Introduction to Nuclear Physics

Rolf Ent (Jefferson Lab)
June 8th, 2017

- General Introduction: Cool facts about QCD and Nuclei
- Why Electron Scattering?
- CEBAF and the Jefferson Lab Experimental Equipment
- Some limited set of Jefferson Lab Findings

Intermezzo

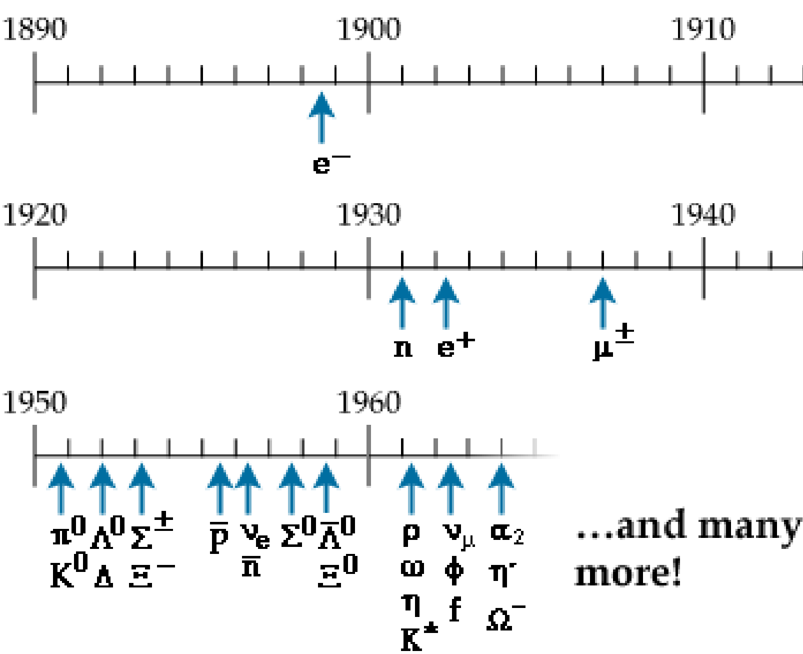
- On to 12 GeV Science …
- … and perhaps an Electron-Ion Collider

Elementary Particles

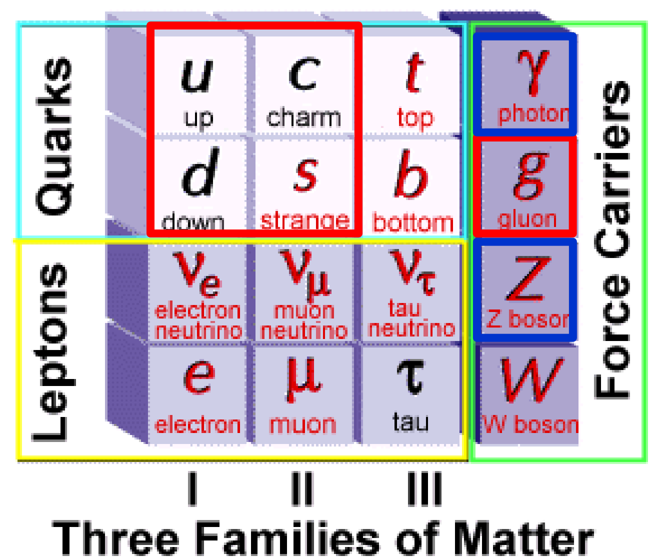
- Protons , neutrons and electrons (**p,n,e**) build all the atoms.
- Proton and neutrons make up 99.9% of the visible mass in the universe.
- Dozens of new particles were discovered in the past century.
- Strong interaction: strength can be 100 times the electromagnetic one

