Global analyses within the small-x resummation collinear approach

...

Underlying QCD characteristics at Small-x

Fred Olness
SMU

Thanks for substantial input from my friends & colleagues

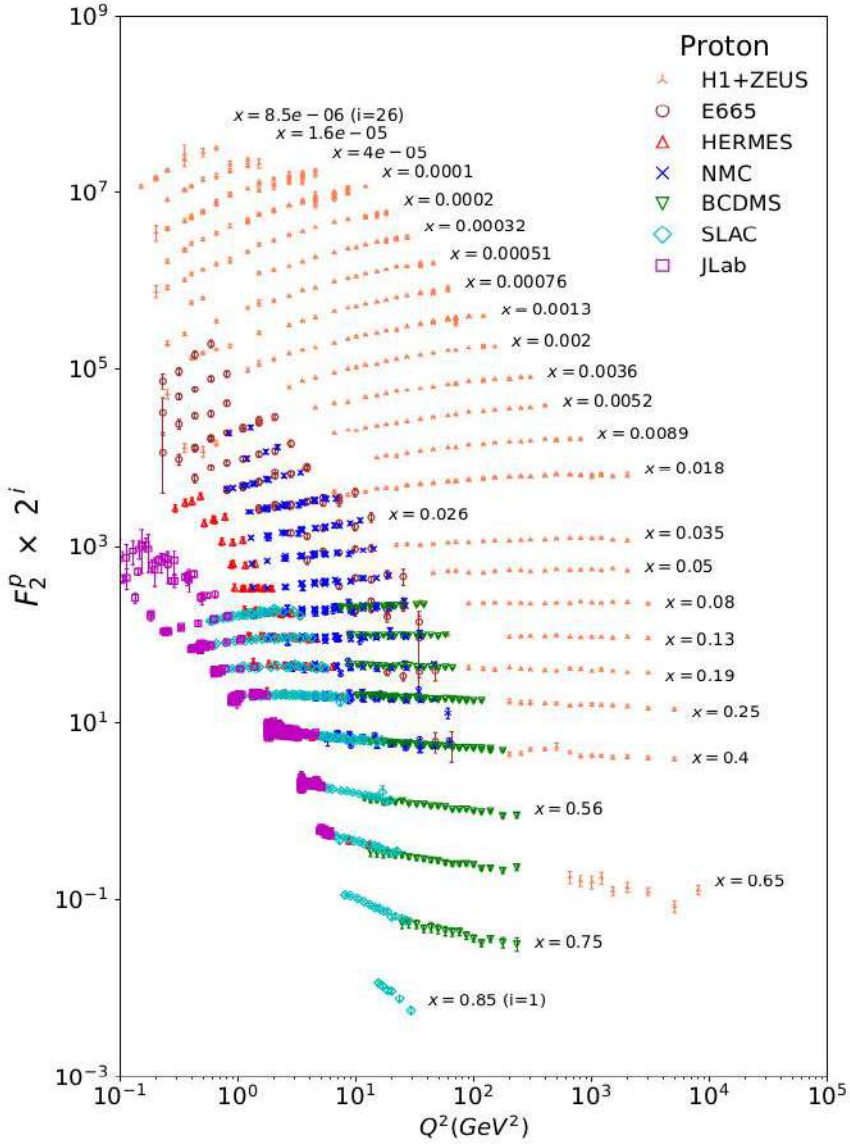
nCTEQ
nuclear parton distribution functions

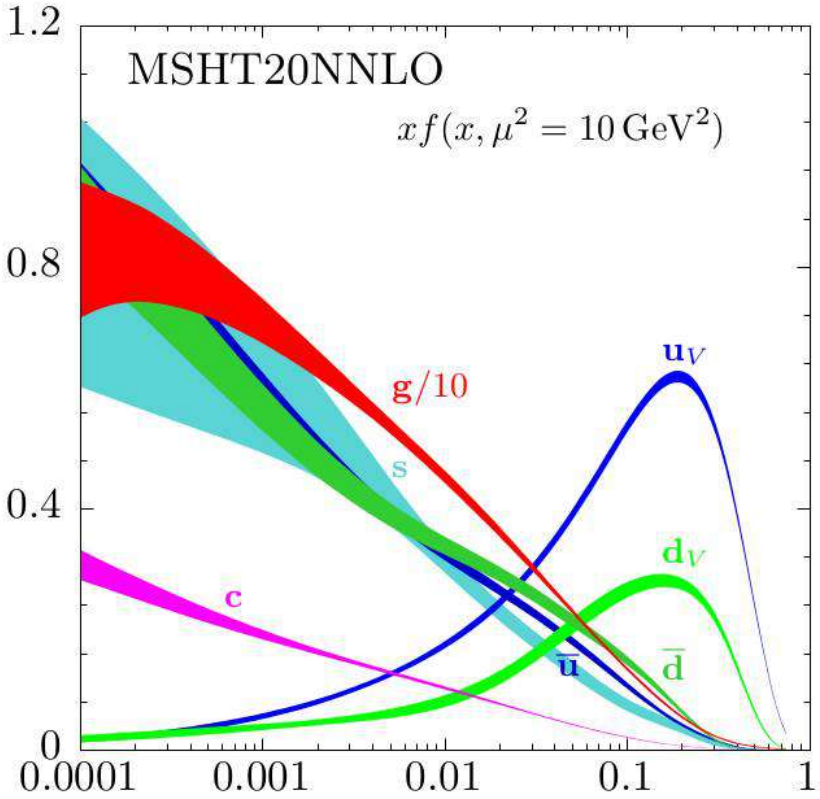
xFitter

CTEQ

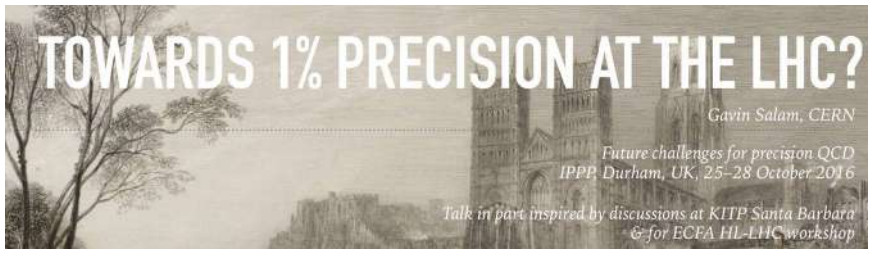
Small-x Physics in the EIC Era
RIKEN BNL Research Center
15-17 December 2021

The incredible success of the QCD Parton Model Framework

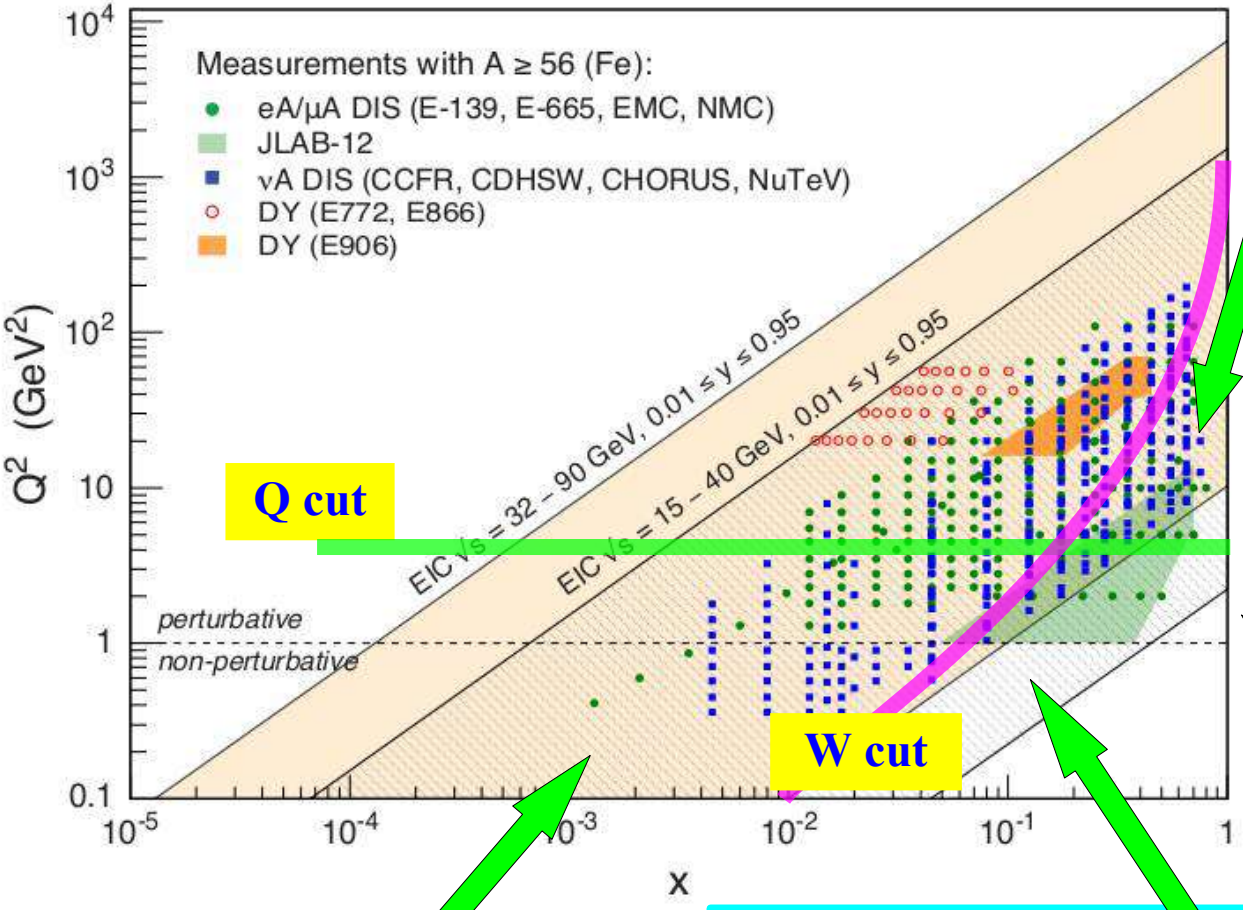




… but, are we only looking under the lamp post



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

Low-x:

Shadowing
Recombination
Resummation
BFKL
Saturation

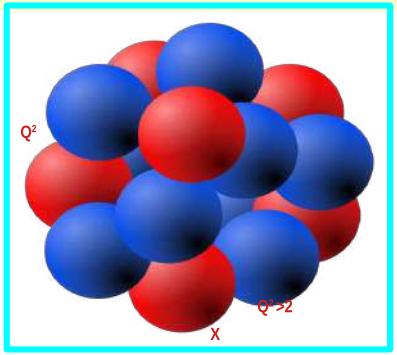
Low-Q^2:

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

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

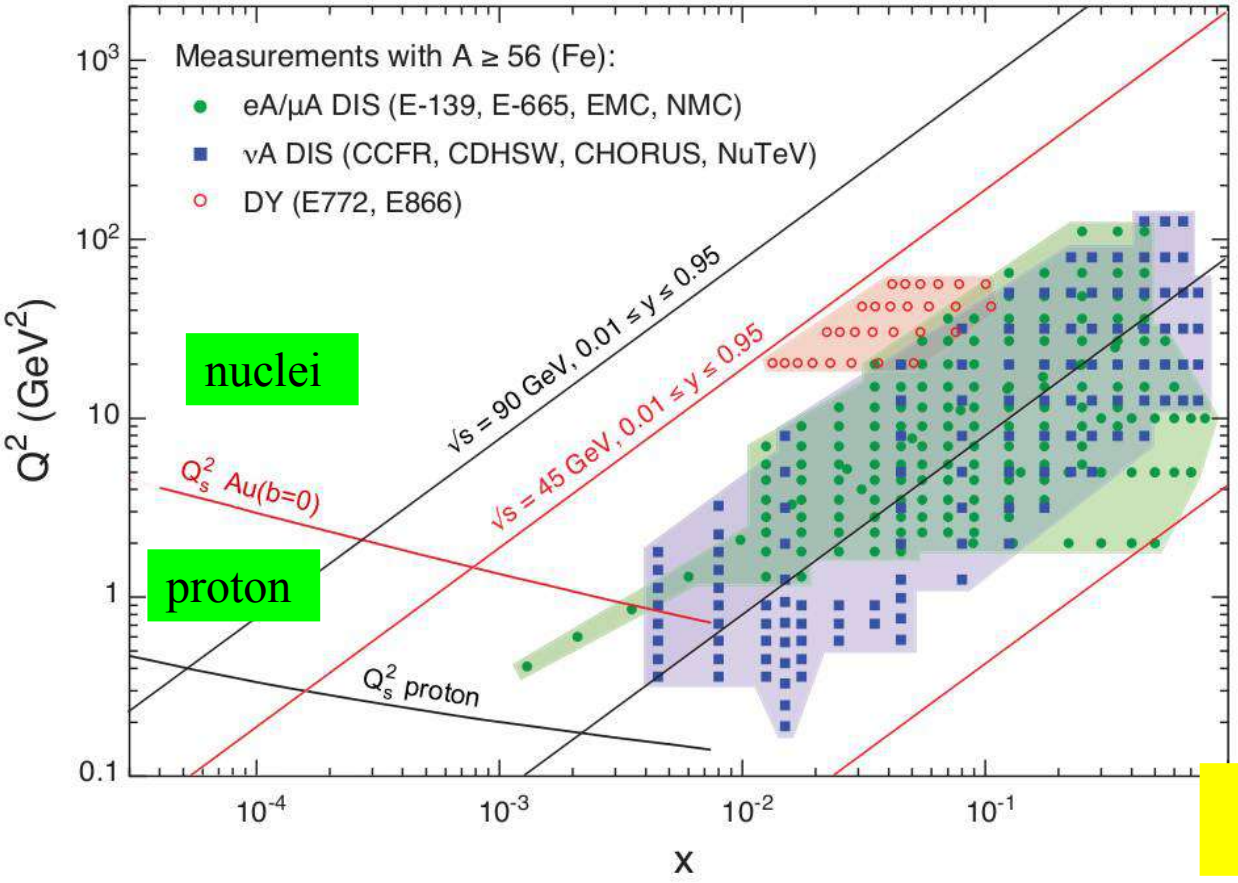


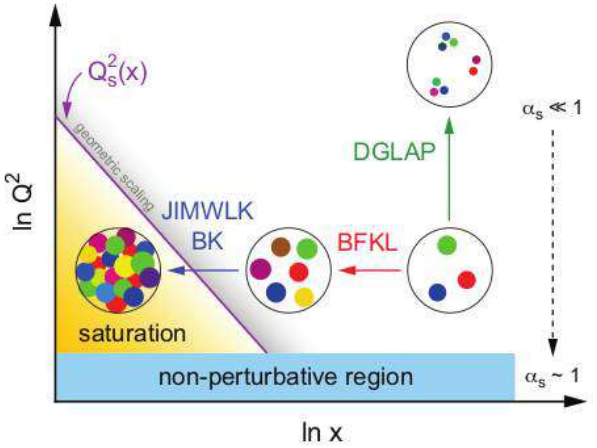
New Phenomena in Corners of Kinematic Plane

Saturation, BFKL, recombination, ...

Can Saturation be Discovered at EIC?

EIC has an unprecedented small-x reach for DIS on large nuclear targets, allowing to seal the discovery of saturation physics and study of its properties:





Yuri Kovchegov (OSU)

MC4EIC: Monte Carlo event simulation for the EIC

start w/ proton

Proton Case

xFitter Analysis w/ HELL Code

Impact of low-x resummation on QCD analysis of HERA data
xFitter Developers' Team: Eur.Phys.J.C 78 (2018) 8, 621

DESY xFitter

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

xFitter

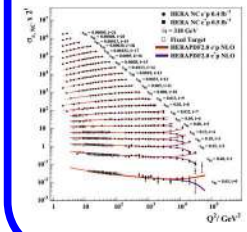
Features & Recent Updates:

- 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



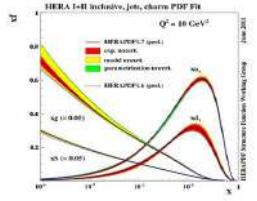
Data: HERA, Tevatron, LHC, fixed target experiments

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

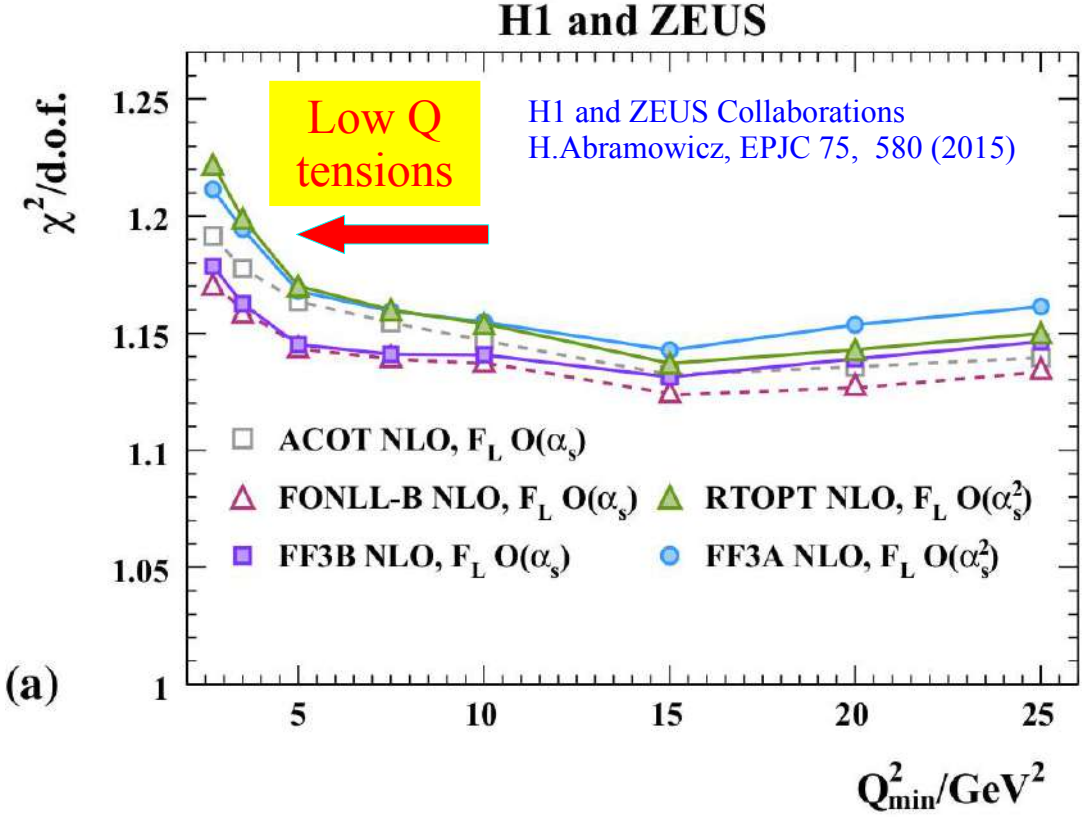
Date	Version
02/2020	2.0.1N Nuclear Daiquiri

xFitter Collaboration Meeting February 2020, DESY

www.xFitter.org

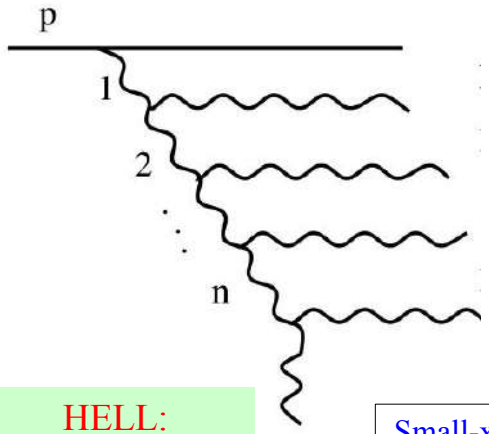
Motivation for Improved Treatment

Small x *(Low Q)*: need to improve fits
NNLO: "fits at NNLO do not improve agreement"



HERAPDF2.0 shows tensions between data and fit, independent of the heavy-flavour scheme used, at low Q^2, i.e. below $Q^2 = 15\,\text{GeV}^2$, and at high Q^2, i.e. above $Q^2 = 150\,\text{GeV}^2$. Comparisons between the behaviour of the fits with different Q^2_{min} values indicate that the NLO theory evolves faster than the data towards lower Q^2 and x. Fits at NNLO do not improve the agreement. HERAPDF2.0 NNLO and NLO have a similar fit quality.

NNLO vs. NLO

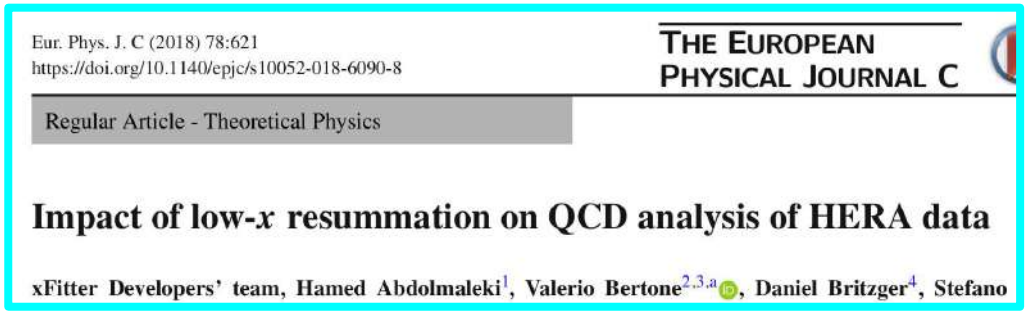


resum logs

$$\alpha_S^n \frac{\ln^k(x)}{x}$$

HELL:
High Energy
Leading Logs

Small-x resummation from HELL
Marco Bonvini, et al.,
Eur.Phys.J.C 76 (2016) 11, 597


