EIC Cold QCD Future Physics Program

(Andreas Metz, Temple University)

- Introduction and overview of currently discussed topics

- 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
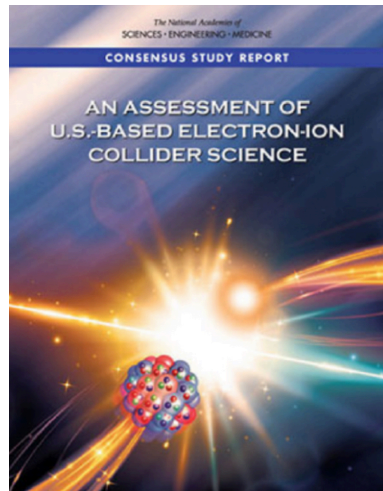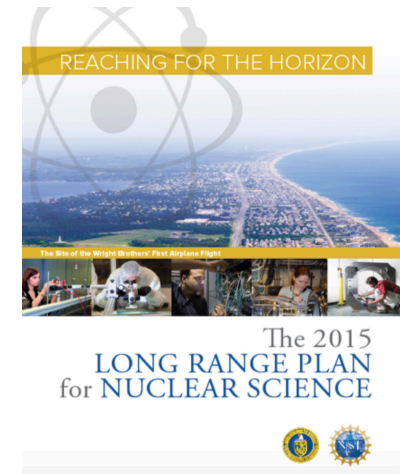 - Weak mixing angle

- Conclusions

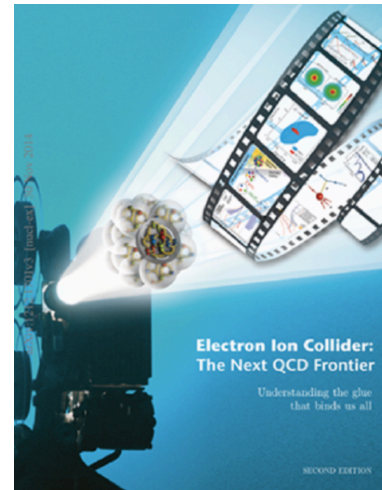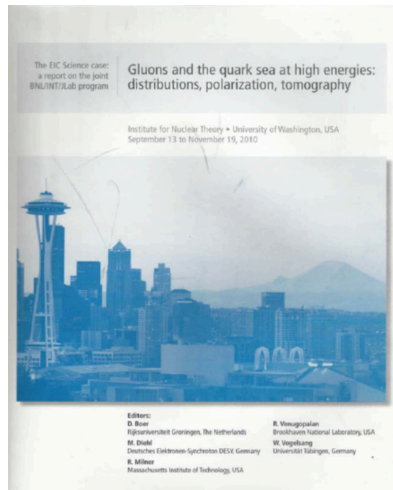Other EIC-talks: I. Vitev: *EIC HF Overview*
F. Ringer: *Jet measurements at the EIC*
Y. Furletova: *EIC Overview*

Key Initiatives and Documents

2018 NAS Report: "The committee finds that the science that can be addressed by an EIC is compelling, fundamental and timely."

EIC Topics from Current Yellow Report 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

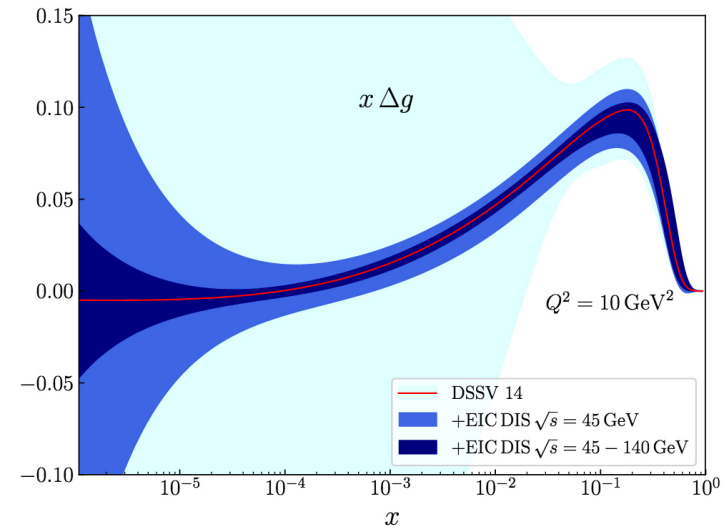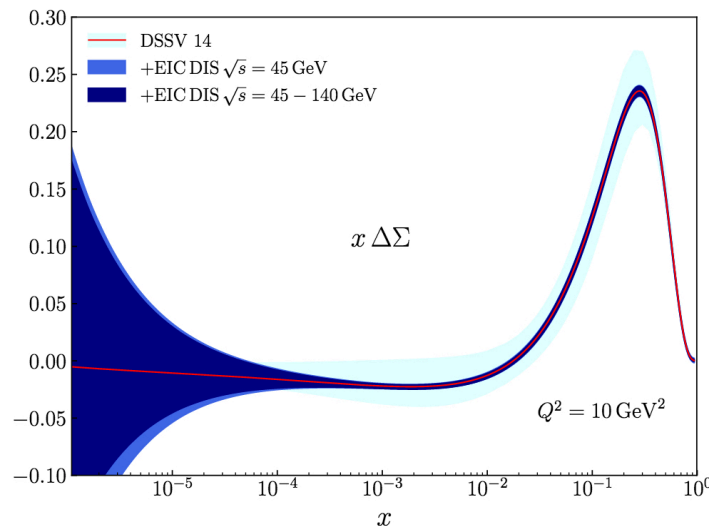### 7.6.2 Radiative corrections at the EIC

