Yellow Report Science Results and Analysis

(Andreas Metz, Temple University)

- Introduction
- Pillars of EIC science program
  - nucleon spin
  - nucleon mass
  - multi-dimensional parton structure
  - gluon saturation
- Some further important (new) topics
  - transversity distribution and tensor charge
  - DIS structure function g_T and multi-parton correlations
- Concluding remarks

supported by the NSF

YR Initiative: Overview

- Main goals:
  - Specify detector requirements $\longrightarrow$ task of PWG
  - How can detector requirements be met ? $\longrightarrow$ task of DWG (talk by Kenneth Barish)

- "By-product:"
  - Update EIC science case $\longrightarrow$ done by PWG

- Organizational Structure of PWG: 5 subgroups
  - Inclusive reactions
  - Semi-inclusive reactions
  - Jets and heavy quarks
  - Exclusive reactions
  - Diffractive reactions and forward tagging

- Some parameters for impact studies of PWG
  - mostly used following beam energies and species

p-e	275 on 18 GeV	100 on 10 GeV	100 on 5 GeV	41 on 5 GeV
d/^{3}He/^{4}He-e	110 on 18 GeV	110 on 10 GeV		41 on 5 GeV
C/^{40}Ca/Cu-e	110 on 18 GeV	110 on 10 GeV		41 on 5 GeV
Au-e	110 on 18 GeV	110 on 10 GeV		41 on 5 GeV

  - mostly used following integrated luminosities

$$\mathcal{L} = 10\,\mathrm{fb}^{-1} \qquad\qquad \mathcal{L} = 100\,\mathrm{fb}^{-1}$$

EIC Topics from YR Outline

7. The EIC Measurements and Studies

7.1 Global Properties and Parton Structure of Hadrons

- 7.1.1 Unpolarized parton structure of the proton and neutron
- 7.1.2 Spin structure of the proton and neutron
- 7.1.3 Parton structure of mesons
- 7.1.4 Origin of the mass of the nucleon and mesons
- 7.1.5 Multi-parton correlations
- 7.1.6 Inclusive diffraction and rapidity gap physics
- 7.1.7 Global event shapes and the strong coupling constant

7.2 Multi-Dimensional Imaging of Nucleons, Nuclei and Mesons

- 7.2.1 Nucleon and meson form factors
- 7.2.2 Imaging of quarks and gluons in position space
- 7.2.3 Imaging of quarks and gluons in momentum space
- 7.2.4 Wigner functions
- 7.2.5 Light (polarized) nuclei

7.3 The Nucleus: A Laboratory for QCD

- 7.3.1 High parton densities and saturation
- 7.3.2 Diffraction
- 7.3.3 Nuclear PDFs
- 7.3.4 Particle propagation through matter and transport properties of nuclei
- 7.3.5 Collective effects
- 7.3.6 Special opportunities with jets and heavy quarks
- 7.3.7 Short-range correlations, origin of nuclear force
- 7.3.8 Structure of light nuclei
- 7.3.9 Coherent and incoherent photoproduction on heavy targets

7.4 Understanding Hadronization

- 7.4.1 Hadronization in the vacuum
- 7.4.2 Hadronization in the nuclear environment
- 7.4.3 Particle production for identified hadron species
- 7.4.4 Production mechanism for quarkonia and exotic states
- 7.4.5 New particle production mechanisms
- 7.4.6 Spectroscopy

7.5 Connections with Other Fields

7.5.1 Electro-weak and BSM physics

7.5.2 Neutrino physics

7.5.3 Cosmic ray/astro-particle physics

7.5.4 Other connections to pp, pA, AA

7.5.5 Connections with HEP and Snowmass Process

7.6 Related Theory Efforts

7.6.1 Lattice QCD

7.6.2 Radiative corrections at the EIC

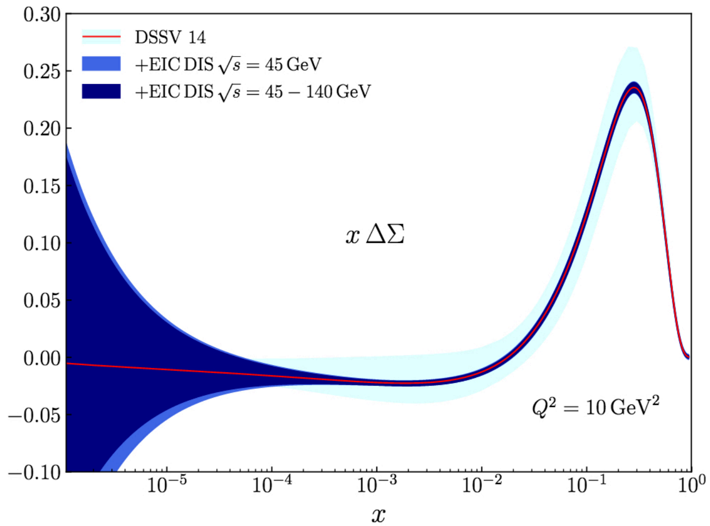
- Many interesting important topics
- Several topics have received little attention so far
- Details of detector requirements discussed in separate chapter (Chapter 8)
- For some topics dependence on $\sqrt{s}$ was studied in detail
  (see some of shorter presentations later)

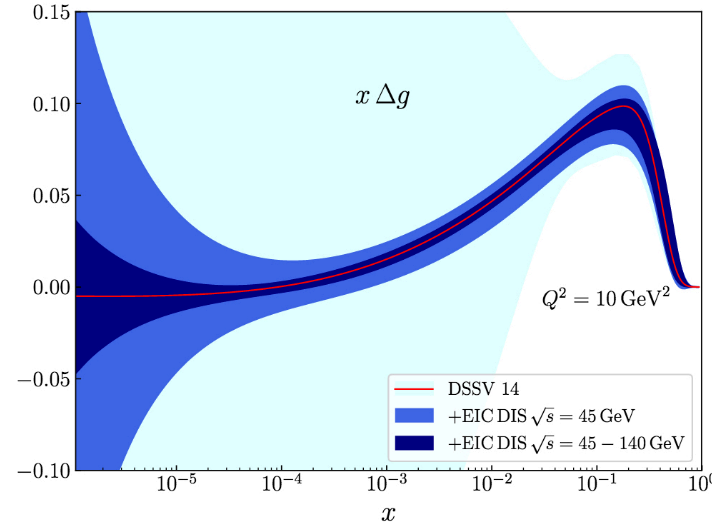
Nucleon Spin

- Spin sum rule (Jaffe, Manohar, 1989)

