Nuclear PDFs & lepton—nucleon scattering

From Quarks to Hadrons

Fred Olness
SMU

Thanks for substantial input
from my friends & colleagues

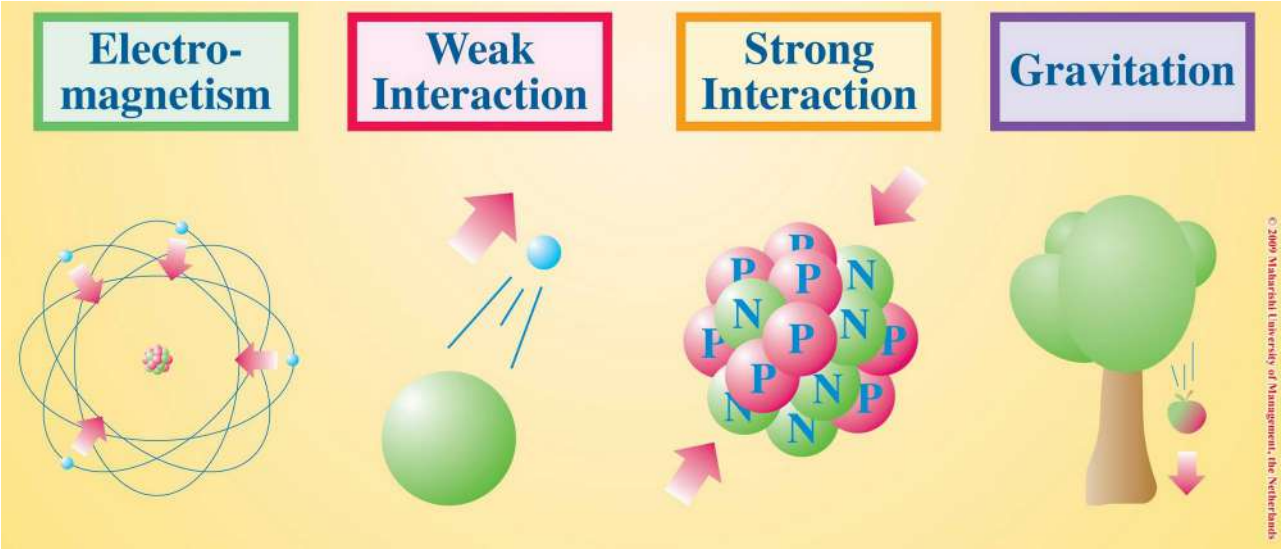
C T E Q

xFitter

nCTEQ
nuclear parton distribution functions

JLab

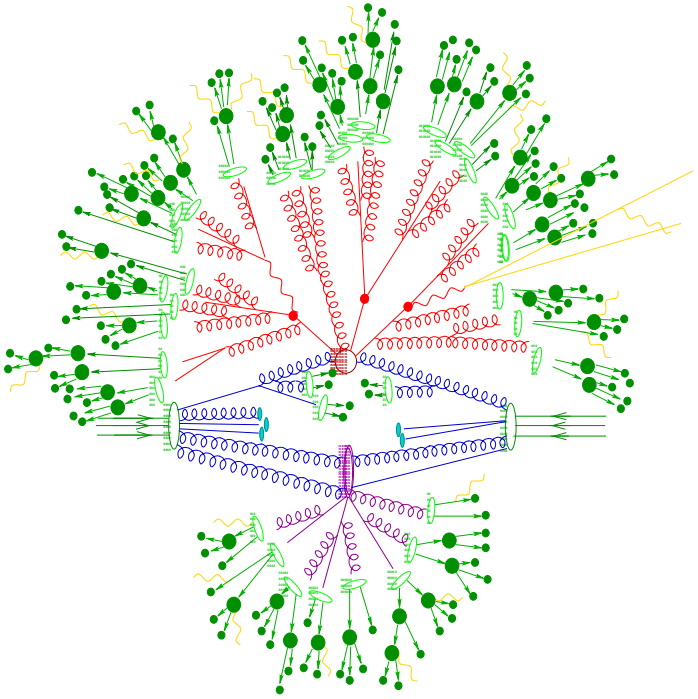
16 July 2020



QCD is our most perfect physical theory

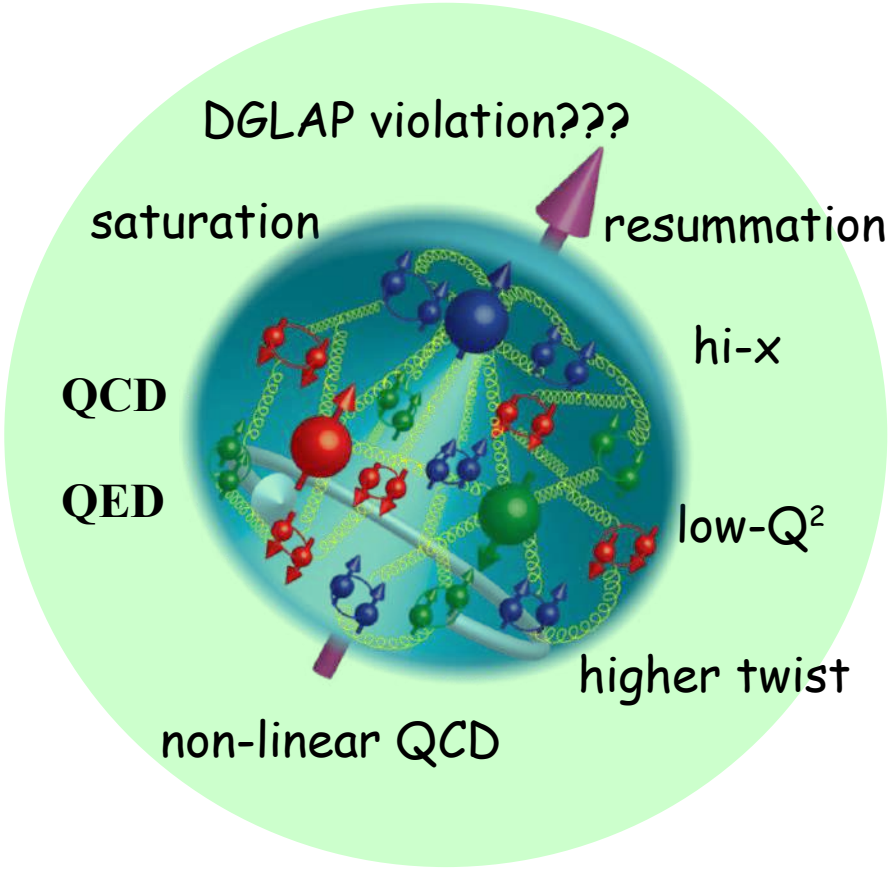
What QCD Tells Us About Nature – and Why We Should Listen. *Frank Wilczek*

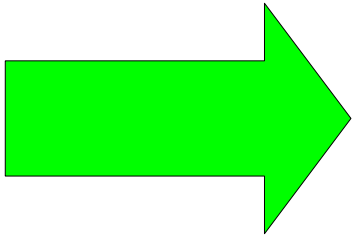
In many respects, our most complex
- asymptotic freedom
- strong color confinement
- … associated manifestations

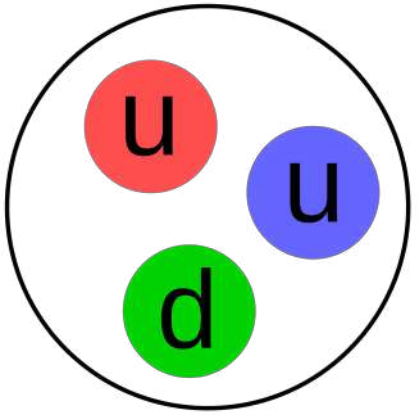


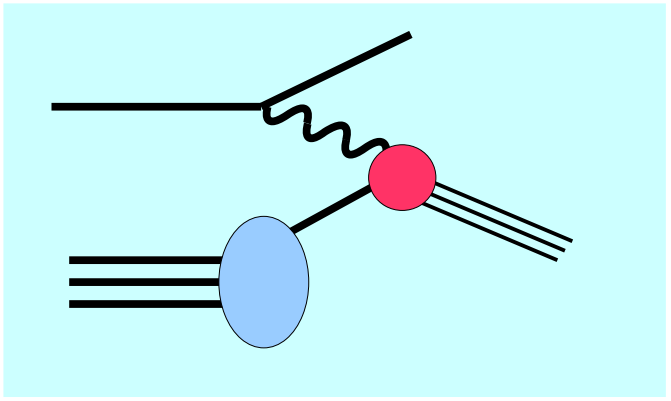
Lessons: The Nature of Nature

"… alien, simple, beautiful, weird, & comprehensible"

