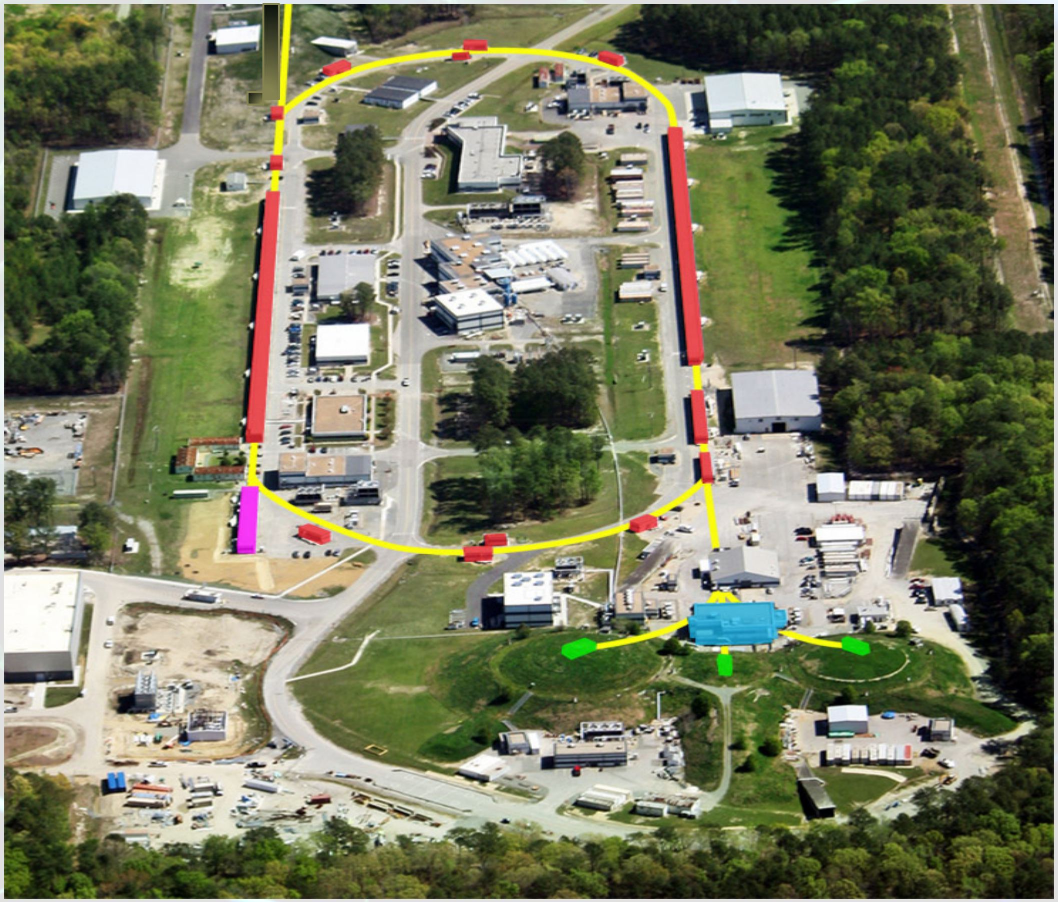
The Particle/Nuclear Interface - II

Thia Keppel

CTEQ Summer School



University of Pittsburgh

July 2017

Jefferson Lab

Thomas Jefferson National Accelerator Facility

Lecture Scheme - I

in·ter·face
ˈin(t)ərˌfās/ *noun*
1. a point where two systems, subjects, etc., meet and interact.

DAY 1

- ✓ Introduction
- ✓ History and Basics of Electron Scattering – *Some Reminders*
- ✓ Jefferson Lab
- ✓ 1D to 3D Nucleon Structure
  - ✓ Form Factors and PDFs
  - Large x
- Nucleons in the Nuclear Medium

DAY 2

- *Finish What I Didn't Yet From Day 1!*
- The Electron Ion Collider

Lecture Scheme - II

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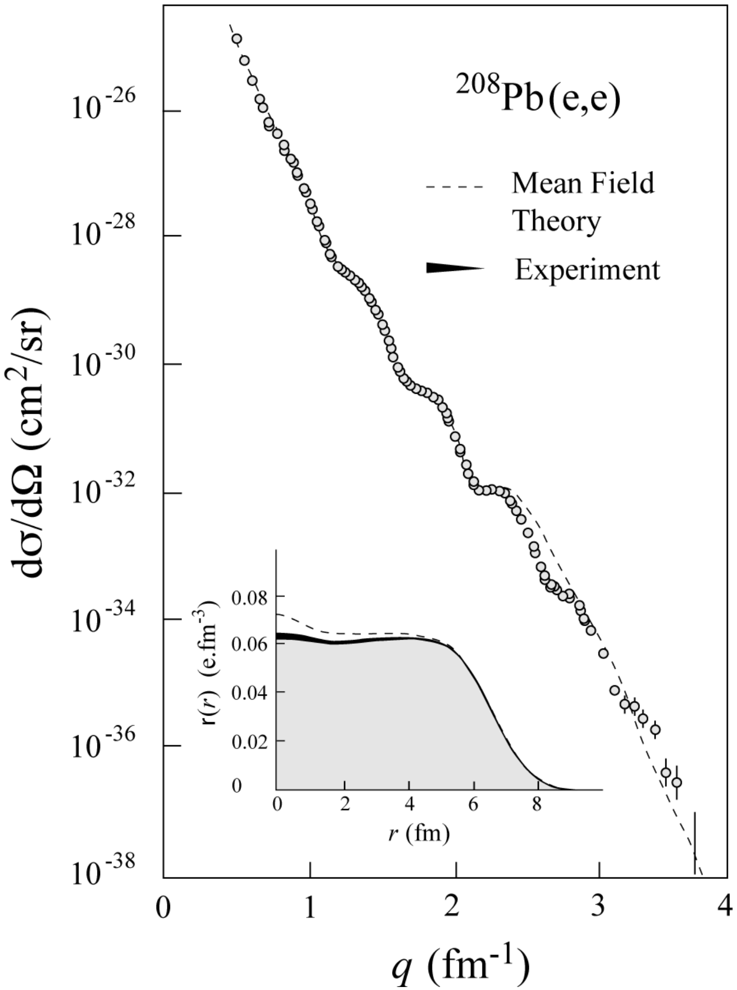
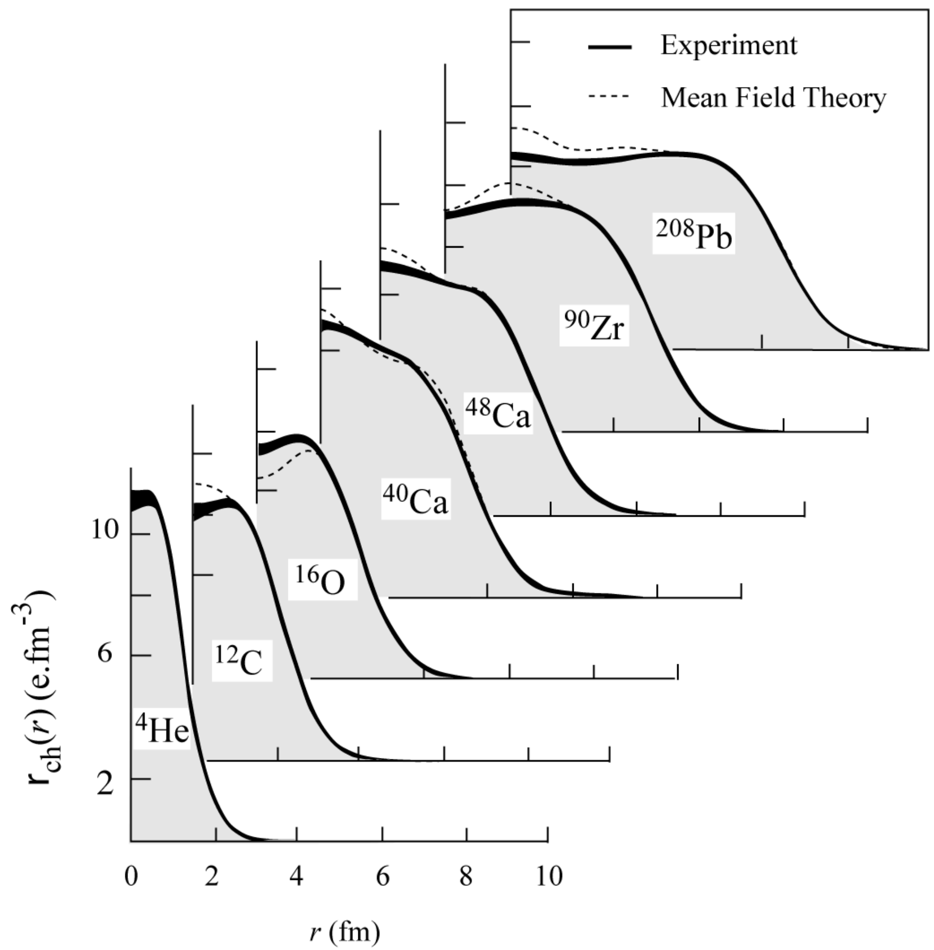
Inclusive Electron-Nucleus Scattering – historical example

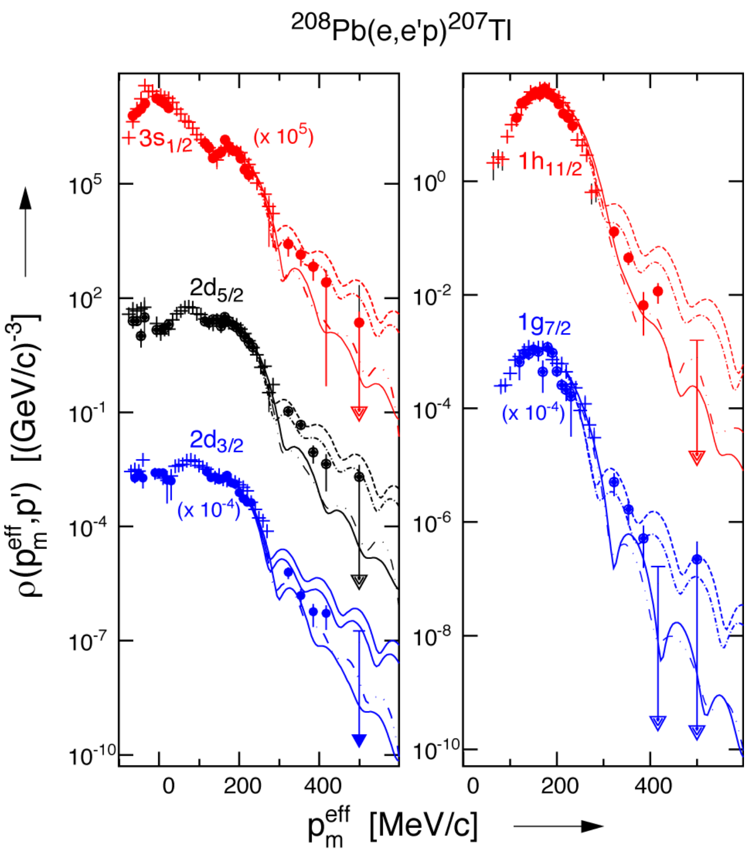
Elastic Scattering → Charge Distributions

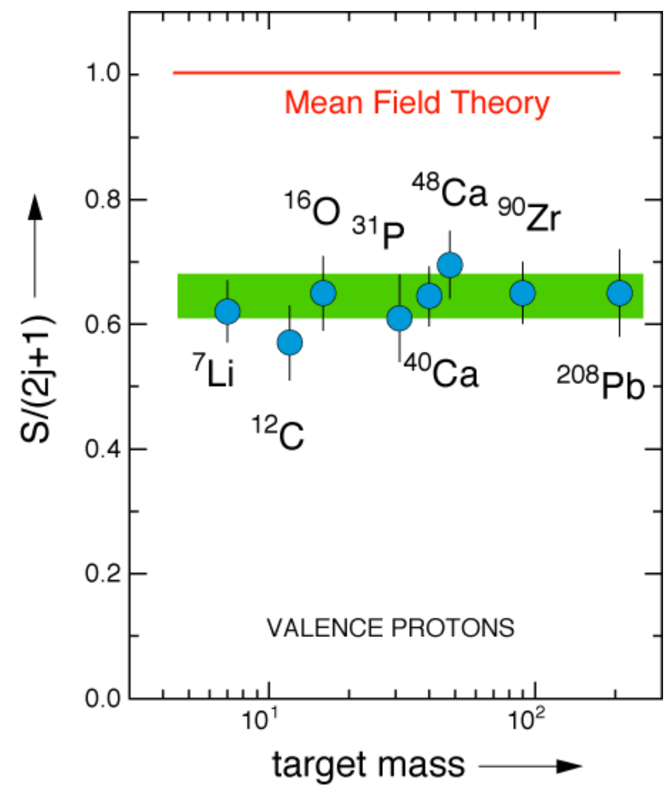




The Classic A(e,e’p)A-1 Problem

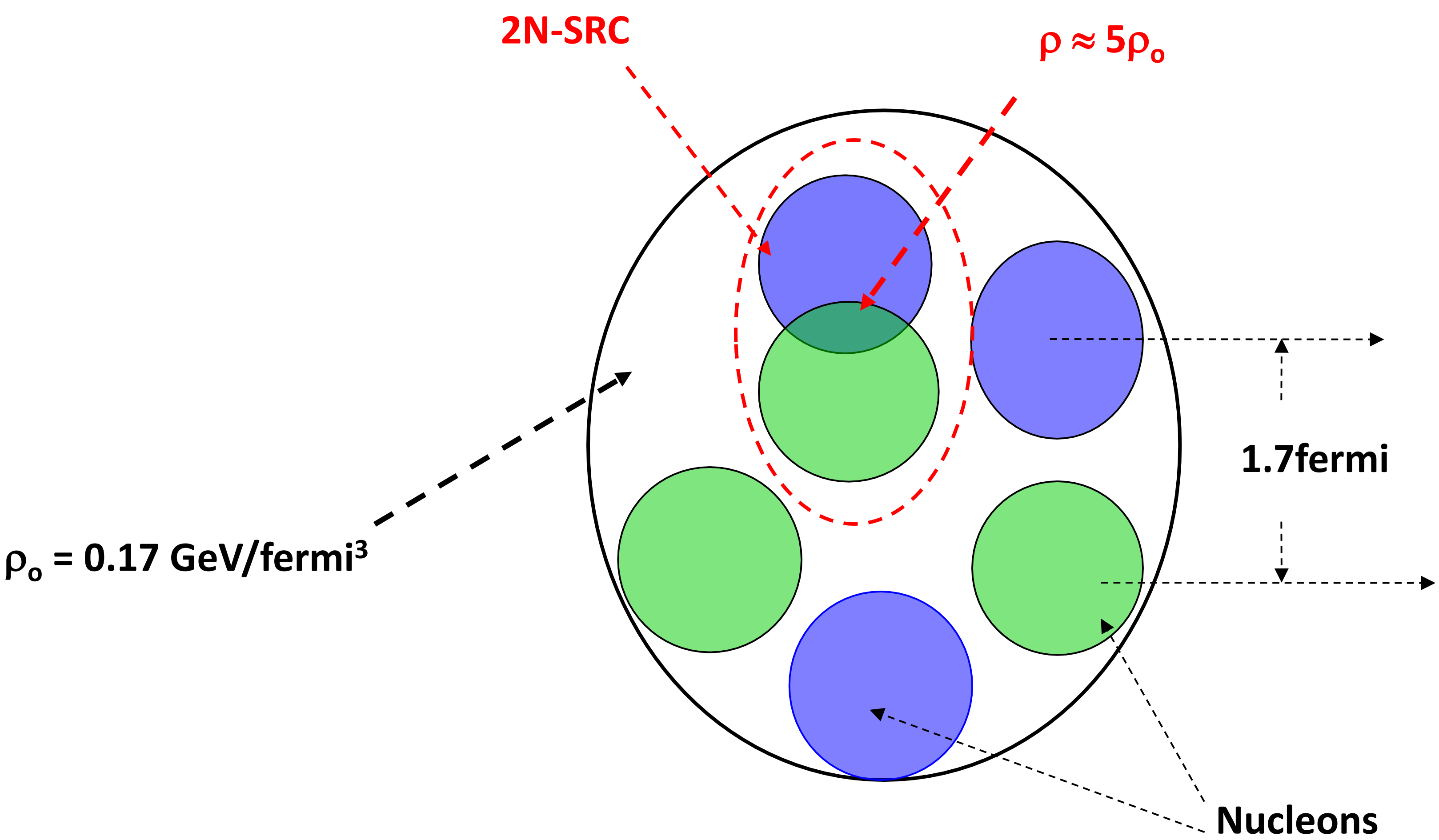
Independent-Particle Shell-Model is based upon the assumption that each nucleon moves independently in an average potential (mean field) induced by the surrounding nucleons





The (e,e'p) data for knockout of valence and deeply bound orbits in nuclei gives spectroscopic factors that are 60 – 70% of the mean field prediction.

Possible Answer: *Short-Range Correlations*

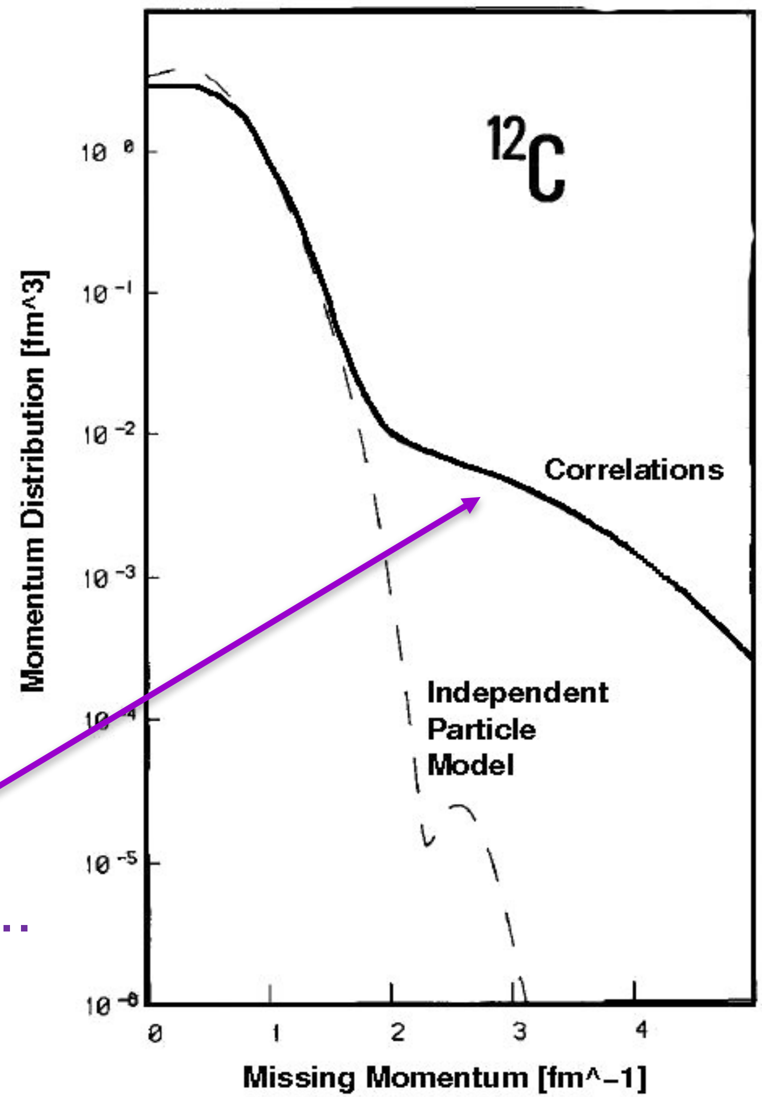


Nucleons are made up of quarks, so does NOT violate Pauli exclusion principle

If Correct Raises More Questions

- What fraction of the momentum distribution is due to 2N-SRC?
- What is the relative momentum between the nucleons in the pair?
- What is the ratio of pp to pn pairs?
- Are these nucleons different from free nucleons (e.g. size)?

Benhar et al., Phys. Lett. **B** 177 (1986) 135.

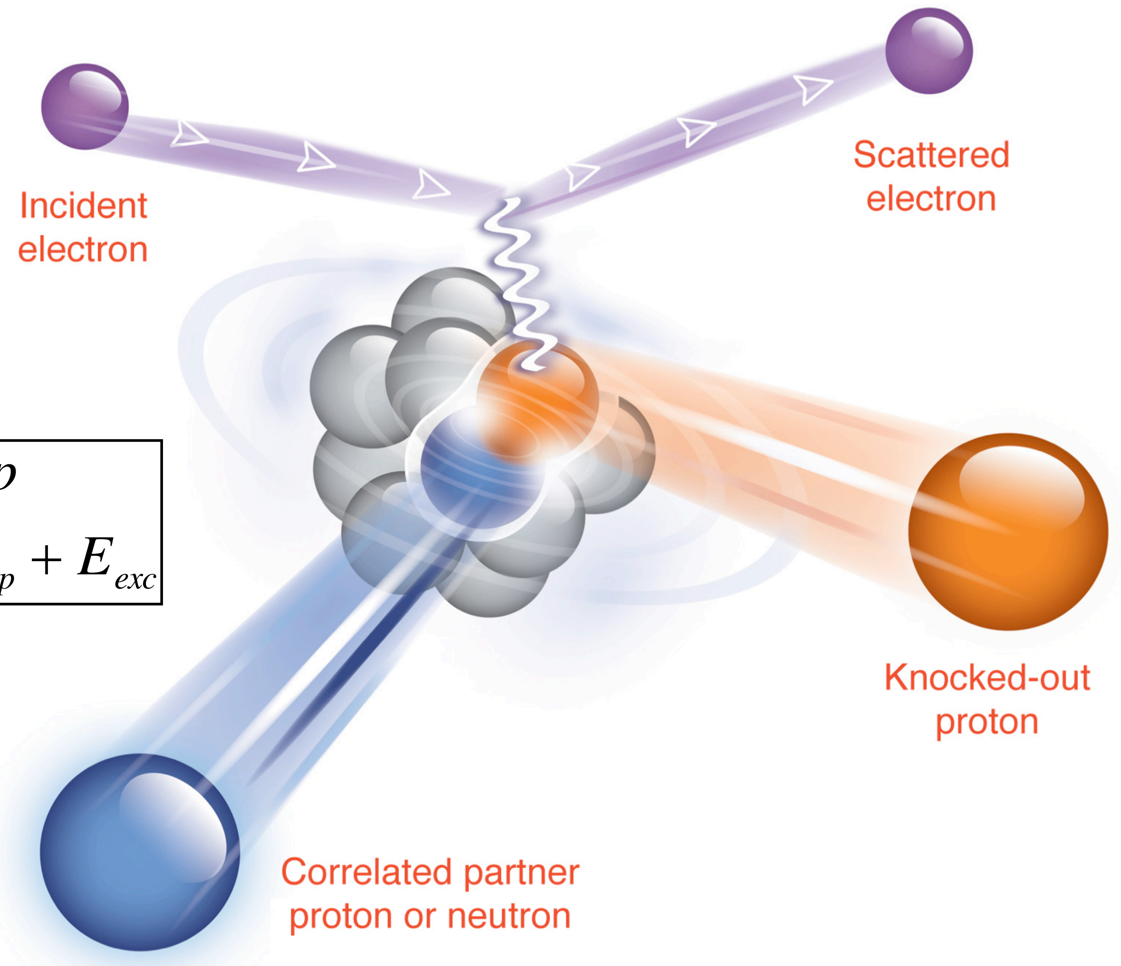


Measure out here…!...

Coincidence (e,e'pN) Exclusive Measurement

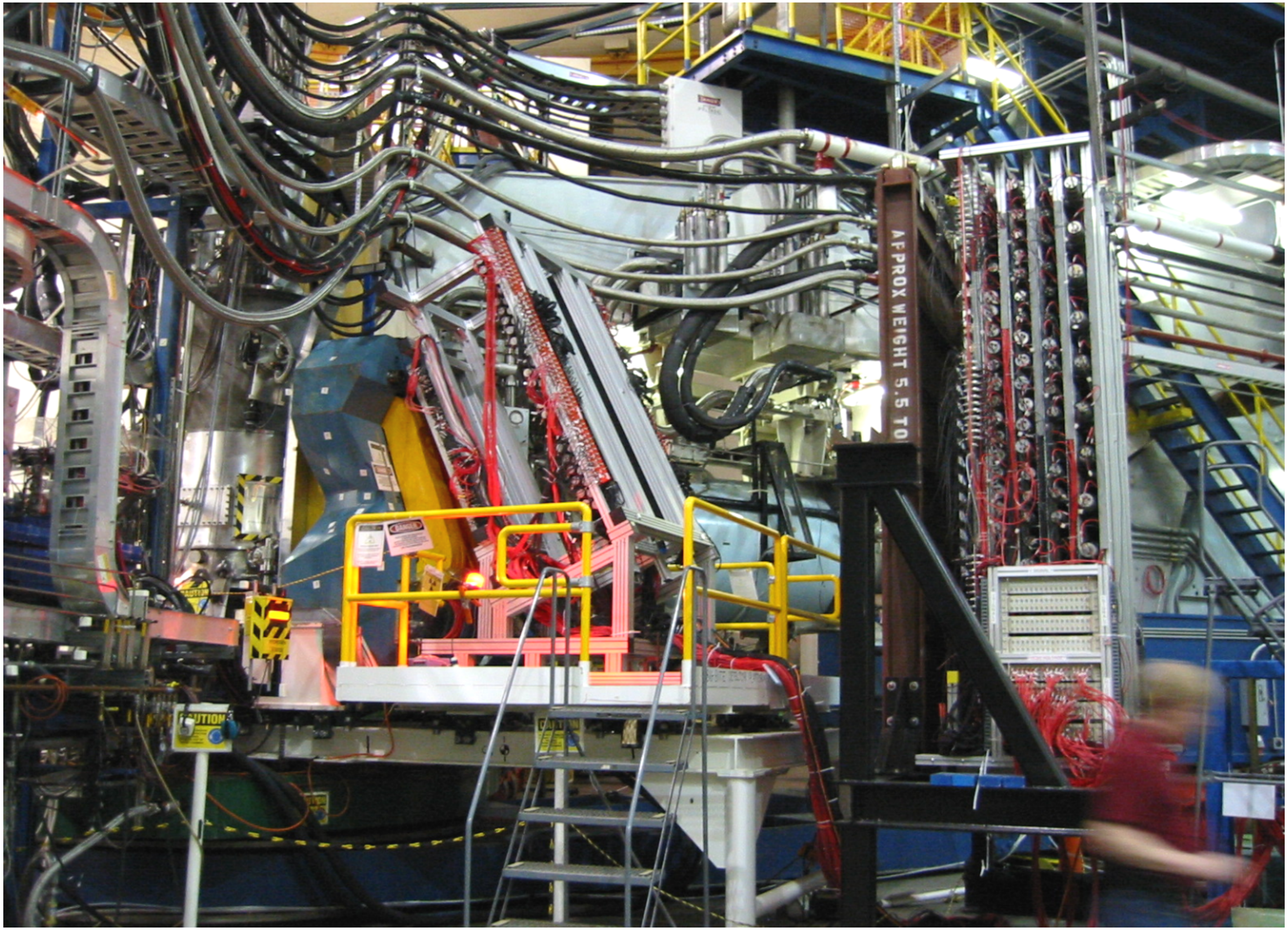
Study nucleon pairs and the fraction that contribute to momentum tail.

$$\boxed{\begin{aligned} p_m &= E_e - E_{e'} - p = q - p \\ E_m &= \omega - T_p - T_{A-1} = E_{sep} + E_{exc} \end{aligned}}$$



x > 1 , Q^2 = 1.5 $[GeV/c]^2$ and missing momentum of 500 MeV/c

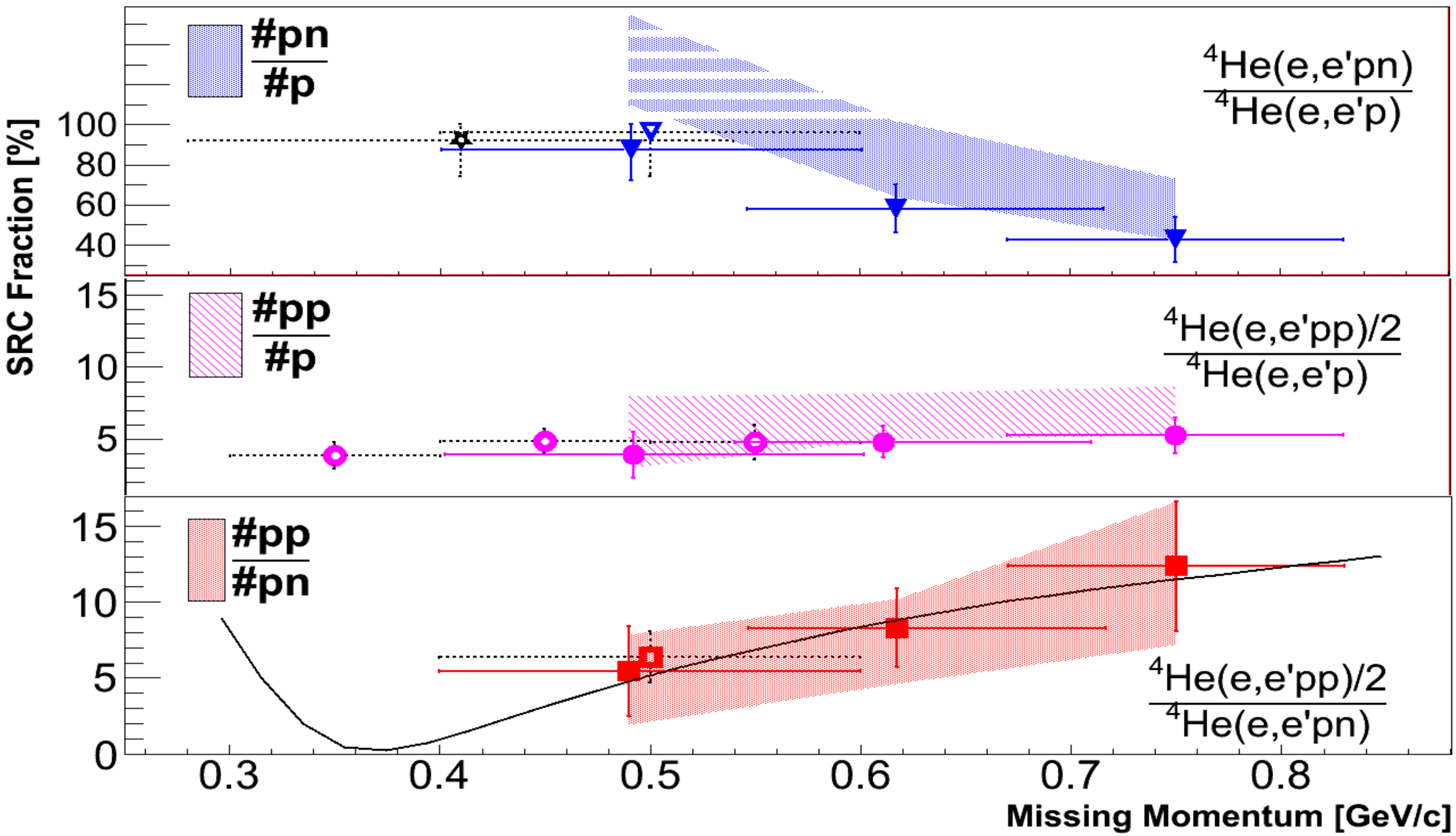
BigBite and Neutron Detector in Hall A



First step along the way to many successful high luminosity, large acceptance measurements.

