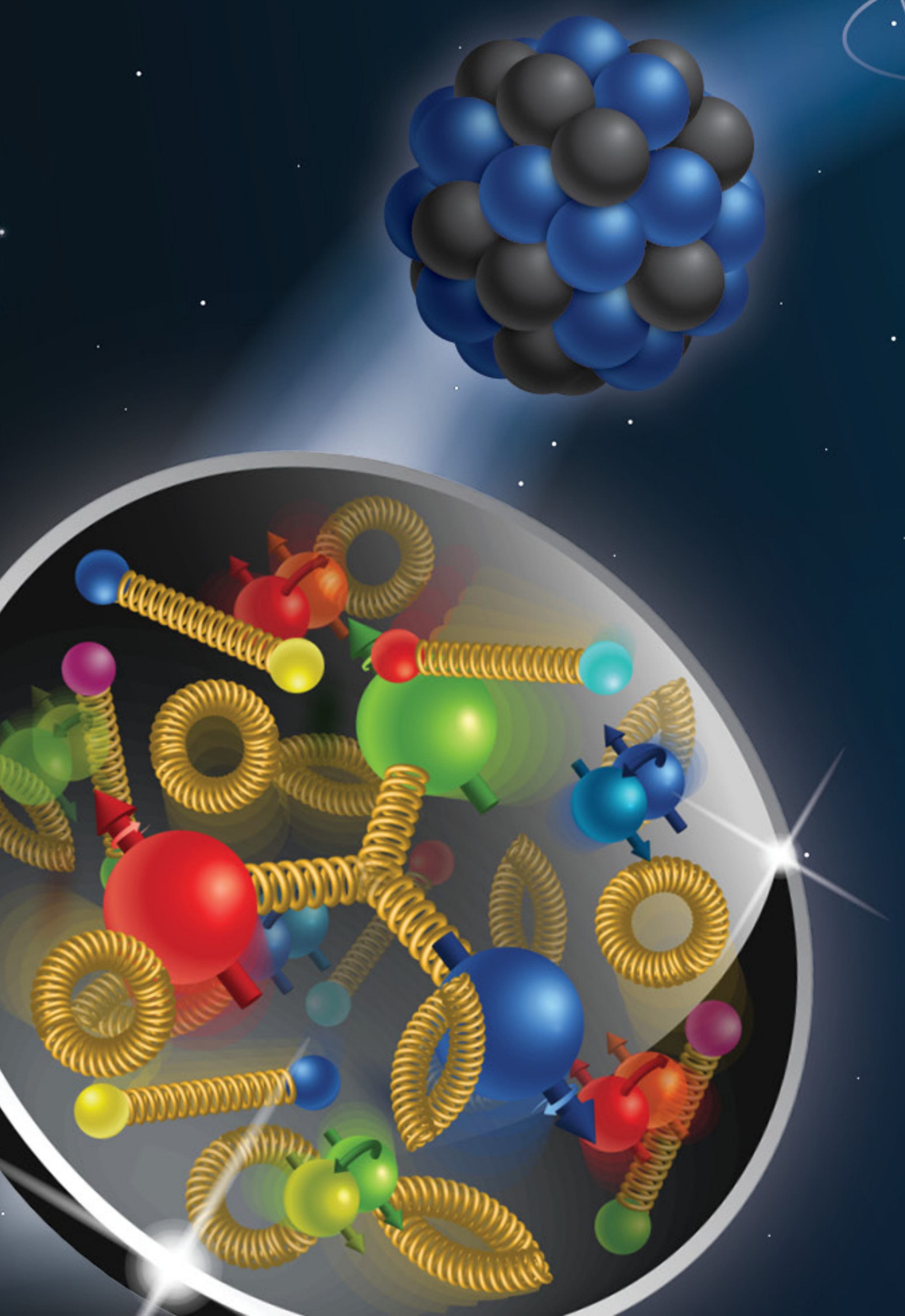
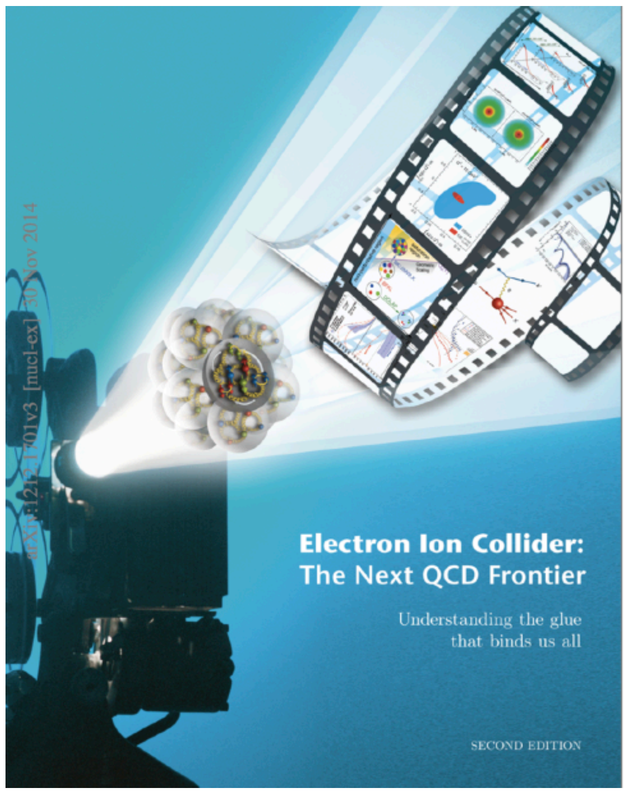


SPIN at the EIC

Alexei Prokudin

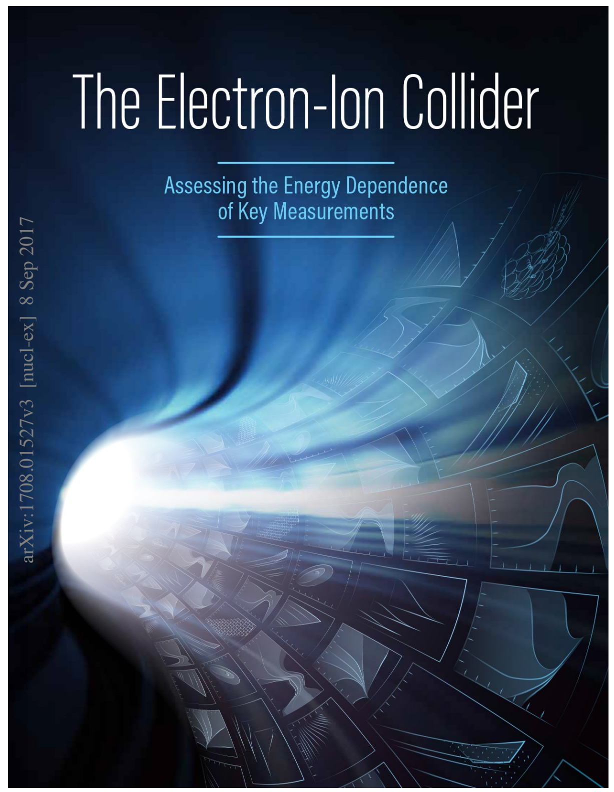
Pennsylvania State University Berks and Jefferson Lab

THE ELECTRON-ION COLLIDER: RELEVANT DOCUMENTS

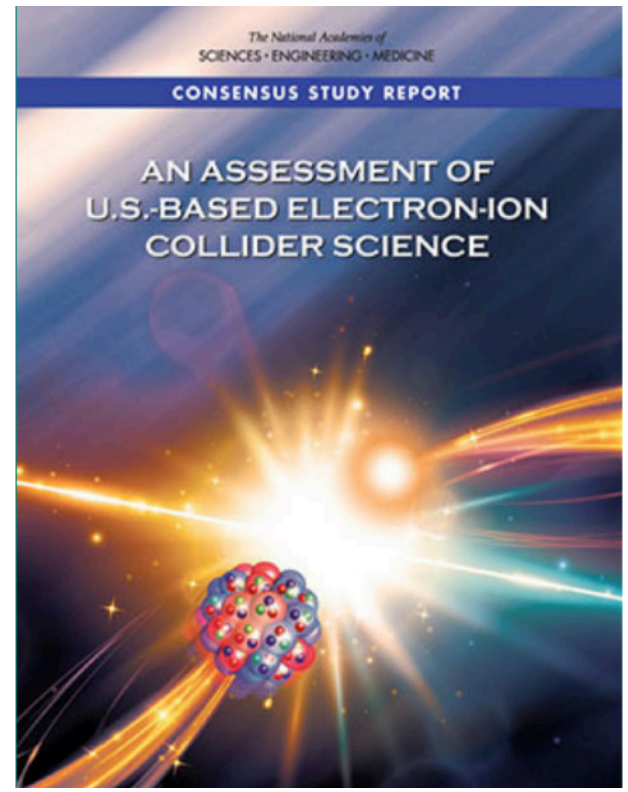


White Paper (2012)
Accardi et al,
arXiv:1212:1701

Yellow Paper (2016)
Accardi et al, Eur. Phys. J. A
(2016) 52: 268



BNL Report (2017)
Aschenauer at el,
arXiv:1708.01527



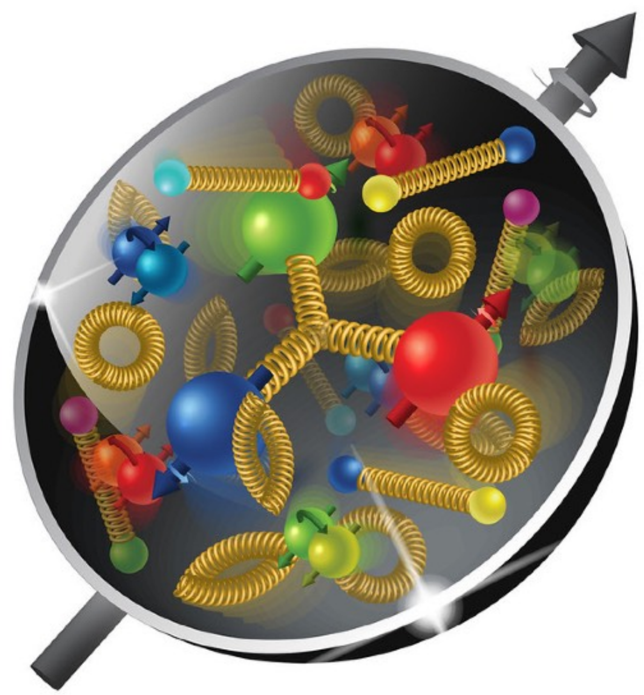
NAS Study (2018)

EIC Yellow Report (2021)
arXiv:2103.05419

WHY SPIN?

