Session B – Round Table (Wednesday, 21 August 2024 at 12:00-13:00):

Precision QCD: What we know what we want to know

Chair: Jianwei Qiu

Panel Members : Ian Cloët - Zein-Eddine Meziani - Wei Wang

Description in the Conference Program:

In recent years, rapid progress has been made on the determination of PDFs and others from Lattice QCD. Very promising results are obtained while there are still some open questions that need to be discussed. New perspectives are also required, and we hope through this round table discussion, new thoughts can be inspired.

Topics and Questions by the Panel:

- **Matching the partons to hadrons (Jianwei Qiu)**
- **Transverse momentum dependent PDFs (Wei Wang)**
- **Intrinsic properties of nucleons and nuclei (Zein-Eddine Meziani)**
- **Nuclear PDFs and Imaging (A>1) (Ian Cloët)**

Additional Topics, Questions and Thoughts from the Audience?

Matching the partons to hadrons:

❑ What we know:

- Owing to the Confinement, NO quarks/gluons (the partons) can be seen in isolation in Detectors
- Any physical observable with identified hadron is NOT perturbatively calculable
- QCD factorization is an approximation – valid for many physical observables at the leading power

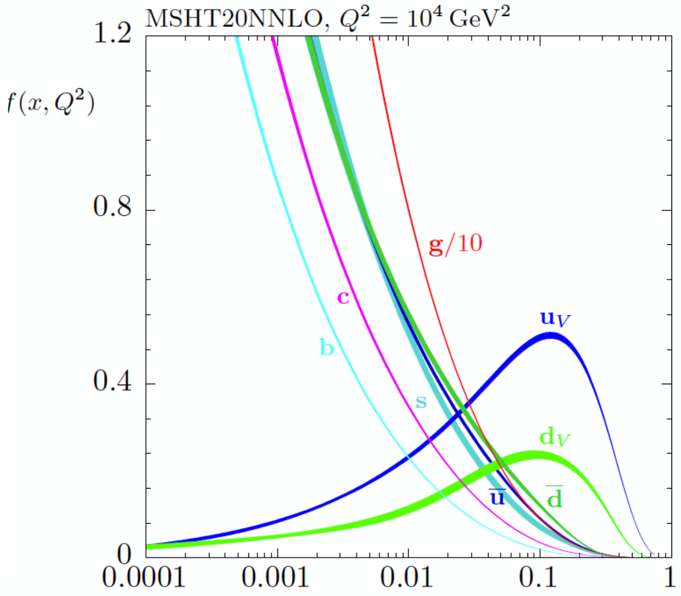
$$\sigma^{\rm phy}_{\{h_i\}}(\{Q_i\}, 1/R_h \sim \Lambda_{\rm QCD}) = \sum_{\{f_i\}} \widehat{H}_{\{f_i\}}(\{x_i\}, \{Q_i\}, \mu) \prod_i \otimes \phi_{f_i/h_i}(x_i, \mu, 1/R_h) + \mathcal{O}(1/R_h Q)^n$$

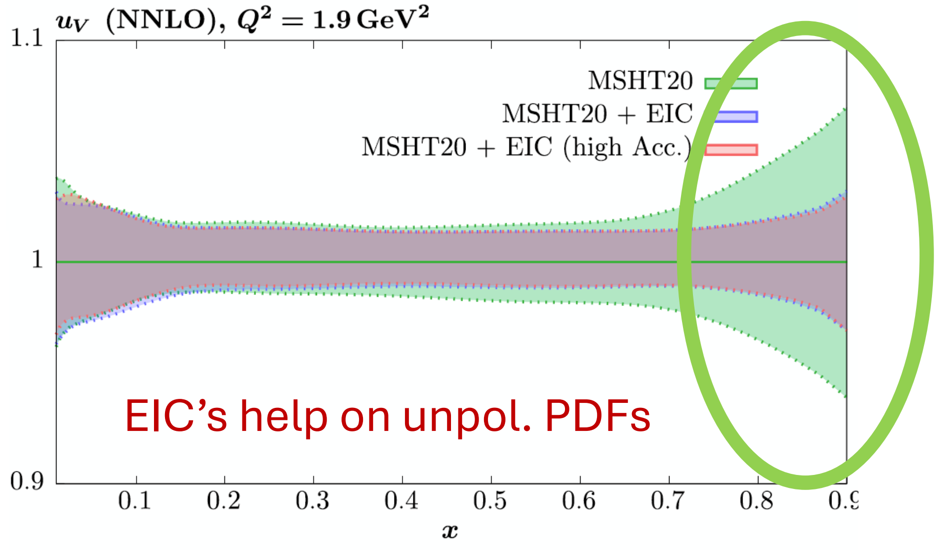
Physical cross section | Calculable partonic "Probe" | Matching Parton to Hadron | Approximation "controllable?"

- QCD factorization works:

MSHT20

Data set	$N_{\rm pts}$	NLO $\chi^2/N_{\rm pts}$	NNLO $\chi^2/N_{\rm pts}$
ATLAS 8 TeV s. diff $t\bar{t}$	25	1.56	0.98
CMS 8 TeV d. diff $t\bar{t}$	15	2.19	1.50
ATLAS 7 TeV W, Z	61	5.00	1.91
ATLAS 8 TeV W	22	3.85	2.61
ATLAS 8 TeV d. diff Z	59	2.67	1.45
ATLAS 8 TeV Z p_T	104	2.26	1.81
ATLAS 8 TeV W + jets	39	1.13	0.60
Total LHC data	1328	1.79	1.33
Total non-LHC data	3035	1.13	1.10
Total	4363	1.33	1.17

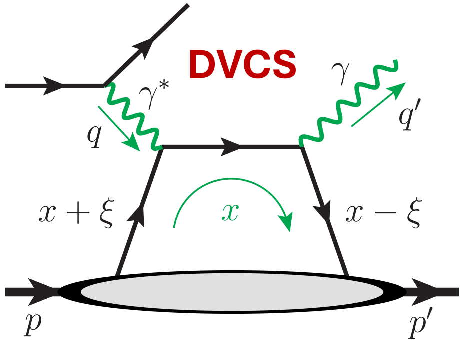




Matching the partons to hadrons:

❑ What we want to know:

- Hadron's 3D partonic structure – confined parton distributions and motions ?
- How to extract the x-dependence of GPDs (moments for GFFs)?



without breaking the hadron!

(ξ,t) fixed by p and p'

$$i\mathcal{M} \propto \int_{-1}^{1} \mathrm{d}x \frac{F(x,\xi,t)}{x-\xi+i\varepsilon} \equiv \text{“}F_0(\xi,t)\text{”}$$

