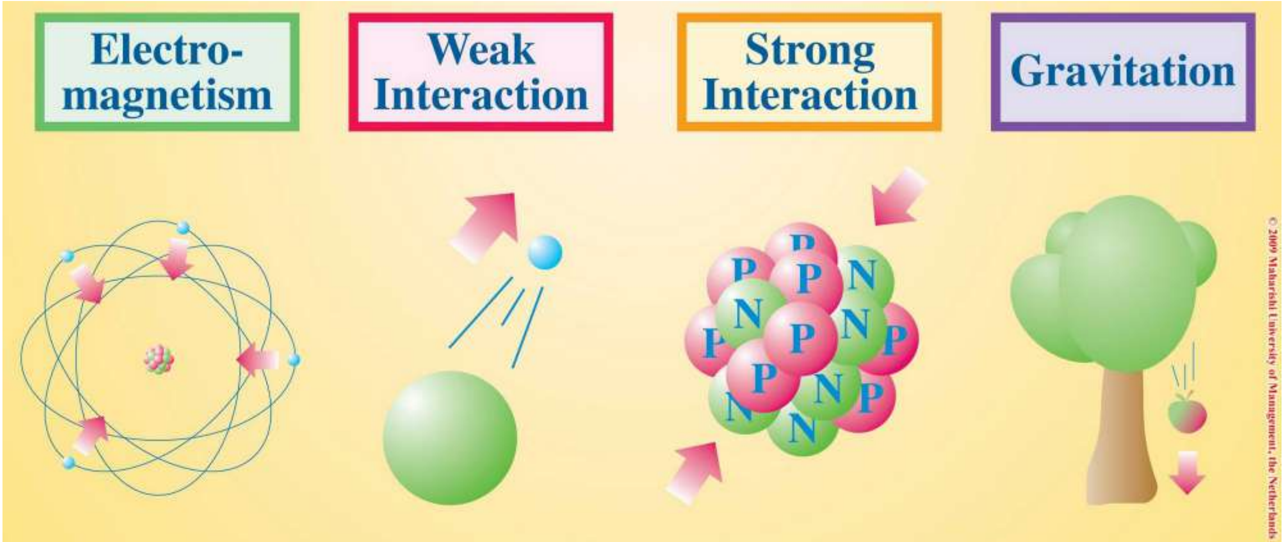
Group on Hadronic Physics (GHP)

13-16 April 2021

“QCD is our most perfect physical theory”

Frank Wilczek

arXiv:hep-ph/9907340



PDFs & nPDFs

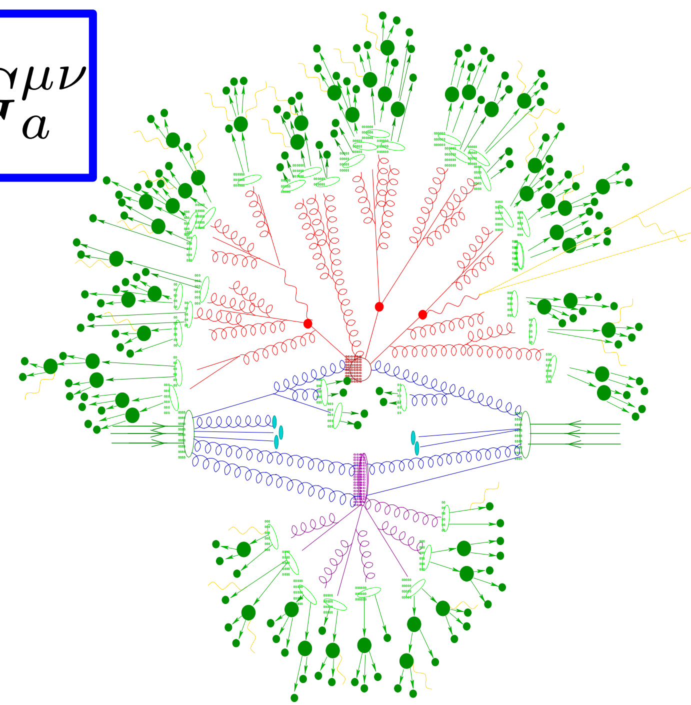
Generalized PDFs

Spin Structure

Lattice QCD

Quark-Gluon Plasma

$$\mathcal{L}_{QCD} = \overline{\psi}_q \left(i\gamma_\mu D^\mu - m_q \right) \psi_q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$



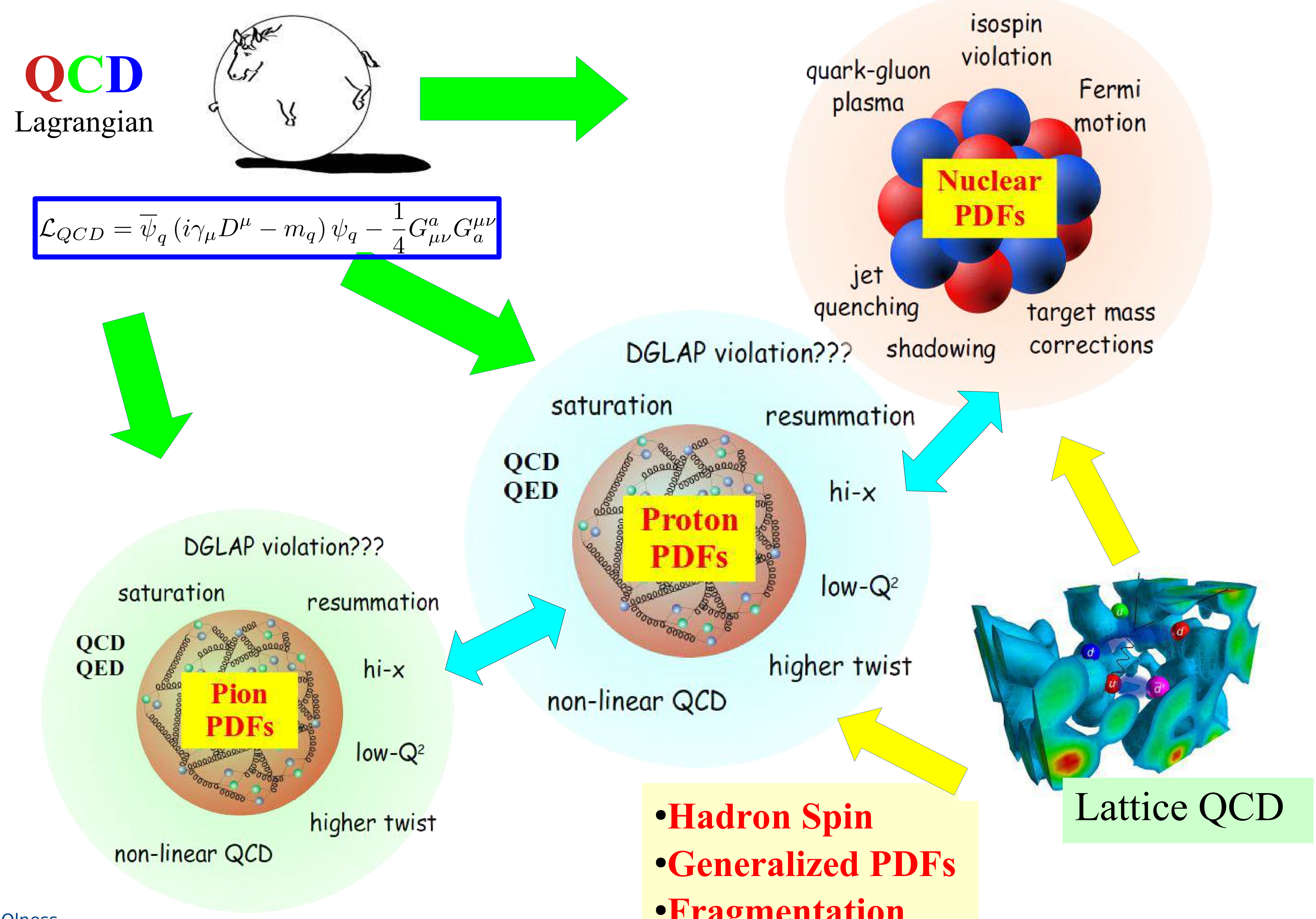
New Experiments

New Data

New Theoretical Techniques

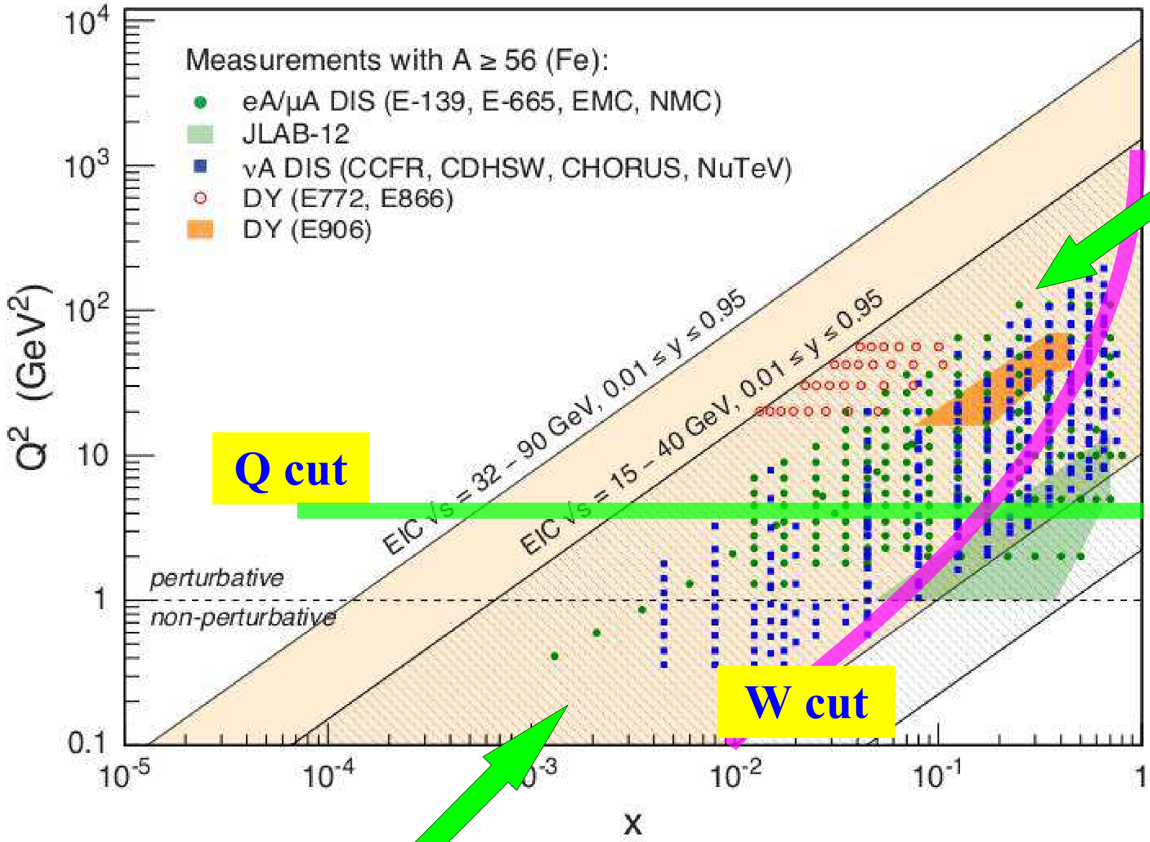
... a chance for momentous advances in our understanding ...