  leptons (e,μ,ν,..): not involved in strong interaction

  hadrons [mesons(π,K,…) and baryons(p,n,…)]: **involved in strong interaction**



Electron Scattering



Quarks & Gluons: QCD

Cool Facts about QCD and Nuclei

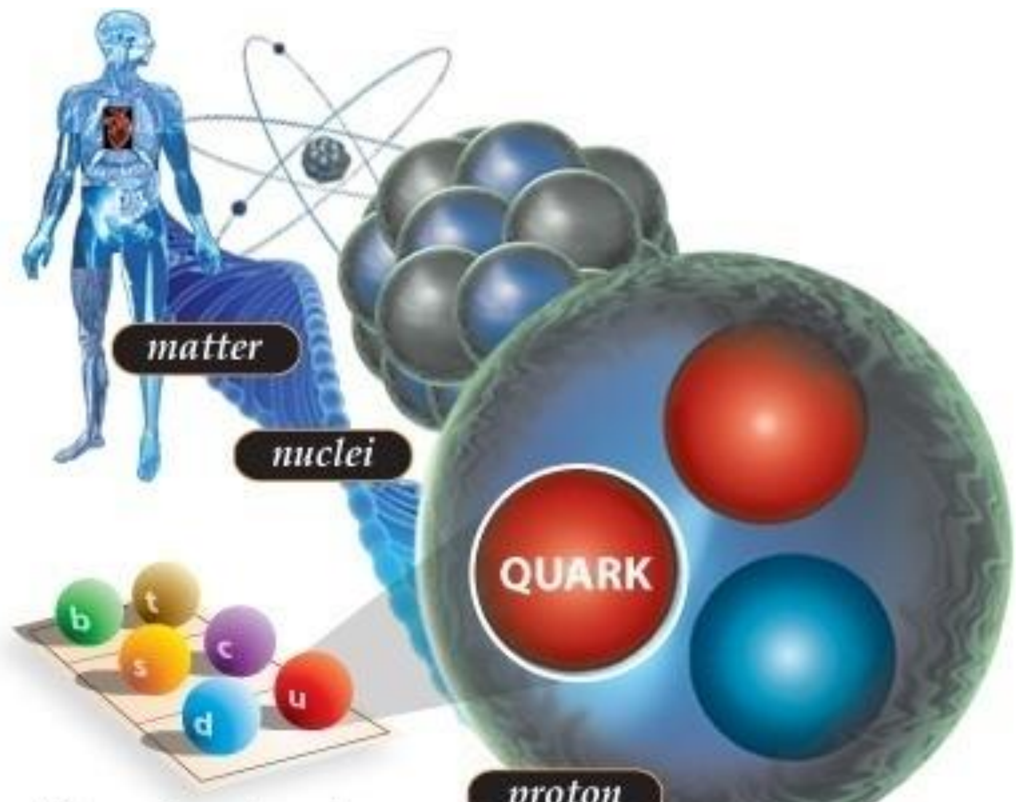
Did you know that … ?

• If an atom was the size of a football field, the (atomic) nucleus would be about the size of a football.

• Despite its tiny dimensions, the nucleus accounts for 99.9% of an atom's mass.

• Protons and neutrons swirl in a heavy atomic nucleus with speeds of up to some $\frac{3}{4}$ of c. More commonly, their speed is some $\frac{1}{4}$ the speed of light. The reason is because they are "strong-forced" to reside in a small space.

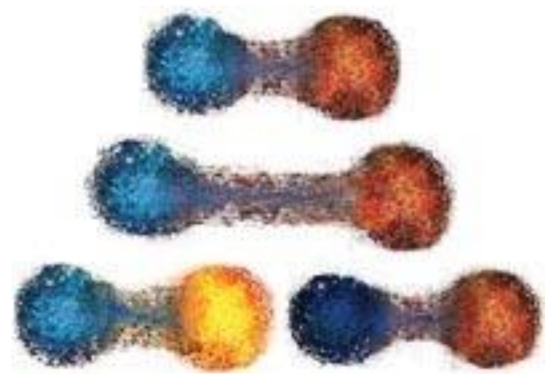
• Quarks (and gluons) are "confined" to the even smaller space inside protons and neutrons. Because of this, they swirl around with the speed of light.

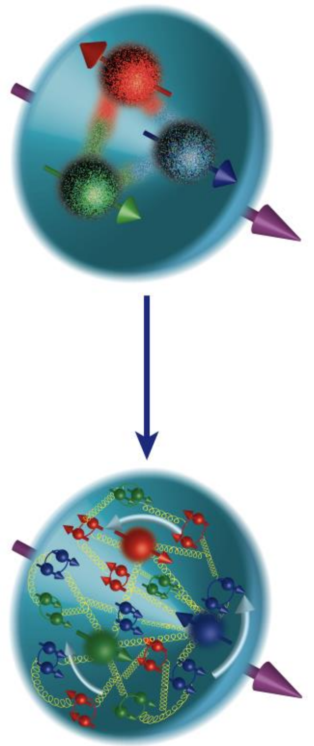


(6 types of quarks: up, down, charm, strange, top and bottom)