- Many interesting important topics

- Several topics have received little attention so far

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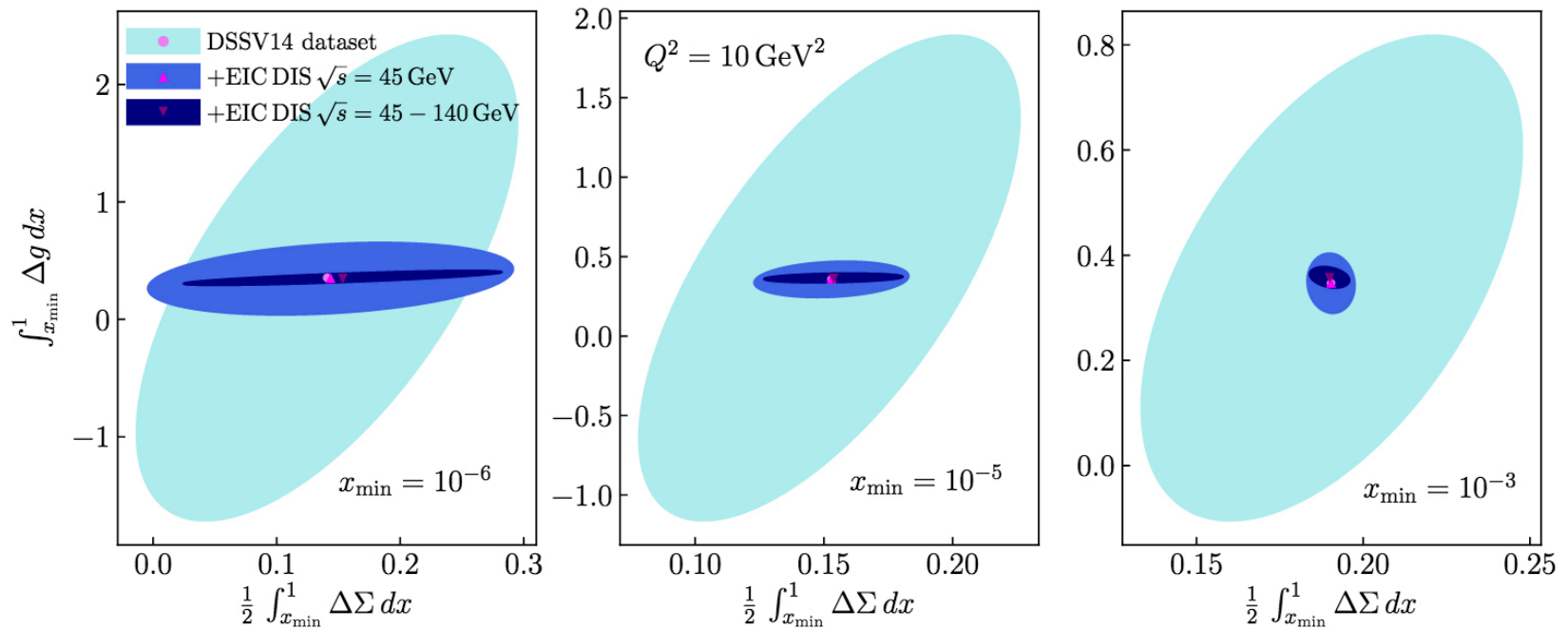
- significant uncertainties in helicity contributions to spin sum rule remain
- small-x behavior of helicity distributions crucial
  (Kovchegov, Pitonyak, Sievert, 2015 / ...)

- Related EIC impact study by JAM Collaboration ongoing

Nucleon Mass

- Forward matrix element of total QCD energy momentum tensor

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

  - both $\langle\, T^{\mu}{}_{\mu}\, \rangle$ and $\langle\, T^{00}\, \rangle$ related to nucleon mass
  - 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 ?

- Decomposition of T^{00} (Rodini, Metz, Pasquini, 2020 / Metz, Pasquini, Rodini, 2020)

$$\mathcal{H}_q = (\psi^\dagger \, i\boldsymbol{D} \cdot \boldsymbol{\alpha} \, \psi)_R \quad \text{quark kinetic plus potential energy}$$

$$\mathcal{H}_m = (m\bar{\psi}\psi)_R \qquad\qquad \text{quark mass term}$$

$$\mathcal{H}_g = \frac{1}{2}(E^2 + B^2)_R \quad \text{gluon energy}$$

  - 3 nontrivial terms (with 2 of them being independent)
  - no contribution from anomaly at operator level

- Comparison with first decomposition of T^{00} (Ji, 1994, 1995)

$$\left(\mathcal{H}_q\right)_{[\text{Ji}]} = (\psi^\dagger \, i\boldsymbol{D} \cdot \boldsymbol{\alpha} \, \psi)_R$$

$$\left(\mathcal{H}_m\right)_{[\text{Ji}]} = \frac{4 + \gamma_m}{4} (m\bar{\psi}\psi)_R$$

$$\left(\mathcal{H}_g\right)_{[\text{Ji}]} = \frac{1}{2}(E^2 + B^2)_R$$

$$\left(\mathcal{H}_a\right)_{[\text{Ji}]} = \frac{\beta}{8g}(F^{\alpha\beta}F_{\alpha\beta})_R$$

