

Updates from nCTEQ

Probing dense nuclear matter

Fred Olness
SMU

*Thanks for substantial input
from my friends & colleagues*



nCTEQ
nuclear parton distribution functions



Precision QCD
CFNS, Stony Brook University
21-25 September 2026

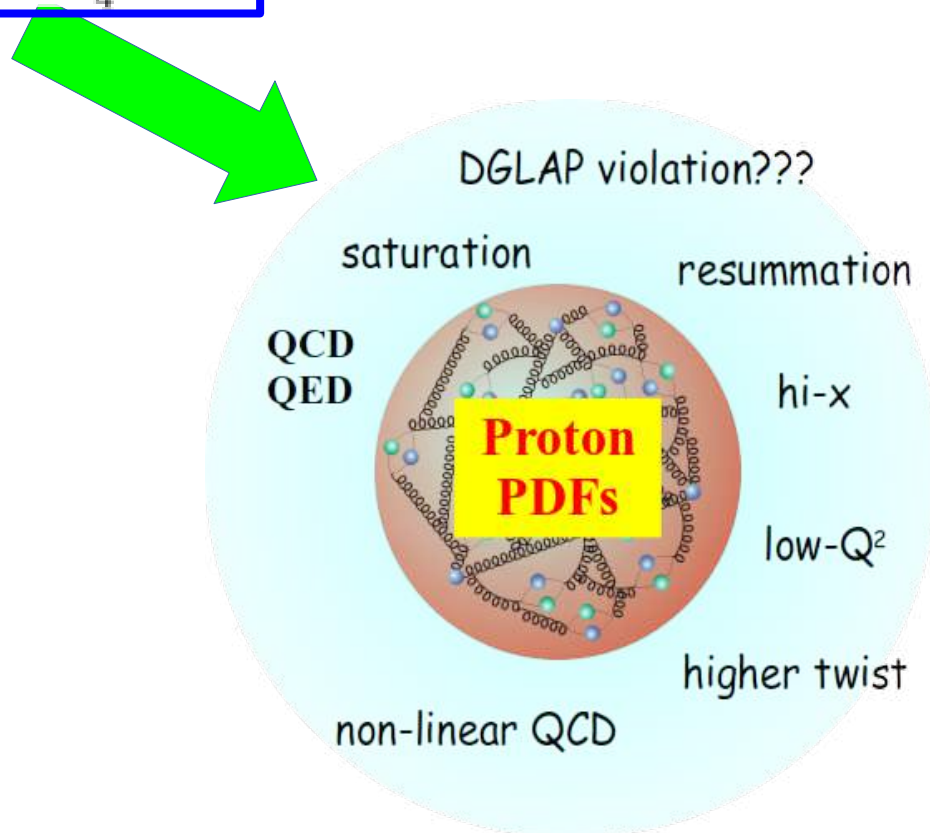
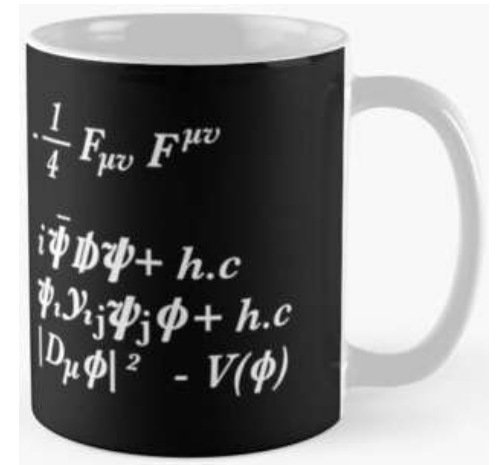
Quantum ChromoDynamics

QCD

Lagrangian

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

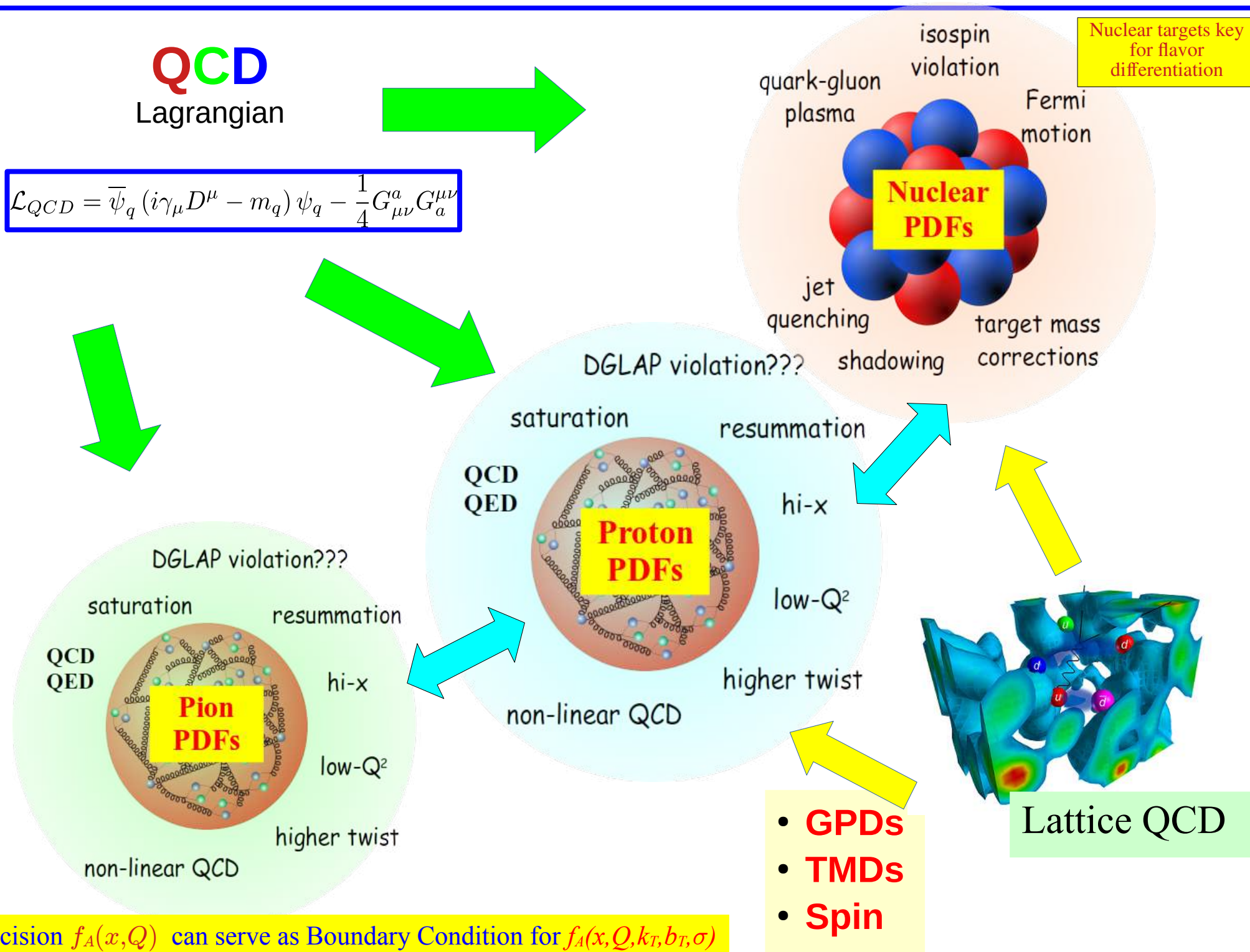
Conjecture: A theory can't be fundamental unless it fits on a coffee mug.



... we can go further

QCD
Lagrangian

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



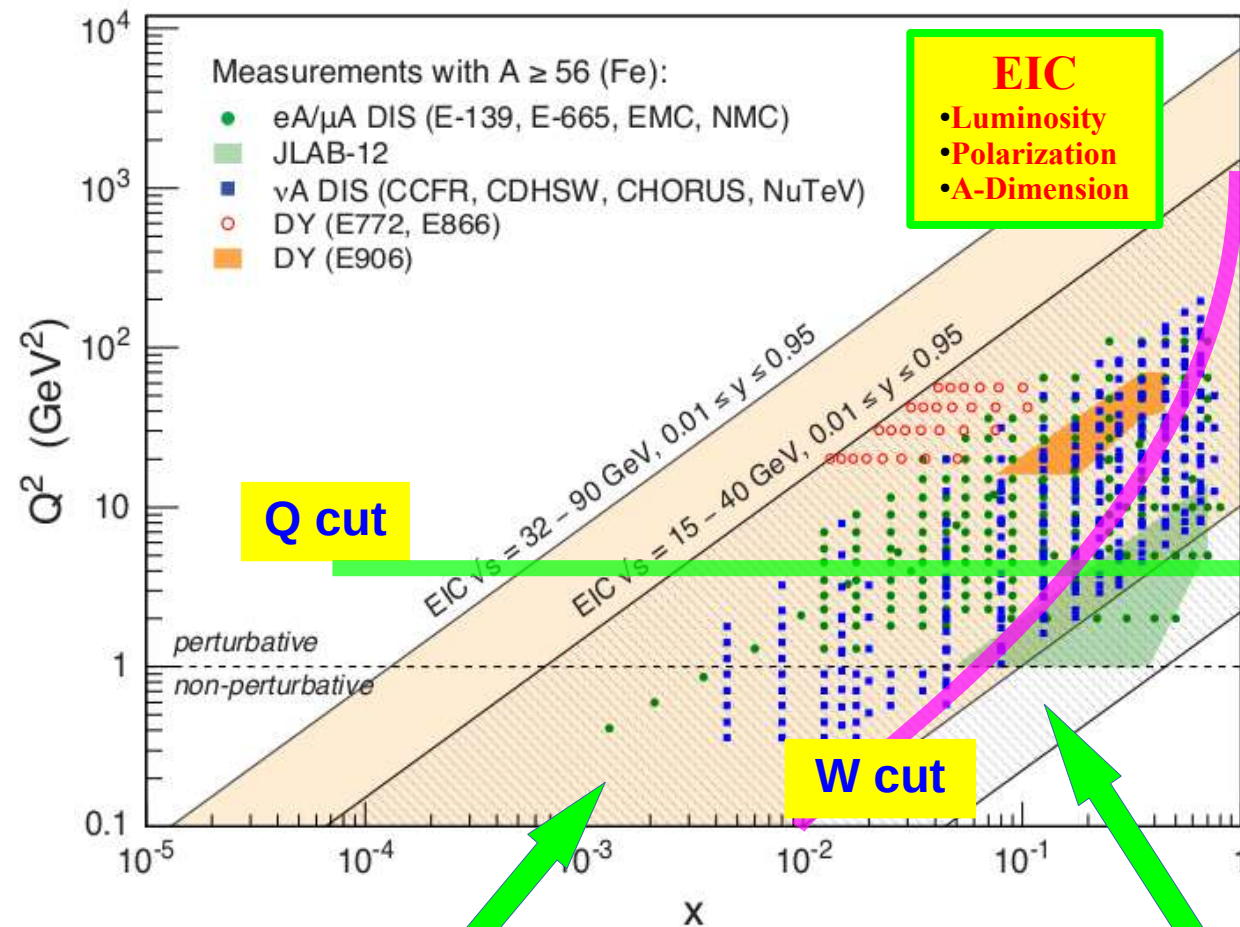
nCTEQ

nuclear parton distribution functions

nCTEQ project is an extension of the CTEQ collaborative effort to determine nuclear parton distribution functions (nPDFs).

Grenoble, April 2024





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

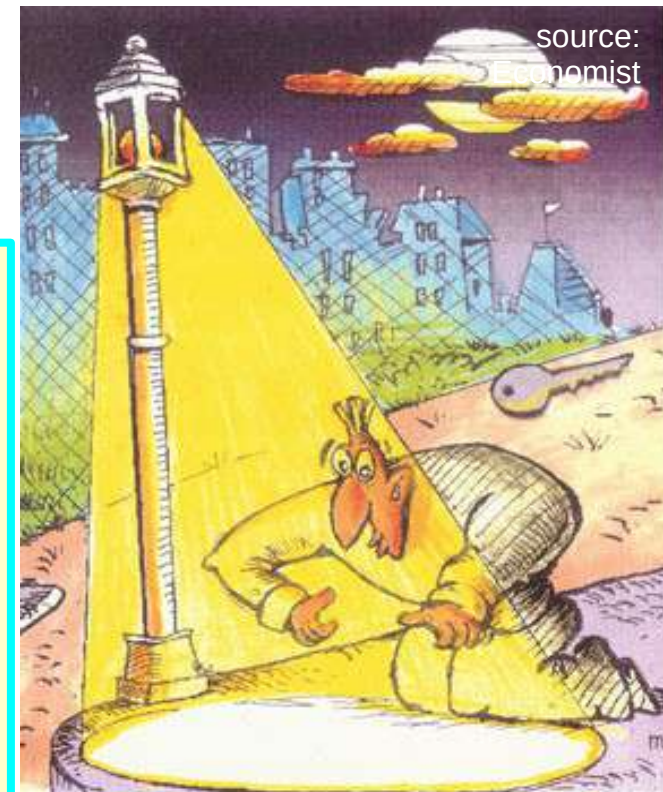
Low- x :

Shadowing
 Recombination
 Resummation
 BFKL
 Saturation

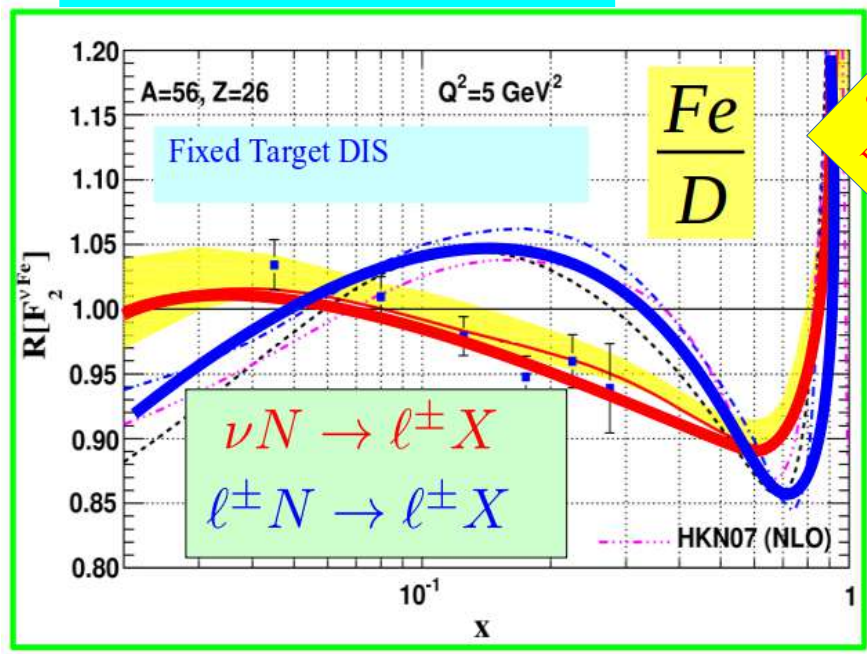


Low- Q^2 :

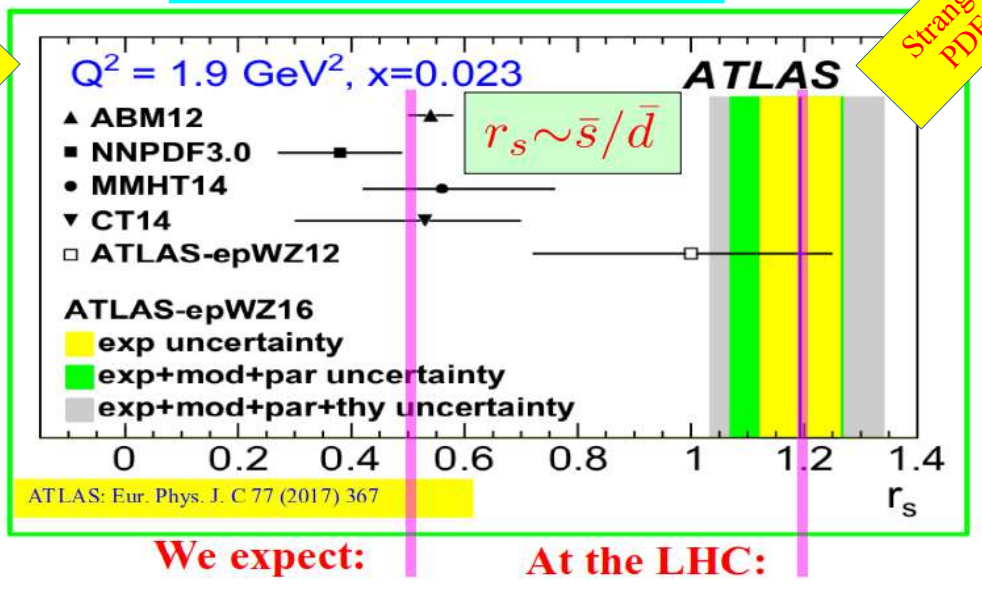
Non-Perturbative interface
 collective effects
 Target Mass Corrections
 pick up M^2/Q^2 higher twist
 F_L at low Q^2 access to $g(x)$
 Run at multiple energies



