# Precision QCD and Nuclear Structure:

## Toward the EIC with Precision nPDFs

Fred Olness
SMU

*Thanks for substantial input*
*from my friends & colleagues*

nCTEQ
nuclear parton distribution functions

xFitter

SURGE COLLABORATION

C T E Q

**2026 Loopfest**
BNL
27-29 May 2026

# QCD: Remarkably successful at describing High Energy Processes

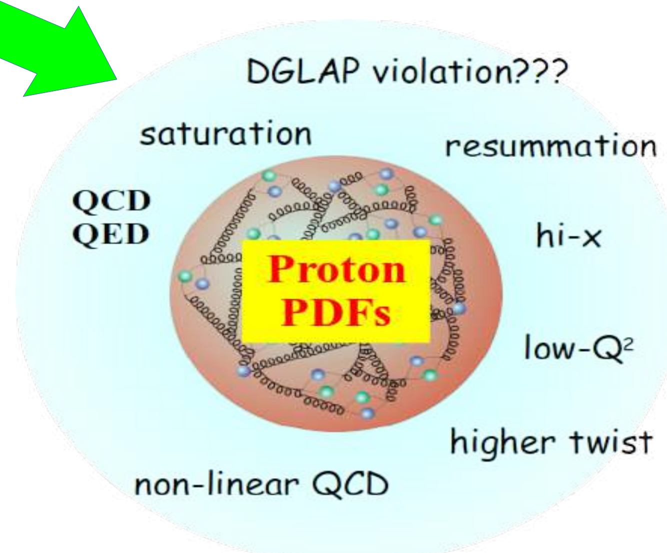
Quantum ChromoDynamics

**QCD**

Lagrangian

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

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


*… we can go further*

DPF/DNP Community Meeting (May 22)

May 21, 2026, 8:45 AM → May 22, 2026, 4:30 PM America/New_York

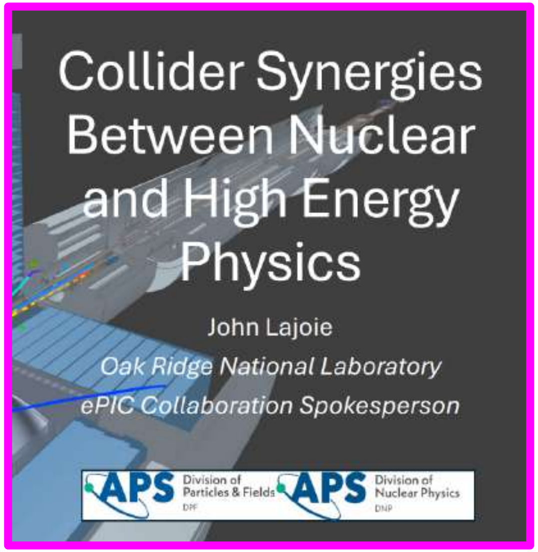
Hitoshi Murayama (University of California Berkeley (US)), Nadia Fomin (University of Tennessee)

Description

APS Division of Particles & Fields DPF — APS Division of Nuclear Physics DNP

HiLumi

HL-LHC PROJECT




FERMI NEWS

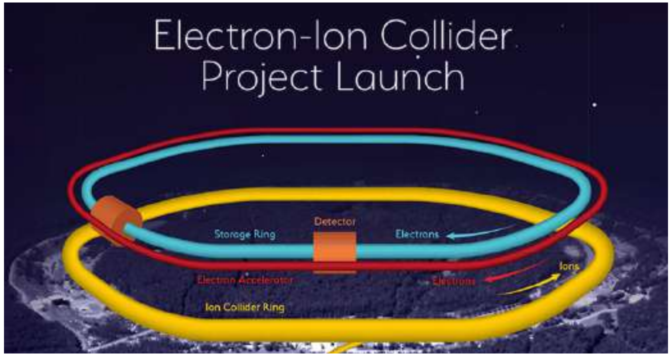
Volume 26 | Friday, Janu

In This Issue | Ferm

**Data Make You Smarter**

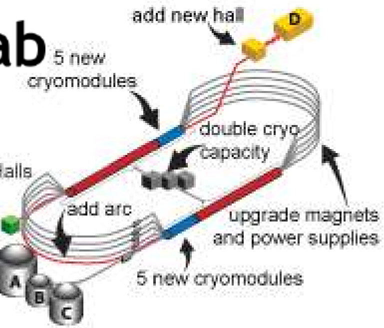
**by Dan Amidei, University of Michig**
**and Chip Brock, Michigan State Uni**

As Collider Run II gets under way with fits a
question its goals. But it would be wrong to




DESY.