Spin is a fundamental degree of freedom originated from the space-time symmetry

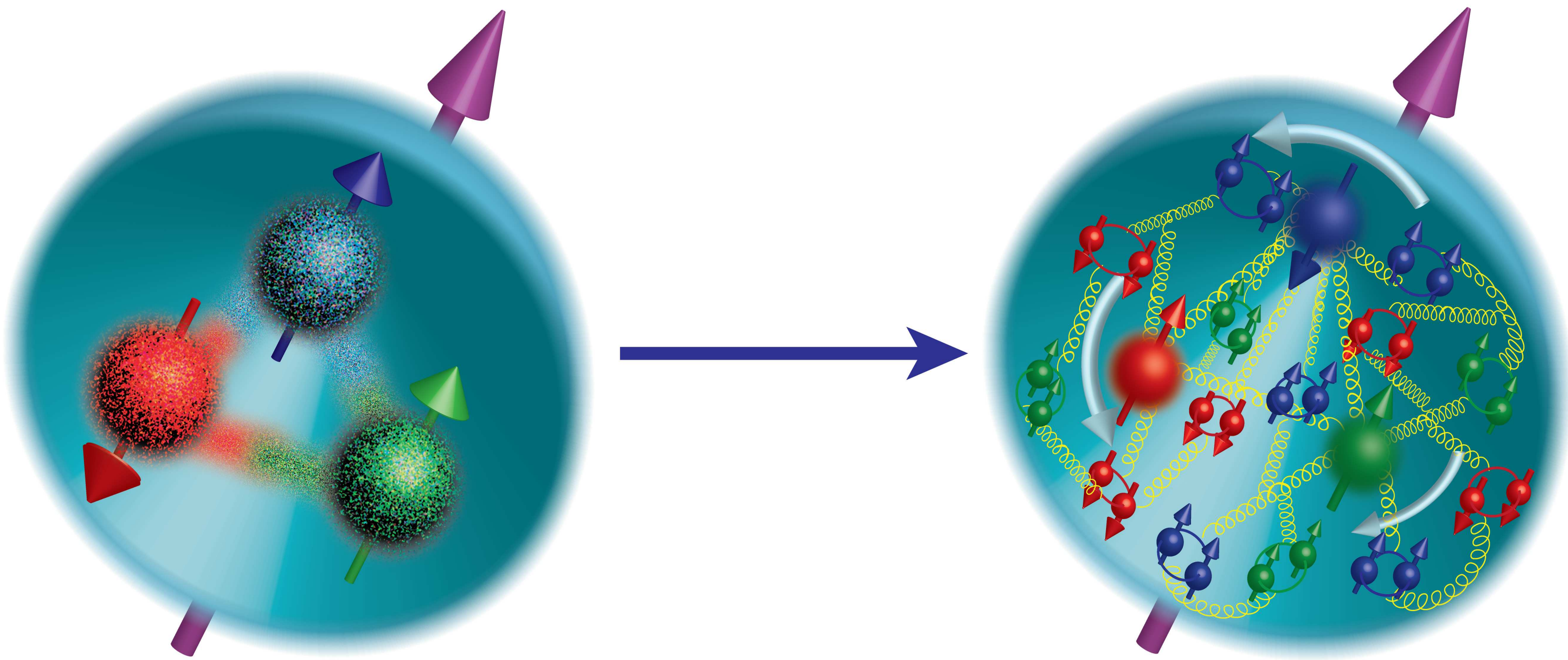
Spin plays a critical role in determining the basic structure of fundamental interactions



Spin provides a unique opportunity to probe the inner structure of a composite system (such as the proton) and hence to test our ability to understand the working of non-perturbative QCD

Test of a theory is not complete without a full exploration of spin-dependent decays and scatterings

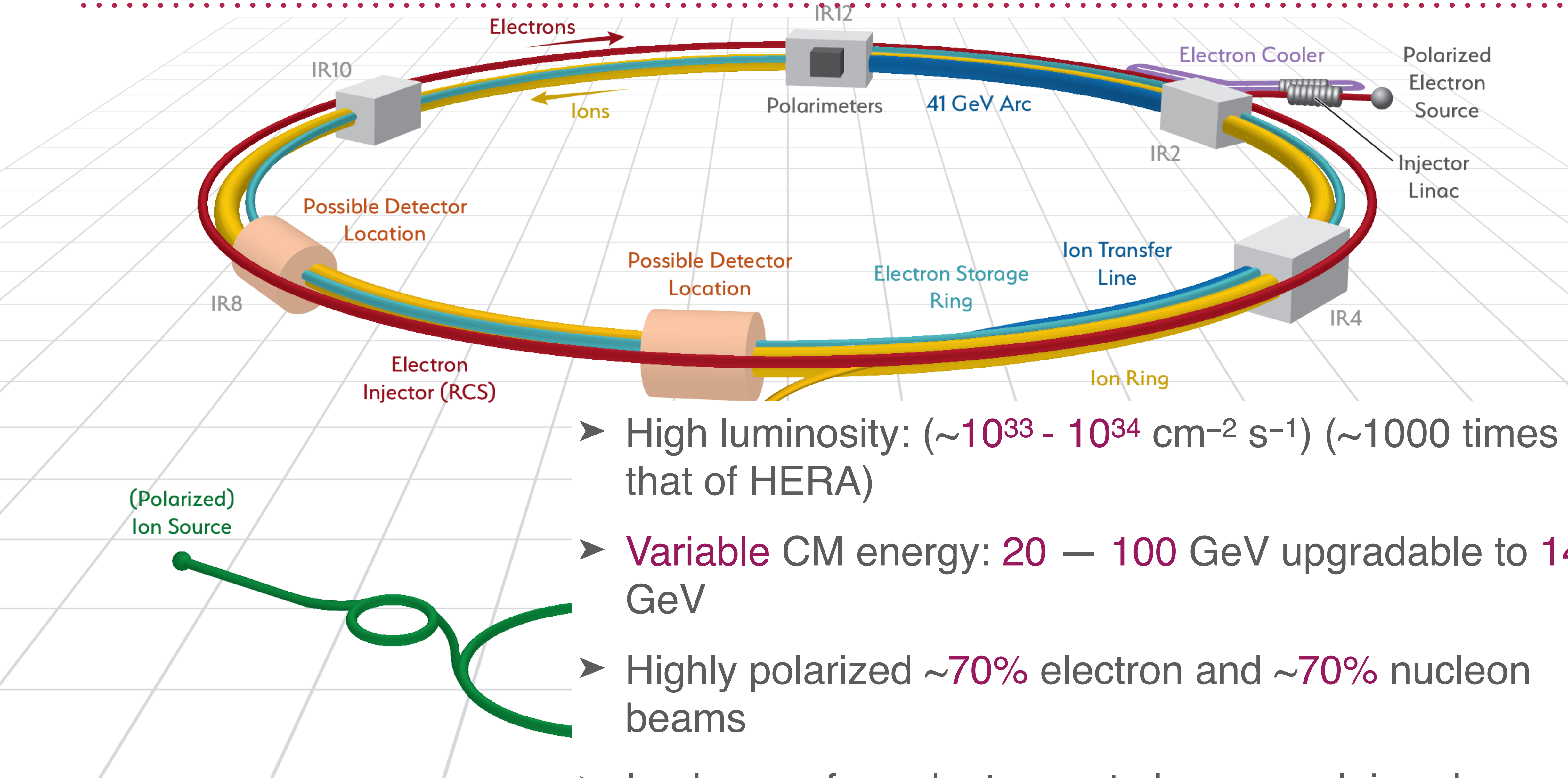
EVOLUTION OF OUR UNDERSTANDING OF THE SPIN STRUCTURE



1980’ - the spin of the nucleon is due to the valence quarks

Modern concept: valence quarks, sea quarks, and gluons together with orbital angular momentum are contributing

THE ELECTRON-ION COLLIDER @ BNL

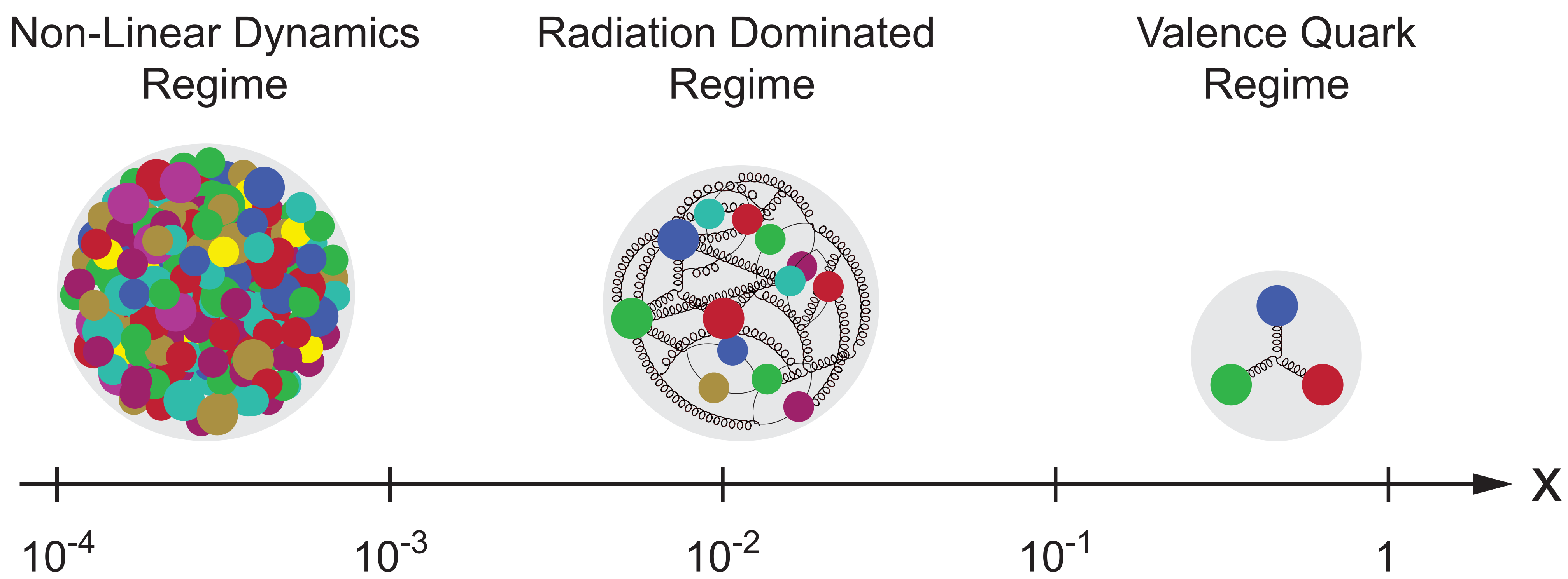


White Paper (2012)
Accardi et al, arXiv:1212:1701

- High luminosity: (~10^{33} - 10^{34} cm^{-2} s^{-1}) (~1000 times that of HERA)
- Variable CM energy: 20 — 100 GeV upgradable to 140 GeV
- Highly polarized ~70% electron and ~70% nucleon beams
- Ion beams from deuterons to heavy nuclei such as gold, lead, or uranium
- Possibility of more than one interaction region (none of the major facilities operates with one detector only - important for discovery potential)

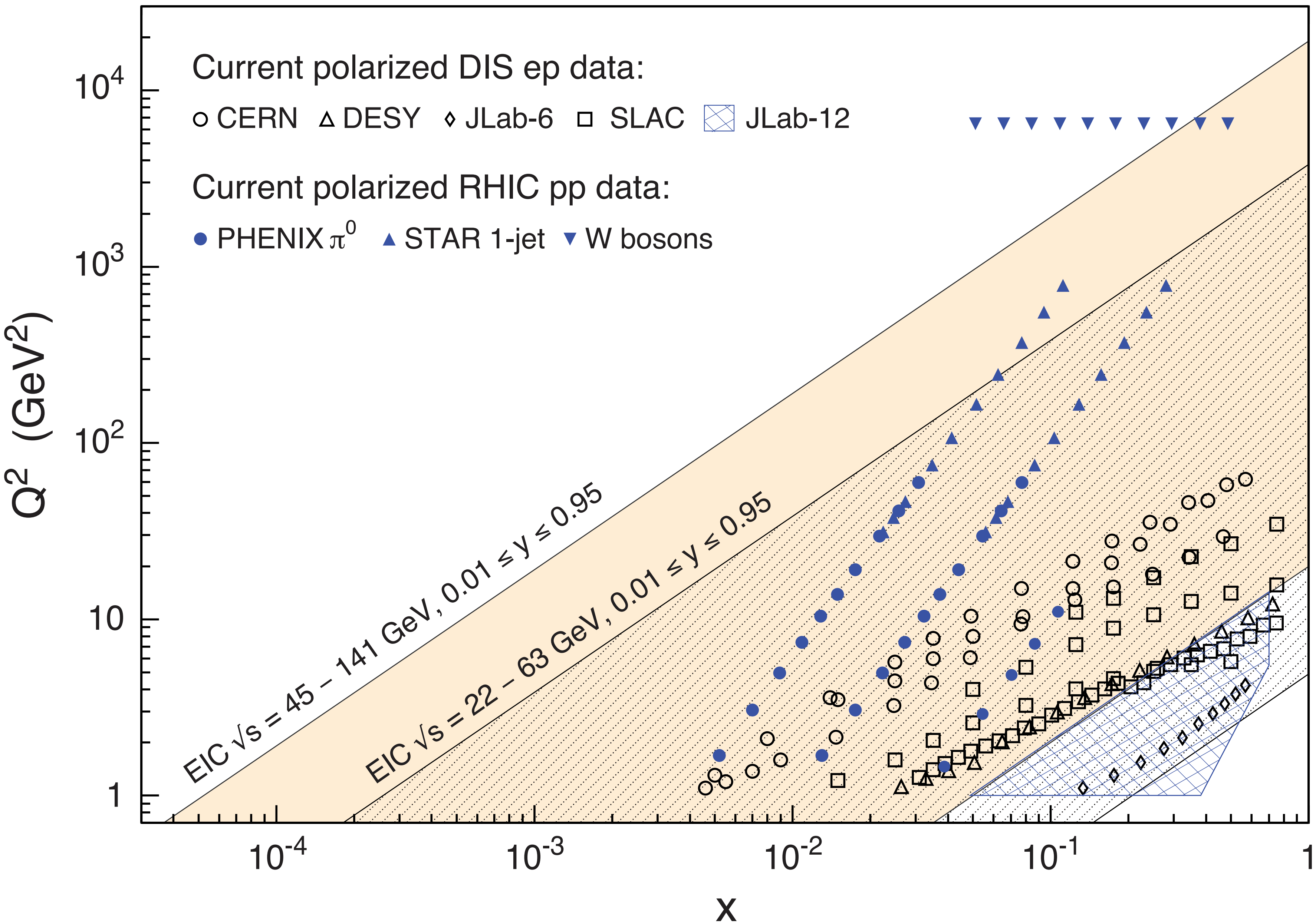
WHAT DO WE STUDY?