From Parameterization to a Deep Understanding … LHC + EIC



How do we get there

EIC Kinematic Plane in $\{x,Q^2\}$



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

Low-Q²:

Non-Perturbative inteface

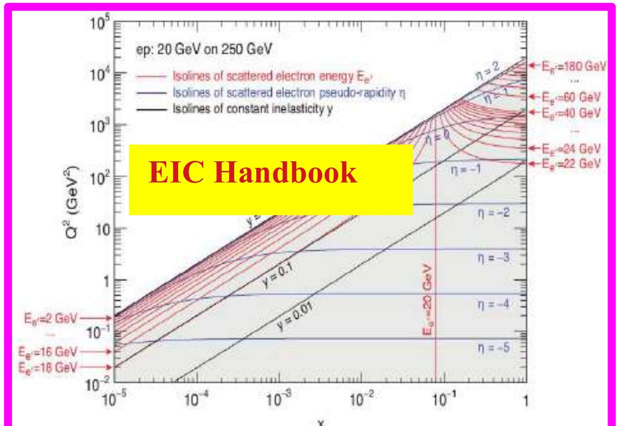
collective effects

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



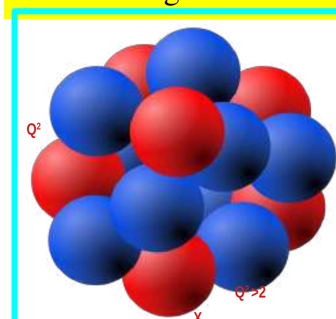
Warm-up:

JLab Data @ Hi-X Low-Q²

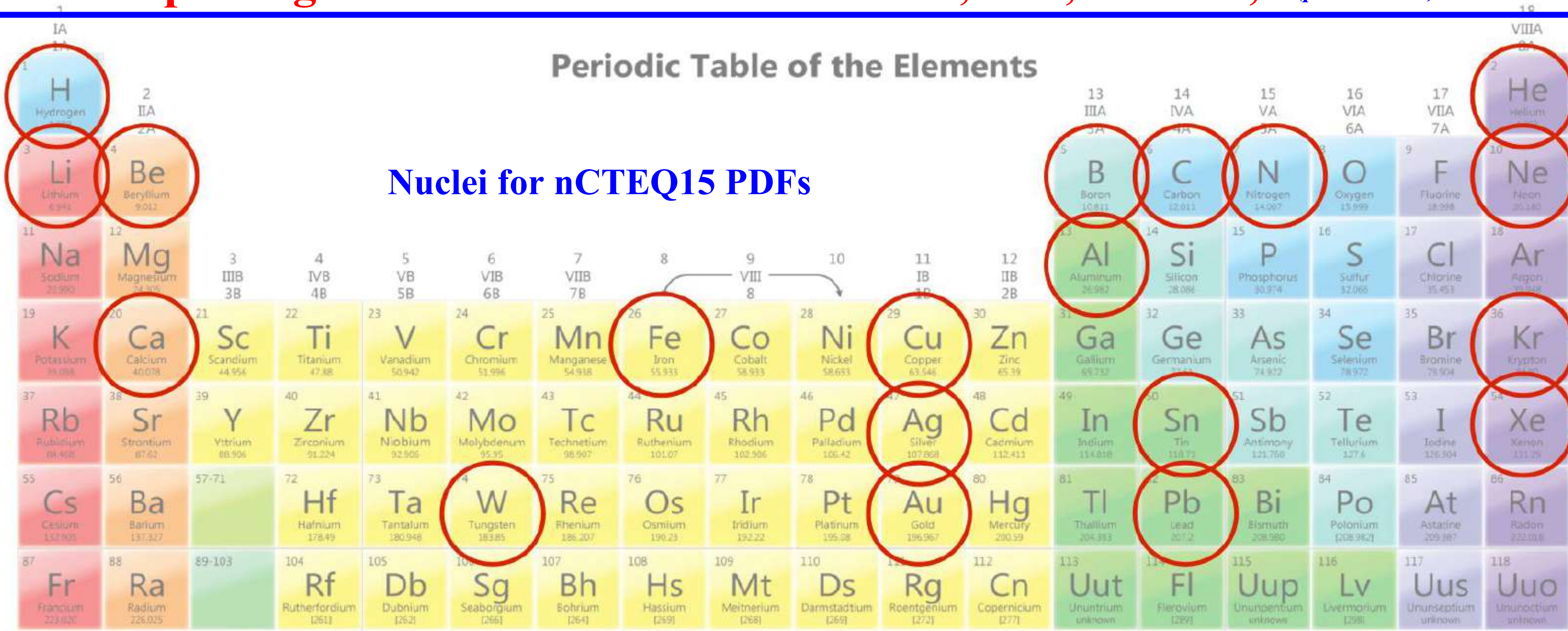
extend nCTEQ framework for this region

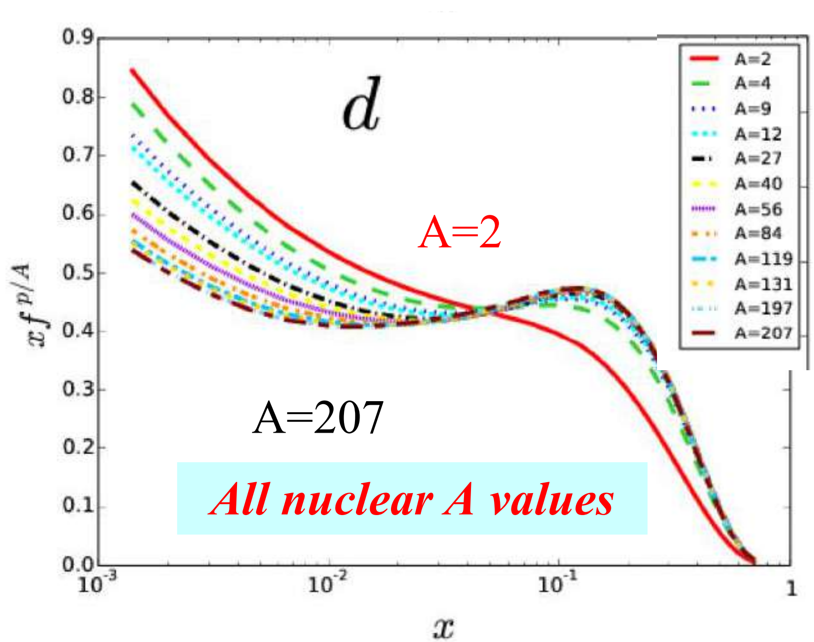
& prepare for EIC

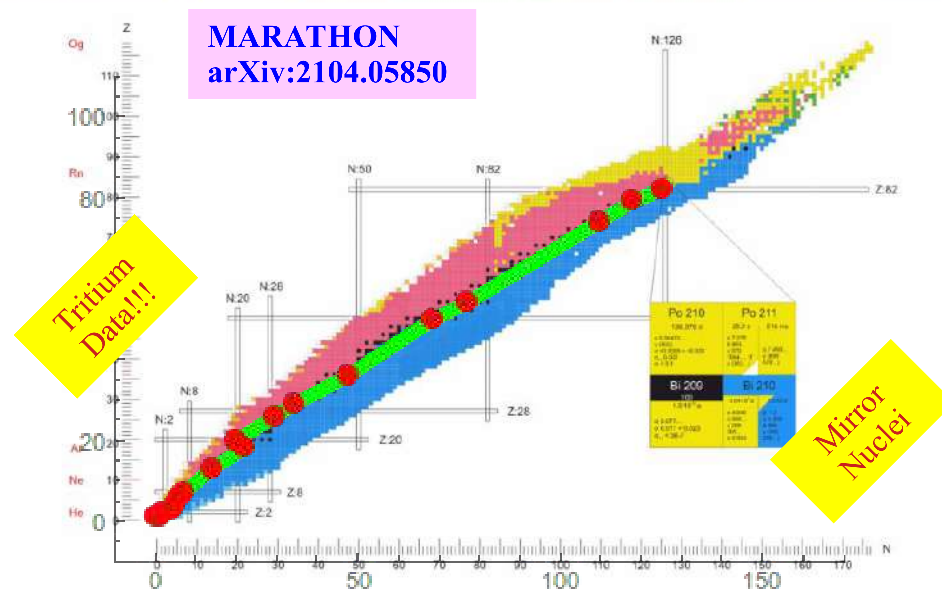
Efrain Segarra w/ **nCTEQ**



Exploring the Nuclear Dimension: DIS, DY, π Prod, *(plus more ...)*







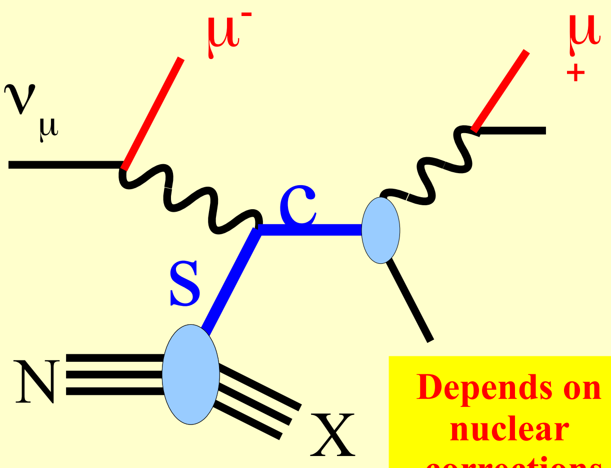
... expand our knowledge of nuclear A dimension

Nuclear PDFs are Essential for Flavor Differentiation

neutrino DIS

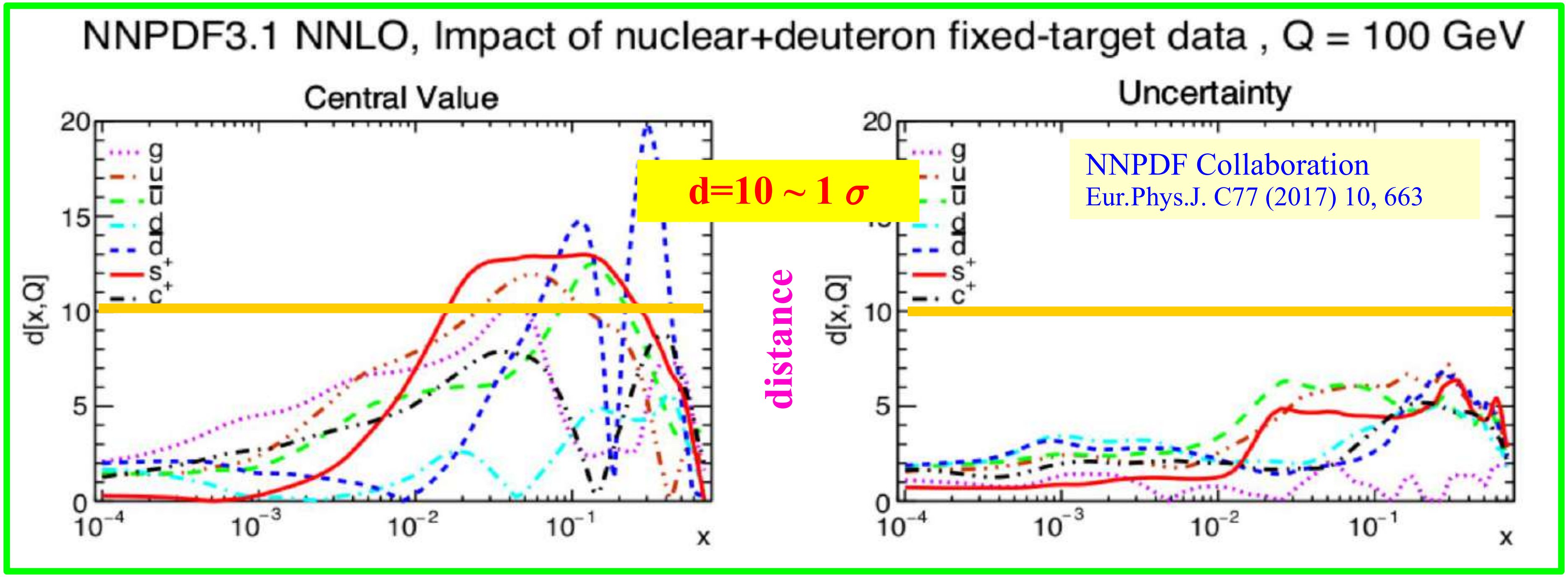
$$F_2^{\nu} \sim \left[d + s + \bar{u} + \bar{c}\right]$$
$$F_2^{\bar{\nu}} \sim \left[\bar{d} + \bar{s} + u + c\right]$$
$$F_3^{\nu} \sim 2\left[d + s - \bar{u} - \bar{c}\right]$$
$$F_3^{\bar{\nu}} \sim 2\left[u + c - \bar{d} - \bar{s}\right]$$

Neutrino DIS



Depends on nuclear corrections

Differentiate flavors of free-proton PDFs:



… essential for Proton PDF goal of <1%

nCTEQ nuclear parton distribution functions

www.ncteq.org

PDF General Issues:

- Proton PDF; nuclear corrections for interpreting heavy target DIS (Ar, Fe, Pb).

