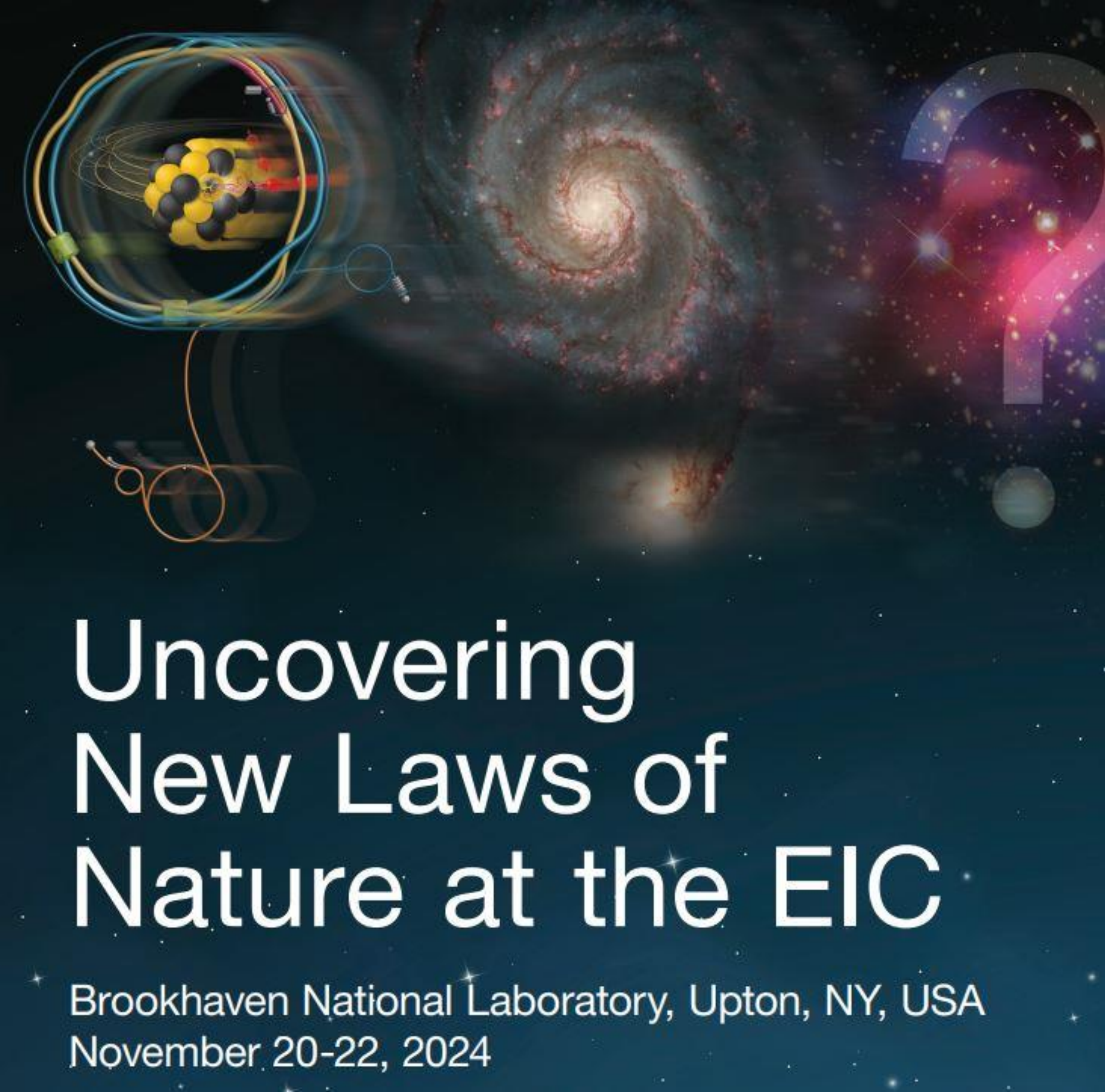


EIC Theory Overview

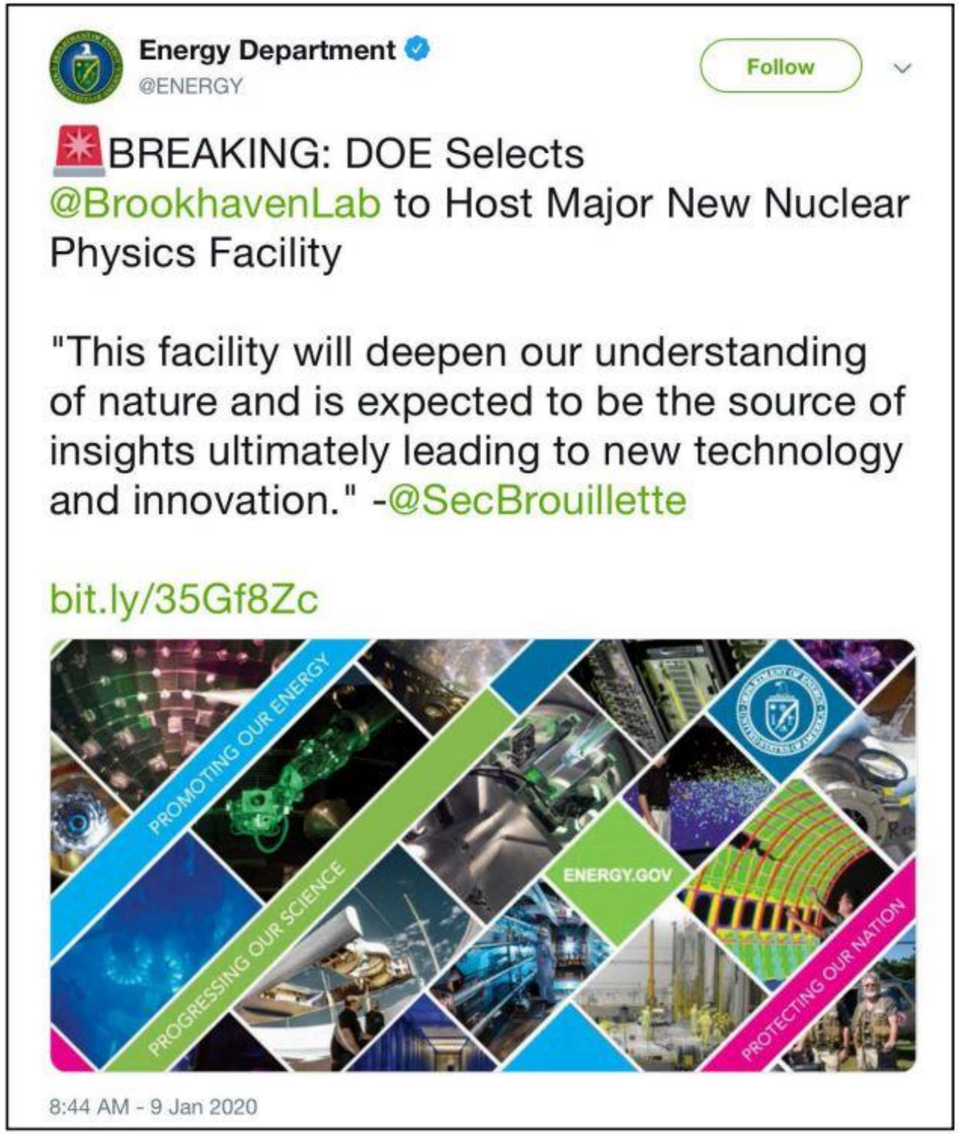
Shohini Bhattacharya
Los Alamos National Laboratory
20 November 2024

LA-UR-24-32210

Preliminary words

I apologize for the non-exhaustive, superficial, biased overview and for any misrepresentation

January 9, 2020


Energy Department
@ENERGY
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BREAKING: DOE Selects @BrookhavenLab to Host Major New Nuclear Physics Facility

"This facility will deepen our understanding of nature and is expected to be the source of insights ultimately leading to new technology and innovation." -@SecBrouillette

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FEDS INVEST IN BROOKHAVEN LAB

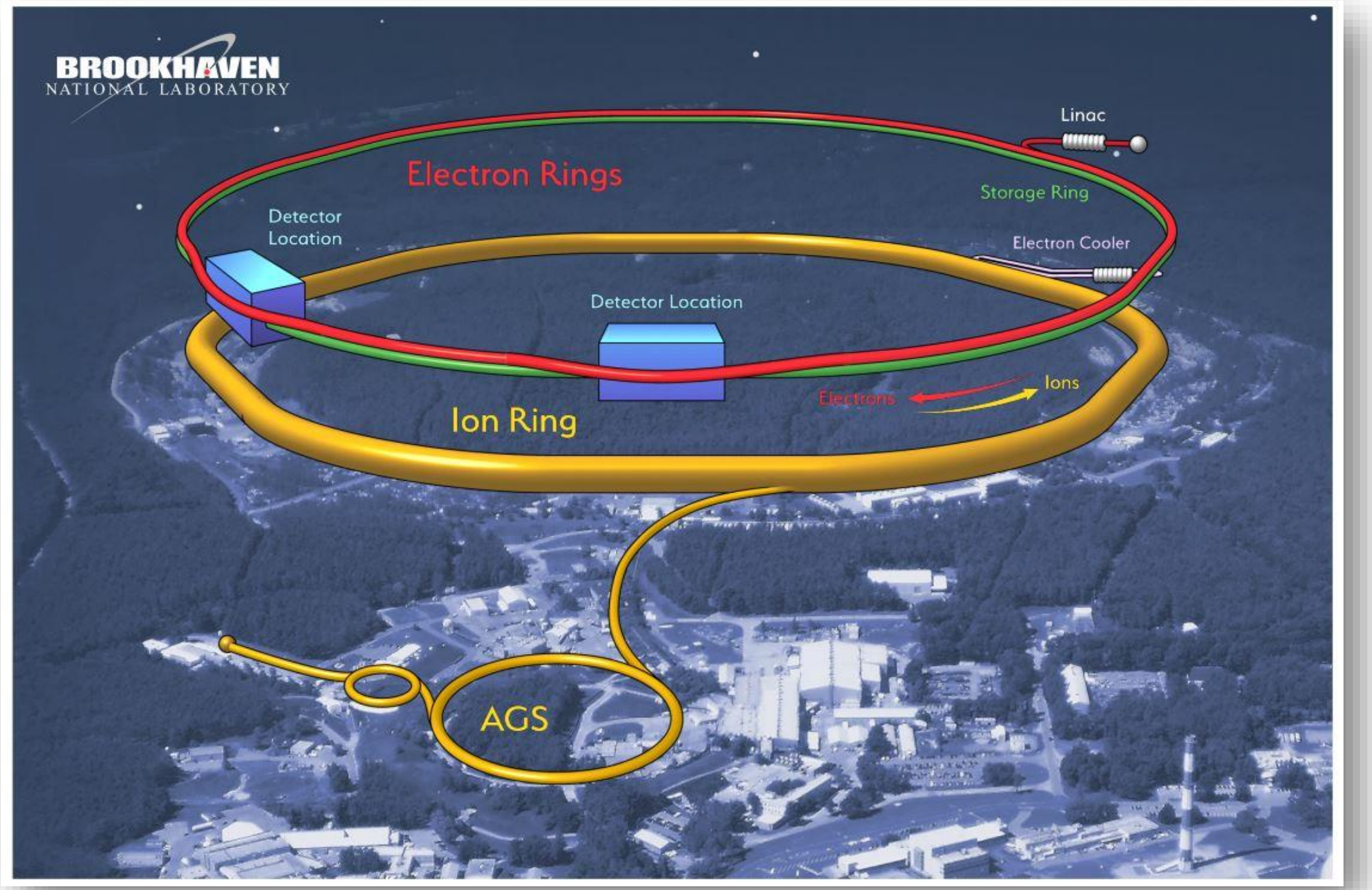
BILLION-DOLLAR BOOST FOR LI

Ion-collider project to cost up to $2.6B and may generate 1,000 jobs

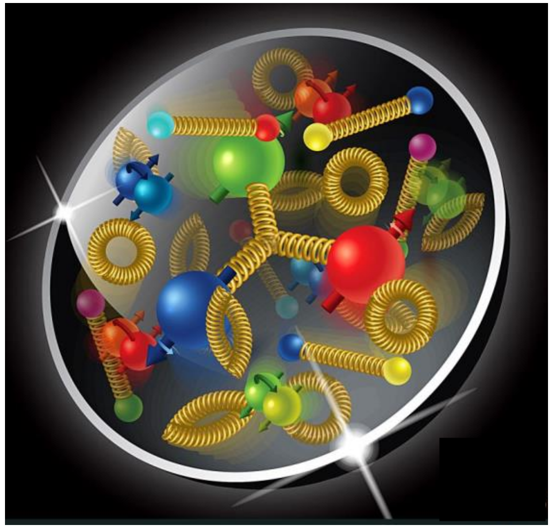
A4

Electron-Ion Collider

EIC: A QCD Lab to explore the structure and dynamics of the visible world



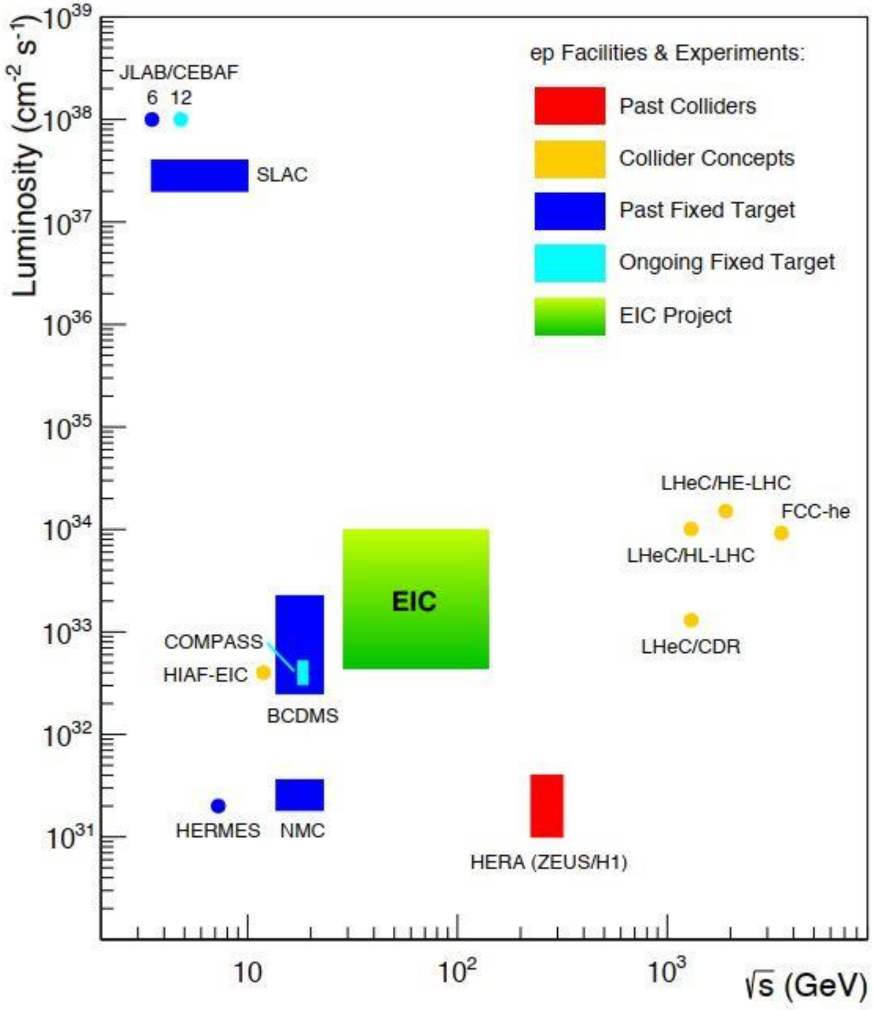
Understanding **emergence of hadronic and nuclear matter** in terms of **quarks and gluons**



Electron-Ion Collider

The uniqueness of EIC

Nycz, Satogata, Pages' talks



EIC:

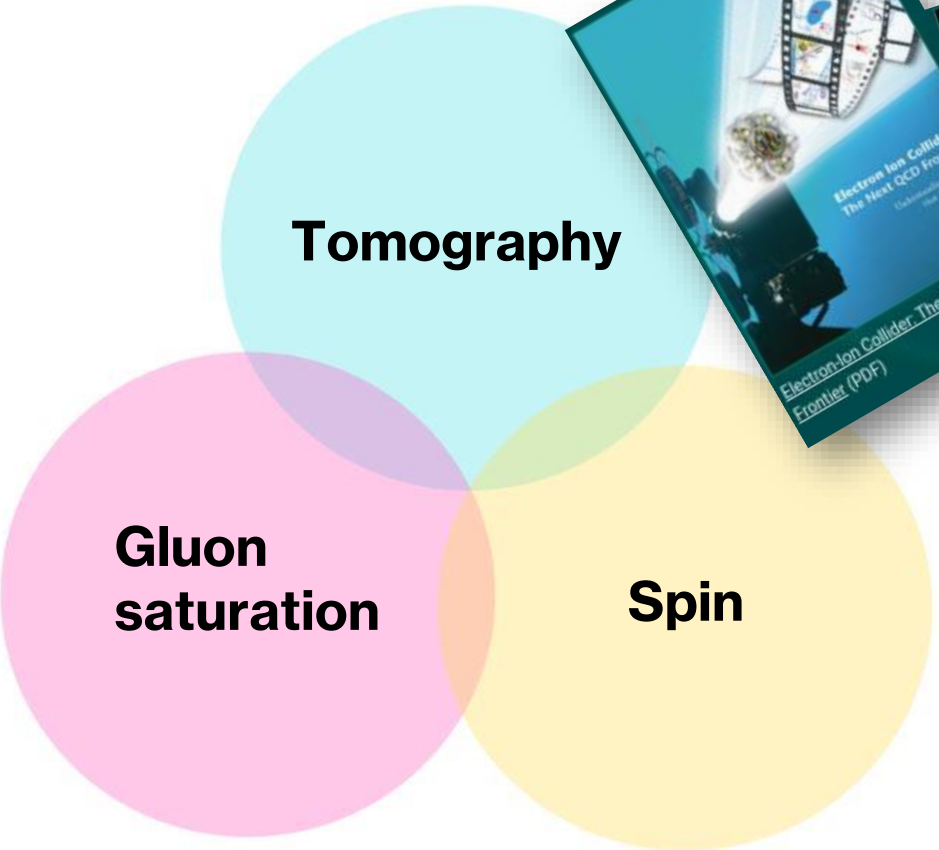
- Highly polarized (70%) e- and p beams
- Ion beams from D to U
- Variable center-of-mass energies from $\sqrt{s}$=20-140 GeV
- High collision luminosity $10^{33\text{-}34}$ cm^{-2}s^{-1} (HERA ~ 10^{31})
- Possibilities of having more than one interaction region

Unprecedented kinematic coverage opens the door to extraordinary physics opportunities, paving the way for a deeper understanding of fundamental phenomena.

Courtesy: T. Ullrich

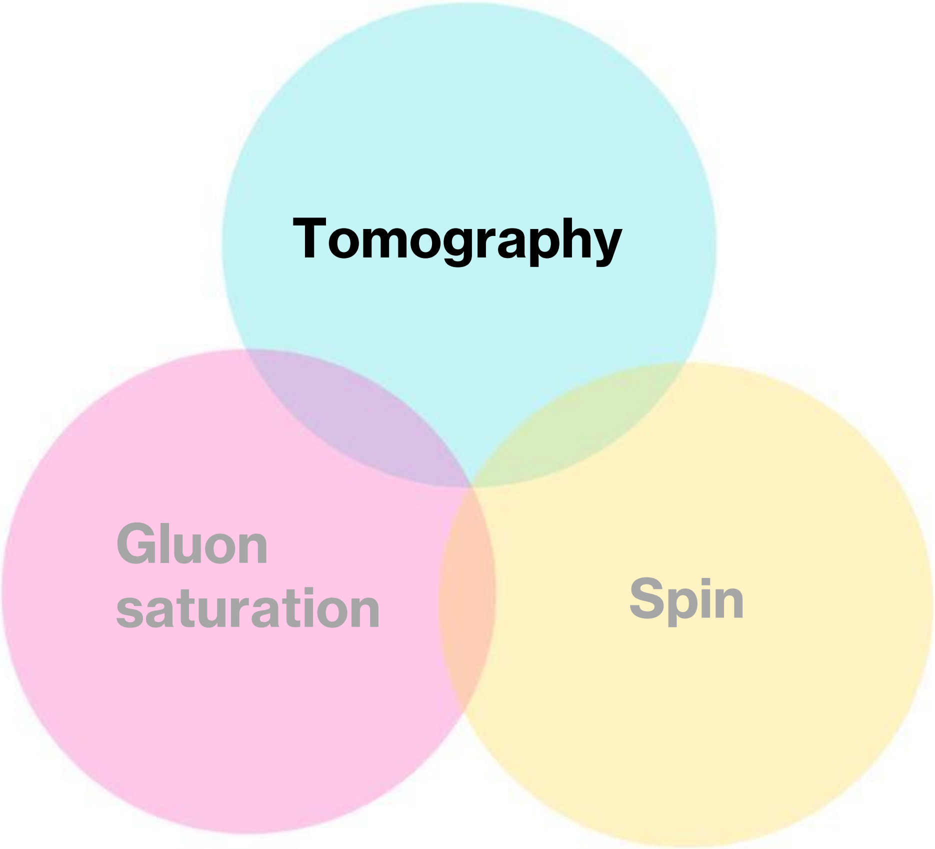
Scientific goals of Electron-Ion Collider

The EIC will strive to answer profound questions related to the 3 pillars:



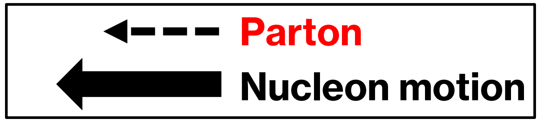
Scientific goals of Electron-Ion Collider

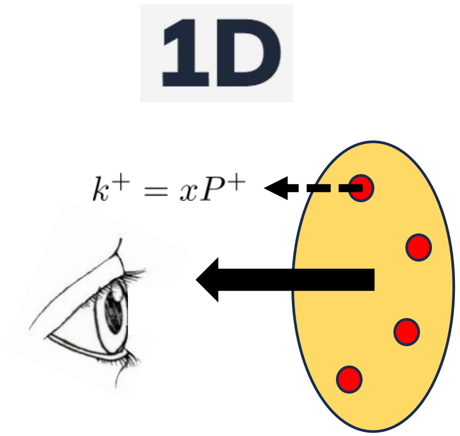
The EIC will strive to answer profound questions related to the 3 pillars:



Nonperturbative functions in QCD

Maps of internal dynamics of partons in multiple dimensions





Parton Distribution Functions

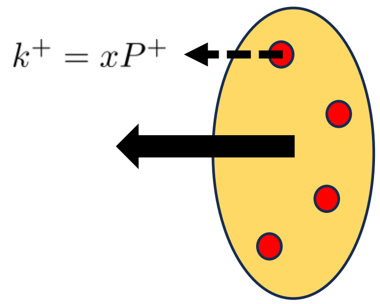
PDFs (x)

Nonperturbative functions in QCD

Maps of internal dynamics of partons in multiple dimensions

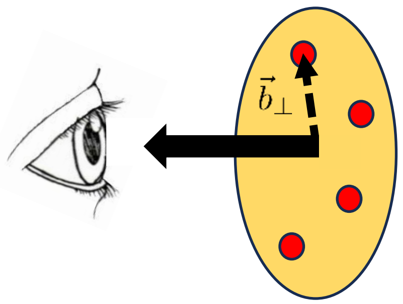
Parton
Nucleon motion

1D



2D

Form Factors



PDFs (x)

FFs (Δ)

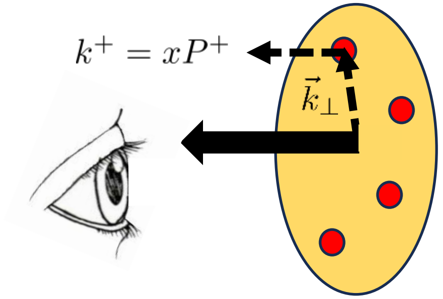
Nonperturbative functions in QCD

Maps of internal dynamics of partons in multiple dimensions

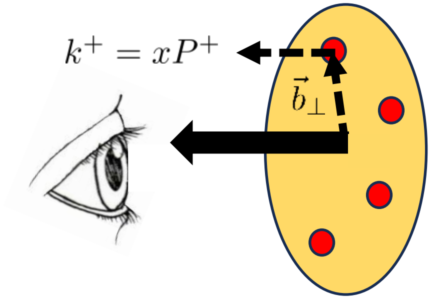
Parton
Nucleon motion

Transverse Momentum-dependent Distributions

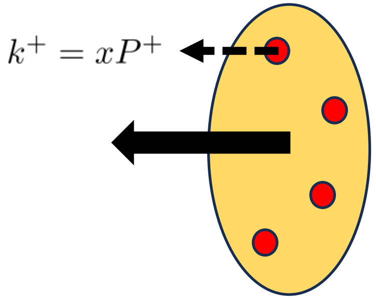
Generalized Parton Distributions



3D



1D

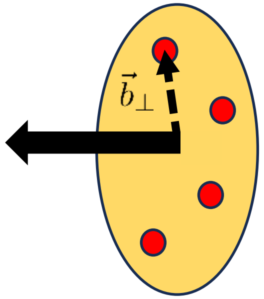


TMDs $(x, \vec{k}_\perp)$ $\xrightarrow{\int d^2\vec{k}_\perp}$ **PDFs** (x)

GPDs (x, Δ) $\xrightarrow{\Delta = 0}$ **PDFs** (x)

GPDs (x, Δ) $\xrightarrow{\int dx}$ **FFs** (Δ)