THE ELECTRON-ION COLLIDER: KINEMATICS



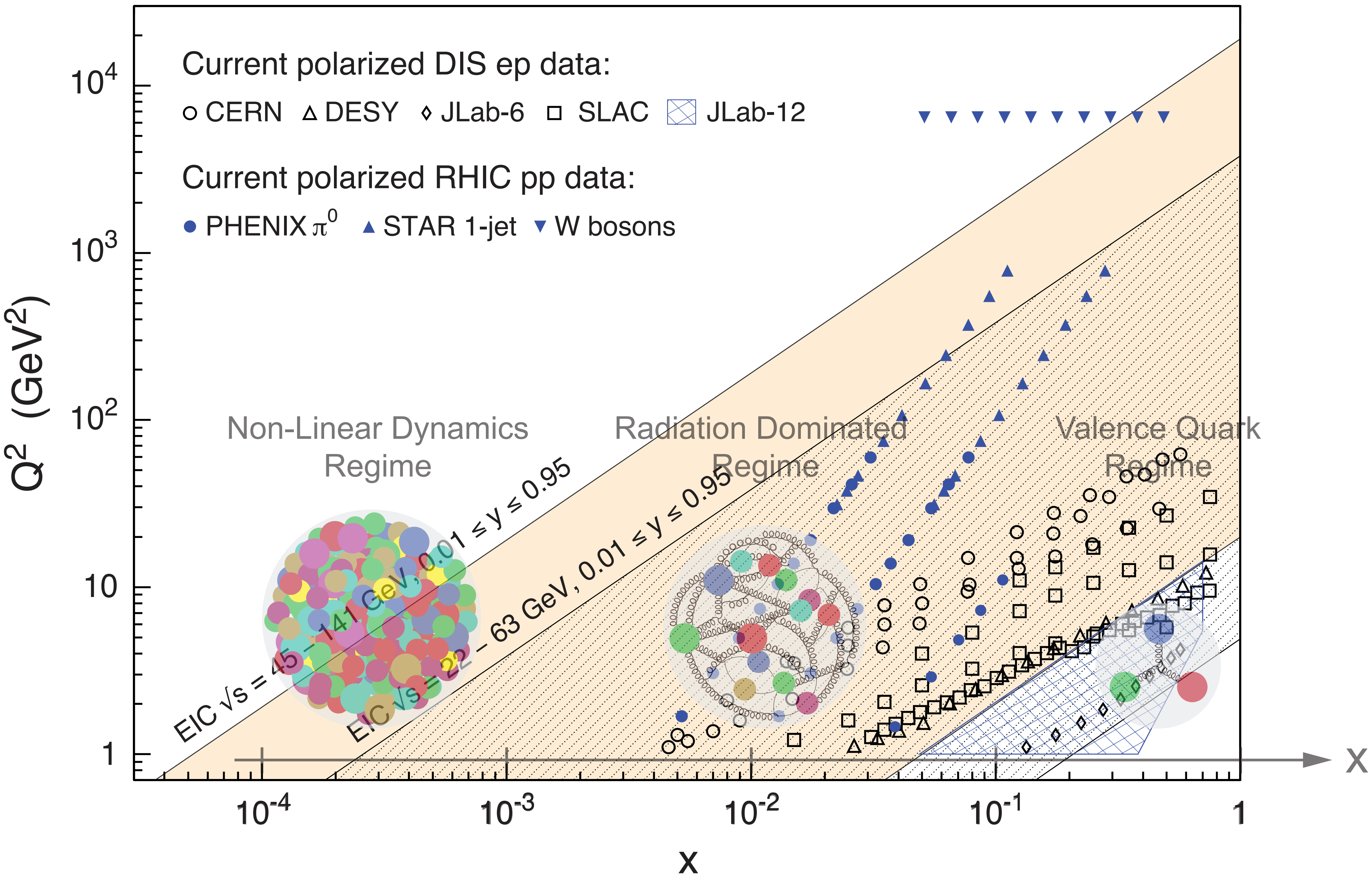
BNL Report (2017)
Aschenauer at el, arXiv:1708.01527

THE ELECTRON-ION COLLIDER: KINEMATICS



BNL Report (2017)
Aschenauer at el, arXiv:1708.01527

THE ELECTRON-ION COLLIDER: KINEMATICS



BNL Report (2017)
Aschenauer at el, arXiv:1708.01527

COLLINEAR SPIN STRUCTURE

Spin-1/2 nucleon can be described by three collinear parton distribution functions (pdf)

N \ q	U	L	T
U	f_1		
L		g_1	
T			h_1

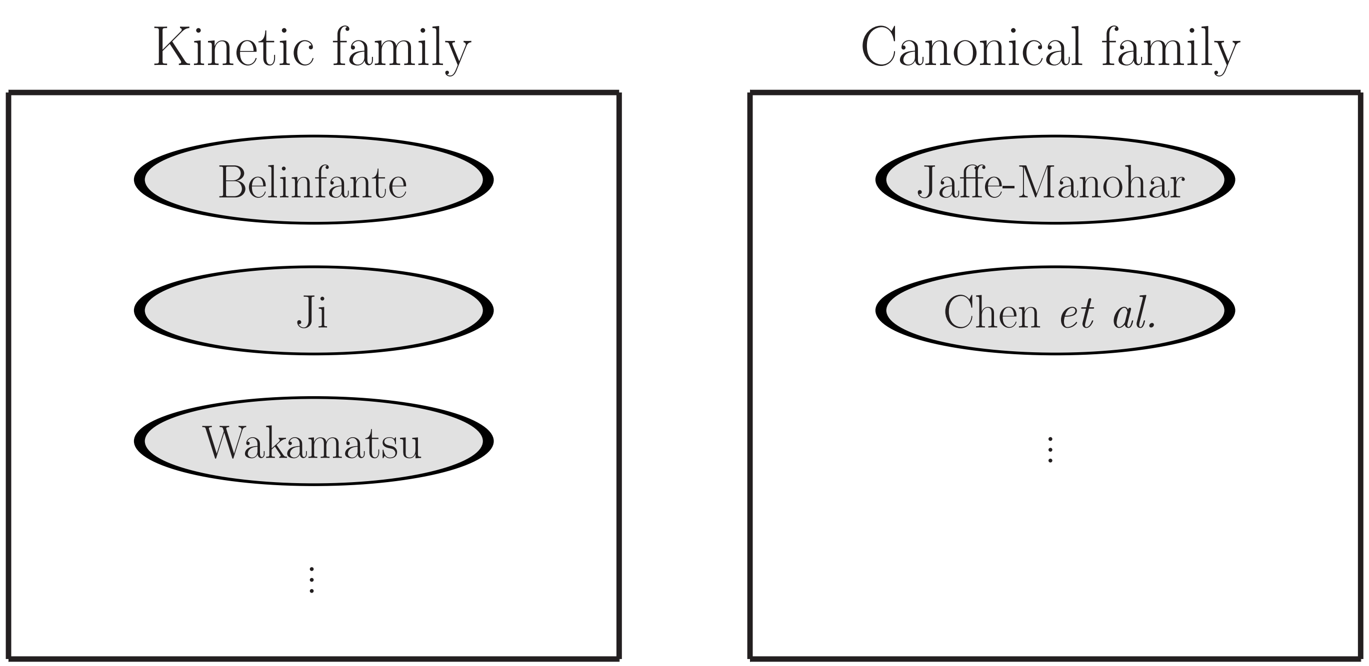
unpolarized pdf

helicity pdf

transversity pdf

SPIN DECOMPOSITION

- The nucleon is a composite system. The spin is carried by its constituents: quarks, anti-quarks and gluons and the angular momentum generated by their motion.
- The nucleon at rest has spin 1/2, however its decomposition in terms of spin and orbital contributions associated with quarks and gluons is not unique.
- There are two types of decompositions of the proton spin operator: kinetic (also known as mechanical) and canonical. These two types differ by how the OAM operator is split into the quark and gluon contributions. They share the same quark spin operator.



R. L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 (1990)
S. Bashinsky and R. L. Jaffe, Nucl. Phys. B 536 (1998)
X. Ji, Phys. Rev. Lett. 78 (1997)
X. -S. Chen, X. -F. Lu, W. -M. Sun, F. Wang and T. Goldman, Phys. Rev. Lett. 100 (2008)
M. Wakamatsu, Phys. Rev. D 83 (2011)
Y. Hatta, Phys. Rev. D 84 (2011)
E. Leader and C. Lorce, Phys.Rept. 541, 163 (2014)
C. Lorcé and B. Pasquini, JHEP 09 (2013)
C. Lorcé and B. Pasquini, Phys. Rev. D 84, (2011)
C. Lorcé, B. Pasquini, X. Xiong and F. Yuan, Phys. Rev. D 85, (2012)
L. Adhikari and M. Burkard, Phys.Rev.D 94 (2016)

- Kinetic family is related to Generalized Parton Distributions, while canonical in light cone gauge is related to collinear helicity distribution functions

LONGITUDINAL SPIN

When the proton or the neutron are polarized, quarks and gluons are polarized as well. Helicity distribution functions: number of quarks/gluons with spin parallel to the nucleon momentum minus the number of quarks/gluons with the spin opposite to the nucleon momentum

$$\Delta f(x,Q^2) = g_1(x,Q^2) \equiv f^+(x,Q^2) - f^-(x,Q^2)$$

The relevant spin decomposition is by Jaffe and Manohar

R. L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 (1990)

$$\frac{1}{2} = S_q + \mathcal{L}_q + S_g + \mathcal{L}_g$$

Related to measured observables:

Quark spin contribution

$$S_q = \frac{1}{2}\int_0^1 \Delta\Sigma(x,Q^2)dx \equiv \frac{1}{2}\int_0^1 (\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s})(x,Q^2)dx$$

Gluon spin contribution

$$S_g = \int_0^1 \Delta g(x,Q^2)dx$$

Difficult to measure in experiment:

$$\mathcal{L}_q + \mathcal{L}_g$$

quark and gluon orbital angular momenta (OAM) via twist-3 GPDs, Wigner functions

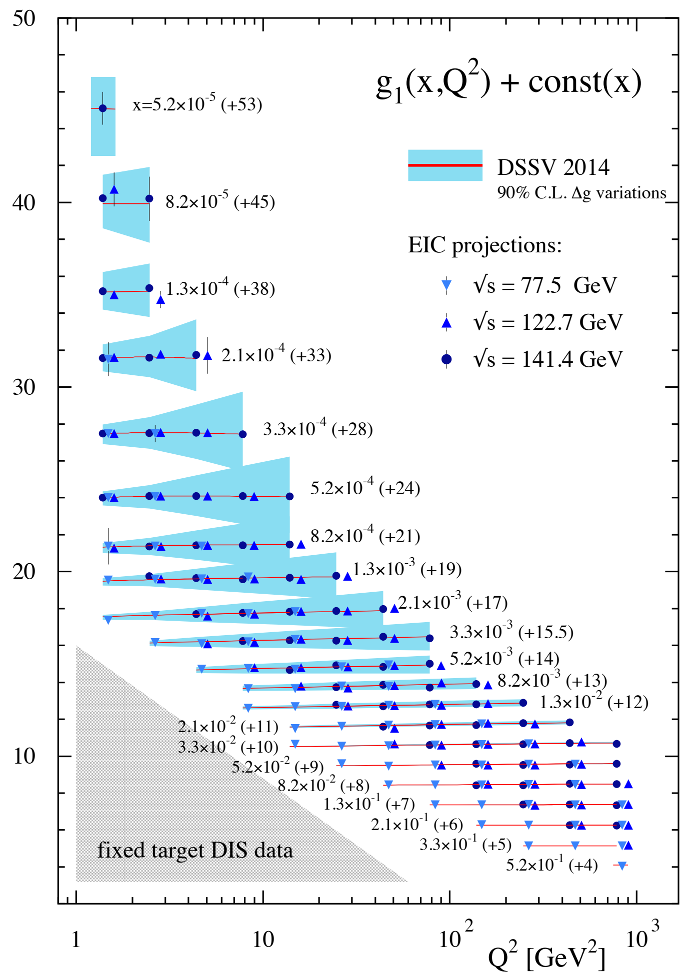
D.V. Kiptily, M.V. Polyakov, Eur. Phys. J. C 37 (2004
A. Courtoy, G. R. Goldstein, J. O. Gonzalez Hernandez, S. Liuti, A. Rajan, PLB 731 (2014)
Y. Hatta, Phys. Lett. B 708 (2012);
Y. Hatta, S. Yoshida, J. High Energy Phys. 1210 (2012

