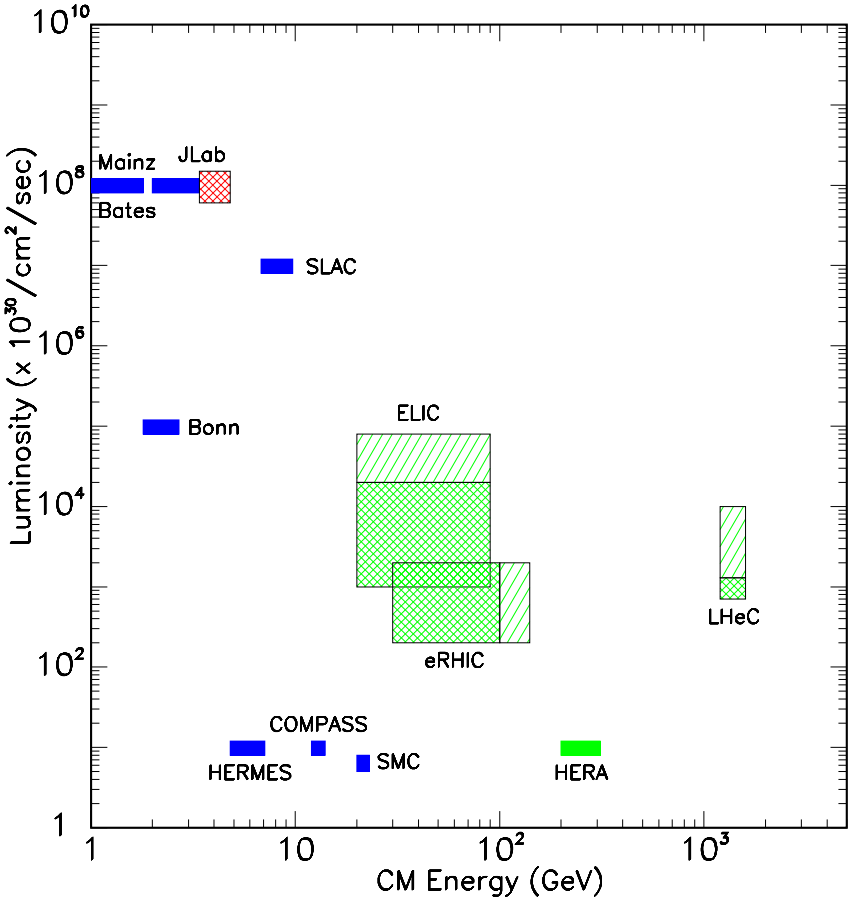
Nuclear physics with an Electron–Ion Collider

C. Weiss (JLab), APS April Meeting 2010, 13–Feb–2010



Luminosity	low-rate processes
Energy	x, Q^2 coverage
Detection	final states, resolution

Polarization, nuclei, . . .

- Landscape of nucleon structure in QCD

  Nucleon as many–body system

  Partonic structure $\leftrightarrow$ dynamics

- Nucleon structure with EIC

  Quark/gluon momentum and spin distributions (PDFs)

  Spatial distributions (GPDs) ← Lumi

  Orbital motion (TMDs) ← Lumi

- Nuclei in QCD and saturation

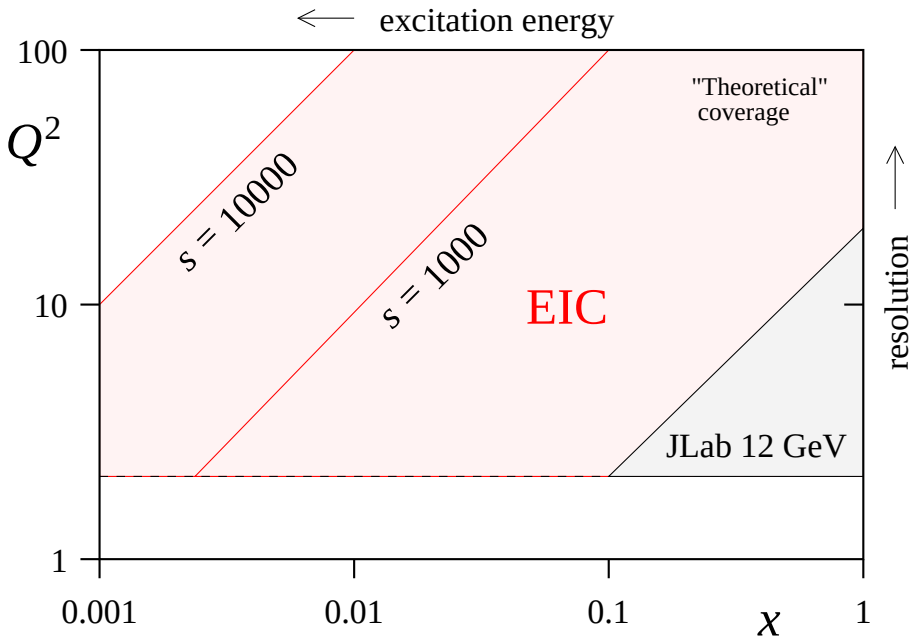
  Nuclear gluons, EMC effect

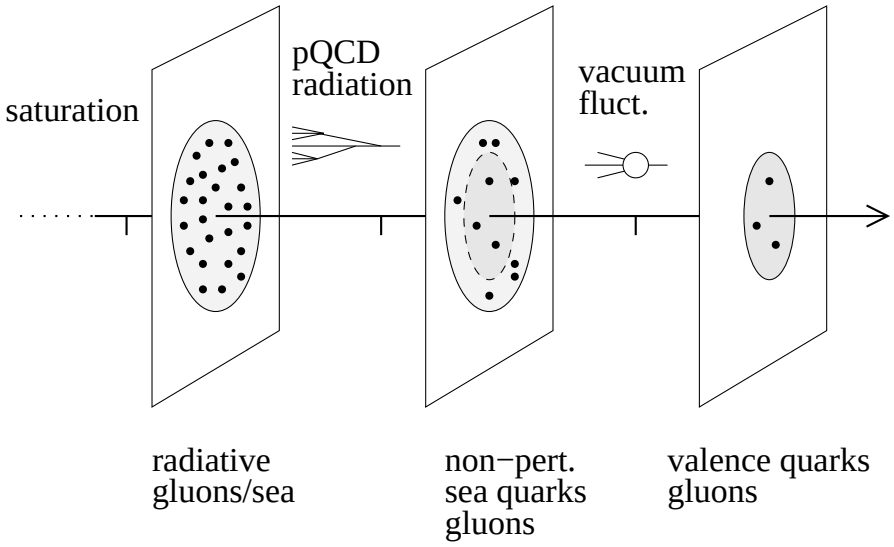
  Color transparency, coherent processes ← Lumi

  Physics of high gluon densities

- Machine concepts and project status

Nucleon structure in QCD: Landscape





- Nucleon in QCD many–body system

  Different components of wave function, effective dynamics

  "Face" changes with excitation energy and resolution scale!

