Probing dense nuclear matter at small x

Updates from SURGE & nCTEQ

Fred Olness
SMU

Thanks for substantial input
from my friends & colleagues

Gluon Saturation, Diffraction
& Multihadron Production at the EIC:
Stony Brook University
14 July 2026

QCD: Remarkably successful at describing High Energy Processes

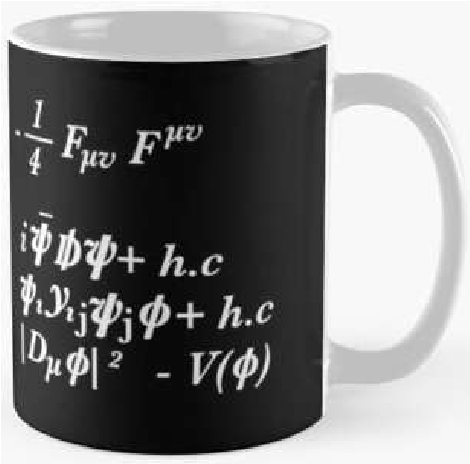
Quantum ChromoDynamics

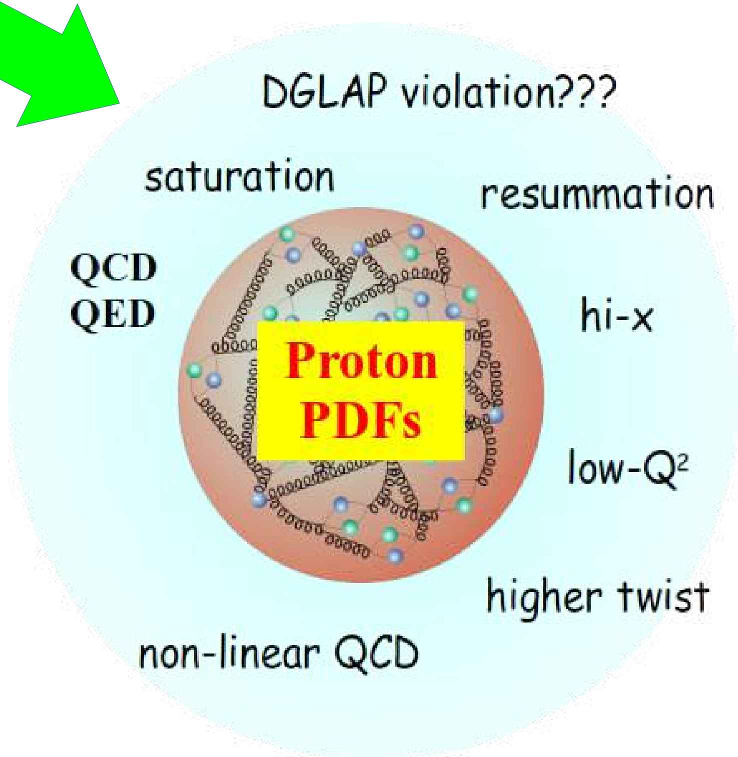
QCD

Lagrangian

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

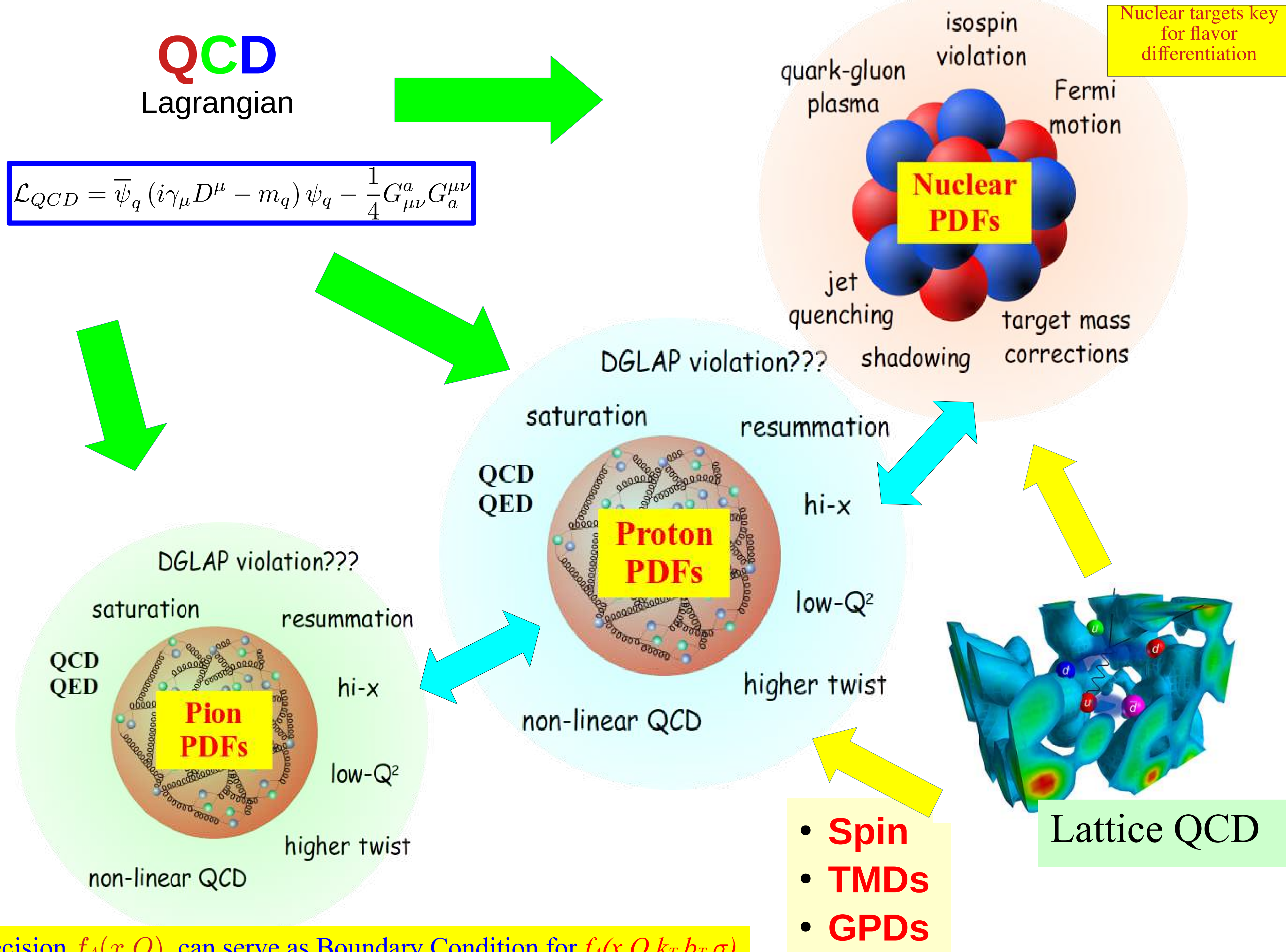
Conjecture: A theory can't be fundamental unless it fits on a coffee mug.





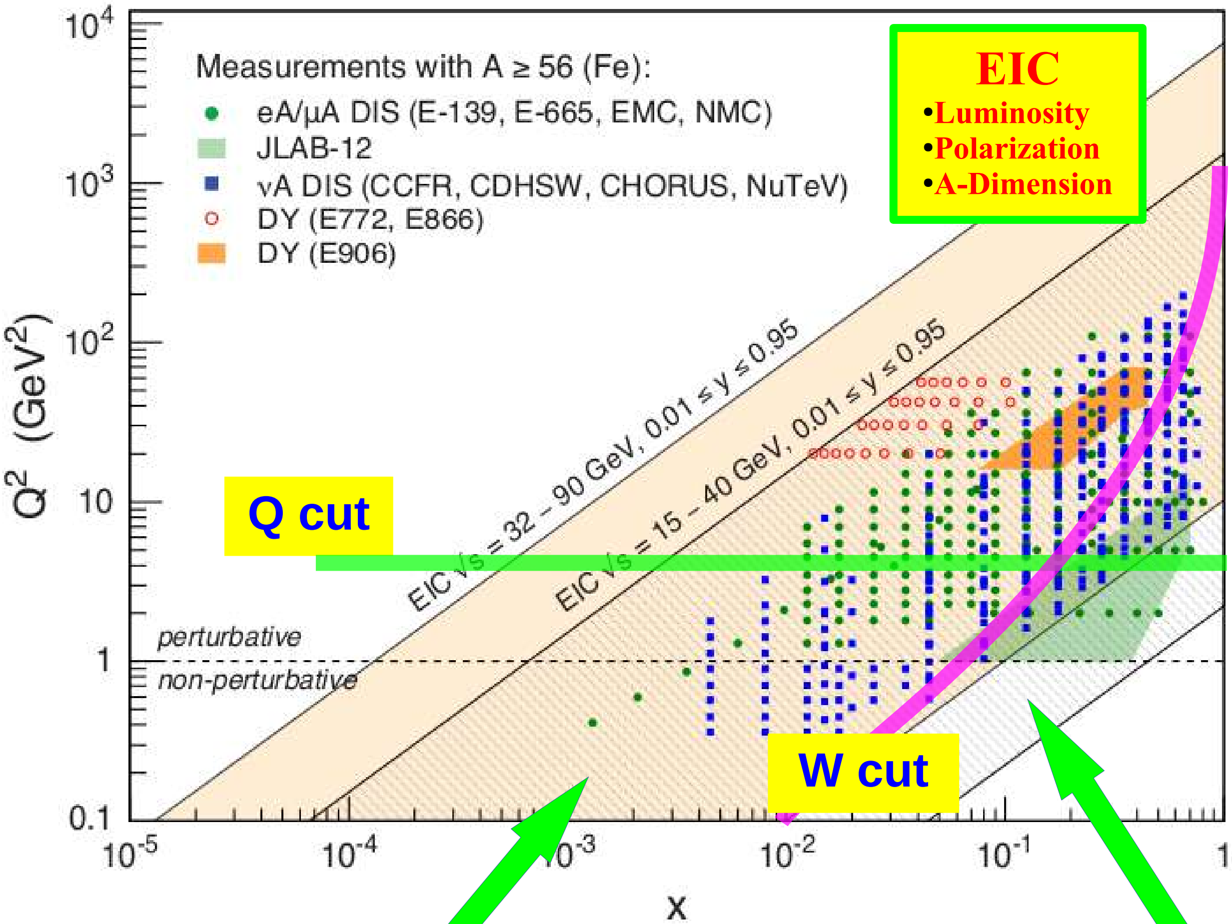
… we can go further

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 Beyond ... into the corners of the $\{x,Q^2\}$ Kinematic Plane



High-x:

Nuclear PDFs: x>1 allowed;

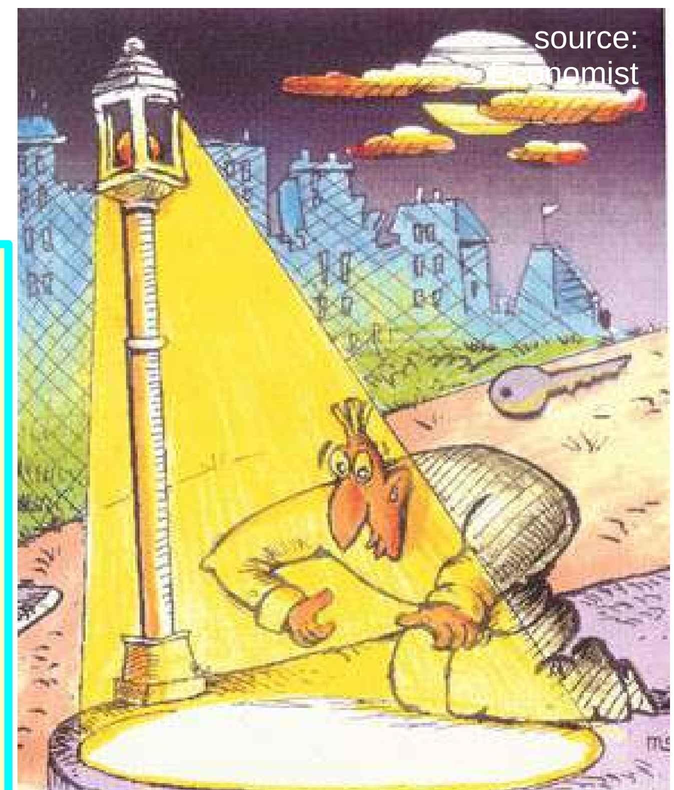
impacts F_2^{Nuc}/F_2^{Iso} in Fermi region

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-Q^2:

Non-Perturbative inteface

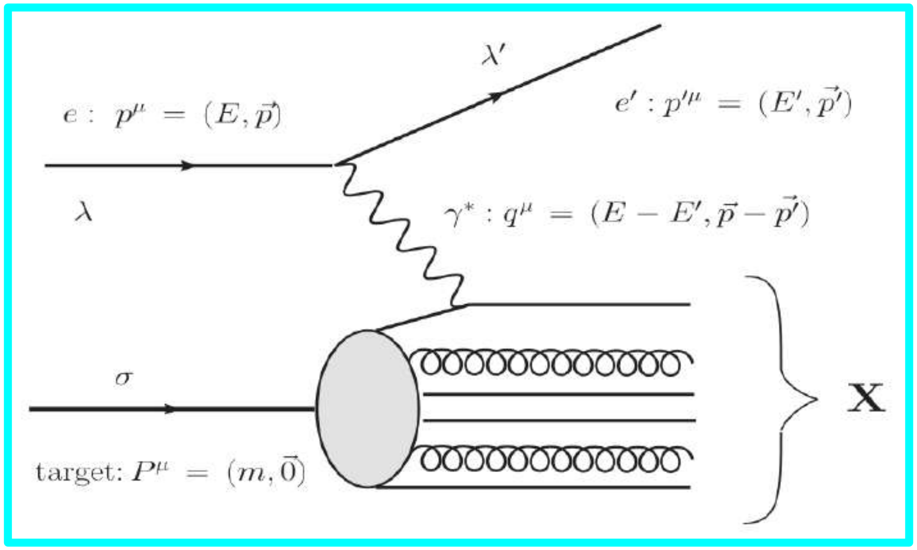
collective effects

Target Mass Corrections

pick up M^2/Q^2 higher twist

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

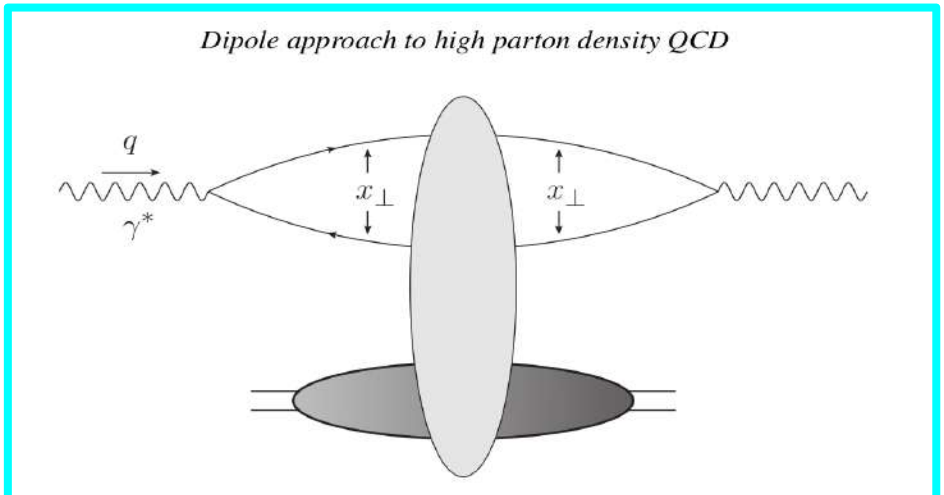
Run at multiple energies



Parton Model

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

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.