nCTEQ15 ν



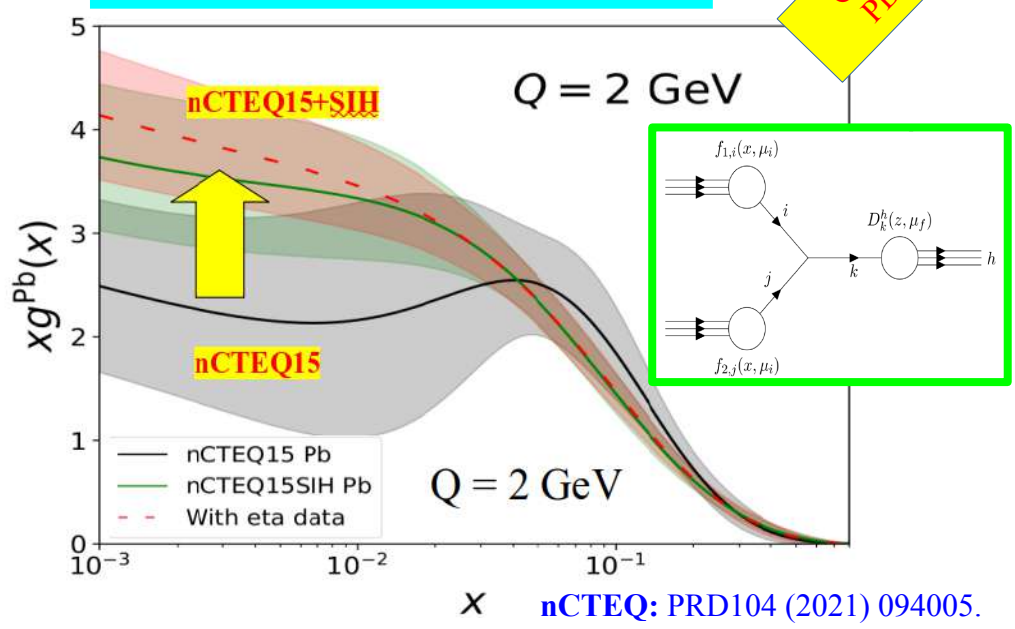
nCTEQ15WZ



nCTEQ: arXiv: 2204.13157

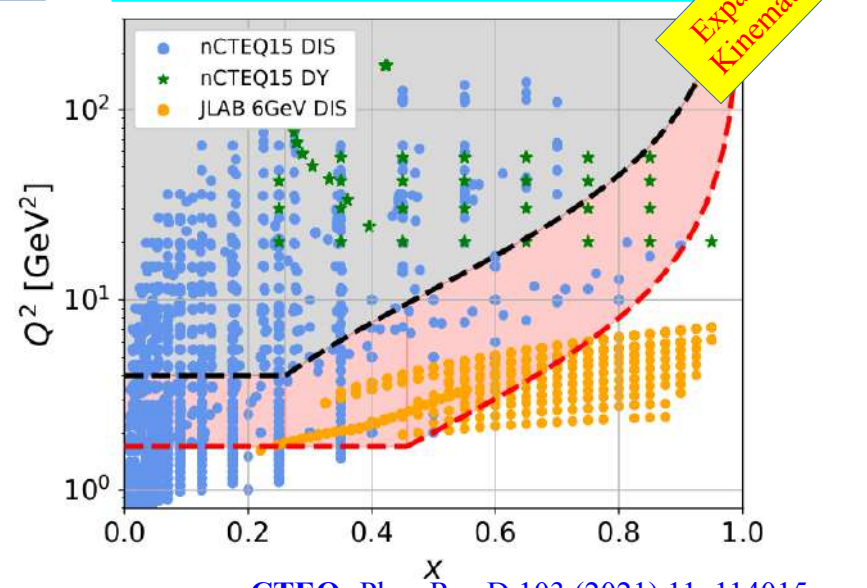
nCTEQ: Phys.Rev.D 104 (2021) 094005

nCTEQ15WZ+SIH



Key for
EIC

nCTEQ15HIX



nCTEQ: PRD104 (2021) 094005.

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

precision $f_A(x,Q)$ can serve as Boundary Condition for $f_A(x,Q,k_T,b_T,\sigma)$

nCTEQ26

NCTEQ

Home

Collaborators

PDF grids & code

• nCTEQ26 Bound

• nCTEQ26 Nucleus

Papers & Talks

Mathematica

• ManeParse

Subversion

Tracker

Wiki

<https://ncteq.hepforge.org/>

nCTEQ

nuclear parton distribution functions

nCTEQ26

nCTEQ26 is a new global analysis of nuclear PDFs that combines most improvements from nCTEQ15XYZ fits and sprinkles new data on top:

- (a) a broad selection of data: neutral- & charged-current DIS including dimuon production, fixed target DY data and light hardron production data including quarkonia production
- (b) extended kinematic cuts for DIS production including most modern TMC corrections
- (c) improved nuclear mass (A) dependence

If you use any of the grids provided here, please cite:

nCTEQ26 LHAPDF Grid Files

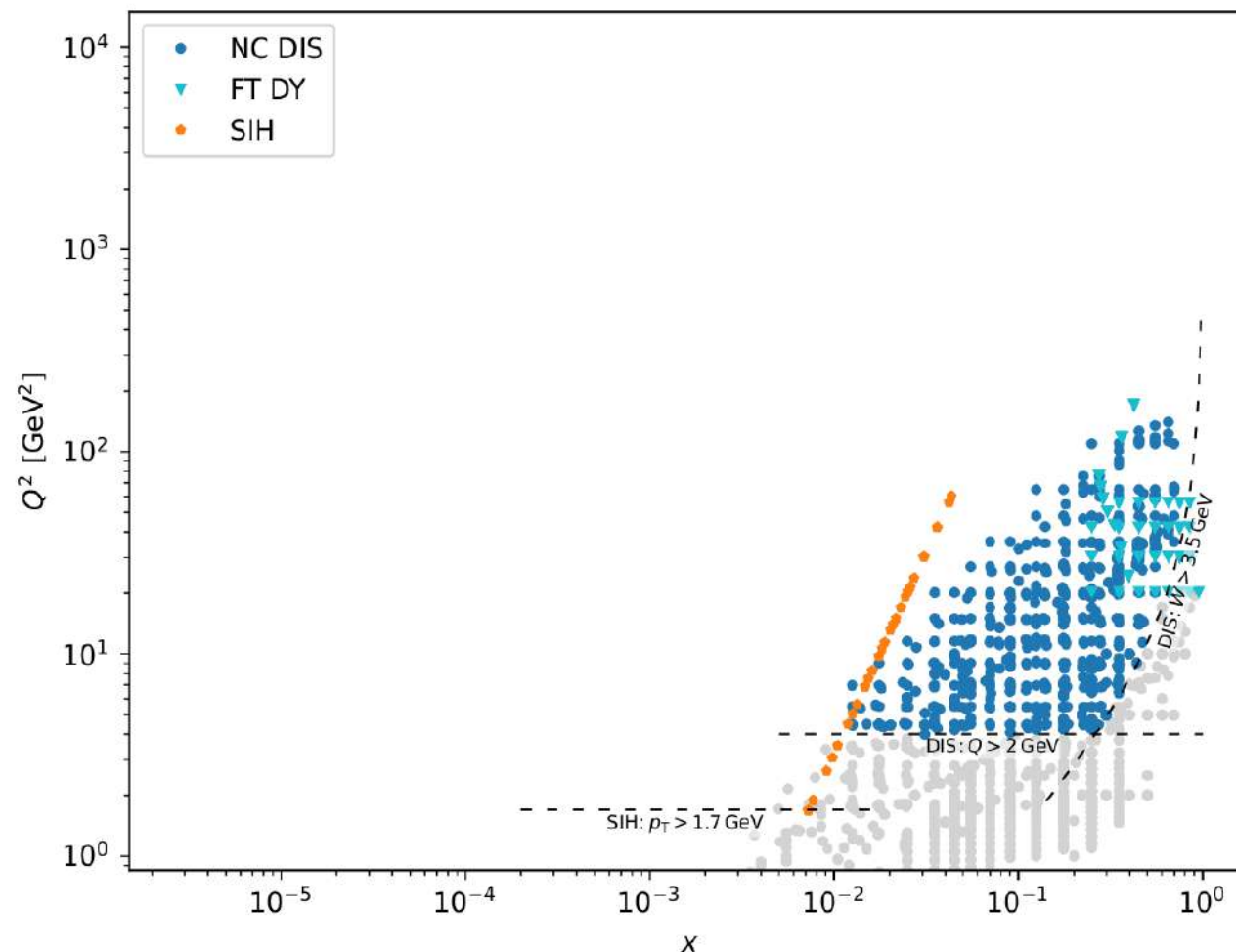
nCTEQ26 nucleus grids

PDF grids for parton inside a nucleus for a selection of nuclei.

- proton-1_1: ([LHAPDF](#))
- deuteron-2_1: ([LHAPDF](#))
- He-3_2: ([LHAPDF](#))
- He-4_2: ([LHAPDF](#))
- Li-6_3: ([LHAPDF](#))
- Li-7_3: ([LHAPDF](#))
- Be-9_4: ([LHAPDF](#))
- B-10_5: ([LHAPDF](#))
- B-11_5: ([LHAPDF](#))
- C-12_6: ([LHAPDF](#))
- N-14_7: ([LHAPDF](#))
- O-16_8: ([LHAPDF](#))
- Ne-20_10: ([LHAPDF](#))

- Al-27_13: ([LHAPDF](#))
- Ar-40_18: ([LHAPDF](#))
- Ca-40_20: ([LHAPDF](#))
- Fe-56_26: ([LHAPDF](#))
- Fe-56_28-iso: ([LHAPDF](#))
- Cu-64_29: ([LHAPDF](#))
- Kr-84_36: ([LHAPDF](#))
- Ag-108_47: ([LHAPDF](#))
- Sn-119_50: ([LHAPDF](#))
- Xe-131_54: ([LHAPDF](#))
- W-182_74: ([LHAPDF](#))
- W-183_74: ([LHAPDF](#))
- W-184_74: ([LHAPDF](#))
- W-186_74: ([LHAPDF](#))
- Pt-195_78: ([LHAPDF](#))
- Au-197_79: ([LHAPDF](#))
- Pb-207_82: ([LHAPDF](#))
- Pb-208_92: ([LHAPDF](#))
- U-238_92: ([LHAPDF](#))

Grids for all full nucleus PDFs ([LHAPDF](#)) 373Mb.

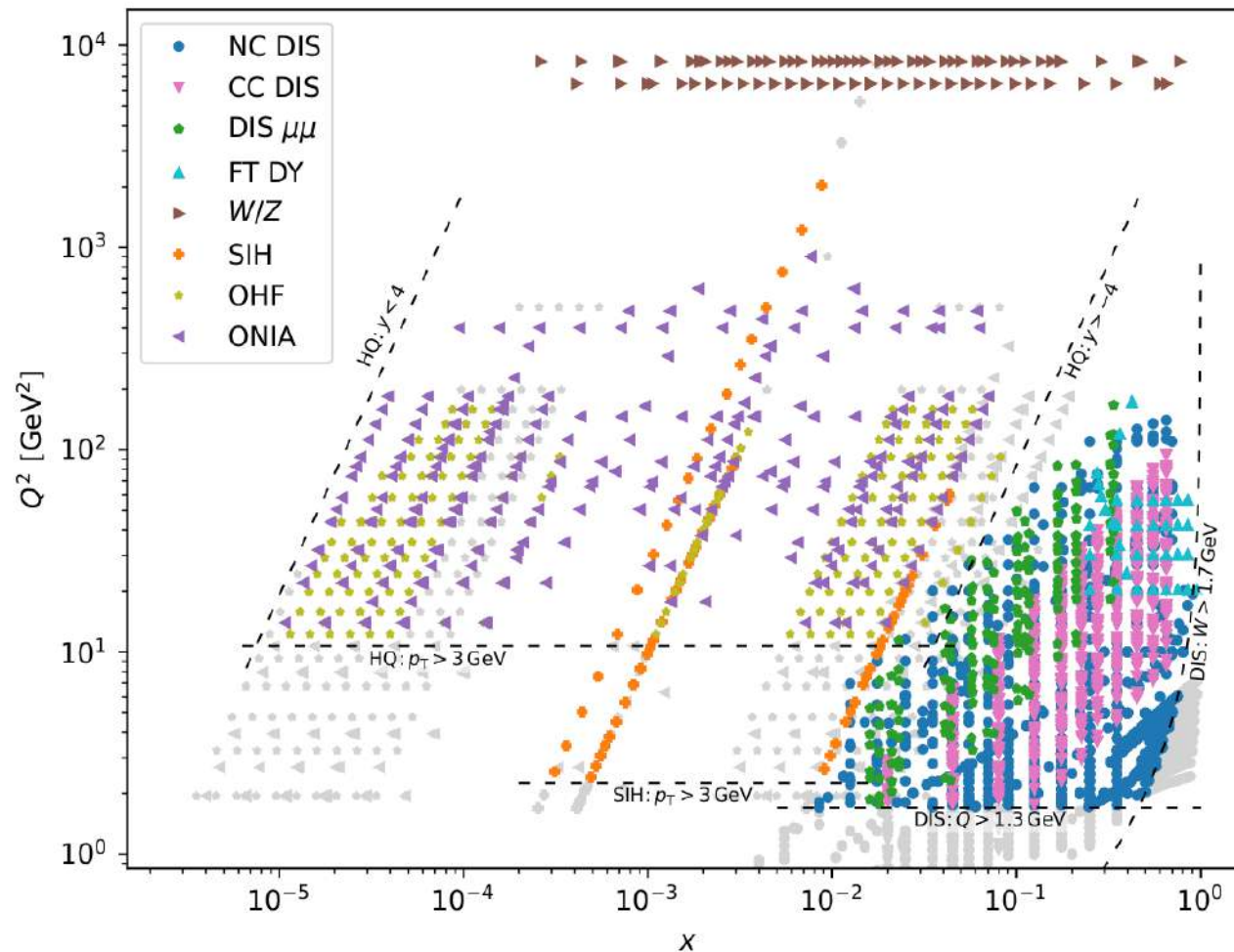


→ DIS, DY, SIH data

→ $N_{\text{data}} = 740$

nCTEQ

nuclear parton distribution functions



PDF Sets on HepForge

- new CC DIS, DIS $\mu\mu$, DY W/Z, HQ data
- $N_{\text{data}} = 3518$
- looser cuts

Jan Wissmann (jan.wissmann@uni-muenster.de)

3 / 47

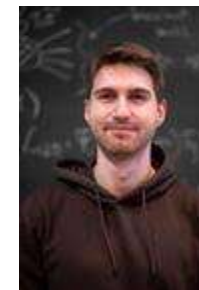
nCTEQ
nuclear parton distribution functions



Tomas
Jezo



Katrin
Greve



Jan
Wissmann



Aleksander
Kusina

- New nPDF release: **nCTEQ26** combines the previous analyses:

- ▶ **nCTEQ15** [PRD 93, 085037 (2016)]

- ★ DIS NC data
- ★ fixed-target DY data
- ★ pion data from RHIC

740 data points

- ▶ **nCTEQ15WZ** [EPJC 80, 968 (2020)]

- ★ LHC W/Z data
- ★ constraints on *gluon* and *strange* nPDFs

LHC W/Z

- ▶ **nCTEQ15HIX** [PRD 103, 114015 (2021); Prog.Part.Nucl.Phys. 136 (2024) 104096]

- ★ JLAB DIS data
- ★ constraints at high- x
- ★ theoretical corrections: TMC, HT, deuteron

Expand {Q,W}

- ▶ **nCTEQ15SIH** [PRD 104 (2021) 9, 094005]

- ★ LHC & RHIC SIH data
- ★ constraints on *gluon* nPDF

SIH Data

- ▶ **nCTEQ15neutrino** [PRD 106 (2022) 7, 074004]

- ★ DIS neutrino data (NuTeV, CHORUS, CDHSW, dimuon)
- ★ compatibility of NC & CC DIS
- ★ flavour separation

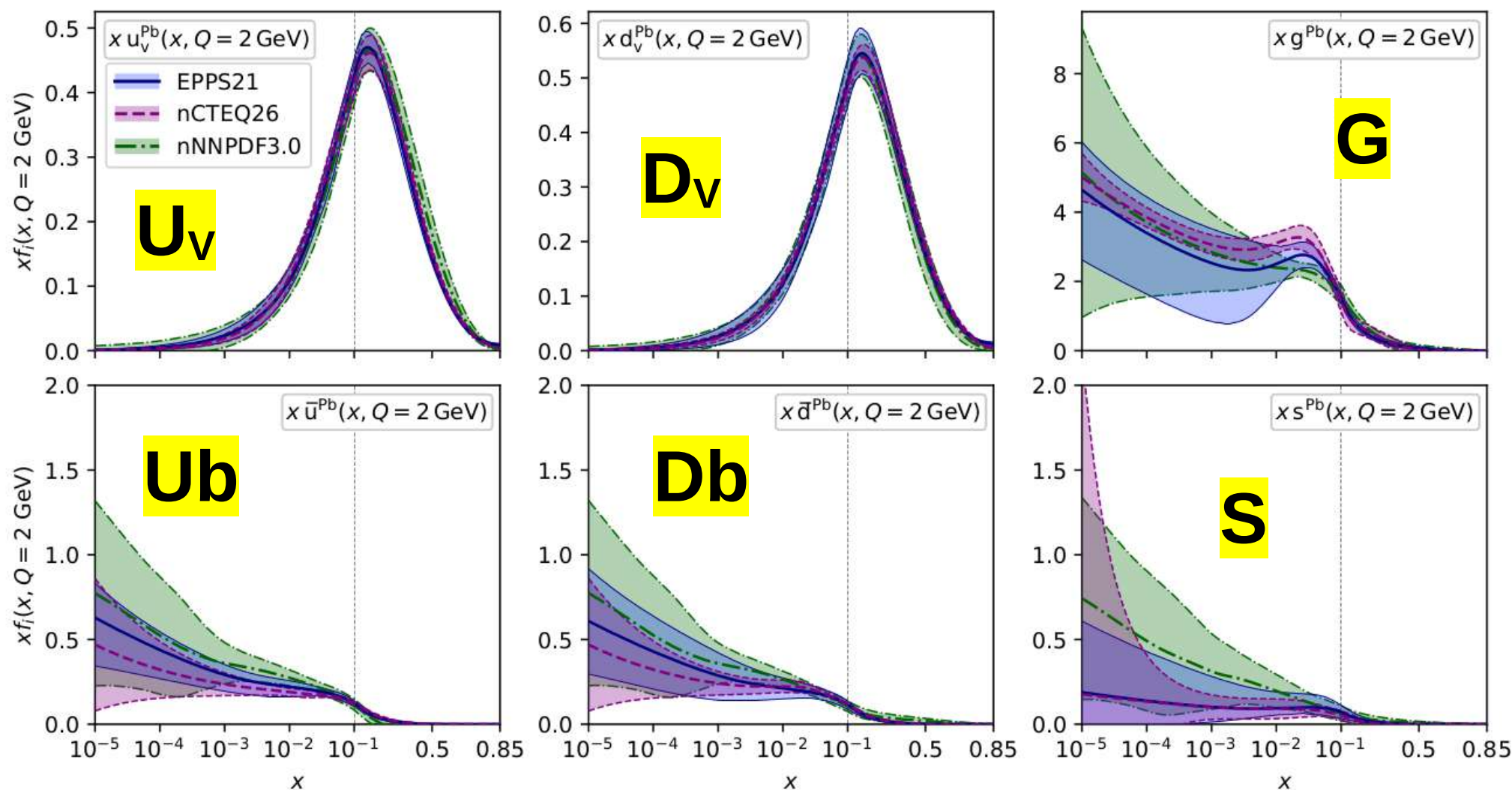
CC DIS

- ▶ **nCTEQ15HQ** [PRL 121, 052004 (2018); PRD 105 (2022) 11, 114043]

