Physics with an Electron Ion Collider

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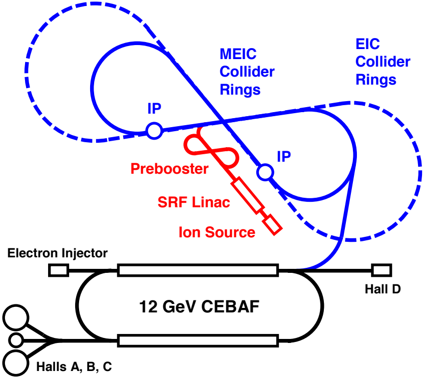
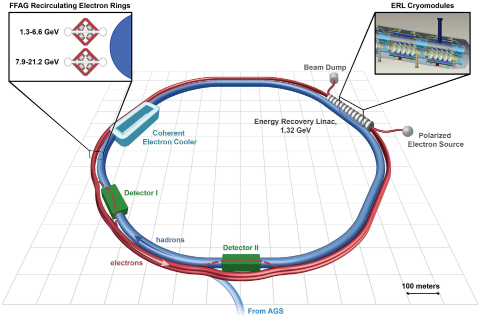
- The EIC Mission: The complex interplay of Dynamics and Structure
- Some highlights from the physics case
- Challenges for theory and experiment
- Conclusions

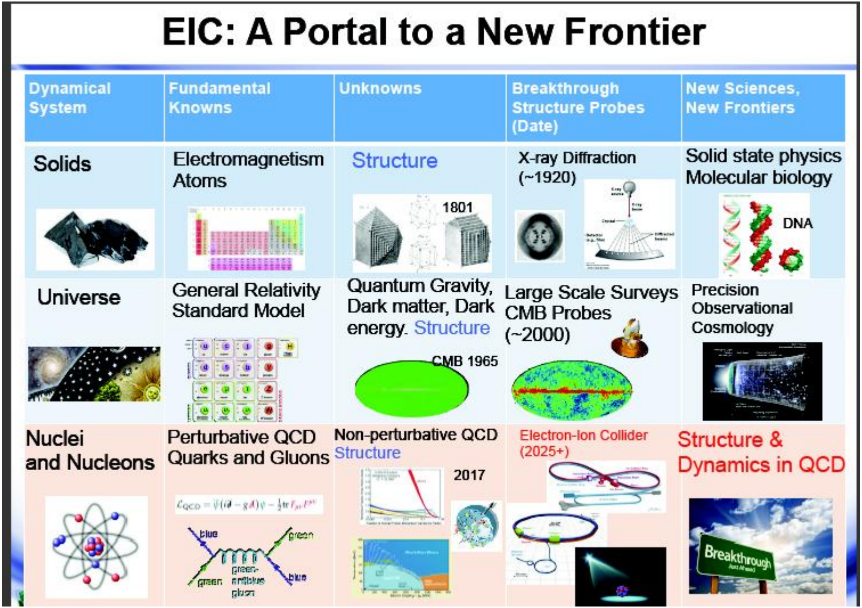
EIC

The design is still changing, e.g.: What has priority, energy or luminosity? A recent review arXiv:1708.01527





2017, Abhay Deshpande for EICUG, NAS



EIC: A Portal to a New Frontier

Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes (Date)	New Sciences, New Frontiers
Solids	Electromagnetism Atoms	Structure 1801	X-ray Diffraction (~1920)	Solid state physics Molecular biology DNA
Universe	General Relativity Standard Model	Quantum Gravity, Dark matter, Dark energy. Structure CMB 1965	Large Scale Surveys CMB Probes (~2000)	Precision Observational Cosmology
Nuclei and Nucleons	Perturbative QCD Quarks and Gluons	Non-perturbative QCD Structure 2017	Electron-Ion Collider (2025+)	Structure & Dynamics in QCD

The selling point of the EIC is to study the combination of "Dynamics & Structure" with unprecedented precision and thus to reach a qualitatively new level of understanding.

$$\begin{aligned} \text{Lattice QCD} &\Rightarrow \text{structure} \\ \text{pQCD} &\Rightarrow \text{dynamics} \end{aligned}$$

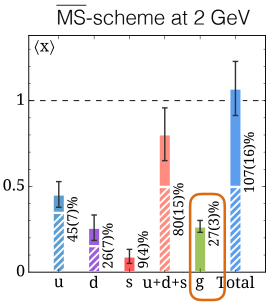
Challenge: Control of systematic errors, e.g. polarimetry

Conclusions: Experiment, pQCD and LQCD can meet the EIC challenge but a lot of work lies ahead. Most crucially, they have to collaborate closely.

Note: A theory prediction has to agree with experiment within the cited systematic error, also in a thousand years from now.

Nucleon gluon momentum fraction

Two direct calculations at the physical point since last year
[C. Alexandrou et al., arXiv:1706.02973]
[Y-B. Yang et al., (χQCD) arXiv:1805.00531]

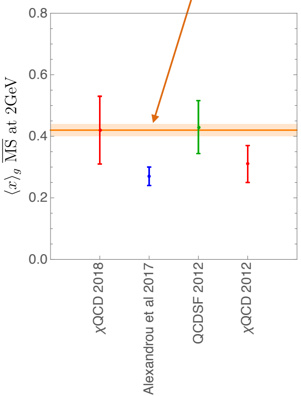


gluon momentum fraction

Solid: disconnected

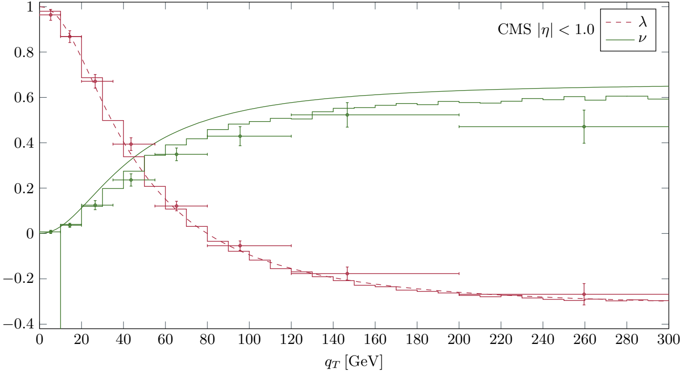
Hashed: connected

CT14NNLO
[S. Dulat et al, PRD 93, 033006 (2016)]