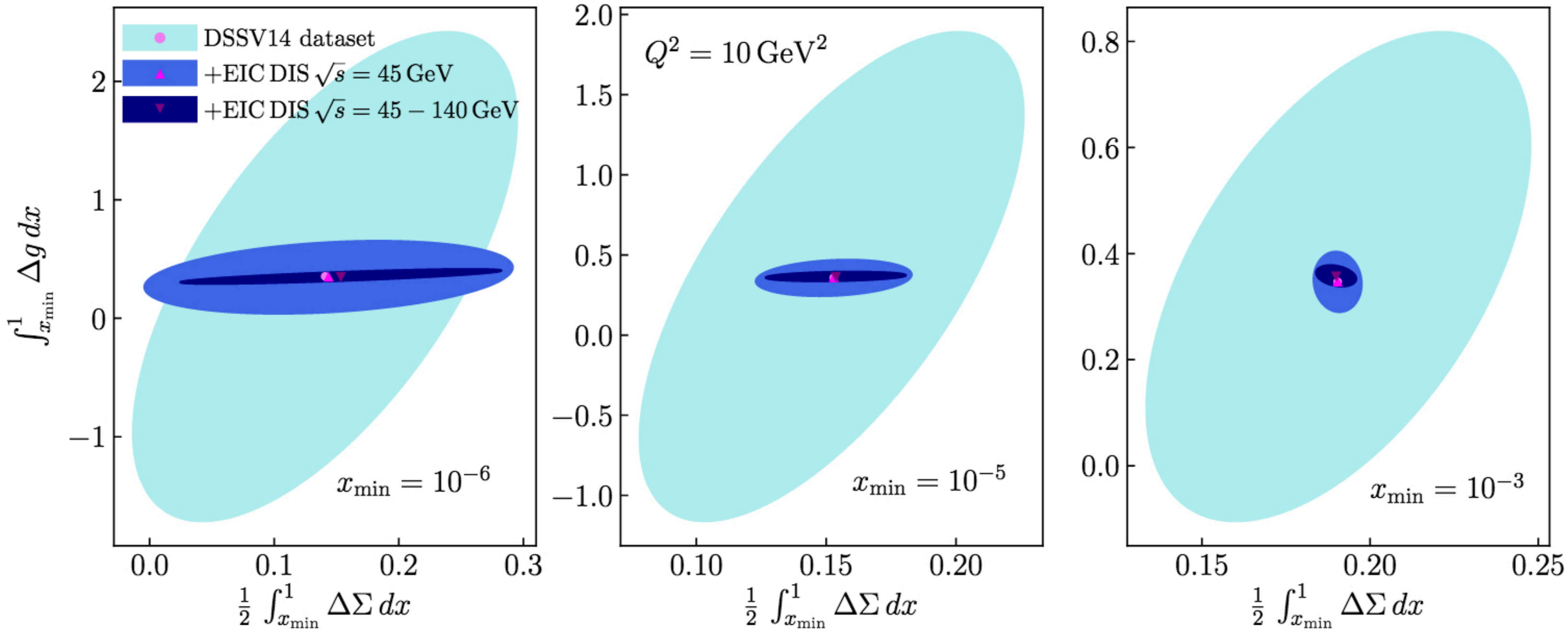
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

- EIC impact study (Aschenauer, Borsa, Lucero, Nunes, Sassot, 2020)
  - EIC pseudo data for inclusive and semi-inclusive DIS (for flavor separation)





  - study suggests remarkable constraints on helicity distributions in x-range 10^{-4} – 10^{-1}
  - large uncertainties below $x \sim 10^{-4}$ (beyond reach of EIC)



- significant uncertainties in helicity contributions to spin sum rule remain
- small-x behavior of helicity distributions crucial
  (Kovchegov, Pitonyak, Sievert, 2015 / ...)

• Related EIC impact study by JAM Collaboration

Nucleon Mass

- Forward matrix element of total QCD energy momentum tensor (EMT)

$$\langle\, T^{\mu\nu}\,\rangle \equiv \langle P|\, T^{\mu\nu}\,|P\rangle = 2P^{\mu}P^{\nu}$$

  - $\langle\, T^{\mu}{}_{\mu}\,\rangle$ and $\langle\, T^{00}\,\rangle$ related to nucleon mass: $\langle\, T^{\mu}{}_{\mu}\,\rangle = \langle\, T^{00}\,\rangle\big|_{\vec{P}=0} = 2M^2$
  - most mass sum rules in literature based on decomposition of $\langle\, T^{\mu}{}_{\mu}\,\rangle$ or $\langle\, T^{00}\,\rangle$ into quark and gluon parts
    (Ji, 1994 / Lorcé, 2017 / Hatta, Rajan, Tanaka, 2018 / Metz, Pasquini, Rodini, 2020)

- Trace anomaly
  (Adler, Collins, Duncan, 1977 / Nielsen, 1977 / Collins, Duncan, Joglekar, 1977 / ...)

$$T^{\mu}{}_{\mu} = (m\bar{\psi}\psi)_R + \gamma_m\,(m\bar{\psi}\psi)_R + \frac{\beta}{2g}(F^{\alpha\beta}F_{\alpha\beta})_R$$

  - anomalous term of operator for EMT trace due to quantum effects
  - what is role of trace anomaly for the nucleon mass ?
  - measurement of trace anomaly needed for phenomenology of mass sum rule ?