2D



Nonperturbative functions in QCD

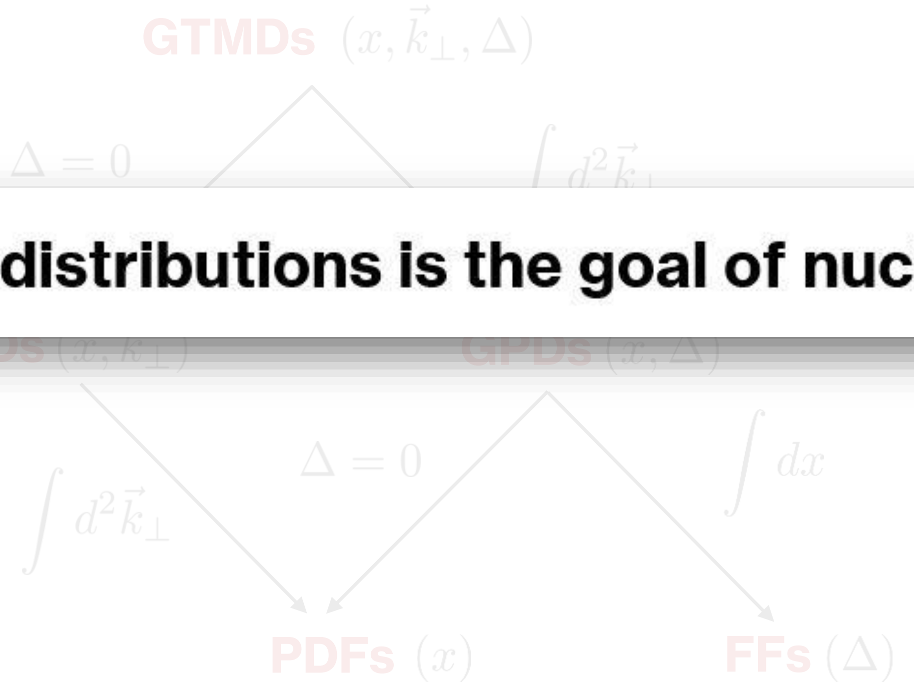
Maps of internal dynamics of partons in multiple dimensions

Generalized Transverse Momentum-dependent Distributions **5D**

$$
\begin{tikzcd}
 & \textbf{GTMDs}\ (x, \vec{k}_\perp, \Delta) \arrow[dl, "\Delta = 0"'] \arrow[dr, "\int d^2\vec{k}_\perp"] & & \\
\textbf{TMDs}\ (x, \vec{k}_\perp) \arrow[dr, "\int d^2\vec{k}_\perp"'] & & \textbf{GPDs}\ (x, \Delta) \arrow[dl, "\Delta = 0"'] \arrow[dr, "\int dx"] & \\
 & \textbf{PDFs}\ (x) & & \textbf{FFs}\ (\Delta)
\end{tikzcd}
$$

Nonperturbative functions in QCD

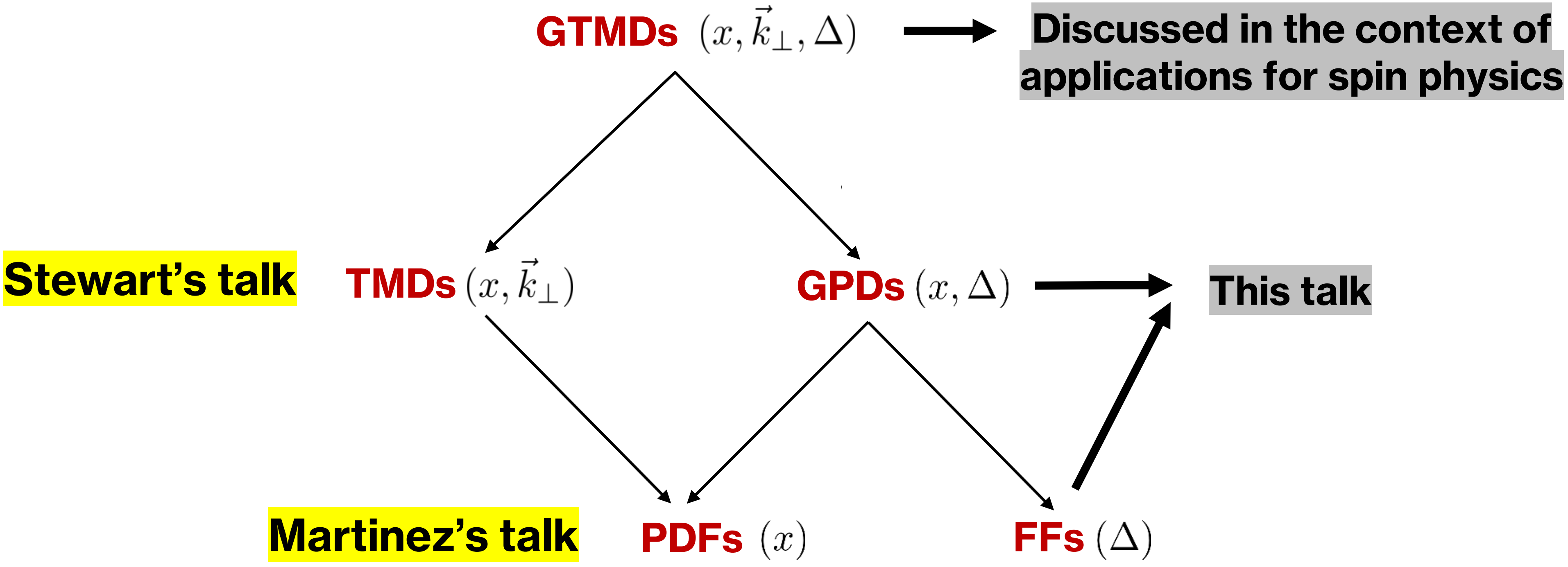
Maps of internal dynamics of partons in multiple dimensions



Mapping these partonic distributions is the goal of nucleon structure studies

Nonperturbative functions in QCD

Maps of internal dynamics of partons in multiple dimensions



Generalized Parton Distributions

Main motivations for studying GPDs

- **Tomography:**

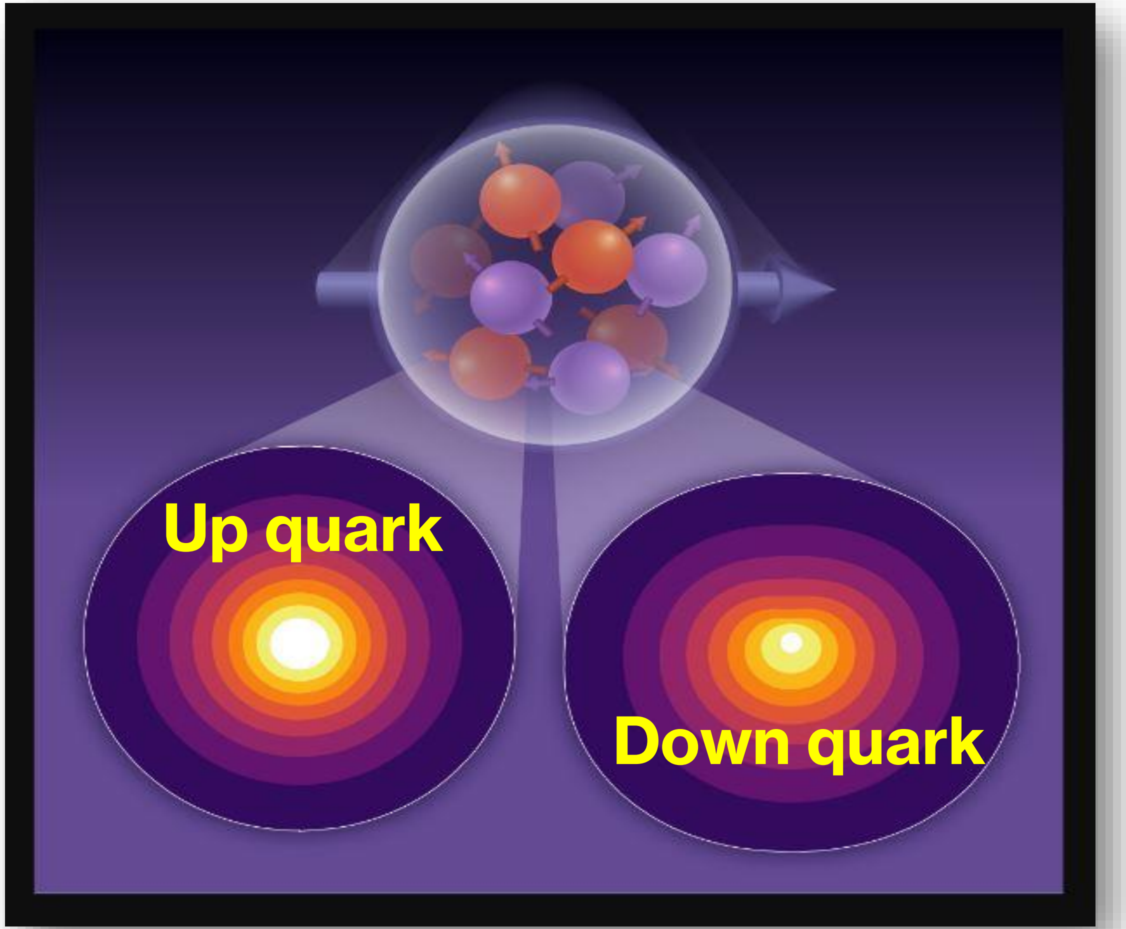
IMPACT PARAMETER SPACE INTERPRETATION FOR GENERALIZED PARTON DISTRIBUTIONS

MATTHIAS BURKARDT*

Department of Physics, New Mexico State University
Las Cruces, New Mexico 88011, U.S.A. †

$$\mathrm{GPD}(x, \xi = 0, \Delta_T) \quad \overset{F.T.}{\longleftrightarrow} \quad f(x, b_T)$$

(BNL/Temple, 2023)



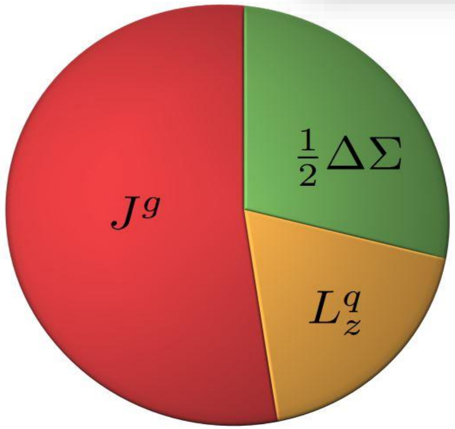
Generalized Parton Distributions

Main motivations for studying GPDs

- **Spin structure of nucleons:**

GAUGE-INVARIANT DECOMPOSITION OF NUCLEON SPIN AND ITS SPIN-OFF *

Xiangdong Ji



$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma(\mu) + L_z^q(\mu)}_{J^q} + J^g(\mu)$$

Total angular momentum of partons:

$$\boxed{J_q = \int_{-1}^{1} dx\, x\, (H_q + E_q)\Big|_{t=0}}$$

Generalized Parton Distributions

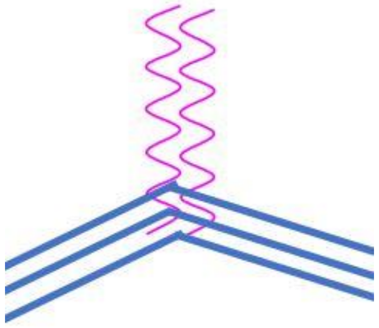
Main motivations for studying GPDs

- **Mechanical properties (pressure, shear) inside nucleon:**

On "dual" parametrizations of generalized parton distributions

M.V. Polyakov[a,b], A.G. Shuvaev[a]

Energy Momentum Tensor (EMT) carries information about mechanical properties:



Gravitational Form Factors

Gravitational Form Factors

$$\langle P_2|\Theta_f^{\mu\nu}|P_1\rangle = \frac{1}{M}\bar{u}(P_2)\left[P^\mu P^\nu A_f + (A_f+B_f)\frac{P^{(\mu}i\sigma^{\nu)\rho}l_\rho}{2} + \frac{D_f}{4}(l^\mu l^\nu - g^{\mu\nu}l^2) + M^2\bar{C}_f g^{\mu\nu}\right]u(P_1)$$

Gravitational Form Factors characterize the EMT in the context of proton scattering with a graviton

Generalized Parton Distributions

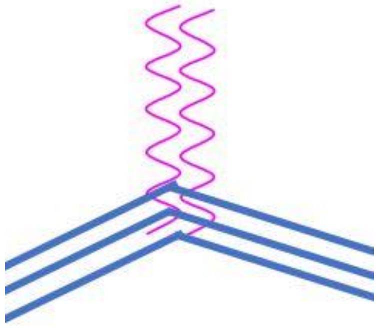
Main motivations for studying GPDs

- **Mechanical properties (pressure, shear) inside nucleon:**

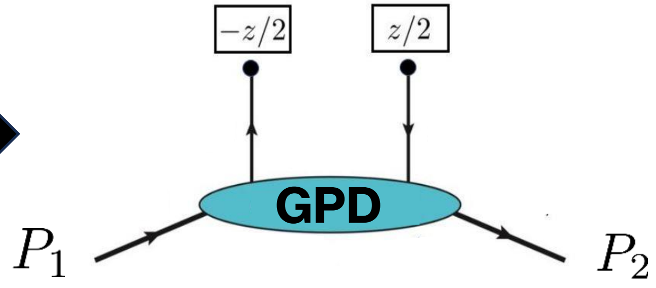
On "dual" parametrizations of generalized parton distributions

M.V. Polyakov[a,b], A.G. Shuvaev[a]

Exploit connections between Gravitational Form Factors and GPDs:



Gravitational Form Factors



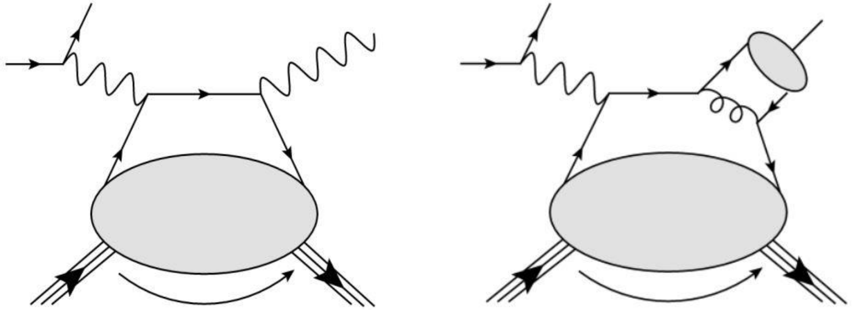
$$A + \xi^2 D = \int_{-1}^{1} dx\, xH$$

$$B - \xi^2 D = \int_{-1}^{1} dx\, xE$$

Generalized Parton Distributions

Key processes for measuring GPDs

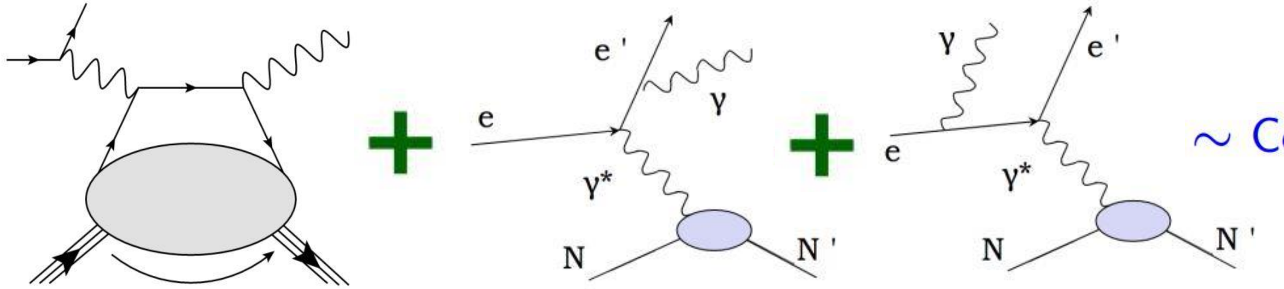
- Deep virtual Compton scattering (**DVCS**), Deep virtual meson production (**DVMP**)



X. Ji, Phys. Rev. D 55, 7114 (1997) A.V. Radyushkin, Phys. Lett. B 385 333 (1996) J. C. Collins et. al. Phys. Rev. D 56 2982 (1997)

Data available
for all those processes

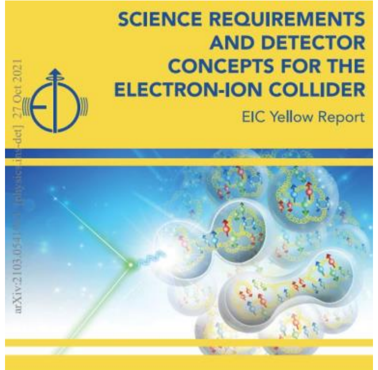
- Interference between DVCS and Bethe-Heitler amplitude plays key role



$\sim$ Compton form factor $\times$ electromagnetic form factor

Generalized Parton Distributions

Tomography: A big objective of mapping GPDs



> Our knowledge of GPDs from DVCS is currently limited and is based on fixed-target experiments at intermediate to high-x or on the HERA collider measurements at low-x. The polarized beams and higher luminosity at EIC, along with forthcoming data from JLab at 12 GeV, will make a very significant impact on those measurements. It is anticipated that measurements made for protons in the range $0.04 \lesssim t < 1.5\,\mathrm{GeV}^2$ will enable maps of parton distributions all the way down to 0.1 fm [7,23]. Such exclusive measurements performed on nuclei will enable us to understand the transverse quark and gluon distributions within.

GPDs are a core EIC physics topic

While experimental data from the EIC provides valuable insights into GPDs in specific kinematic regions, **synergy with new theoretical ideas as well as Lattice QCD calculations is essential to fully addressing the challenges of extracting GPDs**. In particular, Lattice QCD can play a complementary role to the EIC by offering crucial information in different kinematic regions, thereby broadening our understanding of GPDs beyond the reach of experimental data alone.

Generalized Parton Distributions

Challenges

Example of Compton Form Factor (CFF):

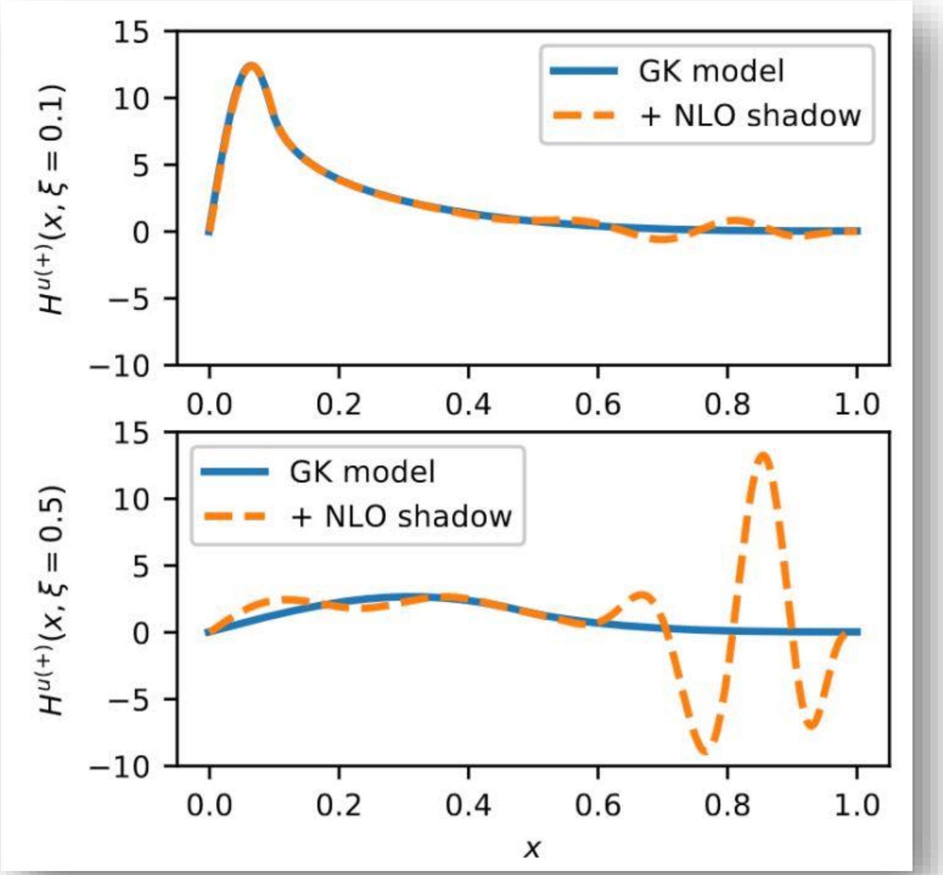
$$\mathcal{H}(\xi, t; \mu) = \sum_q e_q^2 \int_{-1}^{1} dx\, H^q(x, \xi, t; \mu) \left(\frac{1}{\xi - x - i\varepsilon} - \frac{1}{\xi + x - i\varepsilon} \right) + \mathcal{O}(\alpha_s)$$

Extraction of CFFs is difficult (multi-variable problem, complicated structure of cross section, power corrections, ...)

How to get from CFFs to GPDs? (deconvolution problem)

Generalized Parton Distributions

Tremendous Progress



Conceptual problem for model-independent GPD extractions

Deconvolution problem of deeply virtual Compton scattering

V. Bertone,[1,*] H. Dutrieux,[1,†] C. Mezrag,[1,‡] H. Moutarde,[1,§] and P. Sznajder[2,‖]

[1] *IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*

[2] *National Centre for Nuclear Research (NCBJ), Pasteura 7, 02-093 Warsaw, Poland*

- Studied “shadow GPDs” (nontrivial distributions with a null forward limit and negligible contributions to CFFs)
- Since experimental data are obtained at non-zero skewness, the extrapolation towards zero skewness required for proton tomography may suffer from the residual presence of shadow distributions
- Evolution hardly changes this picture

Generalized Parton Distributions

Tremendous Progress

Shedding light on shadow generalized parton distributions

Eric Moffat,[1,2,*] Adam Freese,[3] Ian Cloët,[1] Thomas Donohoe,[1] Leonard Gamberg,[2] W. Melnitchouk,[5,6] Andreas Metz,[4] Alexei Prokudin,[2,5] and Nobuo Sato[5]

- Confirms qualitative finding of Bertone et al

Optimistic situation: Emphasized the ability of QCD evolution to help limit the size of shadow GPDs when constrained by simulated CFFs data over a large range ξ, Q^2

Generalized Parton Distributions

Tremendous Progress

String-based parametrization of nucleon GPDs at any skewness: a comparison to lattice QCD

Kiminad A. Mamo*
Physics Department, William & Mary, Williamsburg, VA 23187, USA

Ismail Zahed†
Center for Nuclear Theory, Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA

- Introduced a string-based parametrization for nucleon quark and gluon GPDs
- Isovector nucleon quark GPD in agreement with existing lattice data

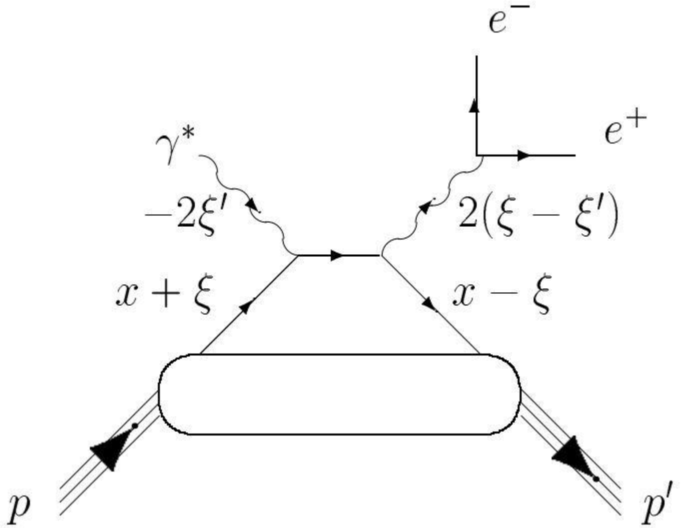
This works facilitates the empirical extraction and global analysis of nucleon GPDs in exclusive processes bypassing the deconvolution problem

Generalized Parton Distributions

Tremendous Progress

Potential way out: other processes with direct sensitivity to x-dependence of GPDs

1) Double DVCS



Double deeply virtual Compton scattering off the nucleon

M. Guidal[1] and M. Vanderhaeghen[2]

Phenomenology of double deeply virtual Compton scattering in the era of new experiments

Generalized Parton Distributions

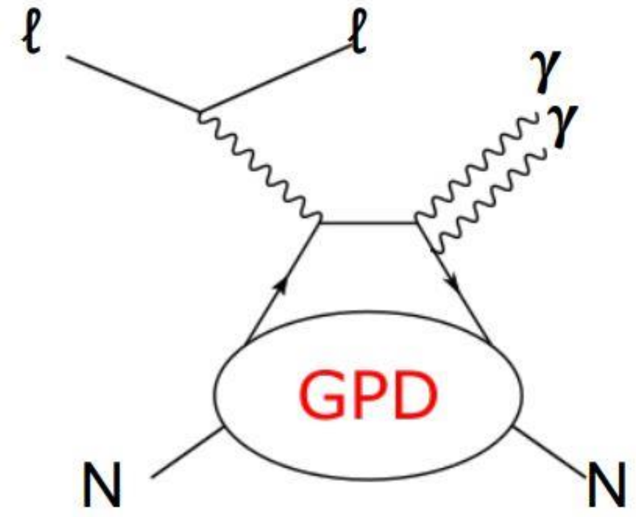
Tremendous Progress

Potential way out: other processes with direct sensitivity to x-dependence of GPDs

2) Diphoton production

Exclusive production of a pair of high transverse momentum photons in pion-nucleon collisions for extracting generalized parton distributions

Jian-Wei Qiu[a,b] Zhite Yu[c]