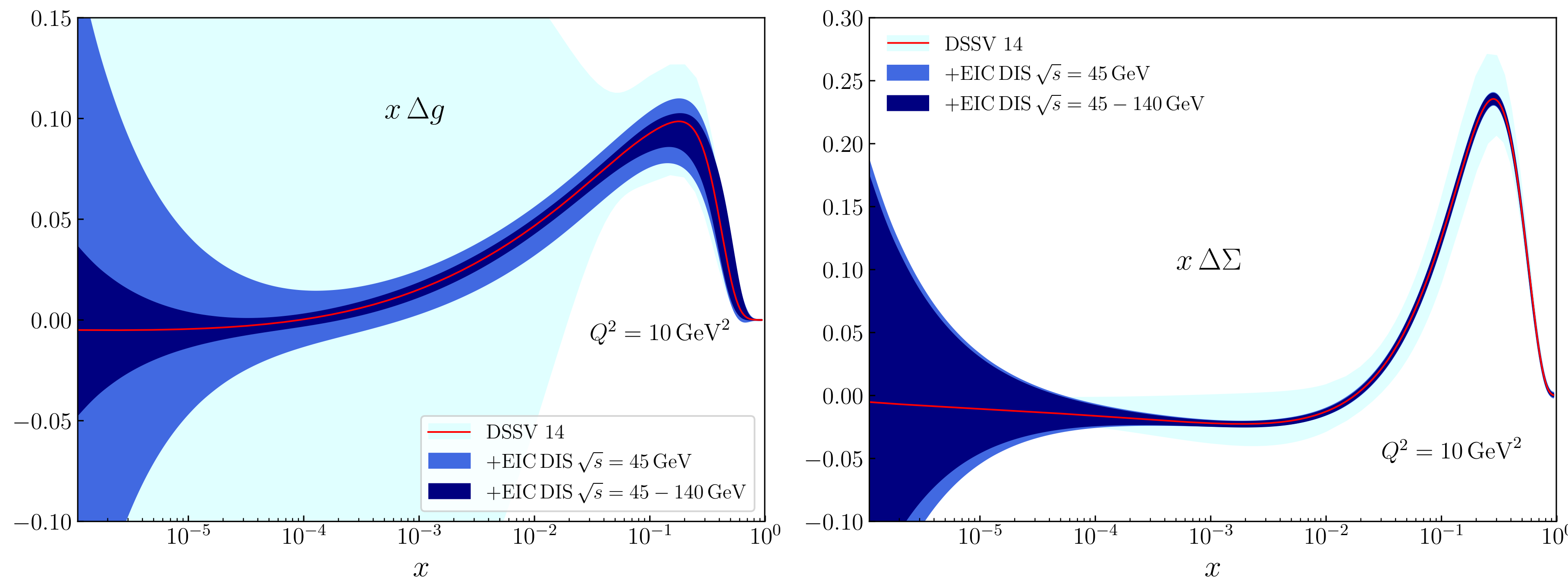
LONGITUDINAL SPIN

- Global QCD analyses are performed to extract helicity pdfs:

  DSSV: D. de Florian, R. Sassot, M. Stratmann and W. Vogelsang, Phys. Rev. Lett. 113 (2014)
  NNPDFpol: E. R. Nocera, R. D. Ball, S. Forte, G. Ridolfi, J. Rojo, Nucl. Phys. B 887 (2014)
  JAM: J. J. Ethier, N. Sato, W. Melnitchouk, Phys. Rev. Lett. 119 (13) (2017)
- At present around $25\ \%$ of the spin is attributed to quarks and anti-quarks.
- The evidence for non-zero gluon contribution, around $30\ \%$, is mainly due to RHIC spin program E. R. Nocera, Impact of Recent RHIC Data on Helicity-Dependent Parton Distribution Functions (2017). arXiv:1702.05077.

The impact of the EIC on determination of the quark and gluon contributions



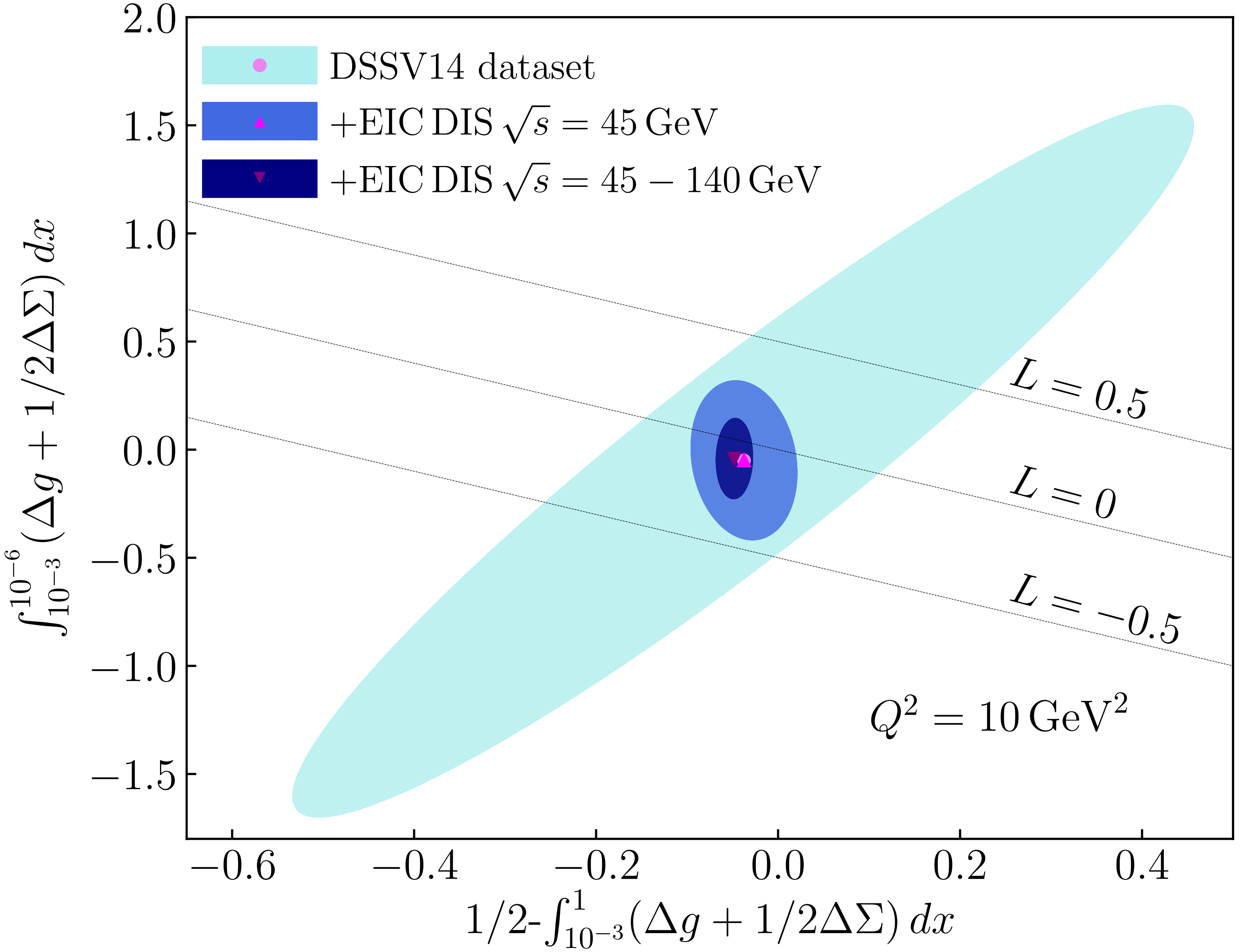


Yellow Report (2021) arXiv:2103.05419

Aschenauer , Sassot, Stratmann, Phys.Rev.D 92 (2015)

LONGITUDINAL SPIN

Studies of the room left for potential OAM contributions at the EIC



Yellow Report (2021) arXiv:2103.05419

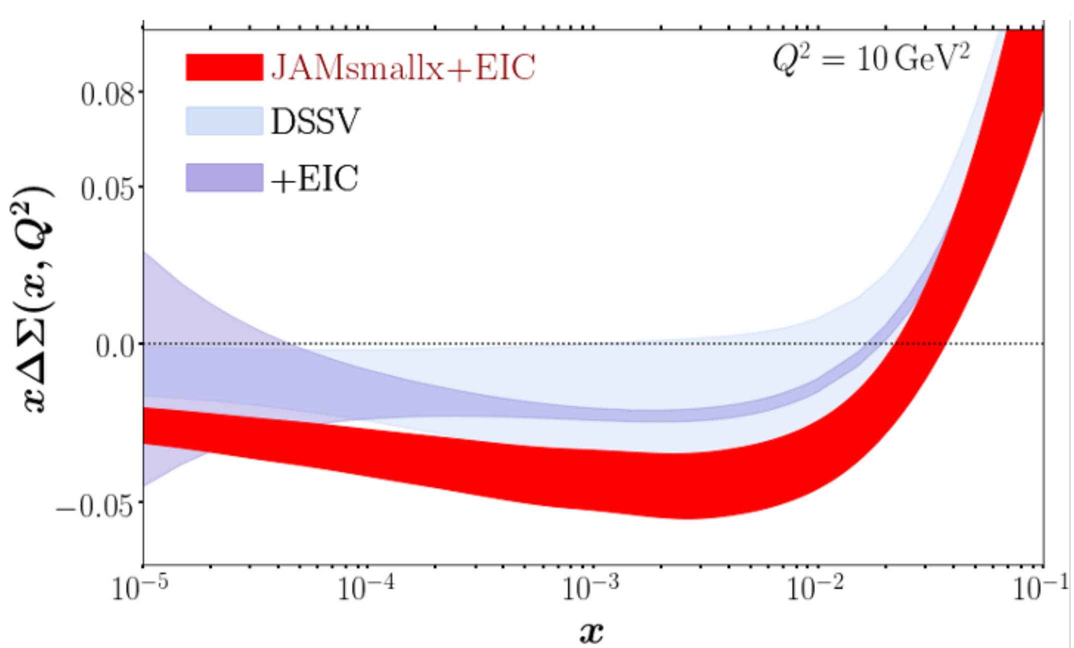
SMALL-x SPIN CHALLENGE

- Can we constrain theoretically the amount of proton spin and OAM coming from small x?
- Existing and future experiments probe the helicity distributions and OAM down to some min x

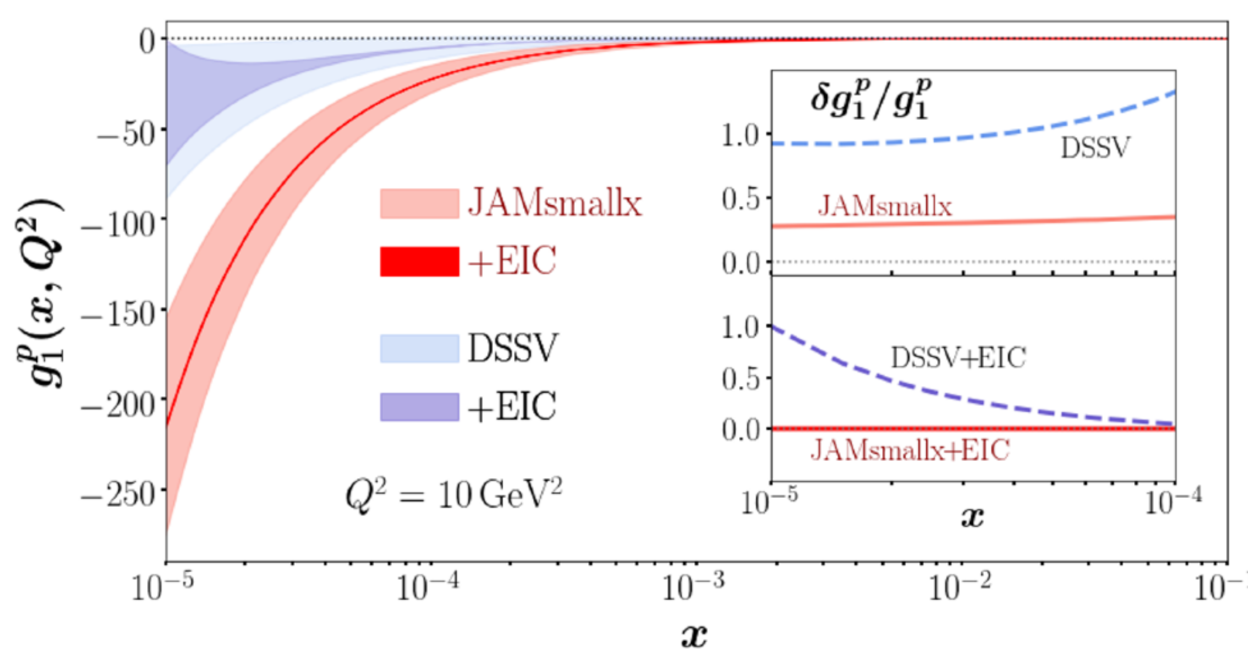
$$S_g = \int_0^1 \Delta g(x, Q^2) dx \qquad S_q = \frac{1}{2} \int_0^1 \Delta\Sigma(x, Q^2) dx$$