Strange quark PDF: s(x)

- Resolve tension between fixed-target (νN, ℓN) and collider expectations ($W^{\pm}$,Z)

Charm & Bottom: c(x) & b(x)

- Multi-scale & resummation issues: Log($m_{c,b}$/Q)
- "Fitted" charm: $c(x)\neq 0$ at m_c
- Intrinsic heavy flavors: $c(x)\neq 0$ at $Q<m_c$

Neutrino cross sections on heavy targets (Ar, Fe, Pb)

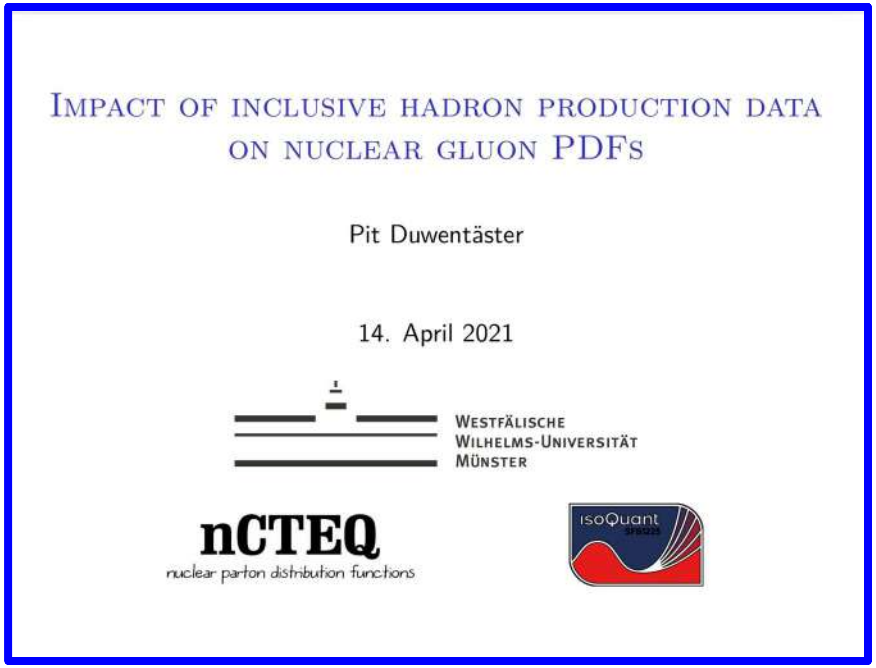
- Universality of Neutral Current (γ) & Charged Current ($W^{\pm}$) processes

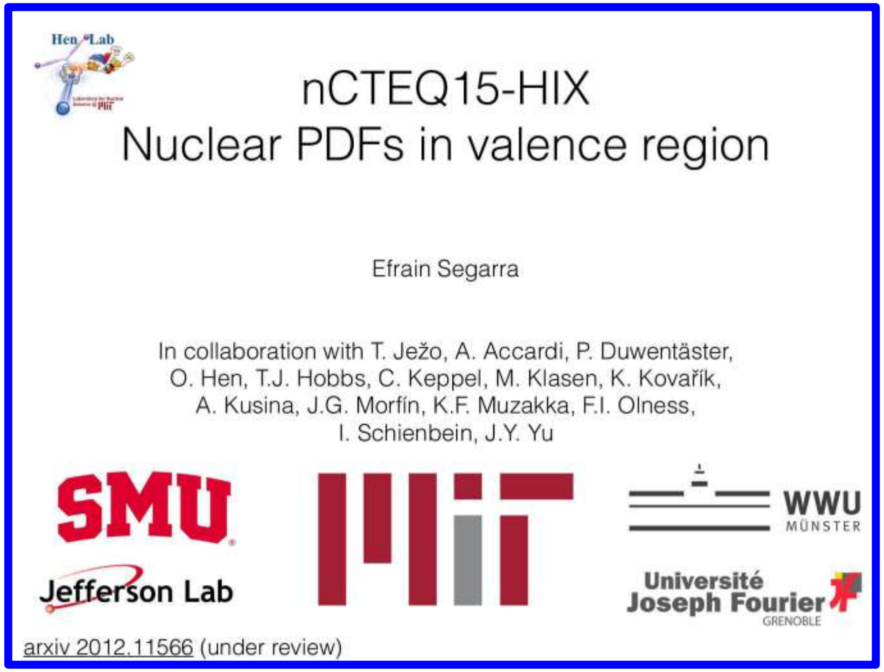
Expanded $\{x,Q^2\}$ Kinematic Regime

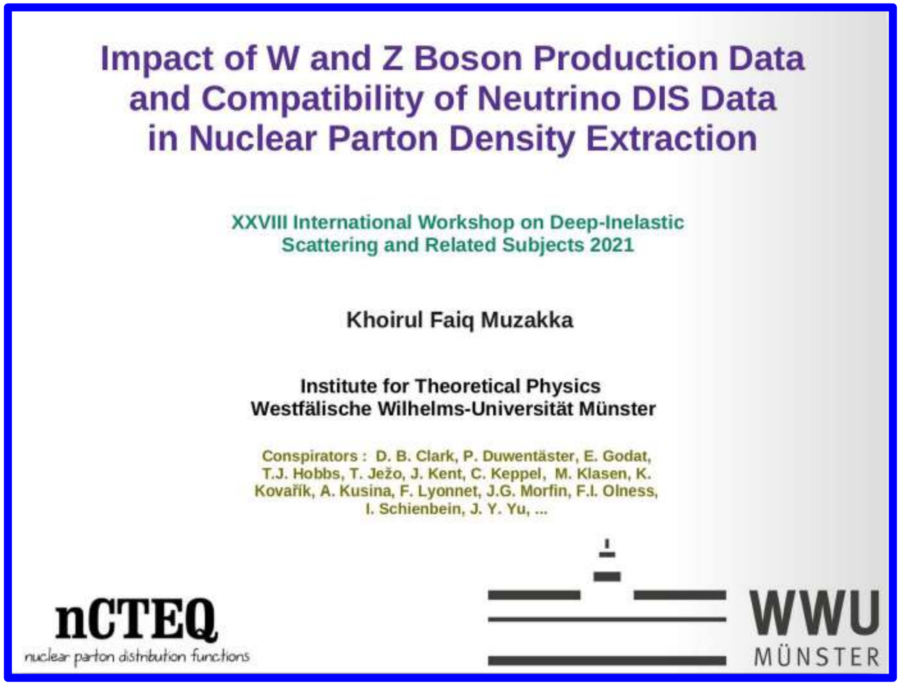
- Small-x saturation, resummation: Log[1/x]
- Large-x higher twist: (M^2/Q^2)
- Low Q^2 non-perturbative effects

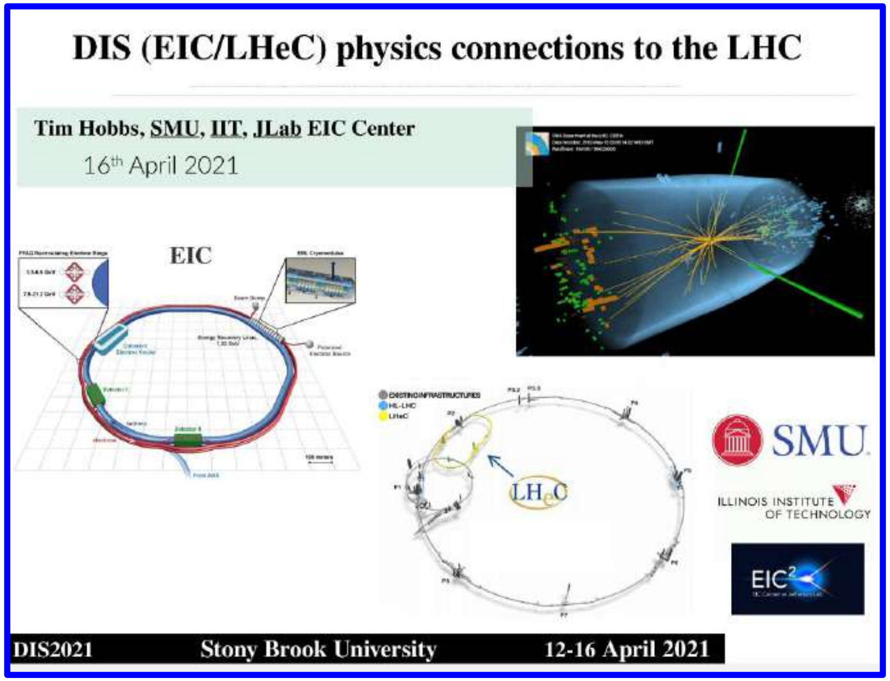
Compilation by Fred Olness with helpful feedback from: Alberto Accardi, Tim Hobbs, Tomas Jezo, Thia Keppel, Michael Klasen, Karol Kovarik, Aleksander Kusina, Jorge Morfin, Pavel Nadolsky, Jeff Owens, Ingo Schienbein, Efrain Segarra, Steve Sekula, Ji-Young Yu

Recent nCTEQ Presentations









Hi-X

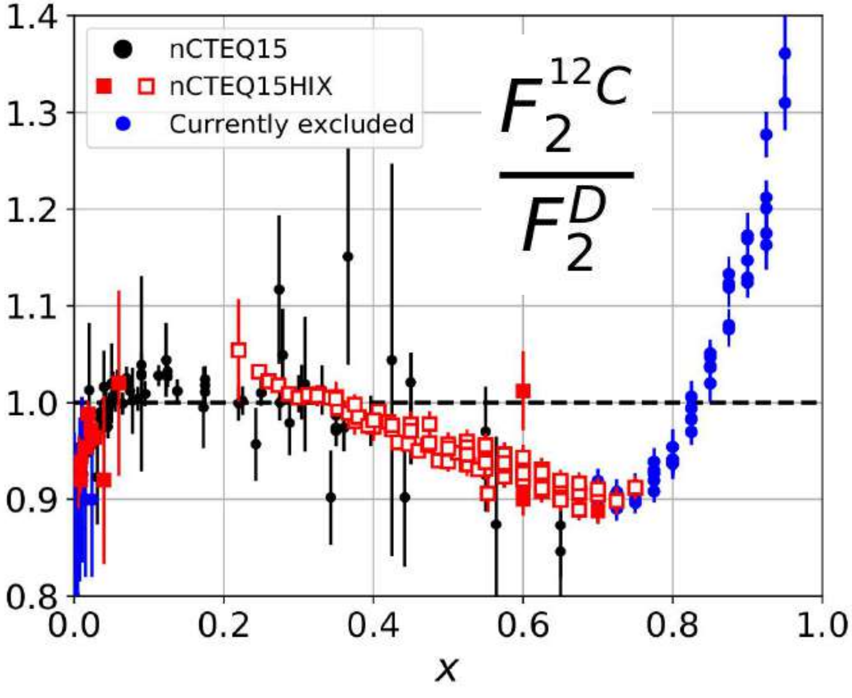
nCTEQ15HIX

nCTEQ15HIX — Extending nPDF Analyses into the High-x, Low-Q^2 Region

E.P. Segarra,[1,*] T. Ježo,[2,†] A. Accardi,[3,4] P. Duwentäster,[5] O. Hen,[1] T.J. Hobbs,[6,4,7] C. Keppel,[4] M. Klasen,[5] K. Kovařík,[5] A. Kusina,[8] J.G. Morfín,[9] K.F. Muzakka,[5] F.I. Olness,[6,‡] I. Schienbein,[10] and J.Y. Yu.[10]

arXiv:2012.11566

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

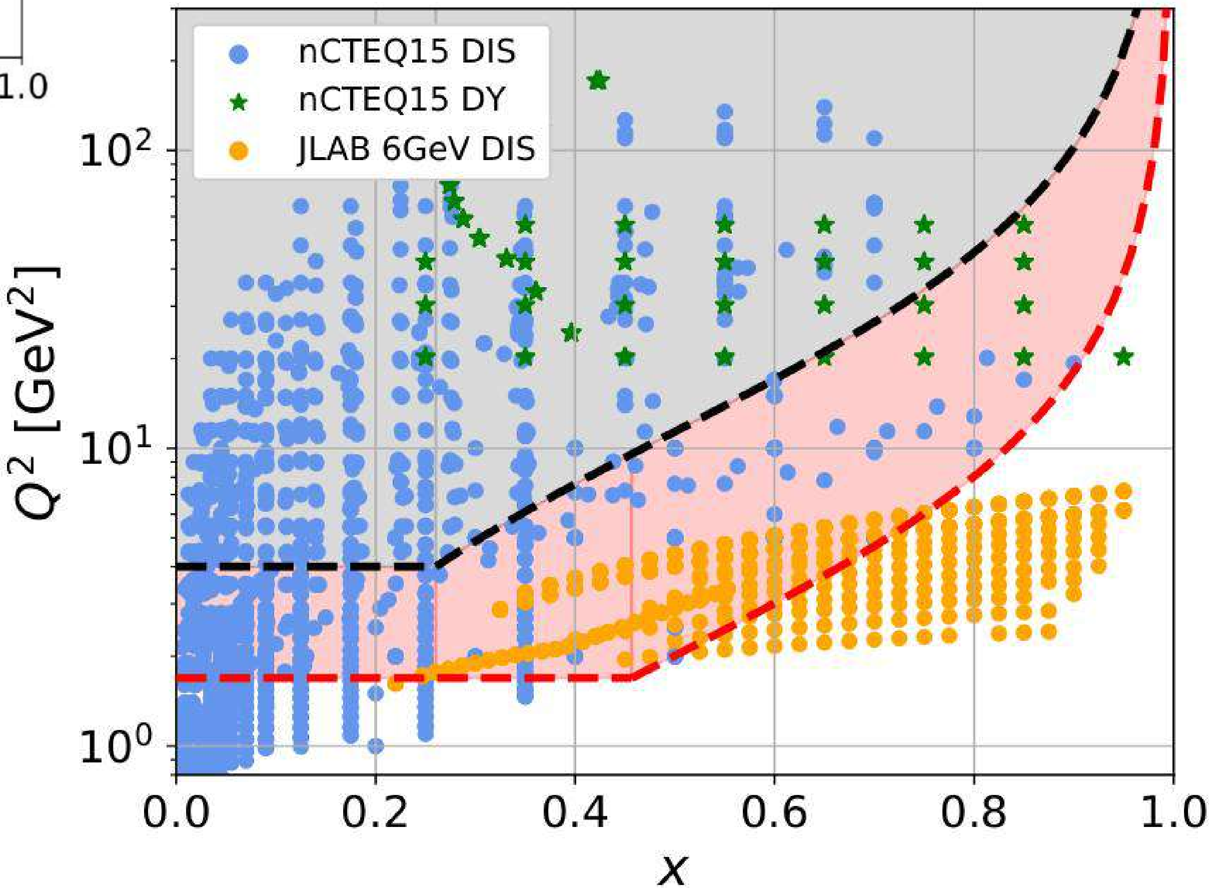
pick up M^2/Q^2 higher twist contributions

