

# 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



Group on Hadronic Physics (GHP)

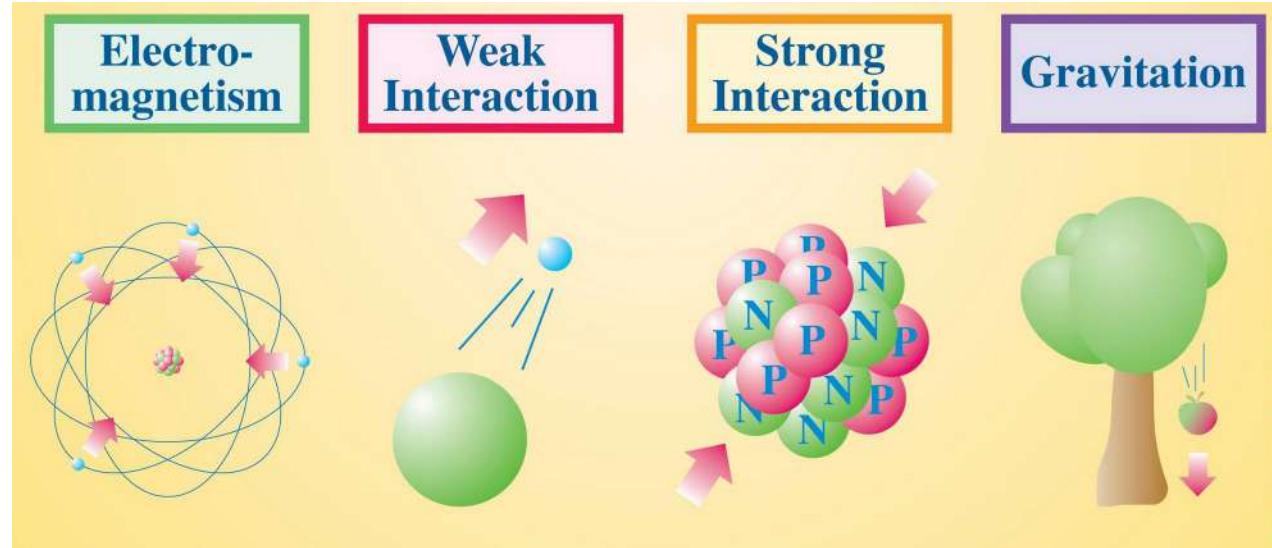
13-16 April 2021

# “QCD is our most perfect physical theory”

Frank Wilczek

2

arXiv:hep-ph/9907340



$$\mathcal{L}_{QCD} = \bar{\psi}_q (i\gamma_\mu D^\mu - m_q) \psi_q - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$$

New Experiments

New Data

New Theoretical Techniques

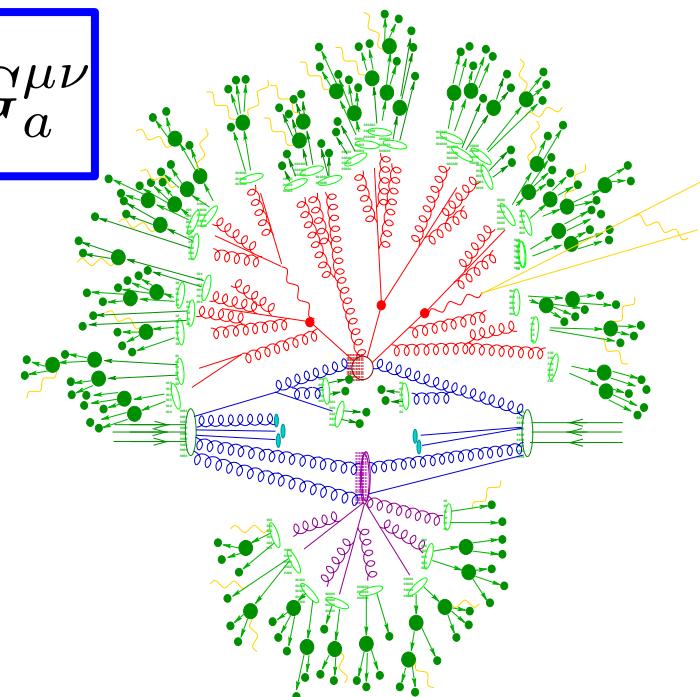
PDFs & nPDFs

Generalized PDFs

Spin Structure

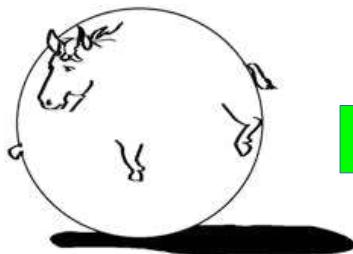
Lattice QCD

Quark-Gluon Plasma

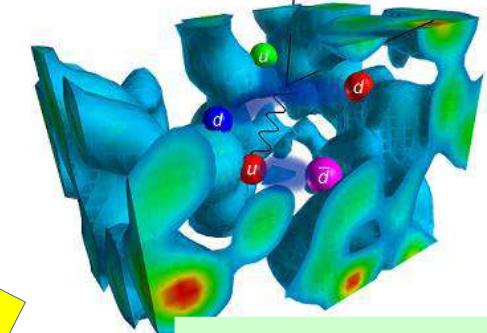
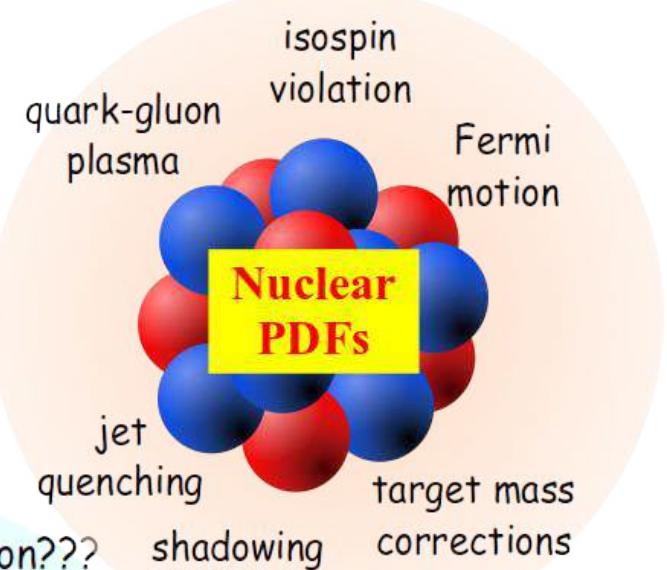
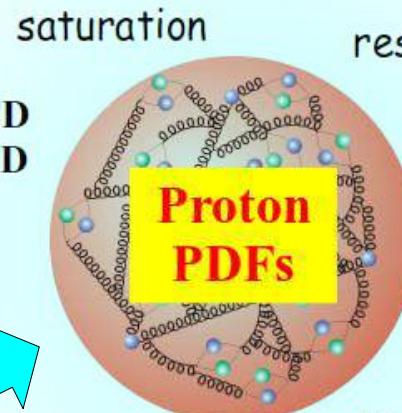
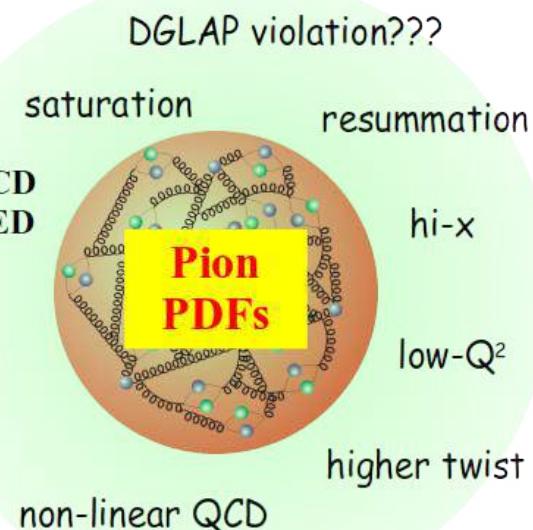


*... a chance for momentous advances in our understanding ...*

**QCD**  
Lagrangian



$$\mathcal{L}_{QCD} = \bar{\psi}_q (i\gamma_\mu D^\mu - m_q) \psi_q - \frac{1}{4} G_a^a G_{\mu\nu}^a G^{a\mu\nu}$$



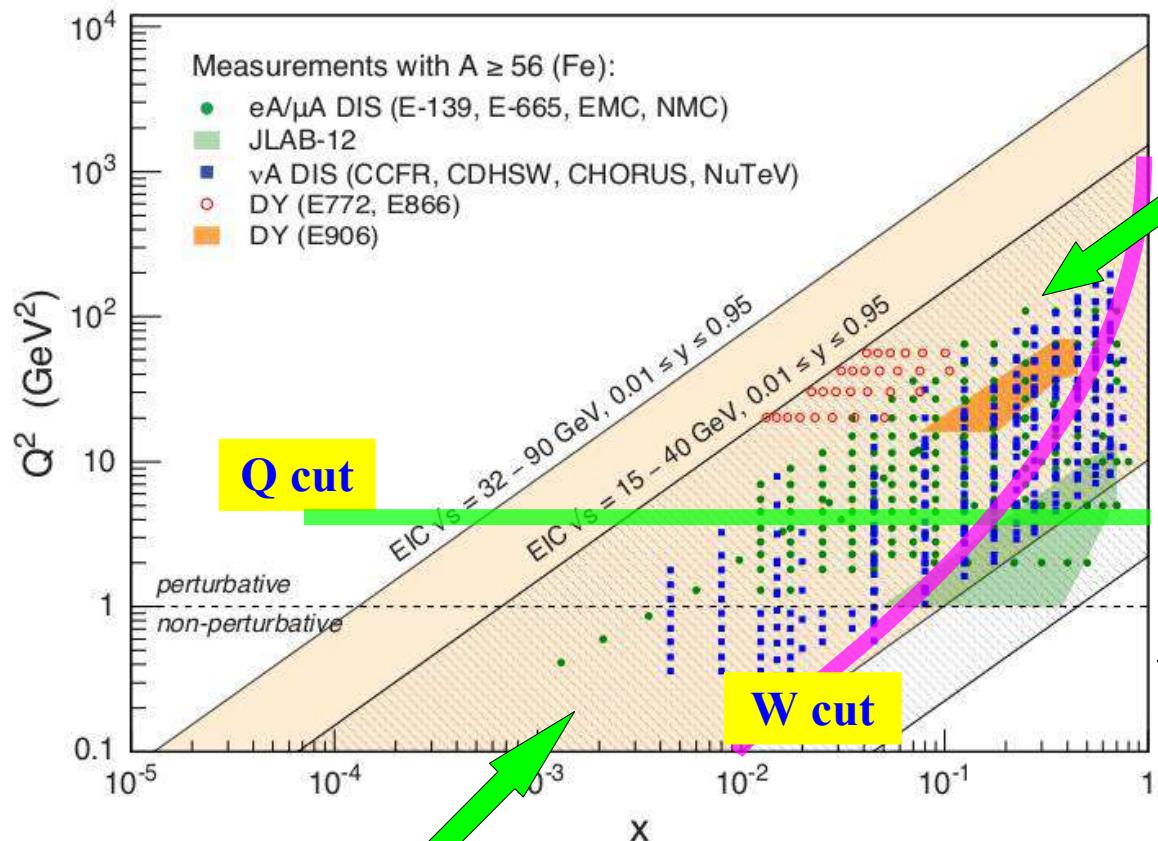
Lattice QCD

- **Hadron Spin**
- **Generalized PDFs**
- **Fragmentation**

# How do we get there

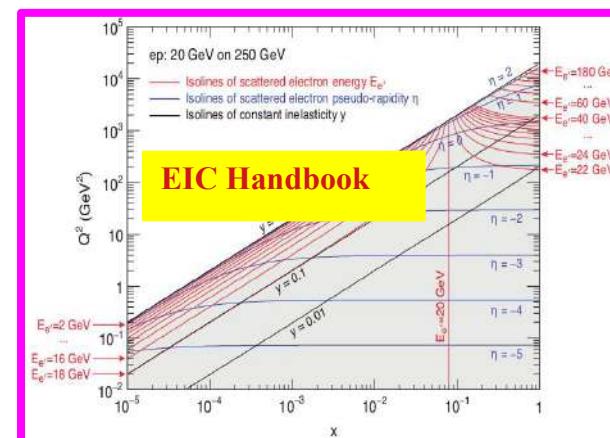


# EIC Kinematic Plane in $\{x, Q^2\}$



## Low- $Q^2$ :

Non-Perturbative interface  
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



