MuIC Phenomenology:

Exploring QCD in extreme kinematic regions

Fred Olness
SMU

nCTEQ
nuclear parton distribution functions

nuclear CTEQ

xFitter

C T E Q

Coordinated Theoretical-Experimental Project on QCD

Thanks for substantial input from my friends & colleagues

CFNS Workshop
5 April 2023

… some history

1998

Fermi National Accelerator Laboratory

FERMILAB-Conf-98/063

Workshop on Physics at the First Muon Collider and Front-End of a Muon Collider: A Brief Summary

S. Geer

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

February 1998

Published Proceedings of the *4th International Conference on Physics Potential and Development of Muon Colliders*, San Francisco, California, December 10-12, 1997

1999

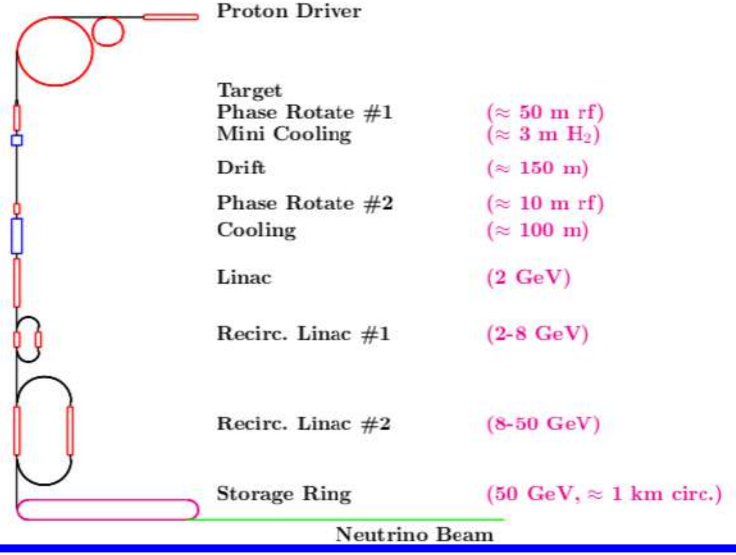
Expression of Interest for R&D towards A Neutrino Factory Based on a Storage Ring and a Muon Collider

Submitted to the National Science Foundation by

The Neutrino Factory and Muon Collider Collaboration

Edited by K.T. McDonald for the Collaboration

(November 7, 1999)



… new history

2023 Energy Frontier

Frontier Conveners: Meenakshi Narain†, Laura Reina, Alessandro Tricoli

Topical Group Conveners: Michael Begel, Alberto Belloni, Tulika Bose, Antonio Boveia, Sally Dawson, Caterina Doglioni, Ayres Freitas, James Hirschauer, Stefan Hoeche, Isobel Ojalvo, Yen-Jie Lee, Huey-Wen Lin, Zhen Liu, Elliot Lipeles, Patrick Meade, Swagato Mukherjee, Pavel Nadolsky, Simone Pagan Griso, Christophe Royon, Michael Schmitt, Reinhard Schwienhorst, Nausheen Shah, Junping Tian, Caterina Vernieri, Doreen Wackeroth, Lian-Tao Wang

Snowmass 2021

For the five year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs factory detector R&D program,
3. Develop an initial design for a first stage TeV-scale Muon Collider in the US,
4. Support critical detector R&D towards EF multi-TeV colliders.

Snowmass Summer Study

https://inspirehep.net/conferences/1803127

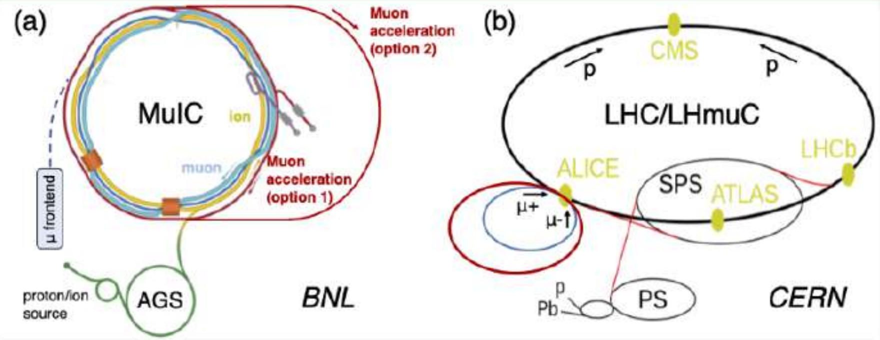
MuIC Kinematics

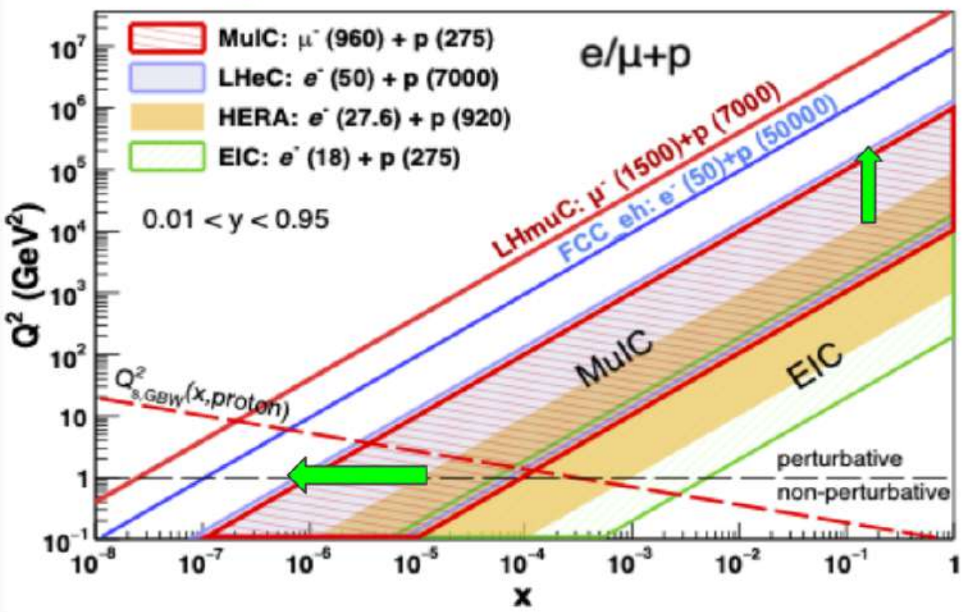
DIS Reach in x and Q^2 for ℓp Collisions

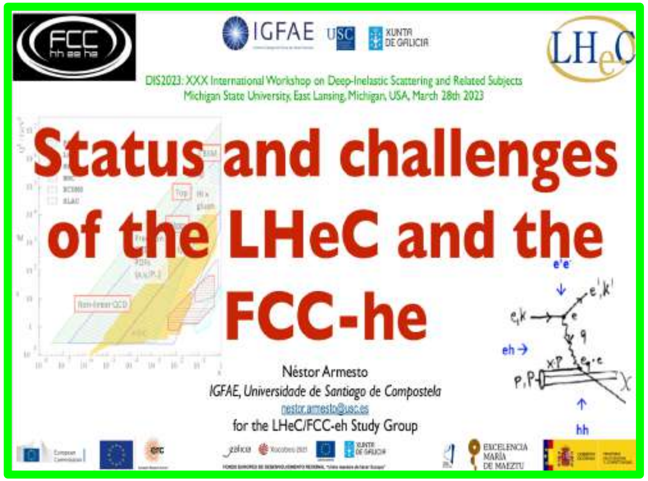
- Expands DIS reach at high Q^2 and low x by 1–3 orders of magnitude over HERA and the EIC

from **Darin Acosta**

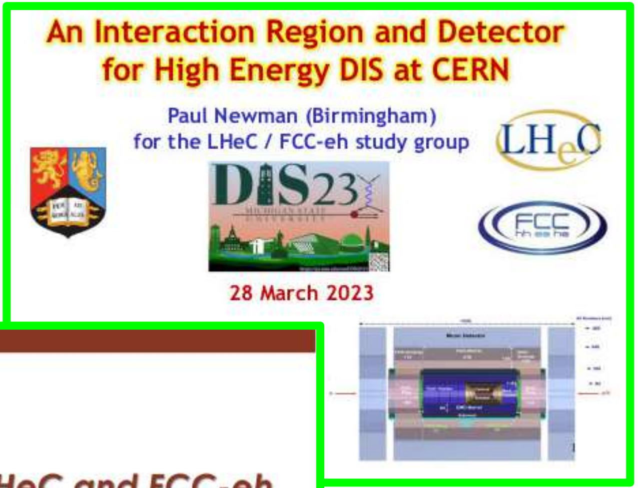
- Coverage of MuIC at BNL is nearly identical with that of the proposed Large Hadron electron Collider (LHeC) at CERN with 50 GeV e^- beam
  - With complementary kinematics
- Coverage of a mu-LHC collider at CERN (LHmuC) would significantly exceed even that of the FCC-eh option of a 50 TeV proton beam with 50 GeV e^- beam