Eur. Phys. J. C (2018) 78:621
https://doi.org/10.1140/epjc/s10052-018-6090-8

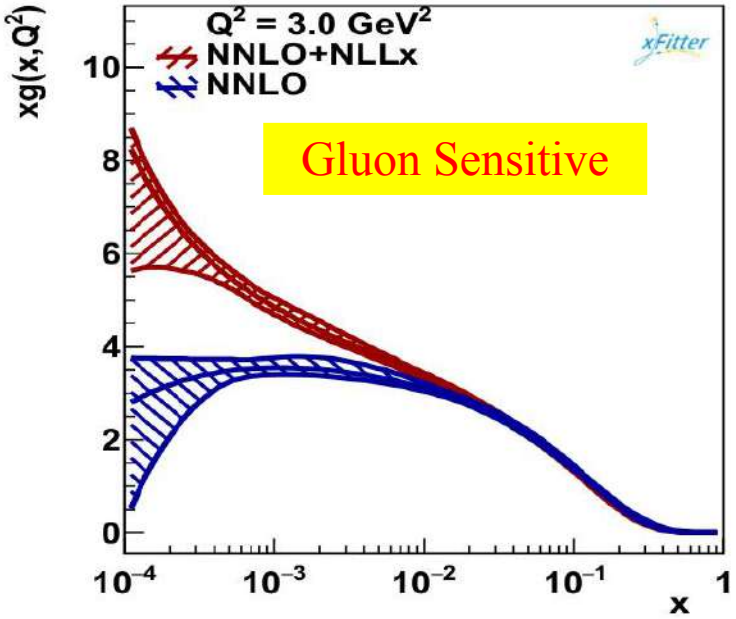
THE EUROPEAN PHYSICAL JOURNAL C

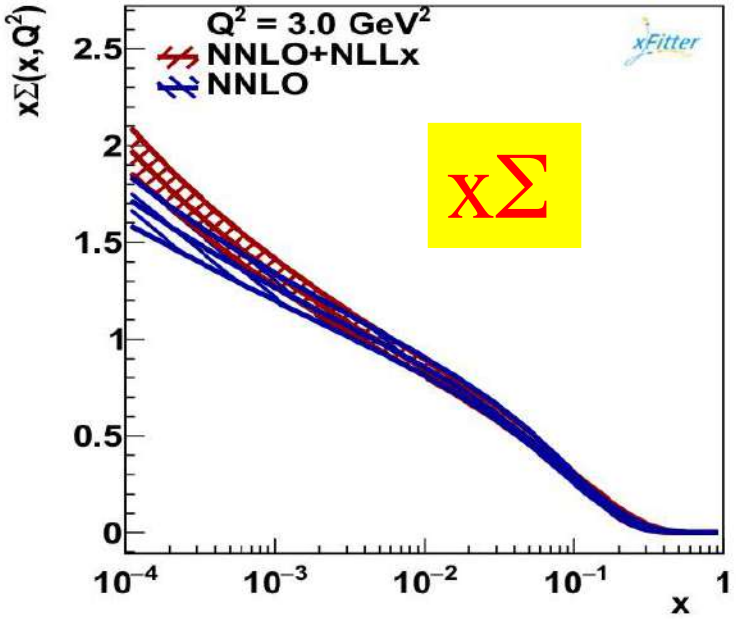
Regular Article - Theoretical Physics

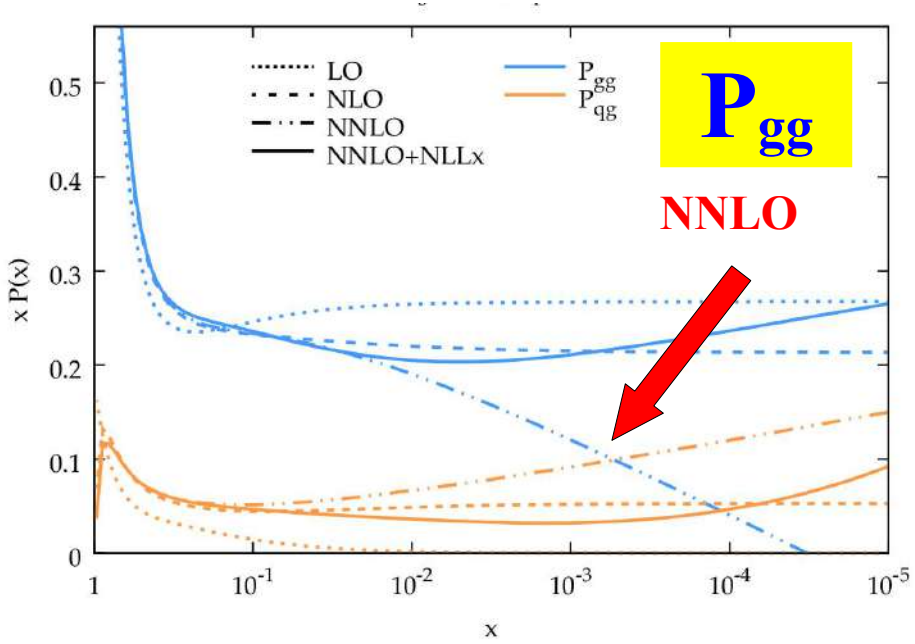
Impact of low-x resummation on QCD analysis of HERA data

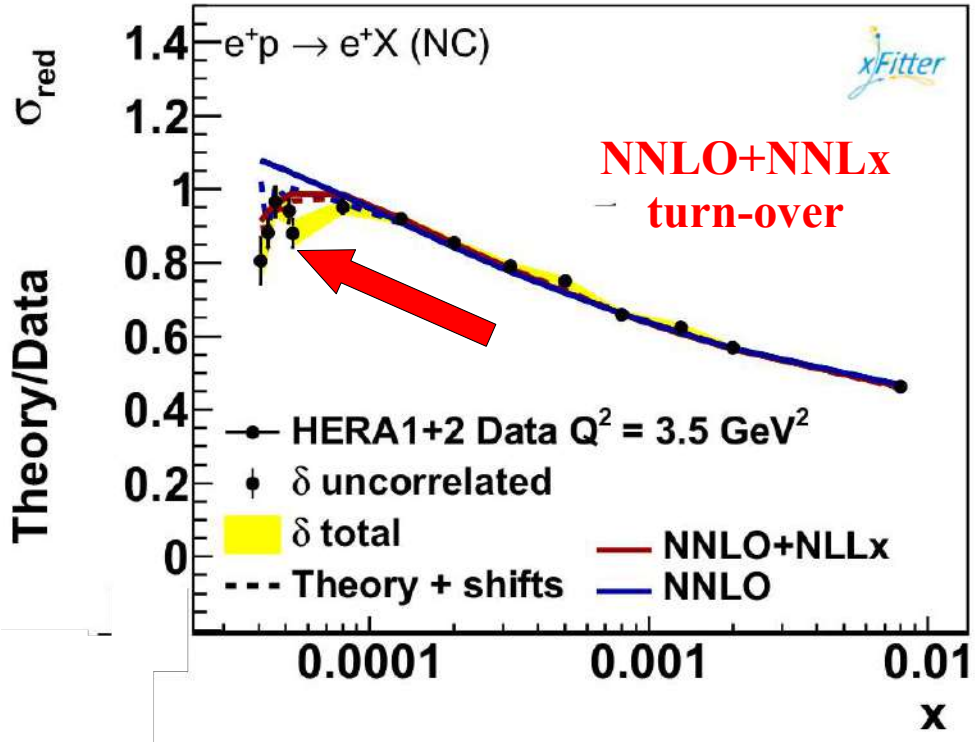
xFitter Developers' team, Hamed Abdolmaleki[1], Valerio Bertone[2,3,a], Daniel Britzger[4], Stefano

xFitter Resummation Study









Impact of low-x resummation on QCD analysis of HERA data
xFitter Developers' Team: Eur.Phys.J.C 78 (2018) 8, 621

F_L is senstive to Gluon and Small-x Treatments

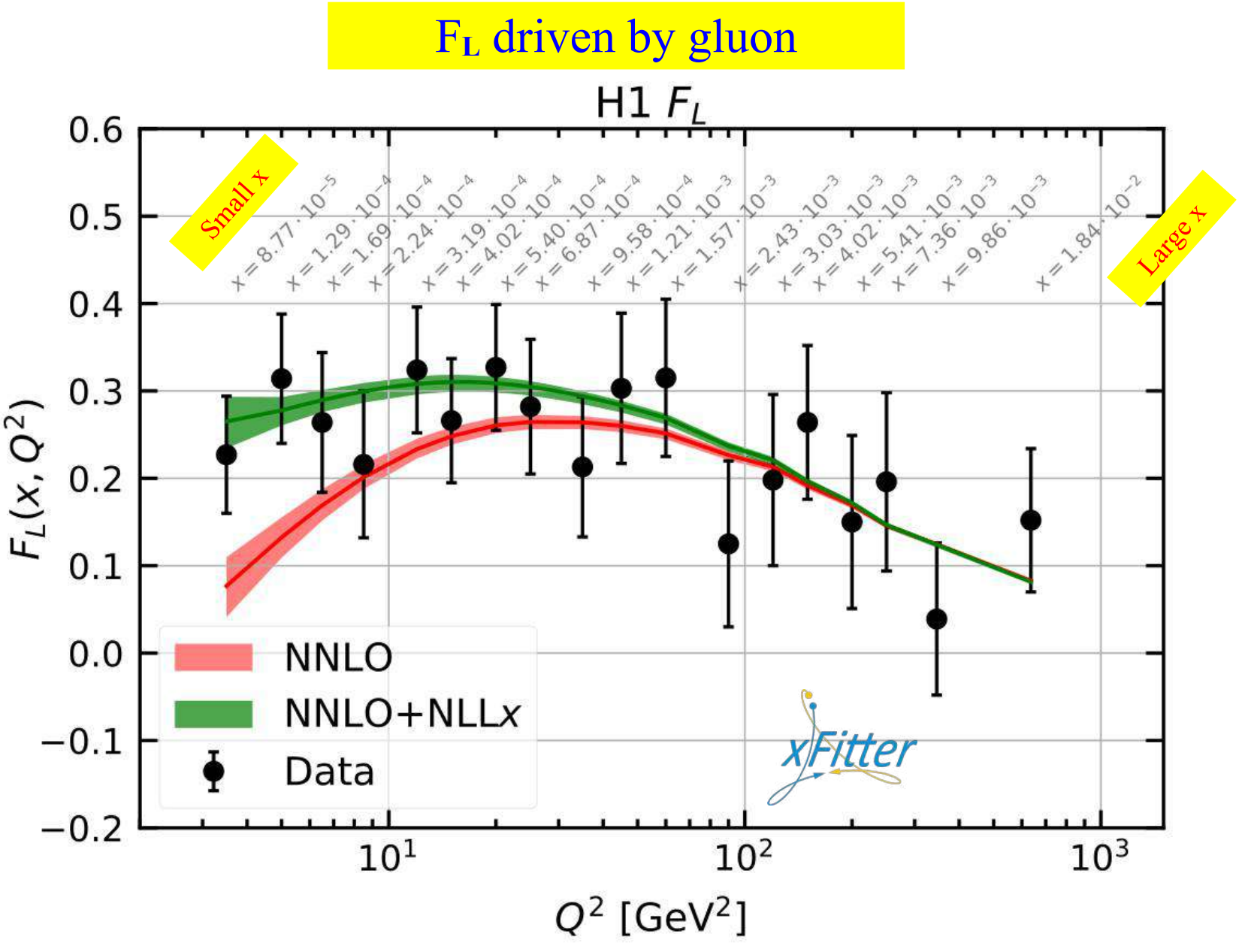


Fig. 8 The H1 extraction of F_L compared to the predictions with and without $\ln(1/x)$ resummation

Proton Case

CT18 & Extensions

BFKL & Saturation

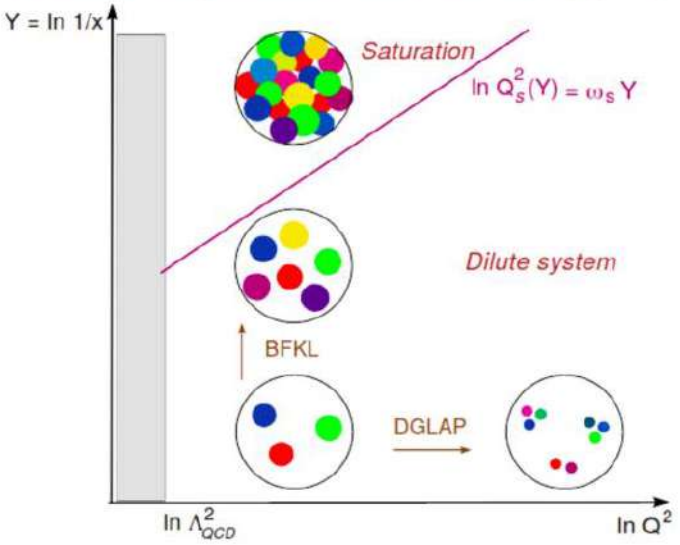
Fitting Challenges at Small x

Non-optimal fit in small x region *(large $W^2 \sim Q^2/x$)*

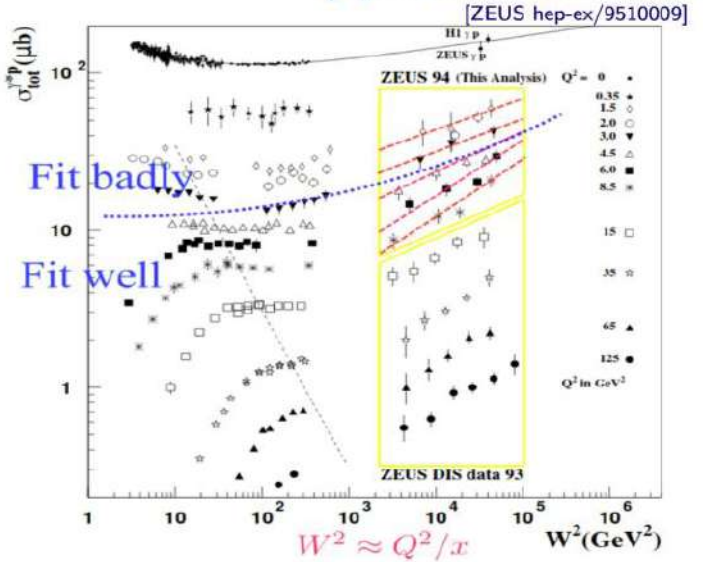
PDFs at small x: resummation or saturation?

Keping Xie
(Pittsburgh) 08 Dec 2021
Snowmass'2021 EF06

QCD dynamics vs (Q, x)



$\gamma^* p$ total cross sectios



- Red lines "fit" $\sigma_{tot}^{\gamma^* p}$ for a fixed Q
- The slope $\sigma \sim 1/x$ changes as a function of (x, Q), predicting the rapid growth of PDFs at $x \to 0$
- For points below the blue line, expectations are consistent with DGLAP. Above, we see deviations.
- The boundary has not been located precisely.