pQCD

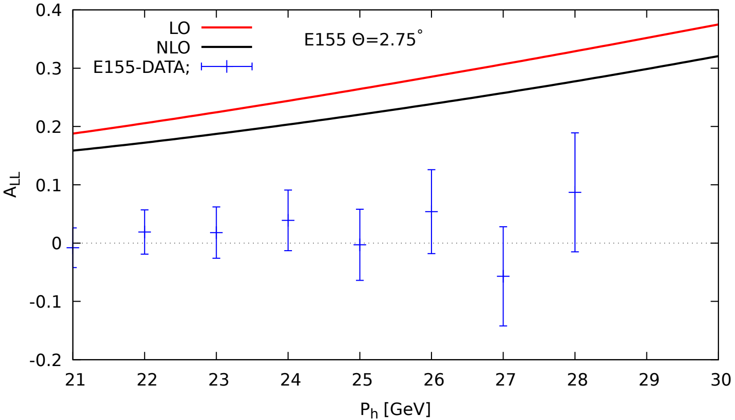
sometimes it works



1605.02625 Lambertsen and Vogelsang; Drell-Yan lepton angular distributions (lines LO; histograms NLO)

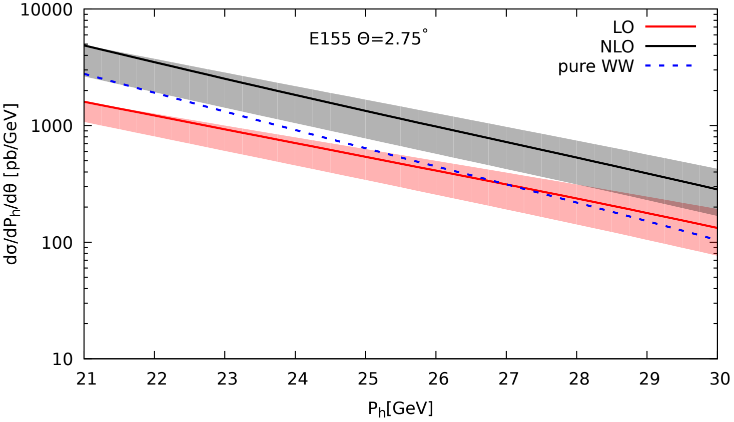
$$\frac{dN}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

and sometimes not yet



1703.10872 Hinderer, Schlegel and Vogelsang;
"Double-longitudinal spin asymmetry in single-inclusive lepton scattering at NLO"

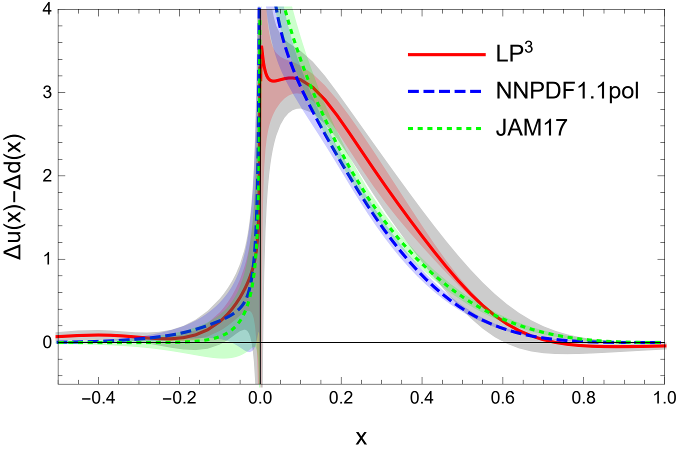
In pQCD you have consistency checks !!!



The unpolarized cross section

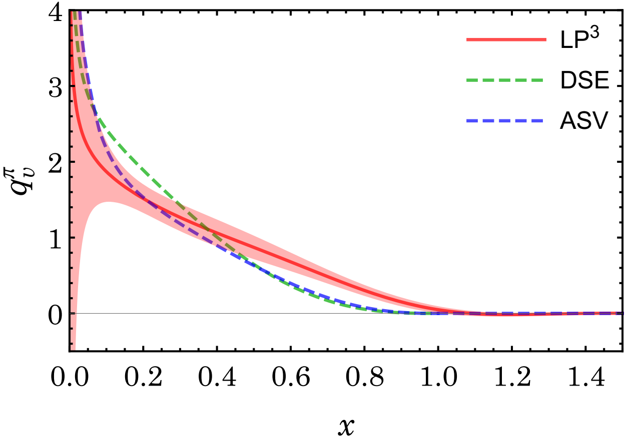
LQCD

sometimes it works

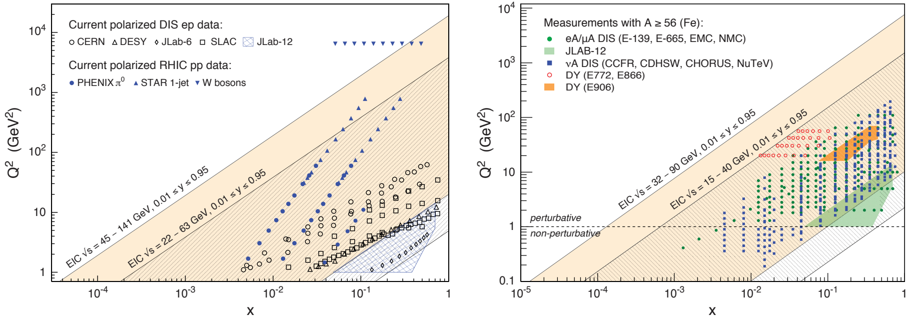


LP^3: polarized nucleon quark PDF from quasi-PDFs (H.-W. Lin et al. 1807.07431

and sometimes not yet



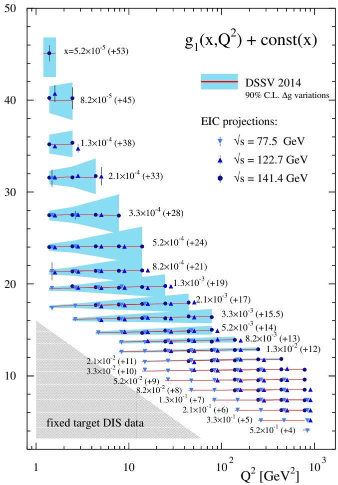
LP3 pion quark PDF from quasi-PDFs (H.-W. Chu et al. 1804.01483)



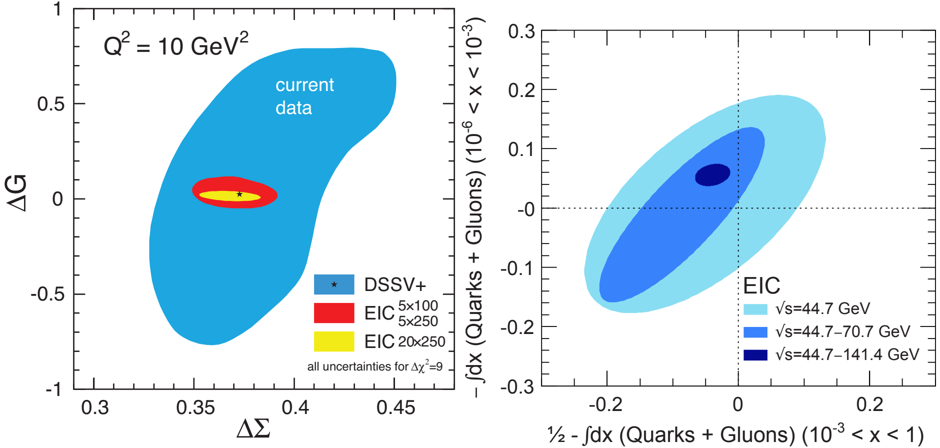
Left: Two different energy ranges from 22–63 GeV (hatched) and from 45–141 GeV (beige) are indicated. Right: The kinematic acceptance in x vs. Q^2

Progress is most dramatic for polarized PDFs because HERA's p-beam was unpolarized.