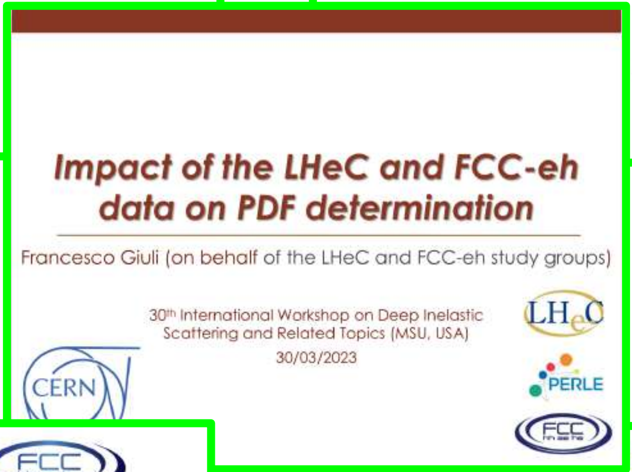





IGFAE
USC
XUNTA DE GALICIA
LHeC
DIS2023: XXX International Workshop on Deep-Inelastic Scattering and Related Subjects
Michigan State University, East Lansing, Michigan, USA, March 28th 2023
Status and challenges of the LHeC and the FCC-he
Néstor Armesto
IGFAE, Universidade de Santiago de Compostela
nestor.armesto@usc.es
for the LHeC/FCC-eh Study Group
EXCELENCIA MARÍA DE MAEZTU


DIS 2023
March 29th, 2023
Michigan State University, East Lansing, Michigan, USA.
DIS23
ELECTROWEAK PRECISION FITS AND CONTACT INTERACTIONS WITH EIC AND LHEC DIS PSEUDO DATA
Chiara Bissolotti
Argonne National Laboratory
In collaboration with:
Radja Boughezal and Kaan Simsek


An Interaction Region and Detector for High Energy DIS at CERN
Paul Newman (Birmingham)
for the LHeC / FCC-eh study group
LHeC
DIS23
28 March 2023


Impact of the LHeC and FCC-eh data on PDF determination
Francesco Giuli (on behalf of the LHeC and FCC-eh study groups)
30th International Workshop on Deep Inelastic Scattering and Related Topics (MSU, USA)
30/03/2023
LHeC
CERN
PERLE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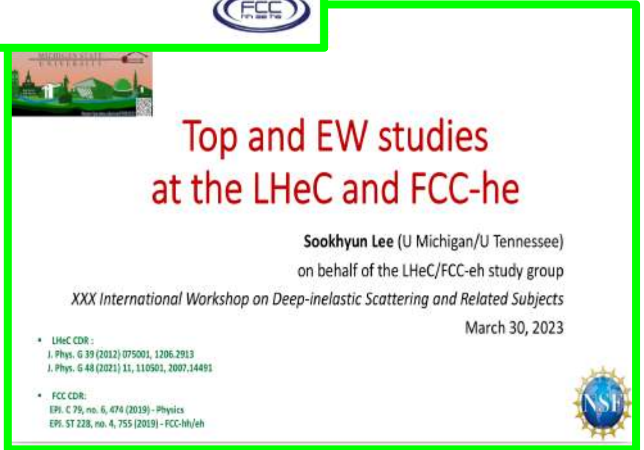
DIS2023: XXX International Workshop on Deep-Inelastic Scattering and Related Subjects


DIS 2023
Michigan State University
27 – 31 March 2023
High energy QCD and eA collisions at the LHeC and FCC-eh
Claire Gwenlan, Oxford
on behalf of the LHeC and FCC-eh study groups
LHeC
PERLE
CERN
UNIVERSITY OF OXFORD


LHeC
Diffraction at LHeC and FCC-eh
Anna Staśto
PennState
Eberly College of Science
DIS2023, March 30, 2023


Top and EW studies at the LHeC and FCC-he
Sookhyun Lee (U Michigan/U Tennessee)
on behalf of the LHeC/FCC-eh study group
XXX International Workshop on Deep-inelastic Scattering and Related Subjects
March 30, 2023
LHeC CDR:
J. Phys. G 39 (2012) 075001, 1206.2913
J. Phys. G 48 (2021) 11, 110501, 2007.14491
FCC CDR:
EPJ. C 79, no. 6, 474 (2019) - Physics
EPJ. ST 228, no. 4, 755 (2019) - FCC-hh/eh
NSF

LHeC Whitepaper

365 pages

day-by-day calendar

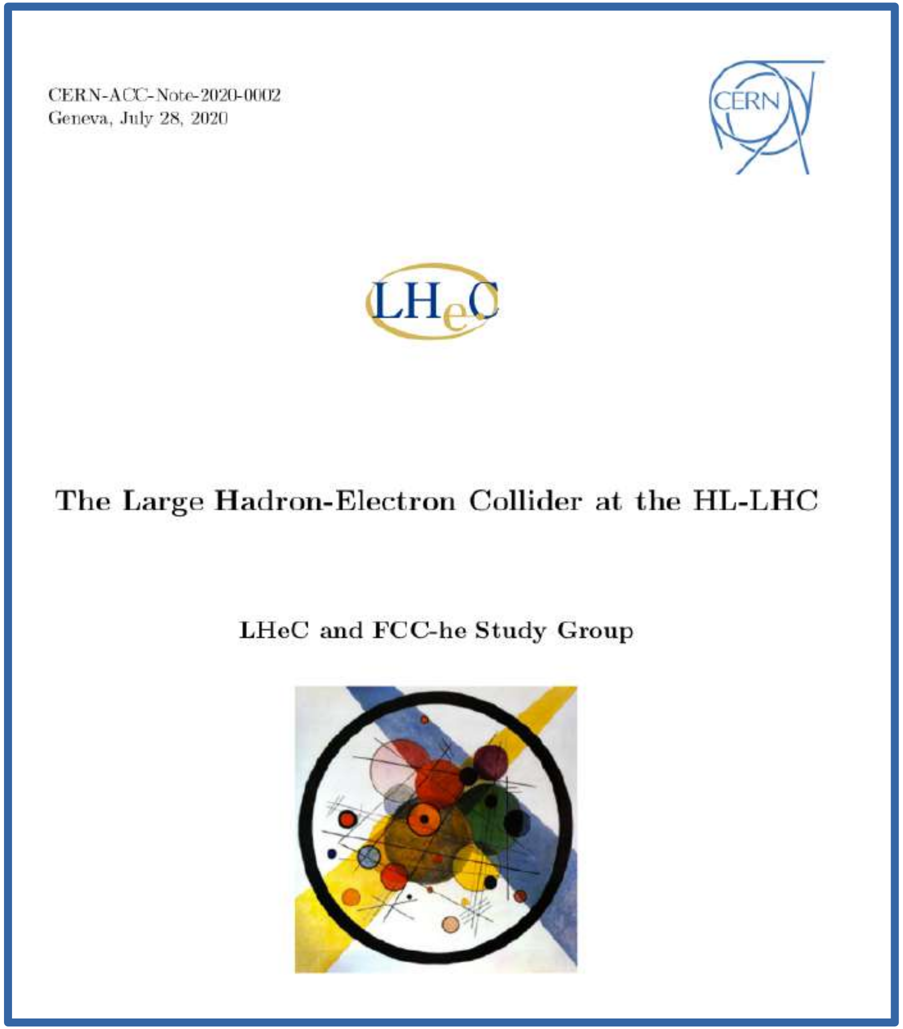
… everything you would like to know …

https://arxiv.org/abs/2007.14491

Journal of Physics G: Nuclear and Particle Physics

https://doi.org/10.1088/1361-6471/abf3ba

lots of material I do not have time to present


CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

LHeC

The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

Outline

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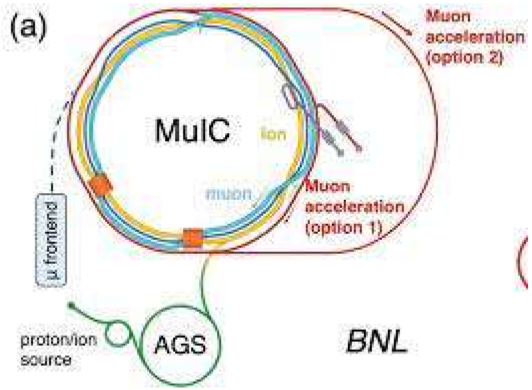
Selected topics ...



- **Perturbative / Non-perturbative transition**
  - How far can we push at low Q, W, & large α_S