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

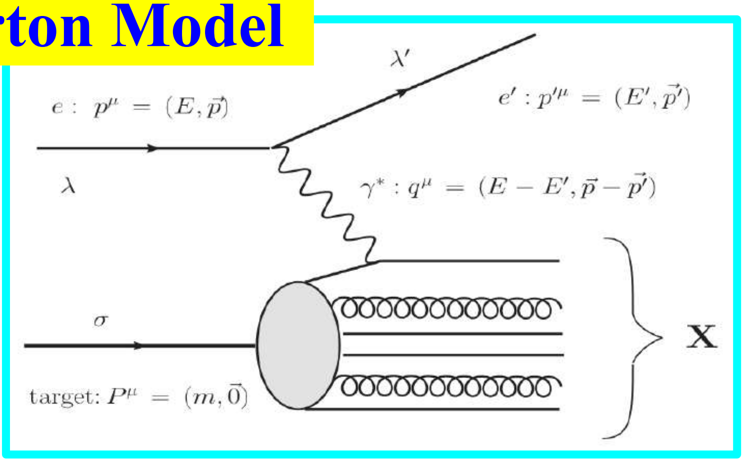
Parton Model & Dipole Model Comparison

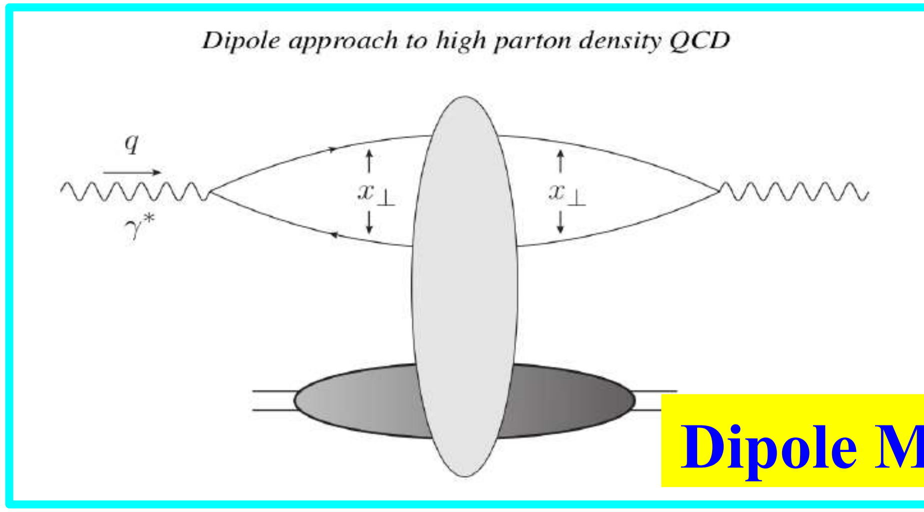
Signatures of gluon saturation from structure-function measurements

Nestor Armesto,[1,*] Tuomas Lappi,[2,3,†] Heikki Mäntysaari,[2,3,‡] Hannu Paukkunen,[2,3,§] and Mirja Tevio[2,3,¶]

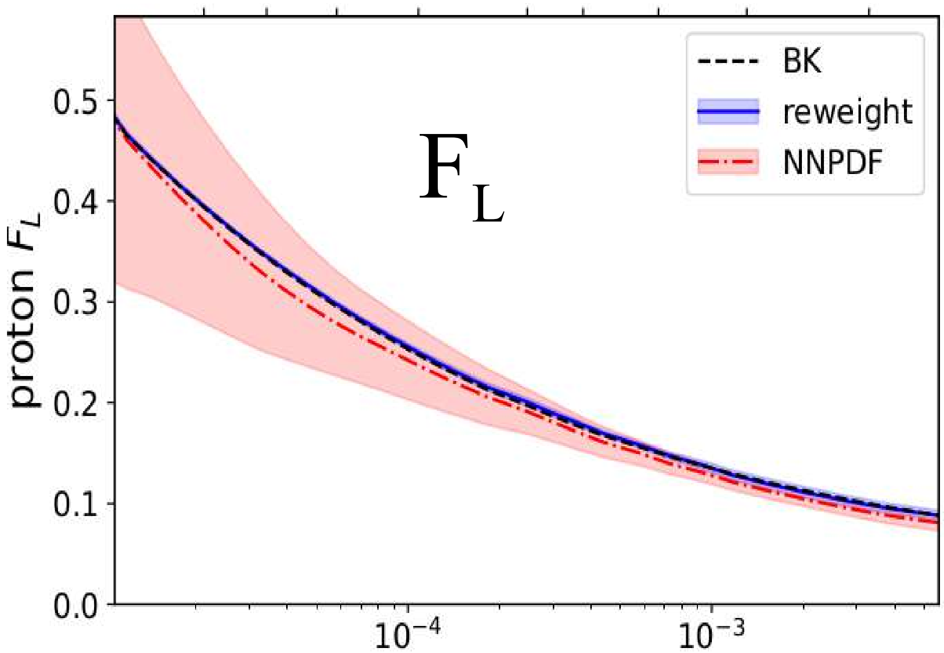
Phys.Rev.D 105 (2022) 11, 114017 • e-Print: 2203.05846 [hep-ph]

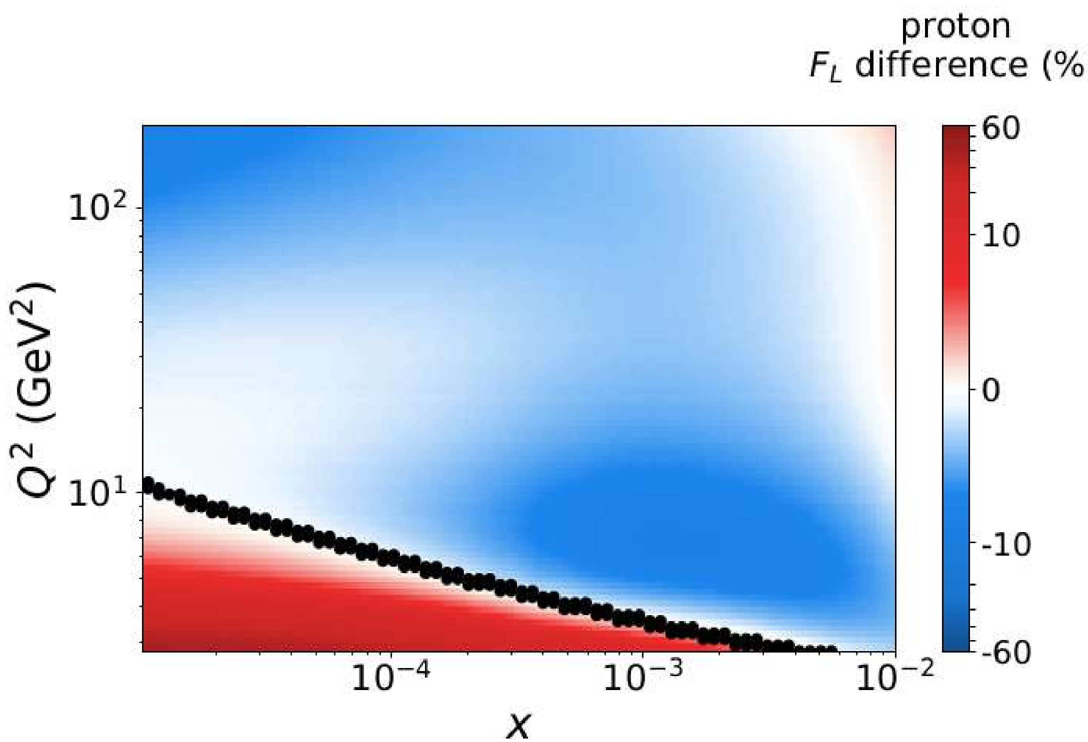
Parton Model





Dipole Model





Parton Model & Dipole Model Comparison

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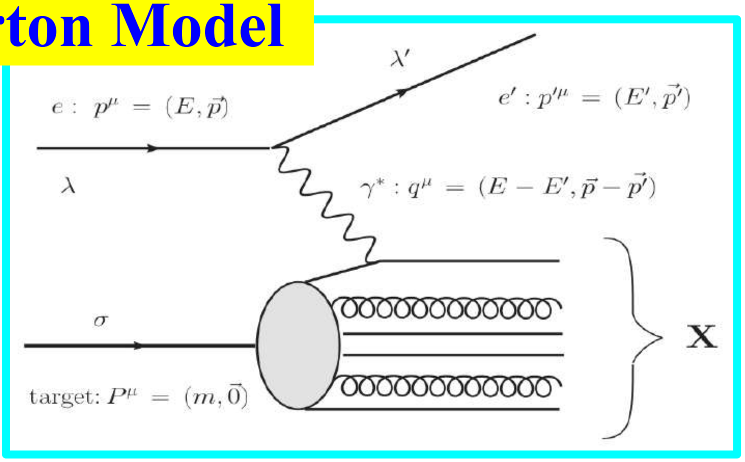
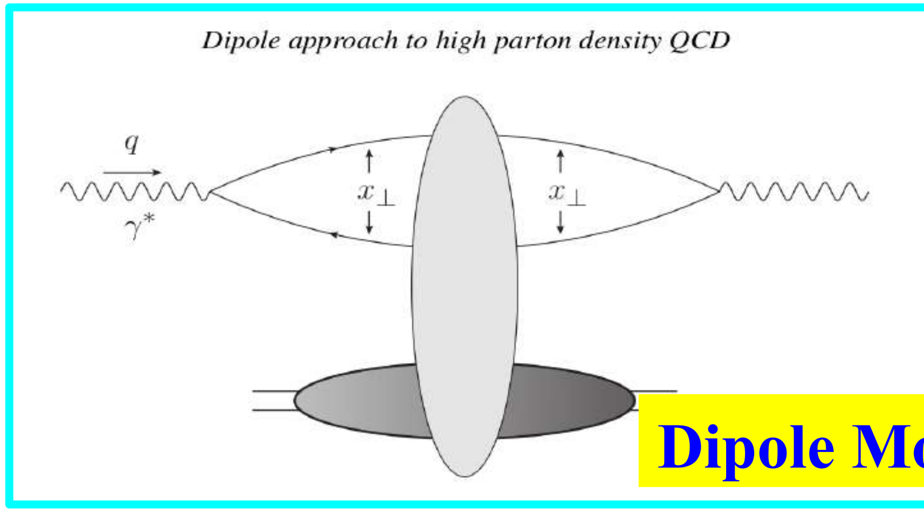




Dipole Model

nCTEQ

nuclear parton distribution functions

SURGE

COLLABORATION

nCTEQ

nuclear parton distribution functions

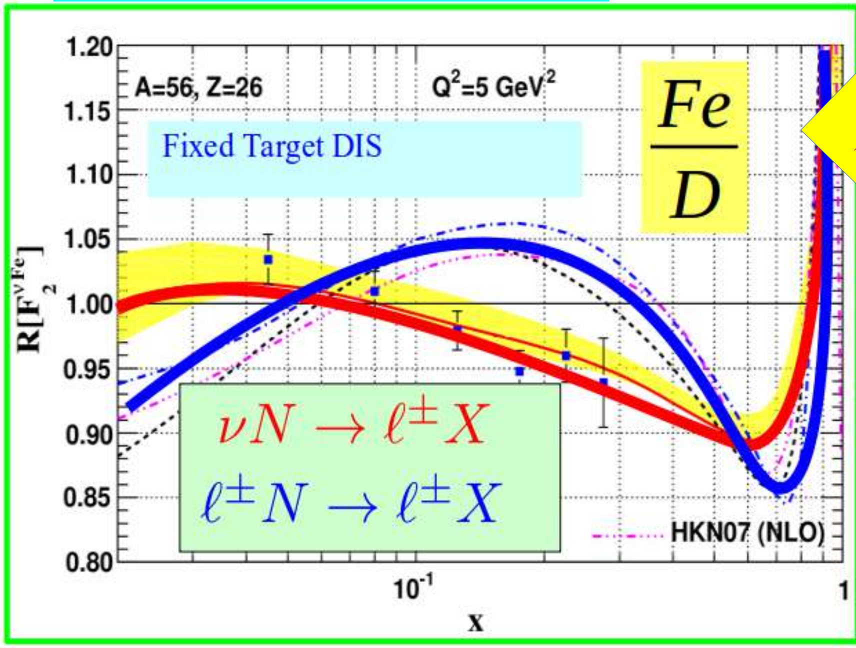
nCTEQ project is an extension of the CTEQ collaborative effort to determine nuclear parton distribution functions (nPDFs).

Towards nCTEQ26

- New nPDF release: **nCTEQ26** combines the previous analyses:
  - **nCTEQ15** [PRD 93, 085037 (2016)]
    - DIS NC data
    - fixed-target DY data
    - pion data from RHIC
  - **nCTEQ15WZ** [EPJC 80, 968 (2020)]
    - LHC W/Z data
    - constraints on *gluon* and *strange* nPDFs
  - **nCTEQ15HIX** [PRD 103, 114015 (2021); Prog.Part.Nucl.Phys. 136 (2024) 104096]
    - JLAB DIS data
    - constraints at high-x
    - theoretical corrections: TMC, HT, deuteron
  - **nCTEQ15SIH** [PRD 104 (2021) 9, 094005]
    - LHC & RHIC SIH data
    - constraints on *gluon* nPDF
  - **nCTEQ15neutrino** [PRD 106 (2022) 7, 074004]
    - DIS neutrino data (NuTeV, CHORUS, CDHSW, dimuons)
    - compatibility of NC & CC DIS
    - flavour separation
  - **nCTEQ15HQ** [PRL 121, 052004 (2018); PRD 105 (2022) 11, 114043]
    - LHC & RHIC HF data
    - constraints on low-x *gluon* nPDF
    - PDF-reweighting + full analysis

