Spatial imaging of the nucleon and nuclei at an Electron-Ion Collider

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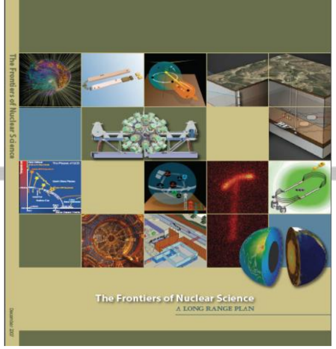
Jefferson Lab

EIC Advisory Committee meeting
Jefferson Lab, April 10, 2011

The science of an EIC



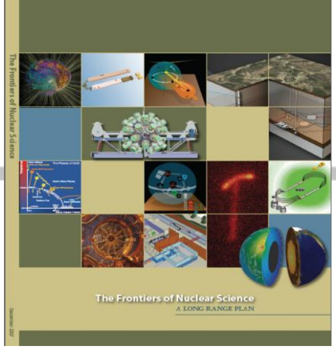
Three major science questions for an EIC from NSAC LRP07:

- What is the internal landscape of the nucleon?
- What is the role of gluons and their self-interactions in nucleons and nuclei?
- What governs the transition of quarks and gluon into pions and nucleons?

EIC science goals:

- Map the spin and spatial structure of quarks and gluons in nucleons
- Discover the collective effects of gluons in atomic nuclei
- Understand the emergence of hadronic matter from quarks and gluons

The science of an EIC



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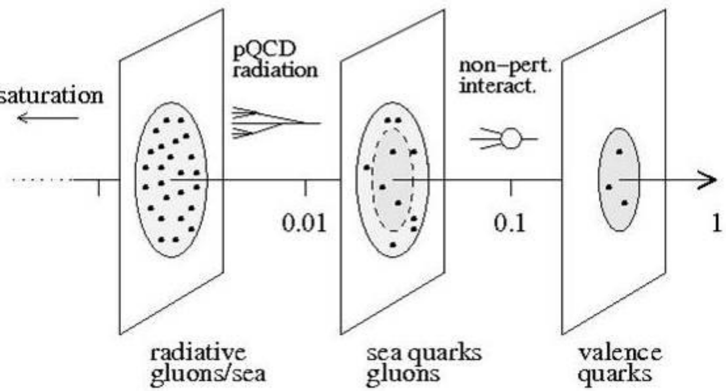
this talk

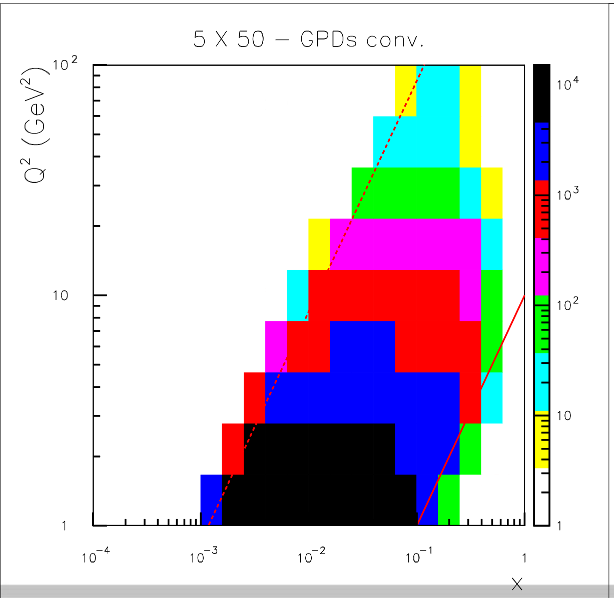
Kinematic coverage at EIC and accessing sea quarks and gluons