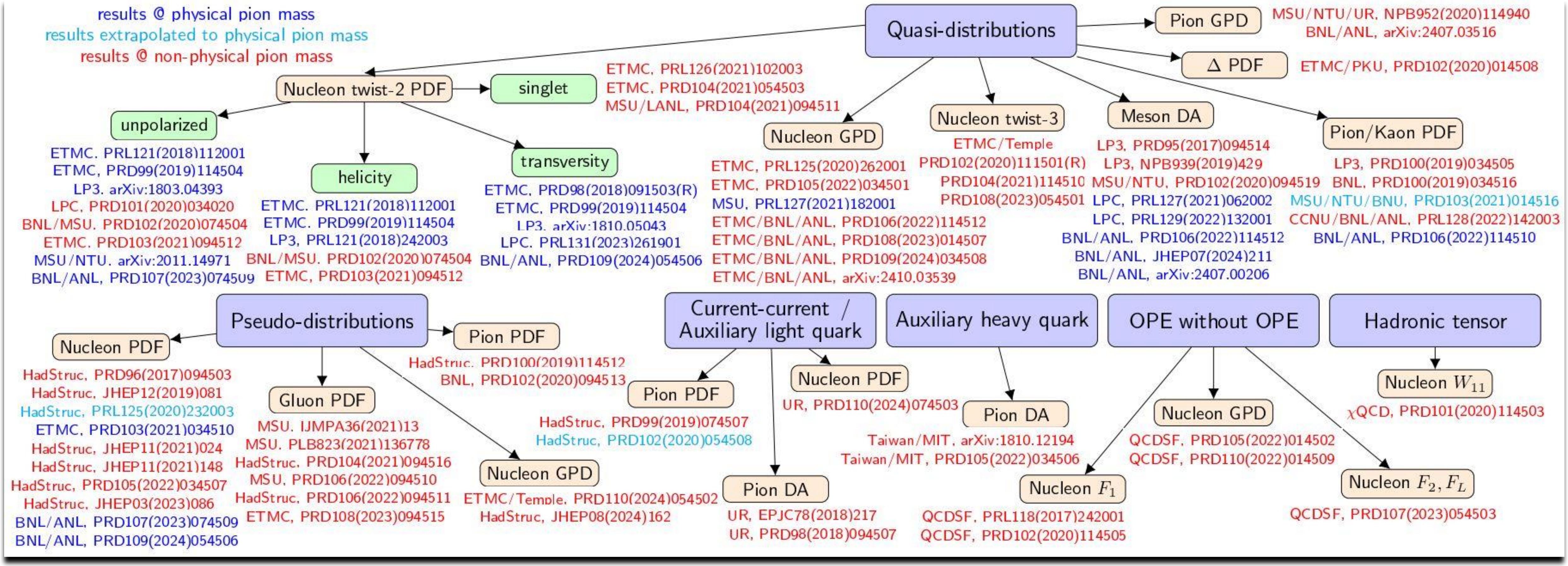
Phenomenology of diphoton photoproduction at next-to-leading order

O. Grocholski,[1,2] B. Pire,[3] P. Sznajder,[2] L. Szymanowski,[2] and J. Wagner[2]

Generalized Parton Distributions

Tremendous Progress

Lattice QCD calculations of **x-dependence** of GPDs & related quantities using Euclidean correlators



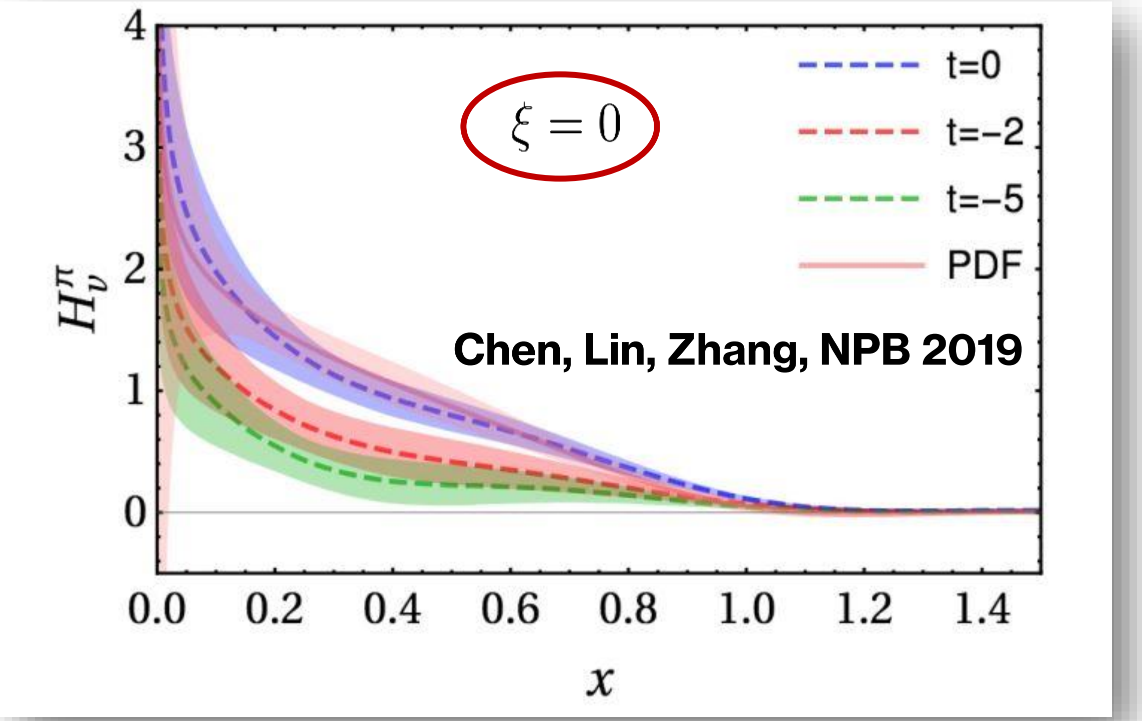
Compilation by K. Cichy

Generalized Parton Distributions

Tremendous Progress

- **Examples of pioneering Lattice QCD results:**

Pion:



- As t increases, distribution flattens

Generalized Parton Distributions

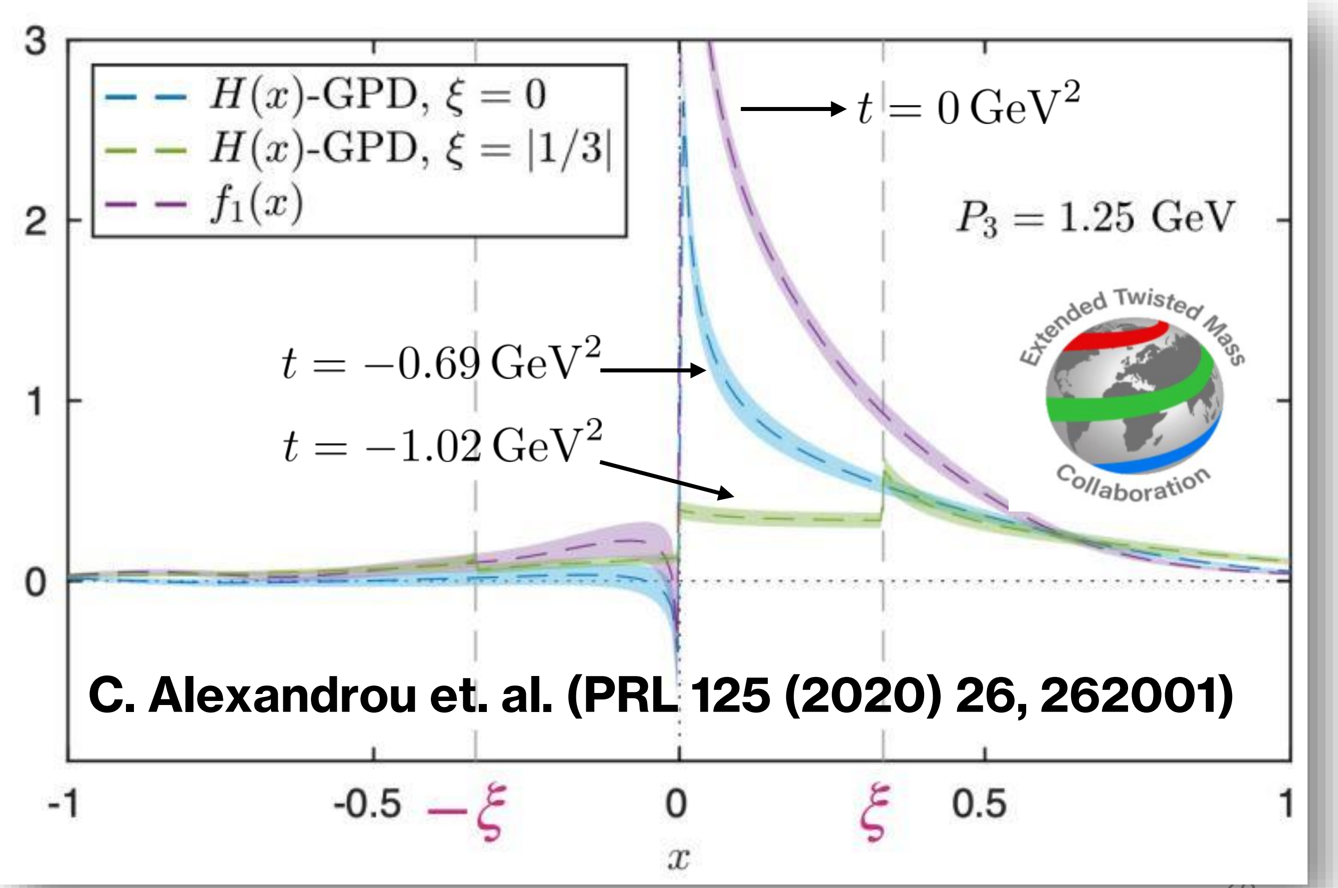
Tremendous Progress

- **Examples of pioneering Lattice QCD results:**

Proton:

- ERBL/DGLAP: Qualitative differences

- As $x \to 1$, qualitative agreement with power counting analysis (Yuan, 0311288)



C. Alexandrou et. al. (PRL 125 (2020) 26, 262001)

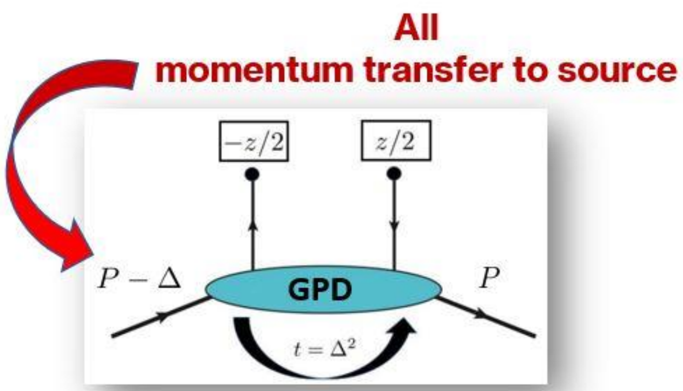
Generalized Parton Distributions

Tremendous Progress

- **Recent faster, cheaper and precise GPD calculations**: exploiting non-symmetric frames

Generalized Parton Distributions from Lattice QCD
with Asymmetric Momentum Transfer: Unpolarized Quarks

Shohini Bhattacharya,[1,*] Krzysztof Cichy,[2] Martha Constantinou,[3,†] Jack Dodson,[3] Xiang Gao,[4] Andreas Metz,[3] Swagato Mukherjee,[1] Aurora Scapellato,[3] Fernanda Steffens,[5] and Yong Zhao[4]

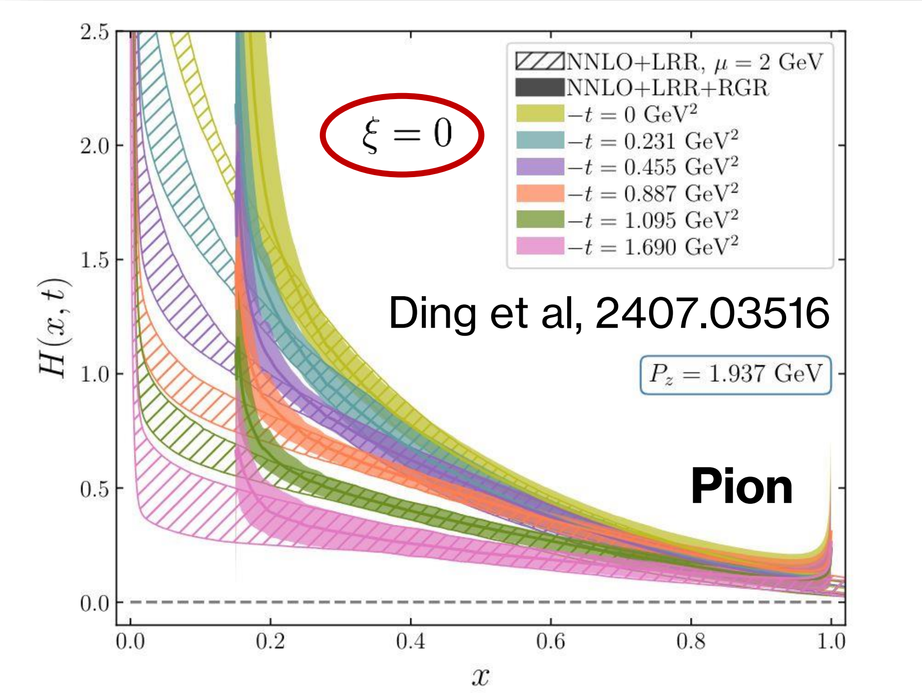


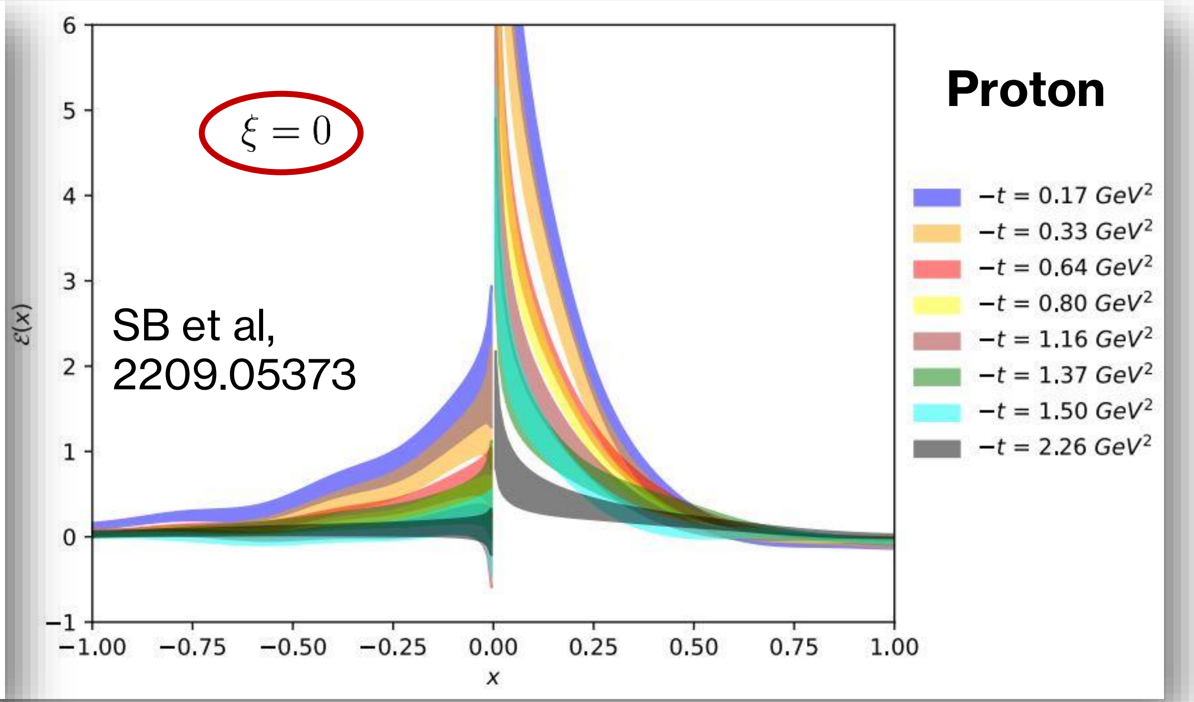
Generalized Parton Distributions

Tremendous Progress

- **Recent faster, cheaper and precise GPD calculations**: exploiting non-symmetric frames

Example:





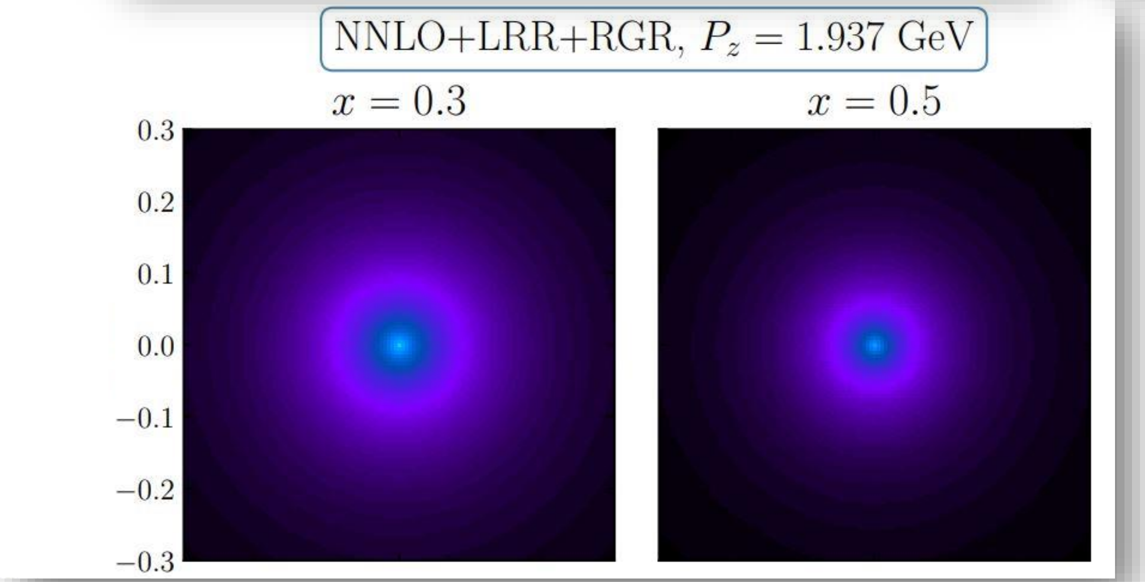
Generalized Parton Distributions

Tremendous Progress

- **Tomography from Lattice QCD**: Moments of GPDs using short-distance factorization

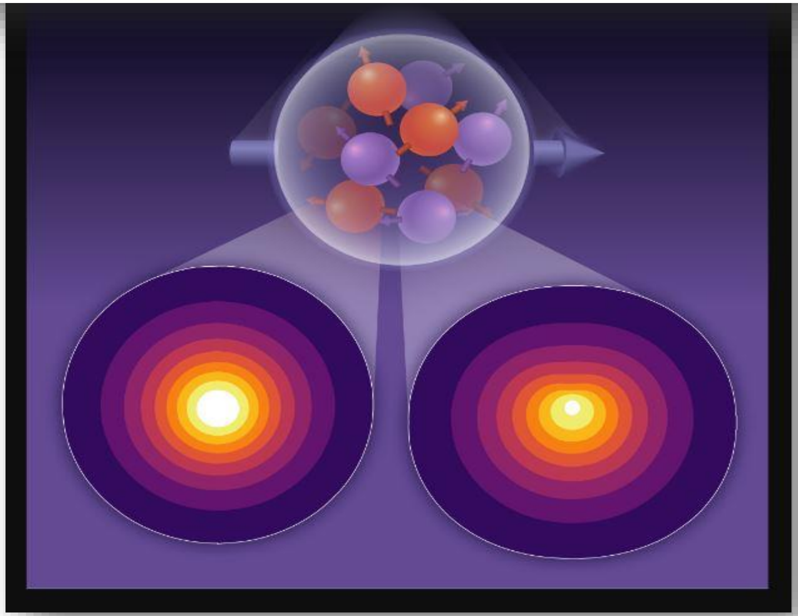
Three-dimensional Imaging of Pion using Lattice QCD: Generalized Parton Distributions

Heng-Tong Ding,[1] Xiang Gao,[2] Swagato Mukherjee,[3] Peter Petreczky,[3] Qi Shi,[1,3,*] Sergey Syritsyn,[4] and Yong Zhao[2]



Moments of proton GPDs from the OPE of nonlocal quark bilinears up to NNLO

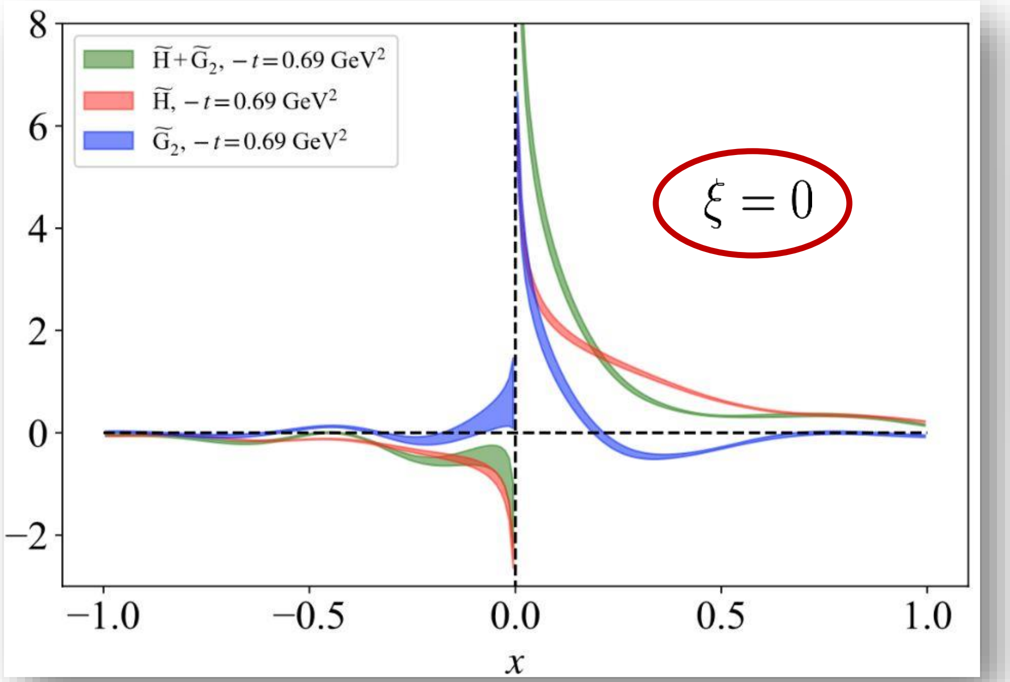
Shohini Bhattacharya,[1] Krzysztof Cichy,[2] Martha Constantinou,[3] Xiang Gao,[4,*] Andreas Metz,[3] Joshua Miller,[3] Swagato Mukherjee,[5] Peter Petreczky,[5] Fernanda Steffens,[6] and Yong Zhao[4]



Generalized Parton Distributions

Tremendous Progress

- First results of quark **twist-3 GPDs**



Chiral-even axial twist-3 GPDs of the proton from lattice QCD

Shohini Bhattacharya[1,2], Krzysztof Cichy[3], Martha Constantinou[1], Jack Dodson[1], Andreas Metz[1], Aurora Scapellato[1], Fernanda Steffens[4]

Generalized Parton Distributions

Tremendous Progress

- New **global analyses** of GPDs

Generalized Parton Distributions

Tremendous Progress

- New **global analyses** of GPDs

Courtesy: Y. Guo

Global GPD Global analysis efforts

Gepard

K. Kumericki et al.
Nucl. Phys. B 794 244-323 (2008)

PARTONS

EXCLAIM

EXCLAIM

EXCLusives via AI and Maching-Learning

Recently funded DOE Topical Collaboration:

QUARK-GLUON TOMOGRAPHY COLLABORATION

Machine Learning Approach

Eric Moffat et al.
Phys. Rev. D 108 3, 036027 (2023)

FemtoNET

M. Almaeen et al.
arxiv: 2207.10766

STRONG 2020

B. Berthou et al.
Eur. Phys. J. C 78 6, 478 (2018)

GUMP

Y. Guo et. al. JHEP 09 215 (2022)
Y. Guo et. al. JHEP 05 150 (2023)

Generalized Parton Distributions

Tremendous Progress

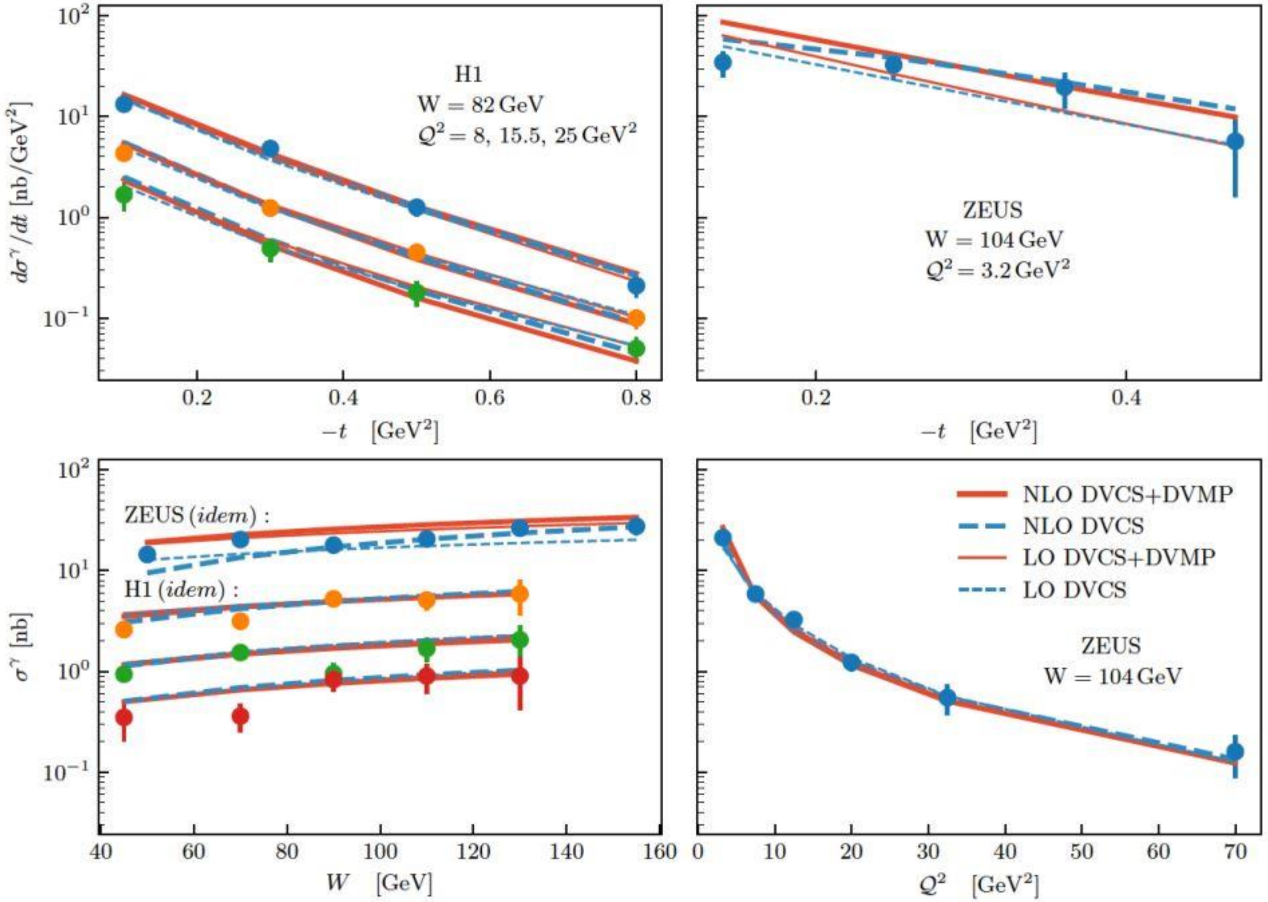
- New **global analyses** of GPDs

NLO corrections to the deeply virtual meson production revisited: impact on the extraction of generalized parton distributions