- Components probed in ep scattering

JLab 12 GeV	Valence region: $3q, 5q$
EIC	Sea quarks, gluons, Q^2 dependence

- Physical properties

  Parton densities

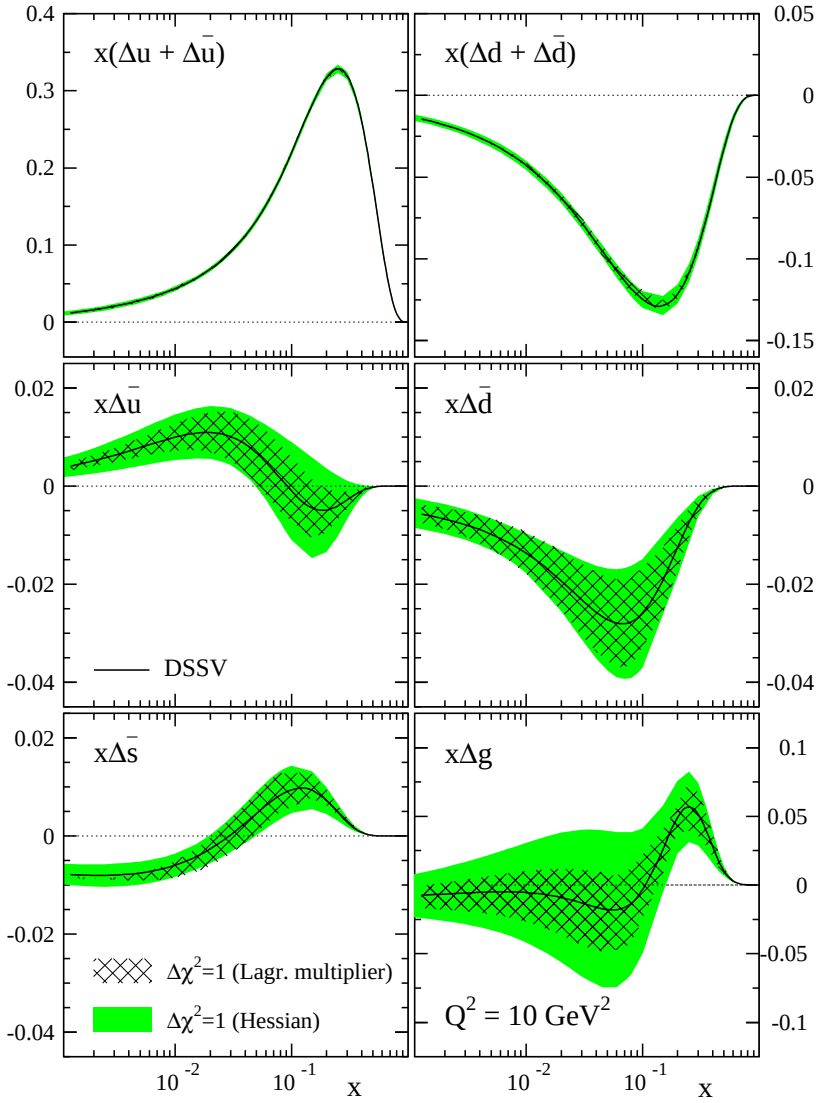
  Transverse spatial distributions

  Orbital motion, angular momentum

  Correlations

  + nuclear modifications

Parton densities: Quark/gluon polarization



DSSV 09, $Q^2 = 10\,\mathrm{GeV}^2$

- Polarized quark/gluon densities from global QCD fits to ep/pp data

  EMC, SMC, SLAC, HERMES, COMPASS, JLAB, RHIC
  De Florian, Sassot, Stratmann, Vogelsang 08

- $\Delta G(x)$ still poorly known!

  Improvement from COMPASS + JLab 12 GeV inclusive data

  Nucleon spin requires quark/gluon orbital angular momenta!

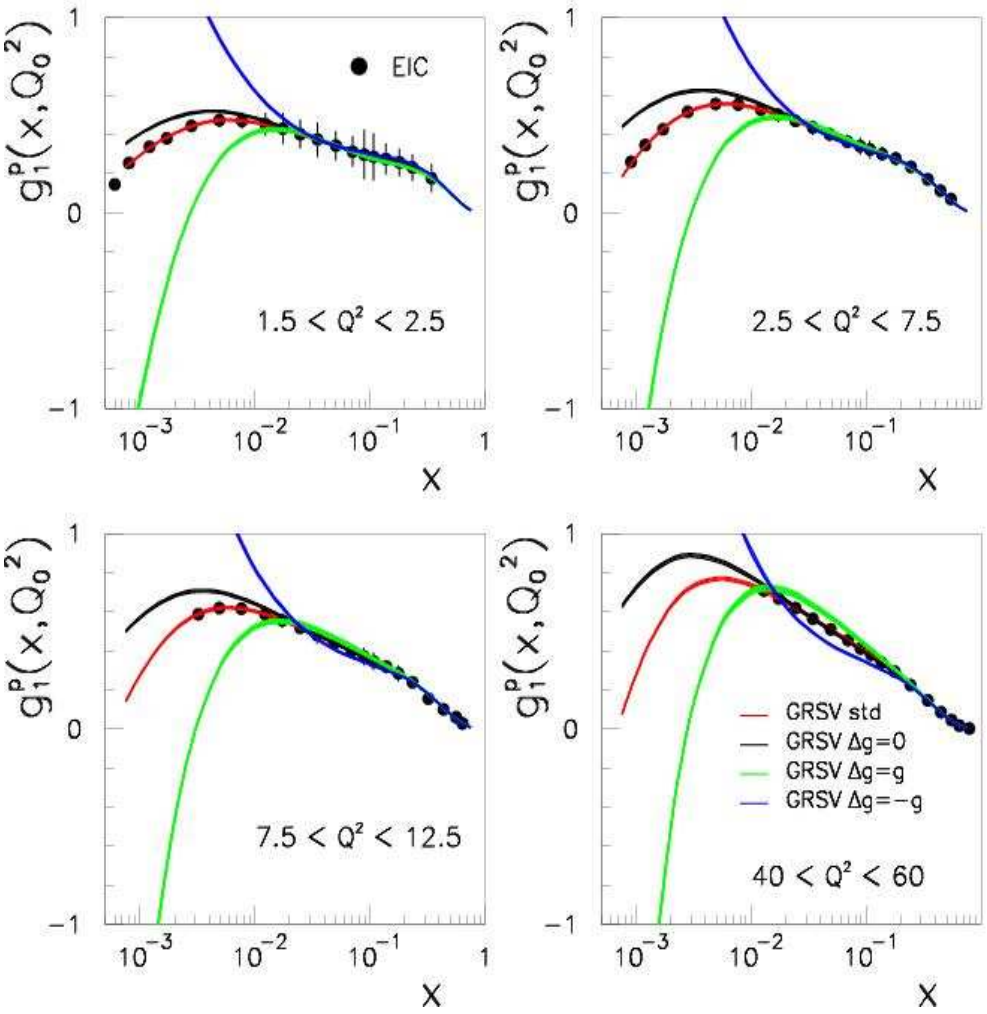
  "Next generation" of dynamical models, lattice QCD calculations

- Flavor distributions $\Delta q(x)$, $\Delta\bar{q}(x)$ from semi–inclusive DIS

  QCD vacuum fluctuations or nucleon's meson cloud?
  Dorokhov, Kochelev; Diakonov et al.

  First hints that $\Delta\bar{u} \neq \Delta\bar{d}$!