- ★ LHC & RHIC HF data
- ★ constraints on low- x *gluon* nPDF
- ★ PDF-reweighting + full analysis

HQ Data

General Properties



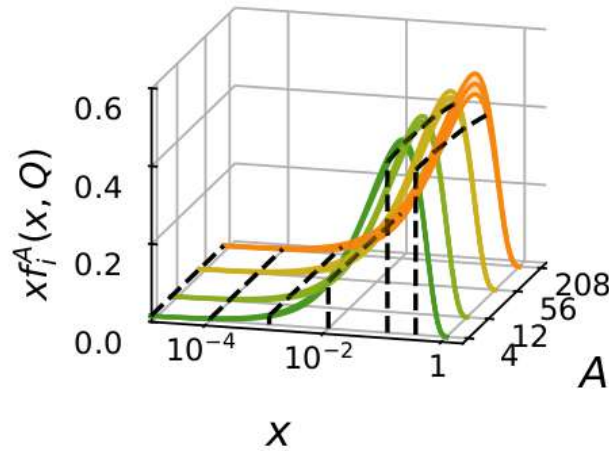
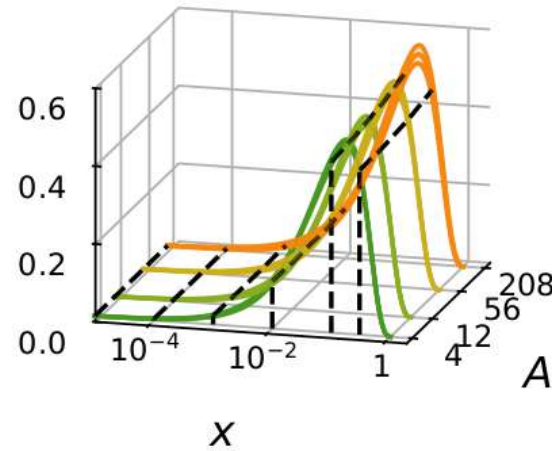
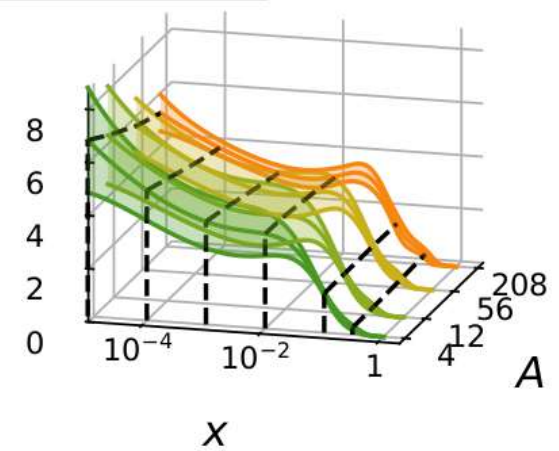
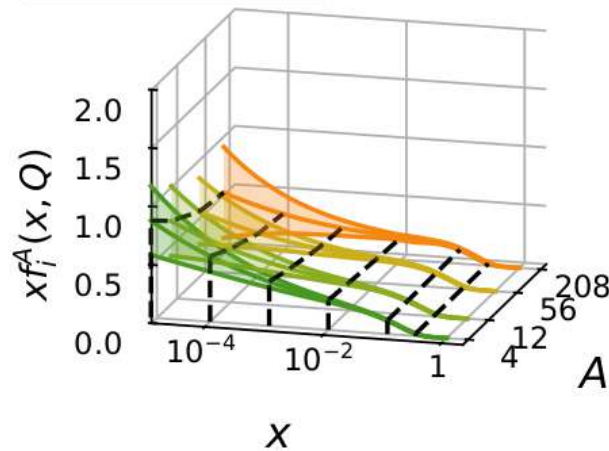
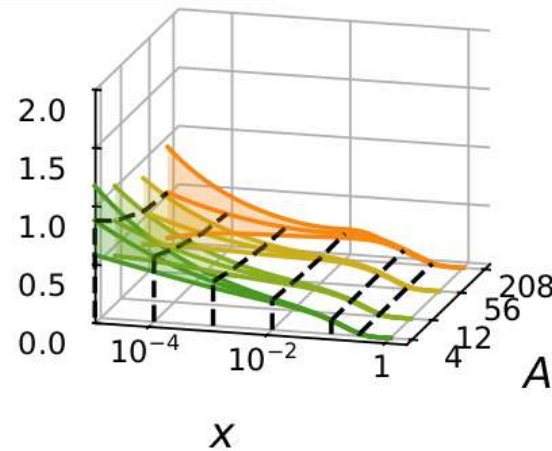
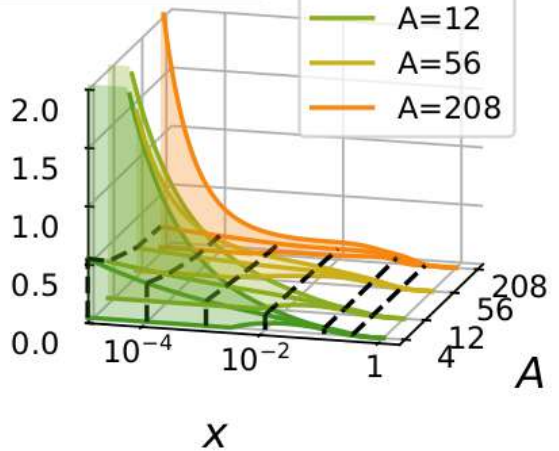
based on CJ15

$$x f_k^{p/A}(x, Q_0) = c_0^k x^{c_1^k} (1-x)^{c_2^k} (1 + c_3^k \sqrt{x} + c_4^k x) \boxed{e^{c_5^k \sqrt{x}}}$$

strange only

Good agreement with other nPDF sets

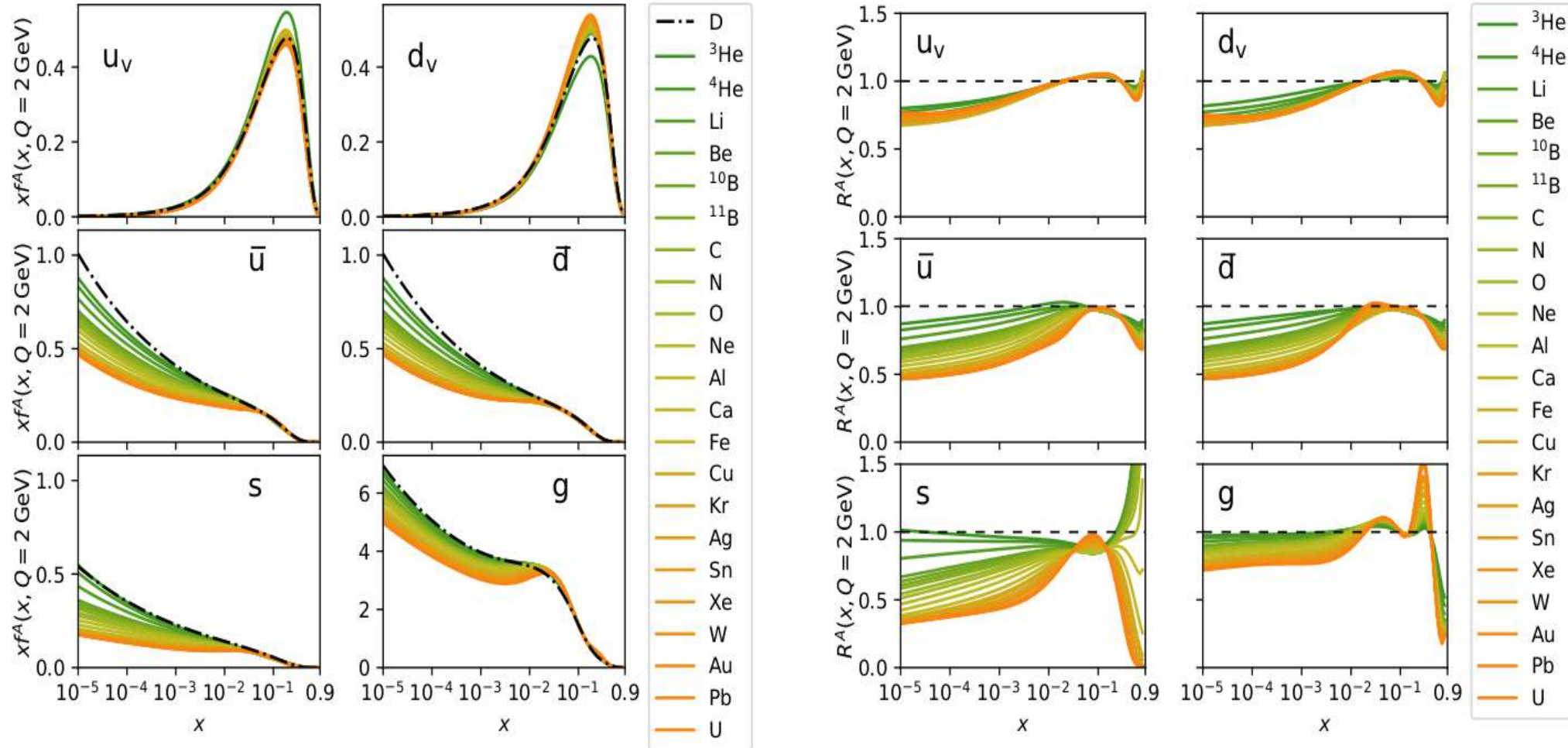
non-trivial

$x u_v(x, Q = 2 \text{ GeV})$  $x d_v(x, Q = 2 \text{ GeV})$  $x g(x, Q = 2 \text{ GeV})$  $x \bar{u}(x, Q = 2 \text{ GeV})$  $x \bar{d}(x, Q = 2 \text{ GeV})$  $x s(x, Q = 2 \text{ GeV})$ 

$$c_j(A) = p_j + a_j \ln A + b_j \ln^2 A.$$

Eliminates correlations of previous

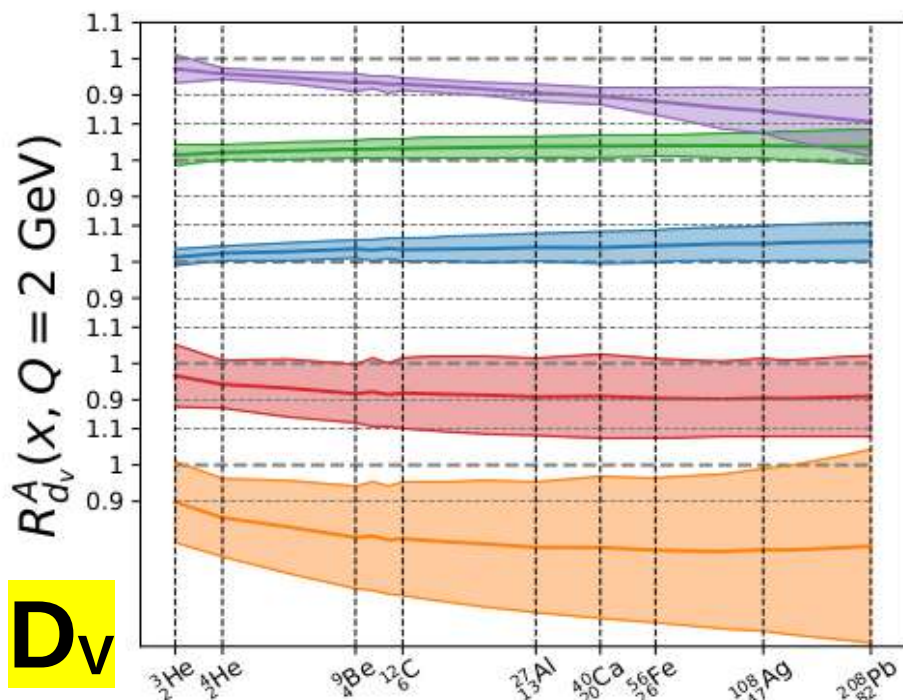
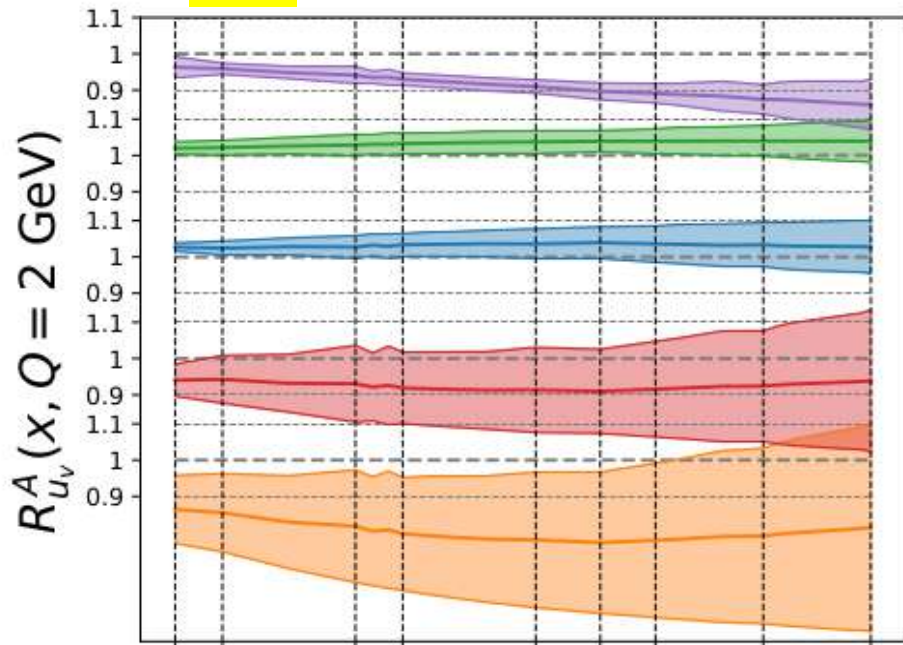
$$p_1 + a_i(1 - A^{b_i})$$