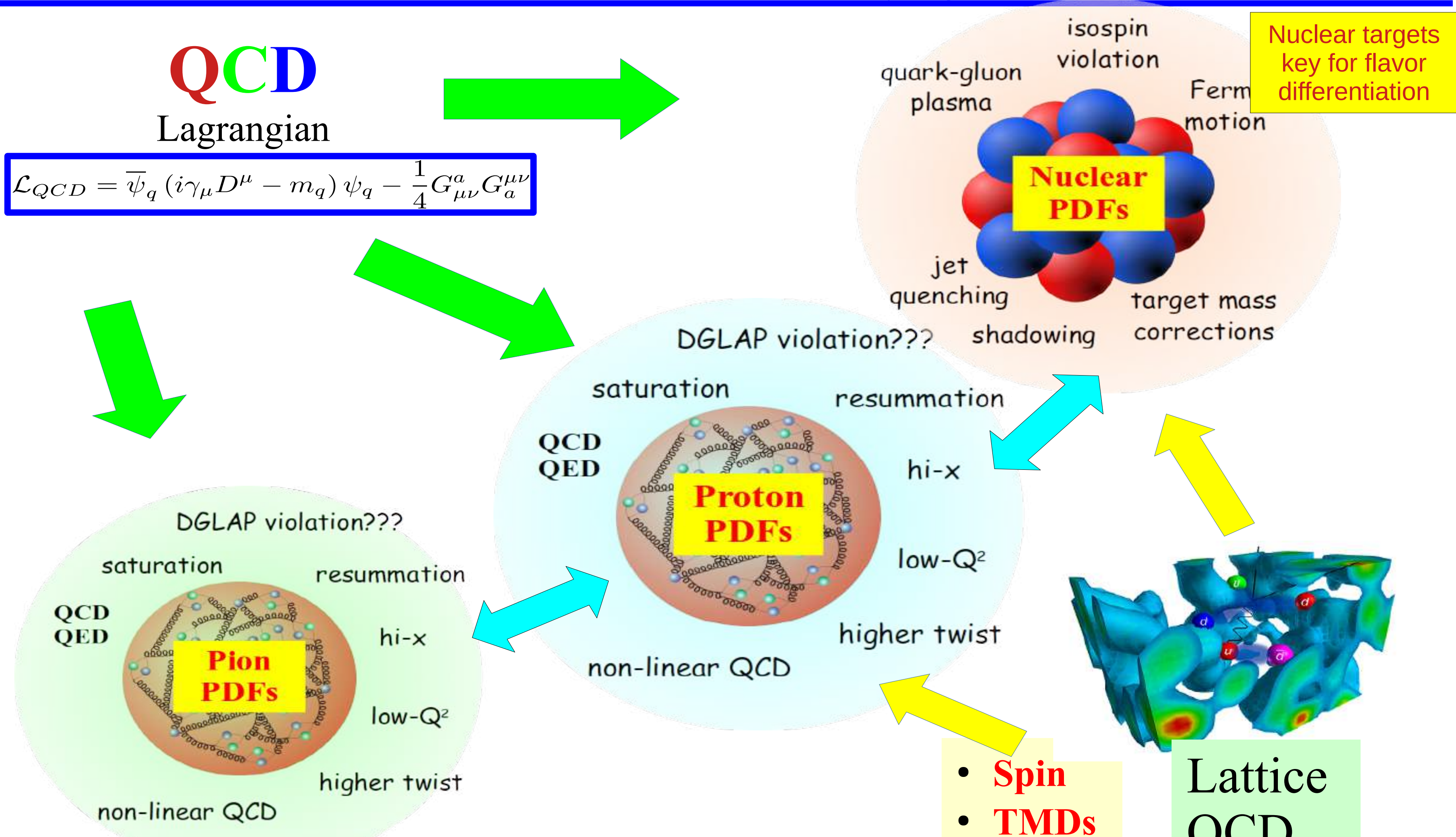

Jefferson Lab




RHIC

relativistic heavy ion collider

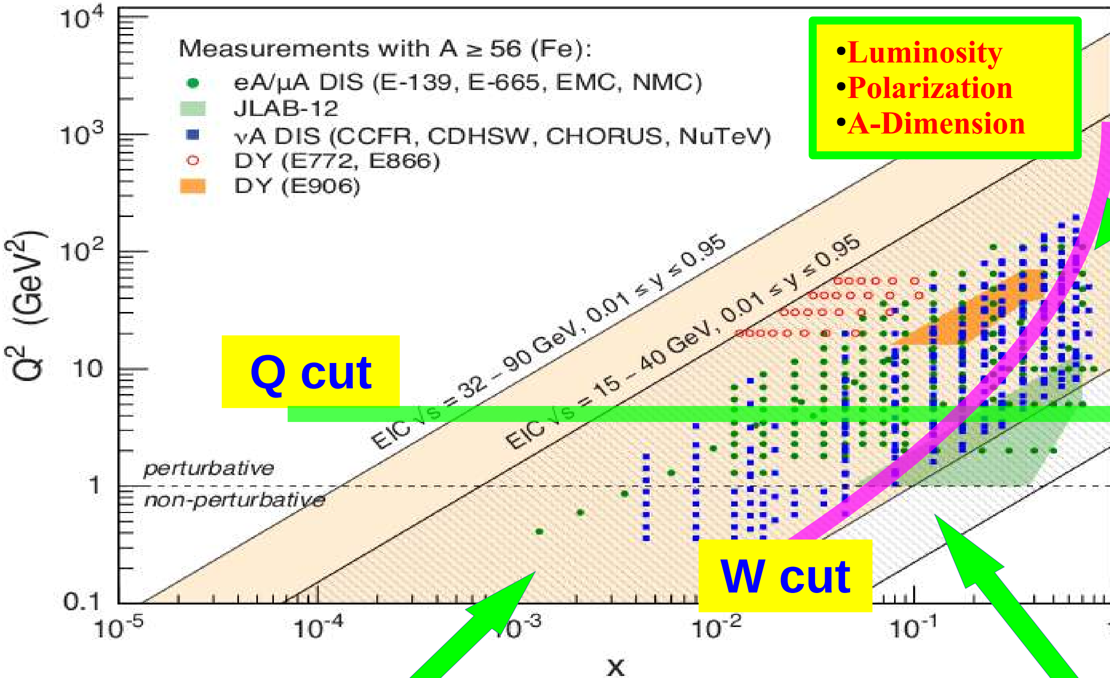
# QCD: From PDFs to the underlying QCD




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

**To boldly go where no analysis has gone before ...**

# To Boldly Go Beyond ... into the corners of the {x,Q²} Kinematic Plane




**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-x:**

Shadowing

Recombination

Resummation

BFKL

Saturation

**Low-Q²:**

Non-Perturbative inteface

collective effects

Target Mass Corrections

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

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

Run at multiple energies

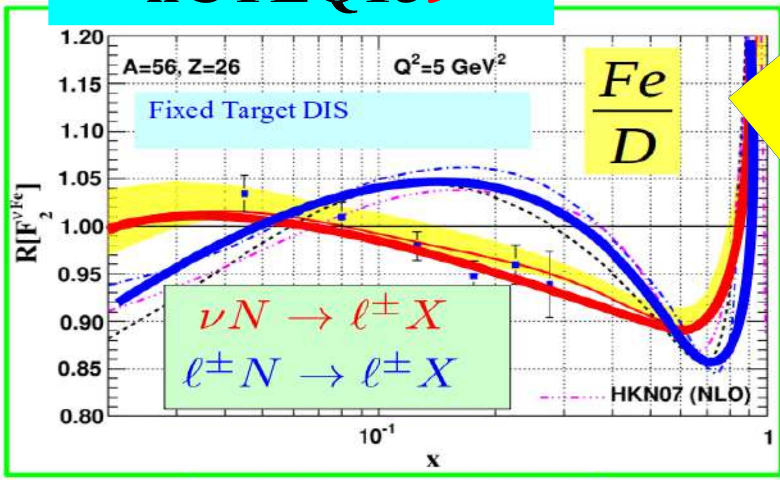
# nCTEQ

nuclear parton distribution functions

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

## nCTEQ15$\nu$

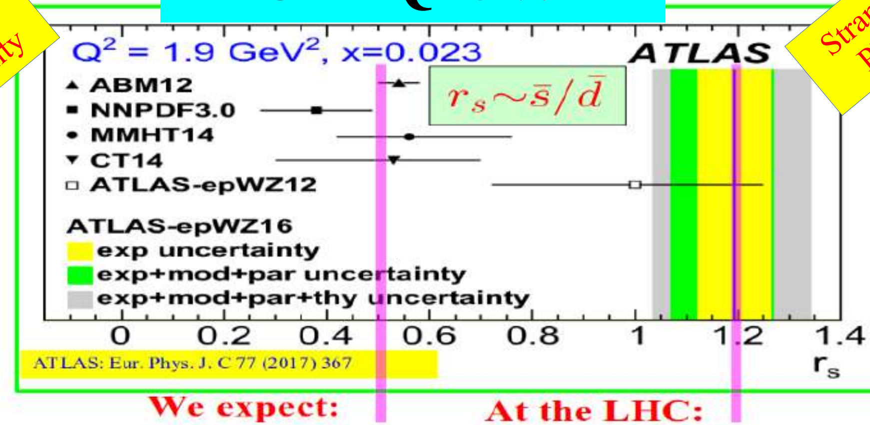
Split Personality




**nCTEQ:** arXiv: 2204.13157

## nCTEQ15WZ

Strange PDF

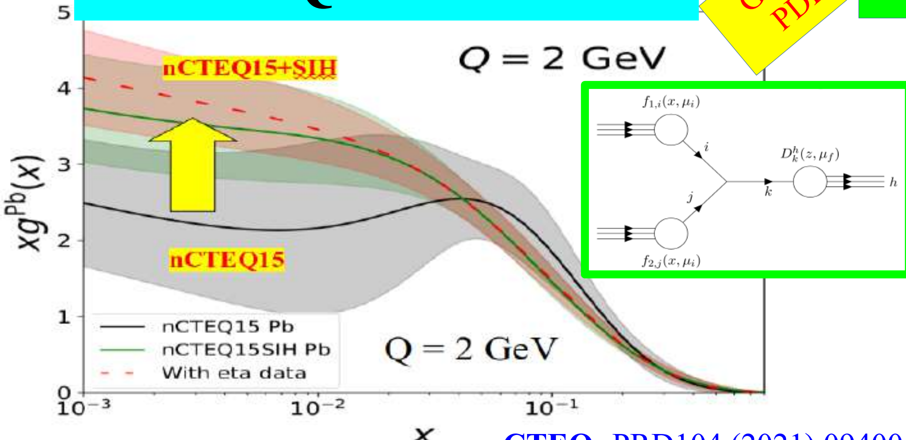



**nCTEQ:** Phys.Rev.D 104 (2021) 094005

**Key for HL-LHC EIC**

## nCTEQ15WZ+SIH

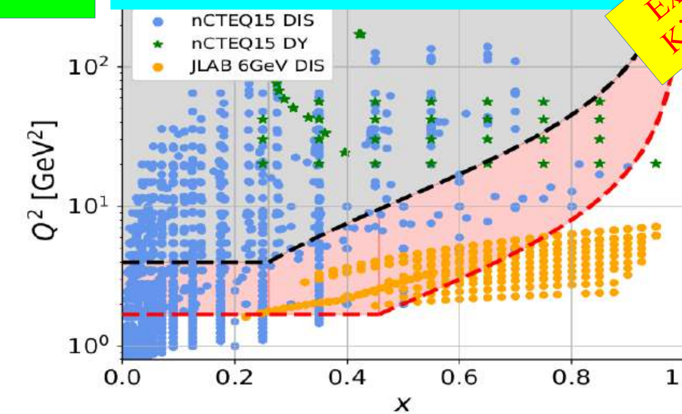
Gluon PDF




**nCTEQ:** PRD104 (2021) 094005.

## nCTEQ15HIX

Expanded Kinematics




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

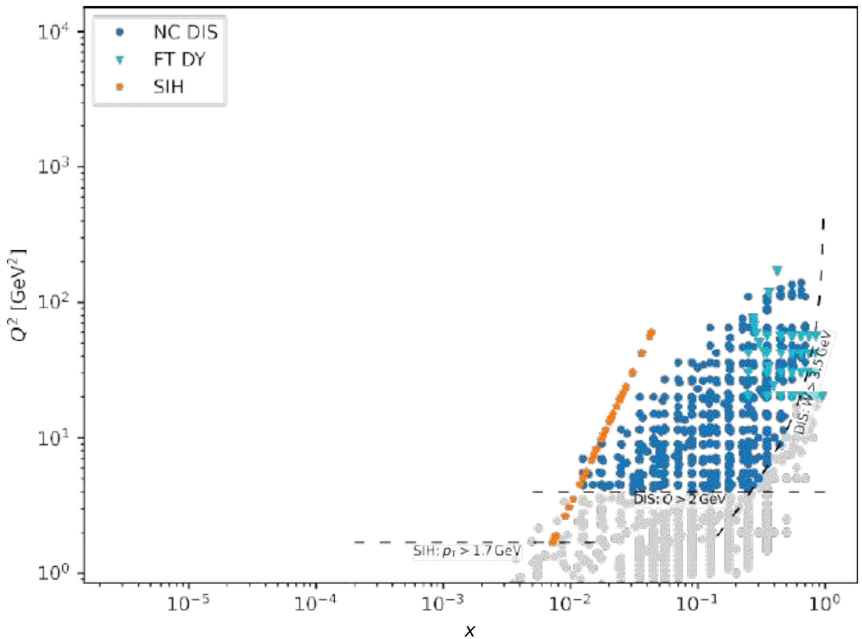
precision $f_A(x,Q)$ can serve as Boundary Condition for $f_A(x,Q,k_T,b_T,\sigma)$

# nCTEQ26

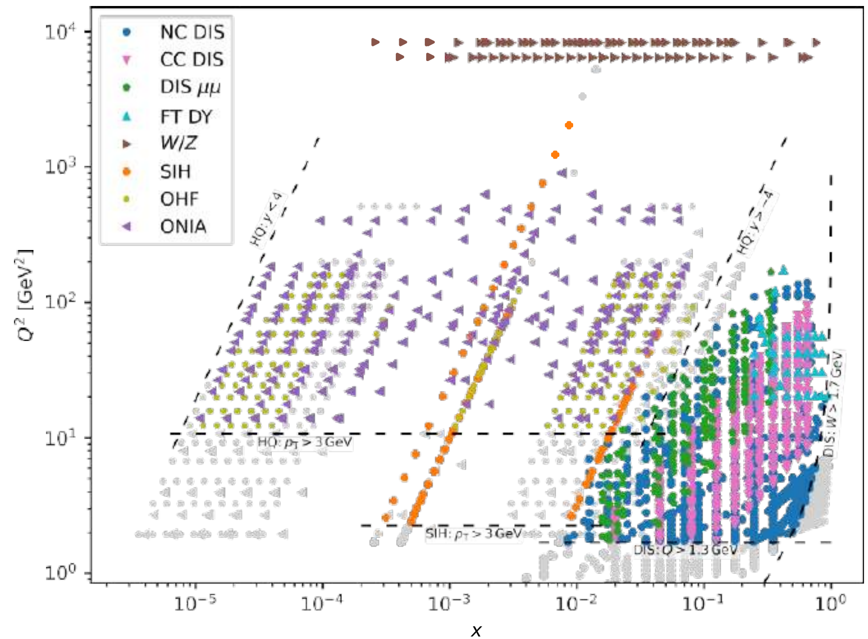
# Data selection: kinematic coverage

- Since nCTEQ15 we expanded on variety, amount, $x$-reach, ...

nCTEQ15




nCTEQ26



# From nCTEQ15 onwards

- nCTEQ15
  - mostly NC DIS, some FT DY, a handfull of SIH (740 pts)

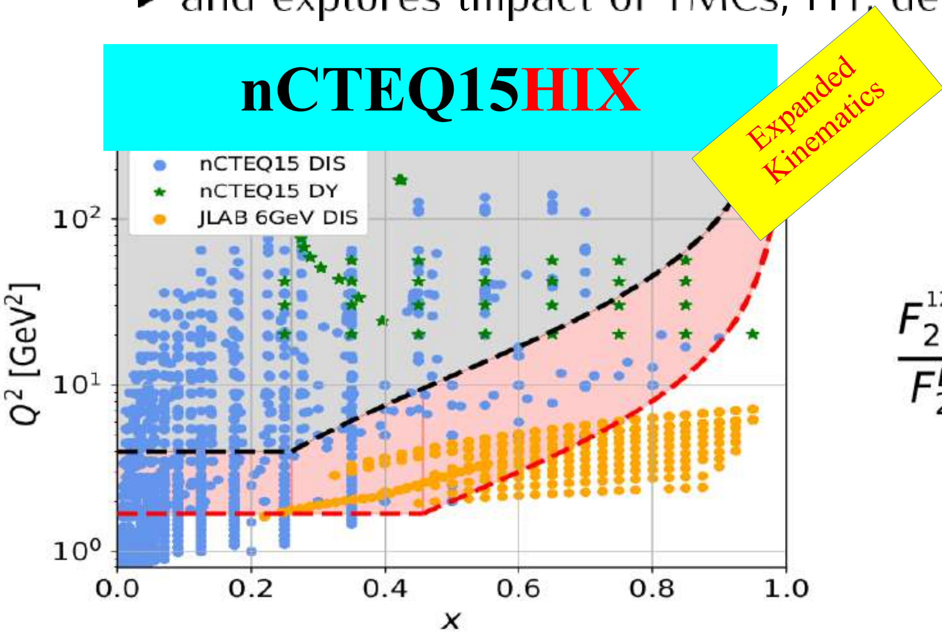
- nCTEQ15 upgrades
  - nCTEQ15WZ ('20): + LHC $W/Z$ data (+120 pts)
  - nCTEQ15HIX ('20): + JLAB NC DIS data + relaxed DIS cuts (+336 pts)
  - nCTEQ15WZSIH ('21): + LHC $W/Z$ and SIH data (+232 pts)
  - nCTEQ15HQ ('22): + LHC $W/Z$ + HQ data (+668 pts)
  - nCTEQ15NU[a] ('22): + LHC $W/Z$ + SIH data + CC DIS (+1206 pts)
  - nCTEQ15SRC ('23): nCTEQ15HIX with SRC-inspired PDF parametrization

[a] Denoted BaseDimuChorus in the publication.