- EMT for individual partons

$$\langle P|\, T^{\mu\nu}_{q,g}\, |P\rangle = 2P^\mu P^\nu\, A_{q,g}(0) + 2M^2 g^{\mu\nu}\, \bar{C}_{q,g}(0)$$

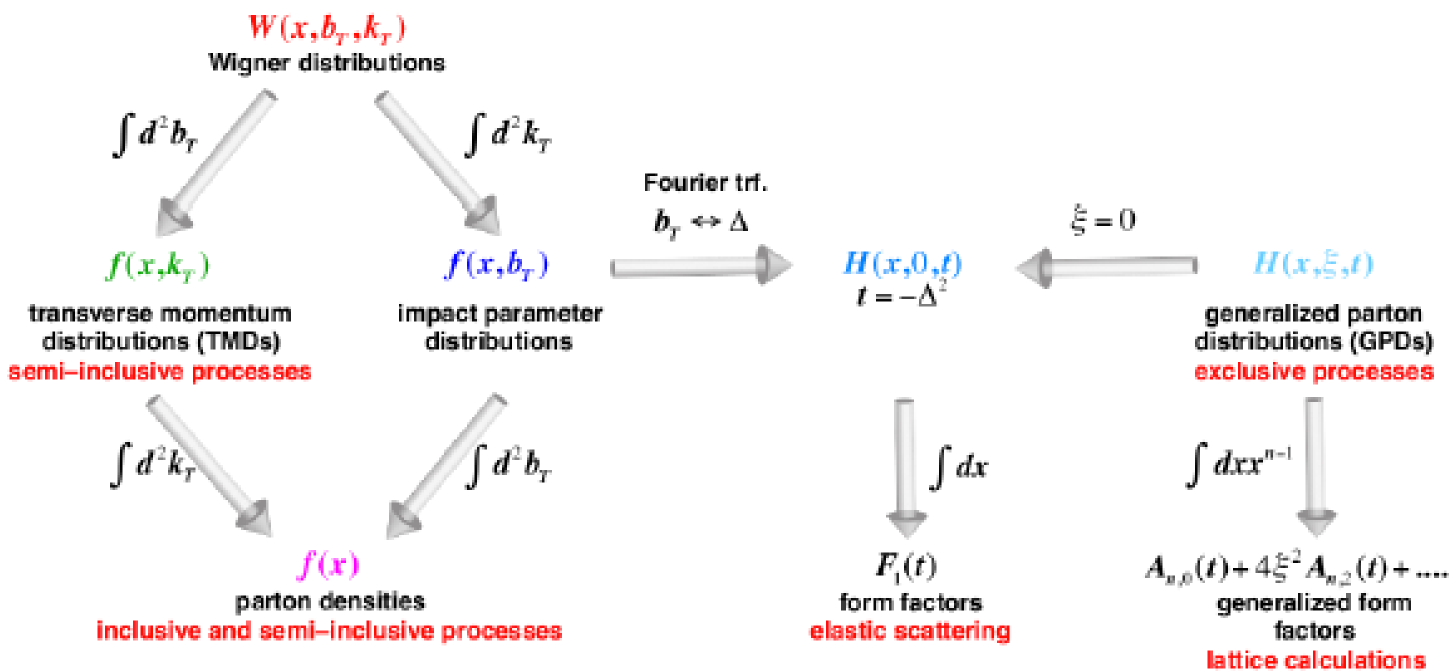
  - conservation of EMT implies

$$A_q(0) + A_g(0) = 1 \qquad\qquad \bar{C}_q(0) + \bar{C}_g(0) = 0$$

  - any mass decomposition has at most two independent terms
    (Lorcé, 2017 / Metz, Pasquini, Rodini, 2020)
  - measurement of trace anomaly needed if constraints of EMT form factors not used

- What is relation to EIC physics ?
  - threshold production of quarkonium could provide direct input for trace anomaly
  - many (recent) studies of this interesting topic
    (Kharzeev, 1996 / Hatta, Yang, 2018 / Mamo, Zahed, 2019 / Boussarie, Hatta, 2020 / Gryniuk, Joosten, Meziani, Vanderhaeghen, 2020 / ...)

Multi-Dimensional Parton Structure of Hadrons



(arXiv:1212.1701)

- Main objects of interest for multi-dimensional imaging
  1. $W(x, \vec{b}_T, \vec{k}_T)$ Wigner distributions (5-D quasi-probability distributions)
  2. $f(x, \vec{b}_T)$ GPDs (in impact parameter space)
  3. $f(x, \vec{k}_T)$ TMDs
- Since EIC White Paper, significant progress concerning measuring Wigner distributions (Hatta, Xiao, Yuan, 2016 / Altinoluk, Armesto, Beuf, Rezaeian, 2015 / ...)

Generalized Parton Distributions

- Main motivations (see also talk by Cédric Mezrag)
  - impact parameter distributions (Burkardt, 2000 / ...)

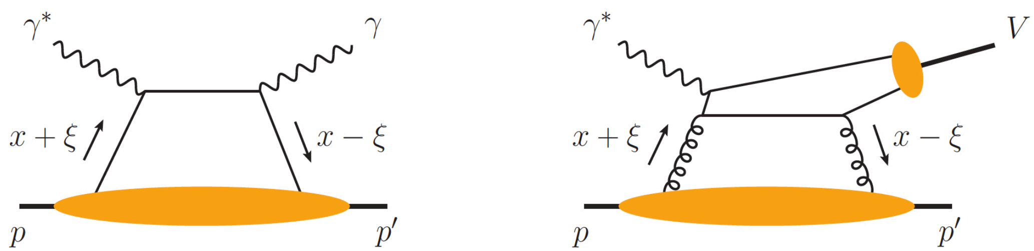
$$f(x, \vec{b}_T) \overset{\mathcal{F.T.}}{\longleftrightarrow} \mathrm{GPD}(x, \xi = 0, \vec{\Delta}_T)$$

  - spin sum rule and orbital angular momentum (Ji, 1996)

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

  - pressure distribution inside nucleon (Polyakov, Shuvaev, 2002 / ...)