$$c_j(A) = p_j + a_j \ln A + b_j \ln^2 A.$$

U_v

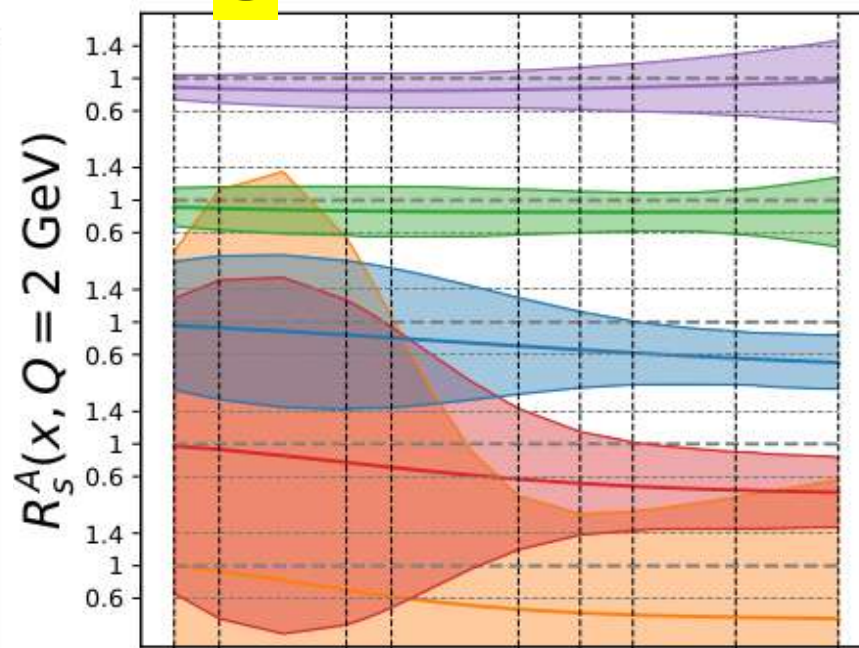
nCTEQ26



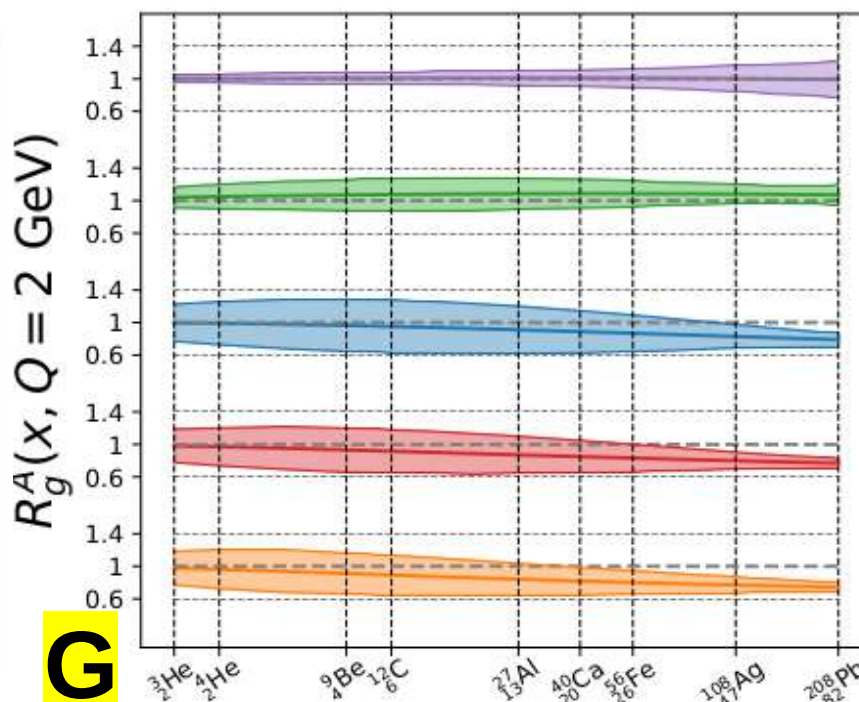
D_v

S

nCTEQ26



$x=0.1$
 $x=0.03$
 $x=0.003$
 $x=0.0003$
 $x=3e-05$

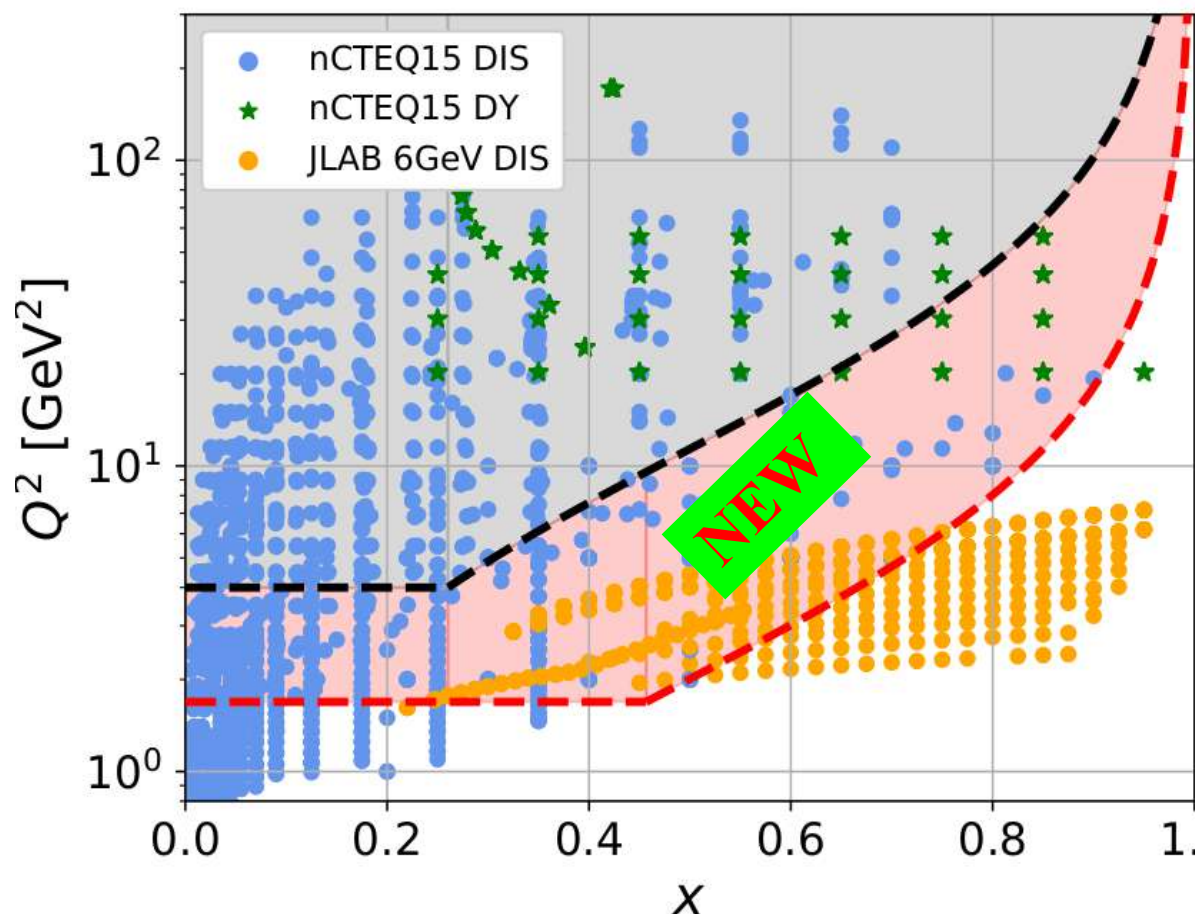


$x=0.1$
 $x=0.03$
 $x=0.003$
 $x=0.0003$
 $x=3e-05$

G

A

A



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 cont.

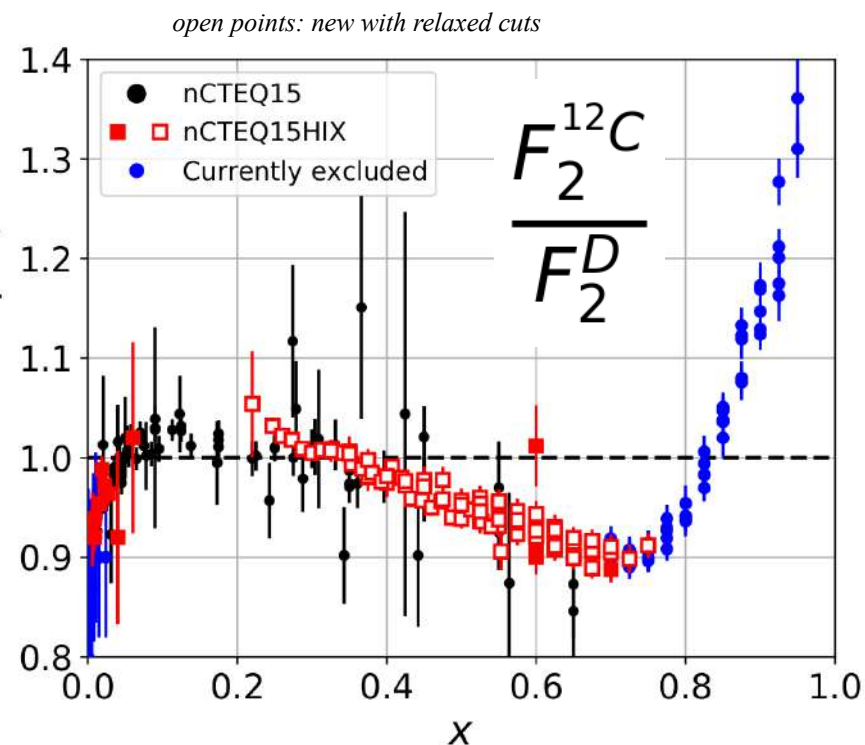
Deuteron Corrections

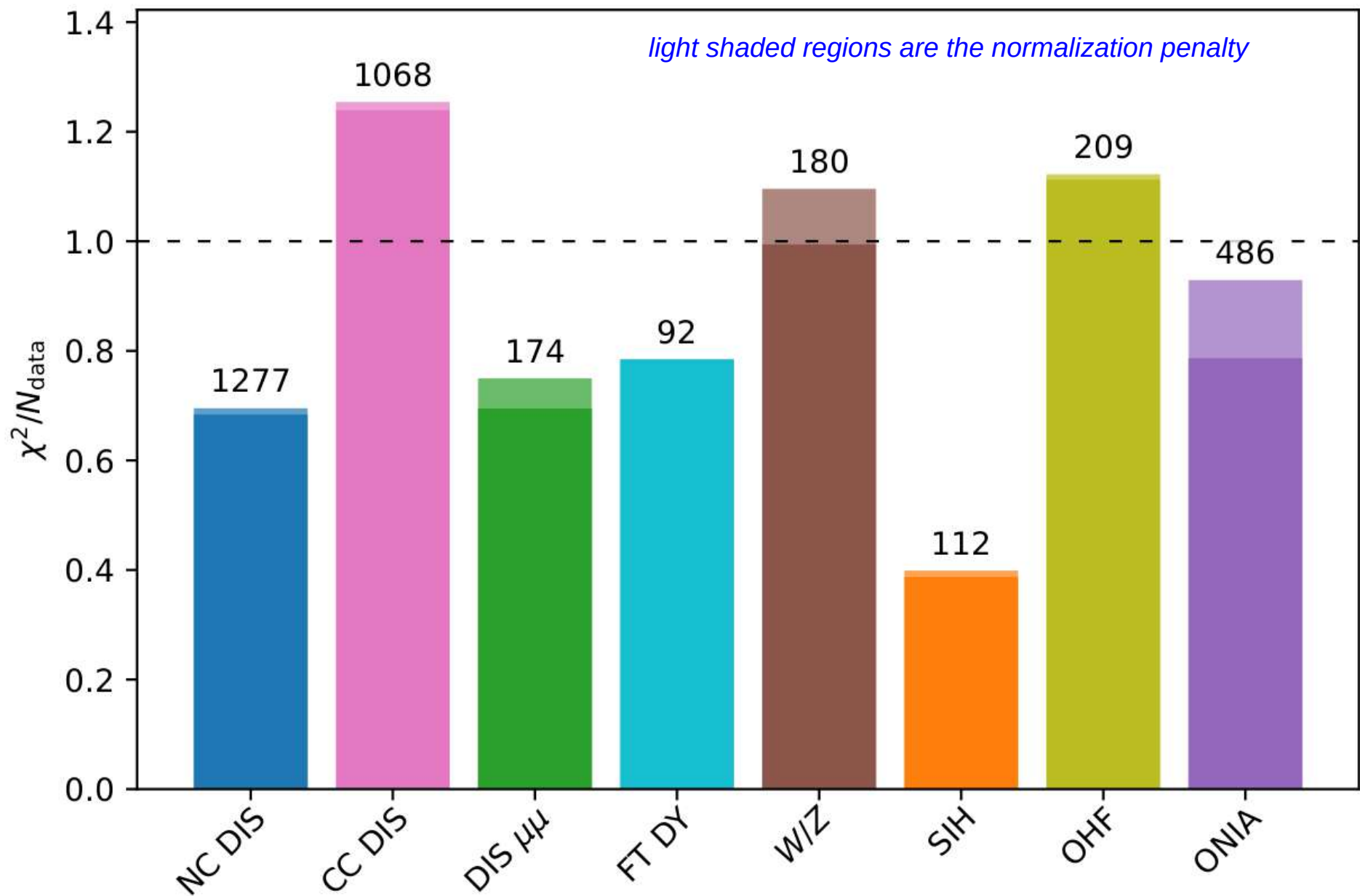
impacts $F_2^{\text{Nuc}}/F_2^{\text{Deuteron}}$ ratio

Extend nCTEQ framework
to accommodate this region

$\{Q, W\} = \{2, 3.5\} \Rightarrow \{1.3, 1.7\}$

nCTEQ15HIX -- Extending nPDF Analyses
into the High- x , Low Q^2 Region
E.P. Segarra, T. Ježo, et al., PRD 103, 114015 (2021)



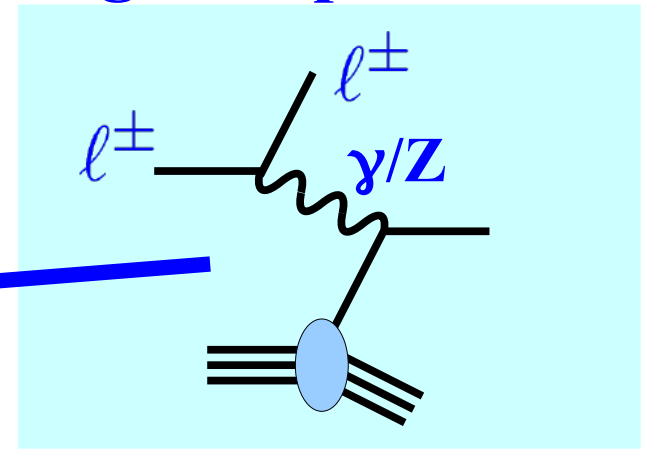


3357.97 for 3598 data points
36 free parameters
 $\chi^2/N_{\text{dof}} = 0.943$.

STRANGE

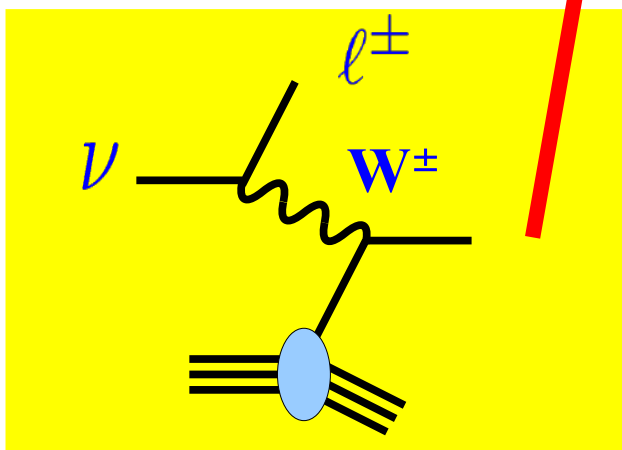
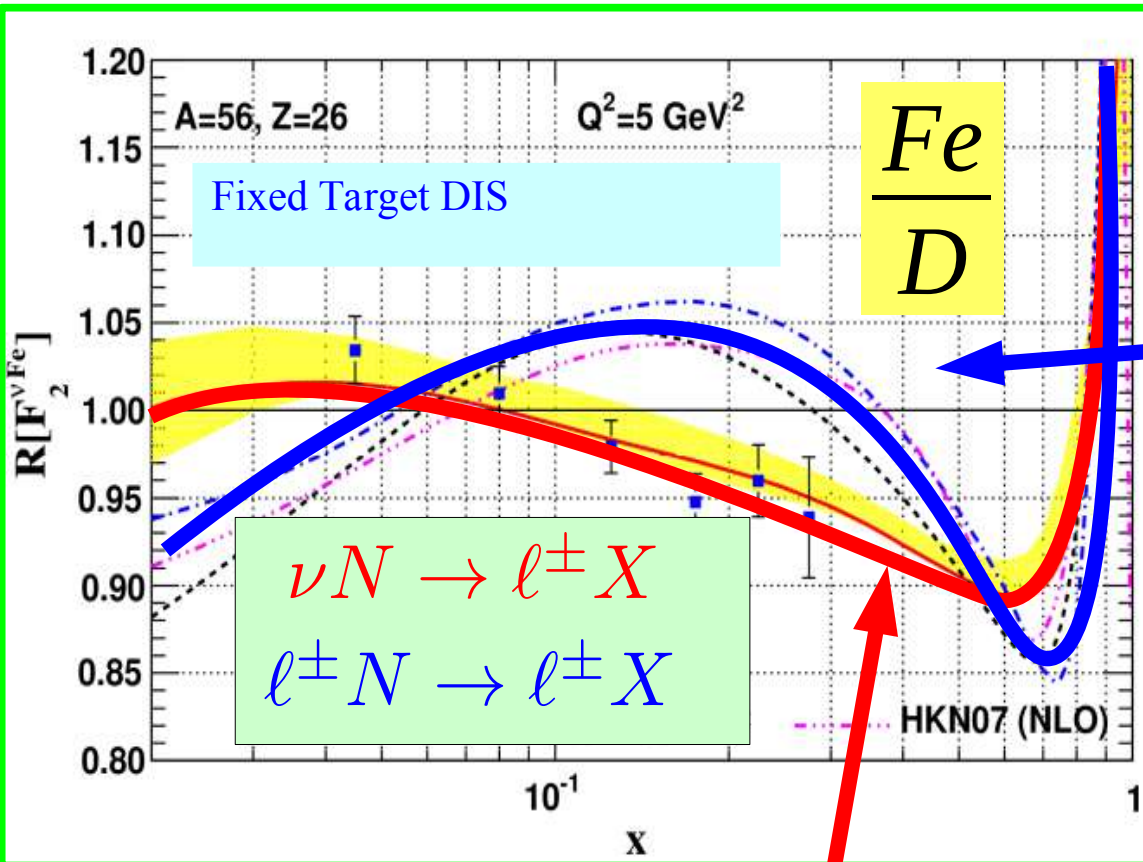


Charged Lepton DIS



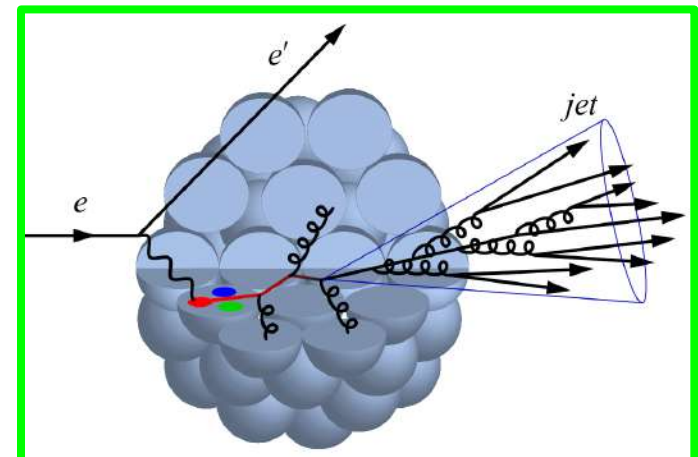
*some caveats
... correlated errors*

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



Neutrino DIS

Depends on nuclear corrections

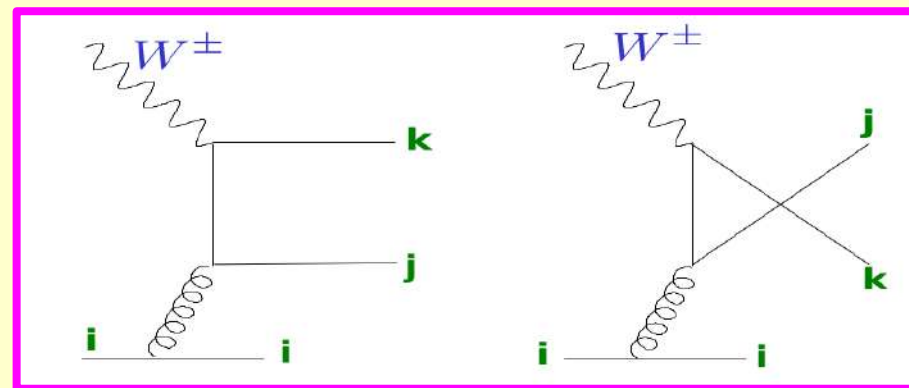


Propagation of γ/W thru nuclei

Fast evaluation of heavy-quark contributions to DIS in APFEL++

P. RISSE^{a,†}, V. BERTONE^b, T. JEŽO^a, M. KLASEN^a, K. KOVAŘÍK^a,
F.I. OLNES^c, I. SCHIENBEIN^d

Phys.Rev.D 112 (2025) 11, 11



APFEL++ – A PDF evolution library in c++

APFEL++

Bertone, arXiv:1708.00911

Available schemes in APFEL++

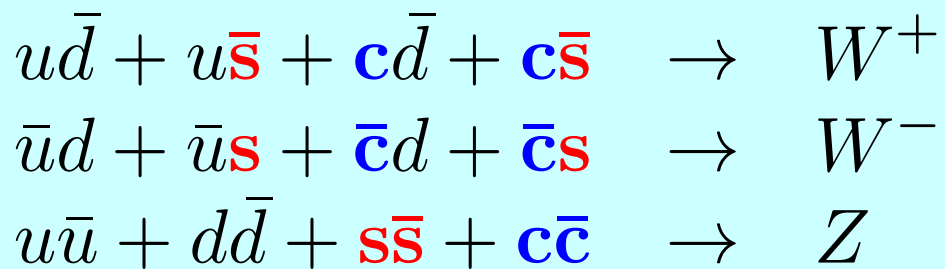
scheme	$\mathcal{O}(\alpha_s)$	NC: F_2	NC: F_3	NC: F_L	CC: F_2	CC: F_3	CC: F_L
ZM	N2LO	✓	✓	✓	✓	✓	✓
FONLL-C	N2LO	✓	✗	✓	✗	✗	✗
ACOT	NLO	✓	✓	✓	✗	✗	✗
sACOT- χ	NLO	✓	✓	✓	✓	✓	✓
approx. sACOT- χ	N2LO	✓	✓	✓	✓	✓	✓