projected EIC accuracy for g_1, 10 fb^{-1}



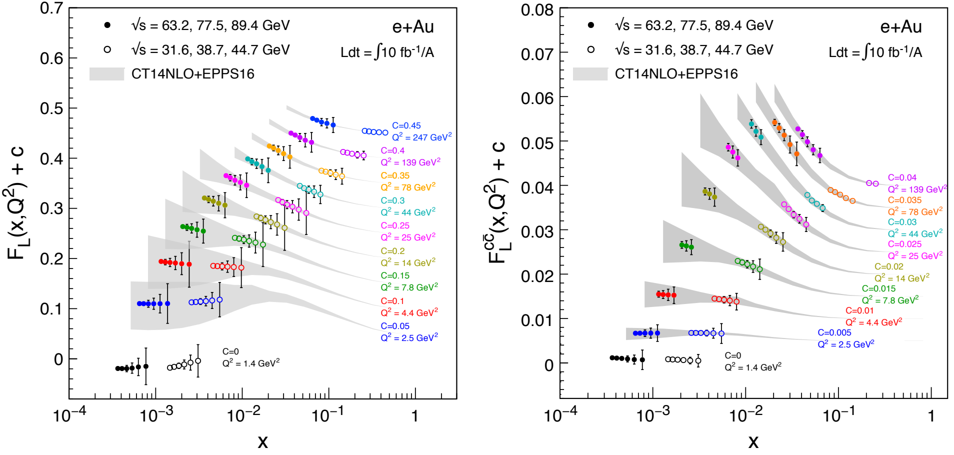
arXiv: 1212.1701 and arXiv:1708.01527 projected quark plus gluon spin contribution at small *x* versus OAM at large *x*



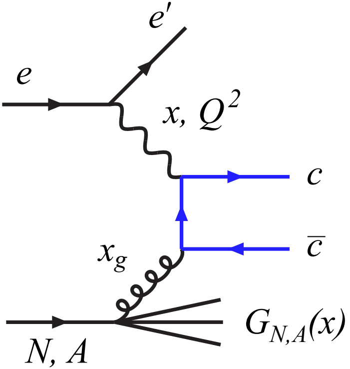
"... it will be critical to constrain experimental systematic uncertainties to below a few percent"

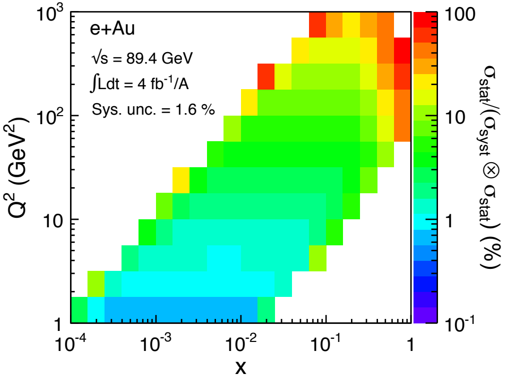
The same holds for theory **!!!**

and for $e + A$

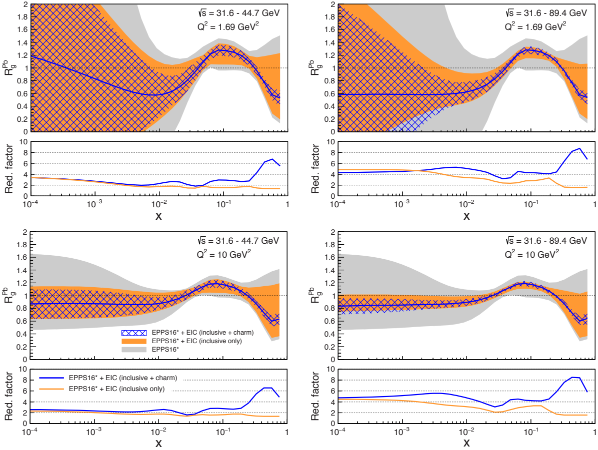


Inclusive (*left*) and charm (*right*) F_L structure function. The gray-shaded bands depict the present uncertainties.



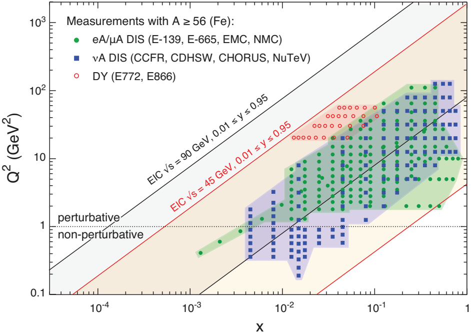


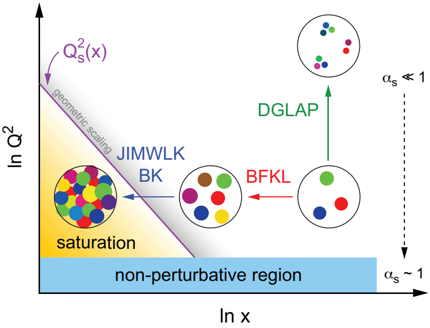
For $\bar{c}c$ production there are also theory issues to be esolved (mass scheme)



The ratio R_g^{Pb} of gluon distributions in a lead nucleus relative to the proton, for the low (*left*) and high (*right*) $\sqrt{s}$, at $Q^2 = 1.69\ \mathrm{GeV}^2$ and $Q^2 = 10\ \mathrm{GeV}^2$ (upper and lower plots, respectively).

The search for saturation



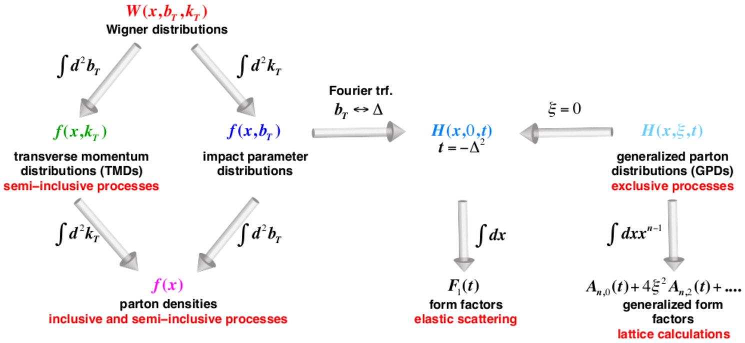


g(x) cannot increase rapidly at small x forever, saturation should eventually occure (Froisard bound). Difficult to find in inclusive DIS, (forward physics see below). In $e + A$ the "oomph factor" $A^{1/3}$ helps crucially. Personal opinion: One should treat

$$e + N \quad \leftrightarrow \quad e + A \quad \leftrightarrow \quad p + A \quad \leftrightarrow \quad A + A$$

with the same techniques

beyond PDFs



GPDs, TMDs, etc., e.g. DAs, DDs are the next logical steps. Because they are multi-variable functions, they can most probably not be determined from experiment alone. Lattice input is needed.