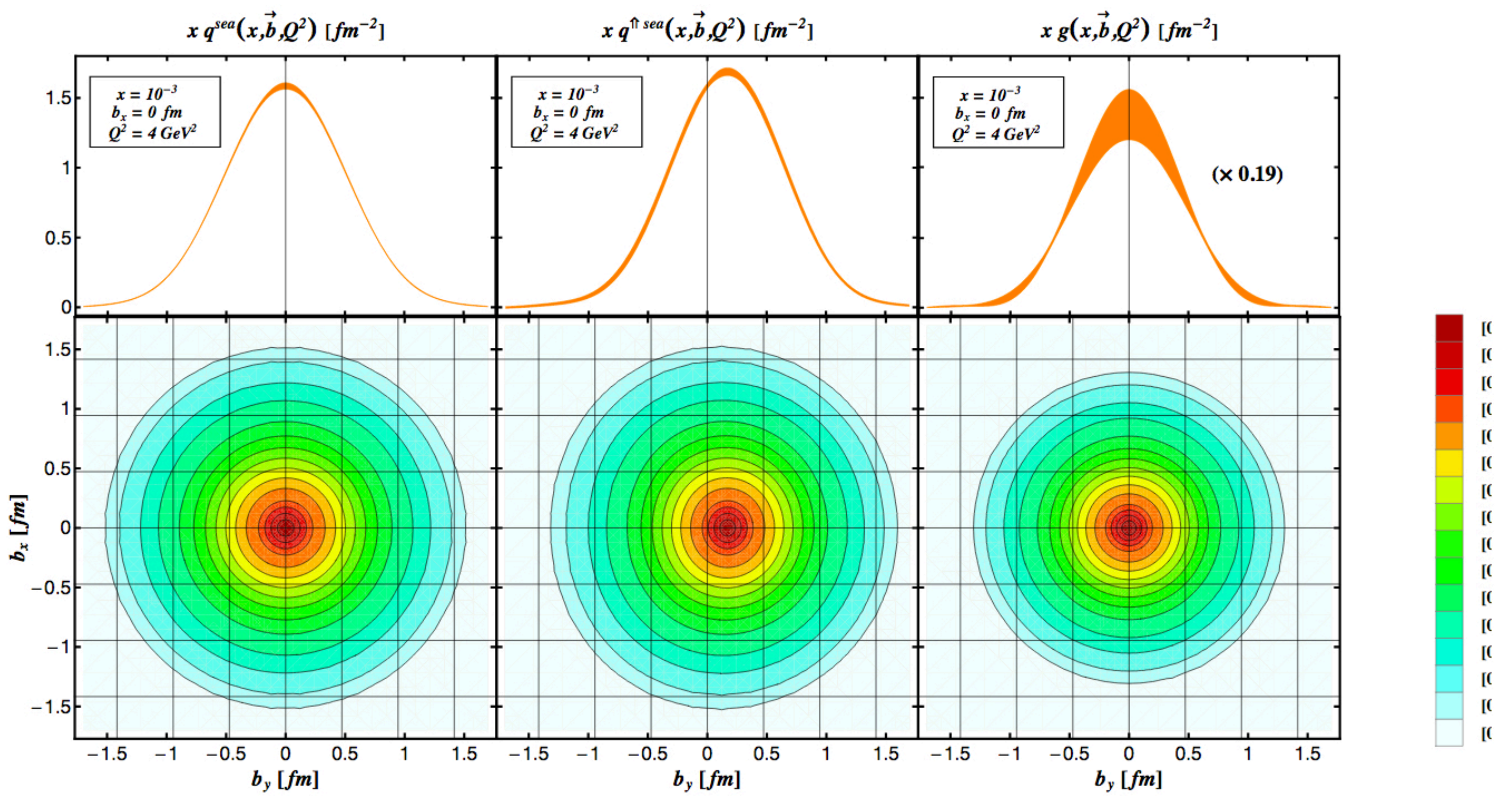
- Important observables for EIC: DVCS and HEMP



(arXiv:1212.1701)

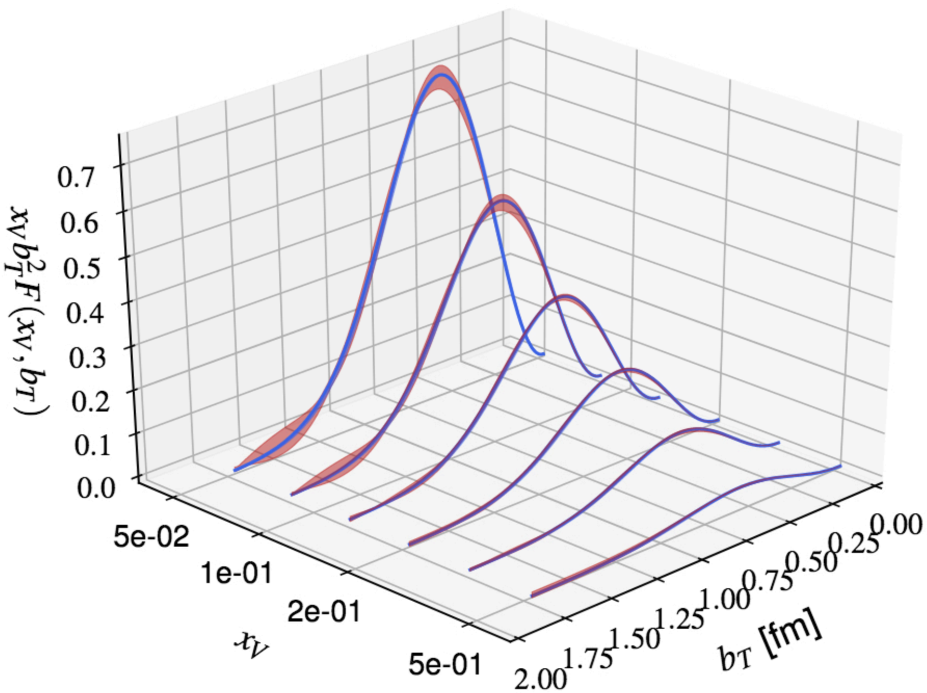
  - DVCS theoretically well under control
  - Higher-order corrections for HEMP can be large
    (Ivanov, Schäfer, Szymanowski, Krasnikov, 2004 / Diehl, Kugler, 2007 / ...)
  - Υ production may also become important channel (for gluons)

- Simultaneous fit of HERA data and EIC pseudo data for DVCS
  (Aschenauer, Fazio, Kumerički, Müller, 2013)



  - focus on sea quarks (including transverse target polarization, E_q) and gluons
  - study suggests remarkable prospects
  - model-independent extraction of impact parameter distributions challenging
  - HEMP will provide further constraints

- Study for Υ production (Joosten, Meziani, 2018)



