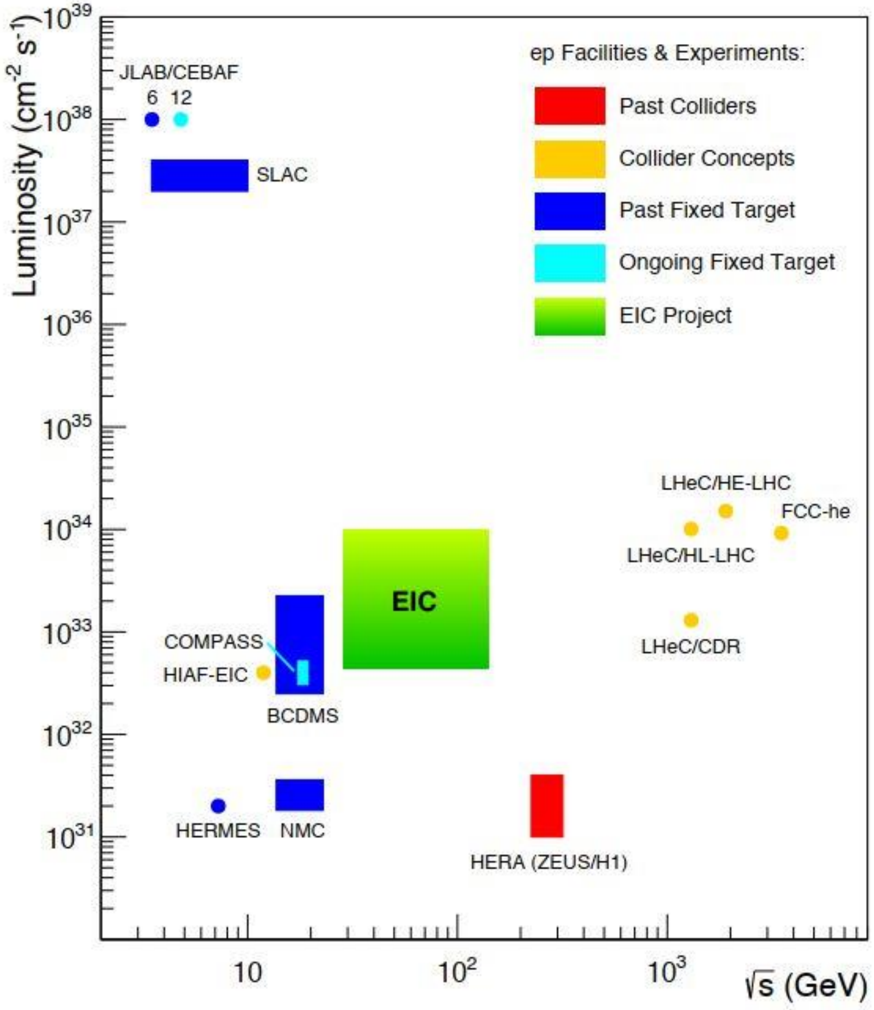
Report on EIC Early Physics Workshop

Shohini Bhattacharya
University of Connecticut
20 May 2025

Electron-Ion Collider

The uniqueness of EIC



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

Preliminary words

ePIC/Early EIC Science workshop (24-25 April, 2025)

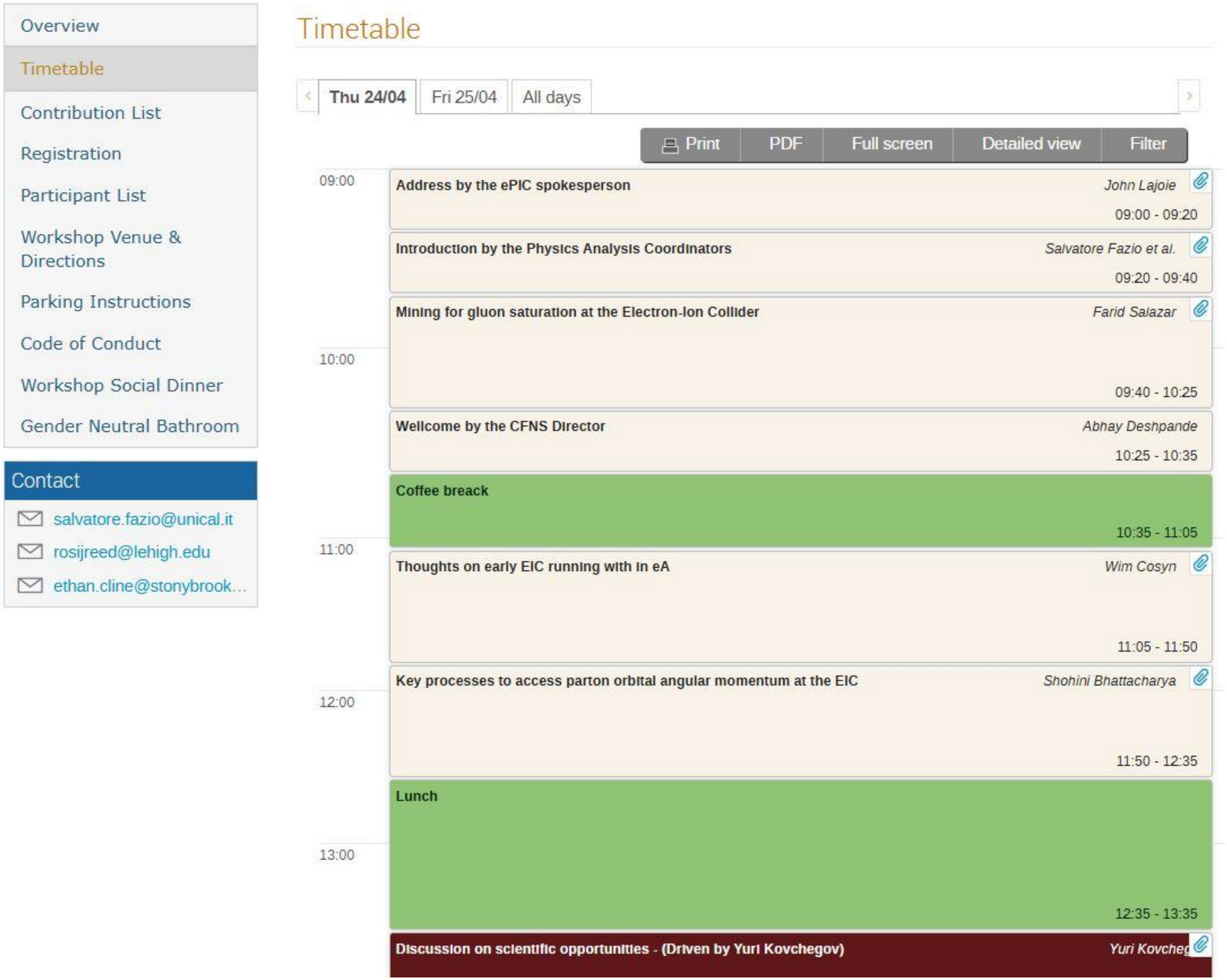
	Species	Energy (GeV)	Luminosity/year (fb-1)	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130	11.4 4.95 - 5.33	LONG	NO TRANS
YEAR 3	e+p	10 x 130	4.95 - 5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250	0.84 6.19 - 9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	0.84 8.65	LONG	N/A TRANS and/or LONG

Note: the eA luminosity is per nucleon

Center for Frontiers in Nuclear Science

…give a talk on impactful measurements that we would be able to make given these constraints

Preliminary words


Overview
Timetable
Contribution List
Registration
Participant List
Workshop Venue & Directions
Parking Instructions
Code of Conduct
Workshop Social Dinner
Gender Neutral Bathroom

Contact
salvatore.fazio@unical.it
rosijreed@lehigh.edu
ethan.cline@stonybrook...

Timetable

Thu 24/04 | Fri 25/04 | All days

Print | PDF | Full screen | Detailed view | Filter

09:00	Address by the ePIC spokesperson	*John Lajoie*	09:00 - 09:20
	Introduction by the Physics Analysis Coordinators	*Salvatore Fazio et al.*	09:20 - 09:40
	Mining for gluon saturation at the Electron-Ion Collider	*Farid Salazar*	09:40 - 10:25
10:00	Wellcome by the CFNS Director	*Abhay Deshpande*	10:25 - 10:35
	Coffee breack		10:35 - 11:05
11:00	Thoughts on early EIC running with in eA	*Wim Cosyn*	11:05 - 11:50
	Key processes to access parton orbital angular momentum at the EIC	*Shohini Bhattacharya*	11:50 - 12:35
12:00	Lunch		12:35 - 13:35
13:00			
	Discussion on scientific opportunities - (Driven by Yuri Kovchegov)	*Yuri Kovcheg*	

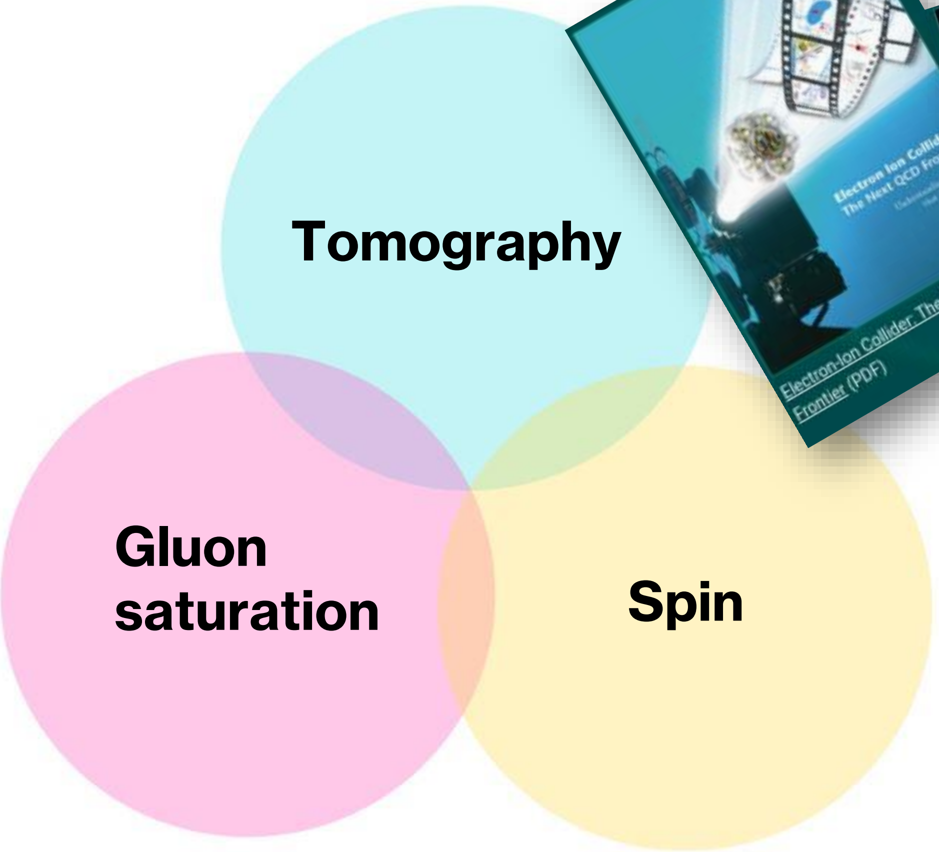
4 theory talks:
Farid Salazar,
Wim Cosyn,
Yuri Kovchegov (discussions),
and me

Preliminary words

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

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

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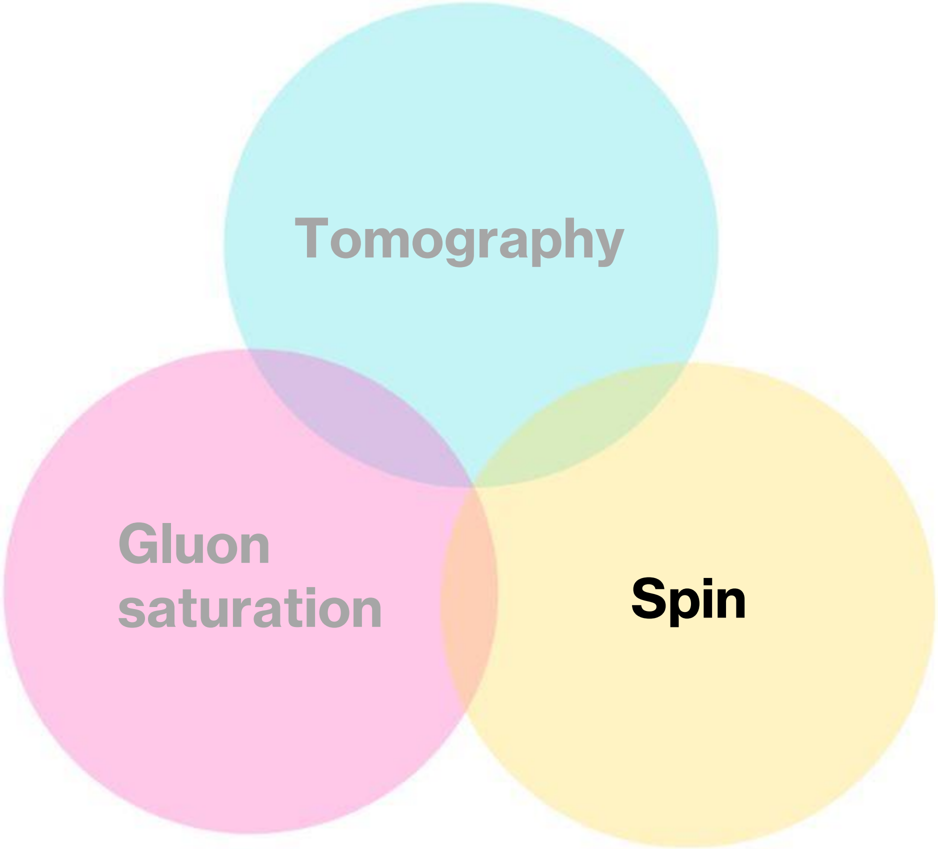
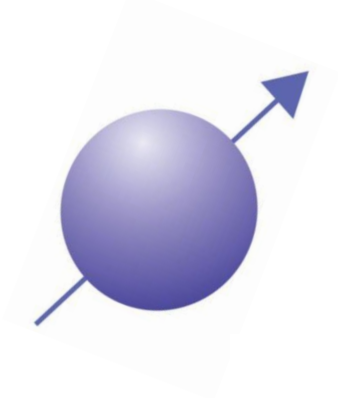


My talk

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)

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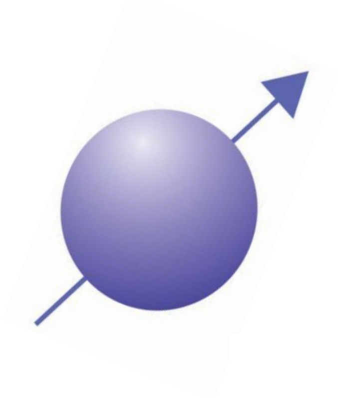


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

Best known $\sim 30\%$

How well do we know? $\sim 40\%$

???????

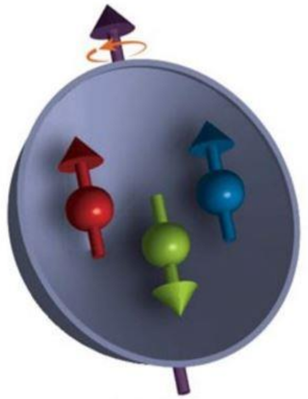
Currently, there are **no** experimental constraints on OAM

Nucleon spin

Naïve quark model expectation

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

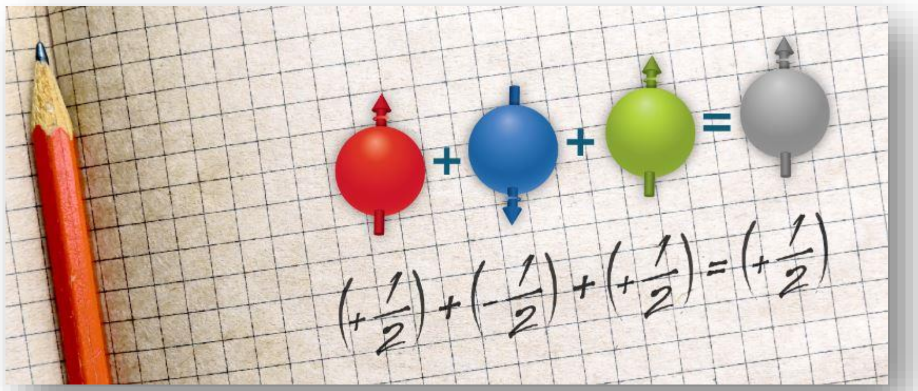
$$\frac{1}{2} = \frac{1}{2} + \frac{1}{2} - \frac{1}{2}$$



$$\boxed{\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{Quark spin}} + \underbrace{\cancel{\Delta G}}_{\text{Gluon spin}} + \underbrace{\cancel{L_z}}_{\text{Orbital Angular Momentum}}}$$

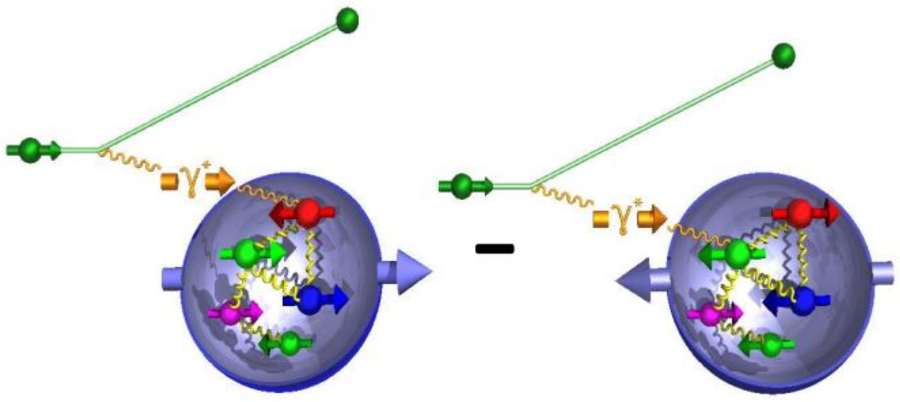
$$\therefore \quad \boxed{\Delta\Sigma = 1}$$

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 :

$$\int_0^1 dx g_1(x) = \frac{1}{9}\boxed{(\Delta u + \Delta d + \Delta s)} \longleftarrow \Delta\Sigma$$

$$+ \frac{1}{12}(\Delta u - \Delta d) + \frac{1}{36}(\Delta u + \Delta d - 2\Delta s)$$

$$+ \mathcal{O}(\alpha_s)$$

Nucleon spin

Spin puzzle

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

$$\Delta\Sigma = 0.060 \pm 0.047 \pm 0.069$$

Recent value:

$$\Delta\Sigma = 0.25 \sim 0.3$$

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

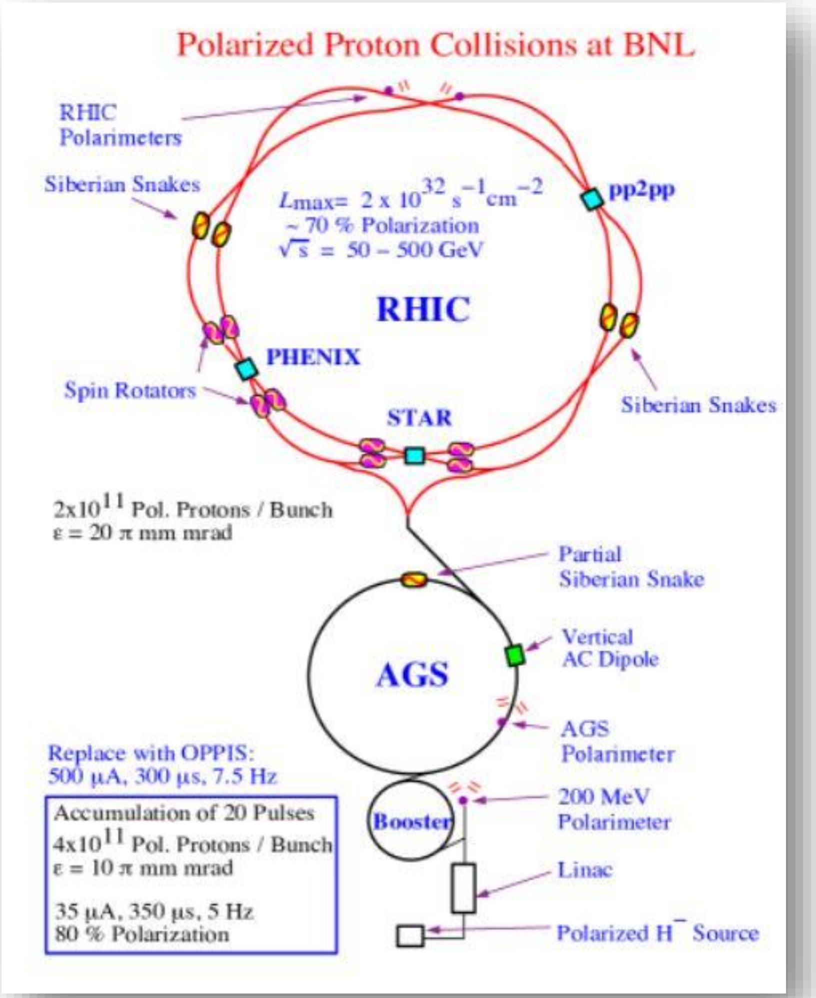
The search for answers turned to Brookhaven Lab, where RHIC was taking shape