Marija Čuić[1], Goran Duplančić[2], Krešimir Kumerički[1], Kornelija Passek-K.[2]

Recent simultaneous fit of DVCS and DVMP

Fit of DVCS data



Generalized Parton Distributions

Tremendous Progress

- New **global analyses** of GPDs

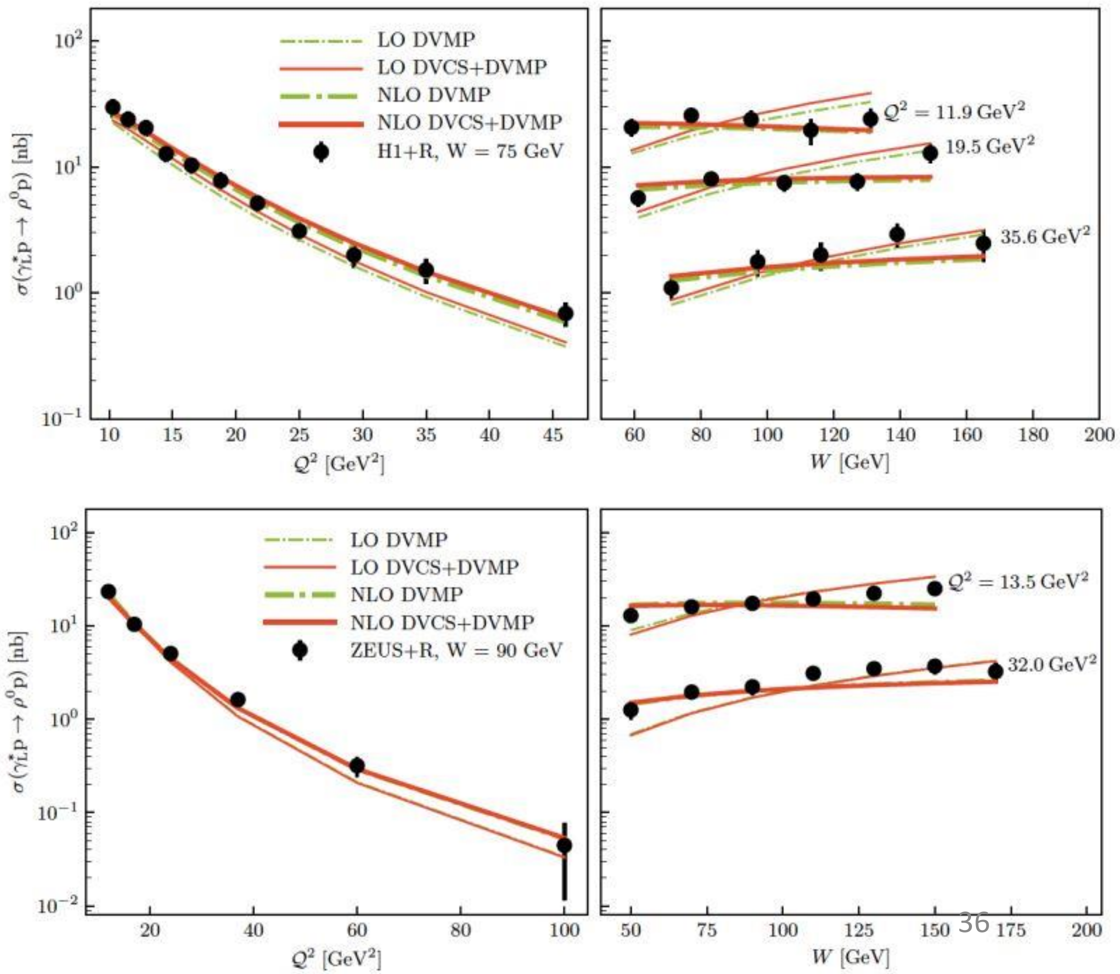
NLO corrections to the deeply virtual meson production revisited: impact on the extraction of generalized parton distributions

Marija Čuić[1], Goran Duplančić[2], Krešimir Kumerički[1], Kornelija Passek-K.[2]

Recent simultaneous fit of DVCS and DVMP:

- Overall finding: successful combined fit at NLO
- Important step forward in this field

Fit of DVMP data



Generalized Parton Distributions

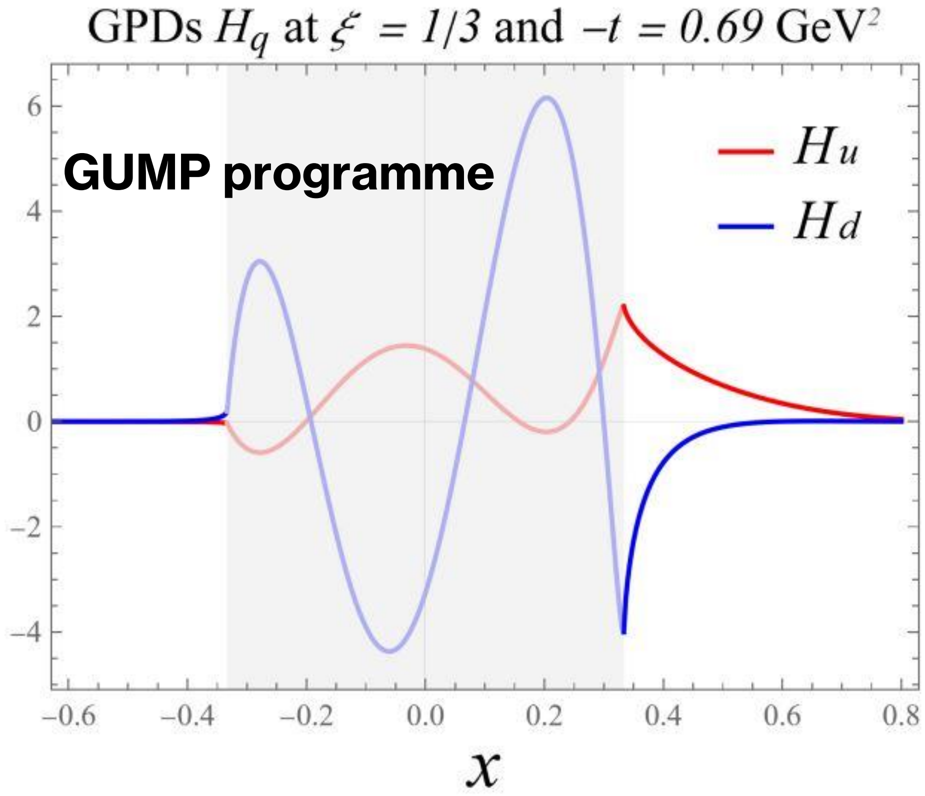
Tremendous Progress

- New **global analyses** of GPDs

Generalized parton distributions through universal moment parameterization: non-zero skewness case

Yuxun Guo[a,d], Xiangdong Ji[a], M. Gabriel Santiago[b], Kyle Shiells[c] and Jinghong Yang[a]

The first global analysis of GPDs combining
Lattice QCD calculations and experimental measurements



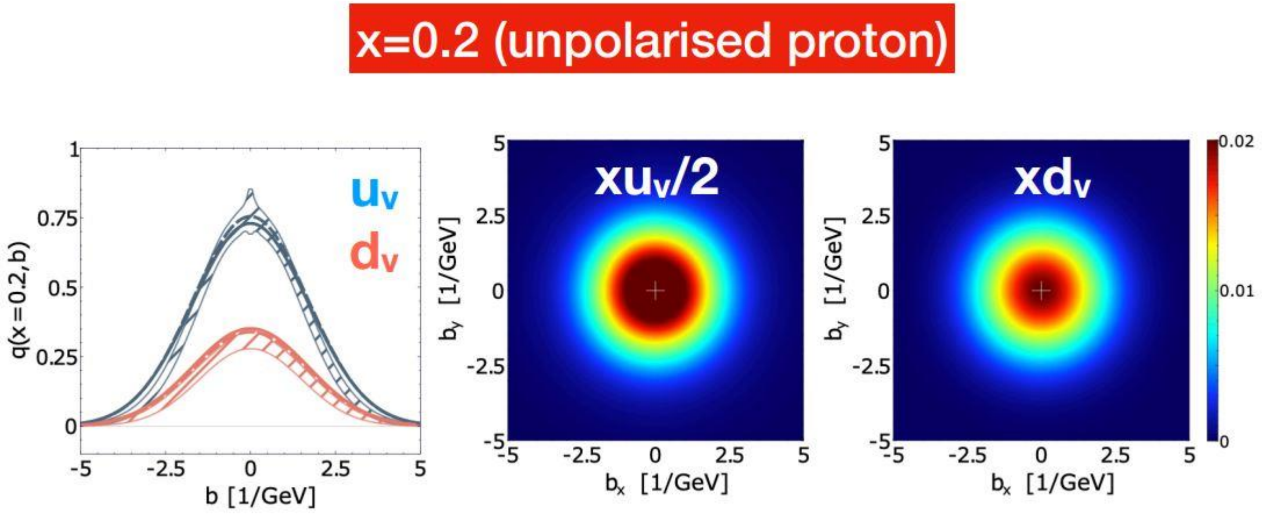
Generalized Parton Distributions

Tremendous Progress

- Recent exploratory work on **integrating lattice QCD results with experimental data**

Nucleon tomography and total angular momentum of valence quarks from synergy between lattice QCD and elastic scattering data

Krzysztof Cichy[1], Martha Constantinou[2], Paweł Sznajder[3], Jakub Wagner[3]



Total angular momentum

Our result
(elastic and lattice-QCD data):

$$J^{u_v} = 0.195 \pm 0.010$$
$$J^{d_v} = 0.0173 \pm 0.0046$$

Diehl-Kroll / EPJC 73, 2397 (2013)
(elastic data):

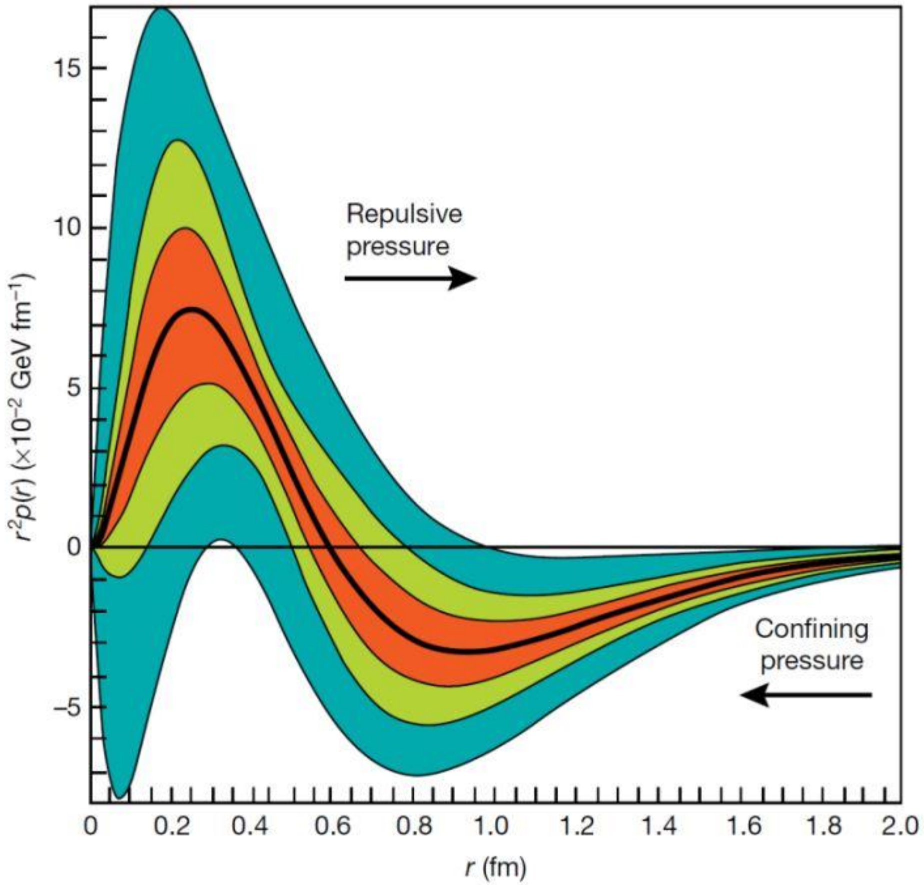
$$J^{u_v} = 0.230^{+0.009}_{-0.024}$$
$$J^{d_v} = -0.004^{+0.010}_{-0.016}$$

Courtesy P. Sznajder

Form Factors

Tremendous Progress

- Extraction of **energy momentum tensor form factor** $D(t)$ from DVCS data



LETTER

https://doi.org/10.1038/s41586-018-0060-z

The pressure distribution inside the proton

V. D. Burkert[1]*, L. Elouadrhiri[1] & F. X. Girod[1]

- Pressure distribution inside proton

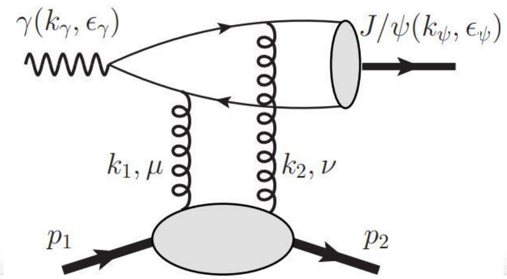
- Mechanical radius of the proton

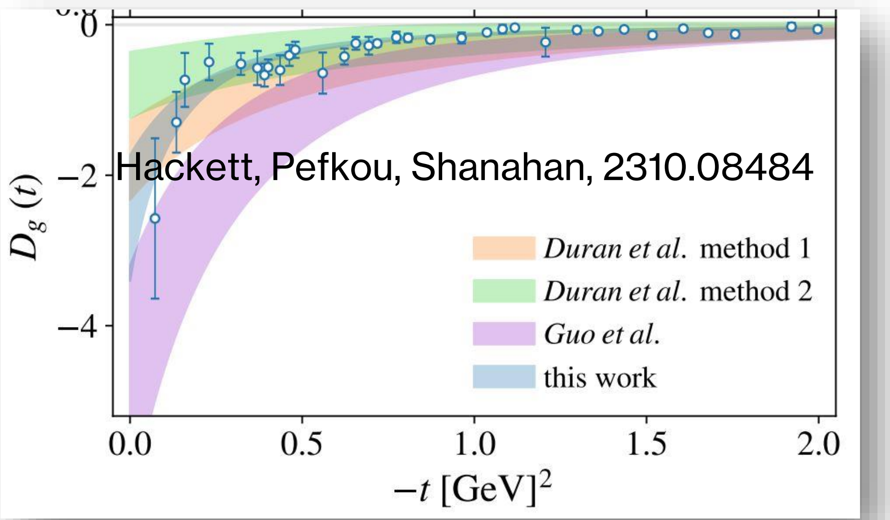
$$r^{\mathrm{mech}}_{p,\mathrm{RMS}} = (0.634 \pm 0.057)\ \mathrm{fm}$$

Form Factors

Tremendous Progress

- Threshold production of **quarkonium and gluon EMT form factors**
  - Recent measurements of *J/Psi* production from JLab
  - Reliable information about gluon EMT form factors from those data (Sun, Tong, Yuan, 2111.07034 / Guo, Ji, Yuan, 2308.13006 / ...)
  - Lattice QCD does significantly contribute (Hackett, Pefkou, Shanahan, 2310.08484 / ...)





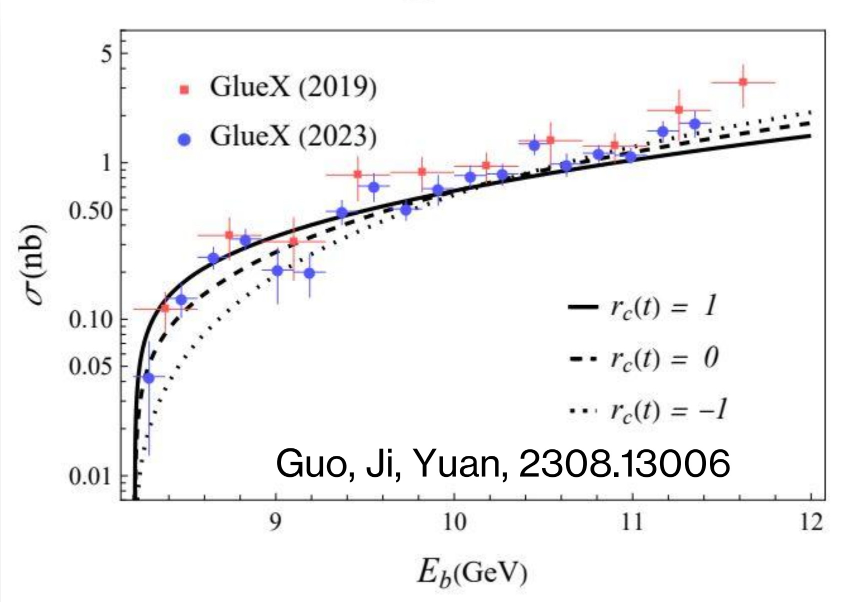
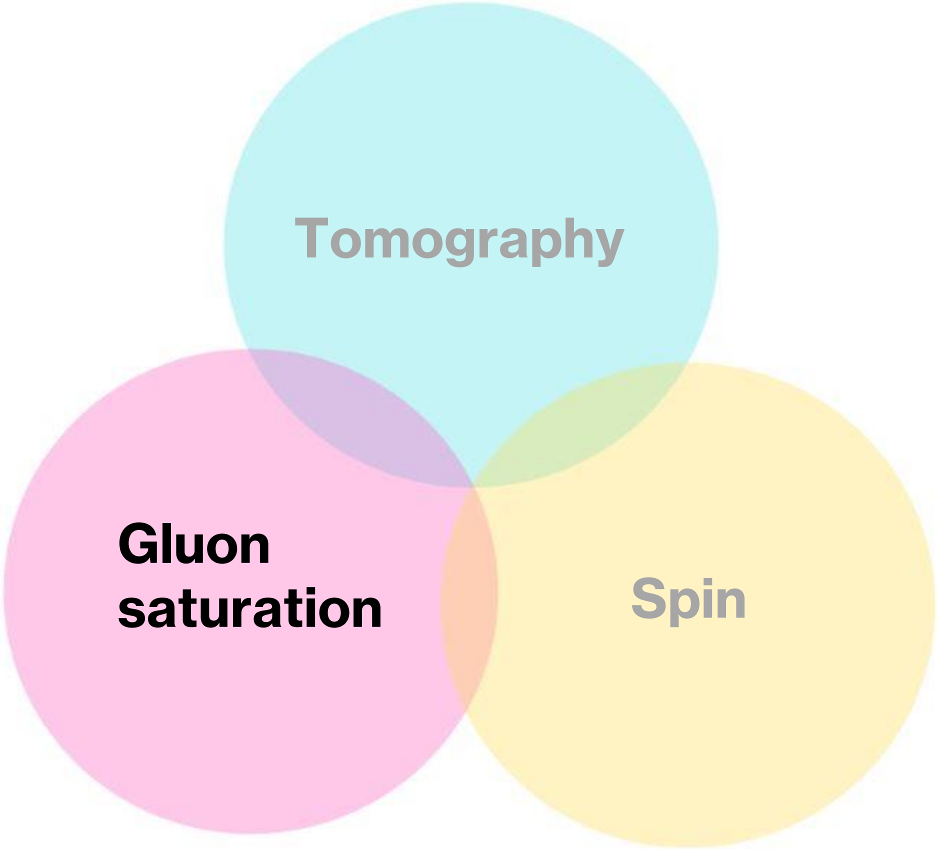


FIG. 9: Total cross sections σ(nb) with different $r_C(t)$ compared to the GlueX measurements. The solid, dashed, and dotted lines correspond to fits with $r_C = 1$, $r_C = 0$, and $r_C = -1$. Normalization factors are determined by the differential cross section only.

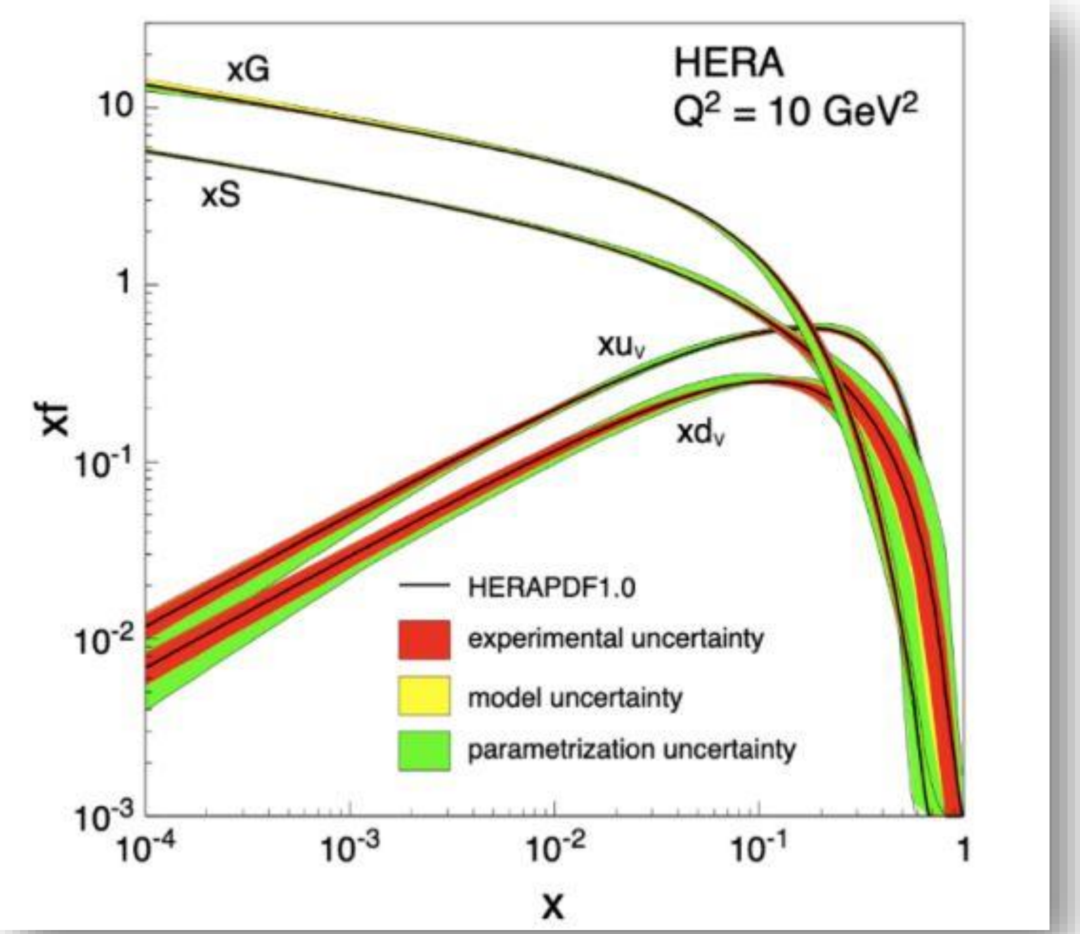
Scientific goals of Electron-Ion Collider

The EIC will strive to answer profound questions related to the 3 pillars:



QCD at small-x

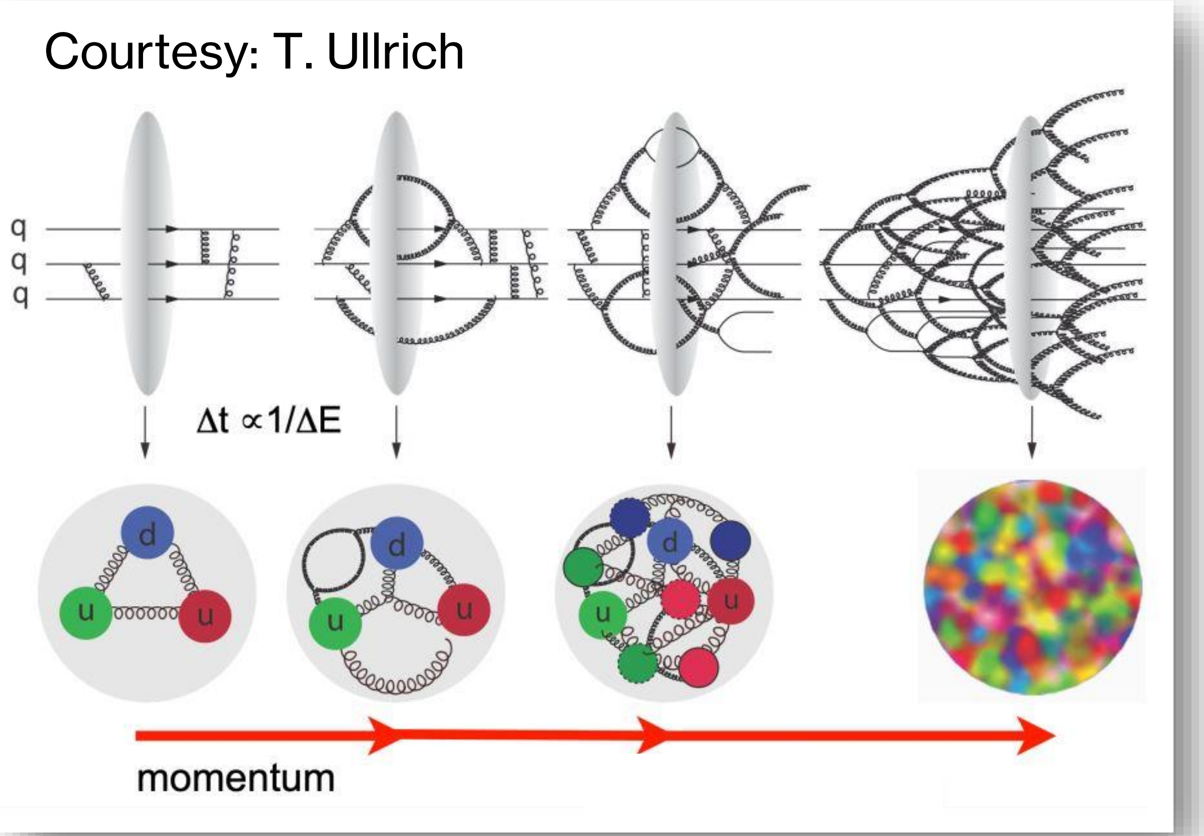
Anatomy of QCD at high energies



A multitude of small-x gluons in a high energy hadron/nucleus

QCD at small-x

Gluon saturation



Partonic picture superseded
by **strong highly occupied fields**

The gluon number eventually saturates, forming the universal QCD matter at high energy called the **Color Glass Condensate (CGC)**