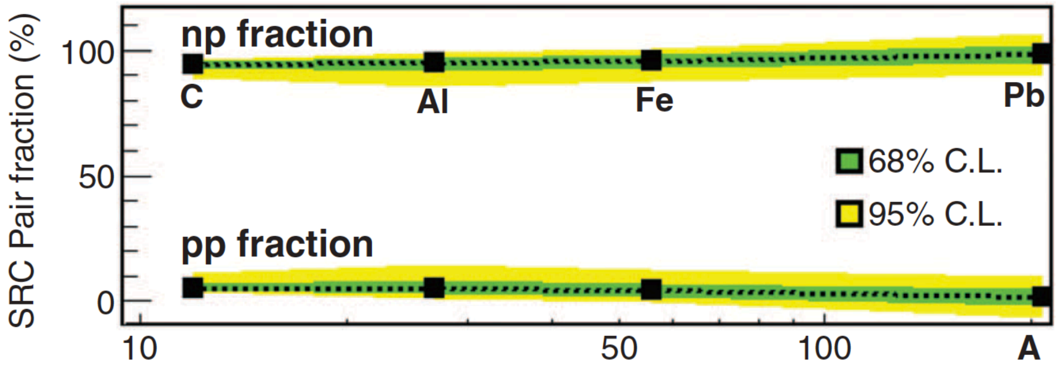
^{4}He(e,e'pN) Results – recoiling neutrons favored

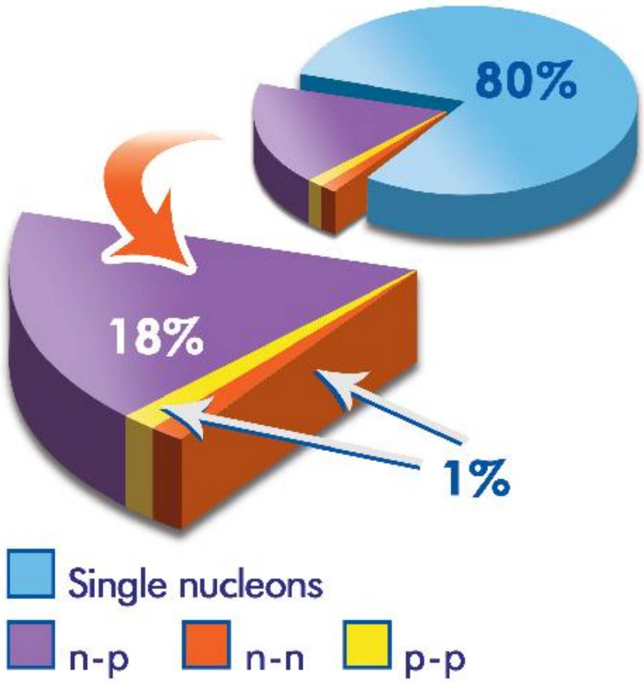
I. Korover *et al.*, Phys. Rev. Lett. **113** (2014) 022501.

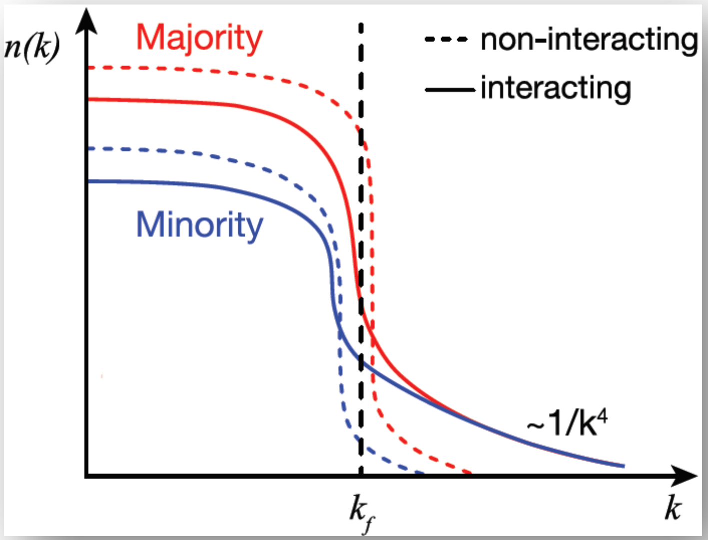


Proton-Neutron Pairing In All Nuclei

Or Hen *et al.* (Jefferson Lab CLAS Collaboration) Science 346 (2014) 614.



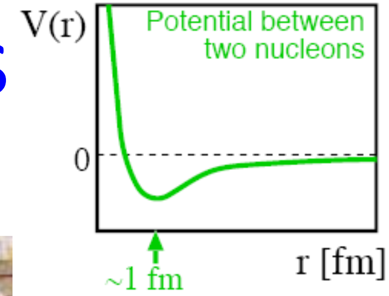




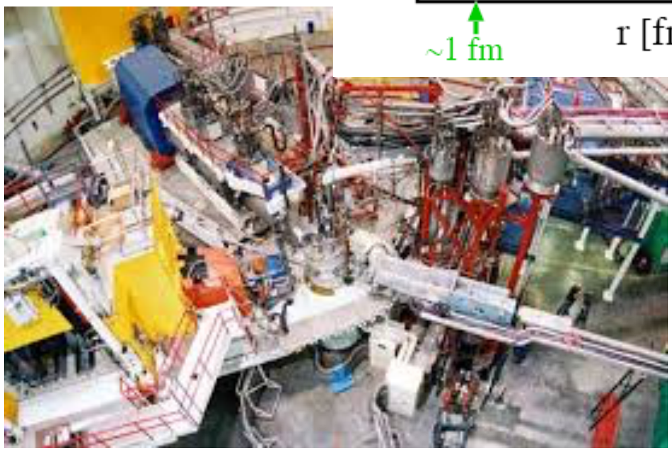
The minority particle will have a higher average kinetic energy then the majority particle.

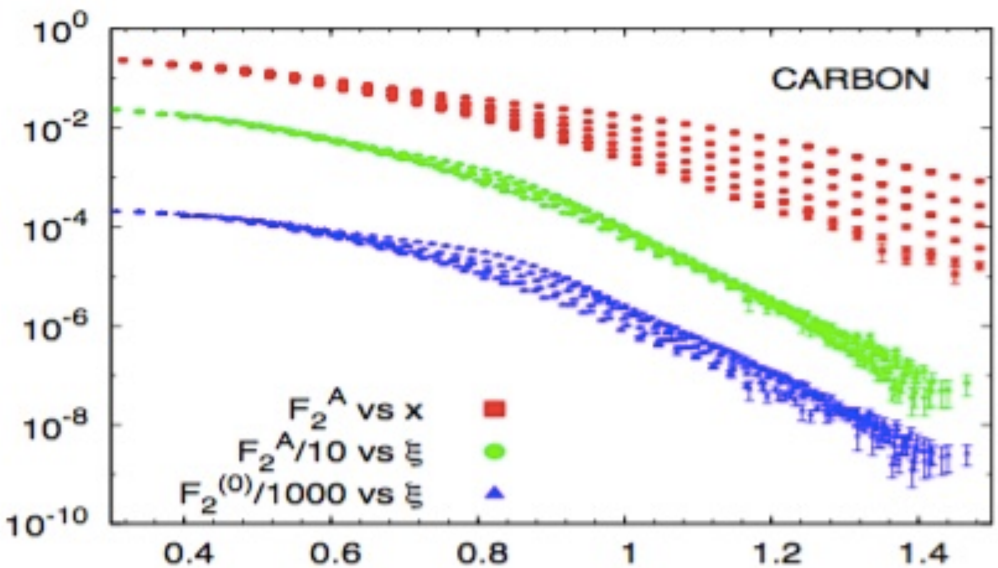
Precision (e,e’) x>1 Cross Sections

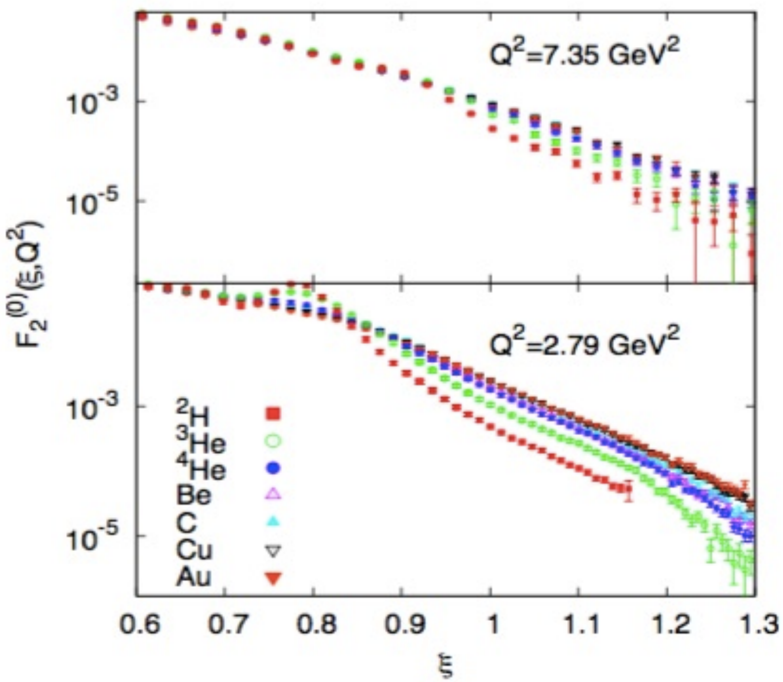
N. Fomin *et al*., Phys. Rev. Lett. **105** (2010) 212502 – JLab Hall C



- Electron-nucleus scattering allows for F_2 structure functions above $x = 1$
- Nucleons are close together and interact via the (poorly-constrained) repulsive core of the N–N interaction, yielding high momentum nucleons.
- Deuteron limited to $x < 2$, etc.
- Deep inelastic probe of very high momentum “superfast” quarks

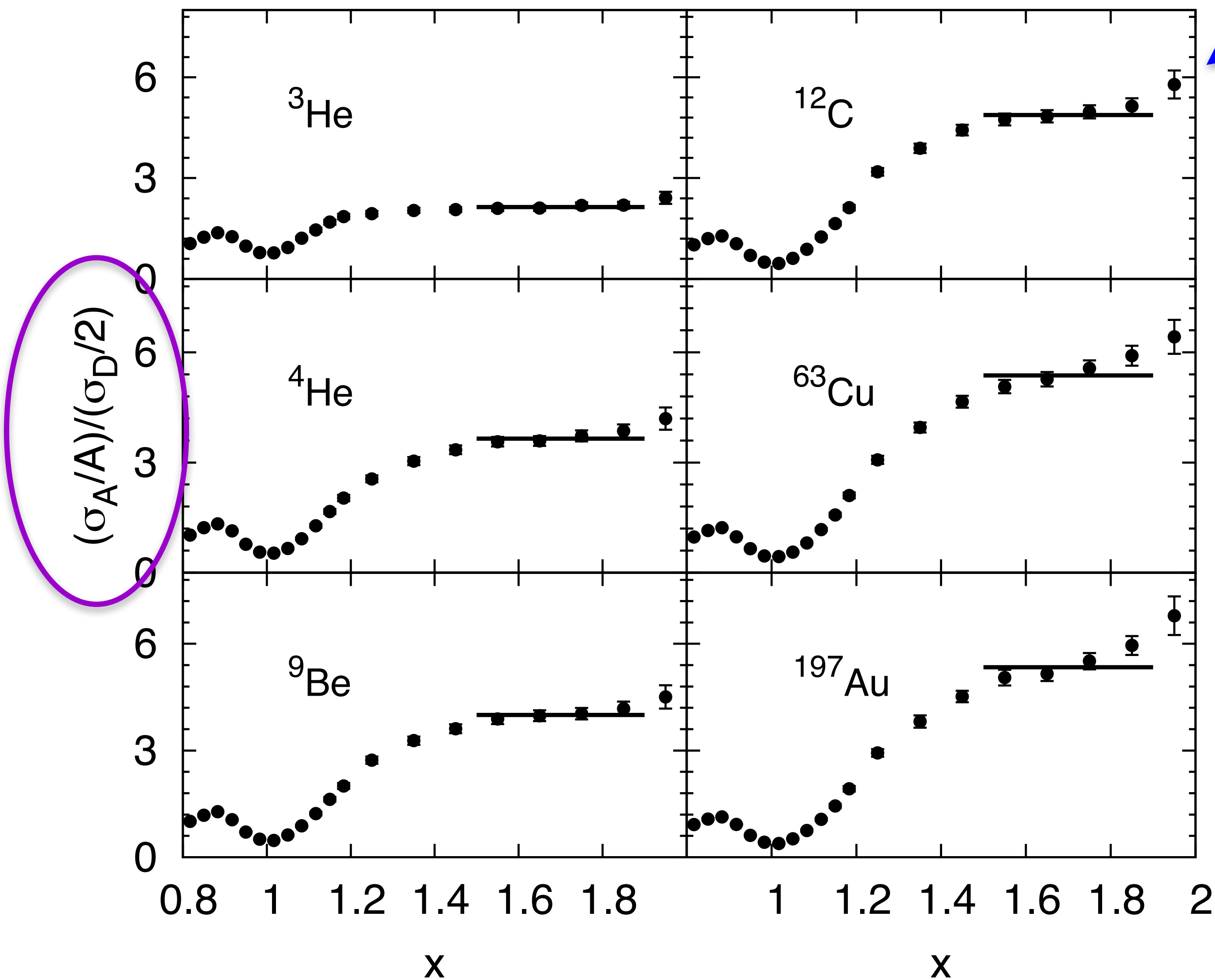






Precision (e,e') *x>1* Cross Section Ratios

N. Fomin *et al.*, Phys. Rev. Lett. **108** (2012) 092502.



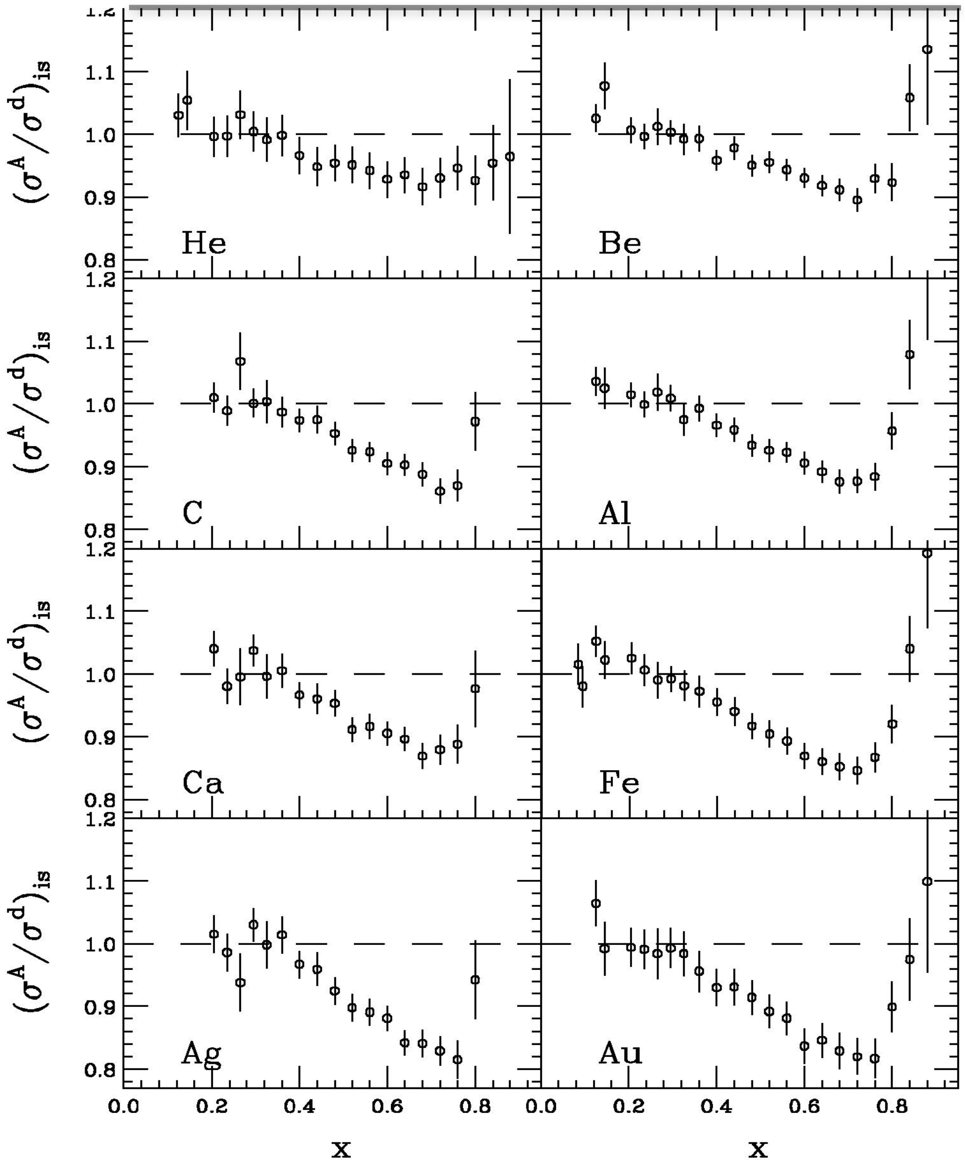
Plateaus seen in the ratio $(\sigma_A/A)/(\sigma_D/2)$

Roughly A independent

Understood as evidence for 2N short range correlations

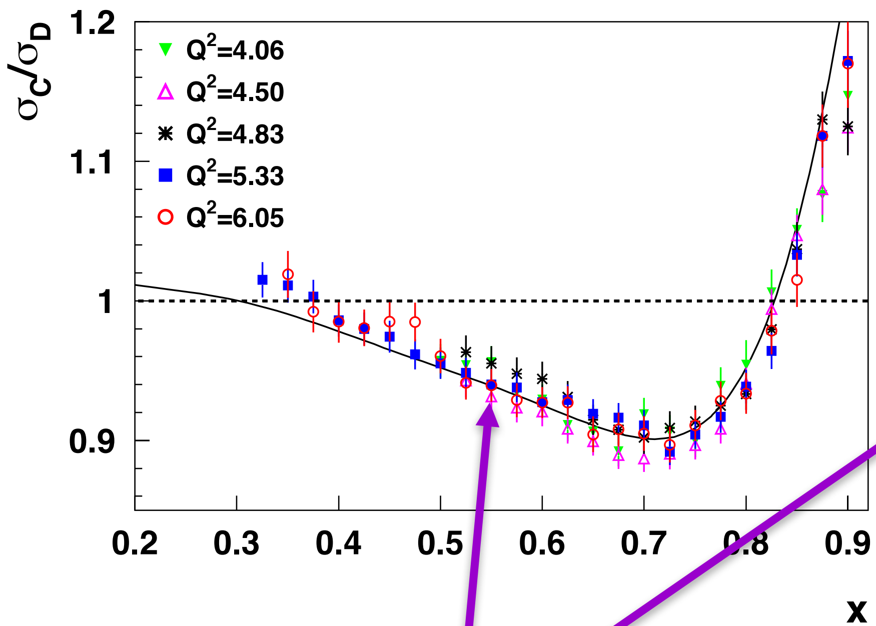
The Deep Inelastic EMC Effect

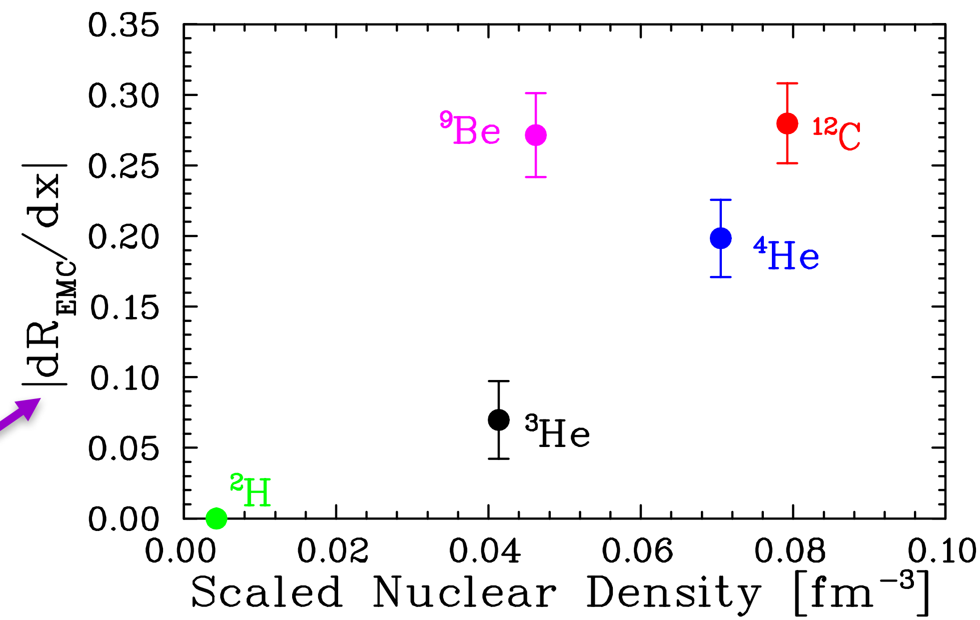
- **The EMC effect is the observation that the ratio of nuclear DIS cross sections to deuterium is not one**
  - EMC paper: J.J. Aubert et al. PLB 123 (1983) 275
  - Simple Parton Counting Expects One
  - ***MANY Explanations, multiple experiments***
- **Behavior**
  - Q^2-independent
  - Universal x-dependence (shape)
  - Magnitude varies with A – ***a density effect?....***



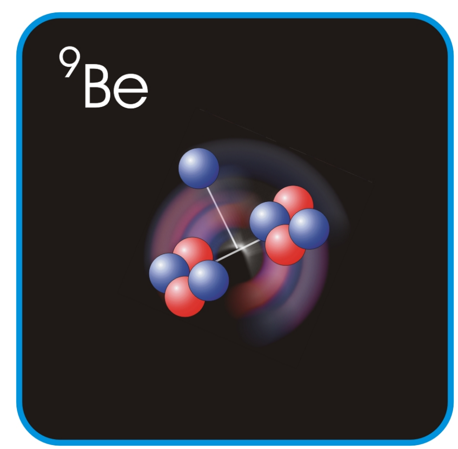
Jefferson Lab EMC Effect Data

J. Seely *et al.*, Phys, Rev. Lett. **103** (2009) 202301.



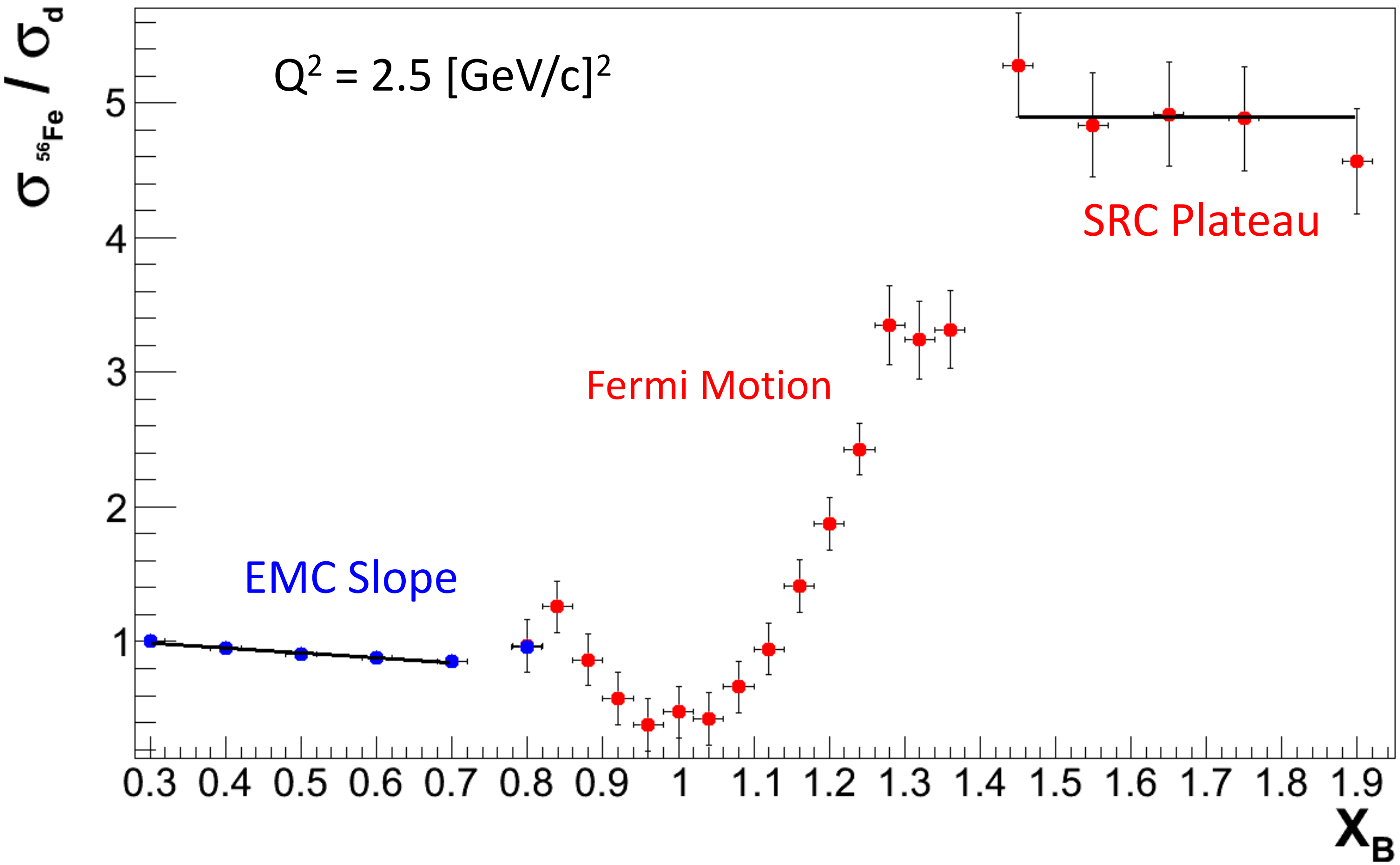


- Slope of ratio σ_A/σ_D at EMC region.
- *EMC effect correlated with* ***local density*** *not average density.*



Holistic View of inclusive EMC & SRC Data

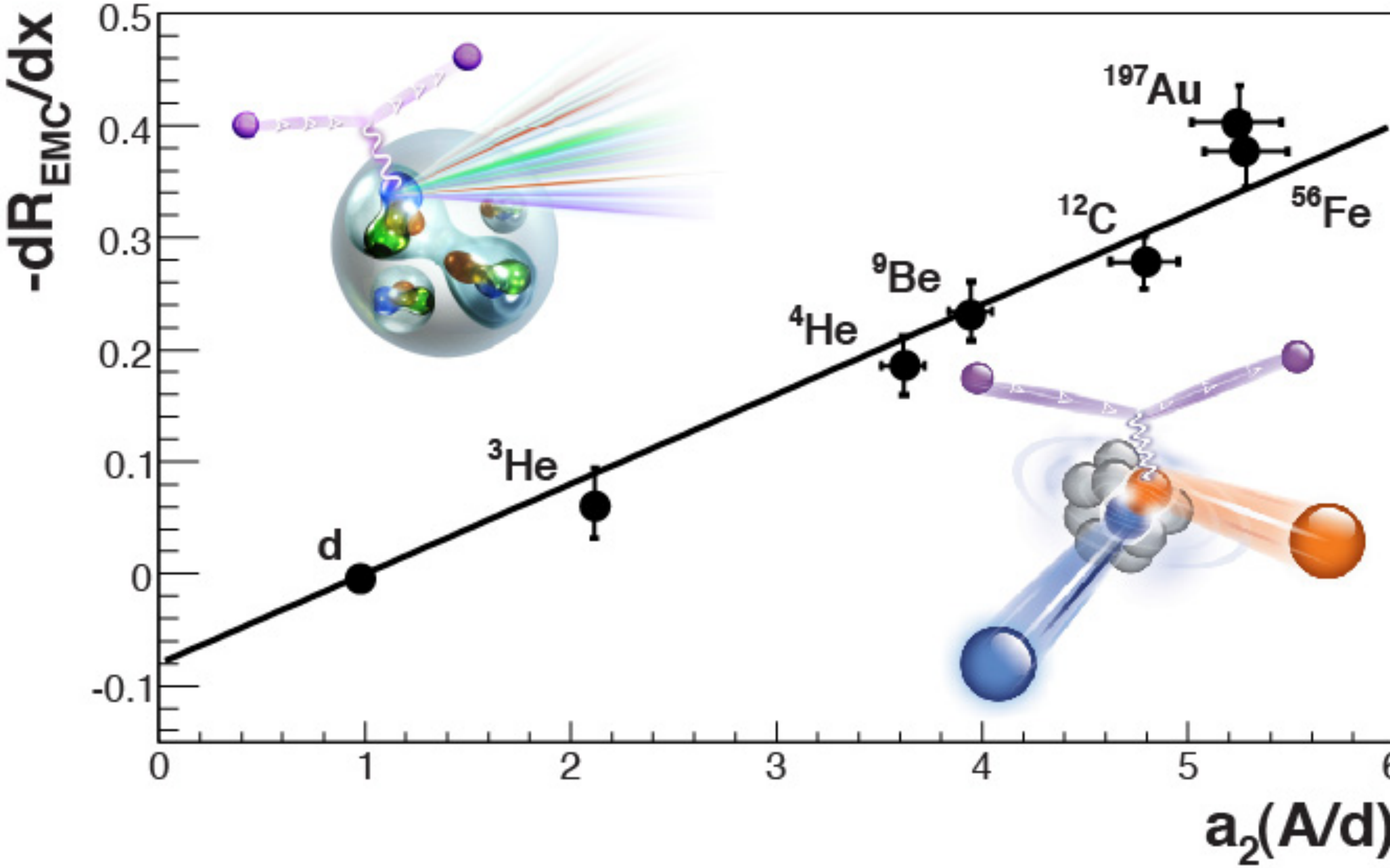
S. Malace, D. Gaskell, D.H., I. Cloet, Int. J. Mod. Phys. E **23** (2014) 1430013



- Scaling plateaus are likely due to proton-nucleon **local density** correlations
- So could the **EMC** slopes (x_B<0.7) and **SRC plateaus** (x_B>1.5) correlated?!