NNLO constraints on proton PDFs from the SeaQuest and STAR experiments and other developments in the CTEQ-TEA global analysis: Marco Guzzi, et al., DIS2021 • e-Print: 2108.06596 [hep-ph]

Impact on PDFs

Study small-x region with BOTH: Saturation & BFKL

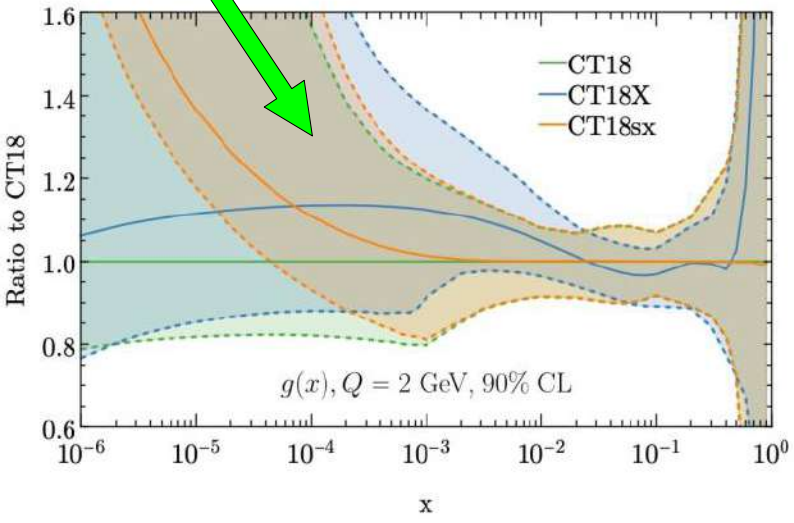
How to treat the low-Q and low-x data?

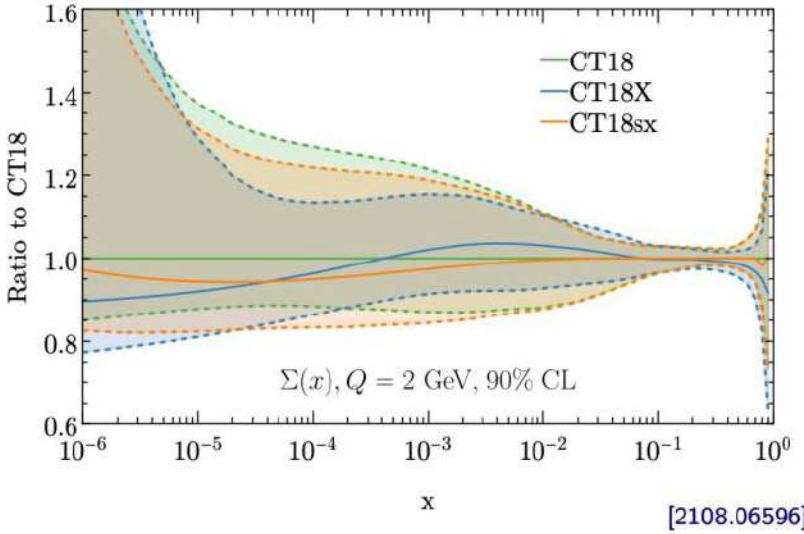
- NNPDF/xFitter: BFKL to resum the small-x log's [1710.05935, 1802.00064]
- CT: x-dependent scale, motivated by saturation effect [Golec-Biernat & Wusthoff, PRD1998]

model saturation

$$\mu^2_{\mathrm{DIS},x} = a_1\left(Q^2 + a_2/x^{a_3}\right)$$

Big g(x) impact!!





[2108.06596]

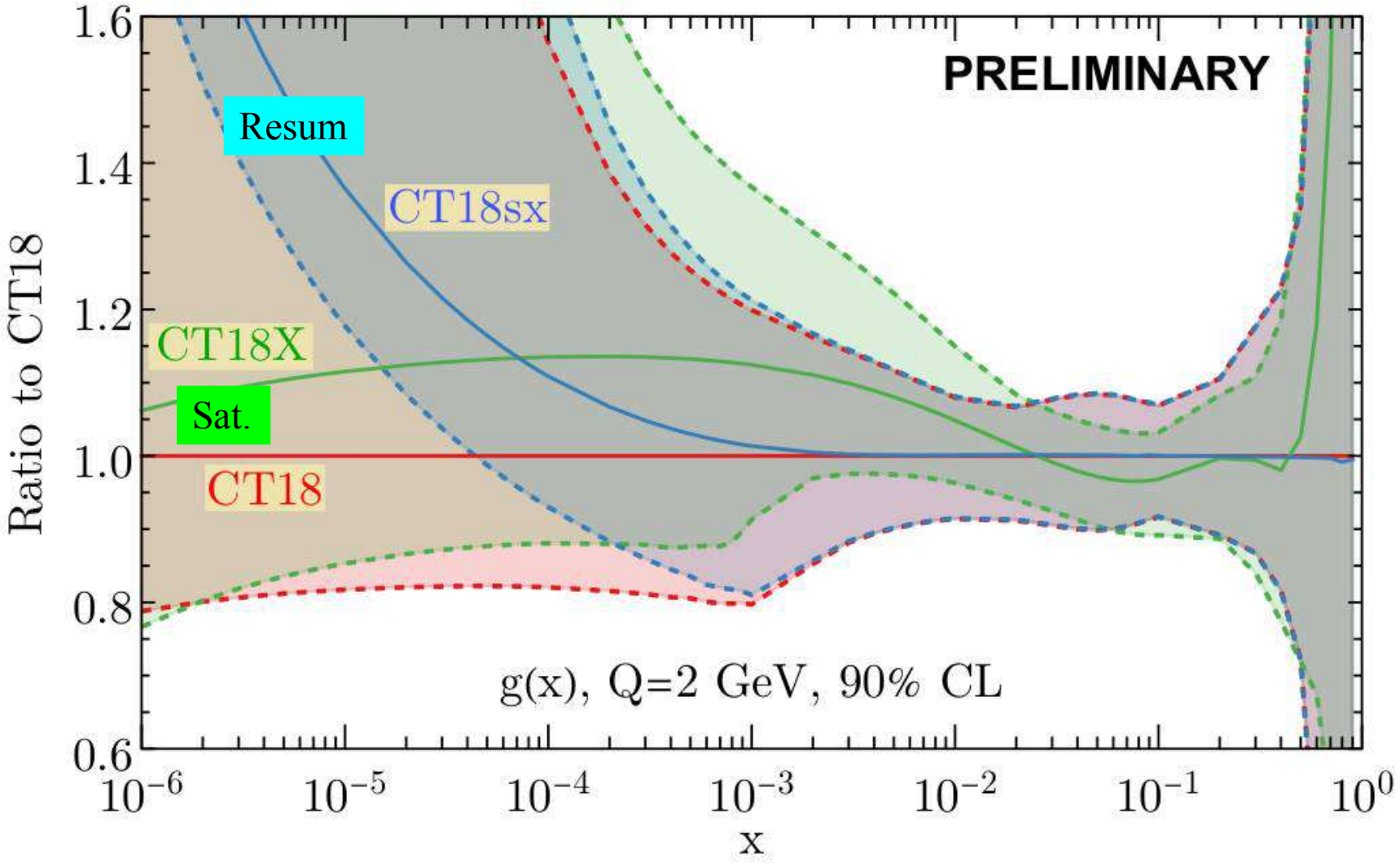
- We obtain the same level of agreement between data and theory
- Both approaches enhance (reduce) the gluon (singlet) PDF at small x and Q.
- At a higher Q, the small-x effect disappear.
- Within the currently accessible experimental region, the PDFs and predicted cross sections agree well between the two approaches.
- Higher-twist effects can also play a similar role [1707.05992].

Gluon is sensitive to small-x treatment

CT18x: Saturation inspired μ modification
CT18sx: w/ HELL small-x resummation code

Saturation inspired x-dependent

$$\mu^2 = a_1\left(Q^2 + \frac{a_2}{x^{a_3}}\right)$$



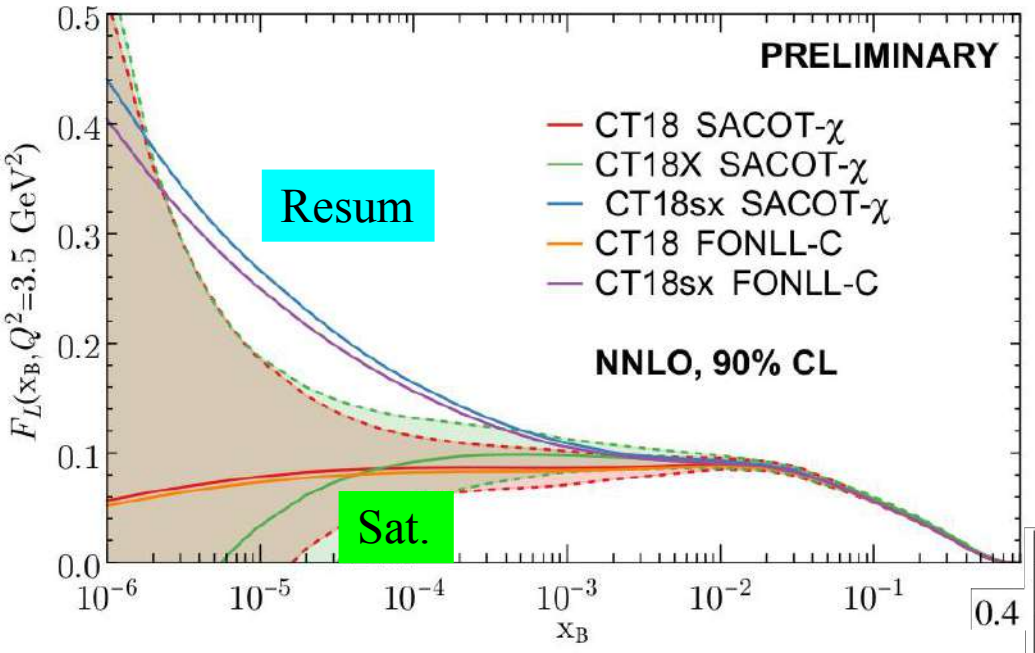
BFKL & Saturation differ at very small x

Small-x resummation from HELL
Marco Bonvini, et al., Eur.Phys.J.C 76 (2016) 11, 597

CT Collaboration: 2108.06596 [hep-ph]

F_L is senstive to Gluon and Small-x Treatments

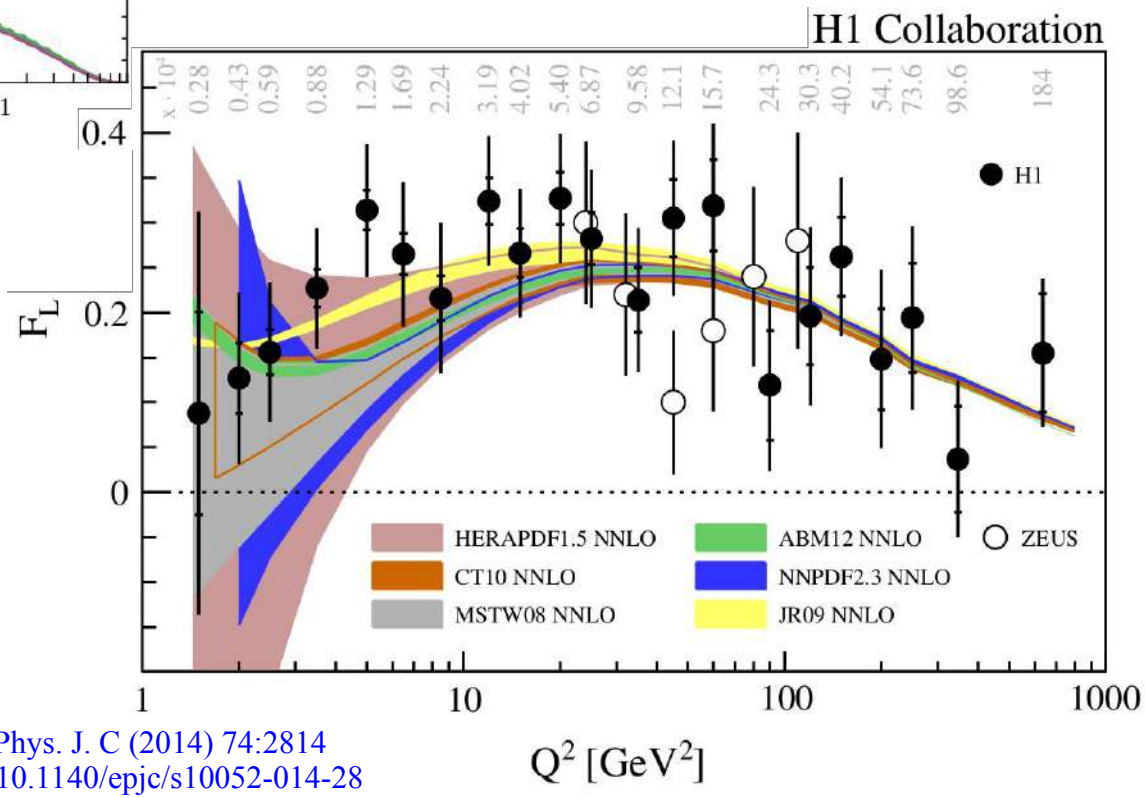
Still, large uncertainty at small x *(low Q^2)*