  - 4 nontrivial terms
  - sum rules differ by $\frac{1}{4}$ of trace anomaly at operator level

- Relation between matrix elements (Metz, Pasquini, Rodini, 2020)

$$\left\langle (\psi^\dagger \, i\boldsymbol{D}\cdot\boldsymbol{\alpha}\,\psi)_R + \frac{1}{2}(E^2 + B^2)_R \right\rangle = \left\langle \gamma_m (m\bar{\psi}\psi)_R + \frac{\beta}{2g}(F^{\alpha\beta}F_{\alpha\beta})_R \right\rangle$$

  - no corresponding relation at operator level
  - knowing trace anomaly means knowing contribution from parton energy to mass

- Phenomenology (Metz, Pasquini, Rodini, 2020)

$$\mathcal{H}_m \; 7.9\% \qquad \mathcal{H}_q \; 33.0\% \qquad \mathcal{H}_g \; 59.1\%$$

  - u, d, s quarks included in $\mathcal{H}_m$
  - heavier quarks contribute significantly to $\mathcal{H}_m$
  - phenomenology depends on renormalization scheme, but not $\mathcal{H}_m$
  - "Only 2% of proton mass due to Higgs mechanism" at variance with QCD

- 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
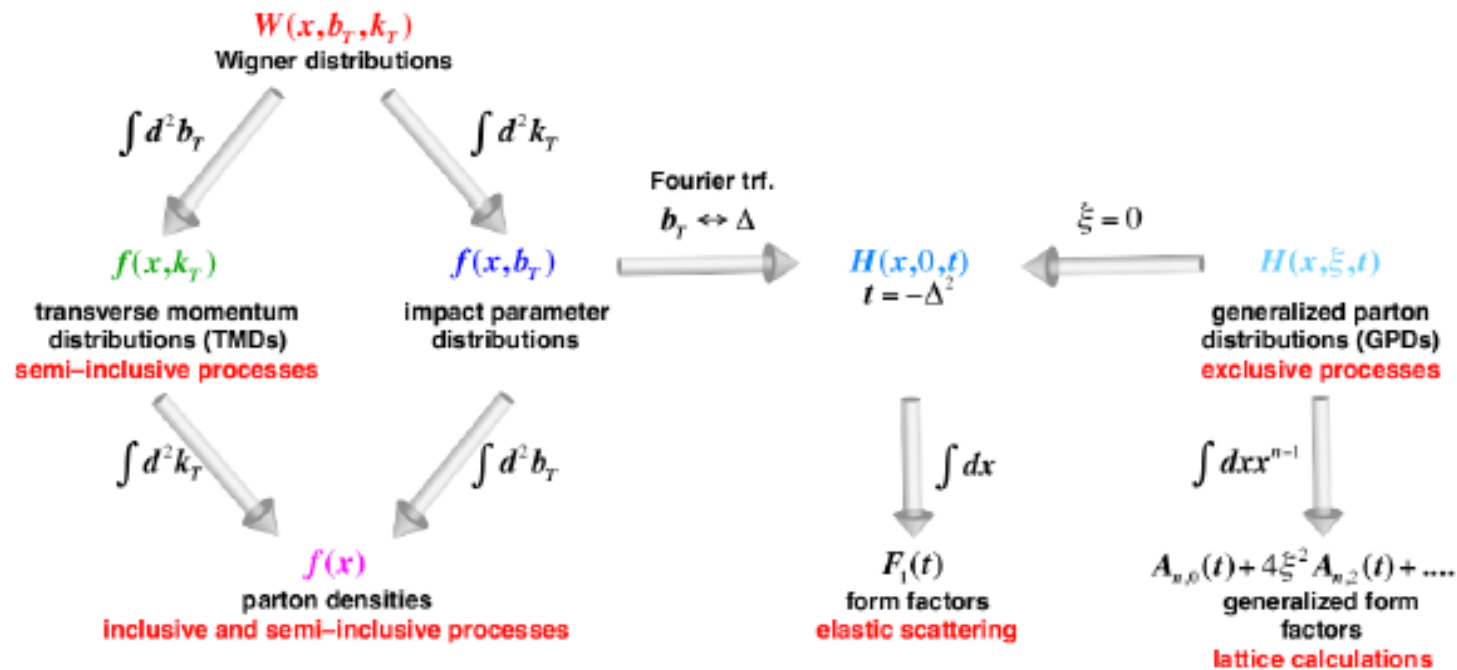
(arXiv:1212.1701)

- 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

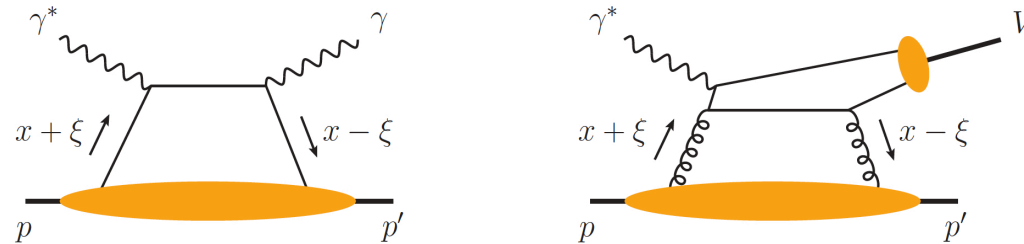 – impact parameter distributions (Burkardt, 2000 / ...)