Definition for DVCS, DVMP:

$$h(P_1) + \Gamma^*(q_1) \to h(P_2) + \Gamma(q_2)$$

with $\Delta_\mu = q_{2\mu} - q_{1\mu}$, $t = \Delta^2$, $P_\mu = (P_{1\mu} + P_{2\mu})/2$
and $\xi = -Q^2/2P \cdot q$

Spin $\frac{1}{2}$ - the nucleon (modulo gauge links)

$$\int \frac{dz^-}{2\pi} e^{ix\bar{P}^+ z^-} \langle P_2 |\, \bar{q}(-\frac{1}{2}z)\, \gamma^+ q(\frac{1}{2}z)\, | P_1 \rangle \Big|_{z^+=0,\, z_\perp=0}$$
$$= \frac{1}{P^+} \left[H_q(x,\xi,t)\, \bar{N}(P_2) \gamma^+ N(P_1) + E_q(x,\xi,t)\, \bar{N}(P_2) \frac{i\sigma^{+\alpha}\Delta_\alpha}{2M} N(P_1) \right]$$

Some properties of GPDs:

• relation to form factors and distribution functions

$$H_q(x,0,0) = q(x) \qquad \int_{-1}^{1} dx H_q(x,\xi,t) = F_{1q}(t)$$

$$\tilde{H}_q(x,0,0) = \Delta q(x) \qquad \int_{-1}^{1} dx H_q(x,\xi,t) = g_{Aq}(t)$$

• GPDs give information on the transverse structure of hadrons in the impact parameter plane.

$$H_q(x,0,b_\perp^2) = \frac{1}{(2\pi)^2} \int d^2\Delta_\perp \; e^{ib_\perp \Delta_\perp} H_q(x,0,\Delta_\perp^2)$$

Ji's sumrule hep-ph/9609381

$$\int dx\, x\Big(H_q(x,\xi,t) + E_q(x,\xi,t)\Big) = A_q(t) + B_q(t)$$
$$J_{q,g} = \frac{1}{2}\Big[A_{q,g}(0) + B_{q,g}(o)\Big]$$

Endless debates as to whether a gauge invariant operator decomposition into S_g and L_g exists. However one can determins S_q and S_g from $\Delta q(x)$ and $\Delta g(x)$ and define the OAM via Ji's sumrule.

The corresponding density, expressed in terms of GPDs

$$\frac{1}{(2\pi)^2}\int d^2\Delta_\perp e^{ib_\perp\cdot\Delta_\perp}\int\frac{dz^-}{2\pi}e^{ix\bar{P}^+z^-}\langle P_2|\,\bar{q}(-\frac{1}{2}z)\,\gamma^+[1+\vec{s}\cdot\vec{\gamma})\gamma_5]q(\frac{1}{2}z)\,|P_1\rangle\Big|_{z^+=0}^{z_\perp=0}$$

$$\begin{aligned} &= \frac{1}{2}\Big[F + s^i F_T^i\Big] \\ &= \frac{1}{2}\Bigg[H - S^i\epsilon^{ij}b^j\frac{1}{m}E' - s^i\epsilon^{ij}b^j\frac{1}{m}\Big(E_T' + 2\tilde{H}_T'\Big) \\ &\quad + s^iS^i\Big(H_T - \frac{1}{4m^2}\Delta_b\tilde{H}_T\Big) + s^i(2b^ib^j - b^2\delta^{ij})S^j\frac{1}{m^2}\tilde{H}_T''\Bigg]\end{aligned}$$

has a simple interpretation:

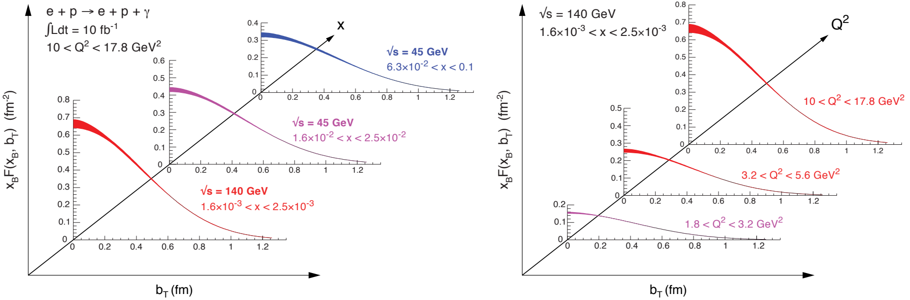
$S^i\epsilon^{ij}b^j$ coupling of proton spin to quark angular momentum

$s^i\epsilon^{ij}b^j$ coupling of quark spin to quark angular momentum

s^iS^i coupling of quark spin and proton spin

Another EIC money plot:

DVCS and the transverse structure of nucleons; here= basically the gluon distribution, but $x_g = x_B(1 + M_{J\psi}^2/Q^2)$



But: Higher Twist and power-corrections ???

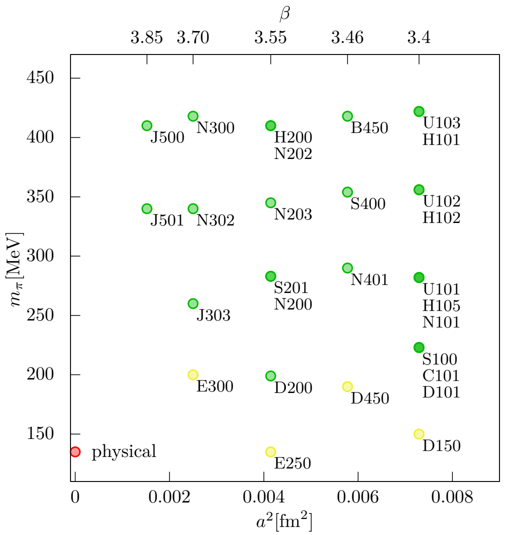
The main problems of LQCD for hadron structure

- the continuum limit $\lim_{a \to 0}$
- operator mixing: The hypercubic group is smaller than that of continuum rotations $\Rightarrow$ operator mixing, e.g. $\langle p|\bar{q}\sigma_{\mu\nu}G^{\mu\nu}q|p'\rangle$ can mix with $\frac{1}{a^2}\langle p|\bar{q}q|p'\rangle$
  In arXiv:0801.3932 we have worked out the group theory