Valerio Bertone



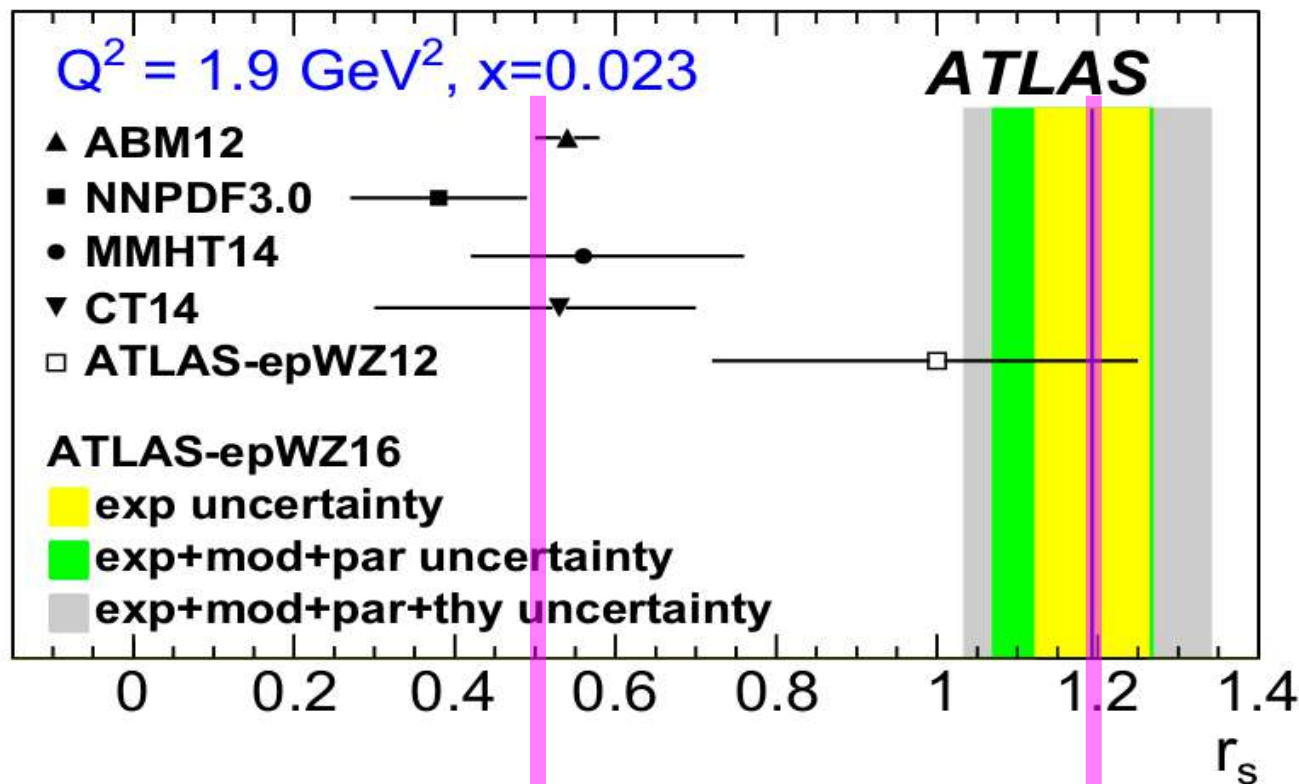
Peter Risse





Surprise:

We expected $r_s = 1/2$
LHC finds $r_s > 1$



Proton case

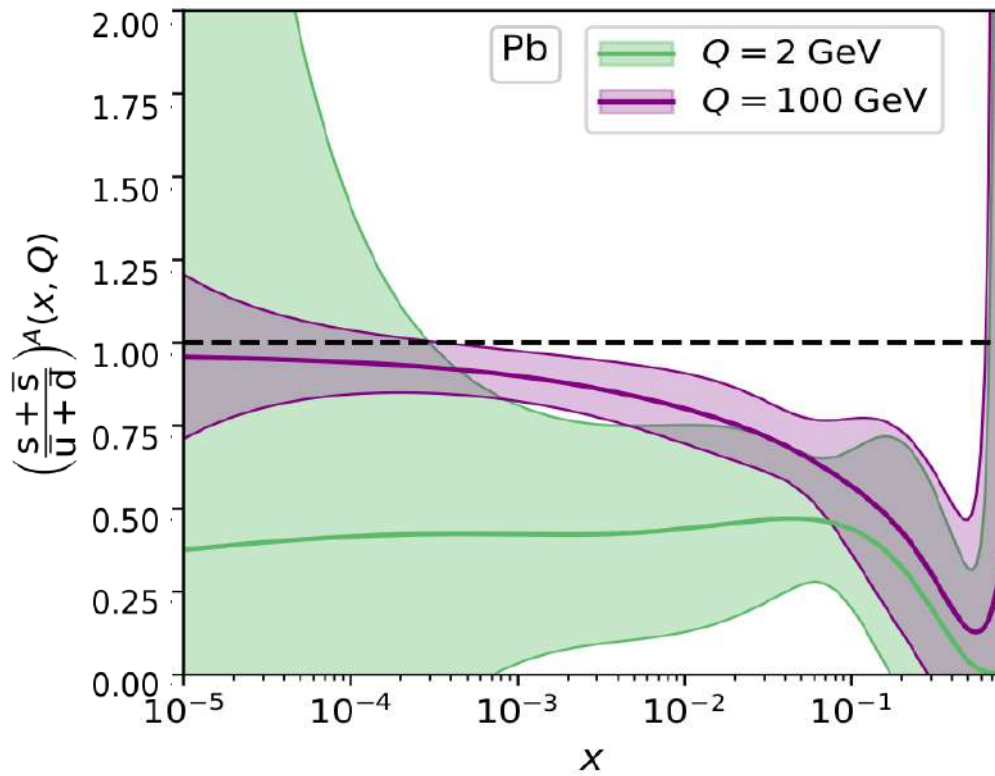
xFitter

$$r_s \sim \bar{s}/\bar{d}$$

We expect:

At the LHC:

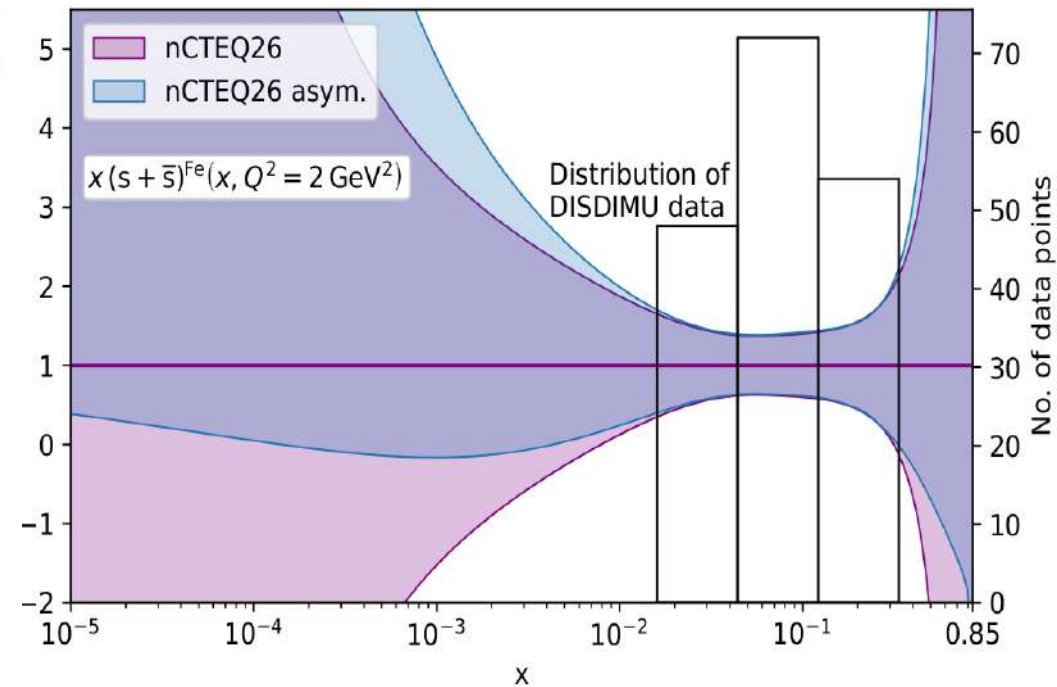
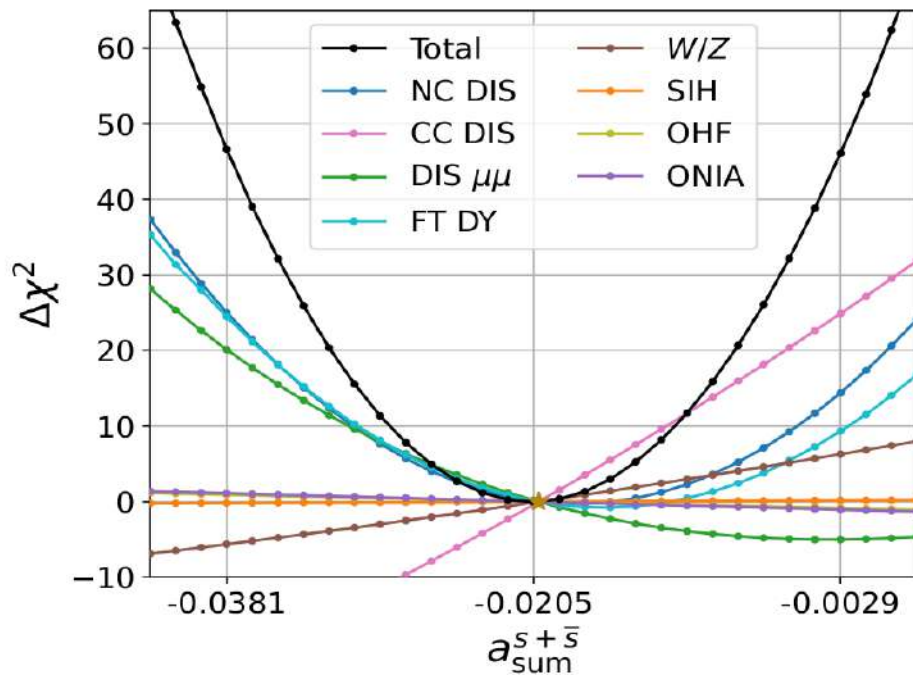
$$r_s = \frac{\bar{s} + s}{2\bar{d}}$$



Asymmetric Uncertainty Band

$$\Delta X^+ = \sqrt{\sum_{k=1}^n [\max(X_k^+ - X_0, X_k^- - X_0, 0)]^2},$$

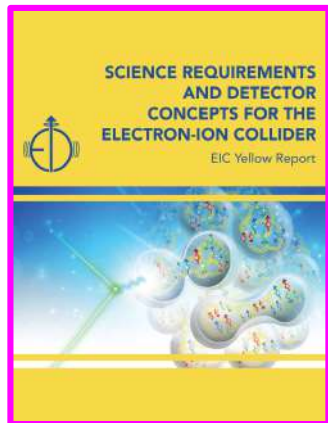
$$\Delta X^- = \sqrt{\sum_{k=1}^n [\max(X_0 - X_k^+, X_0 - X_k^-, 0)]^2},$$