Parton densities: Gluon polarization with EIC



EIC 7/150 GeV, $5\,\mathrm{fb}^{-1}$. R. Ent, A. Bruell

- ΔG from Q^2–dependence of spin structure function $g_1(x, Q^2)$

  Dramatic improvement over existing data

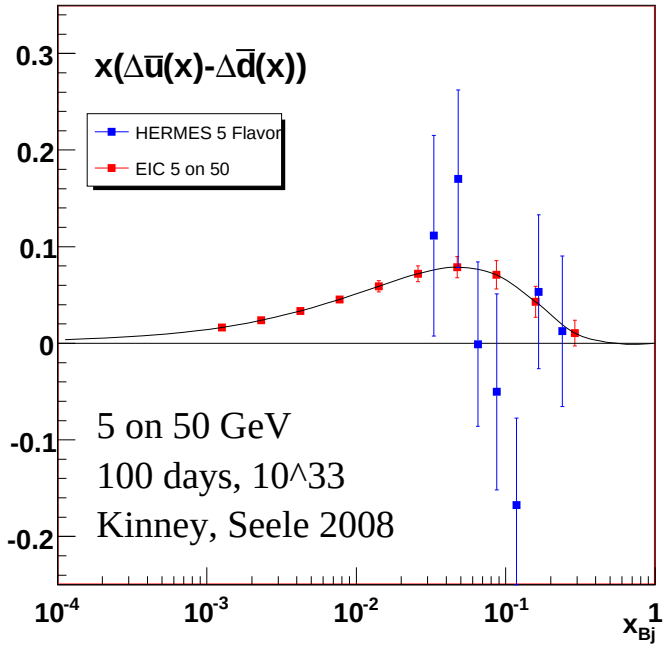
- Experimental requirements

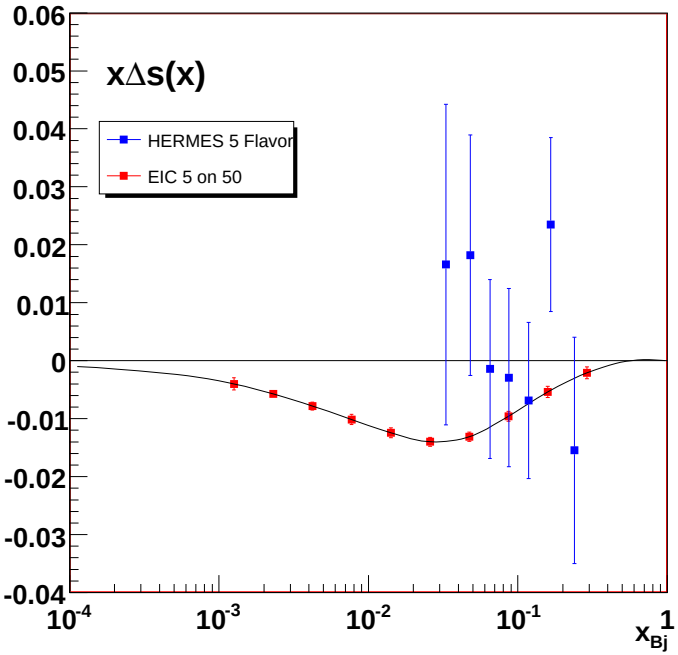
  Wide kinematic coverage in x, Q^2

  Polarization, systematics

- Alt: Gluon polarization through open charm production

Parton densities: Charge/flavor separation





- Quark charge/flavor distributions from semi–inclusive DIS

  Precise mapping of polarized sea
  QCD vacuum in nucleon structure

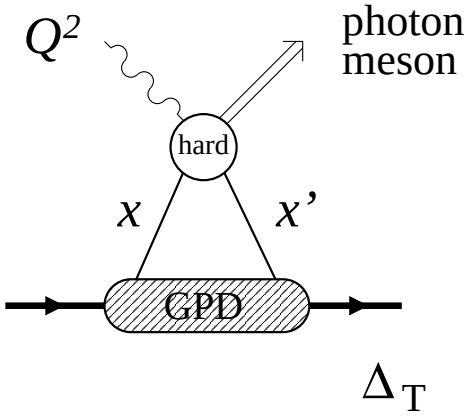
  Requires kinematic reach and luminosity

- Ideal with medium–energy EIC

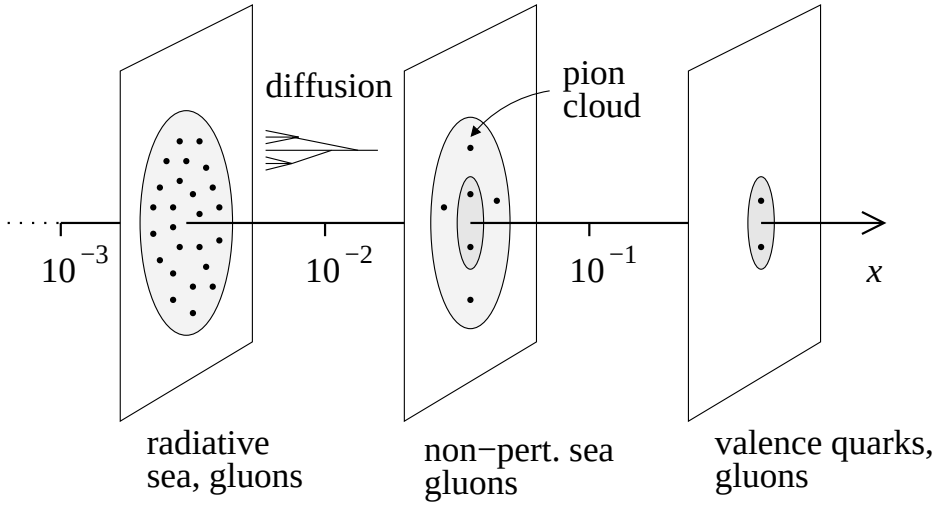
  Better statistics at $x \sim 0.1$

  Good particle ID at lower energies

Transverse imaging: Exclusive processes



Fourier



- How are quarks and gluons distributed in transverse space?

  Fundamental sizes, cf. form factors
  Visualization: 3D Images

  Dynamics: Valence quarks, pion cloud, diffusion in QCD radiation

  Input to MC pp@LHC, saturation

- High–Q^2 exclusive processes

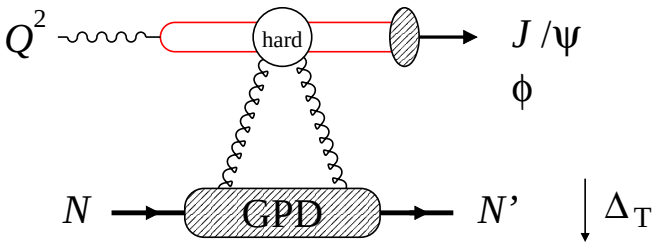
  GPDs ($x' = x$): Form factors of partons with longitudinal momentum fraction x

  Transverse spatial distribution from Δ_T dependence

- JLab 12 GeV: Valence quark GPDs through γ, meson production

  Gluons! Sea quarks! Spin/flavor?

Transverse imaging: Valence gluons



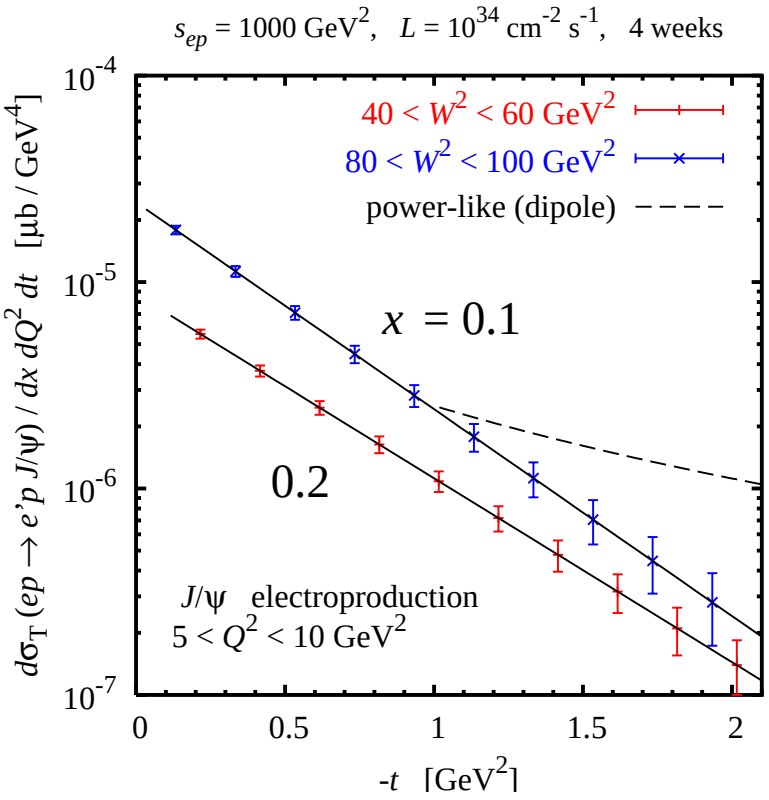
- EIC: Precise gluon imaging through exclusive J/ψ and ϕ

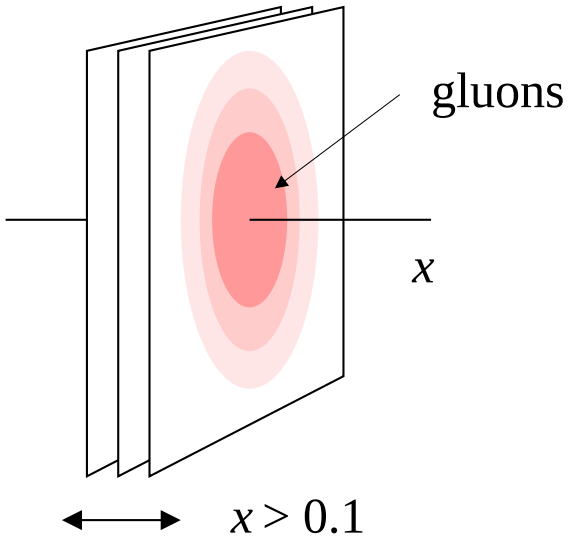
  $x > 0.01$: Map unkown region of non-perturbative gluons!