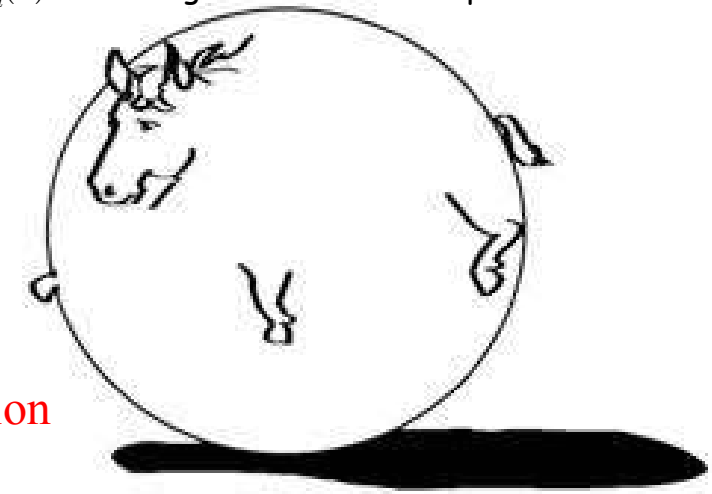








$f_a(x)$ … working in the limit of a spherical horse …



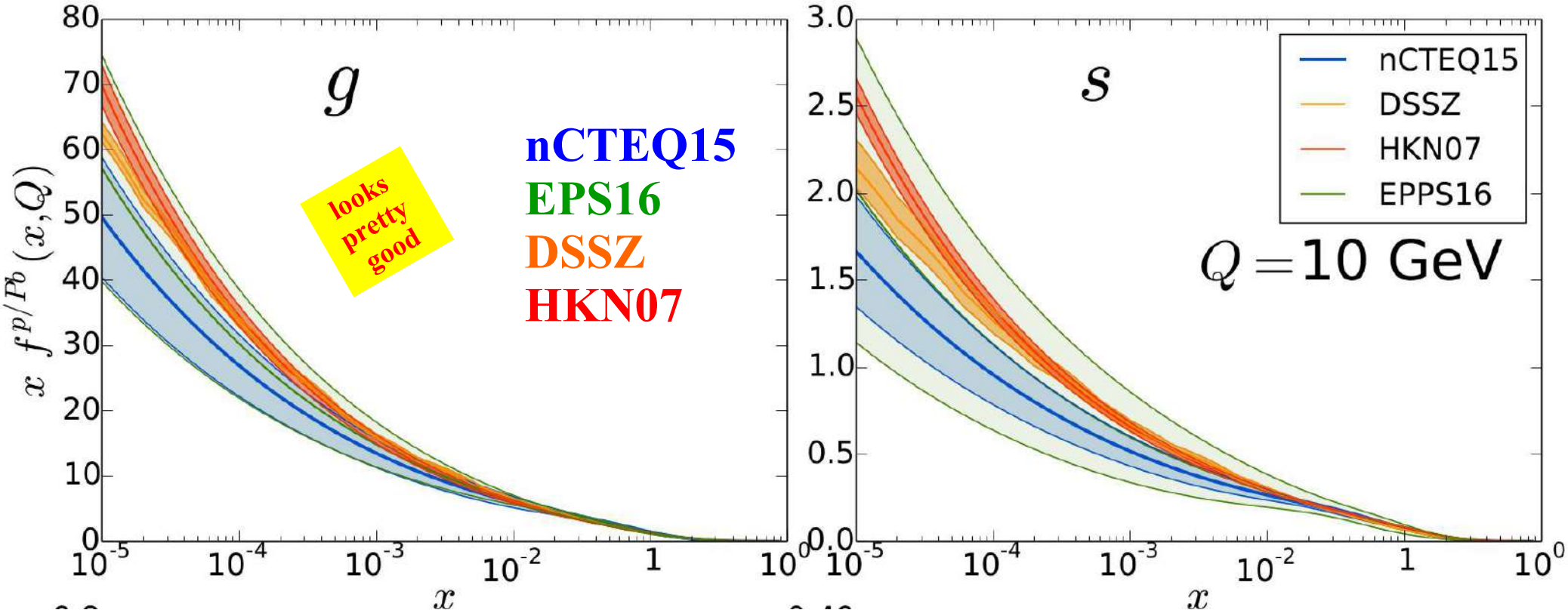
The QCD Parton Model

$$d\sigma = f_a(x,Q) \otimes \hat{\sigma}$$

Parameterized in terms of a single variable x, the momentum fraction

… use DGLAP to determine Q dependence

Nuclear PDFs: Complementary efforts in general agreement

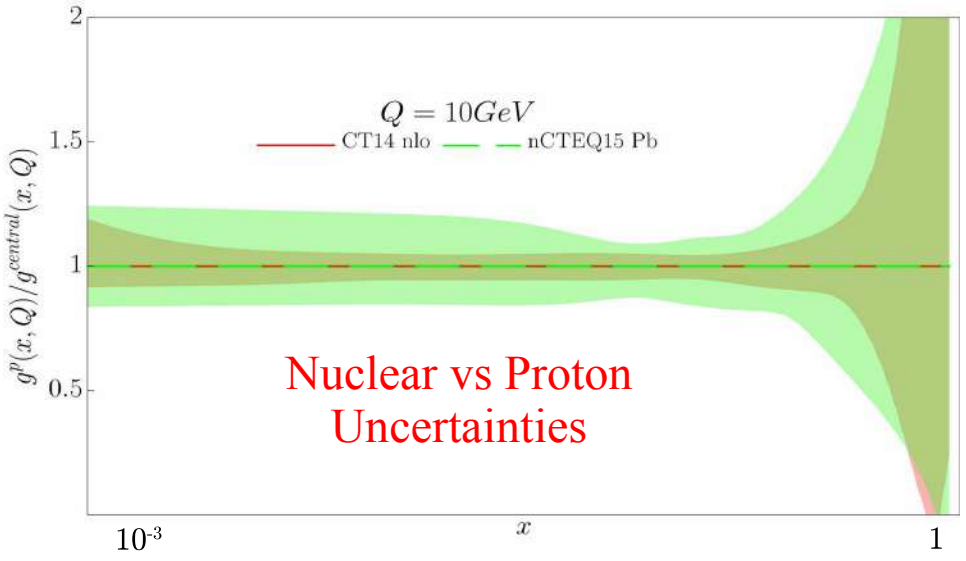


Nuclear PDFs are more complex

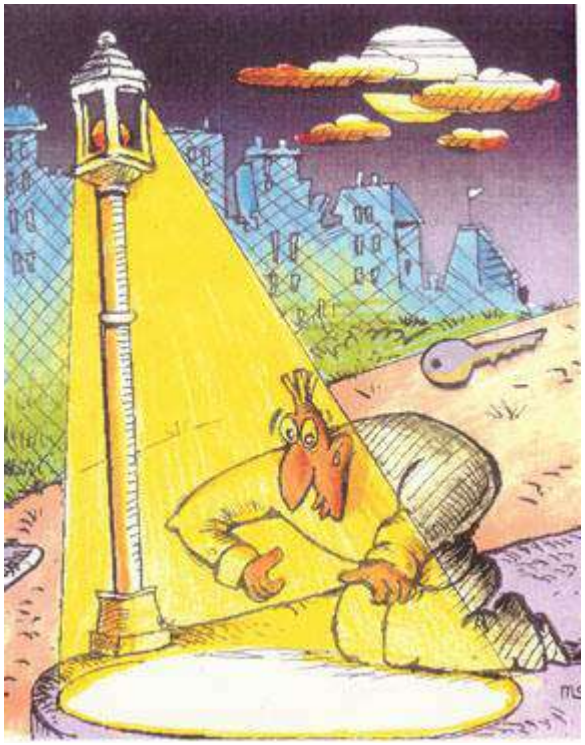
more DOF than Proton case

more "issues" to consider

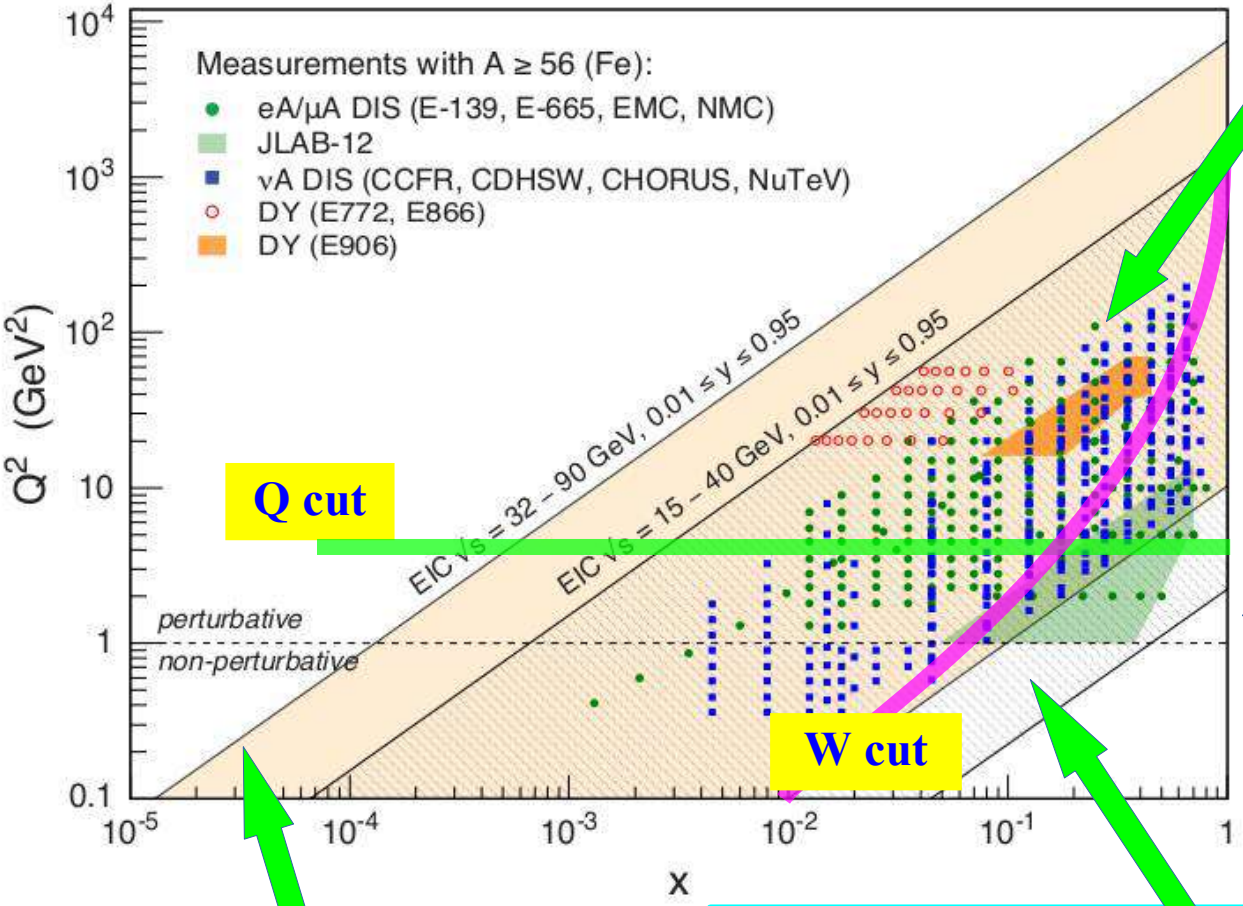
more work to do ...



The Challenges



nPDFs: Extend Kinematic Reach 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

Warm-up:

JLab Data @ Hi-X Low-Q^2

extend nCTEQ framework for this region & prepare for EIC

Low-x:

Shadowing

Recombination

Resummation

Low-Q^2:

Non-Perturbative inteface

collective effects

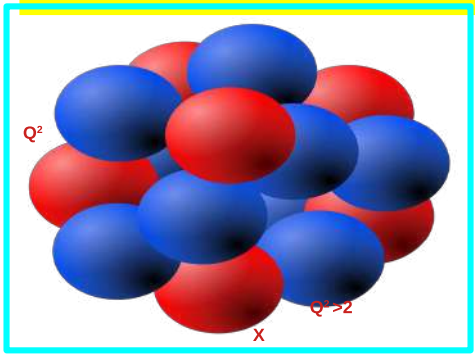
Target Mass Corrections

pick up M^2/Q^2 higher twist

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

Run at multiple energies

Efrain Segarra w/ **nCTEQ**



nCTEQ Wish List

Fred Olness w/ help from: Tim Hobbs, Aleksander Kusina, Pavel Nadolsky, Tomas Jezo, Thia Keppel, Michael Klasen, Karol Kovarik, Jorge Morfin, Ingo Schienbein, Efrain Segarra, Steve Sekula

nCTEQ
nuclear parton distribution functions

CTEQ

Low-Q:

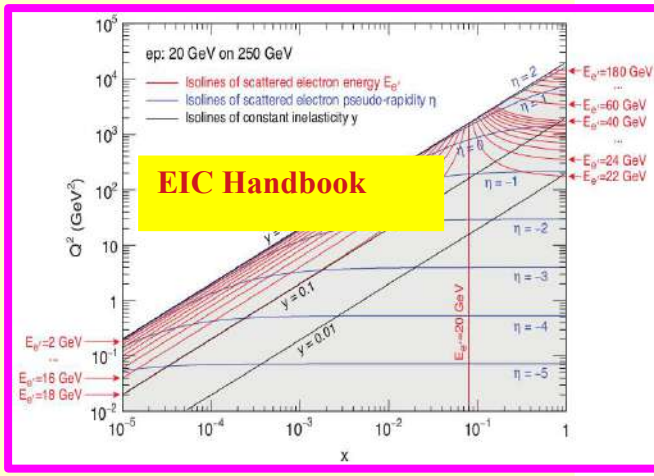
Higher-Twist, Non-Pert, Resummation

Hi-x:

TMC, Nuclear x>1, …

Strange PDF:

Disentangle: 1) proton PDF
2) nuclear corrections
3) flavor components



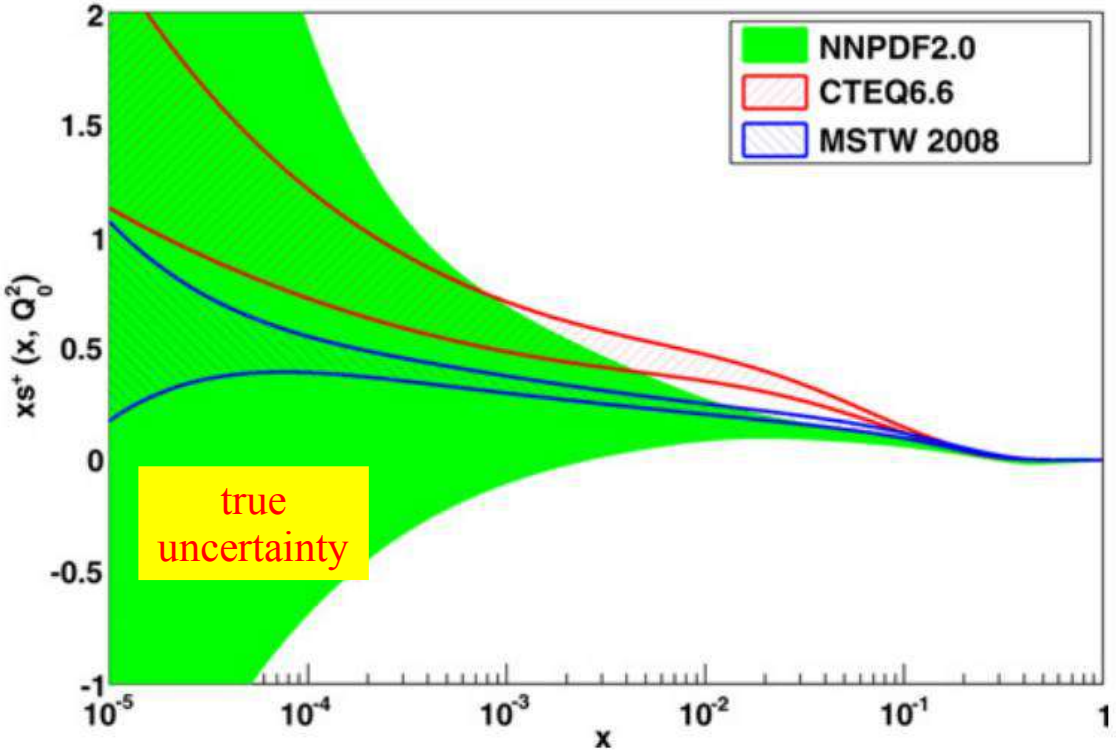
Gluon (& Charm+Bottom):

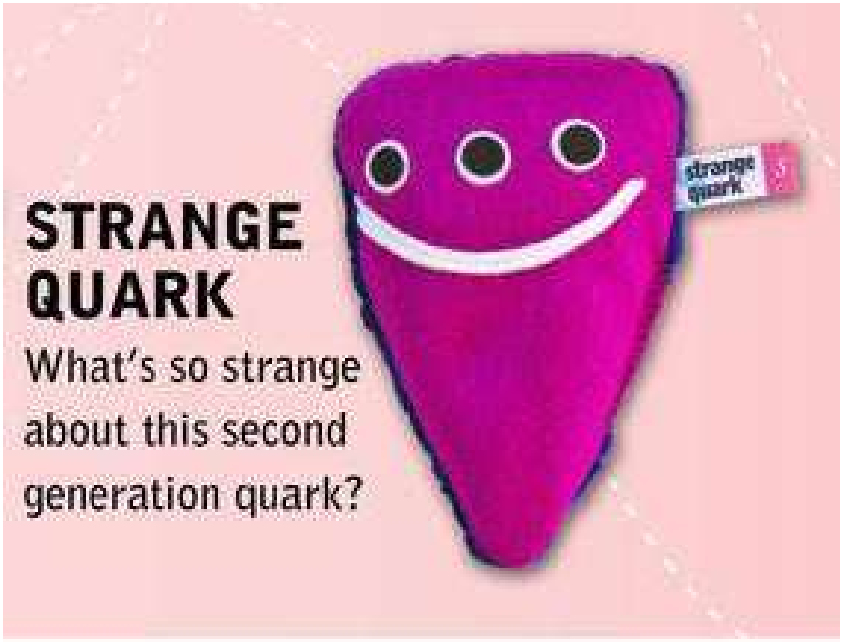
Improve R_G via F_L: window on NLO and mass effects

Nuclear A:

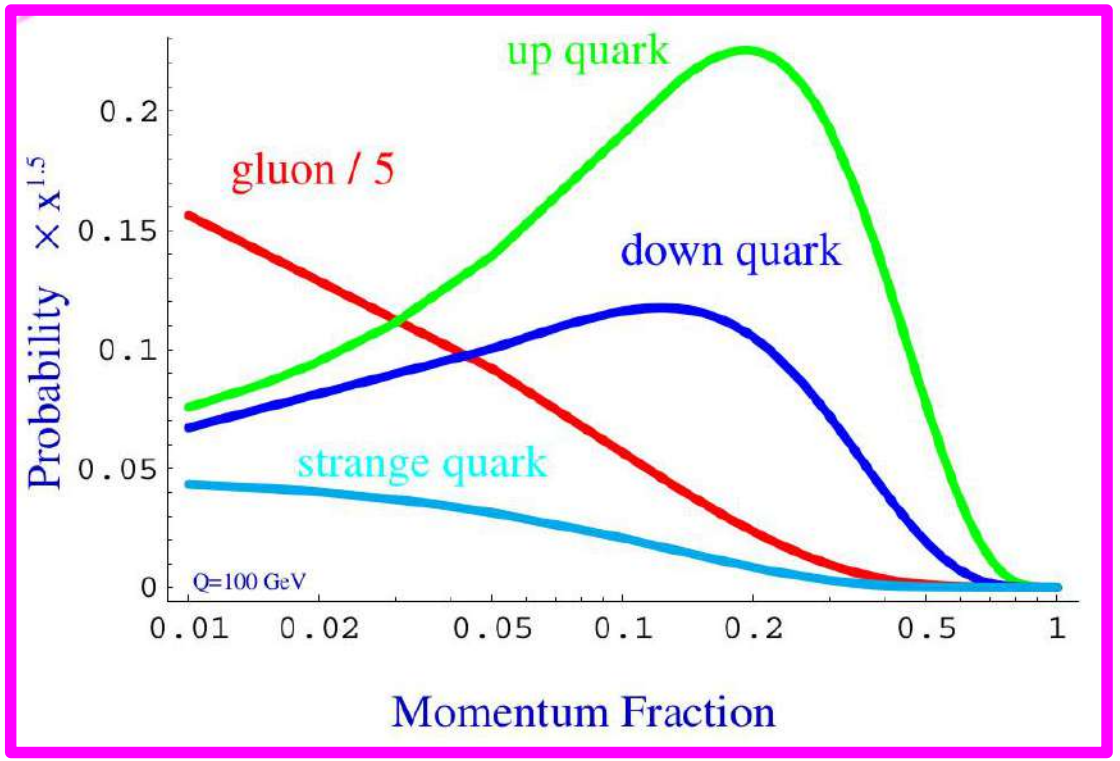
Map out A dependence … and maybe beyond

Case Study: The Strange PDF



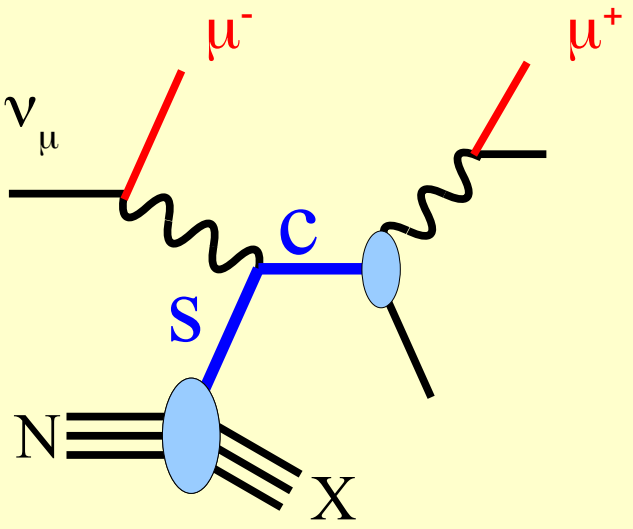


Strange PDF: ν N di-muon Production

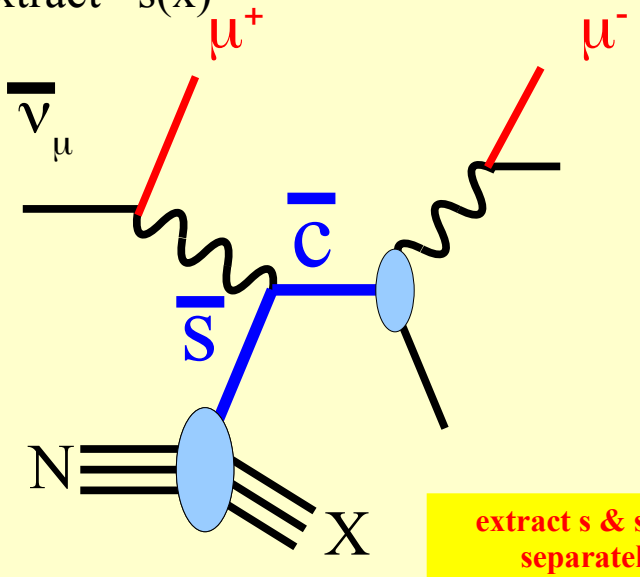


Need to "dig out" s(x) underneath d(x)

Extract s(x)



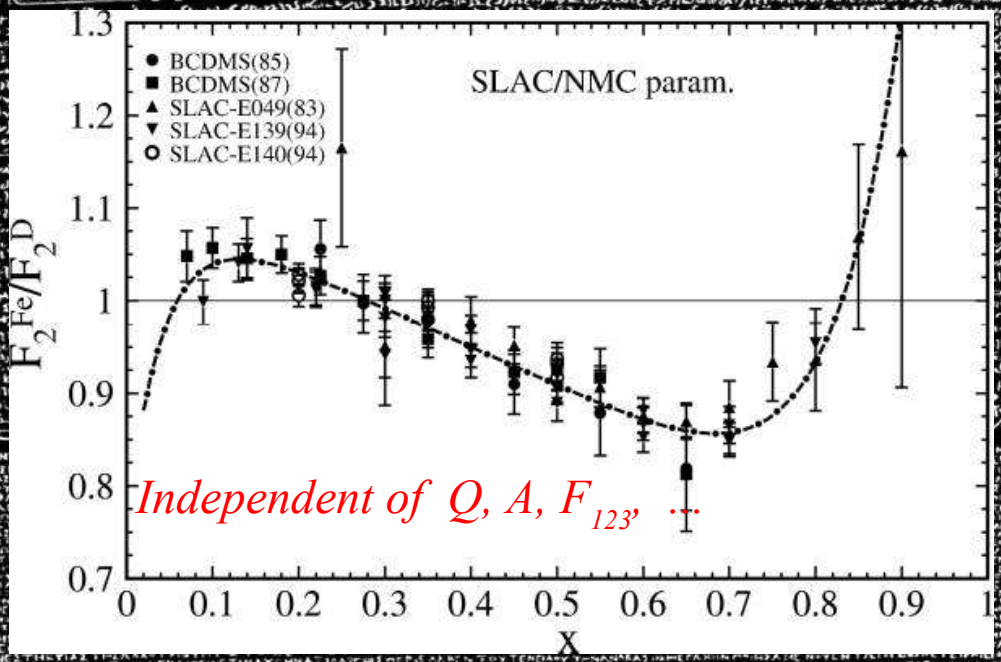
Extract $\bar{s}(x)$



extract s & s-bar separately

Where do nuclear corrections come from ????

We need to deal with the Nuclei

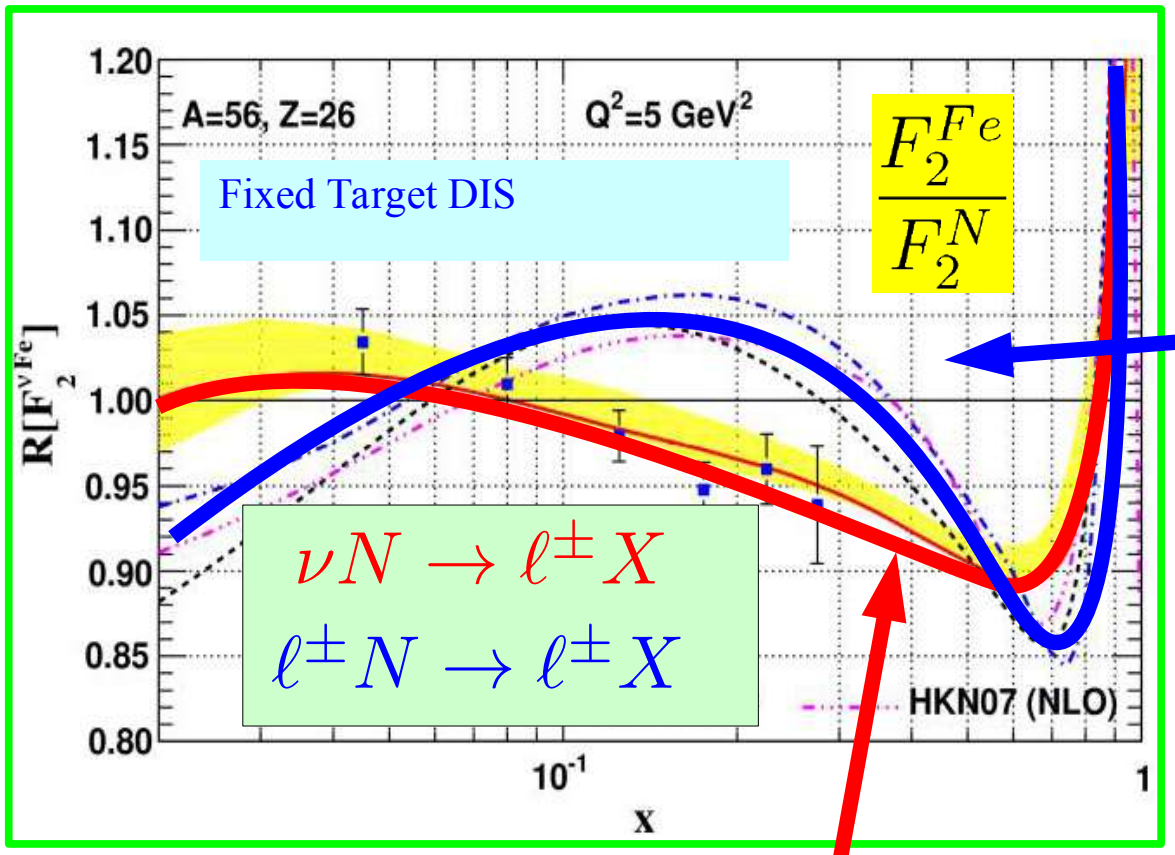


The ratio of iron (Fe) to Deuterium (D)

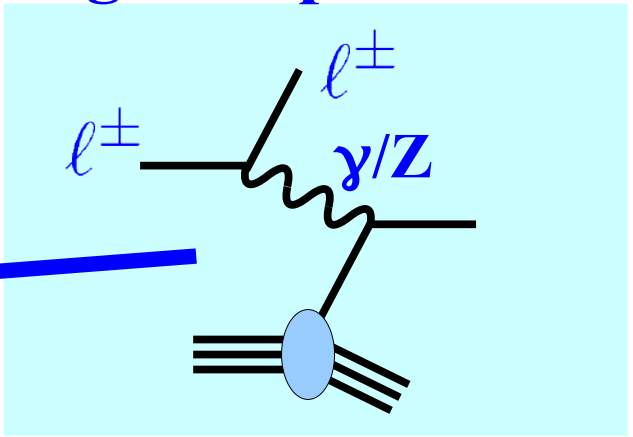
$$\frac{F_2^{Fe}}{F_2^D}$$

Discovered by the French in 1799 at Rosetta, a harbor on the Mediterranean coast in Egypt. Comparative translation of the stone assisted in understanding many previously undecipherable examples of hieroglyphics.

Puzzle: What is the Nuclear Correction

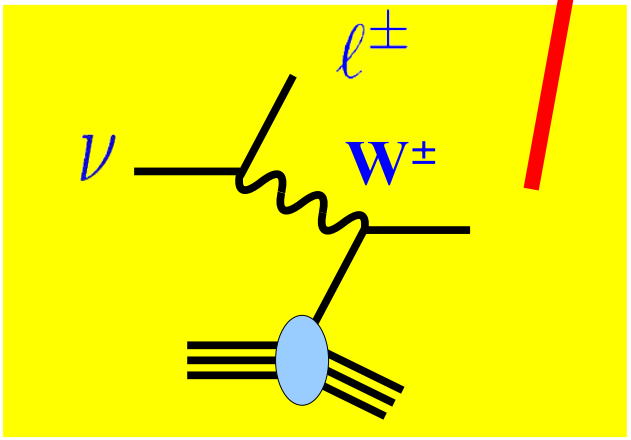


Charged Lepton DIS

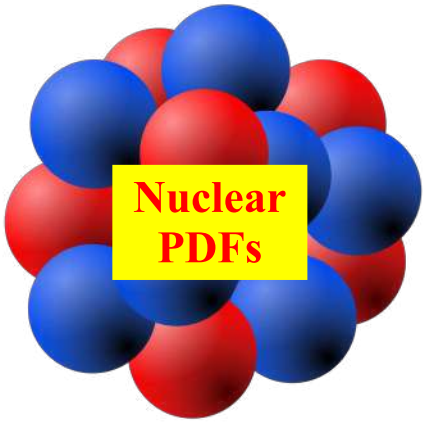


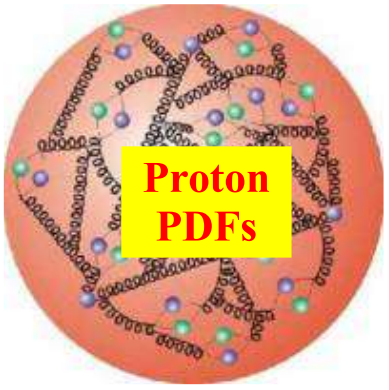
some caveats
... correlated errors

Depends on nuclear corrections



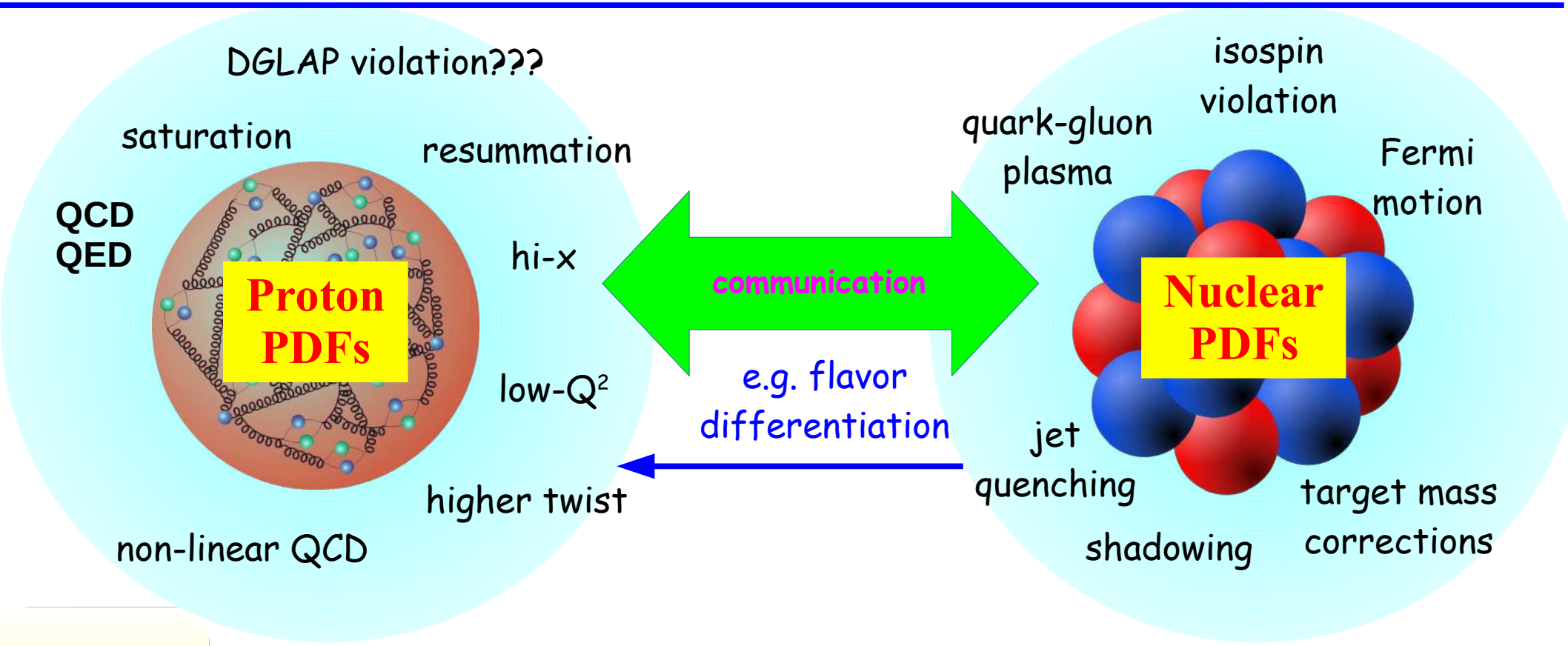
Neutrino DIS





Propagation of γ/W thru nuclei

… the motivation for nCTEQ



T.J. Hobbs
T. Jezo,
C. Keppel,
M. Klasen
K. Kovarik
A Kusina,
J. Morfin,
F. Olness
J. Owens,
I. Schienbein,
J. Yu