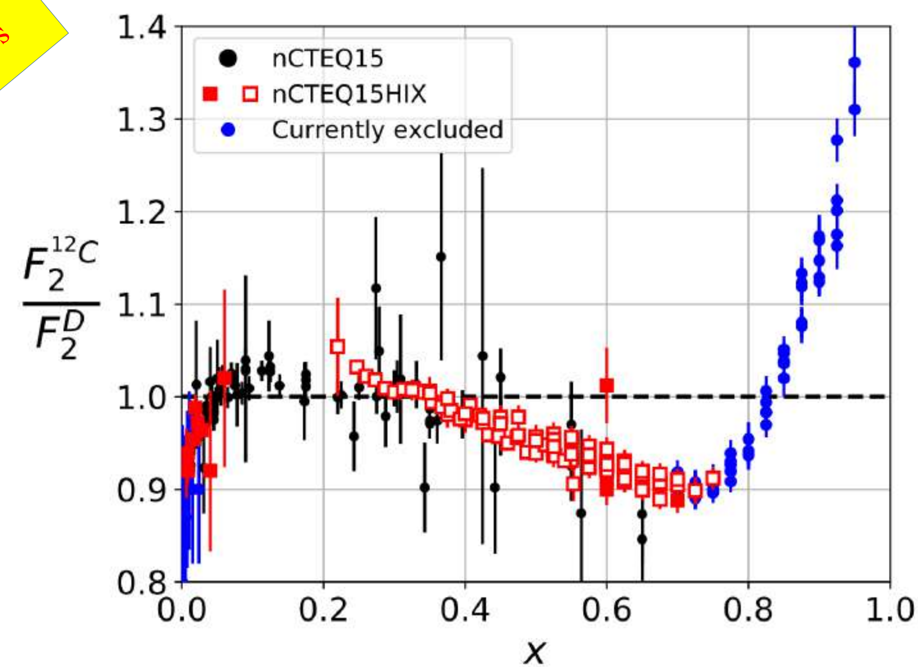
# Key Improvements: Expanded Kinematics

- Valence: nCTEQ15HIX includes very precise JLAB data (+336 pts)
  - and explores impact of TMCs, HT, deuteron correction, high-$x$ rescaling

**nCTEQ15HIX**




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




$\{Q_{cut}, W_{cut}\} = \{2, 3.5\} \Rightarrow \{1.3, 1.7\}$

# Key Improvements: Expanded Kinematics

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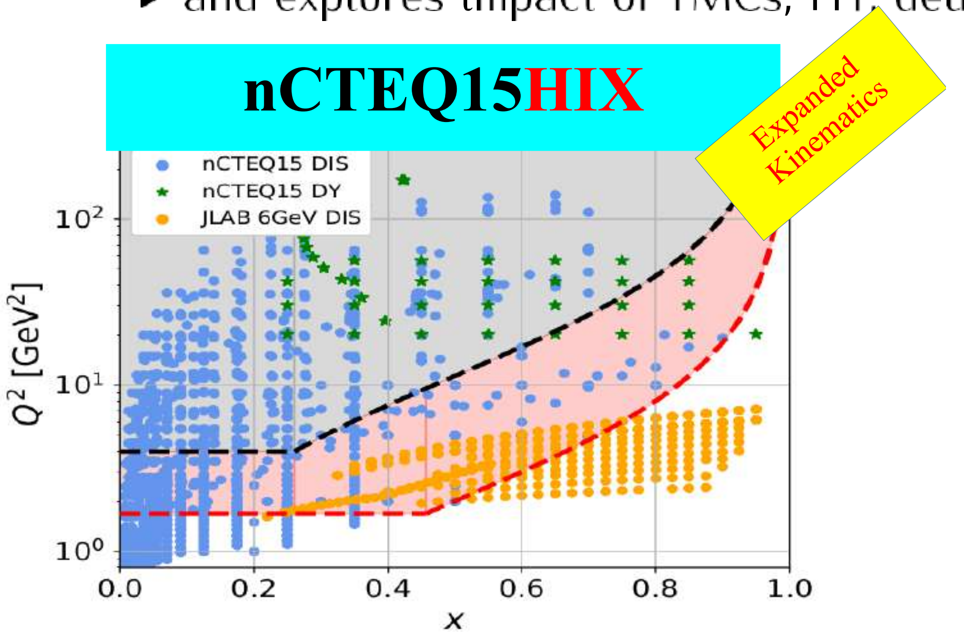
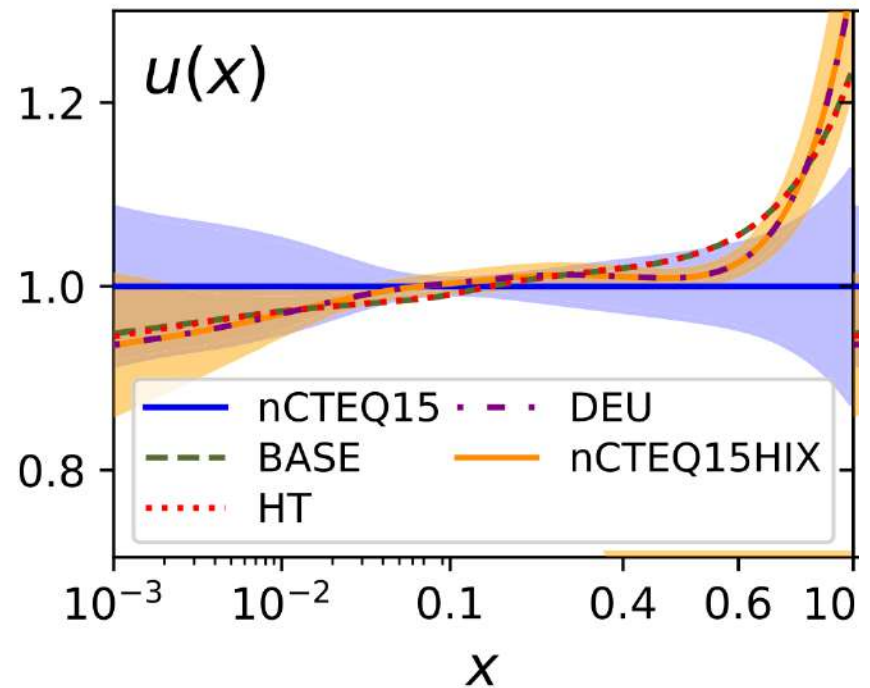



**nCTEQ:** Phys.Rev.D 103 (2021) 11, 114015



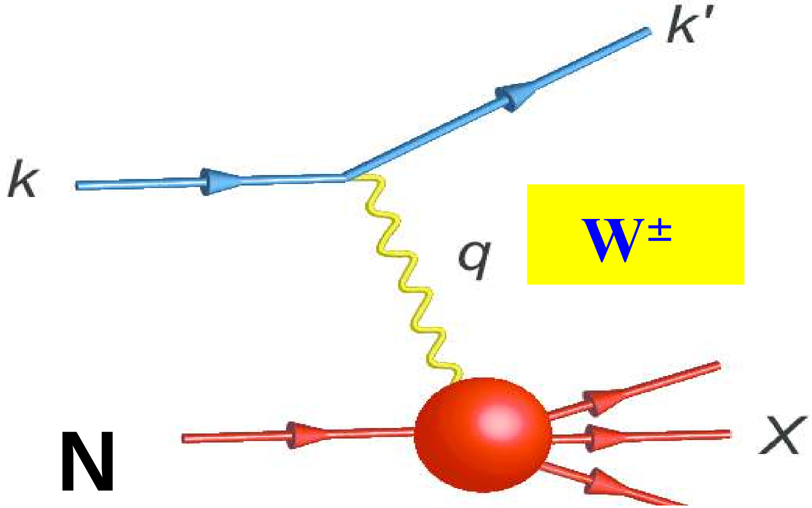

$\{Q_{cut}, W_{cut}\} = \{2, 3.5\} \Rightarrow \{1.3, 1.7\}$

# Nuclear Targets Important for flavor differentiation

Neutrino Deep Inelastic Scattering (DIS)

(nCTEQ) Faiq Muzakka, Karol Kovarik, ...

**Phys.Rev.D 106 (2022) 7, 074004 • e-Print: 2204.13157 [hep-ph]**




**Neutrino DIS**

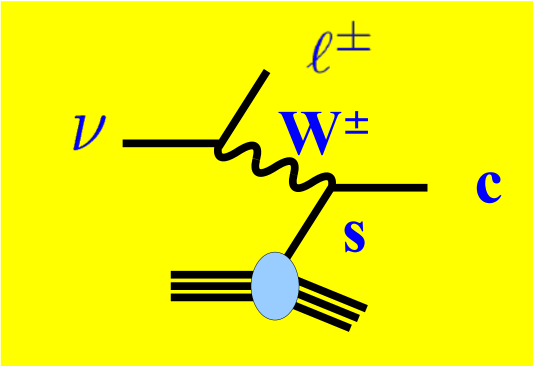
$$F_2^{\nu} \sim \left[d + s + \bar{u} + \bar{c}\right]$$
$$F_2^{\bar{\nu}} \sim \left[\bar{d} + \bar{s} + u + c\right]$$
$$F_3^{\nu} \sim 2\left[d + s - \bar{u} - \bar{c}\right]$$
$$F_3^{\bar{\nu}} \sim 2\left[u + c - \bar{d} - \bar{s}\right]$$

Differentiate flavors of free-proton PDFs:

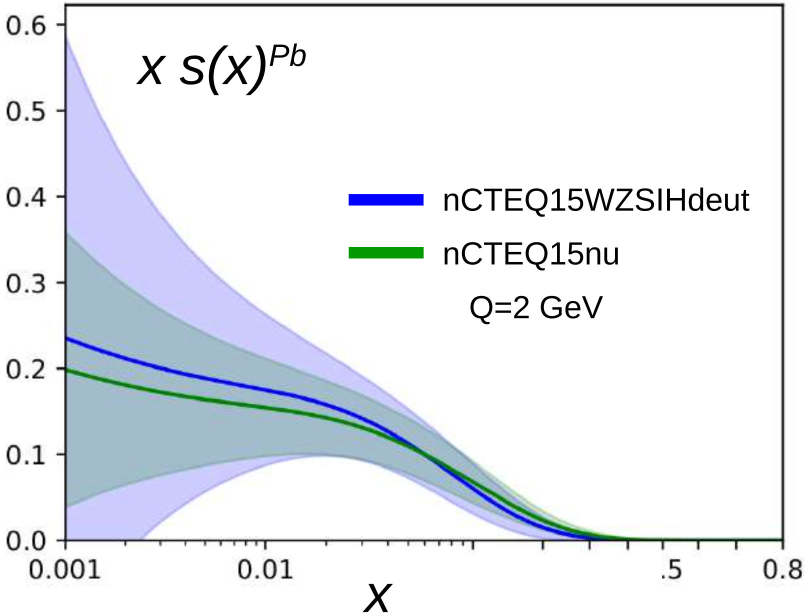
# Key Improvements: νDIS (Strange PDF)

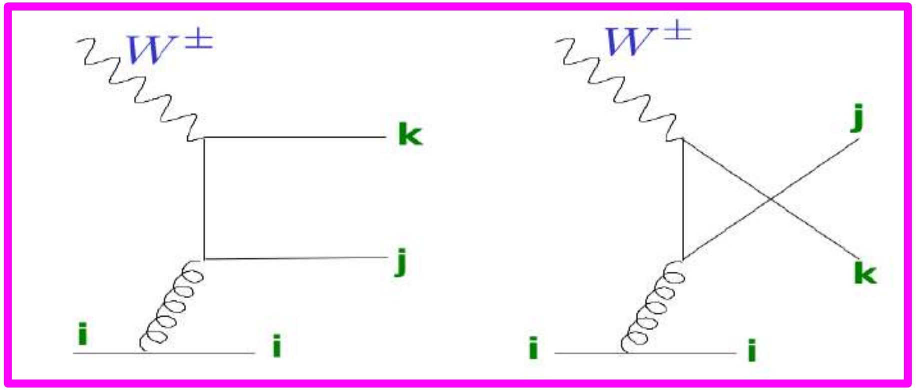
- **Valence**: nCTEQ15HIX includes very precise JLAB data (+336 pts)
- **Strange**: nCTEQ15NU adds bulk of CC DIS data (+1206 pts)
  - constraining strange across a broad range of $x$

## Neutrino DIS




- **Chorus νDIS** (Pb)
- **NuTeV & CCFR Dimuon** (Fe)