(Gribov, Levin, Ryskin (1980); Mueller, Qiu (1986); McLerran, Venugopalan (1993))

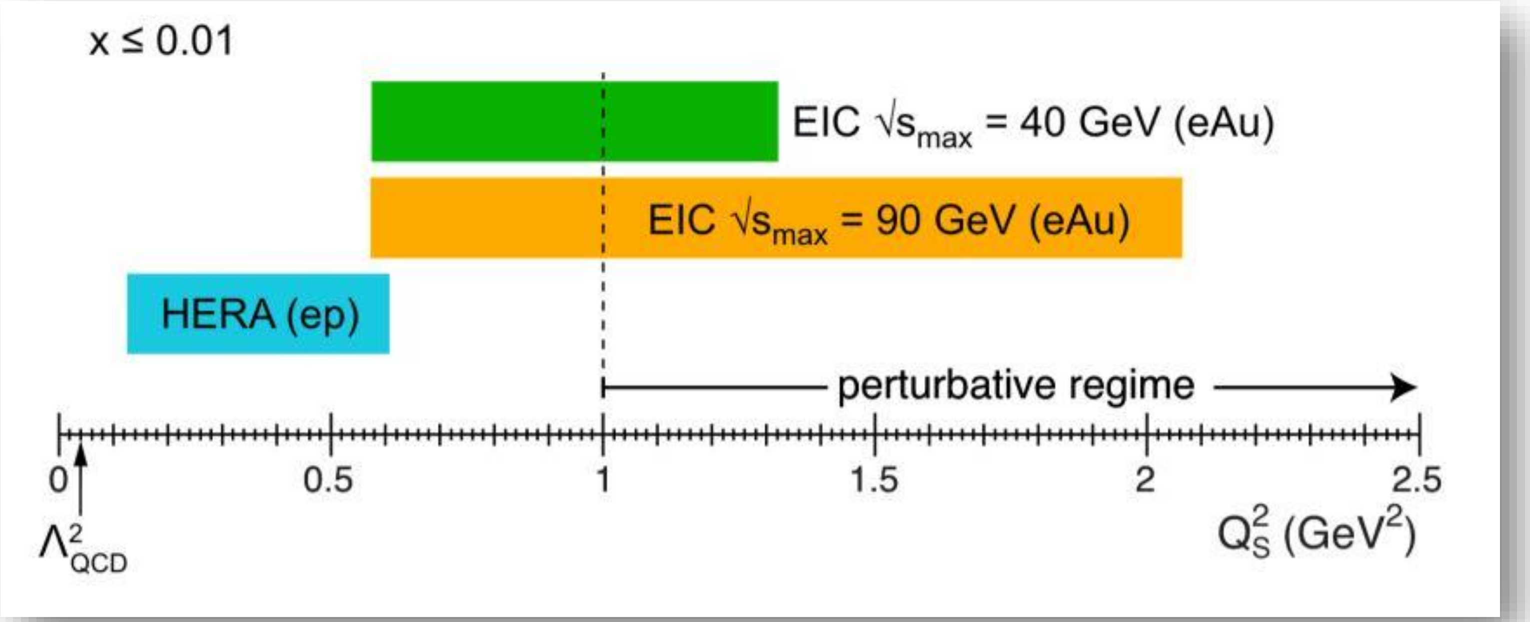
Emergence of an energy and nuclear species dependent momentum scale:

$$\boxed{Q_s^2 \propto A^{1/3} s^{1/3}}$$

Q_s : saturation scale

QCD at small-x

Gluon saturation



$$Q_s^2 \propto A^{1/3} s^{1/3}$$

EIC is an ideal place to study saturation:
Enhanced nuclear saturation momentum: a distinct advantage over HERA

QCD at small-x

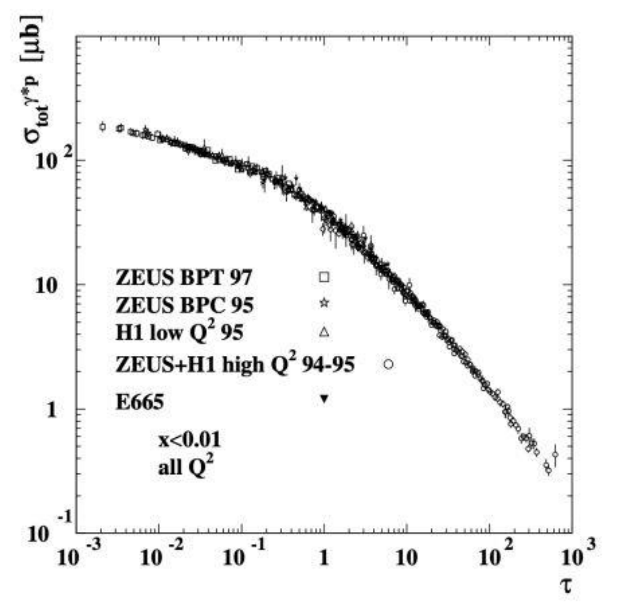
Experimental status

- Heavy-ion collisions, hadronic collisions, UPCs (RHIC, LHC)
- Deep-inelastic scattering (HERA, EIC)
- Inclusive, semi-inclusive, diffractive processes

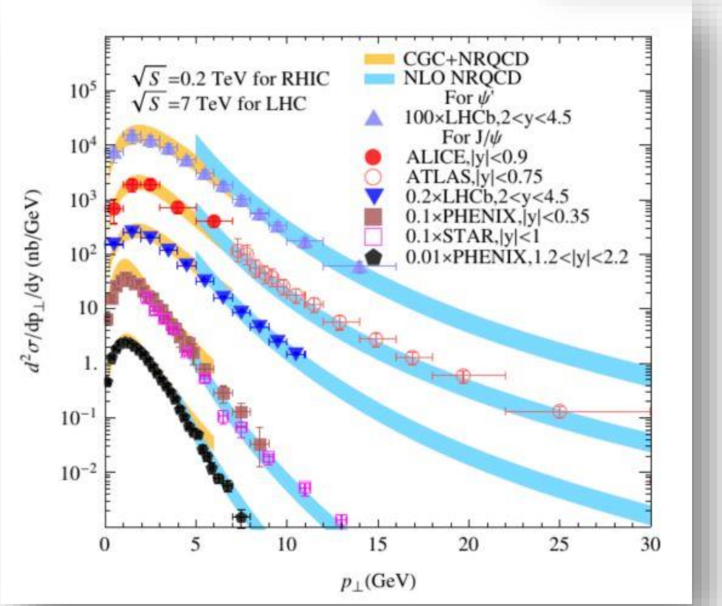
Article

Mining for Gluon Saturation at Colliders

Astrid Morreale [1,‡], Farid Salazar [2,3,4,‡]



Geometric scaling at RHIC



Quarkonium production at RHIC and LHC

Compelling but not definitive evidence yet

QCD at small-x

Tremendous Progress

Precision frontier for gluon saturation: **Evolution equations** at **NLL** accuracy

The evolution of the **BK equation** through the years:

NLL

NLO evolution of color dipoles

Ian Balitsky and Giovanni A. Chirilli

NLL with resummation

HERA data and collinearly-improved BK dynamics

B. Ducloué [a,b], E. Iancu [a,*], G. Soyez [a], D.N. Triantafyllopoulos [c]

QCD at small-x

Tremendous Progress

Precision frontier for gluon saturation: **Evolution equations** at **NLL** accuracy

The evolution of the **JIMWLK equation** through the years:

NLL

Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner evolution at next to leading order.

Alex Kovner[1], Michael Lublinsky[2] and Yair Mulian[2]

NLL with resummation

Collinearly improved JIMWLK evolution in Langevin form

Yoshitaka Hatta[a] and Edmond Iancu[b]

QCD at small-x

Tremendous Progress

Precision frontier for gluon saturation: **Impact factors** at **NLO** accuracy

Structure functions

Photon impact factor in the next-to-leading order

Ian Balitsky
Physics Dept., ODU, Norfolk VA 23529, and
Theory Group, Jlab, 12000 Jefferson Ave,
*Newport News, VA 23606**

Giovanni A. Chirilli

Light quarks

Massive quarks in NLO dipole factorization for DIS: Transverse photon

G. Beuf,[1] T. Lappi,[2,3] and R. Paatelainen[3,4]

Massive quarks

QCD at small-x

Tremendous Progress

Precision frontier for gluon saturation: **Impact factors** at **NLO** accuracy

Diffractive processes in DIS

See also Schindler's talk

Paving the Way Towards Precision Physics in Saturation Studies Through Exclusive Diffractive Light Neutral Vector Meson Production

R. Boussarie
Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, PL-31-342 Kraków, Poland

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Sobolev Institute of Mathematics, 630090 Novosibirsk, Rus

L. Szymanowski
National Centre for Nuclear Research (NCBJ), Warsaw, Po

S. Wallon

Dijets and
Light vector meson

NLO computation of diffractive di-hadron production in a saturation framework

Dihadron

Michael Fucilla,[a,b,c] Andrey Grabovsky,[d,e] Emilie Li,[c] Lech Szymanowski[f] and Samuel Wallon[c]

QCD at small-x

Tremendous Progress

Precision frontier for gluon saturation: **Impact factors** at **NLO** accuracy

Semi-inclusive processes in DIS

Back-to-back inclusive dijets in DIS at small x: Complete NLO results and predictions

Paul Caucal,[1,*] Farid Salazar,[2,3,4,5,†] Björn Schenke,[6,‡] Tomasz Stebel,[7,§] and Raju Venugopalan[6,¶]

Dijets

One-loop corrections to dihadron production in DIS at small x

Filip Bergabo[*] and Jamal Jalilian-Marian[†]

Dihadron

QCD at small-x

Tremendous Progress

Precision frontier for gluon saturation: **Impact factors** at **NLO** accuracy

Semi-inclusive processes in pA

THE NLO INCLUSIVE FORWARD HADRON PRODUCTION IN pA COLLISIONS

Single hadron

GIOVANNI CHIRILLI

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BO-WEN XIAO*

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University Park, PA 16802, USA
and
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FENG YUAN

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Single inclusive jet production in pA collisions at NLO in the small-x regime

Single jet

Hao-yu Liu,[a,b] Kexin Xie,[c] Zhong-Bo Kang[d,e,f] and Xiaohui Liu[a,b,g]

QCD at small-x

Tremendous Progress

Global analysis with implementation of (KPS-CTT) **small-x helicity evolution**

Global analysis of polarized DIS & SIDIS data with improved small-x helicity evolution

Daniel Adamiak,[1,2] Nicholas Baldonado,[3] Yuri V. Kovchegov,[1] W. Melnitchouk,[2] Daniel Pitonyak,[4] Nobuo Sato,[2] Matthew D. Sievert,[3] Andrey Tarasov,[5,6] and Yossathorn Tawabutr[7,8]

- DGLAP-based fits of helicity PDFs are plagued with extrapolation errors at small x
- Derivation and implementation of improved (KPS-CTT) small-x evolution equations

QCD at small-x

Outstanding challenges

- Identification of **novel observables**

Explore the Nucleon Tomography through Di-hadron Correlation in Opposite Hemisphere in Deep Inelastic Scattering

Yuxun Guo[1,*] and Feng Yuan[1,†]

Novel Cross Section Ratios as Possible Signals of Saturation in UPCs

Yuri V. Kovchegov,[1,*] Huachen Sun,[1,†] and Zhoudunming Tu[2,‡]

Direct quarkonium production in DIS from a joint CGC and NRQCD framework

Vincent Cheung,[1,*] Zhong-Bo Kang,[2,3,†] Farid Salazar,[4,5,6,2,3,‡] and Ramona Vogt[1,7,§]

Spatial imaging of polarized deuterons at the Electron-Ion Collider

Heikki Mäntysaari,[1,2] Farid Salazar,[3] Björn Schenke,[4] Chun Shen,[5,6] and Wenbin Zhao[7,8]

QCD at small-x

Outstanding challenges

- Identification of **novel observables**
- **Spin physics** and saturation

Quark and Gluon Helicity Evolution at Small x: Revised and Updated

Florian Cougoulic,[1,*] Yuri V. Kovchegov,[2,†] Andrey Tarasov,[2,3,‡] and Yossathorn Tawabutr[2,§]

QCD at small-x

Outstanding challenges

- Identification of **novel observables**
- **Spin physics** and saturation
- Unification of dilute and dense QCD (beyond CGC)
- How to do **small-x physics** from **Lattice QCD?**

Low and moderate x gluon contribution to exclusive Compton scattering processes

R. Boussarie[a] Y. Mehtar-Tani[b,c]

A unified description of DGLAP, CSS, and BFKL: TMD factorization bridging large and small x

Swagato Mukherjee,[1,*] Vladimir V. Skokov,[2,†] Andrey Tarasov,[2,3,‡] and Shaswat Tiwari[2,§]

QCD at small-x

Outstanding challenges

- Identification of **novel observables**
- **Spin physics** and saturation
- Unification of dilute and dense QCD (beyond CGC)
- How to do **small-x physics** from **Lattice QCD?**

SURGE
COLLABORATION

Recently funded
DOE Topical Collaboration

Discovery and characterization of gluon saturation principal goals of the future Electron-Ion Collider

QCD at small-x

Other novel directions

- Entanglement entropy and saturation

QCD evolution of entanglement entropy

Martin Hentschinski,[1,*] Dmitri E. Kharzeev,[2,3,†] Krzysztof Kutak,[4,‡] and Zhoudunming Tu[3,§]

Kharzeev's talk

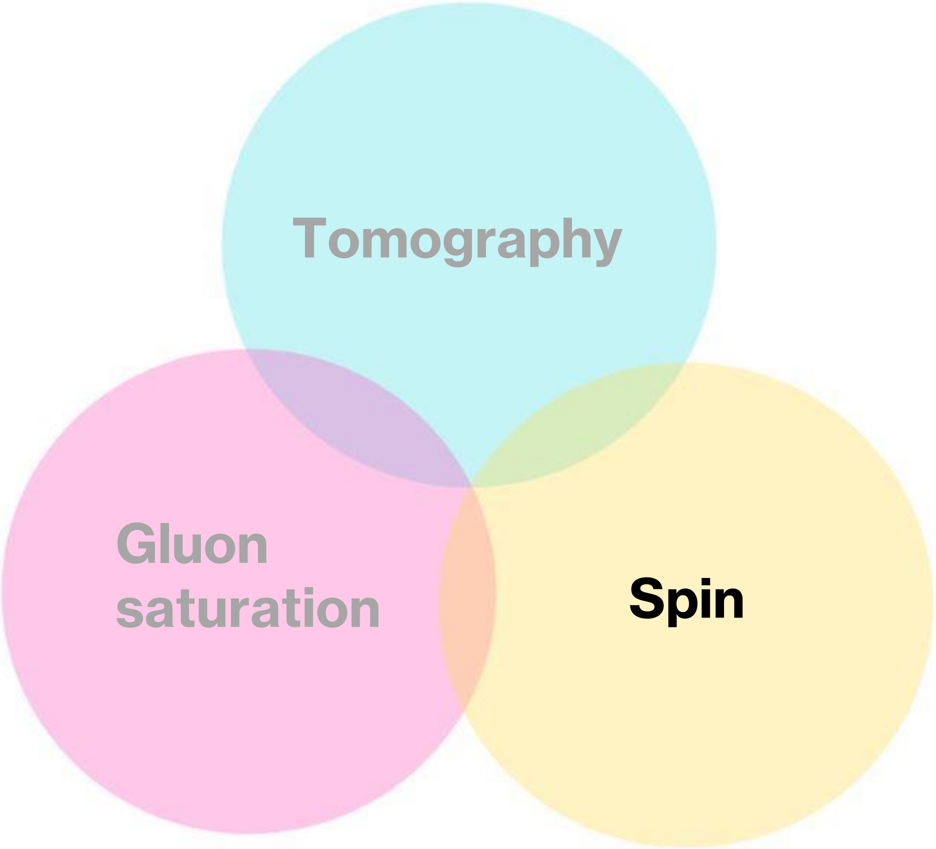
- CGC-blackhole correspondence

Classicalization and unitarization of wee partons in QCD and Gravity: The CGC-Black Hole correspondence

Gia Dvali[1,2] and Raju Venugopalan[3]

Scientific goals of Electron-Ion Collider

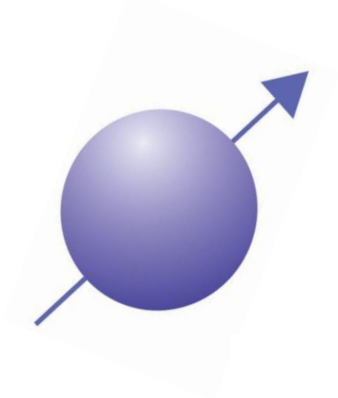
The EIC will strive to answer profound questions related to the 3 pillars:



Nucleon spin

Proton spin decomposition (Jaffe-Manohar spin sum rule)

Spin structure of nucleons in terms of quarks and gluons:



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

Quark helicity

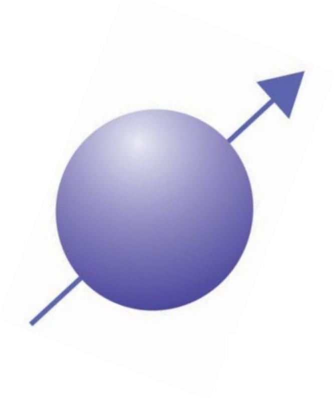
Gluon helicity

Orbital Angular Momentum (OAM) of quarks & gluons

Nucleon spin

Proton spin decomposition (Jaffe-Manohar spin sum rule)

Spin structure of nucleons in terms of quarks and gluons:



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

Quark helicity

Gluon helicity

Orbital Angular Momentum (OAM) of quarks & gluons

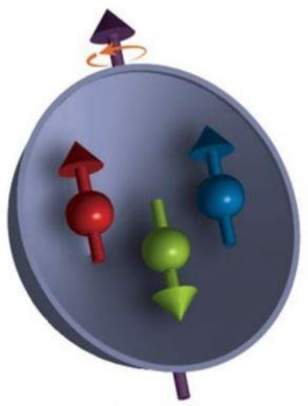
Currently, there are **no** experimental constraints on OAM

Nucleon spin

Naïve quark model expectation

In quark model,
a proton consists of 2 up-quarks and 1 down-quark:

$$\frac{1}{2} = \frac{1}{2} + \frac{1}{2} - \frac{1}{2}$$

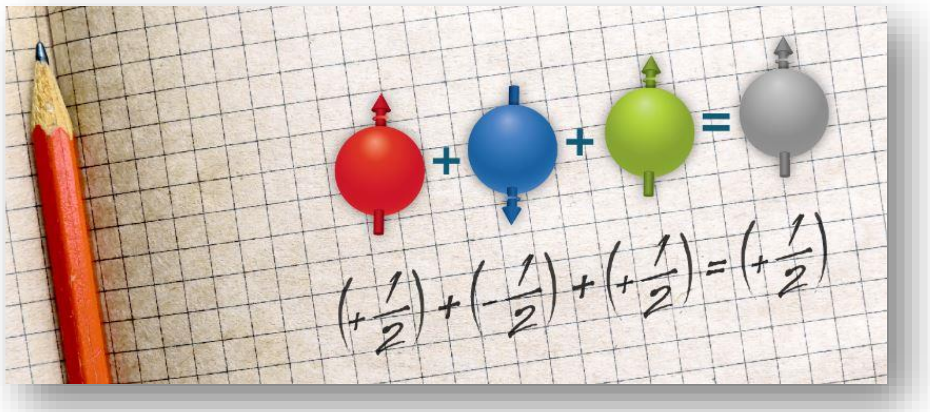


$$\boxed{\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \cancel{\Delta G} + \cancel{L_z}}$$

Quark spin — Gluon spin — Orbital Angular Momentum

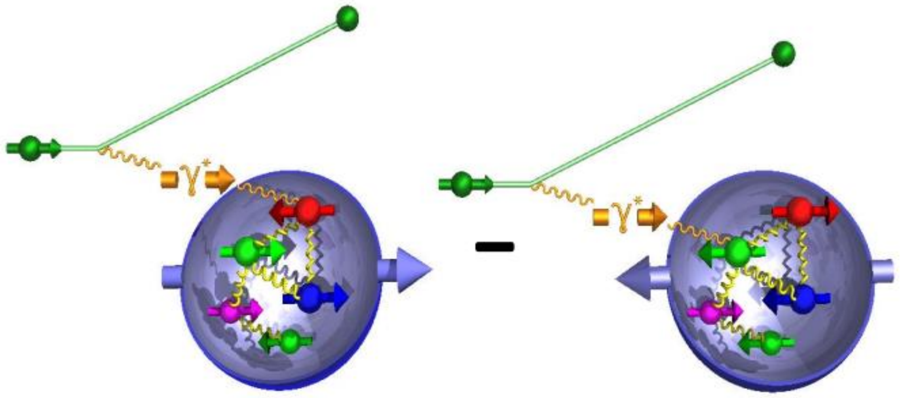
$$\therefore \quad \boxed{\Delta\Sigma = 1}$$

A naïve expectation



Nucleon spin

Spin puzzle



Longitudinal double spin asymmetry in polarized DIS:

$$A_{LL} = \frac{\mu^{\uparrow}p^{\downarrow} - \mu^{\uparrow}p^{\uparrow}}{\mu^{\uparrow}p^{\uparrow} + \mu^{\uparrow}p^{\downarrow}} \sim \left(1 + \frac{\sigma_L}{\sigma_T}\right) \frac{2x g_1}{F_2}$$

First moment of g_1 :

$$\int_0^1 dx g_1(x) = \frac{1}{9}\boxed{(\Delta u + \Delta d + \Delta s)} \leftarrow \Delta\Sigma$$
$$+ \frac{1}{12}(\Delta u - \Delta d) + \frac{1}{36}(\Delta u + \Delta d - 2\Delta s)$$
$$+ \mathcal{O}(\alpha_s)$$

Nucleon spin

Spin puzzle

In 1987, EMC (European Muon Collaboration) announced a **very small value of the quark helicity contribution**

$$\boxed{\Delta\Sigma = 0.060 \pm 0.047 \pm 0.069}$$

Recent value:

$$\boxed{\Delta\Sigma = 0.25 \sim 0.3}$$

Still significantly less than 1

"Spin crisis": Where is the rest of the spin coming from?

Nucleon spin

Spin puzzle

In 1987, EMC (European Muon Collaboration) announced a

The search for answers turned to Brookhaven Lab, where RHIC was taking shape

Recent

Collaboration with Japan's RIKEN pushed the boundary for RHIC's accelerator capabilities

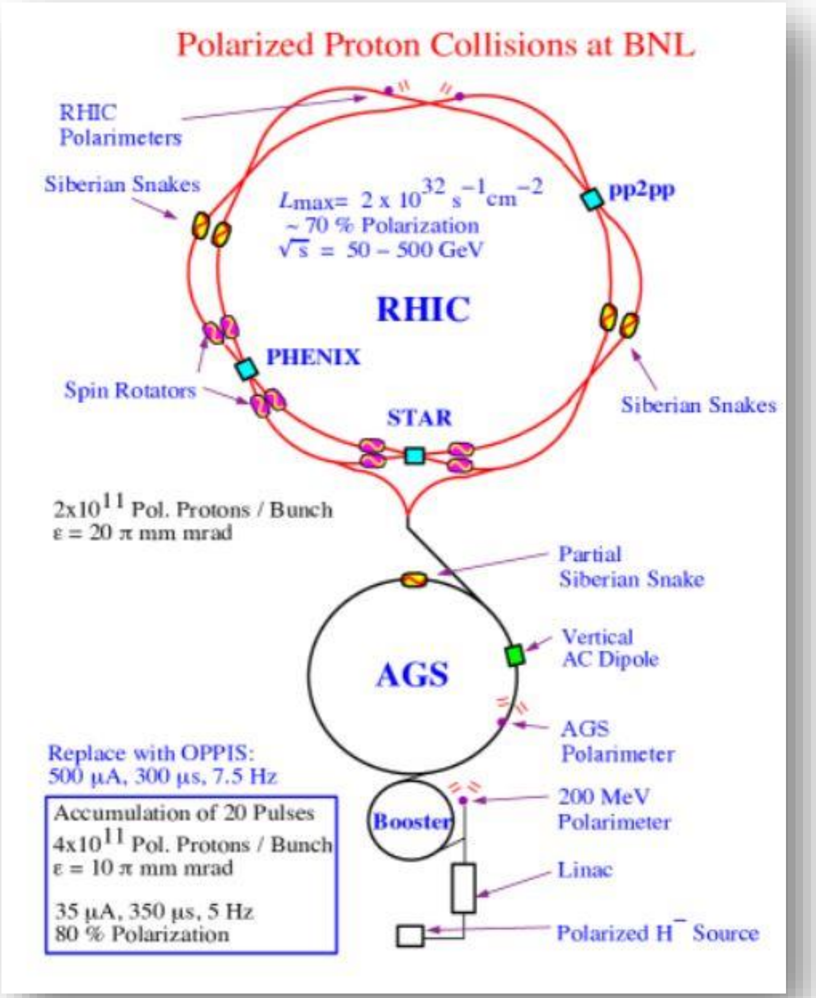
$\Delta\Sigma$

ng from?