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

Still significantly less than 1

Nucleon spin

RHIC spin project

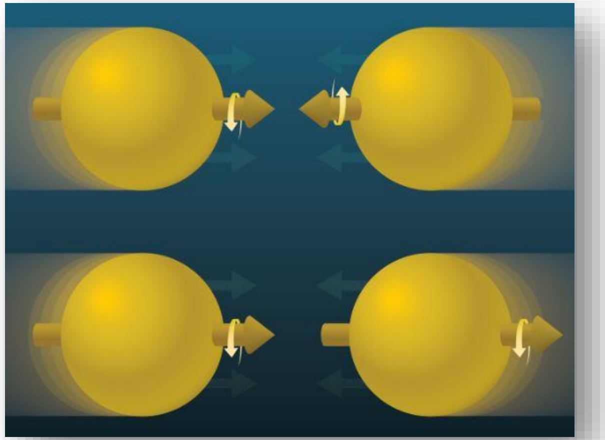


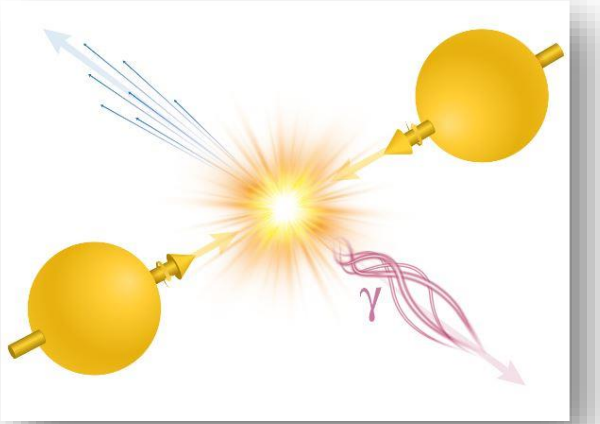
One of the main physics goals is to pin down the **gluon spin** contribution

$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{Quark spin}} + \underbrace{\boxed{\Delta G}}_{\text{Gluon spin}} + \underbrace{L_z}_{\text{Orbital Angular Momentum}}$$

Nucleon spin

RHIC spin project





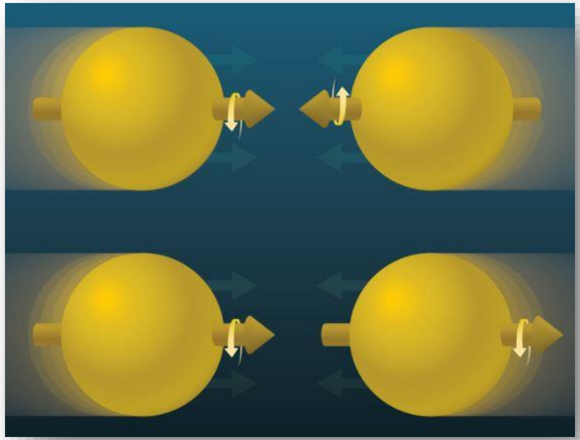
A golden measurement:

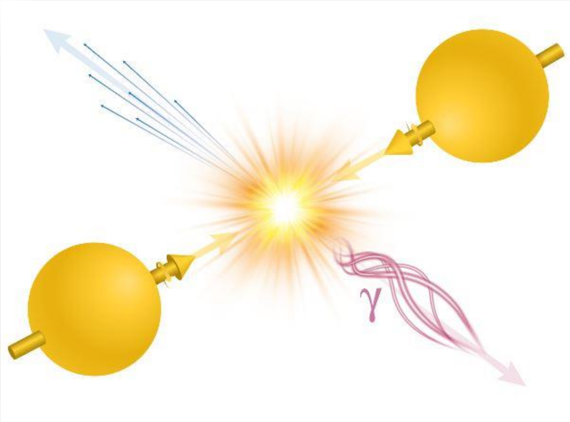
It's a **comparison of the number of "direct photons"** emitted when RHIC collides protons with their spins pointing in opposite directions with the number of direct photons produced when the protons in the two beams are pointing in the same direction.

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§

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

Rodolfo Sassot¶

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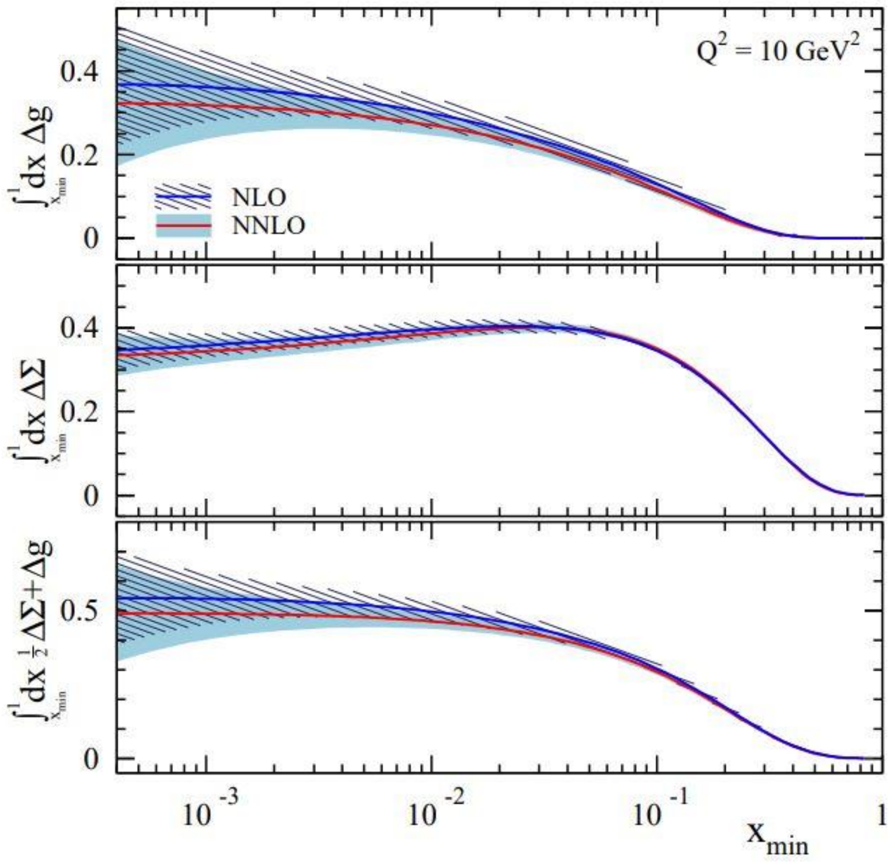

FIG. 5. Truncated first moments of the quark singlet and gluon helicity PDFs at $Q^2 = 10$ GeV^2, and their combined contribution to the proton spin sum rule (bottom panel).

Nucleon spin

Tremendous progress

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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.

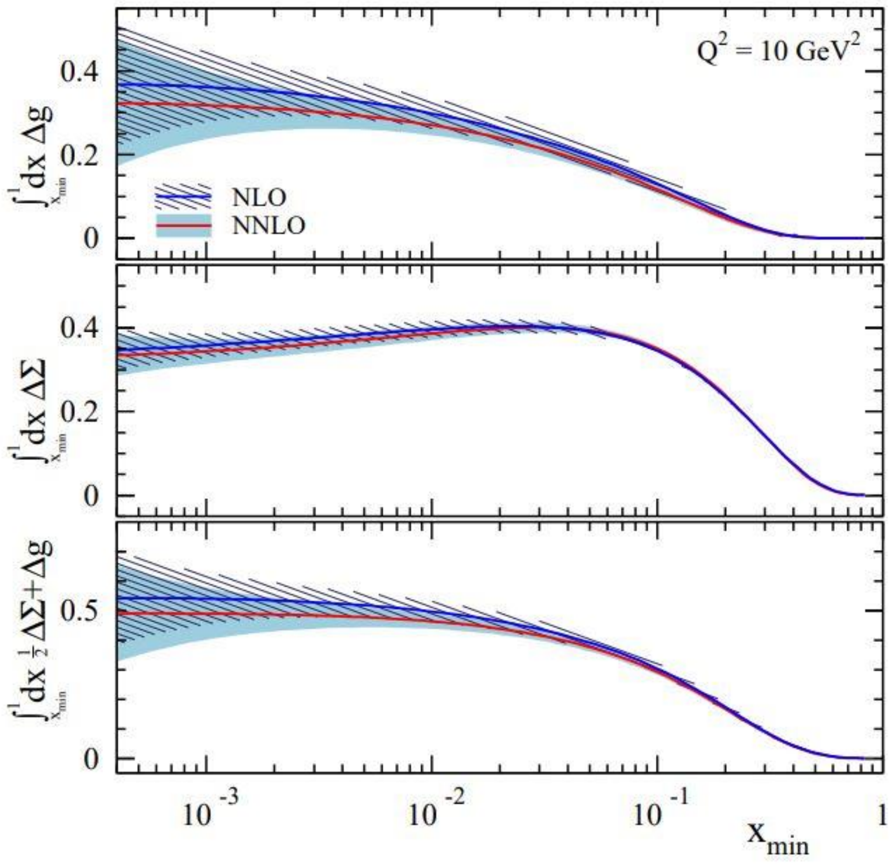

FIG. 5. Truncated first moments of the quark singlet and gluon helicity PDFs at $Q^2 = 10\ \mathrm{GeV}^2$, and their combined contribution to the proton spin sum rule (bottom panel).

Nucleon spin

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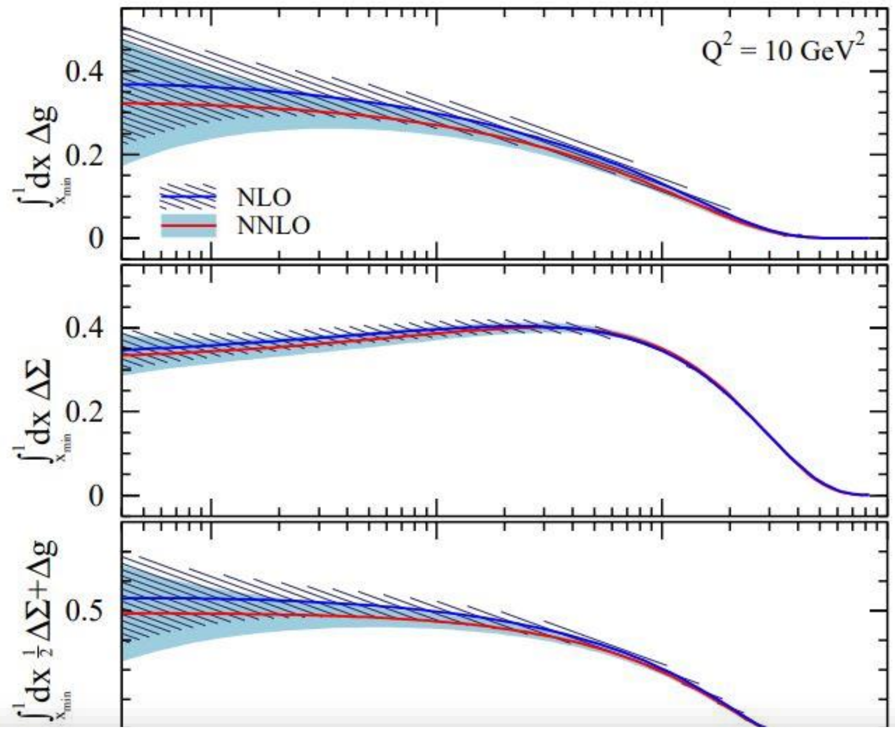


Searches for **observables** sensitive to **Orbital Angular Momentum at the EIC** represent a very active area of research

Nucleon spin

Observables for gluon Orbital Angular Momentum

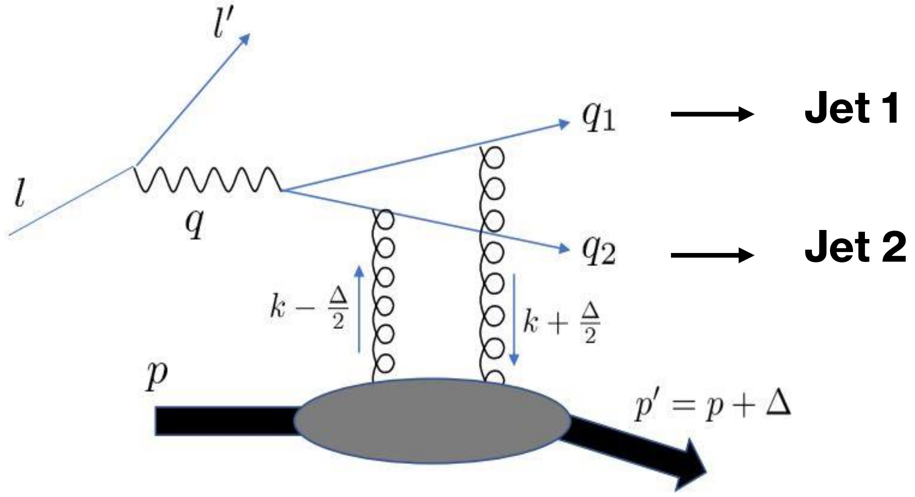
Nucleon spin

Observables for gluon Orbital Angular Momentum

Signature of the gluon orbital angular momentum

Shohini Bhattacharya,[1,*] Renaud Boussarie,[2,†] and Yoshitaka Hatta[1,3,‡]

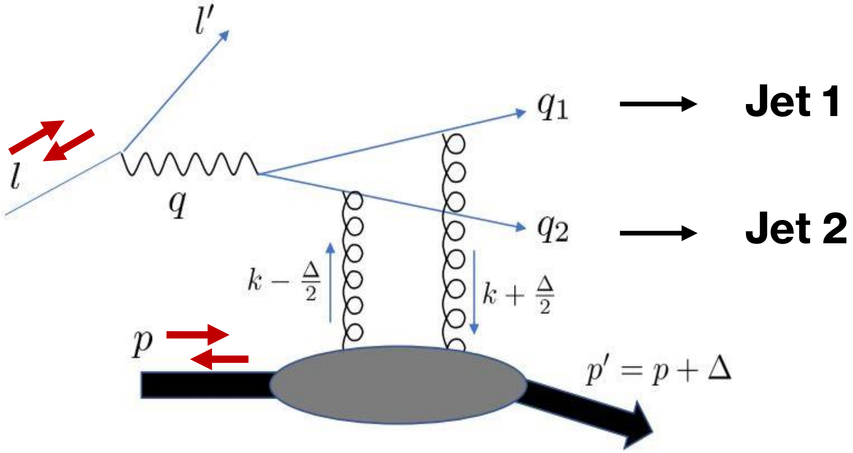
$$e(l) + p(p, \lambda) \to e(l') + j_1(q_1) + j_2(q_2) + p(p', \lambda')$$



Nucleon spin

Observables for gluon Orbital Angular Momentum

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



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

$$+\Re e\left[\mathcal{H}_g^{(1)*}(\xi)\tilde{\mathcal{H}}_g^{(2)}(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$

$$+\Re e\left[\frac{4q_\perp^2}{q_\perp^2+\mu^2}\tilde{\mathcal{H}}_g^{(2)}(\xi)C_g^{(2)}(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$

(SB, Boussarie, Hatta, 2022, 2024)

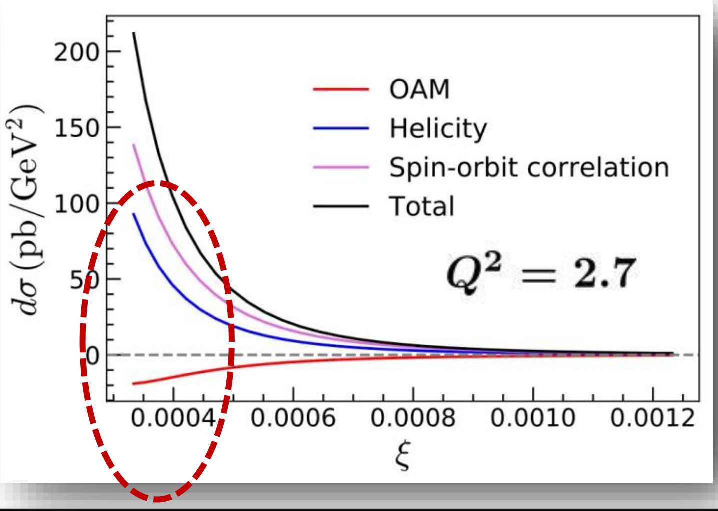
More works on spin asymmetry calculations in diffractive dijets:

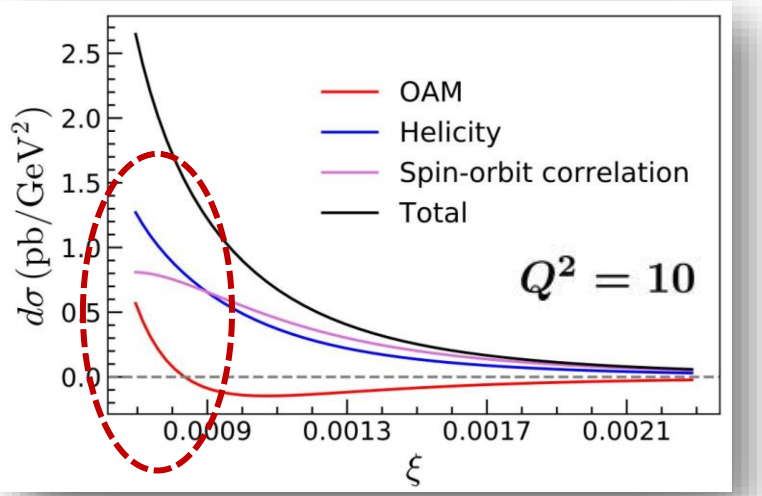
Leading order, unpolarized (twist-2 GPDs): Braun, Ivanov (2005)
Single spin asymmetry: Ji, Yuan, Zhao (2016); Hatta, Nakagawa, Yuan, Xiao, Zhao (2016)

Nucleon spin

Observables for gluon Orbital Angular Momentum

Interplay between OAM and helicity at small x





First quantitative prediction for such an observable at EIC kinematics

Schematic structure of our observable:

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

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

Cancellation expected between helicity & OAM at small x

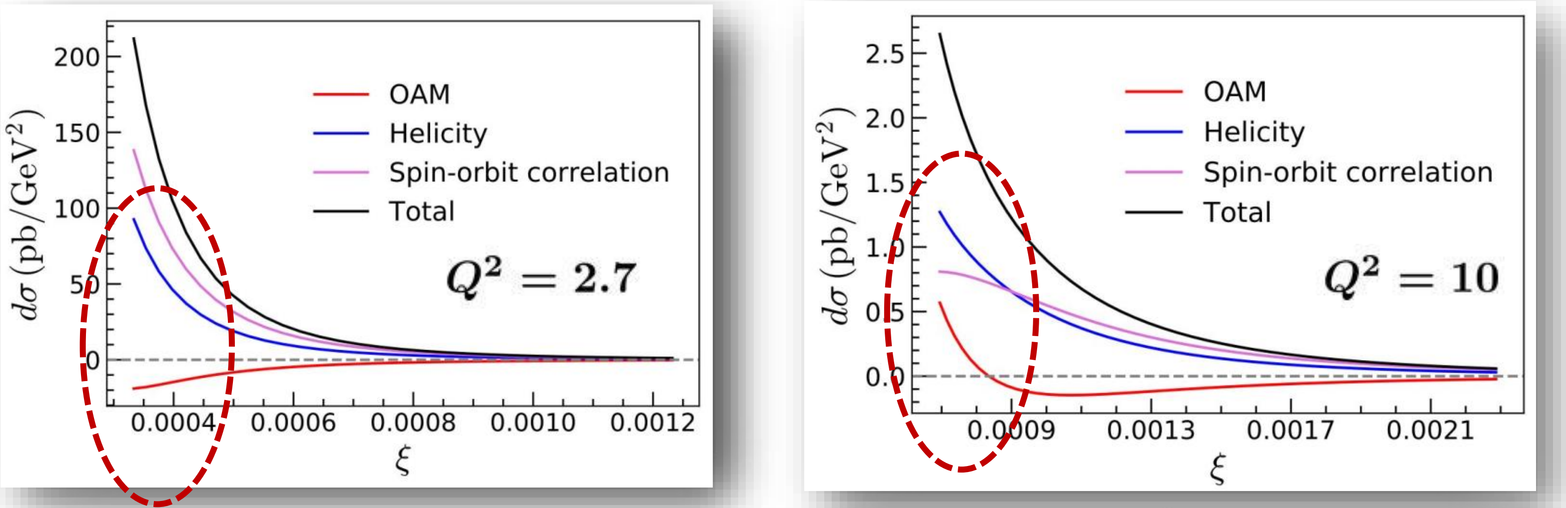
$$\boxed{\Delta G(x) \approx -\frac{2}{1+c} L_g(x)}$$

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

Nucleon spin

Observables for gluon Orbital Angular Momentum

Interplay between OAM and helicity at small x



Might be difficult to reconstruct dijet momentum

Schematic structure of our observable:

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

$\Delta G(x)$ $L_g(x)$

Cancellation expected between helicity & OAM at small x

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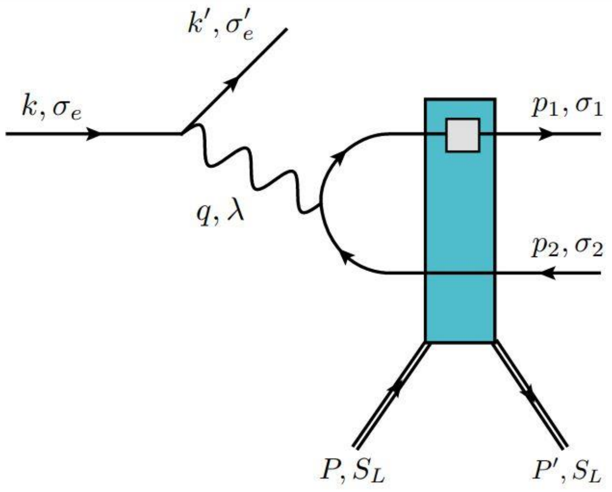
Boussarie, Hatta, Yuan (2019)
Kovchegov, Manley (2023, 2024)

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.

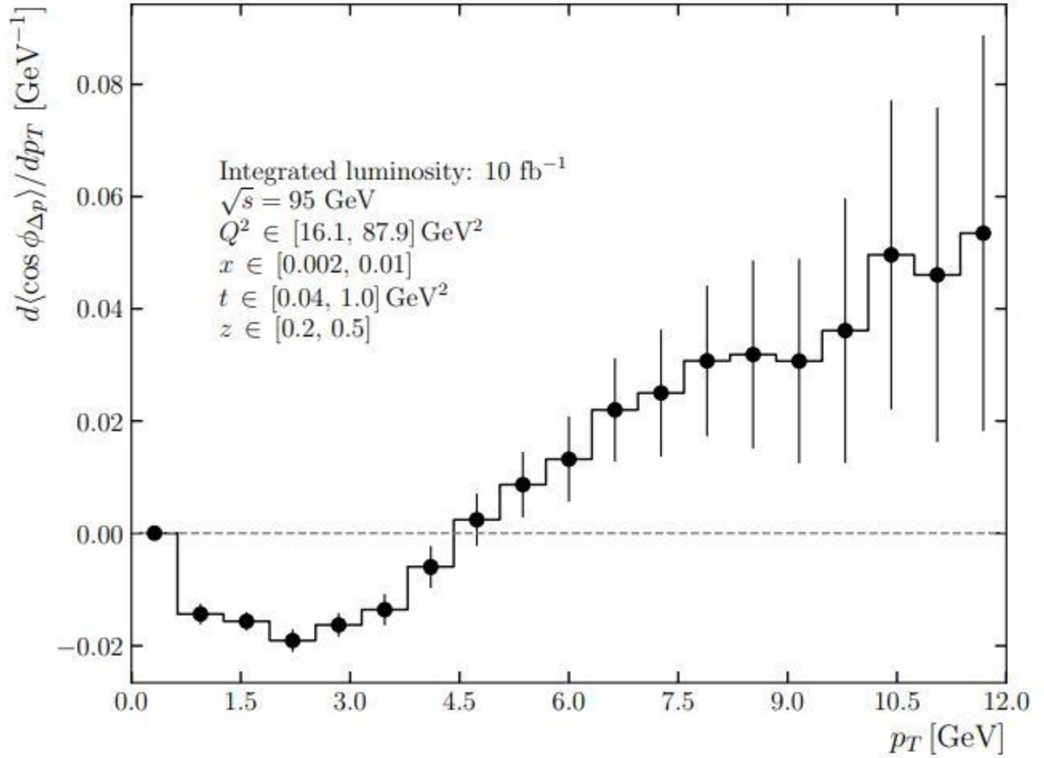
Nucleon spin

Observables for gluon Orbital Angular Momentum

Yuri's discussion talk

Vertical axis – cos $\phi_{\Delta pT}$ harmonic in elastic dijets A_{LL}.

pT = jets b2b momentum
Δ = momentum transfer
assumed int. luminosity = 10 fb^{-1}



JAMsmallx (Brandon Manley) – preliminary!

Sudakov radiations:
Jet angle might be affected by QCD radiations

Nucleon spin

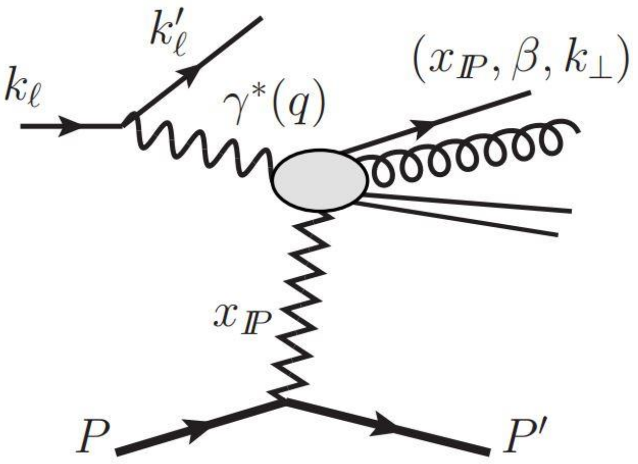
Observables for gluon Orbital Angular Momentum

Going past dijets

Nucleon spin

Observables for gluon Orbital Angular Momentum

Going past dijets: **Semi Inclusive Diffractive Deep Inelastic Scattering**



$$\Delta Y = \ln \frac{1}{\beta}$$

Hatta, Xiao, Yuan (2022)

- Measure invariant mass of diffractively produced system instead of reconstructing jets

$$M_X^2 = \frac{q_\perp^2}{z\bar{z}} = \frac{1-\beta}{\beta} Q^2$$

- Tag hadron species (inclusively) out of diffractively produced system

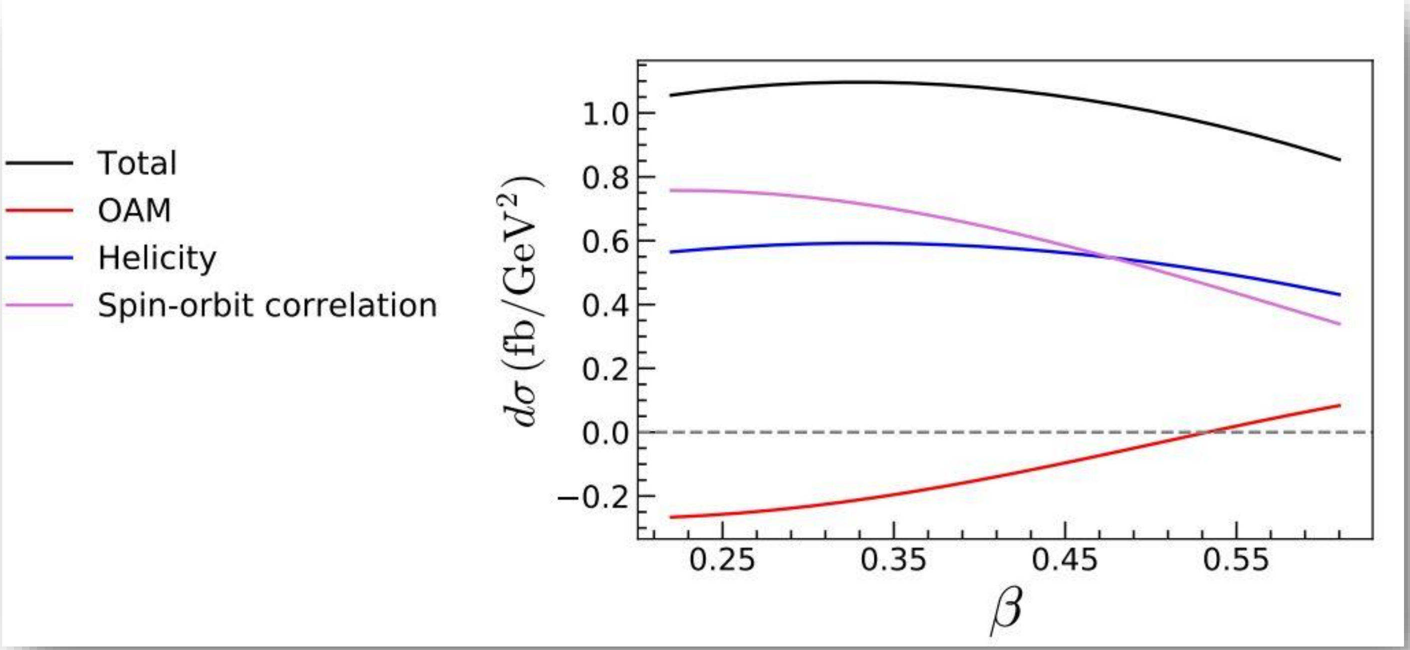
Nucleon spin

Observables for gluon Orbital Angular Momentum

Going past dijets: **Semi Inclusive Diffractive Deep Inelastic Scattering**

Numerical results (SB, Boussarie, Hatta, 2404.04209)**:**

Challenging, yet there is no requirement to reconstruct jets & we still maintain sensitivity to gluon OAM;
Might be an early EIC measurement



Nucleon spin

Observables for quark Orbital Angular Momentum

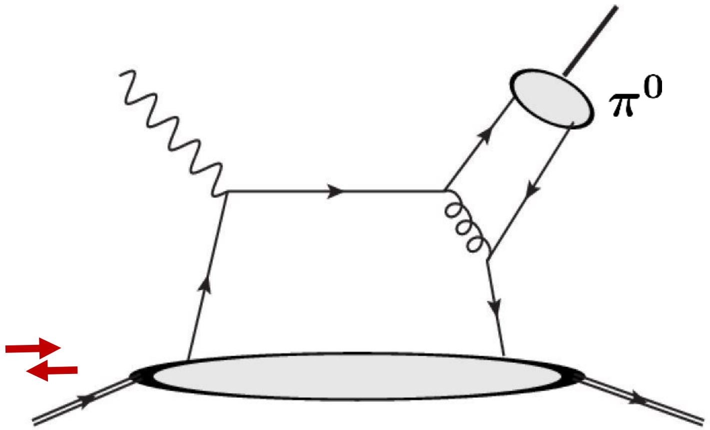
Nucleon spin

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]

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



Nucleon spin

Observables for quark Orbital Angular Momentum

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

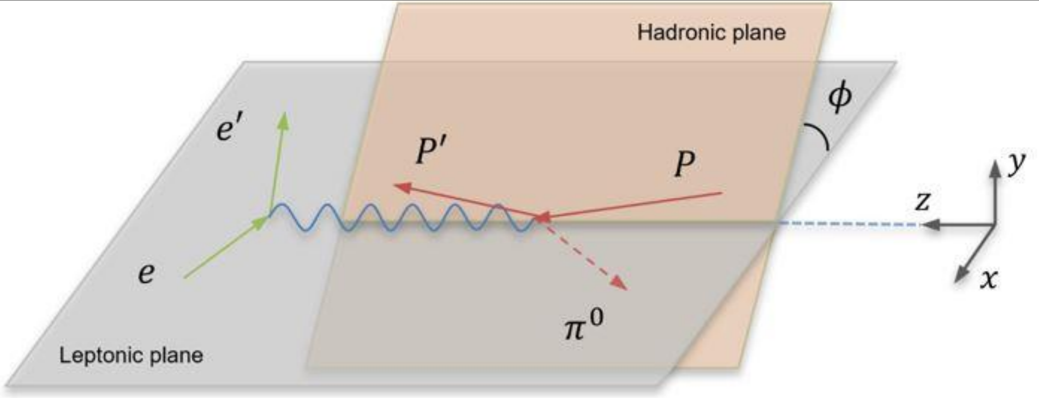
$$\frac{d\sigma}{dt\,dQ^2\,dx_B\,d\phi} = \frac{(N_c^2-1)^2\alpha_{em}^2\alpha_s^2 f_\pi^2 \xi^3 \Delta_\perp^2}{2N_c^4(1-\xi^2)Q^{10}(1+\xi)}\left[1+(1-y)^2\right]$$

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

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

Distinguished experimental signature of quark OAM

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

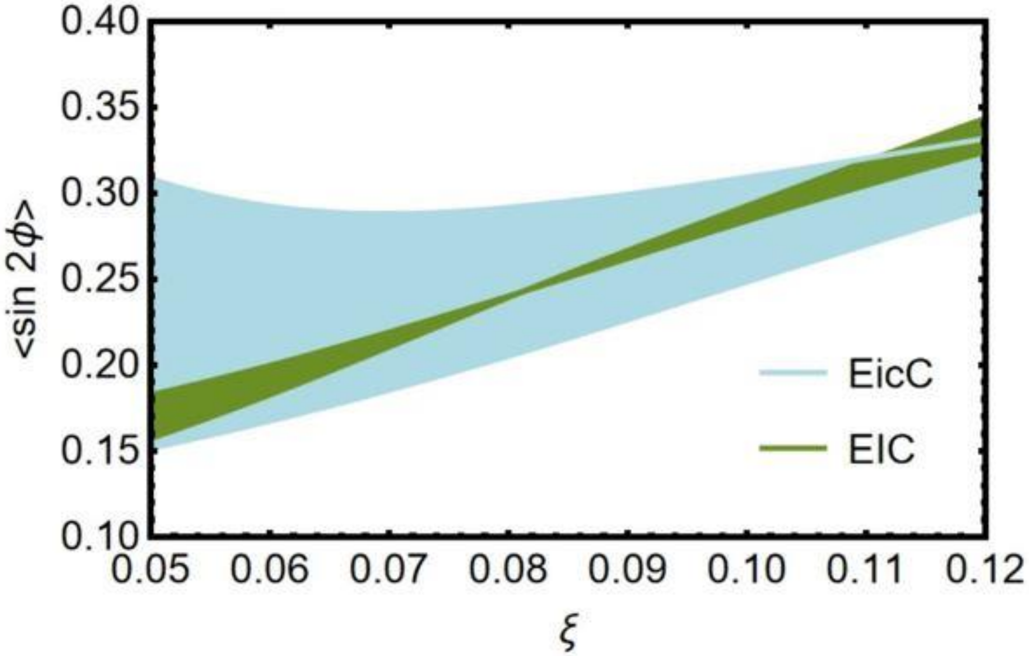


Nucleon spin

Observables for quark Orbital Angular Momentum

Predictions for Electron-Ion Colliders

Asymmetry



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

Might be an early EIC measurement

Findings:

The asymmetries are substantial for both EIC & EicC kinematics

Proton mass

EIC may shed light on the origin of the proton mass
(Not covered in the early science workshop)

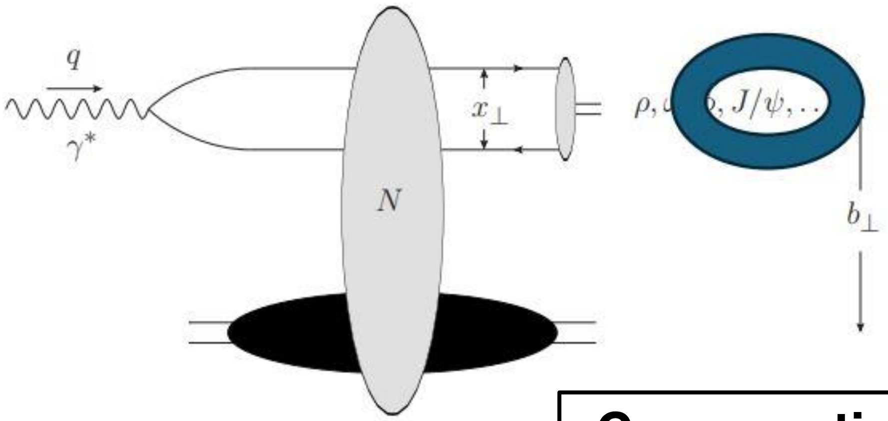
Yuri's discussion talk

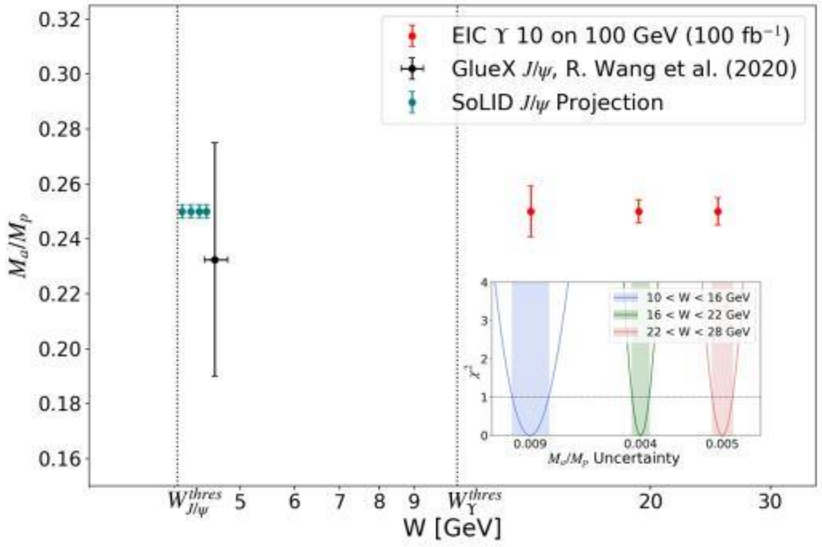
Proton mass

EIC may shed light on the origin of the proton mass
(Not covered in the early science workshop)

Yuri's discussion talk

J/psi or upsilon elastic production near threshold may probe an operator related to the QCD trace anomaly evaluated in the proton state. May measure the trace anomaly contribution to the proton mass.
(D. Kharzeev, 1990s; Y. Hatta, more recently).