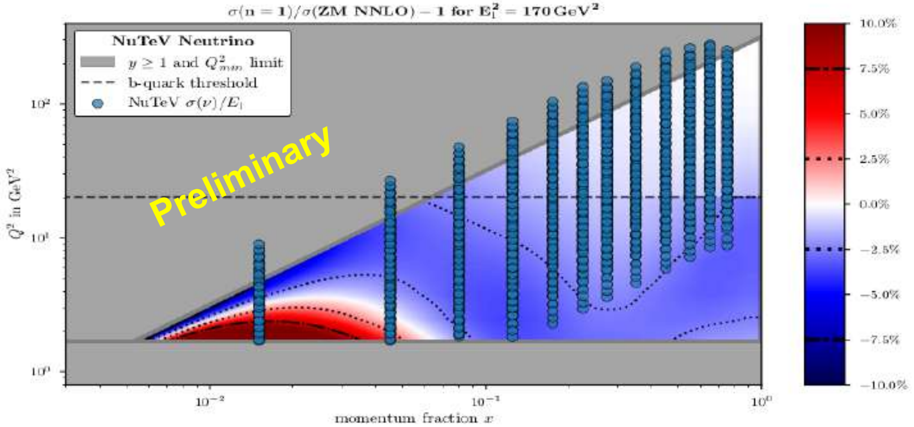

Complex flavor structure

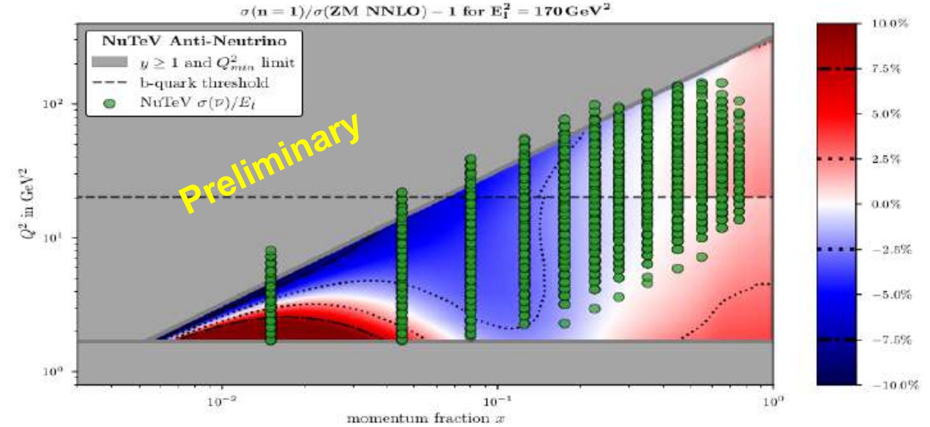
Peter Risse (Muenster)

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

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

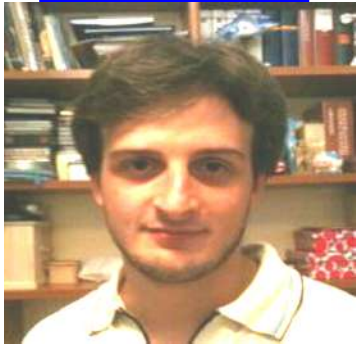
P. Risse[a,†], V. Bertone[b], T. Ježo[a], M. Klasen[a], K. Kovařík[a], F.I. Olness[c], I. Schienbein[d]



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

Valerio Bertone



Peter Risse

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-$\chi$ | NLO | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ |
| approx. sACOT-$\chi$ | N2LO | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ |

# xFitter

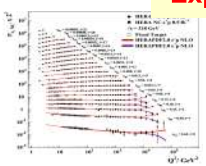
**PROTON** **NUCLEON** **MESON**

**www.xFitter.org**

**Sample data files:**

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

## Experimental Data



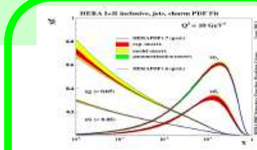
**Data:** HERA, Tevatron, LHC, fixed target experiments

**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<br>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:**

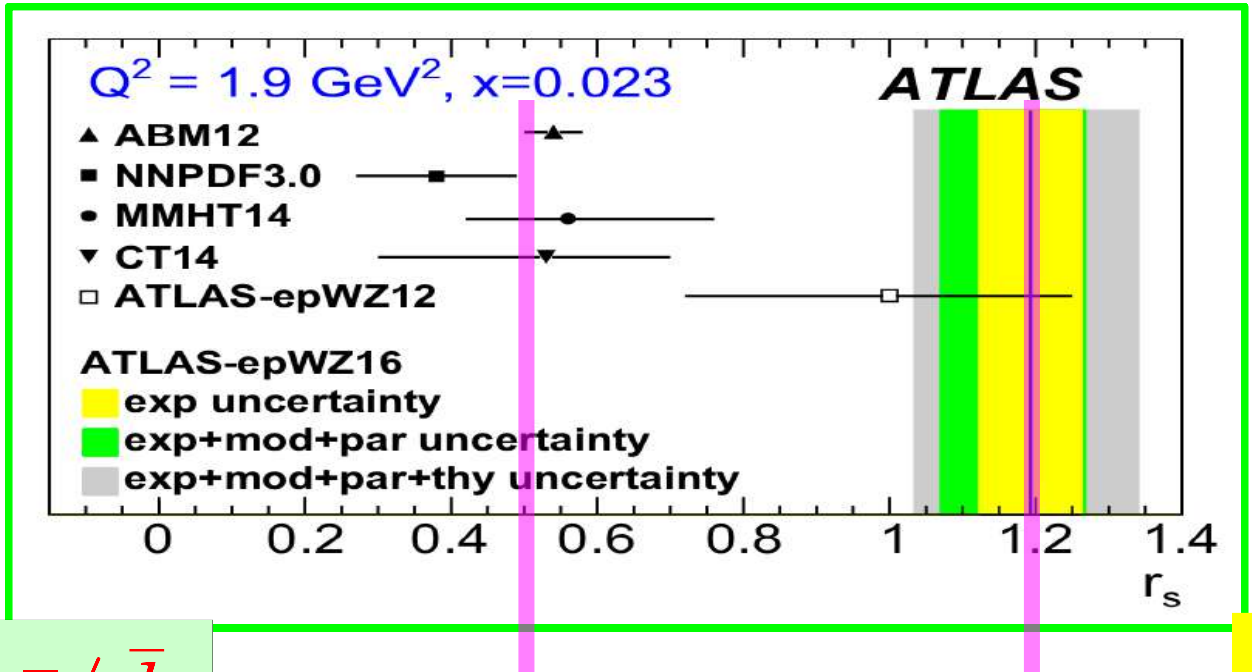
- **NNLO DGLAP**
- Photon PDF & **QED**
- Pole & MS-bar masses
- Profiling and Re-Weighting
- **BFKL interface**
- Heavy Quark Variable Treshold
- Improvements in $\chi^2$ and correlations
- **TMD** PDFs (uPDFs)
- *… and many other*