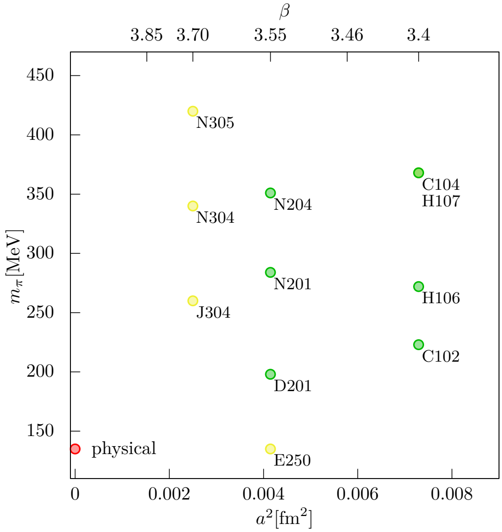
	dimension 9/2 (0 derivatives)	dimension 11/2 (1 derivative)	dimension 13/2 (2 derivatives)
τ_1^4	$\mathcal{O}_1^{(i)}$, $\mathcal{O}_2^{(i)}$, $\mathcal{O}_3^{(i)}$, $\mathcal{O}_4^{(i)}$, $\mathcal{O}_5^{(i)}$		$\mathcal{O}_{DD1}^{(i)}$, $\mathcal{O}_{DD2}^{(i)}$, $\mathcal{O}_{DD3}^{(i)}$
τ_2^4			$\mathcal{O}_{DD4}^{(i)}$, $\mathcal{O}_{DD5}^{(i)}$, $\mathcal{O}_{DD6}^{(i)}$
τ^8	$\mathcal{O}_6^{(i)}$	$\mathcal{O}_{D1}^{(i)}$	$\mathcal{O}_{DD7}^{(i)}$, $\mathcal{O}_{DD8}^{(i)}$, $\mathcal{O}_{DD9}^{(i)}$
τ_1^{12}	$\mathcal{O}_7^{(i)}$, $\mathcal{O}_8^{(i)}$, $\mathcal{O}_9^{(i)}$	$\mathcal{O}_{D2}^{(i)}$, $\mathcal{O}_{D3}^{(i)}$, $\mathcal{O}_{D4}^{(i)}$	$\mathcal{O}_{DD10}^{(i)}$, $\mathcal{O}_{DD11}^{(i)}$, $\mathcal{O}_{DD12}^{(i)}$, $\mathcal{O}_{DD13}^{(i)}$
τ_2^{12}		$\mathcal{O}_{D5}^{(i)}$, $\mathcal{O}_{D6}^{(i)}$, $\mathcal{O}_{D7}^{(i)}$, $\mathcal{O}_{D8}^{(i)}$	$\mathcal{O}_{DD14}^{(i)}$, $\mathcal{O}_{DD15}^{(i)}$, $\mathcal{O}_{DD16}^{(i)}$, $\mathcal{O}_{DD17}^{(i)}$, $\mathcal{O}_{DD18}^{(i)}$

- diverging topological autocorrelation times for $a \to 0$

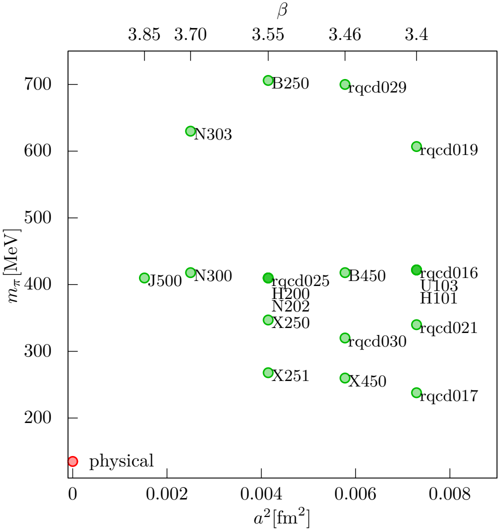
CLS-ensembles with open boundary conditions and physical *Tr* *m*



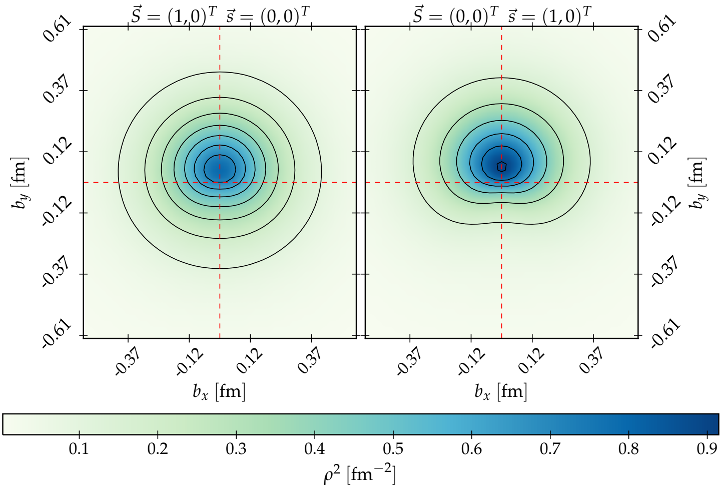
CLS-ensembles with open boundary conditions and physical m_s



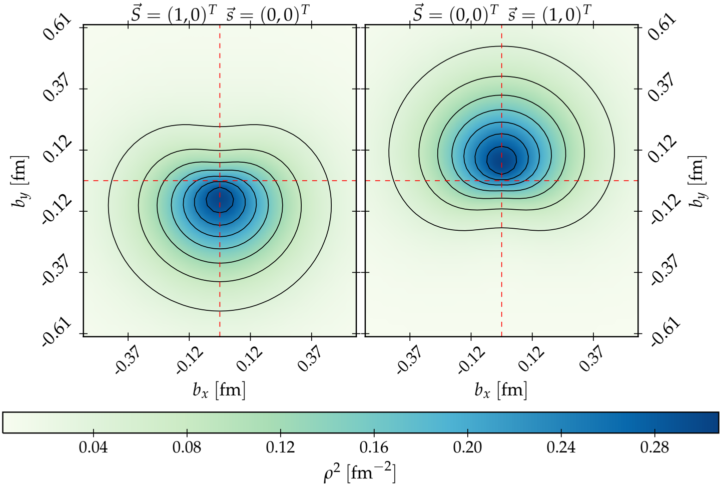
CLS-ensembles with open boundary conditions and symmetric quark masses



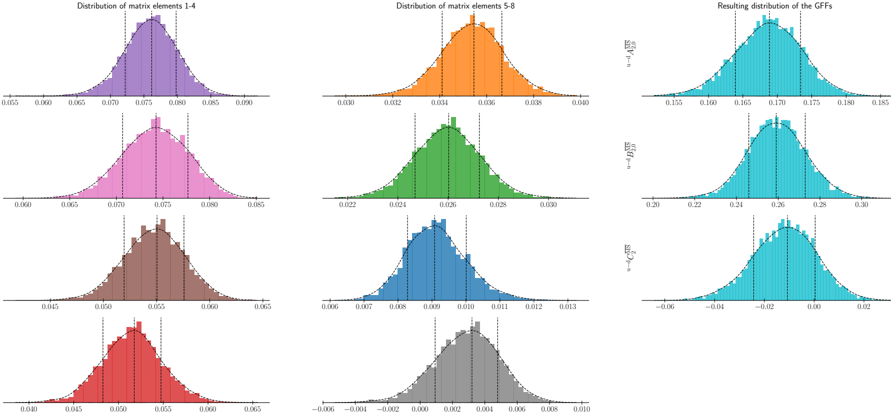
Results for tensor GPDs



transverse densities of x^1 moment for u quarks in a proton



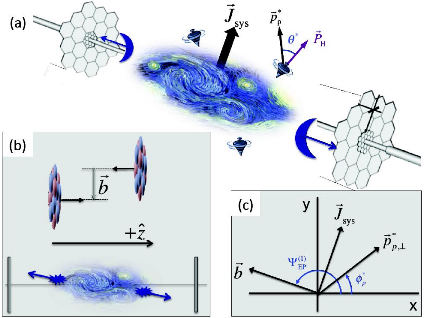
transverse densities of x^1 moment for d quarks in a proton

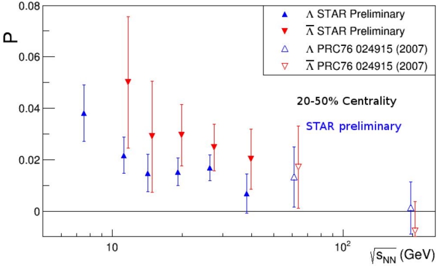


distribution of extrapolated results many fits, defining the systematic error R. Rödl et al.