- If we want to predict helicity PDFs at small x, we need a different evolution equation similar to BK/JIMWLK evolving in x starting from some value of $x \approx 10^{-3}$. Pitonyak, Sievert, Kovchegov (15), (18)
- Potentially negative 10-20% of the proton spin may be carried by small-x quarks helicity (JAMsmallx, preliminary)

JAMsmallx: Adamiak, Melnitchouk, Pitonyak, Sato, Sievert, Kovchegov (2102.06159)



Better constraint at small-x achieved compared to the traditional approaches

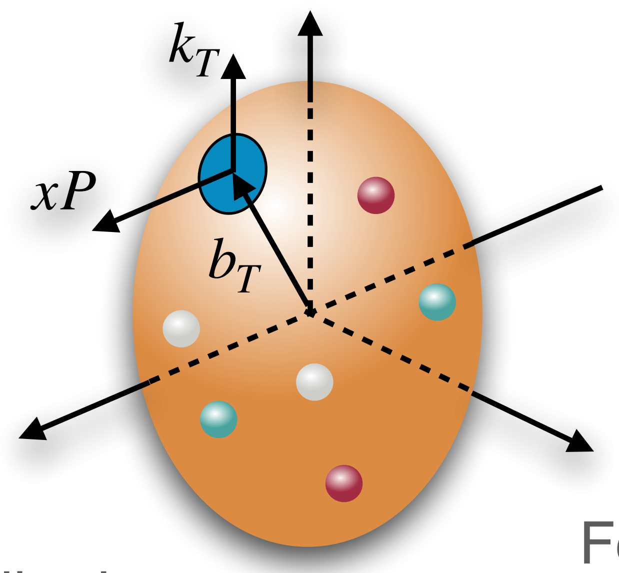


$$g_1(x, Q^2) = \frac{1}{2} \sum_f e_f^2 \left[\Delta q_f + \Delta q_{\bar{f}}\right]$$

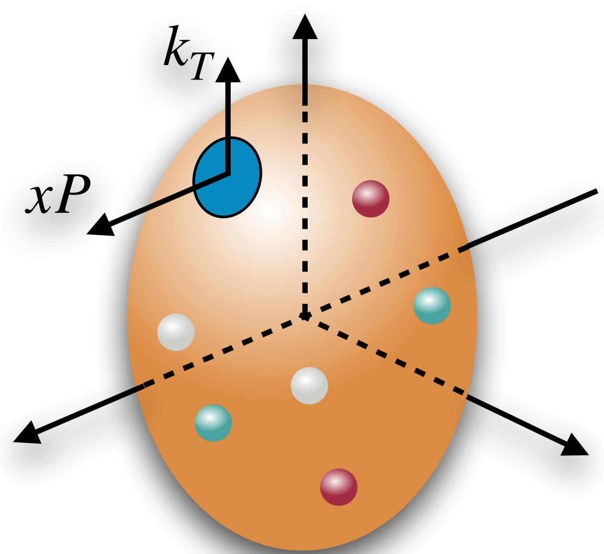
BEYOND THE COLLINEAR PICTURE

WIGNER DISTRIBUTIONS AND THREE DIMENSIONAL STRUCTURE

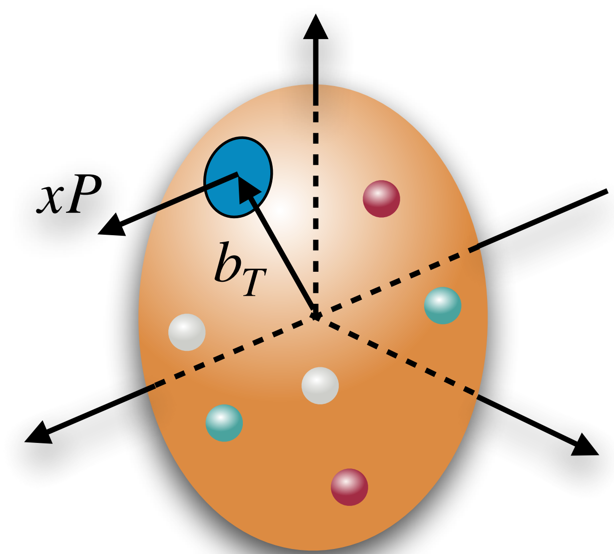
Wigner distributions (Fourier transform of Generalized Transverse Momentum Distributions)



Transverse Momentum Dependent Distributions (TMDs)



Fourier transform of Generalized Parton Distributions (GPDs)

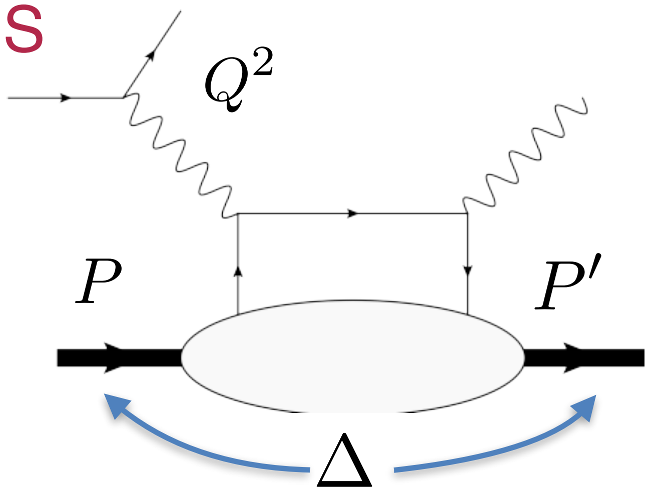


see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

GPD

TMD

DVCS



Ji (1997)
Radyushkin (1997)

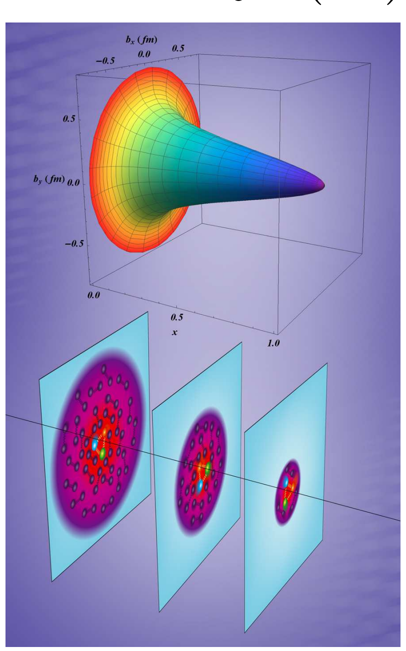
Q^2 ensures hard scale, pointlike interaction

$\Delta = P' - P$ momentum transfer can be varied independently

Connection to 3D structure

Burkardt (2000)
Burkardt (2003)

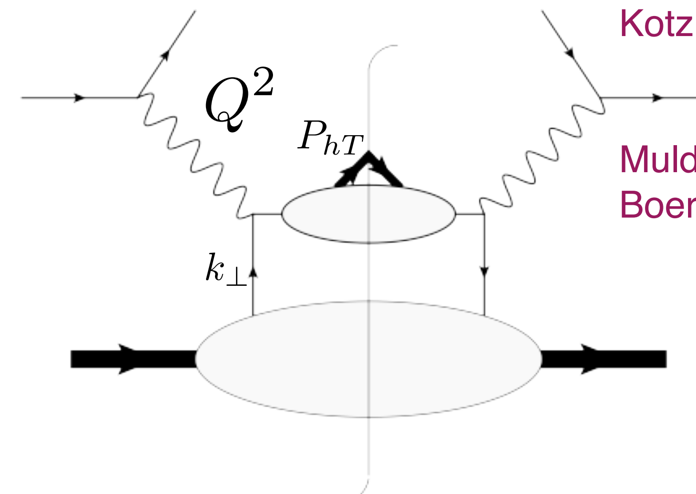
$$\rho(x, \vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{-i\vec{\Delta}_\perp \cdot \vec{b}_\perp} H_q(x, \xi = 0, t = -\vec{\Delta}_\perp^2)$$



Drell-Yan frame $\Delta^+ = 0$

Dupré, Guidal, Niccolai, Vanderhaeghen, arXiv:1704.07330

SIDIS



Kotzinian (1995)

Mulders, Tangerman (1995)
Boer, Mulders (1998)

Q^2 ensures hard scale, pointlike interaction

P_{hT} final hadron transverse momentum can be varied independently

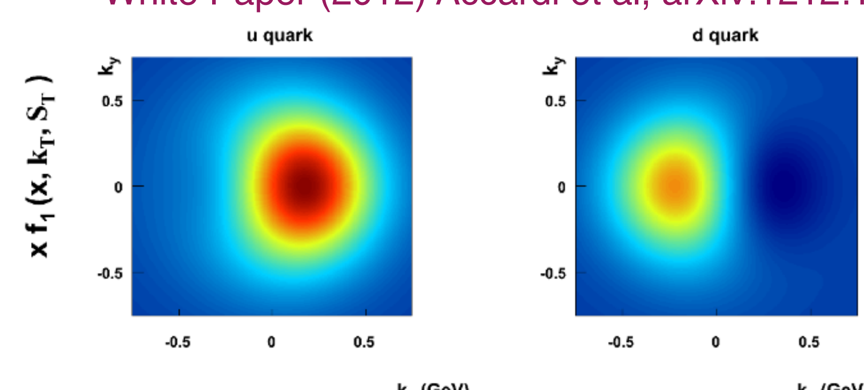
Connection to 3D structure

Ji, Ma, Yuan (2004)
Collins (2011)

$$f(x, \vec{k}_T) = \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{k}_T \cdot \vec{b}_T} \tilde{f}(x, \vec{b}_T)$$

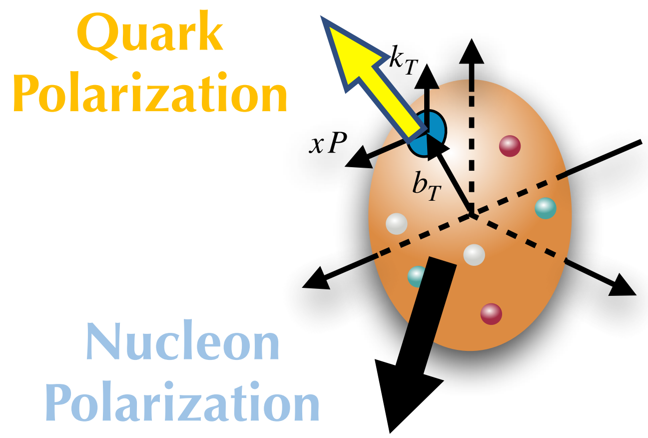
$\vec{b}_T$ is the transverse separation of parton fields in configuration space

White Paper (2012) Accardi et al, arXiv:1212:1701



$$\rho_{1;q\leftarrow h^\uparrow}(x, \boldsymbol{k}_T, \boldsymbol{S}_T, \mu) = f_{1;q\leftarrow h}(x, k_T; \mu, \mu^2) - \frac{k_{Tx}}{M} f_{1T;q\leftarrow h}^{\perp}(x, k_T; \mu, \mu^2)$$

Our understanding of the hadron evolves: SPIN



Nucleon emerges as a strongly interacting, relativistic bound state of quarks and gluons

TMDs

Nucleon Polarization	Quark Polarization: Unpolarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	$f_1(x,k_T^2)$ *Unpolarized*		$h_1^{\perp}(x,k_T^2)$ *Boer-Mulders*
L		$g_1(x,k_T^2)$ *Helicity*	$h_{1L}^{\perp}(x,k_T^2)$ *Kozinian-Mulders,"worm" gear*
T	$f_{1T}^{\perp}(x,k_T^2)$ *Sivers*	$g_{1T}(x,k_T^2)$ *Kozinian-Mulders, "worm" gear*	$h_1(x,k_T^2)$ *Transversity*; $h_{1T}^{\perp}(x,k_T^2)$ *Pretzelosity*

GPDs

Nucleon Polarization	Quark Polarization: Unpolarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	
T	E		$H_T,\ \tilde{H}_T$

Many TMDs and GPDs cannot exist without OAM.