Still significantly less than 1

Nucleon spin

RHIC spin project



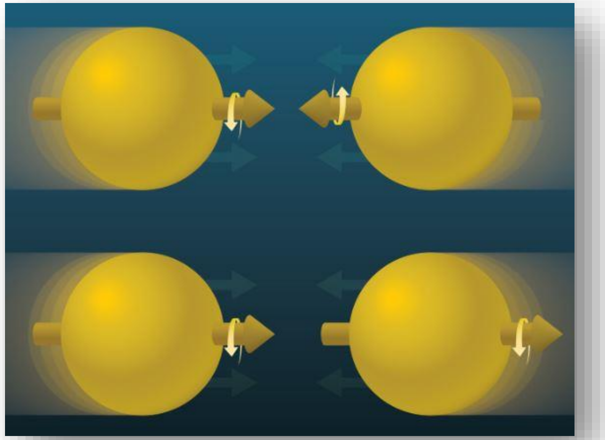
One of the main physics goals is to pin down the **gluon spin** contribution

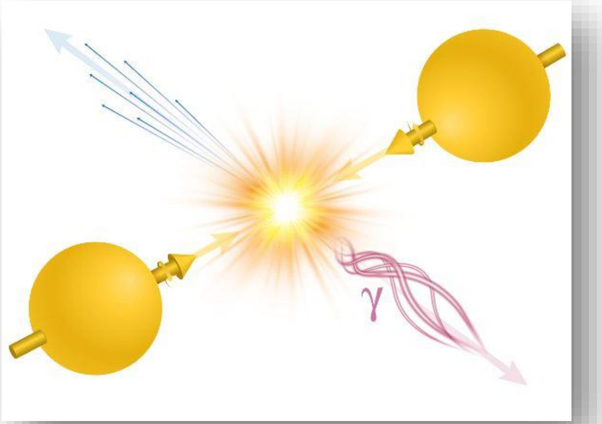
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \boxed{\Delta G} + L_z$$

Quark spin | Gluon spin | Orbital Angular Momentum

Nucleon spin

RHIC spin project





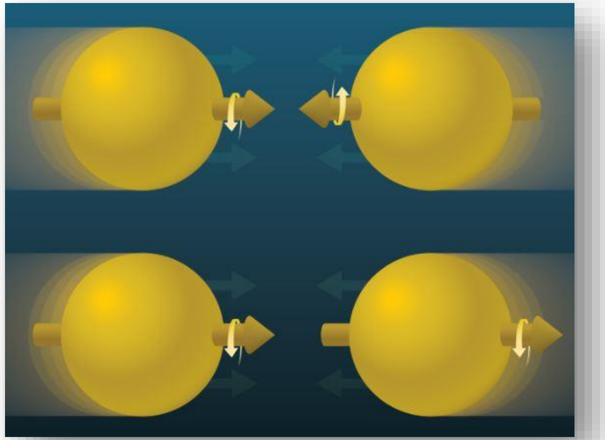
A golden measurement:

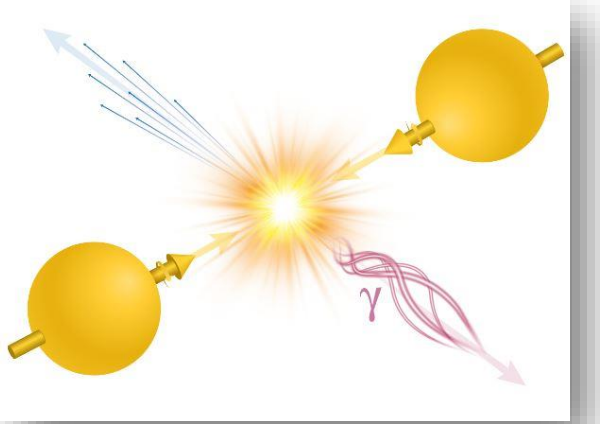
It's a **comparison of the number of "direct photons"** emitted when RHIC collides protons with their spins pointing in opposite directions with the number of direct photons produced when the protons in the two beams are pointing in the same direction.

For reasons having to do with the way quarks and gluons can interact to emit photons (and knowing that net quark spins are positively aligned with proton spin), **seeing a difference would indicate that gluon spins are also aligned, or polarized – and, importantly, in which direction**.

Nucleon spin

RHIC spin project





Direct Photons Point to Positive Gluon Polarization

Results from 'golden measurement' at RHIC's PHENIX experiment show the spins of gluons align with the spin of the proton they're in

June 21, 2023

A new analysis of data from the PHENIX detector at the Relativistic Heavy Ion Collider (RHIC) gives fresh insight into how gluons contribute to proton spin.

Nucleon spin

Tremendous progress

Helicity Evolution at Small x: Revised Asymptotic Results at Large $N_c \& N_f$

Daniel Adamiak,[1,2,*] Yuri V. Kovchegov,[1,†] and Yossathorn Tawabutr[1,3,4,‡]

Renewed interest in **helicity-dependent small-x resummation**

Nucleon spin

Tremendous progress

NNLO Global Analysis of Polarized Parton Distribution Functions

Ignacio Borsa,* Marco Stratmann,† and Werner Vogelsang‡
Institute for Theoretical Physics, University of Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

Daniel de Florian§
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Rodolfo Sassot¶
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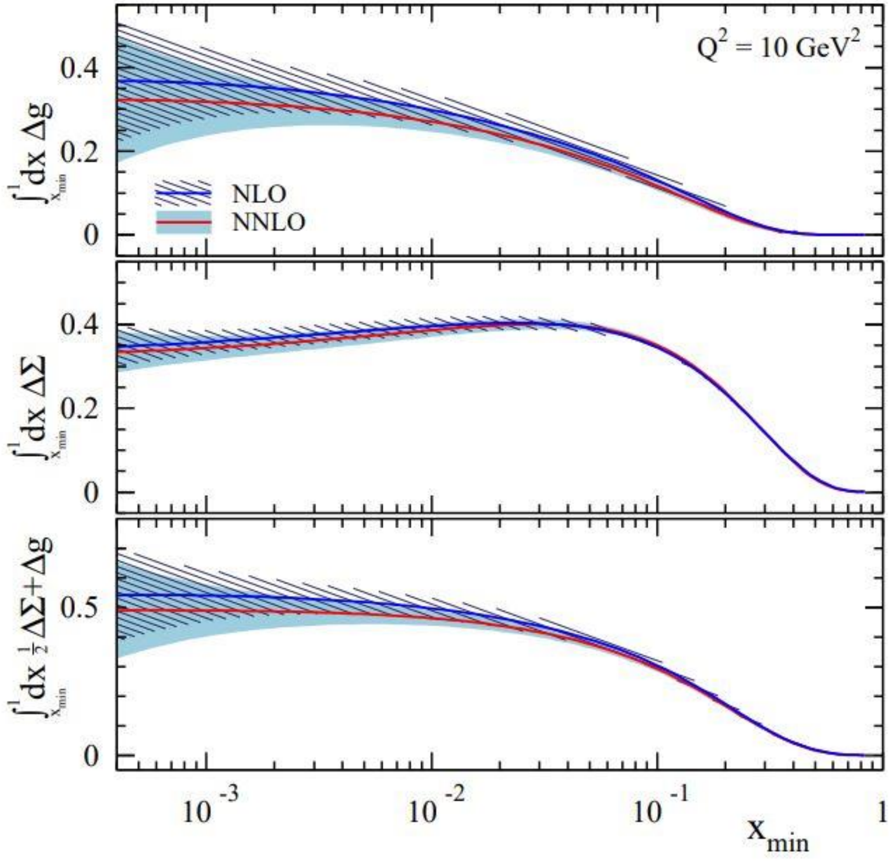

FIG. 5. Truncated first moments of the quark singlet and gluon helicity PDFs at $Q^2 = 10$ GeV^2, and their combined contribution to the proton spin sum rule (bottom panel).

Nucleon spin

Tremendous progress

NNLO Global Analysis of Polarized Parton Distribution Functions

Ignacio Borsa,* Marco Stratmann,† and Werner Vogelsang‡
Institute for Theoretical Physics, University of Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

Daniel de Florian§
International Center for Advanced Studies (ICAS), ICIFI and ECyT-UNSAM, 25 de Mayo y Francia, (1650) Buenos Aires, Argentina

Rodolfo Sassot¶
Departamento de Física and IFIBA, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria, Pabellón 1 (1428) Buenos Aires, Argentina

of the integrals. Remarkably, when combining the two contributions according to their role for the proton spin, one finds a result approaching 1/2 toward lower $x_{\min}$. It will be interesting to see whether future data indeed confirm this indication of a small contribution by orbital angular momenta to the proton spin.

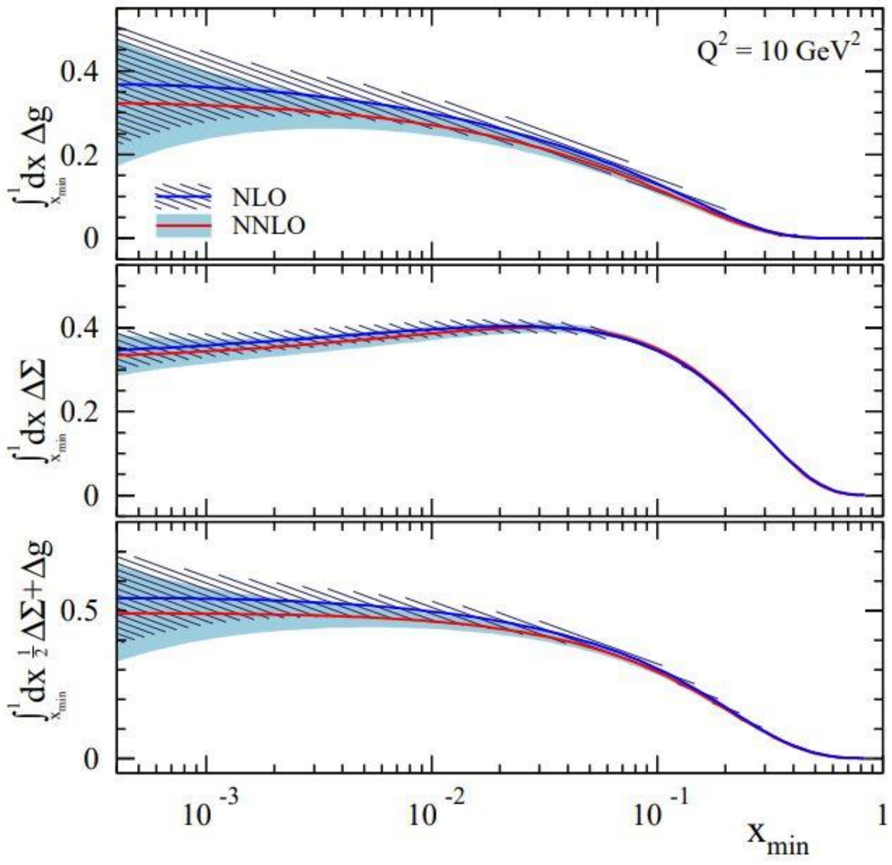

FIG. 5. Truncated first moments of the quark singlet and gluon helicity PDFs at $Q^2 = 10\ \mathrm{GeV}^2$, and their combined contribution to the proton spin sum rule (bottom panel).

Nucleon spin

Tremendous progress

NNLO Global Analysis of Polarized Parton Distribution Functions

Ignacio Borsa,* Marco Stratmann,† and Werner Vogelsang‡
Institute for Theoretical Physics, University of Tübingen,
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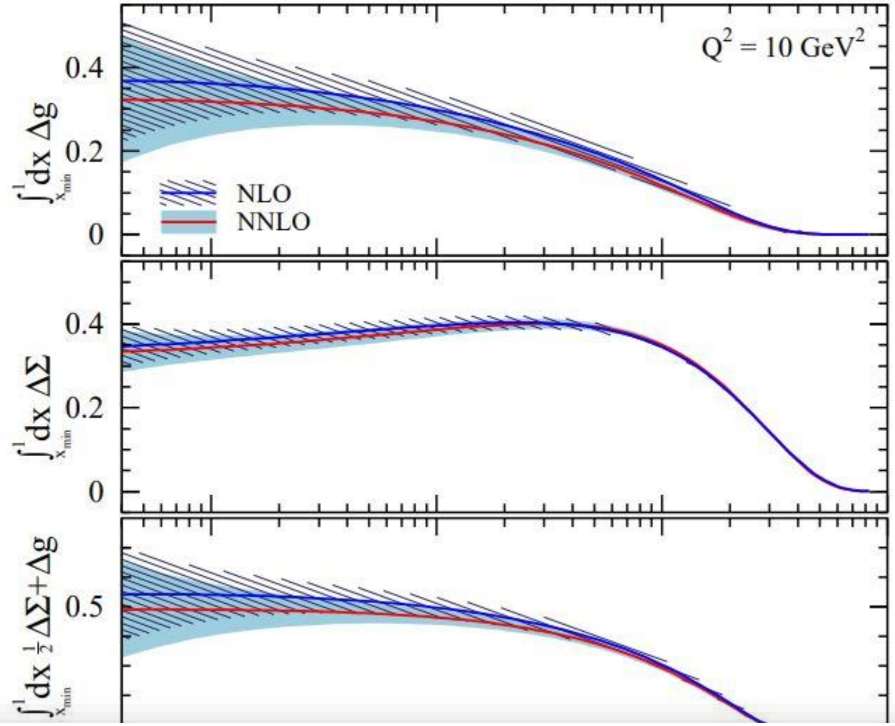
of the integrals. Remarkably, when combining the two contributions according to their role for the proton spin, one finds a result approaching 1/2 toward lower $x_{\rm min}$. It will be interesting to see whether future data indeed confirm this indication of a small contribution by orbital angular momenta to the proton spin.

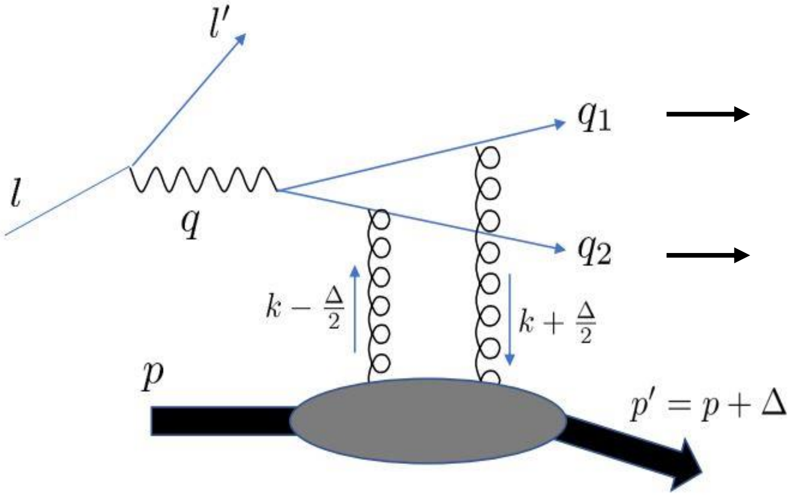


Searches for **observables** sensitive to **Orbital Angular Momentum at the EIC** represent a very active area of research

Nucleon spin

Observables for gluon Orbital Angular Momentum

$$\boxed{e(l) + p(p,\lambda) \to e(l') + j_1(q_1) + j_2(q_2) + p(p',\lambda')}$$



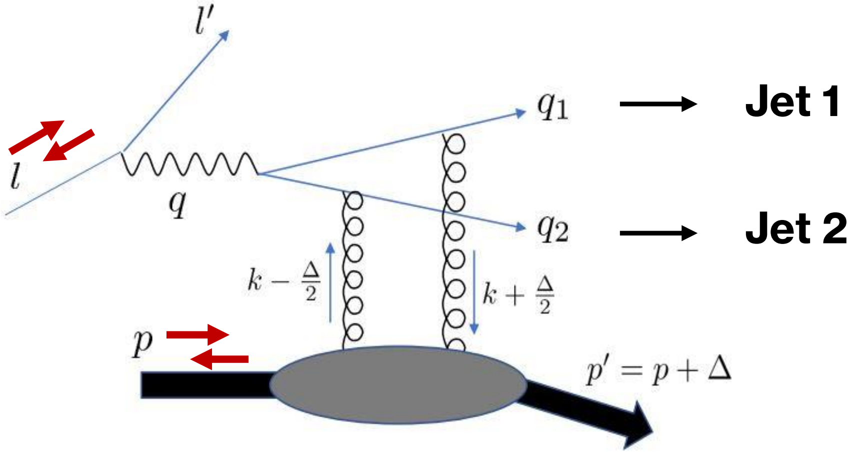
$q_1 \longrightarrow$ **Jet 1**

$q_2 \longrightarrow$ **Jet 2**

Nucleon spin

Observables for gluon Orbital Angular Momentum

Example of an observable (double spin asymmetry) sensitive to OAM, helicity, spin-orbit correlation:



$$
\begin{aligned}
d\sigma^{\mathrm{asym}} \sim & -\Re e\left[\left\{\mathcal{H}_g^{(1)*}(\xi) + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\mathcal{H}_g^{(2)*}(\xi)\right\}\mathcal{L}_g(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp}) \\
& + \Re e\left[\mathcal{H}_g^{(1)*}(\xi)\tilde{\mathcal{H}}_g^{(2)}(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp}) \\
& + \Re e\left[\frac{4q_\perp^2}{q_\perp^2+\mu^2}\tilde{\mathcal{H}}_g^{(2)}(\xi) C_g^{(2)}(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})
\end{aligned}
$$

(SB, Boussarie, Hatta, 2022, 2024)

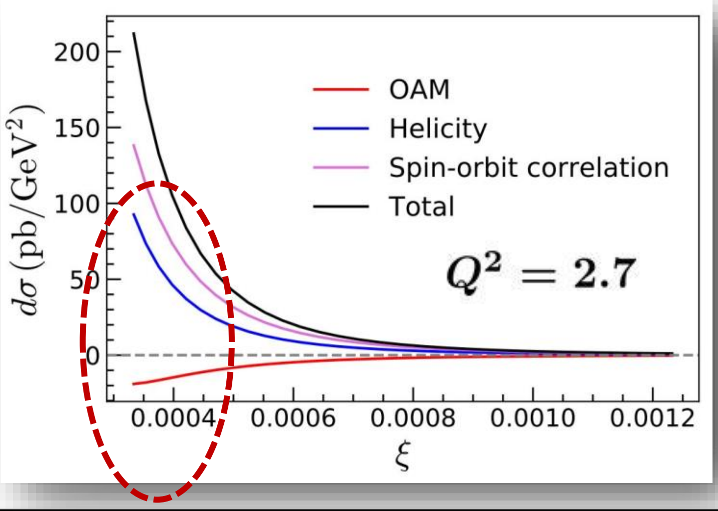
More works on spin asymmetry calculations in diffractive dijets:

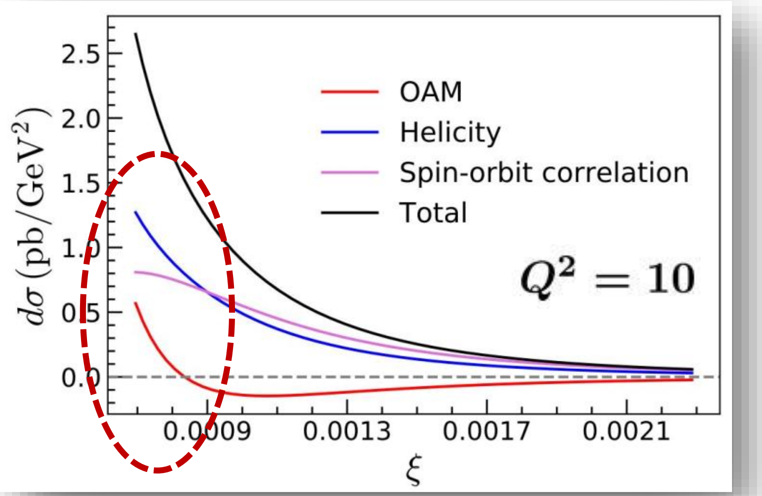
Leading order, unpolarized (twist-2 GPDs): Braun, Ivanov (2005)
Single spin asymmetry: Ji, Yuan, Zhao (2016); Hatta, Nakagawa, Yuan, Xiao, Zhao (2016)

Nucleon spin

Observables for gluon Orbital Angular Momentum

Interplay between OAM and helicity at small x





First quantitative prediction for an OAM observable at EIC kinematics

Schematic structure of our observable:

$$d\sigma^{\text{asym}} \sim \mathcal{H}_g^{(1)*}(\xi)\left(\tilde{\mathcal{H}}_g^{(2)}(\xi) + \frac{q_\perp^2 - Q^2/4}{q_\perp^2 + Q^2/4}\mathcal{L}_g(\xi)\right)$$

$$\tilde{\mathcal{H}}_g^{(2)}(\xi) \downarrow \Delta G(x) \qquad \mathcal{L}_g(\xi) \downarrow L_g(x)$$

Cancellation expected between helicity & OAM at small x

$$\boxed{\Delta G(x) \approx -\frac{2}{1+c} L_g(x)}$$

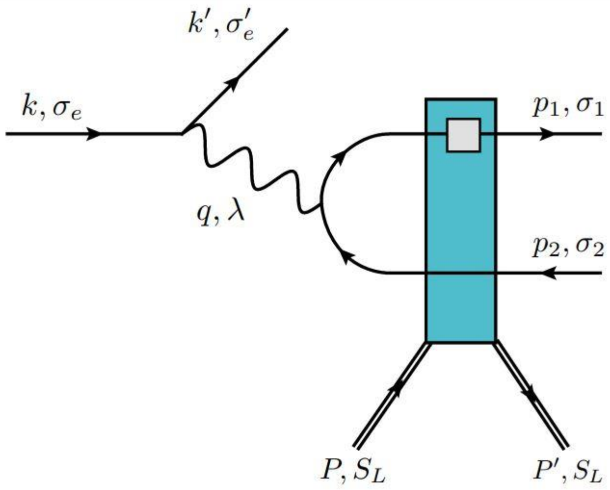
Boussarie, Hatta, Yuan (2019)
Kovchegov, Manley (2023, 2024)

Nucleon spin

Observables for gluon Orbital Angular Momentum

Elastic Dijet Production in Electron Scattering on a Longitudinally Polarized Proton at Small x: A Portal to Orbital Angular Momentum Distributions

Yuri V. Kovchegov* and Brandon Manley†



Single and double spin asymmetry measurements at the future EIC to provide the **first-ever** direct access to the **gluon OAM distributions at small x**, paving the way for new insights into the proton spin puzzle.