**xFitter 2.2.0 Future Freeze**

# LHC W/Z Production

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

**Surprise**:
We expected $r_s = 1/2$
LHC finds $r_s > 1$




Proton case

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

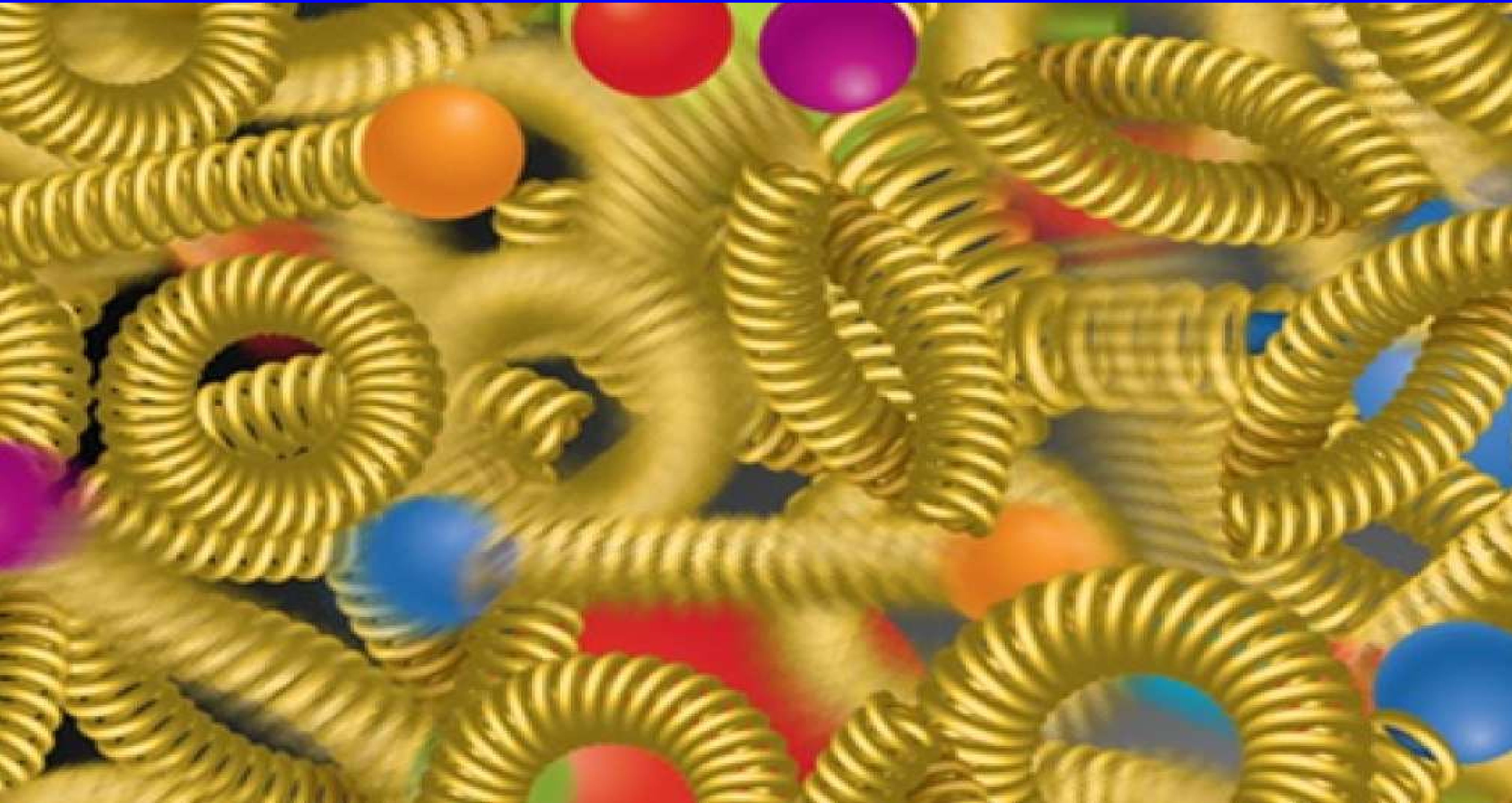
**We expect:**

**At the LHC:**

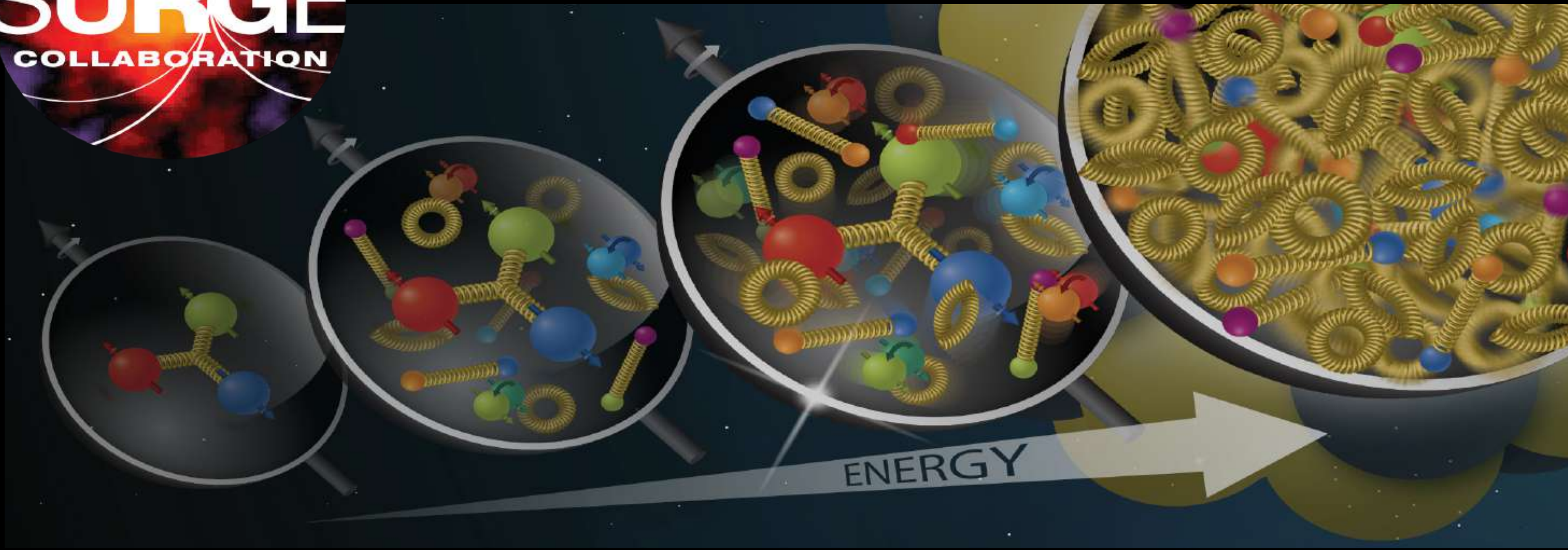
$$r_s = \frac{\bar{s} + s}{2\bar{d}}$$

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

# The Gluon

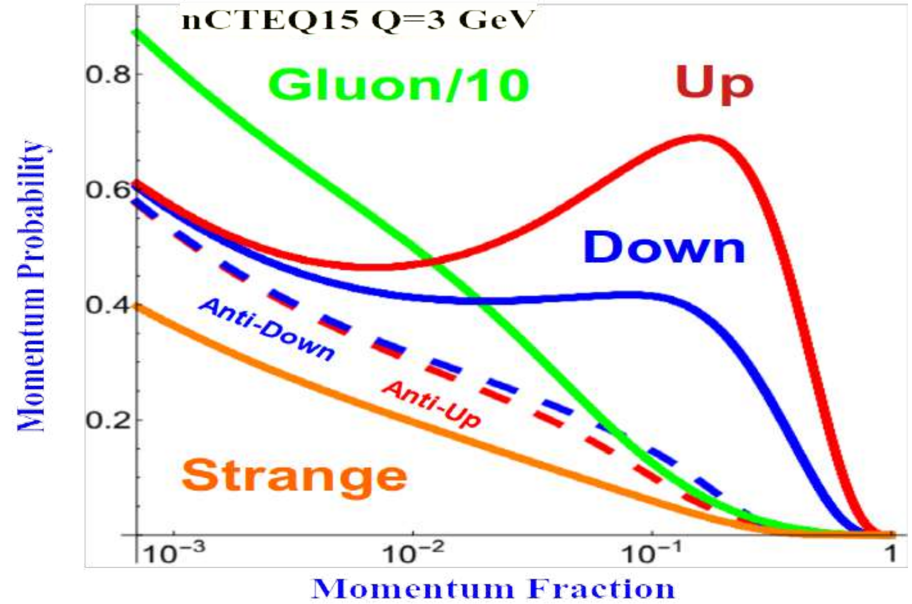


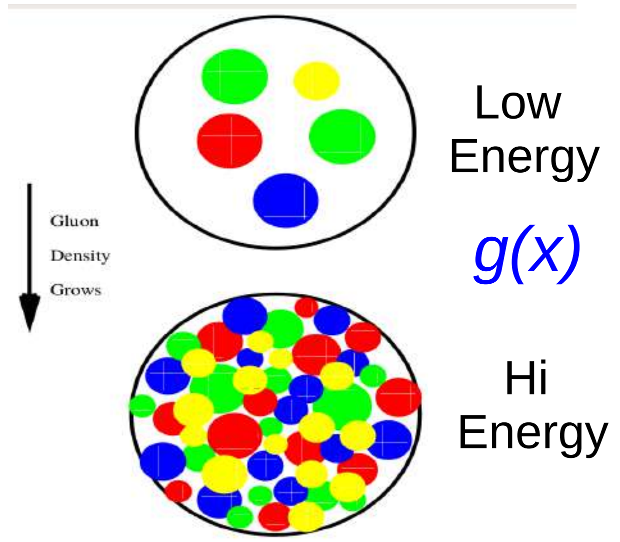
**https://www.bnl.gov/physics/surge/**

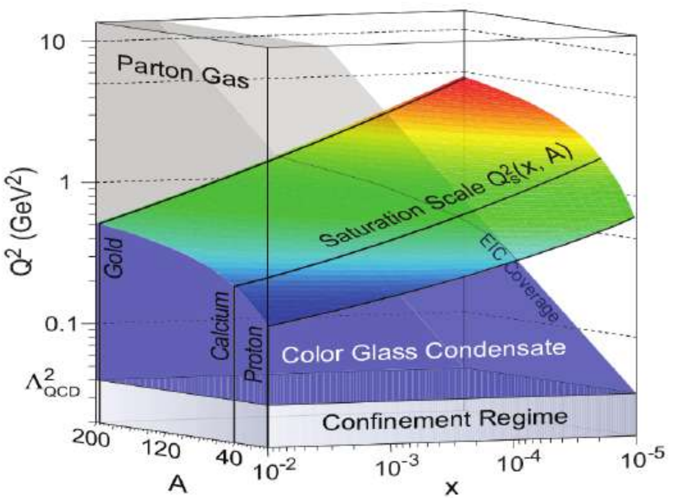



Mission statement: Discover and explore the gluon saturation regime of quantum chromodynamics by advancing calculations to high precision and developing a comprehensive framework to compute observables and compare to a wide range of experimental data, including predictions for the Electron Ion Collider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

# Nuclear Medium Effects at small momentum fraction (x)



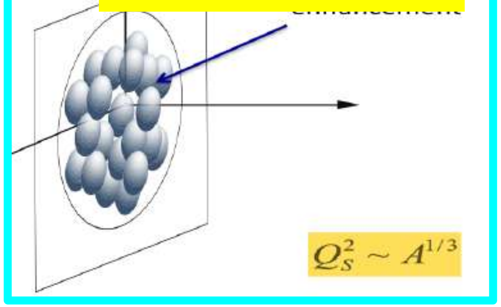




**Nuclear medium effects:**

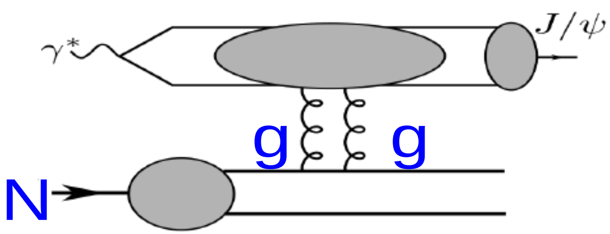
- Quark Gluon Plasma
- Color Glass Condensate
- Recombination
- Saturation
- Resummation
- … *your theory here*

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

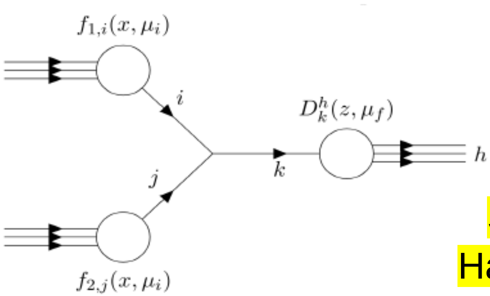


# Key Improvements: Quarkonium & HQ (Gluon PDF)

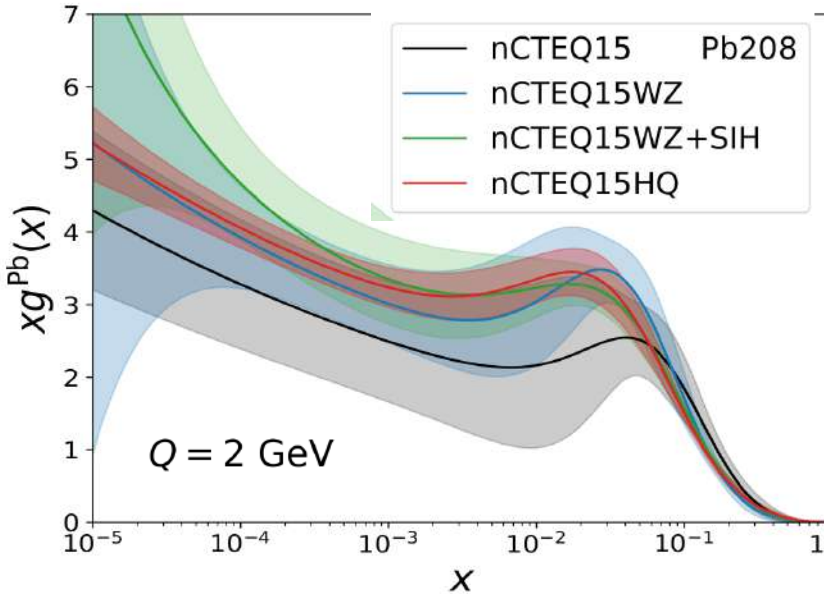
- **Valence**: nCTEQ15HIX includes very precise JLAB data (+336 pts)
- **Strange**: nCTEQ15NU adds bulk of CC DIS data (+1206 pts)
- **Gluon**: nCTEQ15HQ adds quarkonium and open HQ data (+668 pts)
  - providing a handle on gluon with unprecedentend low-$x$ reach




Quarkonia Production



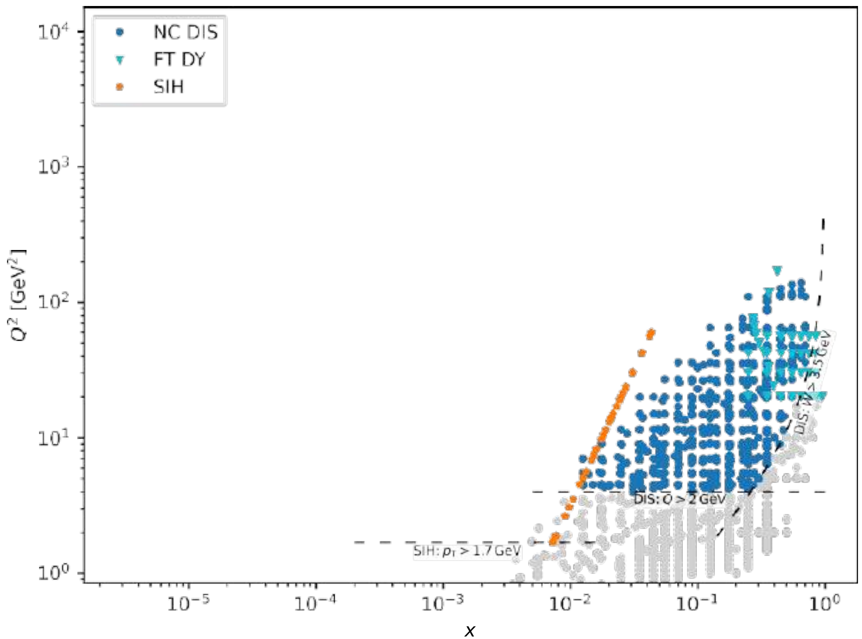

Semi-Inclusive Hadron Production



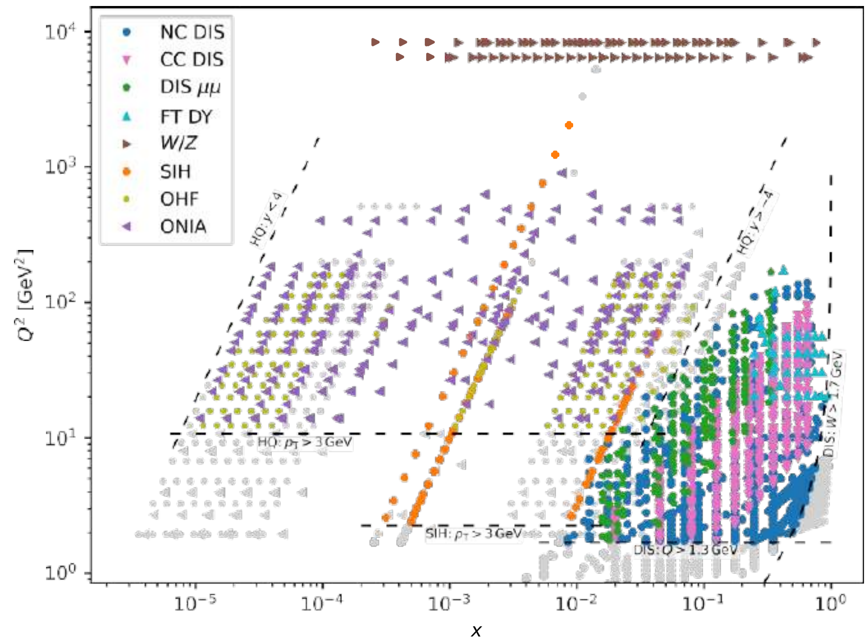
# Data selection: kinematic coverage

- Since nCTEQ15 we expanded on variety, amount, $x$-reach, . . .