GPDs + Shadow GPDs

$$\int_{-1}^{1} \frac{dx\, S(x,\xi)}{x-\xi \pm i\epsilon} = 0$$

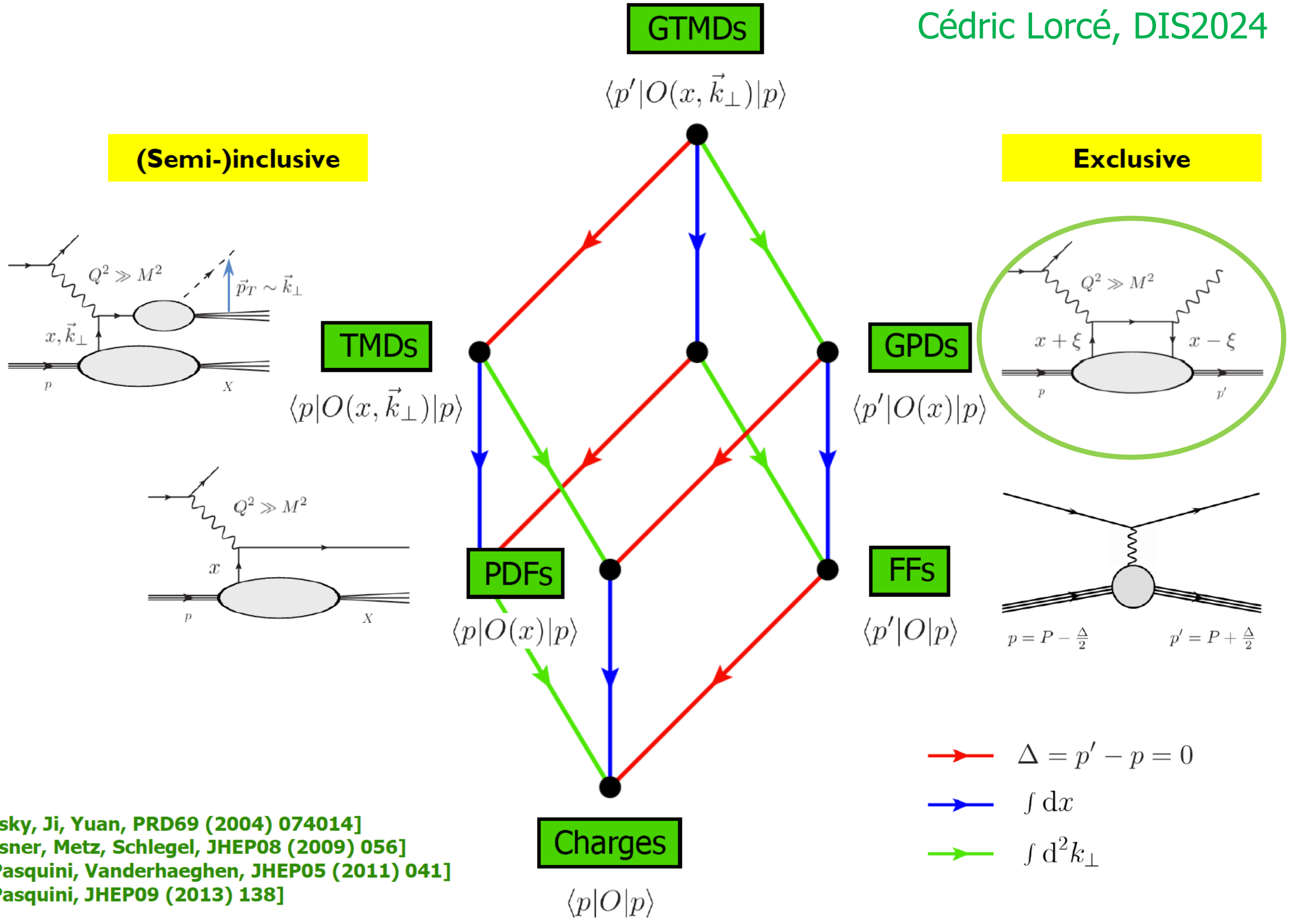
Need new processes:

$$i\mathcal{M} \propto \int_{-1}^{1} \mathrm{d}x \frac{F(x,\xi,t)}{x - x_p(\xi,q) + i\varepsilon}$$

Have x entangled to the measured q !

DDVCS, SDHEP, ..., need more !

Cédric Lorcé, DIS2024



[Belitsky, Ji, Yuan, PRD69 (2004) 074014]
[Meissner, Metz, Schlegel, JHEP08 (2009) 056]
[CL, Pasquini, Vanderhaeghen, JHEP05 (2011) 041]
[CL, Pasquini, JHEP09 (2013) 138]

Matching the partons to hadrons – the role of LQCD:

❑ What we know:

See also Huey-Wen's talk

- LQCD can NOT calculate parton correlation functions (t-dependence of parton correlators) directly ?
- Ji's wonderful idea: to calculate the equal-time version – quasi-PDFs and let $P_z \to \infty$ to get PDFs
- The quasi-PDFs are NOT physical, need renormalization ➡ pseudo-PDFs, ...
- Equal-time quark/gluon correlators are proved to be multiplicative renormalizable !
- Renormalized hadron matrix elements of the equal-time quark/gluon correlators can be factorized !

$$\langle h(P)|\mathcal{O}^{\rm R}_{q,g}(z,\mu_R)|h(P)\rangle = \sum_f \int_{-1}^{1} \frac{dx}{x}\, \widehat{K}_f(xP\cdot z, z^2, \mu_R, \mu_F)\, \phi_{f/h}(x,\mu_F) + \mathcal{O}(z^2)^n$$

Lattice "cross section"

Calculable partonic "Probe"

Matching Parton to Hadron

Approximation "controllable?"

- Matching $\widehat{K}_f$ to NNLO!

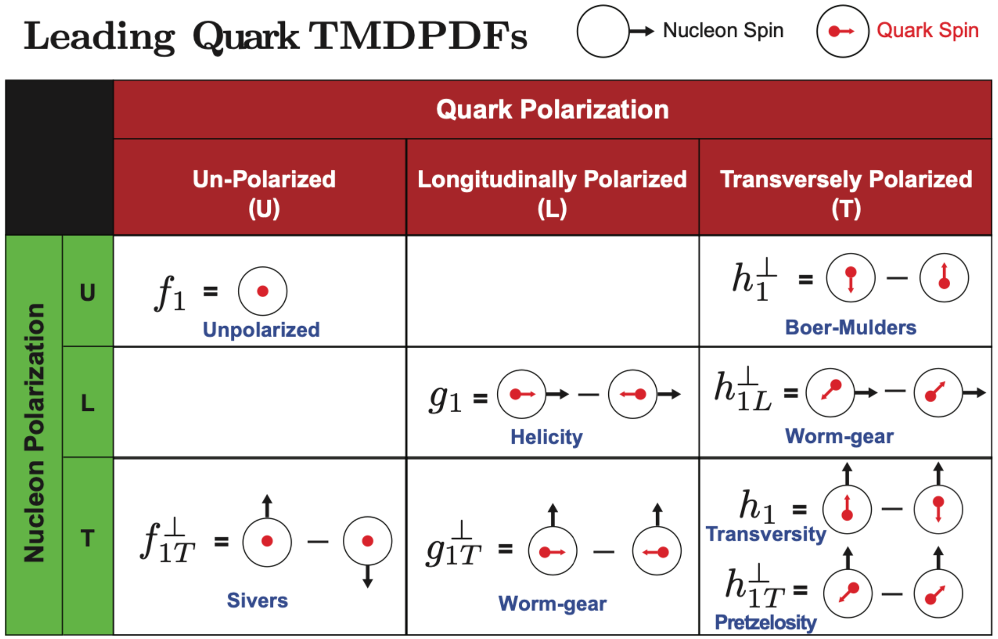
Quasi-PDFs: $\widetilde{\phi}_{(q,g)/h}(\tilde{x},\mu_R) \propto \int_{-\infty}^{\infty} \frac{d(P\cdot z)}{2\pi} e^{i\tilde{x}P\cdot z} \langle h(P)|\mathcal{O}^{\rm R}_{q,g}(z,\mu_R)|h(P)\rangle$

- LQCD data in Global fits: more impactful for polarized PDFs, transversity, GPDs, ..., not yet for PDFs