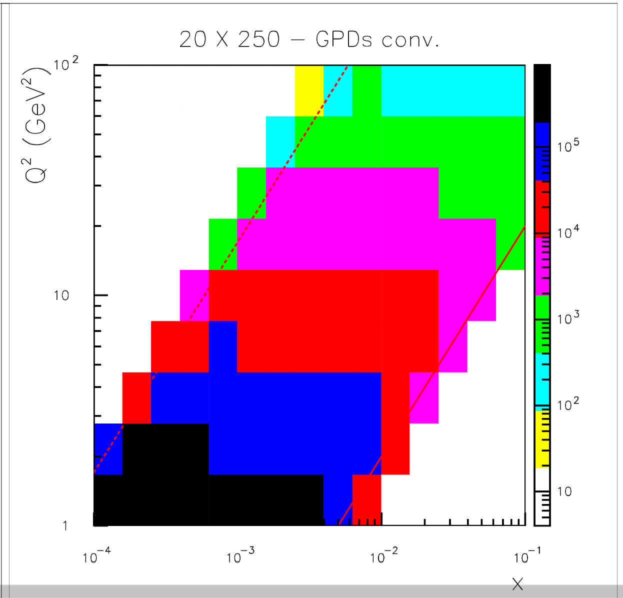
- Nucleon/nucleus is a many-body system
- Deep inelastic scattering (DIS) probes different parton (quark and gluon) components of wave function

Figure due to C. Weiss

√s≈30 GeV



√s≈140 GeV



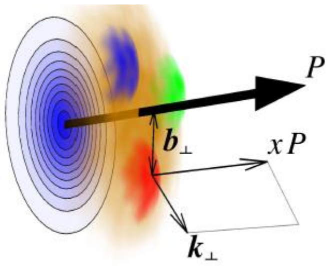
EIC is the machine to study the sea quark and gluon structure of protons/nuclei !

S. Fazio,
INT 10-03 program write-up

Physics of spatial/3D imaging of parton distributions

Two complimentary pictures of the nucleon/nucleus

Generalized parton distributions (GPDs) and dipole amplitudes:
Distributions in (x, b_T)



TMDs:
Distributions in (x, k_T)

- correlations and distributions of partons in the transverse plane (b_T) (tomographic image of nucleon/nucleus at given x, transverse size of parton distributions)

- encode information on non-perturbative dynamics and origin of various parton distributions:
  - orbital angular momentum → helicity sum rule
  - chiral dynamics at large b_T
  - Gribov diffusion at small x

- important for pp and pA phenomenology at RHIC and LHC (b_T dependence of PDFs)

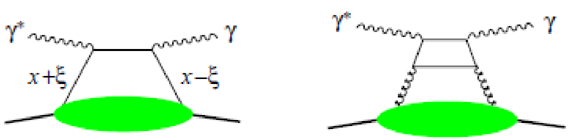
- essentially unknown for sea quarks and gluons → EIC

Science matrix of GPD studies at an EIC

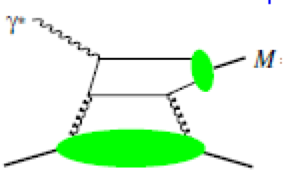
- GPDs are accessed in exclusive reactions; theory (factorization, Q^2 evol.) well-established
- Spatial imaging in b_T via Fourier transform w.r.t. momentum transfer t

Process

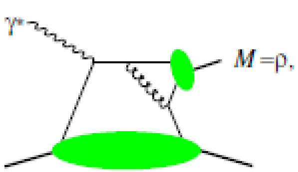
- Deeply virtual Compton scattering (DVCS)



- Production of J/ψ and φ



- Production of ρ^0



Channel

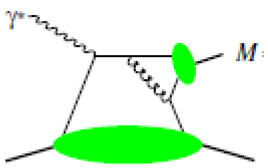
- unpol. singlet quarks and gluons (NLO)
- gluon
- sea quarks and gluon: flavor separation