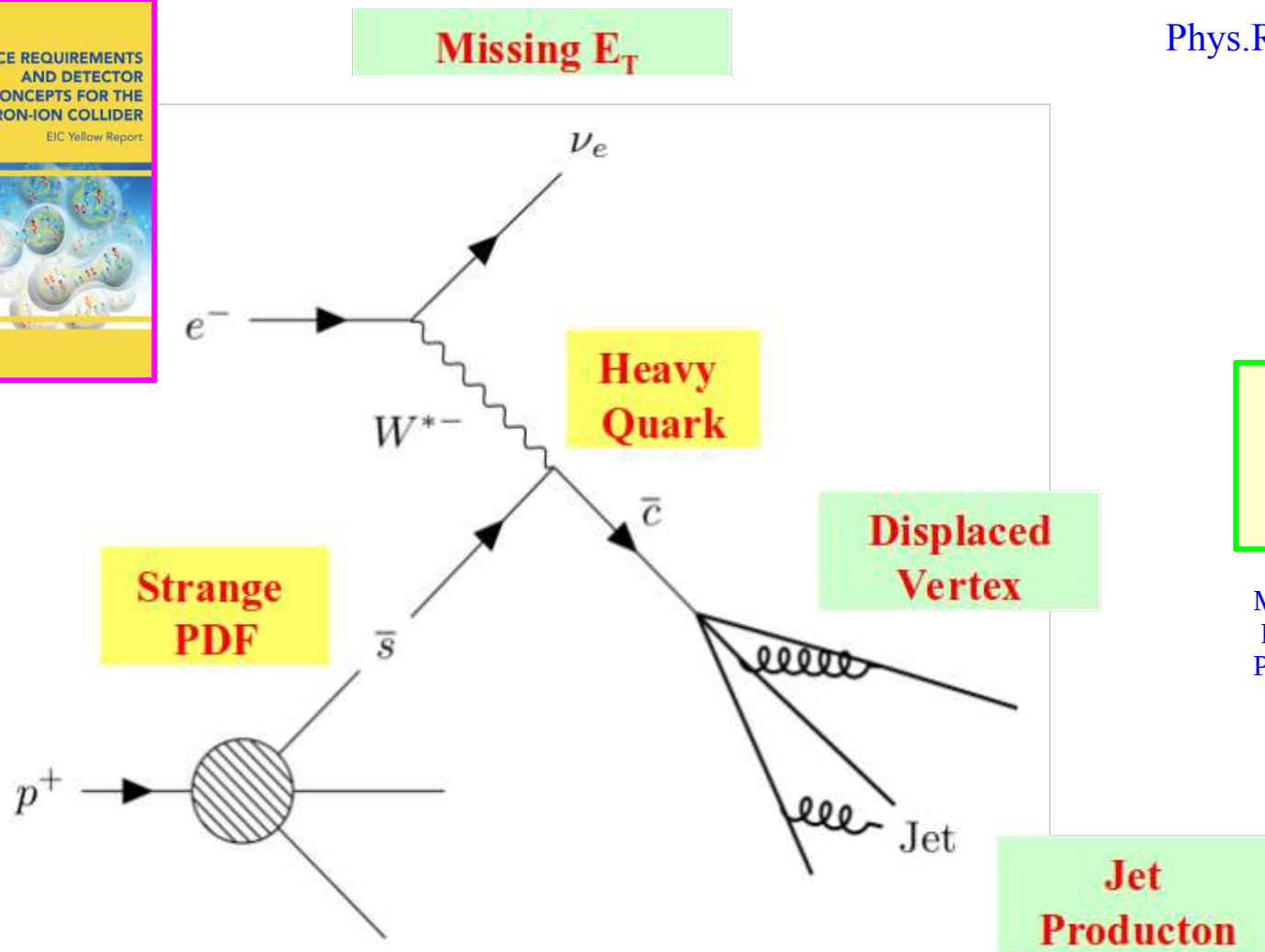
JLAB-PHY-20-3205, SMU-HEP-20-05

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,*}



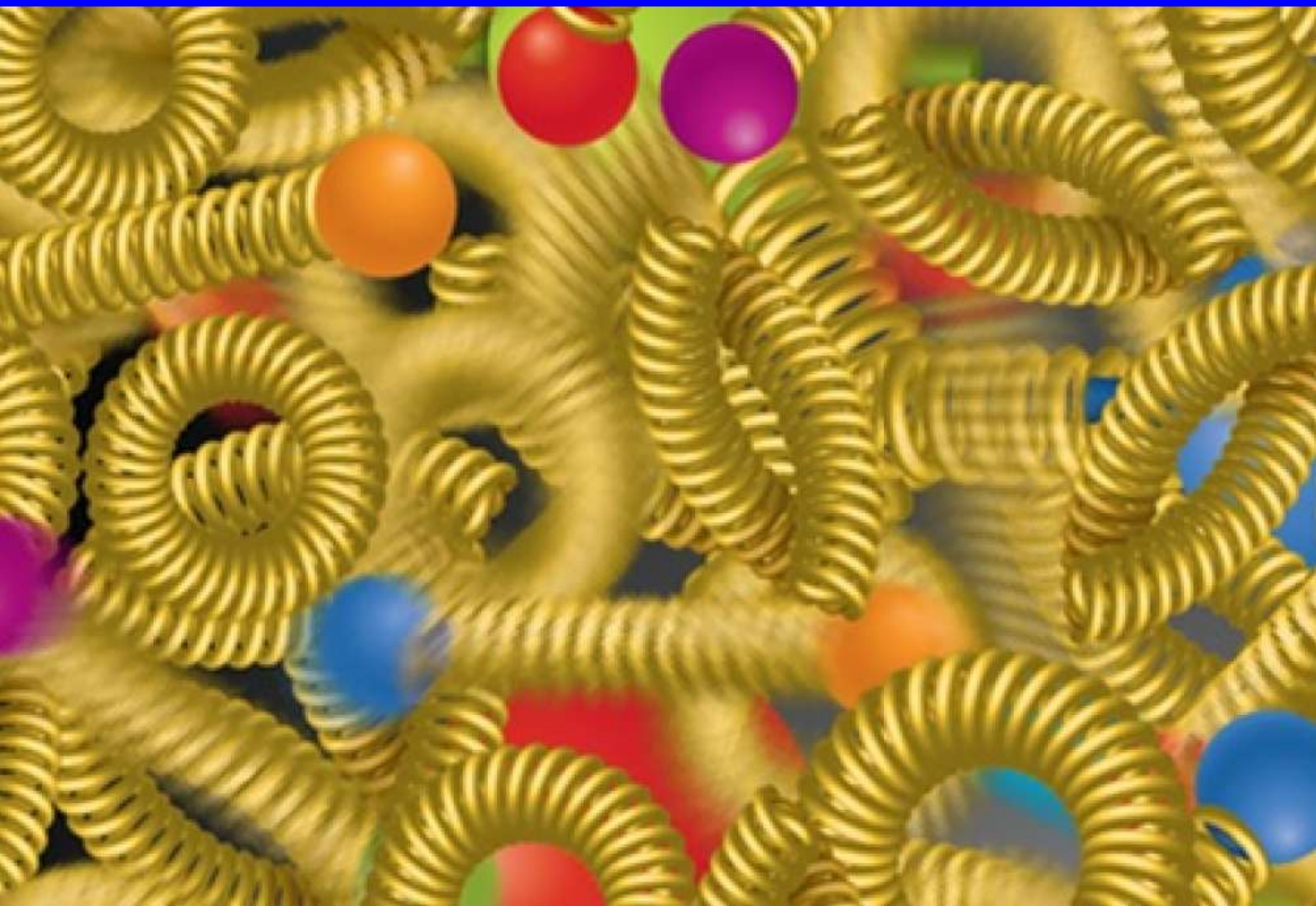
Phys.Rev.D 103 (2021) 7, 074023



**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

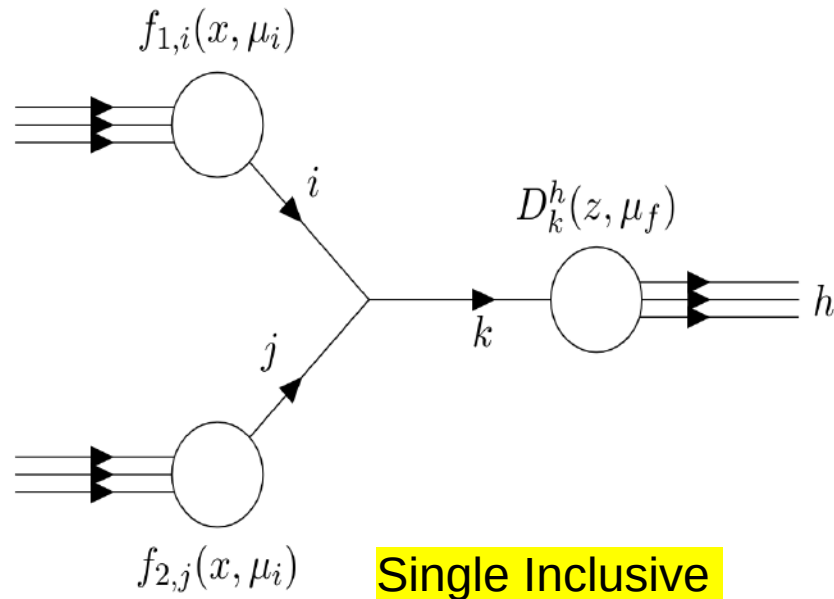
The Gluon



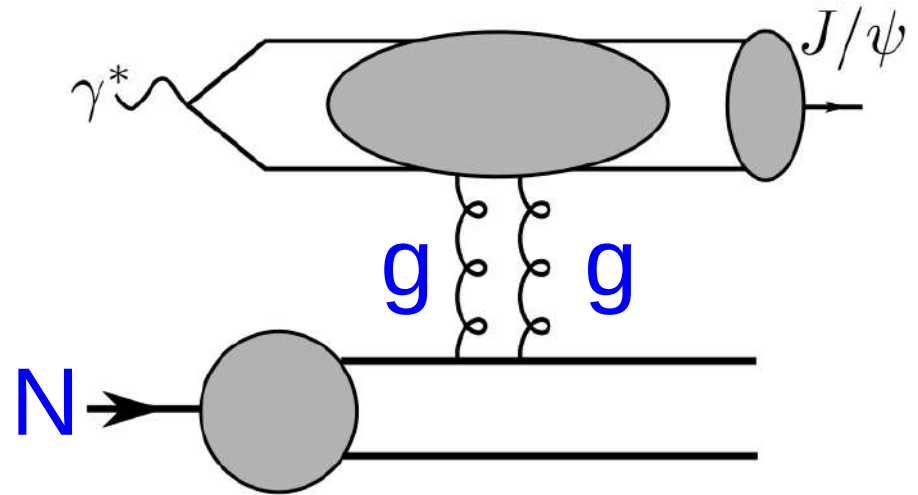
Measuring the nuclear Gluon PDF²⁶

Parton Distribution Functions

(nCTEQ) Pit Duwentaster, Michael Klasen, ...



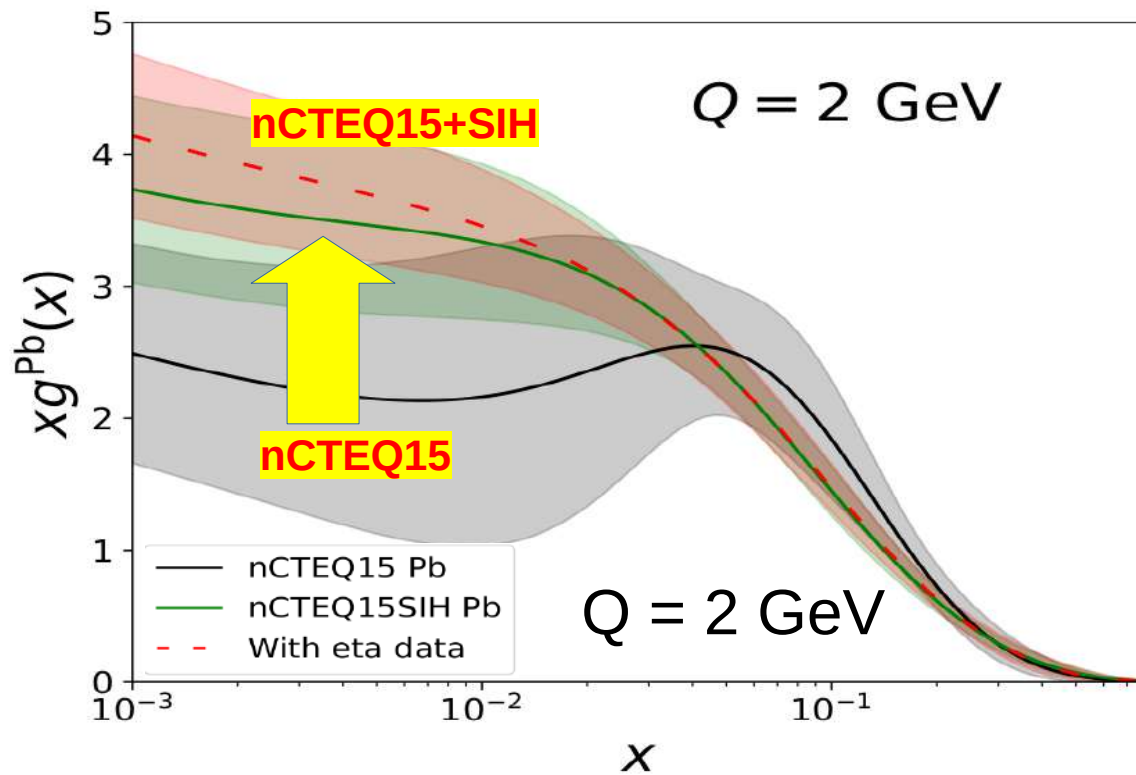
Single Inclusive
Hadron Production



Quarkonia
Production



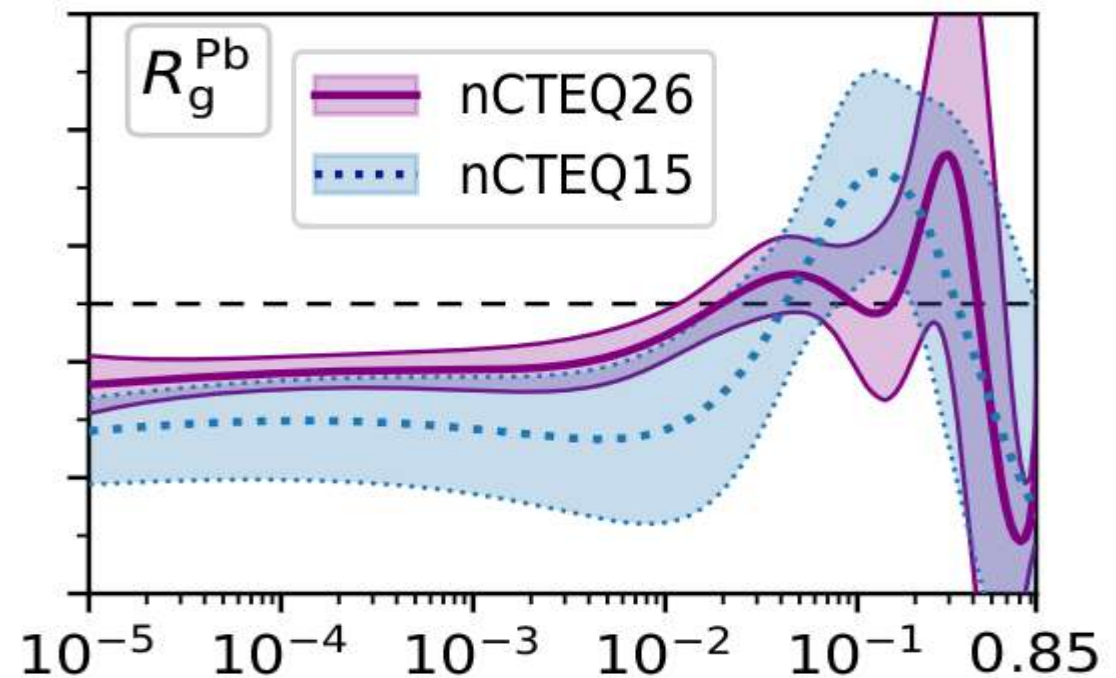
how can we
determine the gluon



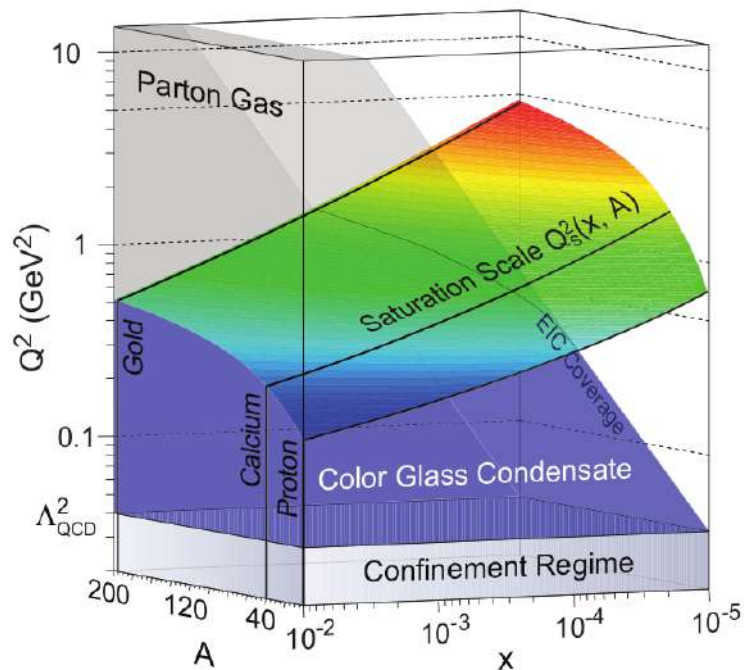
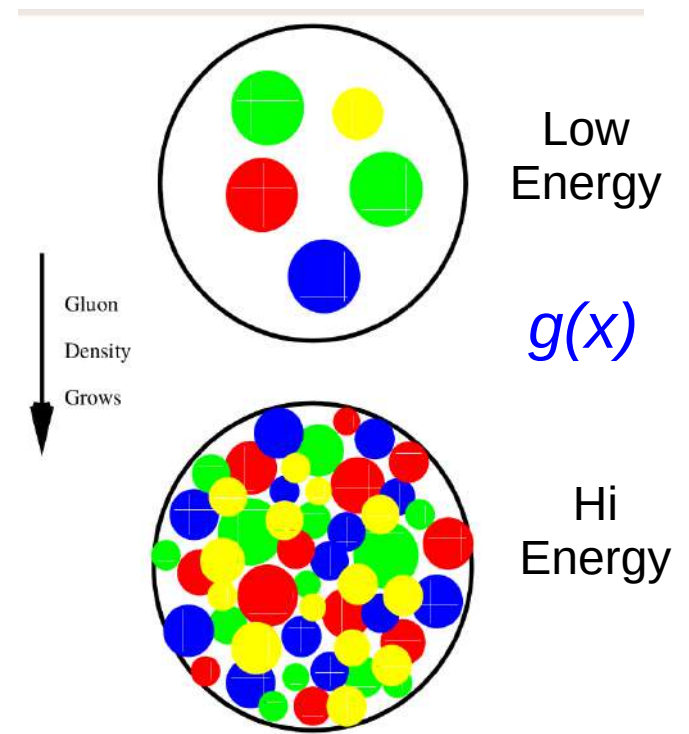
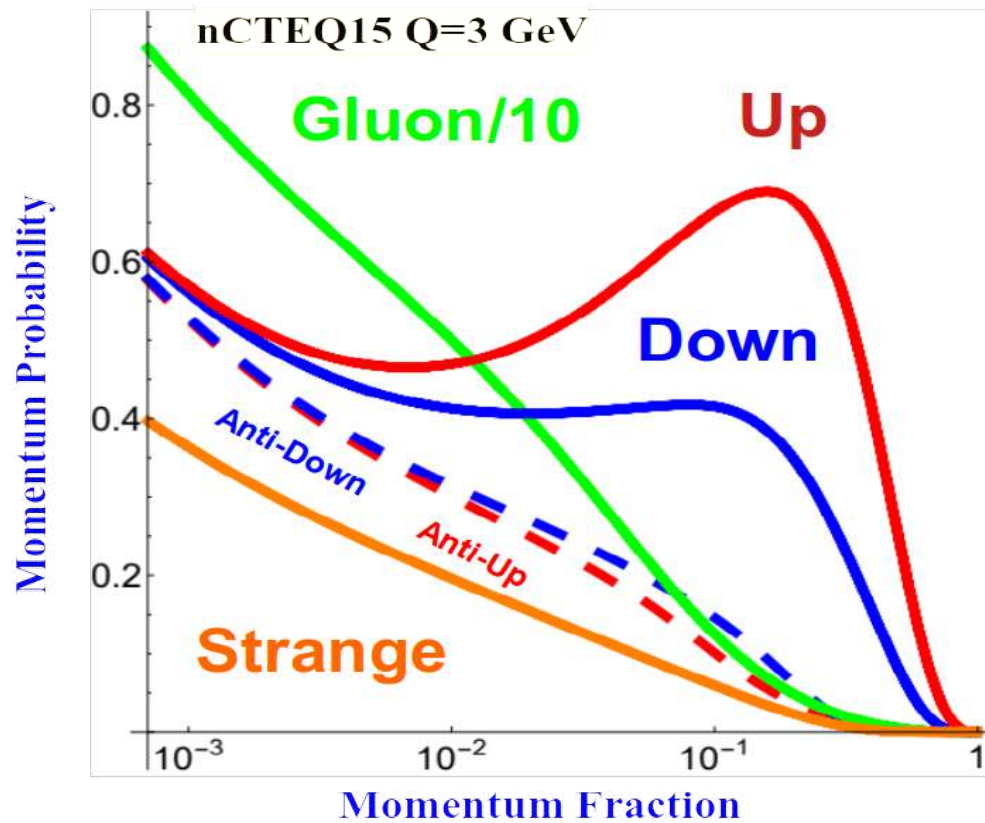
Data set	$\sqrt{s_{NN}}$ [GeV]	Observ.	No. points
PHENIX π^0	200	R_{dAu}	21
PHENIX η	200	R_{dAu}	12
PHENIX $\pi^\pm$	200	R_{dAu}	20
PHENIX $K^\pm$	200	R_{dAu}	15
STAR π^0	200	R_{dAu}	13
STAR η	200	R_{dAu}	7
STAR $\pi^\pm$	200	R_{dAu}	23
ALICE 5 TeV π^0	5020	R_{pPb}	31
ALICE 5 TeV η	5020	R_{pPb}	16
ALICE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

*Gluon
improvement*

*nCTEQ26
vs
nCTEQ15*



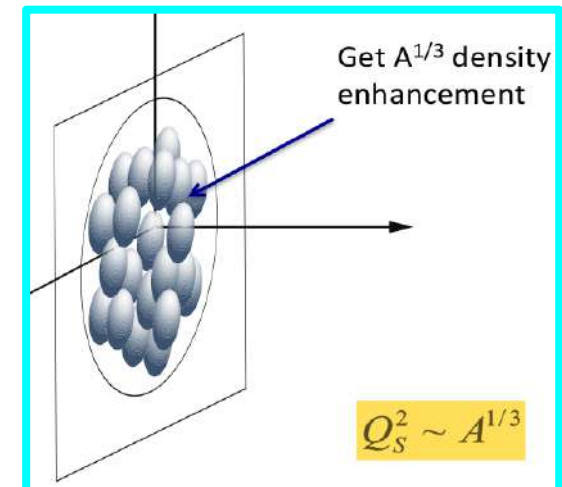
Nuclear Medium Effects at small momentum fraction (x)