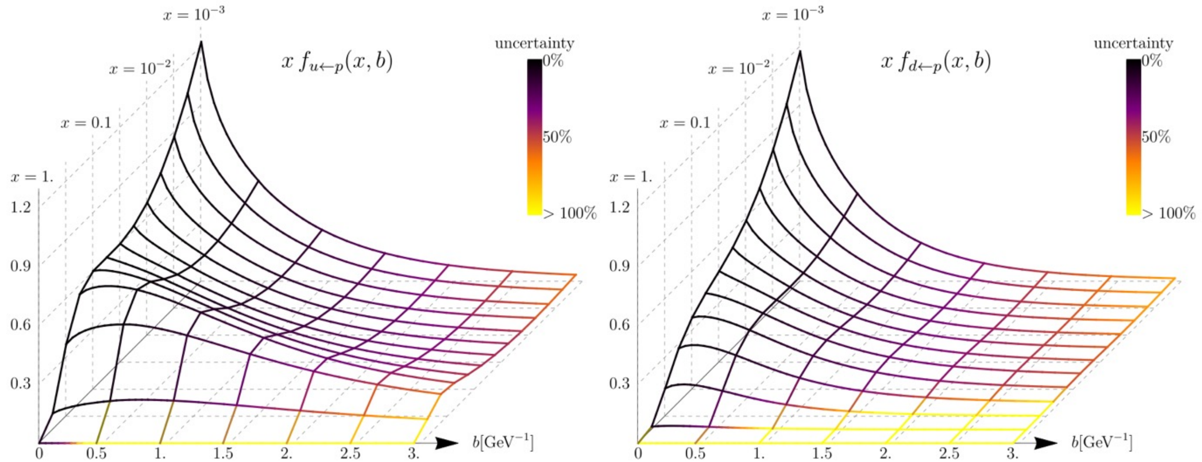
❑ What we want to know:

- Systematic uncertainties from the continue limit, connected diagrams, renormalization, ... ?
- LQCD calculations to generate data that are good for the extraction of x-dependent TMDs, ... ?

Transverse Momentum Dependent PDFs

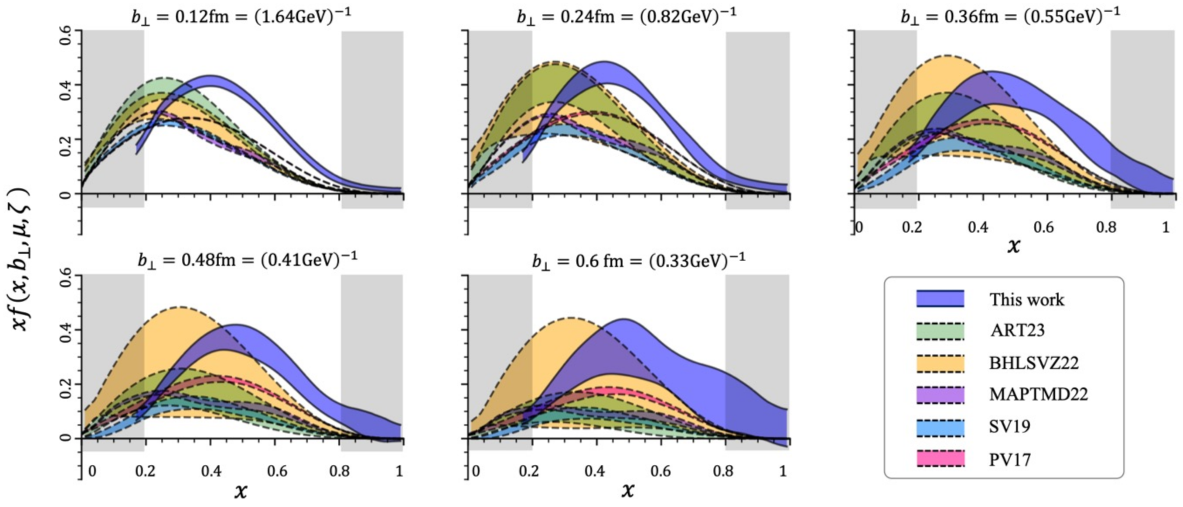


$$F(x,b;\mu,Q^2)=\left(\frac{Q^2}{\zeta_\mu(b)}\right)^{-\mathcal{D}(b,\mu)}F(x,b)$$



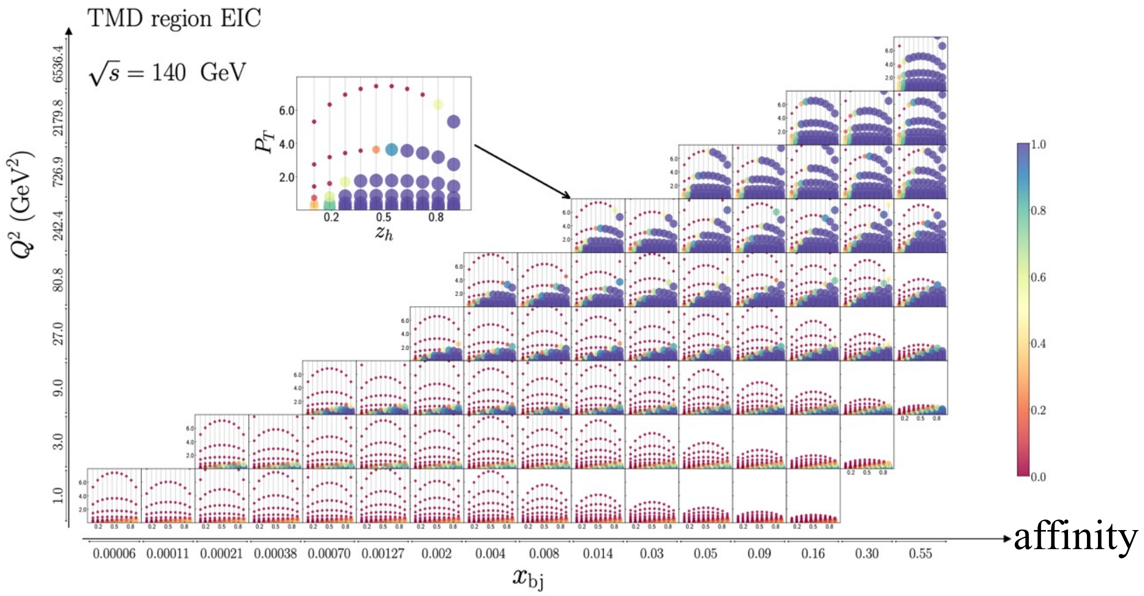
Moos, Scimemi, Vladimirov, Zurita, 2305.07473

- ✓ A lot of data on SIDIS and DY are available.
- ✓ In addition to perturbative constraints, several global analyses of TMDPDFs are obtained.
- ✓ Soft function (intrinsic and CS kernel) has been calculated from several lattice groups (D.Lin's talk on 19/08).
- ✓ A calculation of quark unpolarized isovector TMDPDFs from lattice QCD (a=0.12fm) is available.