nCTEQ15ν

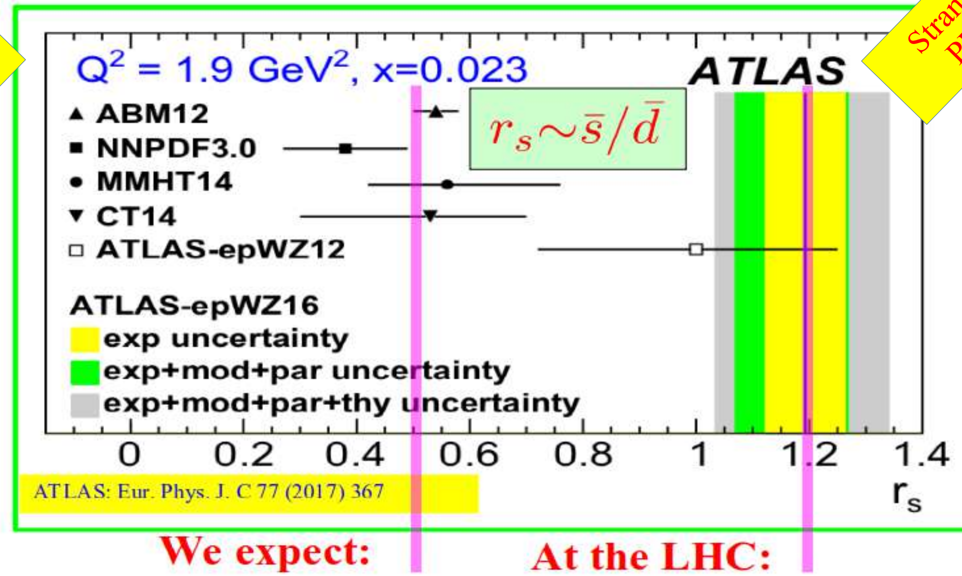
Split Personality



nCTEQ: arXiv: 2204.13157

nCTEQ15WZ

Strange PDF

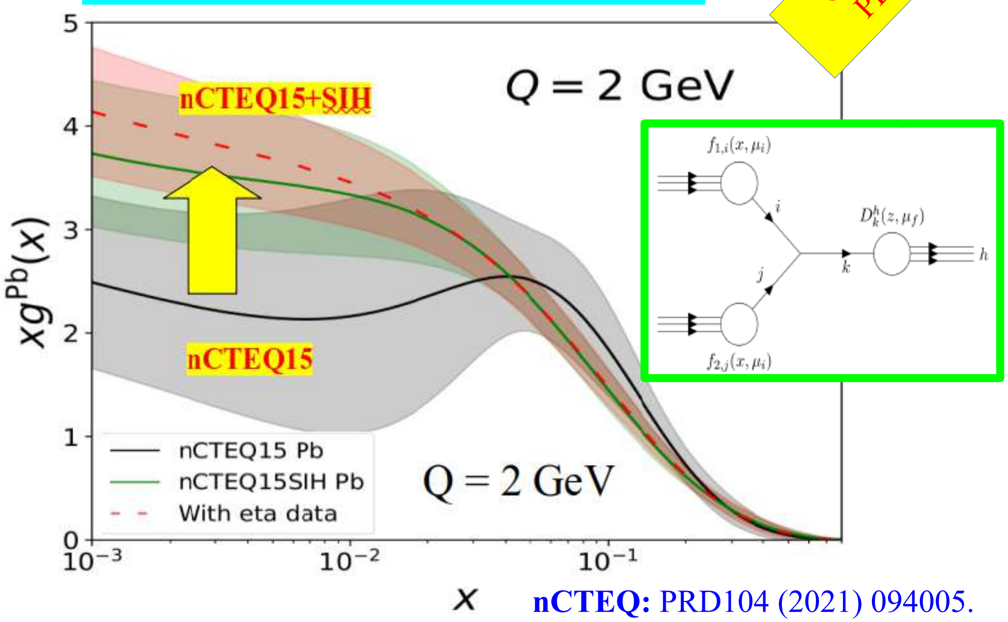


nCTEQ: Phys.Rev.D 104 (2021) 094005

Key for **EIC**

nCTEQ15WZ+SIH

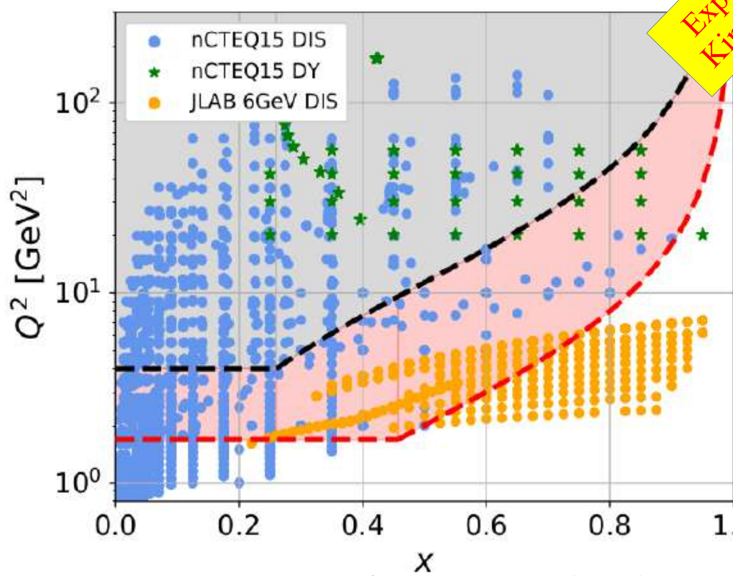
Gluon PDF



nCTEQ: PRD104 (2021) 094005.