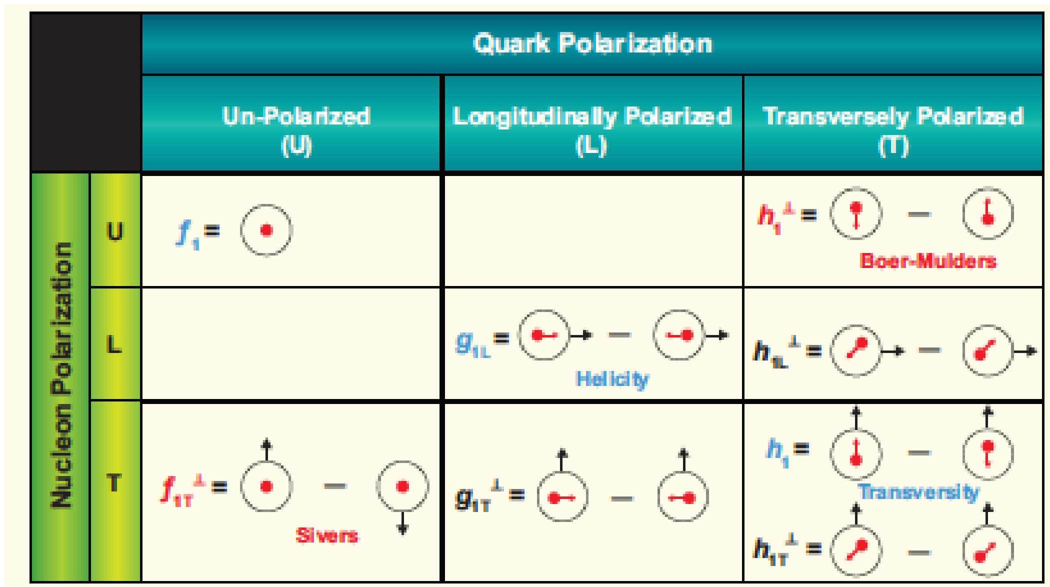
$$x_V = \frac{Q^2 + M_V^2}{2P \cdot q}$$

$$M_\Upsilon^2 \approx 89.5\,\mathrm{GeV}^2$$

  - study for $89.5\,\mathrm{GeV}^2 \leq Q^2 + M_\Upsilon^2 \leq 91\,\mathrm{GeV}^2$ and $\mathcal{L} = 100\,\mathrm{fb}^{-1}$
  - small errors for transverse profiles

Transverse Momentum Dependent Parton Distributions

- Confinement implies (intrinsic) transverse momentum $\rightarrow$ confined motion
- Overview of leading-twist quark TMDs



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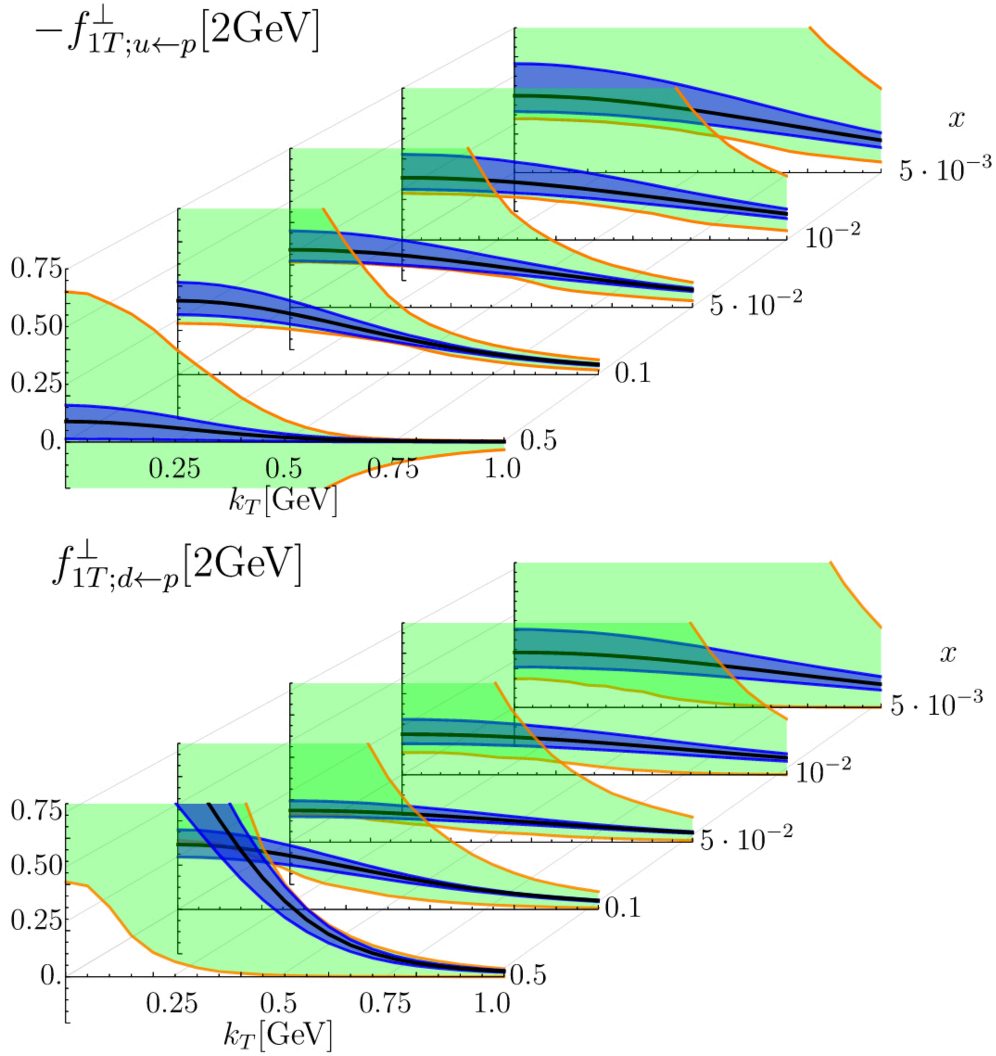
- Important observables for EIC (see also talk by Feng Yuan)
  - semi-inclusive DIS: $\ell\, N \rightarrow \ell\, h\, X\,,\quad \ell\, A \rightarrow \ell\, h\, X$
  - jet production: $\ell\, N \rightarrow \ell\, \text{jet}\, X\,,\quad \ell\, A \rightarrow \ell\, \text{jet}\, X$
  - hadron inside jet: $\ell\, N \rightarrow \ell\, (h, \text{jet})\, X\,,\quad \ell\, A \rightarrow \ell\, (h, \text{jet})\, X$
- Significant recent theory advances related to jet production for TMD studies (Liu, Ringer, Vogelsang, Yuan, 2018 / ...)