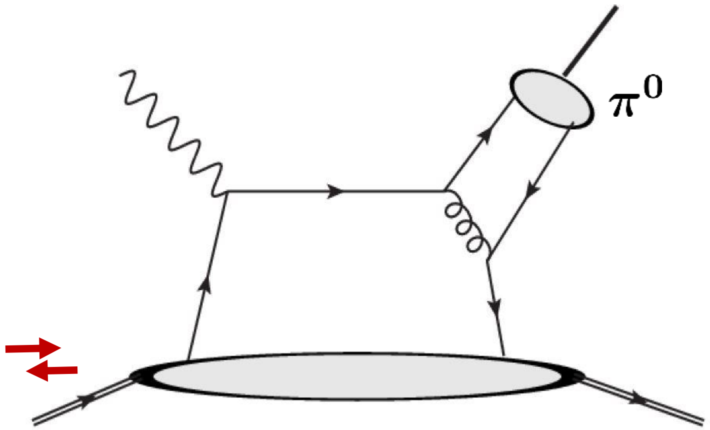
Nucleon spin

Observables for quark Orbital Angular Momentum

Probing quark orbital angular momentum at EIC and EicC

Shohini Bhattacharya,[1] Duxin Zheng,[2] and Jian Zhou[3]

$$\boxed{e(l) + p(p,\lambda) \longrightarrow \pi^0(l_\pi) + e(l') + p(p',\lambda')}$$



Nucleon spin

Observables for quark Orbital Angular Momentum

Example of an observable (single spin asymmetry) sensitive to OAM:

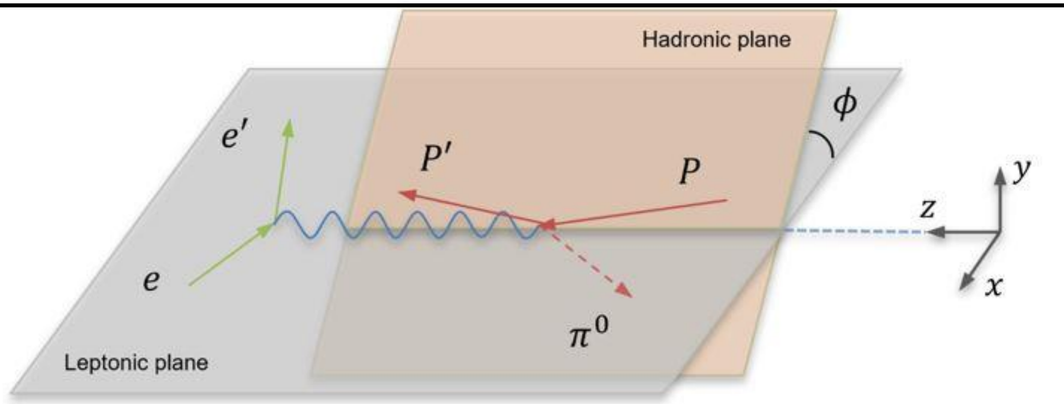
$$\frac{d\sigma}{dtdQ^2dx_Bd\phi} = \frac{(N_c^2-1)^2\alpha_{em}^2\alpha_s^2 f_\pi^2 \xi^3 \Delta_\perp^2}{2N_c^4(1-\xi^2)Q^{10}(1+\xi)}\left[1+(1-y)^2\right]$$

$$\times\left\{\left[|\mathcal{F}_{1,1}+\mathcal{G}_{1,1}|^2+|\mathcal{F}_{1,4}+\mathcal{G}_{1,4}|^2+2\frac{M^2}{\Delta_\perp^2}|\mathcal{F}_{1,2}+\mathcal{G}_{1,2}|^2\right] + \cos(2\phi)a\left[-|\mathcal{F}_{1,1}+\mathcal{G}_{1,1}|^2+|\mathcal{F}_{1,4}+\mathcal{G}_{1,4}|^2\right]\right.$$

$$\left.\boxed{+\lambda\sin(2\phi)\,2a\,\mathrm{Re}\left[\left(i\mathcal{F}_{1,4}+i\mathcal{G}_{1,4}\right)\left(\mathcal{F}_{1,1}^*+\mathcal{G}_{1,1}^*\right)\right]}\right\}$$

Distinguished experimental signature of quark OAM

$$\phi = \phi_{l_\perp} - \phi_{\Delta_\perp}$$

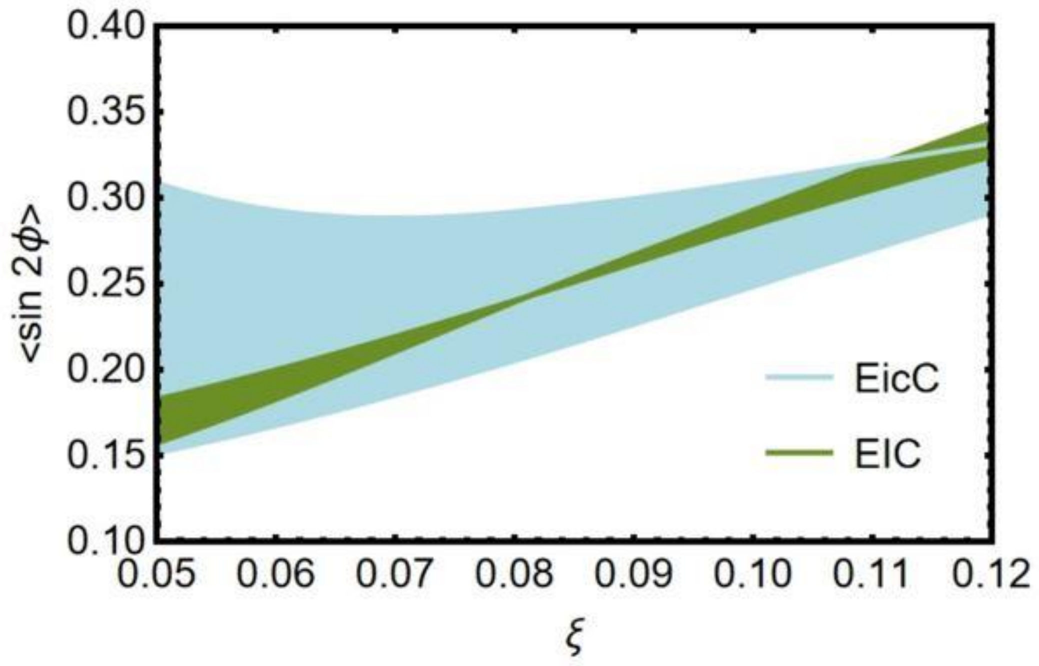


Nucleon spin

Observables for quark Orbital Angular Momentum

Predictions for Electron-Ion Colliders

Asymmetry

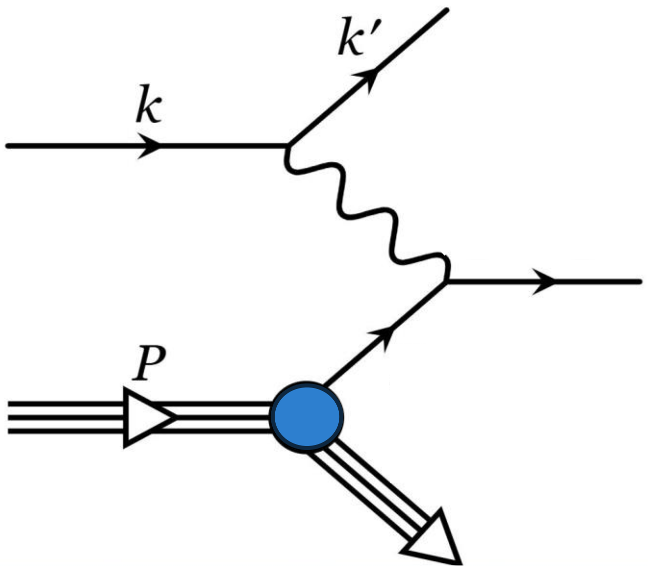


$$\langle \sin(2\phi) \rangle = \frac{\int \frac{d\Delta\sigma}{d\mathcal{P.S.}} \sin(2\phi)\, d\mathcal{P.S.}}{\int \frac{d\sigma}{d\mathcal{P.S.}} d\mathcal{P.S.}}$$

Findings:

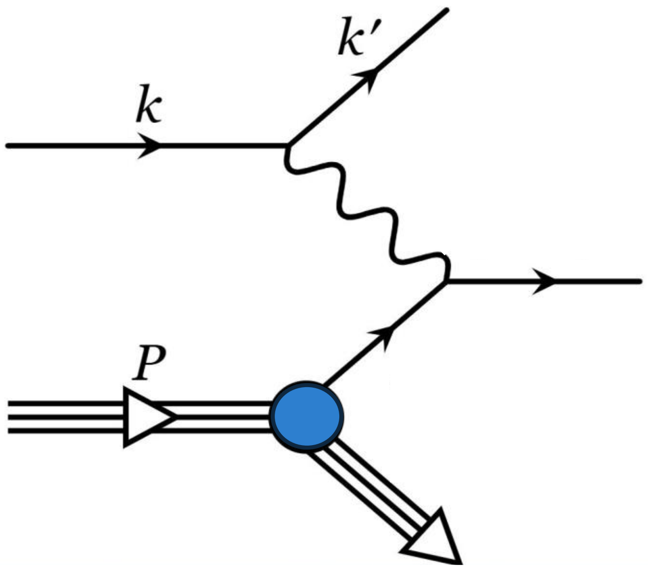
The asymmetries are substantial for both EIC & EicC kinematics

Precision ep physics



Scattering reactions with **polarized or unpolarized electrons** and **protons** are a core component of the physics program at the EIC.

Precision ep physics



Scattering reactions with **polarized or unpolarized electrons** and **protons** are a core component of the physics program at the EIC.

The need for an adequate theoretical framework to match the quality of the EIC data:
Provide **precision computations** of relevant partonic hard-scattering cross sections and splitting functions to the highest possible orders in perturbation theory.

Precision ep physics

Tremendous Progress

The Three-Loop Splitting Functions in QCD:
The Non-Singlet Case
The Singlet Case

S. Moch[a], J.A.M. Vermaseren[b] and A. Vogt[b]

The Three-Loop Splitting Functions in QCD:
The Helicity-Dependent Case

S. Moch[a], J.A.M. Vermaseren[b] and A. Vogt[c]

The DGLAP evolution kernels are now fully known through **NNLO**
(or, to **three loops**), both for the spin-averaged and helicity dependent evolution

Precision ep physics

Tremendous Progress

Four-Loop Non-Singlet Splitting Functions in the Planar Limit and Beyond

S. Moch[a], B. Ruijl[b,c], T. Ueda[b], J.A.M. Vermaseren[b] and A. Vogt[d]

Low moments of the four-loop splitting functions in QCD

S. Moch[a], B. Ruijl[b], T. Ueda[c], J.A.M. Vermaseren[d] and A. Vogt[e]

Five-loop contributions to low-N non-singlet anomalous dimensions in QCD

F. Herzog[a], S. Moch[b], B. Ruijl[c], T. Ueda[d], J.A.M. Vermaseren[a] and A. Vogt[e]

Parts of the **four-loop** splitting functions and the lower **moments of the five-loop** functions have become available for unpolarized evolution

Precision ep physics

Tremendous Progress

NNLO jet production in neutral and charged current polarized deep inelastic scattering

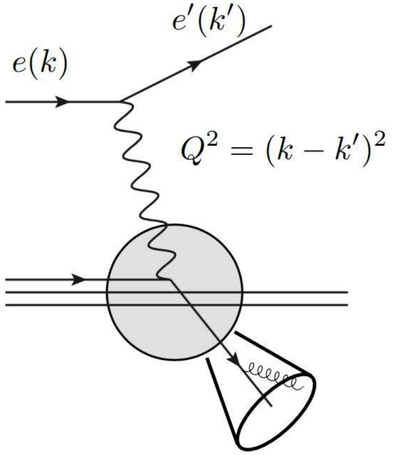
Ignacio Borsa*
Universidad de Buenos Aires and IFIBA, Facultad de Ciencias Exactas y Naturales, Departamento de Física. Buenos Aires, Argentina.

Daniel de Florian† and Iván Pedron‡
International Center for Advanced Studies (ICAS), ICIFI and ECyT-UNSAM, 25 de Mayo y Francia, (1650) Buenos Aires, Argentina

Single-inclusive jet production in electron-nucleon collisions through next-to-next-to-leading order in perturbative QCD

Gabriel Abelof,[1,2,*] Radja Boughezal,[1,†] Xiaohui Liu,[3,‡] and Frank Petriello[1,2,§]
[1]*High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[2]*Department of Physics & Astronomy, Northwestern University, Evanston, IL 60208, USA*
[3]*Maryland Center for Fundamental Physics, University of Maryland, College Park, Maryland 20742, USA*
(Dated: November 9, 2021)

Pertinent **partonic cross sections** of ep scattering at **NNLO** include **inclusive DIS** and **jet production in DIS**



Precision ep physics

Tremendous Progress

Three-loop evolution equation for flavor-nonsinglet operators in off-forward kinematics

V. M. Braun,[a] A. N. Manashov,[b,a] S. Moch[b] and M. Strohmaier[a]

Deeply-virtual Compton scattering at the next-to-next-to-leading order

V. M. Braun,[1,*] Yao Ji,[2,†] and Jakob Schoenleber[1,‡]

[1] *Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany*

[2] *Physik Department T31, James-Franck-Straße 1, Technische Universität München, D-85748 Garching, Germany*

(Dated: November 14, 2022)

Recent **three-loop** results on **evolution equations** and **NNLO** computations of the **DVCS coefficient functions** for GPDs

Precision ep physics

Tremendous Progress

Three-loop evolution equation for flavor-nonsinglet operators in off-forward kinematics

These achievements are important first steps toward a new precision era for EIC theory of ep scattering

Recent **three-loop** results on **evolution equations** and **NNLO** computations of the **DVCS coefficient functions** for GPDs

Precision ep physics

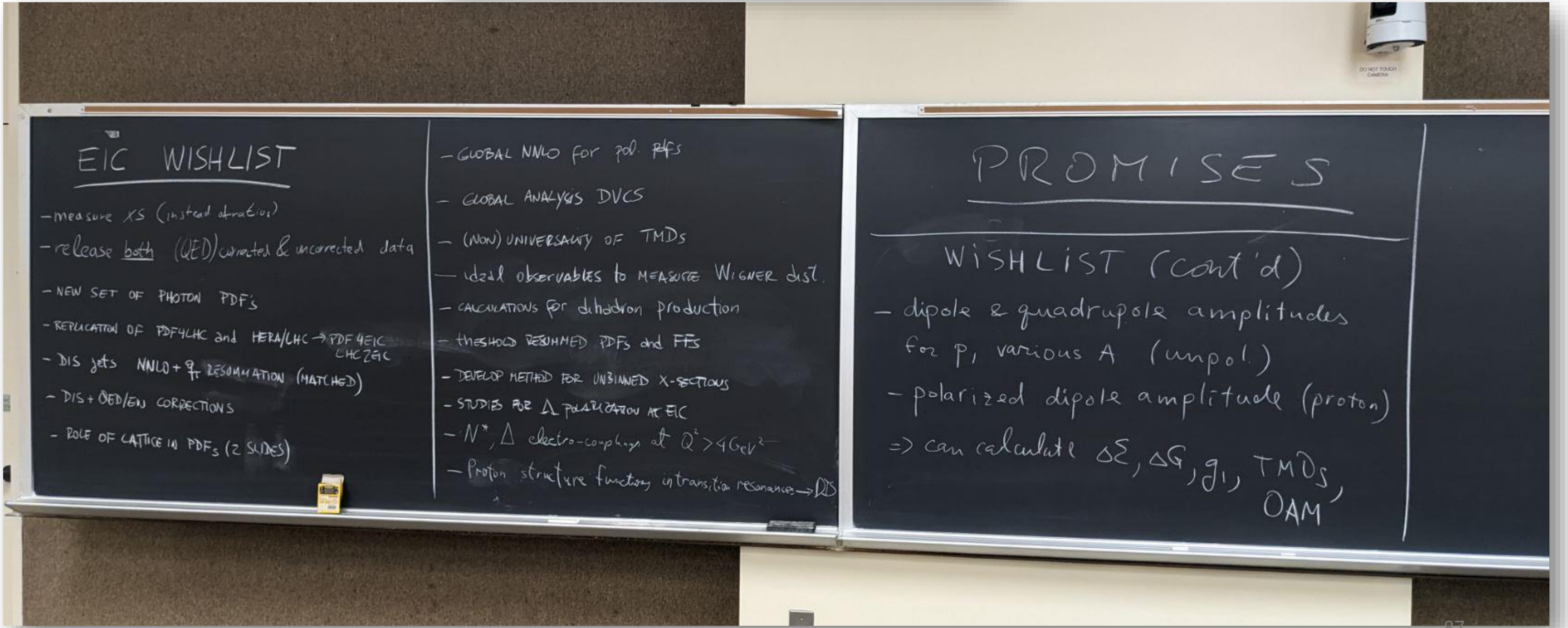
In order to advance precision ep theory for the EIC, a dedicated workshop series "**Precision QCD predictions for ep Physics at the EIC**" was started at the Center for Frontiers in Nuclear Science (CFNS) in Stony Brook

August 1-5, 2022	**Workshop:** **Precision QCD predictions for ep Physics at the EIC** **Location:** Stony Brook University **Organizers:** Daniel de Florian (UNSAM), Werner Vogelsang (Tuebingen)

Center for Frontiers in Nuclear Science

Precision ep physics

Outcome: “EIC wish list”



Precision ep physics

3 successful editions
of the “Precision QCD predictions for ep Physics at the EIC” at Center for Frontiers in Nuclear Science

August 1-5, 2022	**Workshop:** Precision QCD predictions for ep Physics at the EIC **Location:** Stony Brook University **Organizers:** Daniel de Florian (UNSAM), Werner Vogelsang (Tuebingen)
September 18-22, 2023	**Workshop:** Precision QCD Predictions for ep Physics at the EIC (II) **Location:** Stony Brook University **Organizers:** Daniel de Florian (UNSAM), Werner Vogelsang (Universität Tübingen)
Sept 23-27, 2024	**Workshop:** Precision QCD Predictions for ep Physics at the EIC (III): Opportunities with a Second IR **Location:** Stony Brook University **Organizers:** Daniel De Florian (universidad Nacional de San Martin), Abhay Deshpande (Stony Brook University), Rene Fatemi (University of Kentucky), Pawel Nadel-Turonski (University of S. Carolina), Werner Vogelsang (University of Tubingen)

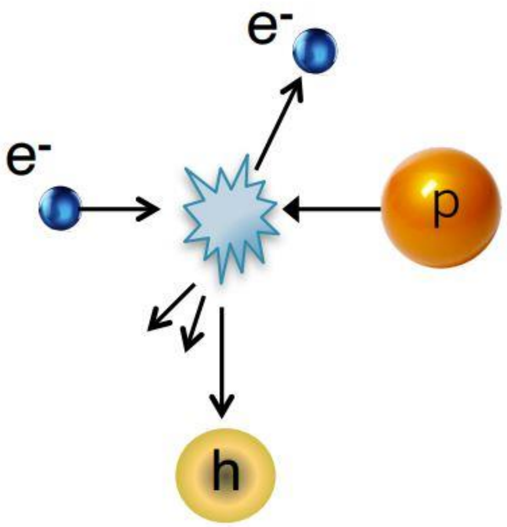
Precision ep physics

Snippets from the workshop

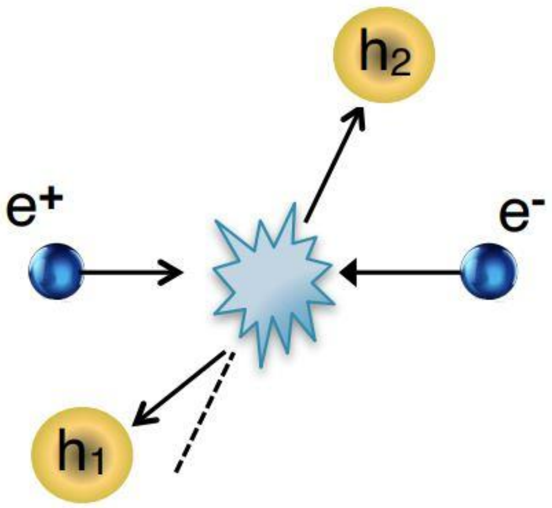
See Florian's talk

- Computation of **QCD higher-order corrections for EIC observables** where not yet available:

  Example: SIDIS, hadron-pair production, etc.



Meng, Olness, Soper (1992)
Ji, Ma, Yuan (2005)
Idilbi, Ji, Ma, Yuan (2004)
Collins (2011)



Collins, Soper (1983)
Collins (2011)

Precision ep physics

Snippets from the workshop

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- Computation of **QCD higher-order corrections for EIC observables** where not yet available:

  Example: SIDIS, hadron-pair production, etc.

- QCD **resummation studies** for the EIC:

  Example: threshold resummation studies for final states produced with large transverse momentum, High-precision resummation of hadronic event shapes in DIS (determinations of the α_s)

Analytic Calculation of 1-Jettiness in DIS at $\mathcal{O}(\alpha_s)$

Ee's talk

Daekyoung Kang,[a] Christopher Lee,[b] and Iain W. Stewart[a]

Probing nuclear dynamics in jet production with a global event shape

Zhong-Bo Kang,[1] Xiaohui Liu,[2,3] Sonny Mantry,[2,3] and Jian-Wei Qiu[4,5]

Precision ep physics

Snippets from the workshop

See Florian's talk

- Computation of **QCD higher-order corrections for EIC observables** where not yet available:

  Example: SIDIS, hadron-pair production, etc.

- QCD **resummation studies** for the EIC:

  Example: threshold resummation studies for final states produced with large transverse momentum,
  High-precision resummation of hadronic event shapes in DIS (determinations of the α_s)

- Phenomenology of the **impact of QED corrections** on extractions of parton distributions

A new approach to semi-inclusive deep-inelastic scattering with QED and QCD factorization

Tianbo Liu,[a] W. Melnitchouk,[b] Jian-Wei Qiu[b,c] and N. Sato[b]

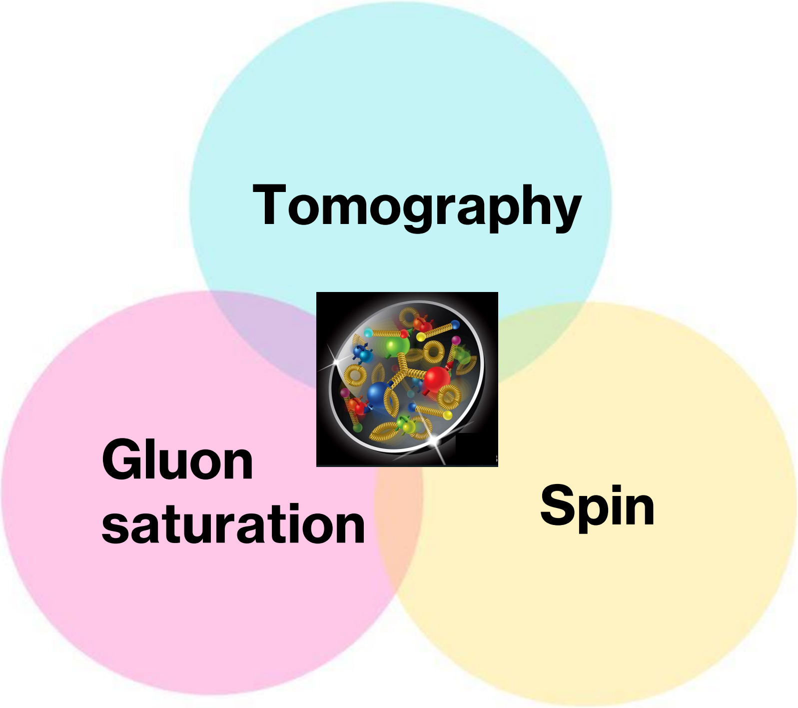
Fundamental symmetries at EIC

EIC: Versatile machine to explore BSM physics

- Charged Lepton Flavor violation **Fuyuto's talk**
- Complementarity of the EIC with the LHC in exploring SMEFT **Boughezal's talk**
- Nucleon electric dipole moments (EDM)
- PDF extractions and BSM implications **Hammou's talk**

Summary

Unveil the "cosmic" interior of nucleons/nuclei

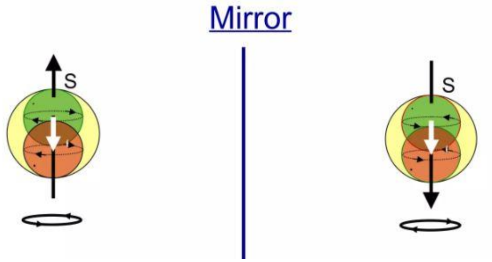


Precision ep physics

$$\tilde{\sigma}^W(\boldsymbol{b}_T) = f_q(x_1) f_{\bar{q}}(x_2) C[\alpha_s] \exp\Big\{ \frac{\alpha_s}{4\pi}\left(d_{12}L_b^2 + d_{11}L_b\right) + \left(\frac{\alpha_s}{4\pi}\right)^2\left(d_{23}L_b^3 + d_{22}L_b^2 + d_{21}L_b\right) + \left(\frac{\alpha_s}{4\pi}\right)^3\left(d_{34}L_b^4 + d_{33}L_b^3 + d_{32}L_b^2 + d_{31}L_b\right)\Big\} + \dots$$

LL NLL NNLL N^3LL

Fundamental symmetries



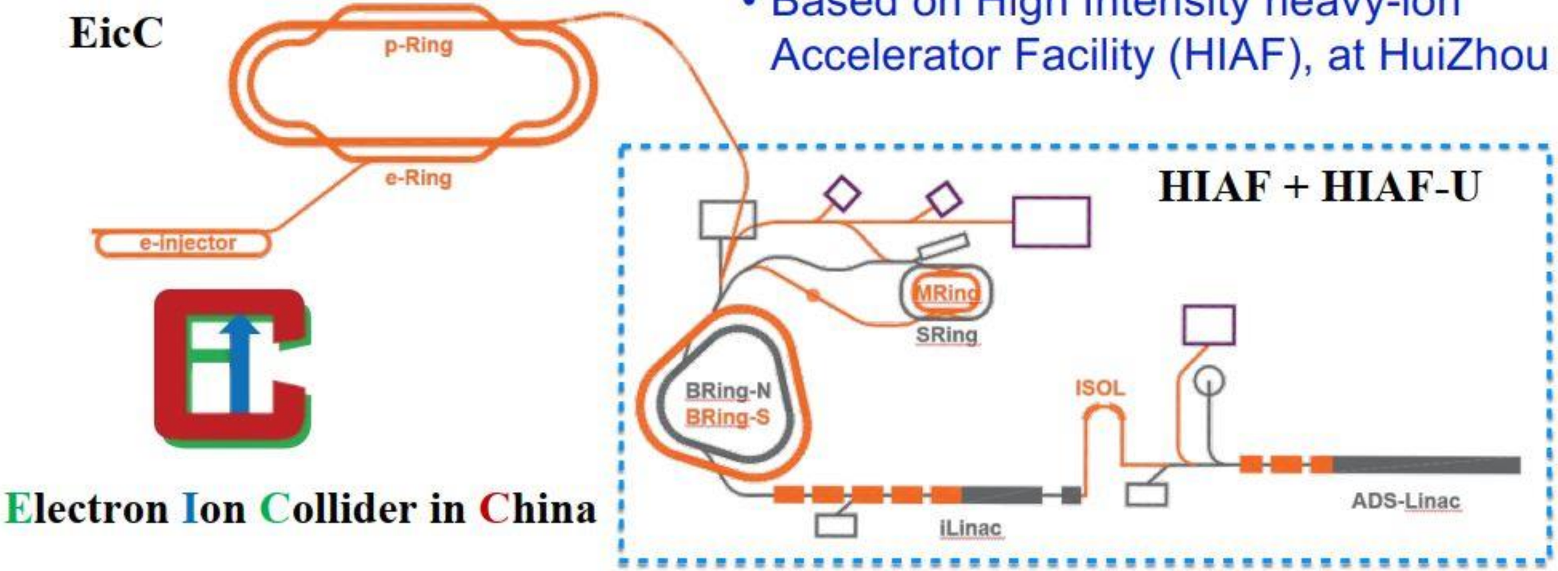
Significant progress has been made, but a decade of challenges, discoveries, and opportunities to contribute lies ahead to fully prepare for the EIC era!