Data from nuclear targets play a key role in the flavor differentiation

nCTEQ

nuclear parton distribution functions

… *not just*

Nuclear PDFs

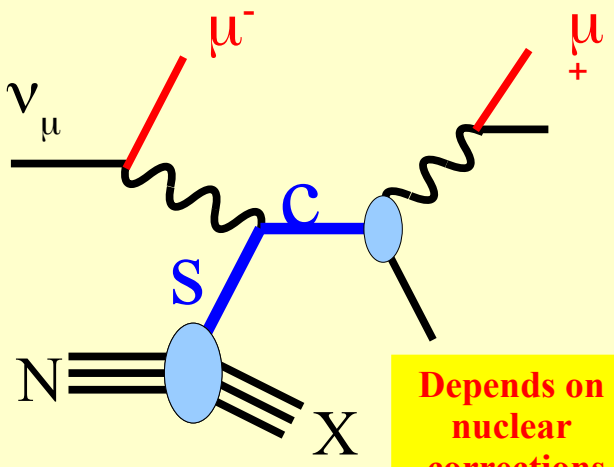
Nuclear PDFs are ESSENTIAL for proton PDFs

neutrino DIS

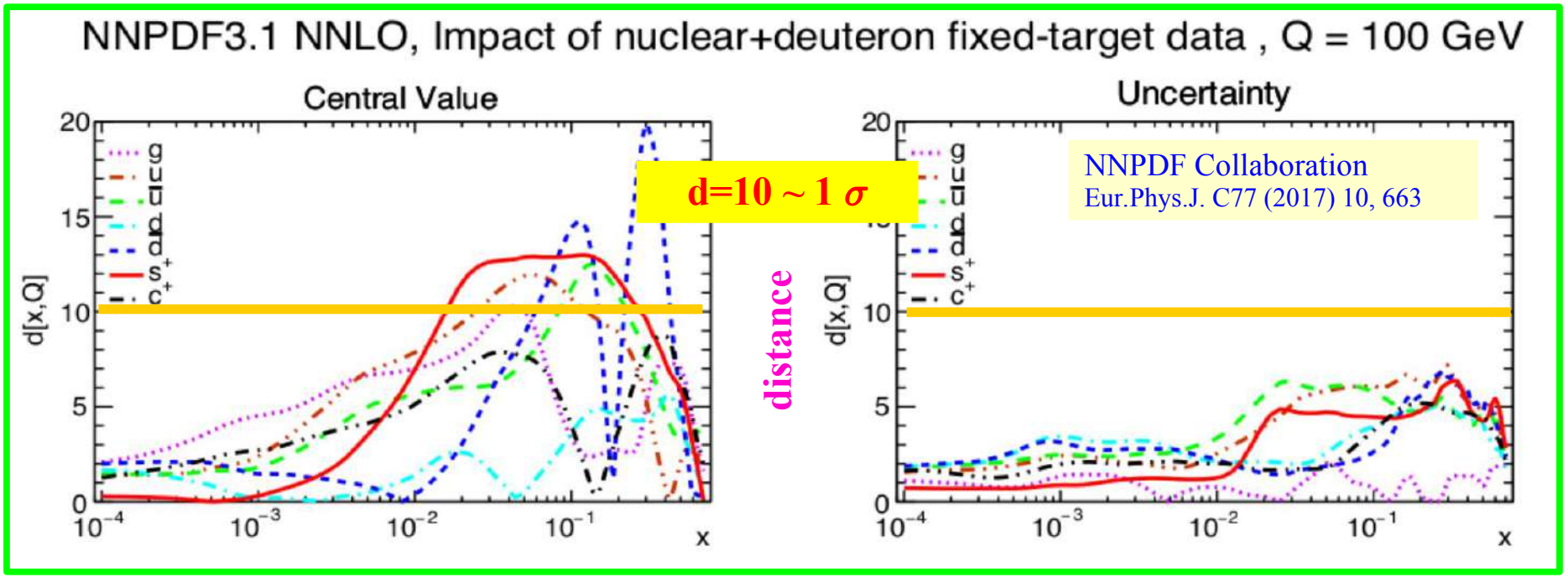
$$F_2^{\nu} \sim \left[d + s + \bar{u} + \bar{c}\right]$$
$$F_2^{\bar{\nu}} \sim \left[\bar{d} + \bar{s} + u + c\right]$$
$$F_3^{\nu} \sim 2\left[d + s - \bar{u} - \bar{c}\right]$$
$$F_3^{\bar{\nu}} \sim 2\left[u + c - \bar{d} - \bar{s}\right]$$

Differentiate flavors of free-proton PDFs:

Neutrino DIS



Depends on nuclear corrections



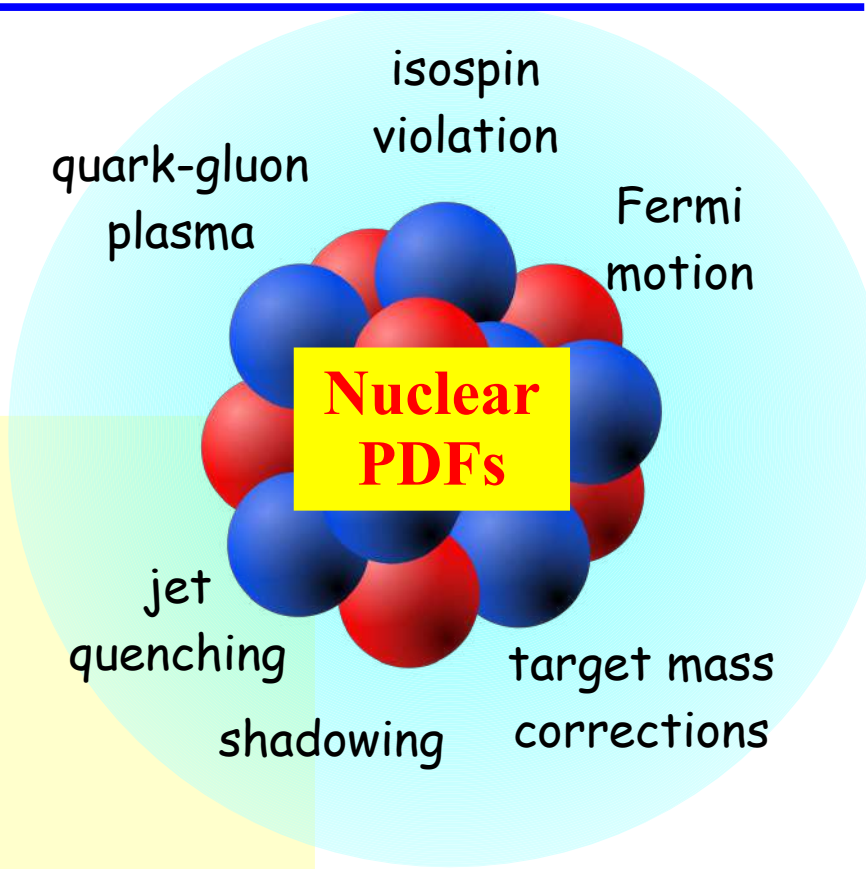
"... for the time being it is still appears advantageous to retain nuclear target data in the global dataset for general-purpose PDF determination"

Nuclear PDF

The Players
The Ingredients

nPDFs

nuclear parton distribution functions



HKN'07: Hirai, Kumano, Nagai
[PRC 76, 065207 (2007)]

DSSZ'11: de Florian, Sassot, Stratmann, Zurita
[PRD 85, 074028 (2012)]

nCTEQ'15: nCTEQ Collaboration
[PRD 93, 085037 (2016)]

EPPS'16: Eskola, Paakkinen, Paukkunen, Salgado
Eur.Phys.J. C77 (2017) no.3, 163

TUJU'19: Tubingen & Jyvaskyla
[Walt, Helenius, Vogelsang Phys. Rev. D 100, 096015 (2019)]

nNNPDF2.0: NNPDF Collaboration
[Khalek, Ethier, Rojo, van Weelden arXiv:2006.14629 (2020)]

Data sets & cuts for nPDF fits

NC DIS & DY

SLAC E-139 & E-049
N = (D, Ag, Al, Au, Be,C, Ca, Fe, He)

CERN BCDMS & EMC & NMC
N = (D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W)

DESY Hermes
N = (D, He, N, Kr)

FNAL E-665
N = (D, C, Ca, Pb, Xe)

FNAL E-772 & E-886
N = (D, C, Ca, Fe,W)

Neutrino DIS*

NuTeV CHORUS CCFR & NuTeV
N = Pb & Fe

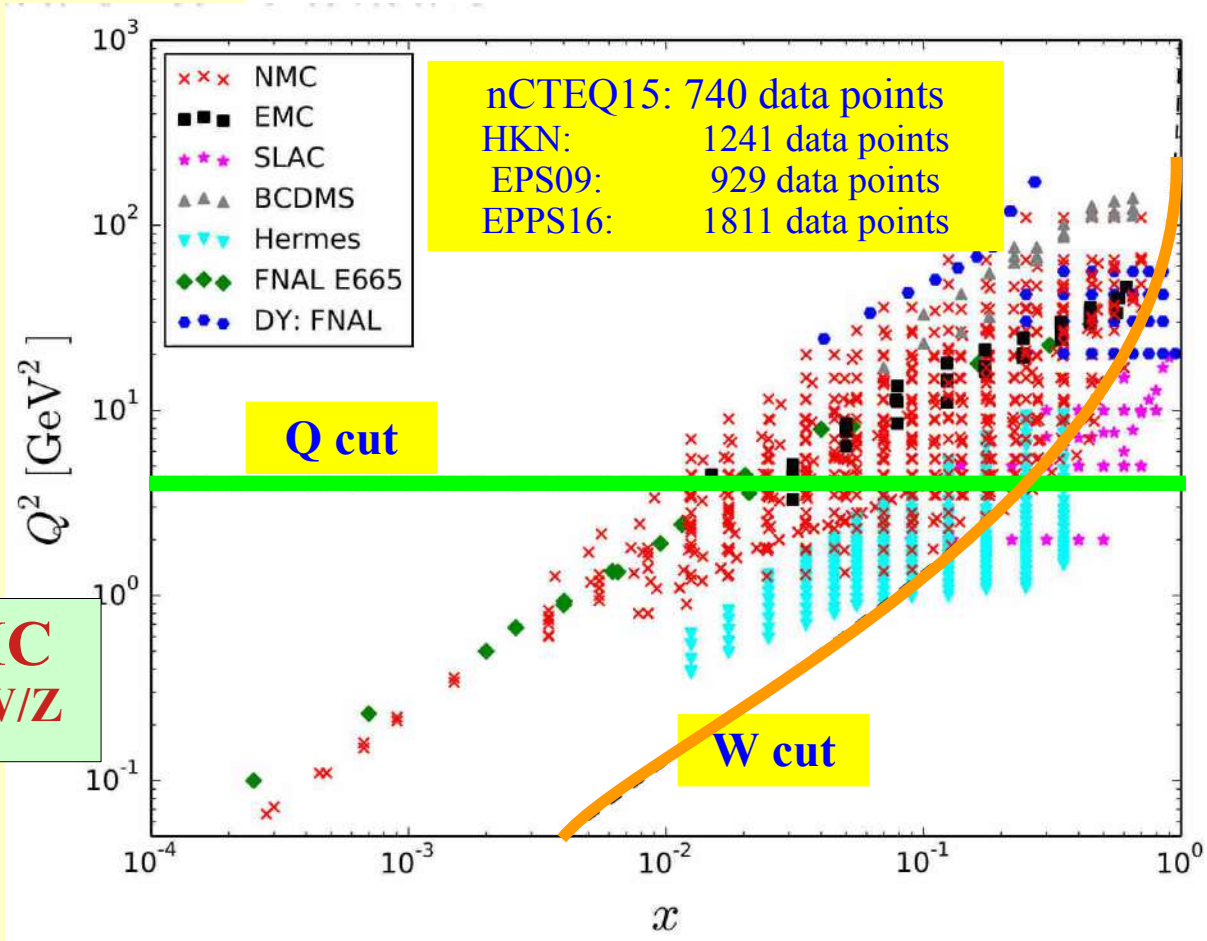
Pion Production:

RHIC: PHENIX & STAR
N = Au

will show comparision w/ LHC pPb

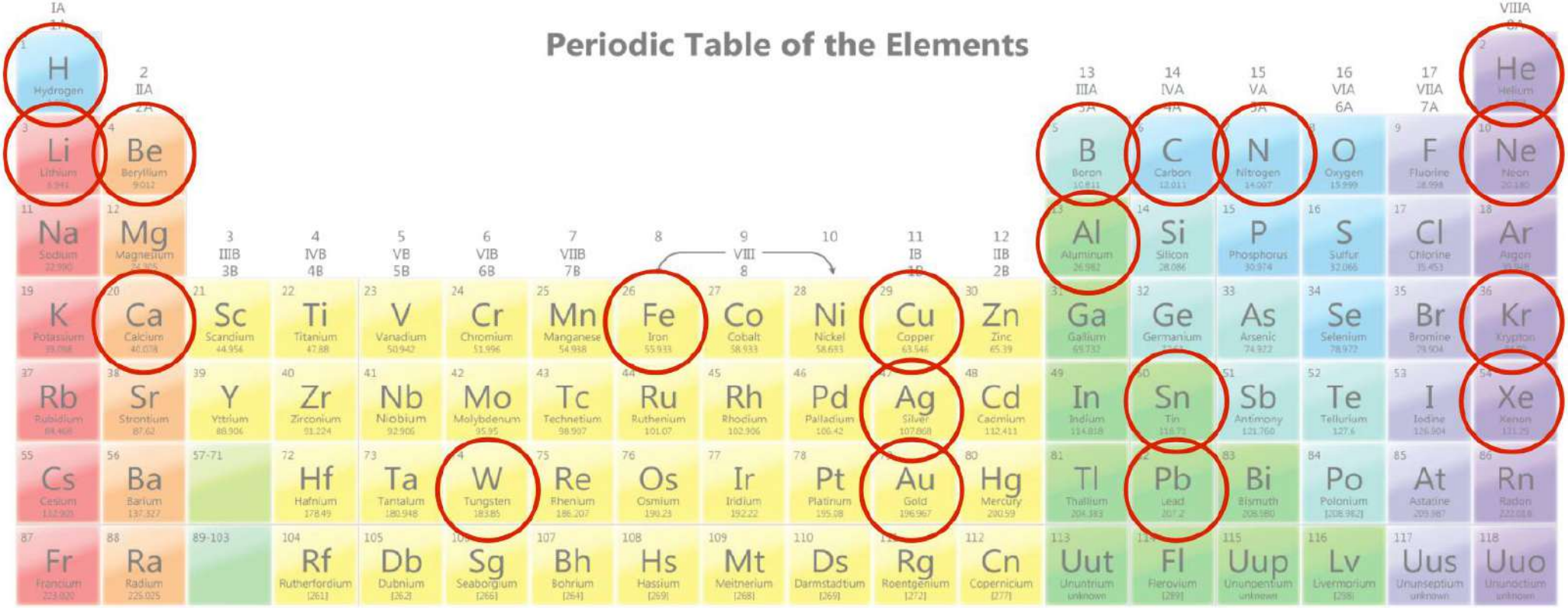
+ LHC
dijet, W/Z

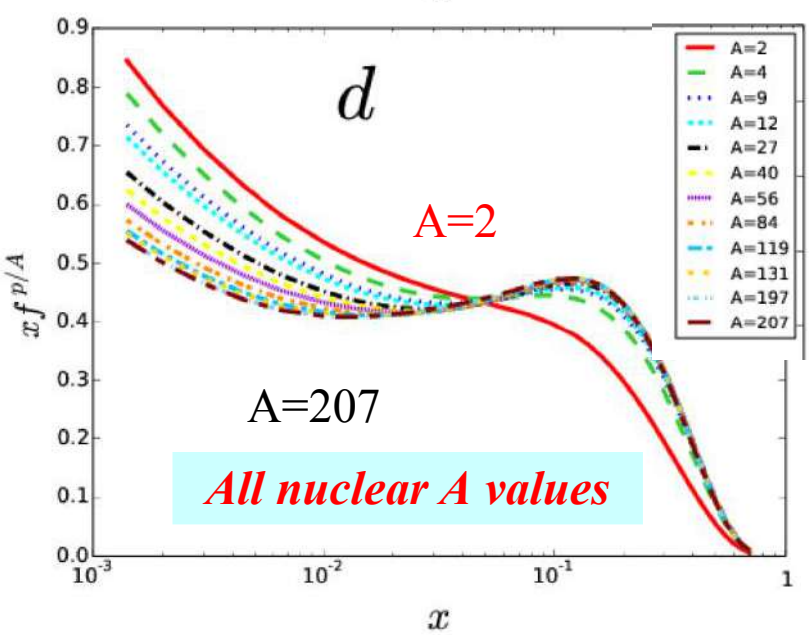
DIS Cuts:
nCTEQ: Q>2.0 & W>3.5
EPPS16: Q>2.0 & W>3.5
EPS09: Q>1.3
HKN: Q>1.0
DSSZ: Q>1.0



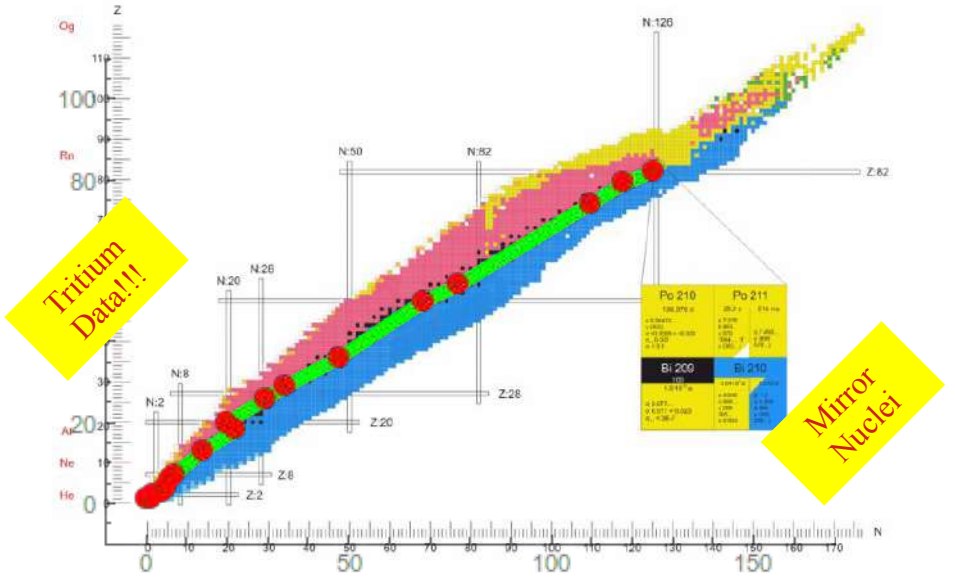
proton vs nuclear: fewer data and more DOF ... impose assumptions on nPDFs

Nuclear PDFs: DIS, DY, π Prod, *(new)* Di-Jet



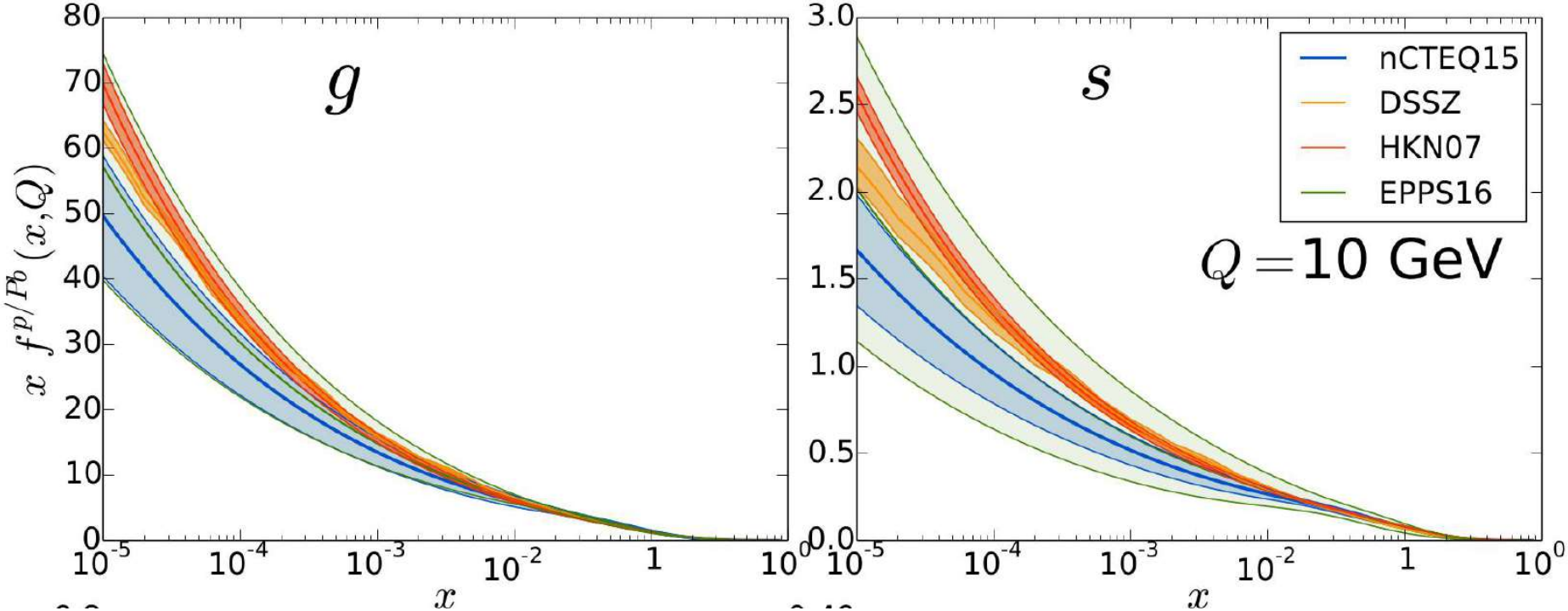


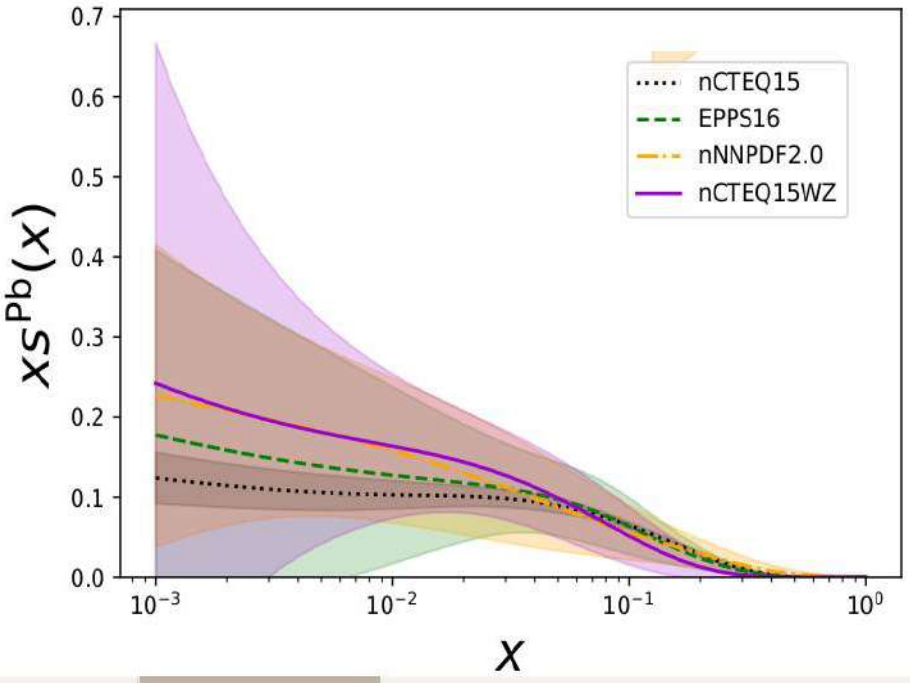
All nuclear A values

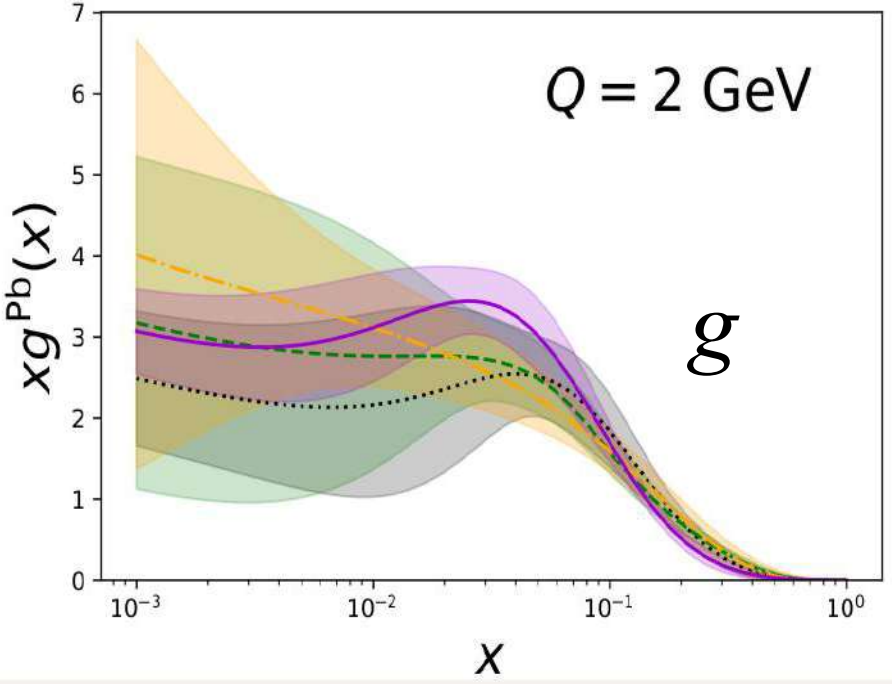


… expand our knowledge of nuclear A dimension

Selected Nuclear PDFs







some details ...

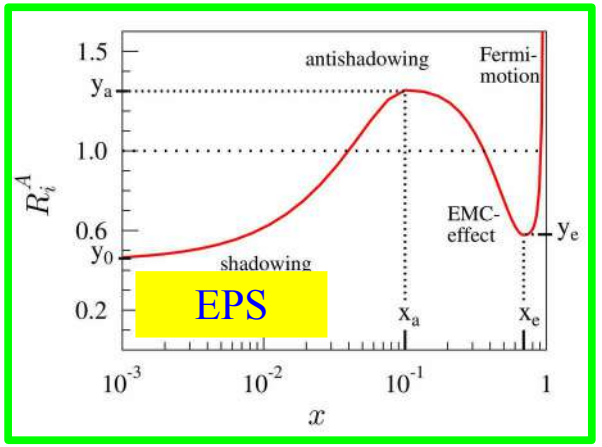
1) Multiplicative nuclear correction factors (HKN, EPPS, DSSZ)

$$f_i^{p/A}(x_N, Q_0) = R_i(x_N, Q_0, A)\; f_i^{free\ proton}(x_N, Q_0)$$

... for example

HKN

$$R_i(x, Q_0, A) = 1 + \left(1 - \frac{1}{A^\alpha}\right) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$$



2) Generalized A-parameterization (nCTEQ)

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

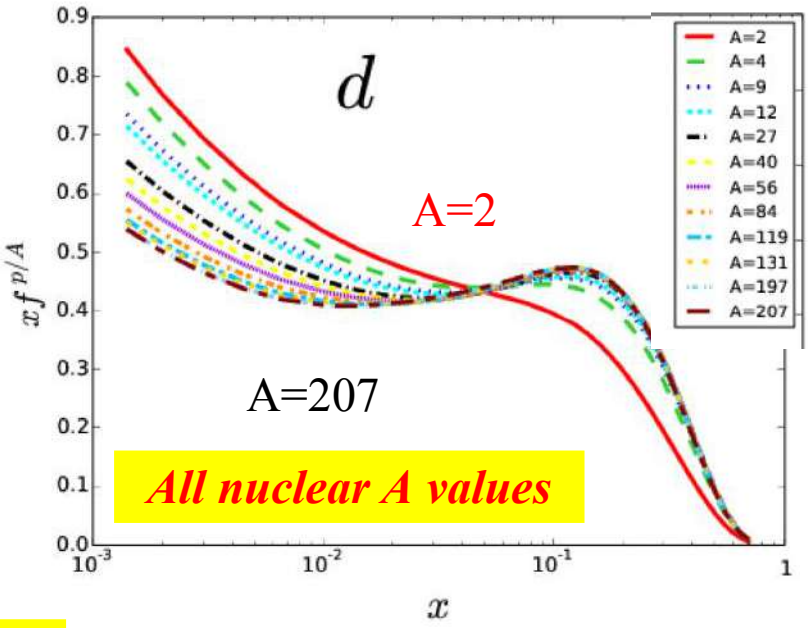
$$f \sim \ldots x^{c_1(A)}(1-x)^{c_2(A)}\ldots$$