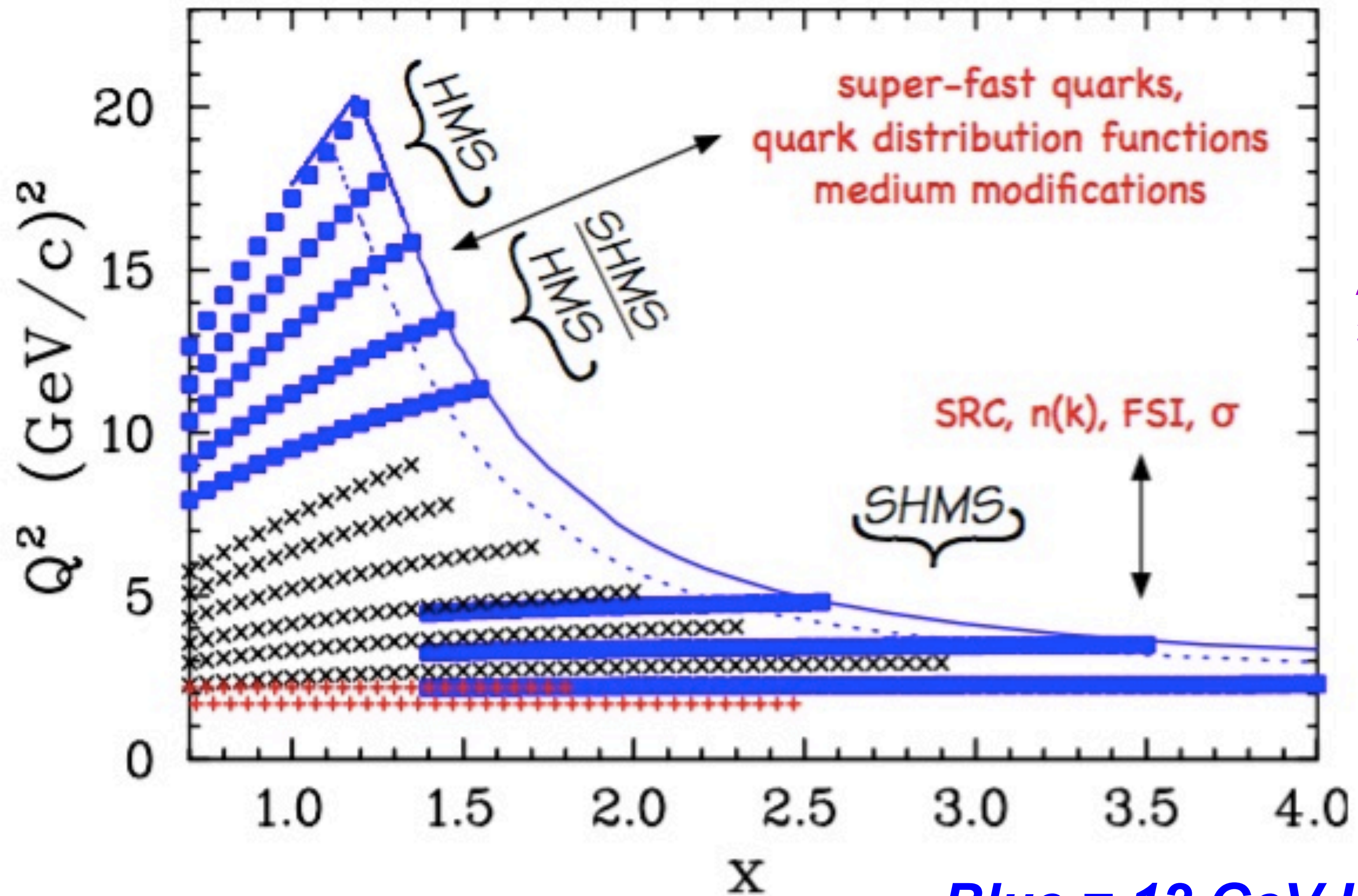
x>1 Ratios and EMC Slope Correlation

L. Weinstein, E. Piasetzky, DH, J. Gomez, O. Hen, and R. Shneor, Phys. Rev. Lett. 106 (2011) 052301.



Origin of the EMC effect? Not a smoking gun, but highly suggestive….

EMC, x>1 experiments to run in JLab Hall C *this Fall*!



3N plateau?

Also ^{3}H, ^{3}He (e,e'p) in Hall A

More!

Black = 6 GeV Hall C

Red = 6 GeV Hall B

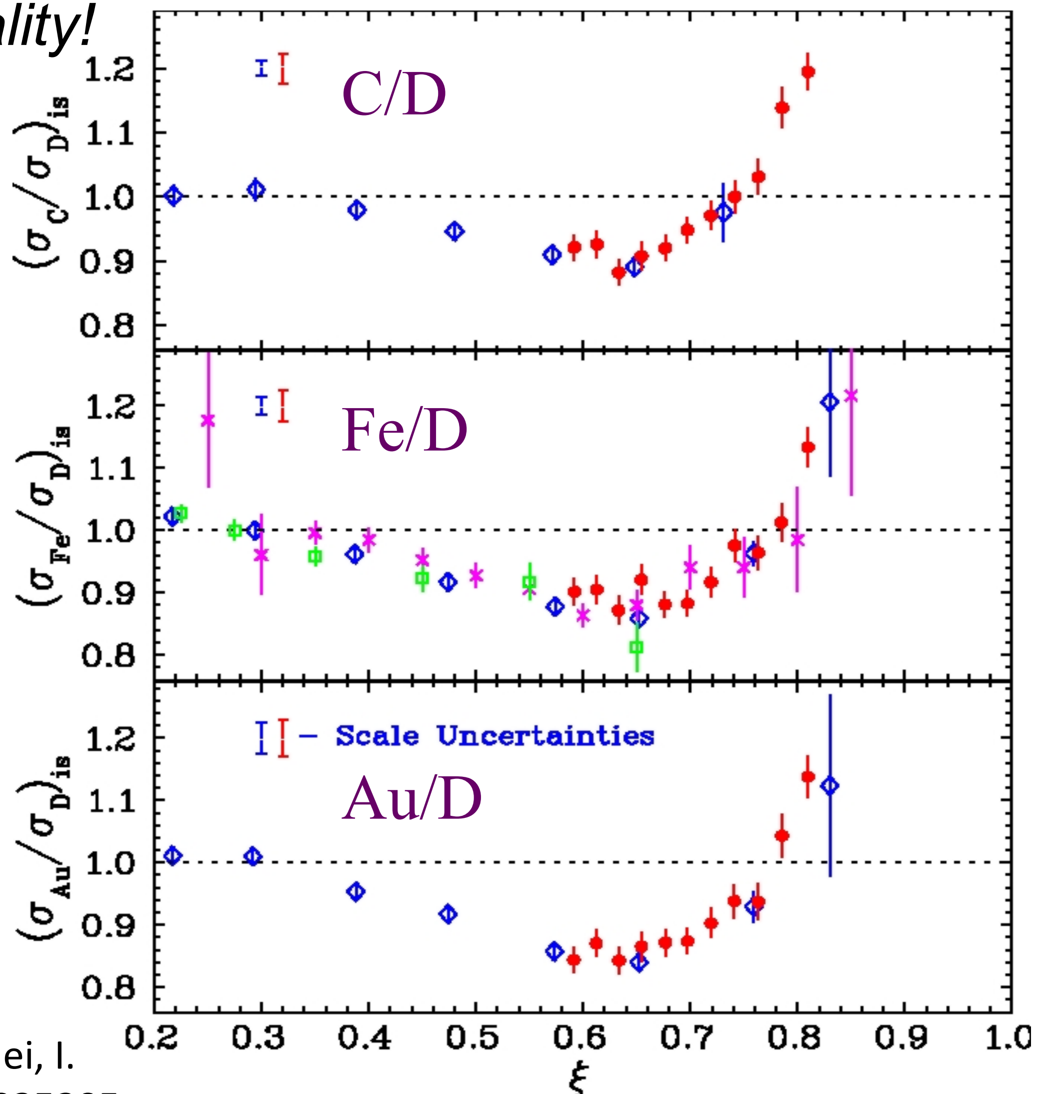
Blue = 12 GeV Hall C!!

(push up in x, Q^2, range of A)

Duality and the EMC Effect (Neutrino friends take note!)

See S. Malace lectures for duality!

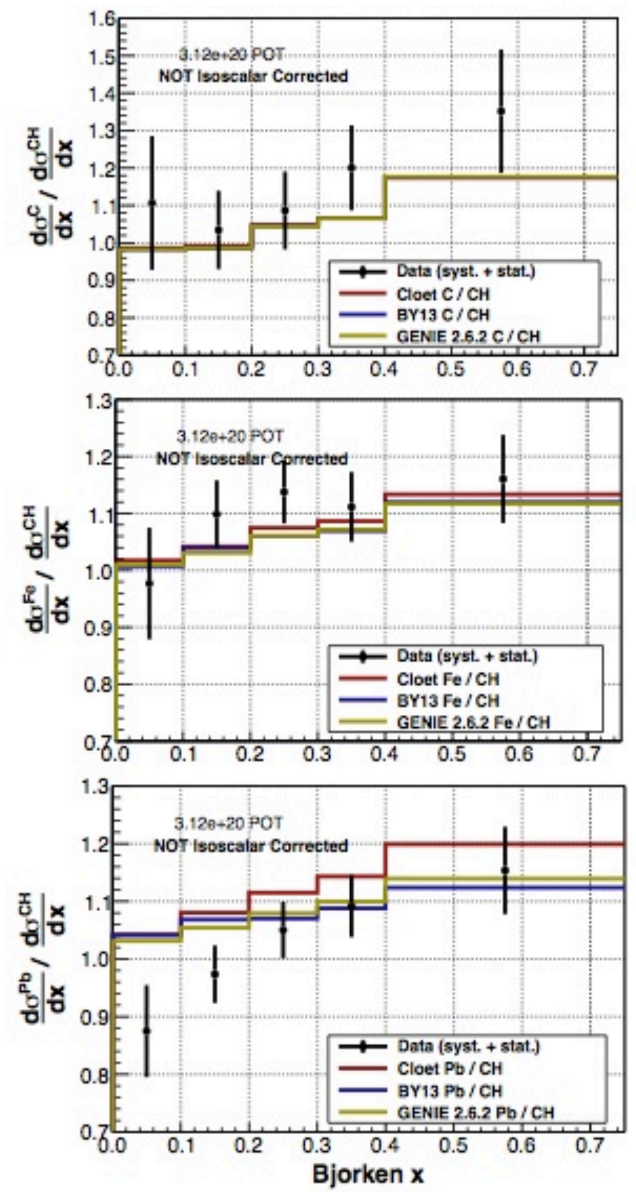
- *Red = resonance region data*
- Blue, purple, green = deep inelastic data from SLAC, EMC
- Medium modifications to the structure functions ***are the same*** in the resonance region as in the DIS
- *Duality observed in nuclei*



J. Arrington, R. Ent, CK, J. Mammei, I. Niculescu, **Phys.Rev. C73 (2006) 035205**

Experimental Studies of Nuclear Effects with Neutrinos:

until recently essentially NON-EXISTENT



J. Mousseau et al., PRL **112** 231801 (2015)

kT detector systems – *nuclear effects can matter!*

Data now coming from MINERvA experiment at Fermilab:

- Neutrino-nucleus scattering
- Cross section measurements possible
- Nuclear ratios

Note *A*-dependence at lowest *x*-bin

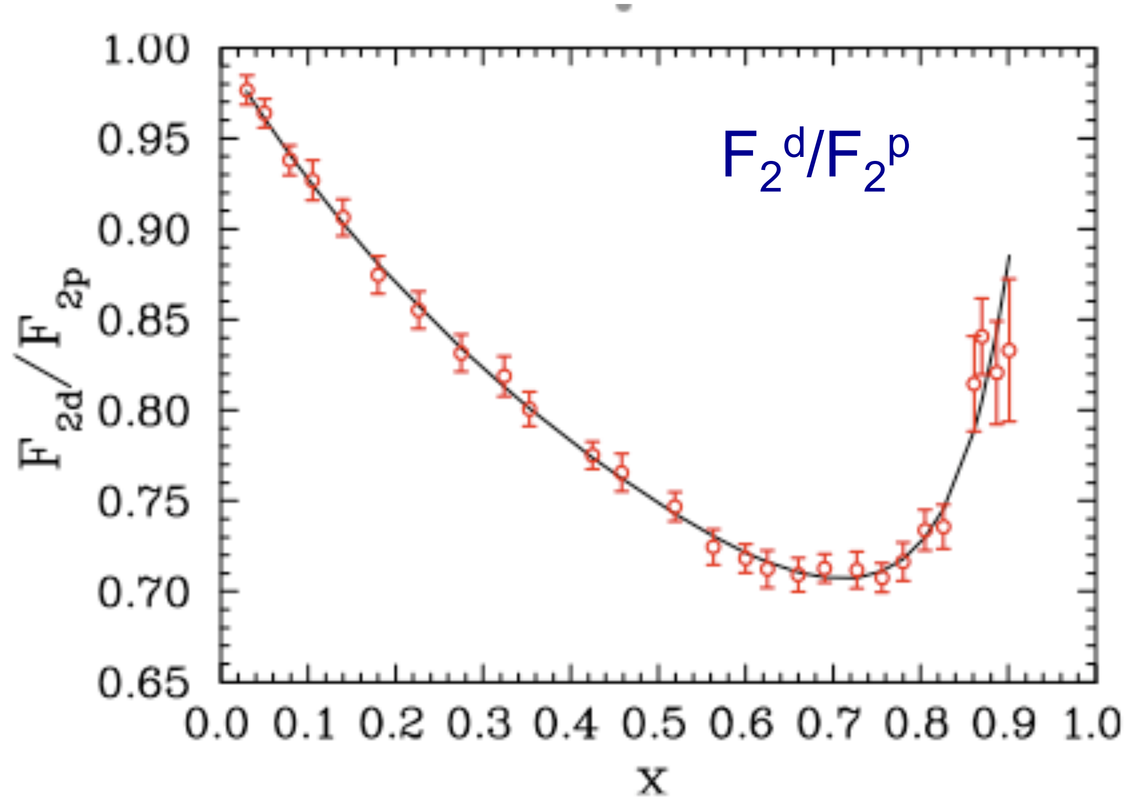
- A drop in x for Pb?
- Data at low Q^2 (< 1 GeV^2)
- Not yet isoscalar corrected
- More and higher energy data en route

Important alert: the deuteron is also a nucleus!

Neutron structure is typically derived from deuterium target data by subtracting proton data

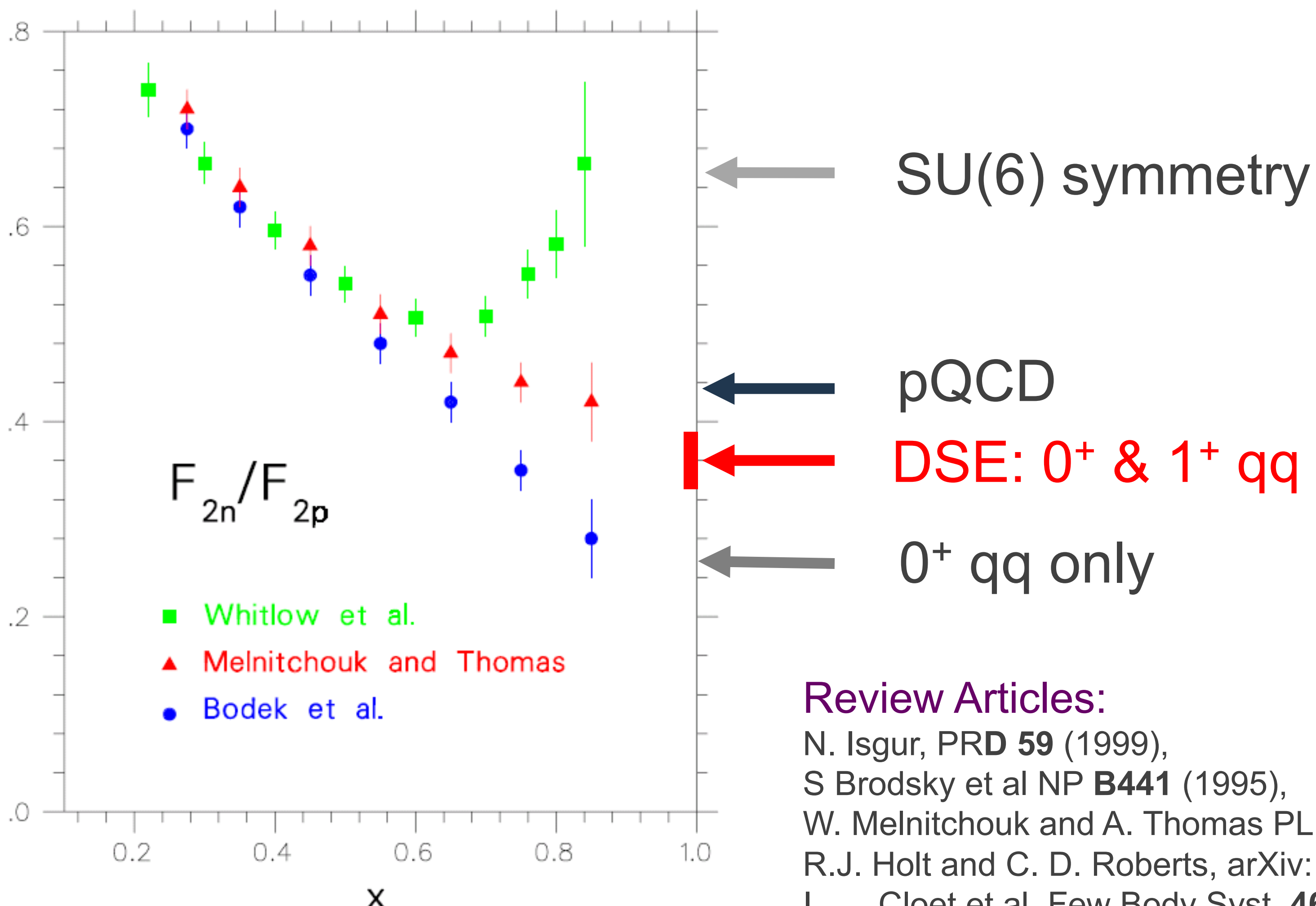
…..but…..

Large uncertainty in unfolding nuclear effects (Fermi motion, off-shell effects, deuteron wave function, coherent scattering, final state interactions, nucleon structure modification ("EMC"-effect),……….



F_2^n/F_2^p (and, hence, d/u) is essentially unknown at large x:

- Conflicting fundamental theory pictures
- Data inconclusive due to uncertainties in deuterium nuclear corrections

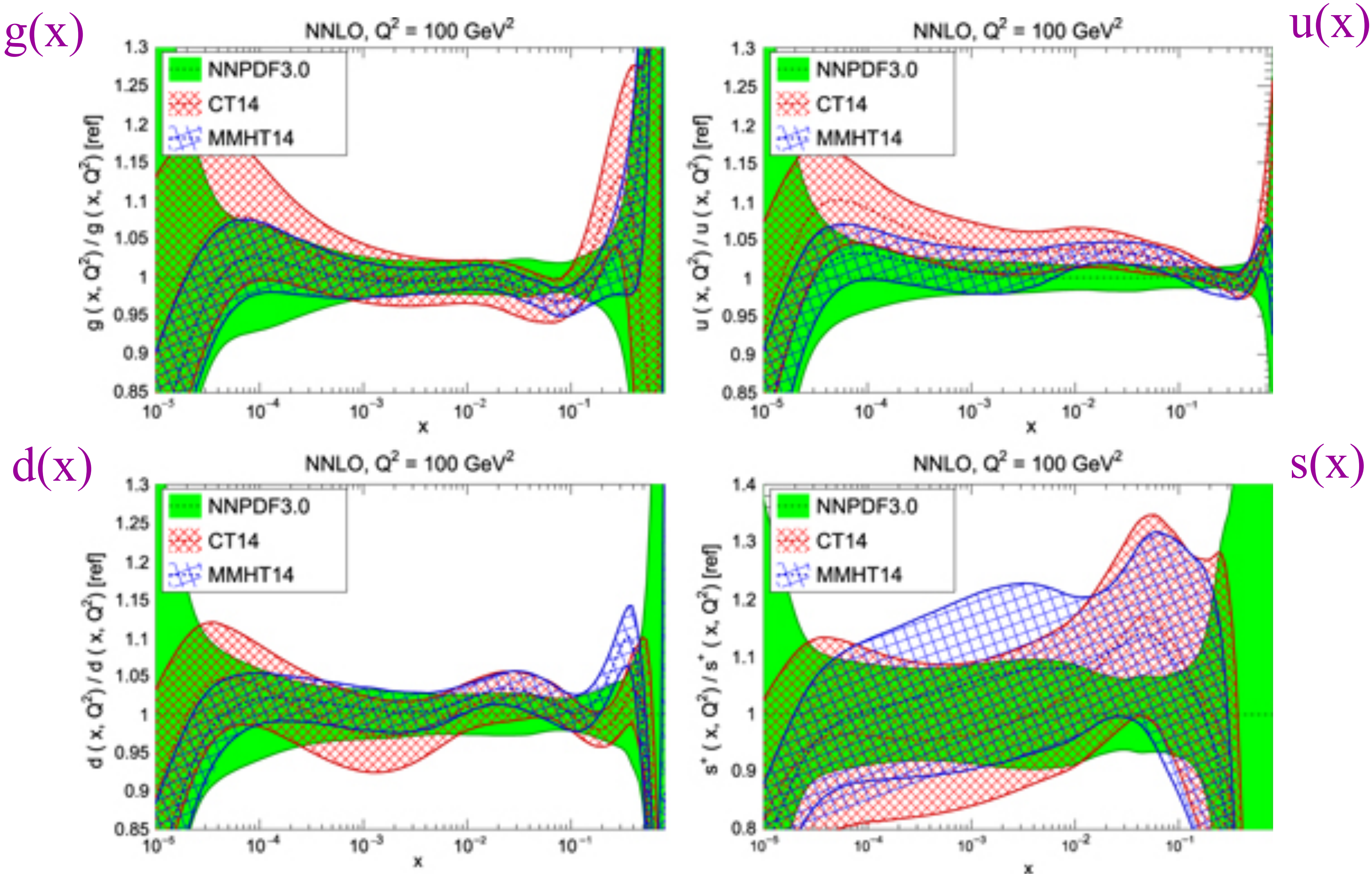


Review Articles:

N. Isgur, PRD **59** (1999),
S Brodsky et al NP **B441** (1995),
W. Melnitchouk and A. Thomas PL **B377** (1996) 11,
R.J. Holt and C. D. Roberts, arXiv:1003.4666 [nucl-th],
I. Cloet et al, Few Body Syst. **46** (2009) 1.

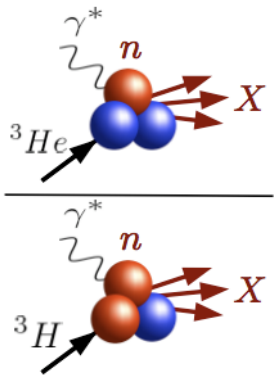
Your textbook may be lying…

Large Uncertainties on Large x Valence pdfs



DIS from A=3 Mirror Nuclei (E12-10-103)

$$R(^3\mathrm{He}) = \frac{F_2^{^3\mathrm{He}}}{2F_2^p + F_2^n}\,, \qquad R(^3\mathrm{H}) = \frac{F_2^{^3\mathrm{H}}}{F_2^p + 2F_2^n}$$

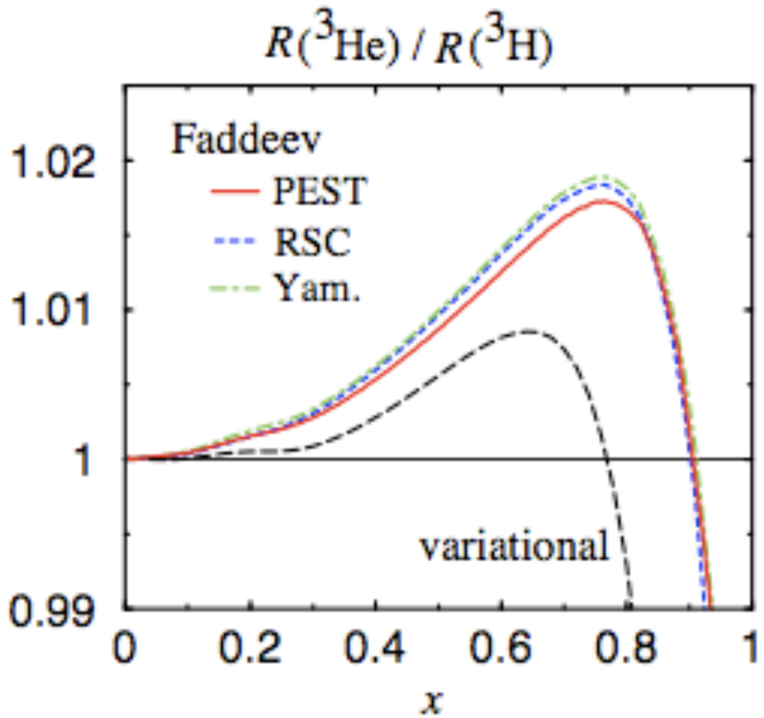


- Mirror symmetry of A=3 nuclei
  - Extract F_2^n/F_2^p from ratio of measured ^{3}He/^{3}H structure functions

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathcal{R}}$$

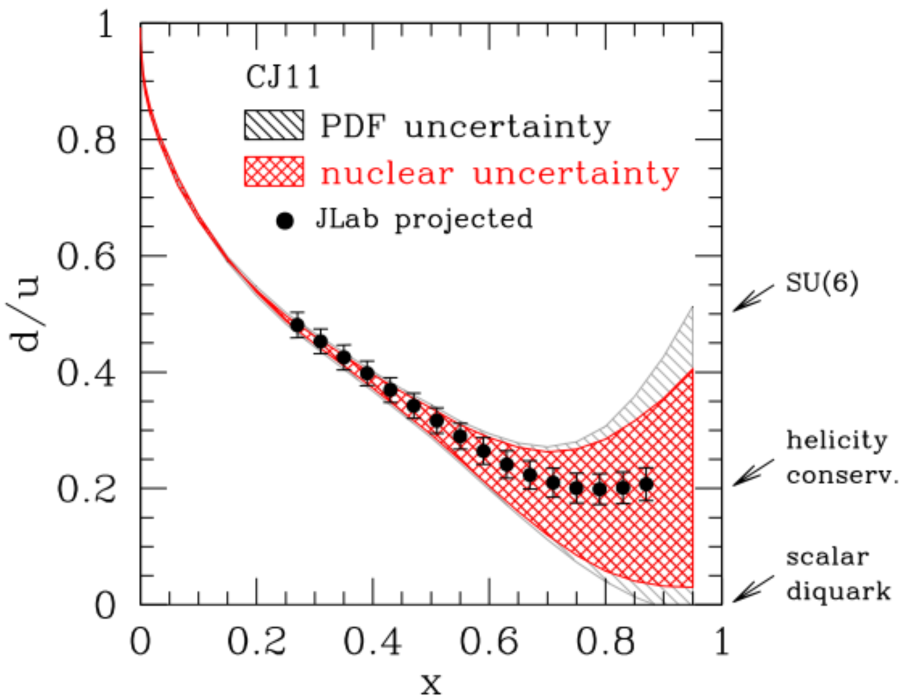
$\mathcal{R}$ = SUPER ratio of "EMC ratios" for ^{3}He and ^{3}H

- Relies only on *difference* in nuclear effects in ^{3}H, ^{3}He
- Calculated to within 1%
- Most systematic and theoretical uncertainties cancel



Tritium Experiment Group Preparations in Jlab Hall A

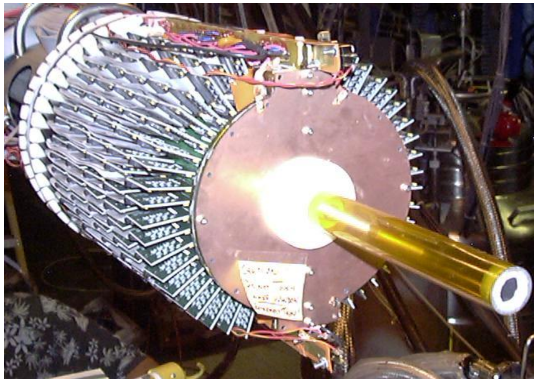
- Four experiments approved
  - 2 PAC 40 “high impact”
- Preparing for Fall 2017 run



- ***Installation currently underway***
  - ✓ Target vent system
  - – Target and safety systems
  - ✓ Scattering chamber rotation
  - ✓ Target installation platform

Other 12 GeV era experiments will also access d/u at large x…

- Tagged deep inelastic scattering
- Parity violating deep inelastic scattering
- Polarized structure functions can provide d/u theory guidance



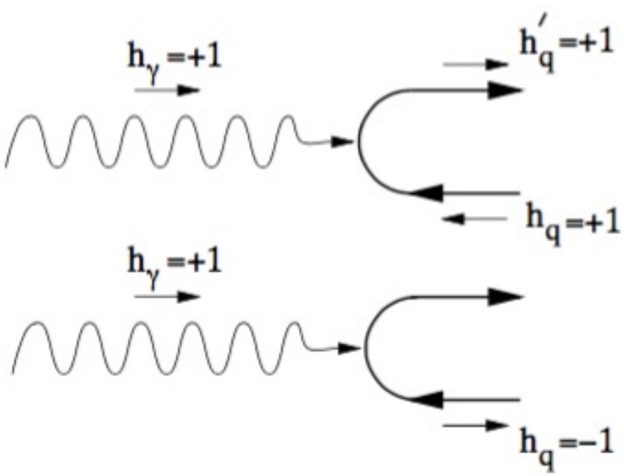
Nucleon Model	F_2^n/F_2^p	d/u	$\Delta u/u$	$\Delta d/d$	A_1^n	A_1^p
SU(6)	2/3	1/2	2/3	-1/3	0	5/9
Valence Quark	1/4	0	1	-1/3	1	1
pQCD	3/7	1/5	1	1	1	1

Hmmm… nuclear medium modifications are interesting...

But, let's check out polarized partons….

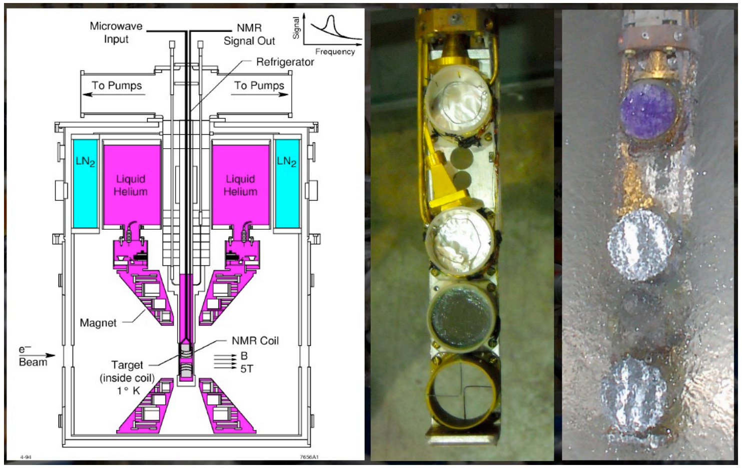
Polarized DIS

- Consider the case when the beam electron and target nucleon are both polarized along the scattering axis….
- Helicity conservation - the virtual γ inherits some of the incident lepton helicity
- The electromagnetic interaction will conserve helicity. So…
- A + (-) helicity quark can only absorb a + (-) helicity photon.
- Study the difference under reversal of electron/photon helicity (or equivalently reversing the target spin)….
- Determine the probability that the struck quark has the same helicity as the incident lepton for a fixed spin orientation of the proton.