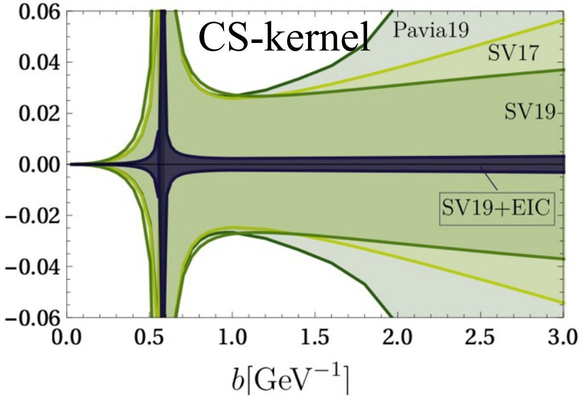


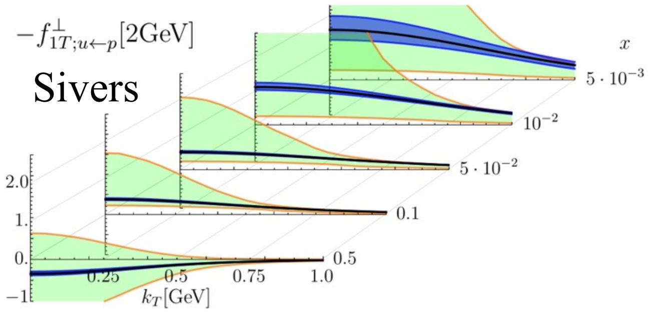
LPC, 2211.02340

Transverse Momentum Dependent PDFs

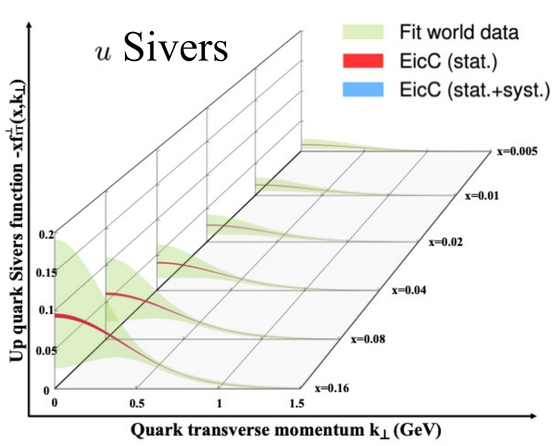


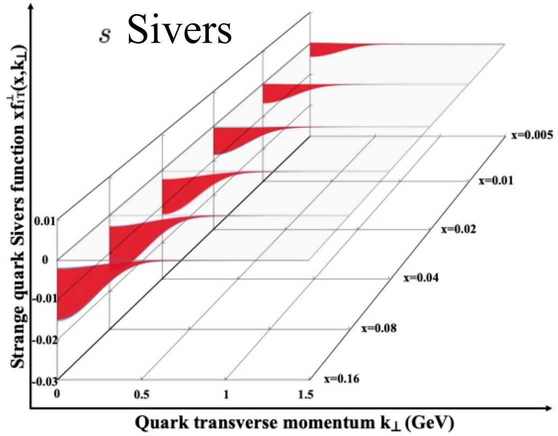
EIC Yellow Report: 2103.05419





- ✓ With more reliable data, to what extent can the global analysis obtain?
- ✓ Can one obtain sophisticated results on TMDPDFs from lattice QCD in a few years?
- ✓ Gluon TMDPDFs (+small x) and subleading twist?
- ✓ TMD fragmentation functions?





Zeng, Liu, Sun, Zhao, 2208.14620

Intrinsic properties of nucleons and nuclei

❑ What do we know?

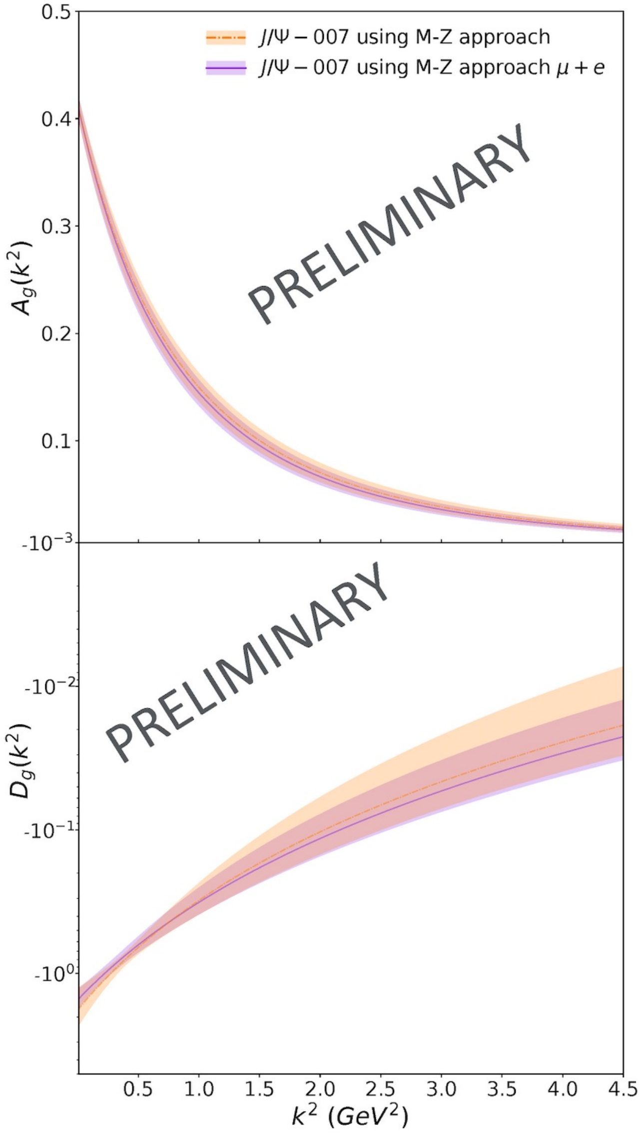
- Total mass, Total charge charge, Total magnetic moment, Total Spin
- Electromagnetic form factors (quarks driven)
  - Current and charge distribution of proton and neutron and nuclei

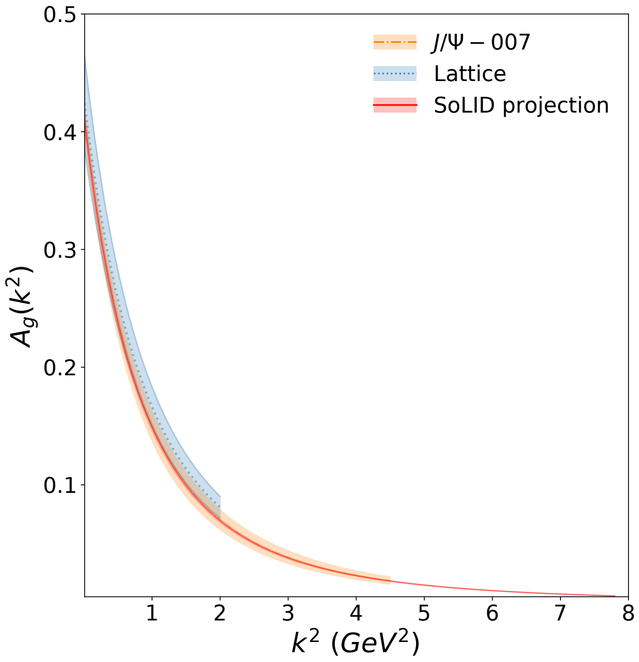
❑ What do we want to know?