On the look-out for links between hadron structure and heavy ion physics: nuclear single-spin asymmetries and nGPDs ?

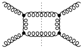
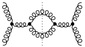
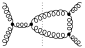
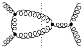
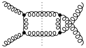
Λ and $\bar{\Lambda}$ produced at mid-rapidity in Heavy Ion Collisions are preferentially polarized along $\vec{J}_{\rm sys}$





STAR; 2016; 32th Winter Workshop on Nuclear Dynamics

TMDs describe unique experimental effects caused by gauge links, QCD is a local gauge theory C.J. Bomhof, P.J. Mulders and F. Pijlman; EPJ C47 (2006) 147; arXiv hep-ph/0601171

	$\Phi_g \propto \langle \frac{1}{2N_c^2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[\Box]\dagger}\mathcal{U}^{[+]\dagger}F(0)\mathcal{U}^{[\Box]}\mathcal{U}^{[+]}] + \frac{1}{2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[+]\dagger}F(0)\mathcal{U}^{[+]}]\Big(\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]}]}{N_c}\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]\dagger}]}{N_c} - \frac{3}{N_c^2}\Big)$ $+\frac{1}{2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[+]\dagger}F(0)\Big\{\frac{1}{2}\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]}]}{N_c}\mathcal{U}^{[-]} + \frac{1}{N_c^2}\mathcal{U}^{[+]}\Big\}]$ $+\frac{1}{2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[-]\dagger}F(0)\Big\{\frac{1}{2}\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]\dagger}]}{N_c}\mathcal{U}^{[+]} + \frac{1}{N_c^2}\mathcal{U}^{[-]}\Big\}]\rangle$ $\Delta_g \propto \langle \frac{1}{2N_c^2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[\Box]}\mathcal{U}^{[-]\dagger}F(0)\mathcal{U}^{[\Box]\dagger}\mathcal{U}^{[-]}] + \frac{1}{2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[-]\dagger}F(0)\mathcal{U}^{[-]}]\Big(\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]}]}{N_c}\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]\dagger}]}{N_c} - \frac{3}{N_c^2}\Big)$ $+\frac{1}{2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[+]\dagger}F(0)\Big\{\frac{1}{2}\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]}]}{N_c}\mathcal{U}^{[-]} + \frac{1}{N_c^2}\mathcal{U}^{[+]}\Big\}]$ $+\frac{1}{2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[-]\dagger}F(0)\Big\{\frac{1}{2}\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]\dagger}]}{N_c}\mathcal{U}^{[+]} + \frac{1}{N_c^2}\mathcal{U}^{[-]}\Big\}]\rangle$
  	$\Phi_g \propto \langle \frac{1}{2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[+]\dagger}F(0)\mathcal{U}^{[-]}]\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]}]}{N_c} + \frac{1}{2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[-]\dagger}F(0)\mathcal{U}^{[+]}]\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]\dagger}]}{N_c}$ $-\frac{1}{2N_c}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[\Box]}]\,\mathrm{Tr}[F(0)\mathcal{U}^{[\Box]\dagger}] - \frac{1}{2N_c}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[\Box]\dagger}]\,\mathrm{Tr}[F(0)\mathcal{U}^{[\Box]}]\rangle$ $\Delta_g \propto \langle \frac{1}{2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[+]\dagger}F(0)\mathcal{U}^{[-]}]\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]}]}{N_c} + \frac{1}{2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[-]\dagger}F(0)\mathcal{U}^{[+]}]\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]\dagger}]}{N_c}$ $-\frac{1}{2N_c}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[\Box]}]\,\mathrm{Tr}[F(0)\mathcal{U}^{[\Box]\dagger}] - \frac{1}{2N_c}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[\Box]\dagger}]\,\mathrm{Tr}[F(0)\mathcal{U}^{[\Box]}]\rangle$
	$\Phi_g \propto \langle \frac{1}{N_c^2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[\Box]\dagger}\mathcal{U}^{[+]\dagger}F(0)\mathcal{U}^{[\Box]}\mathcal{U}^{[+]}] + \mathrm{Tr}[F(\xi)\mathcal{U}^{[+]\dagger}F(0)\mathcal{U}^{[+]}]\Big(\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]}]}{N_c}\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]\dagger}]}{N_c} - \frac{3}{N_c^2}\Big)$ $+\frac{1}{N_c^2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[+]\dagger}F(0)\mathcal{U}^{[+]}] + \frac{1}{N_c^2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[-]\dagger}F(0)\mathcal{U}^{[-]}]$ $+\frac{1}{2N_c}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[\Box]}]\,\mathrm{Tr}[F(0)\mathcal{U}^{[\Box]\dagger}] + \frac{1}{2N_c}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[\Box]\dagger}]\,\mathrm{Tr}[F(0)\mathcal{U}^{[\Box]}]\rangle$ $\Delta_g \propto \langle \frac{1}{N_c^2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[\Box]}\mathcal{U}^{[-]\dagger}F(0)\mathcal{U}^{[\Box]\dagger}\mathcal{U}^{[-]}] + \mathrm{Tr}[F(\xi)\mathcal{U}^{[-]\dagger}F(0)\mathcal{U}^{[-]}]\Big(\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]}]}{N_c}\frac{\mathrm{Tr}\,[\mathcal{U}^{[\Box]\dagger}]}{N_c} - \frac{3}{N_c^2}\Big)$ $+\frac{1}{N_c^2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[+]\dagger}F(0)\mathcal{U}^{[+]}] + \frac{1}{N_c^2}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[-]\dagger}F(0)\mathcal{U}^{[-]}]$ $+\frac{1}{2N_c}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[\Box]}]\,\mathrm{Tr}[F(0)\mathcal{U}^{[\Box]\dagger}] + \frac{1}{2N_c}\,\mathrm{Tr}[F(\xi)\mathcal{U}^{[\Box]\dagger}]\,\mathrm{Tr}[F(0)\mathcal{U}^{[\Box]}]\rangle$