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

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

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

  – 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)
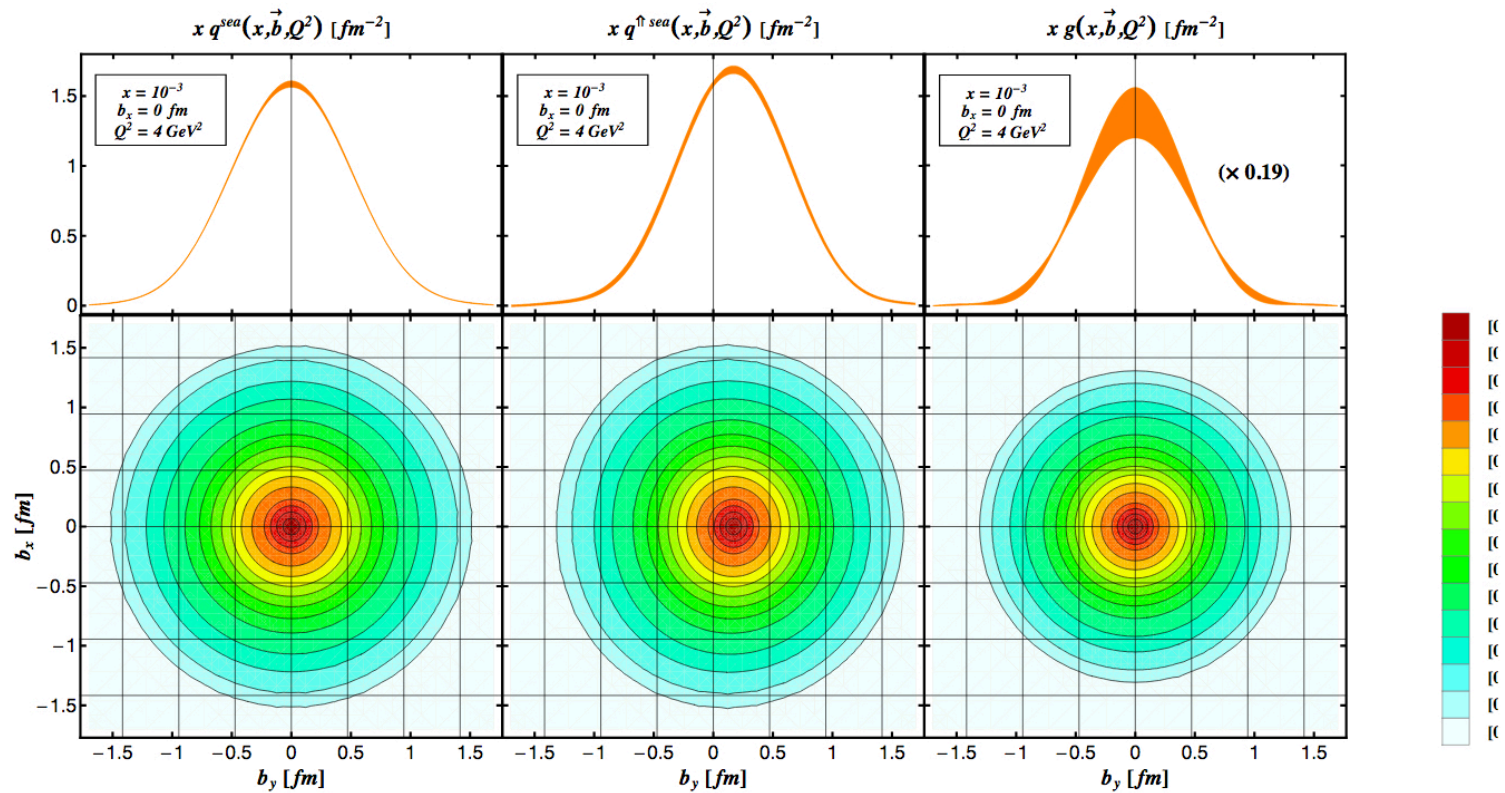
- focus on sea quarks (including transverse target polarization, E_q) and gluons

- study suggests remarkable prospects

- HEMP will provide further constraints

# Transverse Momentum Dependent Parton Distributions

- Confinement implies (intrinsic) transverse momentum $\rightarrow$ confined motion

- Overview of leading-twist quark TMDs

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$ ⊙		$h_1^\perp =$ ⊙ − ⊙ Boer-Mulders
	L		$g_{1L} =$ ⊙ − ⊙ Helicity	$h_{1L}^\perp =$ ⊙ − ⊙
	T	$f_{1T}^\perp =$ ⊙ − ⊙ Sivers	$g_{1T}^\perp =$ ⊙ − ⊙	$h_1 =$ ⊙ − ⊙ Transversity $h_{1T}^\perp =$ ⊙ − ⊙