CT Collaboration: 2108.06596 [hep-ph]

Saturation & Resummation:

again
different behavior
at very small x



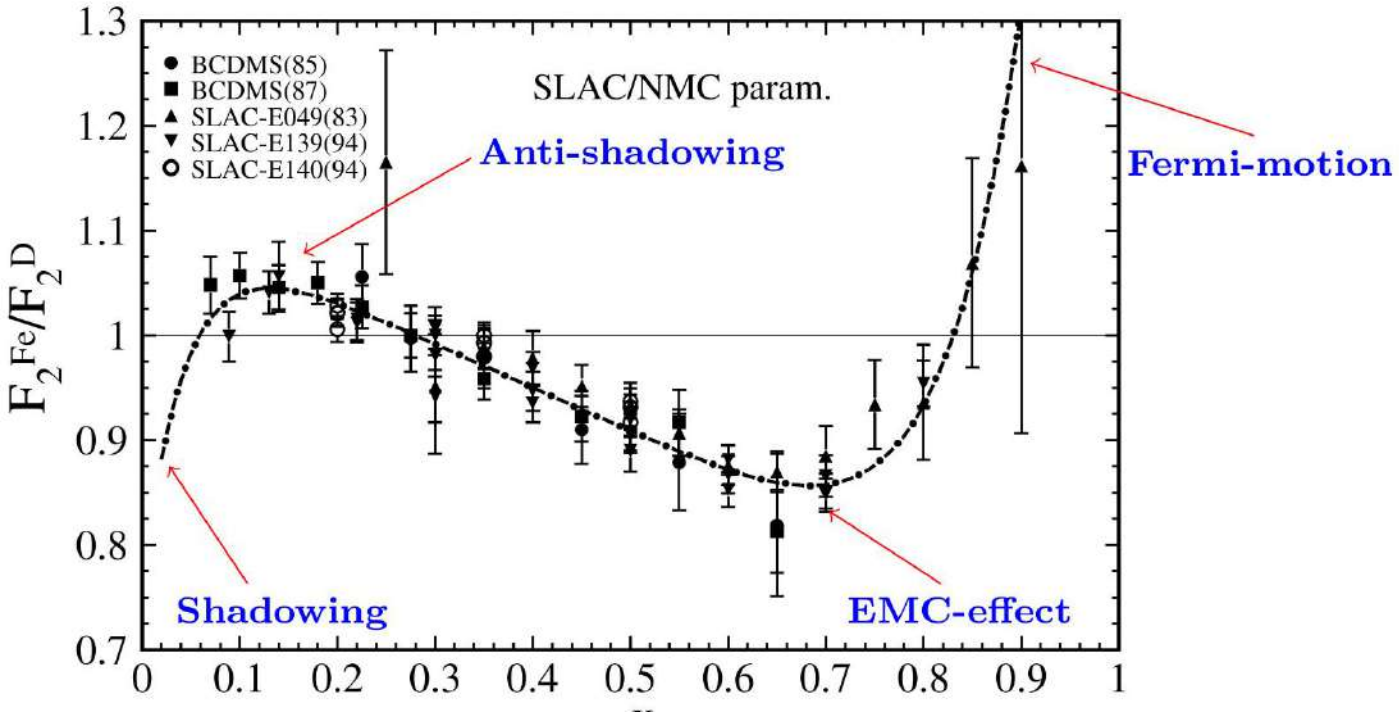
F_L Challenge:

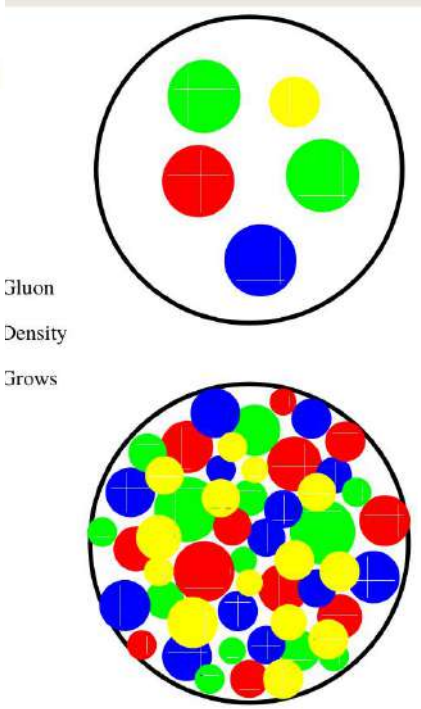
Large Uncertainties at small x

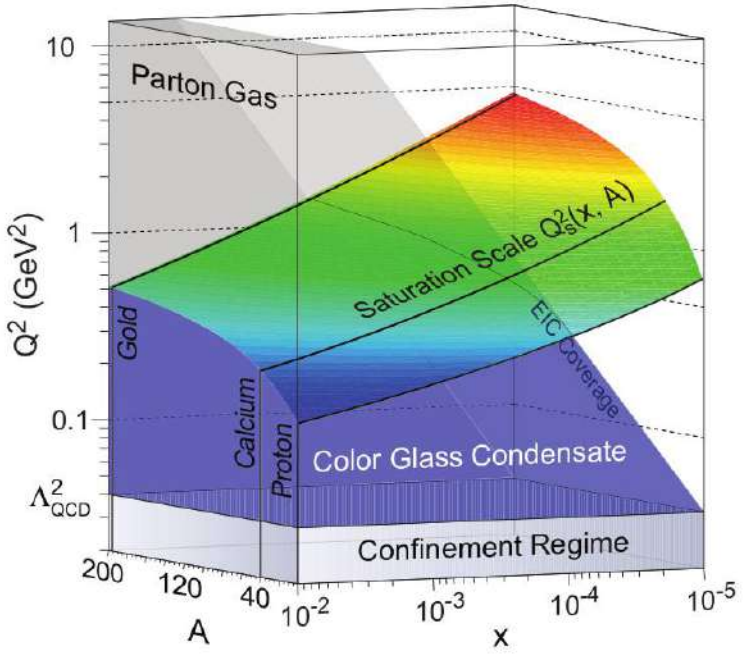
Eur. Phys. J. C (2014) 74:2814
DOI 10.1140/epjc/s10052-014-28

Nuclear Effects

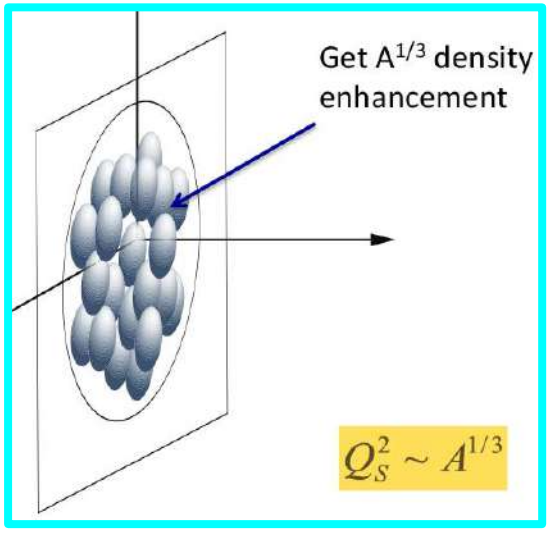
Nuclear Modifications: Expected $A^{1/3}$ Enhancement