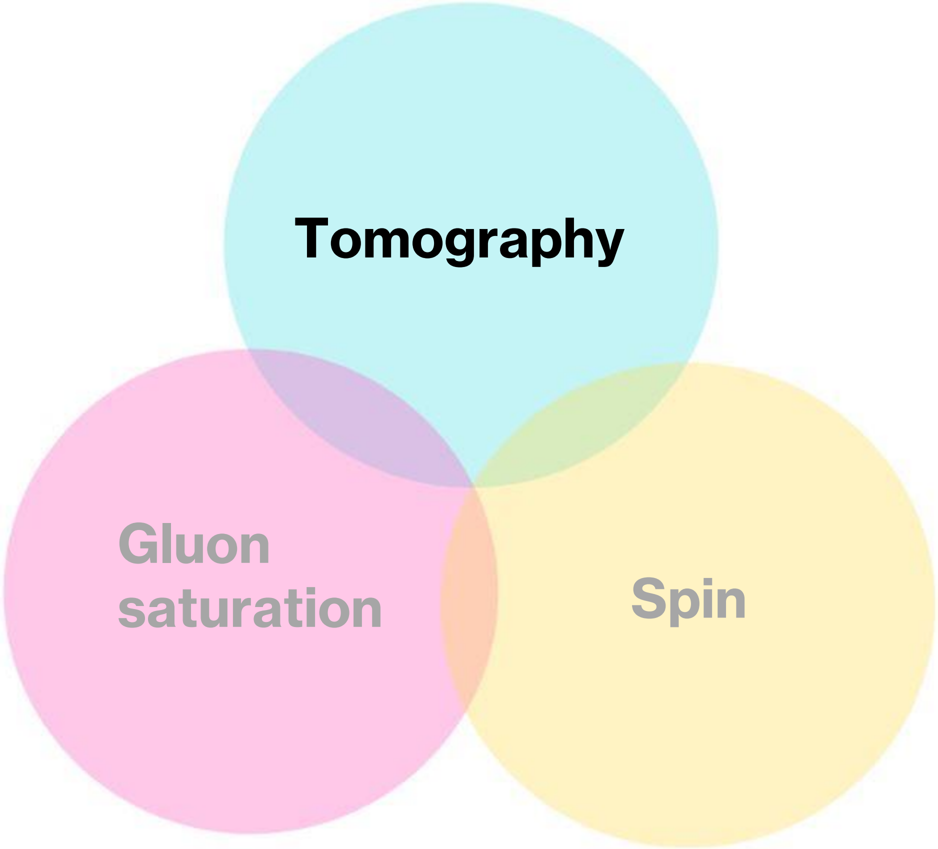


However, this appears to be a luminosity-hungry measurement. Is it for the early EIC?

Cross-sections low at threshold;
Check with S. Joosten (ANL) for simulations;
but for first few years its likely challenging

Scientific goals of Electron-Ion Collider

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



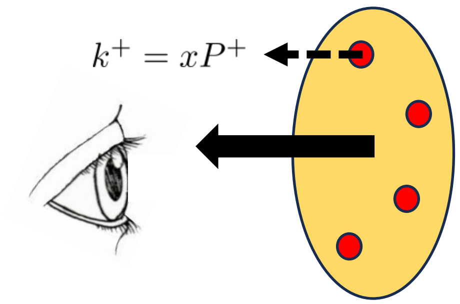
Nonperturbative functions in QCD

Maps of internal dynamics of partons in multiple dimensions

Parton

Nucleon motion

1D



Parton Distribution Functions

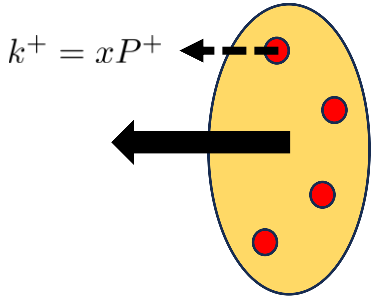
PDFs (x)

Nonperturbative functions in QCD

Maps of internal dynamics of partons in multiple dimensions

Parton
Nucleon motion

1D

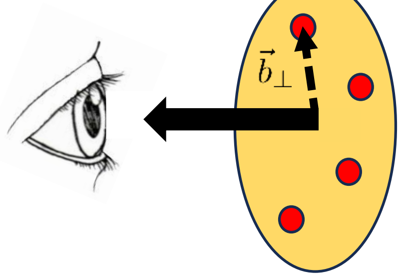


Form Factors

PDFs (x)

FFs (Δ)

2D



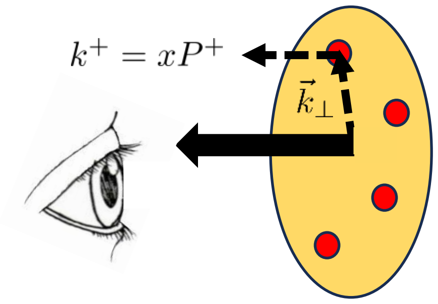
Nonperturbative functions in QCD

Maps of internal dynamics of partons in multiple dimensions

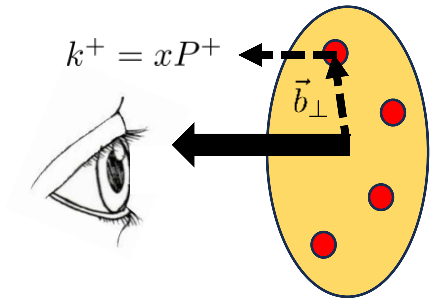
Parton
Nucleon motion

Transverse Momentum-dependent Distributions

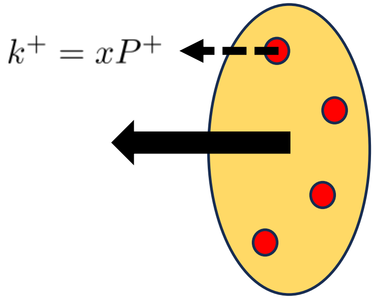
Generalized Parton Distributions



3D



1D



TMDs $(x, \vec{k}_\perp)$

GPDs (x, Δ)

$\int d^2\vec{k}_\perp$

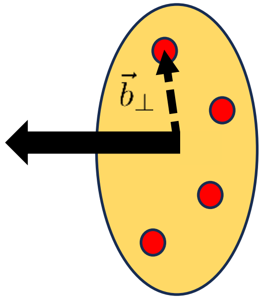
$\Delta = 0$

$\int dx$

PDFs (x)

FFs (Δ)

2D



Nonperturbative functions in QCD

Maps of internal dynamics of partons in multiple dimensions

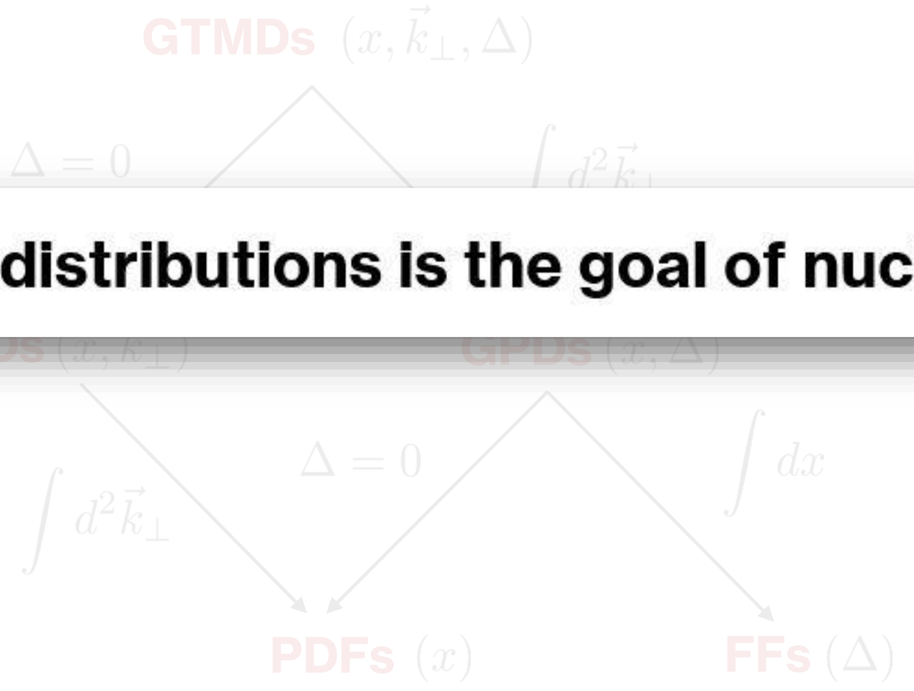
Generalized Transverse Momentum-dependent Distributions

5D

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

Nonperturbative functions in QCD

Maps of internal dynamics of partons in multiple dimensions

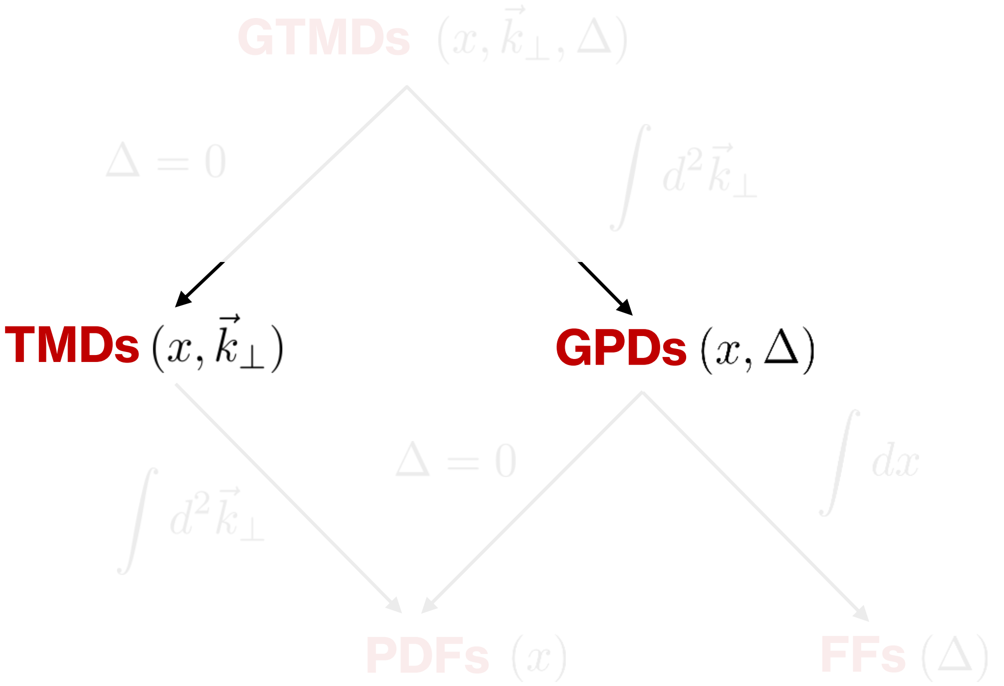


Mapping these partonic distributions is the goal of nucleon structure studies

Nonperturbative functions in QCD

Maps of internal dynamics of partons in multiple dimensions

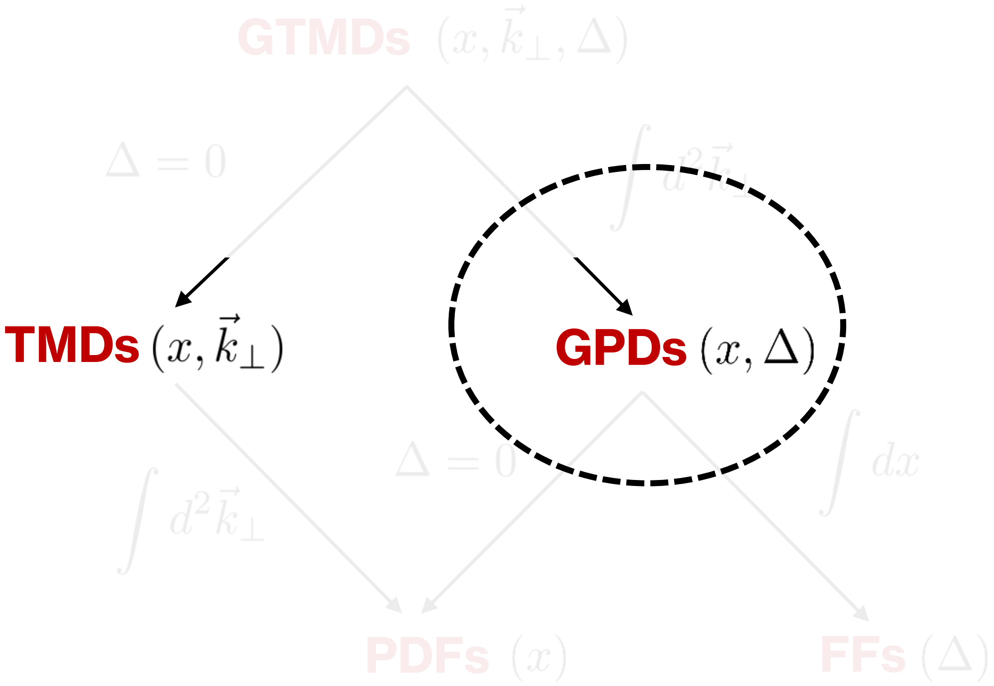
Yuri's discussion talk



Nonperturbative functions in QCD

Maps of internal dynamics of partons in multiple dimensions

Yuri's discussion talk

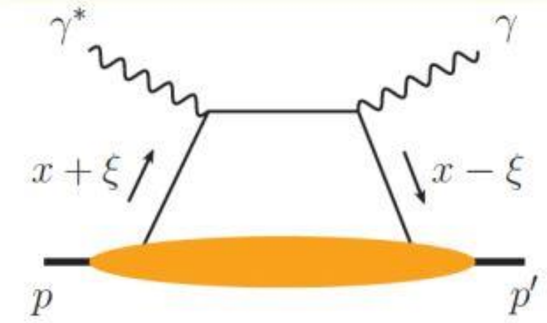


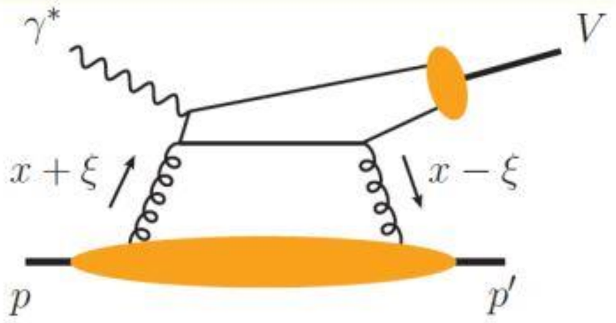
Generalized Parton Distributions (GPDs)

Yuri’s discussion talk

Processes sensitive to GPDs

DVCS and exclusive vector meson production





Both DVCS and DVMP (J Psi) can be an early EIC measurement

DVCS is a rare process (cross section ~α_{EM}^3), hard to measure – is this an early EIC observable?

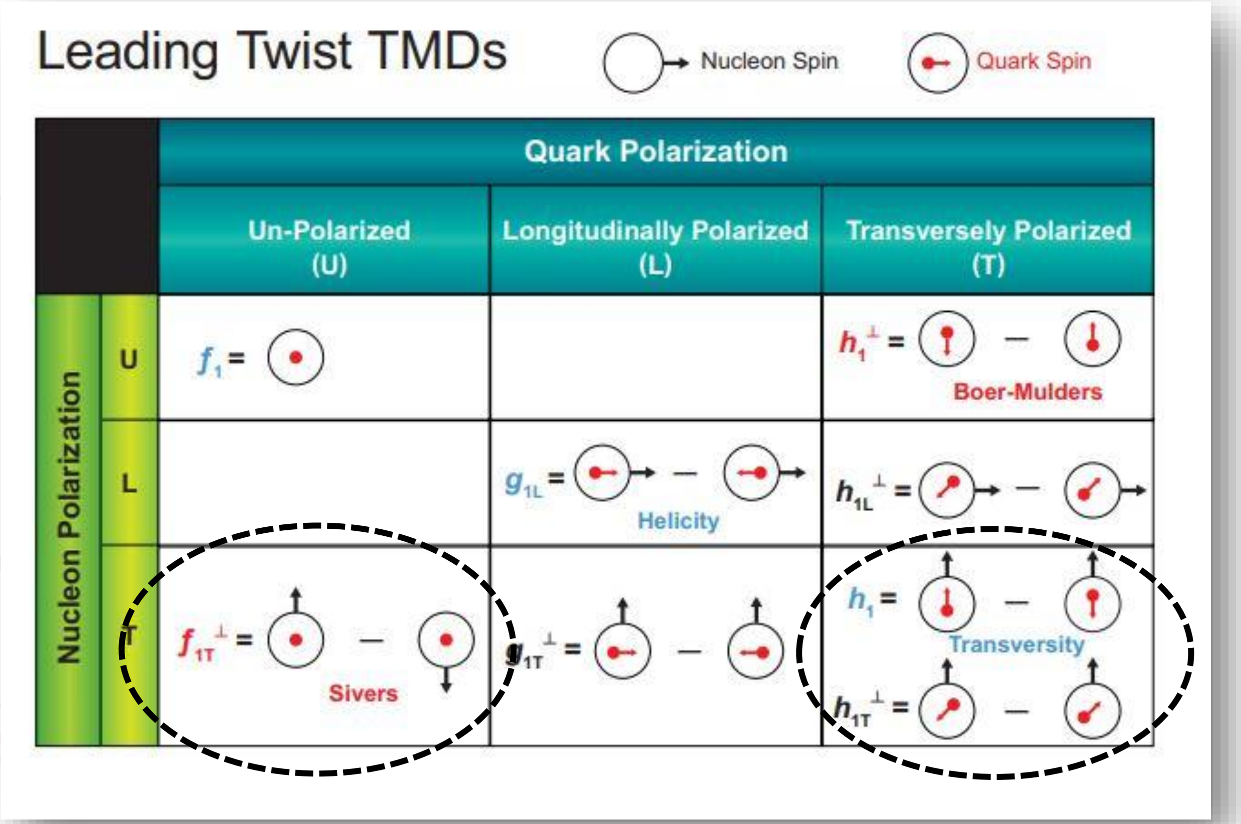
Exclusive vector meson production is not as suppressed: still large rapidity gaps are rare. Can this be an early EIC observable?

Nonperturbative functions in QCD

Maps of internal dynamics of partons in multiple dimensions

Yuri's discussion talk

TMDs $(x, \vec{k}_\perp)$

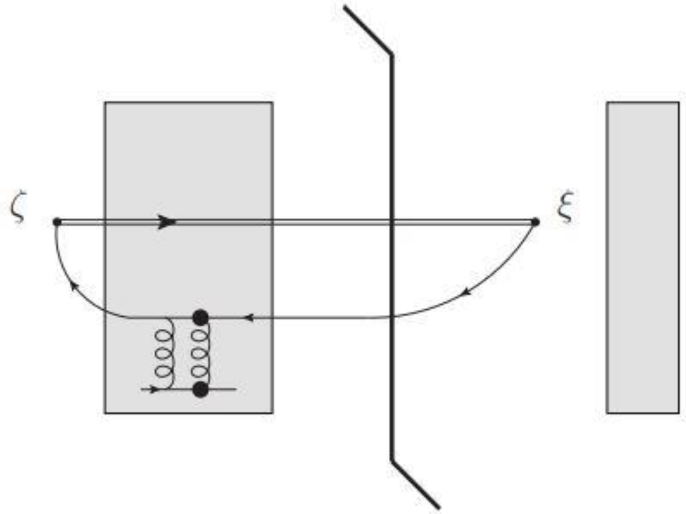


Transverse-momentum dependent Distributions (TMDs)

Yuri's discussion talk

Spin-dependent odderon search

Sivers function



The Siver function at small x is also related to the dipole amplitude from above – only to its C-odd component.