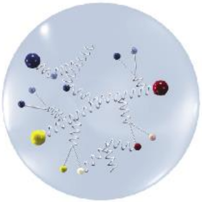
Cool Facts about QCD and Nuclei

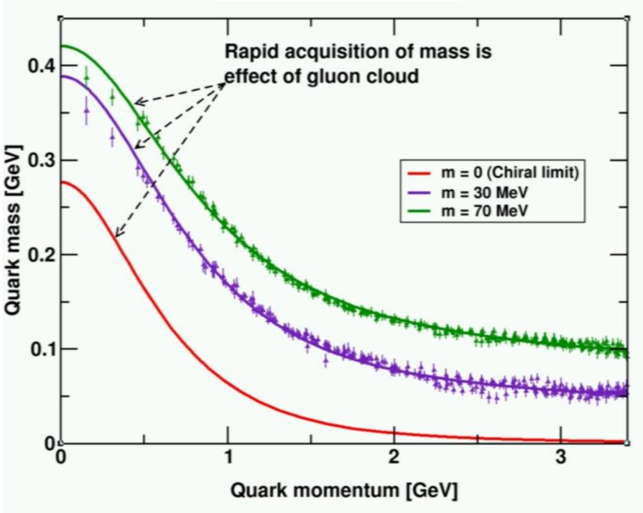
- The strong force is so strong, that you can never find one quark alone (this is called "confinement").
- When pried even a little apart, quarks experience ten tons of force pulling them together again.
- Quarks and gluons jiggle around at nearly light-speed, and extra gluons and quark/anti-quark pairs pop into existence one moment to disappear the next.
- This flurry of activity, fueled by the energy of the gluons, generates nearly all the mass of protons and neutrons, and thus ultimately of all the matter we see.
- Even the QCD "vacuum" is not truly empty. Long-distance gluonic fluctuations are an integral part. Quarks have small mass themselves, but attain an effective larger mass due to the fact that they attract these gluonic fluctuations around them.
- Nuclear physicists are trying to answer how basic properties like mass, shape, and spin come about from the flood of gluons, quark/anti-quark pairs (the "sea"), and a few ever-present quarks.

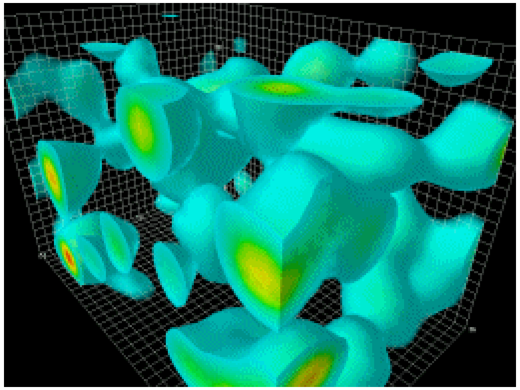




QCD and the Origin of Mass



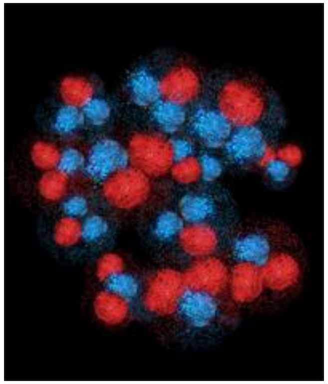


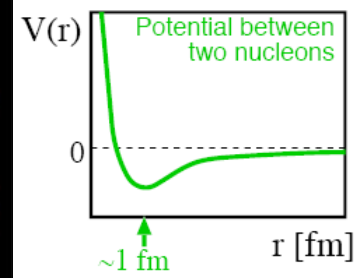


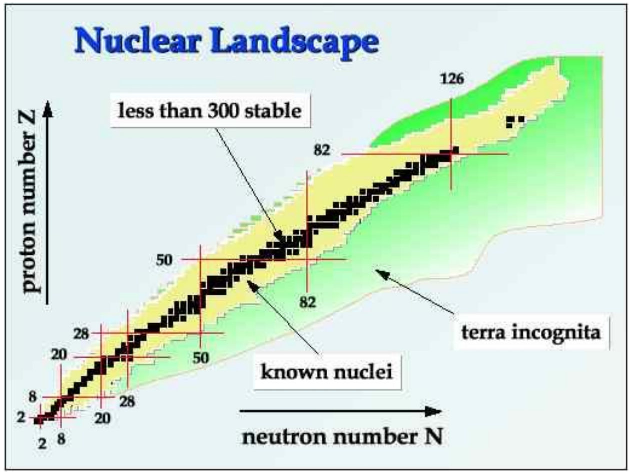
- Mass is an emergent phenomenon!
- Mass from massless gluons and nearly massless quarks
- Most of the proton's mass/energy is due to the self-generating gluon field and the quark-gluon interactions dynamically breaking chiral symmetry
  - Higgs mechanism has no role here.
- The similarity of mass between the proton and neutron arises from the fact that the gluon dynamics are the same
  - Quarks contribute almost nothing.