Leading Twist TMDs

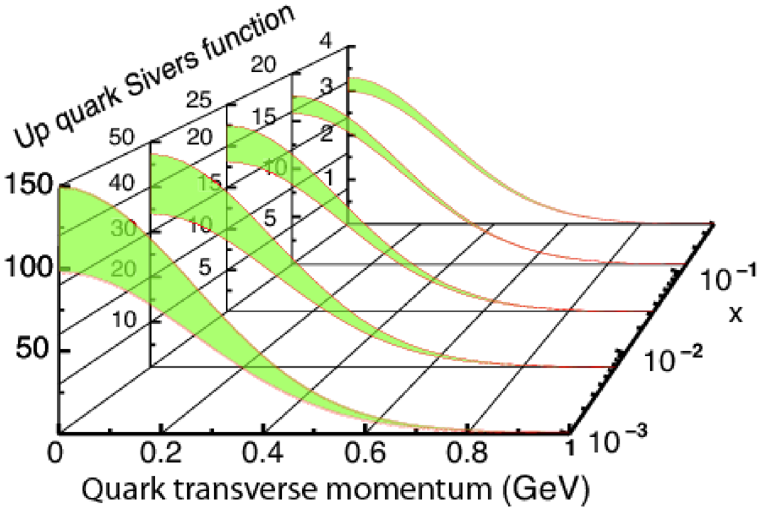
Nucleon Spin

Quark Spin

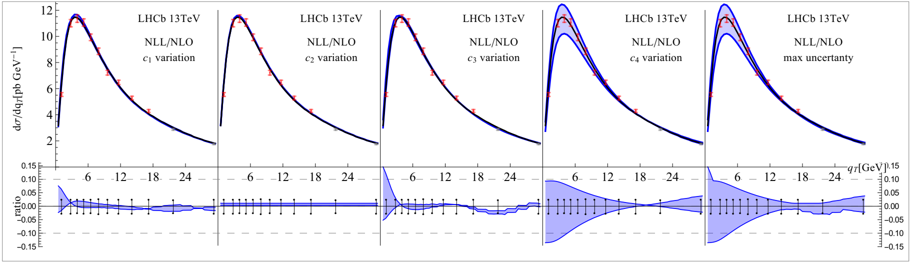
		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$		$h_1^{\perp} =$ — Boer-Mulders
	L		$g_{1L} =$ — Helicity	$h_{1L}^{\perp} =$ —
	T	$f_{1T}^{\perp} =$ — Sivers	$g_{1T}^{\perp} =$ —	$h_1 =$ — Transversity $h_{1T}^{\perp} =$ —

There exist many differnt TMDs

Although there are still open fundamental questions many people are very bussy fitting the data, e.g., for the Sivers function. EIC predictions

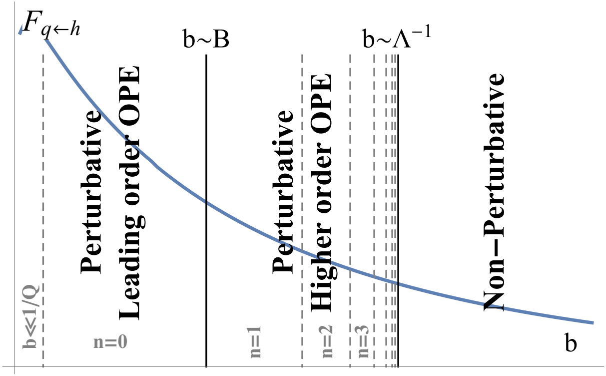


TMDs are also relevant for LHC physics, see, e.g, Scimemi and Vladimirov arXiv:1706.01473 fitting the $p_\perp$ distribution for $p + p \to Z(\ell\ell') + X$ at LHCb (13TeV).



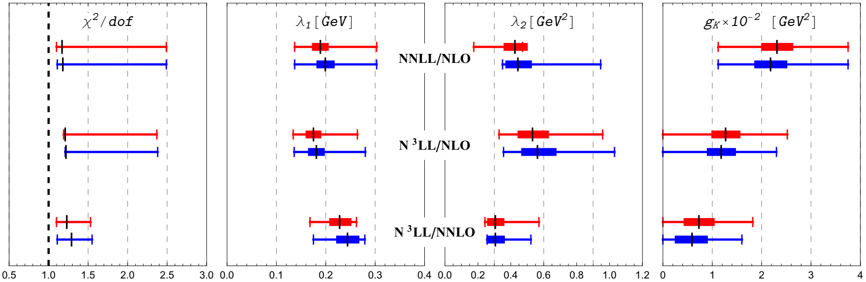
One of the problems: The evolution has non-perturbative pieces

arXiv:1706.01473 I. Scimemi and A. Vladimirov "Analysis of vector boson production within TMD factorization"



TMDs themselves as well as their evolution contain unsuppressed non-perturbative parts, which have to be parameterized.

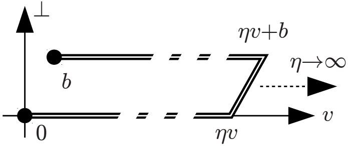
The non-perturbative evolution is parameterized with three parameters $\lambda_1, \lambda_2, g_K$



LHC experimental (fat) and theoretical (thin; from just varying μ and the coefficient function in reasonable bounds) uncertainties for TMDs from DY

TMDs are related to correlators of the type

$$\widetilde{\Phi}^{[\Gamma]}_{\text{unsubtr.}}(b, P, S, \ldots) \equiv \frac{1}{2}\langle P, S|\, \bar{q}(0)\, \Gamma\, \mathcal{U}[0, \eta v, \eta v+b, b]\, q(b)\, |P, S\rangle$$



We simulate for spatial, not light-like separations, but the limit $\hat{\zeta} \to \infty$ of

$$\hat{\zeta} := \frac{v \cdot P}{\sqrt{v^2}\sqrt{P^2}}$$

reproduces the light-cone behavior.

We used RBC/UKQCD (domain wall) and W&M (Clover) ensembles, $N_f = 2 + 1$

ID	Clover	DWF
Fermion Type	Clover	Domain-wall
Geometry	$32^3 \times 96$	$32^3 \times 64$
$a(\mathrm{fm})$	0.11403(77)	0.0840(14)
$m_\pi(\mathrm{MeV})$	317(2)(2)	297(5)
# confs.	967	533
# meas.	23208	4264

only connected diagrams, i.e. $u - d$

$$\widetilde{\Phi}^{[\Gamma]}_{\text{subtr.}}(b,P,S,\ldots) = \widetilde{\Phi}^{[\Gamma]}_{\text{unsubtr.}}(b,P,S,\ldots)\cdot\mathcal{S}\cdot Z_{\mathrm{TMD}}\cdot Z_2$$

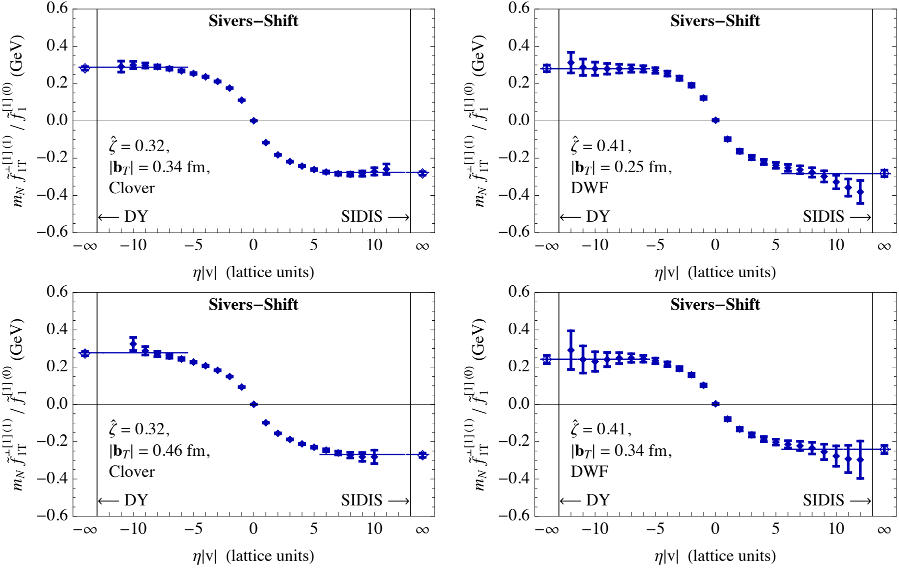
$$\Phi^{[\Gamma]}(x,\boldsymbol{k}_T,P,S,\ldots) = \int\frac{d^2\boldsymbol{b}_{\mathrm{T}}}{(2\pi)^2}\int\frac{d(b\cdot P)}{2\pi P^+}e^{ix(b\cdot P)-i\boldsymbol{b}_{\mathrm{T}}\cdot\boldsymbol{k}_{\mathrm{T}}}\,\widetilde{\Phi}^{[\Gamma]}_{\text{subtr.}}\Big|_{b^+=0}$$

$$\Phi^{[\gamma^+]} = f_1 - \frac{\epsilon_{ij}\boldsymbol{k}_i\boldsymbol{S}_j}{m_N}f_{1T}^{\perp}$$