Nuclear medium effects:

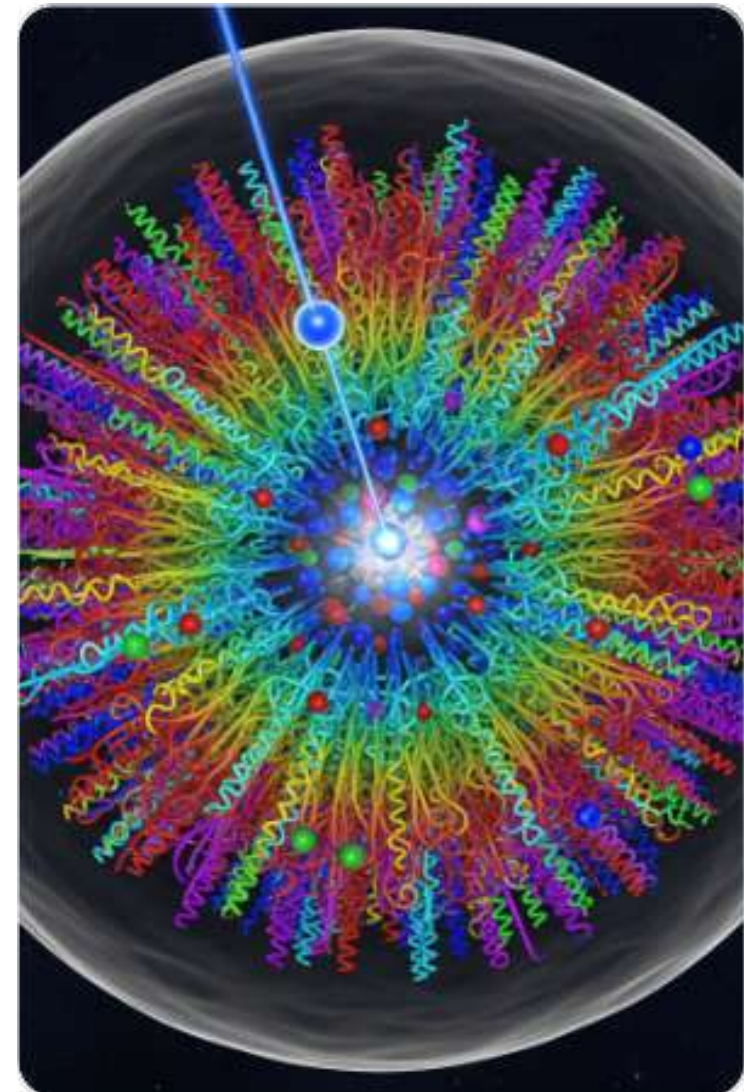
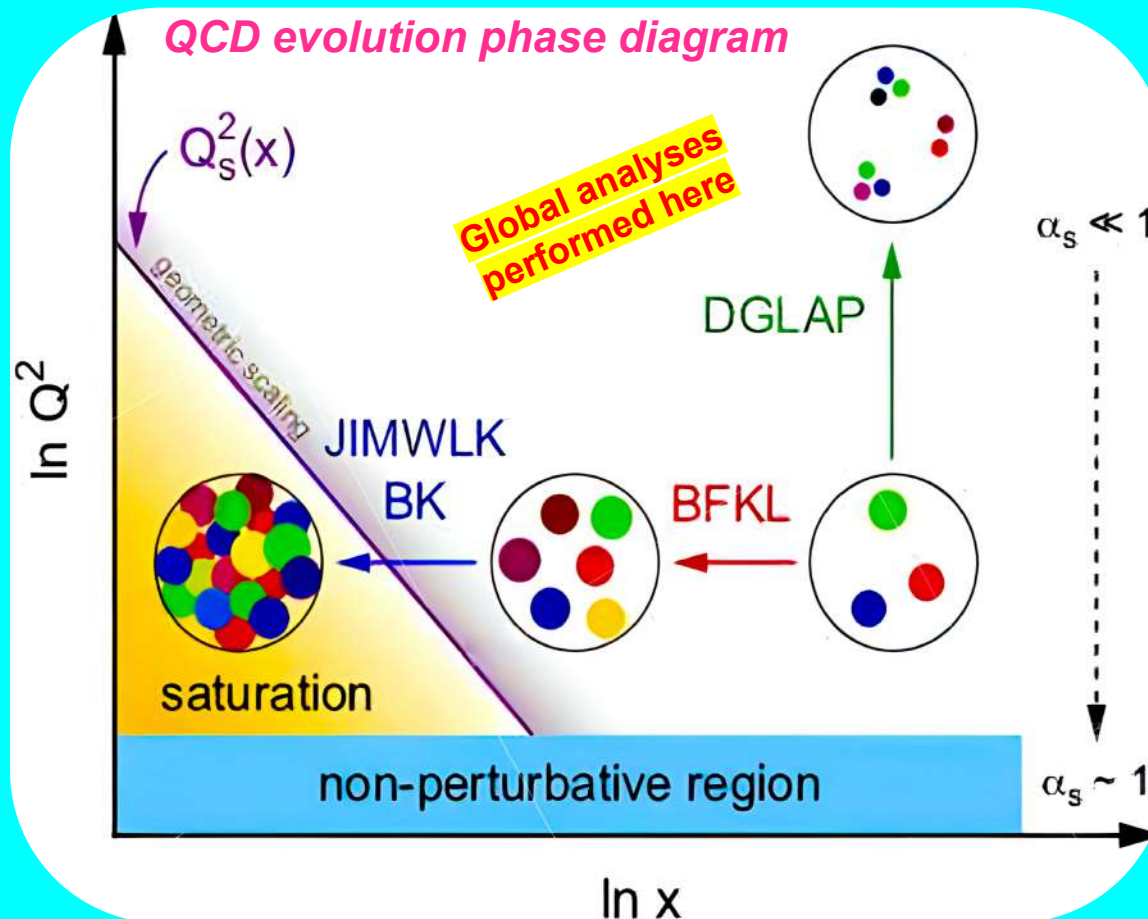
- Quark Gluon Plasma
- Color Glass Condensate
- Recombination
- Saturation
- Resummation
- ... *your theory here*

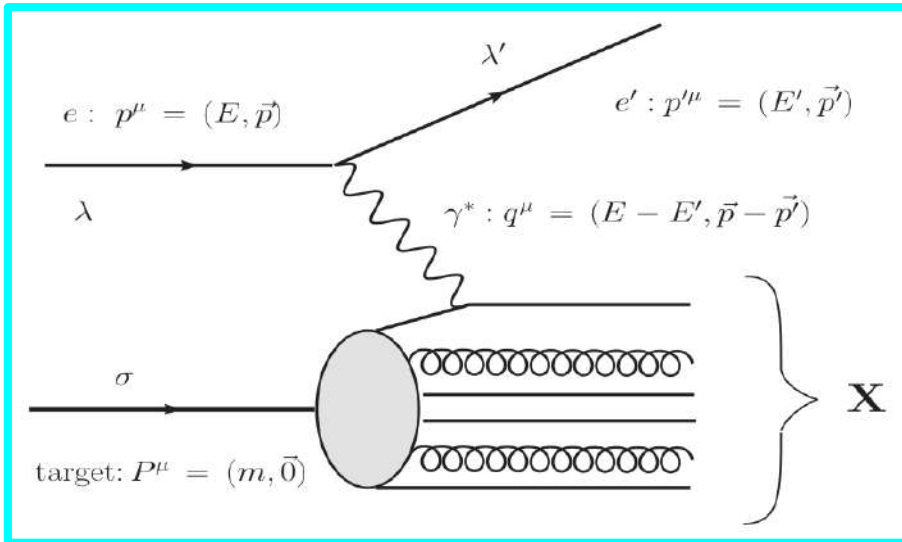
We gain a geometric factor of $A^{1/3}$



SURGE Topical Collaboration

Mission statement: Discover and explore the gluon saturation regime of quantum chromodynamics by advancing calculations to high precision and developing a comprehensive framework to compute observables and compare to a wide range of experimental data, including predictions for the Electron Ion Collider (EIC).





Parton Model

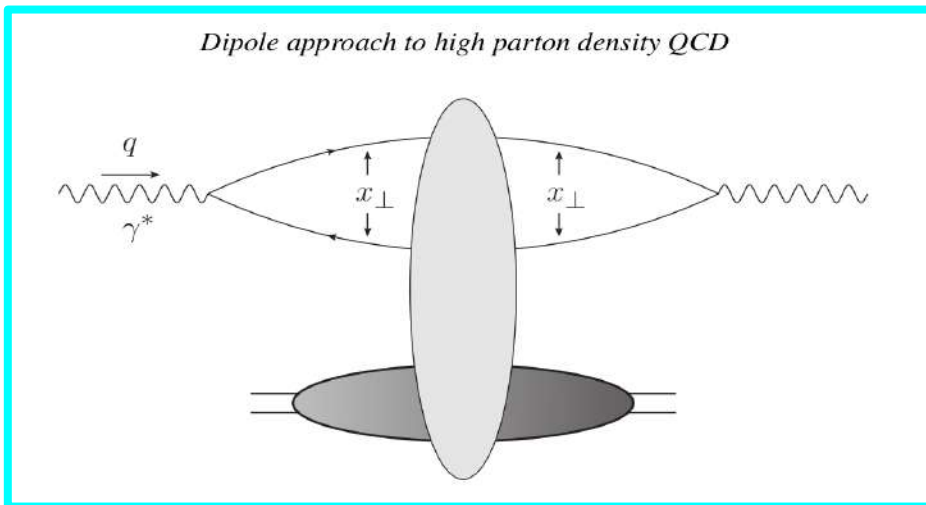
$$\sigma = f_{P \rightarrow a}(x, Q) \otimes \hat{\sigma}_{a\gamma \rightarrow X}(x, \hat{s})$$

Implemented in **xFitter**
uses several numerical “tricks”
for efficient computation

Dipole Model

GOAL: Develop flexible
framework to test
initial/final-state, spin, NLO ...

The dipole model excels at small- x and describes the transition between perturbative and non-perturbative QCD regime. Incorporates “shadowing” or “saturation” which is key for dense gluon configurations.

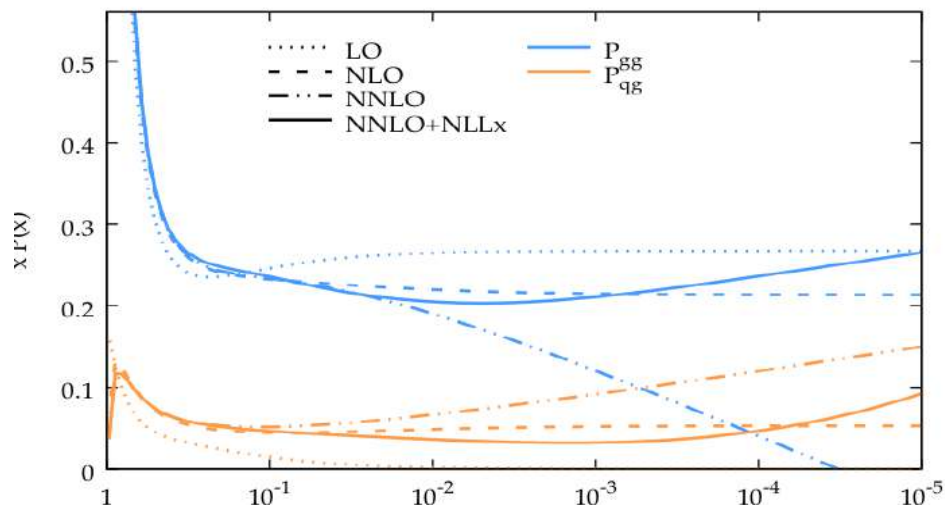
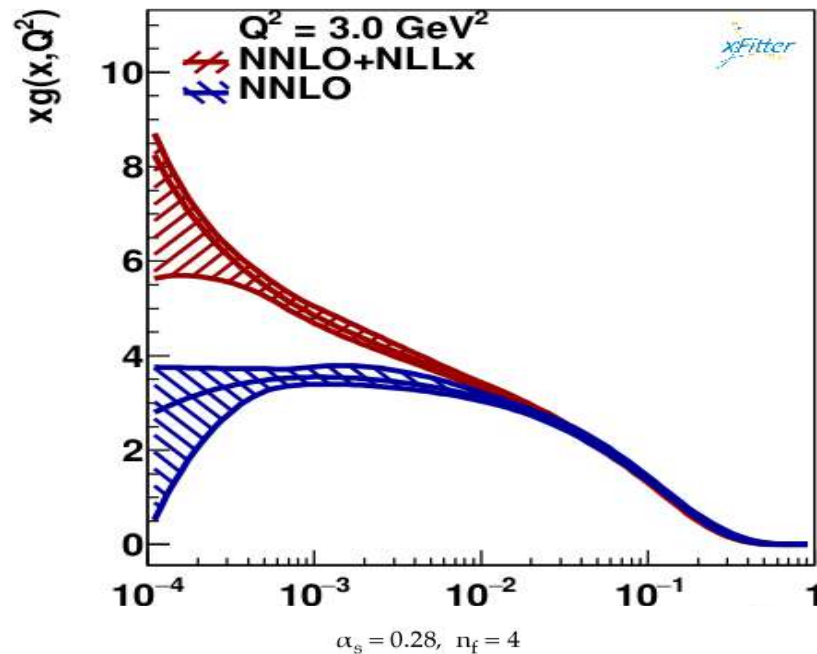


$$\sigma_{tot}^{\gamma^* A}(x, Q^2) \simeq \iint |\Psi^{\gamma^* \rightarrow q\bar{q}}(\vec{x}_\perp, z)|^2 \otimes \sigma_{tot}^{q\bar{q} A}(\vec{x}_\perp, Y)$$



Impact of low- x resummation on QCD analysis of HERA data

xFitter Developers' team: Hamed Abdolmaleki¹, Valerio Bertone^{2,3}, Daniel Britzger⁴, Stefano Camarda⁵, Amanda Cooper-Sarkar⁶, Francesco Giuliani⁶, Alexander Glazov⁷, Aleksander Kusina⁸, Agnieszka Luszczak^{7,9}, Fred Olness¹⁰, Andrey Sapronov¹¹, Pavel Shvydkin¹¹, Katarzyna Wichmann⁷, Oleksandr Zenaiev⁷ and Marco Bonvini¹²



xsect_dipole_proton.c

```
#include <math.h>
#include "xsect_dipole_proton.h"

////////////////////////////////////
// Parametrisation of the dipole-proton cross-section //
// as obtained from high-energy QCD with saturation //
////////////////////////////////////
// This file contains two version of the cross-section //
// The first one is the original from //
// [1] E. Iancu, K. Itakura and S. Munier, //
// Phys.Lett.B590:199-208,2004 [hep-ph/0310338] //
// which includes only light quarks. //
// The second is from //
// [2] G. Soyez, in preparation //
// which also accounts for heavy quarks. //
// They both implement eq. (8) of Ref. 1 or eq. (3) of //
// Ref. 2. Only the parameters of the fit vary. //
// //
// - Arguments: //
// r : dipole size //
// Y : rapidity (Y=log(1/x)) //
// - Returned value: //
// the dipole-proton cross-section (in GeV^{-2}) //
// //
// Additional remarks: //
// - The quark masses are //
// m_{u,d,s}=140 MeV, m_c=1.4 GeV and m_b=4.5 GeV //
// - When the heavy quarks are considered (2nd model), //
// the x value for their contribution has to be //
// shifted to x(1+4 m^2/Q^2) //
////////////////////////////////////
```

CONCLUSIONS

QUARK-GLUON DYNAMICS IN THE NUCLEAR MEDIUM

9 - 13 November 2026

ECT* - Villa Tambosi, Villazzano

This workshop will bring together experimentalists and theorists to discuss recent progress and open questions in understanding how quark and gluon dynamics are modified in the nuclear environment. The workshop aims to foster focused discussion across subfields and to identify key directions for future measurements and theoretical work.

Topics will cover related developments in theory, phenomenology, and experiment in the areas of gluonic components in nuclei, hadronization, partonic structure, nuclear medium effects, short-range correlations, 3D nucleon/nuclear structure, vector mesons, hypernuclei, and connections to the future electron ion collider.

ORGANIZERS

Holly **Szumila-Vance**, Florida International University
Cynthia **Keppel**, 3q Scientific Consulting
Fredrick **Olness**, Southern Methodist University
Matteo **Rinaldi**, INFN Perugia
Misak **Sargsian**, Florida International University

ECT* Director: Prof. Ubirajara van Kolck

The ECT* is part of the Fondazione Bruno Kessler. The Centre is funded by the Autonomous Province of Trento, funding agencies of EU Member and Associated states, and by INFN-TIFPA and has the support of the Department of Physics of the University of Trento.