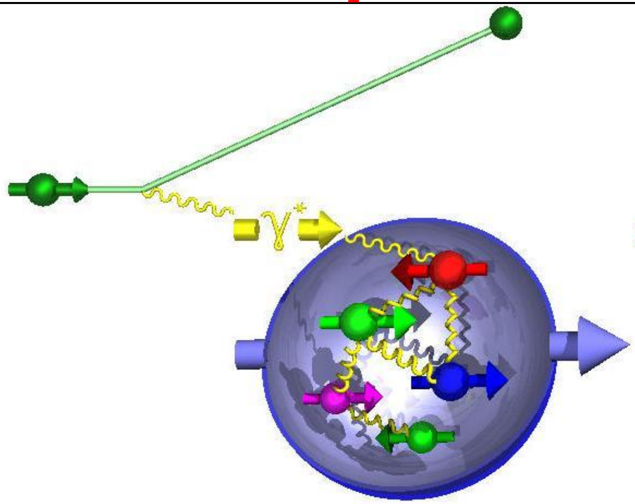
Quark helicity conserved,
$m'_q = m_\gamma + m_q$

Quark helicity not conserved

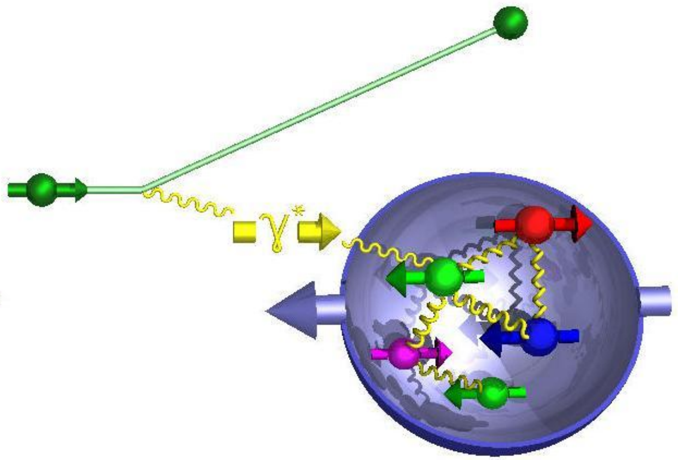


Polarized Structure Functions

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 [\underbrace{\Delta q_i(x) + \Delta \bar{q}_i(x)}_{\Delta q_f(x)}] \qquad \Delta q_i(x) = q_i^+ - q_i^-$$



Parallel electron & quark spins



Anti-parallel electron & quark spins

Polarized deep inelastic electron scattering

Measure yield asymmetry:

$$A_1 = \frac{1}{DP_T P_B} \frac{N_{\uparrow\downarrow} - N_{\uparrow\uparrow}}{N_{\uparrow\downarrow} + N_{\uparrow\uparrow}}$$

In the Quark-Parton Model:

$$A_1 \approx \frac{g_1(x)}{F_1(x)} = \frac{1}{F_1(x)} \sum_f e_f^2 \Delta q_f(x)$$

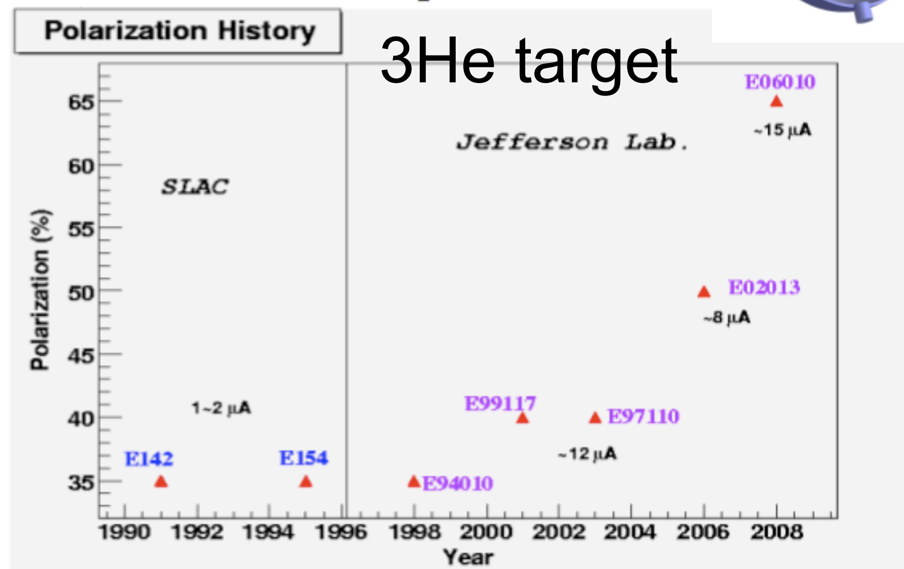
Spin-dependent Structure Function

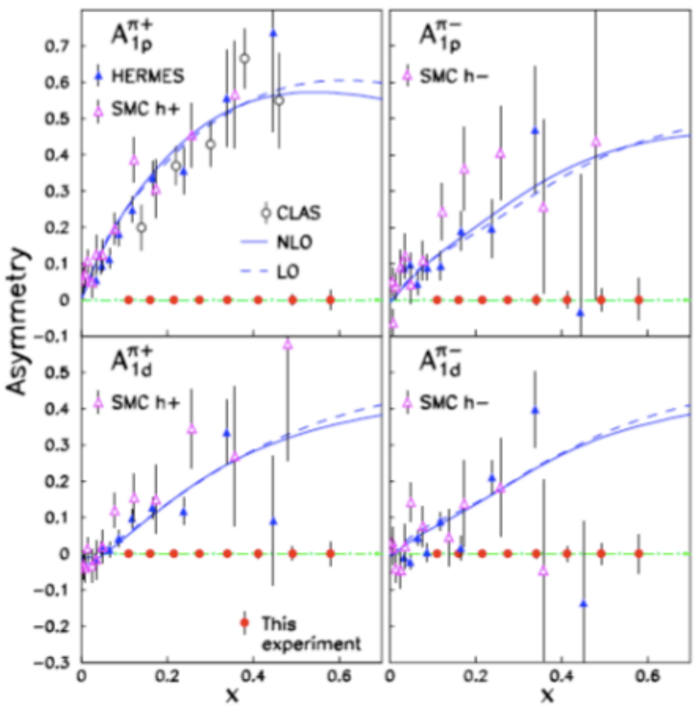
Measuring High-x Structure Functions - polarized

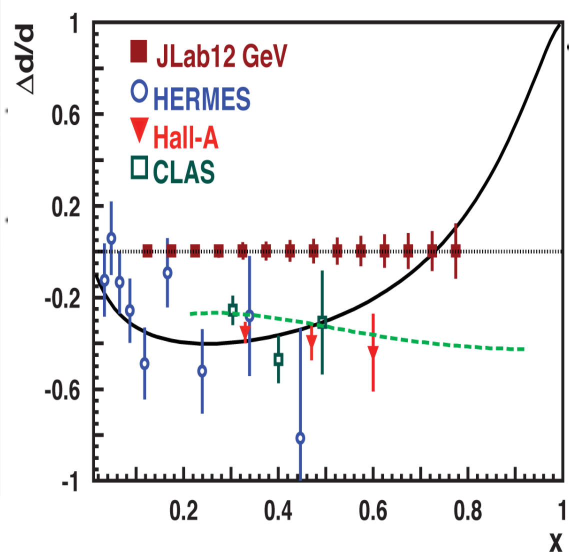
REQUIRES:

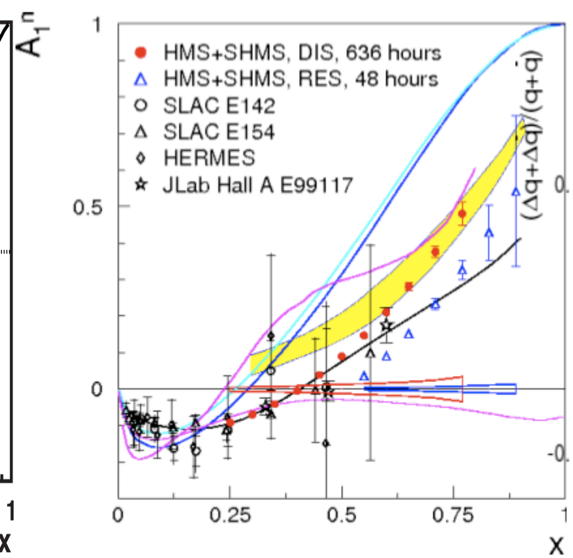
- High beam, target polarization
- High electron current
- Large solid angle spectrometers
- Polarized PDF efforts – JAM
- Broad JLab12 program!

3He target





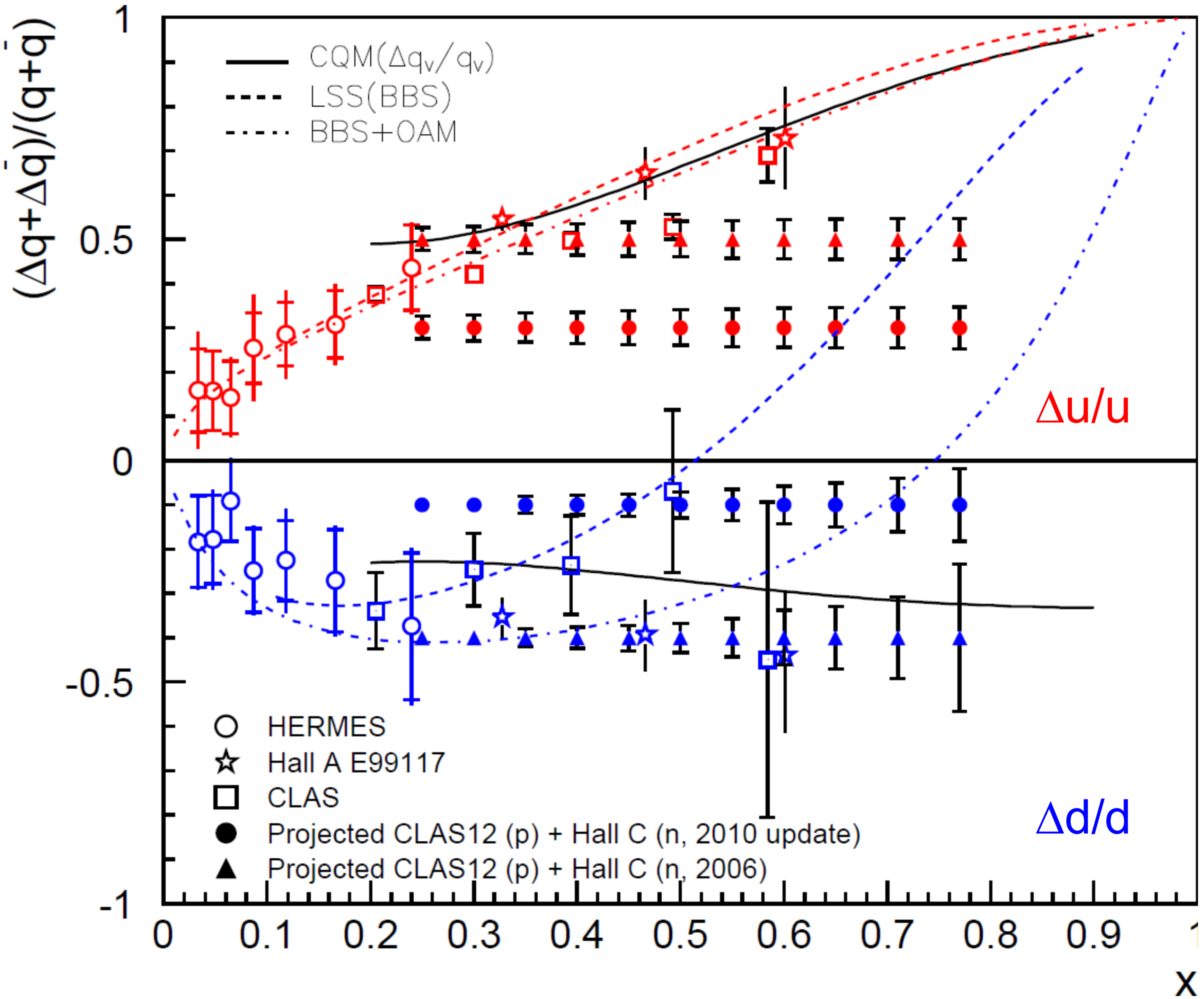




12 GeV Era Polarized PDFs

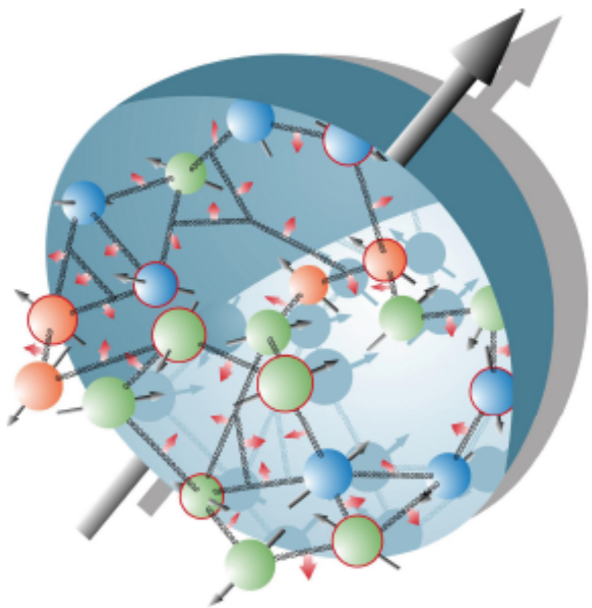
Combine Hall B A_1^p and Hall C A_1^n

→ extract $\Delta u/u$ and $\Delta d/d$



12 GeV will access the regime (x > ~0.3) where valence quarks dominate

The Incomplete Nucleon: The Spin Puzzle



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

- Proton has spin-1/2
- Proton is a composite system consisting of spin-1/2 quarks and spin-1 gluons
- **But…**

- $\Delta S \sim 0.25$ (world DIS)
- ΔG small ~ 0.1 (RHIC+DIS)
- L_q??

Can this puzzle maybe be solved by orbital angular momentum?

Try a cross-product or something three-dimensional….

Classical: $\sim \mathbf{r} \times \mathbf{p}$

I’ve got to move on, but there are a couple more things that deserve a last fast look…..

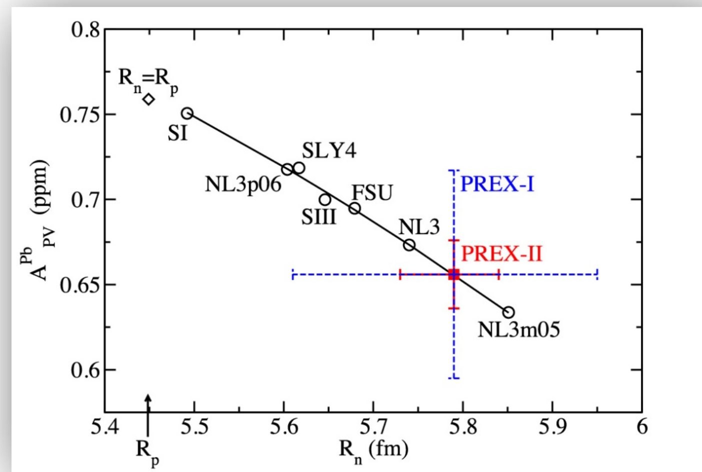
Parity Violation Program at JLab

- Strangeness Form Factors (complete)
  HAPPEX (Hall A)
  G0 (Hall C)

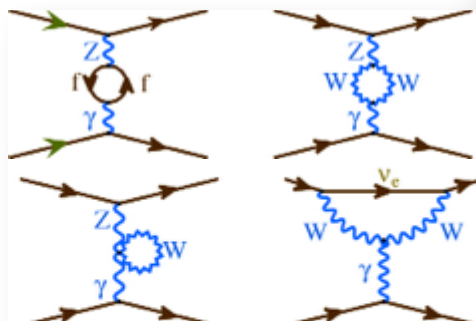
Luminosity, polarization

- PREX neutron skin

  first PREX (^{208}Pb) experiment completed
  PREX-II and CREX (^{48}Ca) preparation ongoing

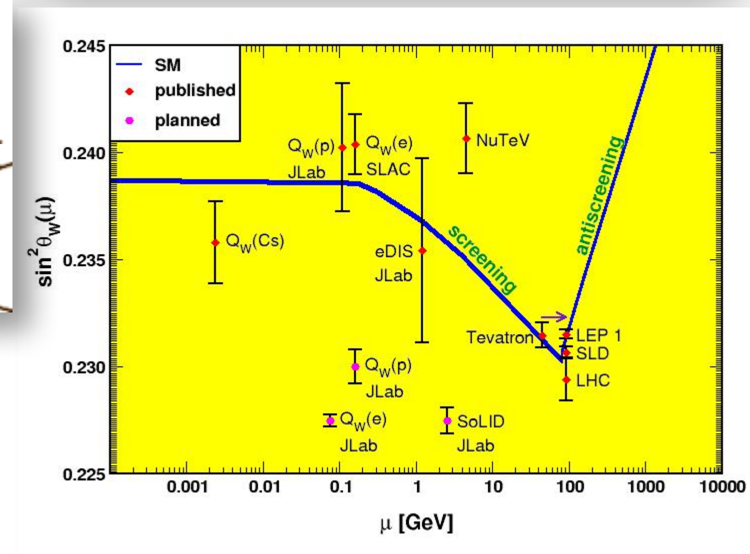


- Qweak (to be released)
  proton weak charge
  lepto-quark couplings

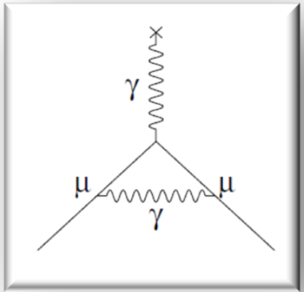


- MOLLER
  electron weak charge
  purely leptonic
  BSM physics at 38 TeV scale!

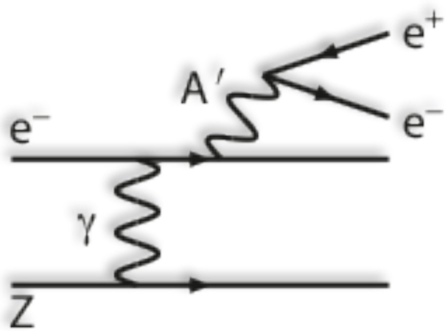
- SoLID
  lepto-quark couplings
  lepto-phobic Z'
  d/u, higher-twist



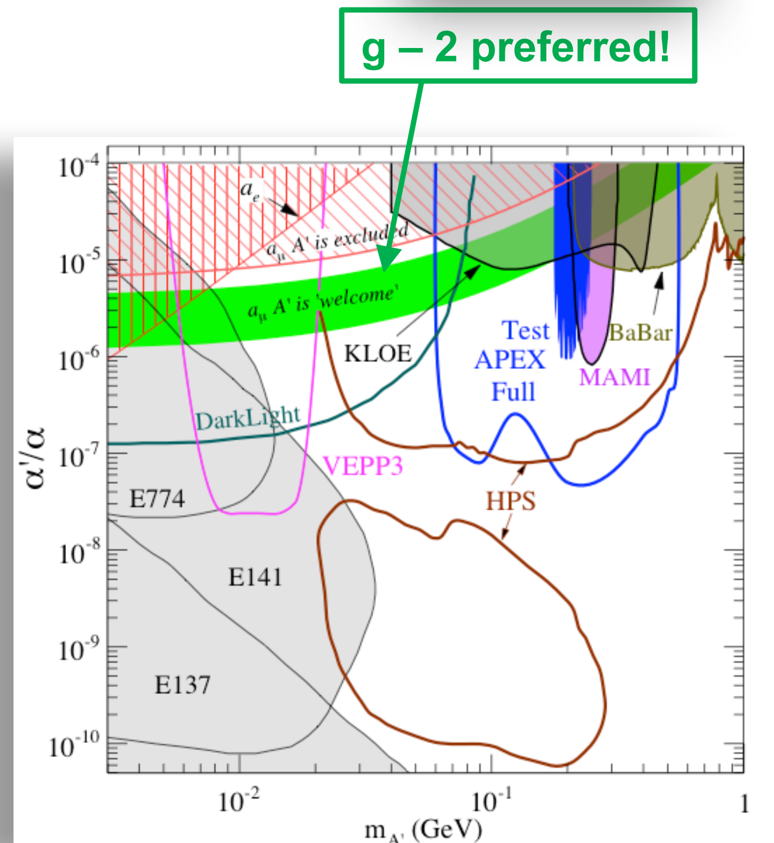
New Opportunity: Searches for A' at Jefferson Lab



- BNL "g-2" expt: $\Delta a_\mu(\text{expt-thy}) = (295 \pm 88) \times 10^{-11}$ ($3.4\,\sigma$)
- No evidence for SUSY at LHC (yet)
- Another solution: A', a massive neutral vector boson



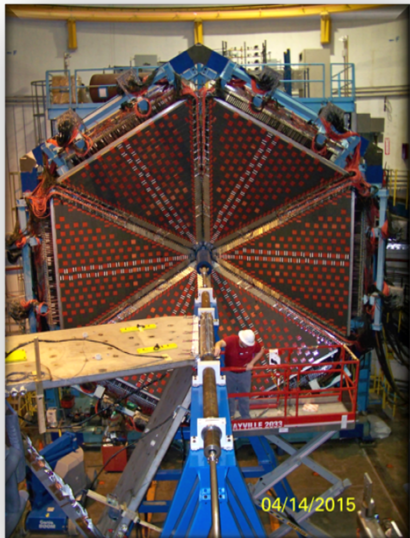
  - also useful for dark matter models

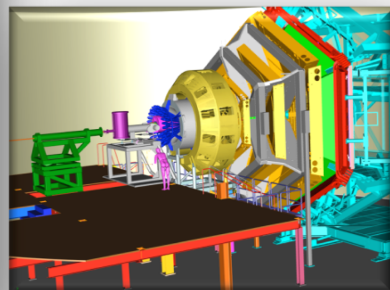


- 3 Jefferson Lab proposals:
  - APEX test run (Hall A) – published
  - HPS test run (Hall B) – complete
    HPS engineering/1st physics run – complete
  - DarkLight test run (FEL) – complete

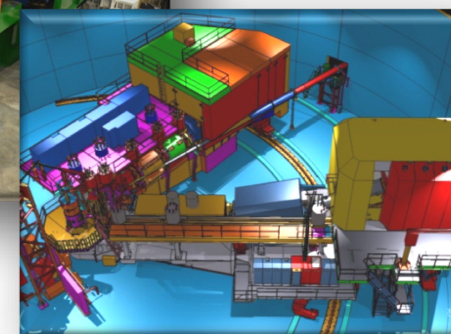
12 GeV JLab - Broad Scientific Capabilities

Hall B **– understanding nucleon structure via generalized parton distributions**

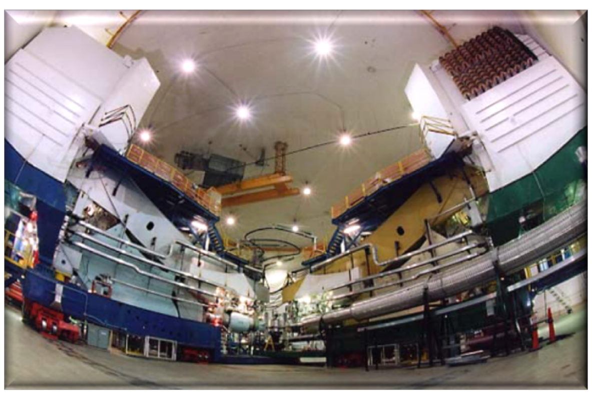


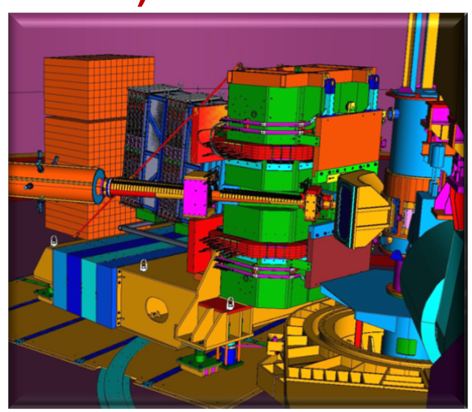


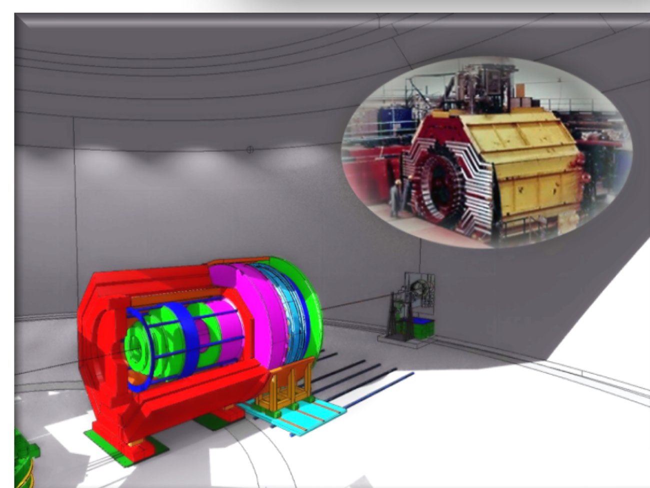
Hall C **– precision determination of valence quark properties in nucleons/nuclei**

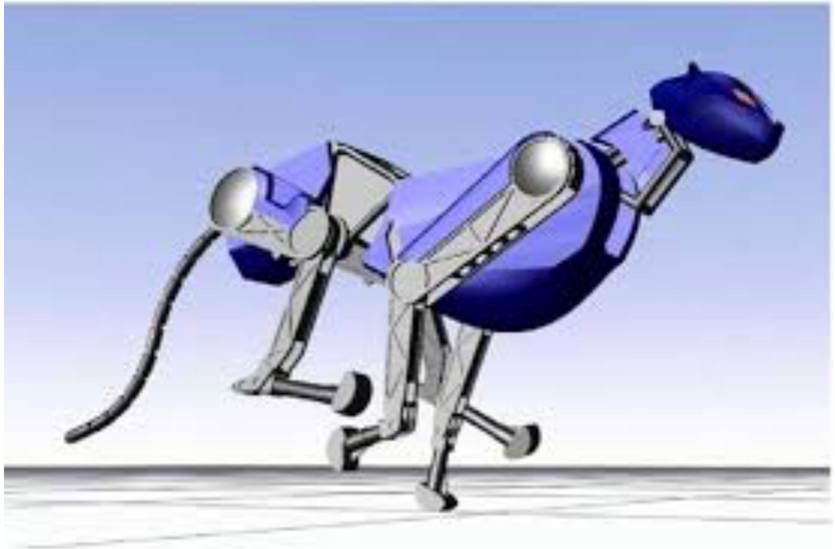


Hall A **– polarized 3He, future new experiments (e.g., SBS, MOLLER and SoLID)**









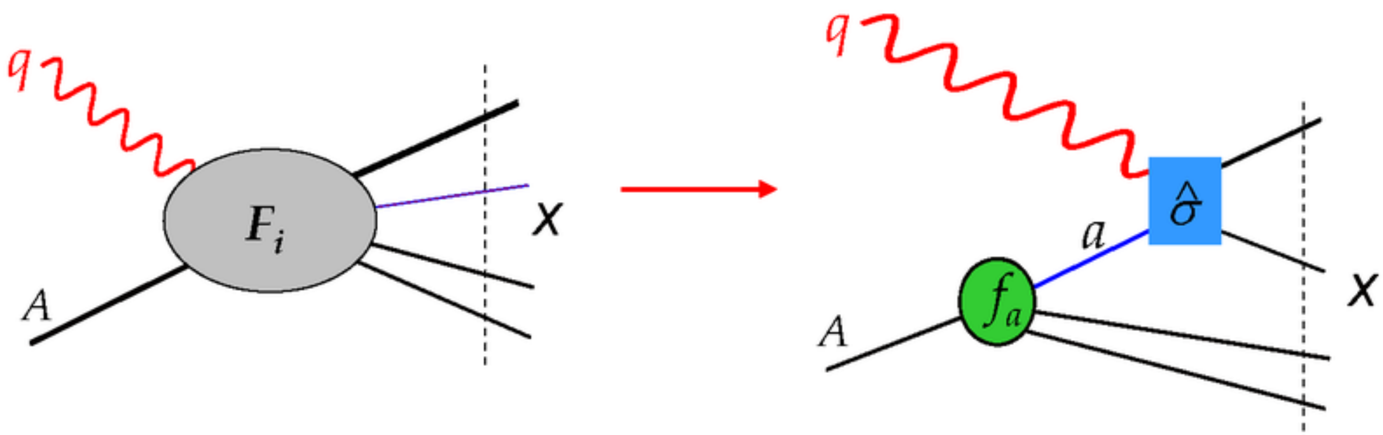
Orbital angular momentum….into the (not so distant) future….

What are we missing?

✓ We discovered that (nearly) massless quarks and gluons make up the nucleon and that QCD governs their interactions.

- We had hoped to find out how quarks and gluons and their interactions give rise to the characteristics of the nucleons.
  - Spin
  - Mass
  - Bulk
- We also hoped that we would be able to find out how NN interactions work in terms of QCD.
  - How nuclear forces arise.
  - How nuclear characteristics come about
- We were able to do this kind of things with EM and atoms.
- *So far we have failed…*

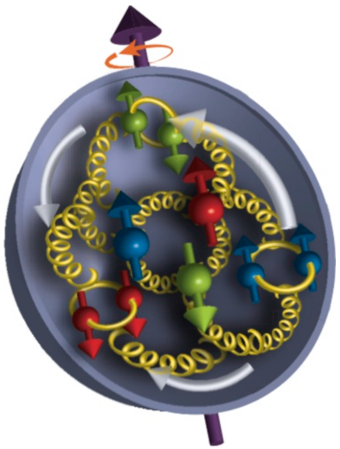
What longitudinal factorization did



$$\lim_{Q^2 \to \text{large},\, x\,\text{fixed}} F_i(x, Q^2) = f_a \otimes \hat{\sigma}$$

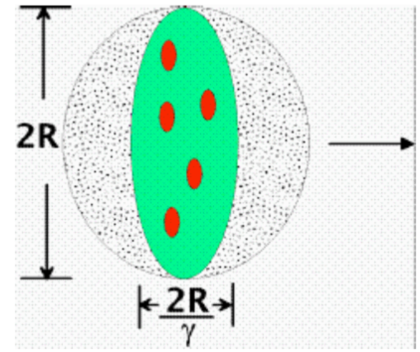
Function only of x (i.e. longitudinal momentum)
Our quarks and gluons as constituents of the proton only exist longitudinally.