Examples: TMD Sivers function $f_{1T}^{\perp}$ and GPD *E*

LONGITUDINAL SPIN

Studies of DVCS process were highly motivated by Ji decomposition

$$\frac{1}{2} = S_q + L_q + J_g$$

X. Ji, Phys. Rev. Lett. 78 (1997) 610

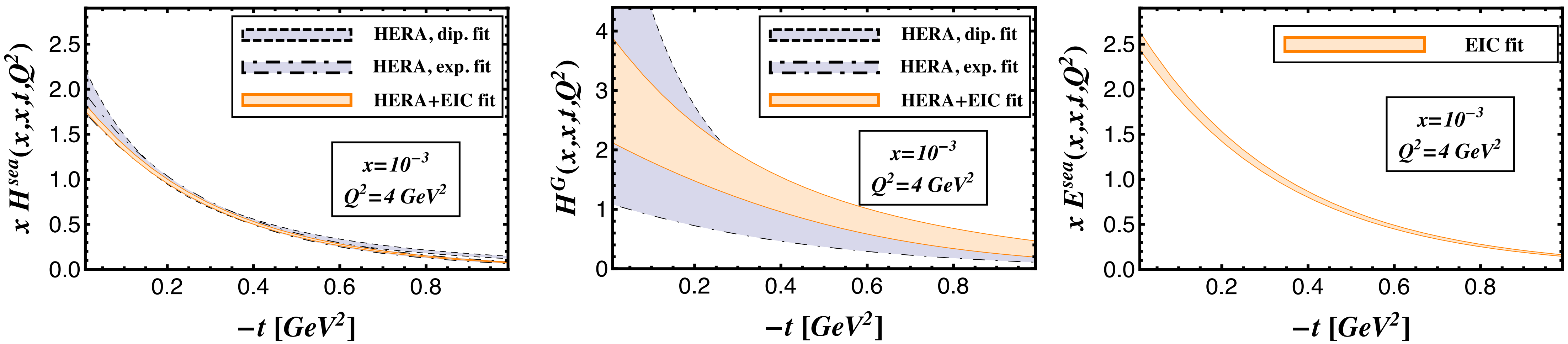
Related to twist-2 GPDs:

$$J_q \equiv S_q + L_q = \frac{1}{2}\int_0^1 \Delta\Sigma(x,Q^2)dx + L_q = \frac{1}{2}\int_{-1}^1 dx\,x\left(H^q(x,\xi=0,t=0) + E^q(x,\xi=0,t=0)\right)$$

$$J_g = \frac{1}{2}\int_{-1}^1 dx\,x\left(H^g(x,\xi=0,t=0) + E^g(x,\xi=0,t=0)\right)$$

These quantities can be computed also in lattice simulations

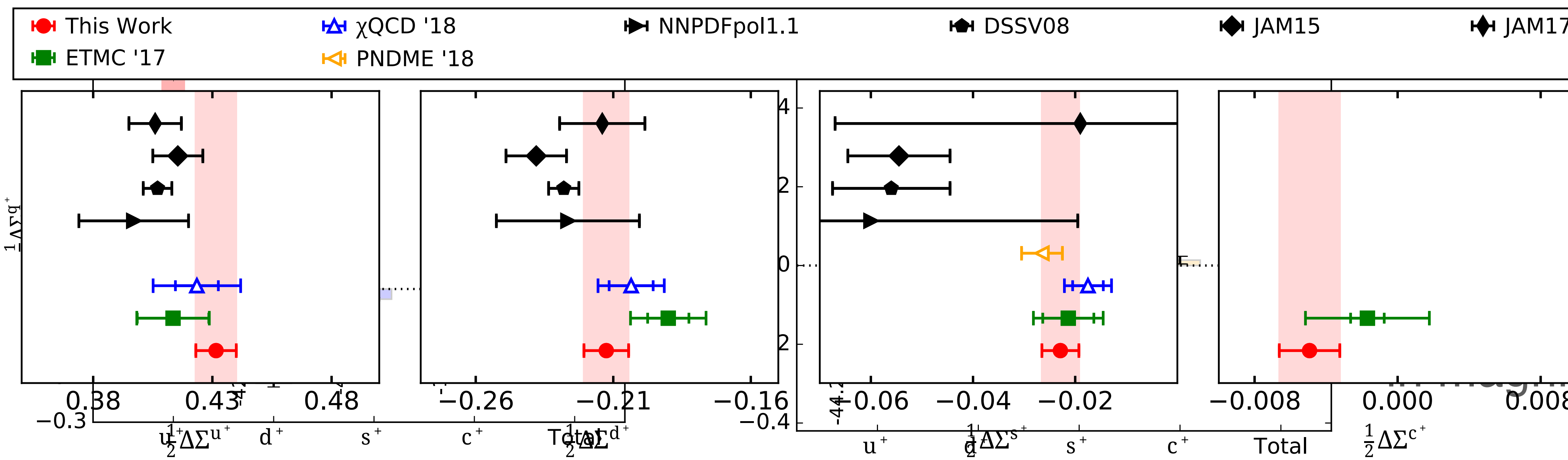
The impact of the EIC on determination of the sea-quark and gluon contributions



E. Aschenauer, S. Fazio, K. Kumericki, D. Mueller, JHEP 09 (2013) 093

LONGITUDINAL SPIN AND LATTICE QCD

- Many methods are explored by lattice QCD to calculate the spin and OAM, subtraction, direct computations See e.g. review of Keh-Fei Liu and Cédric Lorcé, Eur.Phys.J.A 52 (2016)
- Spin contributions can be computed at physical pion mass. An example from ETMC Collaboration C. Alexandrou et al, Phys.Rev.D 101 (2020)

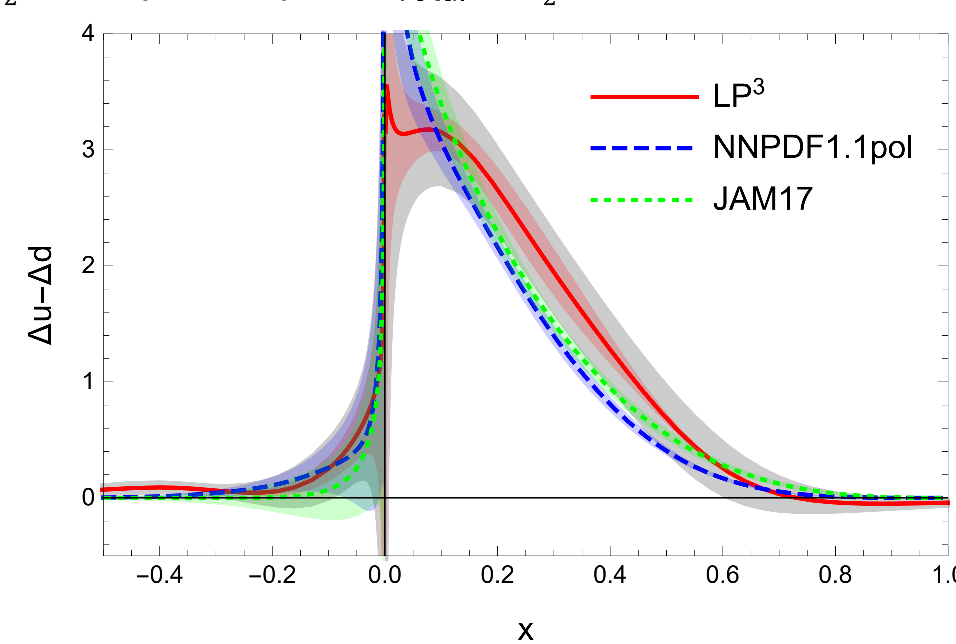


uarks
pposite
s.

Ms are
ately equal
tude

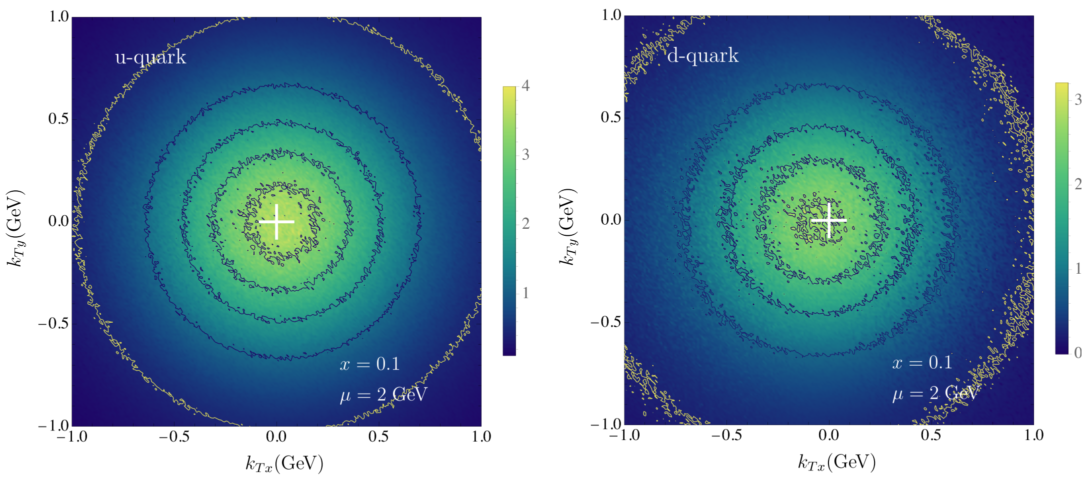
- Lattice QCD computes also the shape of pdfs, GPDs, TMDs using various approaches. An example from LP[3] Collaboration