(arXiv:1212.1701)

- Important observables for EIC
  - semi-inclusive DIS: $\ell\, N \rightarrow \ell\, h\, X\, , \quad \ell\, A \rightarrow \ell\, h\, X$
  - jet production: $\ell\, N \rightarrow \ell\, \mathrm{jet}\, X\, , \quad \ell\, A \rightarrow \ell\, \mathrm{jet}\, X$
  - hadron inside jet: $\ell\, N \rightarrow \ell\, (h, \mathrm{jet})\, X\, , \quad \ell\, A \rightarrow \ell\, (h, \mathrm{jet})\, X$

- Significant recent theory advances related to jet production for TMD studies
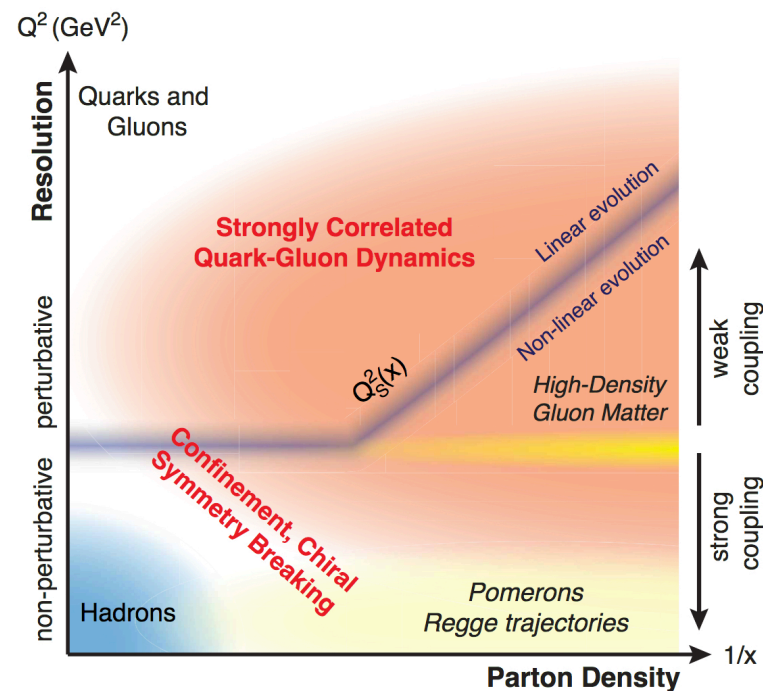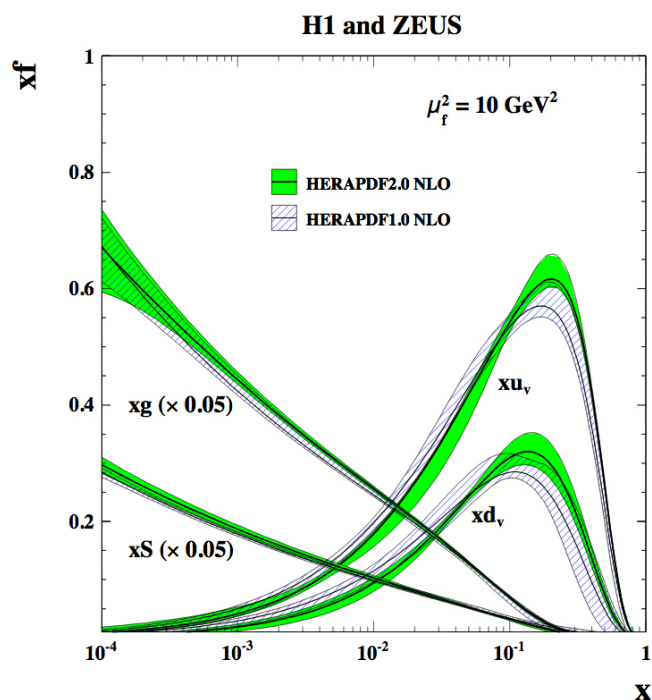 (Liu, Ringer, Vogelsang, Yuan, 2018 / ...)