Special requirements/uniqueness of EIC

- wide kinematic coverage in x and Q^2: access to low x (sea quarks and gluons) and high Q^2 (factorization and Q^2 evolution for constraining parameterizations of GPDs)
- high luminosity for precision and multi-dimensional binning
- L and T polarization (> 70% for collider)
- exclusivity with Roman pots

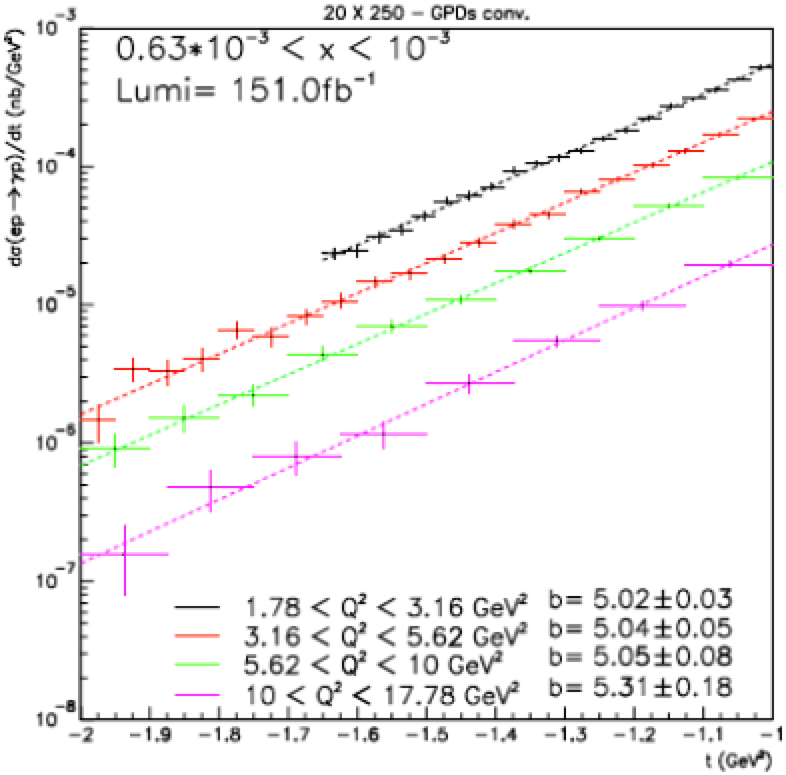
Science matrix of GPD studies at an EIC (Cont.)

- GPDs are accessed in exclusive reactions; theory (factorization, Q^2 evol.) well-established
- Spatial imaging in b_T via Fourier transform w.r.t. momentum transfer t

Process	Channel	Special requirements/uniqueness of EIC
▪ Production of π, K, K*, ρ^+ 	• polarized and unpol. sea and valence quarks, including strangeness • new for collider, natural extension of JLab12 program • tests of factorization	. wide kinematic coverage in x and Q^2: access to low x (sea quarks and gluons) and high Q^2 (factorization and Q^2 evol.) • high luminosity for precision and multi-dimensional binning . L and T polarization (>70% for collider) . exclusivity with Roman pots . L/T separation . more symmetric energies for PID

Example 1: Simulation of DVCS cross section for EIC

Simulated DVCS cross section
(150 fb^{-1})