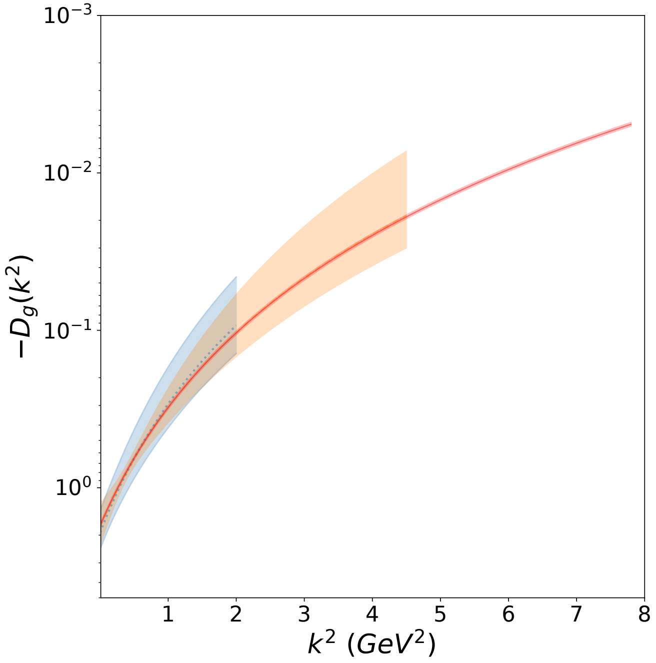
$$\langle N' \mid T^{\mu,\nu}_{q,g} \mid N\rangle$$
$$= \bar{u}(N')\left(A_{g,q}(t)\gamma^{\{\mu}P^{\nu\}} + B_{g,q}(t)\frac{iP^{\{\mu}\sigma^{\nu\}}\rho\Delta_\rho}{2M} + C_{g,q}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} + \bar{C}_{g,q}(t)Mg^{\mu\nu}\right)u(N)$$

- Energy-momentum tensor (gravitational) form factors of quarks and gluons
  - Mechanical properties of the proton/neutron and nuclei
    - Mass density distribution of gluons and quarks
    - Scalar energy density distribution of gluons
    - Pressure density distribution for quarks and gluons
    - If the gluon scalar radius of the nucleon is larger that the charge radius, what is the consequence in nuclei?

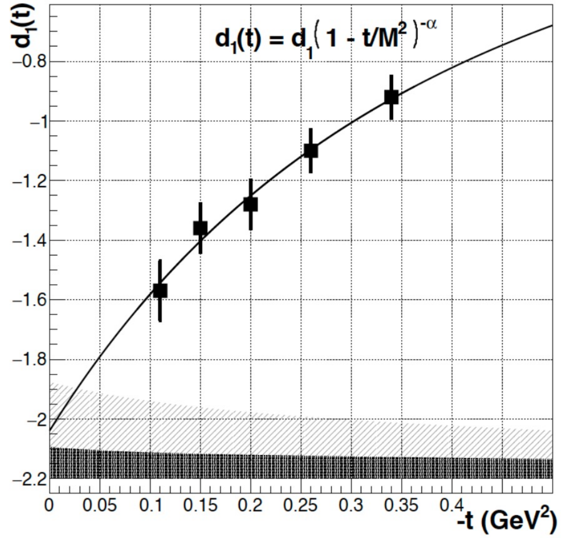
Example gluonic GFFs today & tomorrow: Can we improve on the accuracy?







Quark D GFF



Gluon A & D GFFs (SoLID projections)

Gluonic A & D GFFs

Volker Burkert, L. Elouadrhiri, F.X. Girod, Nature 557 (2018) no.7705, 396-399

B.Duran, et al., proton, Nature 615, no.7954, 813-816 (2023)

K. A. Mamo and I. Zahed, *Phys. Rev. D* **106**, no.8, 086004 (2022)

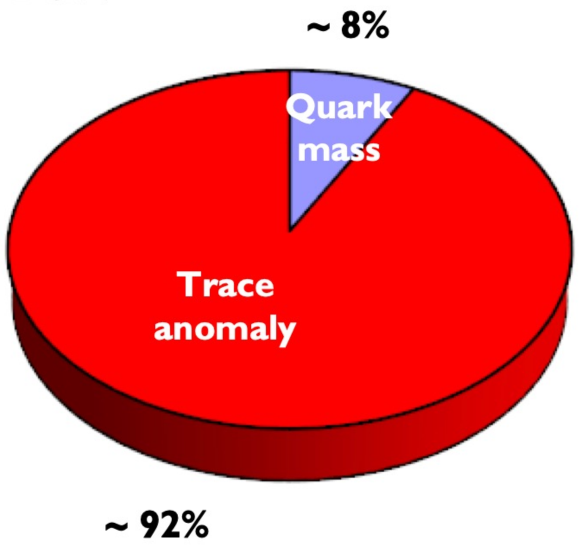
D. A. Pefkou, D. C. Hackett and P. E. Shanahan, *Phys. Rev. D* **105** (2022) no.5, 054509

Different Mass decompositions

Proton Mass budget decompositions C. Lorcé (from 2022 INT workshop)

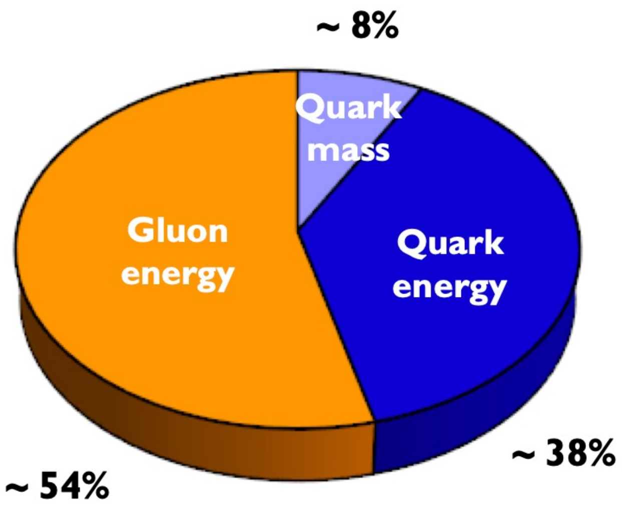
Trace decomposition

$\mu = 2\,\text{GeV}$



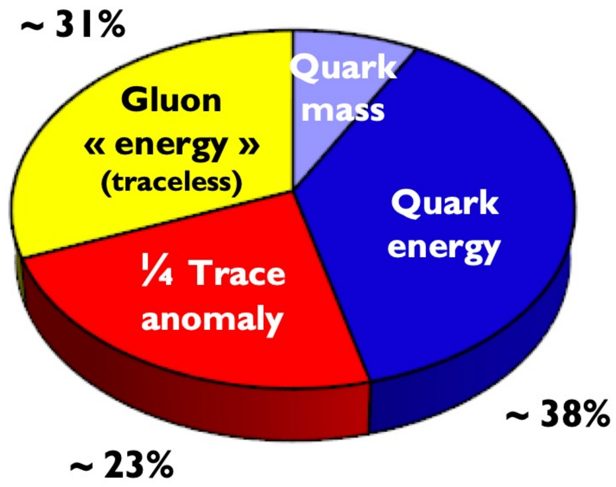
Relies on virial theorem

Energy decomposition



Independent of virial theorem

Ji's decomposition



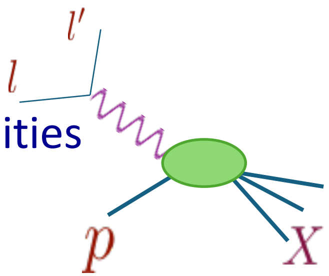
Motivated by virial theorem

The many fronts of experimental studies

Inclusive

Parton distributions

Sum rules and polarizabilities



Since 1998

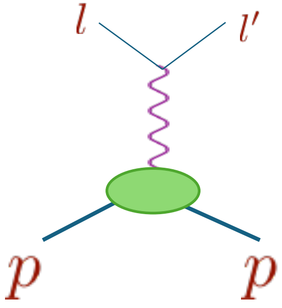
Generalized Parton Distributions (GPDs)

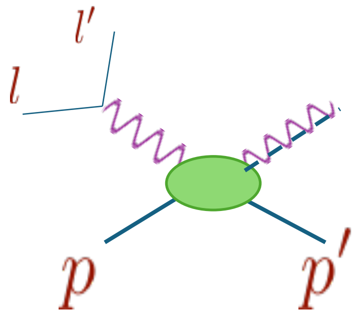
Exclusive reactions In nucleons and nuclei