nCTEQ15

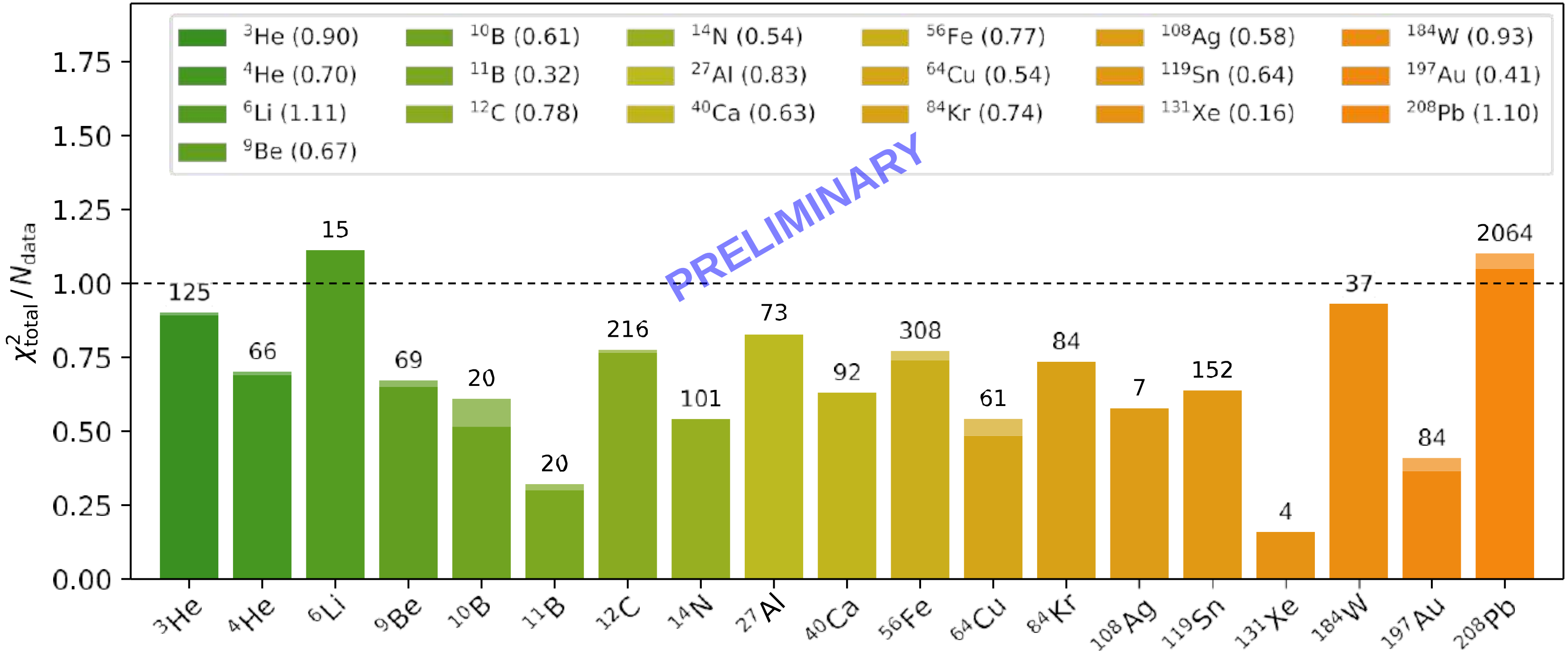



nCTEQ26



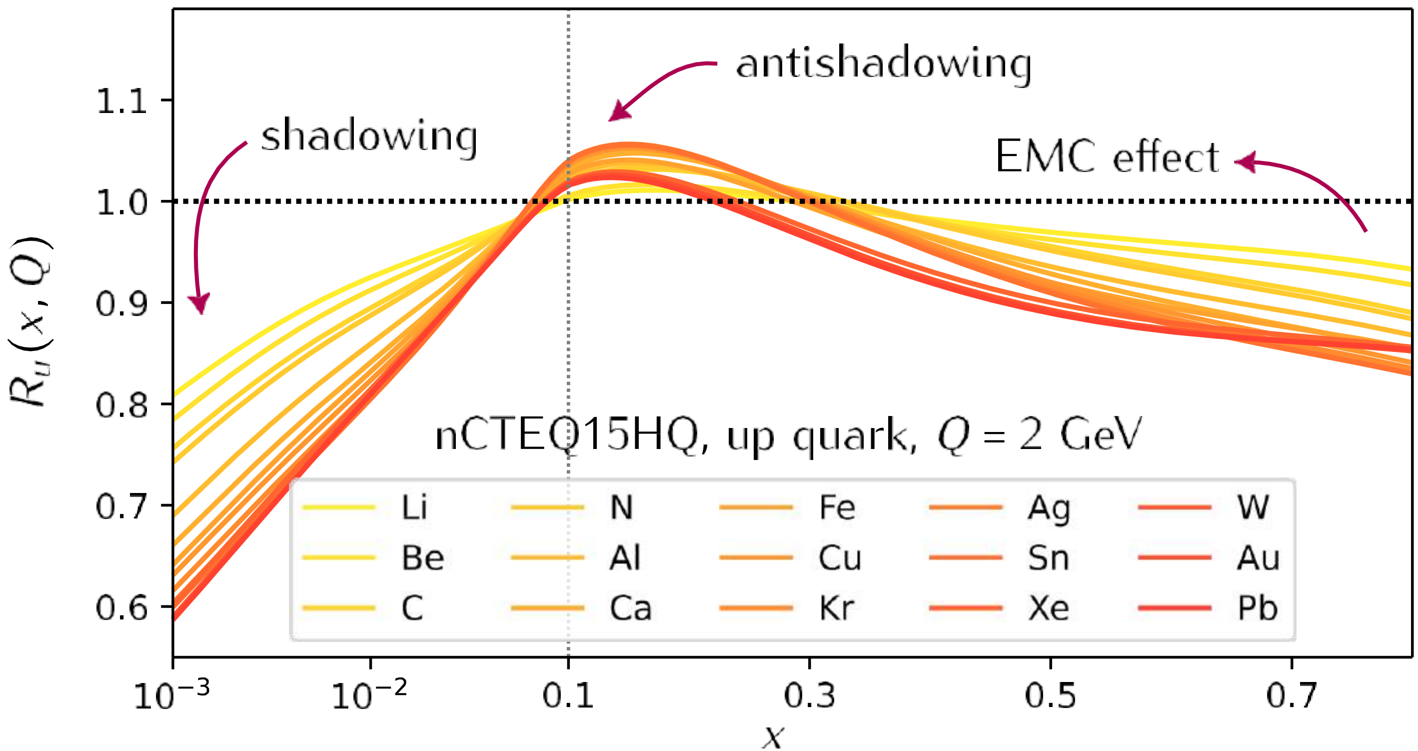
# Data selection: nuclear $A$ coverage

- Extensive $A$ coverage



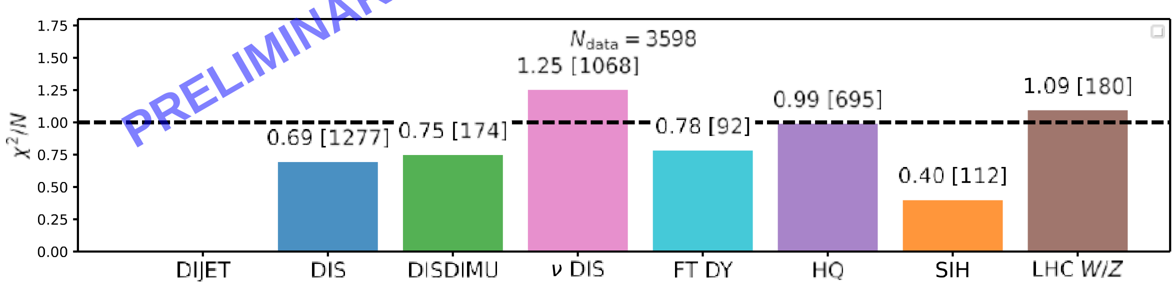
# Theoretical framework: nuclear PDFs

- Example dependence on $A$

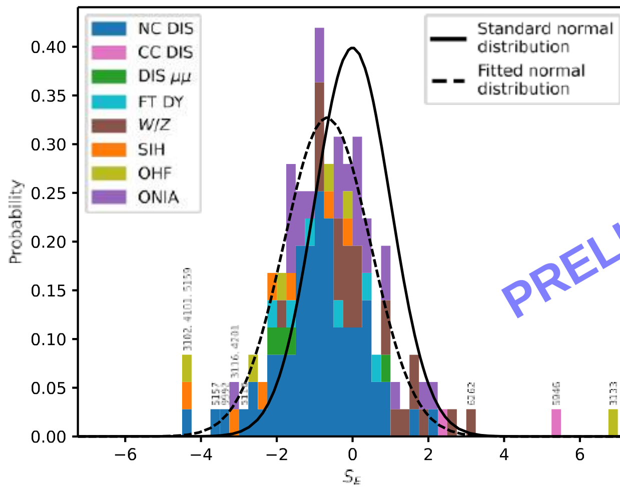


# Results: data description quality

- Overall excellent fit with $\chi^2/N_{\text{dof}} = 0.98$
- Each experiment type well described
  - $\nu$DIS in slight tension
  - SIH overfitted

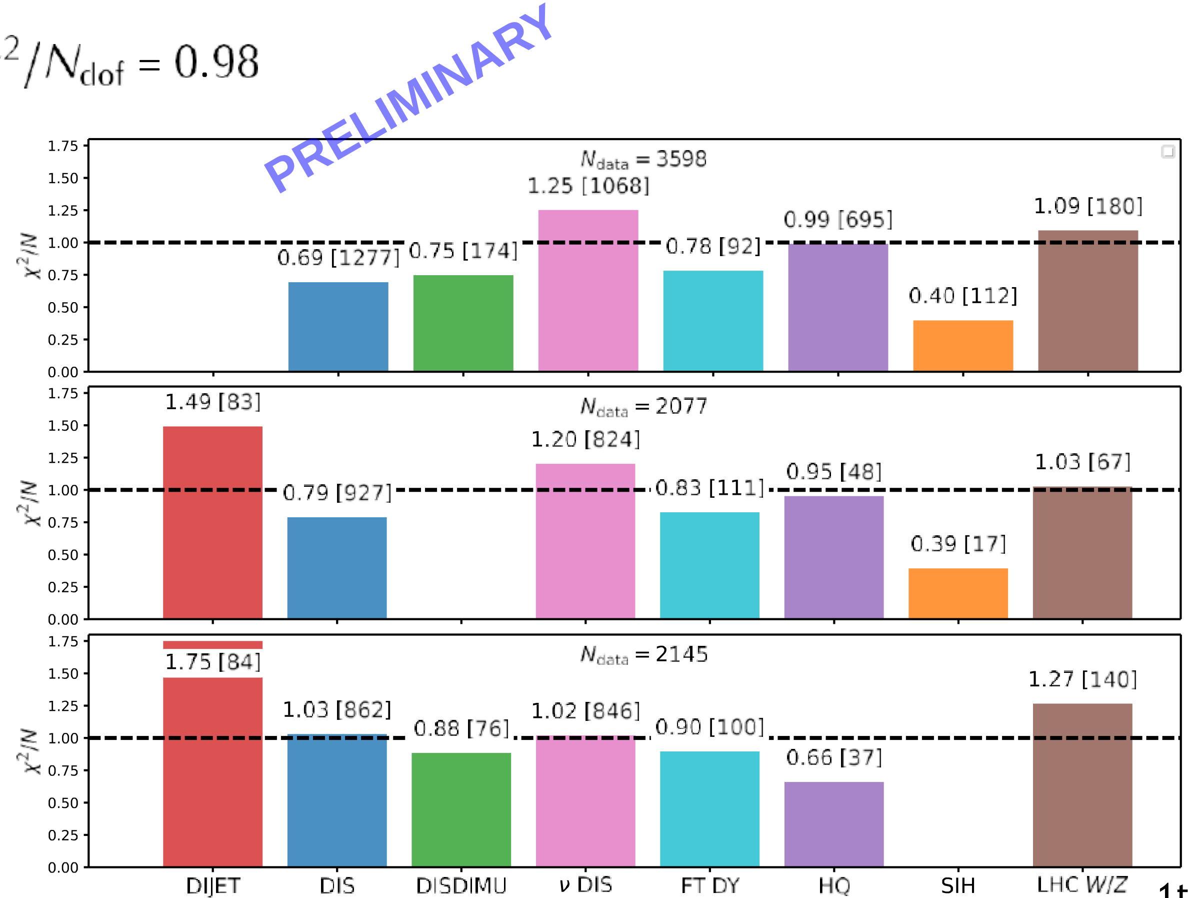



- Well-behaved pull distribution
  - Consistent with an optimal fit
  - Only a handful of outliers