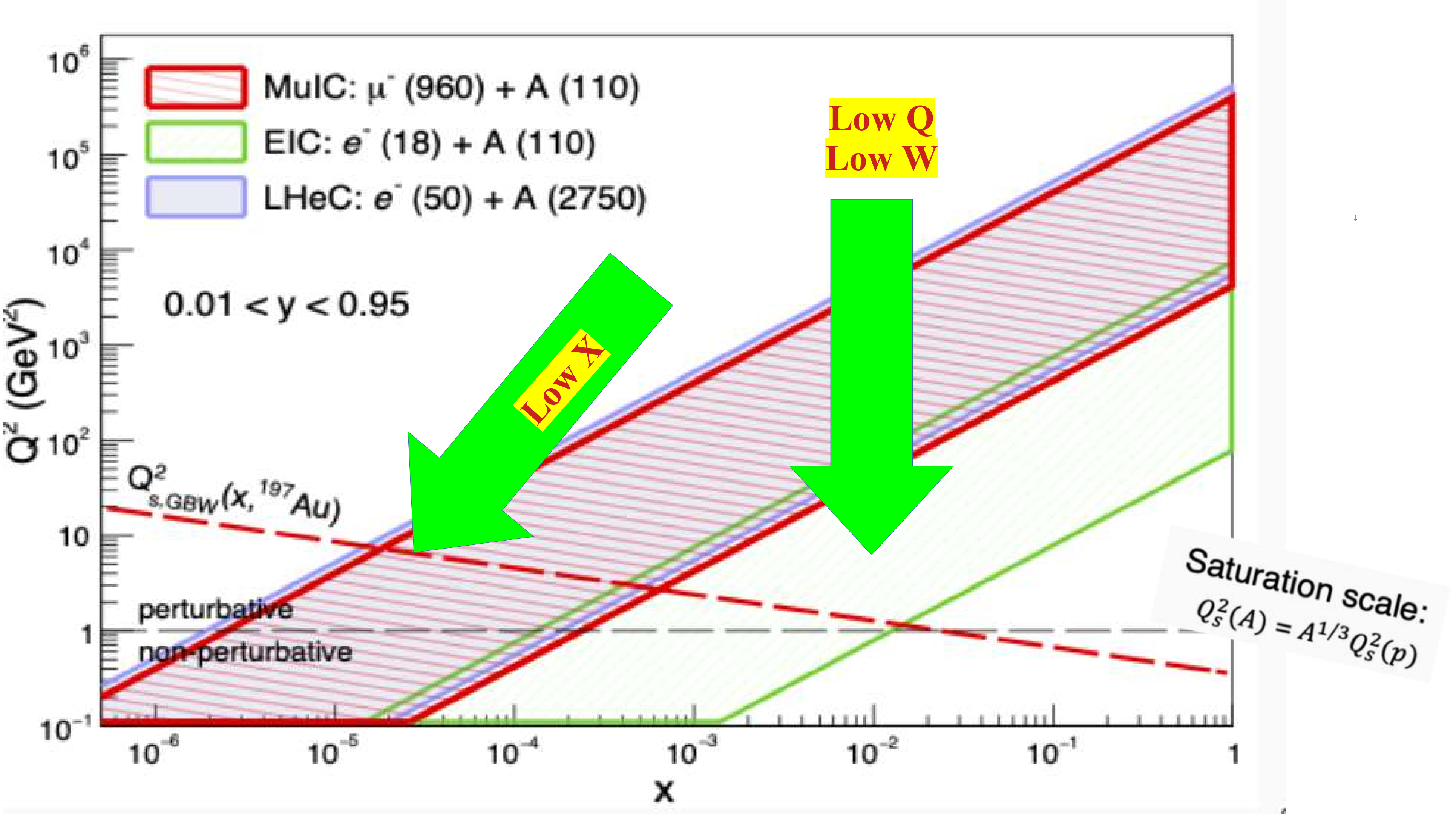
    challenging, but worthwhile

- **Low-x:** *Extend the EIC reach*
  - Saturation, recombination, resummation, collective effects

- **Heavy Quarks:** *Multi-scale challenges*
  - Strange: resolve the current strange PDF ambiguity
  - Charm: threshold production; intrinsic charm???
  - Bottom: complementary testing of charm issues NEW!

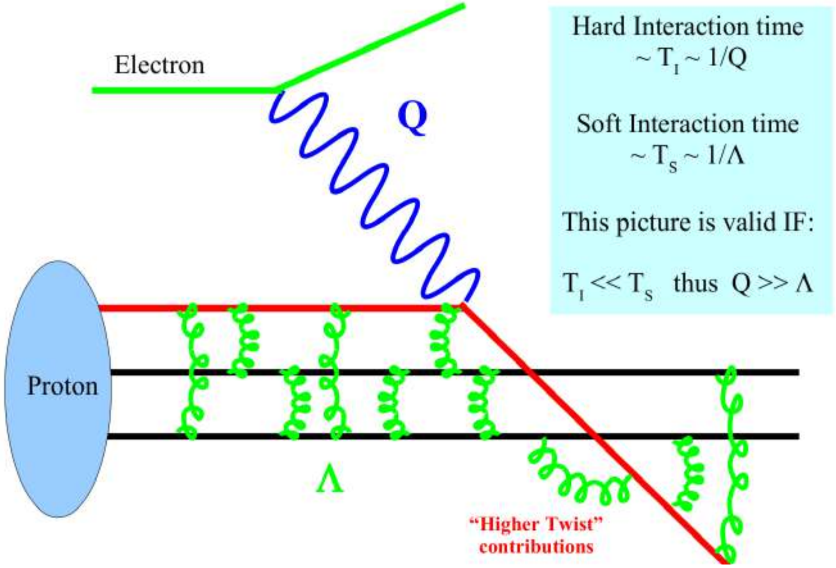
Perturbative Non-perturbative Transition