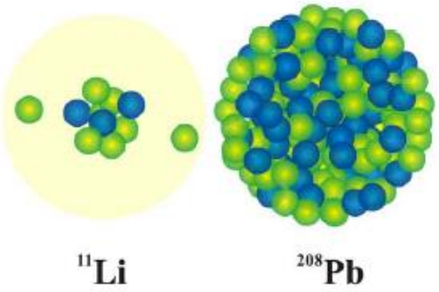
Cool Facts about QCD and Nuclei

- A small fraction of the force between quarks and gluons "leaks out" of protons and neutrons, and binds them together to form tiny nuclei. The long-range part of this process can be well described as if protons and neutrons exchange pions.
- Nuclear physicists are only now starting to understand how this "leakage" occurs, and how it results in the impressive variety of nuclei found in nature.
- A nucleus consisting of some 100 protons and 150 neutrons can be the same size as one with 3 protons and 8 neutrons.
- Despite the variety of nuclei found in nature, we believe we miss quite some more. These are necessary to explain the origin of nuclei and the abundance of elements found in the cosmos.





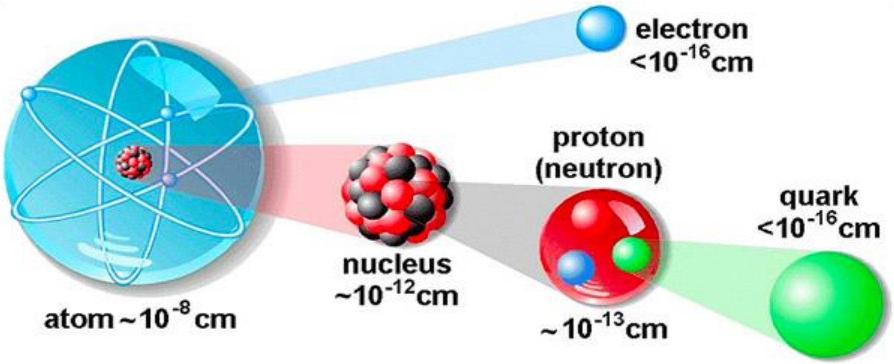




Understanding QCD and the Origin of Mass

- **Nuclear Science:** to discover, explore, and understand all forms of nuclear matter and its benefits to our society

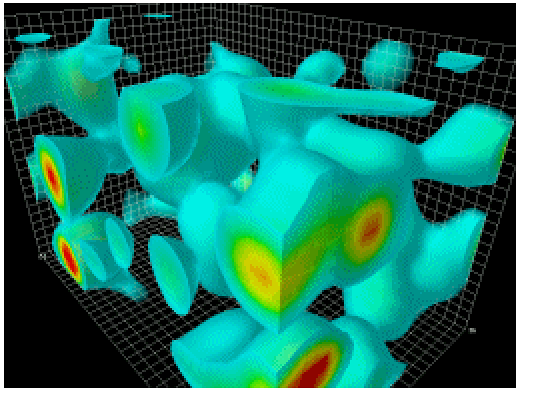
- **Nuclear matter:**
  - the nucleus
  - the nucleons
  - the quarks and gluons



- **QCD:** A fundamental theory for the dynamics of quarks and gluons

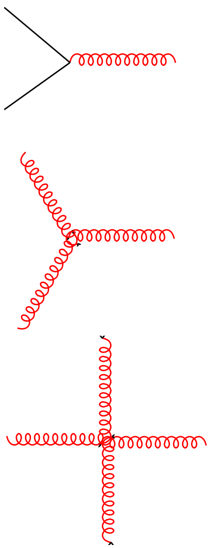
  It describes the formation of all forms of nuclear matter

- **QCD and the Origin of Mass**
  - Most of the proton's mass is due to the self-generating gluon field
  - Higgs mechanism has almost no role here
  - M(up) + M(up) + M(down) ~ 10 MeV << M(proton)