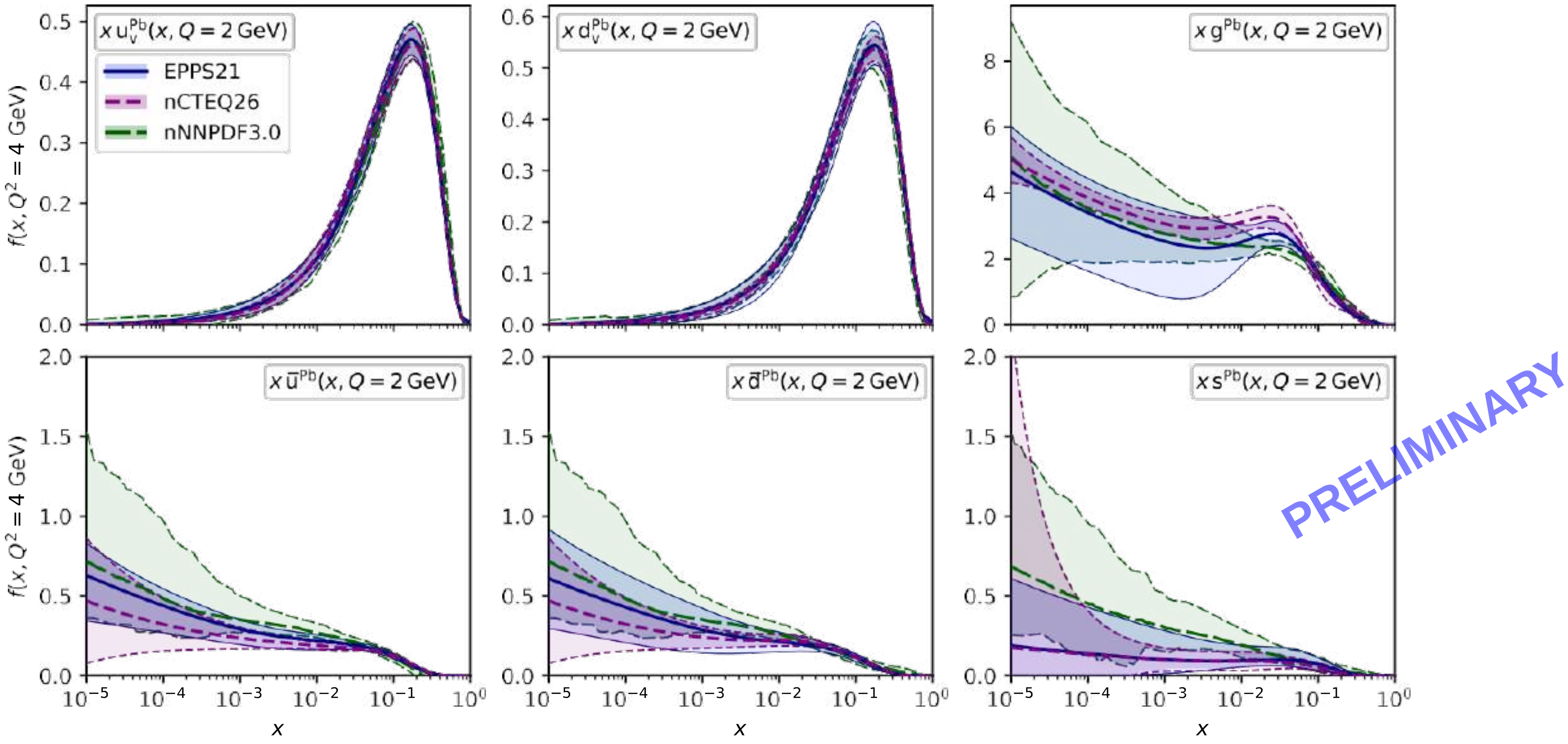
# Results: data description quality

- Overall excellent fit with $\chi^2/N_{\text{dof}} = 0.98$
  - nCTEQ26:
  - EPPS21:
  - nNNPDF3.0:



# Results: Lead PDFs

- PDFs consistent with other extractions, with most notable differences in gluon and strange

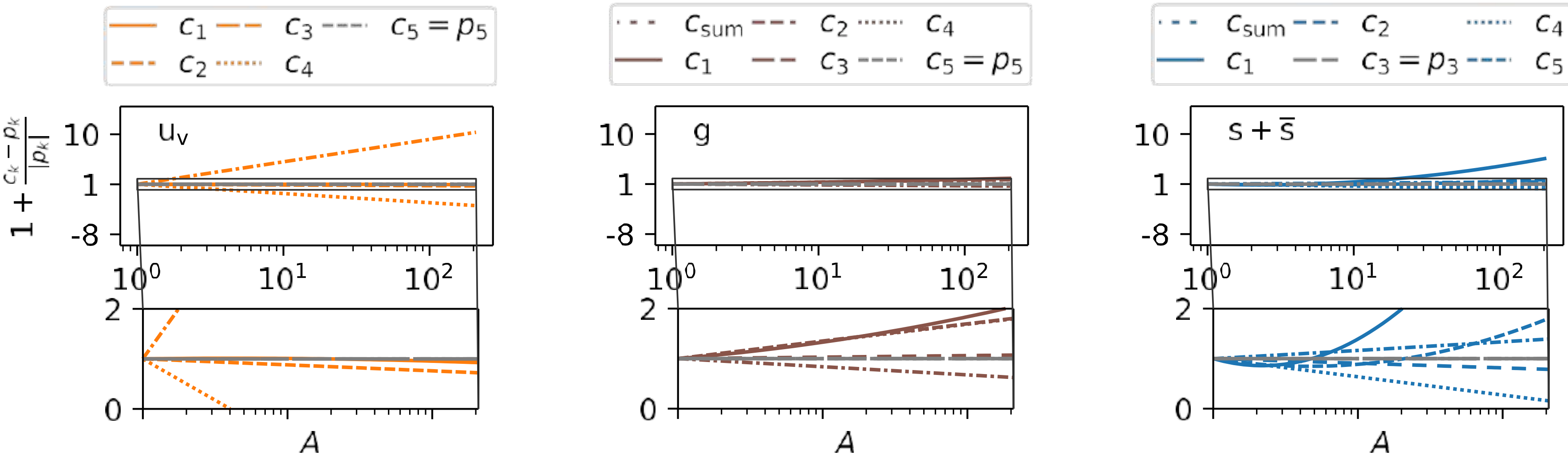


# Results: $A$ dependence

- New $A$ dependence:

$$c_j(A) = p_j + a_j(1 - A^{-b_j}) \quad \Rightarrow \quad \boxed{c_j(A) = p_j + a_j \ln A + b_j \ln^2 A}$$

PRELIMINARY



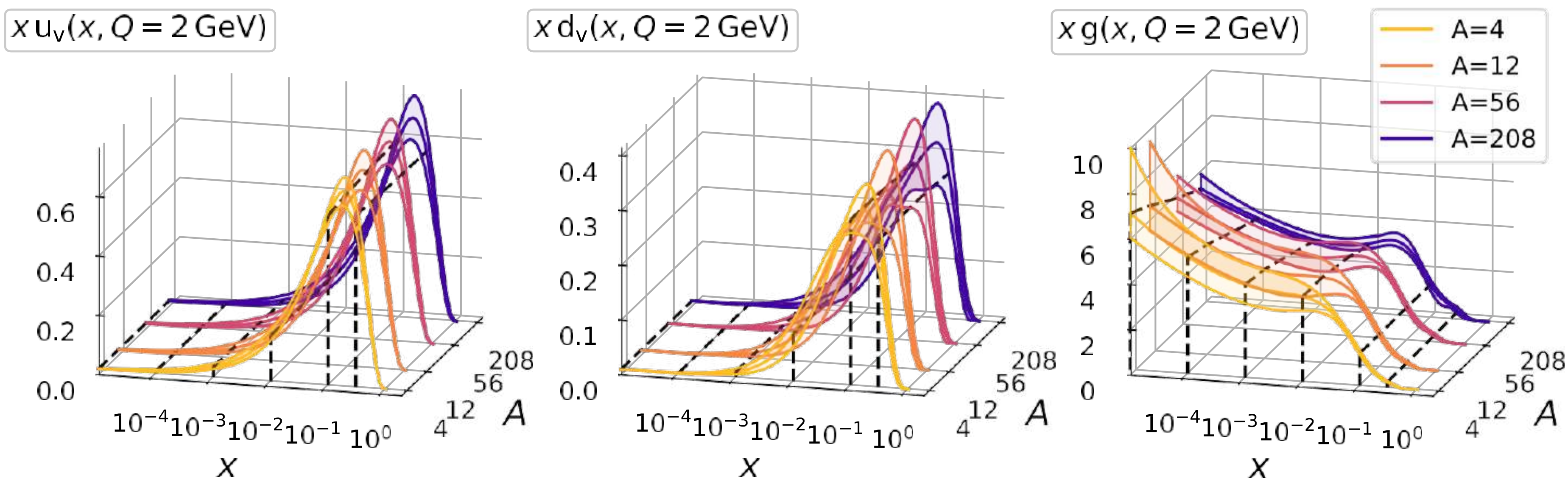

$$xf(x, Q_0) = c_{sum} x^{c_1} (1 - x)^{c_2} (1 + c_3 \sqrt{x} + c_4 x) e^{c_5 \sqrt{x}}$$

# Results: $A$ dependence

**$U_V$ $D_V$ G**

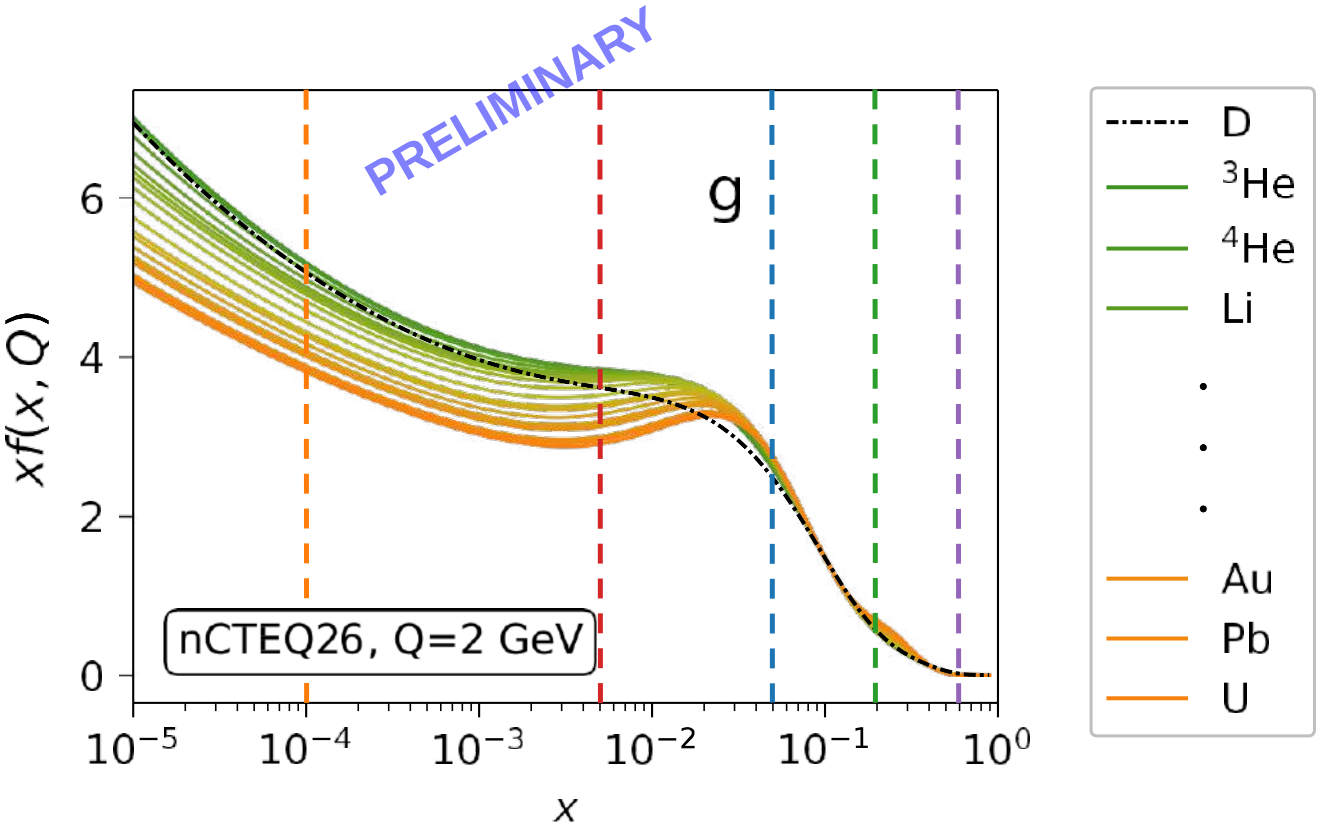
- Valence and gluon PDFs for a few selected nuclei
  - Mild $A$ dependence, shadowing gets more pronounced with $A$