- Experimental requirements

  Recoil detection for exclusivity, t–measurements

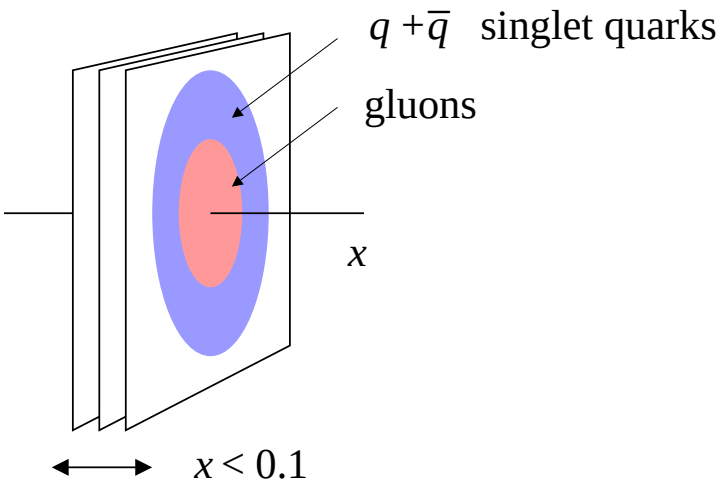
  Luminosity $\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for $x > 0.1$, electroproduction, high–t

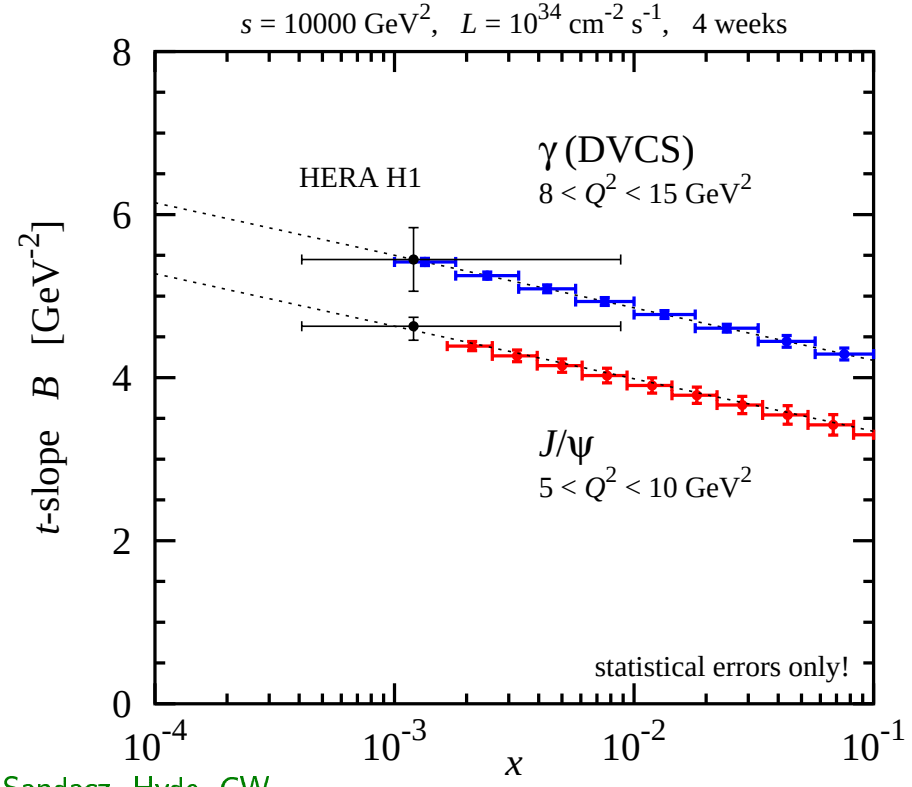




Hyde, CW

Transverse imaging: Gluon vs. quark size





Sandacz, Hyde, CW

- Do singlet quarks and gluons have the same transverse distribution?

  Hints from HERA:
  Area$(q + \bar{q})$ > Area(g)

  Dynamical models predict difference:
  Pion cloud, constituent quark picture

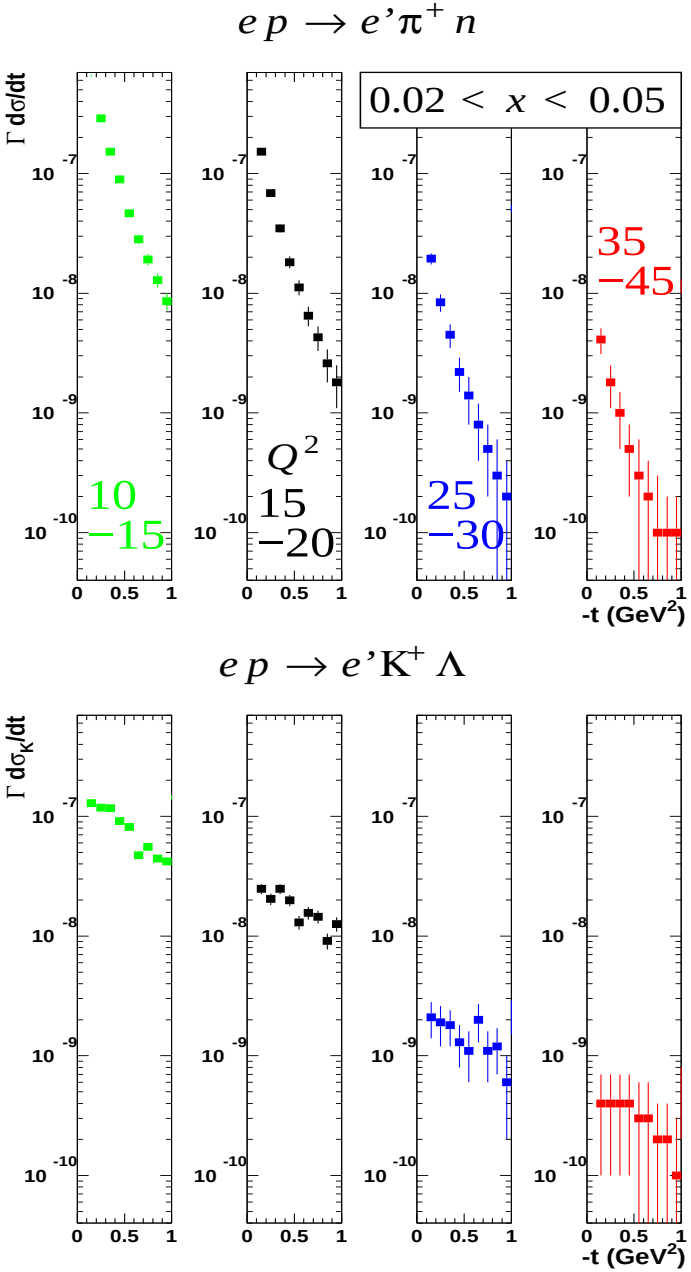
  No difference assumed in present pp MC generators for LHC!

- EIC: Gluon size from J/ψ, singlet quark size from DVCS

  x–dependence: Quark vs. gluon diffusion in wave function

Detailed differential images of nucleon's partonic structure

Transverse imaging: Sea quarks



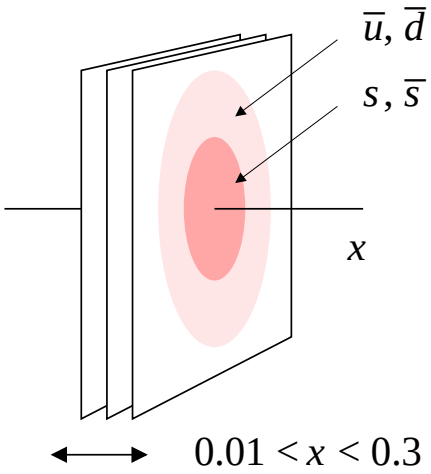
- Do strange and non-strange sea quarks have the same spatial distribution?