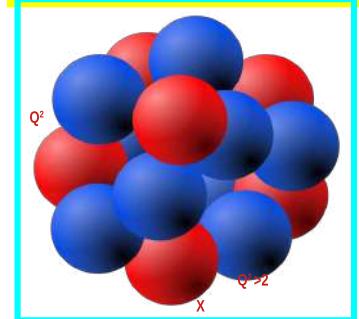
## High-x:

Nuclear PDFs:  $x > 1$  allowed;  
impacts  $F_2^{\text{Nuc}}/F_2^{\text{Iso}}$  in Fermi region  
Target Mass Corrections  
pick up  $M^2/Q^2$  higher twist  
Deuteron Corrections  
impacts  $F_2^{\text{Nuc}}/F_2^{\text{Deuteron}}$  ratio

## Warm-up:

JLab Data @ Hi-X Low-Q<sup>2</sup>  
extend nCTEQ framework for this region  
& prepare for EIC

Efrain Segarra w/ **nCTEQ**

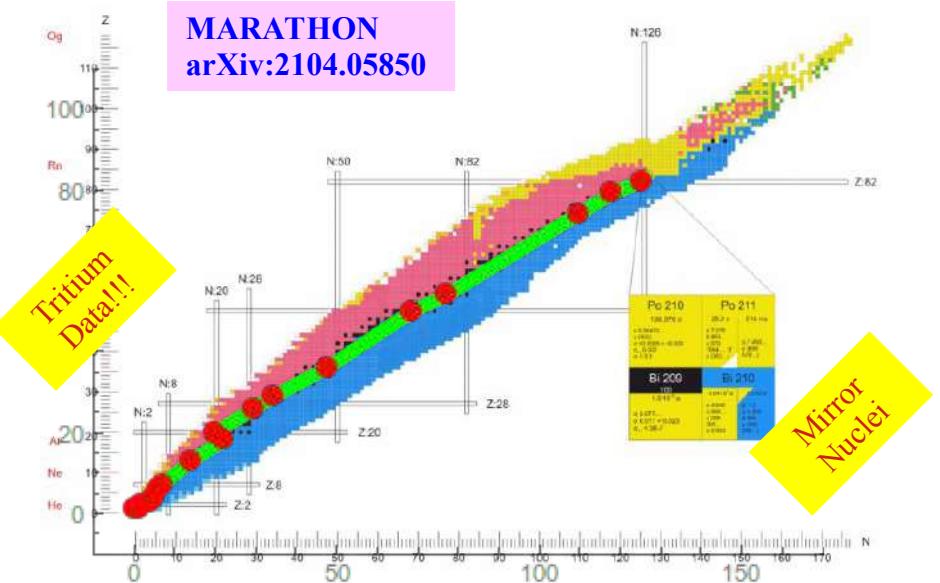
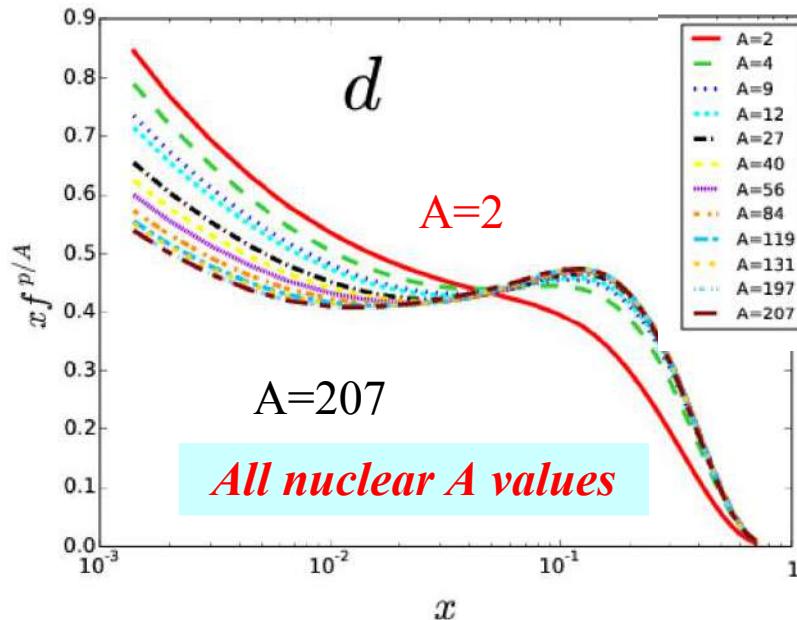


# Exploring the Nuclear Dimension: DIS, DY, $\pi$ Prod, (plus more ...)

6

## Periodic Table of the Elements

1 IA	H Hydrogen	2 IIA	Be Beryllium	3 IIIA		4 IVB	Mg Magnesium	5 VB	Na Sodium	6 VIB		7 VIIIB		8 VIII		13 IIIA	B Boron	14 IVA	C Carbon	15 VA	N Nitrogen	16 VIA	O Oxygen	17 VIIA	F Fluorine	18 VIIIIA	He Helium												
1	1.008	2	9.012	3		4	24.31	5	22.990	6		7		8		13	10.811	14	12.011	15	14.007	16	15.999	17	18.000	18	20.183												
11	Li Lithium	12	Mg Magnesium	19	K Potassium	20	Ca Calcium	21	Sc Scandium	22	Ti Titanium	23	V Vanadium	24	Cr Chromium	25	Mn Manganese	26	Fe Iron	27	Co Cobalt	28	Ni Nickel	29	Cu Copper	30	Zn Zinc	31	Ga Gallium	32	Ge Germanium	33	As Arsenic	34	Se Selenium	35	Br Bromine	36	Kr Krypton
11	6.941	12	24.31	19	39.098	20	40.078	21	44.954	22	47.938	23	50.942	24	51.996	25	54.938	26	55.935	27	56.933	28	58.933	29	63.546	30	65.39	31	69.732	32	74.972	33	78.972	34	79.904	35	83.463	36	83.812
37	Rb Rubidium	38	Sr Strontium	39	Y Yttrium	40	Zr Zirconium	41	Nb Niobium	42	Mo Molybdenum	43	Tc Technetium	44	Ru Ruthenium	45	Rh Rhodium	46	Pd Palladium	47	Ag Silver	48	Cd Cadmium	49	In Indium	50	Sn Tin	51	Sb Antimony	52	Te Tellurium	53	I Iodine	54	Xe Xenon				
55	Cs Cesium	56	Ba Barium	57-71		72	Hf Hafnium	73	Ta Tantalum	74	W Tungsten	75	Re Rhenium	76	Os Osmium	77	Ir Iridium	78	Pt Platinum	79	Au Gold	80	Hg Mercury	81	Tl Thallium	82	Pb Lead	83	Bi Bismuth	84	Po Polonium	85	At Astatine	86	Rn Radon				
87	Fr Francium	88	Ra Radium	89-103		104	Rf Rutherfordium	105	Db Dubnium	106	Sg Seaborgium	107	Bh Bohrium	108	Hs Hassium	109	Mt Meitnerium	110	Ds Darmstadtium	111	Rg Roentgenium	112	Cn Copernicium	113	Uut Ununtrium	114	Fl Flerovium	115	Uup Ununpentium	116	Lv Livermorium	117	Uus UnurSeptium	118	Uuo Ununoctium				
87	223.020	88	226.025			104	[261]	105	[262]	106	[266]	107	[264]	108	[269]	109	[268]	110	[266]	111	[272]	112	[277]	113	[299]	114	[299]	115	[298]	116	[298]	117	[297]	118	[298]				



... expand our knowledge of nuclear  $A$  dimension

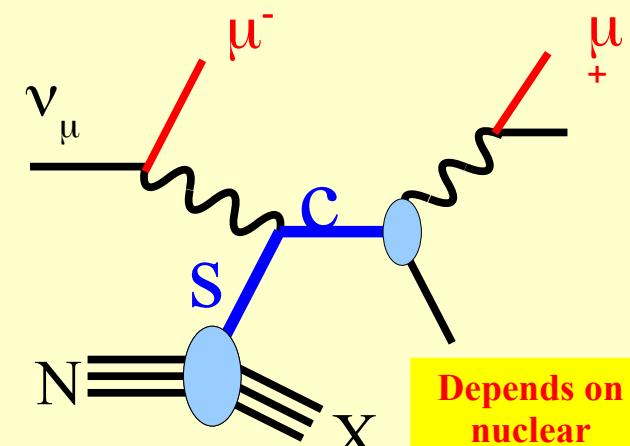
# Nuclear PDFs are Essential for Flavor Differentiation

neutrino DIS

$$\begin{aligned} F_2^\nu &\sim [d + s + \bar{u} + \bar{c}] \\ F_2^{\bar{\nu}} &\sim [\bar{d} + \bar{s} + u + c] \\ F_3^\nu &\sim 2[d + s - \bar{u} - \bar{c}] \\ F_3^{\bar{\nu}} &\sim 2[u + c - \bar{d} - \bar{s}] \end{aligned}$$

Differentiate flavors of free-proton PDFs:

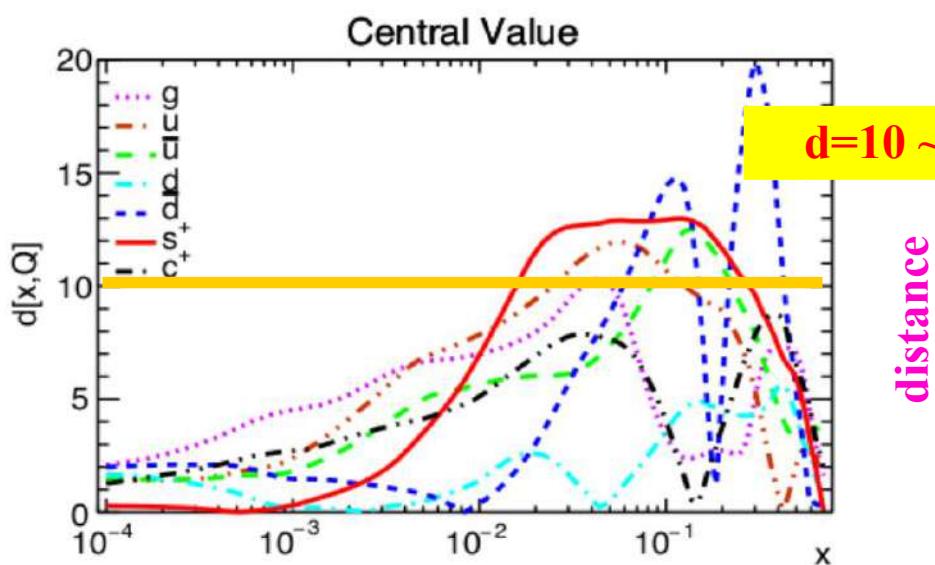
Neutrino DIS



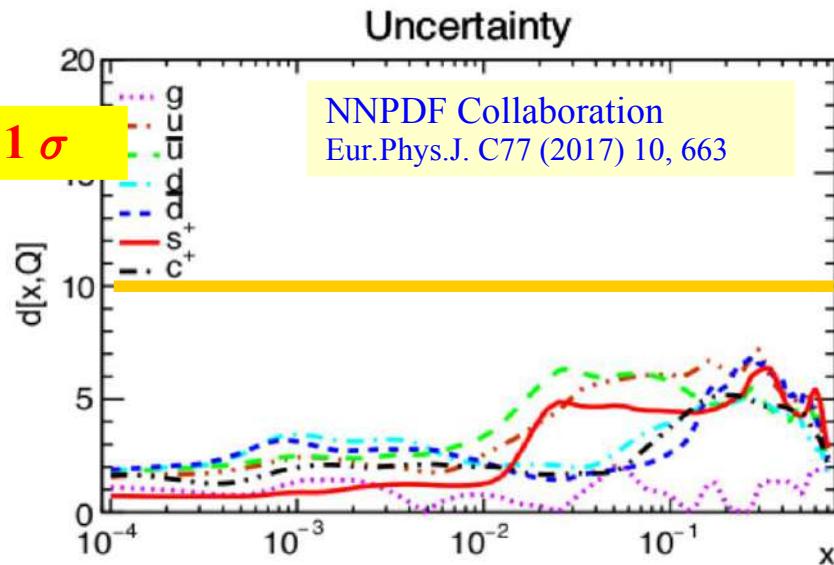
Depends on  
nuclear  
corrections

NNPDF3.1 NNLO, Impact of nuclear+deuteron fixed-target data ,  $Q = 100$  GeV

Central Value



Uncertainty



... essential for Proton PDF goal of <1%

## 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 ( $\nu N$ ,  $\ell N$ ) 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 ( $\gamma$ ) & Charged Current ( $W^\pm$ ) processes