Deuteron Corrections

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

JLab Data @ Hi-X Low-Q^2

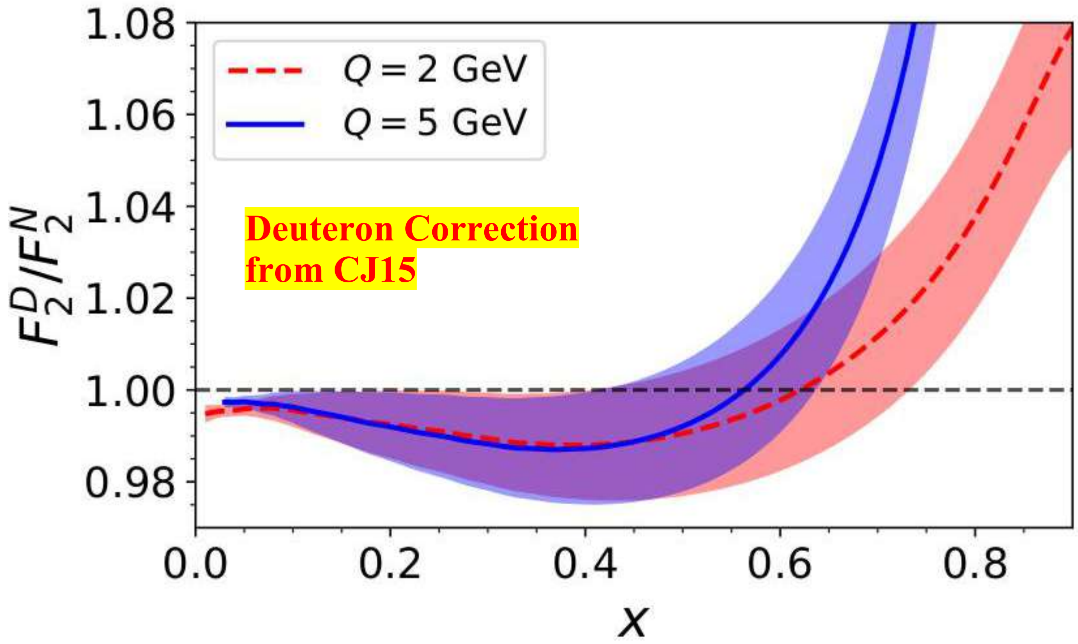
extend nCTEQ framework
to accommodate this region
& prepare for EIC



nCTEQ
nuclear parton distribution functions

F. Olness

nCTEQ15HIX include large x JLab data

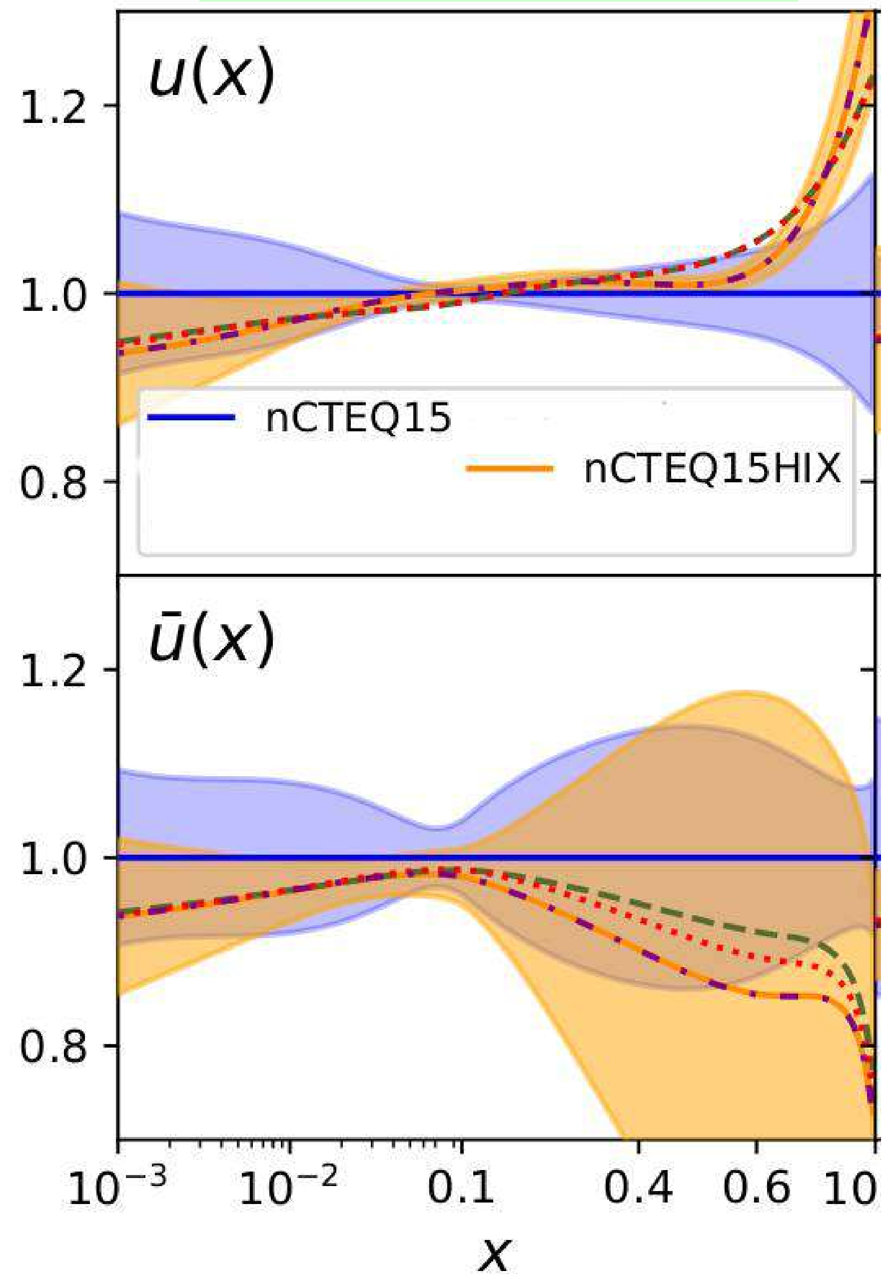


Higher Twist Correction from CJ15

$$F_2^A \rightarrow F_2^A\left[1 + \frac{C_{HT}^A}{Q^2}\right]$$

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

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

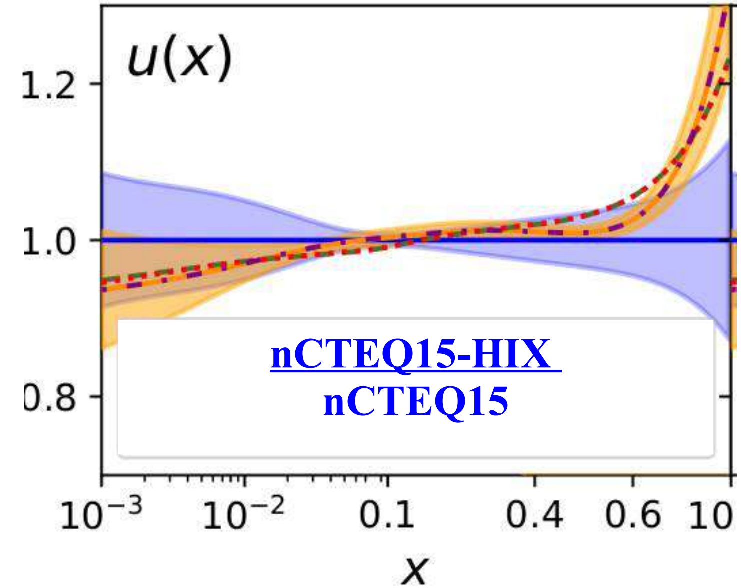


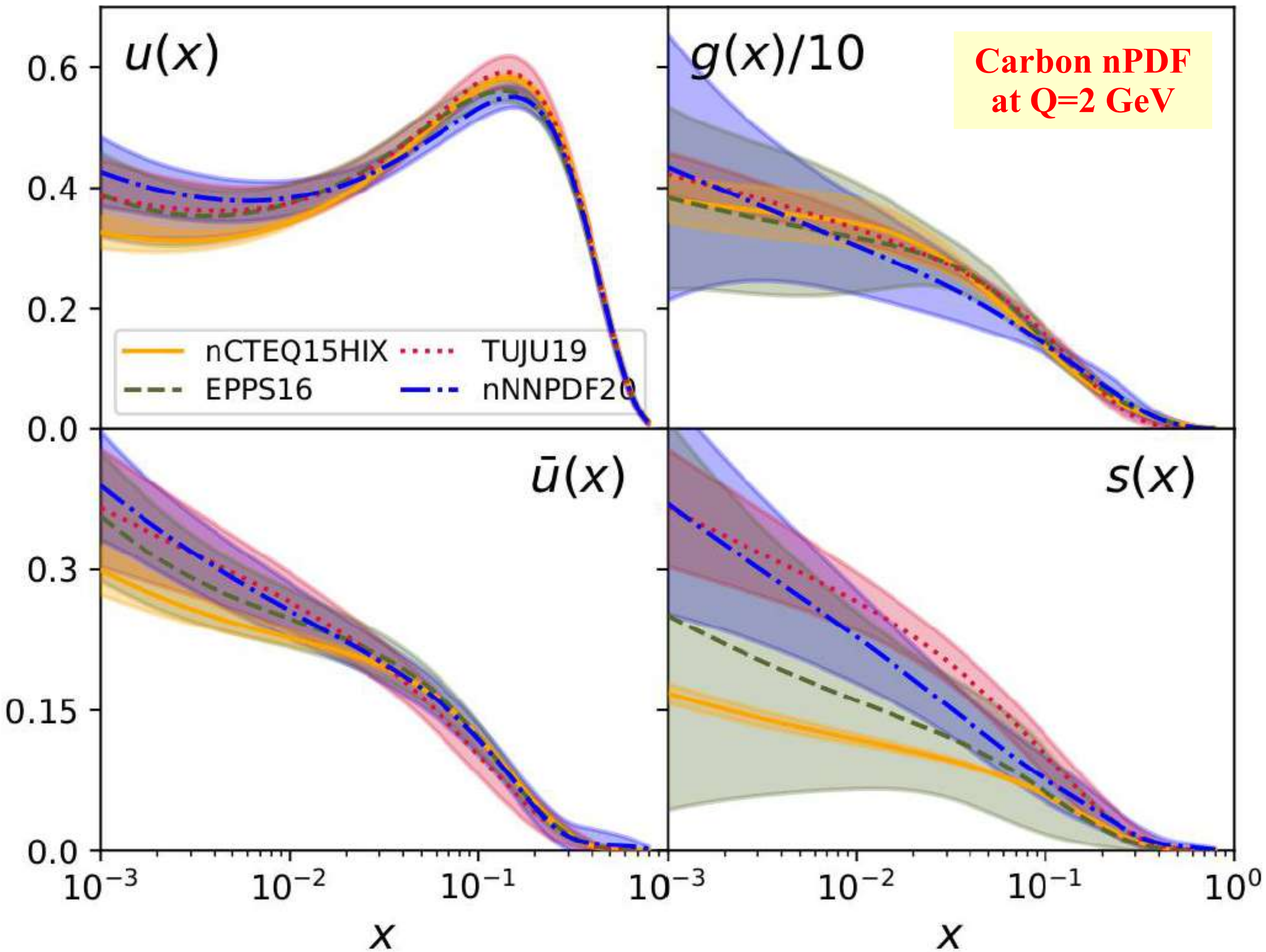
nCTEQ15HIX include large x JLab data

... some recent nPDFs

EPPS16 Eur.Phys.J.C77 (2017) 3,163
nNNPDF2.0 JHEP 09 (2020) 183
TUJU19 PRD100 (2019) 9,096015
nCTEQ15-HIX arXiv:2012.11566
KSASG20 arXiv:2010.00555

nCTEQ15-HIX
updated with
JLab Hi-x data



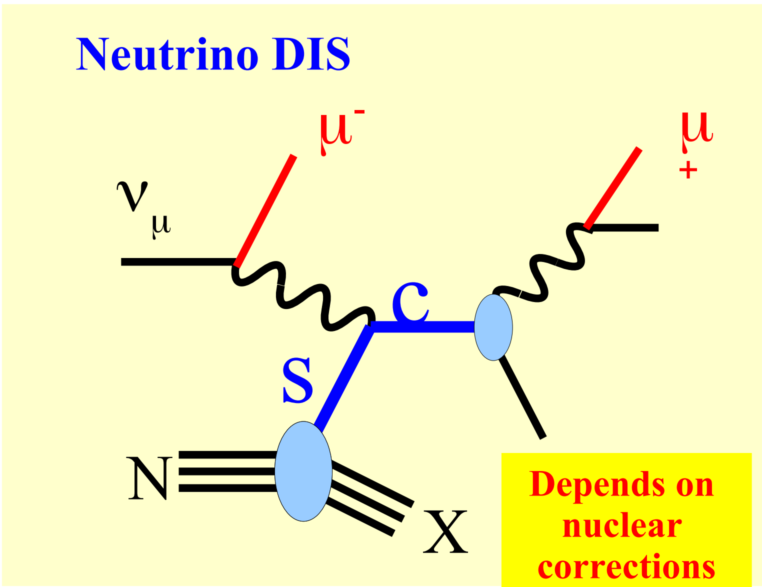


JLab data: Shifts valence PDFs from low to hi-x

Deuteron Corrections Important!!!