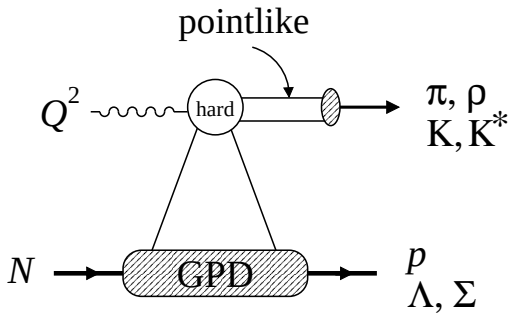
  πN or $K\Lambda$ components in nucleon?
  QCD vacuum fluctuations?

- EIC: Exclusive π and K production

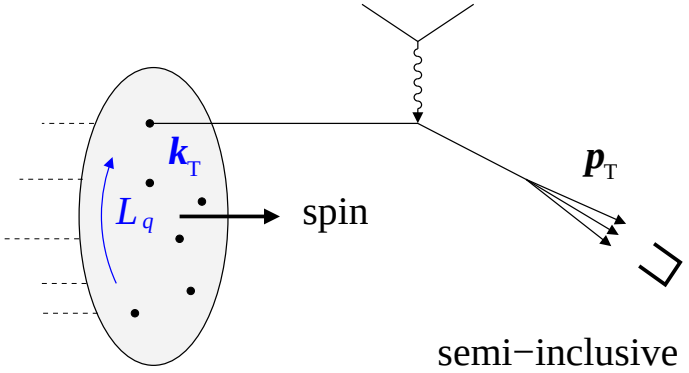
  Requires $Q^2 > 10\,\mathrm{GeV}^2$ for pointlike regime

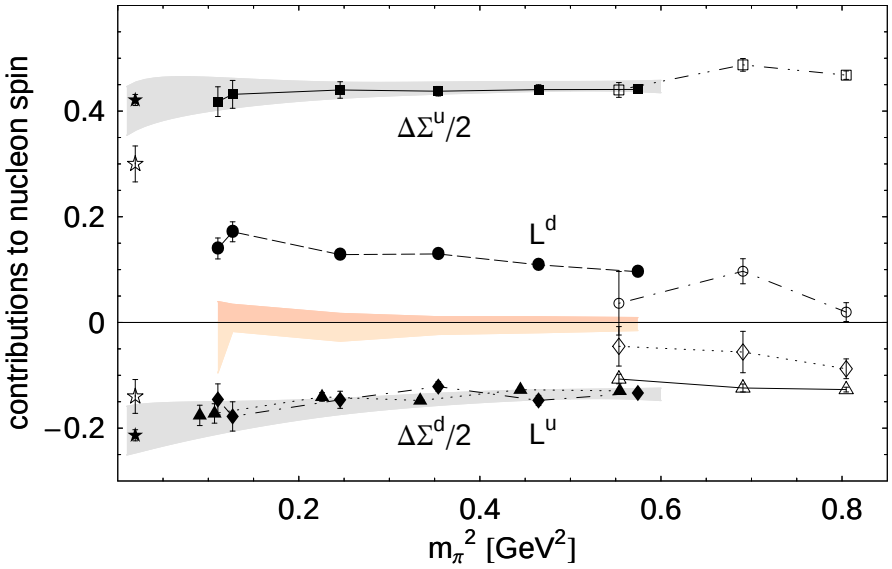
  High luminosity for low rates,
  differential measurements in x, t, Q^2





Orbital motion: Semi–inclusive DIS





Lattice shows large isovector $L_u - L_d$.
Hägler et al. 08

- What is the transverse motion of quarks and gluons in the nucleon?

  Transverse momentum distributions:
  Low k_T non-perturbative, high k_T pQCD

  Correlation with nucleon/parton spin:
  Spin–orbit interactions, deformation

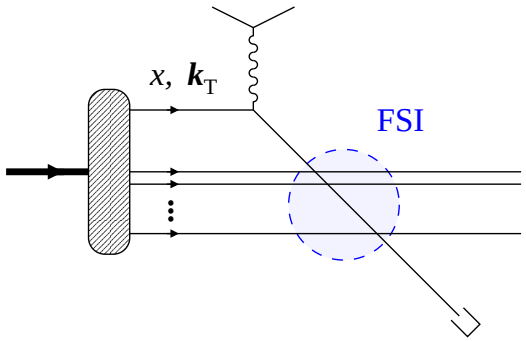
  Orbital angular momenta L_q, L_g sizable,
  needed to explain nucleon spin

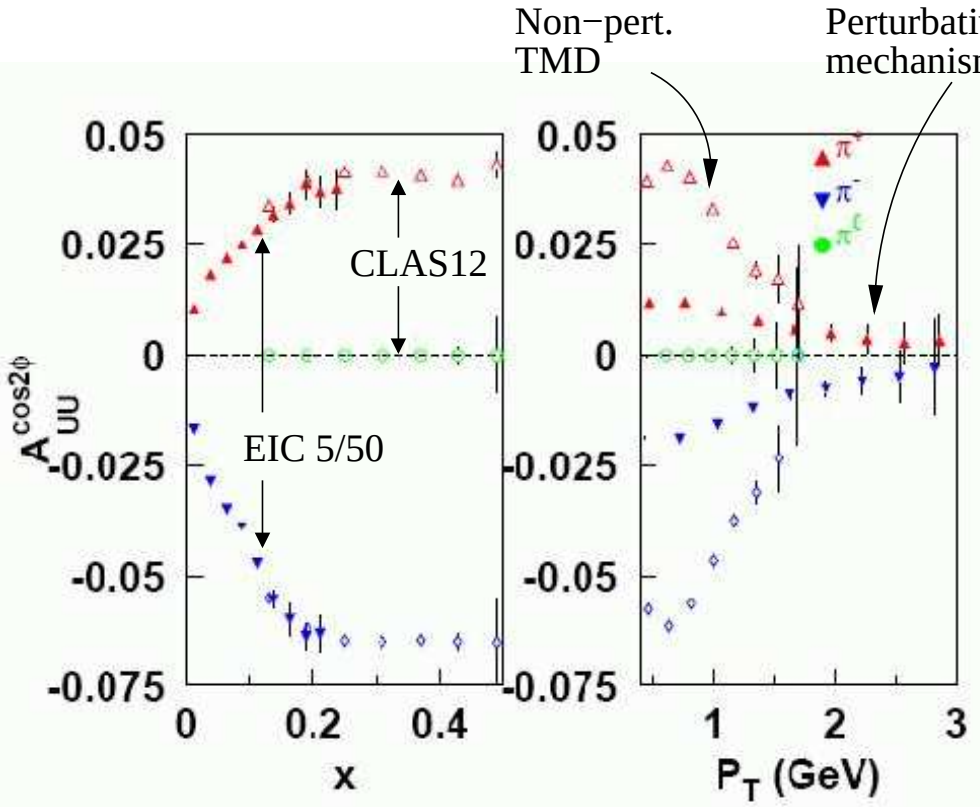
- Semi–inclusive DIS with p_T dependence

  New theoretical framework: TMDs

  Existing data raise many interesting questions
  HERMES, COMPASS, JLab ep
  FNAL, RHIC pp

Orbital motion: TMDs with EIC





Boer–Mulders asymmetry: Transverse polarization of quark through spin–orbit interactions

- EIC: Comprehensive program of p_T/spin–dep. semi-inclusive DIS

  Fully differential measurements in x, Q^2, z, ϕ, p_T

  Control reaction mechanism: Q^2 dependence, transition low $\rightarrow$ high p_T

  Detailed extraction of TMDs and anglar momentum information

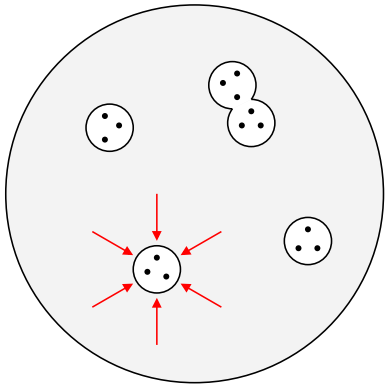
- Experimental requirements

  Luminosity: Differential measurements, low rates at high p_T, polarization

  Kinematic coverage: Q^2 reach at fixed x
  easier with medium–energy EIC!