MuIC Kinematics



Perturbative / Non-perturbative transition

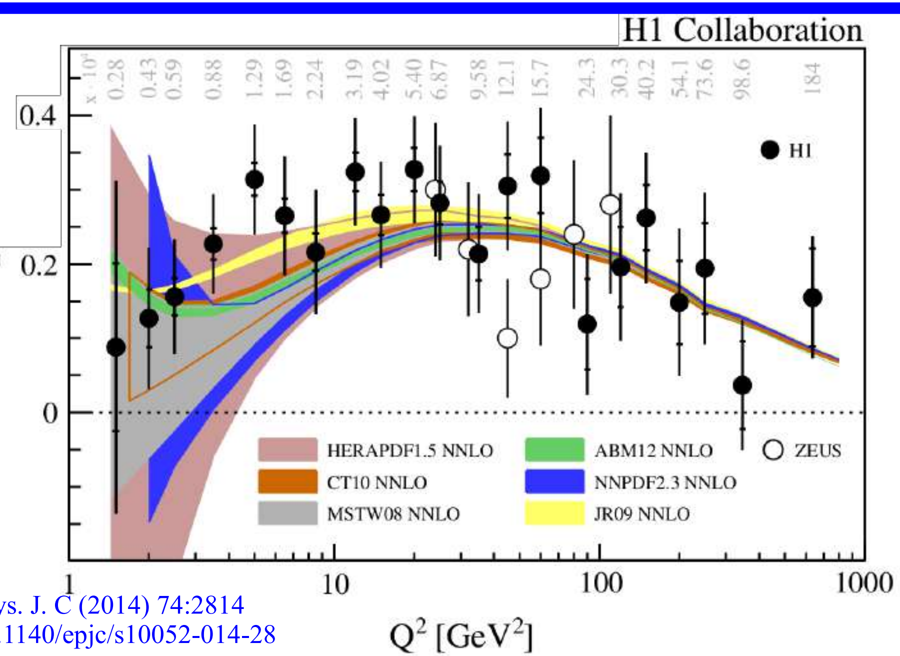
… not typically included



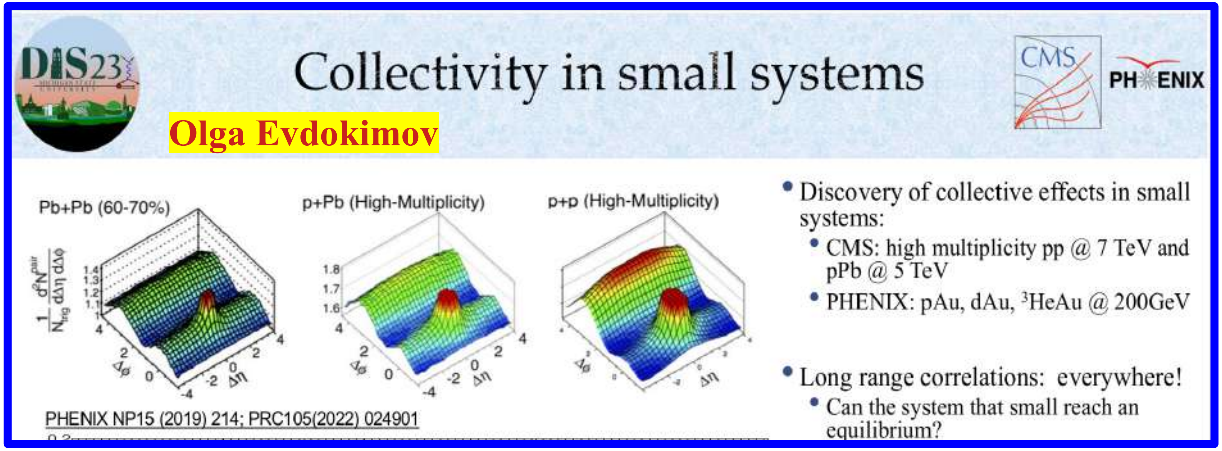
Higher Twist

$$F_i^{HT} = F_i \left(1 + \frac{A_i^{HT}}{Q^2} \right)$$

HT Improves F_L fit



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

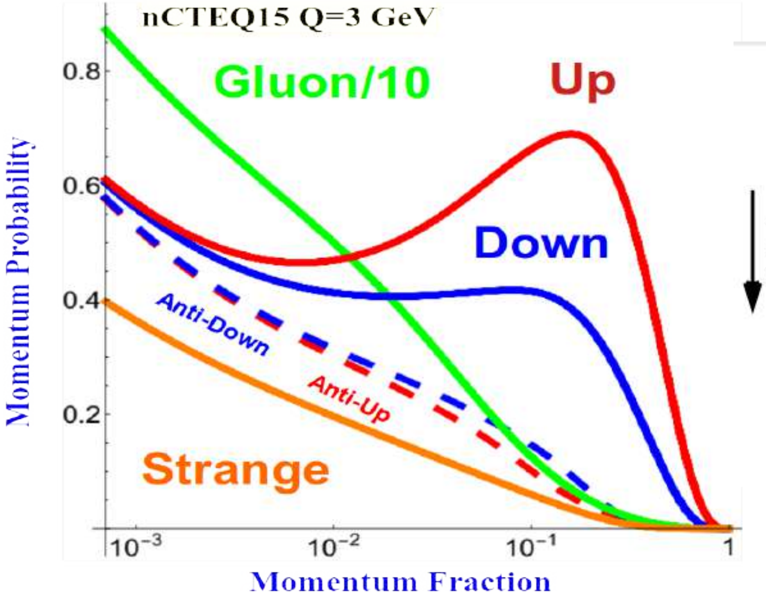


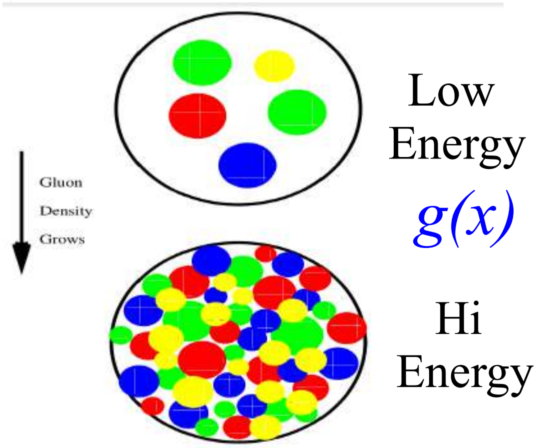
Low-x

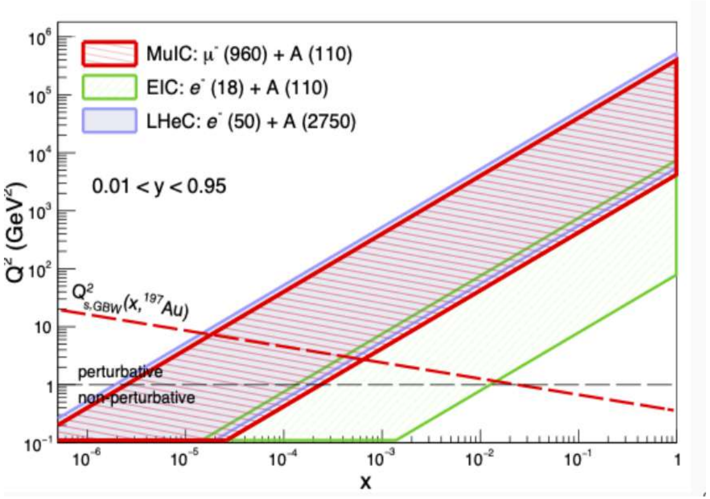
NEW!

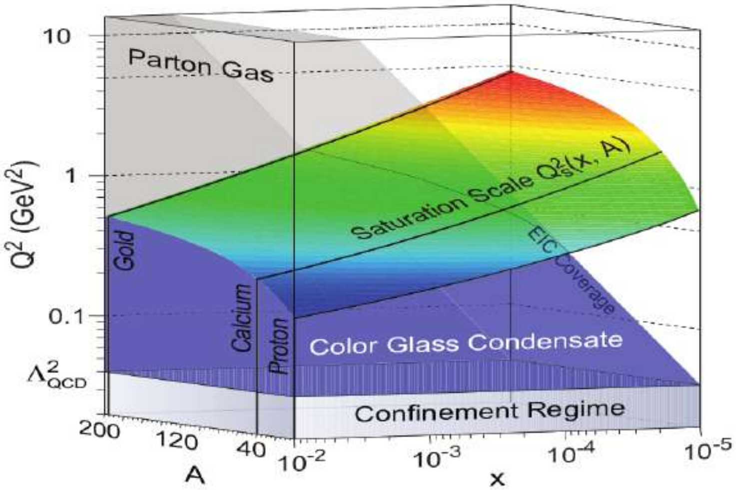
MuIC can greatly extend this region

Nuclear Medium Effects at small momentum fraction (x)





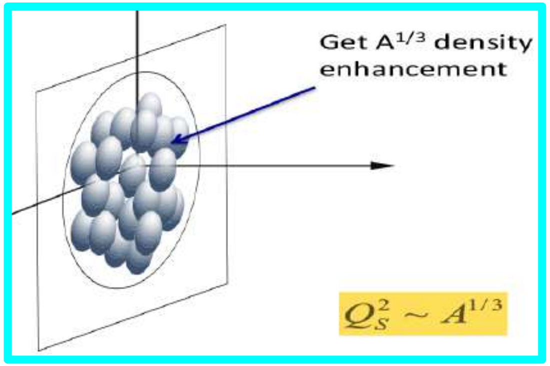




Nuclear medium effects:

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

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



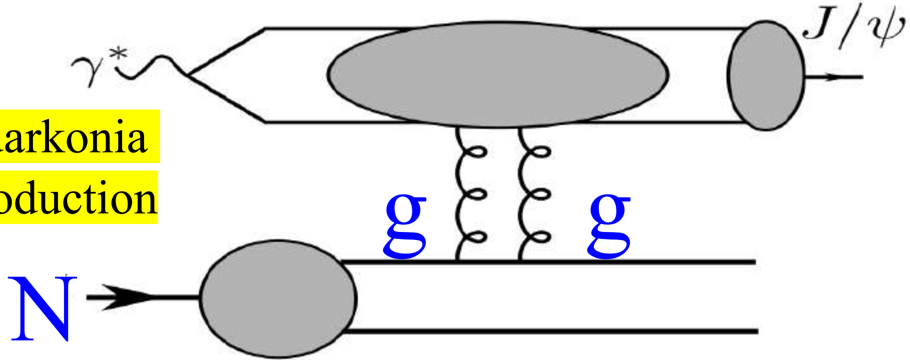
Review: Edmond Iancu & Raju Venugopalan: arXiv:0303204