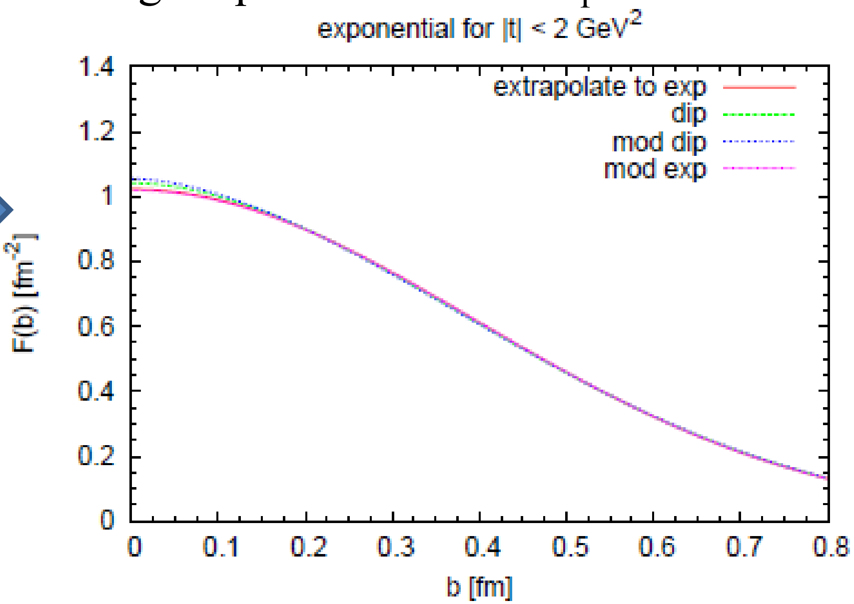


S. Fazio

- The slope of the t dependence can be extracted with 1% accuracy due to high luminosity!
(compare to ~10% accuracy at HERA)

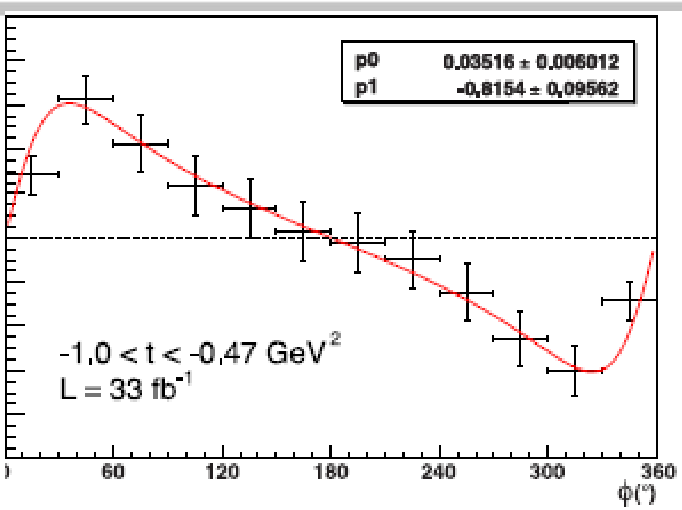
- Extracted transverse distribution of "singlet quarks" down to $b_T \approx 0.05$ fm

F.T.



E. Aschenauer, M. Diehl, S. Fazio
(from the write-up of the INT10-03 program)

Example 2: Simulated DVCS beam-spin asymmetry



$$A_{LU} = \frac{d\sigma^{\leftarrow} - d\sigma^{\rightarrow}}{d\sigma^{\leftarrow} + d\sigma^{\rightarrow}}$$

20x250 GeV

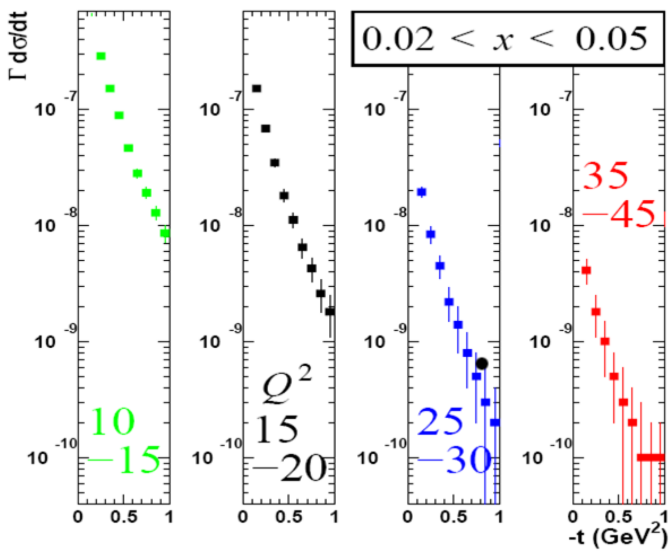
- in typical kinematic bin $1.6 \times 10^{-3} < x < 2.5 \times 10^{-2}$ and $3.2 < Q^2 < 5.6$
- 3 months with 50% efficiency at $L = 10^{34}$ will provide 10-15% accuracy on Im H for singlet quarks
- using L and T polarized hadron beam, will access other GPDs