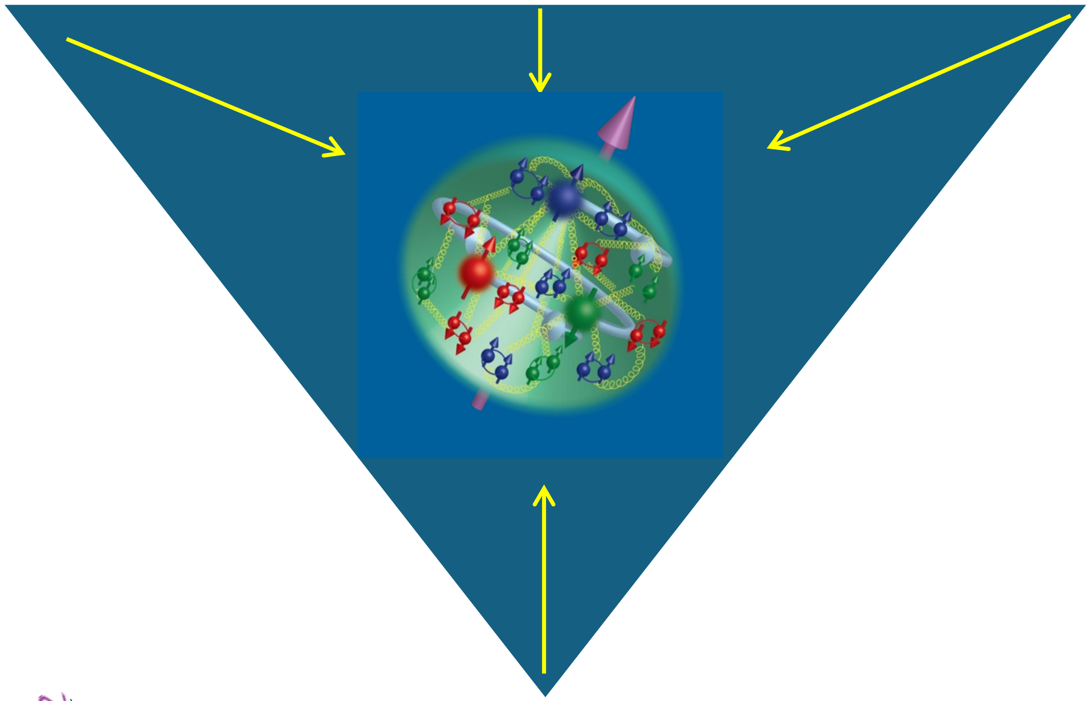
Elastic form factors

Deep Virtual Compton Scattering

Deep Virtual Meson Production







Electroweak

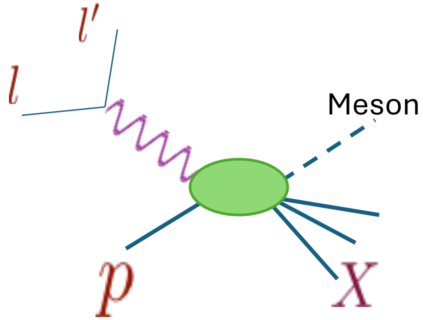
probe to hadronic systems

Since 2002

Transverse Momentum Distributions (TMDs)

Semi-Inclusive DIS In nucleons and nuclei

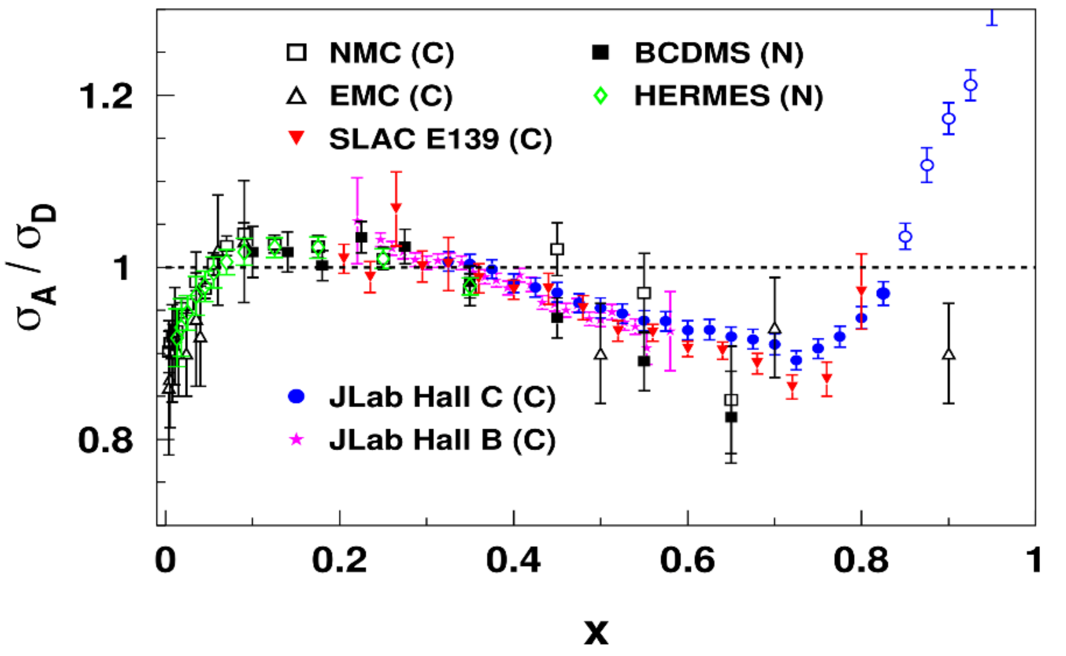
Distributions and Fragmentation functions

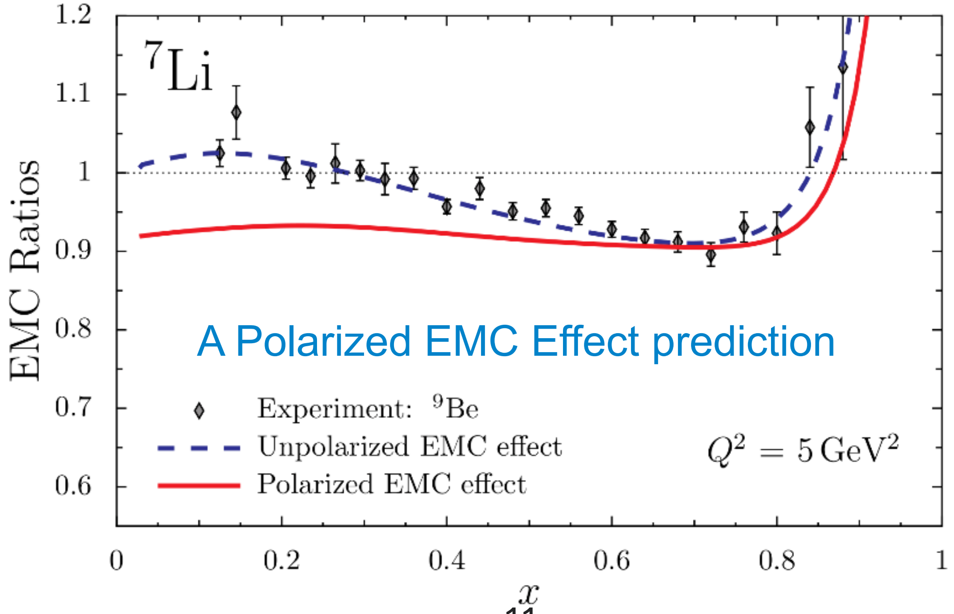


NUCLEAR PDFS & IMAGING

- Little is known about Nuclear PDFs
  - EMC Effect provides an enduring puzzle at the intersection of QCD and traditional nuclear structure approaches
- To gain deeper insight into QCD and Nuclei need to address several interesting questions, for example:
  - What is the quark flavor dependence of nuclear PDFs/EMC effect?
  - How are gluon PDFs modified by the nuclear medium?
  - Observation of the gluon transversely PDF in $J \geq 1$ nuclei (e.g. ^{2}H or ^{6}Li) first direct evidence for non-nucleonic components in nuclei
  - Can the new PDFs that appear in $J \geq 1$ nuclei, such as $b_1(x)$, also provide inside into QCD effects in the NN potential?
- As a first step, important to obtain data on polarized nuclear PDFs (e.g. in ^{6}Li, ^{7}Li, and other light nuclei)
  - Will address the question: How is quark spin impacted by the nuclear medium?
  - For example, is quark spin converted to quark orbital angular momentum by the nuclear medium?