  Detection: Particle ID, π/K etc.

Nuclei in QCD: Basic questions



- How does nuclear binding influence the nucleon's fundamental quark/gluon structure?

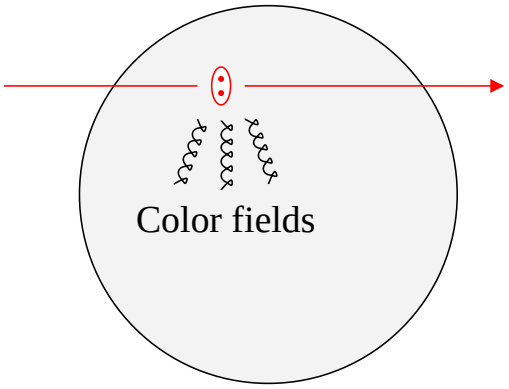
  Long–range forces in QCD, effective theories

  Short–range NN interaction,
  dense matter, neutron stars

- How do small–size quark/gluon configurations interact with hadronic matter?

  Color transparency — fundamental property of QCD as gauge theory

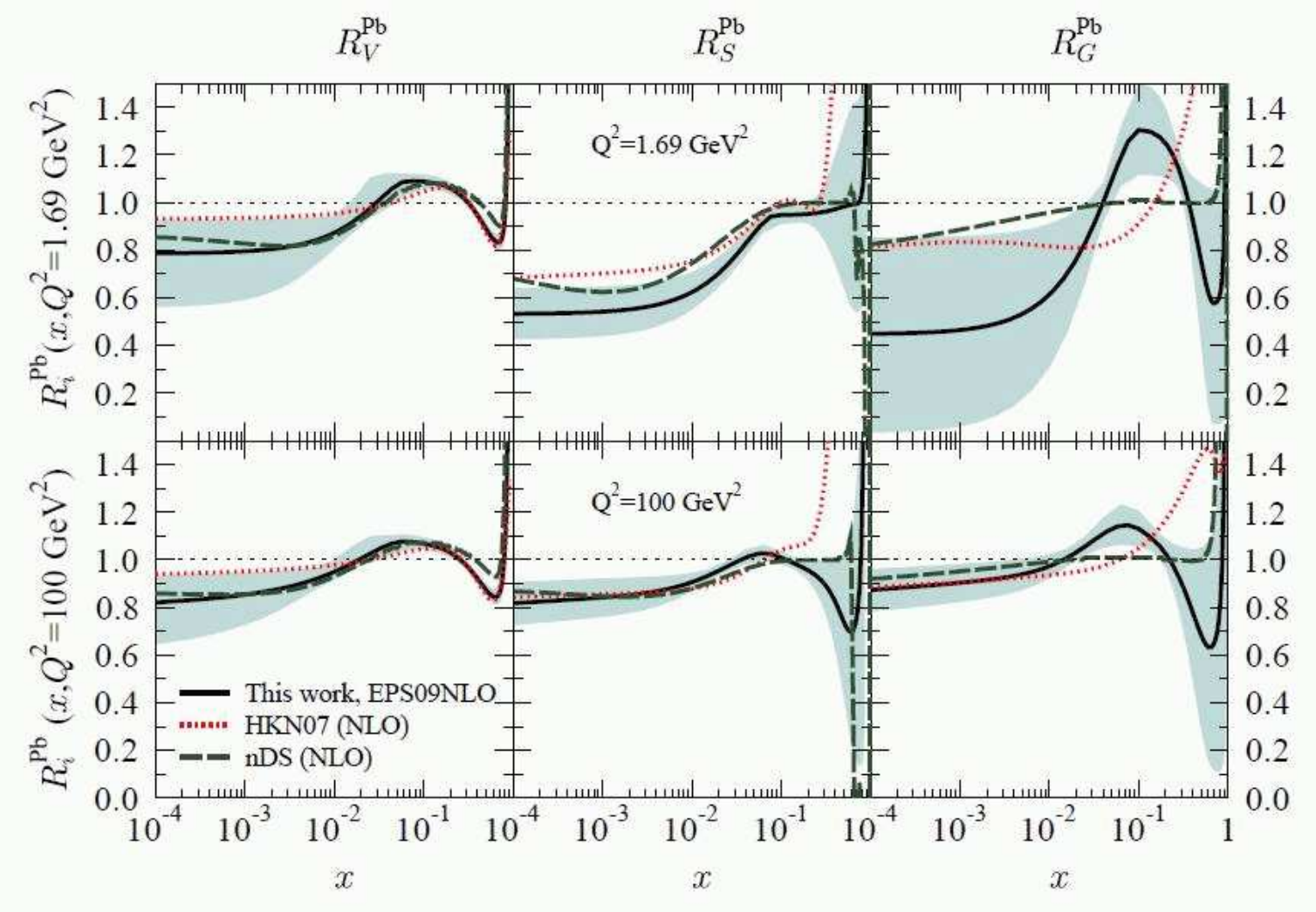
  Probe local color fields in nuclei,
  coherence effects



- Existing data

  Nuclear modification of PDFs Gluons? Spin/flavor?
  Short–range correlations in nuclei JLab 6/12
  Color transparency HERA, HERMES, JLab 6/12

Nuclei in QCD: Nuclear PDFs

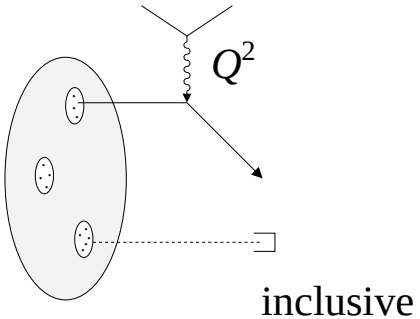


- Uncertaintanties of present nuclear parton densities Eskola et al. 2009, EPS09

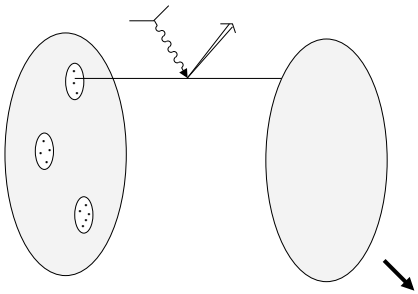
  Valence quarks poorly constrained, gluon essentially unknown!

  Essential input for saturation studies $Q_s(x, A)$

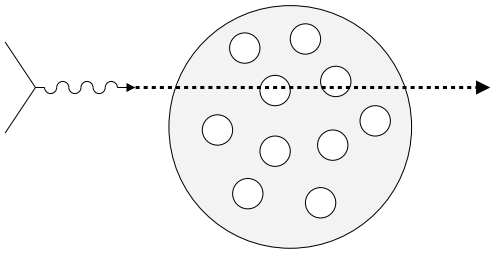
Nuclei in QCD: New probes with EIC



inclusive



coherent



transparency

- Nuclear gluons and sea quarks from inclusive DIS: "EMC effect"

  Gluons: Q^2 dependence, longit. structure F_L
  Sea quarks: Isospin dependence, polarization
  large x, Q^2 coverage