R. Geraud, H. Moutarde, F. Sabatie, INT write-up

Example 3: Production of π^+

$ep \rightarrow e'\pi^+ n$

5x50 GeV



- probes polarized quark GPDs Htilde and Etilde
- flavor structure u-d
- replacing π^+ by K^+ → will probe 2u-d-s
- requires luminosity and L/T separation, but does not need high energy

T. Horn, INT write-up

Spatial imaging of sea quarks and gluons in nuclei

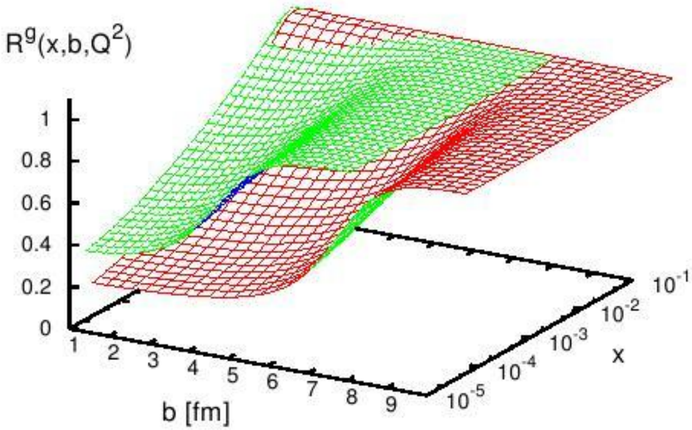
• GPDs in nuclei can be accessed in exclusive reactions with nuclei (DVCS, J/ψ production); the same physics motivation as for proton
• Integral part of studies of the gluon density in nuclei
• First time at collider; essentially unknown (!)
• Dependence on b_T is very (!) important for modeling pA collisions at RHIC and LHC
• Predicted theoretically in the leading twist theory of nuclear shadowing

$$R^j(x,b,Q^2) = \frac{f_{j/A}(x,Q^2,b)}{A\,T_A(b) f_{j/N}(x,Q^2)} = \frac{H_A^j(x,\xi=0,b,Q^2)}{A\,T_A(b) f_{j/N}(x,Q^2)}.$$

• Nuclear suppression (shadowing)is larger at small b and x

• Average transverse size of the distribution of partons in b-plane, <b²>, increases

→ can be tested experimentally in DVCS and VM production

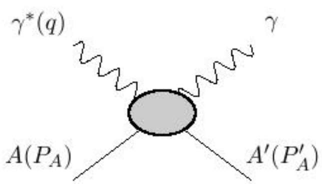


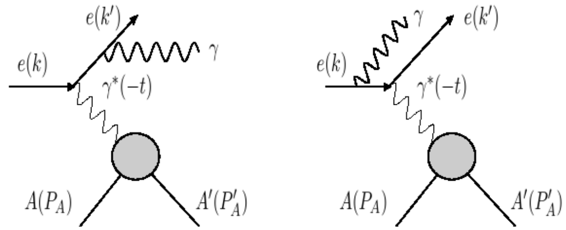
Gluons in ^{40}Ca and ^{208}Pb, Q^2=4 GeV^2

L. Frankfurt, V. Guzey, M. Strikman, INT write-up

Spatial imaging of sea quarks and gluons in nuclei (Cont.)