nCTEQ15HIX

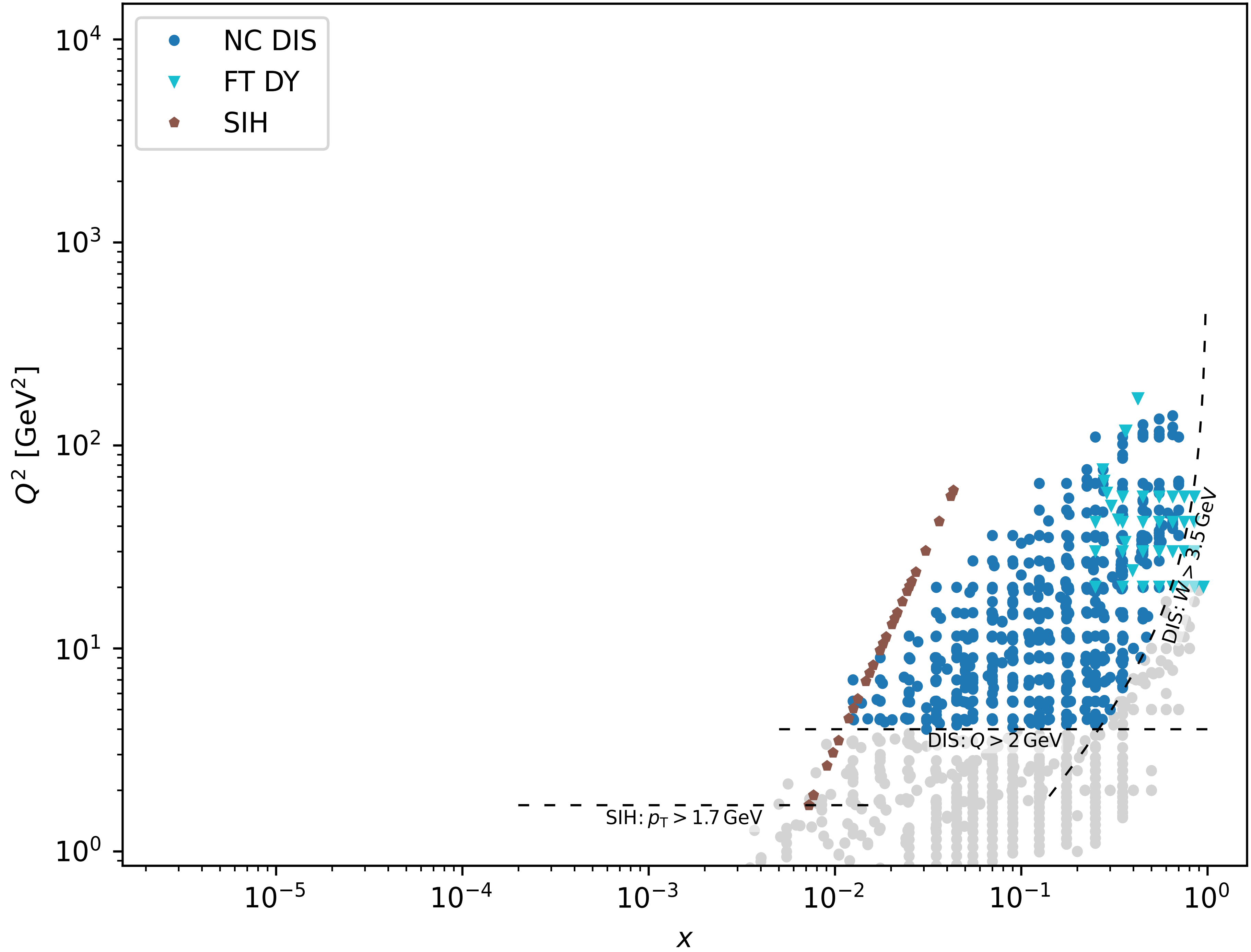
Expanded Kinematics



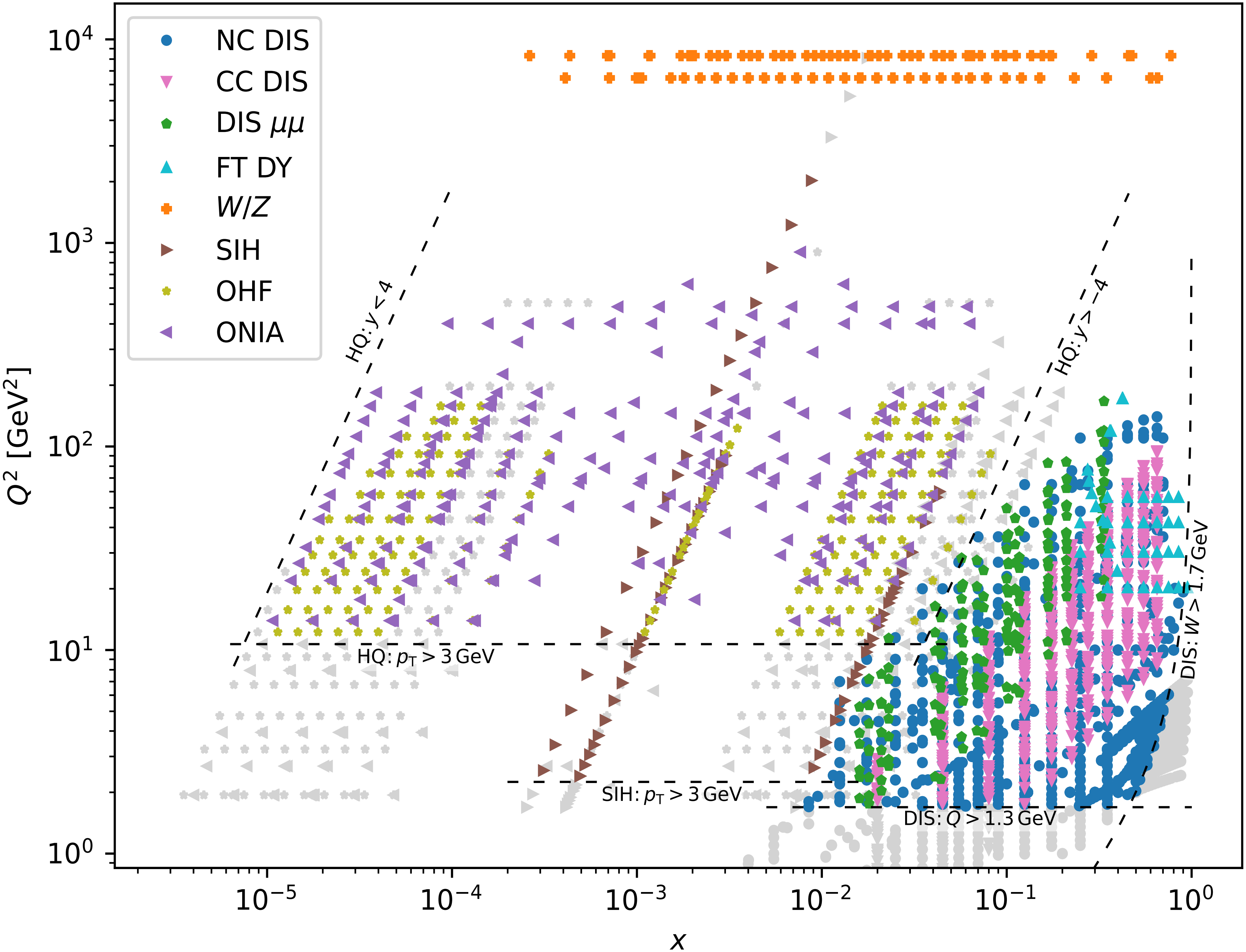
nCTEQ: Phys.Rev.D 103 (2021) 11, 114015

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

nCTEQ15 ~700 data



nCTEQ26 ~3500 data



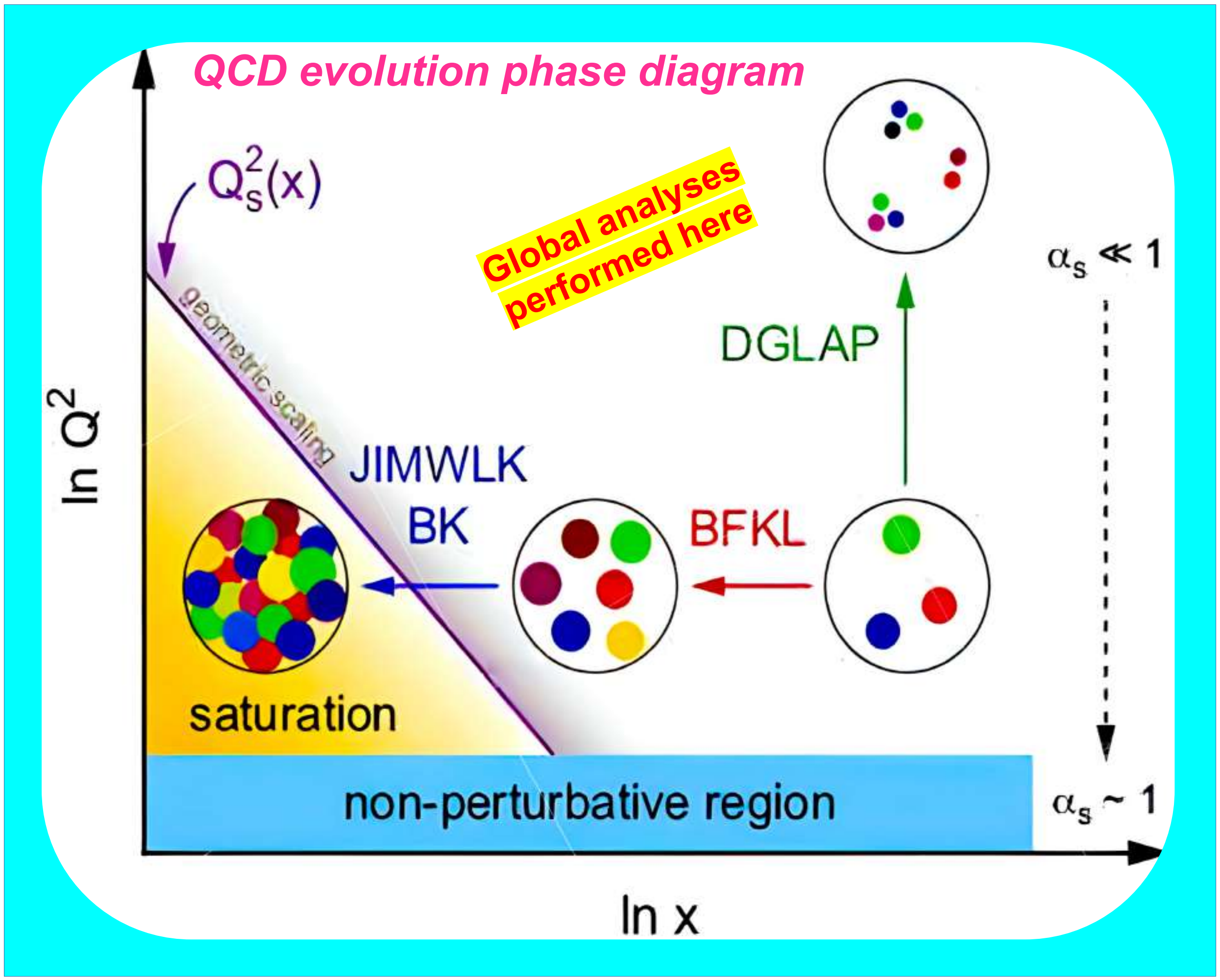
nCTEQ: Recap

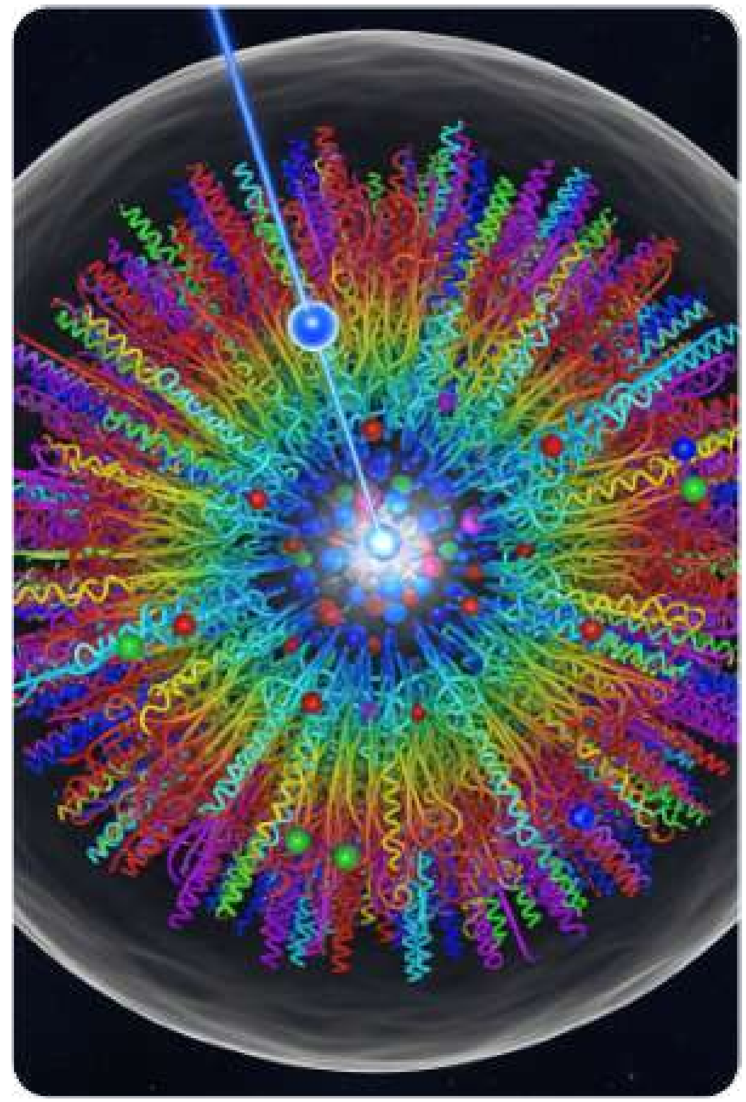
Precision nPDFs provide the essential foundation
for exploring the frontiers of QCD,
including the high-density gluon regime
where novel collective and non-perturbative phenomena
are expected to emerge.

... now let's explore the dense gluon regime

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).





Brookhaven National Laboratory

U.S. DEPARTMENT of ENERGY

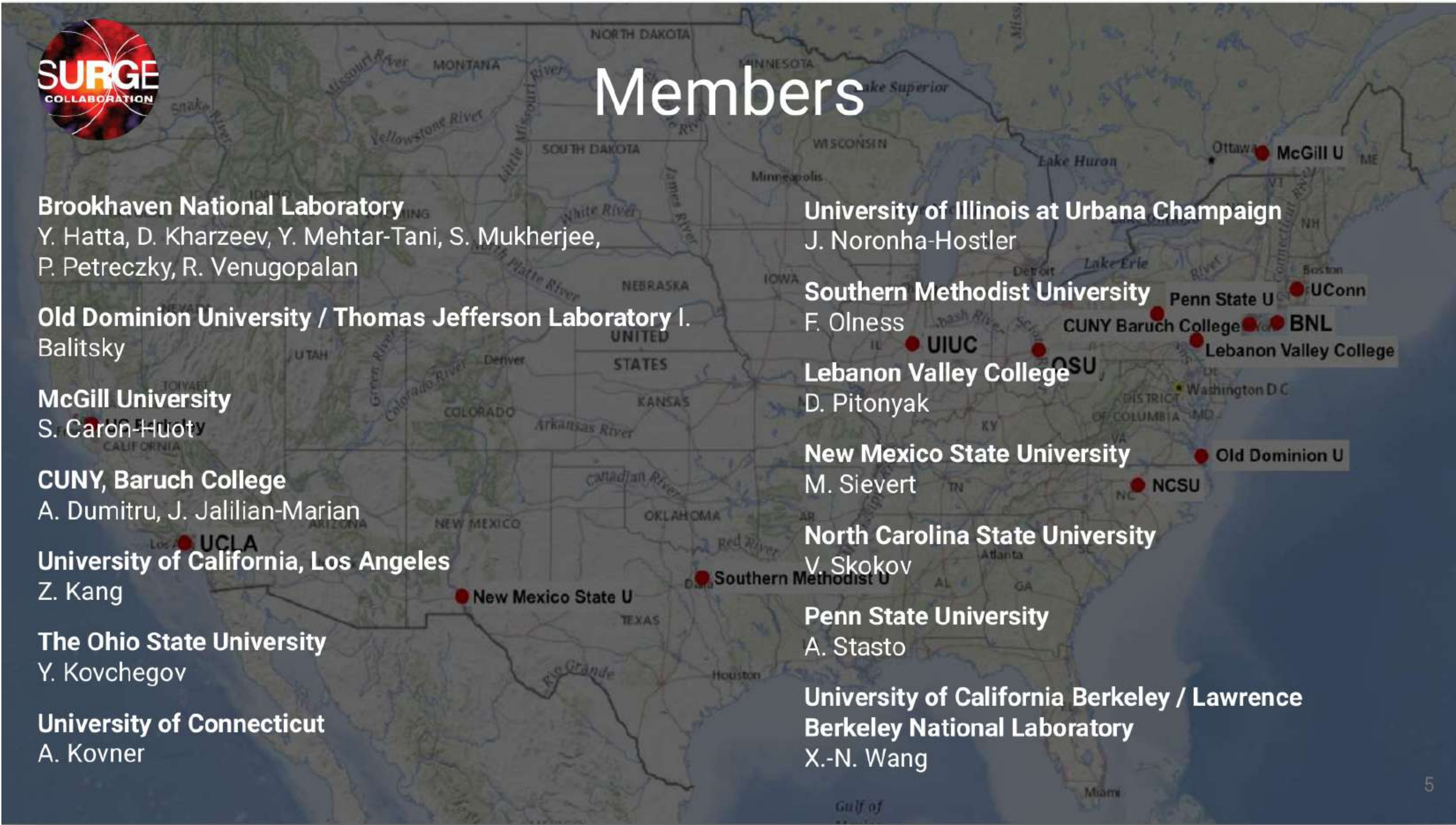
SURGE Collaboration

The Saturated Glue (SURGE) Collaboration is a Topical Collaboration in Nuclear Theory, funded by the US Department of Energy, Office of Science, Office of Nuclear Physics for the period 2023-2027.

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

SURGE COLLABORATION

The SURGE Collaboration aims at the discovery and exploration of the gluon saturation regime in quantum chromodynamics (QCD)



SURGE: Modular Structure Essential: Input Needed

GOAL: Sketch a work-flow for the global analysis framework.
The calculation must be FAST to be adaptable for a fitting loop

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

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

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

The SMU Team

Fred Olness

Brandon Stevenson grad student

Rebecca Preston grad student

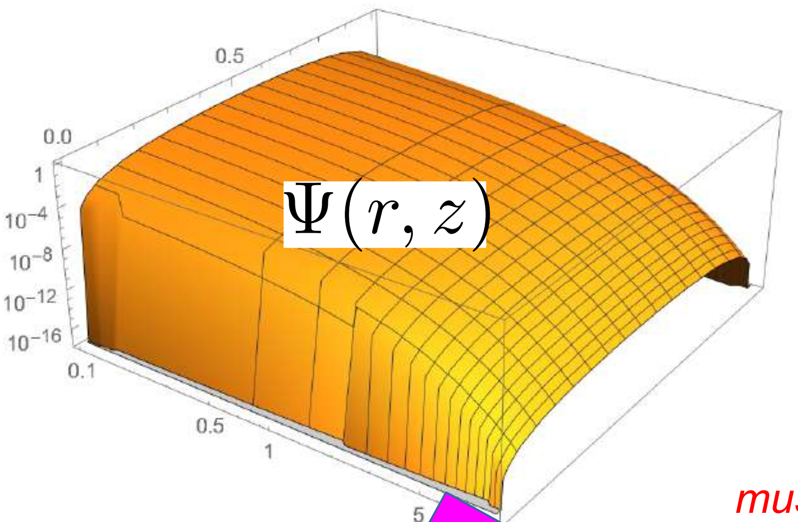
Junaid Khan grad student

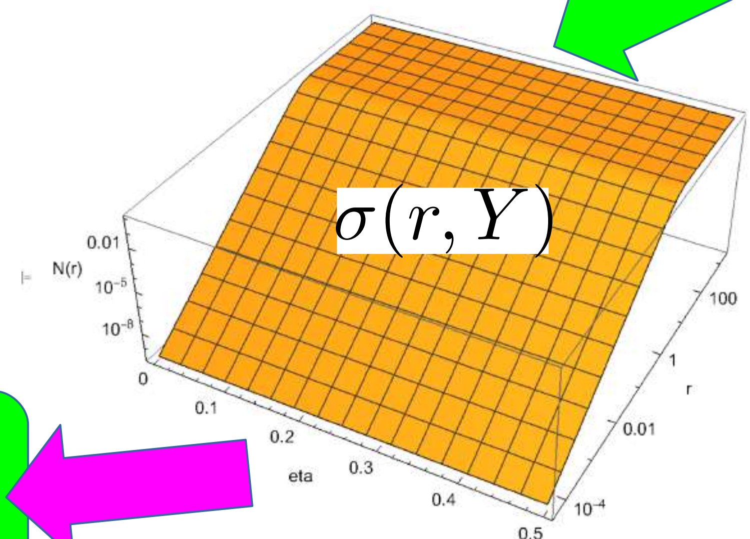
Peter Risse Postdoc

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

Photon light-front wave function

Dipole–nucleus cross section





must be fast!!!

Convolution
2D Grid-based calc

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

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

xFitter

Photon light-front wave function — Dipole target scattering amplitude

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

Photon light-front wave function

$\Psi(\gamma^* \to q\bar{q})$

LO: Analytic functions

NLO: i) K-Factors

ii) Grid Methods

Fred has experience

Peter has experience

Short-cuts

Example:

LO

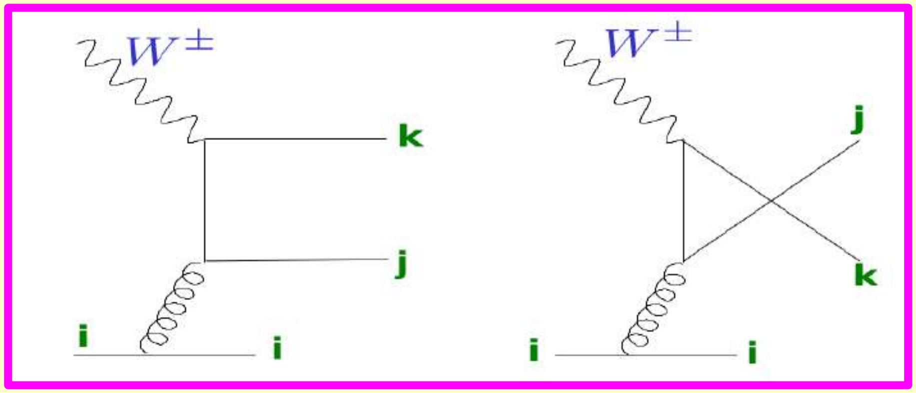
$$|\Psi_L^{\gamma^* \to q\bar{q}}(\vec{x}_\perp, z)|^2 = 2N_c \sum_f \frac{\alpha_{EM} Z_f^2}{\pi} 4Q^2 z^3 (1-z)^3 \left[K_0(x_\perp a_f)\right]^2 .$$

We can relate to usual structure functions

$$F_2(x, Q^2) = \frac{Q^2}{4\pi\alpha_{\rm em}} \left(\sigma_T^{\gamma^* A} + \sigma_L^{\gamma^* A}\right),$$

$$F_L(x, Q^2) = \frac{Q^2}{4\pi\alpha_{\rm em}} \sigma_L^{\gamma^* A}.$$

e.g., Extensible to Spin



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++

APFEL++

Bertone, arXiv:1708.00911

Valerio Bertone

Peter Risse

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	✓	✓	✓		✓	✓	✓

Dipole Model … *Dipole target scattering amplitude*

Photon light-front wave function **Dipole target scattering amplitude**

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

$$N(\eta, r) \equiv \sigma_{tot}^{q\bar{q}A}$$

$$\eta = Y = \ln(x_0, x)$$

Balitsky-Kovchegov Equation

$$\frac{\partial N(\eta, r)}{\partial \eta} = \int d^2\mathbf{r}_1 K(\mathbf{r}, \mathbf{r}_1, \mathbf{r}_2)\Big[N(\eta, r_1) + N(\eta, r_2) - N(\eta, r) - N(\eta, r_1)N(\eta, r_2)\Big]$$

the quadratic term includes the nonlinear saturation effects that tame the growth of gluon densities at small x

Feature	BFKL	BK	JIMWLK
Type	Linear	Non-linear (Dipole)	Non-linear (Functional)
Physics	Gluon emission	Emission + Recombination	Full CGC Color Fields
Limit	Dilute ($x \sim 10^{-2}$)	Large N_c Saturation	General Saturation
Complexity	Simple	Moderate	Very High

There are primarily four dipole amplitude models:

MV$^\gamma$ Model	**rcMV$^\gamma$ Model**
$x = \frac{(r^2 Q_{s0}^2)^\gamma}{4} \ln\left(\frac{1}{r\Lambda_{\rm QCD}} + e\right)$ $N^{{\rm MV}^\gamma}(r) = \begin{cases} 1-\exp(-x), & x > 10^{-6} \\ x, & \text{otherwise} \end{cases}$	$x = \frac{r^2 Q_{s0}^2}{4} \cdot \alpha_s(r) \cdot \frac{N_c}{\pi}\left(1 + \ln\left(\frac{\alpha_s^{\rm freeze}}{\alpha_s(r)}\right)\right)$ $N^{\rm rcMV}(r) = \begin{cases} [1-\exp(-x^\gamma)]^{1/\gamma}, & x > 10^{-4} \\ x, & \text{otherwise} \end{cases}$
GBW Model	**GBW$^\gamma$ Model**
$N^{\rm GBW}(r) = 1 - \exp\left(-\frac{r^2 Q_{s0}^2}{4}\right)$	$x = \left(\frac{r^2 Q_{s0}^2}{4}\right)^\gamma$ $N_0^{{\rm GBW}^\gamma}(r) = \begin{cases} [1-\exp(-x)]^{1/\gamma}, & \frac{r^2 Q_{s0}^2}{4} > 10^{-4} \\ \frac{r^2 Q_{s0}^2}{4}, & \text{otherwise} \end{cases}$