H. -W. Lin et al Phys.Rev.Lett. 121 (2018)



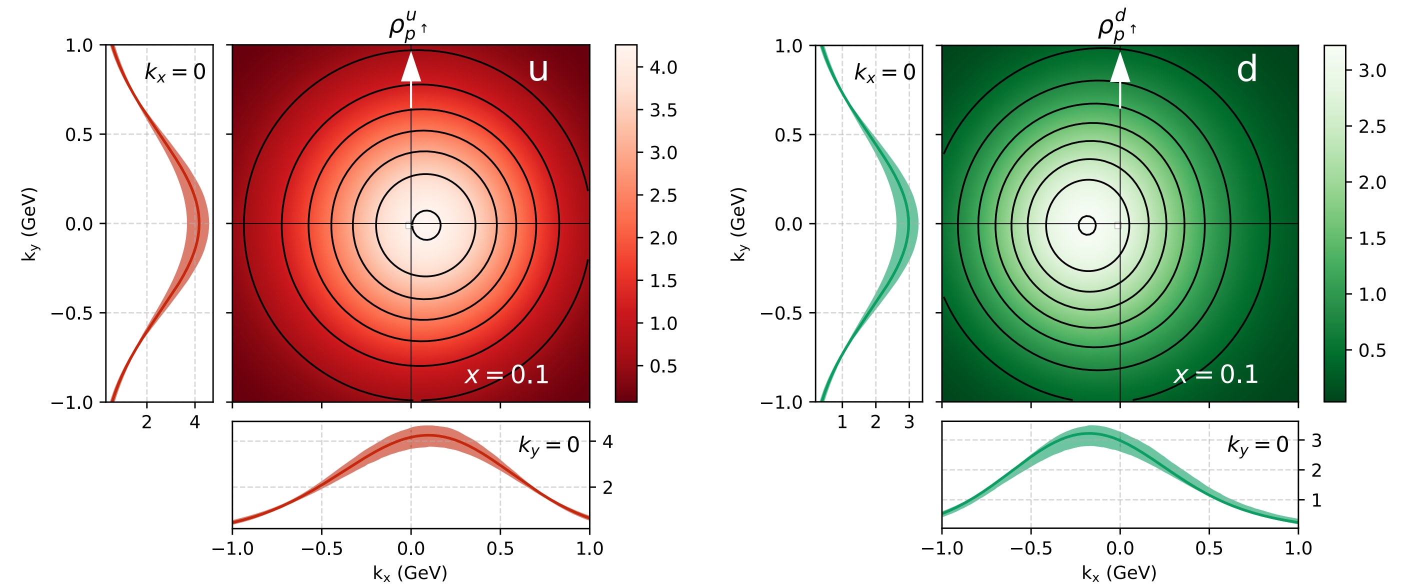
NUCLEON TOMOGRAPHY – THE FINAL GOAL OF THE EIC

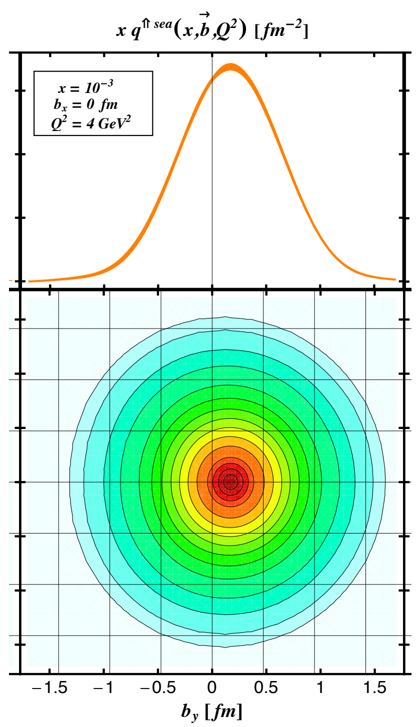
$$\rho_{1;q\leftarrow h^{\uparrow}}(x, \boldsymbol{k}_T, \boldsymbol{S}_T, \mu) = f_{1;q\leftarrow h}(x, k_T; \mu, \mu^2) - \frac{k_{Tx}}{M} f_{1T;q\leftarrow h}^{\perp}(x, k_T; \mu, \mu^2)$$



M. Bury, A. Prokudin, A. Vladimirov, Phys.Rev.Lett. 126 (2021)

A. Bacchetta, F. Delcarro, C. Pisano, M. Radici (2020)



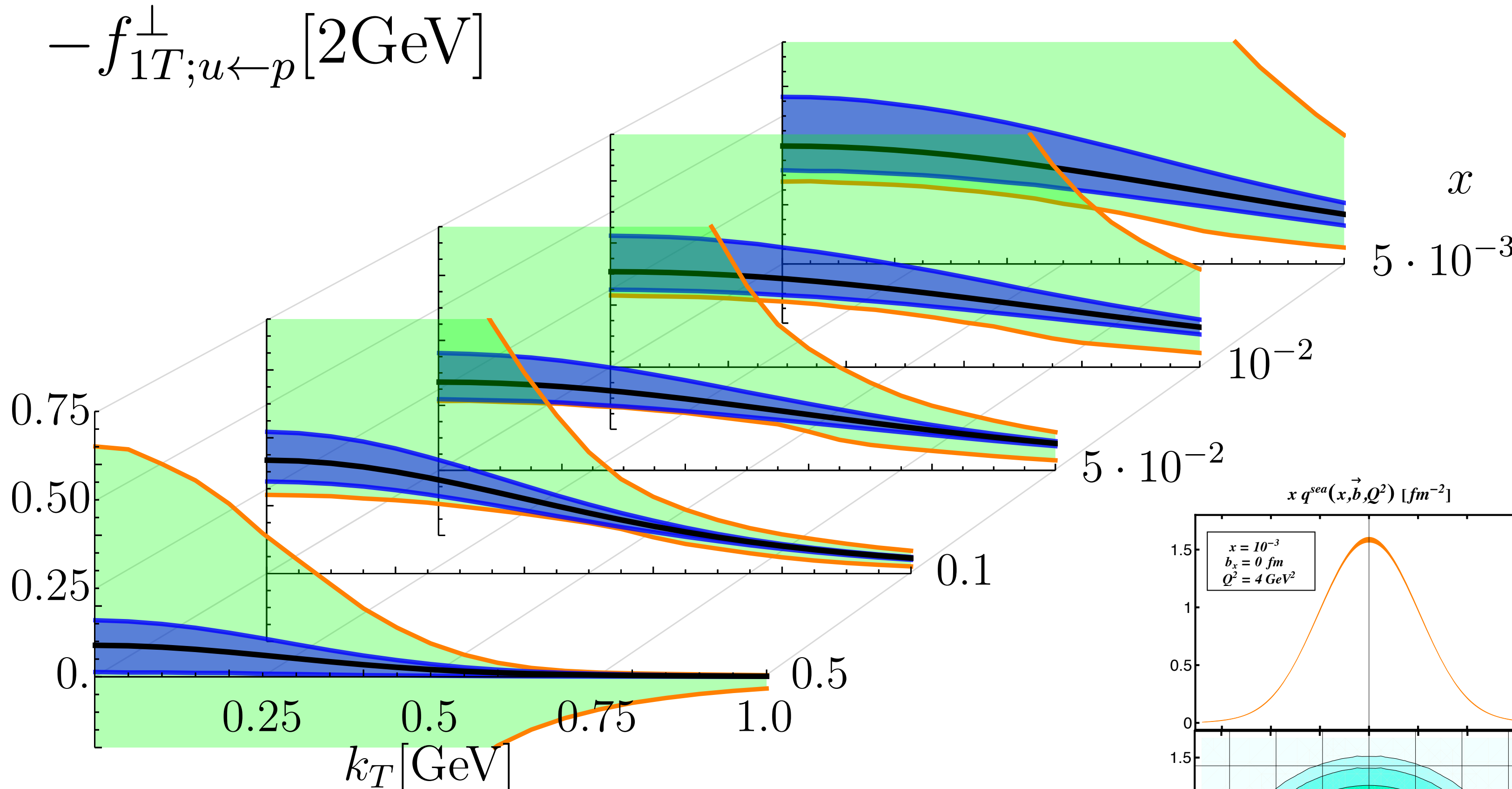


$$q^{\Uparrow}(x, \vec{b}, \mathcal{Q}^2) = q(x, \vec{b}, \mathcal{Q}^2) - \frac{1}{2M_p}\frac{\partial}{\partial b_y} E(x, \vec{b}, \mathcal{Q}^2)$$

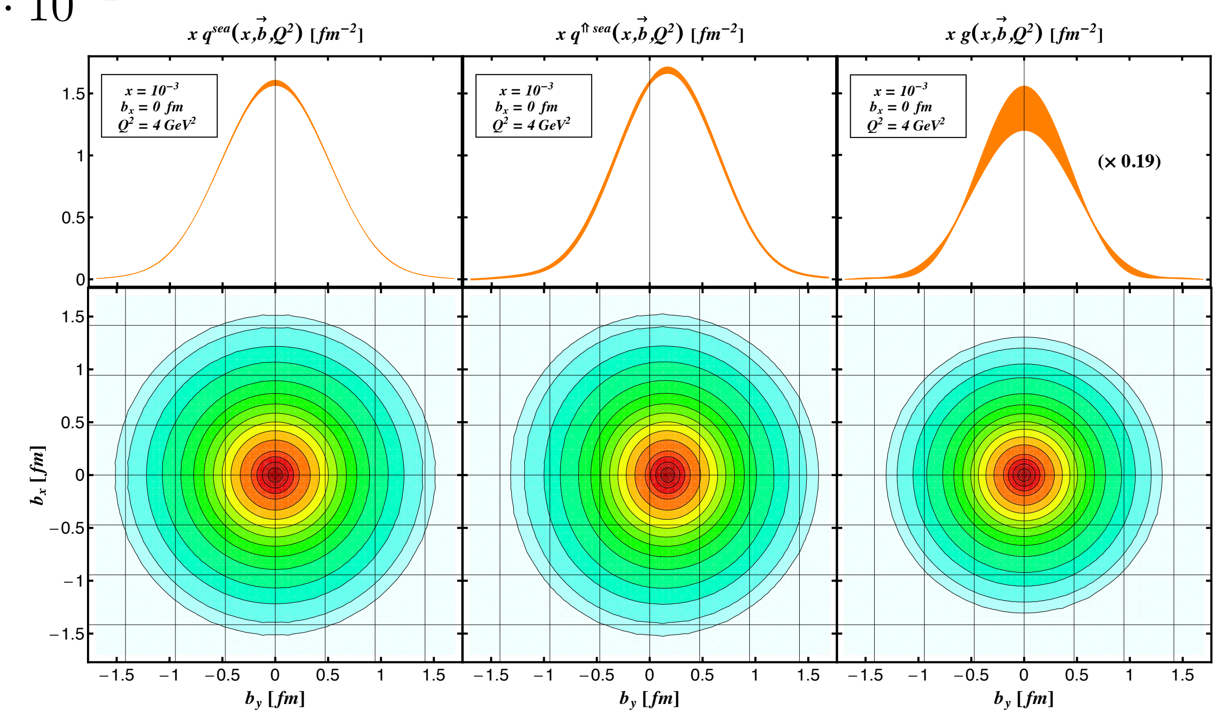
E. Aschenauer, S. Fazio, K. Kumericki, D. Mueller, JHEP 09 (2013) 093

- The shift in the transverse plane is generated by the Sivers function and GPD *E* that cannot exist without OAM
- The opposite signs of the shift is consistent with lattice QCD findings on the opposite signs of the OAM for u and d quarks

THE SIVERS FUNCTION AND GPD E AT THE EIC



A. Vladimirov for EIC Yellow Report (2021) arXiv:2103.05419



$x\ =\ 0.001\ \text{and}\ \mathcal{Q}^2\ =\ 4\,\text{GeV}^2$

E. Aschenauer, S. Fazio, K. Kumericki, D. Mueller, JHEP 09 (2013) 093

- The impact of the EIC is very substantial

TRANSVERSE SPIN

- The situation is more subtle due to the fact that boost and rotations do not commute
- Two sum rules are proposed

E. Leader, PRD 85 (2012), canonical

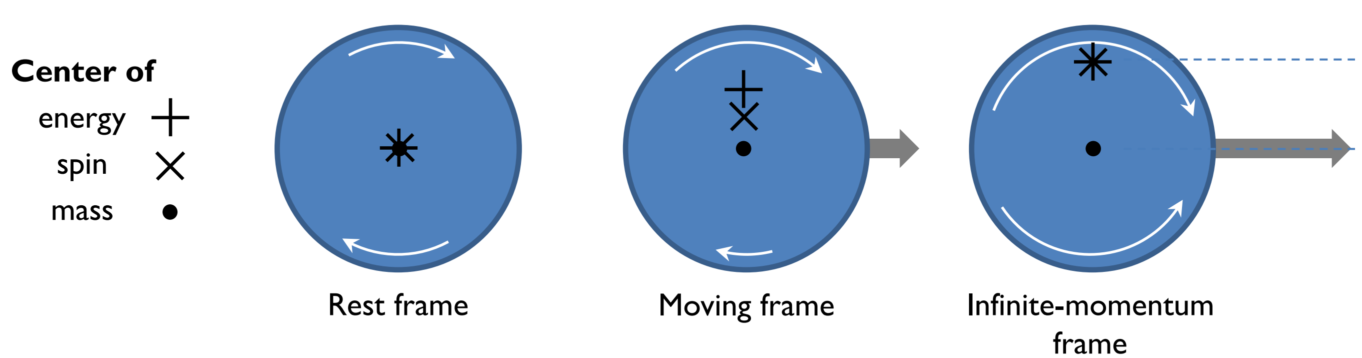
$$\langle J_a^T \rangle = \frac{1}{2}\left[\int_{-1}^{1} dx x H^a(x,\xi=0,t=0) + \frac{p_0}{M}\int_{-1}^{1} dx x E^a(x,\xi=0,t=0)\right]$$

X. Ji and F. Yuan, PLB 810 (2020), covariant

$$\langle J_a^T \rangle = \frac{p_0}{2M}\left[\int_{-1}^{1} dx x H^a(x,\xi=0,t=0) + \int_{-1}^{1} dx x E^a(x,\xi=0,t=0)\right]$$

- Both turn out to be correct and correspond to different definitions of the relativistic center of the system: Leader - spin, Ji-Yuan - mass