Limits of Longitudinal Information



infinite momentum frame

What we know



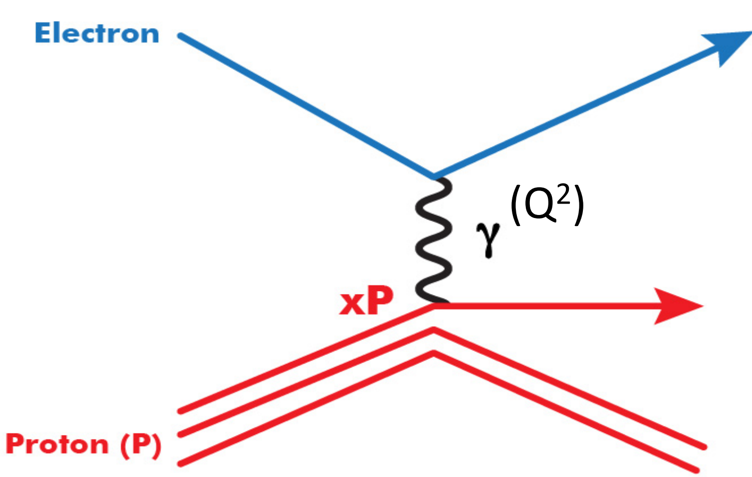
What is the quark and gluon structure of the proton?
-orbital motion?
-color charge distribution?
-how does the mass come about?
-origin of nucleon-nucleon interaction?

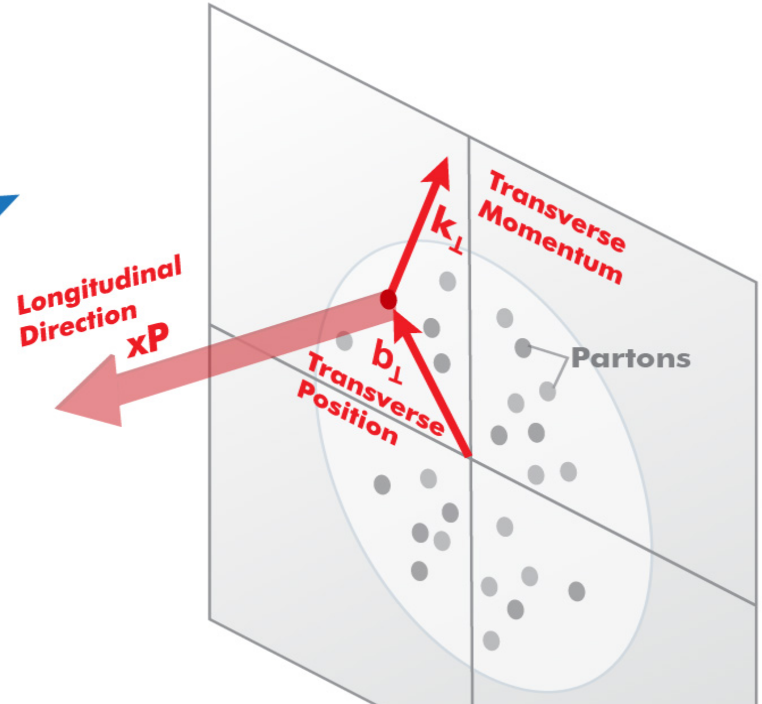
Parton frozen transversely. Framework does not incorporate any transverse information.

But this was the only way to define quark-gluon structure of proton in pQCD.

Progress in pQCD Theory (~1980-~2010)

Factorization II



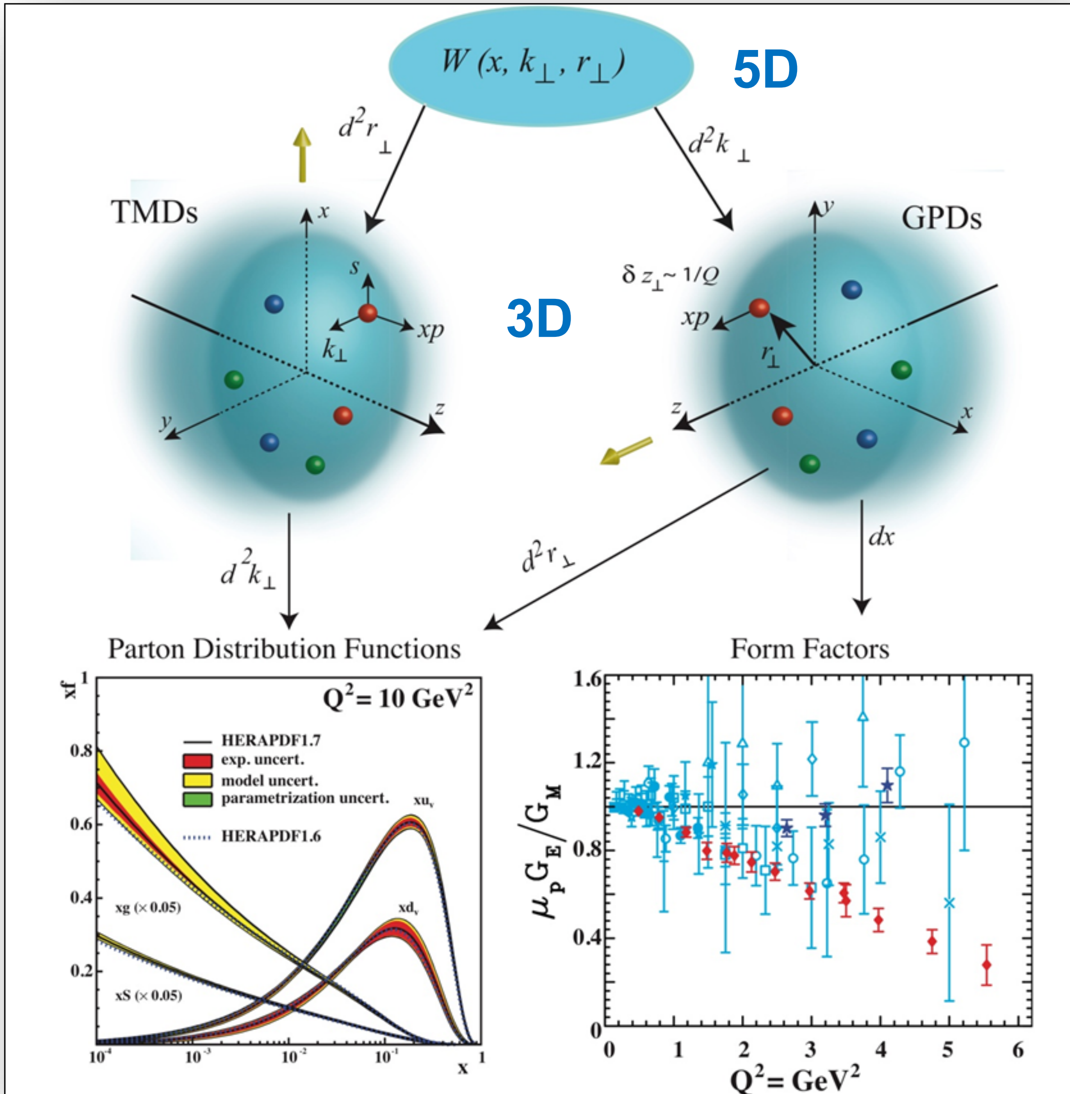


Parton Distribution Functions:
Longitudinal only—
No way to interpret nucleon partonic structure in rest frame

3D (Transverse) Structure
TMD's, GPD's—
Now we know what to measure to understand the 3D structure of nucleons

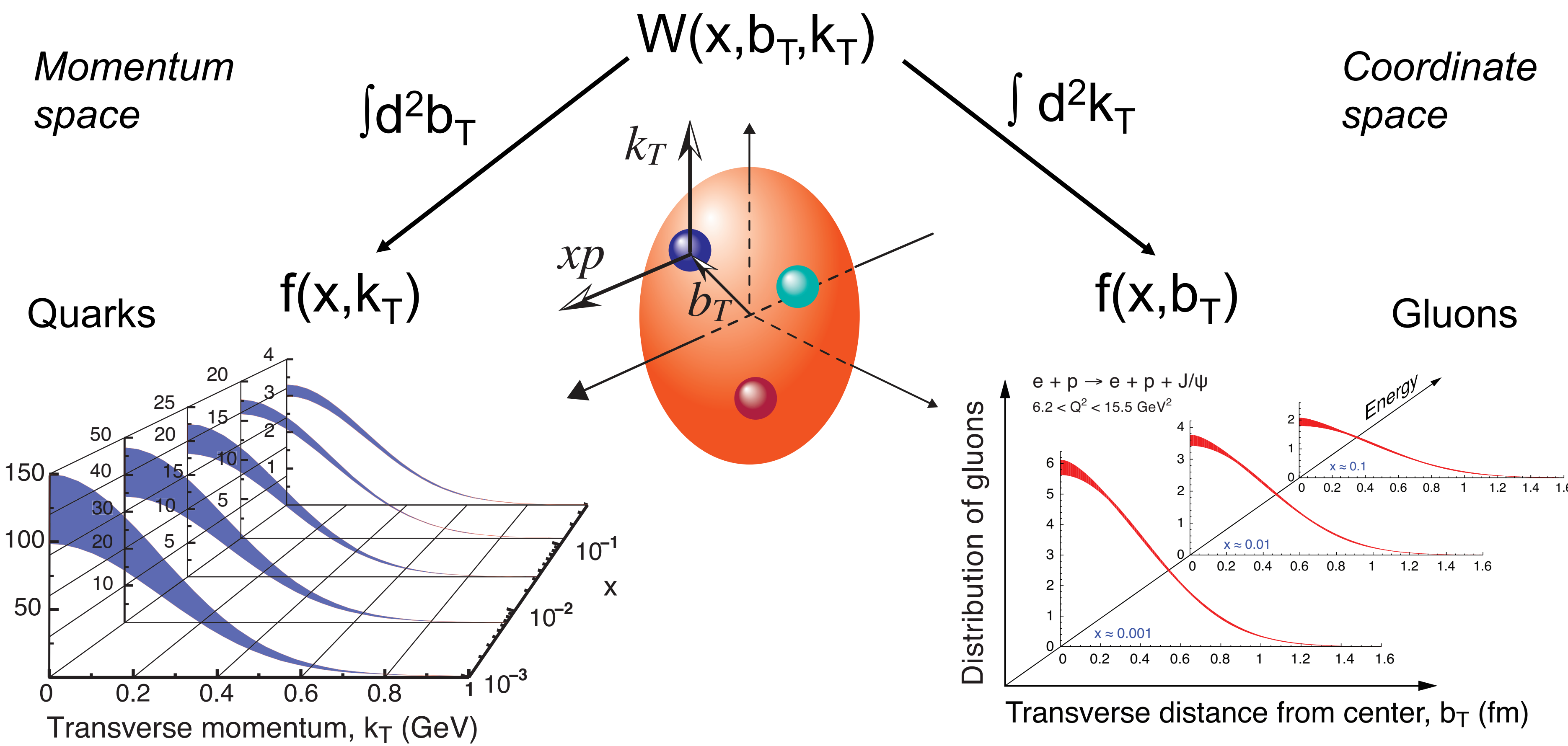
Transverse Momentum Dependent Distributions (TMD): k_t
Generalized Parton Distributions (GPD): b_t

New Paradigm for Nucleon Structure



- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)
- GPDs
  - Spatial imaging (exclusive DIS)
- Requires
  - High luminosity
  - Polarized beams and targets

3D Imaging of Quarks and Gluons



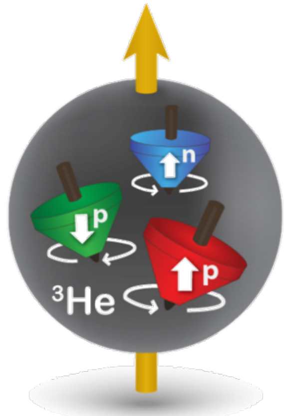
Spin-dependent 3D momentum space images from semi-inclusive scattering

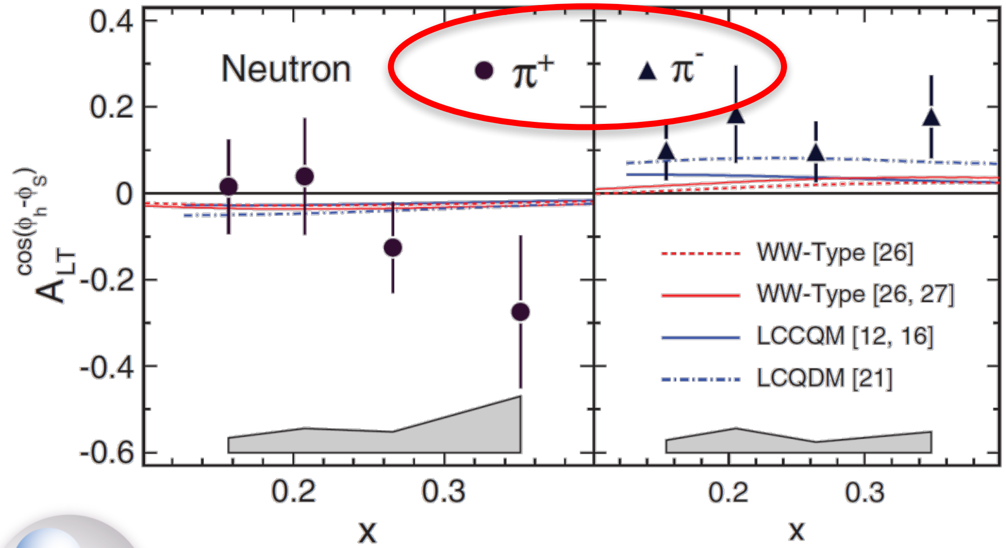
Spin-dependent 2D (transverse spatial) + 1D (longitudinal momentum) coordinate space images from exclusive scattering

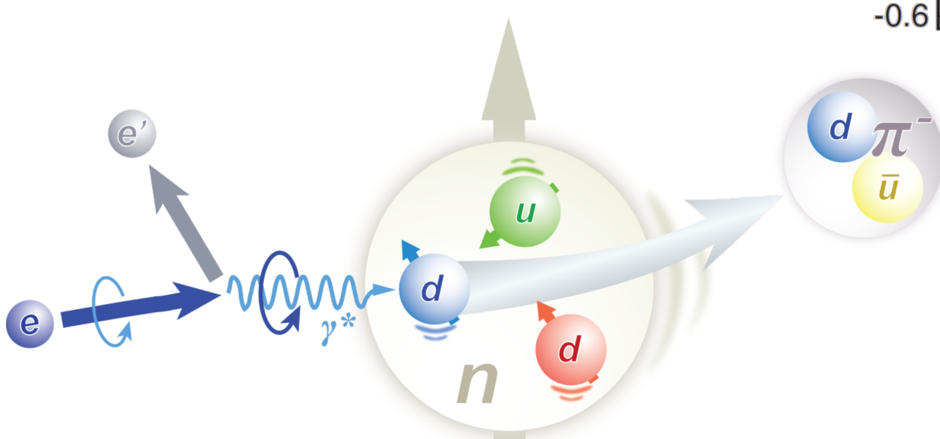
SIDIS Observables Reveal Interesting Behavior of Quarks

Huang, *et. al.* PRL. 108, 052001 (2012)

Target: **transversely** **polarized ^{3}He ~ polarized neutron**





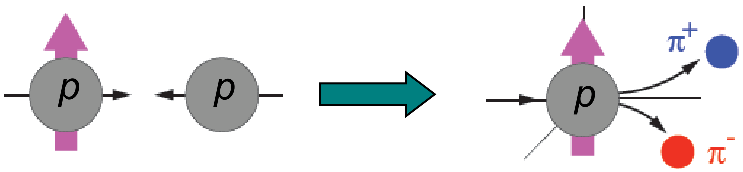


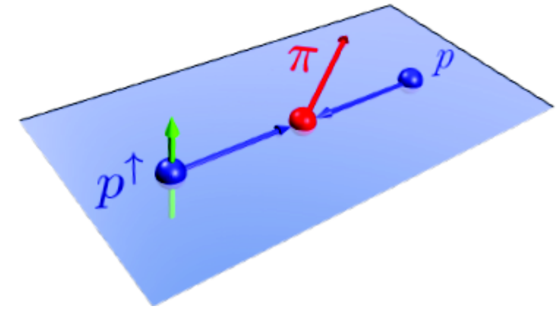
- A non-vanishing quark "transversal helicity" distribution, reveals alignment of quark spin transverse to neutron spin direction
- Indicative of quark orbital motion
- Foundation for future mapping in four kinematic dimensions (x, Q^2, z, p_T) of transverse-momentum dependent parton distributions

JLab measurements of ^{3}He (neutron) single-spin asymmetries

X. Qian *et al.*, PRL 107, 072003 (2011)

Transverse SSA in Proton-Proton Reactions

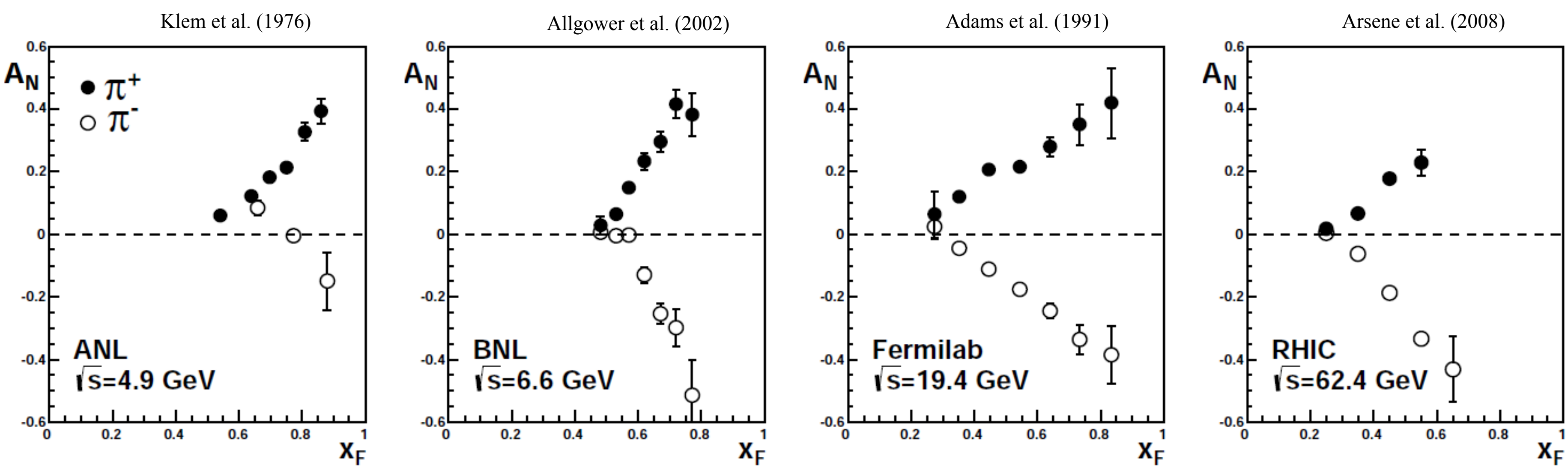




$$A_N = \frac{1}{P_{\text{beam}}} \frac{N^{\pi}_{\text{left}} - N^{\pi}_{\text{right}}}{N^{\pi}_{\text{left}} + N^{\pi}_{\text{right}}}$$

In collinear picture, the QCD predict small SSAs with transversely polarized protons colliding at high energies

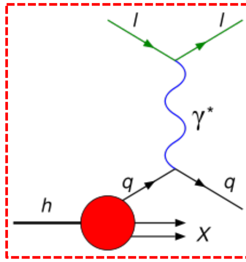
$$A_N \sim \alpha_s m_q / P_{h\perp}$$



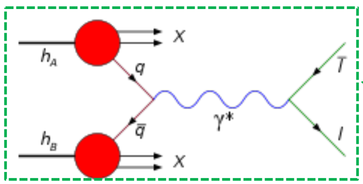
C. Aidala et al., Rev. Mod. Phys. 85, 655

Much Data = Parton Distributions Functions

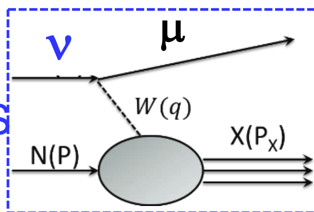
charged lepton DIS: CERN, SLAC, JLab



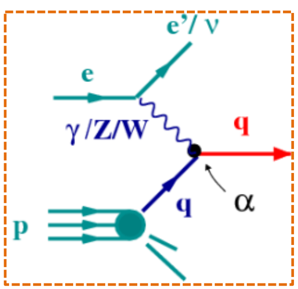
Drell-Yan: Fermi Lab

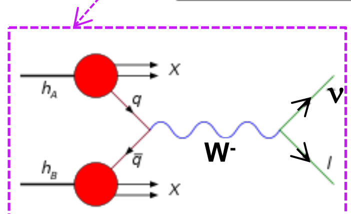


neutrino DIS



charged lepton DIS, high energy: HERA





Fermi Lab Tevatron

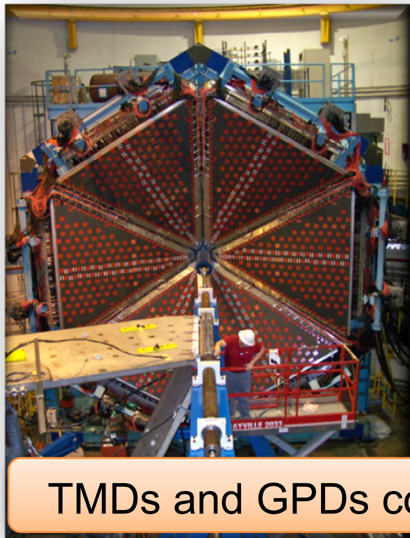
Example of global data set used to extract nucleon's unpolarized, 1D PDFs (The NNPDFs Collaboration)

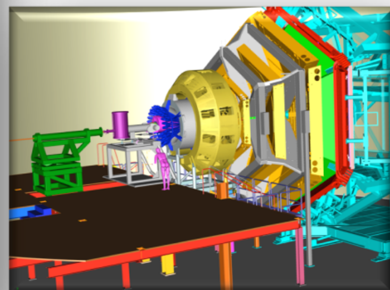
Process		Partons	x range
$\ell^\pm \{p,n\} \to \ell^\pm X$	fixed target	$q, \bar{q}, g$	$x \gtrsim 0.01$
$\ell^\pm n/p \to \ell^\pm X$		d/u	$x \gtrsim 0.01$
$pp \to \mu^+\mu^- X$		$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
$pn/pp \to \mu^+\mu^- X$		$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
$\nu(\bar{\nu}) N \to \mu^-(\mu^+) X$		$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
$\nu N \to \mu^-\mu^+ X$		s	$0.01 \lesssim x \lesssim 0.2$
$\bar{\nu} N \to \mu^+\mu^- X$		$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
$e^\pm p \to e^\pm X$	collider	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
$e^+ p \to \bar{\nu} X$		d, s	$x \gtrsim 0.01$
$e^\pm p \to e^\pm c\bar{c} X$		c, g	$0.0001 \lesssim x \lesssim 0.01$
$e^\pm p \to \text{jet} + X$		g	$0.01 \lesssim x \lesssim 0.1$
$p\bar{p} \to \text{jet} + X$		g, q	$0.01 \lesssim x \lesssim \boxed{0.5}$
$p\bar{p} \to (W^\pm \to \ell^\pm \nu) X$		$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
$p\bar{p} \to (Z \to \ell^+\ell^-) X$		d	$x \gtrsim 0.05$

Will need to be true as well for "3D" PDFs!

12 GeV JLab - Broad Scientific Capabilities

Hall B **– understanding nucleon structure via generalized parton distributions**

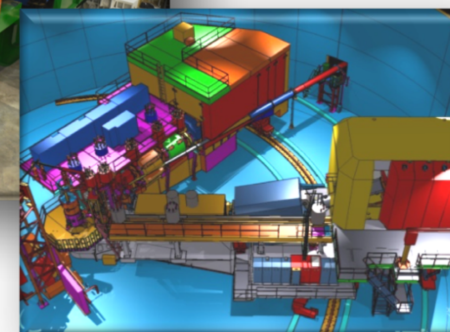




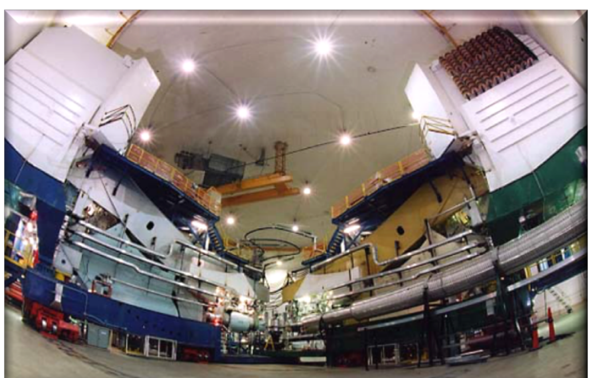
TMDs and GPDs comprehensive study

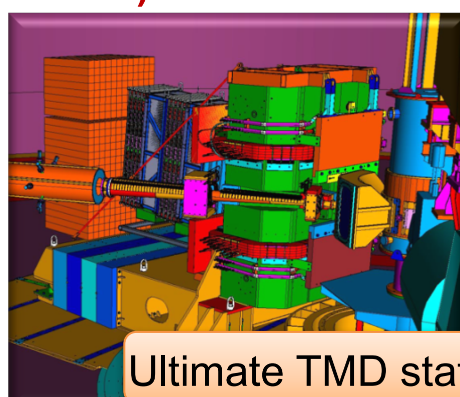
Hall C **– precision determination of valence quark properties in nucleons/nuclei**

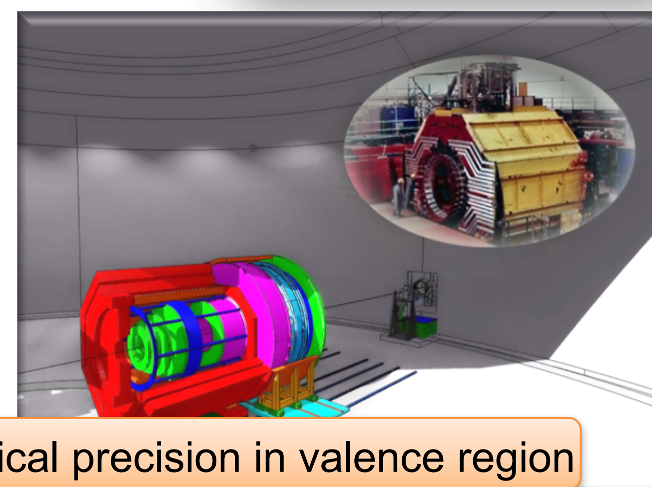
SIDIS/DES cross-section factorization tests



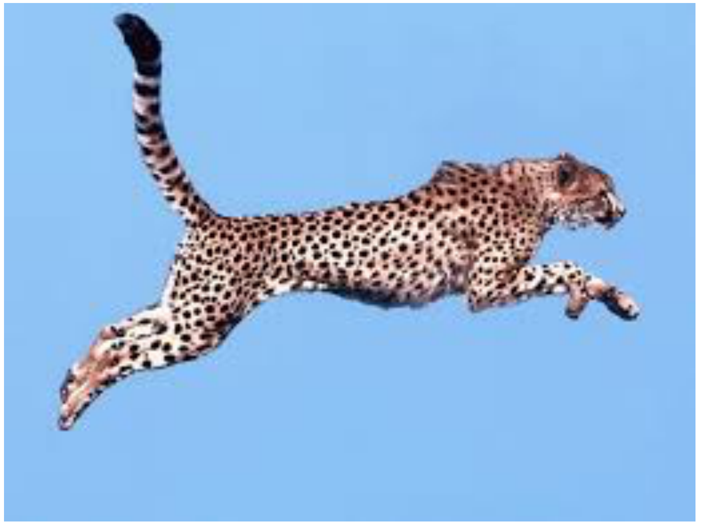
Hall A **– polarized 3He, future new experiments (e.g., SBS, MOLLER and SoLID)**







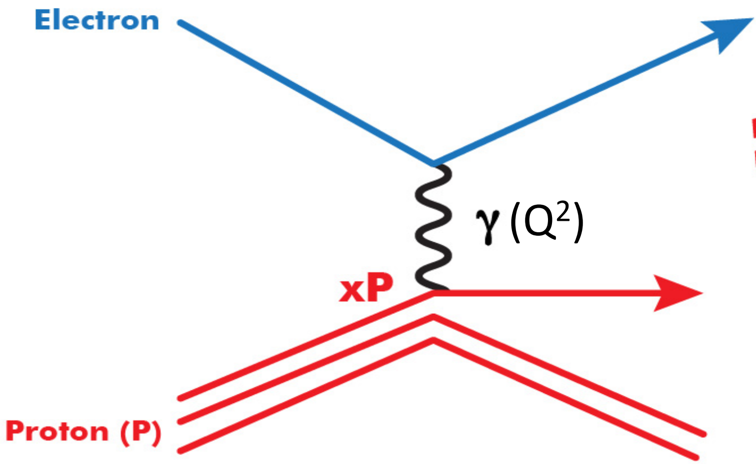
Ultimate TMD statistical precision in valence region

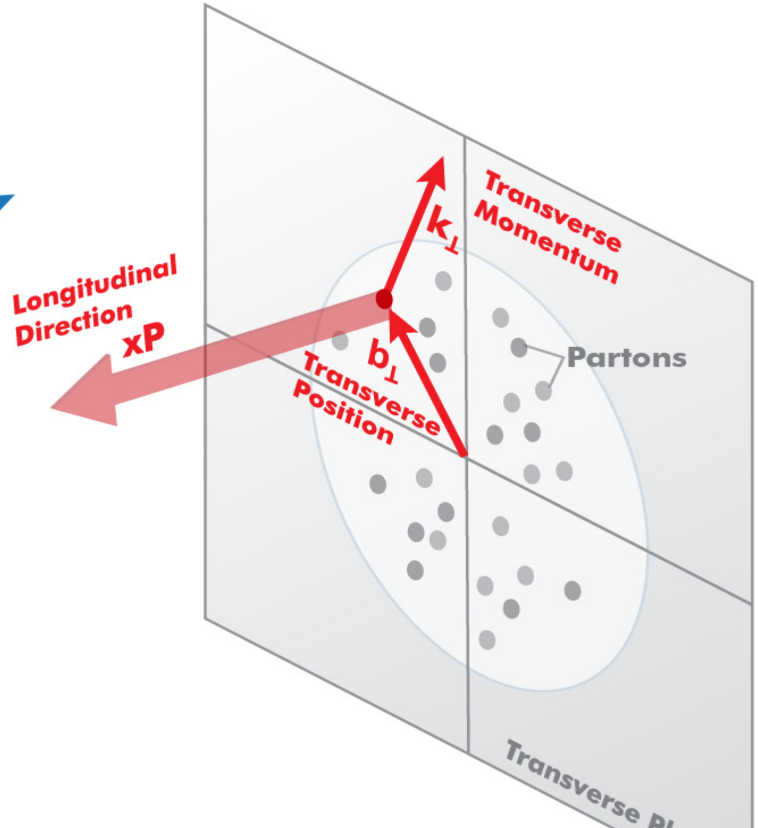


THE NEXT LEAP FORWARD: EIC

Experimental Challenge of the EIC

$Q^2 = sxy, \quad s = 4E_eE_p$



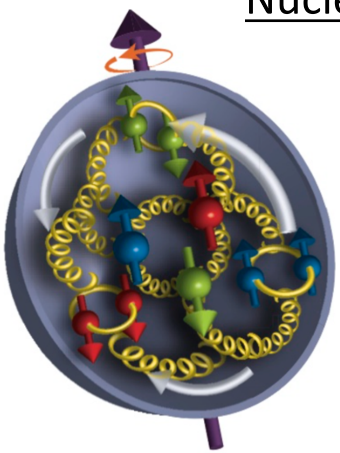


On one hand: need high beam energies to resolve partons in nucleons.
Q^2 needs to be up to ~1000 GeV^2

On the other: need to resolve quantities (k_t, b_t) of order a few hundred MeV in the proton. Limits proton beam energy. High Lumi needed.