  Neutron structure from spectator tagging in $D(e, e'p)X$
  forward p/n detection

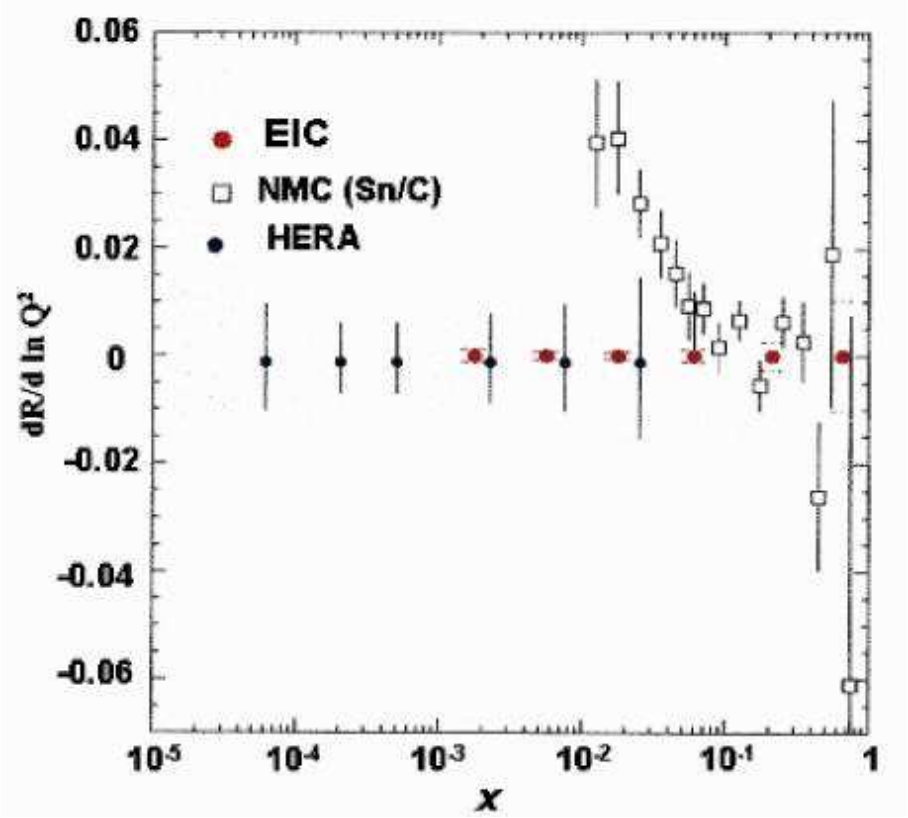
- Fundamental quark/gluon radii from coherent nuclear processes $A(e, e'M)A$

  New class of "QCD form factors"
  Impact parameter dependent shadowing
  luminosity, recoil detection – challenging!

- Color transparency in meson production

  Color fields in nuclei
  luminosity; x range $\rightarrow$ coherence length

Nuclei in QCD: Nuclear gluon density



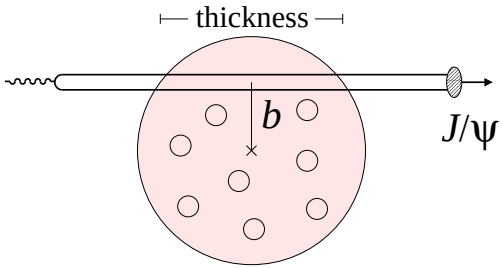
T. Sloan, 10/250 GeV. Similar results at lower energies!

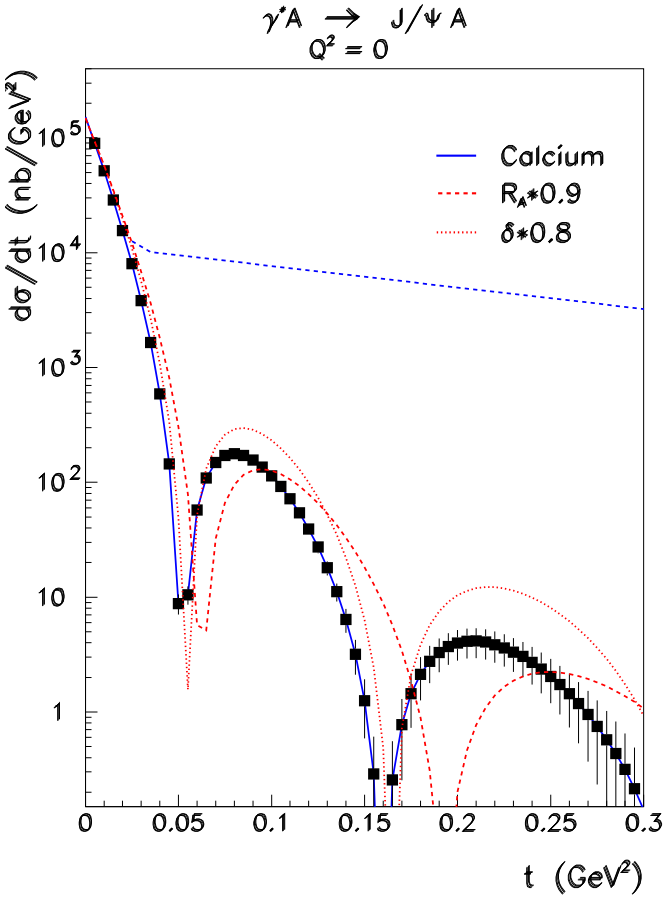
- Nuclear gluon density from Q^2 dependence of inclusive structure function

$$g_A(x, Q^2) \sim \frac{\partial}{\partial Q^2} F_{2A}(x, Q^2)$$

- EIC: Dramatic improvement in precision, accurate Q^2 dependence

Nuclei in QCD: Coherent processes





Caldwell, Kowalski, arXiv:0909.1254

- Transverse distribution of gluons in nuclei from coherent J/ψ production

  Fundamental characteristic: Quark–gluon origin of nucleon–nucleon forces

  New approach to nuclear shadowing: Thickness $\leftrightarrow$ impact parameter b

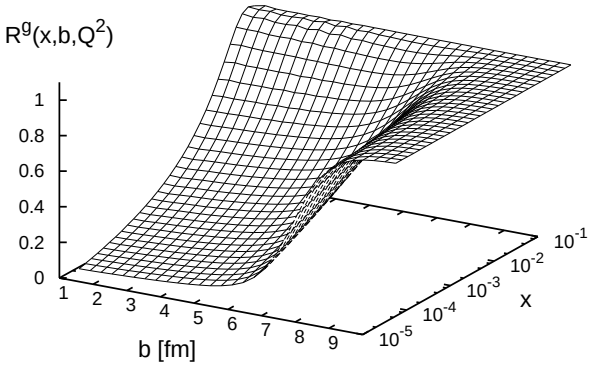
  Theoretical predictions Goeke, Guzey, Siddikov 09

- Experimental challenges

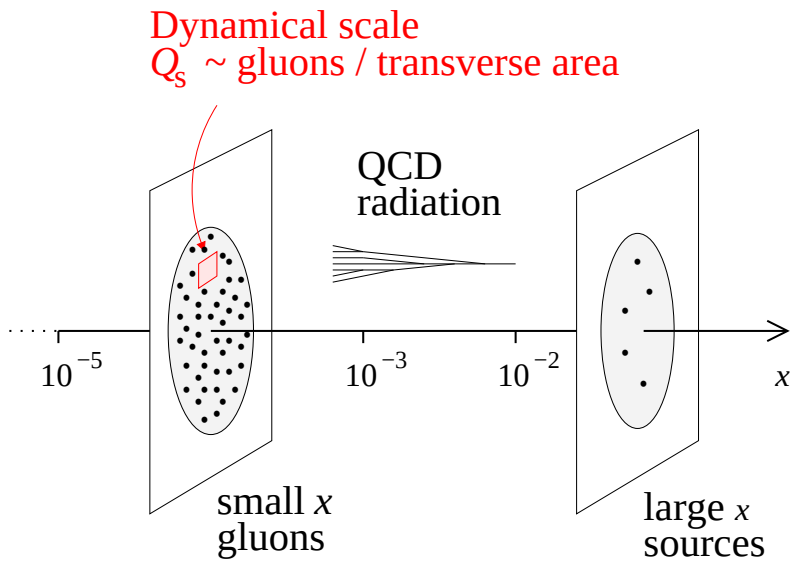
  Detection at very low $t \sim$ (few fm)$^{-2}$