Its leading small-x asymptotics is given by **the spin-dependent odderon** (D. Boer, M. G. Echevarria, P. Mulders and J. Zhou '15):

$$f_{1T}^{\perp q}(x, k_T^2) \sim \text{Fourier}\quad \text{transform}\,\{\mathcal{O}(x_\perp, b_\perp, Y)\}$$

The Sivers function also depends on the sub-eikonal dipole amplitude (YK, M. G. Santiago, 2209.03538 [hep-ph]; 2108.03667 [hep-ph]) – this generates a correction to the above odderon contribution.

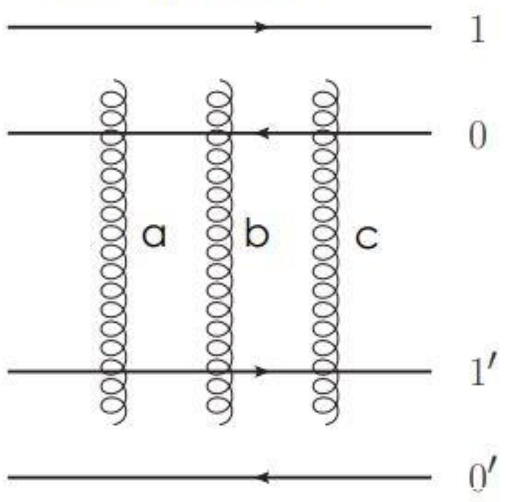
Transverse-momentum dependent Distributions (TMDs)

Yuri's discussion talk

Spin-dependent odderon search

Odderon as a 3-gluon exchange

- In perturbation theory, the C-odd exchange can be due to
  - 1-gluon exchange: yes, it is C-odd, but not color-singlet, cannot give an elastic amplitude.
  - 2-gluon exchange: can be color-singlet, but not C-odd. (Each gluon has C=-1.)
  - 3 gluon exchange: can be both color-singlet and C-odd! That's the Odderon at the lowest order.



Note that the gluons must be in a symmetric d^{abc} color state ($d^{abc} = 2\,\mathrm{tr}[t^a\,\{t^b, t^c\}]$). If the color group was SU(2), there would be no Odderon.

Disconnected gluon lines imply sum over all possible gluon connections to the quark and anti-quark lines.

TOTEM and D0 Collaborations announced the odderon discovery in pp vs. ppbar elastic scattering in late 2020. Results from other experiments are needed to seal the discovery.

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Transverse-momentum dependent Distributions (TMDs)

Yuri's discussion talk

Spin-dependent odderon search

x-Dependence of A_N

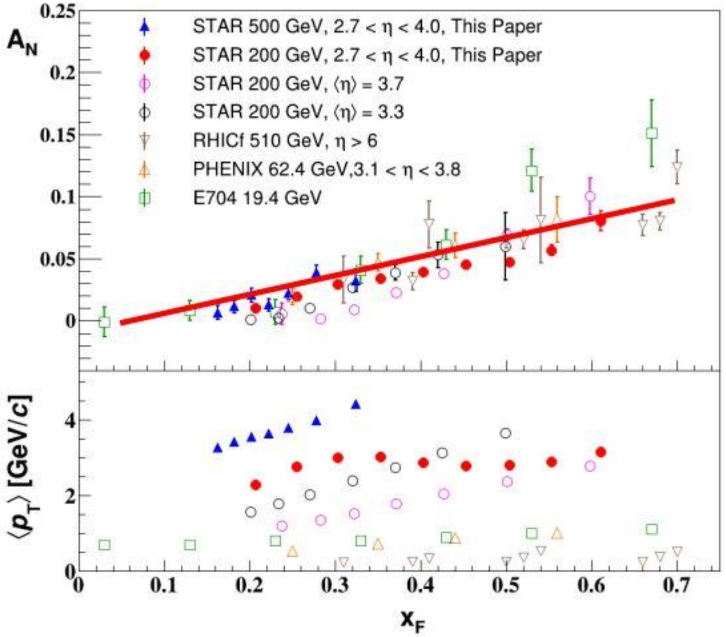
Sivers function at small x scales as

$$f_{1T}^{\perp NS}(x \ll 1, k_T^2) = C_O(x, k_T^2)\,\frac{1}{x} + C_1(x, k_T^2)\left(\frac{1}{x}\right)^{3.4\sqrt{\frac{\alpha_s N_c}{4\pi}}}$$

- The spin-dependent odderon (D. Boer, M. G. Echevarria, P. Mulders and J. Zhou '15) gives the first term above. It predicts **A_N=const(x).**
- The second term is due to sub-eikonal small-x evolution (YK, M.G. Santiago, '22), with the power of x also close to 1.

$$A_N \sim x\, f_{1T}^{\perp}$$

π^0's, STAR, arXiv:2012.11428 [hep-ex]



- The data indicates more like A_N~x, albeit at not very small x. **Can STAR measure A_N precisely at very low x_F? This may confirm the odderon discovery at the Tevatron+LHC.**
- **Can the EIC help find the spin-dependent odderon? test the sub-eikonal x-dependence?**

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Likely an early EIC measurement

Transverse-momentum dependent Distributions (TMDs)

Yuri's discussion talk

Pinning down transversity TMD

Transversity

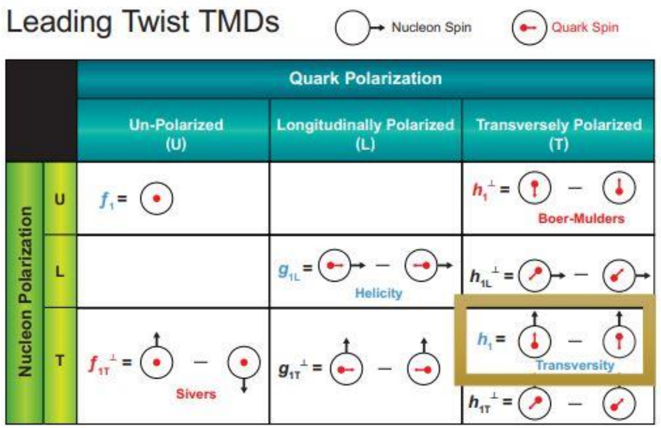
- Another fundamental object, but C-odd, hence hard to measure.
- Related to the proton's tensor charge.

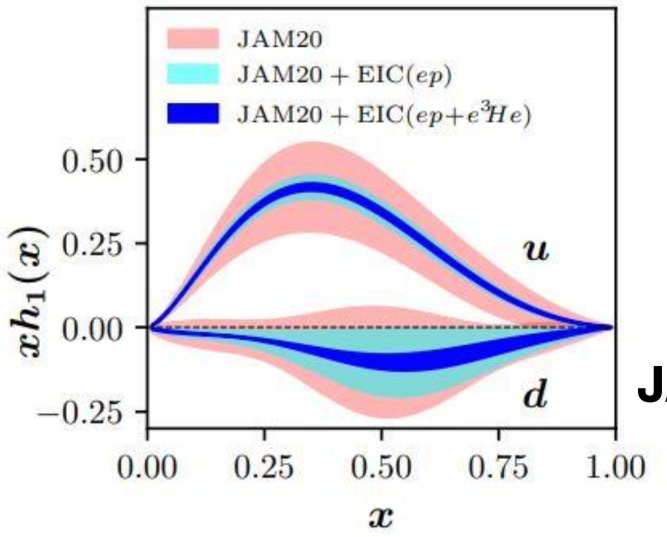
$$\delta q(Q^2) = \int_0^1 dx\, h_1(x, Q^2)$$

- Transversity can be extracted from A_{UT} at RHIC due to the Collins effect,

  $A_{UT} \sim$ transversity $\times$ interference fragmentation function.
- See pioneering work by M. Radici and A. Bacchetta, '18.
- EIC would certainly help narrow down the error bars.

STAR, 2205.11800 [hep-ex]



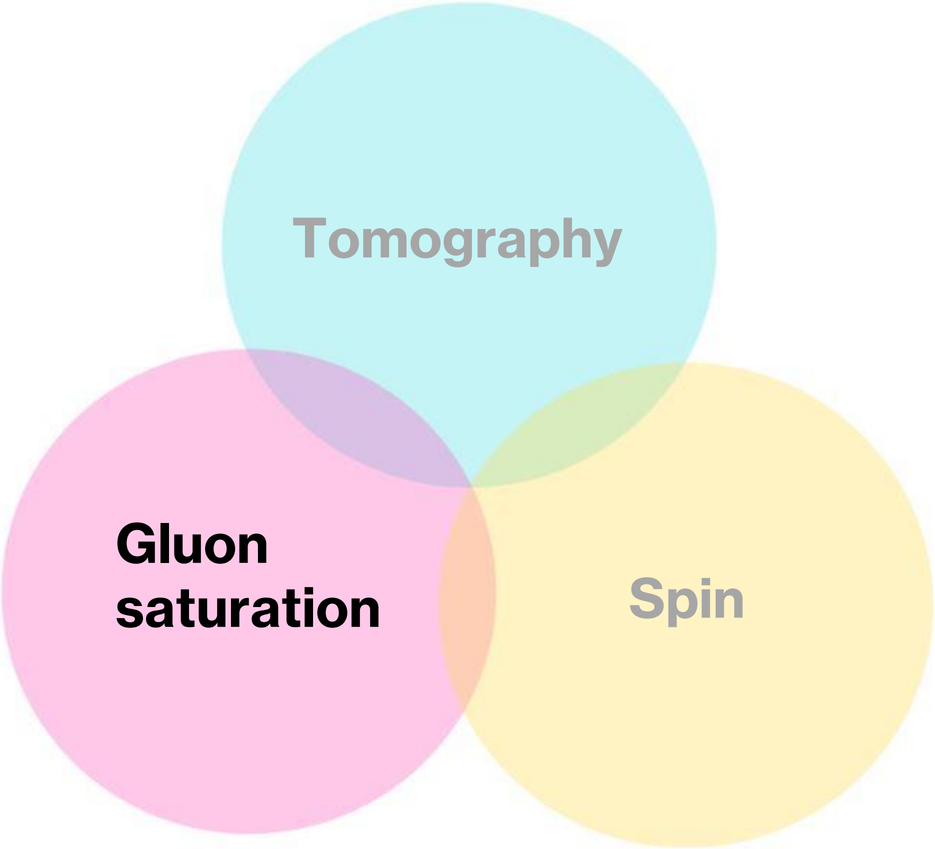


JAM collaboration

Likely an early EIC measurement

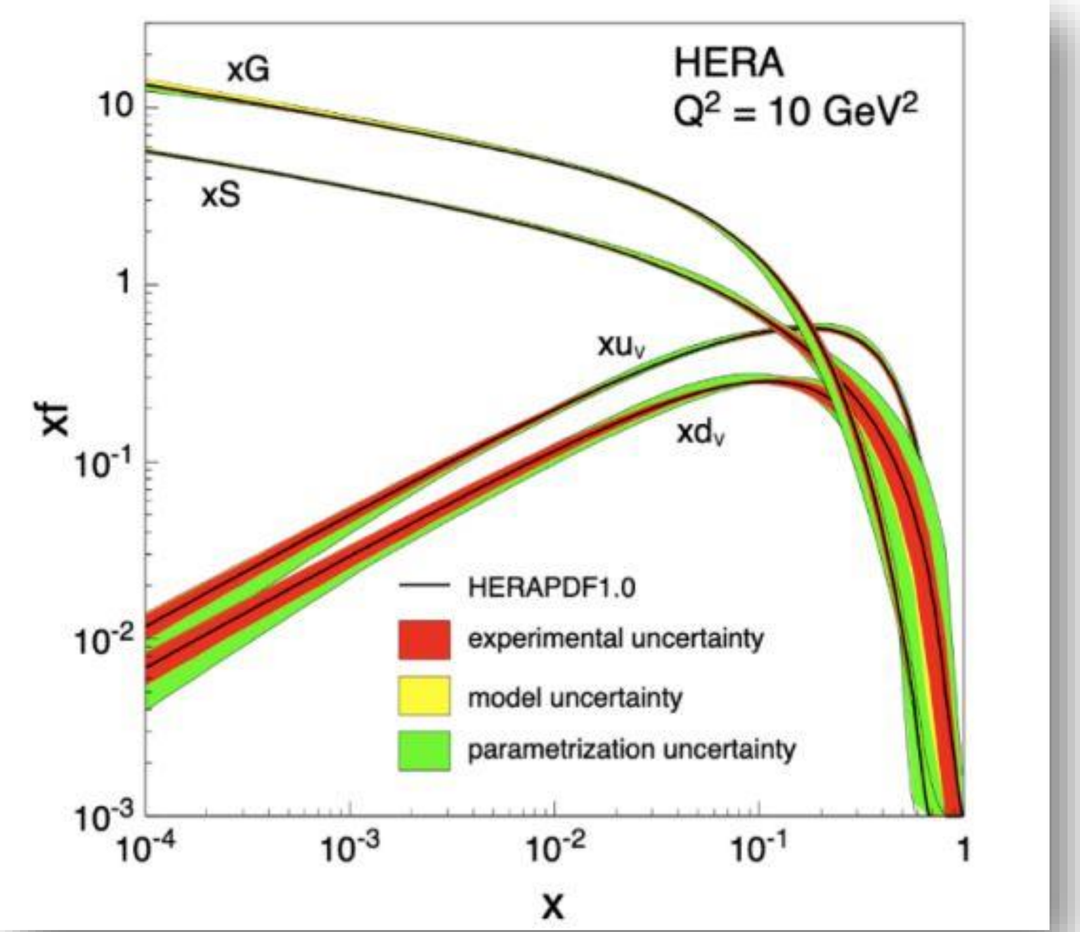
Scientific goals of Electron-Ion Collider

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



QCD at small-x

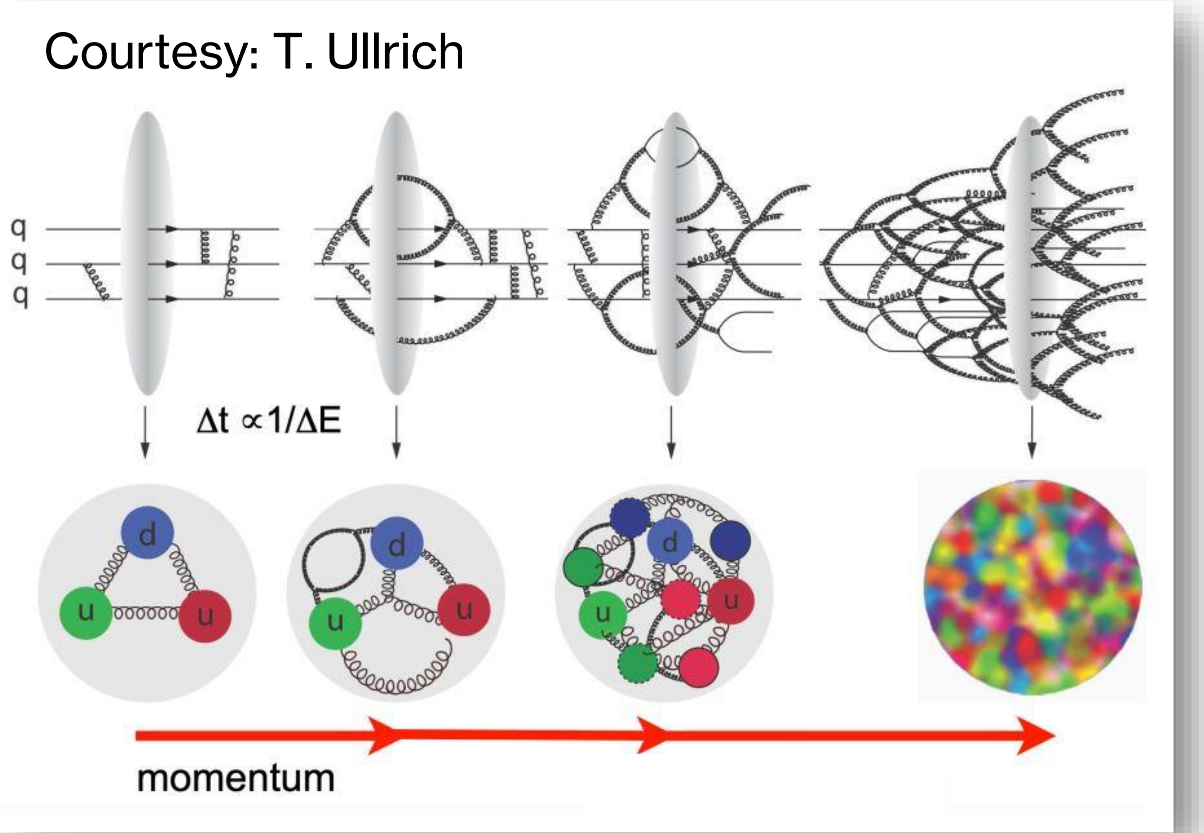
Anatomy of QCD at high energies



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))

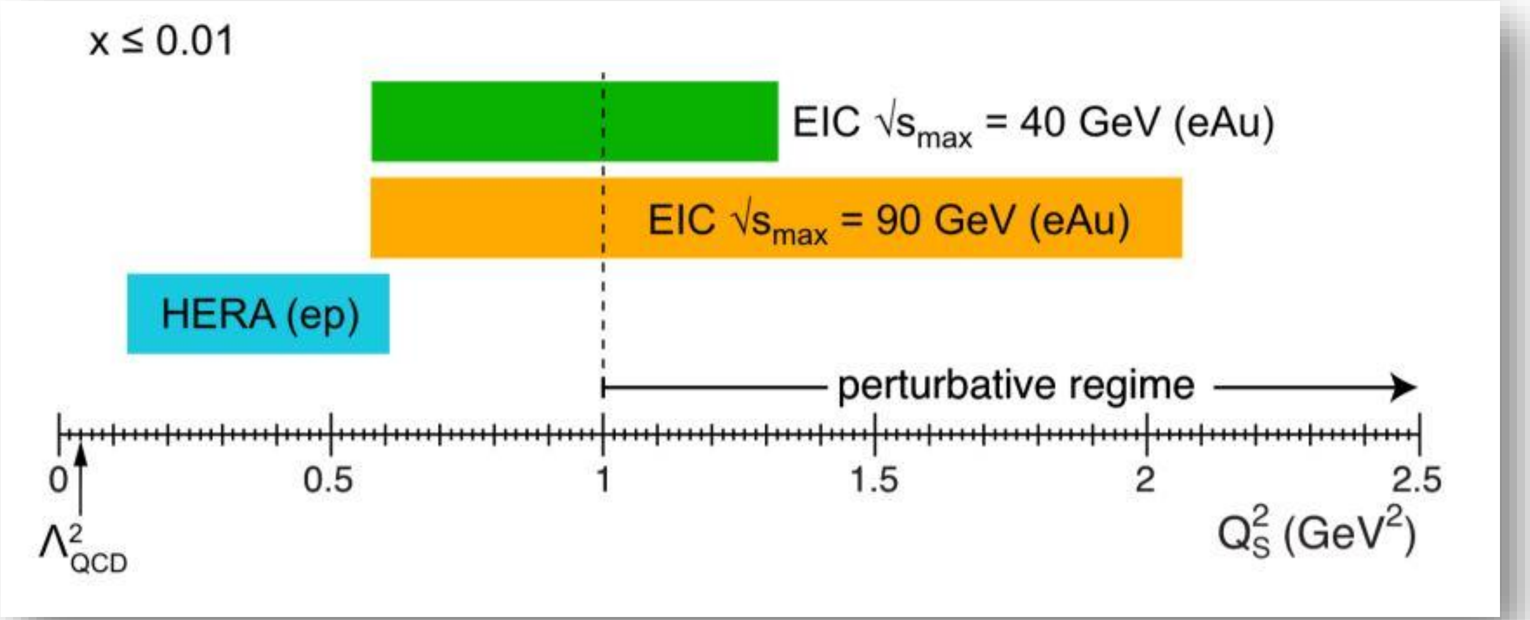
Emergence of an energy and nuclear species dependent momentum scale:

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

Q_s : saturation scale

QCD at small-x

Gluon saturation



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

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

QCD at small-x

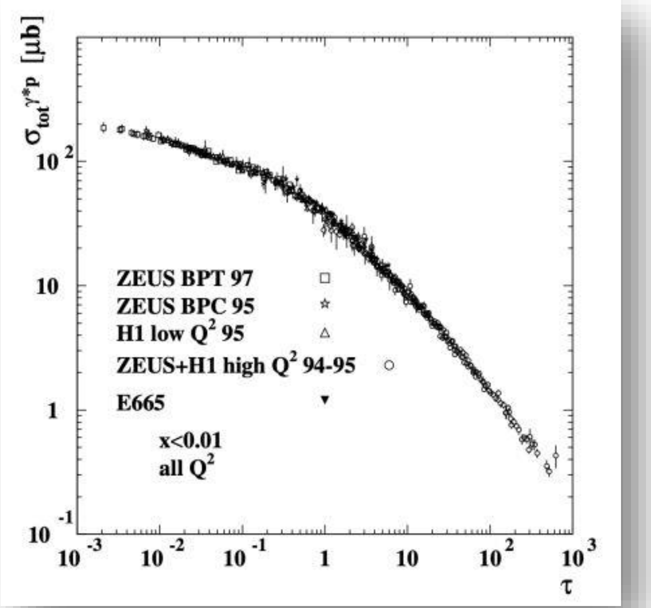
Experimental status

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

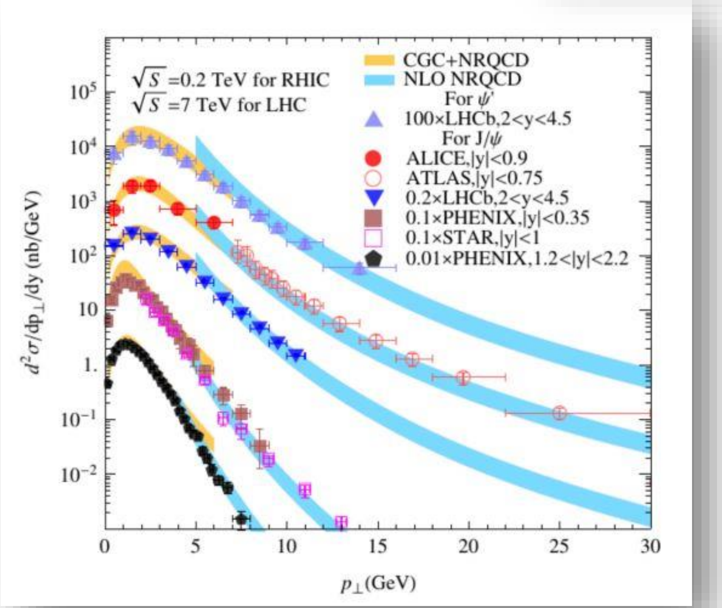

Article

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

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

A. V. Grabovsky
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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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University Park, PA 16802, USA
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Berkeley, CA 94720, USA

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]

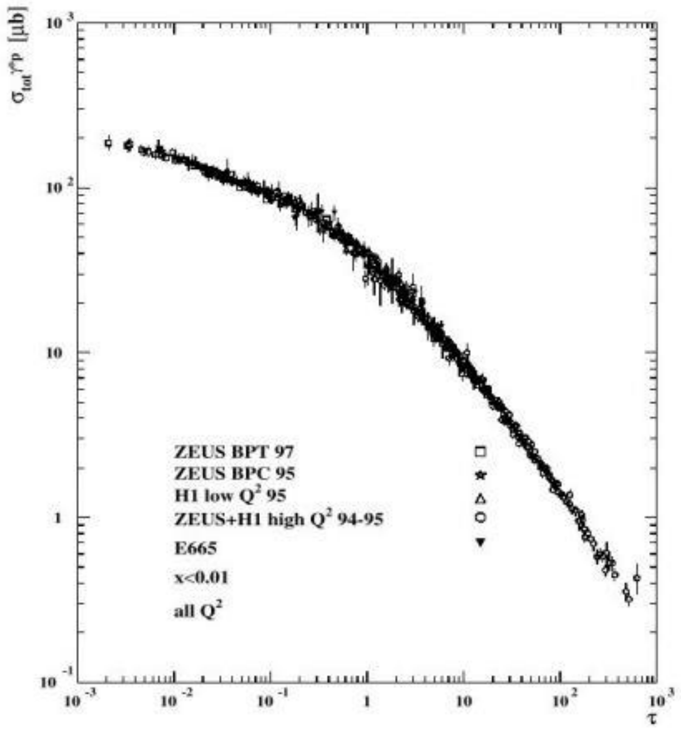
- DGLAP-based fits of helicity PDFs are plagued with extrapolation errors at small x
- Derivation and implementation of improved (KPS-CTT) small-x evolution equations

QCD at small-x

Farid's talk

Prospects in inclusive processes

Structure functions: geometric scaling



$$\sigma_r(x, y, Q^2) = F_2(x, Q^2) - \frac{y^2}{1 + (1-y)^2} F_L(x, Q^2)$$

- DIS cross-section generically depends on Q^2 and x
- HERA data shows signs of scaling: $\tau = Q^2/Q_s^2(x)$

$$Q_s^2(x) = Q_{s,0}^2(x_0/x)^\lambda$$

- Can we observe geometric scaling for different nuclear species?
- Will we observe the nuclear size dependence of the saturation scale?

$$Q_s^2(x, A) = Q_{s,0}^2(x_0/x)^\lambda A^{1/3}$$

Geometric scaling with nuclei species at EIC: Smoking gun for saturation

Early EIC measurement

8

QCD at small-x

Farid's talk

Prospects in inclusive processes

Early EIC measurement

Structure functions: linear vs non-linear evolution

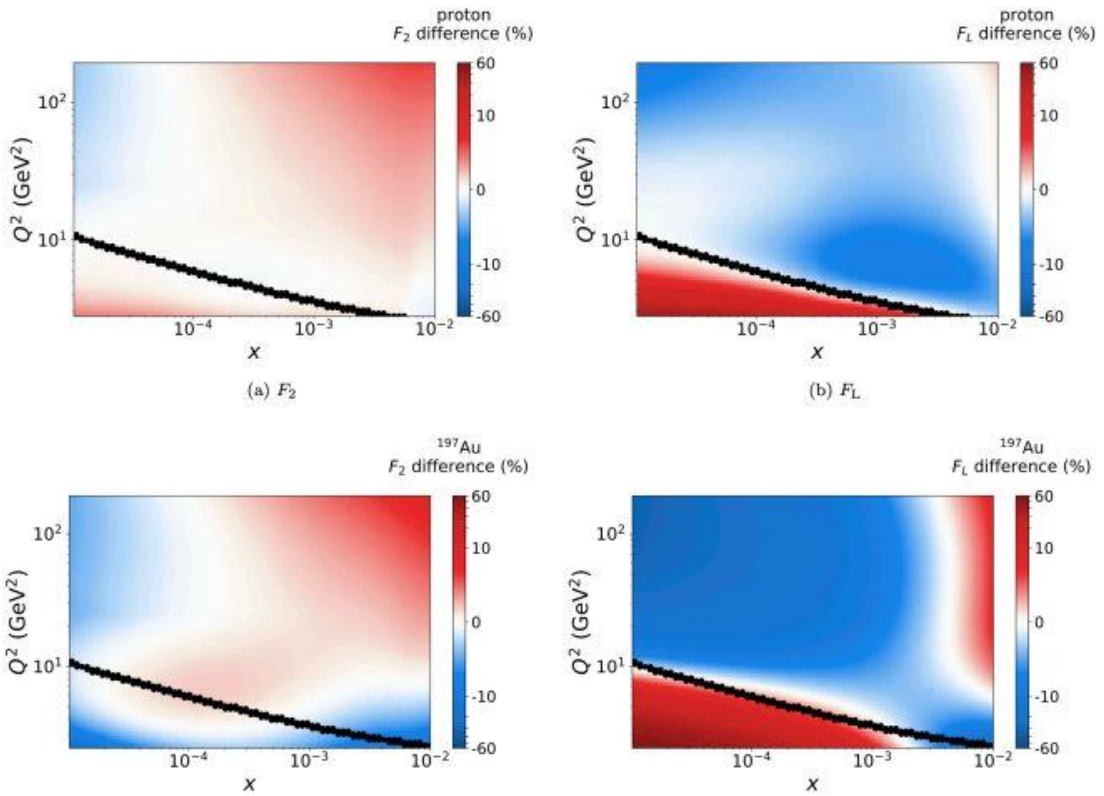
- Difference in predictions for $F_{2,L}$:
  linear (collinear/DGLAP)
  non-linear (dipole/Balitsky-Kovchegov)

$$(F_{2/L}^{\rm BK} - F_{2/L}^{\rm DGLAP,Rew})/F_{2/L}^{\rm BK}$$

- Stronger effects for F_L than F_2

- Stronger effects for γAu than γp

- It would be interesting to incorporate small-x evolution into DGLAP via BFKL (à la) and compare with non-linear BK



(a) F_2 (b) F_L

(a) F_2 (b) F_L

Armesto, Lappi, Mäntysaari, Paukkunen, Tevio (2022)

See also Marquet, Moldes, Zurita (2017)

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QCD at small-x

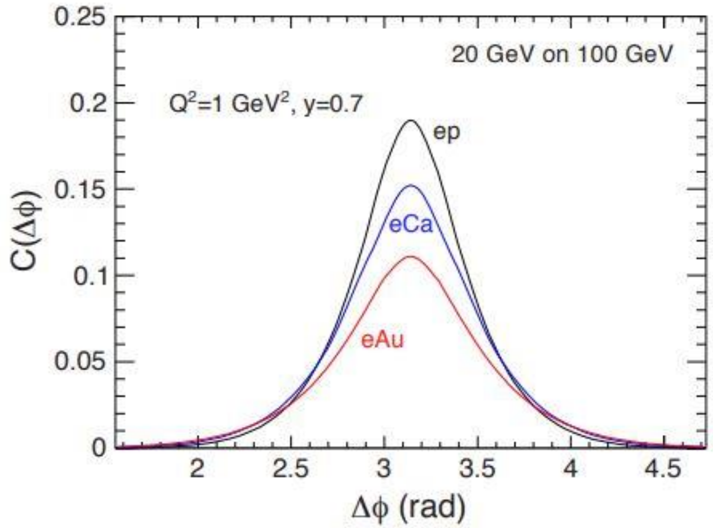
Yuri, Farid's talks

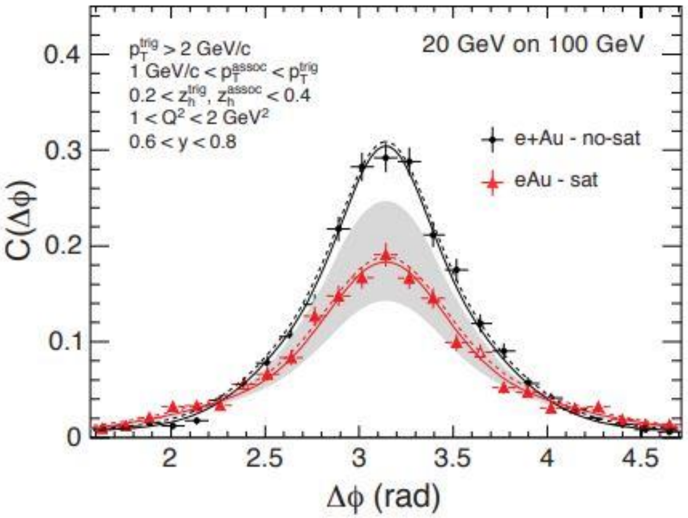
Prospects in semi-inclusive processes

Di-hadron Correlations

Depletion of di-hadron correlations is predicted for e+A as compared to e+p. (Dominguez et al '11; Zheng et al '14). This is a signal of saturation.

Early EIC measurement



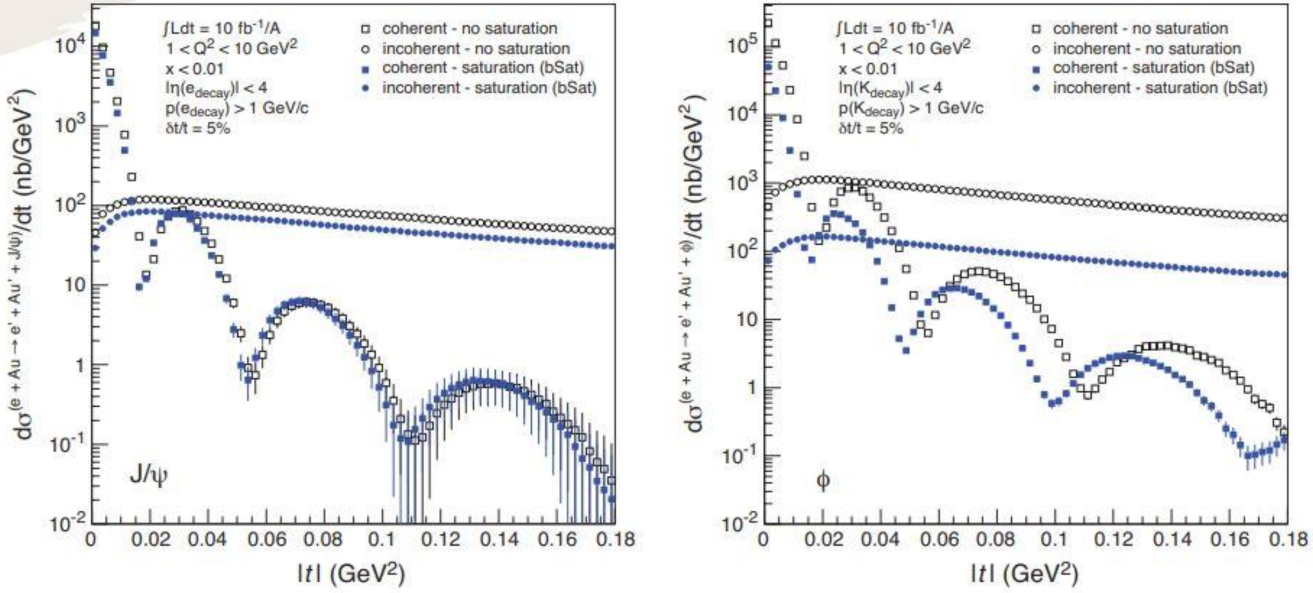


QCD at small-x

Yuri, Farid's talks

Prospects in exclusive processes

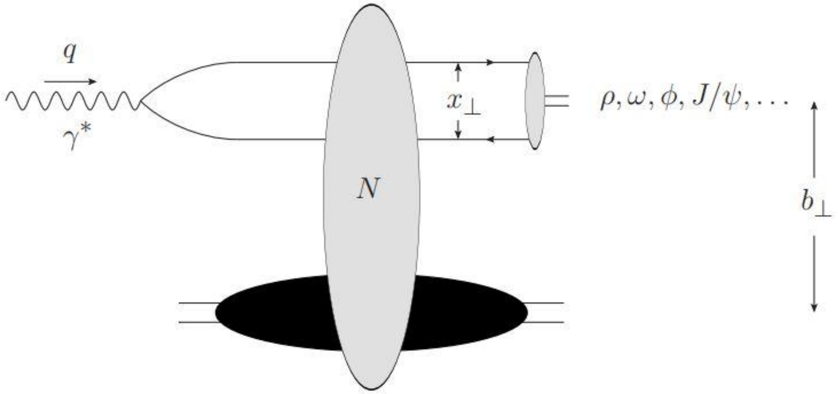
Exclusive VM Production as a Probe of Saturation



Plots by T. Toll and T. Ullrich using the Sartre event generator
(b-Sat (=GBW+b-dep+DGLAP) + WS + MC, from the 2012 EIC White Paper).

- J/psi is smaller, less sensitive to saturation effects
- Phi meson is larger, more sensitive to saturation effects

Early EIC measurement



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

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- Identification of **novel observables**
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- 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,§]

- 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]

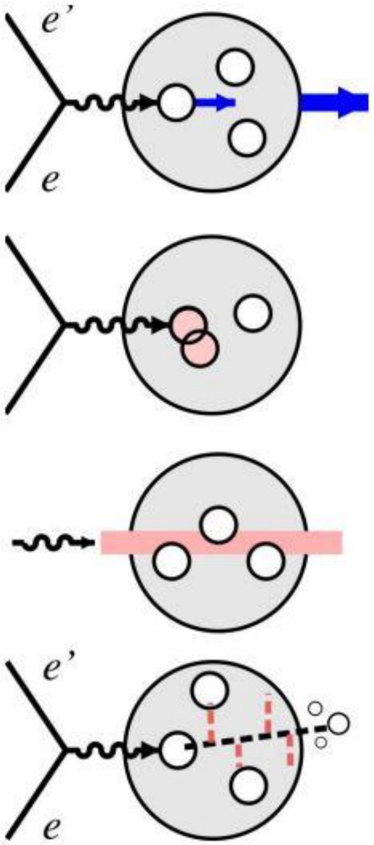
All about eA physics

Wim's talk

All about eA physics

Wim's talk

EIC physics with nuclei



- Partonic structure of nuclei
  - Collinear pdfs, diffractive
  - 3D imaging of nuclear bound states (TMDs, GPDs)
  - Neutron structure (polarized)
- Nuclear interactions and structure
  - Medium modifications
  - Short-range correlations, QCD origin of core of NN interaction
  - Shape deformations
  - Non-nucleonic components
- Coherence and saturation
  - Interaction of high-energy probe with coherent quark-gluon fields $\rightarrow$ talk Salazar
- Hadronization in the medium
  - Space-time picture
  - Transport of hadrons in cold hadronic matter

All about eA physics

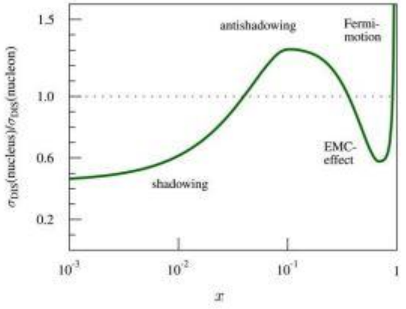
Wim's talk

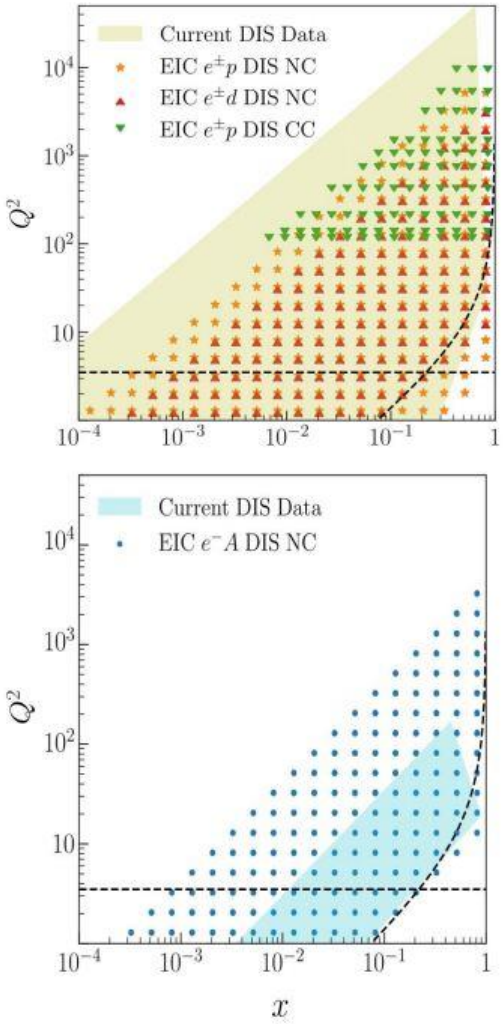
Prospects

Nuclear pdfs

- First collider with ep, ed, eA
  - Global analysis (biases)
  - Day 1 measurements (high precision, new x & Q^2 regions)
  - Fits without assumed A-dependence

- Medium modifications
  - (anti)shadowing, EMC
  - First for gluons
  - Q^2, A dependence





[Abdul Khalek et al, PRD2021]