15

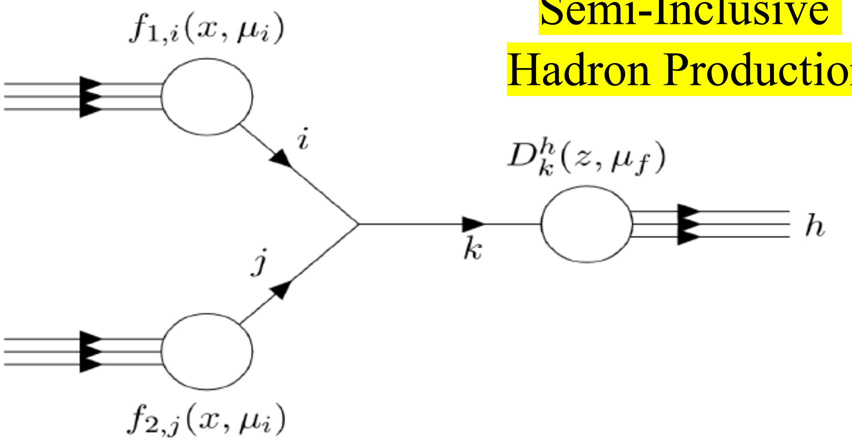
Measuring the nuclear Gluon PDF

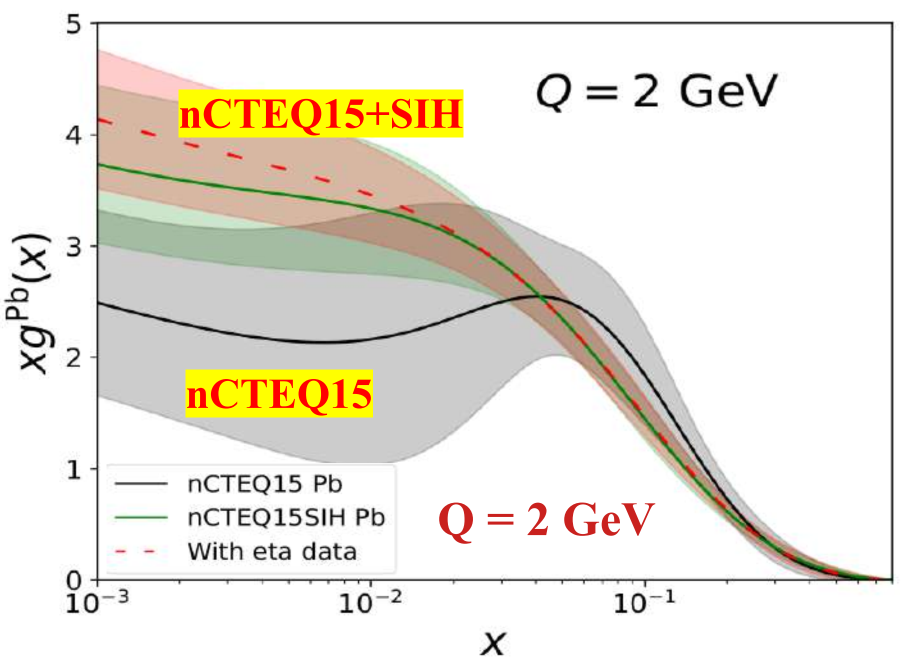
how can we determine the gluon

Quarkonia Production



Semi-Inclusive Hadron Production





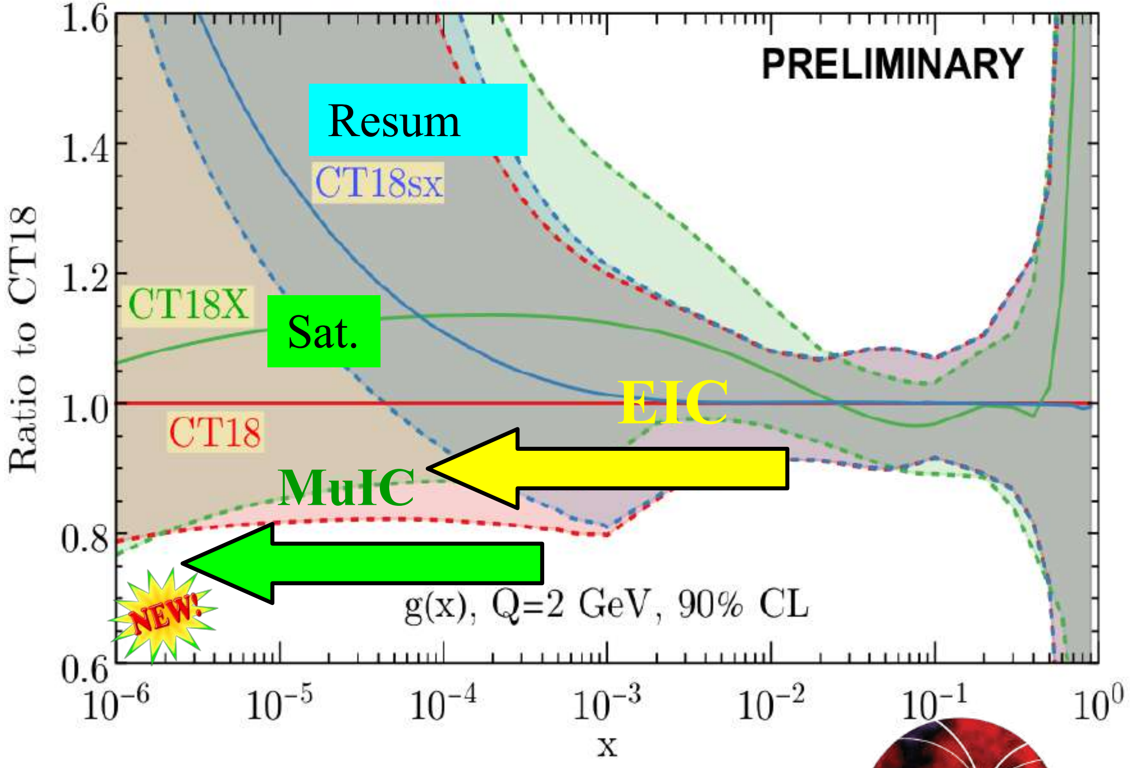
Semi-Inclusive Hadron Production
Heavy Quark Production

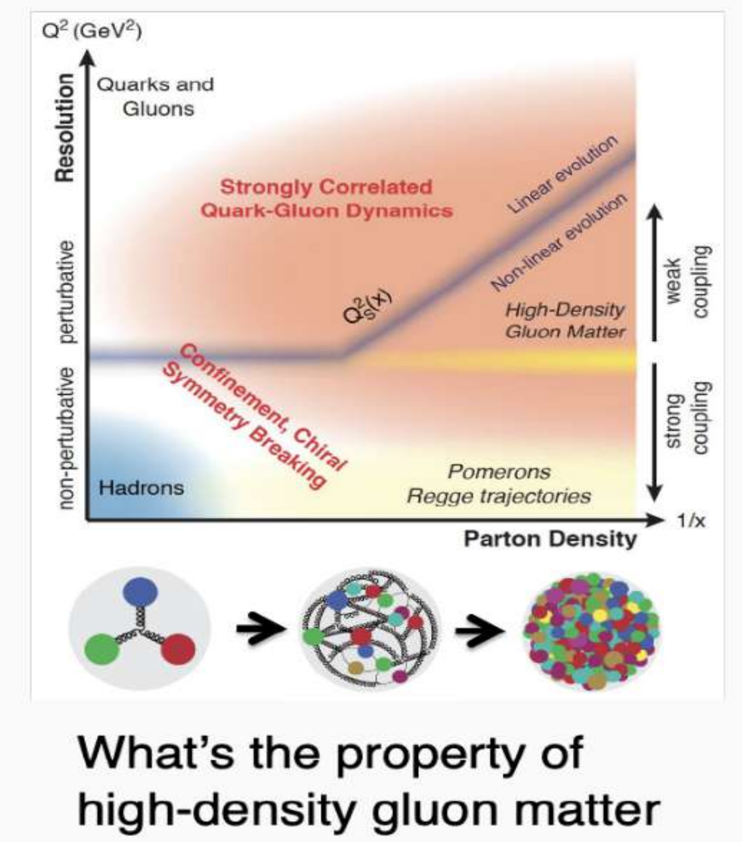
Gluon is sensitive to small-x treatment

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

Saturation inspired x-dependent

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





CT Collaboration: 2108.06596 [hep-ph]

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

SURGE collaboration will examine

Heavy Quarks

strange
charm
bottom

… multi-scale problem

Multi-Scale Problems are Challenging

Two-Loop Total Cross Section e^+e^-: One Scale

$$\sigma(Q^2)=\sigma_0\left\{1+\frac{\alpha_s(Q^2)}{4\pi}(3C_F)+\left[\frac{\alpha_s(Q^2)}{4\pi}\right]^2\left[-C_F^2\left[\frac{3}{2}\right]+C_FC_A\left[\frac{123}{2}-44\zeta(3)\right]+C_FTn_f(-22+16\zeta(3))\right]\right.$$

Two-Loop Drell-Yan Cross Section: Two Scales

Ref: CTEQ Handbook

$$\begin{aligned}
H_{q\bar q}^{(2),S+V}(z)=&\left[\frac{\alpha_s}{4\pi}\right]^2\delta(1-z)\Bigg\{C_AC_F\left[\left[\tfrac{193}{3}-24\zeta(3)\right]\ln\left[\frac{Q^2}{M^2}\right]-11\ln^2\left[\frac{Q^2}{M^2}\right]-\tfrac{12}{5}\zeta(2)^2+\tfrac{592}{9}\zeta(2)+28\zeta(3)-\tfrac{1535}{12}\right]\\
&+C_F^2\left[\left[18-32\zeta(2)\right]\ln^2\left[\frac{Q^2}{M^2}\right]+\left[24\zeta(2)+176\zeta(3)-93\right]\ln\left[\frac{Q^2}{M^2}\right]\right.\\
&\left.+\tfrac{8}{5}\zeta(2)^2-70\zeta(2)-60\zeta(3)+\tfrac{511}{4}\right]\\
&+n_fC_F\left[2\ln^2\left[\frac{Q^2}{M^2}\right]-\tfrac{34}{3}\ln\left[\frac{Q^2}{M^2}\right]+8\zeta(3)-\tfrac{112}{9}\zeta(2)+\tfrac{127}{6}\right]\Bigg\}\\
&+C_AC_F\left[-\tfrac{44}{3}\mathcal{D}_0(z)\ln^2\left[\frac{Q^2}{M^2}\right]+\left\{\left[\tfrac{536}{9}-16\zeta(2)\right]\mathcal{D}_0(z)-\tfrac{176}{3}\mathcal{D}_1(z)\right\}\ln\left[\frac{Q^2}{M^2}\right]\right.\\
&\left.-\tfrac{176}{3}\mathcal{D}_2(z)+\left[\tfrac{1072}{9}-32\zeta(2)\right]\mathcal{D}_1(z)+\left[56\zeta(3)+\tfrac{176}{3}\zeta(2)-\tfrac{1616}{27}\right]\mathcal{D}_0(z)\right]\\
&+C_F^2\left[\left[64\mathcal{D}_1(z)+48\mathcal{D}_0(z)\right]\ln^2\left[\frac{Q^2}{M^2}\right]+\left\{192\mathcal{D}_2(z)+96\mathcal{D}_1(z)-\left[128+64\zeta(2)\right]\mathcal{D}_0(z)\right\}\ln\left[\frac{Q^2}{M^2}\right]\right.\\
&\left.+128\mathcal{D}_3(z)-(128\zeta(2)+256)\mathcal{D}_1(z)+256\zeta(3)\mathcal{D}_0(z)\right]\\
&+n_fC_F\left[\tfrac{8}{3}\mathcal{D}_0(z)\ln^2\left[\frac{Q^2}{M^2}\right]+\left[\tfrac{32}{3}\mathcal{D}_1(z)-\tfrac{80}{9}\mathcal{D}_0(z)\right]\ln\left[\frac{Q^2}{M^2}\right]+\tfrac{32}{3}\mathcal{D}_2(z)-\tfrac{160}{9}\mathcal{D}_1(z)+\left[\tfrac{224}{27}-\tfrac{32}{3}\zeta(2)\right]\mathcal{D}_0(z)\right].
\end{aligned}$$

New territory

$\ln(m_b/Q)$
can spoil
perturbation
expansion

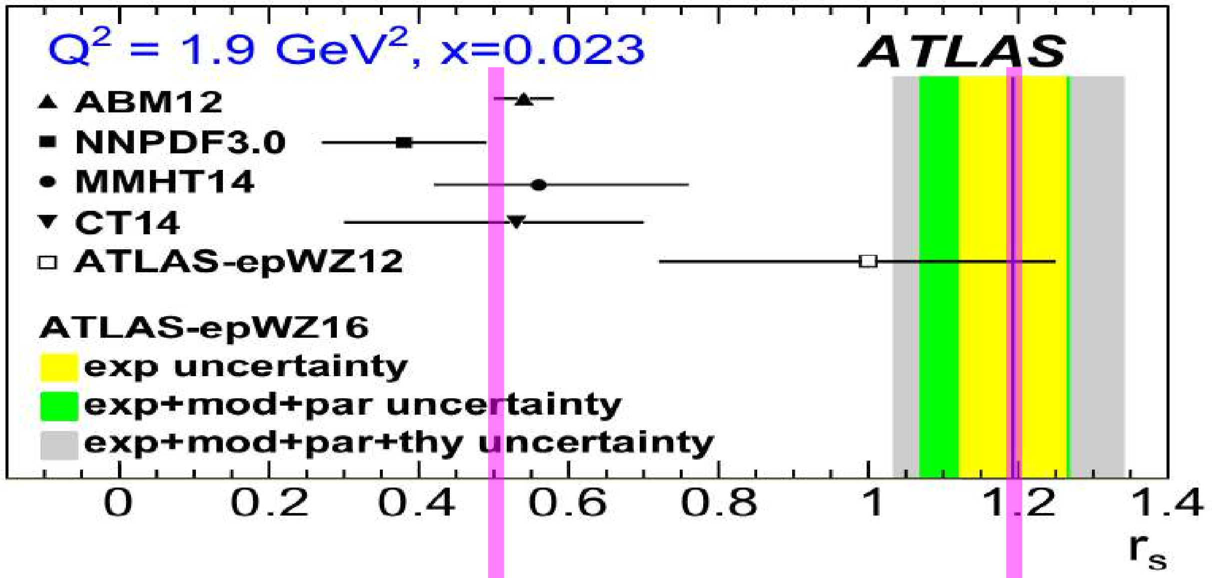
$\{m_c, m_b\}$
ideal theoretical
testing ground