Running coupling constant :

Golec-Biernat–Wusthöff (GBW)
McLerran-Venugopalan (MV) ,

$$\alpha_s = \frac{12\pi}{(33.0 - 2.0N_f)\log\left[\left(\mu_0^{\frac{1}{c}} + \left(\frac{4C^2}{\Lambda_{\rm QCD}^2 r^2}\right)^{\frac{1}{c}}\right)^c\right]}$$

Parameters & Initial Conditions

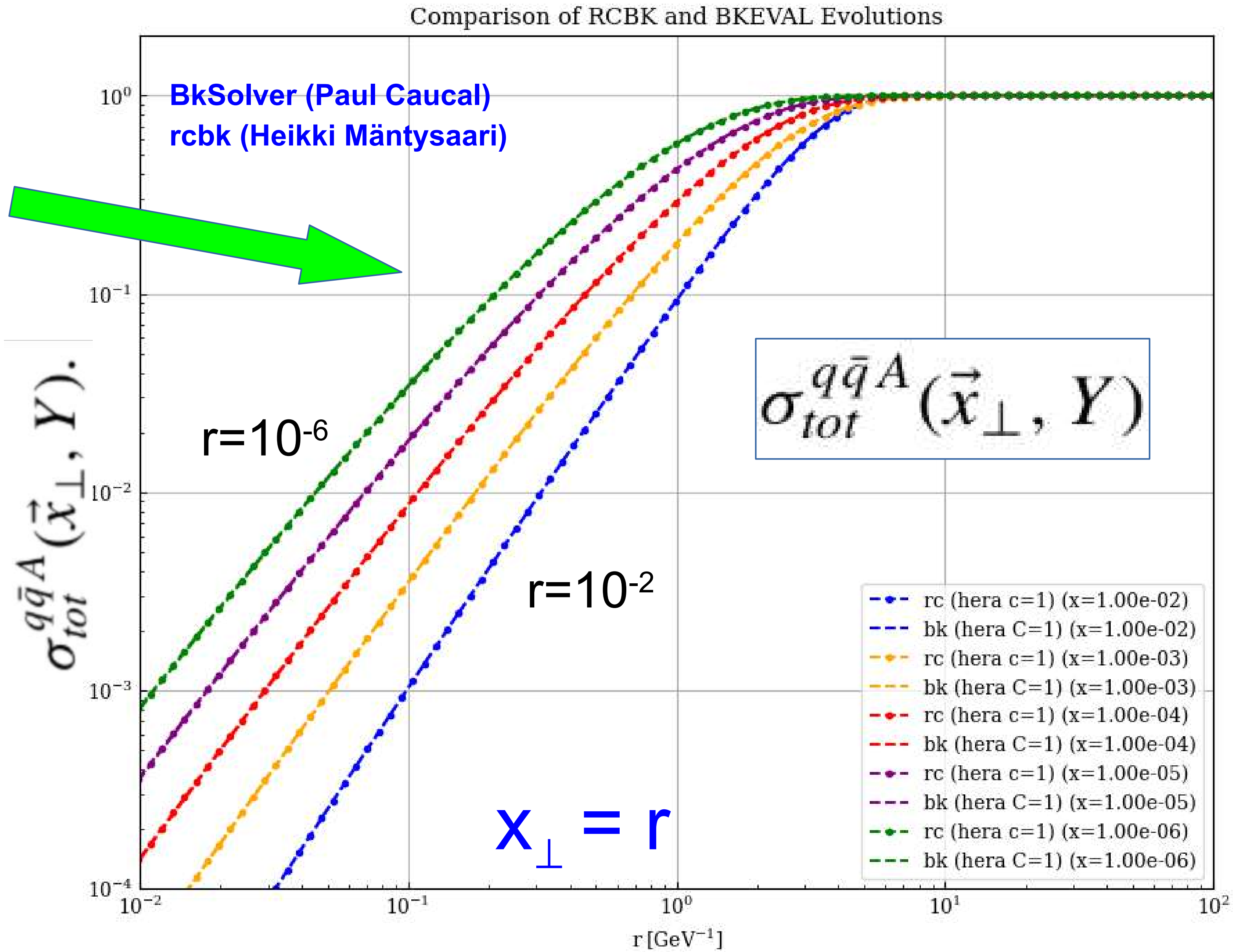
Parameter	bkEval	rcBK	Description
Initial Condition	MV$^\gamma$	MV$^\gamma$	Dipole amplitude initial model
Evolution Type	Balitsky	Balitsky	BK equation solver type
Model Parameters			
Q_{s0}^2	$Q_{s0} = 0.4062019$ GeV	$Q_{s0}^2 = 0.165$ GeV^2	Initial saturation scale
γ	1.135	1.135	Anomalous dimension in MV$^\gamma$ model
α_s	Evolving with r	Evolving with r	Strong coupling constant
α_s^{freeze}	0.762	0.762	Freeze value to limit $\alpha_s(r)$ in the IR region
Λ_{QCD}	0.241 GeV	0.241 GeV	QCD scale parameter
C or C^2	$C = 2.51992$	$C^2 = 6.35$	Coefficient in running coupling formula
e_c	1	1	Smoothing constant in running coupling equation
Grid Parameters			
Grid Points	$N_u = 421,\ N_\theta = 21$	150 (step factor 1.10305)	Grid discretization for dipole sizes
Dipole Size Range	$u = \log(r) \in [-10, 4.605]$	$r \in [4.5 \times 10^{-5}, 100]$	Range of dipole size (log-scale for bkEval, linear for rcBK)
Rapidity Range	$\eta_f = 15.0,\ N_\eta = 150$	$y \in [0, 15]$, step 0.1	Rapidity evolution range

TABLE I. Comparison of parameters used in `bkEval` and `rcBK` codes with MV$^\gamma$ initial condition.

Cross Check: Numerical Solution of BK Evolution

Two sets of lines per color

Excellent agreement



Cross Check: We see we have good agreement across all x values for two different data generators, the RCBK code and BKeval code with all internal settings matching.

Machine Learning Models

- **Need fast evolution** ***(the WHY)***
- Could optimize a program, but ...
  - BFKL, BK, JIMWLK
  - LO, NLO, ...
- **Try Machine Learning** ***(the HOW)***
  - Fast, flexible
  - Improved over interpolation

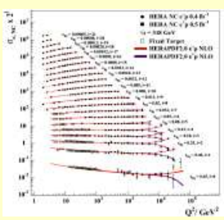
xFitter

PROTON NUCLEON MESON

www.xFitter.org

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

Experimental Data



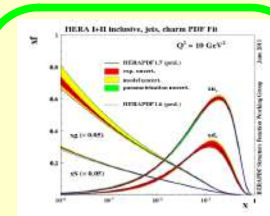
Data: HERA, Tevatron, LHC, fixed target experiments

Processes: Inclusive DIS, Jets, Drell-Yan, Diffraction, Top production, W and Z production

Theory Calculations

HQ Schemes: MSTW, NNPDF, ABM, ACOT
Jets, W, Z: FastNLO, ApplGrid
Top: Hathor
Evolution: QCDNUM, APFEL, k_T
Other: NNPDF reweighting, TMDs, Dipole Model, ...

xFitter



Parton Distribution Functions: PDF, Updf, TMD

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

Theoretical Cross Sections

Comparisons to other PDFs (LHAPDF)

extensions include nuclear PDFs

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

xFitter 2.2.0 Future Freeze

xFitter Collaboration

xFitter Background

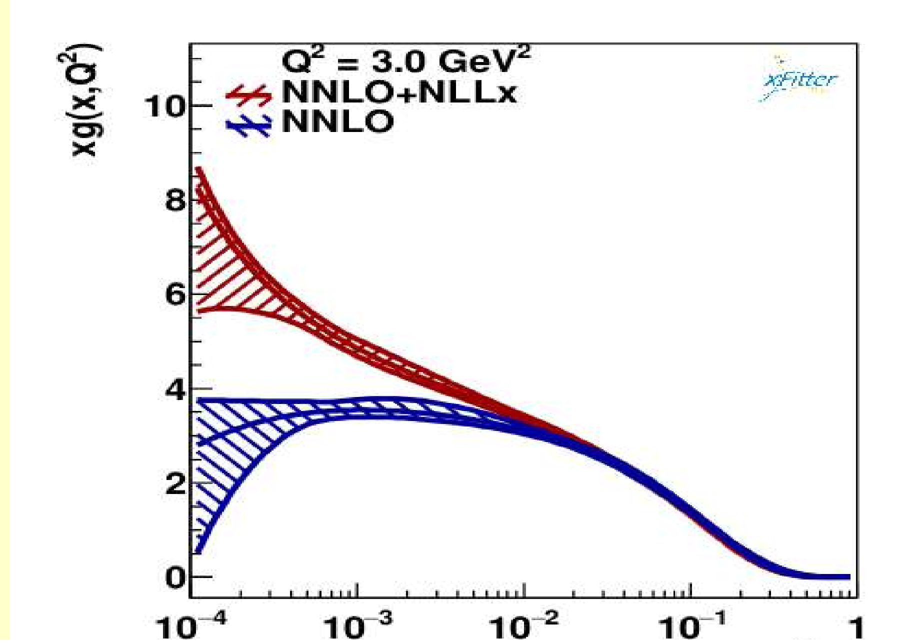
Impact of low-x resummation on QCD analysis of HERA data

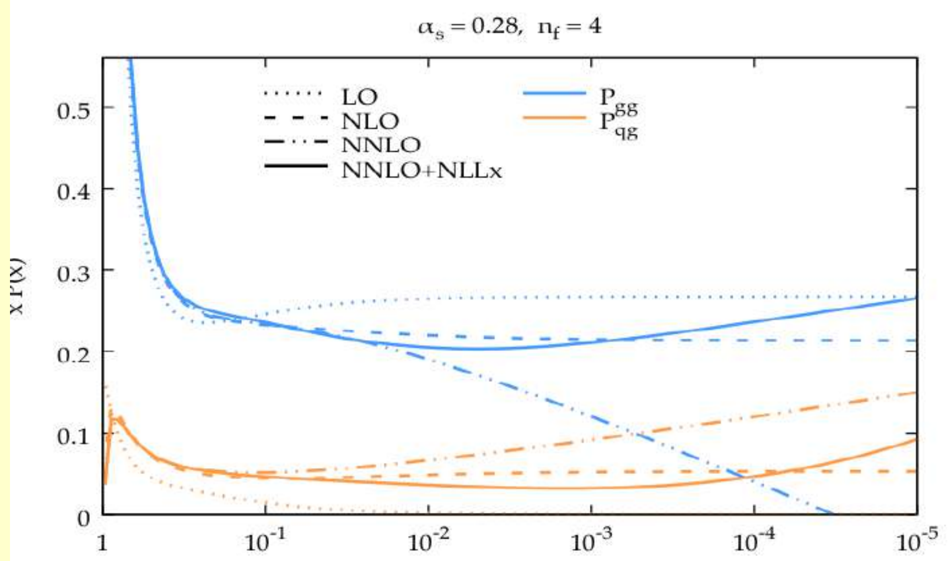
xFitter Developers' team: Hamed Abdolmaleki [1], Valerio Bertone [2,3], Daniel Britzger [4], Stefano Camarda [5], Amanda Cooper-Sarkar [6], Francesco Giuli [6], Alexander Glazov [7], Aleksander Kusina [8], Agnieszka Luszczak [7,9], Fred Olness [10], Andrey Sapronov [11], Pavel Shvydkin [11], Katarzyna Wichmann [7], Oleksandr Zenaiev [7] and Marco Bonvini [12]