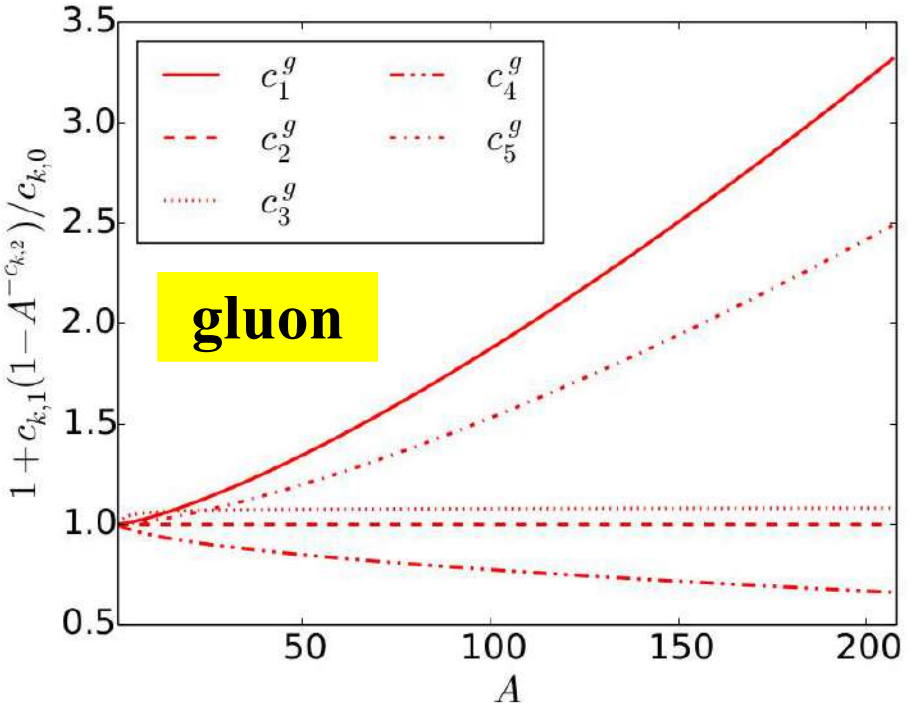
$$c_k \sim c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right)$$

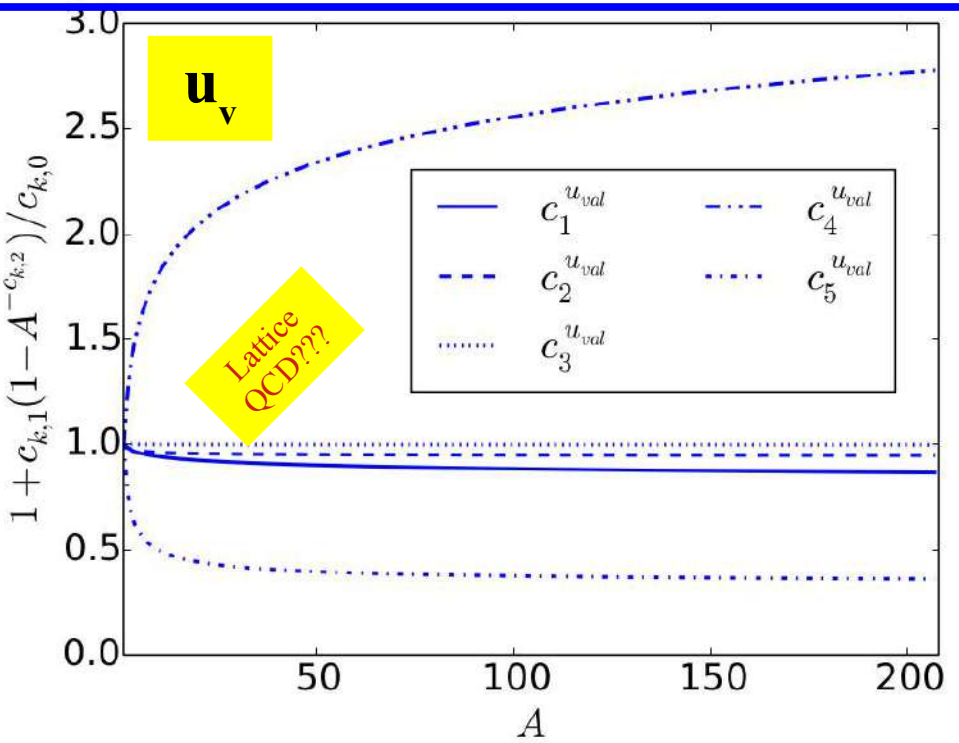
Proton

Nuclear

use proton as a Boundary Condition







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

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

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

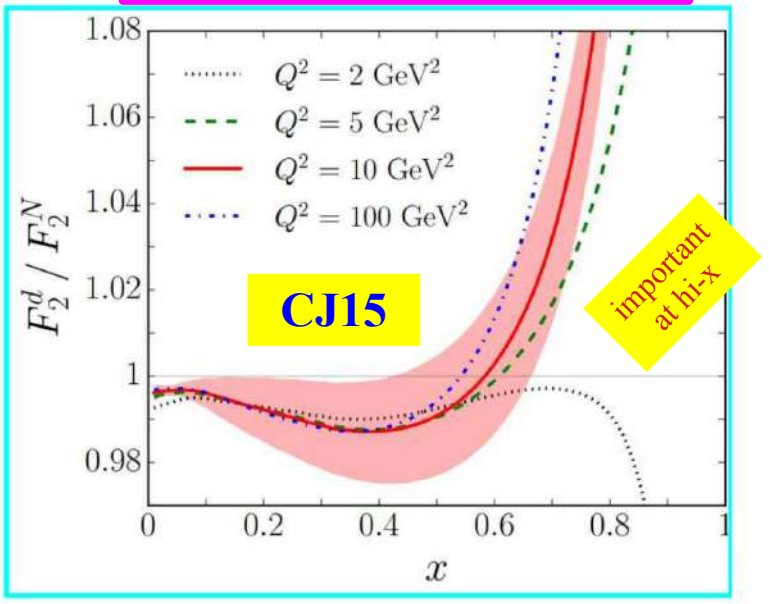
Proton

Nuclear

use proton as a Boundary Condition

To Do: Deut Corr

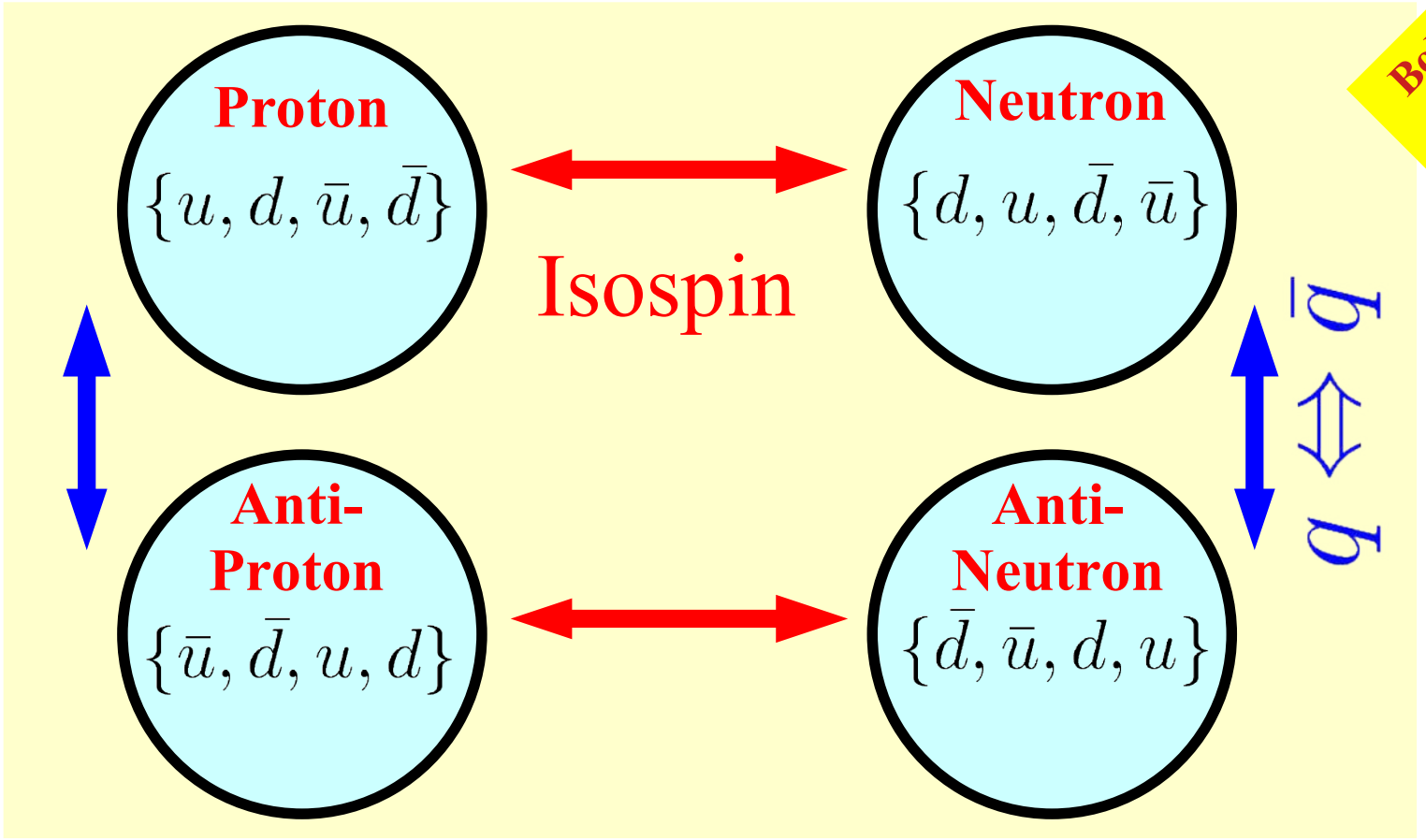
Deuteron Correction



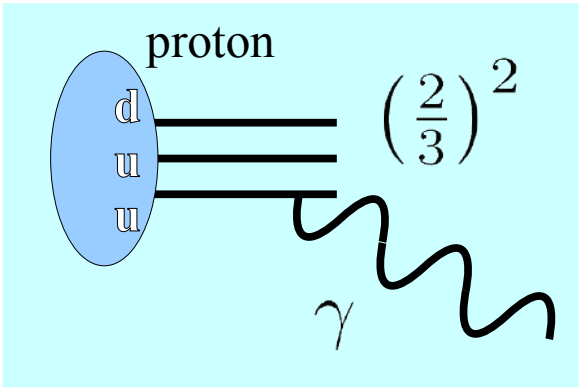
Isospin Symmetry used to relate PDFs

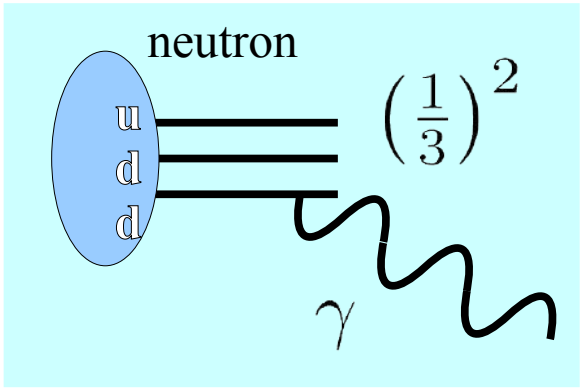
$\alpha_s^2 \sim \alpha$

"New" Photon PDFs



BoNuS data!!!



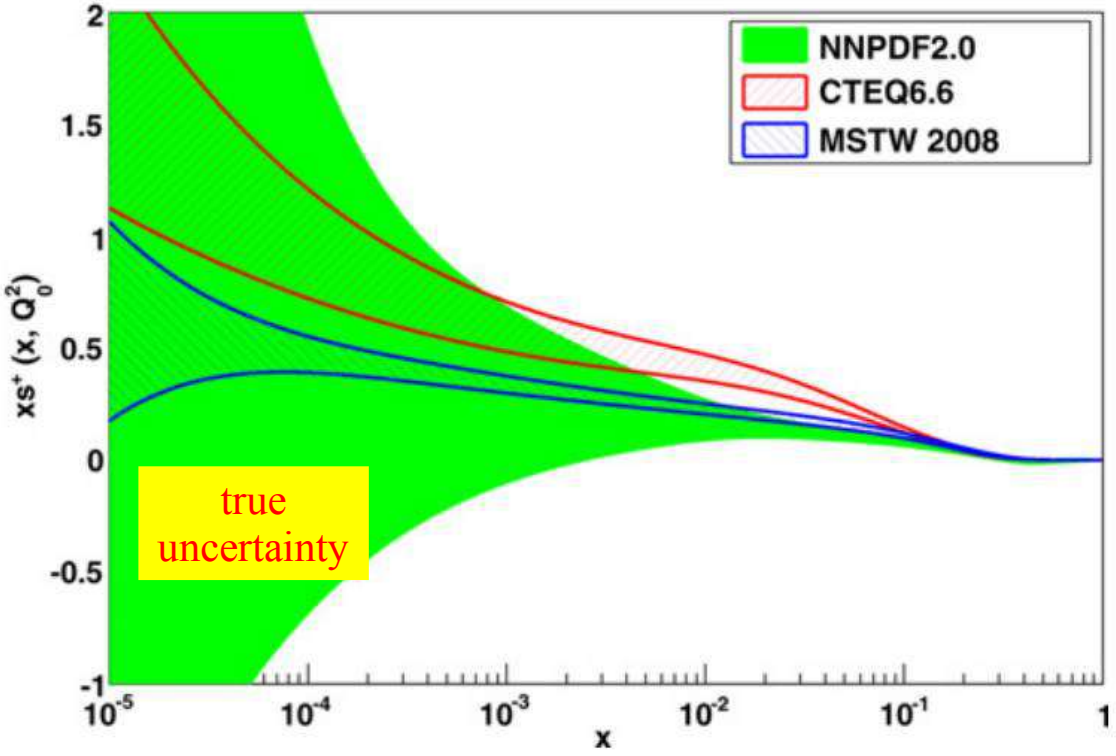


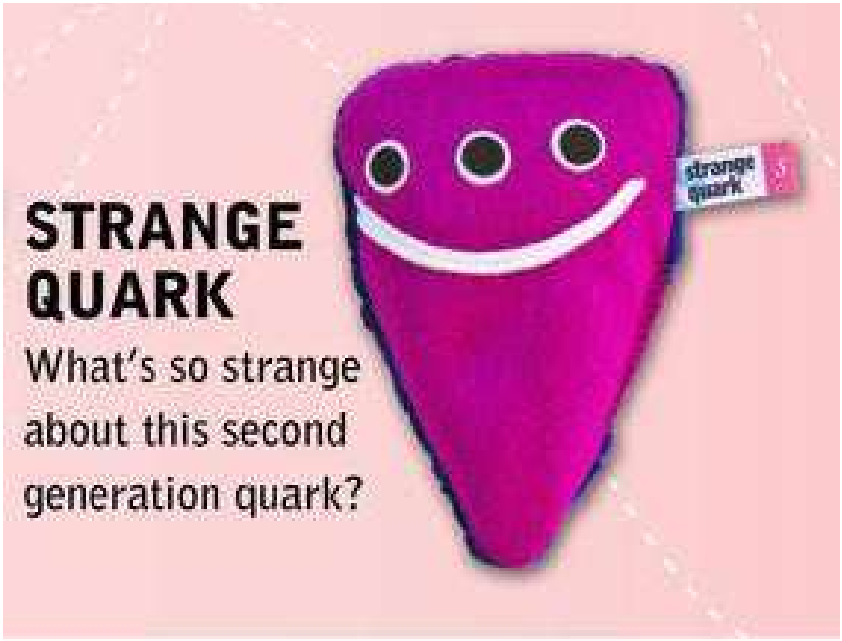
Isospin terms are comparable to NNLO QCD