Electron-Ion Collider: Cannot be HERA or LHeC: proton energy (TeV) too high

Understanding the Nucleon at the Next Level



Nucleon: A many-body system with challenging characteristics

Relativistic (M_{proton} >> M_{quark})

Strongly Coupled (QCD)

Quantum Mechanical (Superposition of configurations)

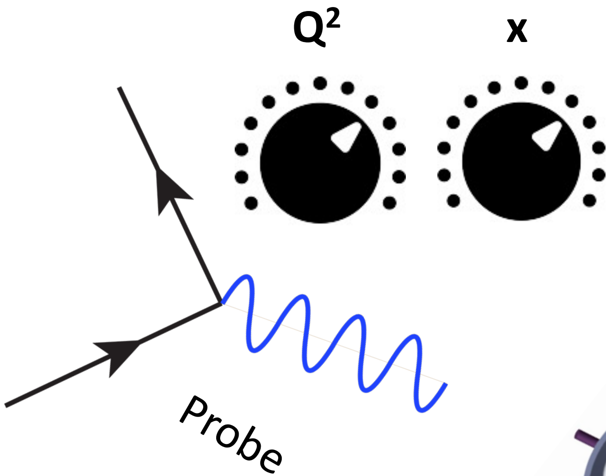
Measure in the Multi-Body regime:
- Region of quantum fluctuation + non-perturbative effects → dynamical origin of mass, spin.

For the first time, get (almost?) all relevant information about quark-gluon structure of the nucleon

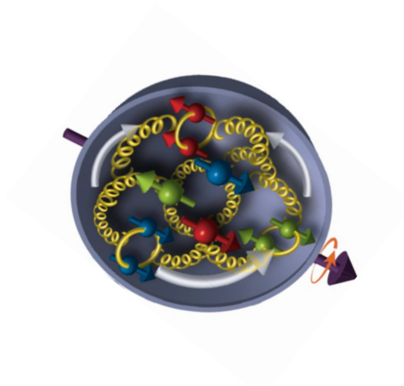
Designing EIC → Designing the right probe

- Resolution appropriate for quarks and gluons
- Ability to project out relevant Q.M. configurations

Parameters of the Probe

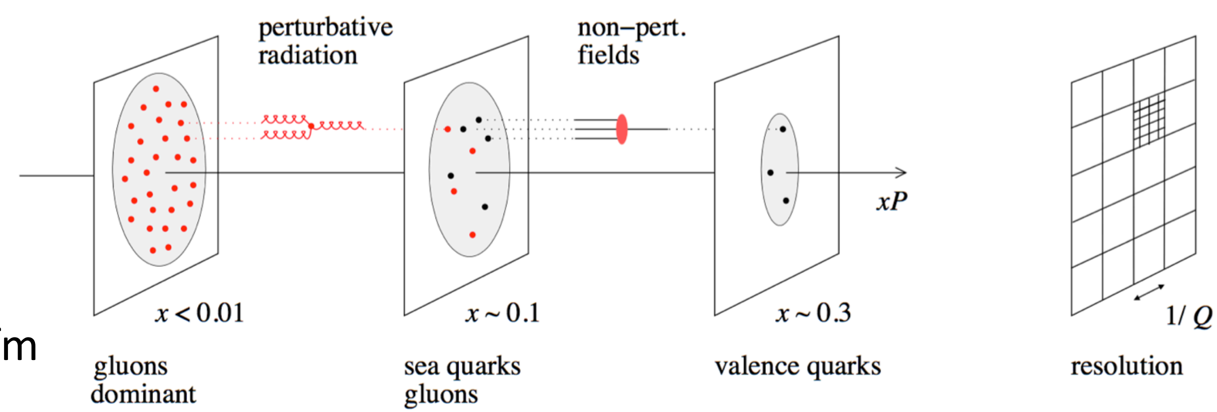


Ability to change **x** projects out different configurations where different dynamics dominate

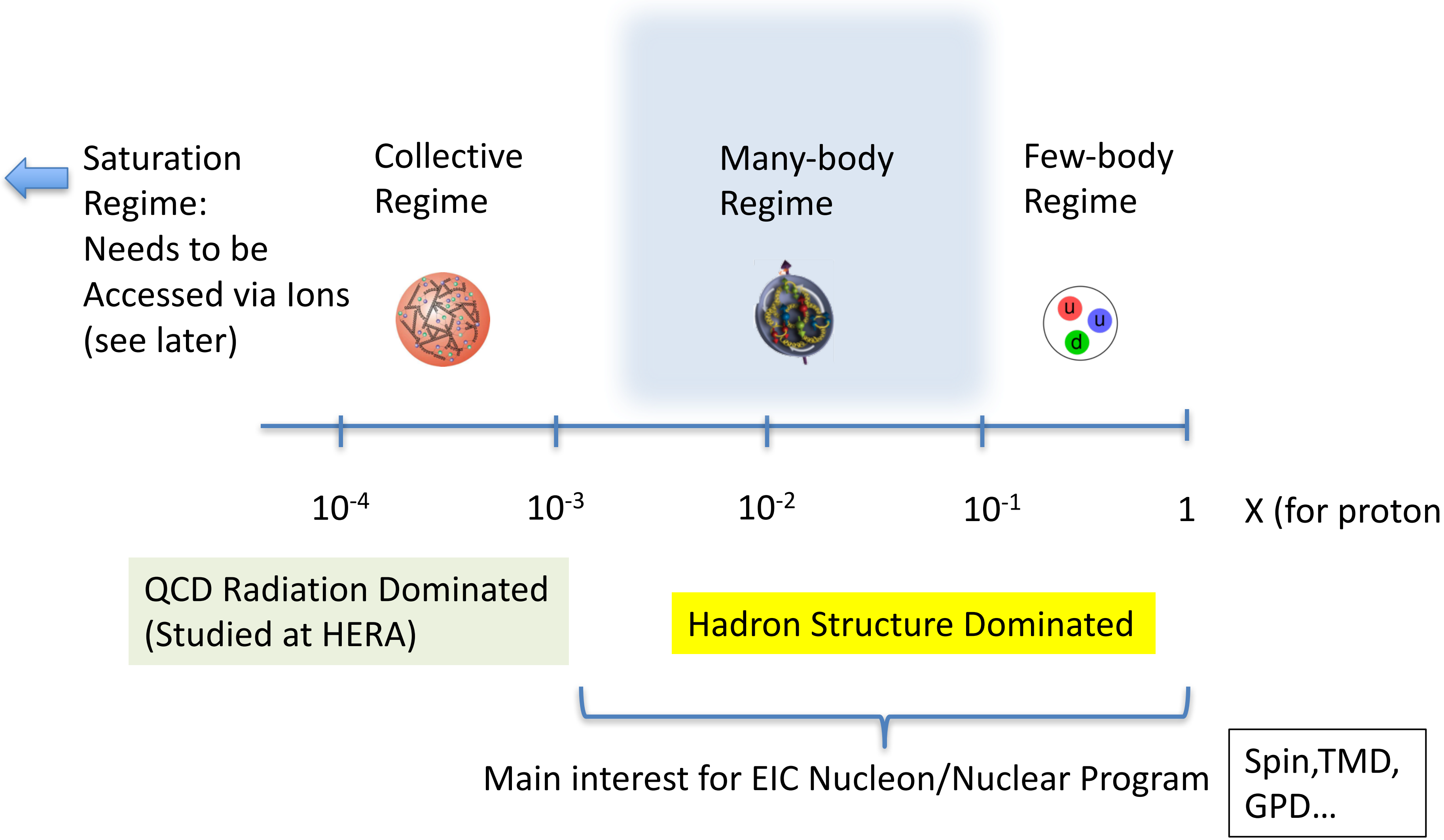


Ability to change **Q^2** changes the resolution scale

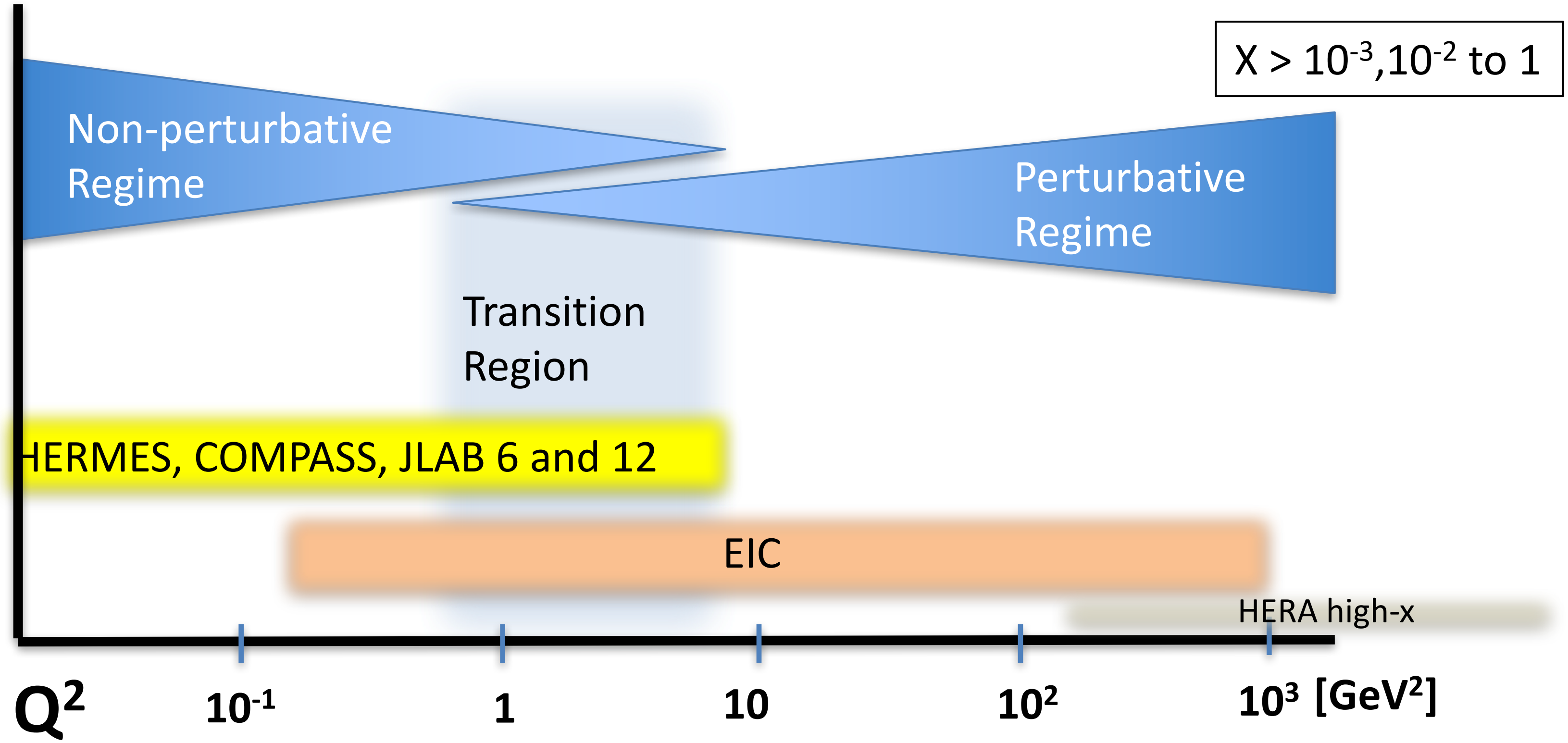
Q^2= 400 GeV^2 => 1/Q = .01 fm



Where EIC Needs to be in x (Nucleon)



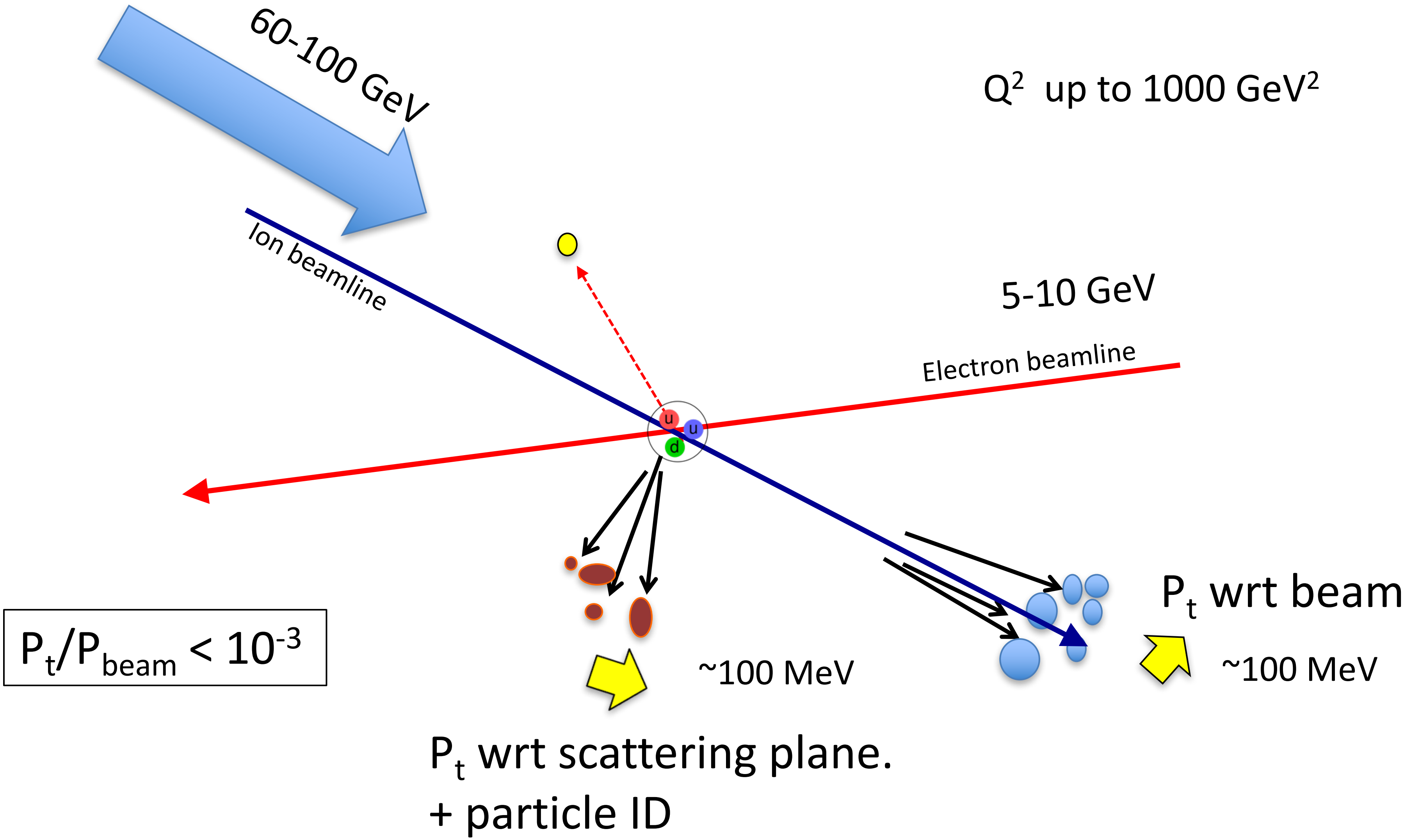
Where EIC needs to be in Q^2



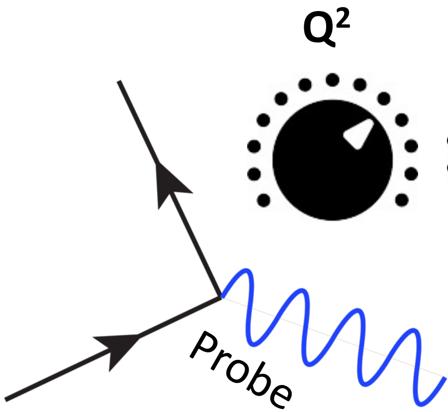
- Include non-perturbative, perturbative and transition regimes
- Provide long evolution length and up to Q^2 of ~1000 GeV^2 (~.005 fm)
- Overlap with existing measurements

Disentangle Pert./Non-pert., Leading Twist/Higher Twist

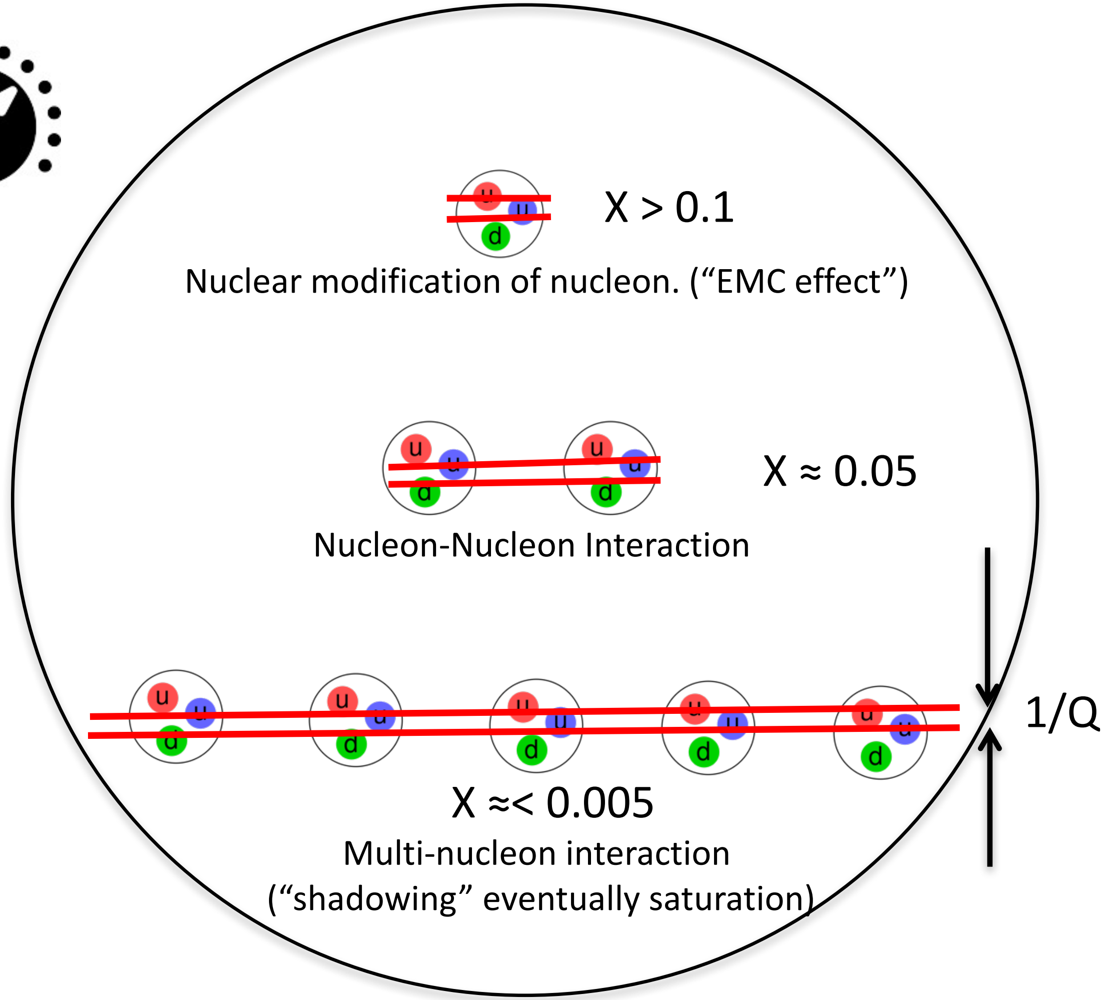
Measuring k_t and b_t



Parameters of the Probe *(Nuclei)*

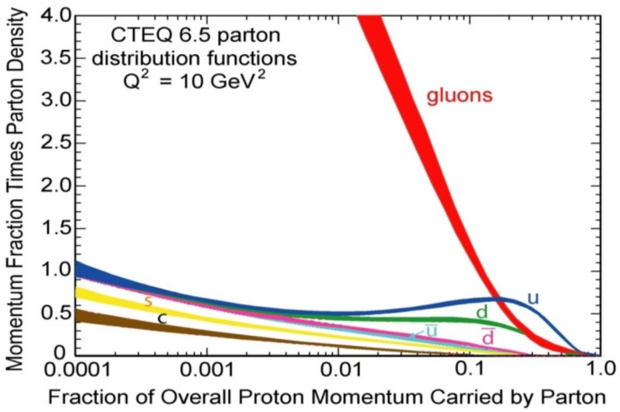


Probing the nucleon interaction in the nuclei
(note this is different from correlation measurements)

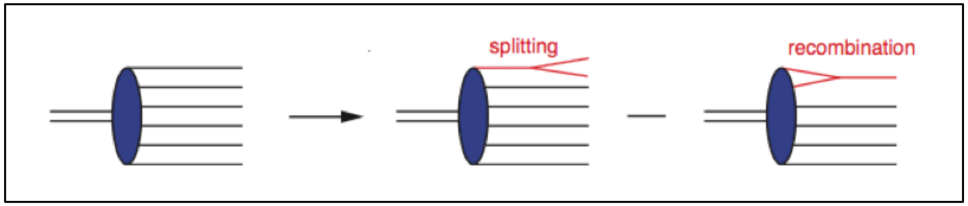


Note: the x range for nuclear exploration is similar to the nucleon exploration

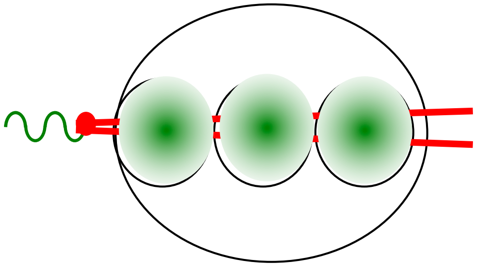
QCD at Extremes: Parton Saturation



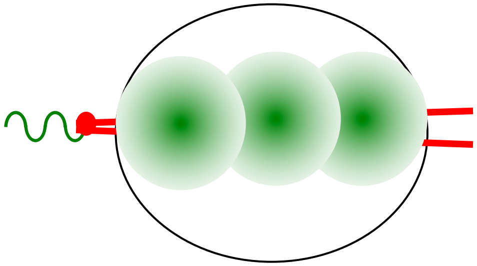
HERA discovered a dramatic rise in the number of gluons carrying a small fractional longitudinal momentum of the proton (i.e. small-x).



This cannot go on forever as x becomes smaller and smaller: parton recombination must balance parton splitting.
i.e. Saturation—unobserved at HERA for a proton. (expected at extreme low x)

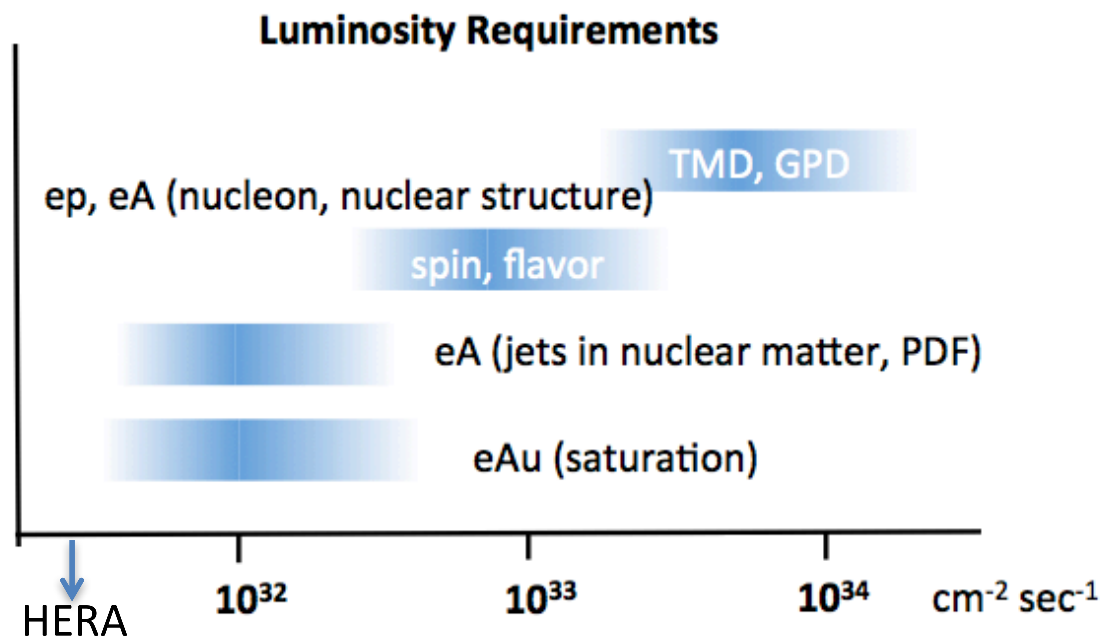


In nuclei, the interaction probability enhanced by $A^{1/3}$



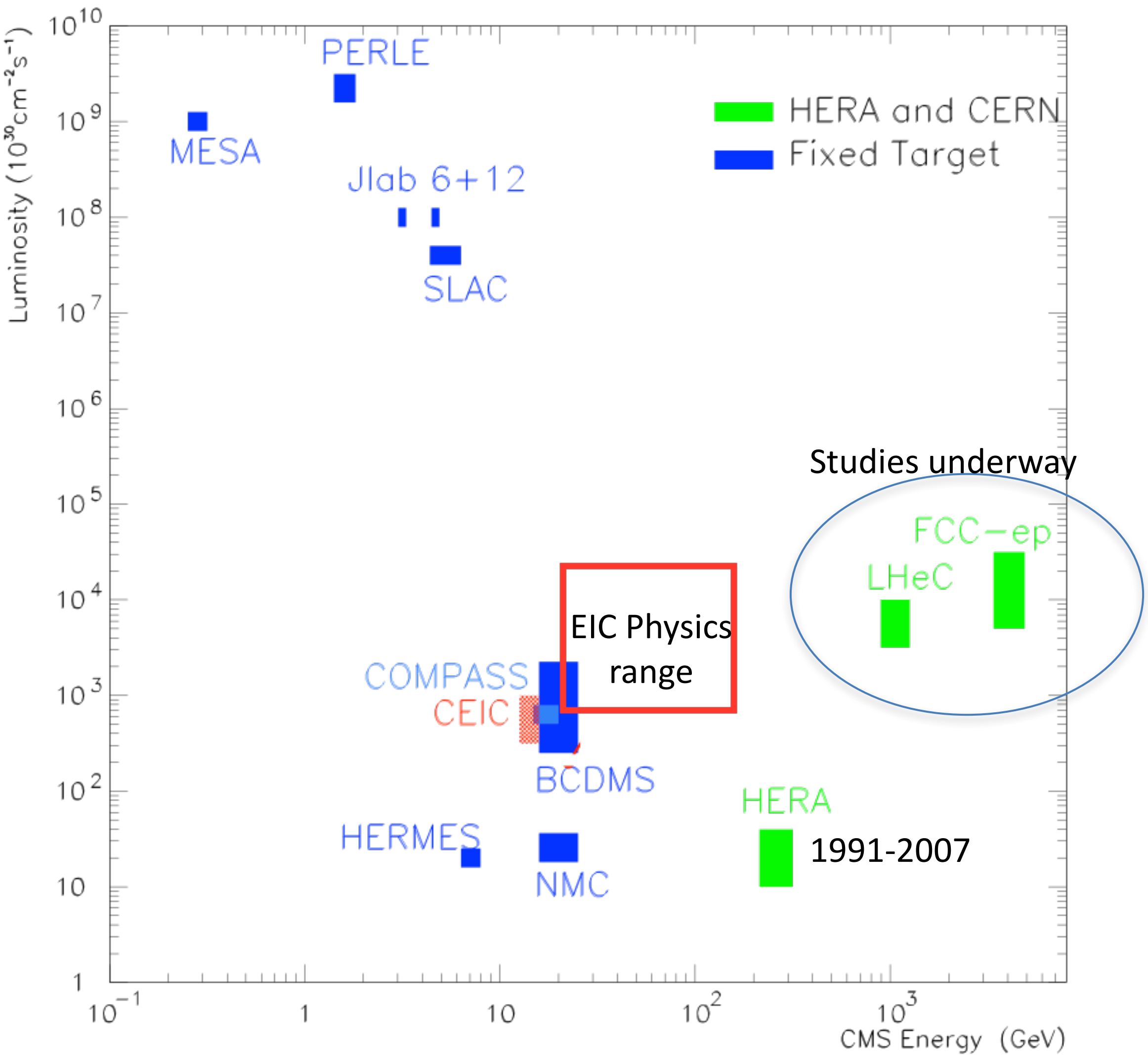
Will nuclei saturate faster as color leaks out of nucleons?

Luminosity/Polarization Needed



Central mission of EIC (nuclear and nucleon structure) requires high luminosity and polarization (>70%).