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

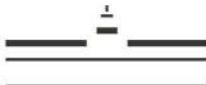
- Small- $x$  saturation, resummation:  $\log[1/x]$
- Large- $x$  higher twist:  $(M^2/Q^2)$
- Low  $Q^2$  non-perturbative effects

# Recent nCTEQ Presentations

IMPACT OF INCLUSIVE HADRON PRODUCTION DATA  
ON NUCLEAR GLUON PDFS

Pit Duwentäster

14. April 2021



WESTFÄLISCHE  
WILHELMUS-UNIVERSITÄT  
MÜNSTER

**nCTEQ**  
nuclear parton distribution functions





**nCTEQ15-HIX**  
Nuclear PDFs in valence region

Efrain Segarra

In collaboration with T. Ježo, A. Accardi, P. Duwentäster,  
O. Hen, T.J. Hobbs, C. Keppel, M. Klasen, K. Kovářík,  
A. Kusina, J.G. Morfin, K.F. Muzakka, F.I. Olness,  
I. Schienbein, J.Y. Yu

**SMU**  **MIT**   
**Université Joseph Fourier** 

arxiv 2012.11566 (under review)

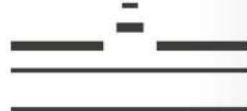
Impact of W and Z Boson Production Data  
and Compatibility of Neutrino DIS Data  
in Nuclear Parton Density Extraction

XXVIII International Workshop on Deep-Inelastic  
Scattering and Related Subjects 2021

Khoirul Faiq Muzakka

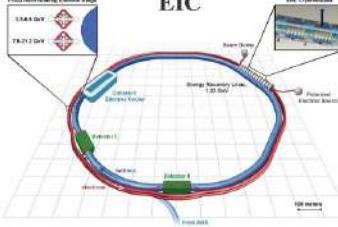
Institute for Theoretical Physics  
Westfälische Wilhelms-Universität Münster

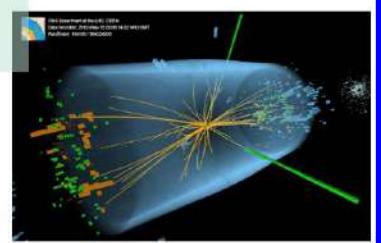
Conspirators : D. B. Clark, P. Duwentäster, E. Godat,  
T.J. Hobbs, T. Ježo, J. Kent, C. Keppel, M. Klasen, K.  
Kovářík, A. Kusina, F. Lyonnet, J.G. Morfin, F.I. Olness,  
I. Schienbein, J. Y. Yu, ...

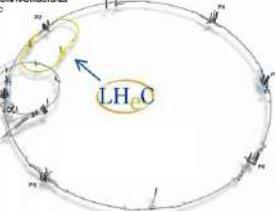
 

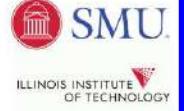
**DIS (EIC/LHeC) physics connections to the LHC**

Tim Hobbs, SMU, IIT, JLab EIC Center  
16<sup>th</sup> April 2021







  
ILLINOIS INSTITUTE  
OF TECHNOLOGY

EIC<sup>2</sup> 

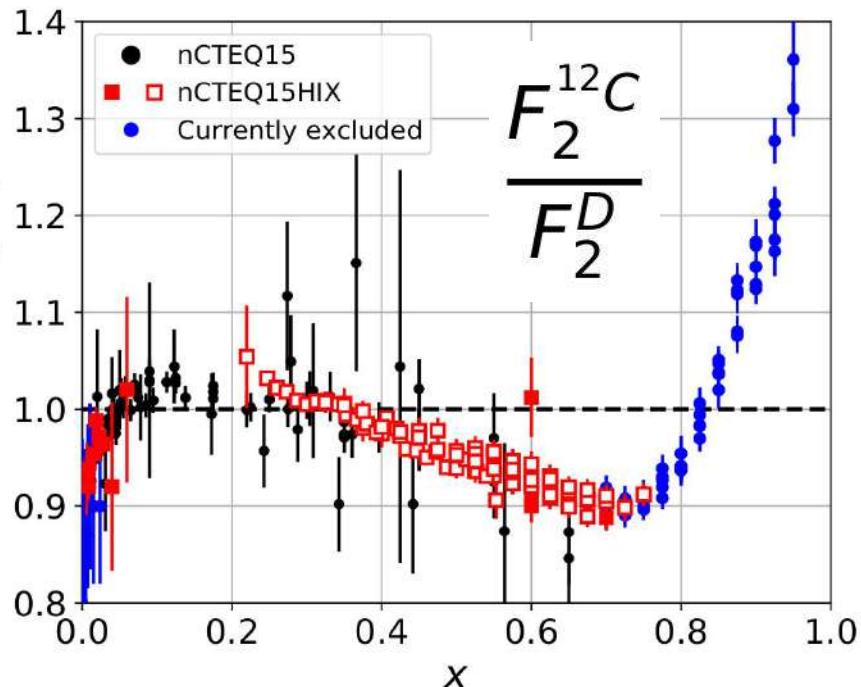
DIS2021 Stony Brook University 12-16 April 2021

# Hi-X

# nCTEQ15HIX

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

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



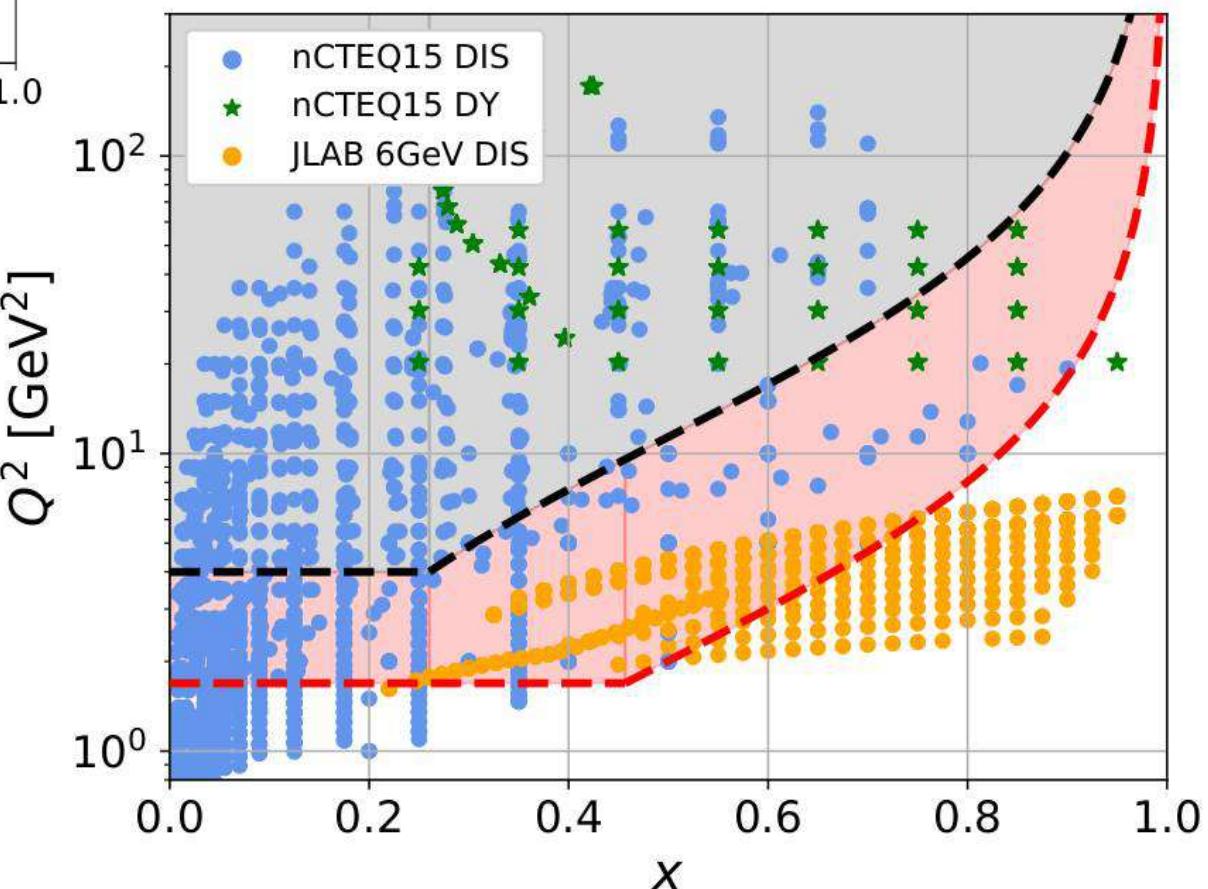
**JLab Data @ Hi-X Low- $Q^2$**   
extend nCTEQ framework  
to accommodate this region  
& prepare for EIC

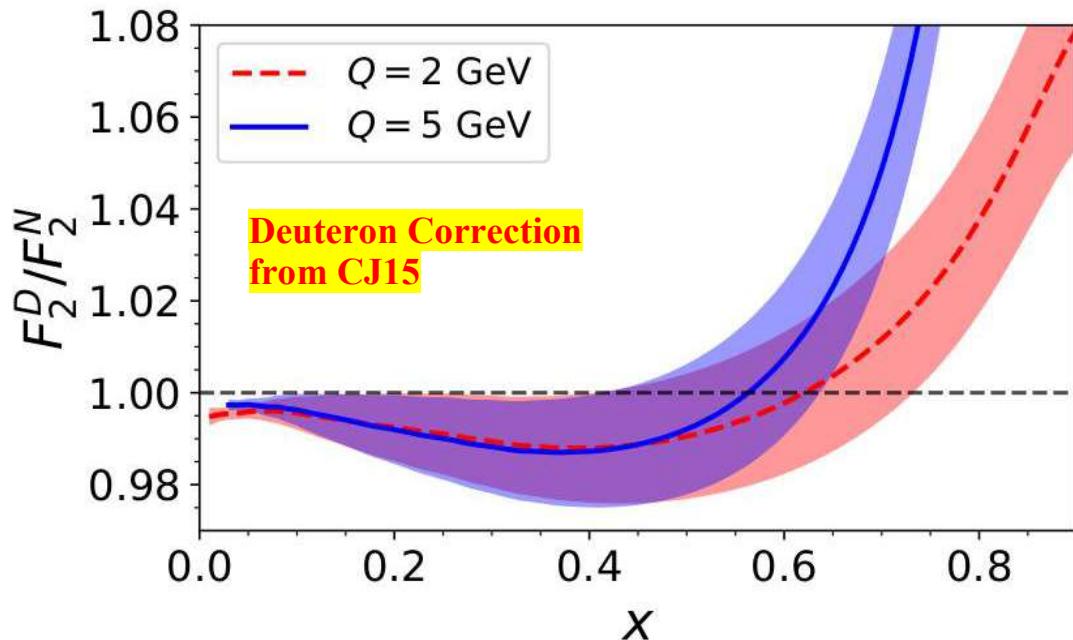
Nuclear PDFs:  $x > 1$  allowed;  
impacts  $F_2^{\text{Nuc}} / F_2^{\text{Iso}}$  in Fermi region