HT from CJ15 improves fit

Strange PDF



Eur. Phys. J. C (2020) 80:968
https://doi.org/10.1140/epjc/s10052-020-08532-4

THE EUROPEAN PHYSICAL JOURNAL C

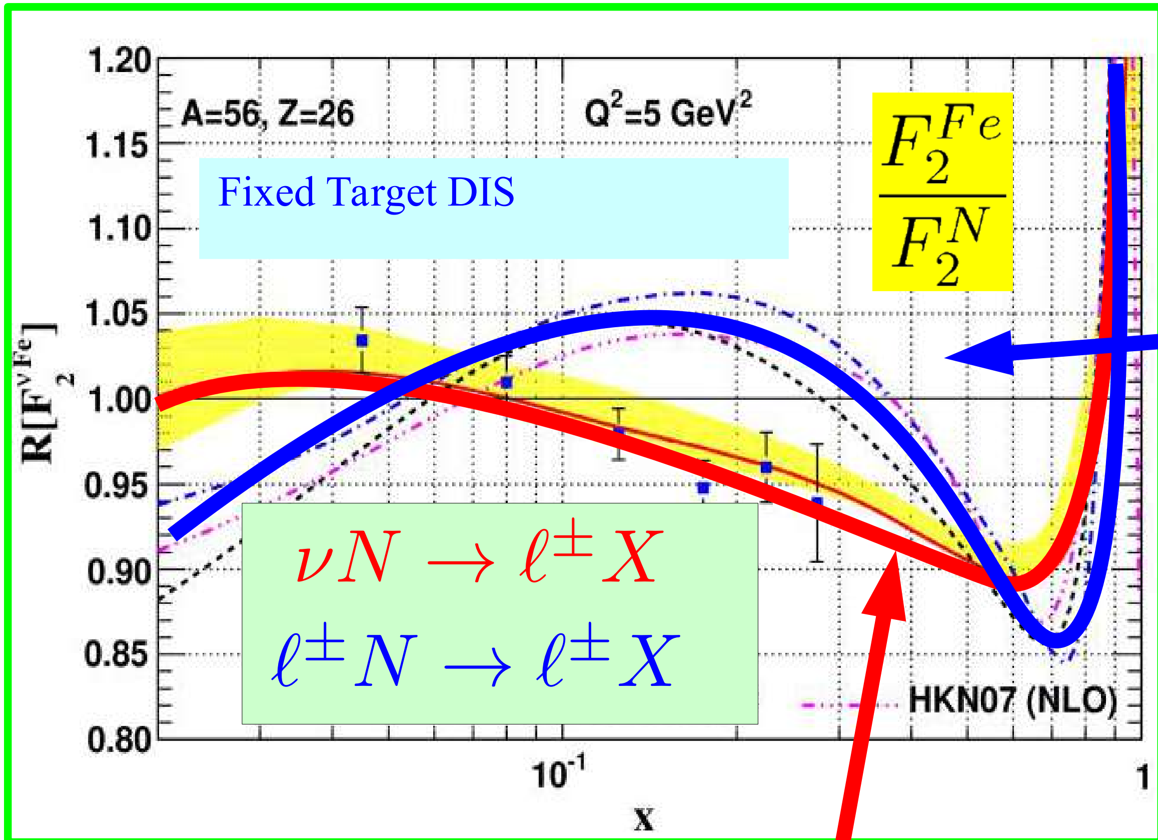
Check for updates

Regular Article - Theoretical Physics

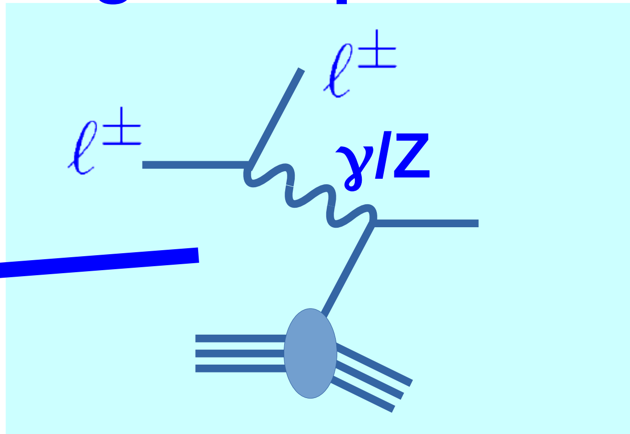
Impact of LHC vector boson production in heavy ion collisions on strange PDFs

A. Kusina[1,a], T. Ježo[2,b], D. B. Clark[3], P. Duwentäster[4], E. Godat[3], T. J. Hobbs[3,5], J. Kent[3], M. Klasen[4], K. Kovařík[4,c], F. Lyonnet[3], K. F. Muzakka[4], F. I. Olness[3,d], I. Schienbein[6,e], J. Y. Yu[6]

Puzzle: What is the Nuclear Correction



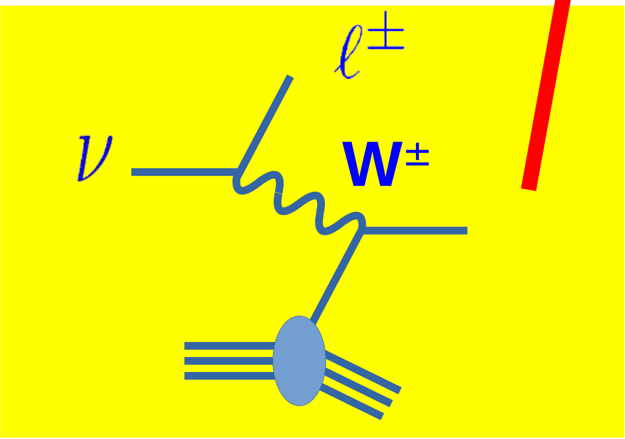
Charged Lepton DIS



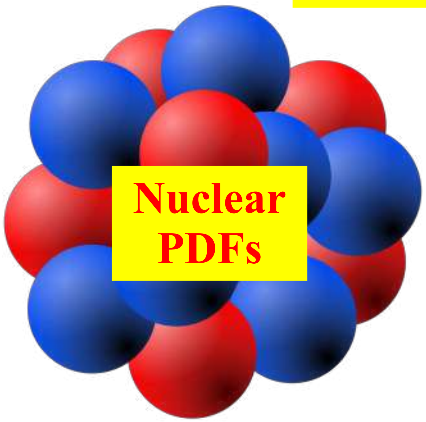
some caveats
… correlated errors

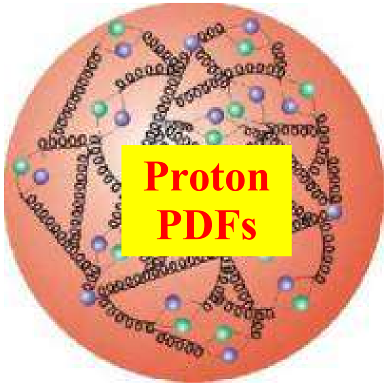
Depends on nuclear corrections

Propagation of γ/W thru nuclei



Neutrino DIS





re-examination by nCTEQ

View from the LHC pp: Strange PDF from ATLAS & CMS

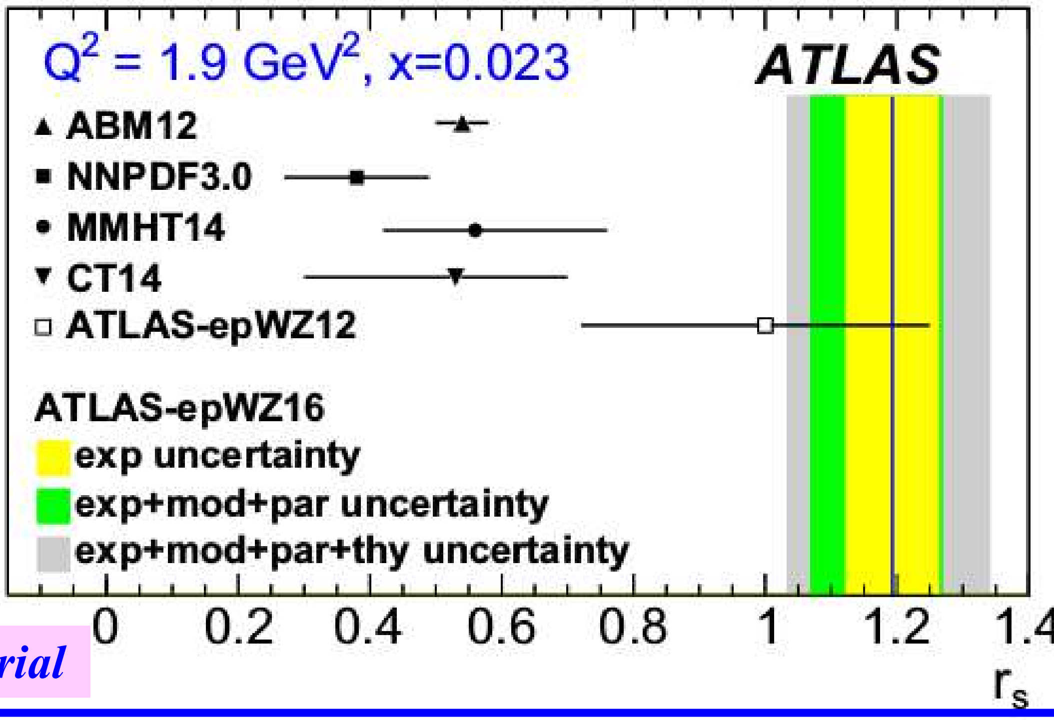
ATLAS: Eur. Phys. J. C (2017) 77:367

Inclusive W/Z

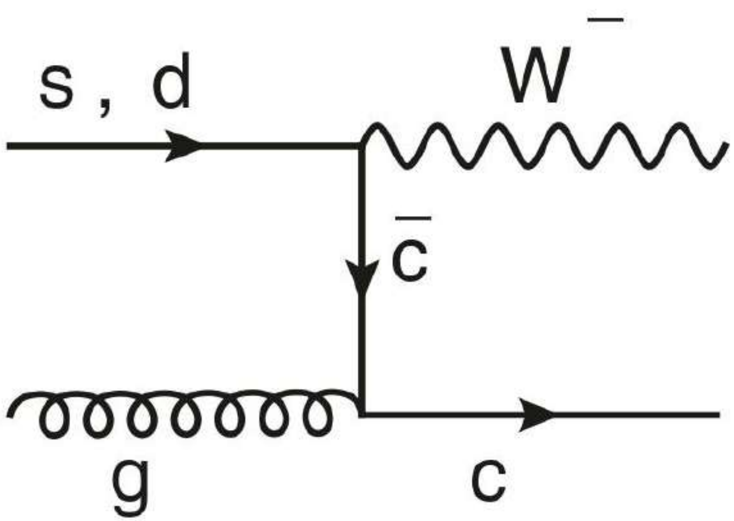
$$u\bar{d} + u\bar{s} + c\bar{d} + c\bar{s} \rightarrow W^+$$
$$\bar{u}d + \bar{u}s + \bar{c}d + \bar{c}s \rightarrow W^-$$
$$u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} \rightarrow Z$$