EMC Effect observed in unpolarized DIS



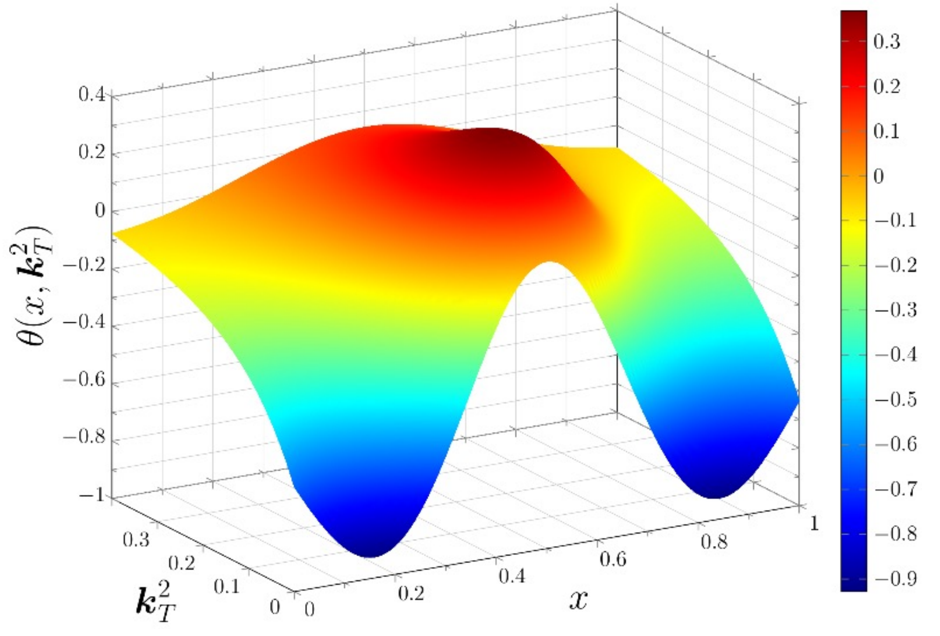


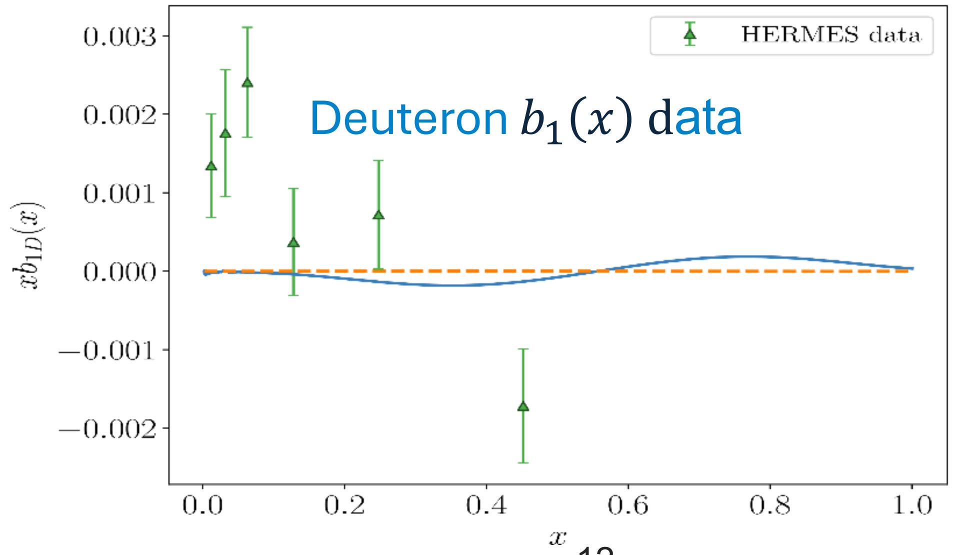
MOMENTUM TOMOGRAPHY

leading twist		quark operator		
		γ^+	$\gamma^+\gamma_5$	$\gamma^+\gamma^i\gamma_5$
target polarization	U	$f_1 =$ unpolarized		$h_1^\perp = \ -$ Boer-Mulders
	L		$g_1 = \ -$ helicity	$h_{1L}^\perp = \ -$ worm gear 1
	T	$f_{1T}^\perp = \ -$ Sivers	$g_{1T} = \ -$ worm gear 2	$h_1 = \ -$ transversity $h_{1T}^\perp = \ -$ pretzelosity
	TENSOR	$\theta_{LL}(x, \boldsymbol{k}_T^2)$ $\theta_{TT}(x, \boldsymbol{k}_T^2)$ $\theta_{LT}(x, \boldsymbol{k}_T^2)$	$g_{1TT}(x, \boldsymbol{k}_T^2)$ $g_{1LT}(x, \boldsymbol{k}_T^2)$	$h_{1LL}^\perp(x, \boldsymbol{k}_T^2)$ $h_{1TT}, \quad h_{1TT}^\perp$ $h_{1LT}, \quad h_{1LT}^\perp$

- TMDs enable the study of the EMC Effect as a function of transverse momentum
- Tensor polarization in spin-1 target gives 3 additional *T*-even and 7 additional *T*-odd quark TMDs
- These new TMDs are related to $b_1(x)$ PDF
  - Impossible to explain HERMES data with only bound nucleon degrees of freedom — need exotic QCD states, 6q bags, etc

Ninomiya, Bentz and ICC, Phys. Rev. C **96**, no.4, 045206 (2017)