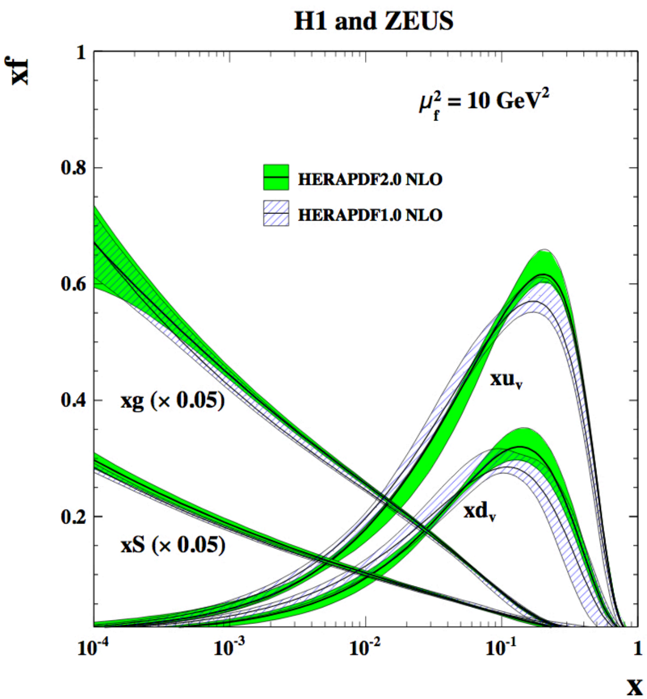
- Example: EIC impact study for Sivers function $f_{1T}^{\perp}$
  (Bury, Prokudin, Vladimirov, 2020 / ...)

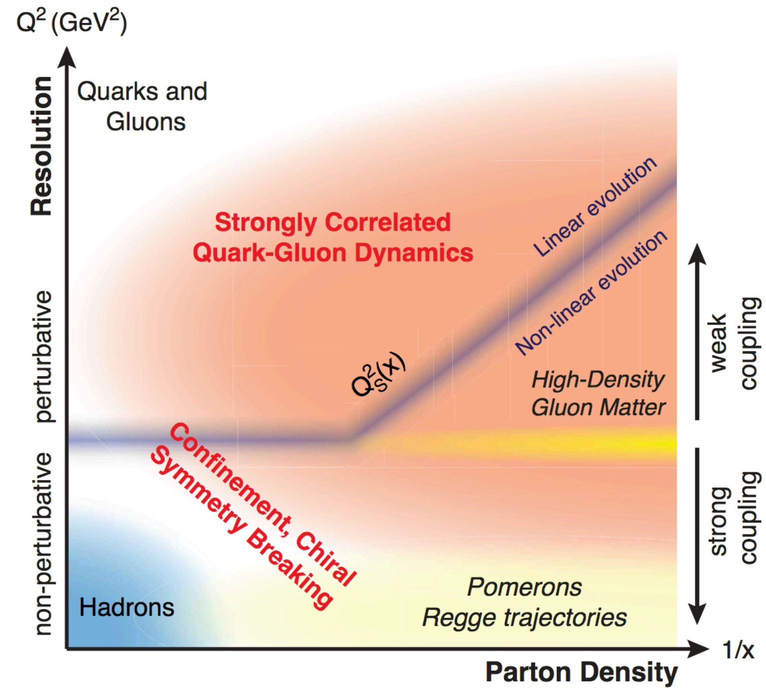


  - current uncertainty of Sivers function somewhat under debate, but definitely large
  - study suggests remarkable prospects

Gluon Saturation

- Basic idea and big picture

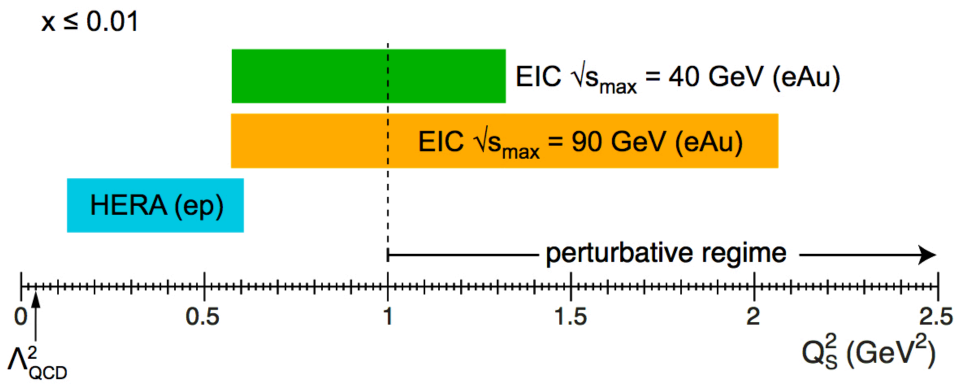




(arXiv:1708.01527)

  - gluon distribution cannot keep rising forever when going to lower x
  - gluons split $(g \to gg)$ and, once density gets too large, re-combine $(gg \to g)$
  - saturation is expected to start at certain x, below (saturation) scale $Q_s^2(x)$
  - new state of high-density gluon matter (color glass condensate)