Target Mass Corrections  
pick up  $M^2/Q^2$  higher twist contributions

Deuteron Corrections

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

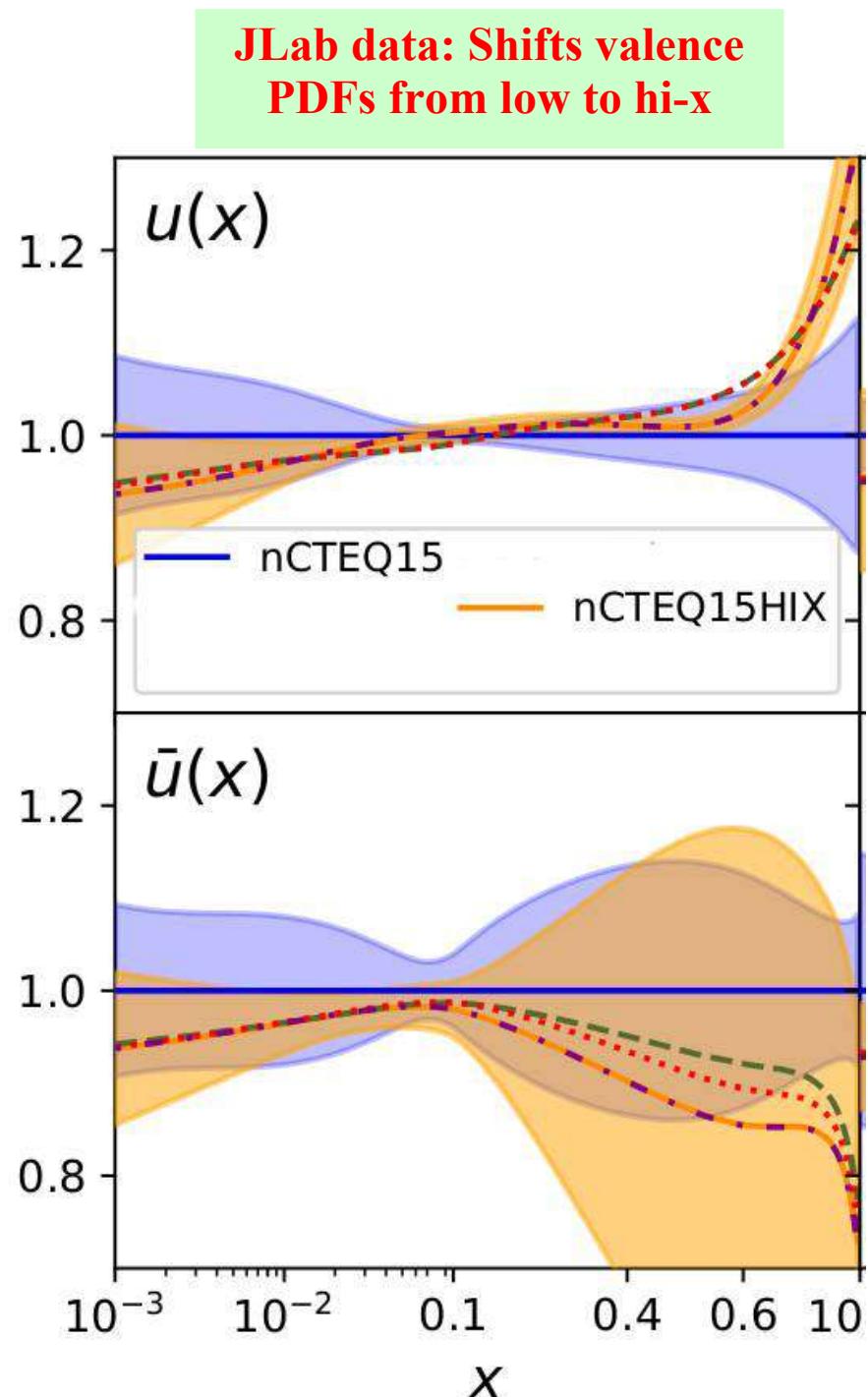




Higher Twist Correction from CJ15

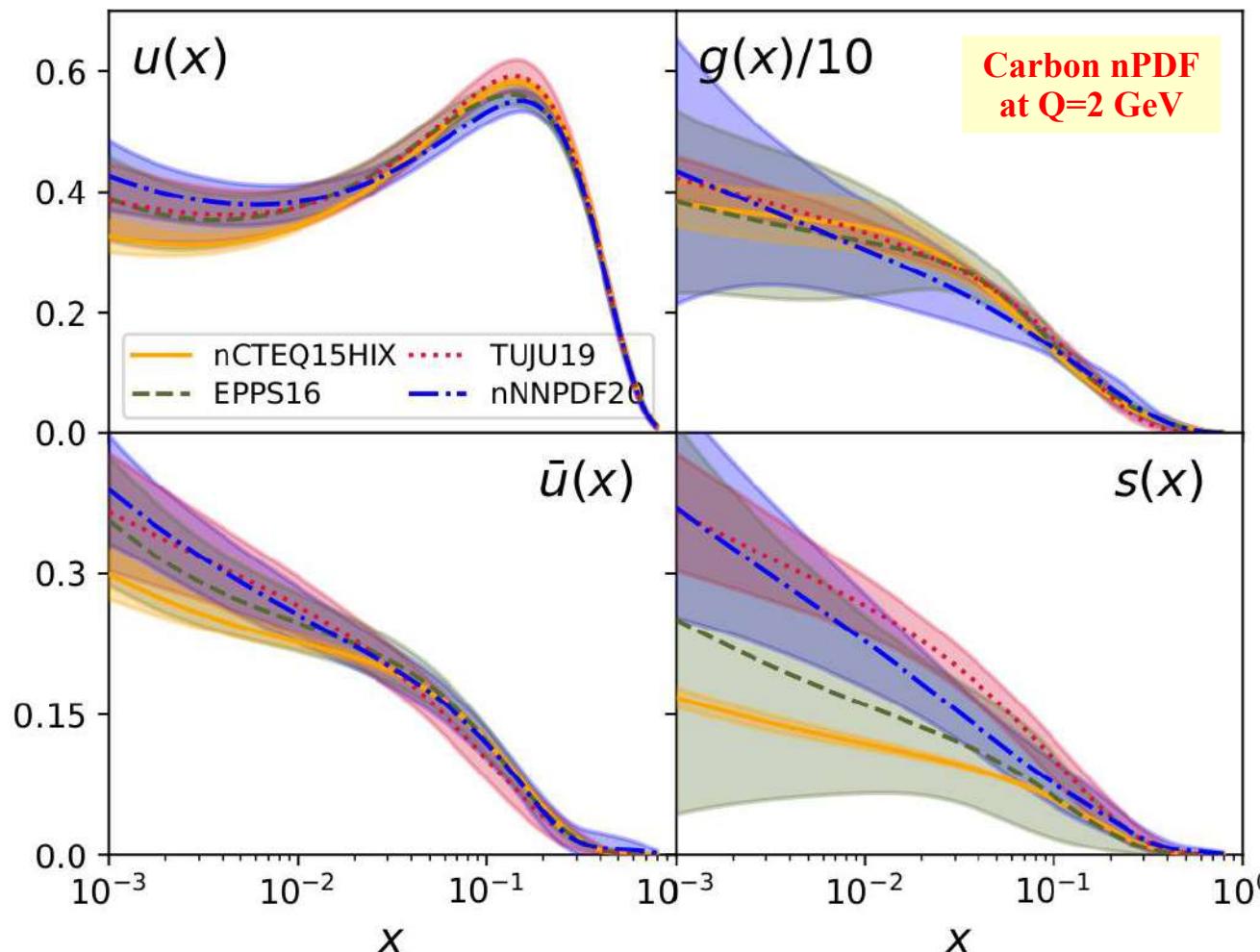
$$F_2^A \rightarrow F_2^A \left[ 1 + \frac{C_{HT}^A}{Q^2} \right]$$

Fit	$\chi^2$	$N_{data}$	$\chi^2/N_{dof}$	$Q_{cut}$	$W_{cut}$
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

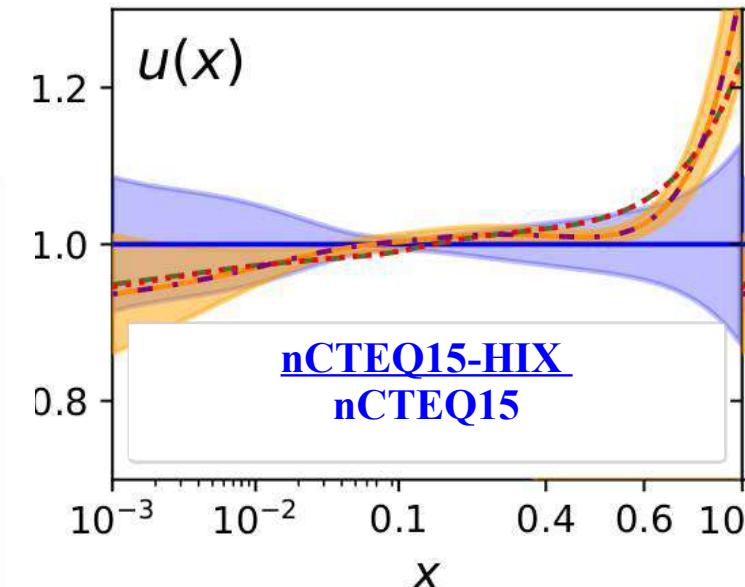


... some recent  $nPDFs$

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



**nCTEQ15-HIX**  
updated with  
JLab Hi-x data



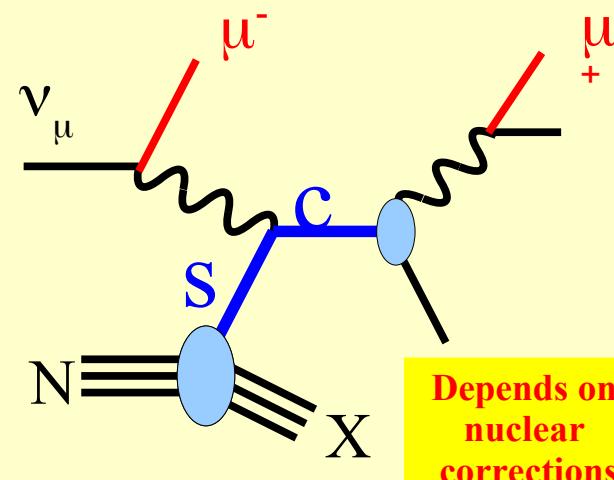
**JLab data: Shifts valence PDFs from low to hi-x**

Deuteron Corrections  
Important!!!

HT from CJ15  
improves fit

# Strange PDF

## Neutrino DIS



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

THE EUROPEAN  
PHYSICAL JOURNAL C



Regular Article - Theoretical Physics

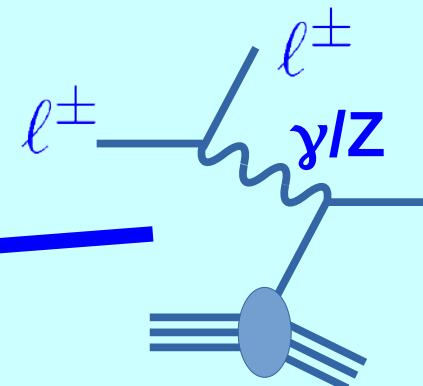
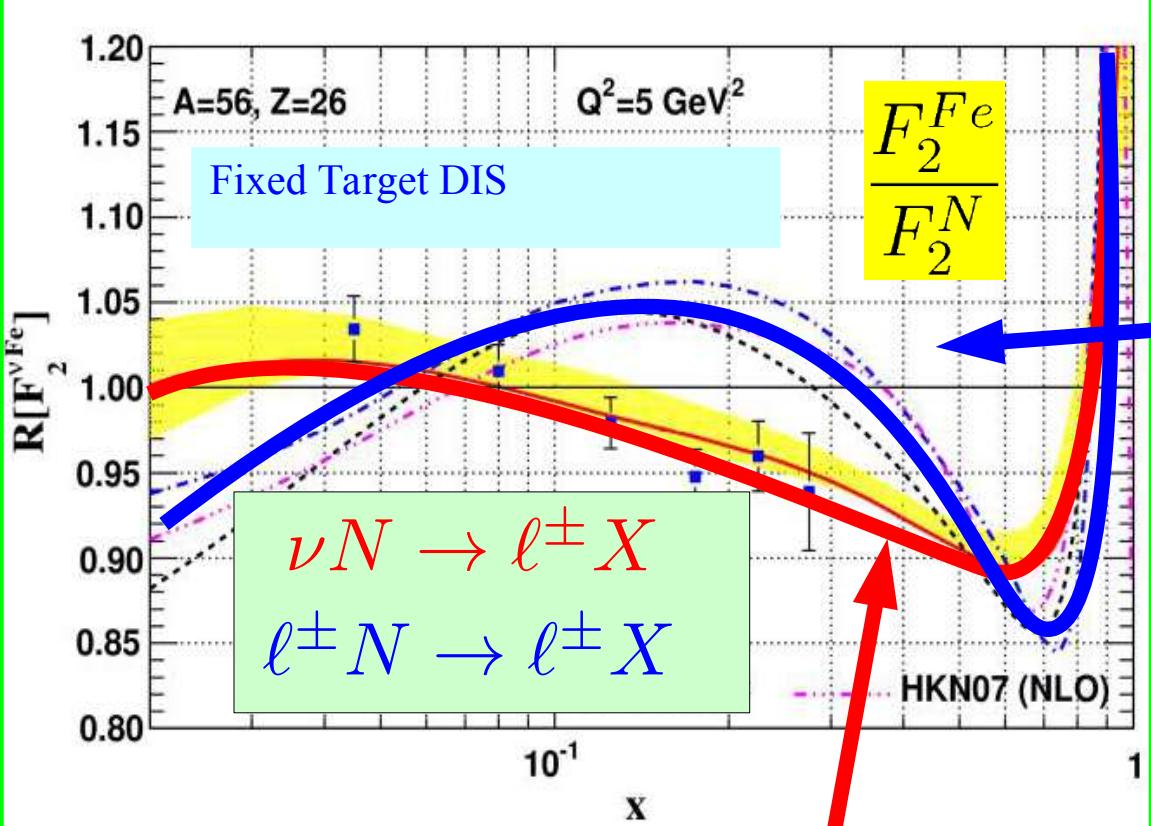
## Impact of LHC vector boson production in heavy ion collisions on strange PDFs