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)                         //
////////////////////////////////////////////////////////
```





Machine Learning Models

- **Need fast evolution** ***(the WHY)***
- Could optimize a program, but ...
  - BFKL, BK, JIMWLK
  - LO, NLO, ...
- **Try Machine Learning** ***(the HOW)***
  - Fast, flexible
  - Improved over interpolation

1) MLP (Multi-Layer Perceptron) Model

Junaid Khan

Brandon Stevenson

Neural Network Setup

- **Input features**: **x, r, C, Qs0, γ**
- **Input model: McLerran-Venugopalan**
- **Target**: N(x,r) dipole cross section
- **Architecture**: 3 hidden layers (64, 64, 32 neurons) with ReLU activation
- **Output layer**: Linear

Training Details

- Optimizer: **AdamW**
    - AdamW adaptively adjusts the learning rate for each parameter based on estimates of the first and second moments of the gradients. This allows for faster convergence and can handle sparse gradients effectively.
- Learning rate: **Exponentially decaying**
- Loss function: **Custom** **(scaled MSE: Mean Absolute Error.)**

  Dataset split: **80/10/10** (train/validation/test)

$$\mathrm{MSE} = \frac{1}{N}\sum_{i=1}^{N}\left(y_i^{\mathrm{pred}} - y_i^{\mathrm{true}}\right)^2$$

$$L = \frac{1}{N}\sum_{i=1}^{N}\frac{\mathrm{MSE}}{(0.01\, y_i^{\mathrm{true}} + \varepsilon)^2}$$

MLP Compare Predicted vs True values

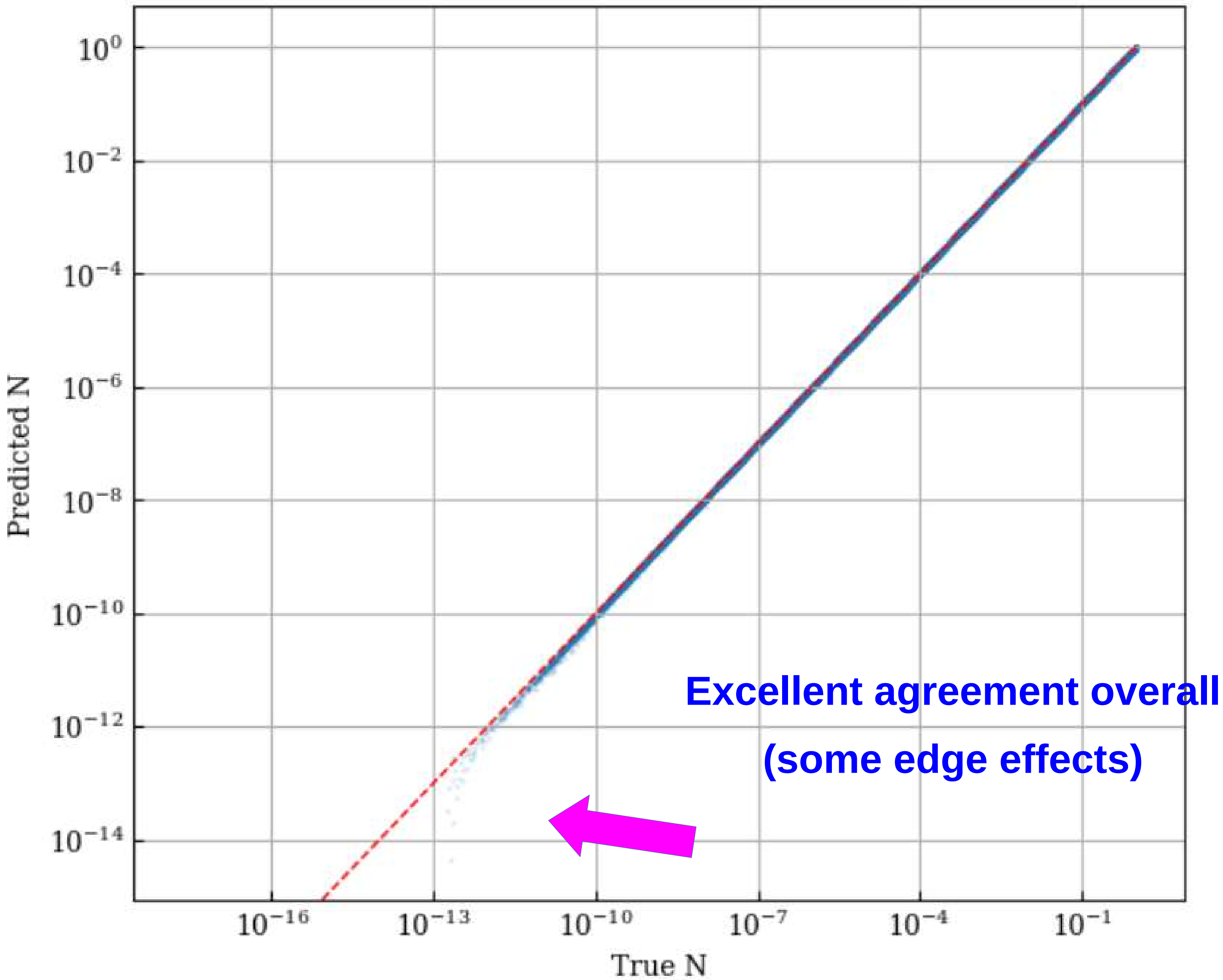
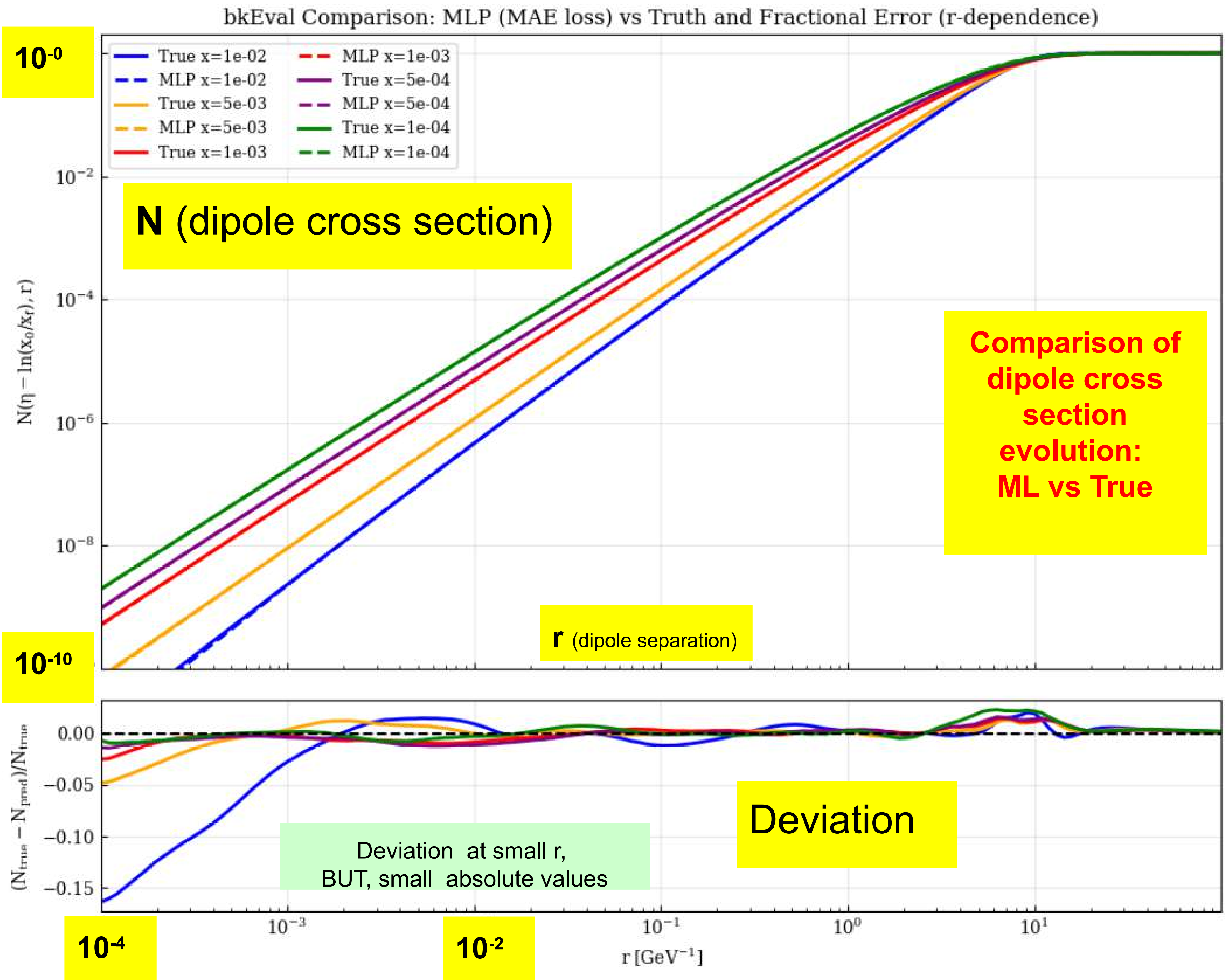


FIG. 1. True vs. predicted N values from the MLP on the test set. The dashed red line indicates perfect agreement.


bkEval Comparison: MLP (MAE loss) vs Truth and Fractional Error (r-dependence)
True x=1e-02
MLP x=1e-02
True x=5e-03
MLP x=5e-03
True x=1e-03
MLP x=1e-03
True x=5e-04
MLP x=5e-04
True x=1e-04
MLP x=1e-04
10-0
10-10
N (dipole cross section)
Comparison of dipole cross section evolution: ML vs True
r (dipole separation)
Deviation
Deviation at small r, BUT, small absolute values
10-4
10-2
r [GeV-1]
N(η = ln(x0/xf), r)
(Ntrue − Npred)/Ntrue

2) DeepONet


Brandon Stevenson   Junaid Khan

DeepONet attempts to learn non-linear operators accurately. Many applications to physics.

“DeepONet: Learning nonlinear operators for identifying differential equations based on the universal approximation theorem of operators” https://arxiv.org/pdf/1910.03193