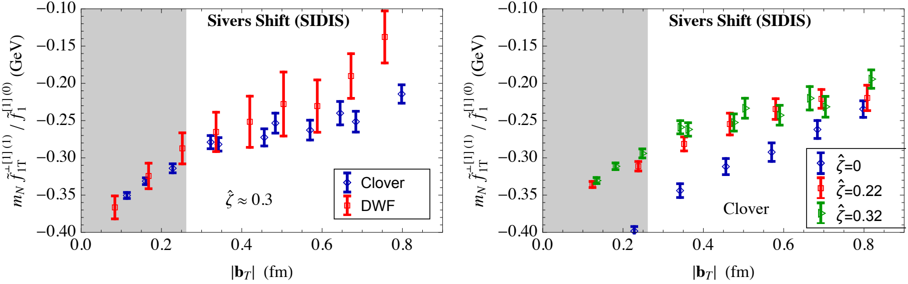
$$\tilde{f}^{[m](n)}(\boldsymbol{b}_{\mathrm{T}}^2,\ldots) = n!\left(-\frac{2}{m_N^2}\partial_{\boldsymbol{b}_{\mathrm{T}}^2}\right)^n\int_{-1}^{1}dx x^{m-1}\int d^2\boldsymbol{k}_{\mathrm{T}}e^{i\boldsymbol{b}_{\mathrm{T}}\cdot\boldsymbol{k}_{\mathrm{T}}}f(x,\boldsymbol{k}_{\mathrm{T}}^2)$$

$$\langle\vec{k}_y\rangle_{TU}(\boldsymbol{b}_{\mathrm{T}}^2;\ldots) = m_N\frac{\tilde{f}_{1T}^{\perp[1](1)}(\boldsymbol{b}_{\mathrm{T}}^2;\ldots)}{\tilde{f}_1^{[1](0)}(\boldsymbol{b}_{\mathrm{T}}^2;\ldots)}$$

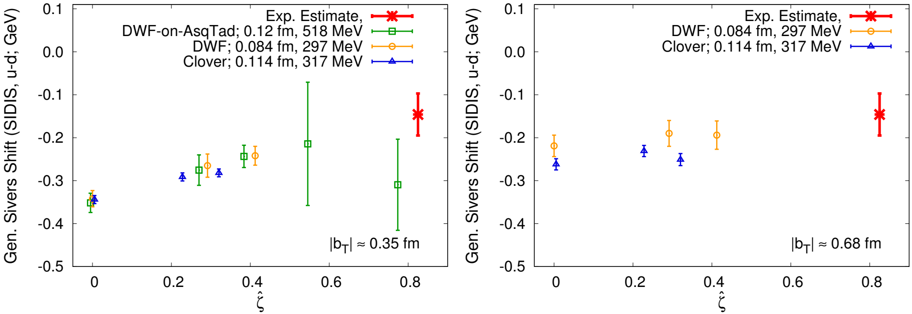
limits: $\eta|v|\to\infty$ and $b_T\gg a$ and $\hat{\zeta}\to\infty$



Sivers shift



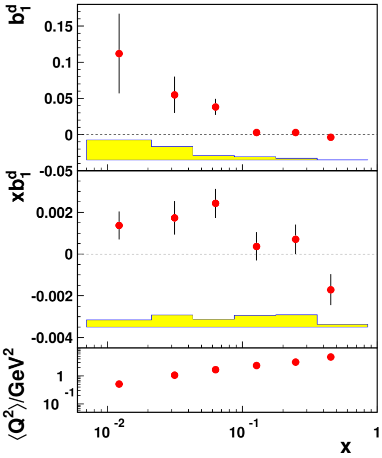
Sivers shift



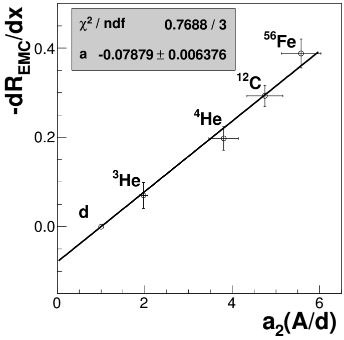
Comparison with experiment

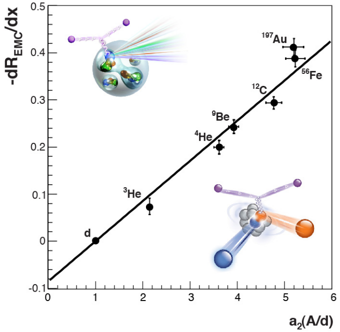
Plus there might be completely unexpected physics

HERMES: For the deuteron b_1 is surprisingly large
hep-ex/0506018



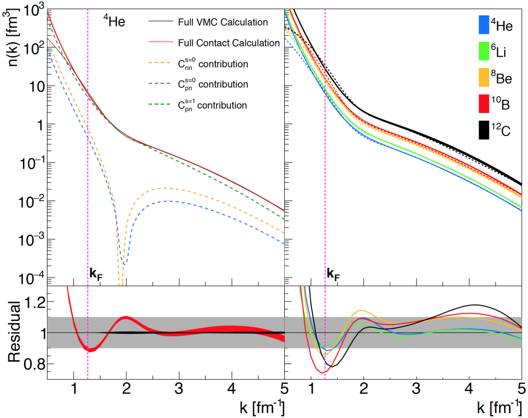
Is there a relation to nuclear physics?
Based on JLab measurements a peculiar correlation between EMC effect and Short Range Correlations was observed
Weinstein, Piasetzky, Higinbotham, Gomez, Hen and Shneor, PRL **106** (2011) 052301; arXiv:1009.5666





Left: The original figure from arXiv:1009.5666 Right: An updated figure from arXiv:1708.08581

In R. Weiss et al. arXiv:1612.00923 it is claimed that the SRC are dominated by the deuteron channel



Comparison of results for the one-body momentum densities from Variational Monte Carlo (VMC) and the “contact theory”. Left: contribution of different two-body channels to SRC pairs. The original figure from arXiv:1009.5666 Right: An updated figure from arXiv:1708.08581

Mainz 2009: “Physics Case for ENC@FAIR”

The combination of experiment, lattice QCD and analytic QCD would allow in the comming decades to understand the internal structure of hadrons for the first time in detail.

Since then experimental and accelerator techniques, LQCD and pQCD have made tremendous progress, but more progress is **absolutely needed** to match the EIC challenges