- Example: EIC impact study for Sivers function $f_{1T}^{\perp}$

  (Vladimirov, Seidl, Bury, Prokudin, ..., work in progress)
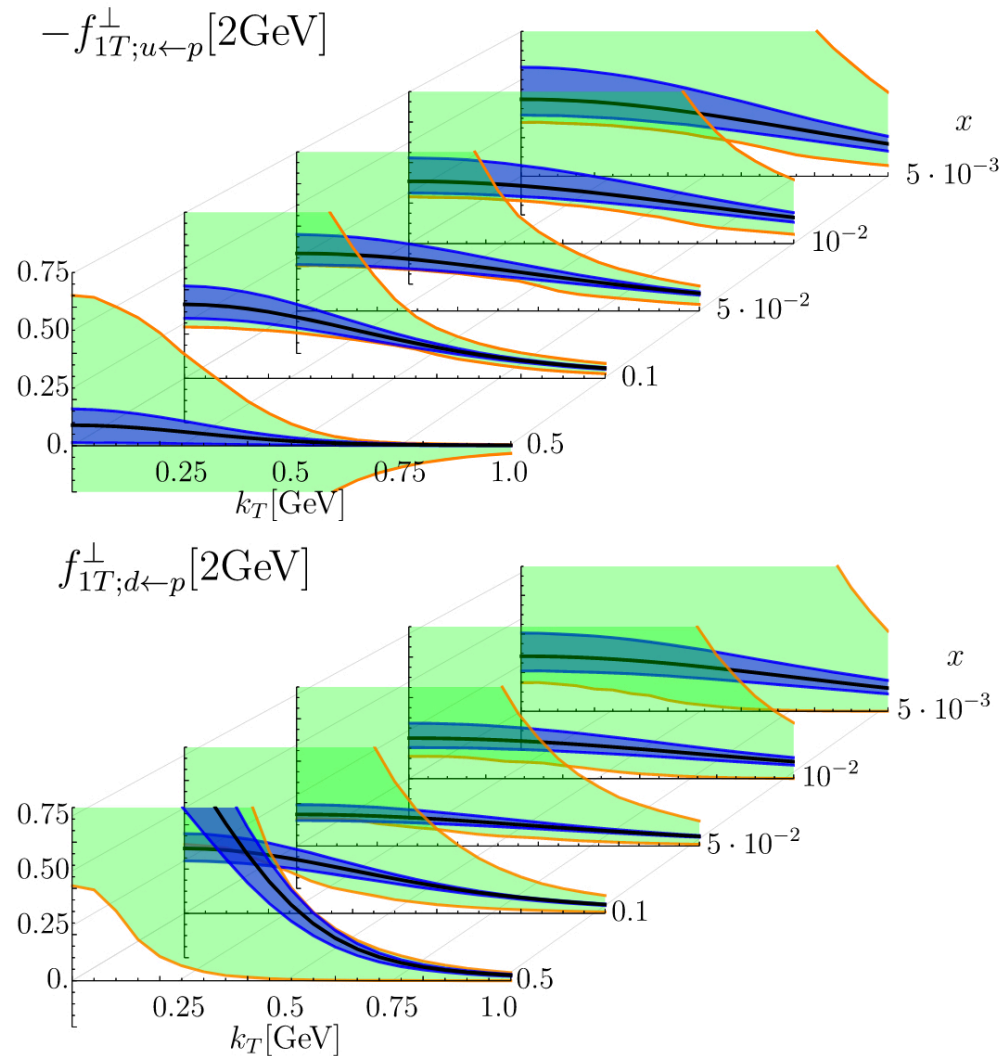
  - current uncertainty of Sivers function somewhat under debate, but definitely large
 - study suggests remarkable prospects

Gluon Saturation

- Basic idea and big picture

(arXiv:1708.01527)

- – gluon distribution cannot keep rising forever when going to lower x
- – gluons split $(g \rightarrow gg)$ and, once density gets too large, re-combine $(gg \rightarrow g)$
- – 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: $Q_s^2 \sim A^{1/3}$

x ≤ 0.01
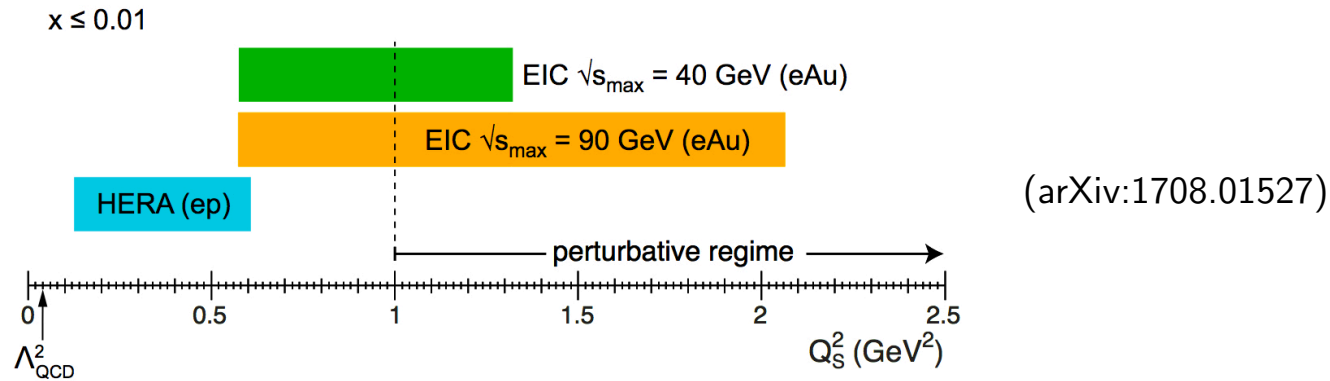
(arXiv:1708.01527)