Two sub-networks a branch and trunk. Branch and Trunk network can be any network, MLP (dense connection) chosen for simplicity. Trunk network also uses a simple fourier features layer to give access to high dimensional information.

DeepONet

With test dataset, Varying **C** and **QS0** and 11,998,500 data points:

Training time: ~1 hour, 100 epochs

Size of keras model save: 11mb

Inference time: less than 1 second for full grid

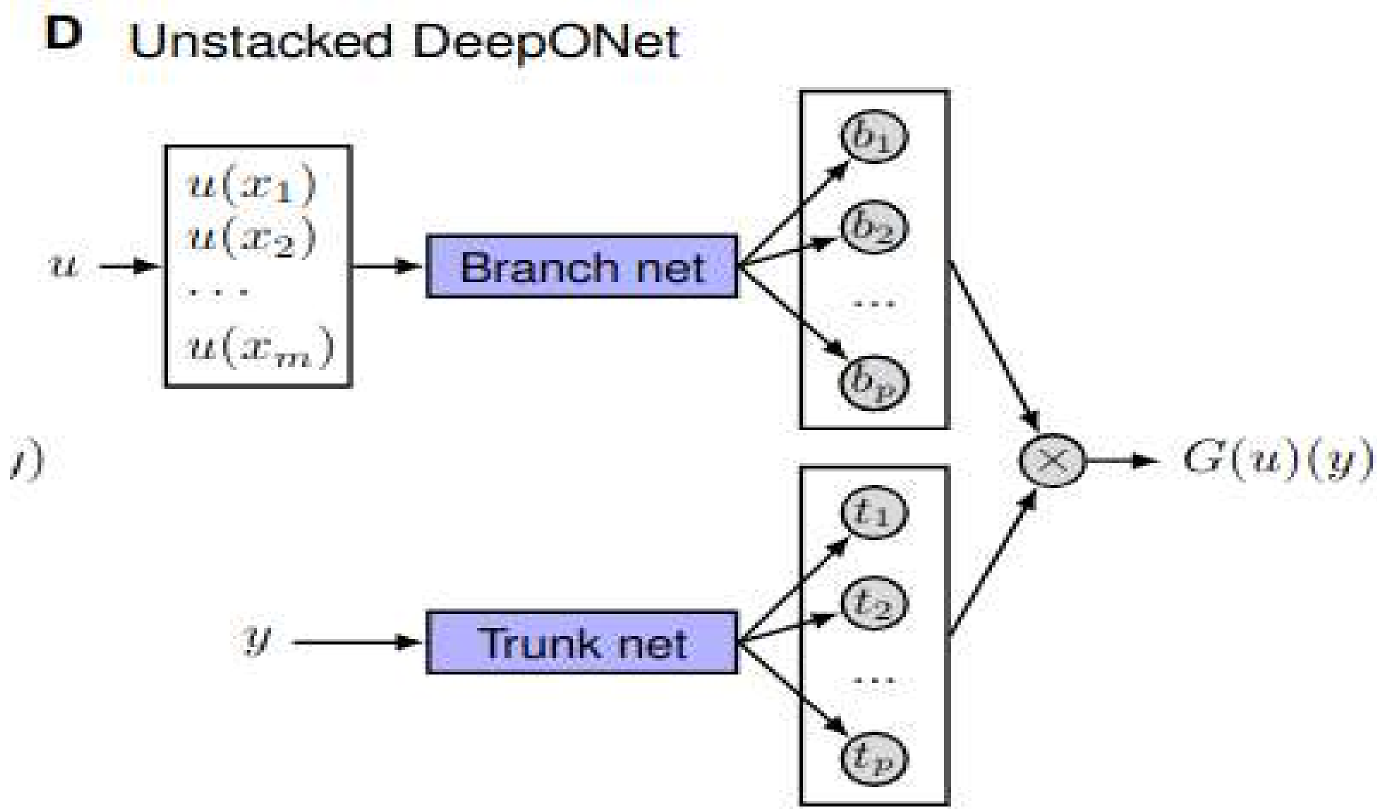
DeepONet

Theorem 1 (Universal Approximation Theorem for Operator). *Suppose that σ is a continuous non-polynomial function, X is a Banach Space, $K_1 \subset X$, $K_2 \subset \mathbb{R}^d$ are two compact sets in X and $\mathbb{R}^d$, respectively, V is a compact set in $C(K_1)$, G is a nonlinear continuous operator, which maps V into $C(K_2)$. Then for any $\epsilon > 0$, there are positive integers n, p, m, constants $c_i^k, \xi_{ij}^k, \theta_i^k, \zeta_k \in \mathbb{R}$, $w_k \in \mathbb{R}^d$, $x_j \in K_1$, $i = 1, \ldots, n$, $k = 1, \ldots, p$, $j = 1, \ldots, m$, such that*

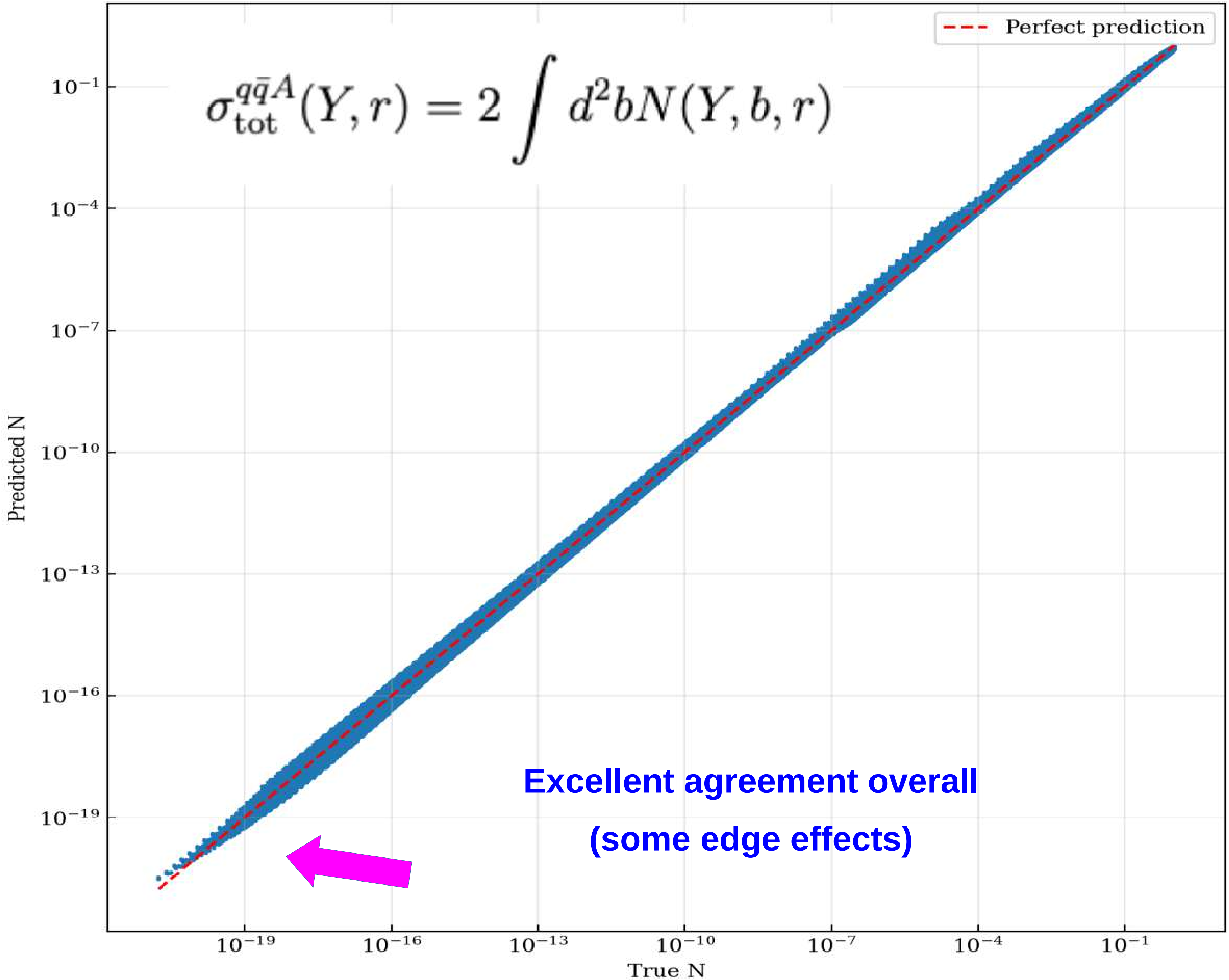
We learn G

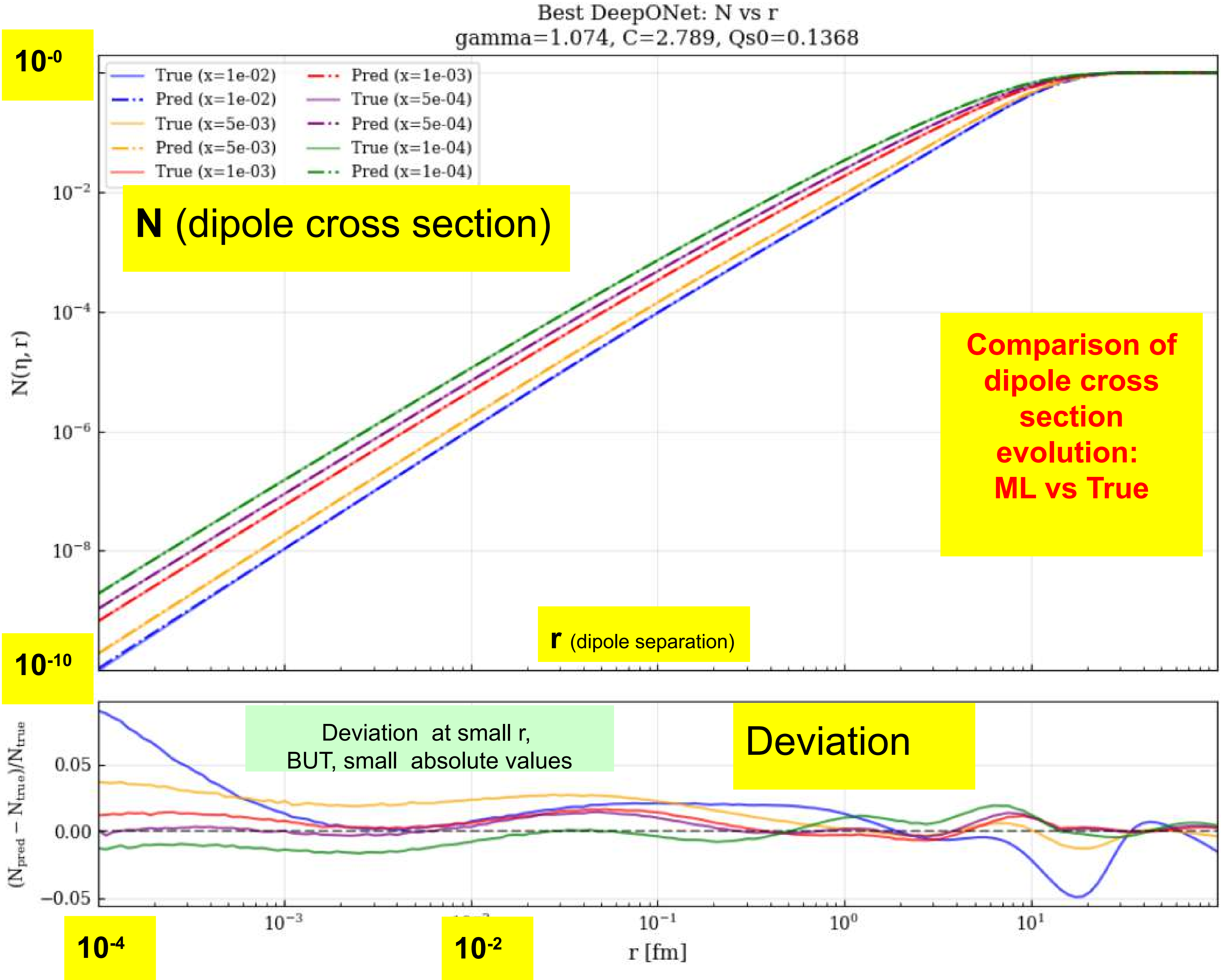
$$\left| G(u)(y) - \sum_{k=1}^{p} \underbrace{\sum_{i=1}^{n} c_i^k \sigma\left(\sum_{j=1}^{m} \xi_{ij}^k u(x_j) + \theta_i^k \right)}_{branch} \underbrace{\sigma(w_k \cdot y + \zeta_k)}_{trunk} \right| < \epsilon \quad (1)$$

holds for all $u \in V$ and $y \in K_2$.



DeepONet: Compare Predicted vs True values




Best DeepONet: N vs r
gamma=1.074, C=2.789, Qs0=0.1368
True (x=1e-02)
Pred (x=1e-02)
True (x=5e-03)
Pred (x=5e-03)
True (x=1e-03)
Pred (x=1e-03)
True (x=5e-04)
Pred (x=5e-04)
True (x=1e-04)
Pred (x=1e-04)
10-0
10-10
N (dipole cross section)
N(η, r)
Comparison of dipole cross section evolution: ML vs True
r (dipole separation)
(Npred − Ntrue)/Ntrue
Deviation at small r,
BUT, small absolute values
Deviation
10-4
10-2
r [fm]

3) Convolutional Neural Network (CNN)

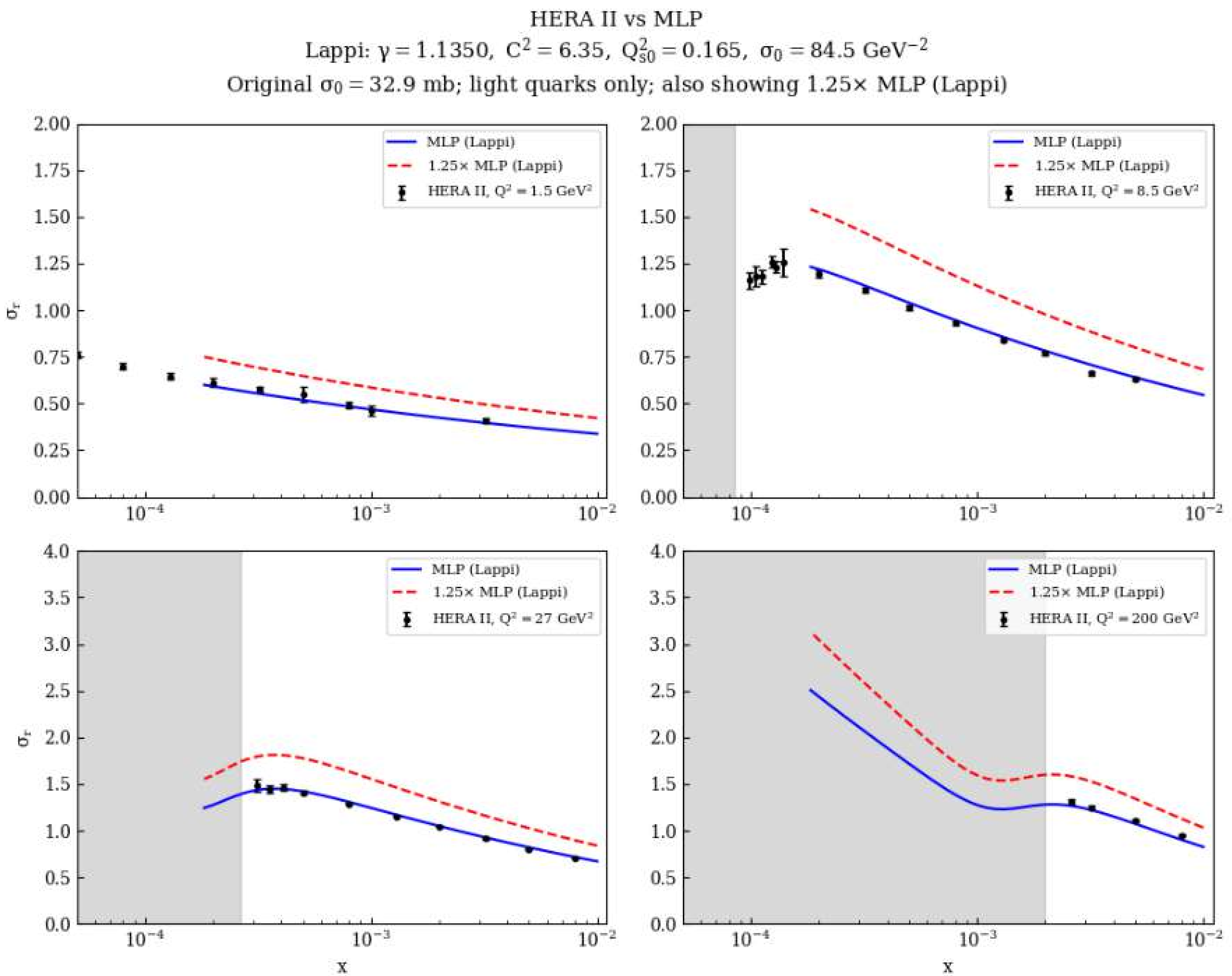
Junaid Khan

Brandon Stevenson

... in progress ...

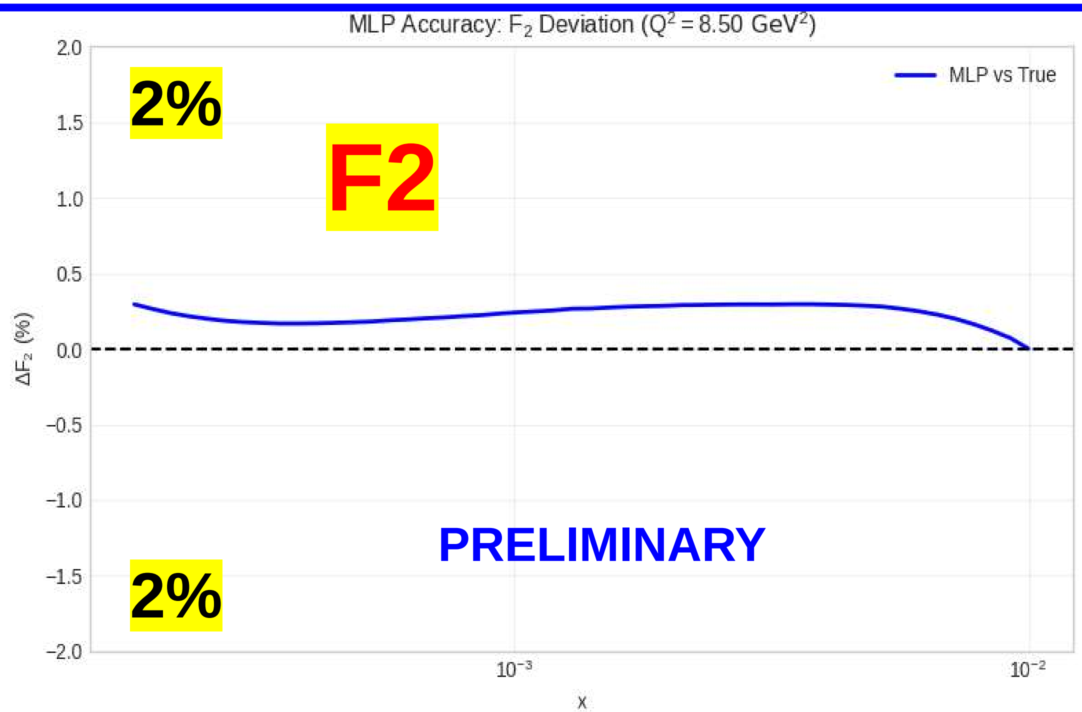
Does it work?

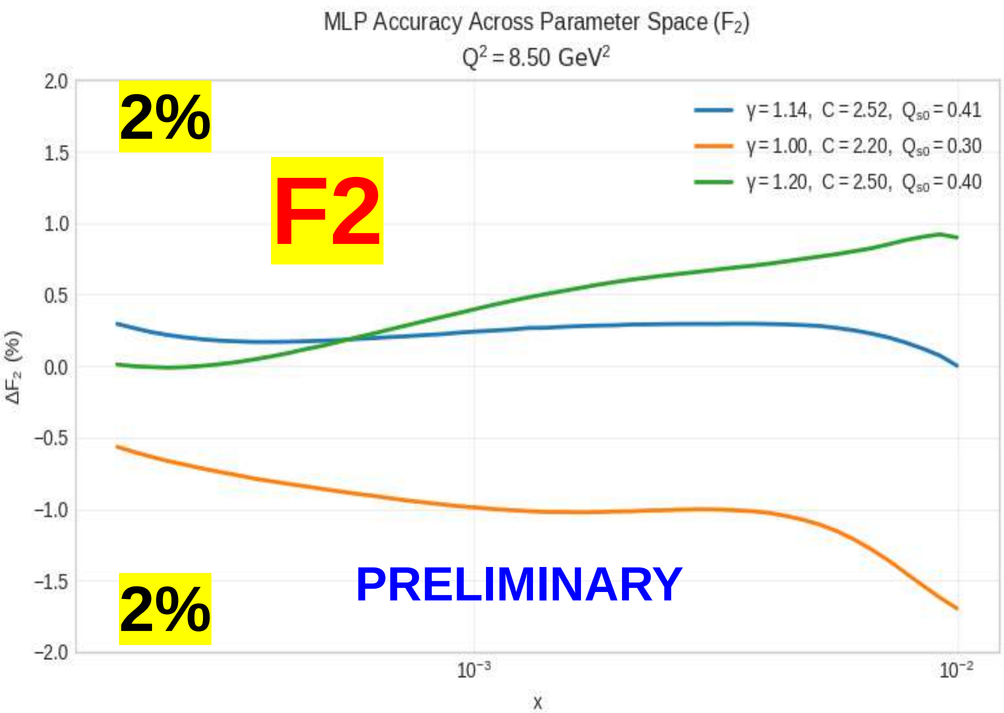
What are the uncertainties?

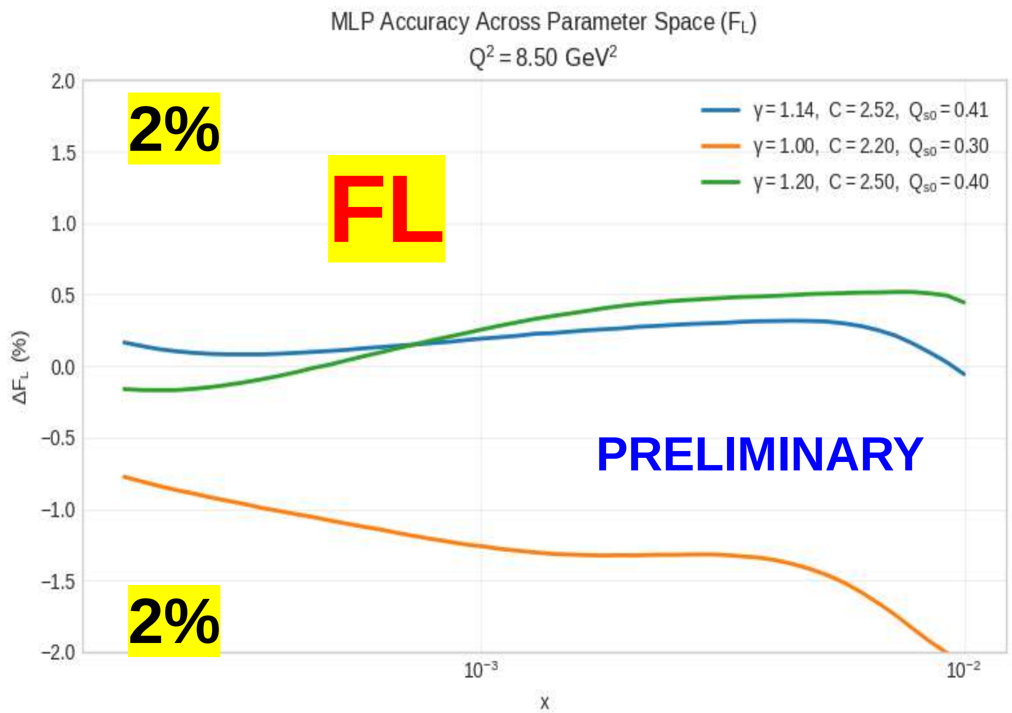

HERA II vs MLP
Lappi: γ = 1.1350, C² = 6.35, Q²s0 = 0.165, σ0 = 84.5 GeV⁻²
Original σ0 = 32.9 mb; light quarks only; also showing 1.25× MLP (Lappi)
MLP (Lappi)
1.25× MLP (Lappi)
HERA II, Q² = 1.5 GeV²