PRELIMINARY



# Results: $A$ dependence GLUON

- To capture $A$ dependence in more detail we introduce slices in $x$ ($Q$ fixed)

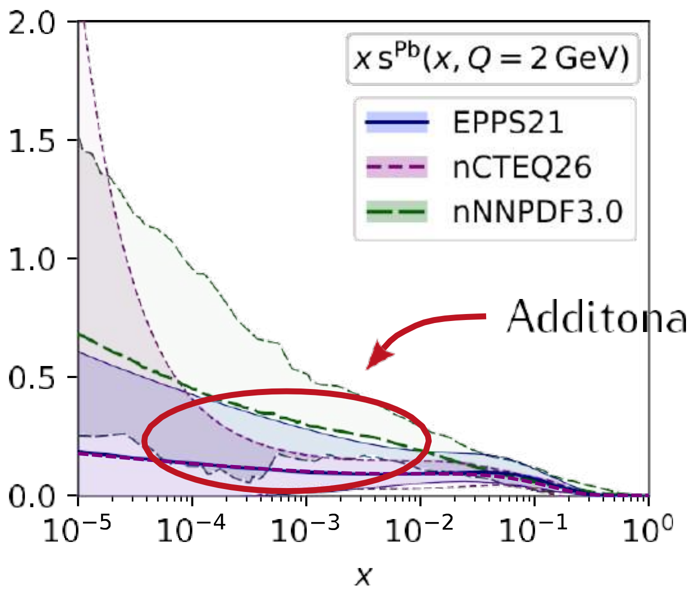


# Results: strange uncertainty

**STRANGE**

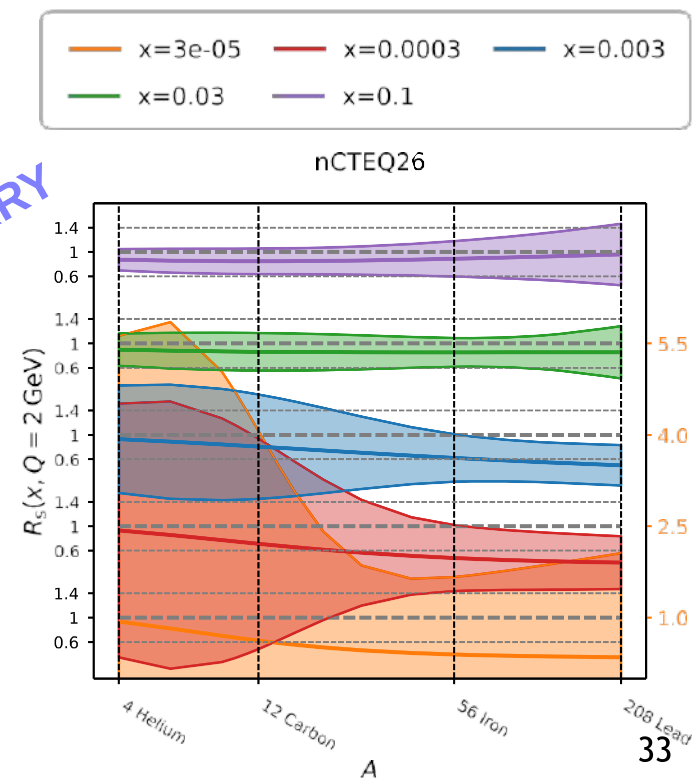
- Strange uncertainty is substantial in low $x$
  - Imporant role by an extra parameter:

$$xs(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} (1 + c_3\sqrt{x} + c_4 x) e^{c_5 \sqrt{x}}$$




Additonal flexibility

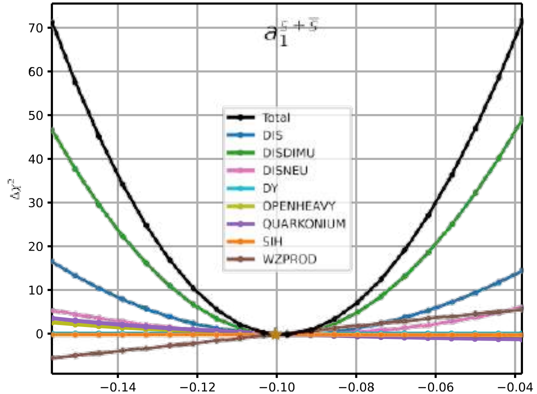
PRELIMINARY

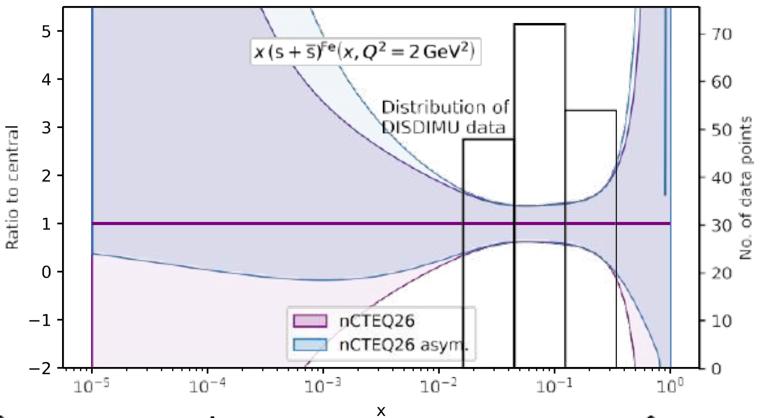


# Results: strange uncertainty

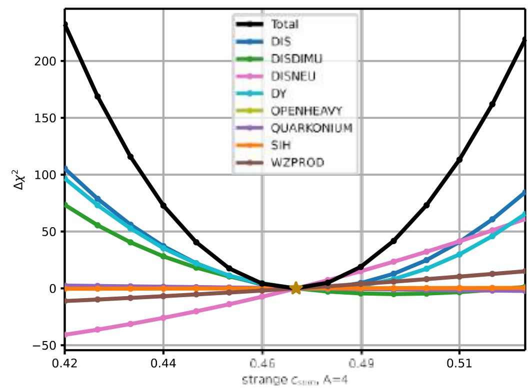
**STRANGE**

- Strongest constraint from charm dimuon data




  - ▸ $\nu$DIS and dimuon data prefer different total strange momentum fraction




PRELIMINARY

# nCTEQ26

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS
FONDAZIONE BRUNO KESSLER

WORKSHOP

# 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 Gazzolii – 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


**SUPPORTING INSTITUTIONS**

INFN FIU FLORIDA INTERNATIONAL UNIVERSITY Jefferson Lab

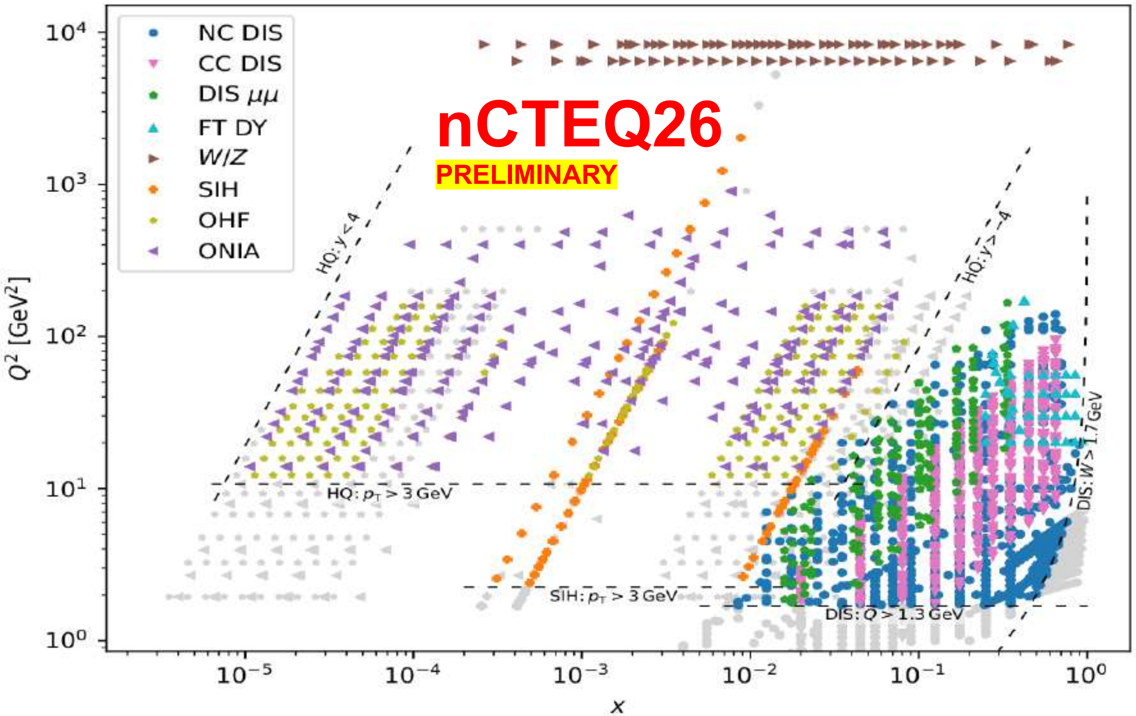
# QUARK-GLUON DYNAMICS IN THE NUCLEAR MEDIUM

## 9 – 13 November 2026

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.

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

# nCTEQ26 Updates:




- Wealth of new data & processes
- Updated theory & methodology
- Updated proton baseline
- Updated x-parametrization
- New A-parametrization

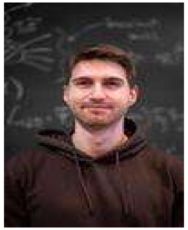
- Good data description overall
- Particular focus on:
  - A-dependence
  - strange & gluon uncertainties

**nCTEQ**

nuclear parton distribution functions

Tomas Jezo

Katrin Greve



Jan Wissmann

Aleksander Kusina

# Backup

# The xFitter Team

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## Steering Committee


Björn Schenke


Anna Stasto


Zhongbo Kang


Jaki Noronha-Hostler


Matt Sievert

# Topics and working groups



**Initial state WG**
Improve the initial conditions for evolution for unpolarized and polarized observables.

**Small x evolution + NLO calculations WG**
Non-linear evolution at NLO and beyond, computation and implementation of impact factors

**Spin WG**
Analyze role saturation in the polarized observables. Elucidate the role of chiral anomaly in small x helicity evolution.

**Final states WG**
Construct a framework for hadronization in a saturated environment, including development of MC generator based on CGC calculations

**Global analysis WG**
To establish saturation, perform comprehensive global analysis quantifying and minimizing uncertainties, extracting universal building blocks of high energy factorization.

- Initial state **(Vladi Skokov)**
- Small x evolution + NLO calculations **(Zhongbo Kang)**
- Spin **(Yuri Kovchegov)**
- Framework and global analysis **(Fred Olness)**
- Final state **(Xin-Nian Wang)**

SURGE COLLABORATION