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

# Puzzle: What is the Nuclear Correction

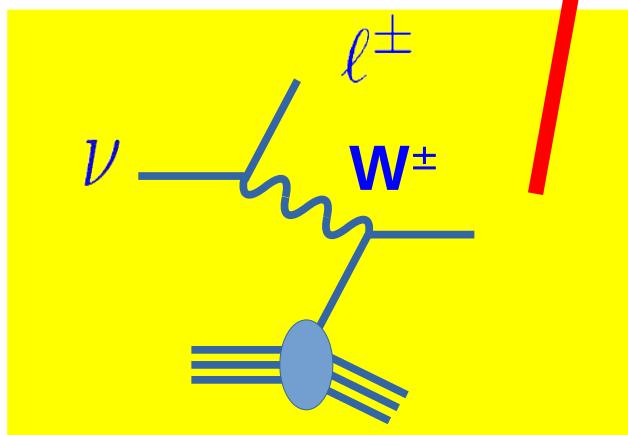
15

## Charged Lepton DIS

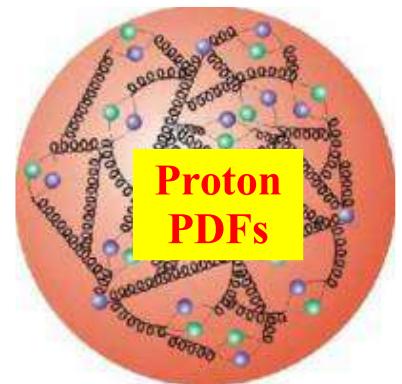
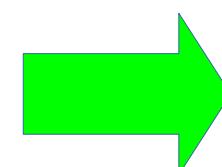
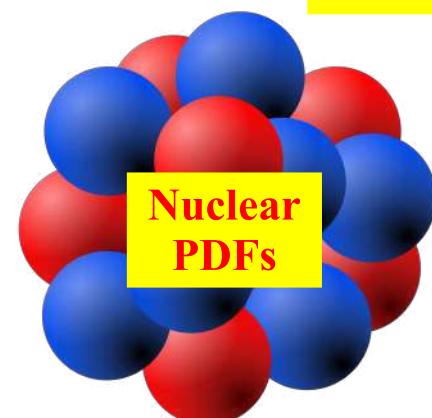


some caveats  
... correlated errors

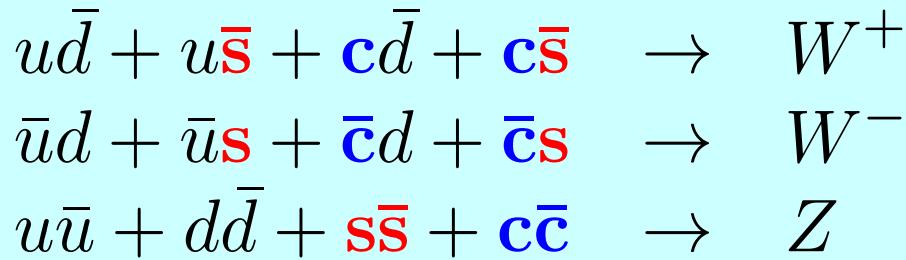
Depends on nuclear corrections  
Propagation of  $\gamma/W$  thru nuclei



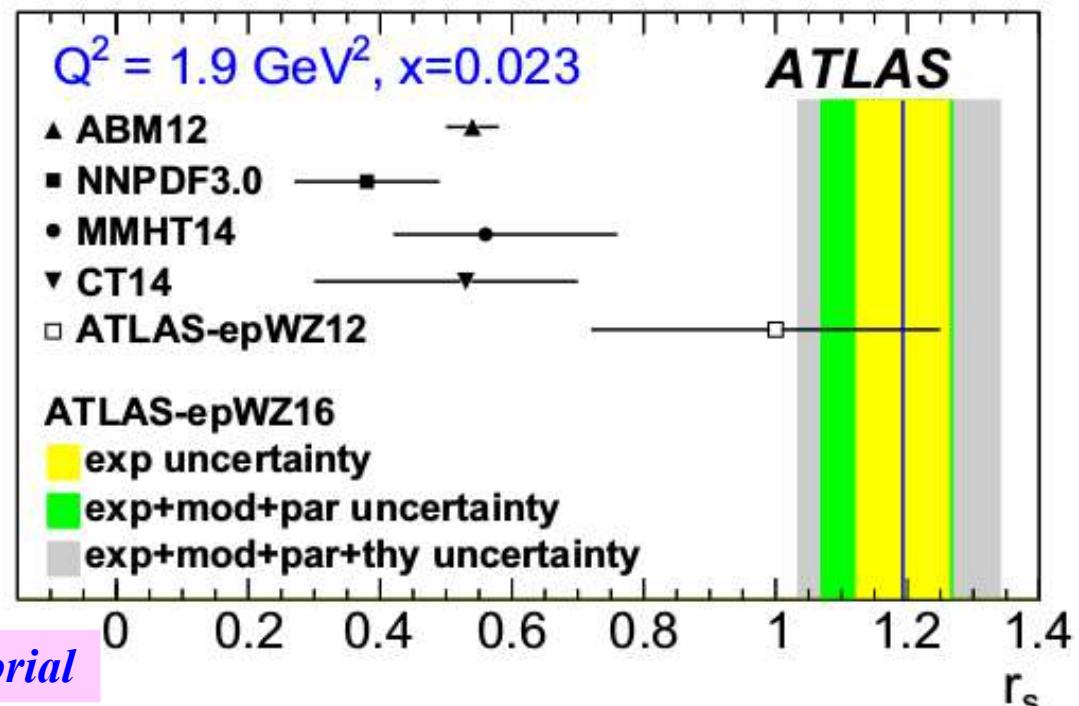
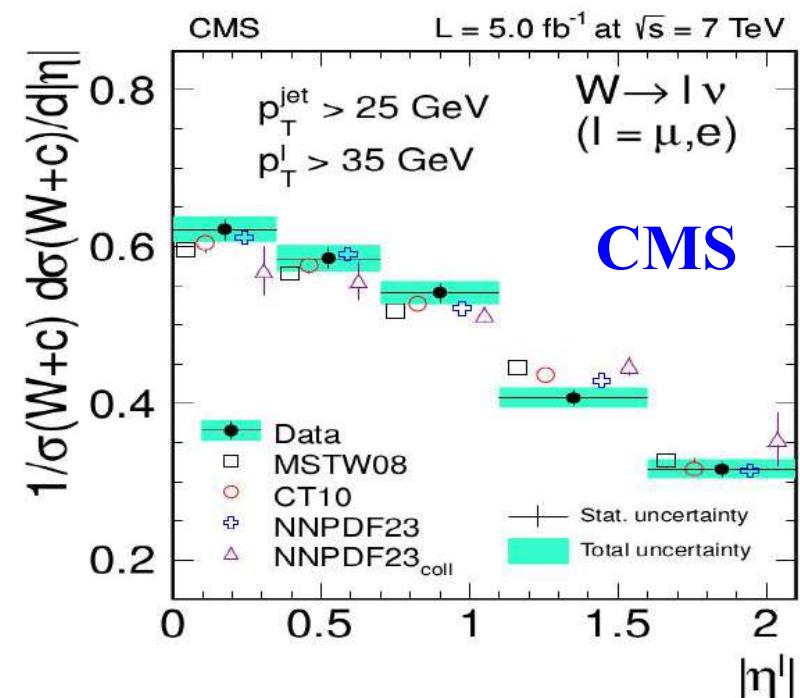
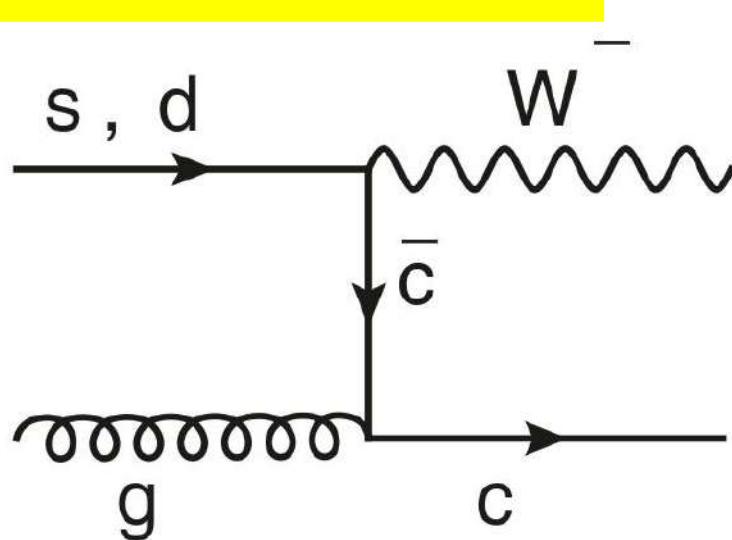
## Neutrino DIS