HERA II, Q² = 8.5 GeV²
HERA II, Q² = 27 GeV²
HERA II, Q² = 200 GeV²
σr
x

Uncertainties: ML vs. True

Preliminary uncertainties appear to be satisfactory given typical theoretical and experimental uncertainties



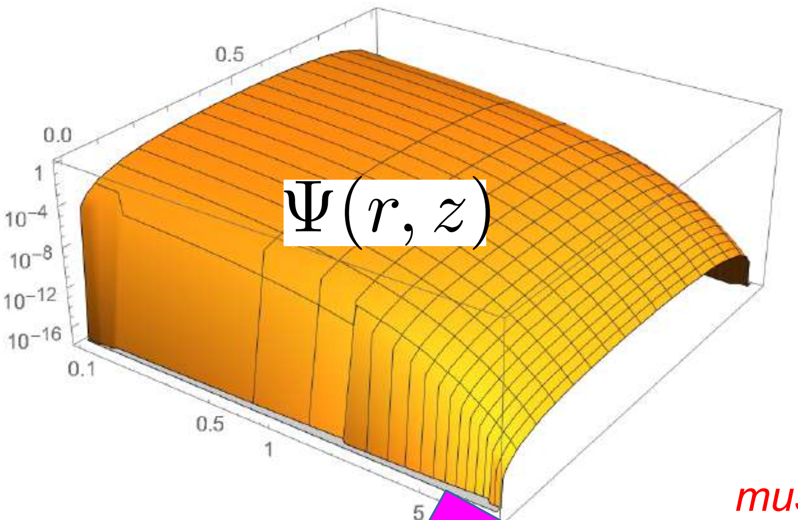


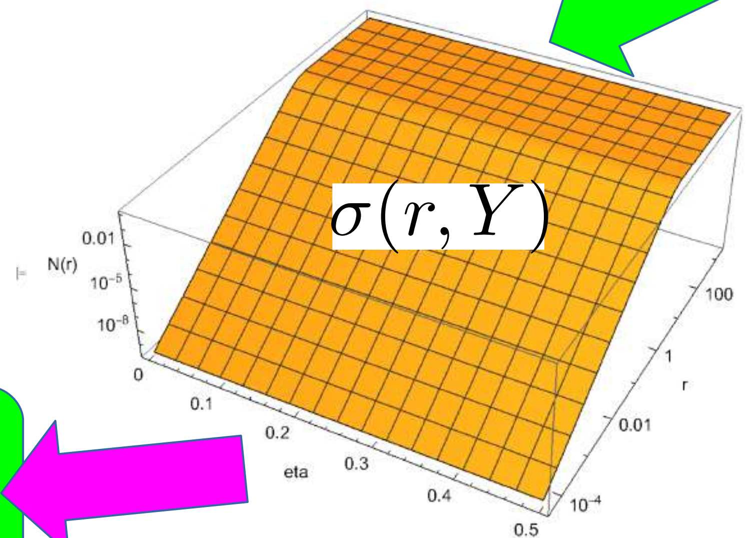


$$\sigma_{tot}^{\gamma^* A}(x, Q^2) = \int \frac{d^2 x_\perp}{4\pi} \int_0^1 \frac{dz}{z(1-z)} |\Psi^{\gamma^* \to q\bar{q}}(\vec{x}_\perp, z)|^2 \sigma_{tot}^{q\bar{q}A}(\vec{x}_\perp, Y).$$

Photon light-front wave function

Dipole–nucleus cross section





must be fast!!!

Convolution

2D Grid-based calc

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

… F_2 & F_L

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

xFitter

FONDAZIONE BRUNO KESSLER

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

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

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Jefferson Lab

QUARK-GLUON DYNAMICS IN THE NUCLEAR MEDIUM

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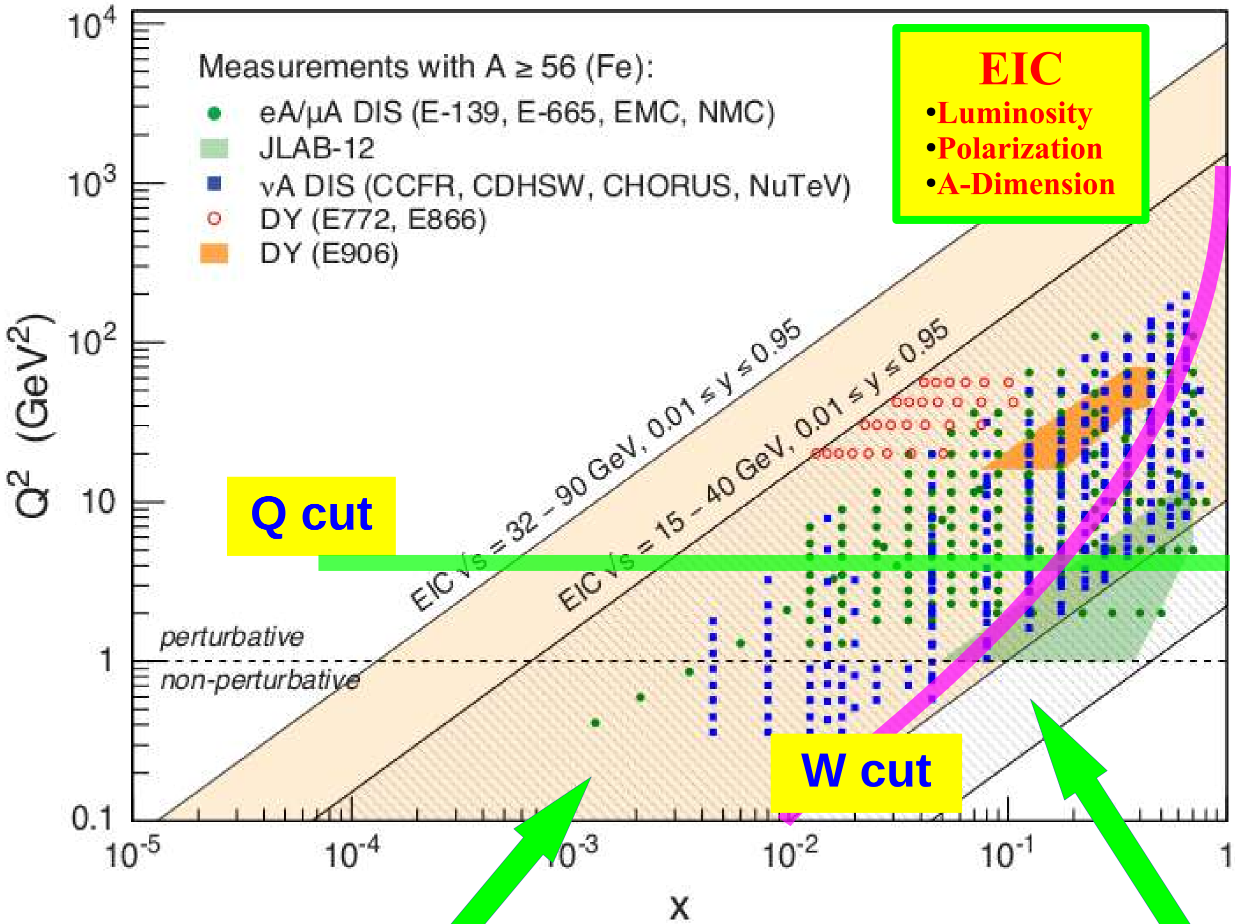
https://indico.ectstar.eu/event/276/

Conclusion

To Boldly Go Beyond ... into the corners of the $\{x,Q^2\}$ Kinematic Plane



High-x:

Nuclear PDFs: x>1 allowed;

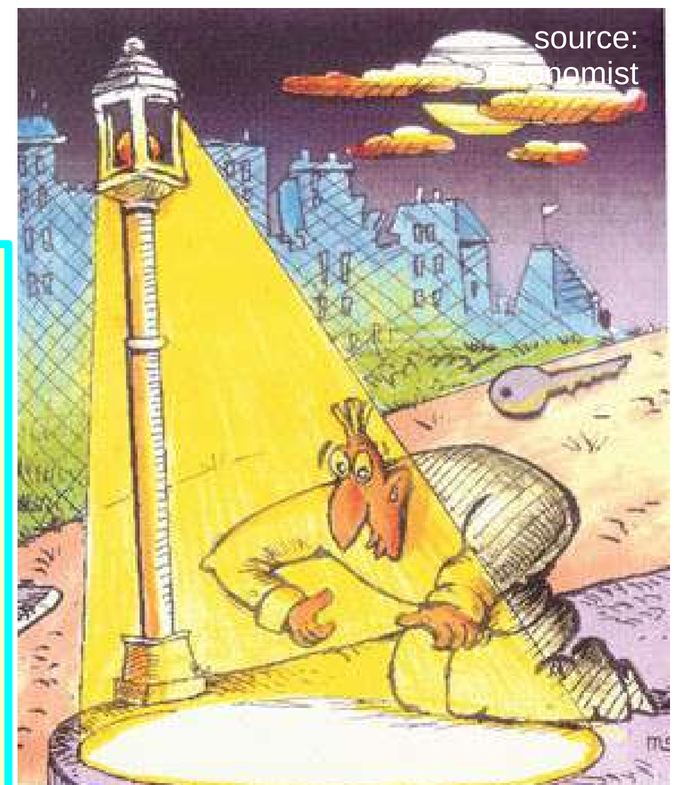
impacts F_2^{Nuc}/F_2^{Iso} in Fermi region

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-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

Status Summary:

Dipole Calculation:

- Working Python Framework to compute σ^{tot} and F2, FL
- Reasonable agreement with e.g., HERA data *(need to fit)*
- Grid methods enable fast calculation

BK Evolution:

- Full evolution codes: [BKsolver, rcbk] validated
  - Try ML for inner fitting loop

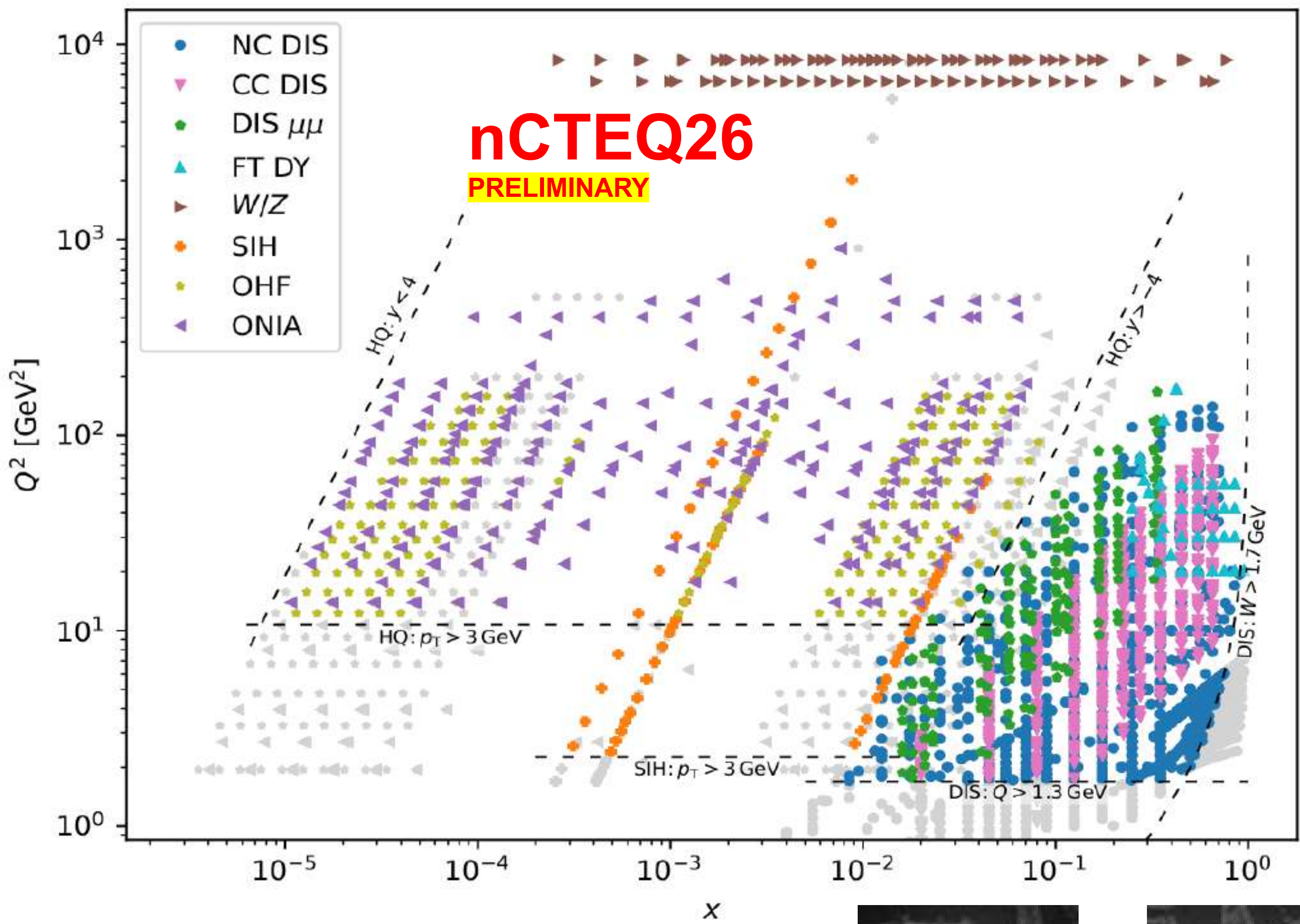
ML approach to BK Evolution

- Reasonable approximation across kinematics [preliminary]
- Fast enough for flexible fits

Other evolution models:

- Could extend to other models: BFKL, JIMWLK, … DGLAP??
- Could ‘warm-up’ running BK with LO & NLO

nCTEQ26 Updates:



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

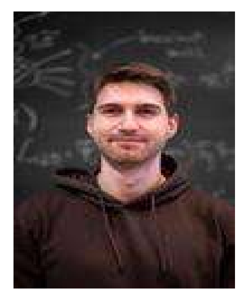
- Good data description overall
- Particular focus on:
  - A-dependence
  - strange & gluon uncertainties

nCTEQ

nuclear parton distribution functions


Tomas Jezo


Katrin Greve


Jan Wissmann


Aleksander Kusina