Back-up slides

Last words

Nice complementarity between EIC and EicC

- Based on High Intensity heavy-ion Accelerator Facility (HIAF), at HuiZhou



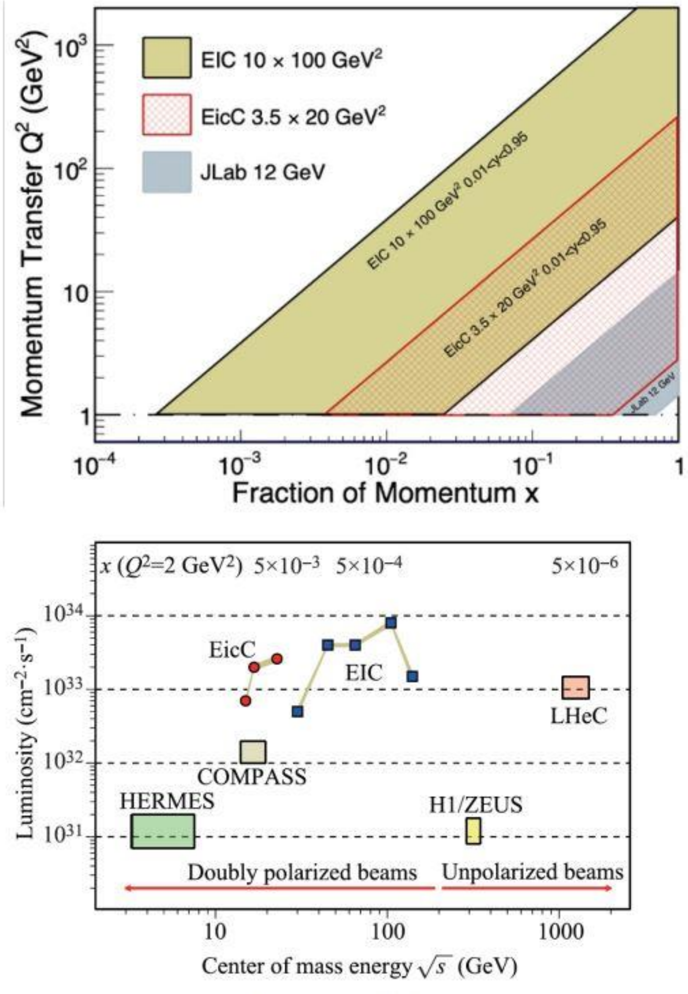
[Figure by EicC Accelerator WG]

- ➢ Energy in c.m.: 15 ~ 20 GeV
- ➢ Electron beam: 3.5 GeV, polarization ~ 80%
- ➢ Proton beam: 20 GeV, polarization ~ 70%
- ➢ Luminosity: $\gtrsim 2 \times 10^{33}$ cm$^{-2}\cdot$ s^{-1}
- ➢ Other available polarized ion beams: d, $^{3}He^{++}$
- ➢ Available unpolarized ion beams: $^{7}Li^{3+}$, $^{12}C^{6+}$, $^{40}Ca^{20+}$, $^{197}Au^{79+}$, $^{208}Pb^{82+}$, $^{238}U^{92+}$

Courtesy: Qinghua Xu

Last words

Nice complementarity between EIC and EicC



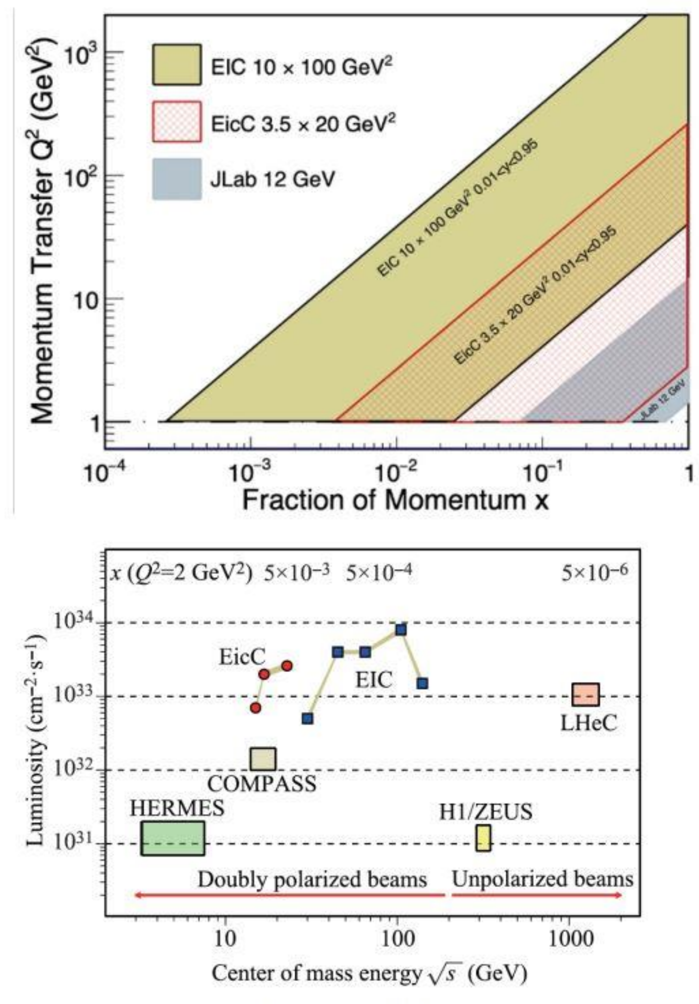
[Figures from EicC White paper]

- **Nucleon spin structure**

  EicC is optimized to systematically explore the gluon and sea quarks in moderate-x regime

Last words

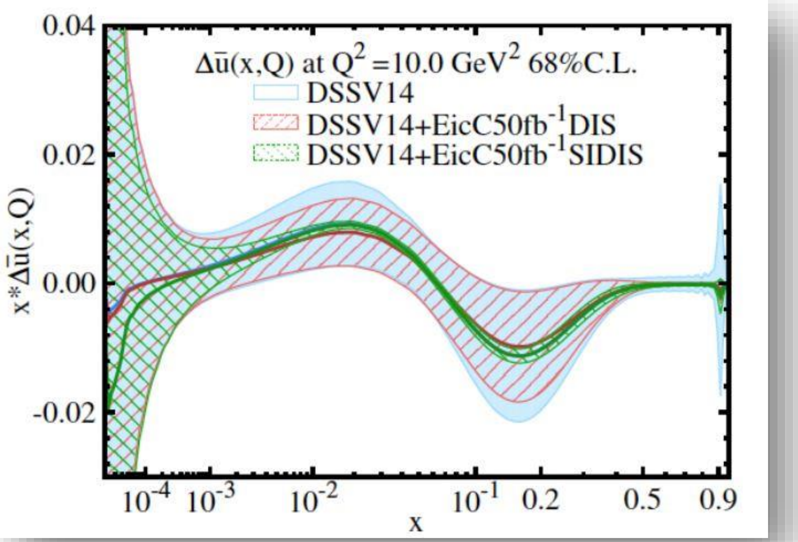
Nice complementarity between EIC and EicC

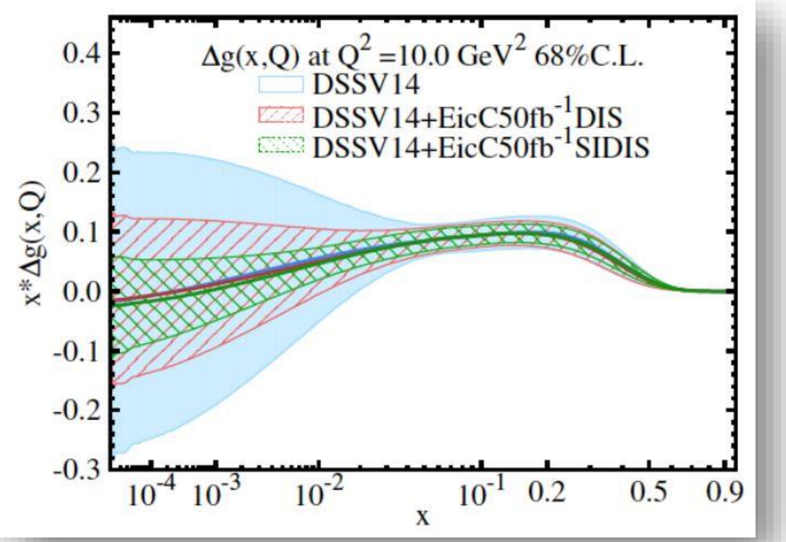


[Figures from EicC White paper]

- **Nucleon spin structure**

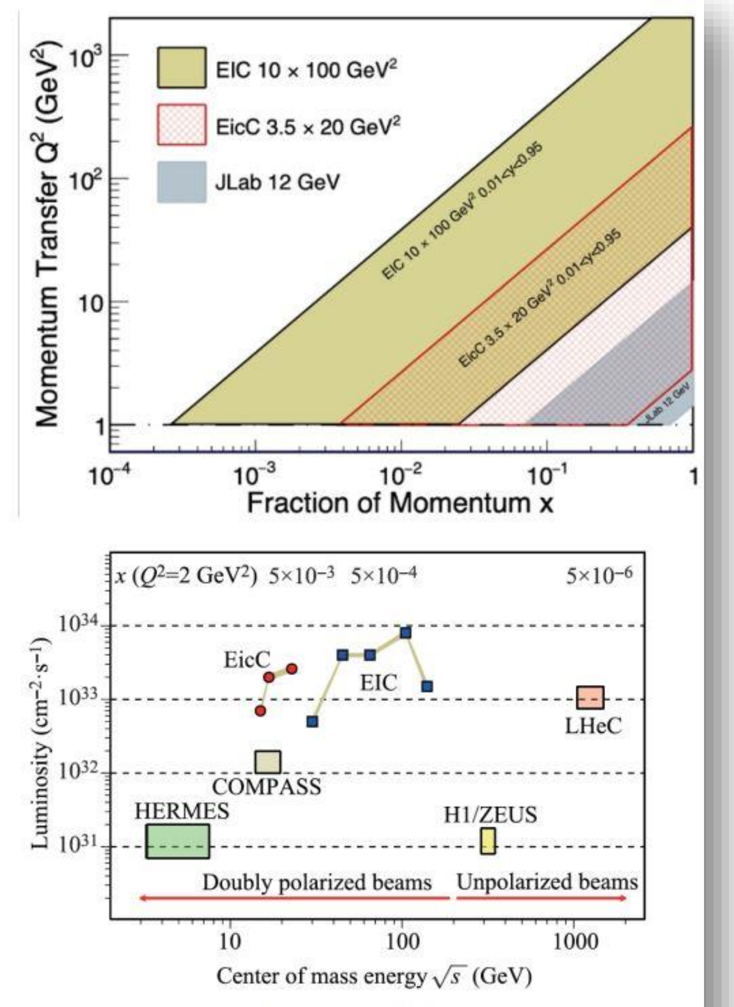
Interesting impact studies





Last words

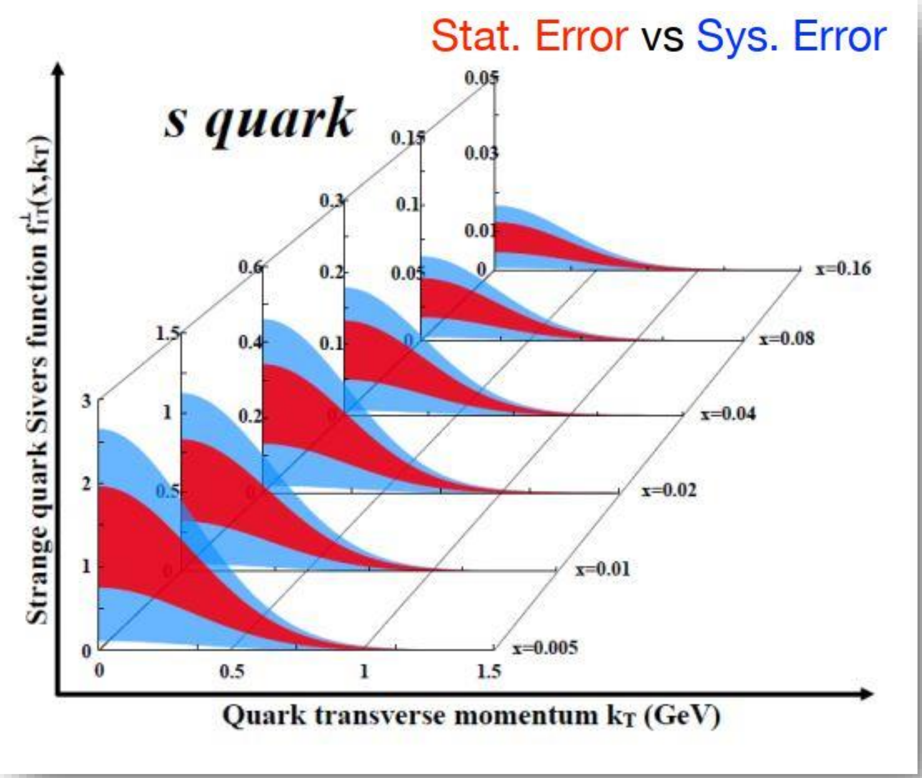
Nice complementarity between EIC and EicC



[Figures from EicC White paper]

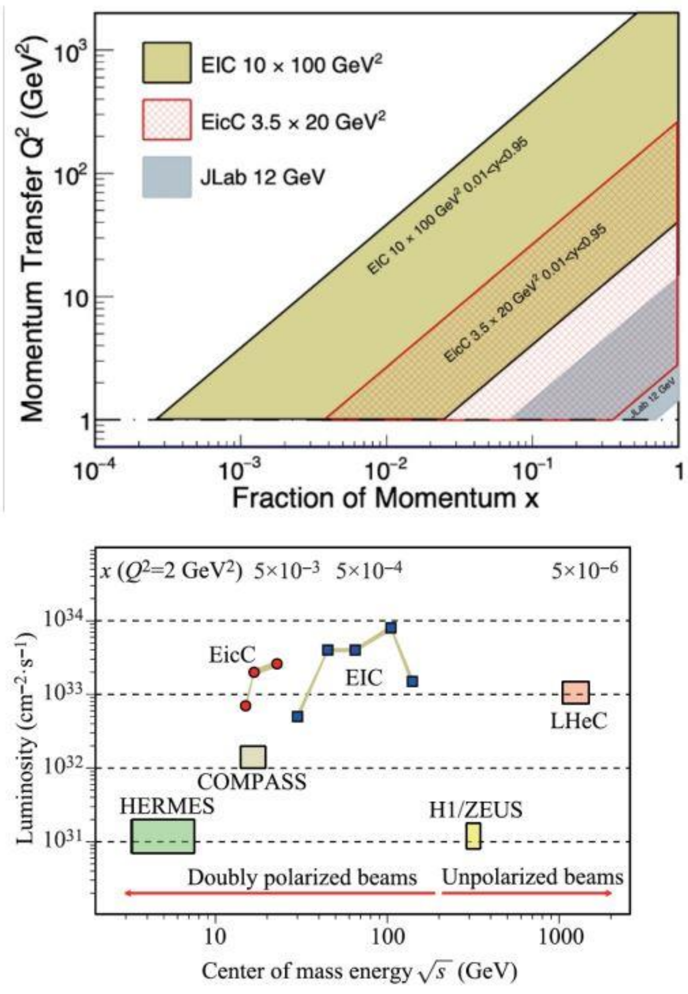
- **Nucleon spin structure**

Interesting impact studies



Last words

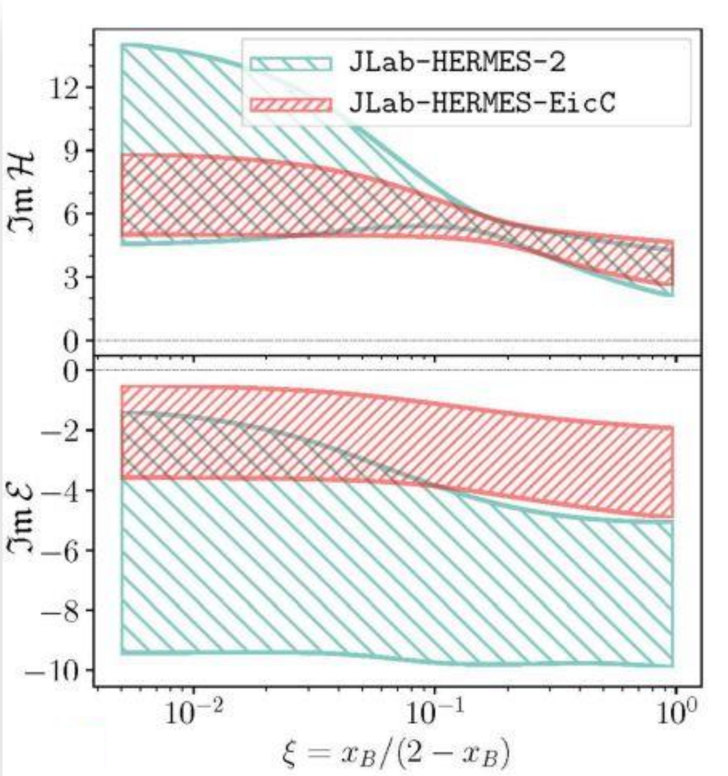
Nice complementarity between EIC and EicC



[Figures from EicC White paper]

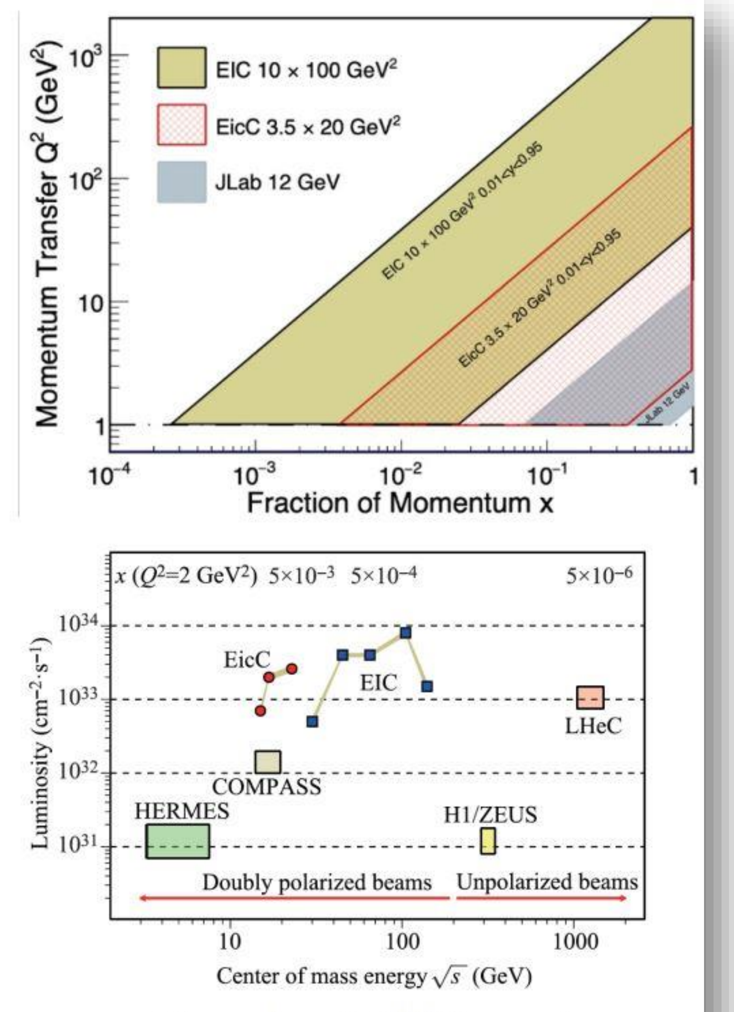
- **Nucleon spin structure**

Interesting impact studies



Last words

Nice complementarity between EIC and EicC



[Figures from EicC White paper]

- **Nucleon spin structure**

  EicC is optimized to systematically explore the gluon and sea quarks in moderate-x regime

- **Proton mass:**

  Mass decomposition [Ji, 95]

$$\boxed{M = M_q + M_m + M_g + M_a}$$

M_q : quark energy

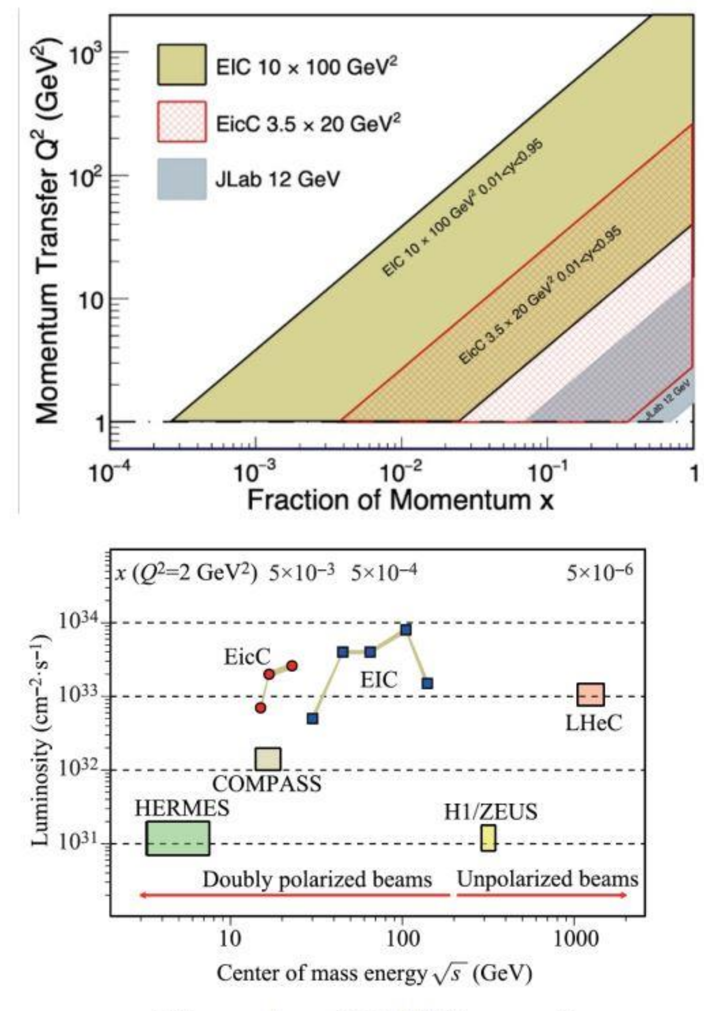
M_m : quark mass (condensate)

M_g : gluon energy

M_a : trace anomaly

Last words

Nice complementarity between EIC and EicC



[Figures from EicC White paper]

- **Nucleon spin structure**

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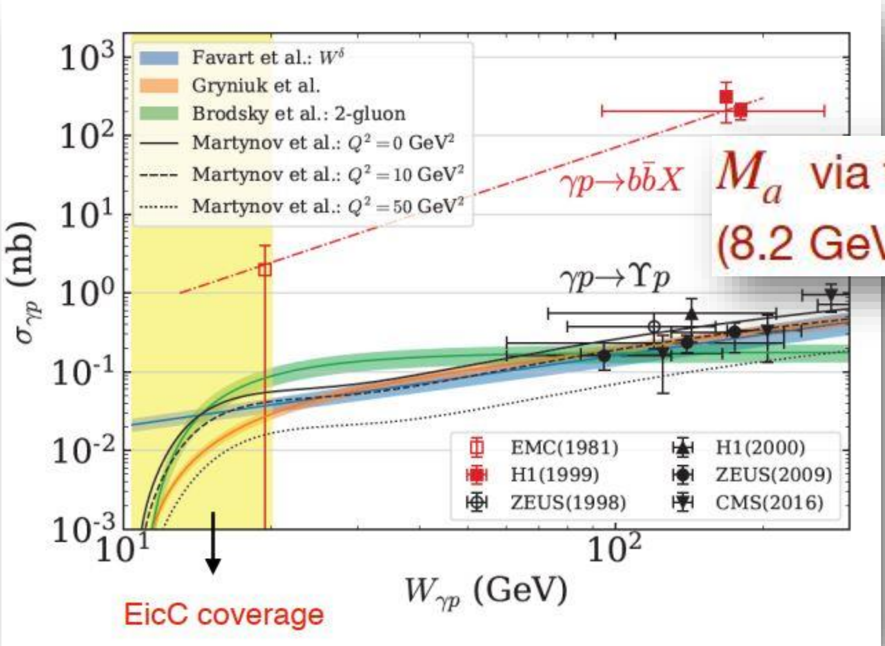
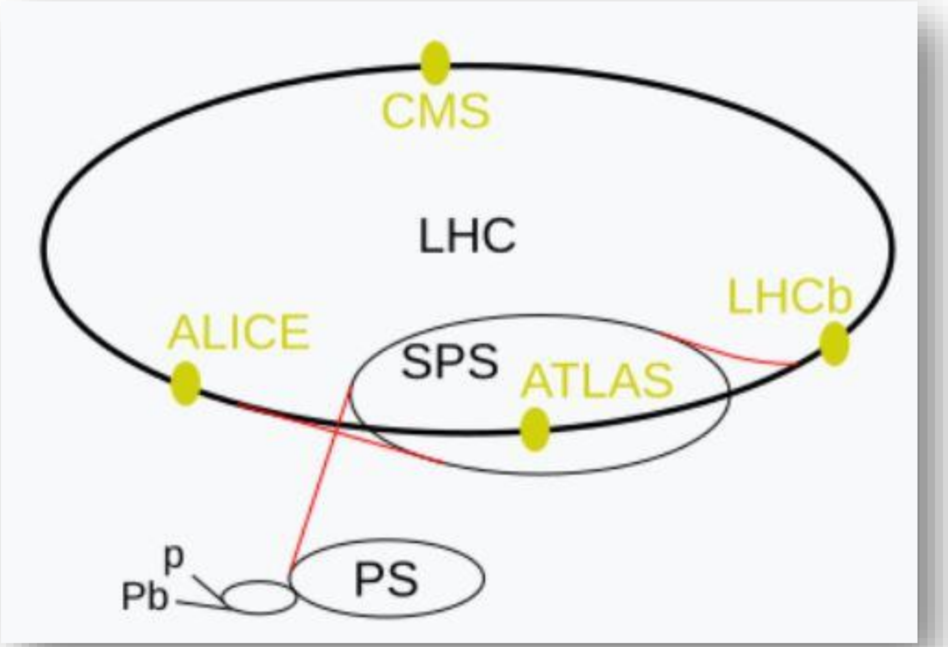
- **Proton mass:**



M_a via threshold production of J/ψ (8.2 GeV, JLab) and Υ (12 GeV)

Last words

Nice complementarity between EIC and LHC



EIC

- Ep and eA processes
- Polarization
- High luminosity (~HERA $\mathbf{10^{2-3}}$)
- Many possible exclusive channels

LHC

- Large $\boldsymbol{Q^2}$ lever arm (TMD evolution)
- W/Z production
- Mostly (semi)inclusive

String-based parametrization of GPDs

from data [75]. One approach to bypass the deconvolution problem, is to parametrize the conformal moments of GPDs [71, 72], which are highly constrained by Lorentz invariance (polynomiality condition), and can be interpreted in terms of t-channel spin-j resonances [63, 64].

For a fixed Mandelstam t and positive skewness η, GPDs exhibit distinct behaviors in two kinematic regimes: the DGLAP regime for $|x| > \eta$ and the ERBL regime for $|x| < \eta$. In the DGLAP regime, the dynamics correspond to either quark or antiquark momentum redistribution, while in the ERBL regime, it is akin to the emission of meson-like quark-antiquark pairs [13, 14].

We propose to use the holographic string-based approach (see the review [76], and references therein), to leverage the holographic principle to bypass the de-convolution issue entirely. By employing