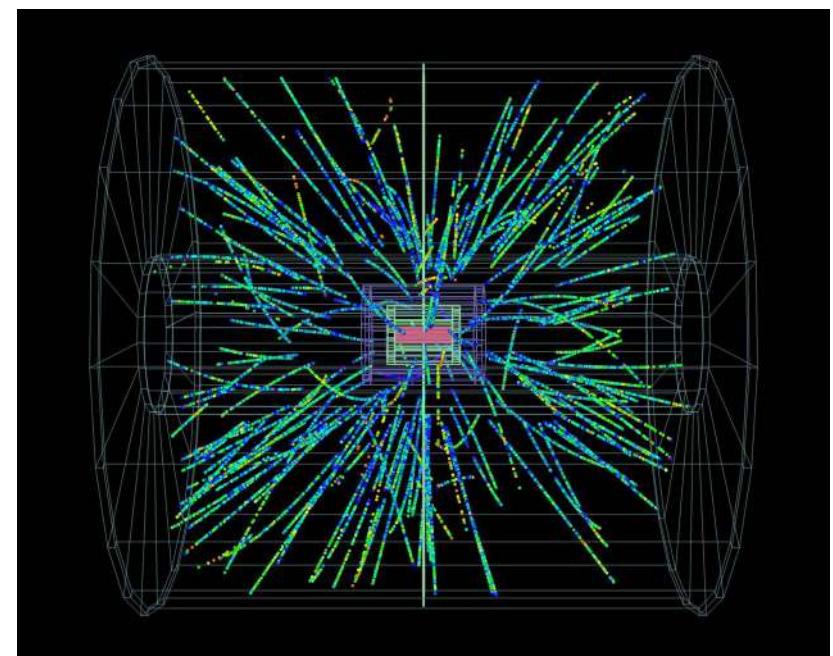
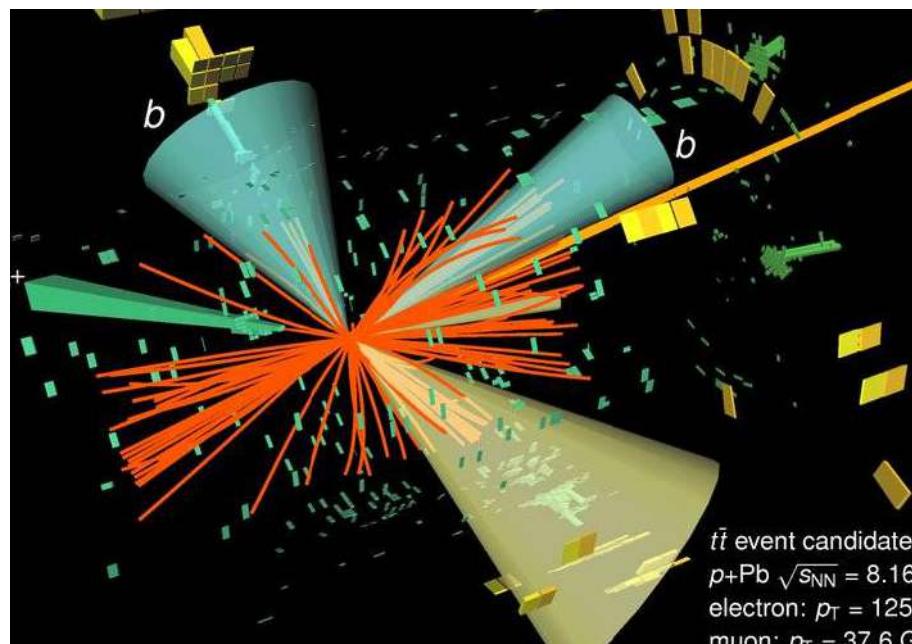
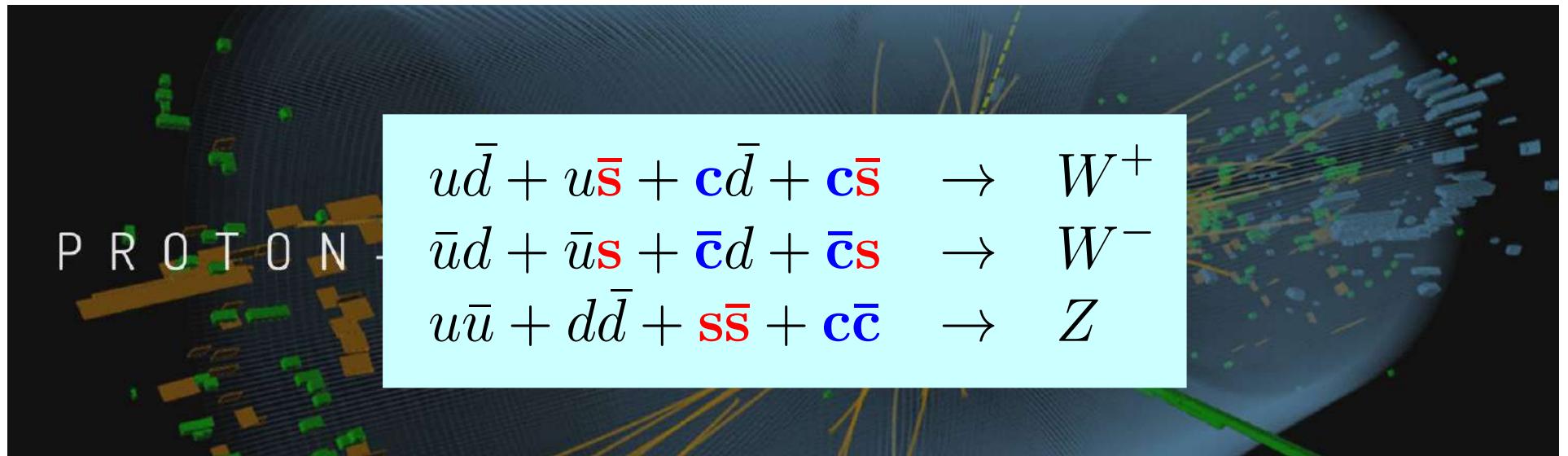
re-examination by nCTEQ

**Inclusive W/Z**


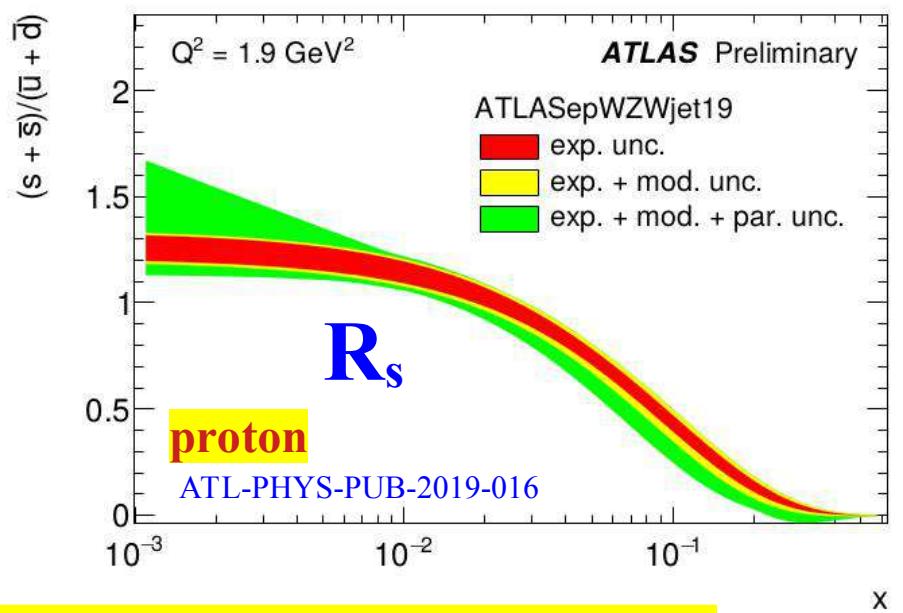
$$r^s(x, Q) = \frac{\bar{s}(x, Q) + s(x, Q)}{2\bar{d}(x, Q)}$$

*xFitter tutorial*

**Associated W+c**


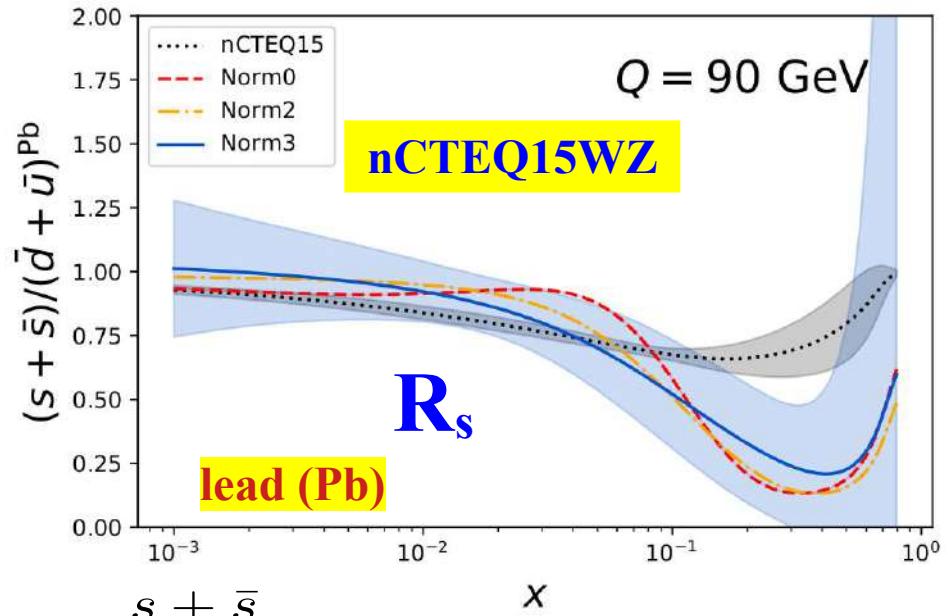
# LHC Heavy Ion: proton -- lead



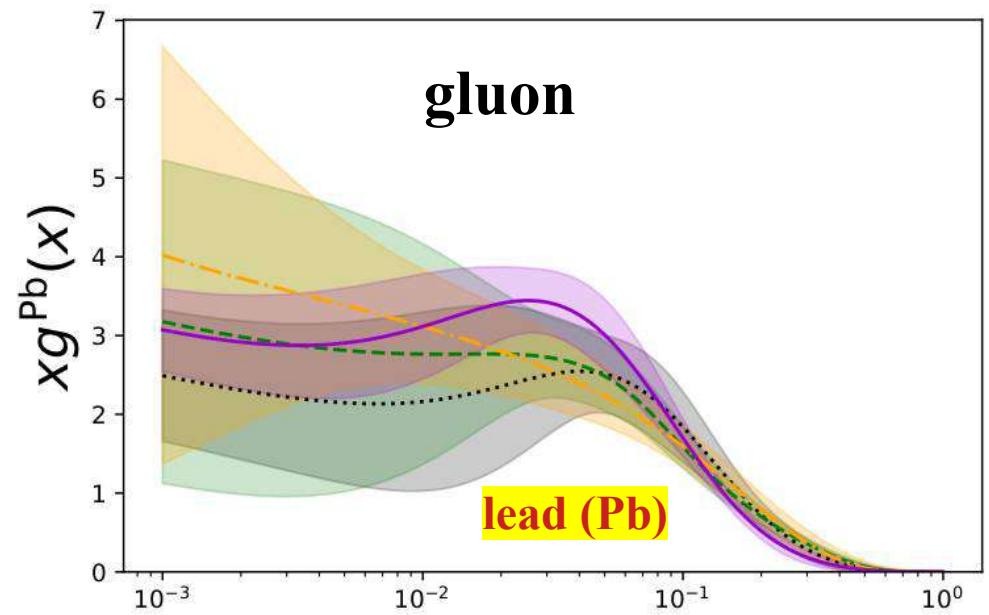
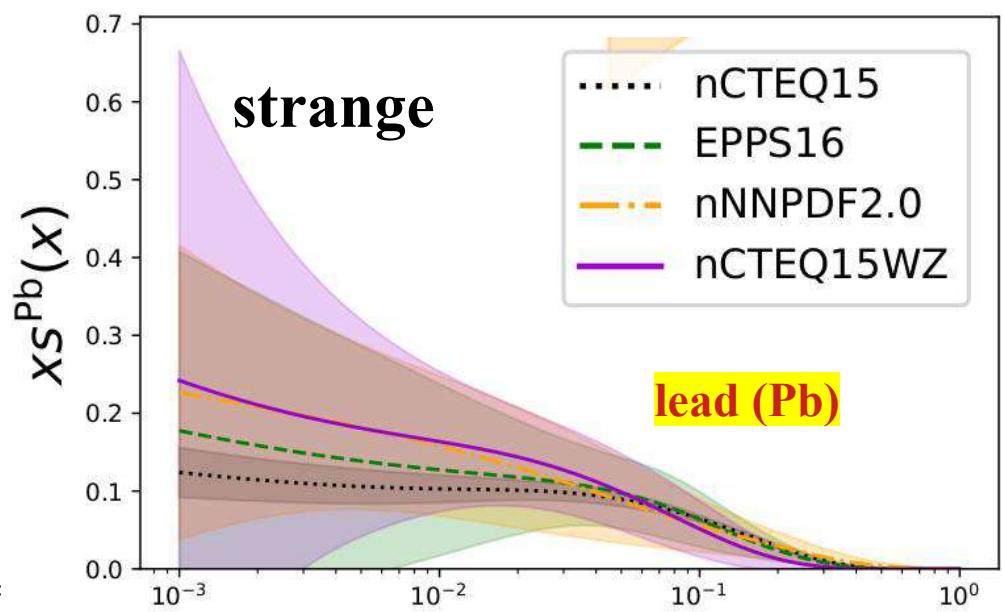
## nuclear PDFs for lead (Pb)