Strange

Surprise: … LHC sees more strange than expected

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

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



We expect: **At the LHC:**

Proton case

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

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

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

We observe similar effects in pPb

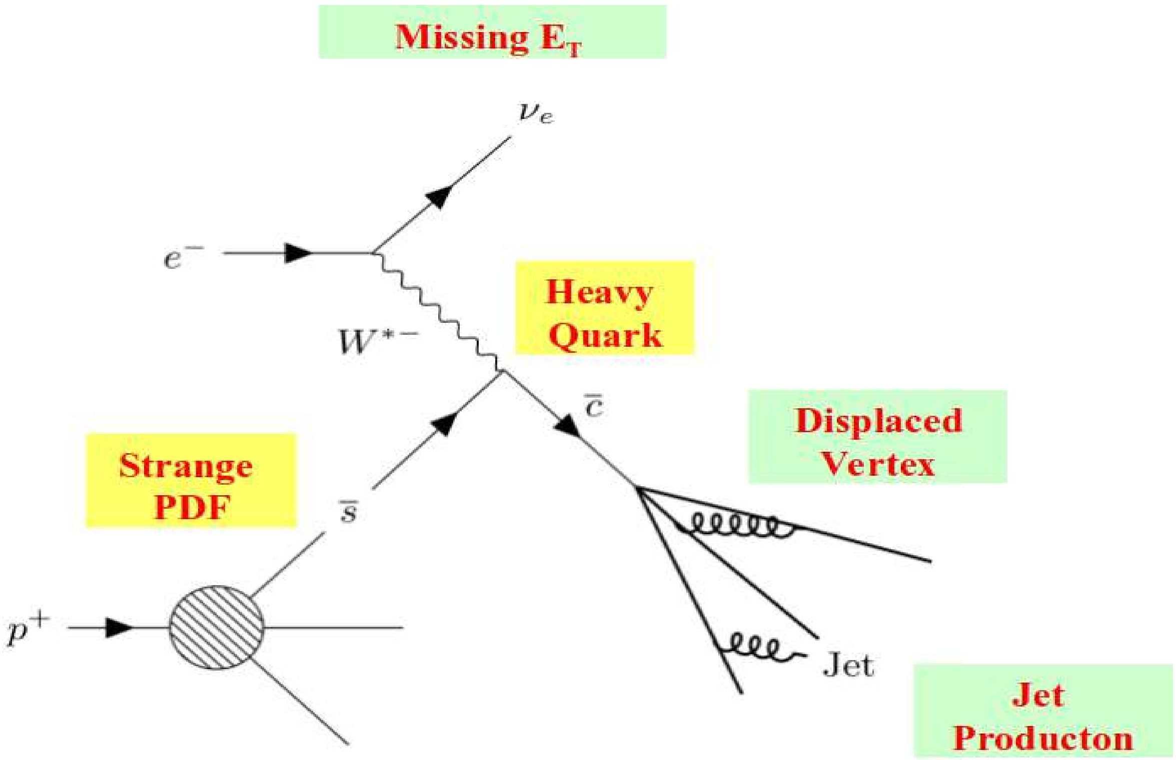
Charm Jets at the EIC

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

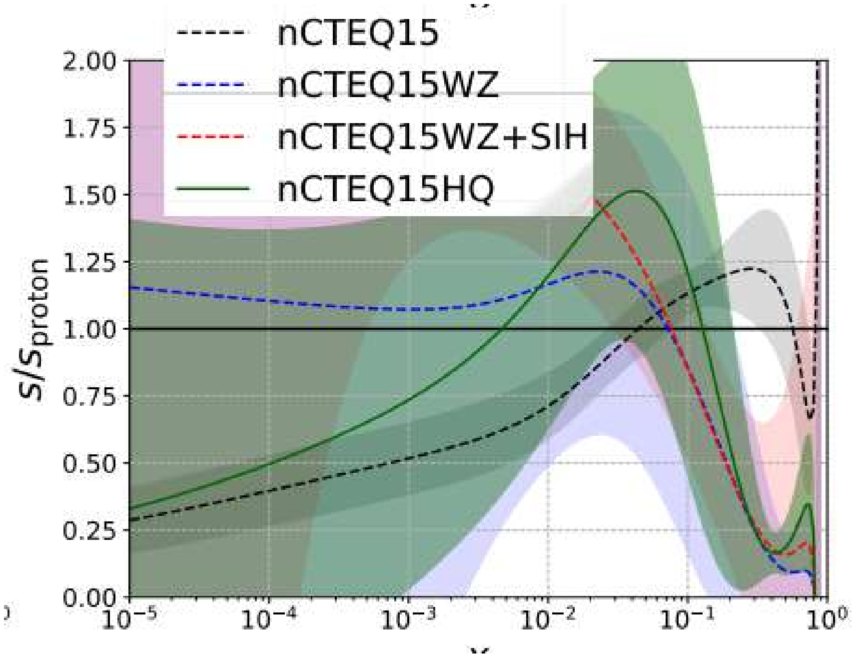
JLAB-PHY-20-3205, SMU-HEP-20-05

Charm jets as a probe for strangeness at the future Electron-Ion Collider

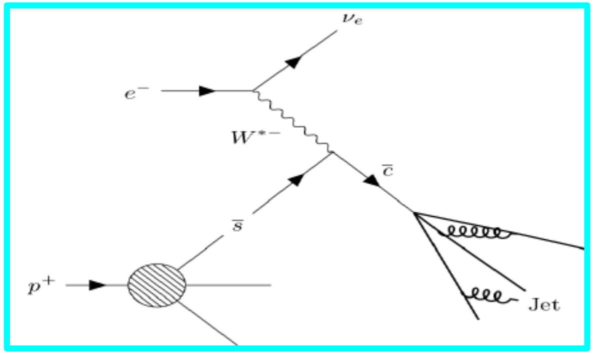
Miguel Arratia,[1,2] Yulia Furletova,[2] T. J. Hobbs,[3,4] Fredrick Olness,[3] and Stephen J. Sekula[3,*]



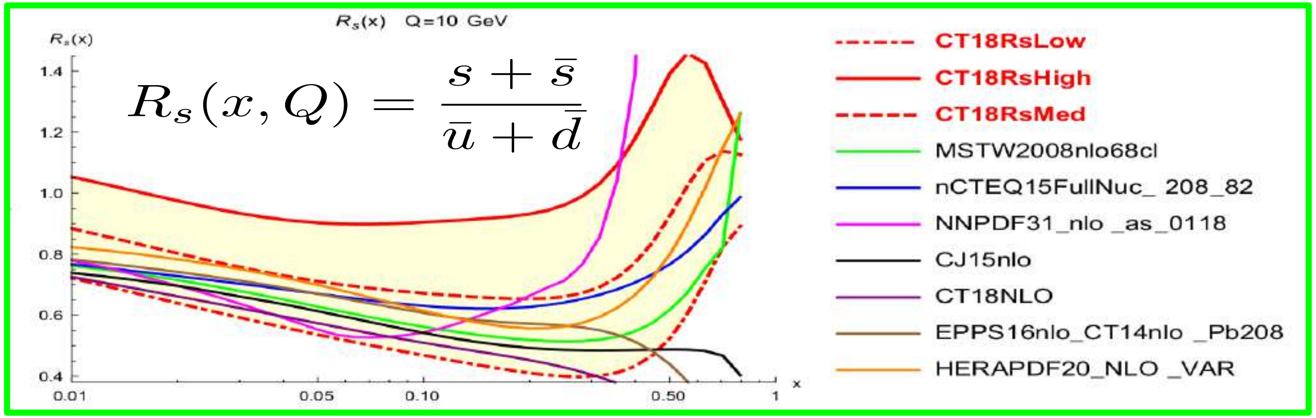
Large Strange Uncertainty

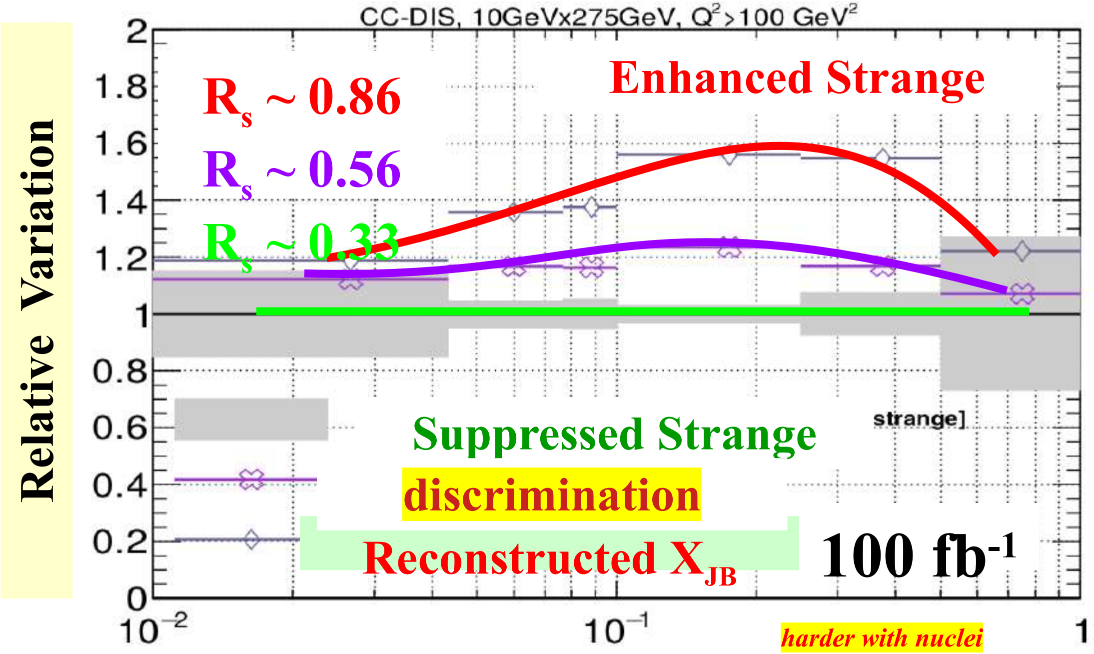


The Strange PDF from Charm Jets at the EIC



W+s → c_{jet}





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

Charm

Charm: … intrinsic charm controversy

Article

Evidence for intrinsic charm quarks in the proton

https://doi.org/10.1038/s41586-022-04998-2
Received: 18 January 2022
Accepted: 20 June 2022
Published online: 17 August 2022
Open access
Check for updates