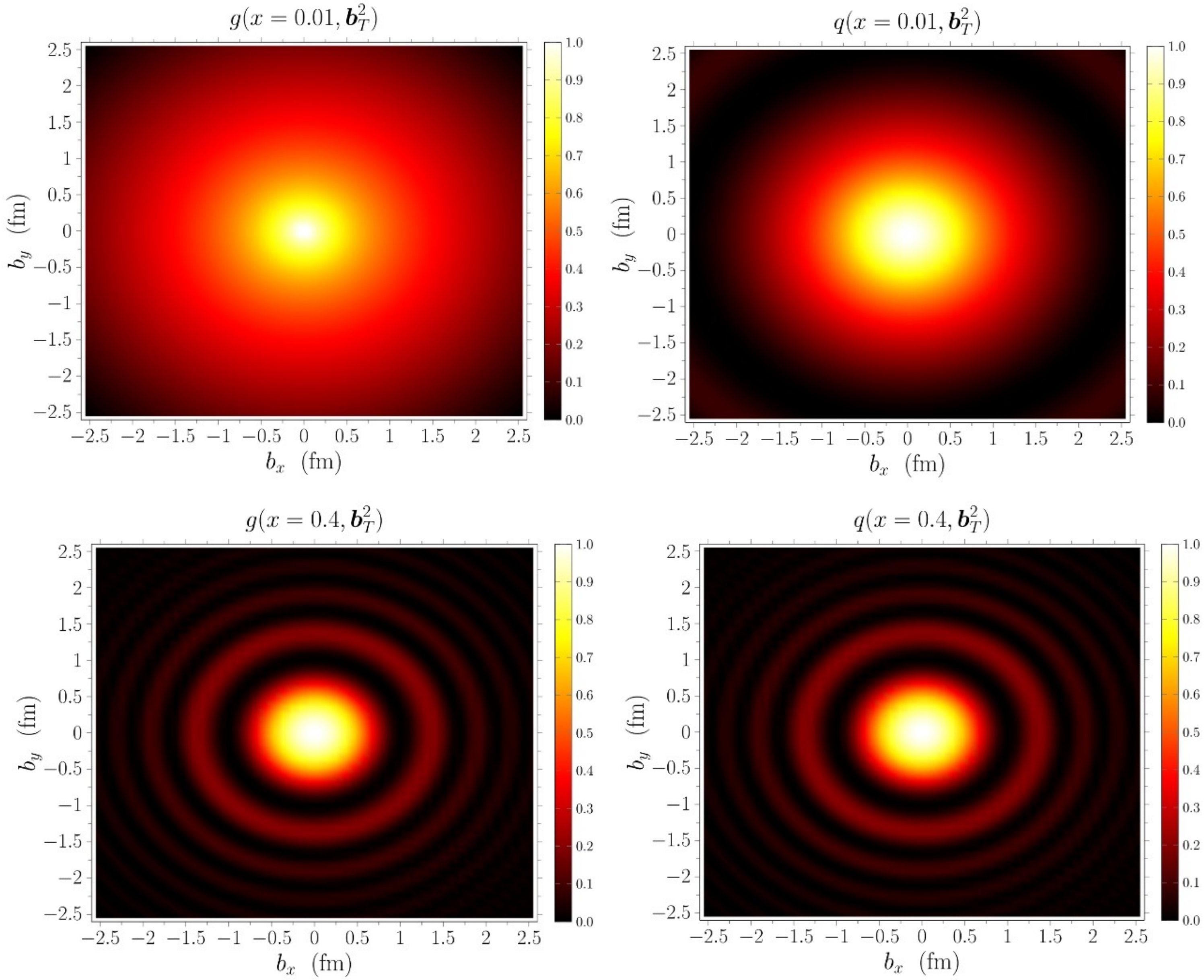




SPATIAL TOMOGRAPHY

- Spatial Imaging of nuclei via GPDs can provide rich insights into QCD
- Key physics questions include:
  - How does the NN interaction arise from QCD?
  - How do quark/gluon confinement length scales change in medium?
- Insights can be by obtained by comparing quark and gluon distributions for slices in x and b_T^2
- Can also study quark and gluon gravitational form factors; mass/energy radii for quarks and gluons, etc.
- Nuclear PDFs & Imaging are essential for comprehensive understanding of QCD

Images represent naïve expectations for ^{4}He



Backup Slides

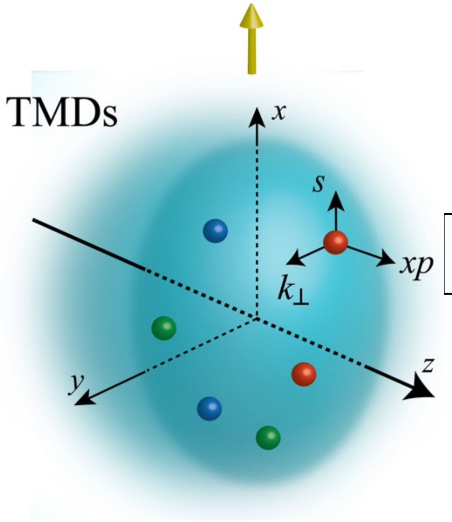
Unified View of Nucleon Structure

$W_p^u(x,k_T,r_T)$ Wigner distributions

Transverse Momentum Dist. (TMD)

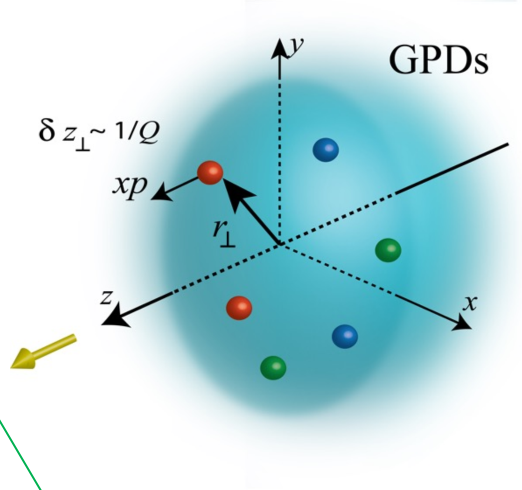
Tomography

Generalized Parton Dist. (GPD)



dr_T

d^2k_T



TMD $f_1^u(x,k_T)$, $h_1^u(x,k_T)$

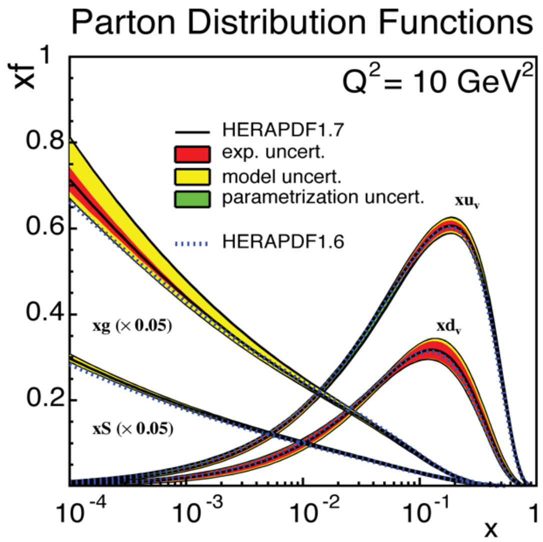
GPD

d^2k_T

d^2r_T

dx & Fourier Transformation

Electromagnetic Form Factor $G_E(Q^2)$, $G_M(Q^2)$



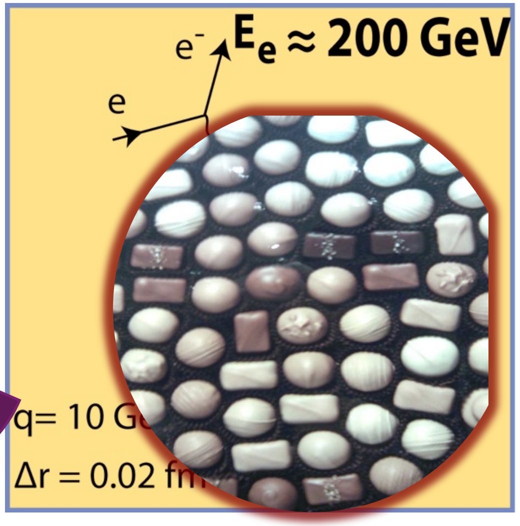
PDFs
$f_1^u(x)$, ..
$h_1^u(x)$

1D

Nucleon gravitational form factors A, B, C and C_bar; (quarkonic & gluonic) Mass density, Pressure density, Shear Forces density

Probing deeper for the fundamental degrees of freedom, quarks and gluons

Quarks



Emergent Phenomenon