- Advantage of eA over ep collisions: $Q_s^2 \sim A^{1/3}$



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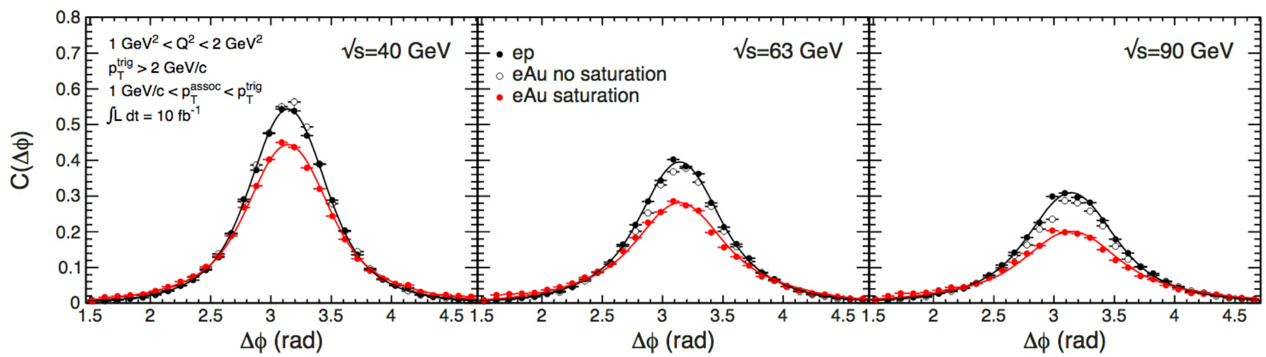
- Key observable 1: di-hadron correlations in eA collisions



(arXiv:1708.01527)

  - saturation leads to suppression of back-to-back di-hadron correlations
  - di-hadron correlations in ep vs eA (relative effect increases as $\sqrt{s}$ increases)

- Key observable 2: diffractive scattering
  - cross sections depend on square of gluon distribution

Transversity Distribution and Tensor Charge

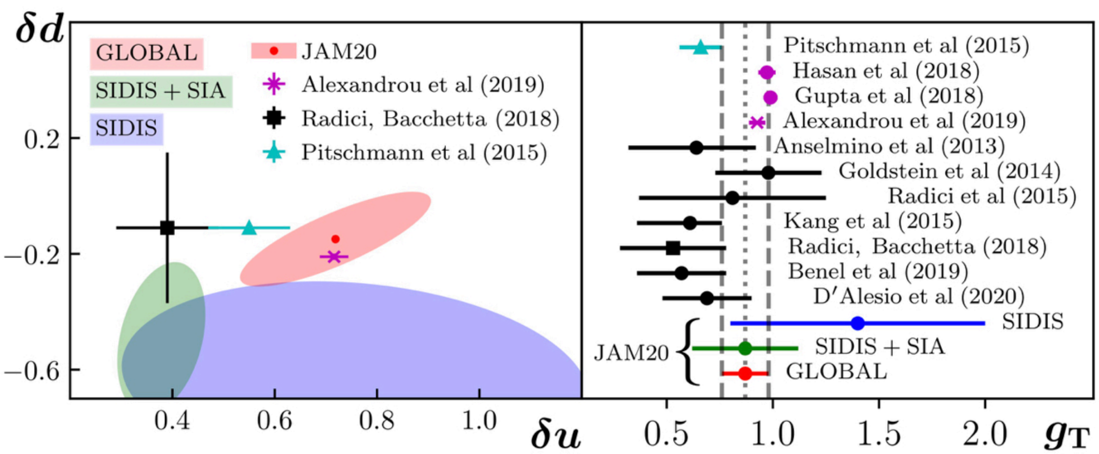
- Transversity $h_1(x)$ is key quantity characterizing nucleon spin structure
- Tensor charge

$$\delta q = \int_0^1 dx \left(h_1^q(x) - h_1^{\bar{q}}(x)\right) \qquad g_T = \delta u - \delta d$$

- Tensor charge from global analysis (at scale $\mu = 2\,\mathrm{GeV}$)

(Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato, 2020)

(courtesy by D. Pitonyak)



$$\text{SIDIS} \to (\text{SIDIS} + \text{SIA}) \to \text{GLOBAL}: \boldsymbol{g_T} = 1.4(6) \to 0.87(25) \to \mathbf{0.87(11)}$$

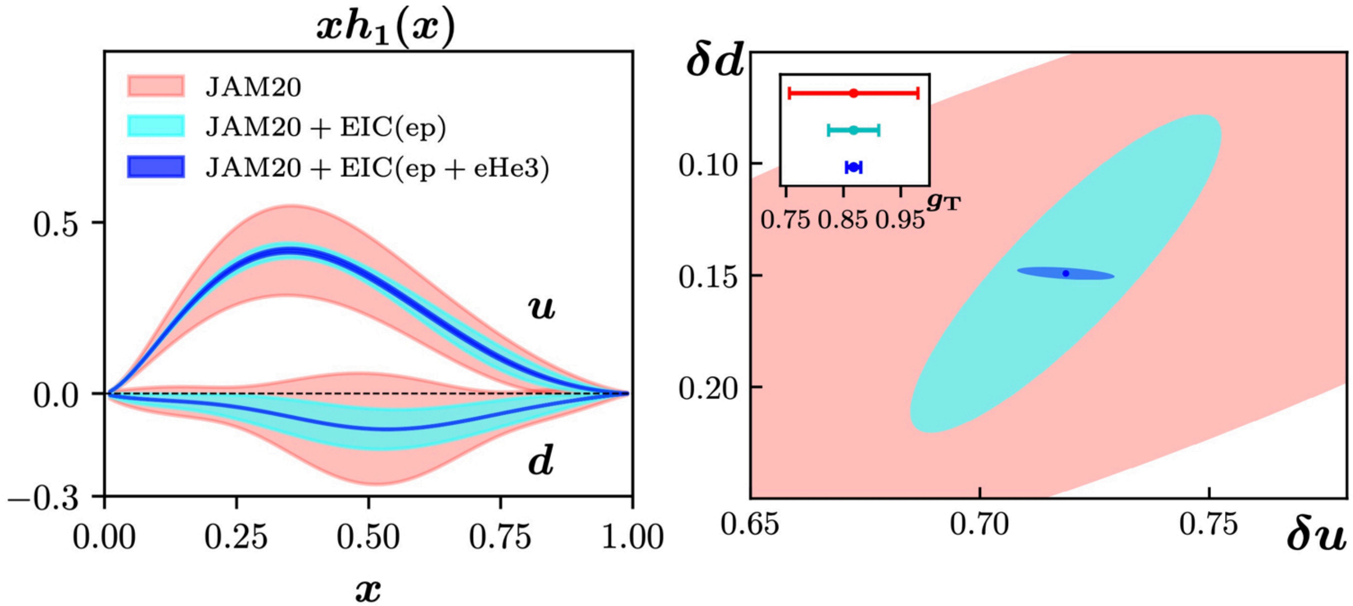
- This is the most precise phenomenological determination of g_T to date