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



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

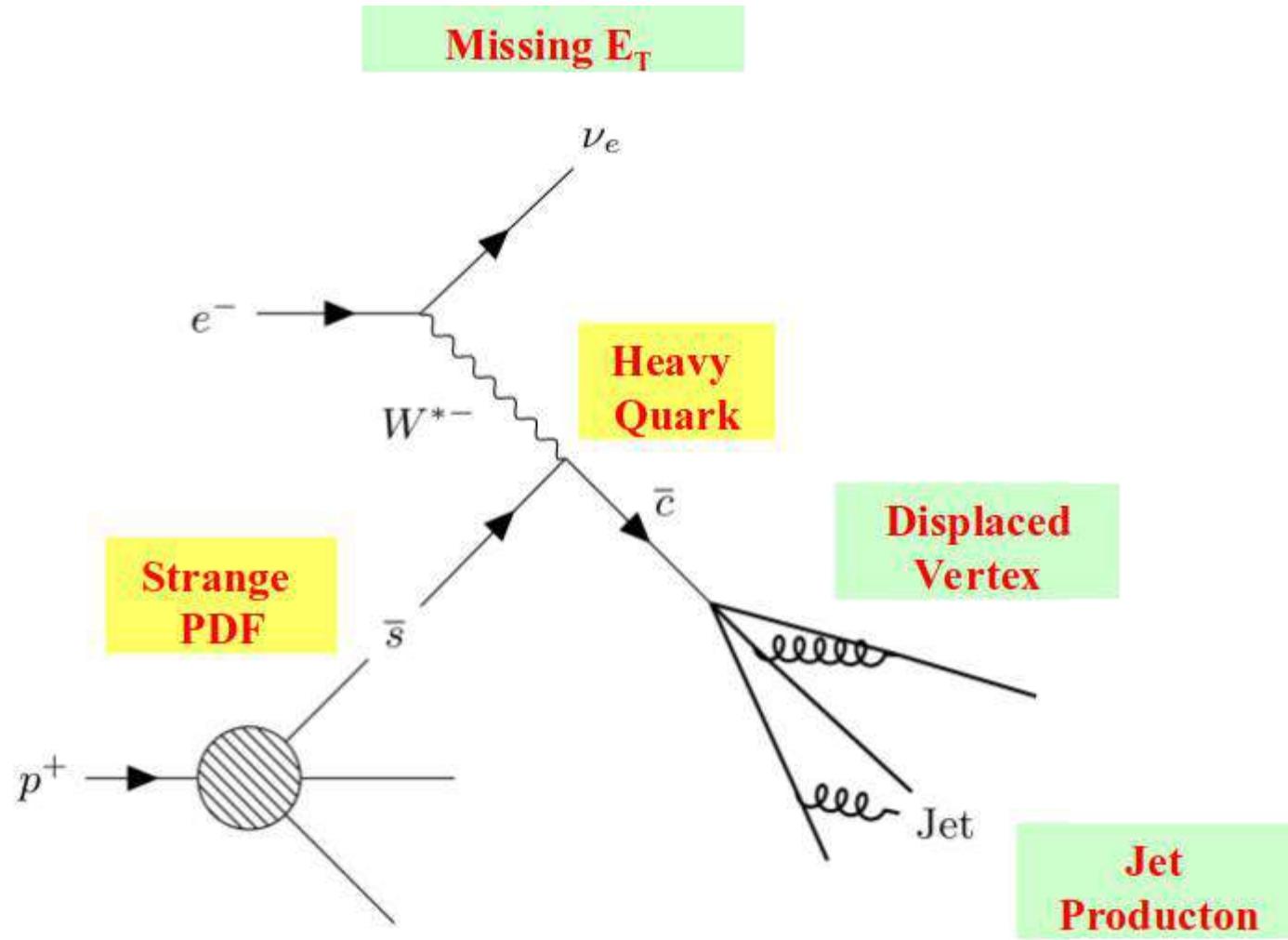


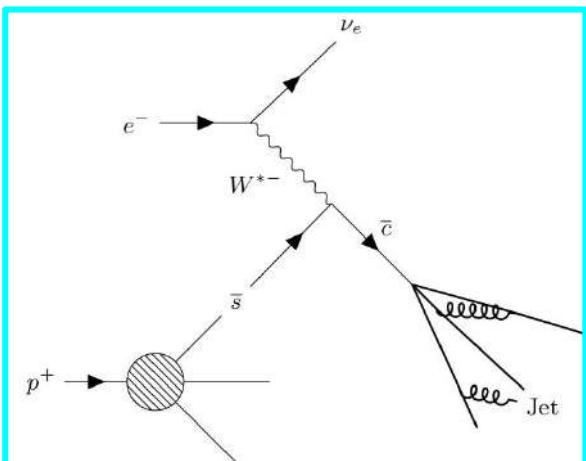
# Charm Jets at the EIC

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

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

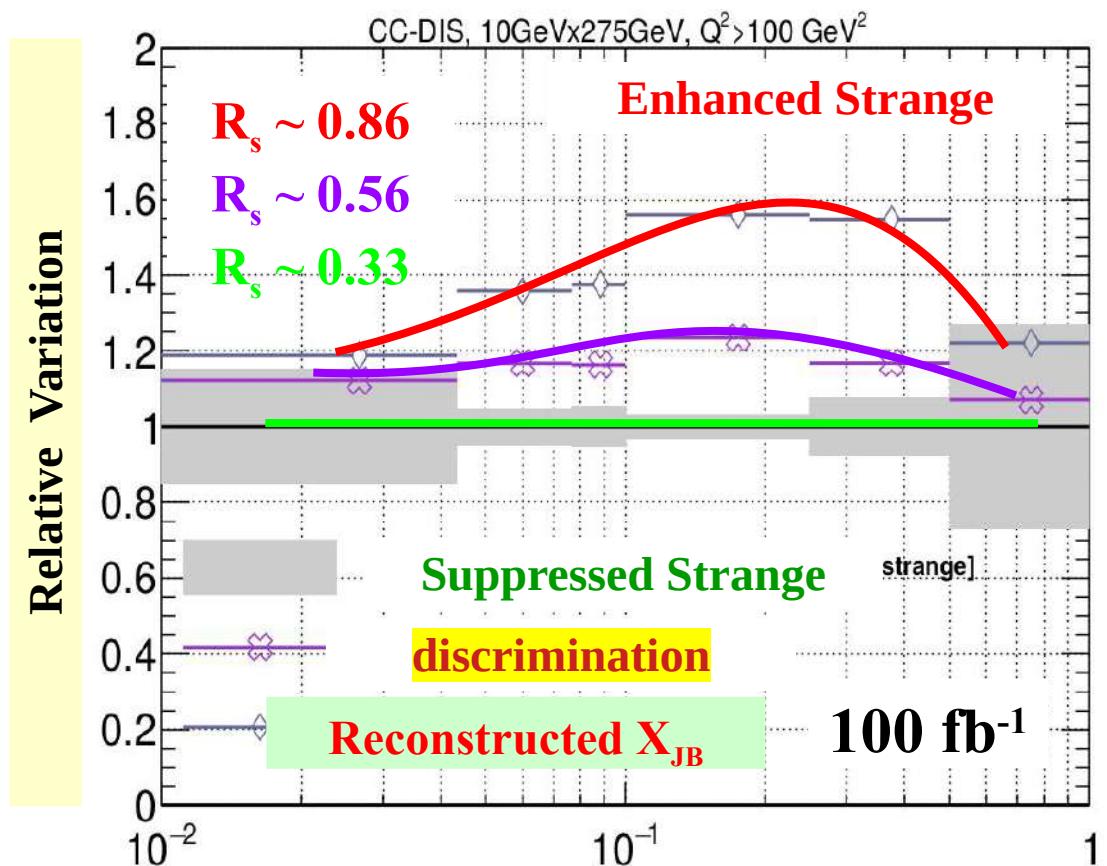
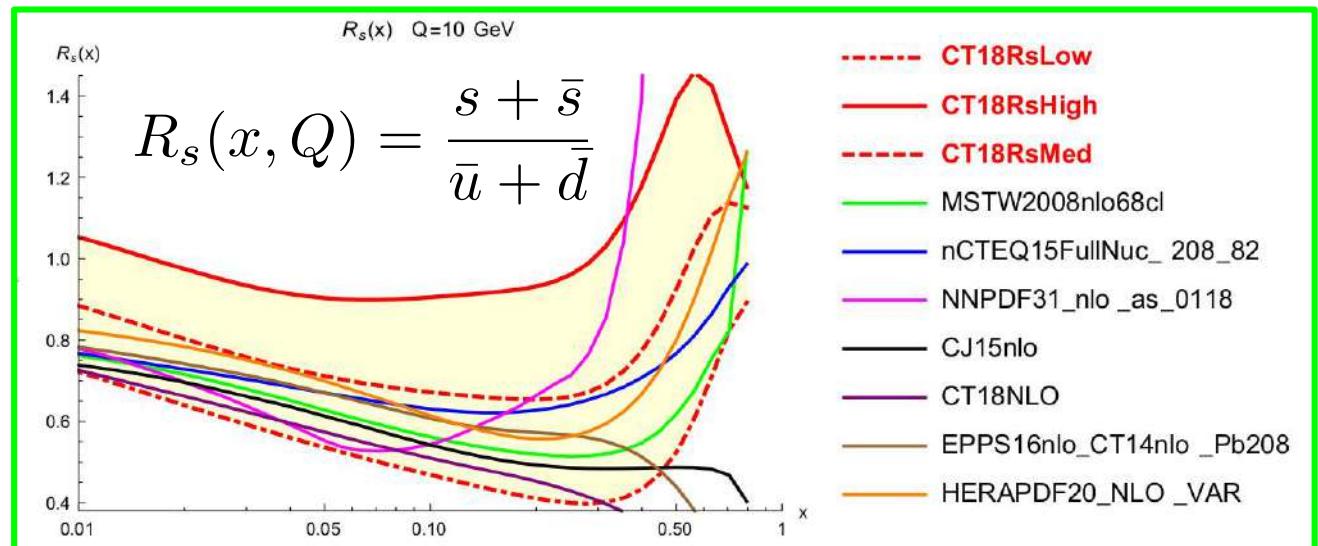
Miguel Arratia,<sup>1,2</sup> Yulia Furletova,<sup>2</sup> T. J. Hobbs,<sup>3,4</sup> Fredrick Olness,<sup>3</sup> and Stephen J. Sekula<sup>3,\*</sup>



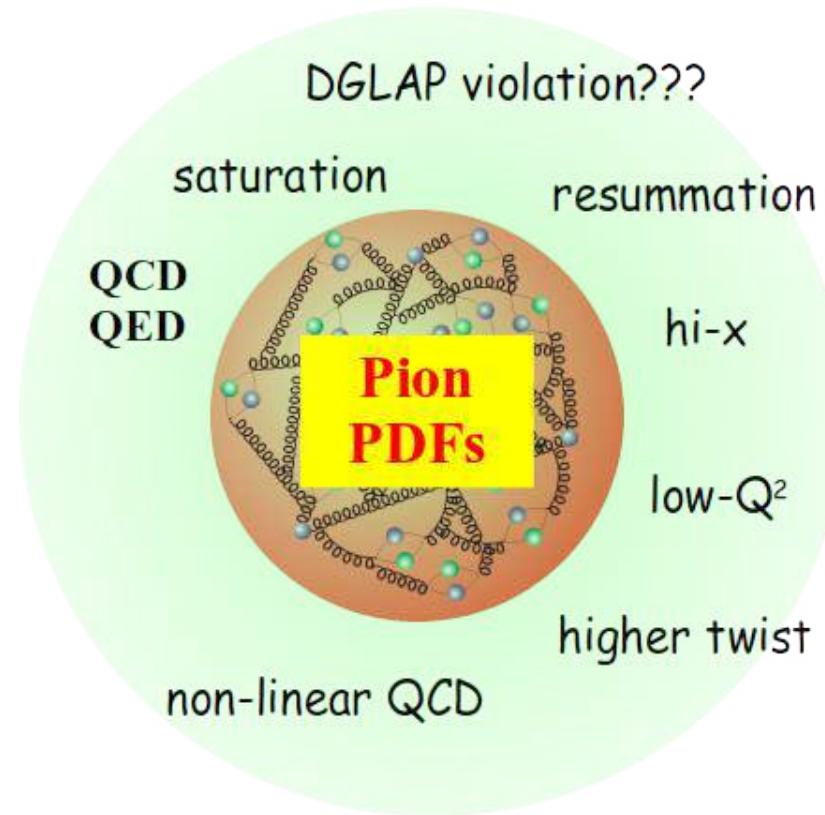


**W+S  $\rightarrow$  C<sub>jet</sub>**

**Clear measure of Strange PDF beyond uncertainties**



# Pion PDFs



## Parton Distribution Functions of the Charged Pion Within The xFitter Framework

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

# xFitter



[www.xFitter.org](http://www.xFitter.org)