Past, Existing and proposed DIS Facilities

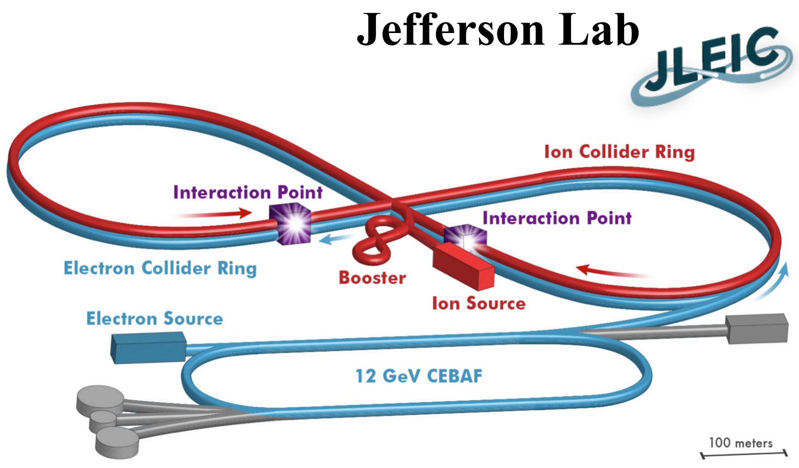


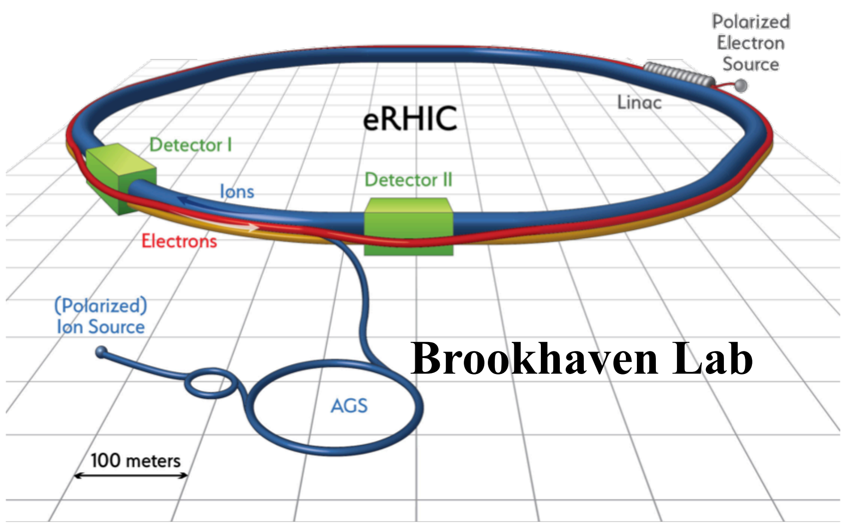
EIC will be a unique facility.

No other machine, existing or planned, can address the physics of interest satisfactorily.

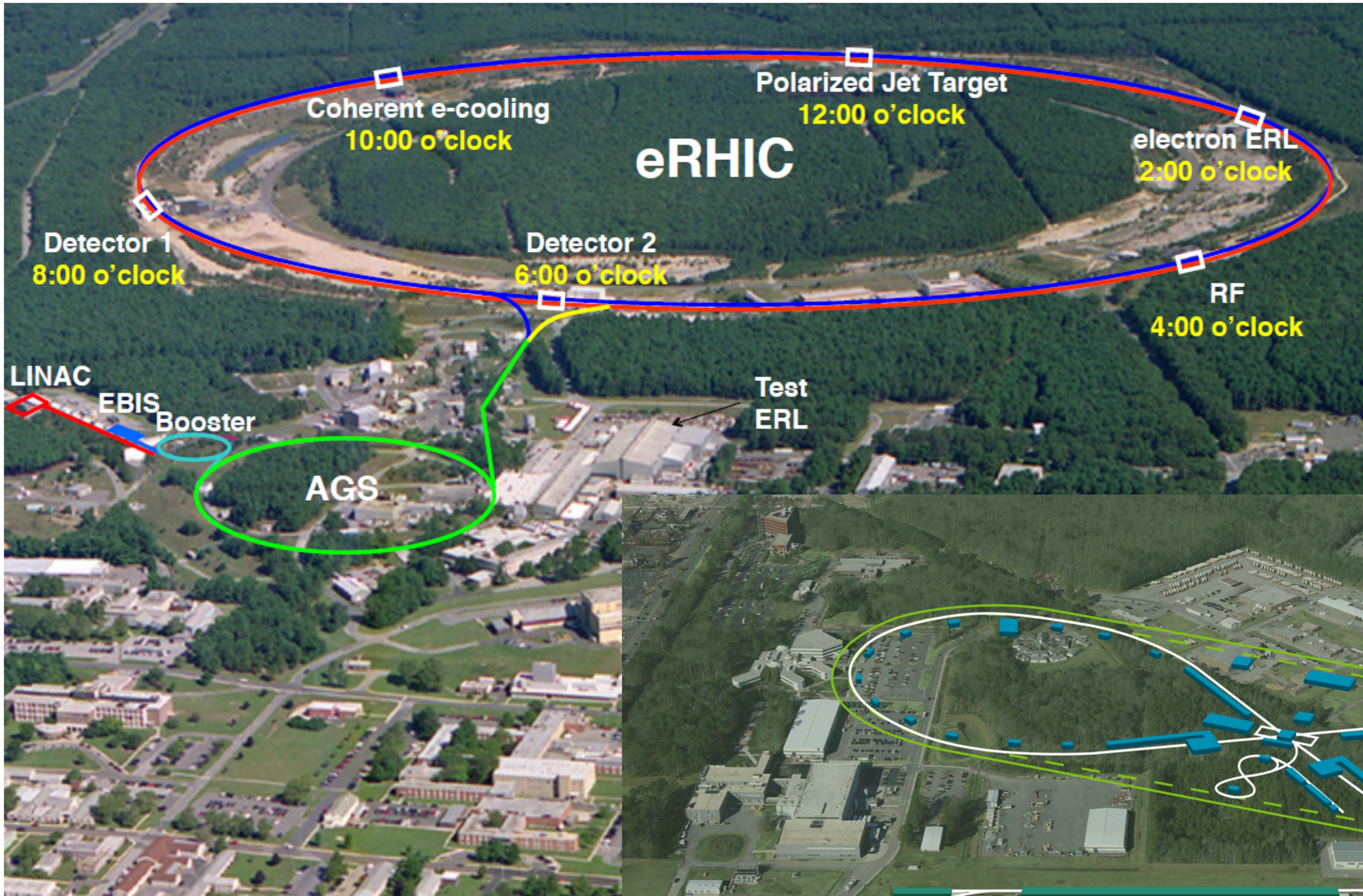
EIC Parameters

- US EIC Machine design aims from the EIC Whitepaper
  - Highly polarized (~70%) electron and nucleon beams.
  - Ion beams from deuterons to the heaviest nuclei (uranium or lead).
  - Variable center of mass energies from ~20 - ~ 100 GeV, upgradable to ~140 GeV.
  - High luminosity: ~$10^{33\text{-}34}$ cm^{-2} s^{-1}
  - Possibility of having more than one interaction region.
- Two proposed realization plans
  - Jefferson Lab: building on the existing 12 GeV CEBAF. JLEIC Design.
  - BNL: building on the existing RHIC. eRHIC Design.
  - Recent review of acc. R&D
- Similar performances, cost
- US EIC will likely be down-selected from one of these proposals.
- *CD0 2018?*

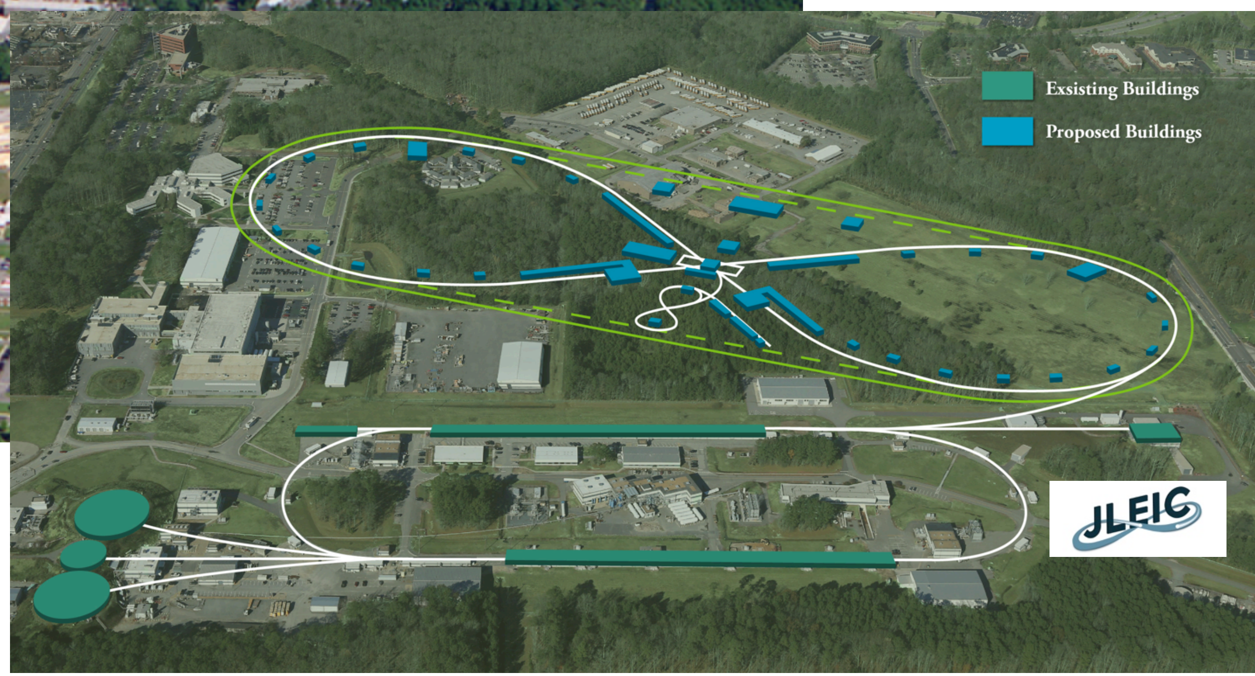




US-Based EIC Proposals

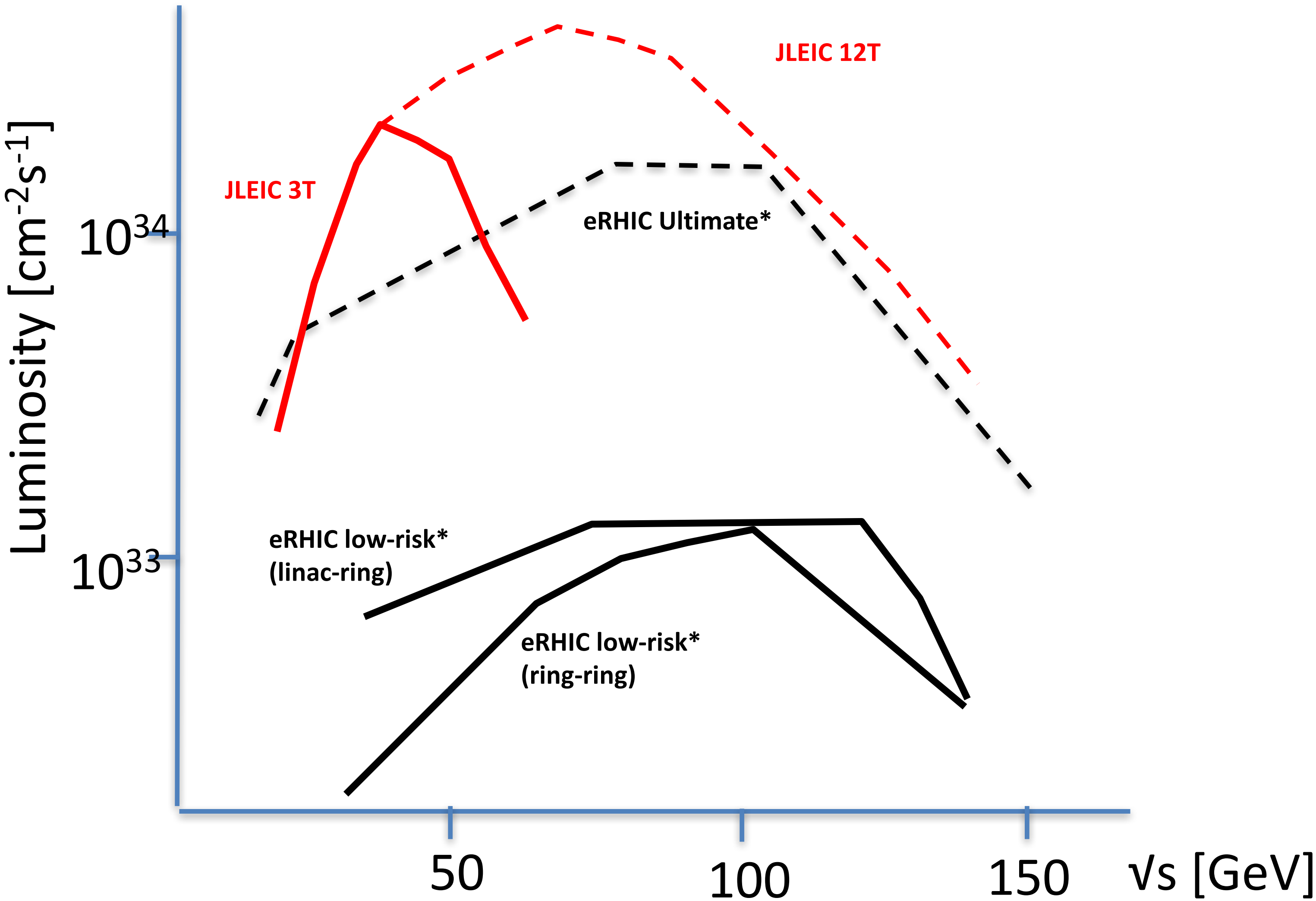


Brookhaven Lab
Long Island, NY



Jefferson Lab
Newport News, VA

Comparison JLEIC and eRHIC (Jan. 2017)



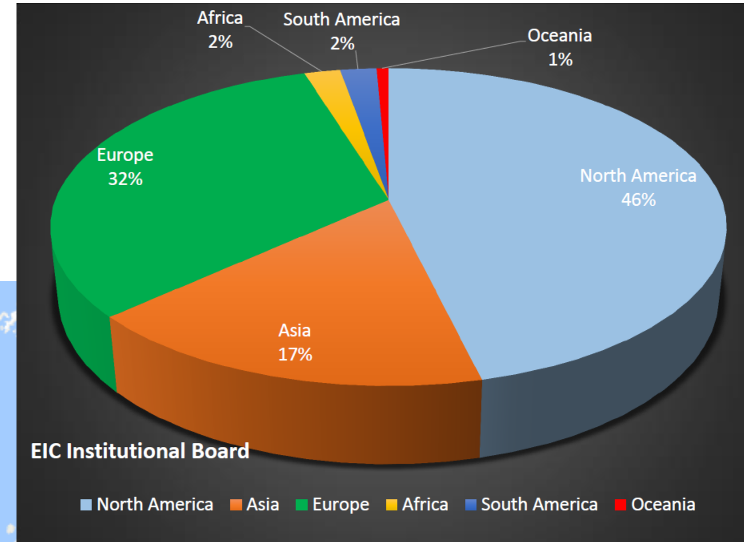
*eRHIC parameters taken from F. Willike slides (F. Pilat talk) from EIC opportunities meeting for INFN, Genova (17 January, 2017)
JLEIC parameters can be found at eic.jlab.org/wiki (January, 2017 update)

Worldwide Interest in EIC Physics

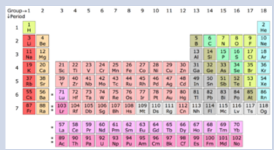
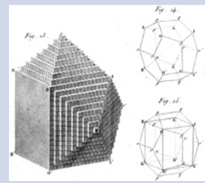
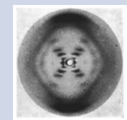
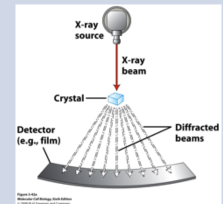
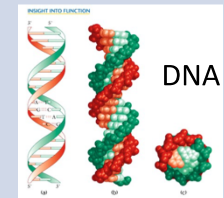
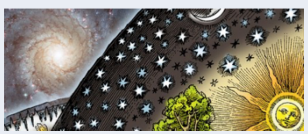
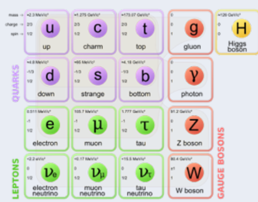
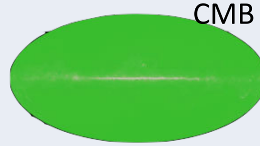
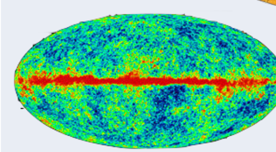
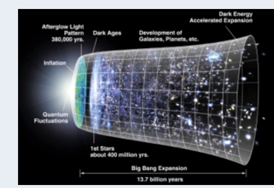
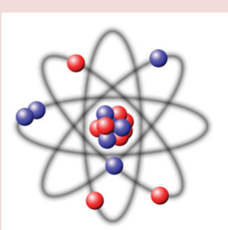
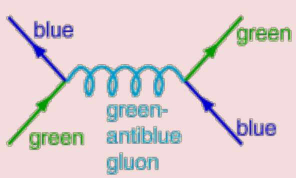
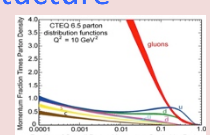
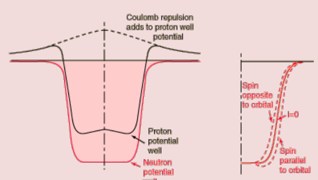
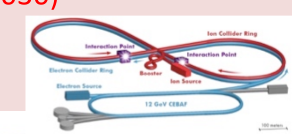
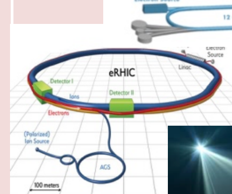
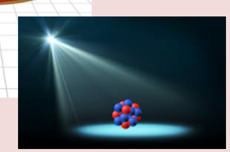
The EIC Users Group: EICUG.ORG

(no students included as of yet)

692 collaborators, 29 countries, 157 institutions... (June 7, 2017)



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 $\mathcal{L}_{QCD} = \overline{\psi}(i\partial\!\!\!/ - gA\!\!\!/)\psi - \frac{1}{2}\mathrm{tr}\, F_{\mu\nu}F^{\mu\nu}$ 	Non-perturbative QCD Stucture  2017 	Electron-Ion Collider (2030)   	Structural QCD Nuclear Physics 

Questions?....

Backups!

Neutron Structure Function provides access to d(x) PDF

Parton model:

$$F_2^p = x\left[\tfrac{4}{9}(u+\bar{u}) + \tfrac{1}{9}(d+\bar{d}) + \tfrac{1}{9}(s+\bar{s})\right]$$

$$u_p(x) = d_n(x) \equiv u(x)$$

$$F_2^n = x\left[\tfrac{4}{9}(d+\bar{d}) + \tfrac{1}{9}(u+\bar{u}) + \tfrac{1}{9}(s+\bar{s})\right]$$

$$\frac{F_2^n}{F_2^p} = \frac{u+\bar{u}+4(d+\bar{d})+s+\bar{s}}{4(u+\bar{u})+d+\bar{d}+s+\bar{s}}$$

$$\frac{F_2^n}{F_2^p} = \frac{[1+4(d/u)]}{[4+(d/u)]}$$

u quark dominance,

d/u –> 0

F_2^n/F_2^p –> 1/4

200 Partons

sea quark dominance F_2^n/F_2^p –> 1

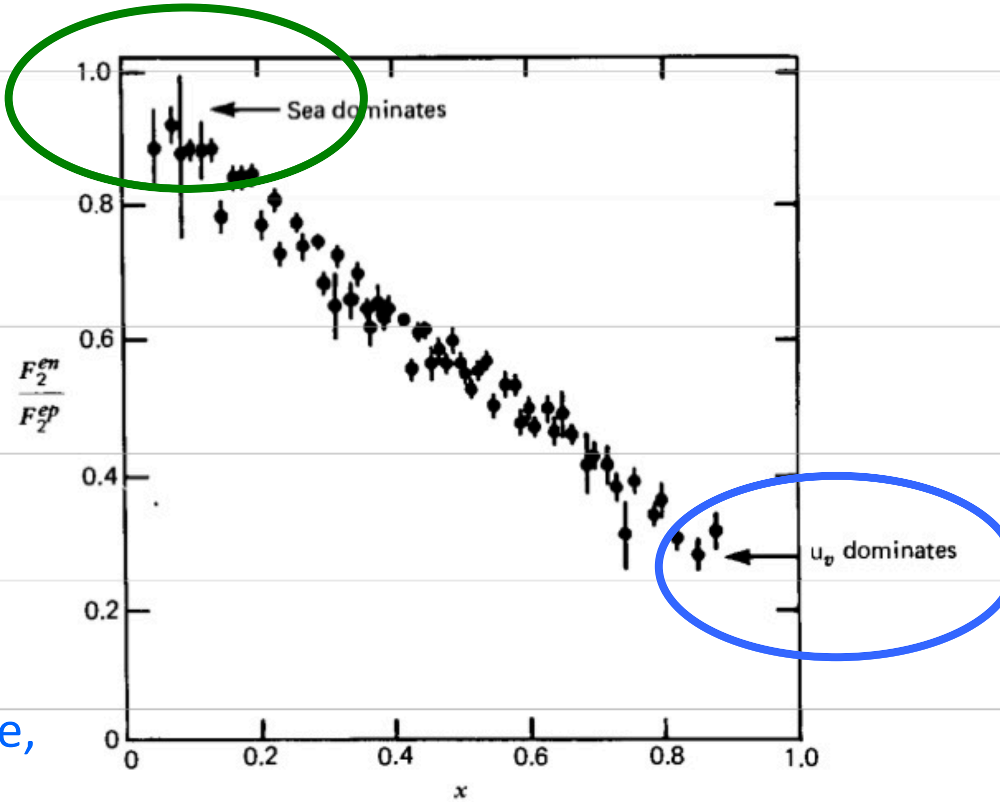
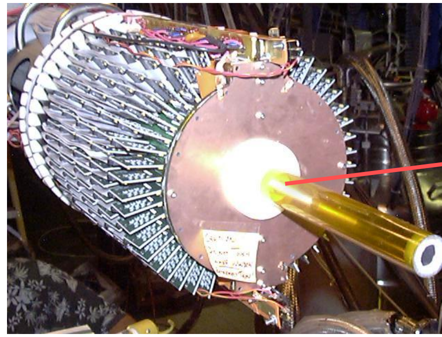
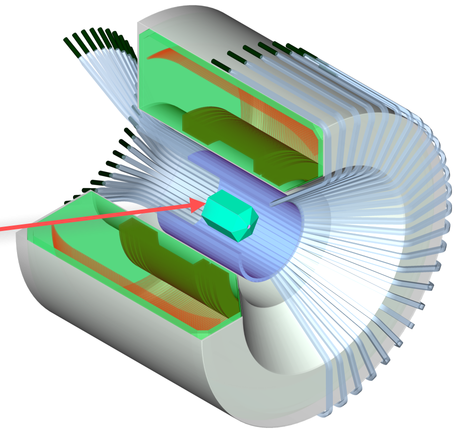


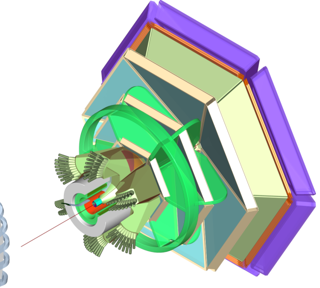
Fig. 9.6 The ratio F_2^{en}/F_2^{ep} as a function of x, measured in deep inelastic scattering. Data are from the Stanford Linear Accelerator.

Plan to run in first 1-2 years of Hall B CLAS12

E12-06-113 "BONUS12"

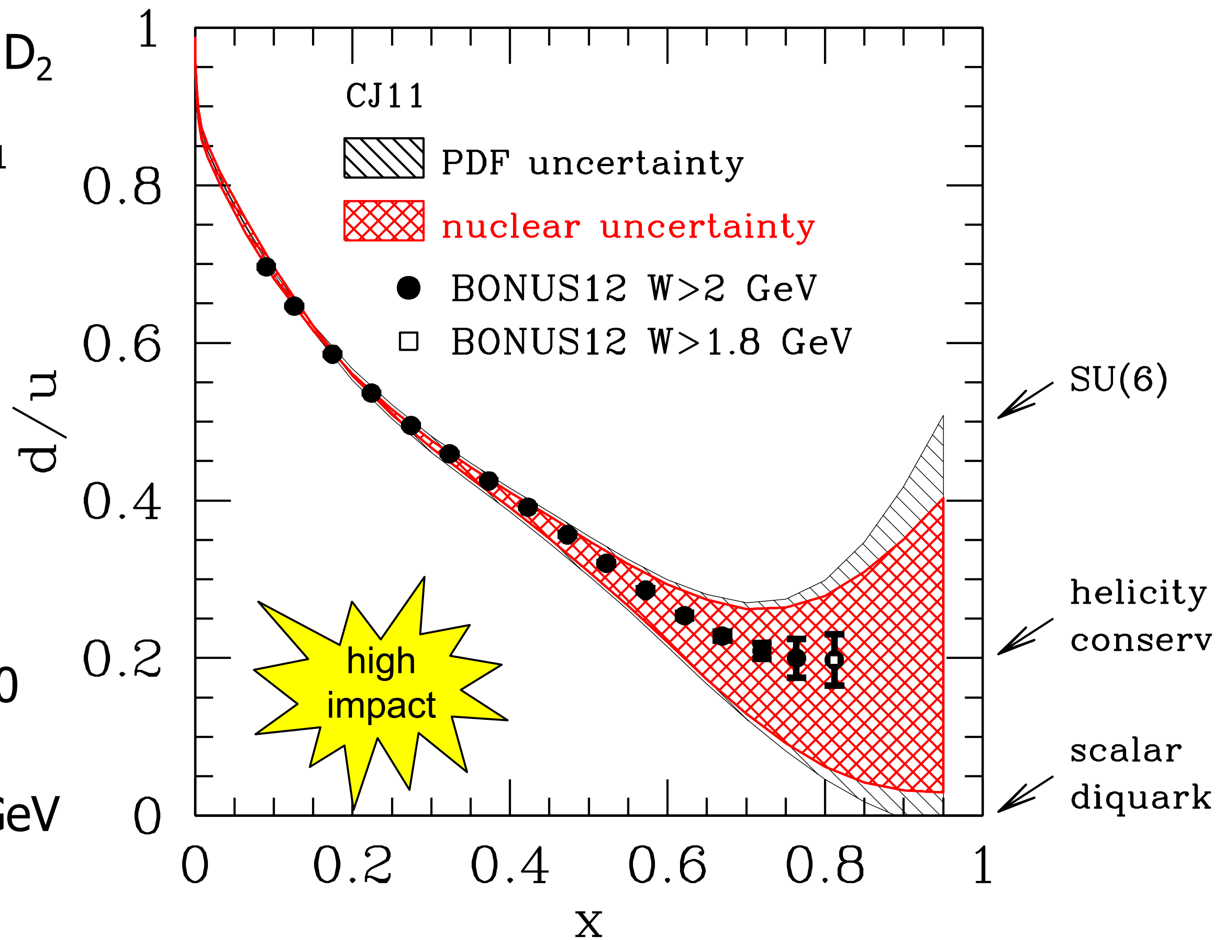






CLAS12 Central Detector

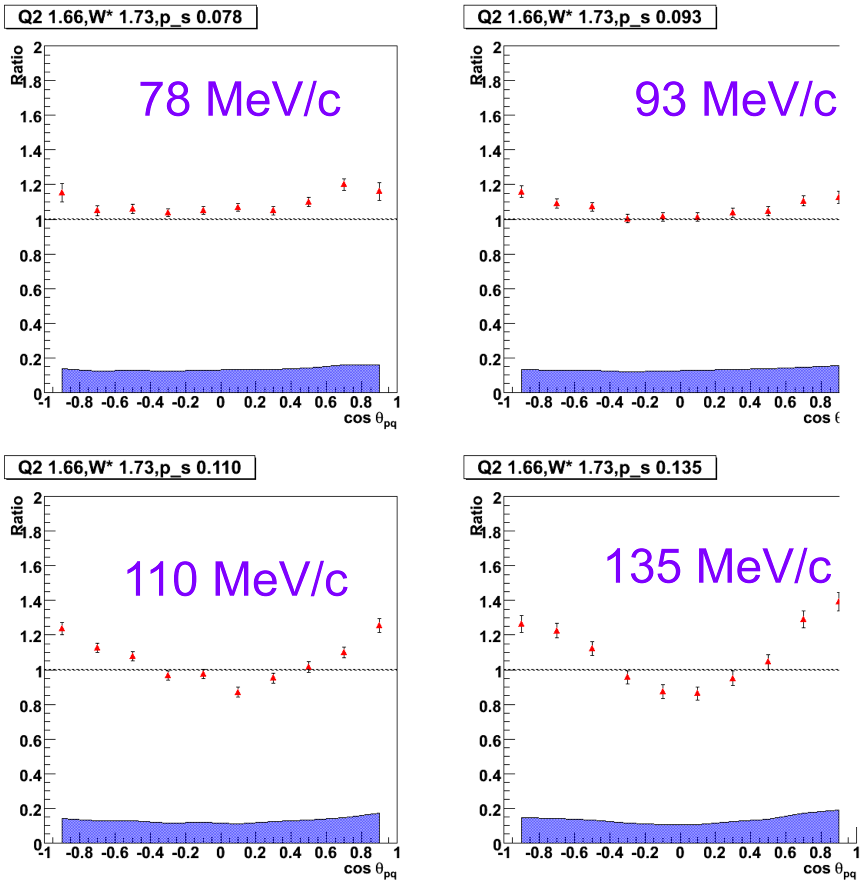
- Data taking of 35 days on D_2 and 5 days on H_2 with $L = 2 \cdot 10^{34}\ \mathrm{cm^{-2}\ sec^{-1}}$
- **Planned** BoNuS detector DAQ and trigger **upgrade**
- DIS region with
  - $Q^2 > 1\ \mathrm{GeV}^2/c^2$
  - $W^* > 2$ GeV
  - $p_s < 100$ MeV/c
  - $\theta_{pq} > 110°$
- Largest value for $x^* = 0.80$ (bin centered $x^* = 0.76$)
- Relaxed cut of $W^* > 1.8$ GeV gives max. $x^* = 0.83$



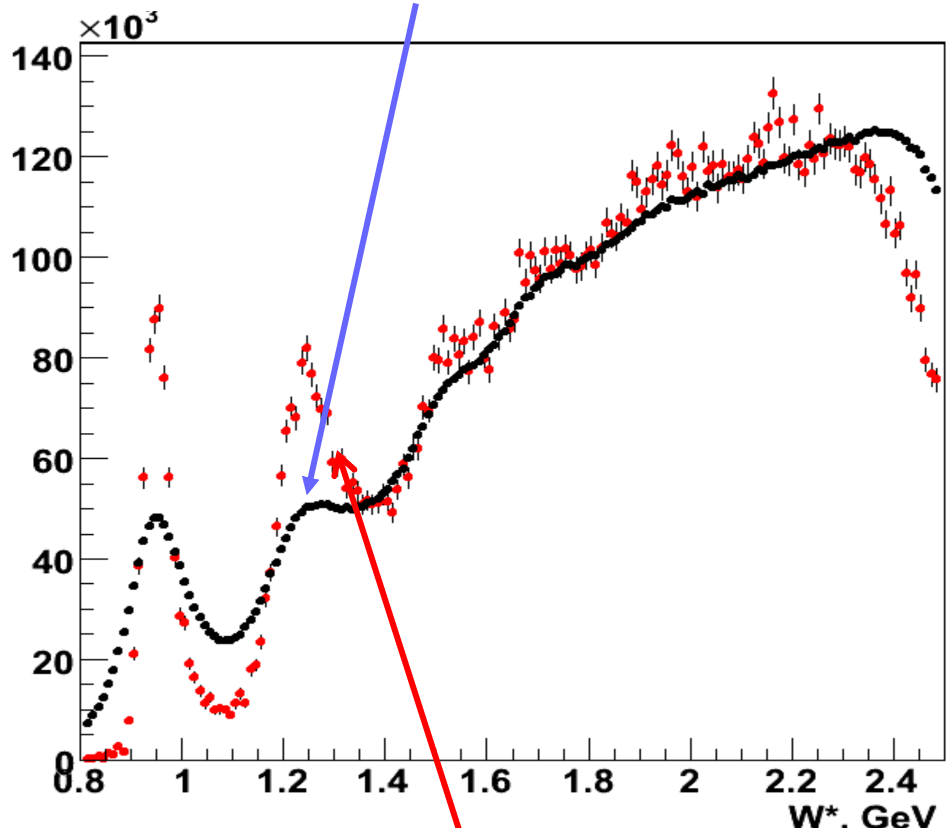
The technique works!