Article

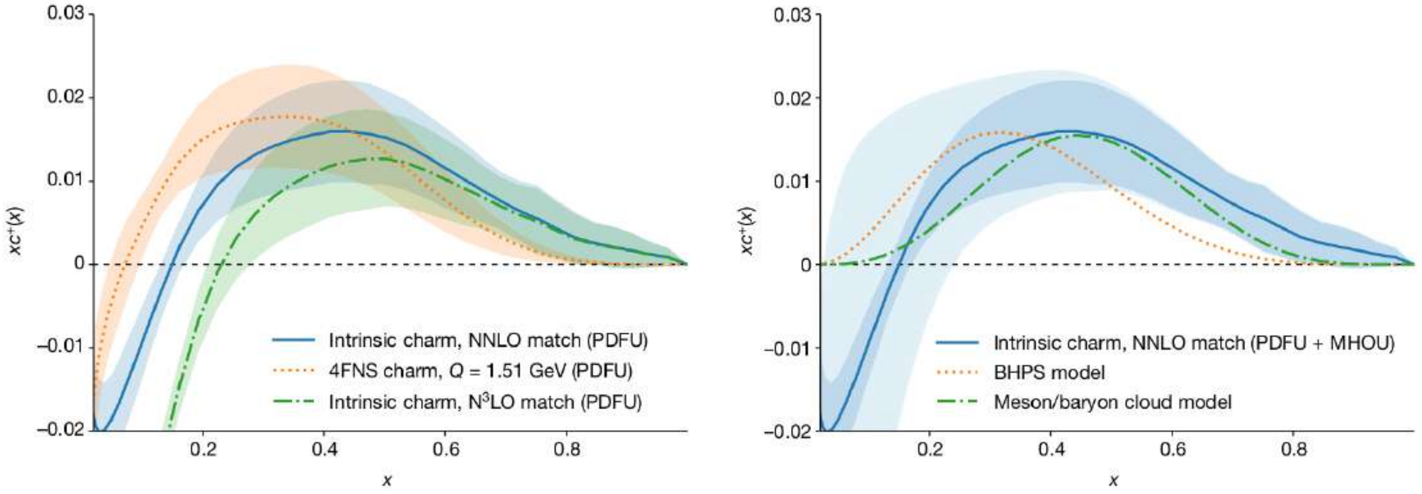


Fig. 1 | The intrinsic charm PDF and comparison with models. Left, the purely intrinsic (3FNS) result (blue) with PDFU alone, compared to the 4FNS PDF, which includes both an intrinsic and a radiative component, at $Q = m_c = 1.51$ GeV (orange). The purely intrinsic (3FNS) result obtained using N^{3}LO matching is also shown (green). Right, the purely intrinsic (3FNS) final result with total uncertainty (PDFU + MHOU), with the PDFU indicated as a dark shaded band; the predictions from the original BHPS model[1] and from the more recent meson/baryon cloud model[5] are also shown for comparison (dotted and dot-dashed curves, respectively).

- threshold important
- non-monotonic shape
- $\ln(m_c/Q)$ terms

Bottom

Multi-Scale Problems are Challenging

Two-Loop Total Cross Section e^+e^-: One Scale

$$\sigma(Q^2)=\sigma_0\left\{1+\frac{\alpha_s(Q^2)}{4\pi}(3C_F)+\left[\frac{\alpha_s(Q^2)}{4\pi}\right]^2\left[-C_F^2\left[\frac{3}{2}\right]+C_FC_A\left[\frac{123}{2}-44\zeta(3)\right]+C_FTn_f(-22+16\zeta(3))\right]\right.$$

NEW!

Two-Loop Drell-Yan Cross Section: Two Scales

$$\begin{aligned}
H_{q\bar q}^{(2),S+V}(z)=&\left[\frac{\alpha_s}{4\pi}\right]^2\delta(1-z)\left\{C_AC_F\left[[\tfrac{193}{3}-24\zeta(3)]\ln\left[\frac{Q^2}{M^2}\right]-11\ln^2\left[\frac{Q^2}{M^2}\right]-\tfrac{12}{5}\zeta(2)^2+\tfrac{592}{9}\zeta(2)+28\zeta(3)-\tfrac{1535}{12}\right]\right.\\
&+C_F^2\left[[18-32\zeta(2)]\ln^2\left[\frac{Q^2}{M^2}\right]+[24\zeta(2)+176\zeta(3)-93]\ln\left[\frac{Q^2}{M^2}\right]\right.\\
&\left.+\tfrac{8}{5}\zeta(2)^2-70\zeta(2)-60\zeta(3)+\tfrac{511}{4}\right]\\
&\left.+n_fC_F\left[2\ln^2\left[\frac{Q^2}{M^2}\right]-\tfrac{34}{3}\ln\left[\frac{Q^2}{M^2}\right]+8\zeta(3)-\tfrac{112}{9}\zeta(2)+\tfrac{127}{6}\right]\right\}\\
&+C_AC_F\left[-\tfrac{44}{3}\mathcal{D}_0(z)\ln^2\left[\frac{Q^2}{M^2}\right]+\{[\tfrac{536}{9}-16\zeta(2)]\mathcal{D}_0(z)-\tfrac{176}{3}\mathcal{D}_1(z)\}\ln\left[\frac{Q^2}{M^2}\right]\right.\\
&\left.-\tfrac{176}{3}\mathcal{D}_2(z)+[\tfrac{1072}{9}-32\zeta(2)]\mathcal{D}_1(z)+[56\zeta(3)+\tfrac{176}{3}\zeta(2)-\tfrac{1616}{27}]\mathcal{D}_0(z)\right]\\
&+C_F^2\left[[64\mathcal{D}_1(z)+48\mathcal{D}_0(z)]\ln^2\left[\frac{Q^2}{M^2}\right]+\{192\mathcal{D}_2(z)+96\mathcal{D}_1(z)-[128+64\zeta(2)]\mathcal{D}_0(z)\}\ln\left[\frac{Q^2}{M^2}\right]\right.\\
&\left.+128\mathcal{D}_3(z)-(128\zeta(2)+256)\mathcal{D}_1(z)+256\zeta(3)\mathcal{D}_0(z)\right]\\
&+n_fC_F\left[\tfrac{8}{3}\mathcal{D}_0(z)\ln^2\left[\frac{Q^2}{M^2}\right]+[\tfrac{32}{3}\mathcal{D}_1(z)-\tfrac{80}{9}\mathcal{D}_0(z)]\ln\left[\frac{Q^2}{M^2}\right]+\tfrac{32}{3}\mathcal{D}_2(z)-\tfrac{160}{9}\mathcal{D}_1(z)+[\tfrac{224}{27}-\tfrac{32}{3}\zeta(2)]\mathcal{D}_0(z)\right].
\end{aligned}$$

Ref: CTEQ Handbook

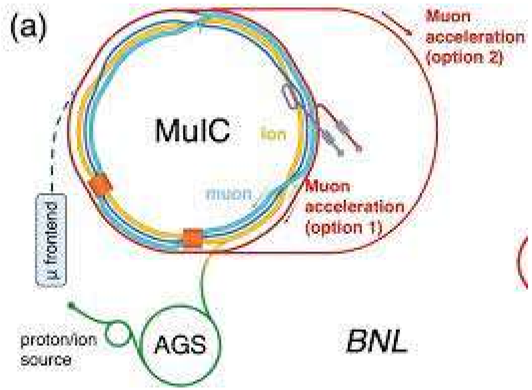
MuIC: new territory

$\ln(m_b/Q)$ can spoil perturbation expansion

$\{m_c, m_b\}$ ideal theoretical testing ground

Conclusions

Conclusions: **Build on & extend EIC Program**



- **Perturbative / Non-perturbative transition**
  - How far can we push at low Q, W, & large α_S