- Key observable 1: di-hadron correlations in eA collisions
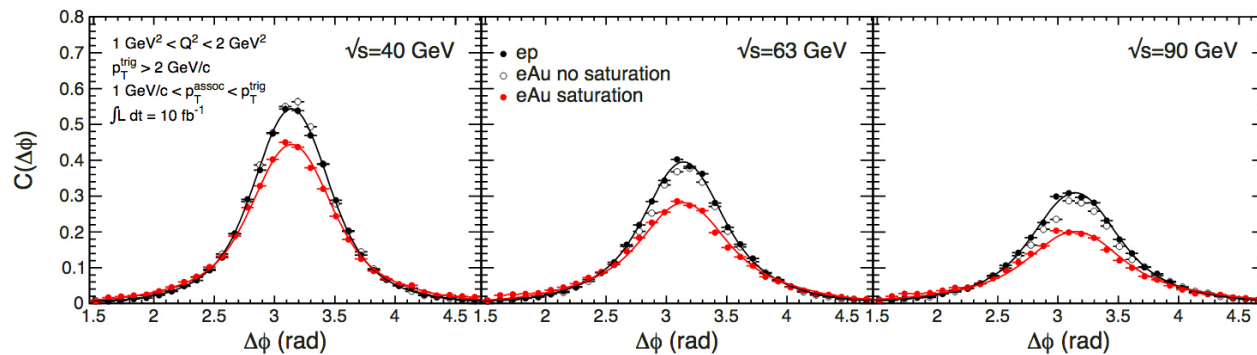
(arXiv:1708.01527)

- 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
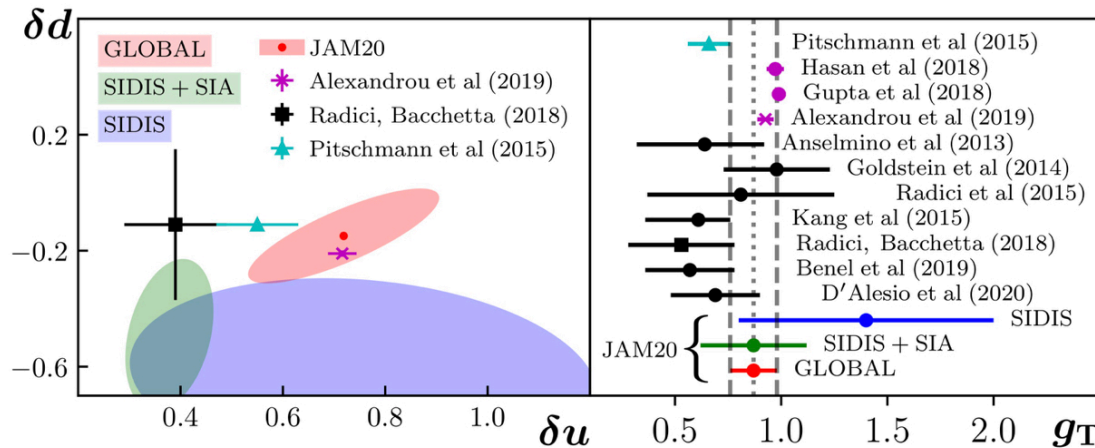
Transversity Distribution and Tensor Charge

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

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

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

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

(courtesy by D. Pitonyak)

$$\mathrm{SIDIS} \to (\mathrm{SIDIS} + \mathrm{SIA}) \to \mathrm{GLOBAL}:\ g_T = 1.4(6) \to 0.87(25) \to \mathbf{0.87(11)}$$
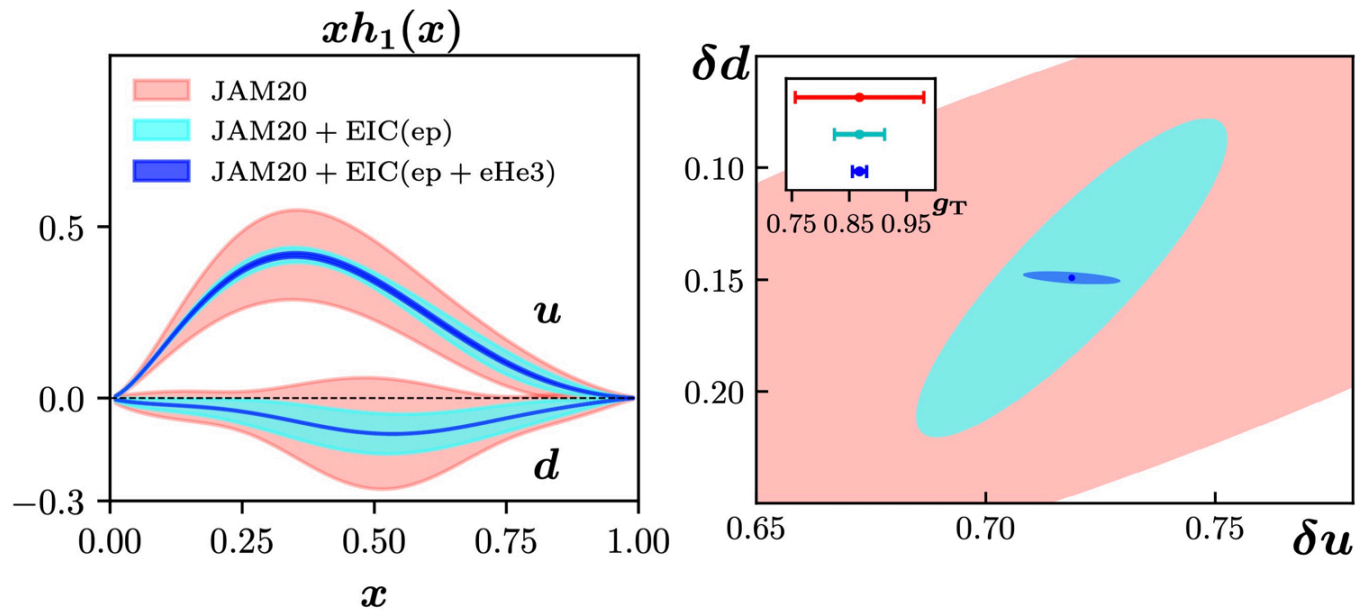
➢ This is the most precise phenomenological determination of g_T to date