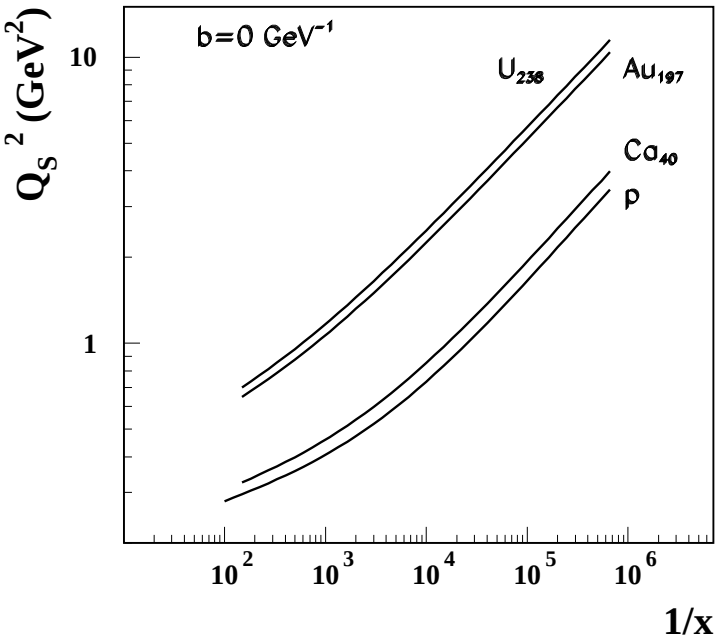
  Beam optics: Intrinsic k_T

  Veto nuclear breakup, excitations (theory)



Nuclei in QCD: Saturation





Kowalski, Teaney 03

- New dynamical scale in small–x partonic wave function $Q_s(x)$

  Gluon density grows through QCD radiation

  Theory: Non–linear QCD evolution, Color Glass Condensate

  McLerran, Venugopalan; Balitsky, Kovchegov, JIMWLK

- New phenomena

  Breakdown of Bjorken scaling in F_L, F_2

  High p_T in forward particle production

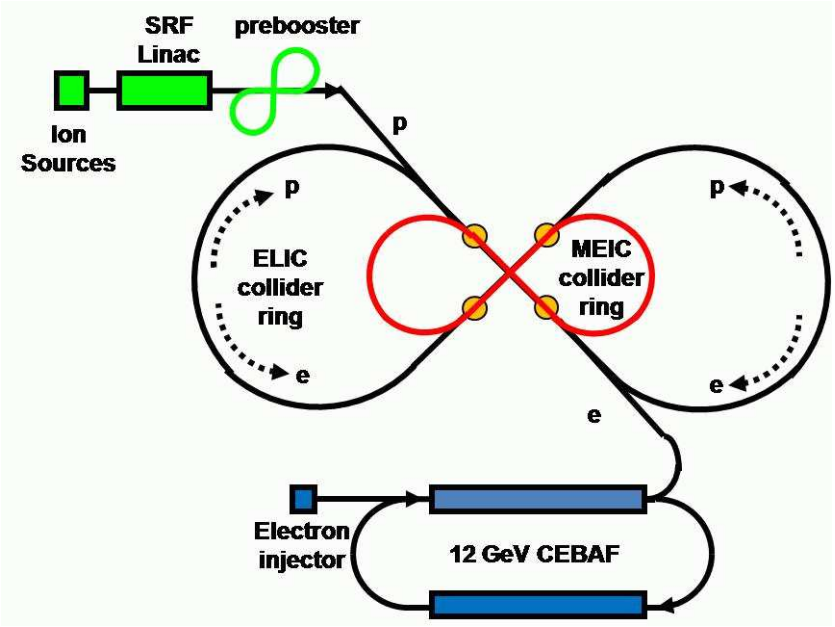
  Multiple hard processes, correlations

- Expected to be enhanced in nuclei

  $Q_s(x) \sim A^{1/3}$ without shadowing, depends on nuclear gluon density

- EIC: Broad program to study saturation through inclusive/diffractive/exclusive processes

Facilities: High–luminosity EIC at JLab



- Designed to deliver high luminosity over wide range of CM energies optimal for nucleon structure
- Conceptual design on–going

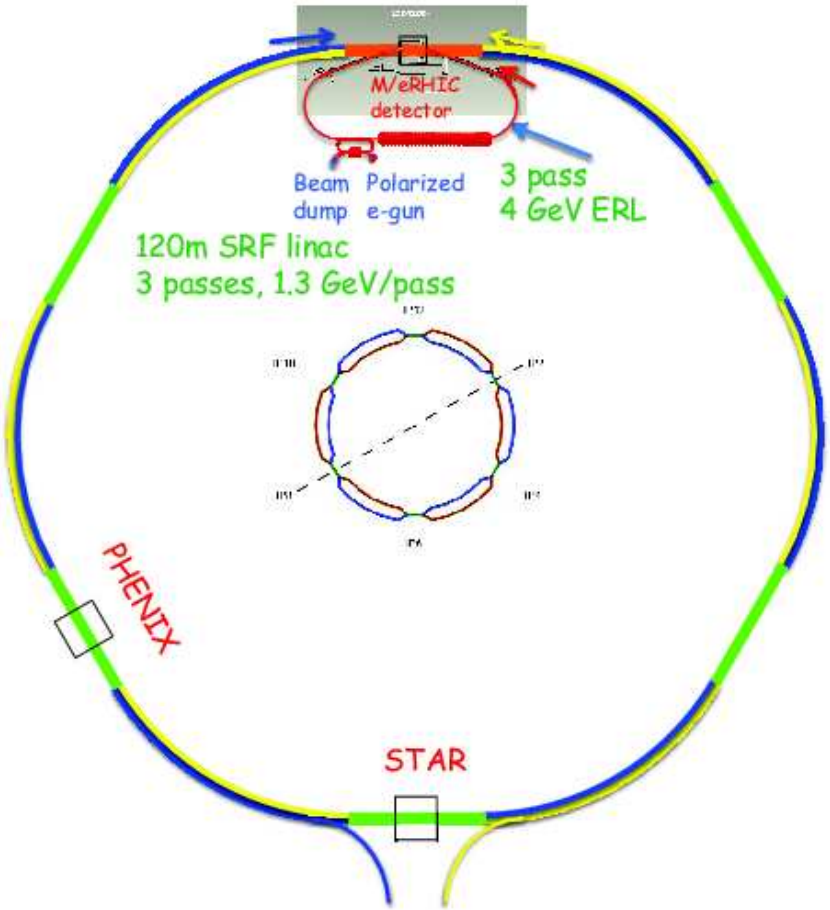
  Presented to EIC Advisory Committee
  Feb–09 and Nov–09
- Possible upgrade to high–energy ELIC (10/250 GeV, $L \sim 10^{35}$) but distinct medium–energy physics program!

Energy	E_e/E_p	$= 3 - 11/20 - 60$ GeV
	s_{ep}	$= 280 - 2640$ GeV^2
Luminosity	$\sim 10^{34}$ cm^{-2} s^{-1}	
Circumf.	$\sim$ 600 m	

Excellent polarization through "Figure–8"
Ion beams, incl. deuterium
Up to four interaction points

http://www.jlab.org/meic/

Facilities: MeRHIC/eRHIC at BNL



MeRHIC layout

- MeRHIC: Medium–energy eRHIC

  4/250 GeV pol. protons, $s = 4000\,\mathrm{GeV}^2$,
  $L \sim 10^{32} - 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

  ERL + detector at IP2 of RHIC

  90% of hardware useable for
  high-energy eRHIC

- eRHIC: High–energy and
  high–luminosity phase

  20/325 GeV pol. protons, $L \sim 10^{33} - 10^{34}$

  30/120 GeV/N ions at 1/5 full lumi,
  20/120 GeV/N at full lumi

- Possible energy/luminosity upgrades

Facilities: Project status

- Recommended as future project in 2007 NSAC Long–Range Plan

- EIC accelerator and physics R&D at BNL and JLab

  International EIC Advisory Committee, two reviews
  of physics and accelerator designs Feb–09 and Nov–09

  Supported by Lab users

- EIC Collaboration http://web.mit.edu/eicc/

  Formed 2007, over 100 physicists from > 20 institutions,
  advancing physics and accelerator R&D for EIC

  Semi–annual collaboration meetings/workshops

  Working toward recommendation in 2012 NSAC LRP

- Related projects

  LHeC at CERN: ep/eA collider using LHC proton/ion ring

  ENC at GSI: ep collider using GSI proton high–energy storage ring

Summary

- A high–luminosity EIC will provide tremendous new opportunities for studying nucleon structure and nuclei in QCD

- Much work to be done

  Accelerator/detector R&D

  Next–level process simulations with detailed physics output

  Concepts and program development

- Needs support of broad community to become reality!