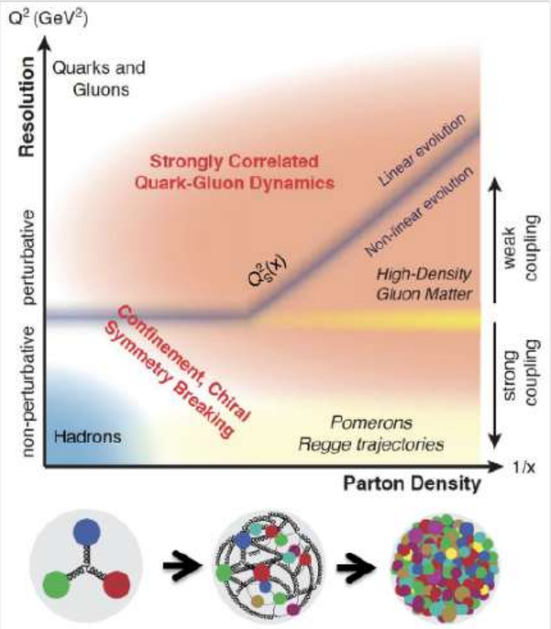
    challenging, but worthwhile

- **Low-x:** *Extend the EIC reach*
  - Saturation, recombination, resummation, collective effects

- **Heavy Quarks:** *Multi-scale challenges*
  - Strange: resolve the current strange PDF ambiguity
  - Charm: threshold production; intrinsic charm???
  - Bottom: complementary testing of charm issues

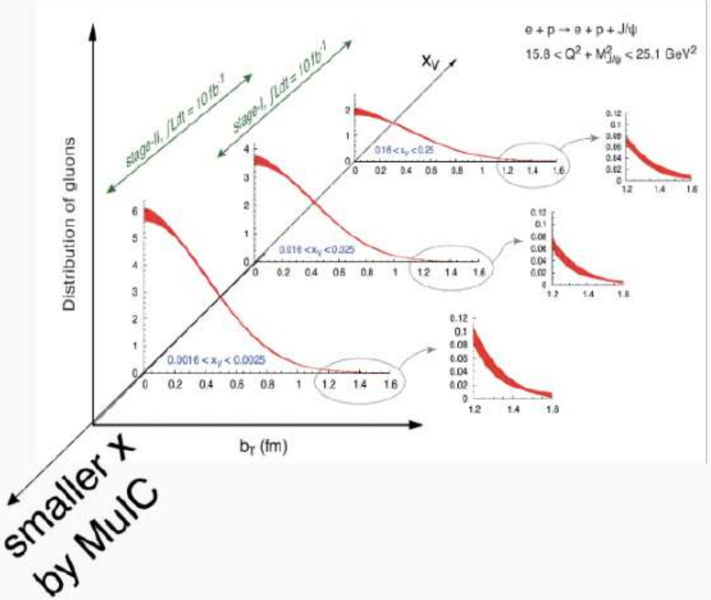
Nuclear Physics at the MuIC

Gluon saturation



What's the property of high-density gluon matter

3D Nucleon structure

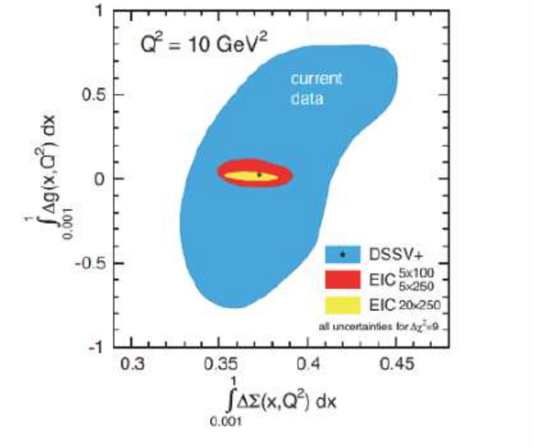


Nucleon spin puzzle

"Helicity sum rule"

$$\frac{1}{2}\hbar = \frac{1}{2}\Delta\Sigma + \Delta G + \sum_q L_q^z + L_g^z$$

quark contribution; gluon contribution; orbital angular momentum



MuIC to reach $x \sim 10^{-5}$

Energy Configurations and Luminosity

Parameter	BNL options: MuIC			MuIC2	LHmuC	
$\sqrt{s_{\mu p}}$ (TeV)	0.33	0.74	1.0	→ 2.0	6.5	
$L_{\mu p}$ (10^{33}cm^{-2}s^{-1})	0.07	2.1	4.7		2.8	
Int. Lumi. (fb^{-1}) per 10 yrs	6	178	400		237	
Staging options		Muon		Proton	Muon	Proton
Beam energy (TeV)	0.1	0.5	0.96	0.275 → 1.0	1.5	7
N_b (10^{11})	40	20	20	3	20	2.2
f^{μ}_{rep} (Hz)	15	15	15		12	
Cycles per μ bunch, N^{μ}_{cycle}	1134	1719	3300		3300	
$\varepsilon^*_{x,y}$ (μm)	200	25	25	0.3	25	2.5
$\beta^*_{x,y}$ @IP (cm)	1.7	1	0.75	5	0.5	15
Trans. beam size, $\sigma_{x,y}$ (μm)	48	7.6	4.7	7.1	3	7.1

← LHC option

← √s

← Estimate of lumi

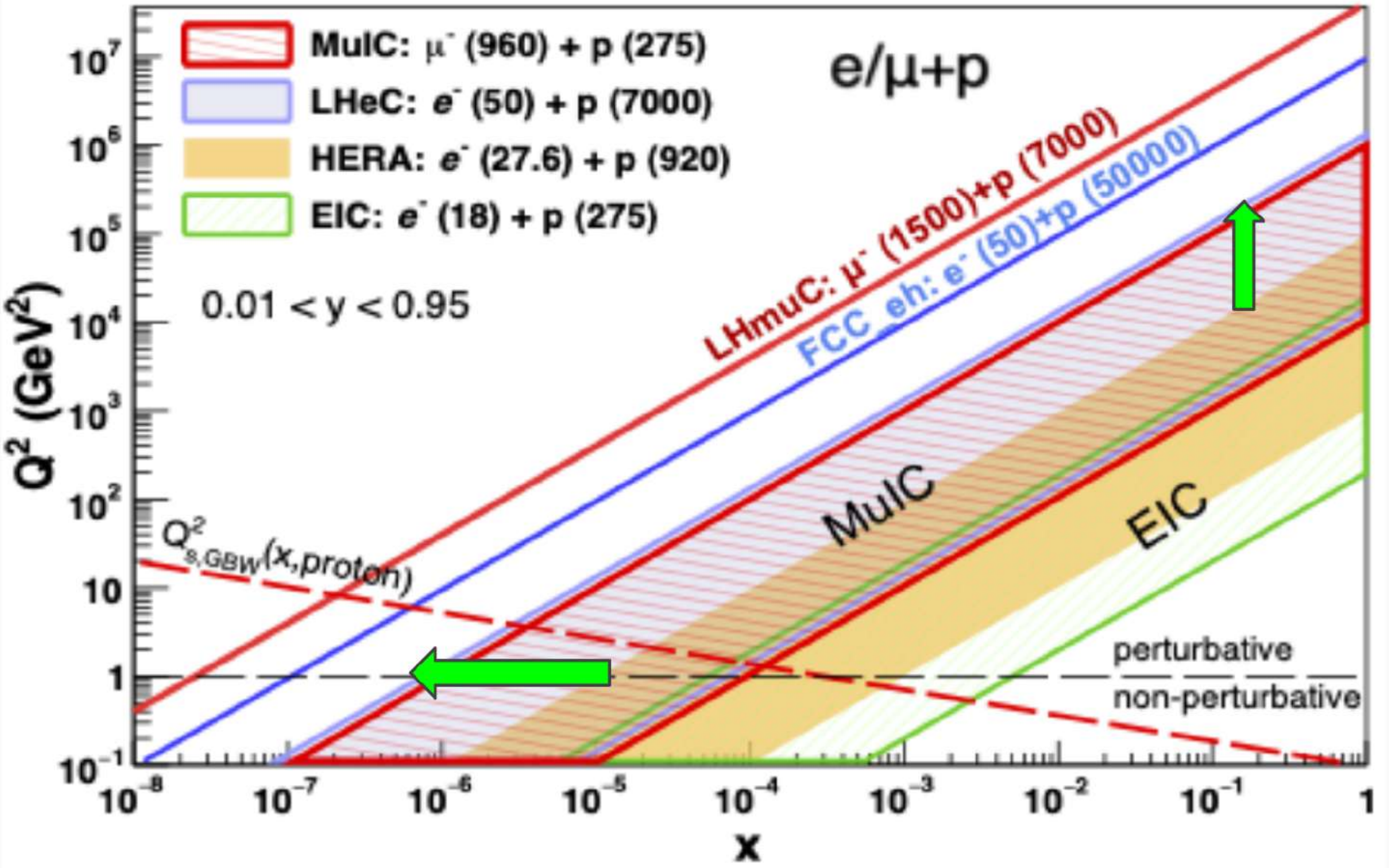
← Beam energies

$$\mathcal{L}_{\mu p} = \frac{N^{\mu} N^{p}}{4\pi \max[\sigma^{\mu}_{x}, \sigma^{p}_{x}] \max[\sigma^{\mu}_{y}, \sigma^{p}_{y}]} \min[f^{\mu}_{c}, f^{p}_{c}] H_{hg},$$

$$\sigma^{\mu,p}_{x,y} = \sqrt{\varepsilon^{*}_{x,y} \beta^{*}_{x,y} m^{\mu,p} / E^{\mu,p}}$$

↑ Upgrade hadron ring

Muon Collider parameters + BNL/EIC and LHC proton beam parameters



MuIC: μ⁻ (960) + p (275)
LHeC: e⁻ (50) + p (7000)
HERA: e⁻ (27.6) + p (920)
EIC: e⁻ (18) + p (275)
e/μ+p
0.01 < y < 0.95
LHmuC: μ⁻ (1500)+p (7000)
FCC_eh: e⁻ (50)+p (50000)
MuIC
EIC
$Q^2_{s,GBW}(x,\text{proton})$
perturbative
non-perturbative
Q^2 (GeV^2)
x