➢ 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: $g_1(x, Q^2)$ $g_T(x, Q^2)$

- Wandzura-Wilczek approximation (Wandzura, Wilczek, 1977)

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

- $g_T^{\text{twist-3}}$ 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)
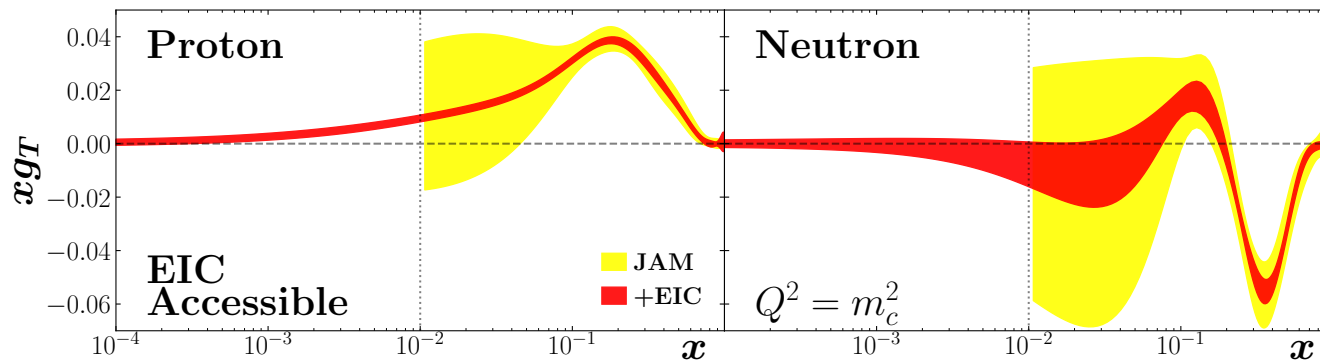
- new fit of available data on g_T, and fit including EIC pseudodata

- 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

Weak mixing angle

- Scale dependence of weak mixing angle contains information about BSM physics

- Previous EIC impact studies exist (e.g., Zhou, Deshpande, Huang, Kumar, Riordan, 2016)

- New EIC impact study (Cocuzza, Melnitchouk, Metz, Sato, ..., work in progress)
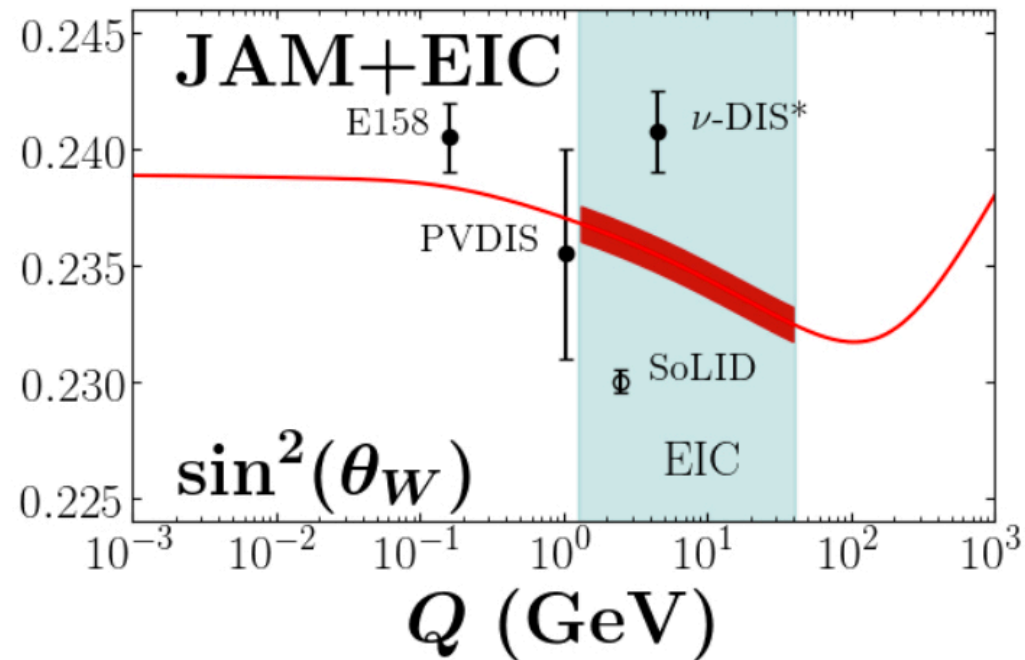
- parity-violating inclusive DIS for p and d targets

- simultaneous fit of unpolarized PDFs and $\sin^2 \theta_W$

- EIC can provide important constraints for considerable range of Q

- also shown are data points at similar Q, plus projected error for SoLID

Conclusions

- EIC is next major QCD frontier

- CD-0 approval by DOE was crucial milestone

- Many physics questions can be addressed for the first time or, at least, at a new level

- Strong interest in community to further EIC science case

- Hopefully, second detector will be added

- Further support for faculty positions will be critical for full success of project

- EIC likely to also provide exciting unexpected results