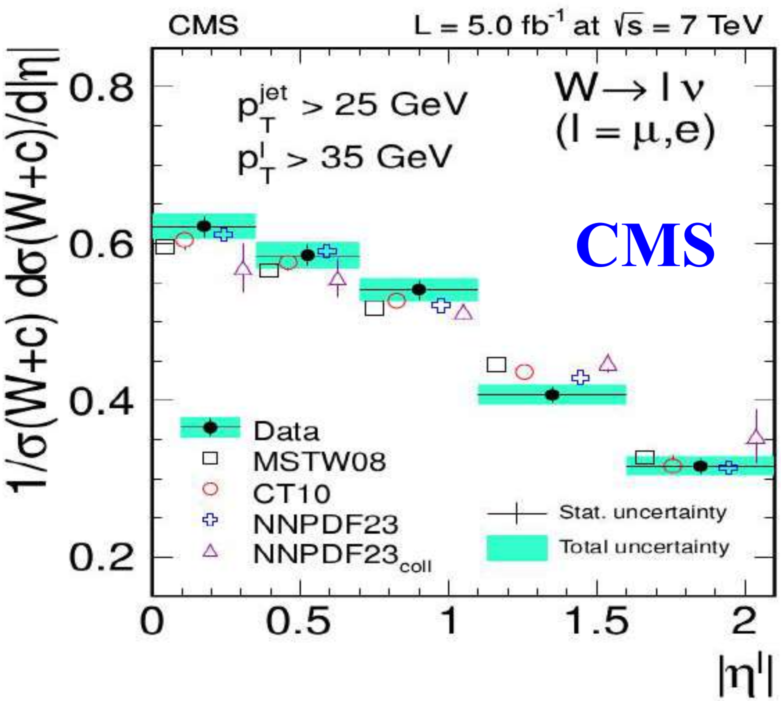
$$r^s(x,Q) = \frac{\bar{s}(x,Q) + s(x,Q)}{2\bar{d}(x,Q)}$$

xFitter tutorial

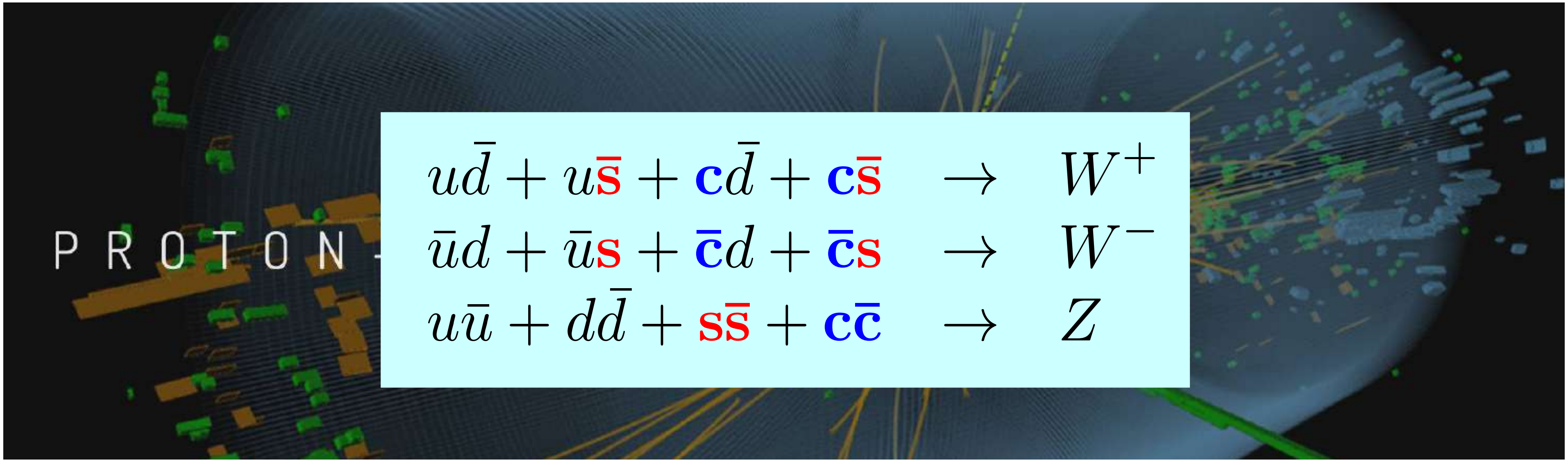


Associated W+c

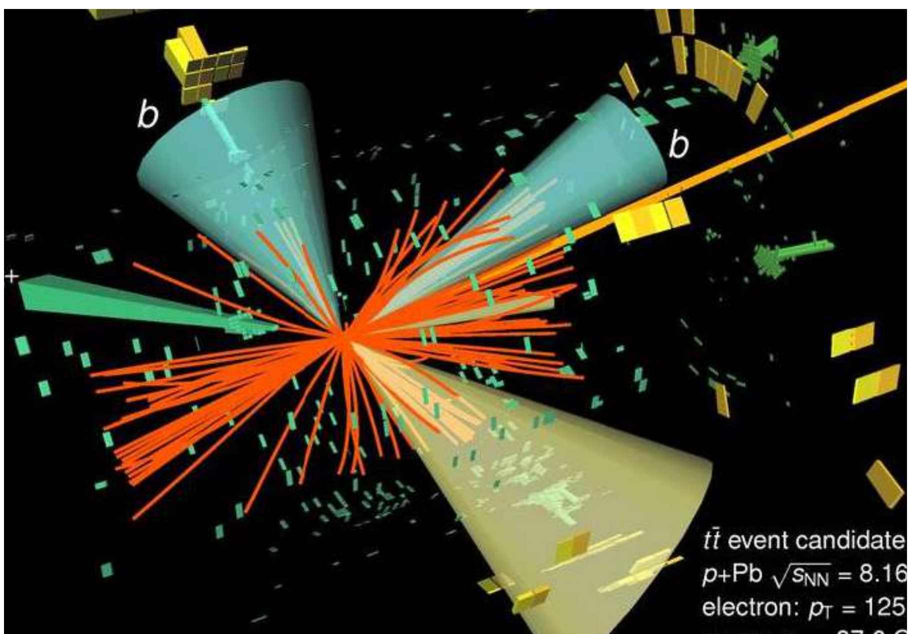


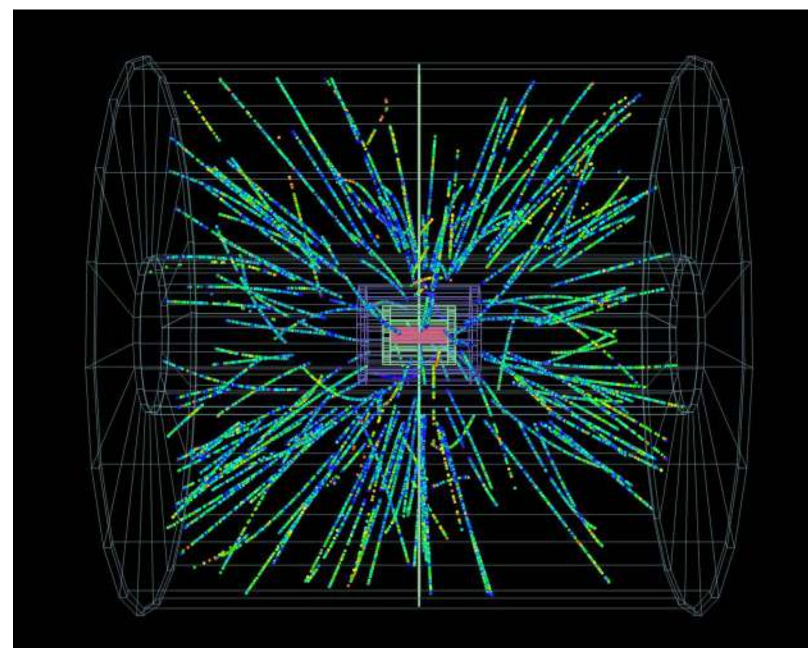


LHC Heavy Ion: proton -- lead



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

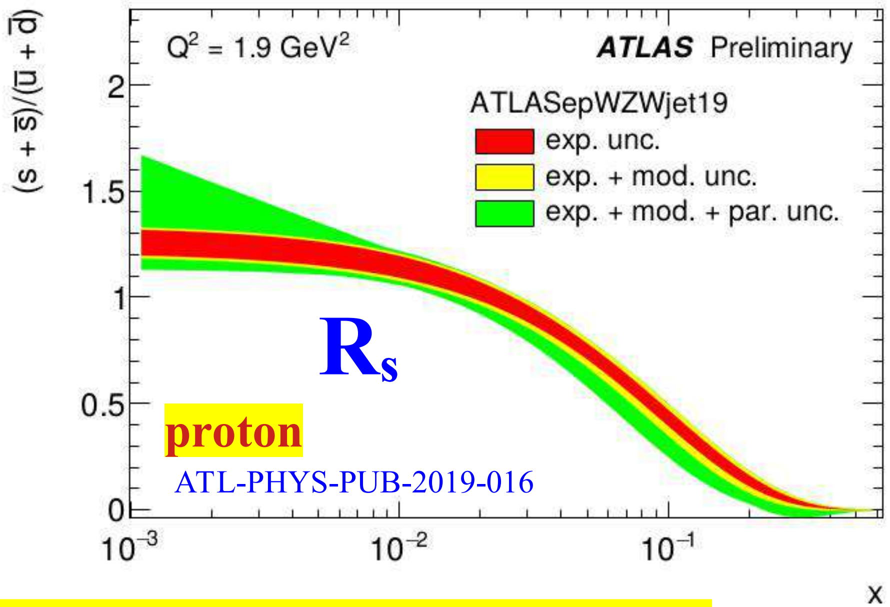


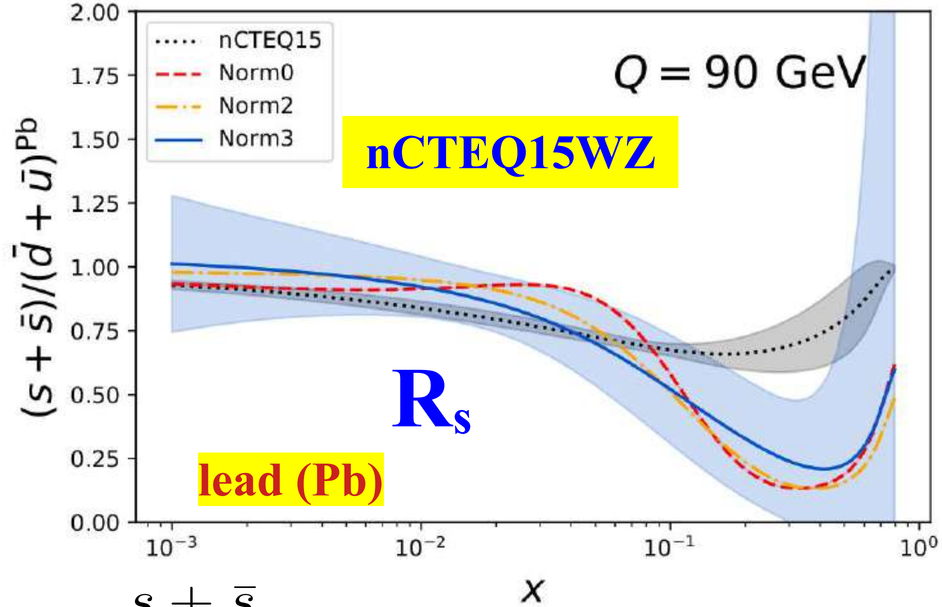


Heavy Ion W/Z Production at LHC nCTEQ15WZ

nuclear PDFs for lead (Pb)