QCD & EW Corrections do NOT factorize

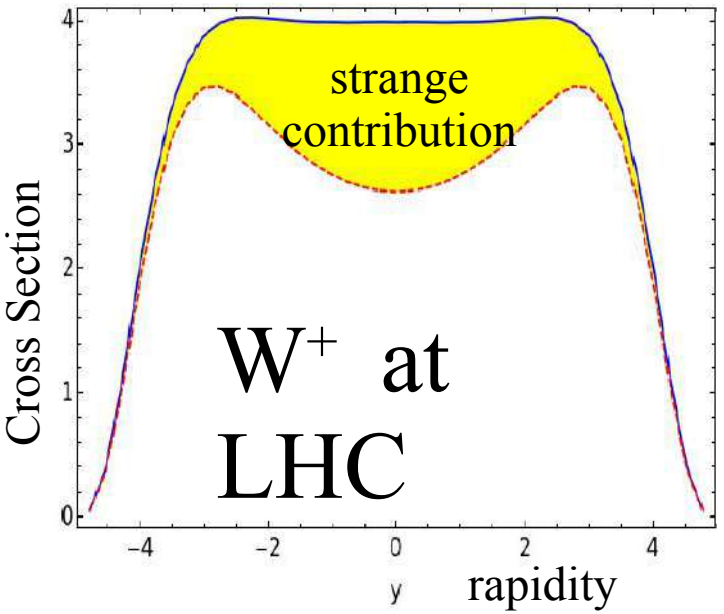
A Review of Target Mass Corrections.
Ingo Schienbein et al,
J.Phys.G35:053101,2008.

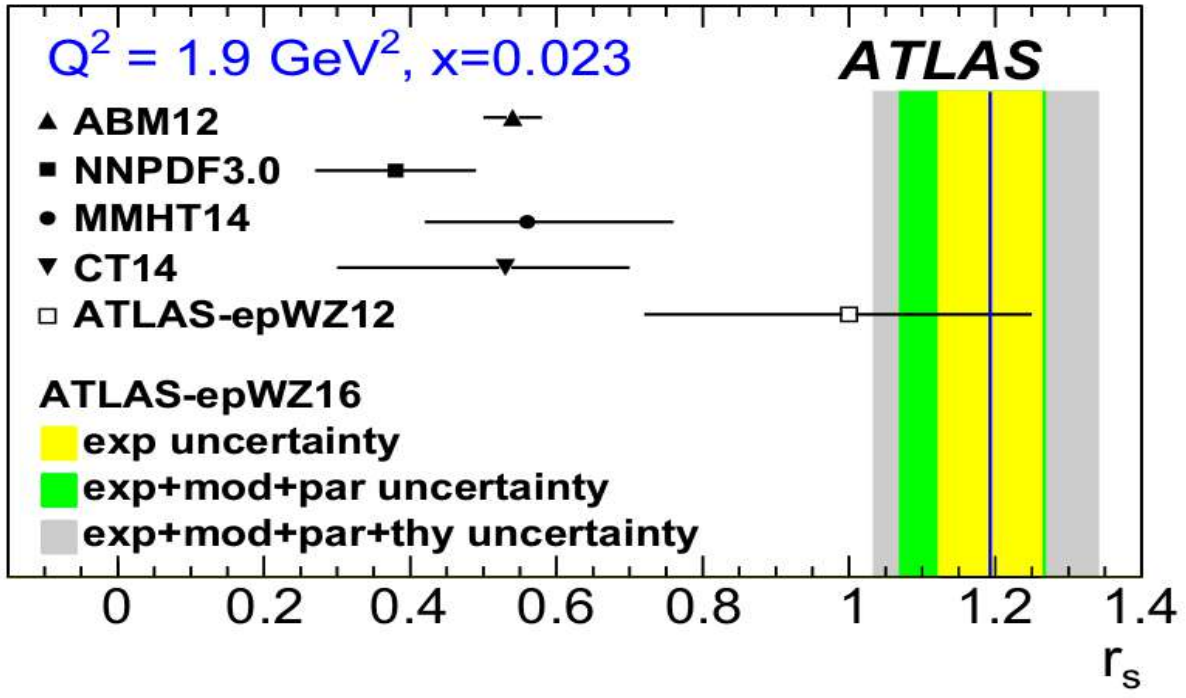
Revisit: The Strange PDF





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



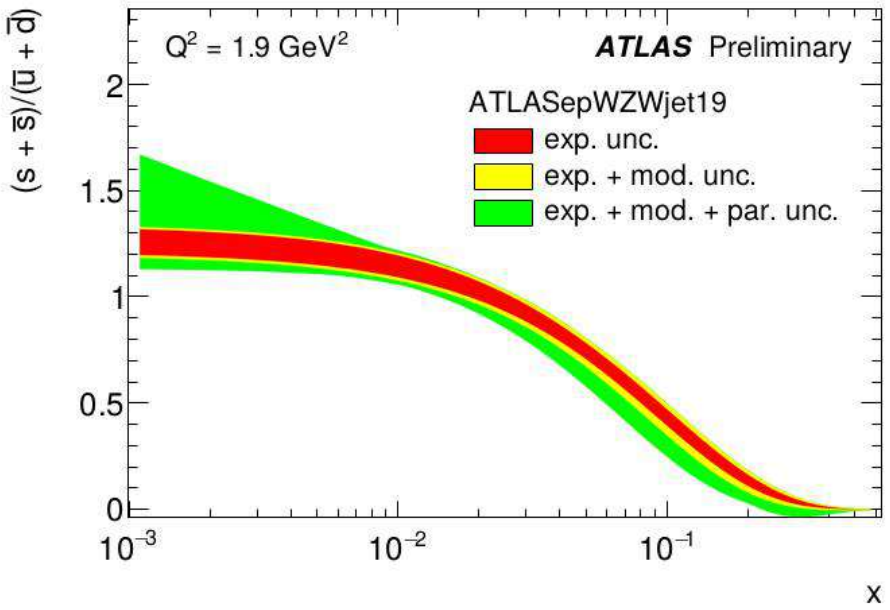


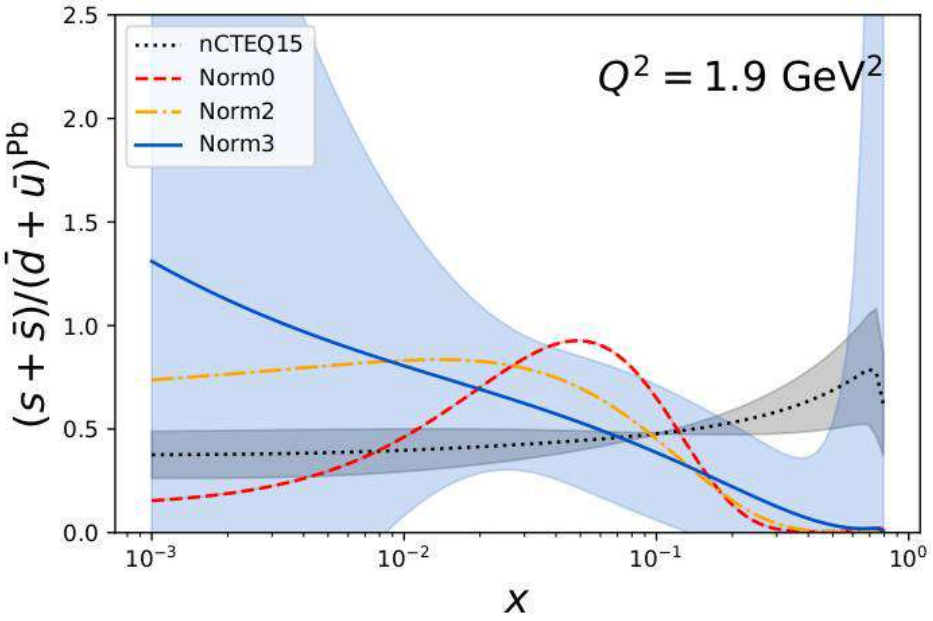
$$r^s(x,Q) = \frac{\bar{s}(x,Q) + s(x,Q)}{2\bar{d}(x,Q)}$$

Do it yourself!!!
Try **xFitter**

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

W/Z Production at LHC and the strange PDF

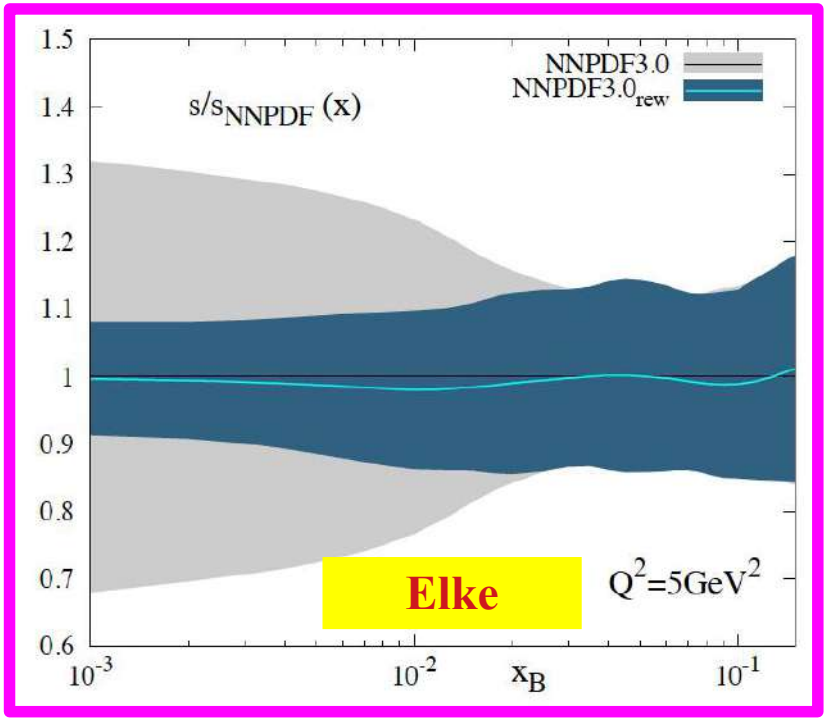




Are the data increasing the strange PDF because that is dictated by nature,

or

is the fit simply exploiting s(x) because that is least constrained flavors?



xFitter

DESY xFitter

xFitter/xFitterTalks » xFitter/../xFitterDevel.. »

xFitter

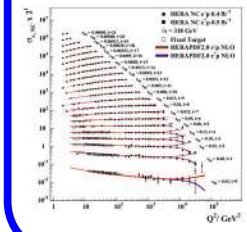
Features & Recent Updates:

- Photon PDF & QED
- Pole & MS-bar masses
- Profiling and Re-Weighting
- Heavy Quark Variable Treshold
- Update χ^2 and correlations
- TMD PDFs (uPDFs)
- *... and many other*

Sample data files:

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

Experimental Data



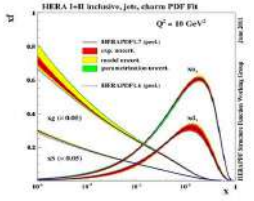
Data: HERA, Tevatron, LHC, fixed target experiments

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

xFitter 2.0.1
Old Fashioned

Date	Version
02/2020	2.0.1N Nuclear Daiquiri

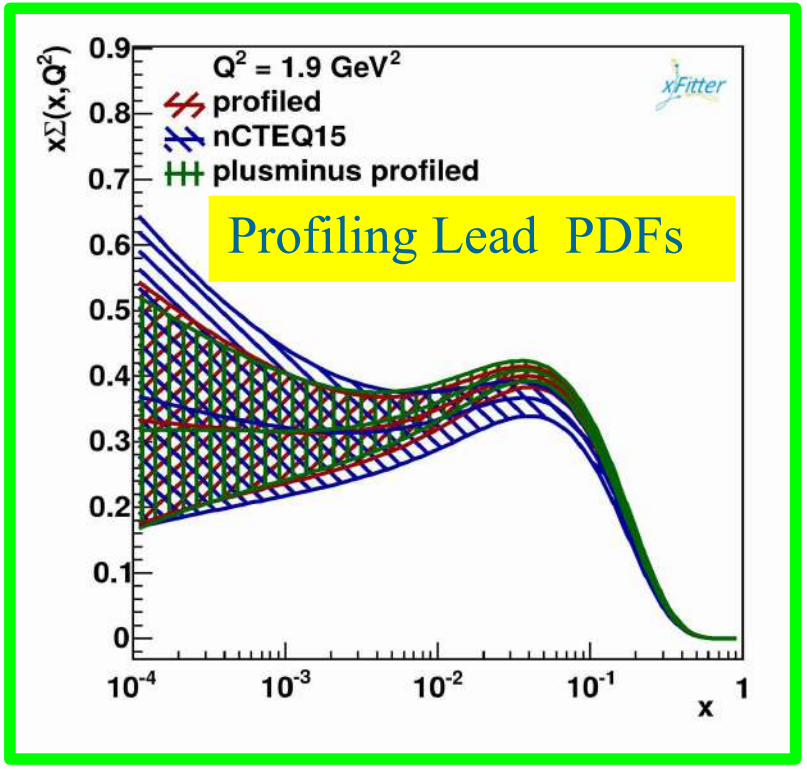
xFitter Collaboration Meeting February 2020, DESY