Early EIC measurement

All about eA physics

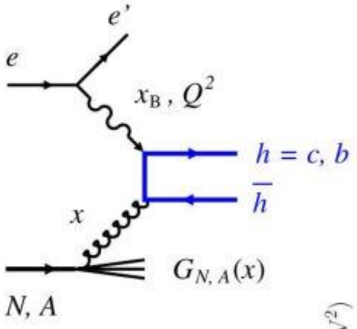
Wim's talk

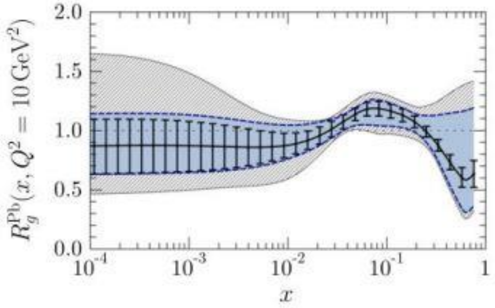
Prospects

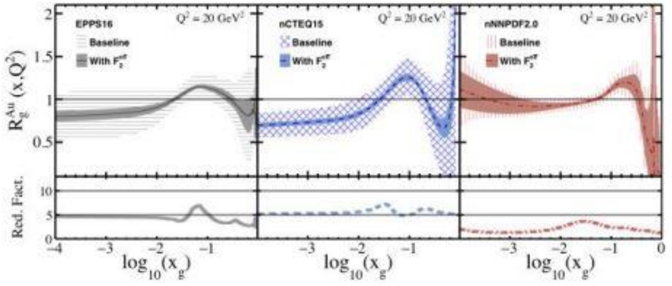
Nuclear gluons

- Open charm production
  - → photon-gluon fusion
  - → 10%-1% of DIS events
  - → O(10E6-10E5) events for $10 fb^{-1}$
- Probes the gluon density at fixed scale
  - → heavy quark mass
- Gluonic EMC-effect / anti-shadowing

[E. Chudakov et al., JoP: Conf Series 770 012042 ('16)]
[E. C. Aschenauer et al., PRD 96 114005 ('17)]
[M. Kelsey et al., PRD 104 054002 ('21)]







Likely an early EIC measurement

All about eA physics

Wim's talk

Prospects

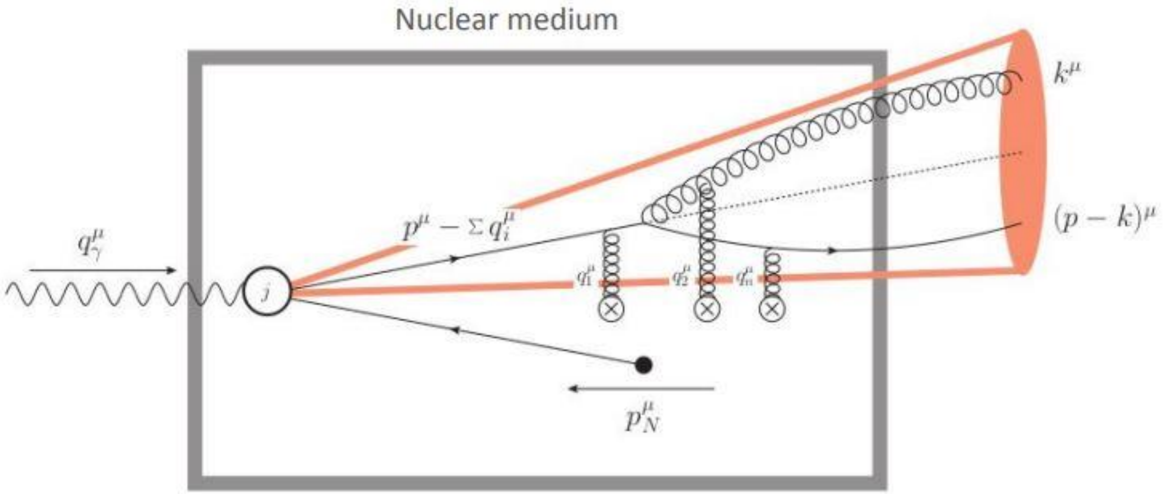
Hadronization and particle propagation in medium

- If hadronization is in- or outside nucleus depends on *A*, energy and hadron mass
  ↪ space-time picture poorly understood
  ↪ heavy quarks hadronize within ⟶ differentiate between energy loss / absorption

- Hadron multiplicities, jet measurements

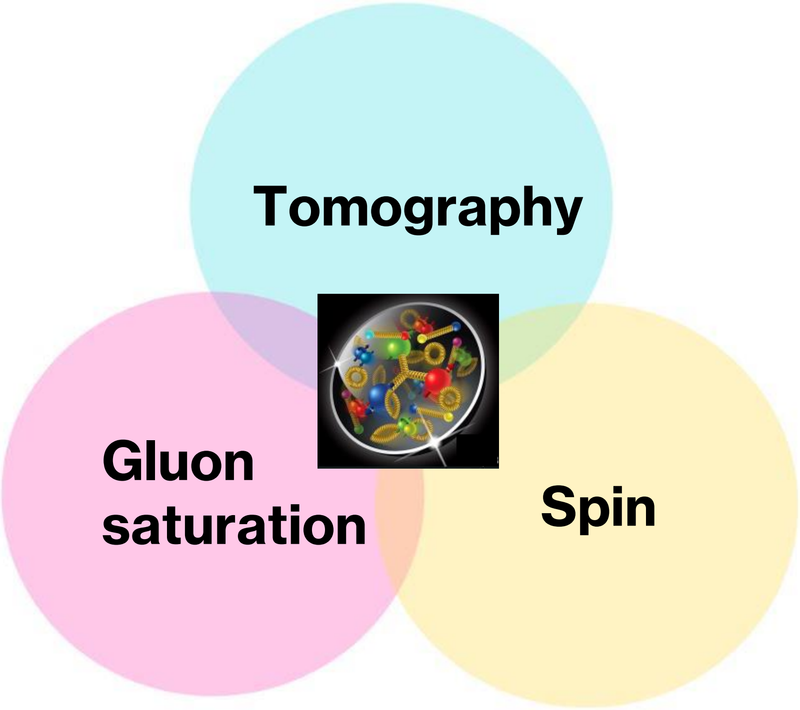
- $\hat{q}$ (=<t_{medium}>/L) quantifies parton energy loss
  ↪ not well constrained at the moment
  ↪ affects SSA in nuclear SIDIS

More theory calculations needed



Summary

Unveil the "cosmic" interior of nucleons/nuclei



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

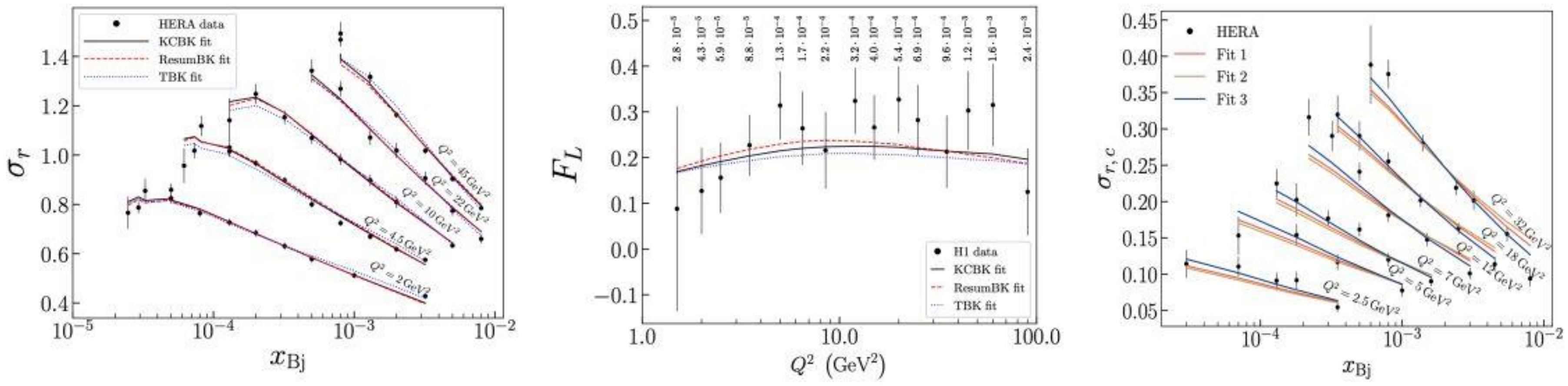
QCD at small-x

Farid's talk

Prospects in inclusive processes

Structure functions: F_2 and F_L

- CGC at NLO provides a good simultaneous description of structure functions including charm



Beuf, Lappi, Hänninen, Mäntysaari (2020)

Precision physics (NLO)

Early EIC measurement

- However, F_2 has large non-perturbative contributions. It would be best to focus on F_L or $F_{2,c}$
- Confront CGC to nuclear structrure functions at the EIC

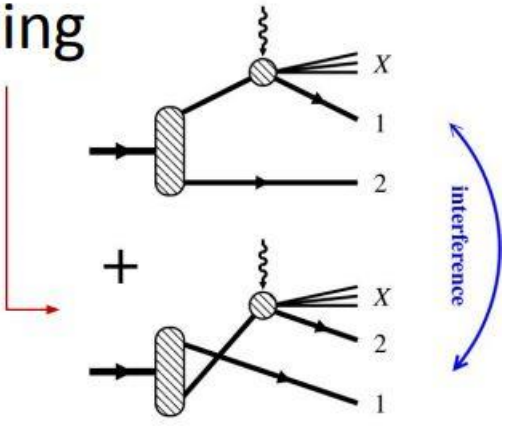
All about eA physics

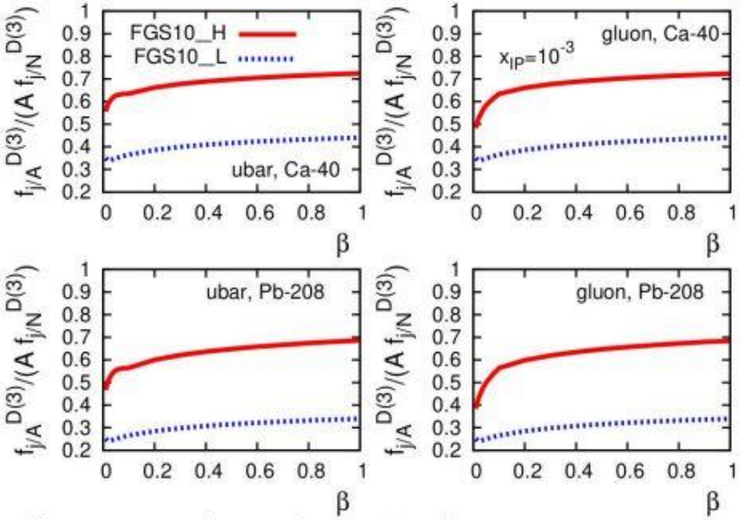
Wim's talk

Prospects

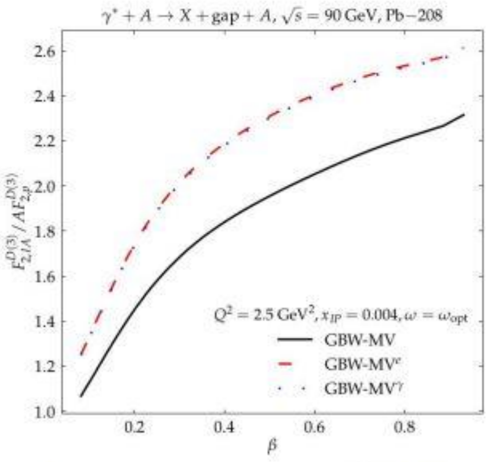
Nuclear diffractive pdfs: saturation vs LT shadowing

- LT nuclear shadowing predicts reduction of A/p ratio (interference)
- Gluon Saturation predices enhancement
- Measurement will discriminate





[Frankfurt, Guzey, Strikman, PhysRep 2012]

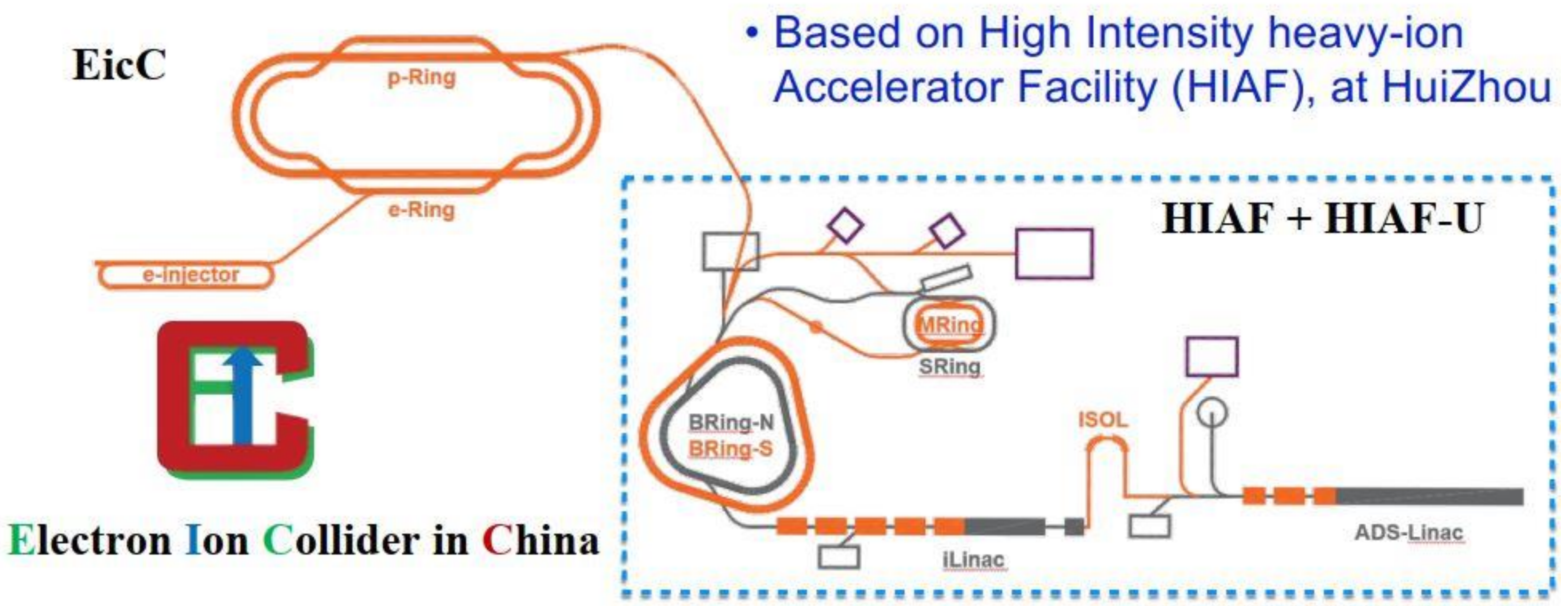


[Lappy, Le, Mantysaari, 2307.16486]

Early EIC measurement

Last words

Nice complementarity between EIC and EicC



[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

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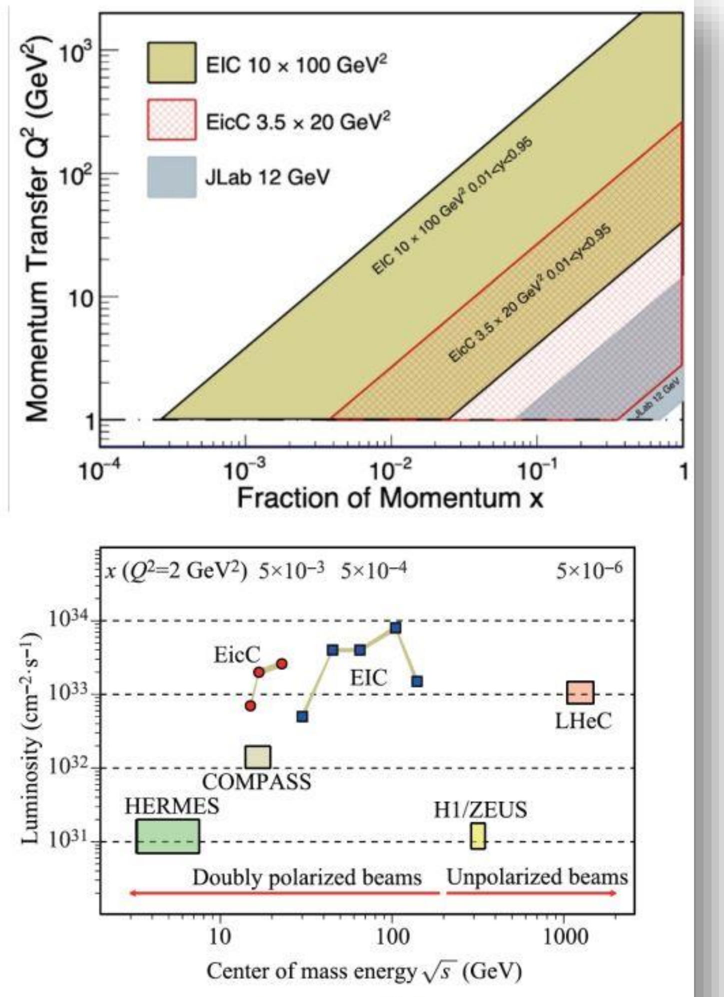

[Figures from EicC White paper]

- **Nucleon spin structure**

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

Last words

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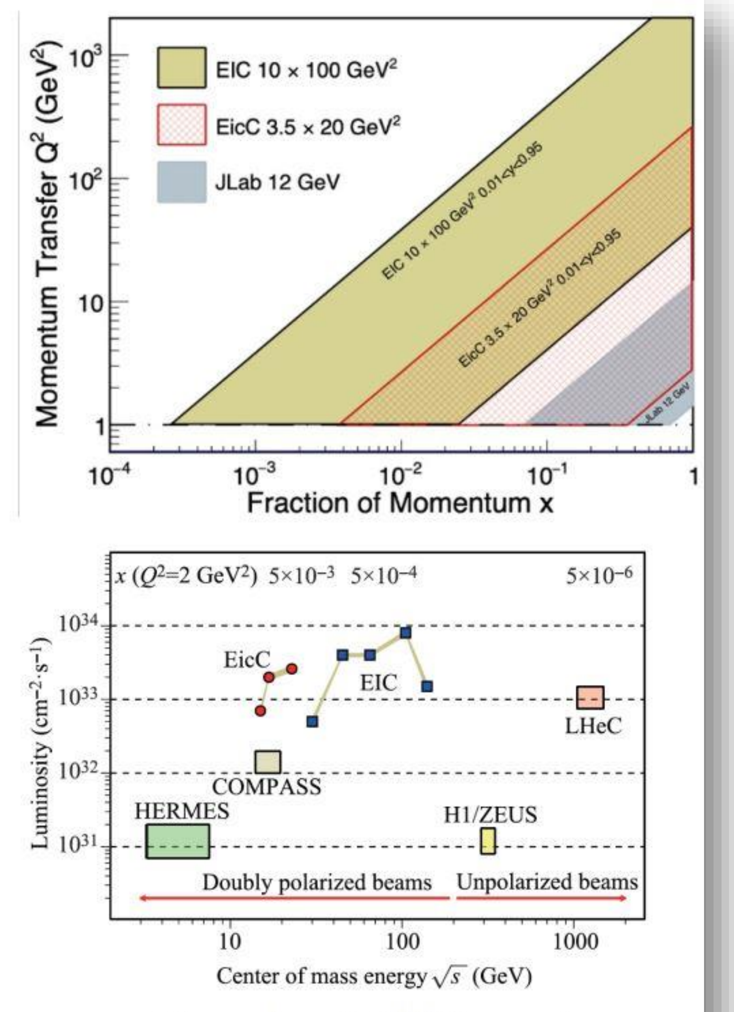
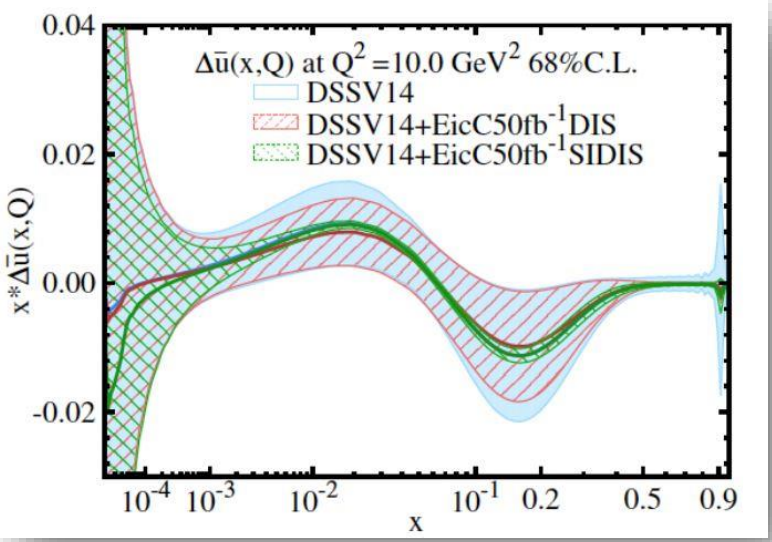
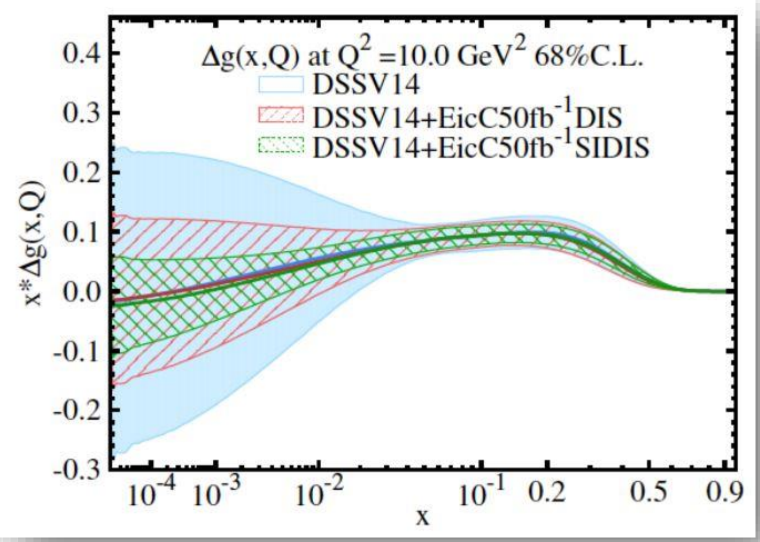