## Sample data files:

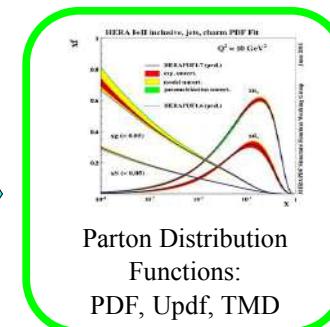
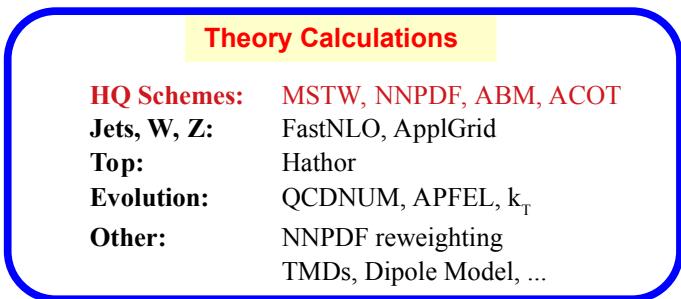
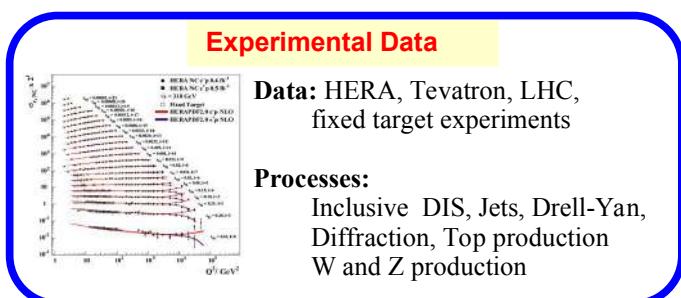
LHC: ATLAS, CMS, LHCb

Tevatron: CDF, D0

HERA: H1, ZEUS, Combined

Fixed Target: ...

User Supplied: ...



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

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 Threshold  
Improvements in  $\chi^2$  and correlations  
TMD PDFs (uPDFs)  
... and many other

**xFitter 2.0.1**  
**Old Fashioned**

# xFitter Pion PDFs



<https://www.xfitter.org/>

# xFitter

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

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

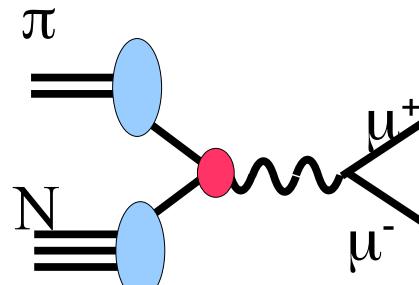
Experiment	$\chi^2/N_{\text{points}}$
E615	206/140
NA10 (194 GeV)	107/67
NA10 (286 GeV)	95/73
WA70	64/99



## Pions ( $\pi^-$ ) on Tungsten

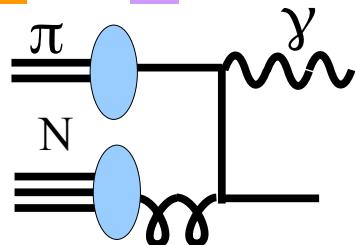
**E615**  $E_\pi = 252 \text{ GeV}$

**NA10**  $E_\pi = 194 \text{ GeV}$  &  $286 \text{ GeV}$



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

**WA70**  $\pi^+$   $\pi^-$



## NLO computation with MCFM / APPLGRID

- theory errors from  $\alpha_s$ , and nPDF uncertainties
- uncertainties include scale variations.
  - for factorization scale variation  
modify APPLGRID for two PDFs

# xFitter Pion PDFs

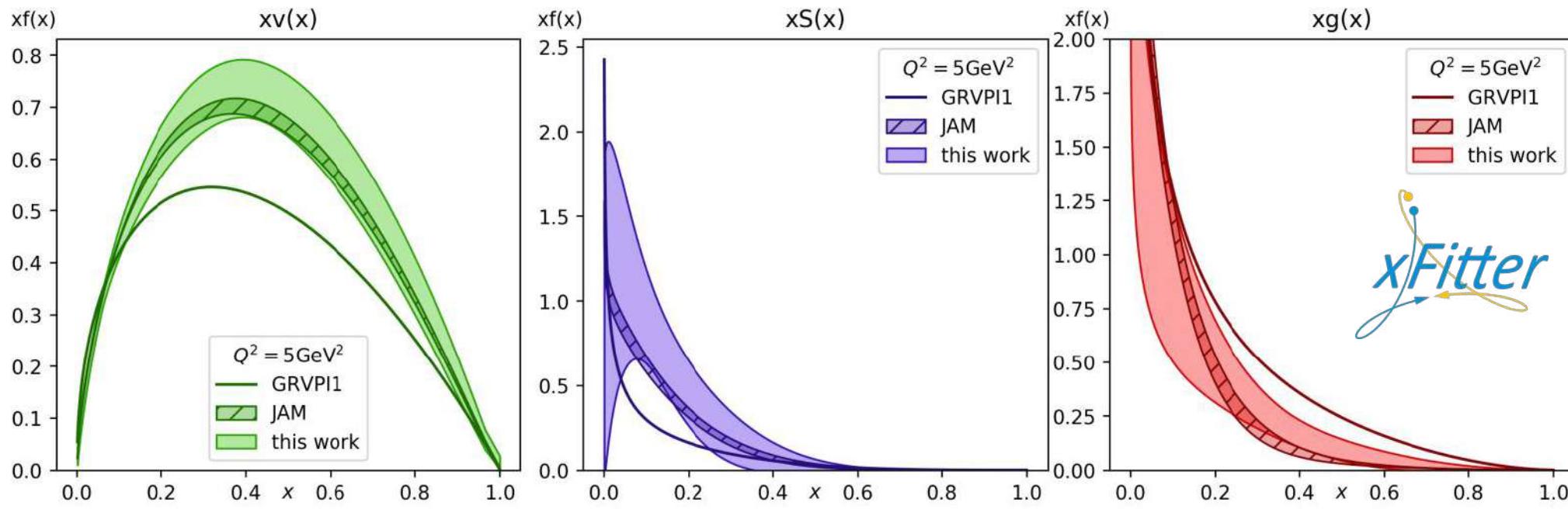
Experiment	Normalization uncertainty	$\chi^2 / N_{\text{points}}$
E615	15 %	206/140
NA10 (194 GeV)	6.4%	107/67
NA10 (286 GeV)	6.4%	95/73
WA70	32%	64/99

$$xv(x) = A_v x^{B_v} (1-x)^{C_v} (1 + D_v x^\alpha),$$

$$xS(x) = A_S x^{B_S} (1-x)^{C_S} / \mathcal{B}(B_S + 1, C_S + 1),$$

$$xg(x) = A_g (C_g + 1) (1-x)^{C_g},$$

	$\langle xv \rangle$	$\langle xS \rangle$	$\langle xg \rangle$	$Q^2 = 24$ (GeV $^2$ )
JAM [26]	$0.54 \pm 0.01$	$0.16 \pm 0.02$	$0.30 \pm 0.02$	1.69
JAM (DY)	$0.60 \pm 0.01$	$0.30 \pm 0.05$	$0.10 \pm 0.05$	1.69
this work	$0.55 \pm 0.06$	$0.26 \pm 0.15$	$0.19 \pm 0.16$	1.69
Lattice-3 [16]	$0.428 \pm 0.030$			4
SMRS [20]	$0.40 \pm 0.02$			4
Han et al. [42]	$0.428 \pm 0.03$			4
DSE [7]	$0.52$			4
this work	$0.50 \pm 0.05$	$0.25 \pm 0.13$	$0.25 \pm 0.13$	4
JAM	$0.48 \pm 0.01$	$0.17 \pm 0.01$	$0.35 \pm 0.02$	5
this work	$0.49 \pm 0.05$	$0.25 \pm 0.12$	$0.26 \pm 0.13$	5
Lattice-1 [14]	$0.558 \pm 0.166$			5.76
Lattice-2 [15]	$0.48 \pm 0.04$			5.76
this work	$0.48 \pm 0.05$	$0.25 \pm 0.12$	$0.27 \pm 0.13$	5.76
WRH [21]	$0.434 \pm 0.022$			27
ChQM-1 [11]	$0.428$			27
ChQM-2 [13]	$0.46$			27
this work	$0.42 \pm 0.04$	$0.25 \pm 0.10$	$0.32 \pm 0.10$	27
SMRS [20]	$0.49 \pm 0.02$			49
this work	$0.41 \pm 0.04$	$0.25 \pm 0.09$	$0.34 \pm 0.09$	49



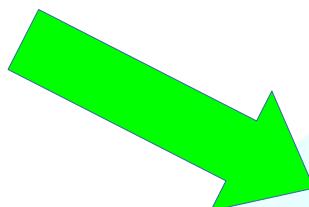
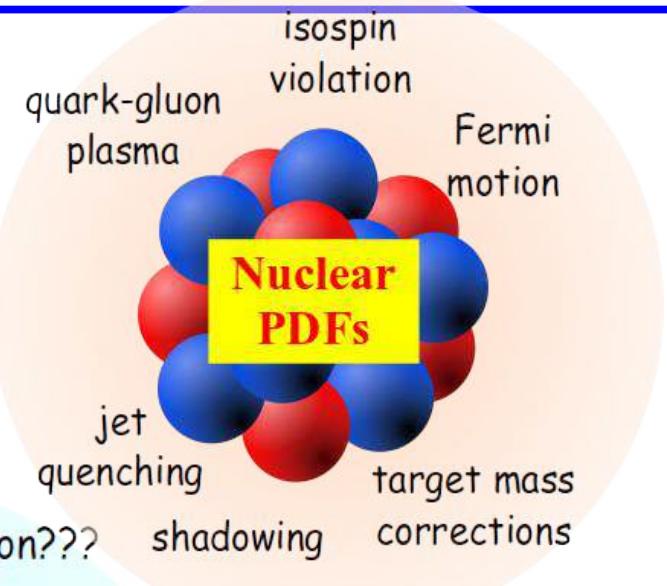
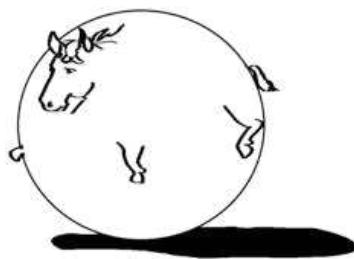
# Conclusion

One accurate  
**measurement**  
尺 is worth 尺  
**a thousand**  
expert opinions

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

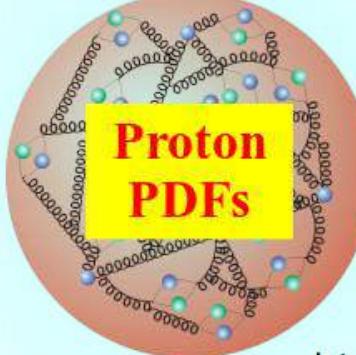
**QCD**  
Lagrangian

$$\mathcal{L}_{QCD} = \bar{\psi}_q (i\gamma_\mu D^\mu - m_q) \psi_q - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}$$



saturation

QCD  
QED



resummation

hi-x

low- $Q^2$

higher twist

QCD  
QED

resummation

hi-x

low- $Q^2$

higher twist

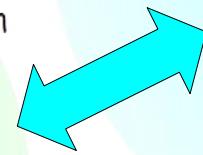
QCD  
QED

DGLAP violation???

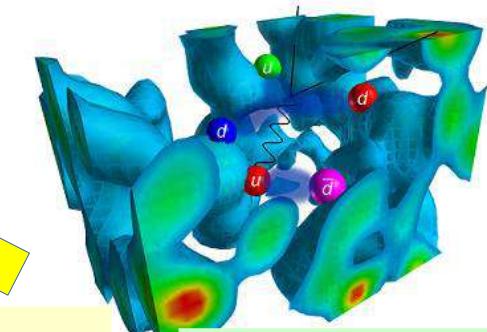
saturation

Pion  
PDFs

non-linear QCD



non-linear QCD



- Hadron Spin
- Generalized PDFs

Lattice QCD