www.xFitter.org

Versatility of xFitter

xFitter Meeting: Krakow March 2018

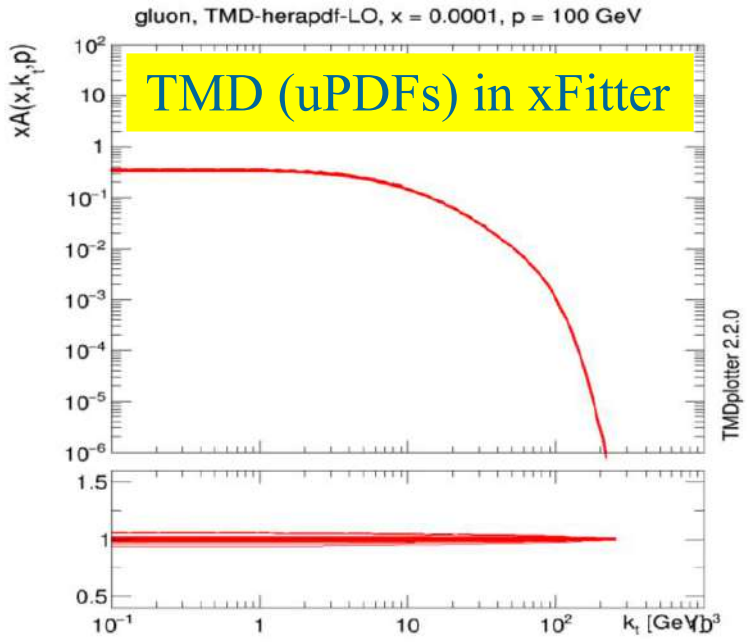
www.xFitter.org



Profiling Lead PDFs

xFitter

TMDs from fits - comparison of LO and NLO

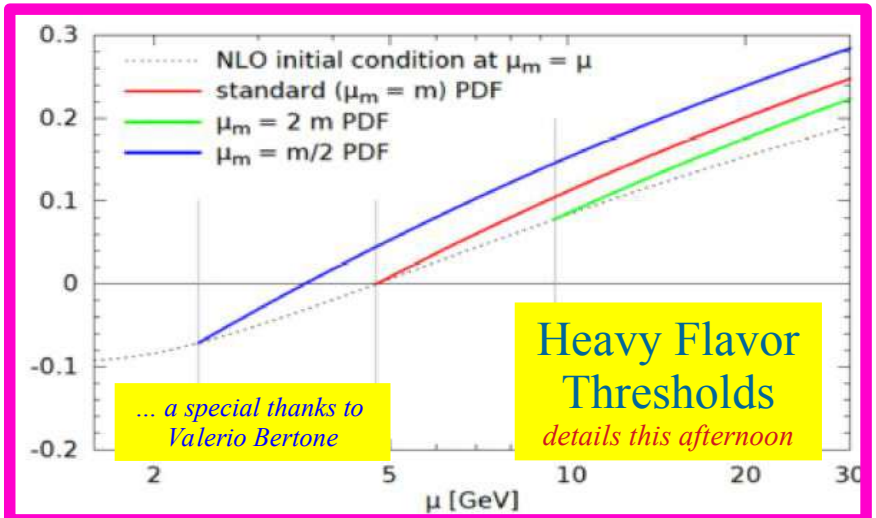


TMD (uPDFs) in xFitter

TMDs with experimental uncertainties.

Used for LHC PDF analyses

nPDFs with xFitter
Marina Walt
U. Tuebingen



... a special thanks to Valerio Bertone

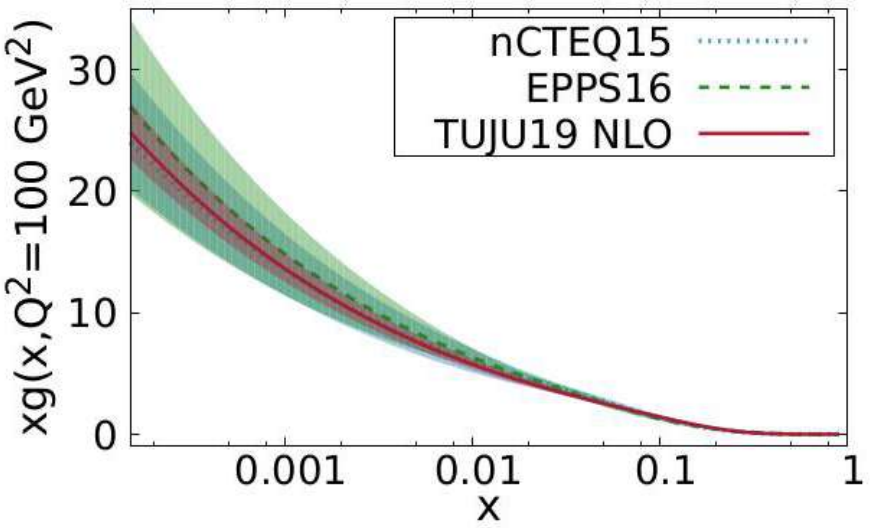
Heavy Flavor Thresholds
details this afternoon

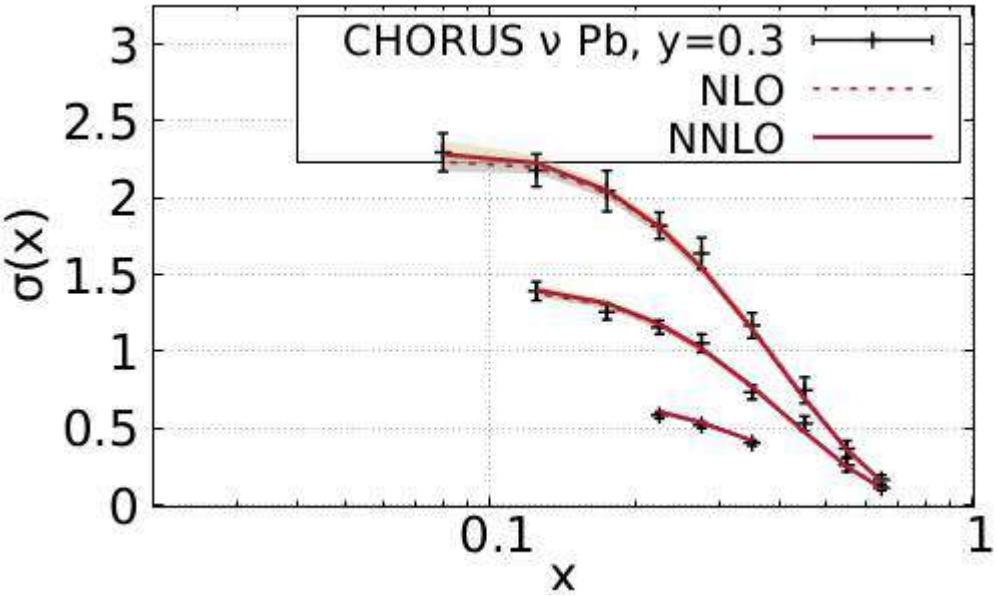
Nuclear PDFs with xFitter

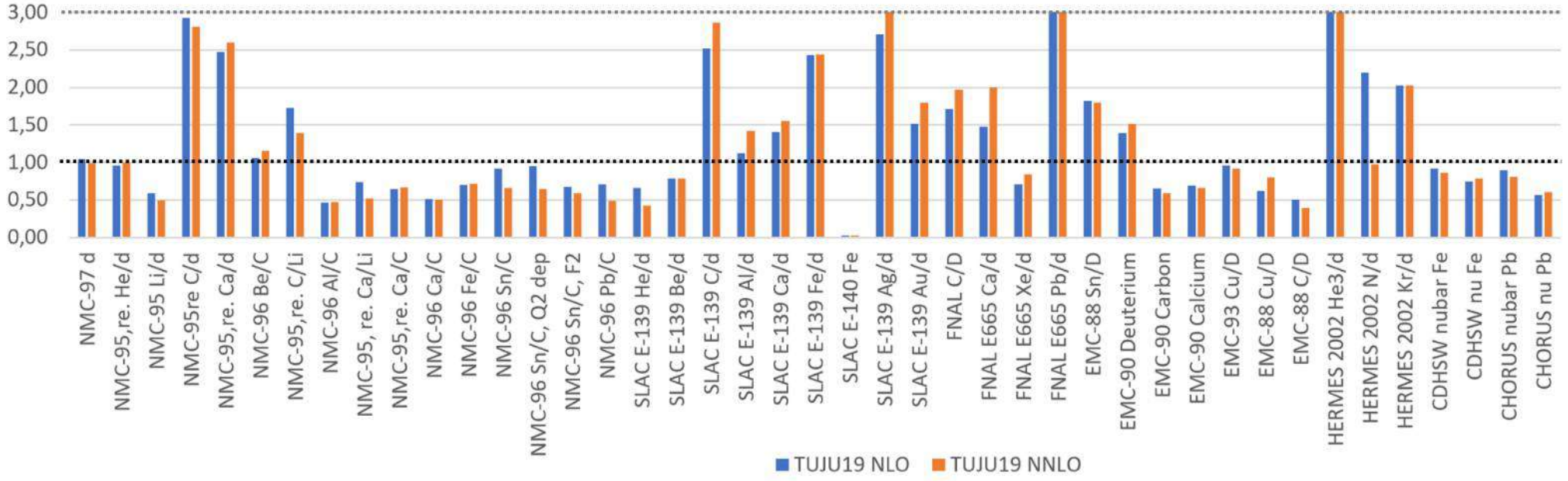
nPDFs with xFitter
Marina Walt
U. Tuebingen

www.xFitter.org

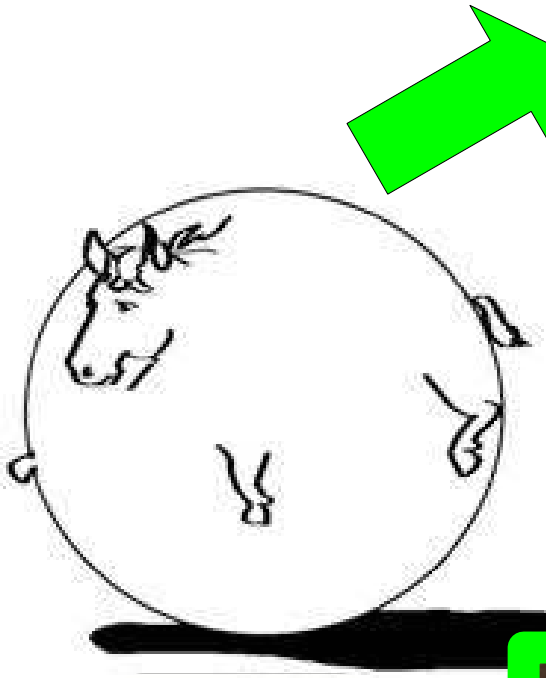
Phys.Rev.D 100 (2019) 9, 096015 • e-Print: 1908.03355 [hep-ph]

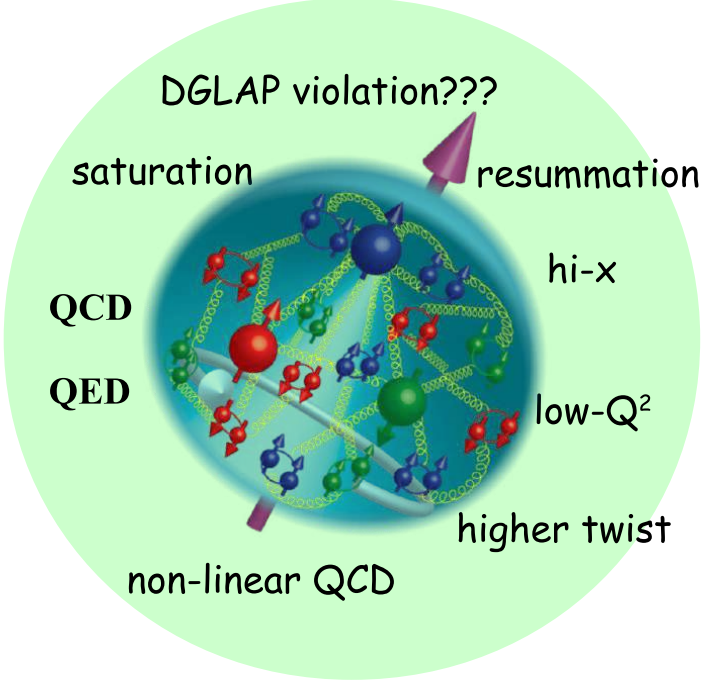


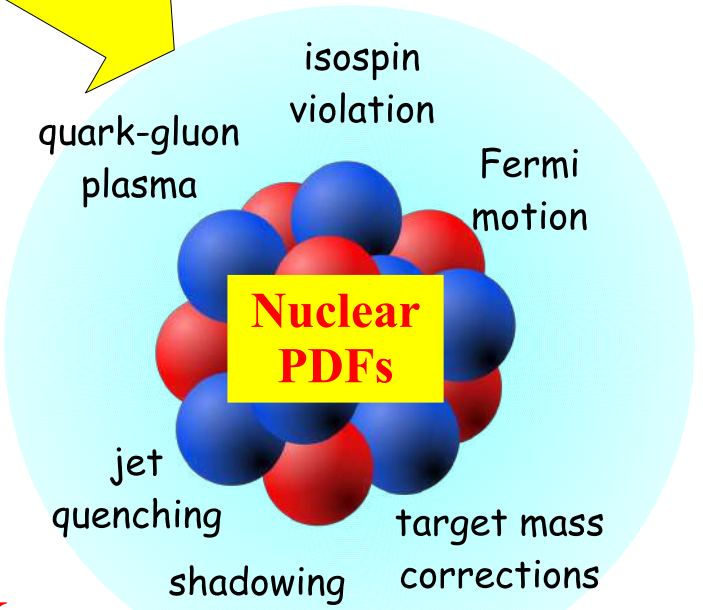




Conclusion







nCTEQ … *hard at work*

T.J. Hobbs
T. Jezo,
C. Keppel,
K. Kovarik
M. Klasen
A Kusina,
J. Morfin,
F. Olness
J. Owens,
I. Schienbein,
J. Yu

nCTEQ Wish List

Fred Olness w/ help from: Tim Hobbs, Aleksander Kusina, Pavel Nadolsky, Tomas Jezo, Thia Keppel, Michael Klasen, Karol Kovarik, Jorge Morfin, Ingo Schienbein, Efrain Segarra, Steve Sekula

nCTEQ
nuclear parton distribution functions

CTEQ

Low-Q:

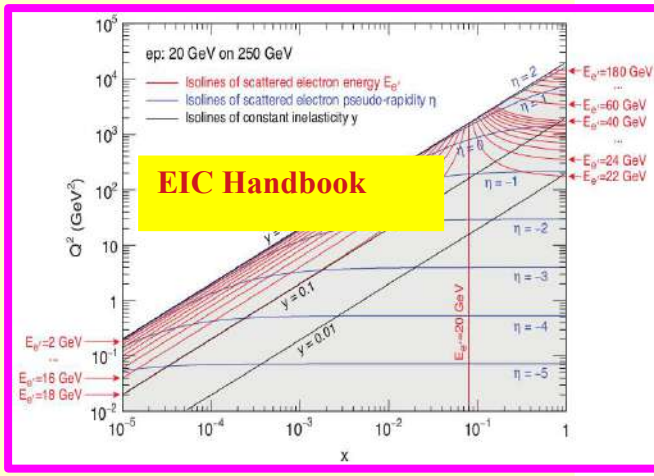
Higher-Twist, Non-Pert, Resummation

Hi-x:

TMC, Nuclear x>1, …

Strange PDF:

Disentangle: 1) proton PDF
2) nuclear corrections
3) flavor components



Gluon (& Charm+Bottom):

Improve R_G via F_L: window on NLO and mass effects

Nuclear A:

Map out A dependence … and maybe beyond