DVCS interferes with Bethe-Heitler (BH) process



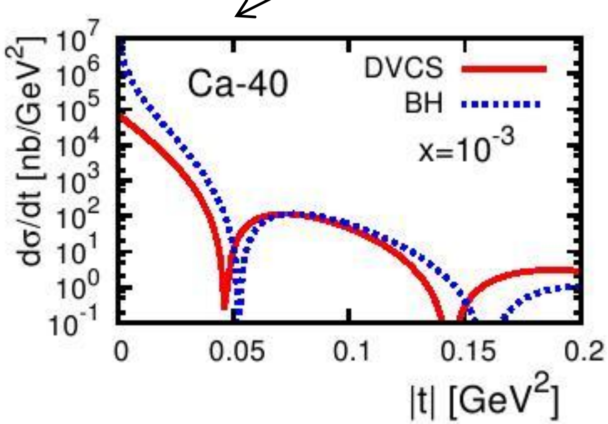


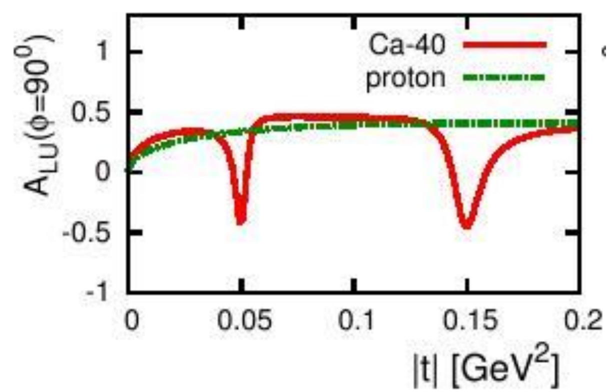
shadowed

not-shadowed

$<b^2>_{DVCS}$ > $<b^2>_{BH}$

$$A_{LU}(\phi) = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}} \propto \sin\phi \frac{H_A(\xi,\xi,t)F_A(t)}{F_A^2(t)}$$





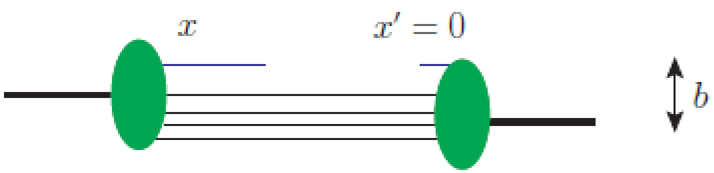
- Need to guarantee full exclusivity → experimental challenge
- Position of minima depend on the interplay between LT shadowing and saturation → MC simulations, W.A.Horowitz: T. Toll and T. Ullrich, INT write-up

Reconstructing quark and gluon GPDs using unique EIC capabilities (and available manpower)

DVCS MC simulations
S. Fazio
F. Sabatie *et al.*
T. Horn
T. Toll and T. Ulrich

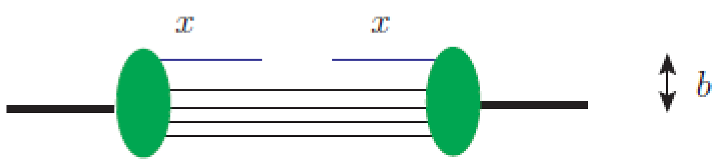
EIC data on exclusive reactions
- high accuracy
- wide x and Q^2 coverage
- different polarizations
- many observables

Stage-1 imaging:
Extraction of GPDs in b-space
on the cross-over line GPD($x, \xi=x, b_T$)



Stage-2: Full extraction of GPD(x, ξ, b_T)
by fitting the data using flexible parameterization of GPDs and taking advantage of wide x-Q^2 coverage
D. Mueller *et al.*
H. Moutarde *et al.*

- ξ=0 limit and probabilistic interpretation
- evaluation of moments & comparison to lattice
- spin sum rule & orbital angular momentum



Summary

A future high-energy and high-luminosity Electron-Ion Collider with polarized beams will have excellent capabilities for precision studies of the spatial/3D sea quark and gluon structure of the nucleon and nuclei in exclusive processes.