For the organization please contact: Barbara Gazzoli - ECT* Secretariat - Villa Tambosi - Strada delle Tabarelle 286 | 38123 Villazzano (Trento) - Italy
Tel.: (+39-0461) 314763, E-mail: gazzoli@ectstar.eu or visit <http://www.ectstar.eu>



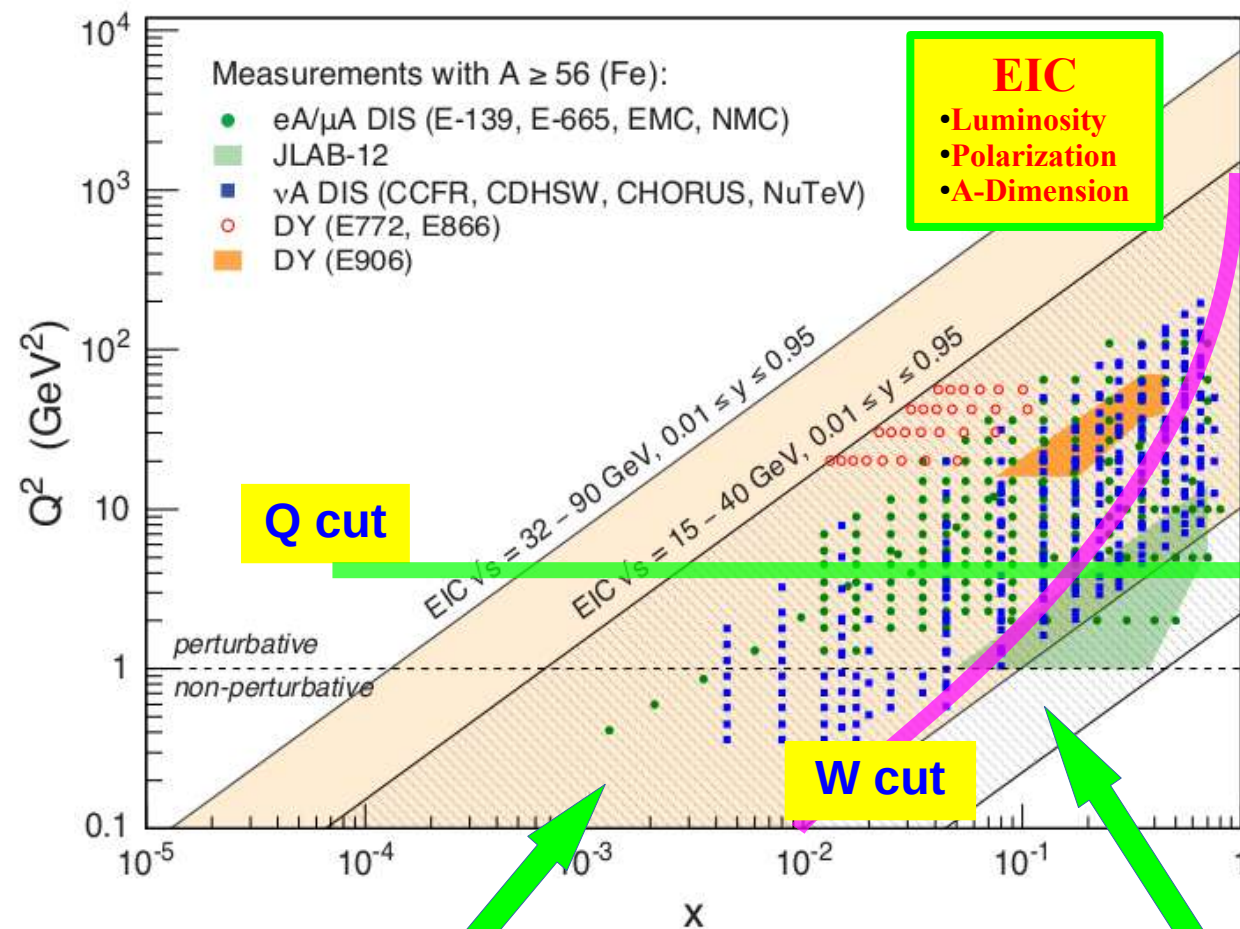
QUARK-GLUON DYNAMICS IN THE NUCLEAR MEDIUM



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<https://indico.ectstar.eu/event/276/>



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

Low- x :

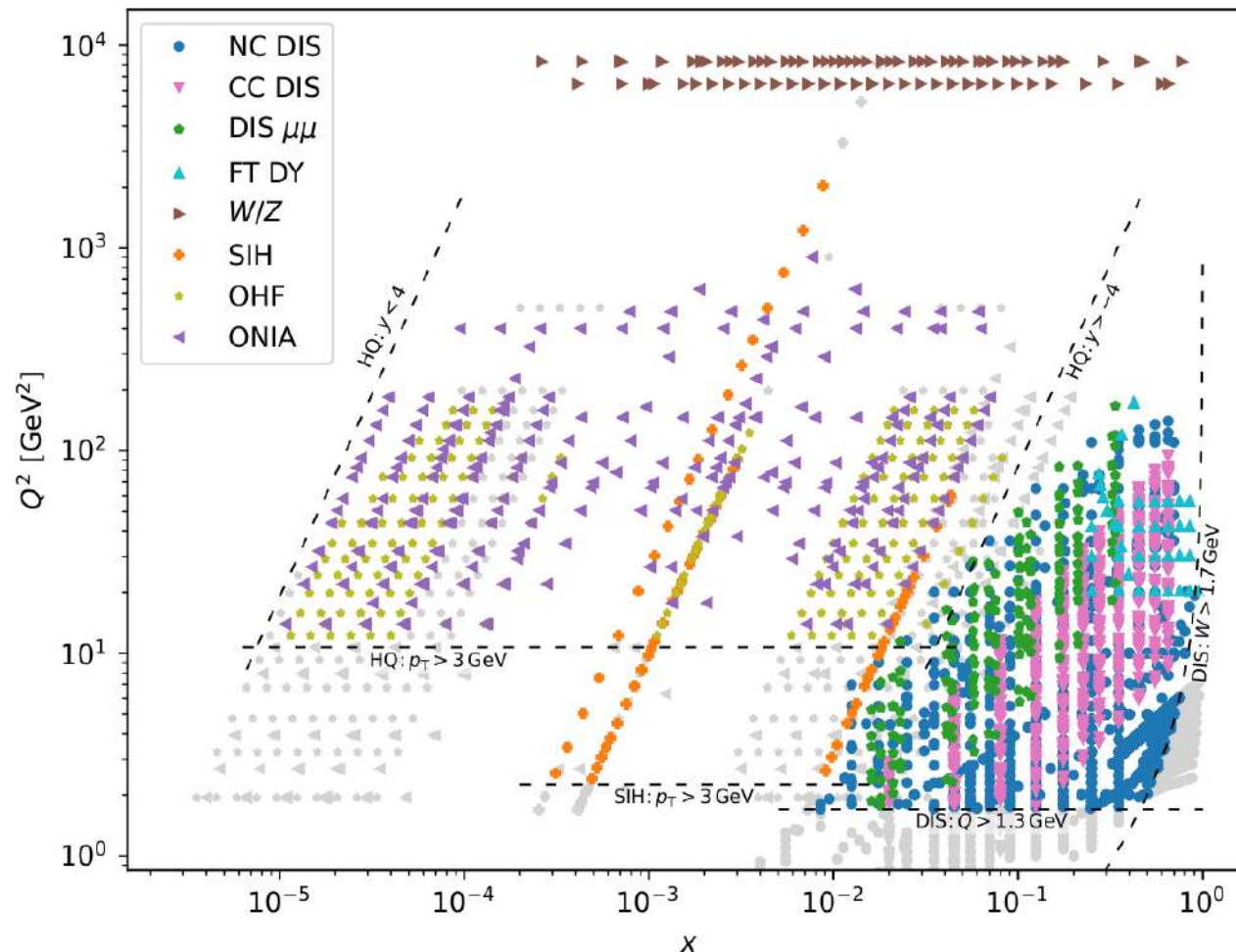
Shadowing
 Recombination
 Resummation
 BFKL
 Saturation



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





PDF Sets on HepForge

- new CC DIS, DIS $\mu\mu$, DY W/Z, HQ data
- $N_{\text{data}} = 3518$
- looser cuts

Jan Wissmann (jan.wissmann@uni-muenster.de)

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nCTEQ
nuclear parton distribution functions



Tomas
Jezo



Katrin
Greve



Jan
Wissmann



Aleksander
Kusina

PDF Tools

xFitter



Sample data files:

LHC: ATLAS, CMS, LHCb

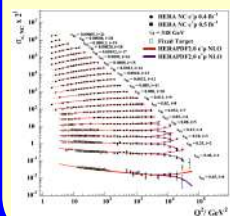
Tevatron: CDF, D0

HERA: H1, ZEUS, Combined

Fixed Target: ...

User Supplied: ...

Experimental Data



Data: HERA, Tevatron, LHC,
fixed target experiments

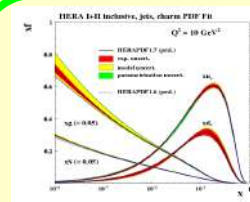
Processes:

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:

NNLO DGLAP

Photon PDF & **QED**

Pole & MS-bar masses

Profiling and Re-Weighting

BFKL interface

Heavy Quark Variable Threshold
Improvements in χ^2 and correlations

TMD PDFs (uPDFs)

... and many other

xFitter 2.2.0
Future Freeze

Probing Dense Nuclear Matter at Small-x

SURGE Global Analysis WG

GOAL: Sketch a work-flow for a global analysis framework.

Fred Olness
(SMU)

The SMU Team



Fred
Olness



Brandon
Stevenson
grad student



Rebecca
Preston
grad student



Junaid
Khan
grad student



Peter
Risse
Postdoc

with contributions from many others including



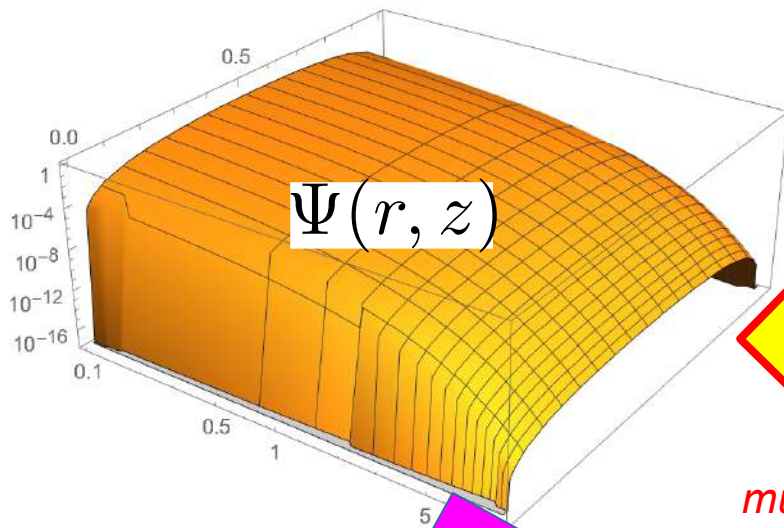
nCTEQ
nuclear parton distribution functions



$$\sigma_{tot}^{\gamma^* A}(x, Q^2) = \int \frac{d^2 x_{\perp}}{4\pi} \int_0^1 \frac{dz}{z(1-z)} |\Psi^{\gamma^* \rightarrow q\bar{q}}(\vec{x}_{\perp}, z)|^2 \sigma_{tot}^{q\bar{q} A}(\vec{x}_{\perp}, Y).$$

Photon light-front
wave function

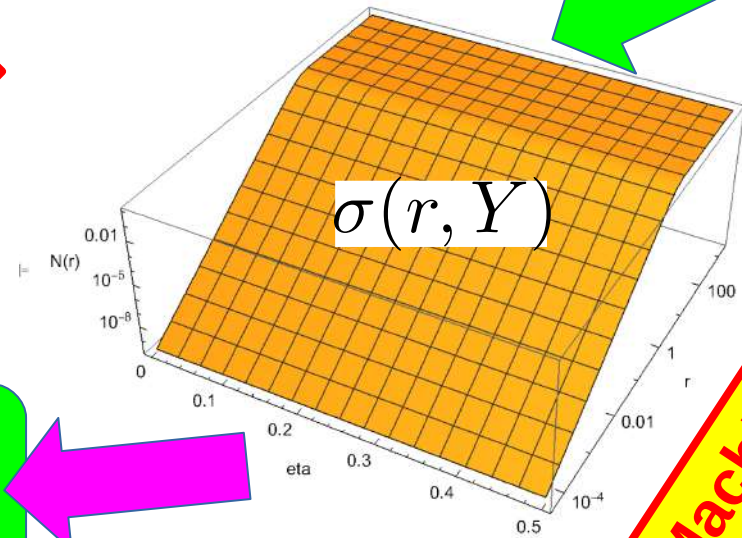
Dipole-nucleus
cross section



Grid
Method

must be fast!!!

Convolution
2D Grid-based calc

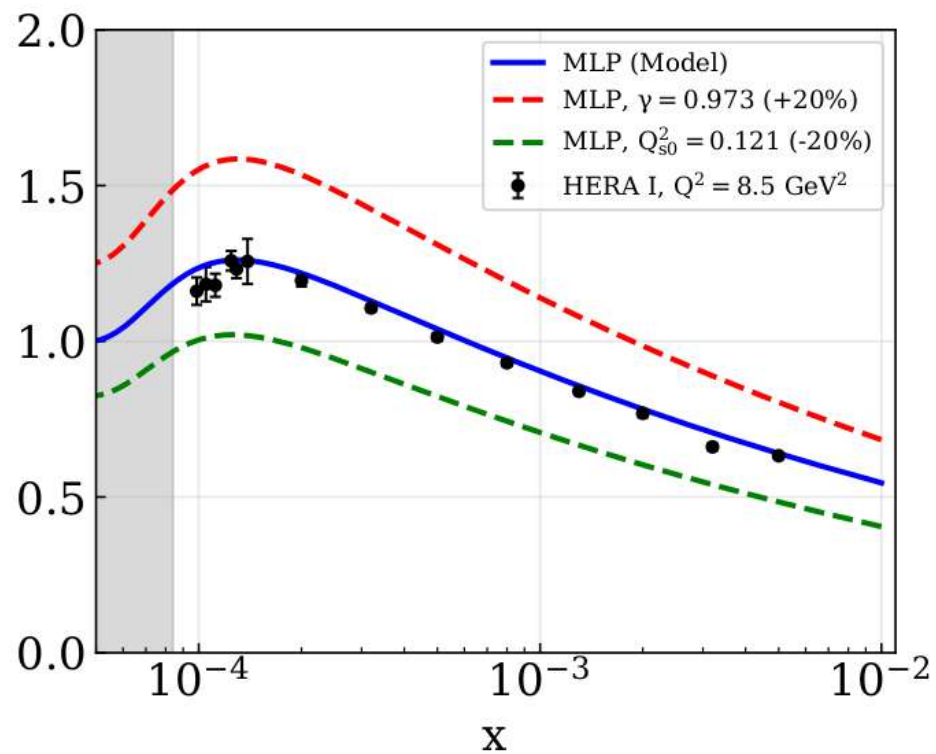
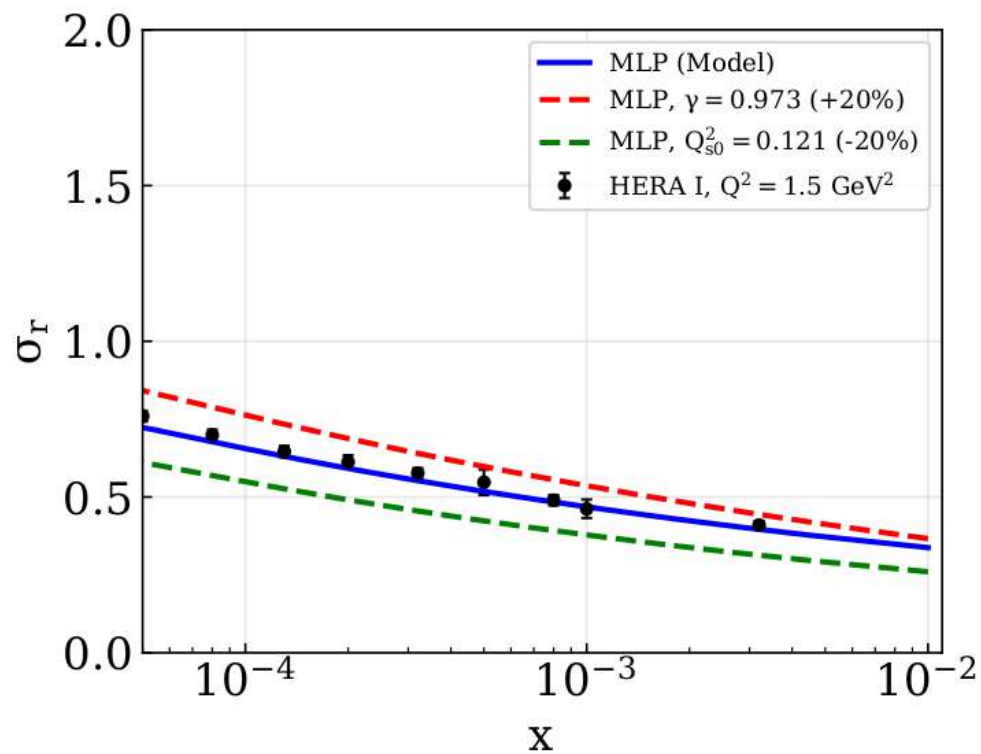


Machine
Learning

$\sigma_{tot}^{\gamma^* A}(x, Q^2)$
... F_2 & F_L

$$\chi^2 = \frac{(D - T)^2}{\sigma^2}$$

*x*Fitter



Impact of inclusive hadron production data on nuclear gluon PDFs

P. Duwentäster^{1,*}, L. A. Husová², T. Ježo³, M. Klasen¹, K. Kovařík¹,
A. Kusina⁴, K. F. Muzakka¹, F. I. Olness⁵, I. Schienbein⁶ and J. Y. Yu⁵

¹ Institut für Experimentelle Kernphysik, Universität Bonn, 53115 Bonn, Germany

<https://arxiv.org/abs/2105.09873>

TABLE II. Overview of the available sets of FFs $D_i^h(z, Q)$ and their available particles.

FF	Ref.	Year	Available particles
BKK	[59]	1994	$\pi_0, \pi^\pm, K^\pm$
KKP	[60]	2000	$\pi_0, \pi^\pm, K^\pm$
KRETZER	[61]	2000	$\pi_0, \pi^\pm, K^\pm$
HKNS07	[62]	2007	$\pi_0, \pi^\pm, K^\pm$
AKK	[63]	2008	$\pi_0, \pi^\pm, K^\pm$
NNFF	[64]	2017	$\pi_0, \pi^\pm, K^\pm$
JAM20	[65]	2021	$\pi_0, \pi^\pm, K^\pm$
DSS14	[40]	2014	$\pi_0, \pi^\pm$
DSS17	[66]	2017	$K^\pm$
AESSS	[67]	2011	η