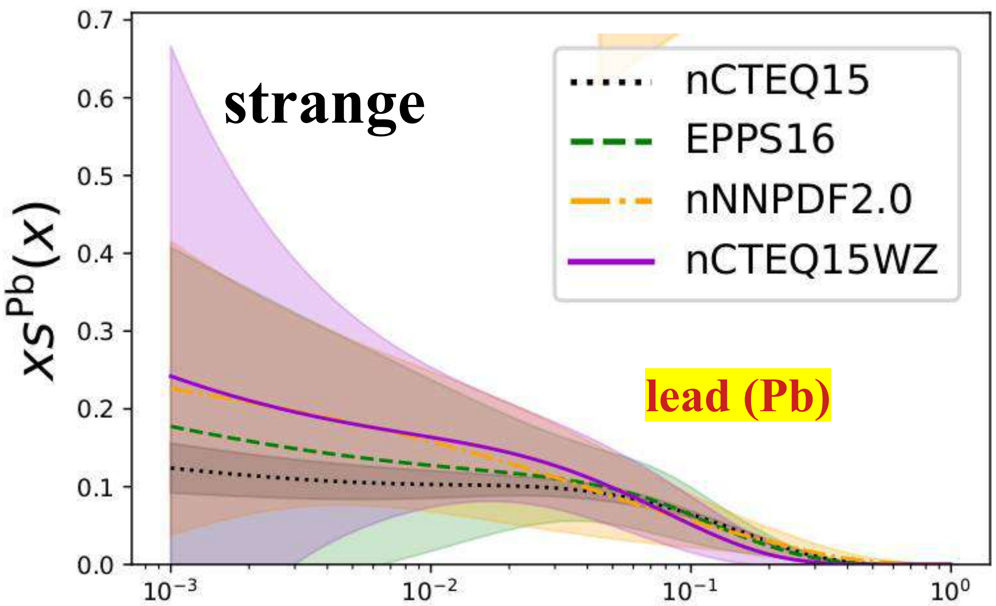
Eur.Phys.J.C 80 (2020) 10, 968

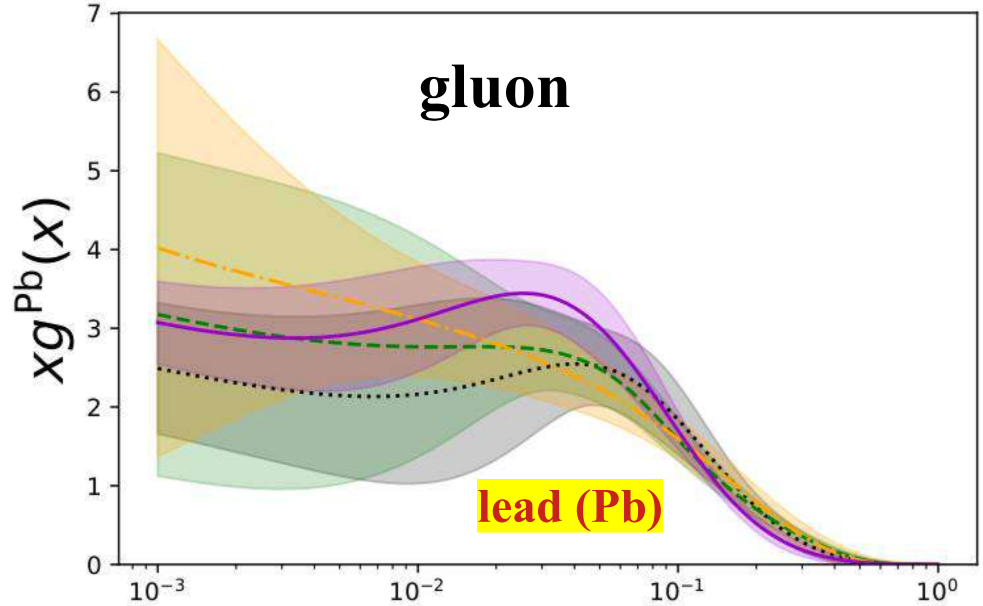




W/Z influence nPDF s(x) and g(x)

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



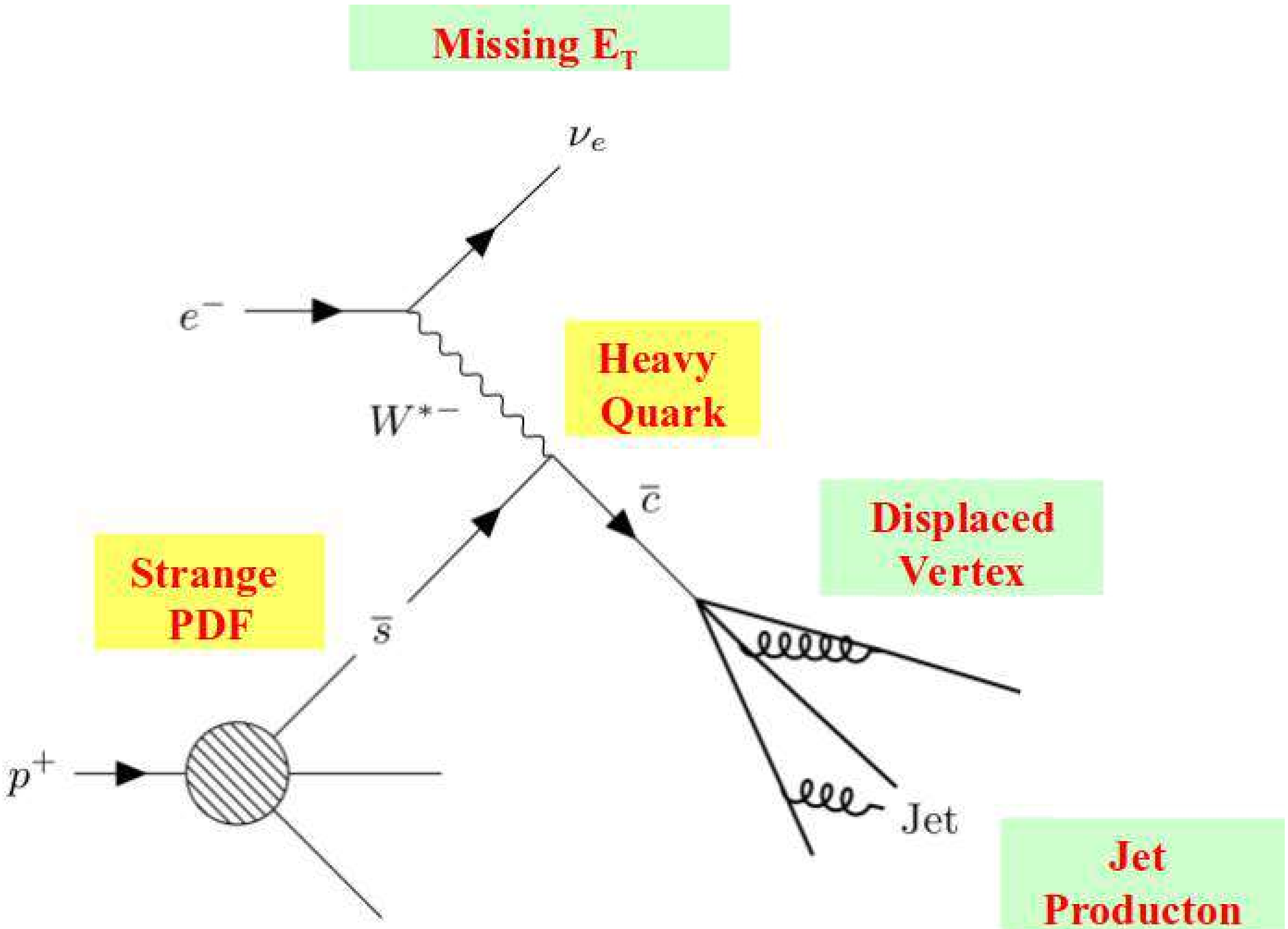


Charm Jets at the EIC

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

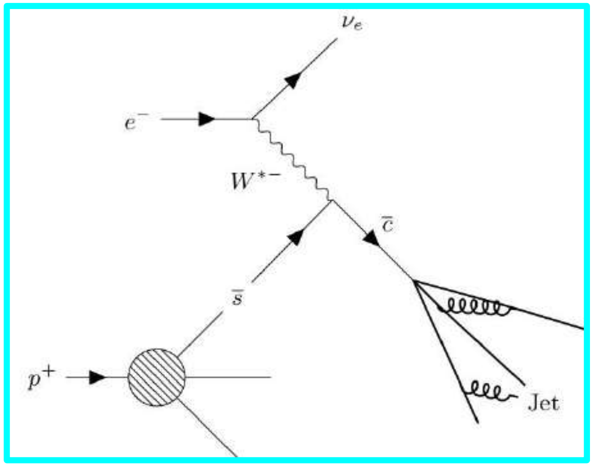
Charm jets as a probe for strangeness at the future Electron-Ion Collider