C. Lorcé, EPJC 81 (2021)



TRANSVERSITY

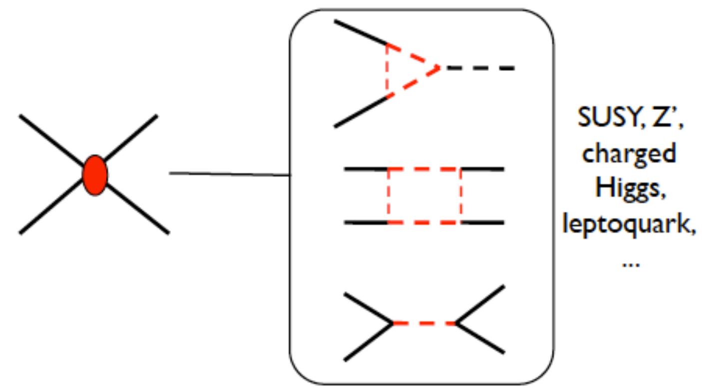
- The only source of information on tensor charge of the nucleon

$$\delta q \equiv g_T^q = \int_0^1 dx \; \left[h_1^q(x, Q^2) - h_1^{\bar{q}}(x, Q^2)\right]$$

- Tensor couplings, not present in the SM Lagrangian, could be the footprints of new physics at higher scales

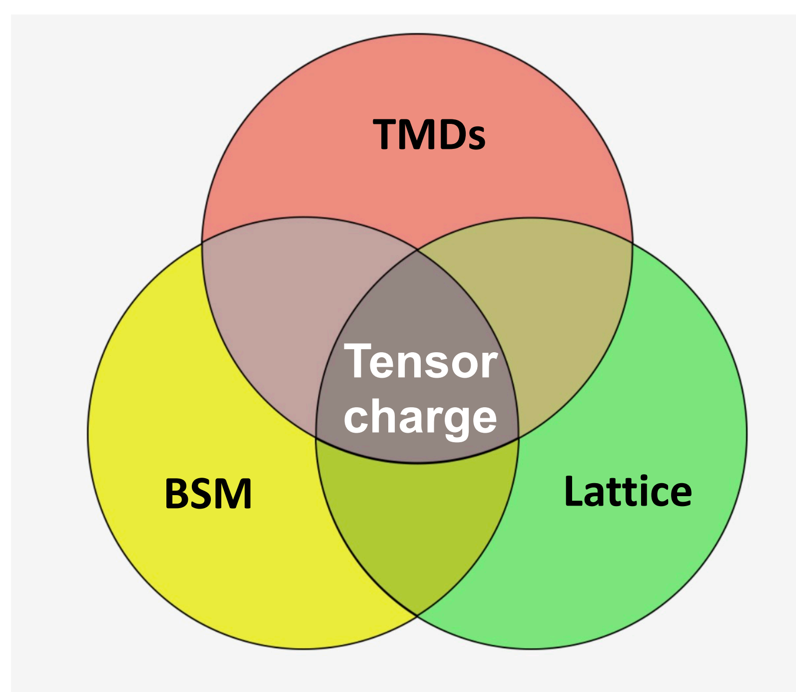
Bhattacharya et al, PRD 85 (12)
Pattie et al., P.R. C88 (13)

$\varepsilon_T \, g_T \approx M_W^2 / M_{BSM}^2$



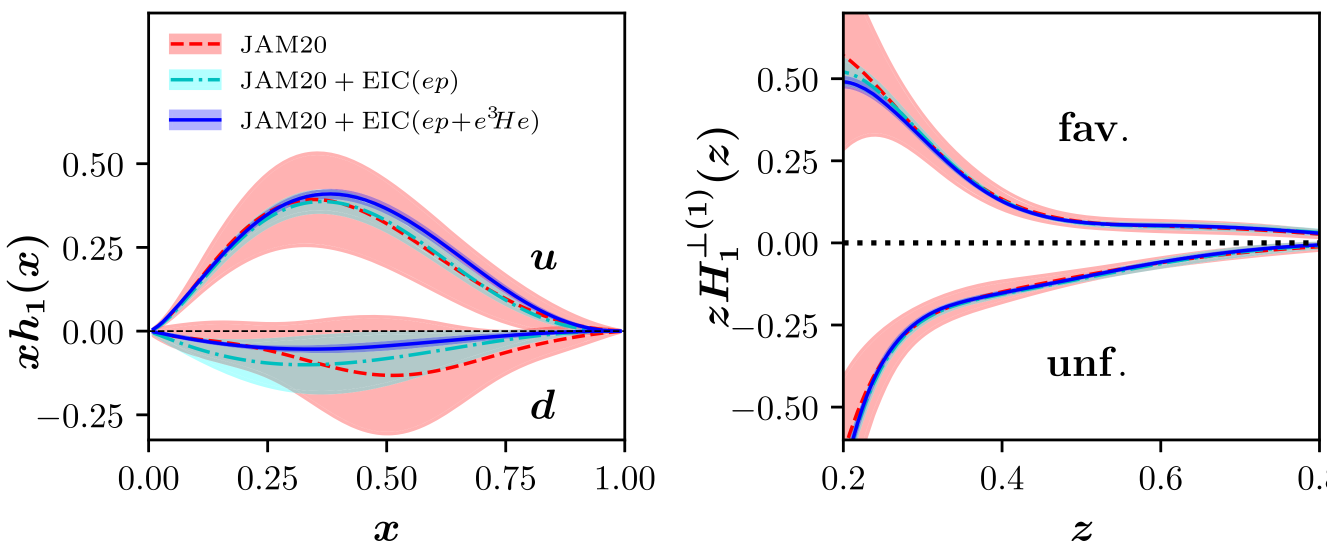
- Tensor charge is extensively studied on the lattice

Gupta et al, (18), Alexandrou et al., (19)

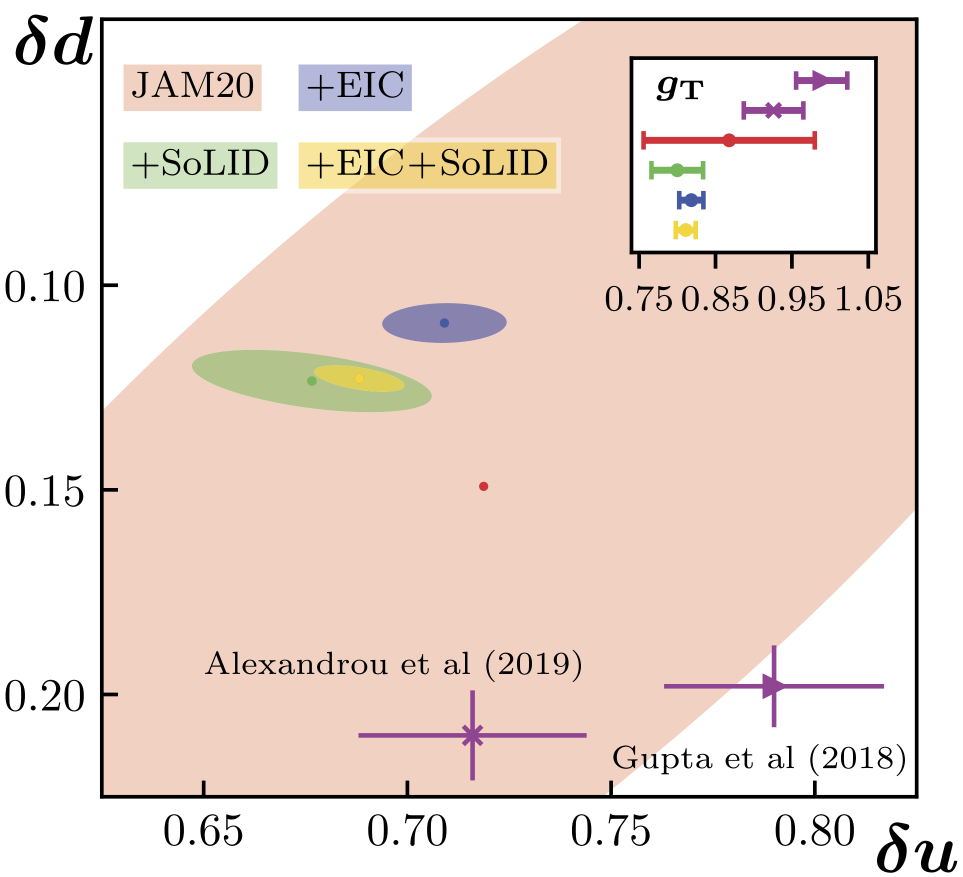


TENSOR CHARGE AT THE EIC AND JLAB

L. Gamberg, Z. Kang, D. Pitonyak, A. Prokudin, N. Sato Phys.Lett.B 816 (2021)

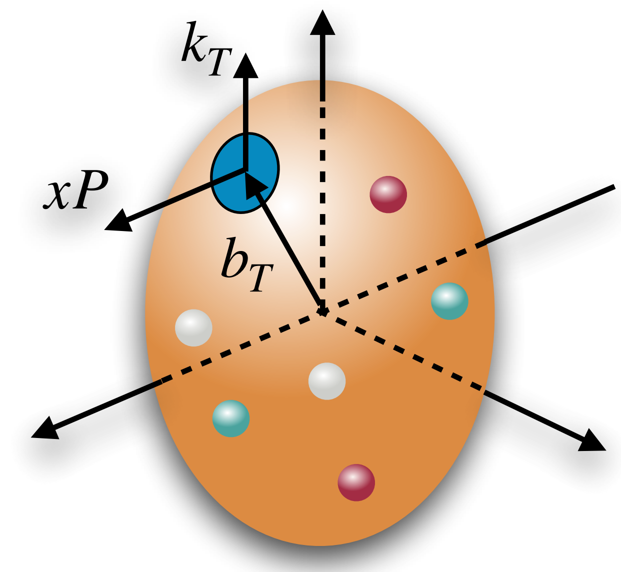


JAM20: Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato, Phys.Rev.D 102 (2020)



- EIC data will allow to have g_T extraction at the precision at the level of lattice QCD calculations
- JLab 12 data will allow to have complementary information on tensor charge to test the consistency of the extraction and expand the kinematical region

WIGNER DISTRIBUTIONS AND THE SPIN



- Wigner distributions have information on both position and motion

$$W(x,\vec{k},\vec{b}) = \int \frac{dz^- d\vec{z}}{2(2\pi)^3} \int \frac{d\vec{\Delta}}{(2\pi)^2}\, e^{ixP^+z^- - i\vec{k}\cdot\vec{z}} \langle P'S|\bar{\psi}(\vec{b}-\vec{z}/2)\gamma^+\psi(\vec{b}+\vec{z}/2)|PS\rangle$$

- The most intuitive definition of OAM involves Wigner functions

$$L_z = \int dx d^2\vec{b} d^2\vec{k} (\vec{b}\times\vec{k})_z W(x,\vec{b},\vec{k})$$

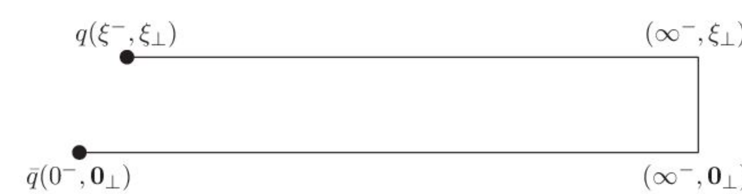
C. Lorcé, B. Pasquini, Phys. Rev. D 84, (2011)
C. Lorcé, B. Pasquini, X. Xiong and F. Yuan, Phys. Rev. D 85, (2012)

- The gauge link makes this definition gauge invariant and the two choices:

Straight link - kinetic OAM, Ji: L_q X. Ji, X. Xiong and F. Yuan, Phys. Rev. D 88, no. 1, (2013)

Y. Hatta, PLB 708 (2012) 186

Stapple-like link - canonical OAM, Jaffe-Manohar: $\mathcal{L}_q$



- The difference between the two $\mathcal{L}_q - L_q$ is related to the torque force experienced by the struck quark and generated by the final state interactions M. Burkardt, Phys. Rev. D 88 (2013)

- How to fully access Wigner distributions in experiments is still to be explored

CONCLUSIONS

- There has been a lot of progress in understanding of the spin in the last decades
- Spin studies are synergistic with many other areas, in particular with lattice QCD
- The EIC is going to have a huge impact on our understanding of the sea quarks and gluons, the spin, and the multi-dimensional nucleon structure
- In this talk I concentrated on the spin of the nucleon. Equally exiting and interesting discussion is about the spin 1 systems such as deuteron
- In preparation of the talk I benefited a lot from discussions with my colleagues: Martha Constantinou, Cedric Lorce, Yoshitaka Hatta, Daniel Pitonyak, and Yuri Kovchegov