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



Review: Edmond Iancu & Raju Venugopalan: arXiv:0303204

focus on gluon

Gluon PDF

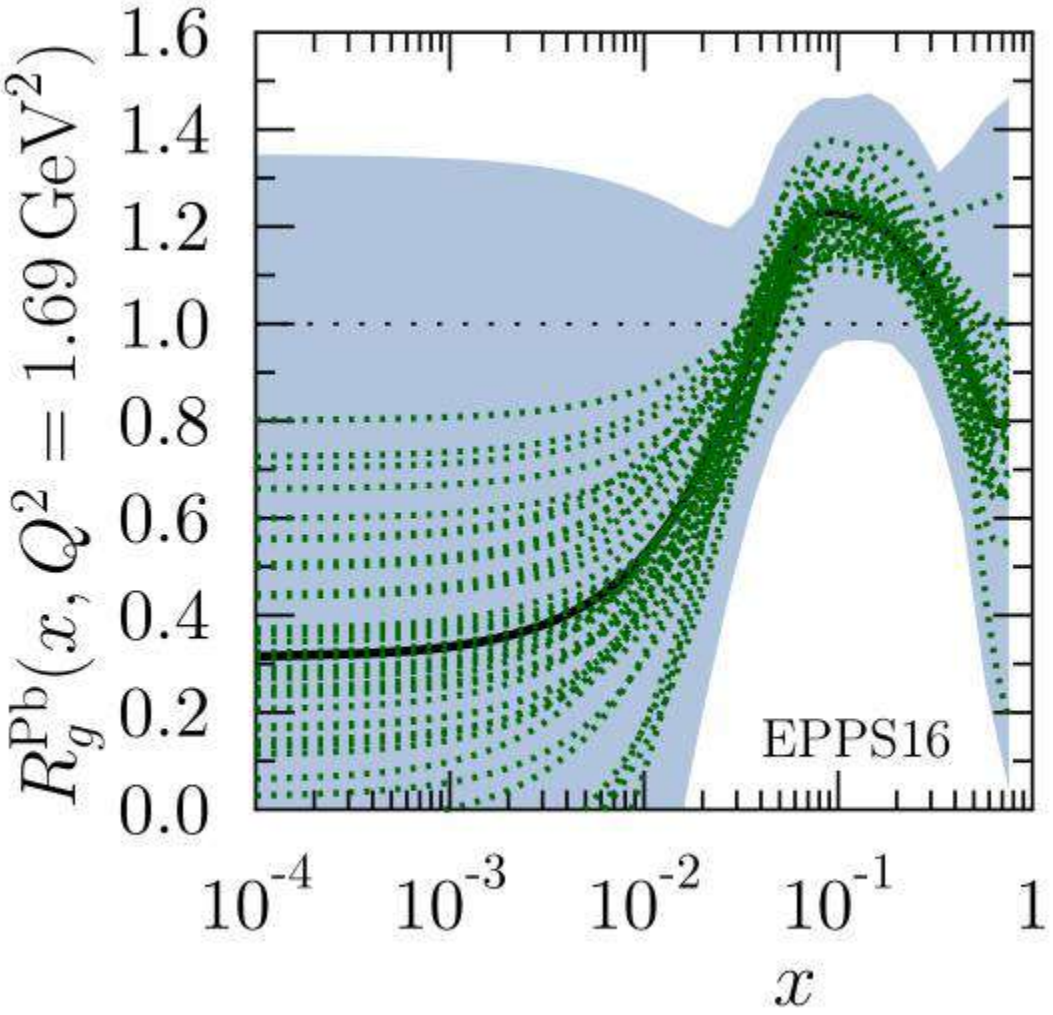
1) J/Psi Production

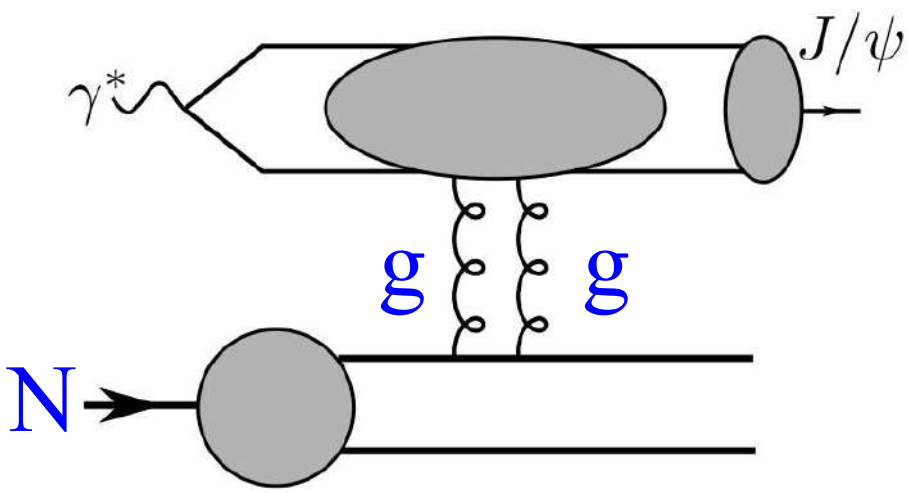
&

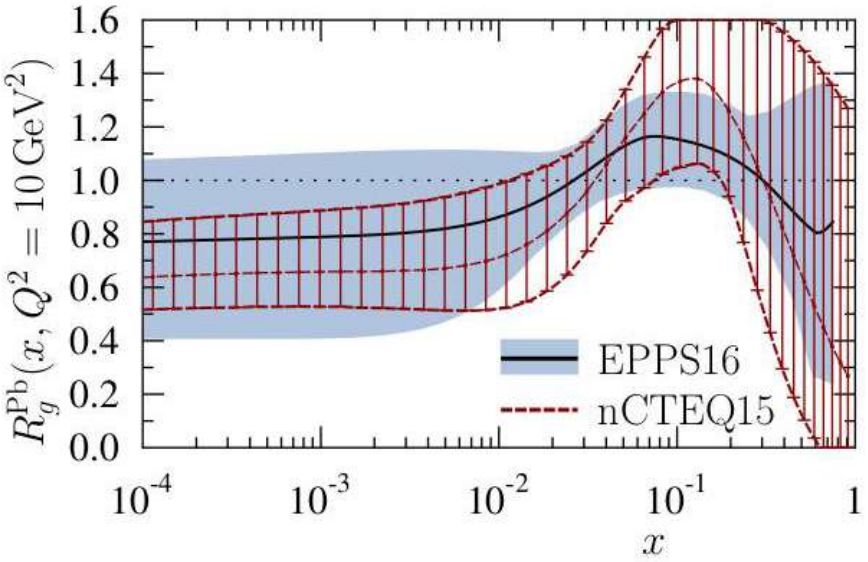
2) Semi-Inclusive Hadron Production

Heavy FlavorProduction: Effective Probe of Gluon PDF

Nuclear Gluon PDF
Large uncertainties
Strong shadowing at small x







Caution: EPPS16 errors are probably more realistic at small x than nCTEQ15

nNNPDF provide complementary approach

Heavy FlavorProduction: Effective Probe of Gluon PDF

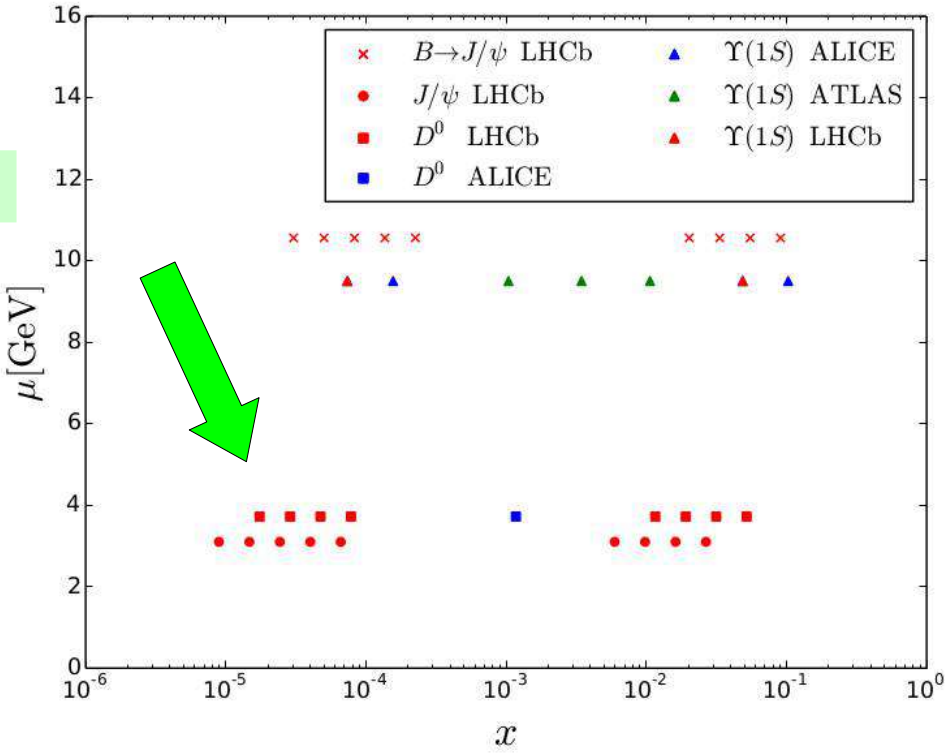
Kusina
Lansberg
Schienbein
Shao

Small-x gluon from pPb LHC heavy-flavour data

[PRL 121, 052004 (2018)]

	D^0	J/ψ	$B \to J/\psi$	$\Upsilon(1S)$
μ_0	$\sqrt{4M_{D^0}^2 + P_{T,D^0}^2}$	$\sqrt{M_{J/\psi}^2 + P_{T,J/\psi}^2}$	$\sqrt{4M_B^2 + \left(\frac{M_B}{M_{J/\psi}} P_{T,J/\psi}\right)^2}$	$\sqrt{M_{\Upsilon(1S)}^2 + P_{T,\Upsilon(1S)}^2}$
$p+p$ *data*	LHCb [1]	LHCb [2,3]	LHCb [2,3]	ALICE [4], ATLAS [5], CMS [6], LHCb [7,8]
R_{pPb} data	ALICE [9], LHCb [15]	ALICE [10,11], LHCb [16,12]	LHCb [12]	ALICE [13], ATLAS [14], LHCb [17]

very small x



A. Kusina (INP PAN, Krakow)
Aussois Quarkonium & QCD meeting
joined session with GDR-QCD WG1
Aussois, 23 June 2021

34 / 40

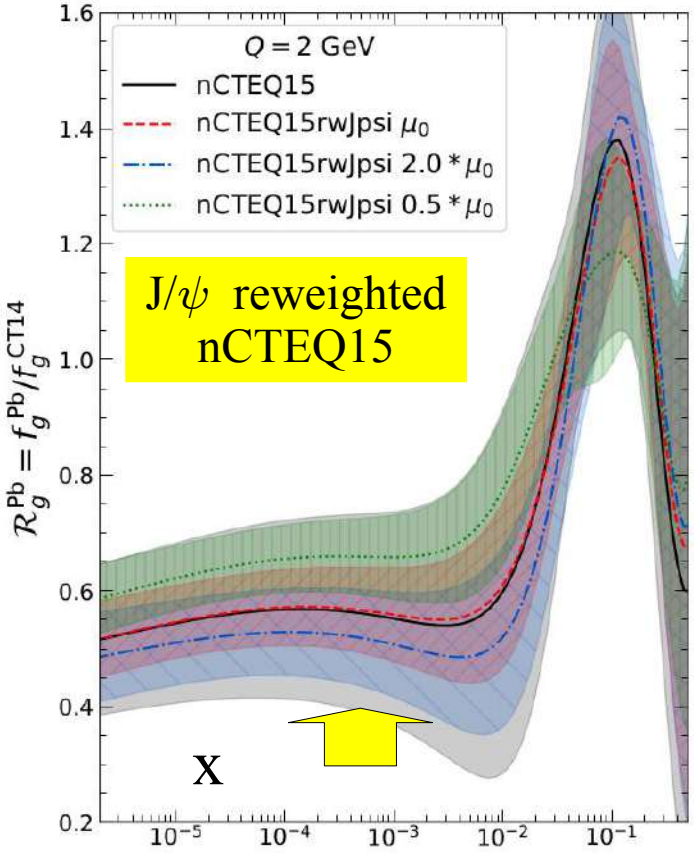
A. Kusina (INP PAN, Krakow)
Aussois Quarkonium & QCD meeting
joined session with GDR-QCD WG1
Aussois, 23 June 2021

Expected nuclear effects on heavy quark(onium) production in pA collisions

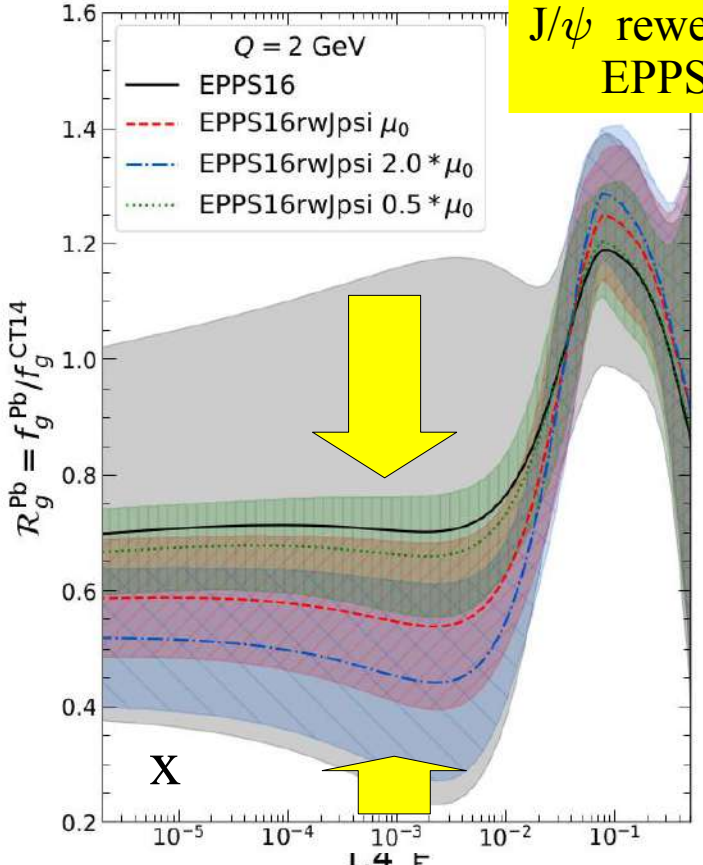
- Nuclear modification of PDFs: initial-state effect
- Energy loss (w.r.t. pp collisions): initial-state or final-state effect
- Break up of the quarkonium in the nuclear matter: final-state effect
- Break up by comoving particles: final-state effect
- Colour filtering of intrinsic QQ pairs: initial-state effect
- ...

- We assume leading twist factorization is valid – ONLY modifications of PDFs are present → "shadowing-only" hypothesis.

Heavy-Flavor Production Data at the LHC:

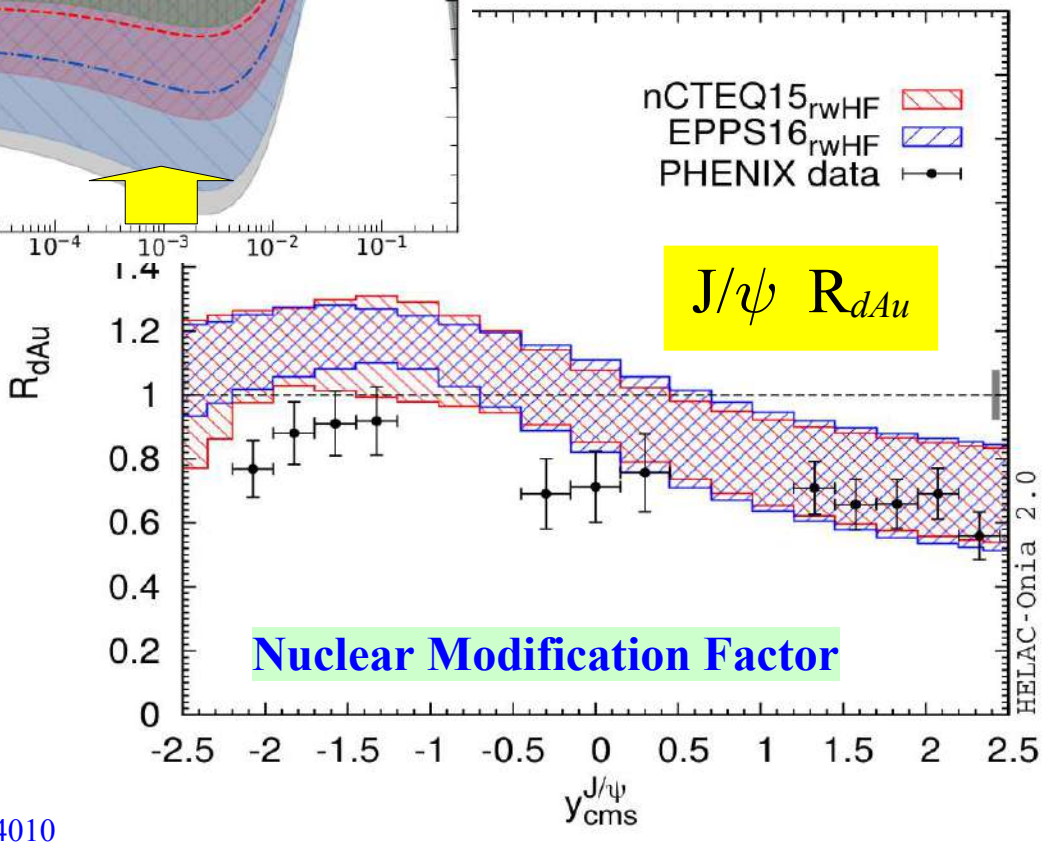


J/ψ reweighted nCTEQ15



J/ψ reweighted EPPS16

Nuclear Correction Ratio



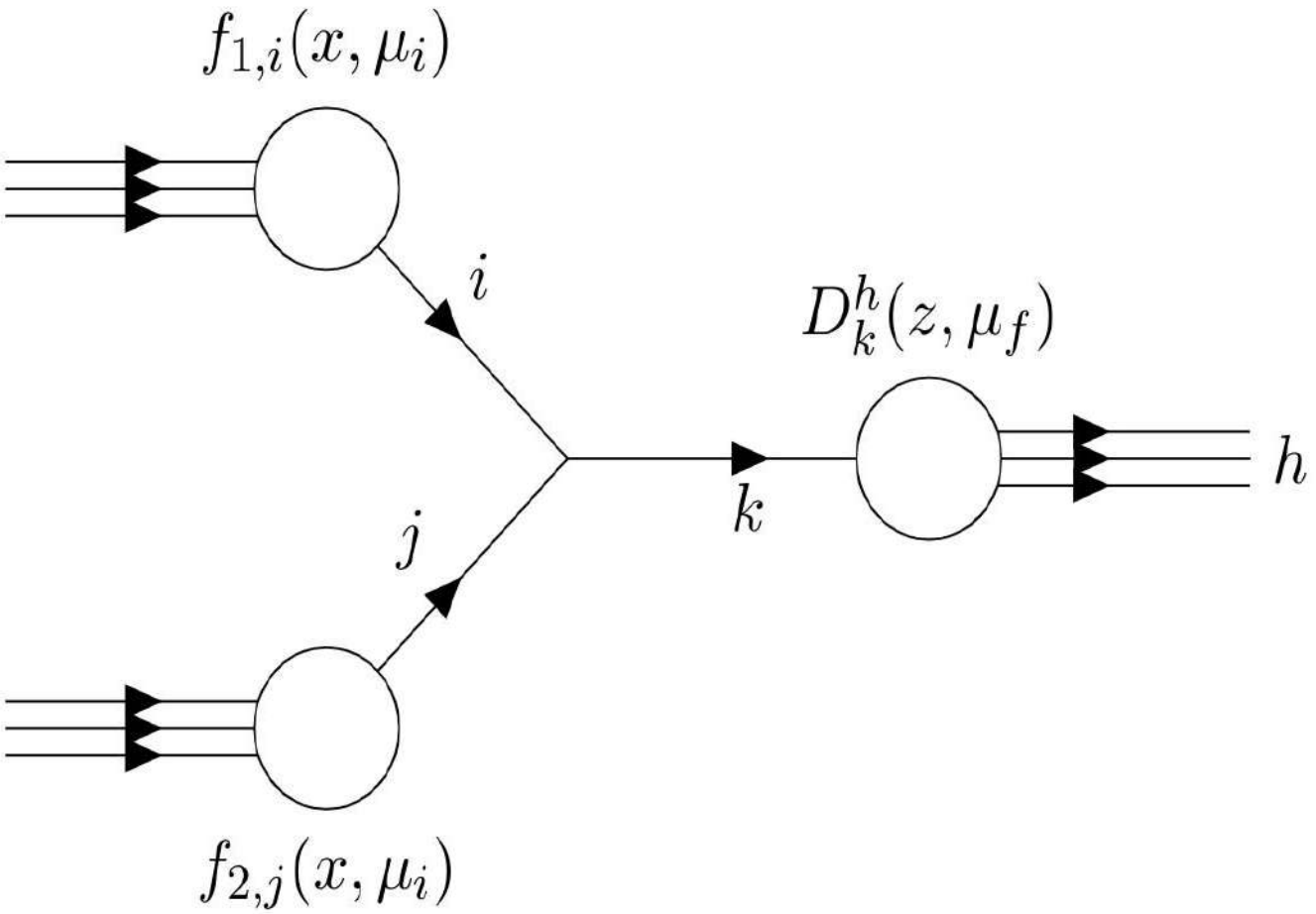
J/ψ R_{dAu}

Nuclear Modification Factor

Heavy Flavor Data provides significant constraints on nuclear gluon

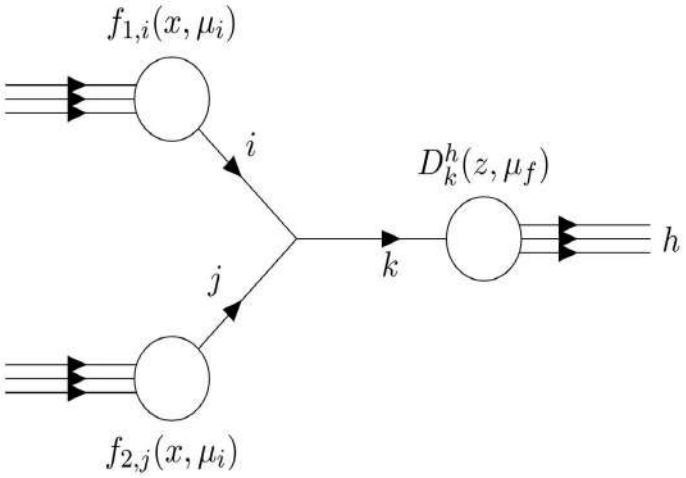
Reweighted nuclear PDFs using heavy-flavor production data at the LHC
A. Kusina, J.P. Lansberg, I. Schienbein, H.-S. Shao. PRD104 (2021) 1, 014010

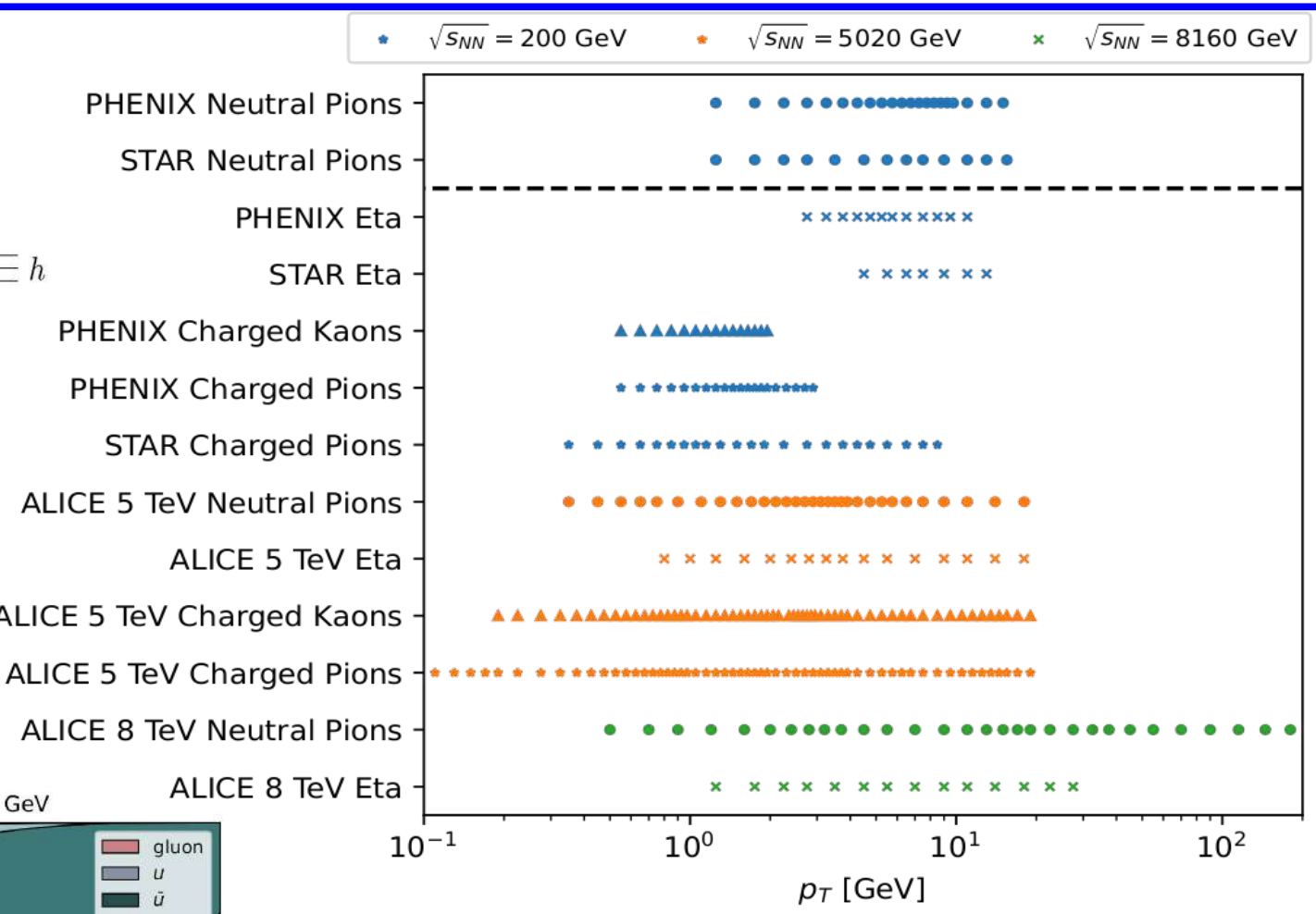
Semi-Inclusive Hadron Production

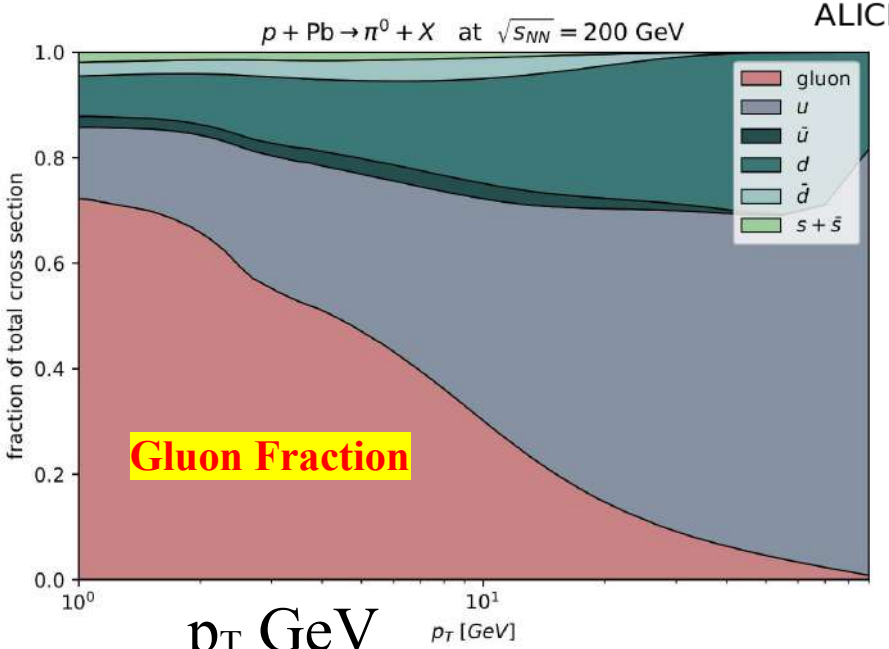


Impact of inclusive hadron production data on nuclear gluon PDFs
nCTEQ: P. Duwentäster, et al., PRD104 (2021) 094005.