[Figures from EicC White paper]

- **Nucleon spin structure**

Interesting impact studies





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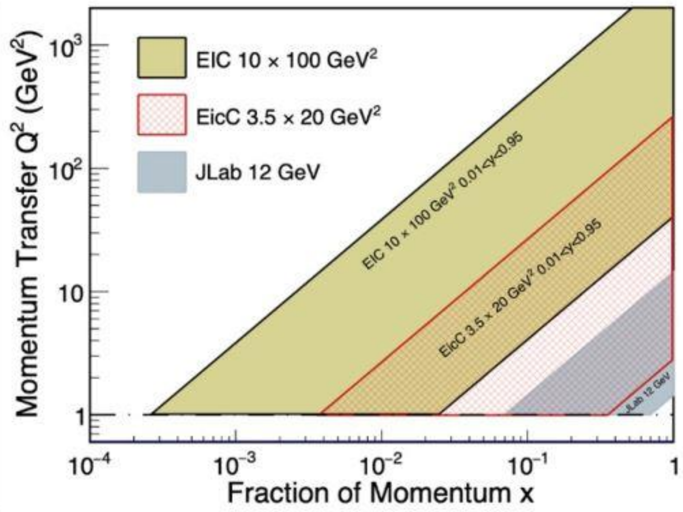

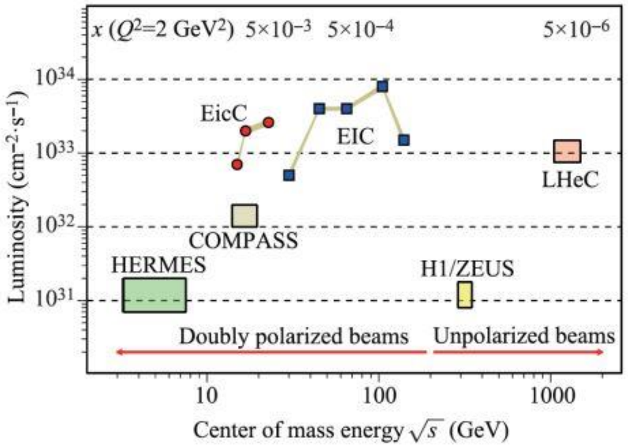

[Figures from EicC White paper]

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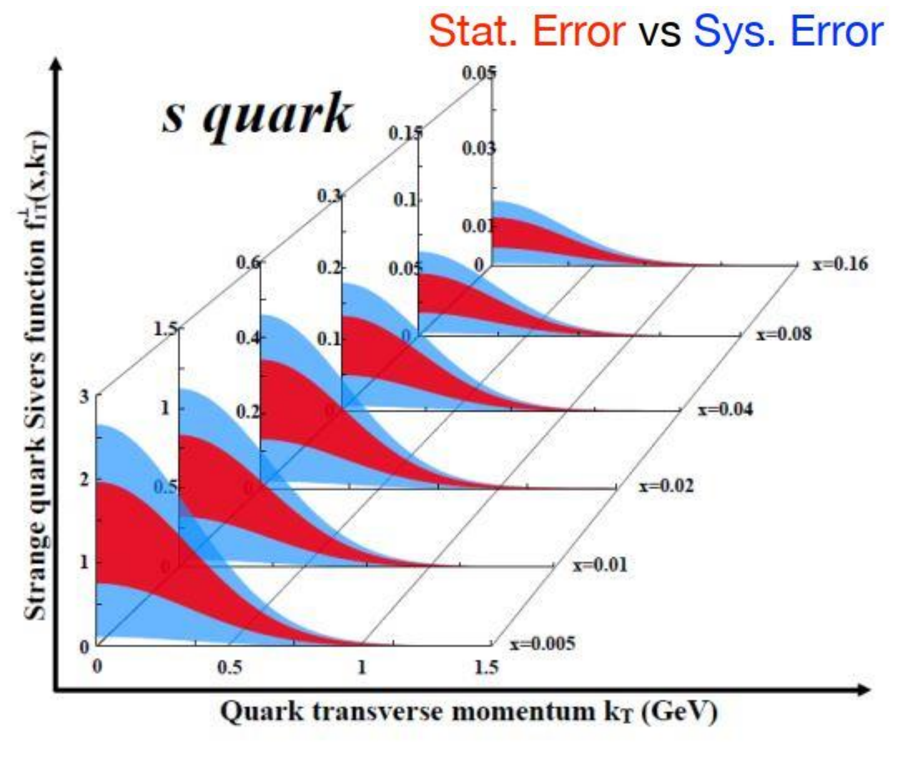

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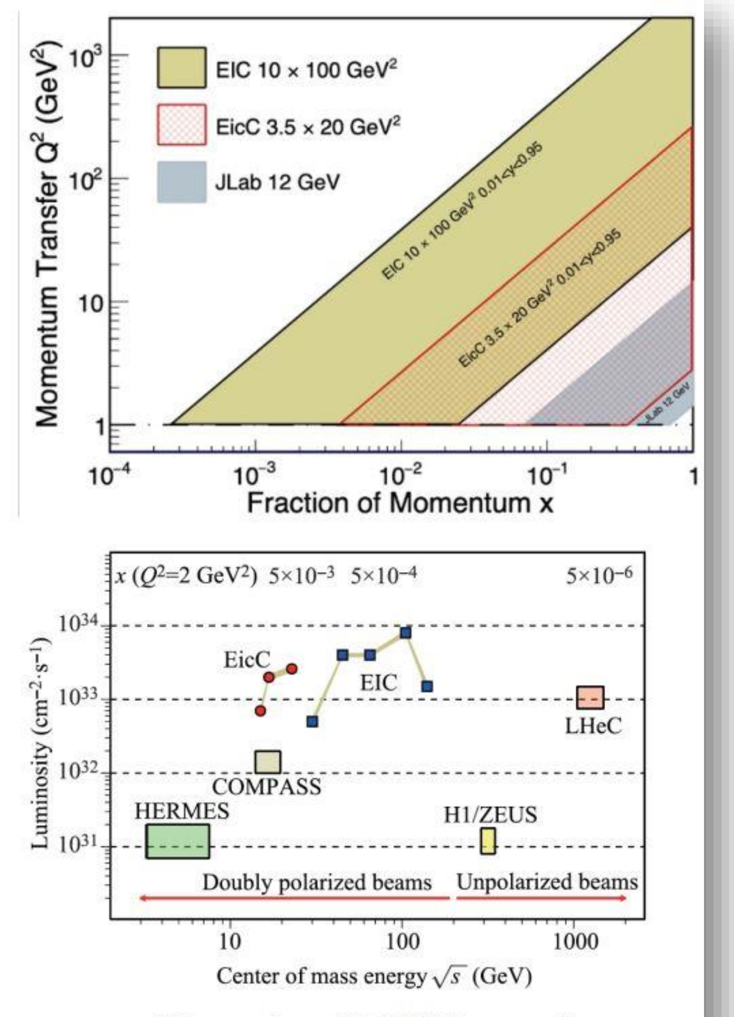

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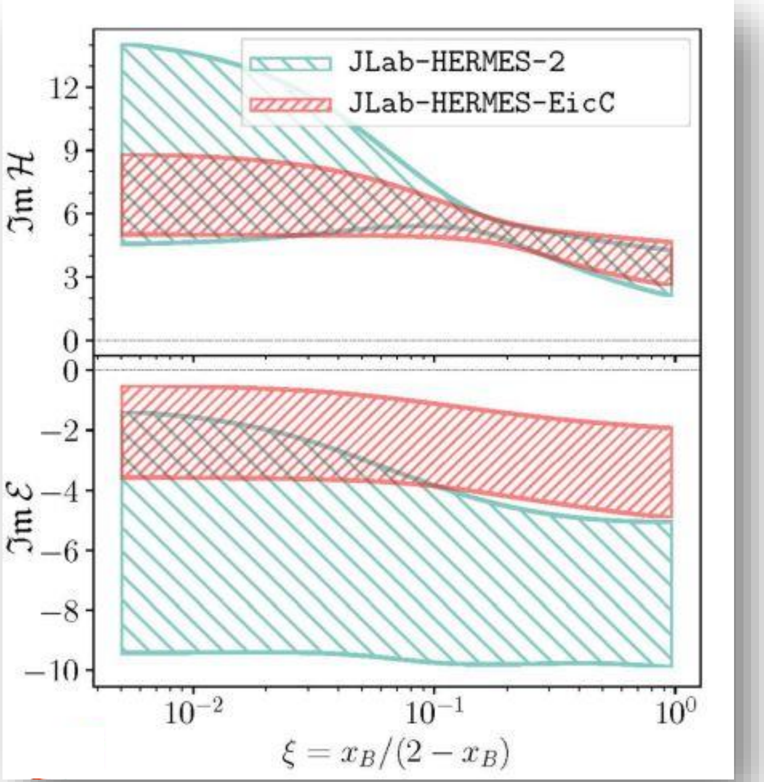

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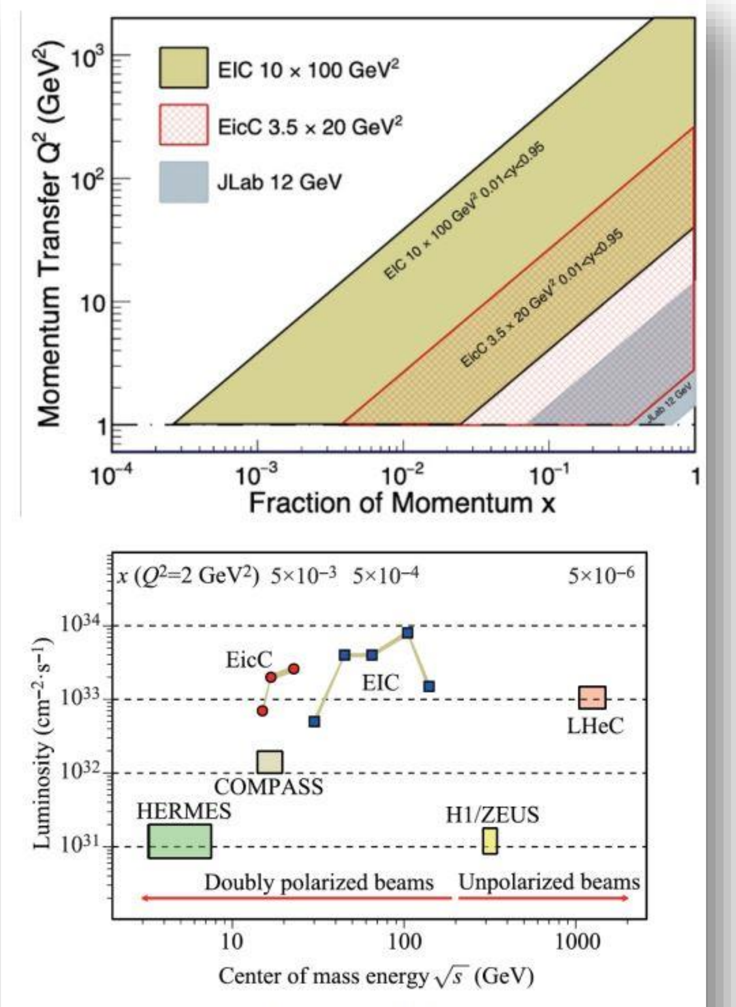

[Figures from EicC White paper]

- **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

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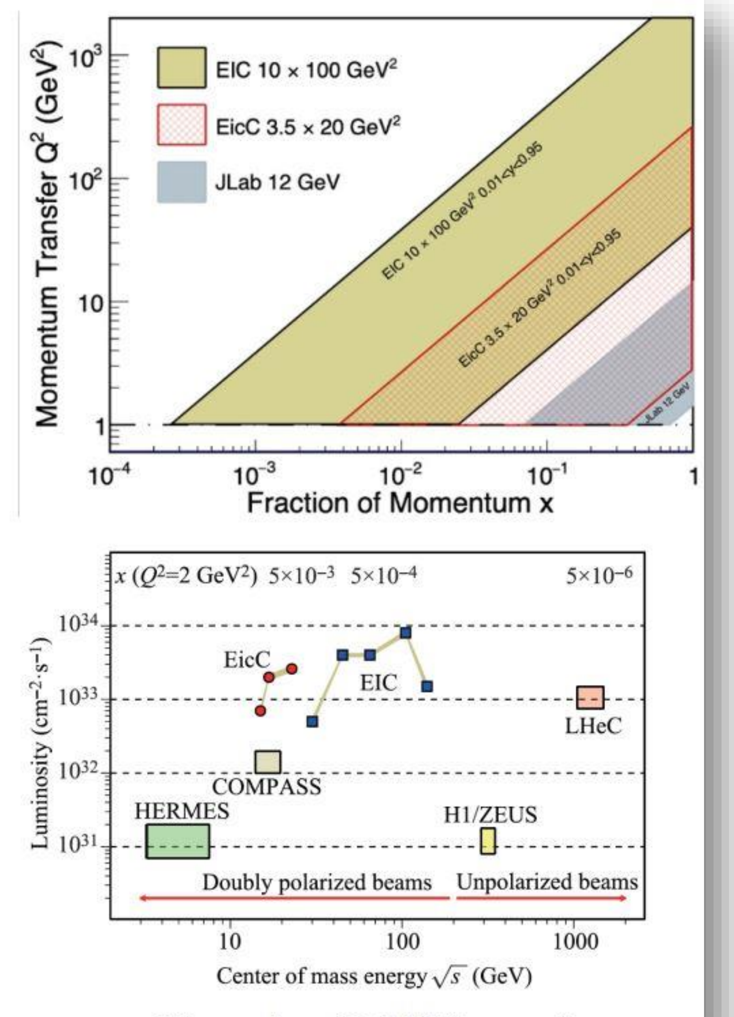

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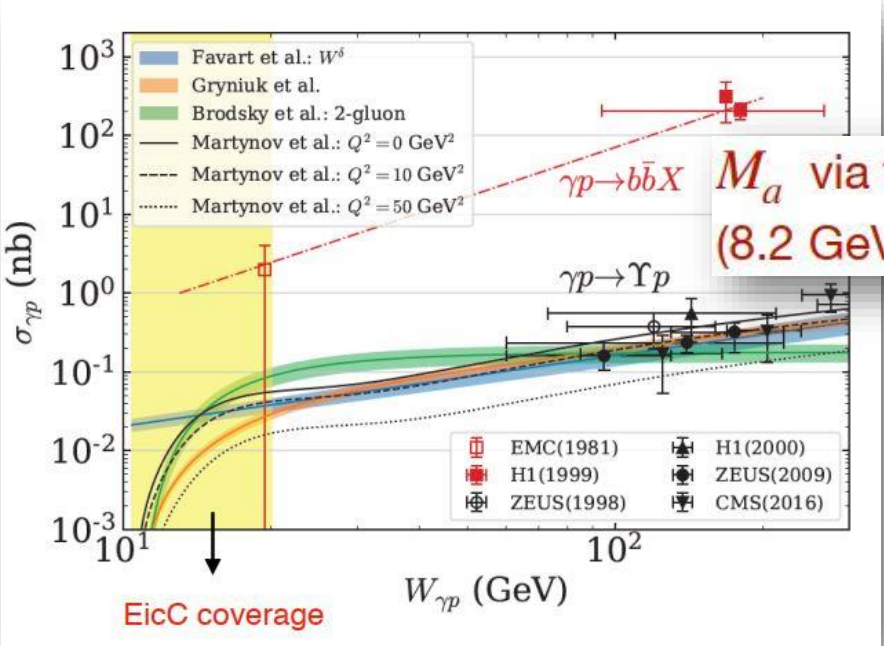
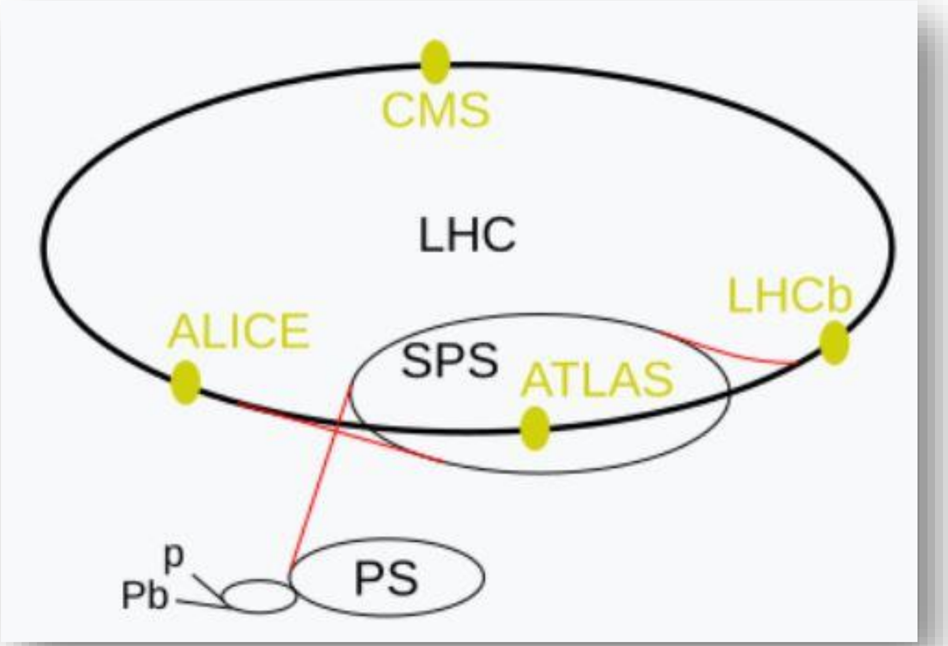


M_a via threshold production of J/ψ (8.2 GeV, JLab) and Υ (12 GeV)

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