angle - momentum dependence

$$W^2 = M^2 + 2M\nu - Q^2$$



$\cos\theta_{pq}$ $\cos\theta_{pq}$

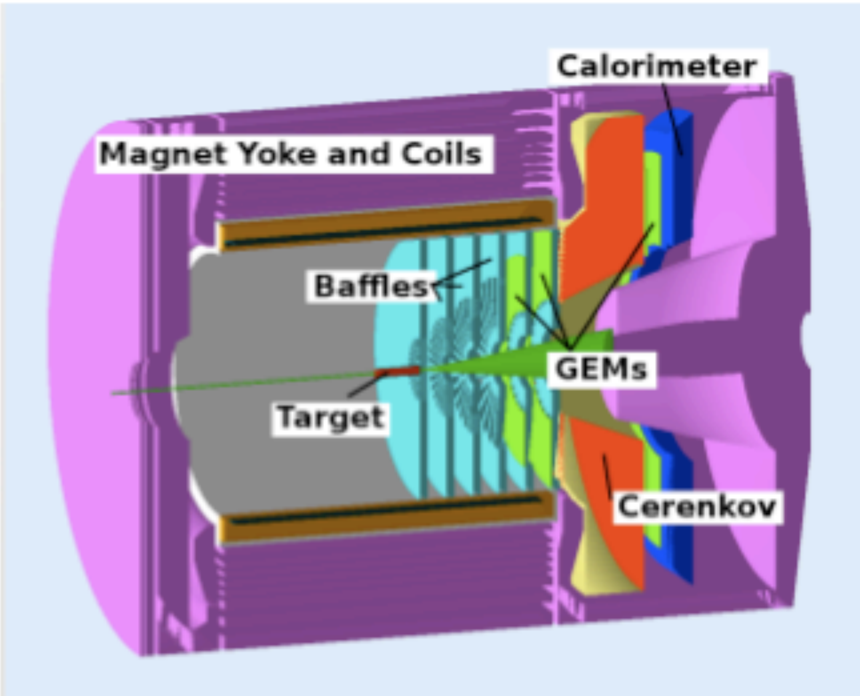


$$W^{*2} = (p_n + q)^2 = p_n^{\mu} p_{n\mu} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2$$

$$\approx M^{*2} + 2M\nu(2 - \alpha_S) - Q^2$$

PVDIS Measurements - SoLID Proposed Setup

Solenoidal **L**arge **I**ntensity **D**evice - 12 GeV Hall A at JLab
Parity-violating DIS program on deuterium and hydrogen



SoLID provides large acceptance

- $2 < p < 8$ GeV
- $2 < Q^2 < 10$ GeV^2
- $0.2 < x_{\rm bj} < 1$
- Acceptance $\sim 40\%$
- Lumin $\sim 5 \times 10^{38}$ Hz/cm^2

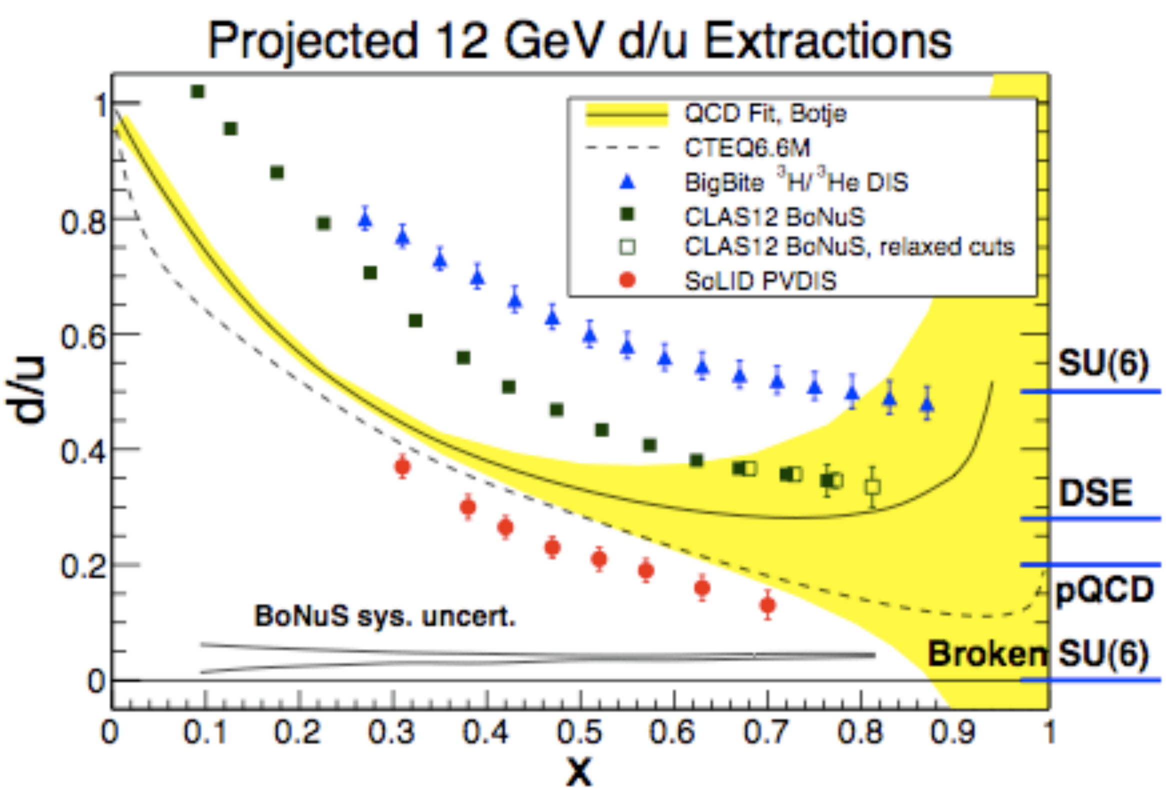
$$A_{\rm PV} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x)\right]$$

$$a_1(x) = 2\frac{\sum C_{1q}e_q(q+\bar{q})}{\sum e_q^2(q+\bar{q})},\ a_3(x) = 2\frac{\sum C_{2q}e_q(q-\bar{q})}{\sum e_q^2(q+\bar{q})}$$

Clean Measurement of d/u with PVDIS

For high x on proton target:

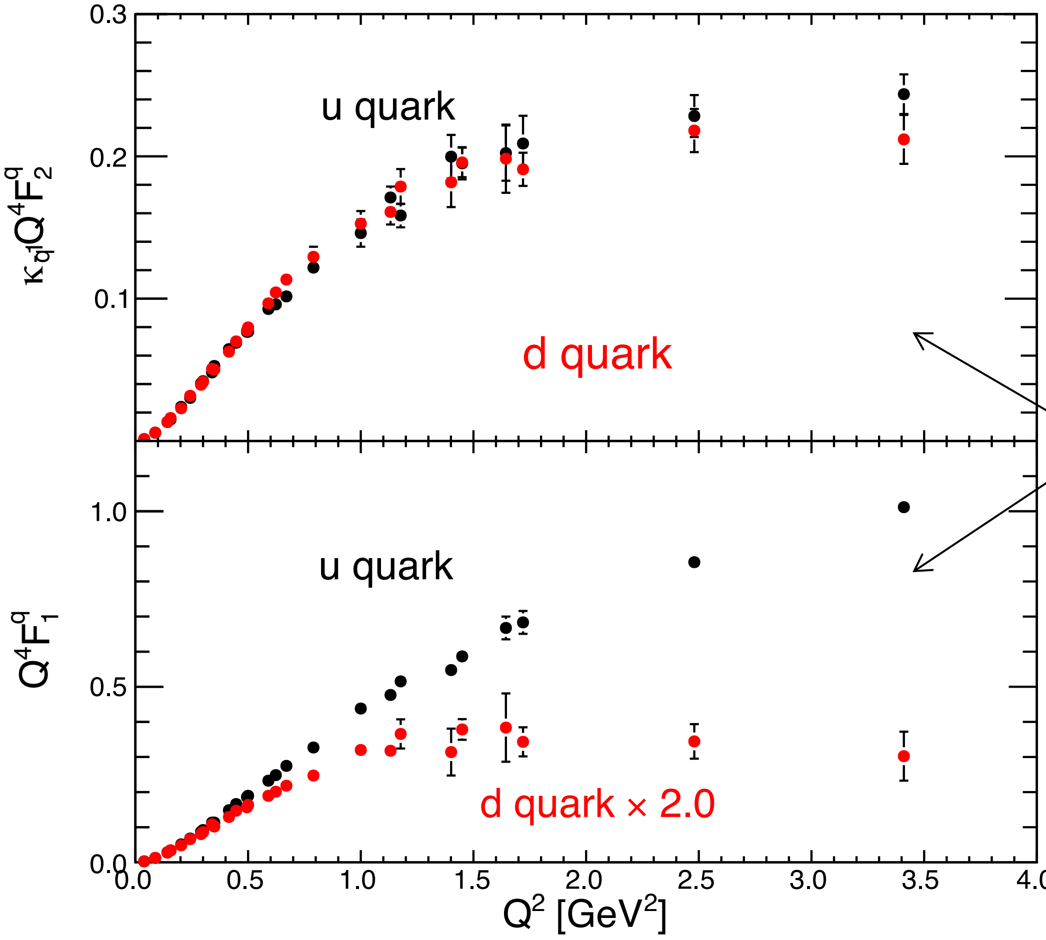
$$a_1^p(x) = \left[\frac{12C_{1u}u(x) - 6C_{1d}d(x)}{4u(x) + d(x)}\right] \approx \left[\frac{1 - 0.91d(x)/u(x)}{1 + 0.25d(x)/u(x)}\right]$$



- Three JLab 12 GeV experiments:
  - CLAS12 BoNuS - spectator tagging
  - BigBite - DIS $^3H/^3He$ Ratio
  - SoLID - PVDIS *ep*
- The SoLID extraction of d/u is made directly from *ep* DIS: *no nuclear corrections*

DSE - Wilson *et al.*, Phys Rev C**89**, 025205 (2012)

Flavor Disparity in the Nucleon



CJRW (u/d with new GEn data)

Phys. Rev. Lett. 106 (2011)

Qattan, Arrington (2-γ effects)

Phys.Rev. C86 (2012) 065210

M.Diehl and P.Kroll (GPDs)

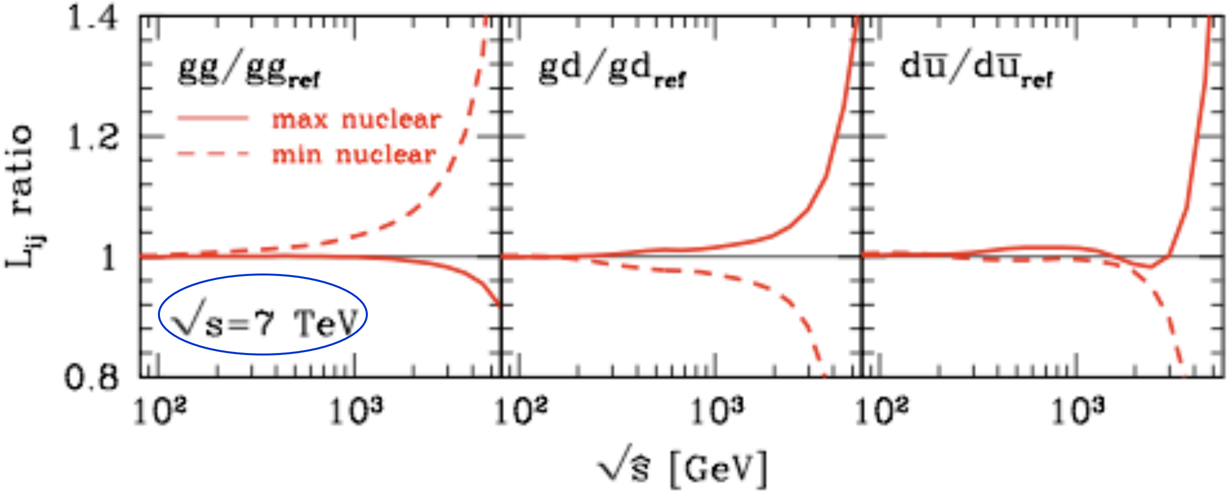
Eur.Phys.J. C73 (2013) 2397

Using the D&K table of F^u, F^d

The down quark contribution to the F_1 proton form factor is strongly suppressed at high Q^2

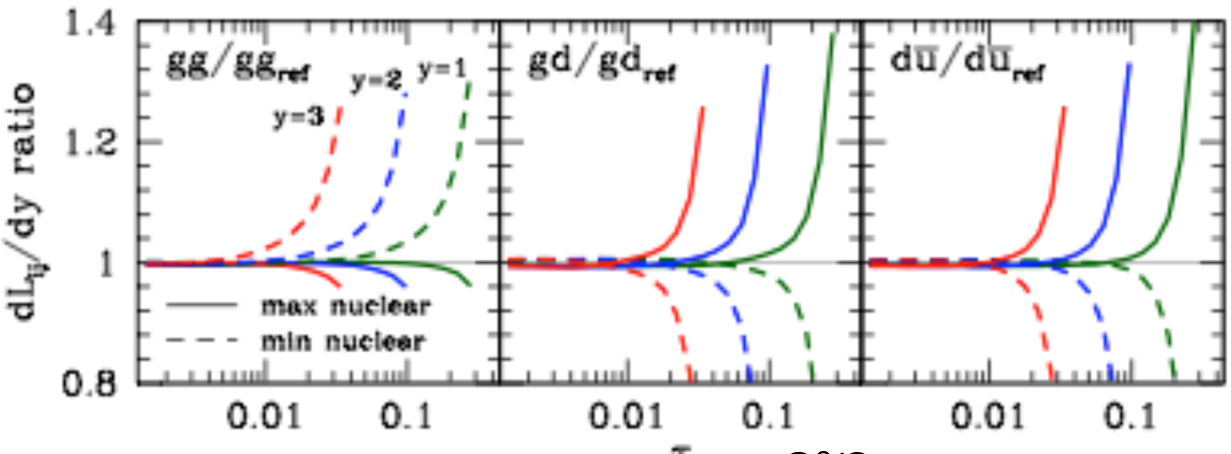
When the virtual photon of 3 GeV^2 interacts with the down quark the proton more likely falls apart than in the case of the up quark

Implications for Collider Experiments



Uncertainty induced by nuclear corrections extends to rather small scales $\sqrt{\hat{s}}$, and grows quickly above 5–10% as $\sqrt{\hat{s}}$ exceeds 1 TeV.

fixed rapidity y = 1, 2, 3



$\tau = Q^2/S$

Larger rapidity = more sensitive to large-x region for a given mass. For example, nuclear uncertainty becomes relevant at rapidity larger than 2 for W production at the Tevatron.

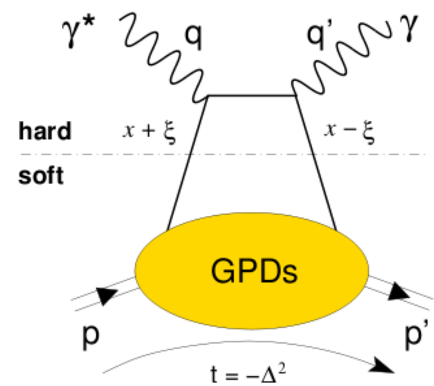
The gg, gd, du luminosities impact the main channel(s) for Higgs production, jet production, "standard candle" cross section for W^- production, respectively.

Nucleon Structure: the 3D World

- Generalized Parton Distributions: form factors of only those quarks in the nucleon carrying a certain fixed momentum fraction x

Deeply Virtual Compton Scattering (**DVCS**):

→ **GPDs** -- amplitude for "kicking out" a parton of the fast moving nucleon by the virtual photon and "putting it back" with a different momentum after radiating a real photon



$$P = \frac{p+p'}{2}$$

$$\Delta = p - p'$$

$$x = \frac{k^+}{P^+}$$

$$\xi = -\frac{\Delta^+}{2P^+}$$

→ **4 GPDs** defined through matrix elements of quark and gluon operators:

$$\boldsymbol{H(x,\xi,t)} \quad \boldsymbol{E(x,\xi,t)} \quad \boldsymbol{\widetilde{H}(x,\xi,t)} \quad \boldsymbol{\widetilde{E}(x,\xi,t)}$$

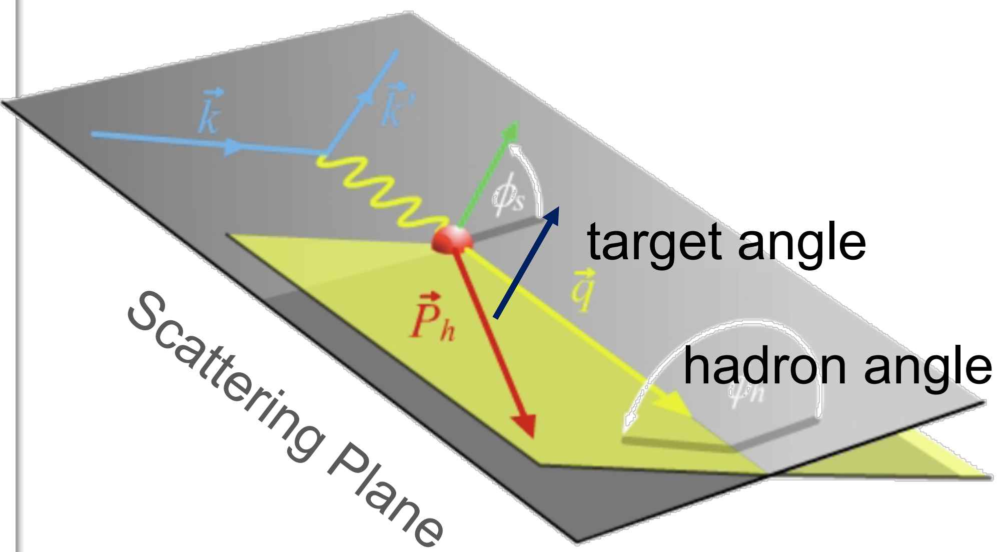
→ Pauli, Dirac form factors lowest x-moments of H and E: $\boldsymbol{F_1} = \int dx\, H(x,\xi,t)$ $\boldsymbol{F_2} = \int dx\, E(x,\xi,t)$

→ In the limit of p = p' H become the usual PDF: $H_q(x,\xi=0,t=0) = q(x) = \frac{1}{2}(\boldsymbol{q\uparrow(x)} + \boldsymbol{q\downarrow(x)})$

$$\widetilde{H}_q(x,\xi=0,t=0) = \Delta q(x) = \frac{1}{2}(\boldsymbol{q\uparrow(x)} - \boldsymbol{q\downarrow(x)})$$

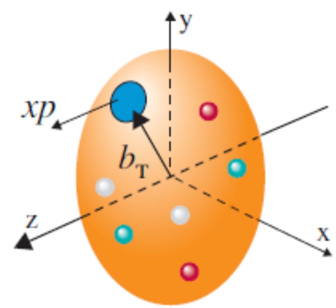
TMDs Accessible through Semi-Inclusive Physics

- Separate Sivers and Collins effects



Naturally, two scales:
- High Q: localized probe to "see" quarks and gluons
- Low P_T: sensitive to confining scale to "see" their confined motion

\+ Theory input: TMD QCD factorization
TMD QCD evolution



- **Sivers** angle, effect in distribution function: **(ϕ_h-ϕ_s)**

Or other combinations: Pretzelosity: **($3\phi_h$-ϕ_s)**

- **Collins** angle, effect in fragmentation function: **(ϕ_h+ϕ_s)**

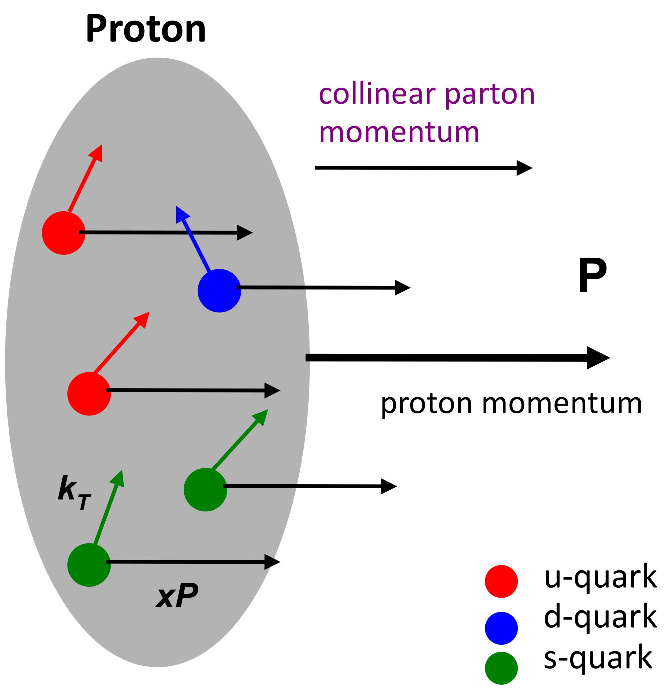
Collinear Parton Distribution Functions

In DIS nucleon structure is described by three collinear PDFs:

Momentum distribution – $q(x, Q^2)$

Helicity distribution - $\Delta q(x, Q^2)$

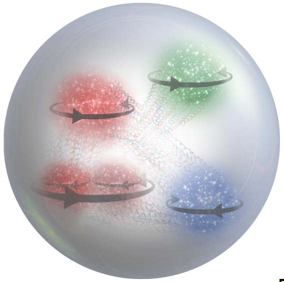
Transversity distribution - $h(x, Q^2)$



- The helicity dependent parton distributions ("spin-dependent PDFs") describe the number density of partons with given longitudinal momentum x and given polarization in a hadron polarized longitudinally with respect to its motion.

- The transverse momentum distributions ("TMDs") describe the number density of partons with given transverse momentum x in a hadron. ***We'll come back to this….***

Features of 3D Distributions/TMDs



$$f^a(x, k_T^2; Q^2)$$

Ex. TMD PDF for a given combination of parton and nucleon spins

$$\boxed{\sigma = \sum_q e_q^2 f(x) \otimes D(z)}$$

$$\downarrow$$

$$f^a(x, k_T^2; Q^2)$$

nucleon polarization \ quark polarization	U	L	T
U	f_1		$h_1^{\perp}$ Boer-Mulders
L		g_1 helicity	$h_{1L}^{\perp}$ worm-gear
T	$f_{1T}^{\perp}$ Sivers	g_{1T} worm-gear	h_1 transversity, $h_{1T}^{\perp}$ pretzelosity

- transverse position and momentum of partons are correlated with the spin orientations of the parent hadron and the spin of the parton itself
- transverse position and momentum of partons depend on their flavor
- transverse position and momentum of partons are correlated with their longitudinal momentum
- spin and momentum of struck quarks are correlated with remnant
- quark-gluon interaction play a crucial role in kinematical distributions of final state hadrons, both in semi-inclusive and exclusive processes

Polarized Parton Distributions

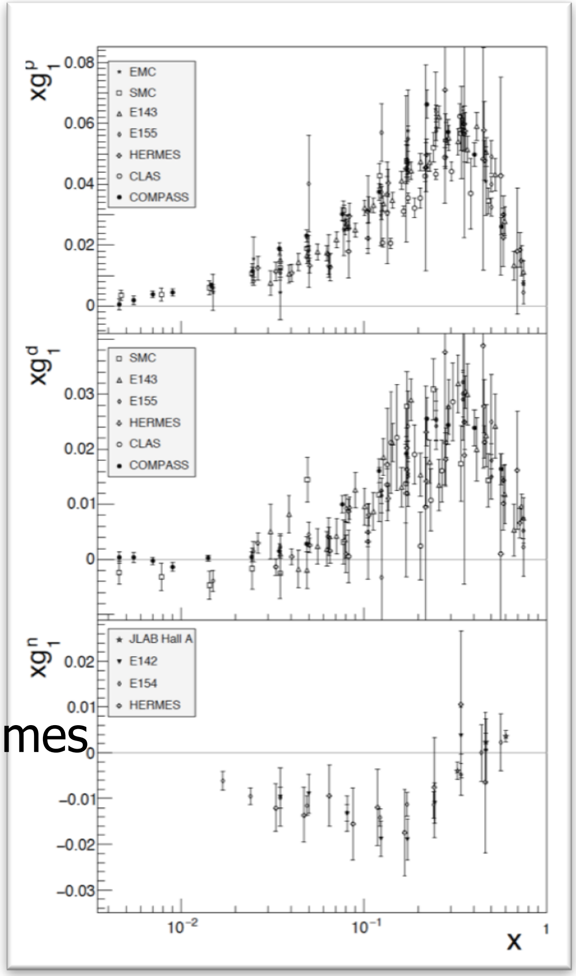
$$\Gamma_1^{p,n} \equiv \int_0^1 g_1^{p,n}(x_B)dx_B = \frac{1}{2}\sum_f e_f^2(\Delta q_f^{p,n} + \Delta\bar{q}_f^{p,n})$$

$$\Delta\Sigma \equiv (\Delta u(x) + \Delta\bar{u}(x)) + (\Delta d(x) + \Delta\bar{d}(x)) + (\Delta s(x) + \Delta\bar{s}(x))$$

$$\Gamma_1 \equiv \int_0^1 g_1(x_B)dx_B = \underbrace{\frac{1}{6}F + \frac{1}{18}D}_{\text{From hyperon decays}} + \frac{1}{9}\Delta\Sigma$$

- Measurement of $\Gamma_1{}^p$, $\Gamma_1{}^n$
- Constraint based on neutron and hyperon beta decay lifetimes
- Assumption of SU(3) flavor symmetry
- Global fit with DGLAP Q^2 evolution

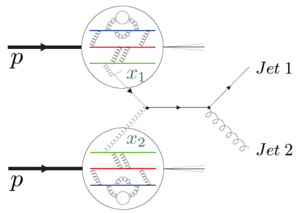
$$\Delta\Sigma \approx 0.25$$



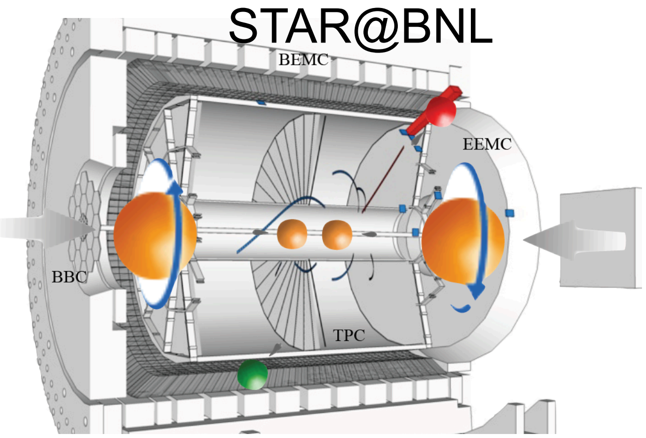
arX:1209.2803

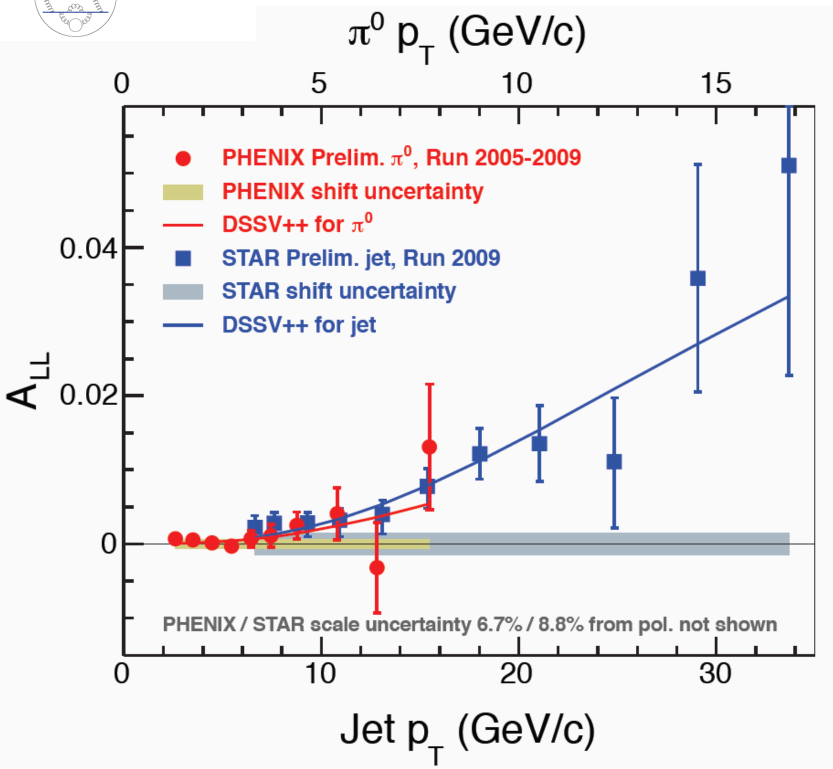
Only small fraction of the proton spin is carried by the quarks & antiquarks!!

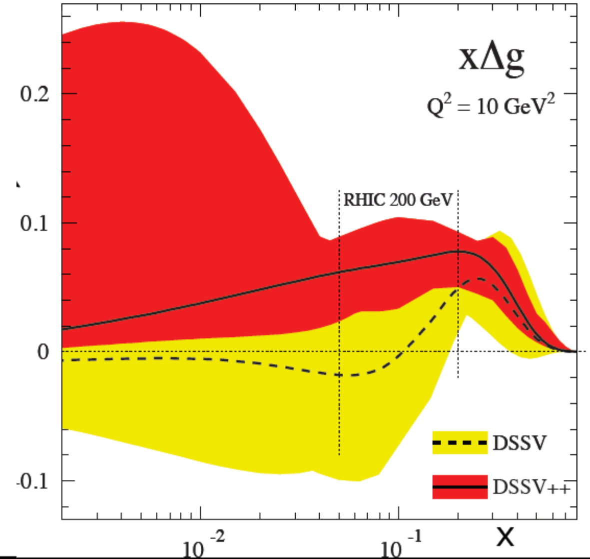
Gluon Helicity



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_1 P_2} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$







Indication of small, but non-0 Δg from RHIC data, in particular STAR jet results

$$\int_{0.05}^{0.2} \Delta g(x)\, dx = 0.1 \pm^{0.06}_{0.07}$$