Semi-Inclusive Hadron (SIH) Production:







Gluon Fraction

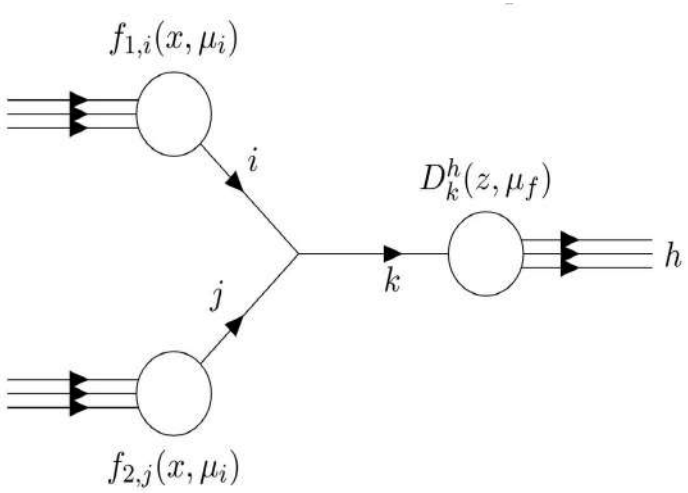
p_T GeV

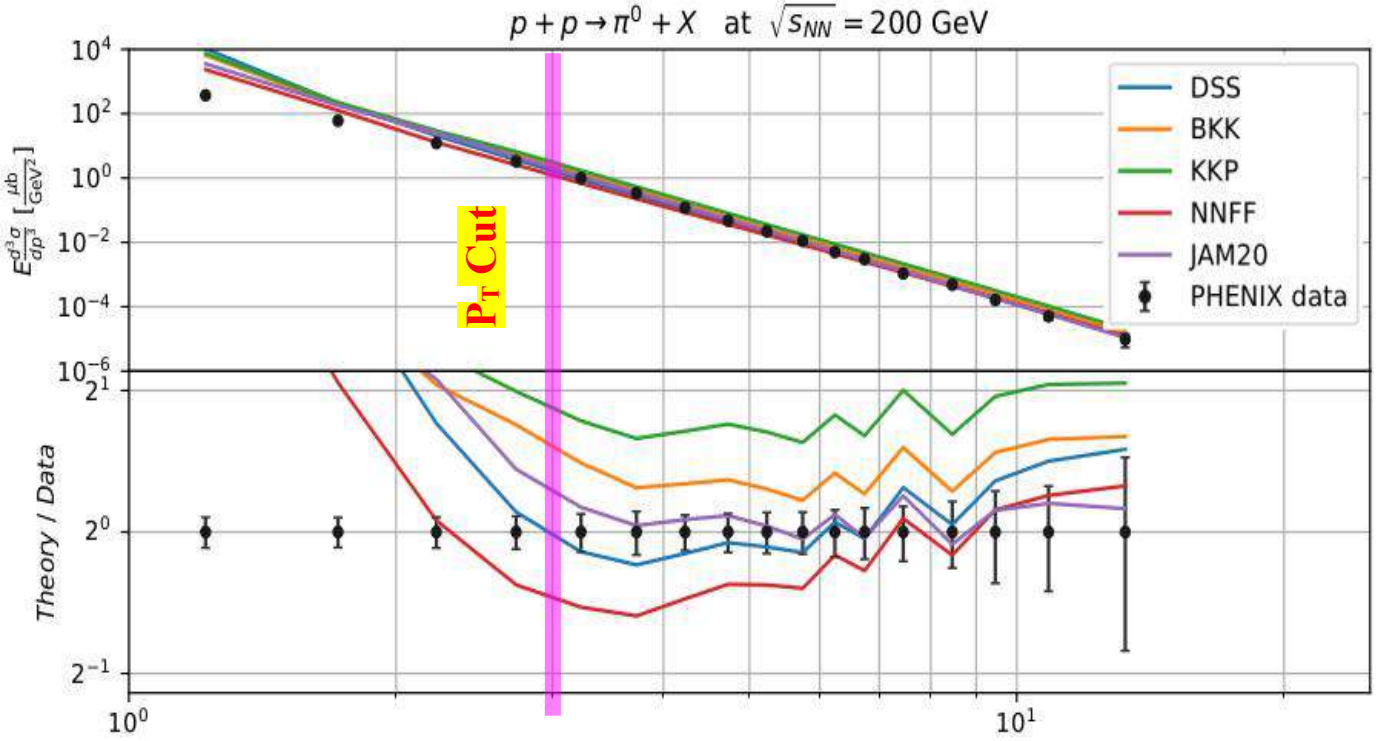
Low P_T ⇒ Large gluon contribution

Cut on P_T to avoid non-perturbative regions

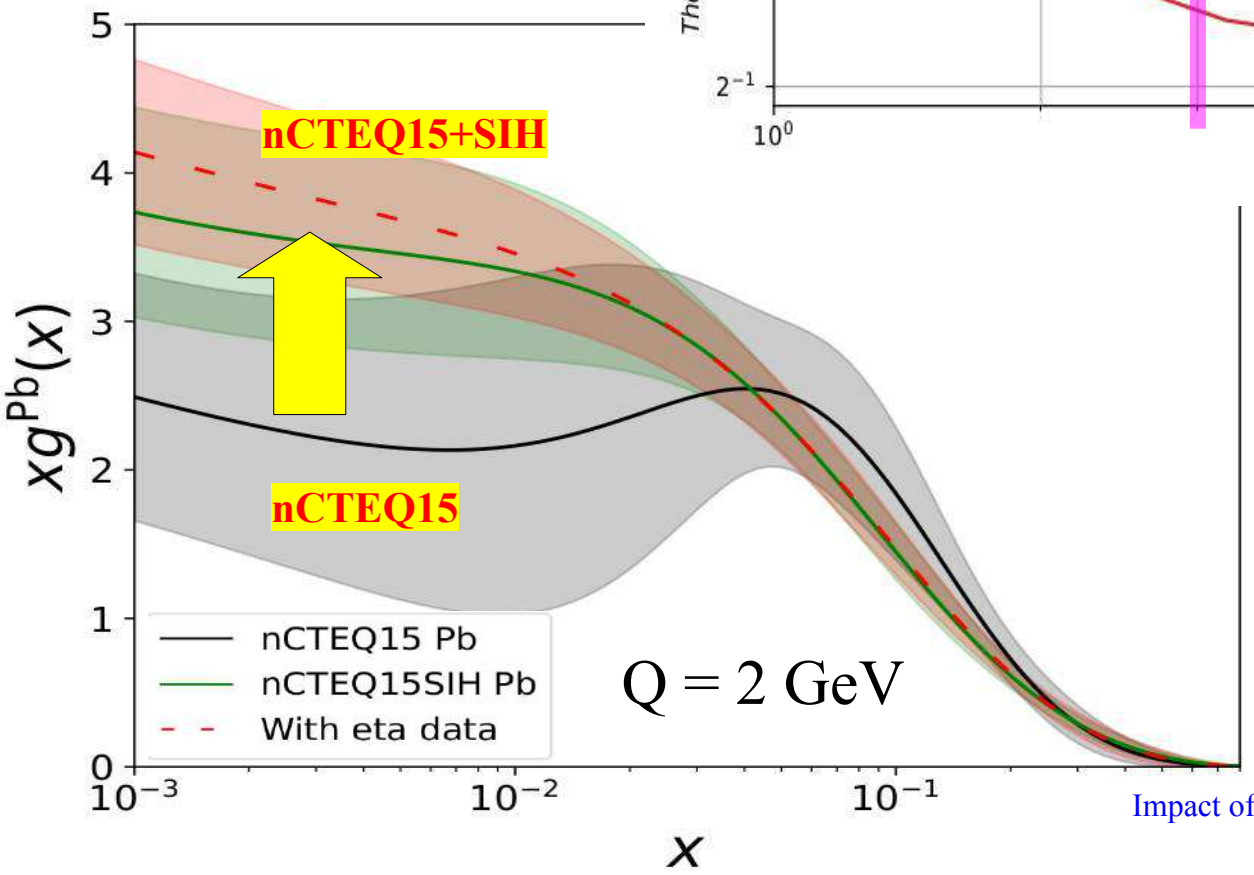
Impact of inclusive hadron production data on nuclear gluon PDFs
nCTEQ: P. Duwentäster, et al., PRD104 (2021) 094005.

New Phenomena in Corners of Kinematic Plane





Cut on P_T to avoid non-perturbative regions

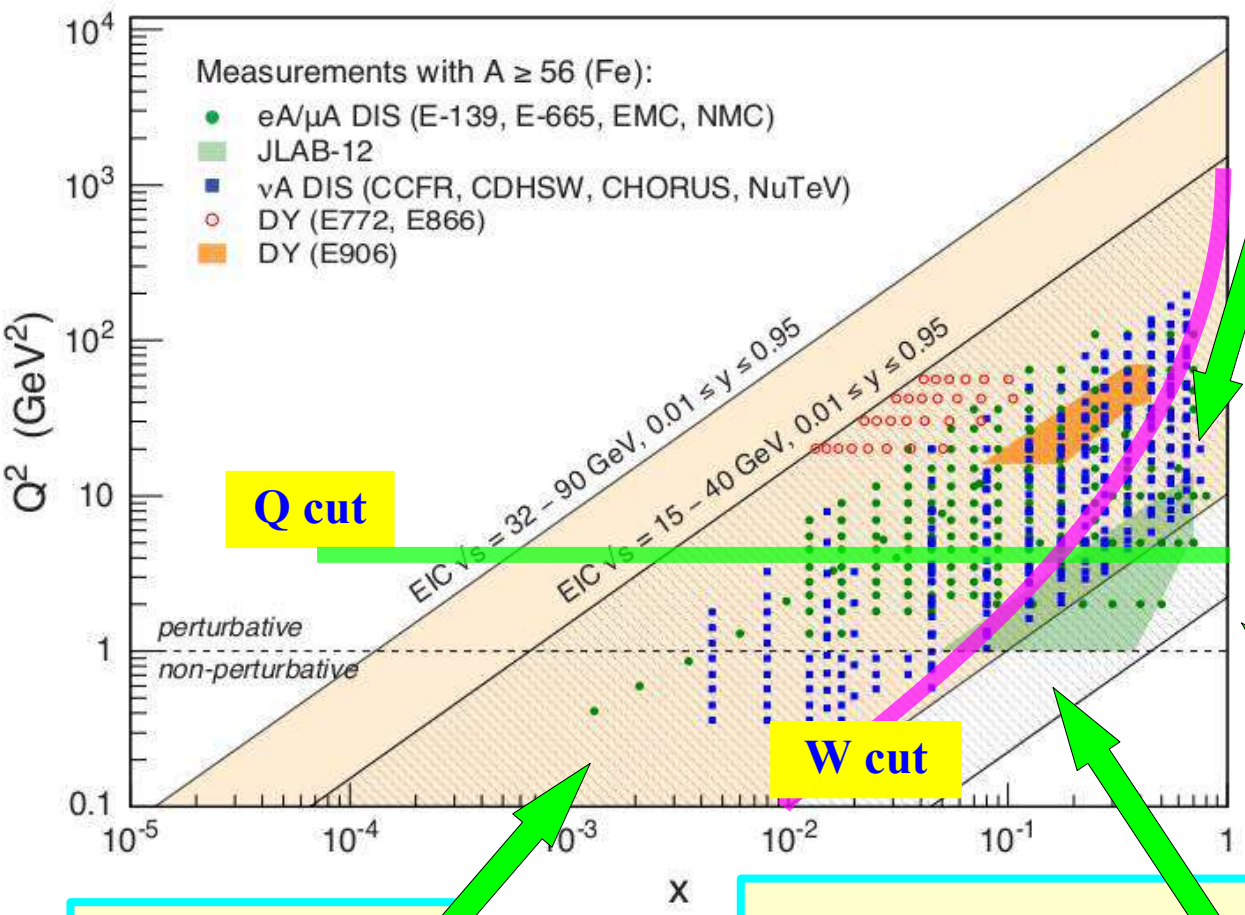


Semi-Inclusive Hadron production also helps

Could we go lower in P_T?

Impact of inclusive hadron production data on nuclear gluon PDFs
nCTEQ: P. Duwentäster, et al., PRD104 (2021) 094005.

CONCLUSIONS



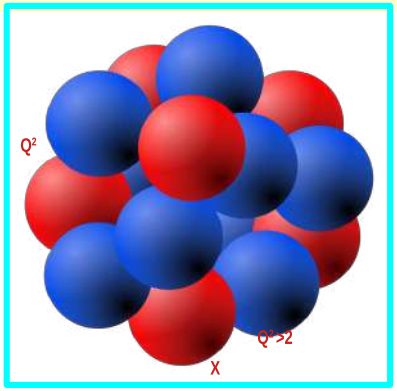
High-x:

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

JLab Data @ Hi-X Low-Q²
extend nCTEQ framework for this region
& prepare for EIC



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

… combine with complementary approaches (3D-PDFs, Lattice QCD) ⇒ **"solve" QCD**