- Our tensor charges, especially δu, show excellent agreement with lattice:
  $\delta u = 0.72(19),\ \delta d = -0.15(16)$

- EIC impact study

  (Pitonyak, Seidl, Gamberg, Kang, Prokudin, Sato, work in progress)

(courtesy by D. Pitonyak)



JAM20	JAM20+EIC(ep)	JAM20+EIC(ep+eHe3)
$\delta u = 0.72 \pm 0.19$	$\delta u = 0.719 \pm 0.034$	$\delta u = 0.719 \pm 0.011$
$\delta d = -0.15 \pm 0.16$	$\delta d = -0.149 \pm 0.071$	$\delta d = -0.149 \pm 0.003$
$g_T = 0.87 \pm 0.11$	$g_T = 0.869 \pm 0.044$	$g_T = 0.869 \pm 0.012$

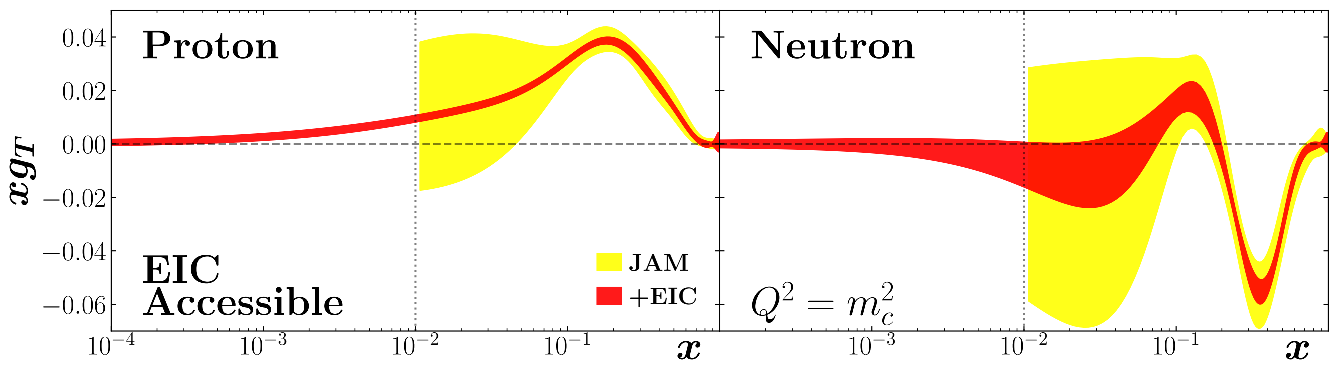
  - study suggests remarkable prospects
  - errors for g_T somewhat better than current lattice calculations

DIS Structure Function g_T and Multi-Parton Correlations

- Polarized DIS parameterized through two structure functions: $g_1(x, Q^2) \quad g_T(x, Q^2)$
- Wandzura-Wilczek approximation (Wandzura, Wilczek, 1977)

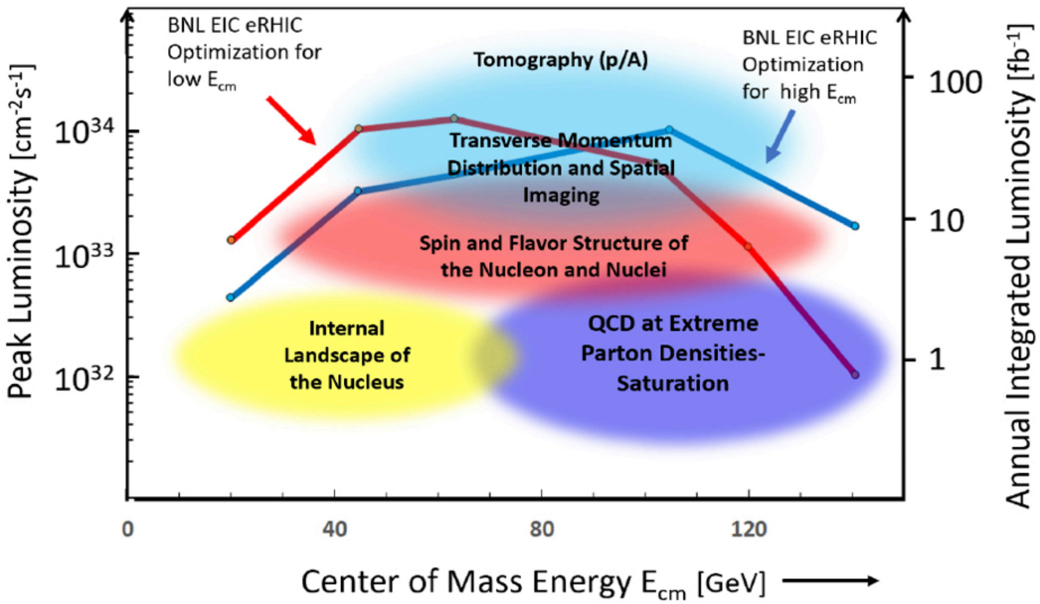
$$g_T = g_T^{\text{WW}} + g_T^{\text{twist-3}} \qquad\qquad g_T^{\text{WW}}(x) = \int_x^1 \frac{dy}{y}\, g_1(y)$$

- $g_T^{\text{twist-3}}$ gives information on quark-gluon-quark correlations (going beyond densities), also related to transverse force acting on quarks and Sivers effect (Burkardt, 2008)
- EIC impact study (Cocuzza, Gamberg, Melnitchouk, Metz, Pitonyak, Sato, ..., work in progress)



  - new fit of available data on g_T, and fit including EIC pseudodata
  - significant constraints in x-range 10^{-4} – 10^{-1}
  - study suggests remarkable prospects
  - $g_T^{\text{twist-3}}$ can likely be extracted over large x-range

Concluding Remarks



- Gluon saturation and spin sum rule studies require highest possible energies
- For many other topics largest possible energy range desirable
  - making connection with data from fixed-target experiments
  - making connection with collider data, exploring sea quarks and gluons
- High luminosity, over wide range of $\sqrt{s}$ very important for 3D imaging
- Further studies needed for detailed comparison between two IRs