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

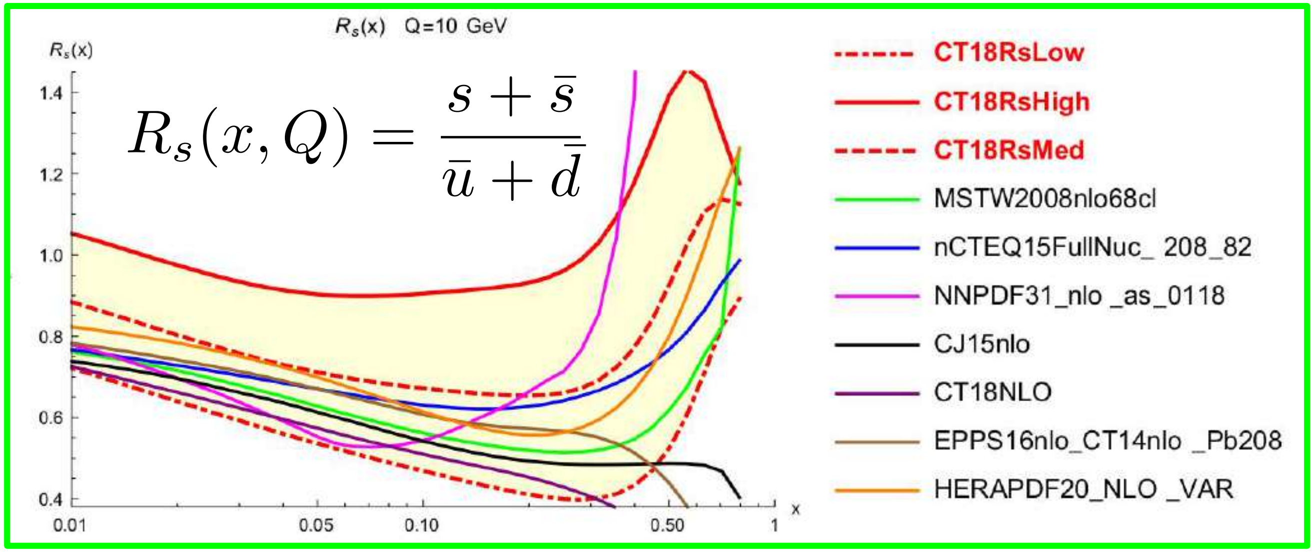


arXiv:2006.12520

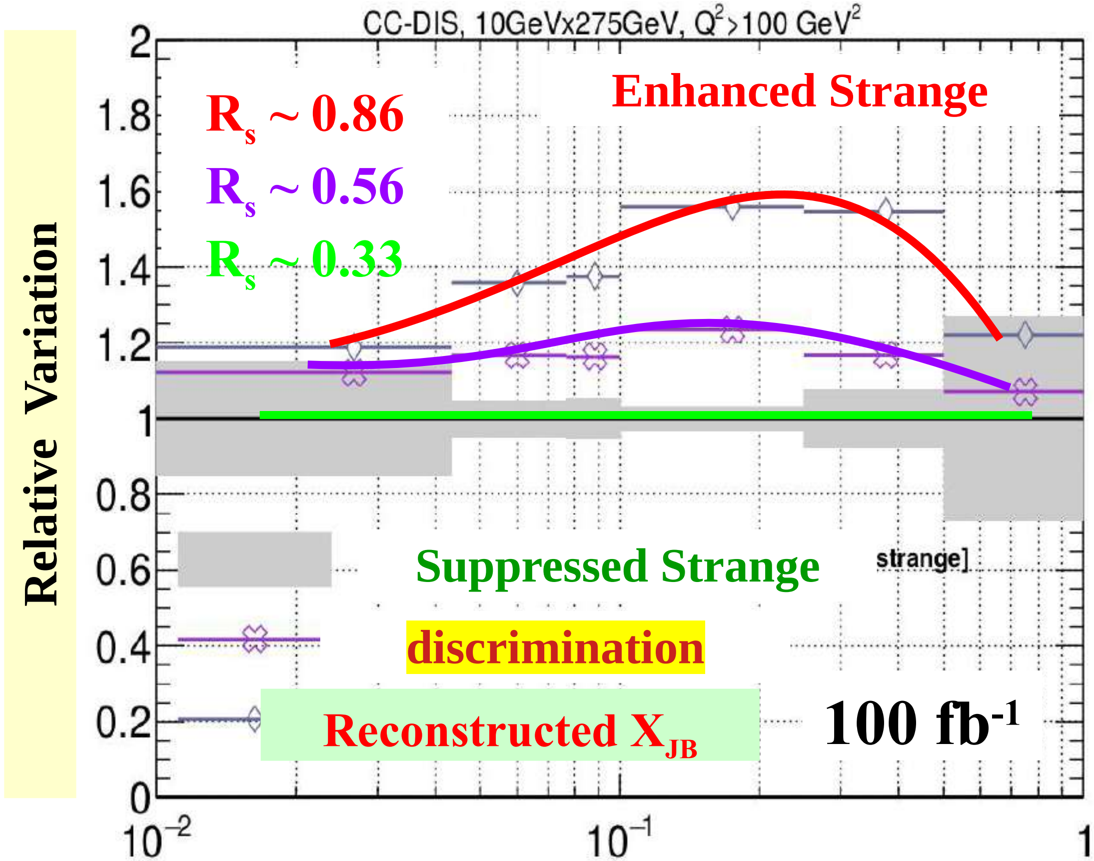
Charm Jets at the EIC ⇒ The Strange PDF



W+s → c_{jet}

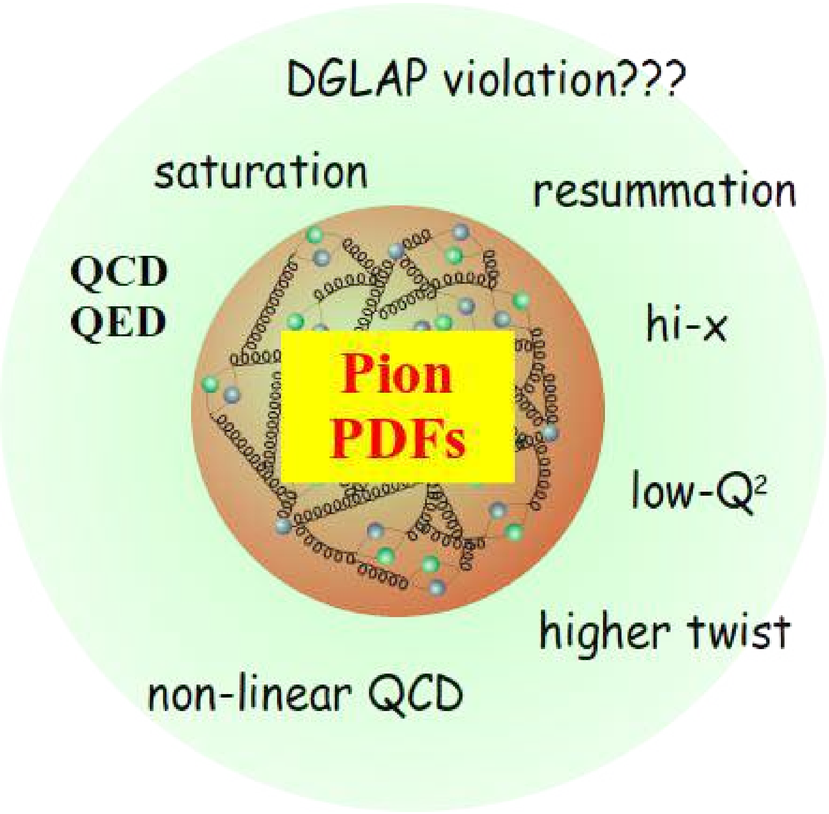


Clear measure of Strange PDF beyond uncertainties



M. Arratia, Y. Furletova, T.J. Hobbs, F. Olness, S.J. Sekula, arXiv:2006.12520,

Pion PDFs



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]

arXiv:2002.02902 [hep-ph]

xFitter

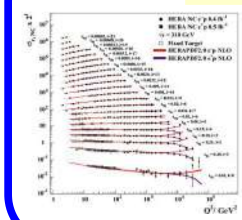
PROTON NUCLEON MESON

www.xFitter.org

Sample data files:

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

Experimental Data



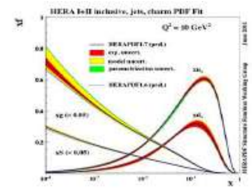
Data: HERA, Tevatron, LHC, fixed target experiments

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 2.0.1 Old Fashioned

xFitter Pion PDFs

https://www.xfitter.org/

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

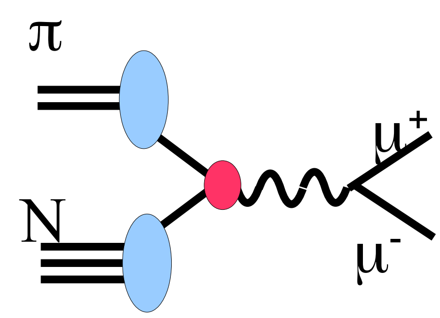
Special thanks to: Ivan Novikov, Alexander Glazov, Oleksandr Zenaiev

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

Pions (π^-) on Tungsten

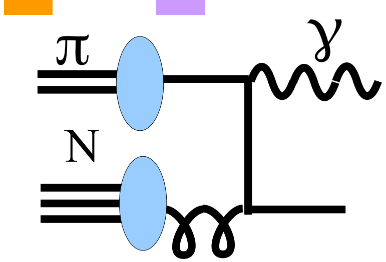
E615 E_π = **252 GeV**

NA10 E_π = **194 GeV** & **286 GeV**



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

WA70 π^+ π^-



NLO computation with MCFM / APPLGRID

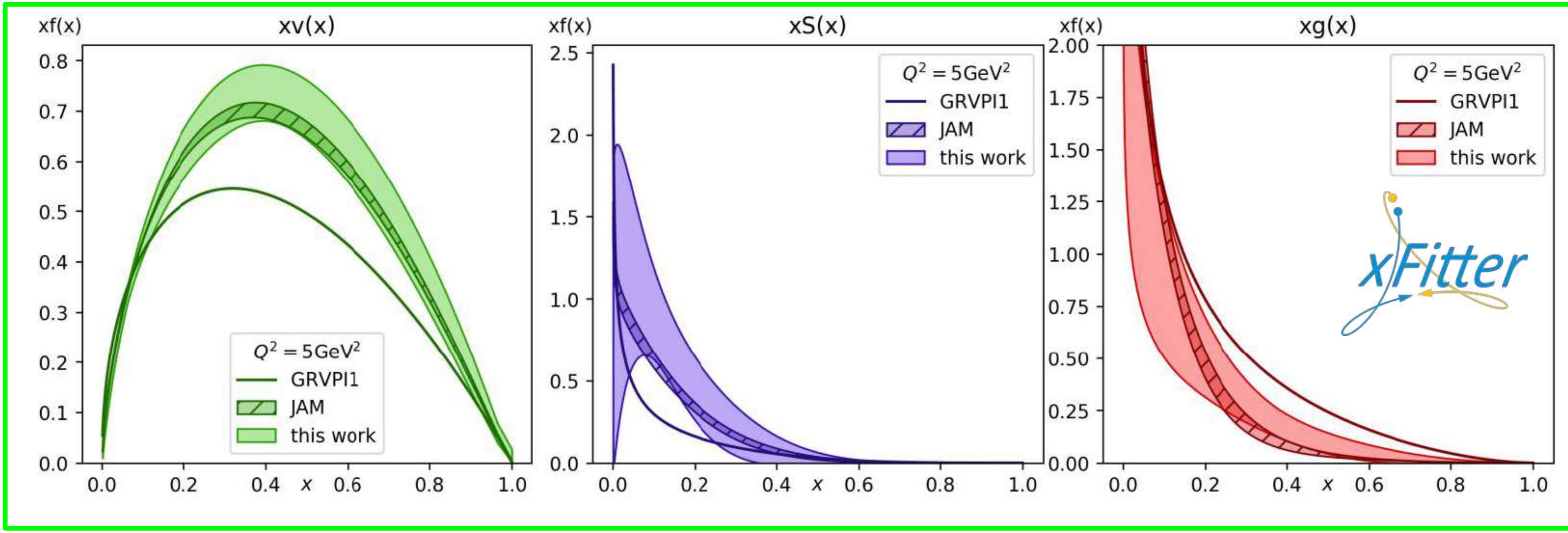
- theory errors from α_s, and nPDF uncert
- uncertainties include scale variations.
  - for factorization scale variation modify APPLGRID for two PDFs

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



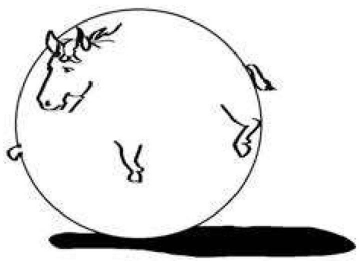
Conclusion

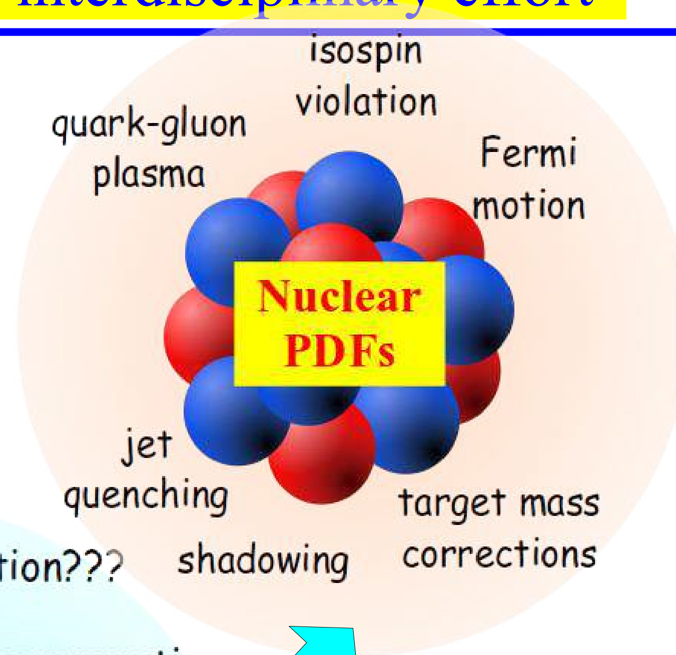
... and we're going to have a lot of new measurements

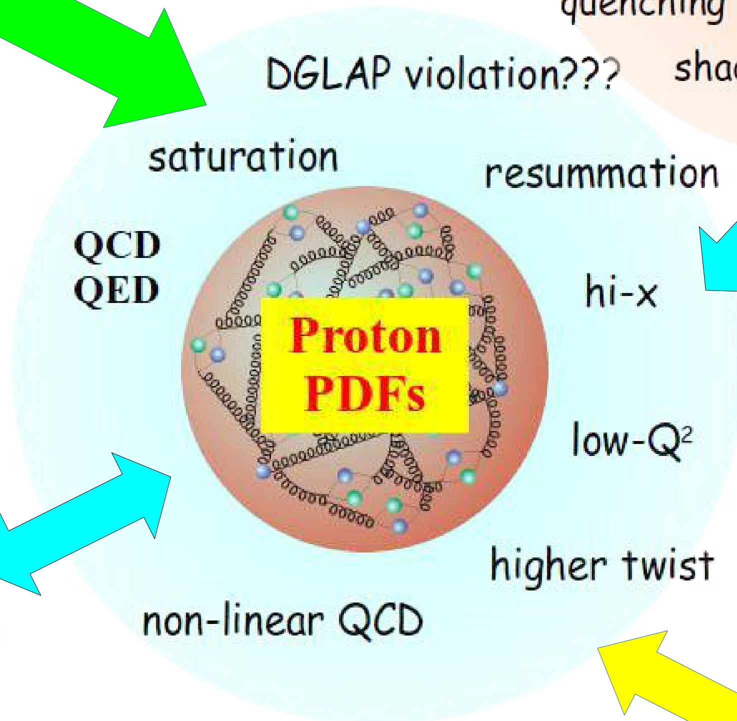
"Solving" QCD: ... concerted interdisciplinary effort

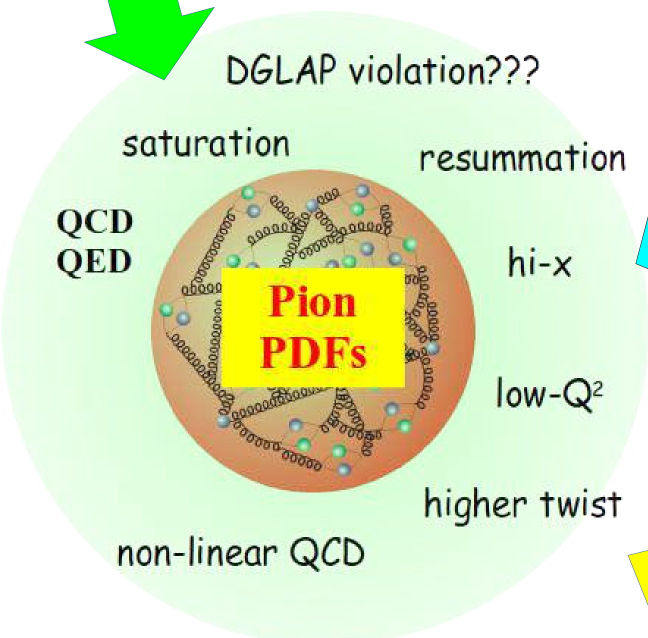
QCD Lagrangian

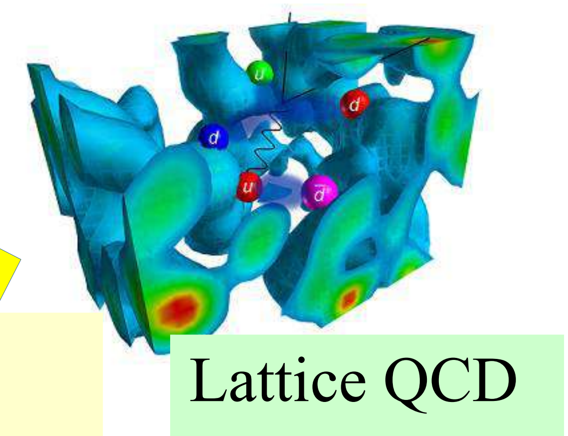
$$\mathcal{L}_{QCD} = \overline{\psi}_q \left(i\gamma_\mu D^\mu - m_q \right) \psi_q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$











- Hadron Spin
- Generalized PDFs