QCD and Nuclei

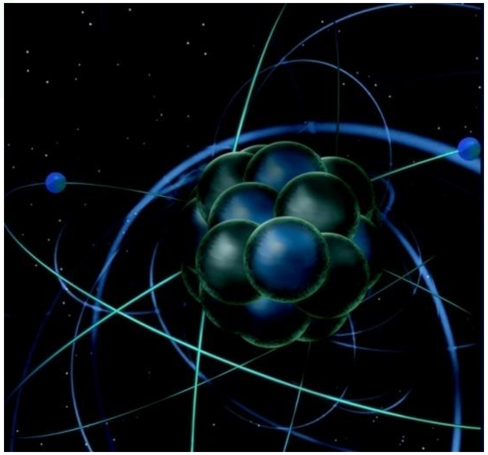
Gluons mediate the strong (color) force, just like photons mediate the electromagnetic force, but … gluons interact with themselves … which gives QCD unique properties



$$L_{QCD} = -\frac{1}{4} F^{a\mu\nu} F^{a}_{\mu\nu} + \sum_j \bar{q}_j (i\gamma^\mu D_\mu - m_j) q_j$$

$$F^{a}_{\mu\nu} \equiv \delta_\mu A^a_\nu - \delta_\nu A^a_\mu - g f^{abc} A^b_\mu A^c_\nu$$

$$D_\mu \equiv \delta_\mu + i g A^a_\mu \frac{\lambda_a}{2}$$



<u>QCD Lagrangian: quarks and gluons</u>

Nuclear Physics Model is an effective (but highly successful!) model using free nucleons and mesons as degrees of freedom.

The Double-Faced Strong Force

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi}(33 - 2n_f)\log\left(\frac{Q^2}{\mu^2}\right)}$$

<u>Confinement</u>

Nucleons

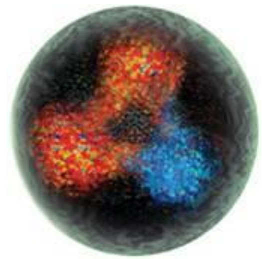
$Q < \Lambda$

$\alpha_s(Q) > 1$

Constituent Quarks

$Q > \Lambda$

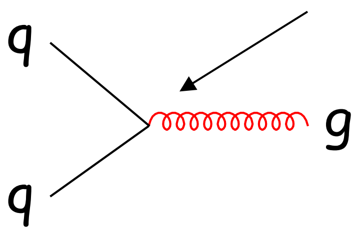
$\alpha_s(Q)$ large

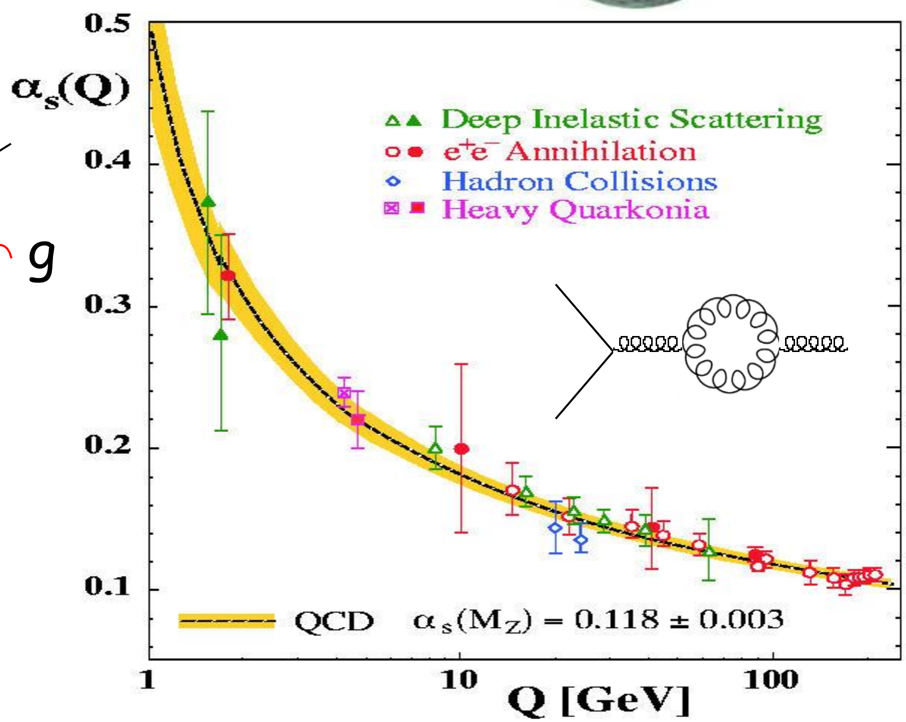


Asymptotically Free Quarks

$Q \gg \Lambda$

$\alpha_s(Q)$ small





One parameter, Λ_{QCD},
~ Mass Scale or
Inverse Distance Scale
where $a_s(Q) = \infty$

"Separates" Confinement and Perturbative Regions

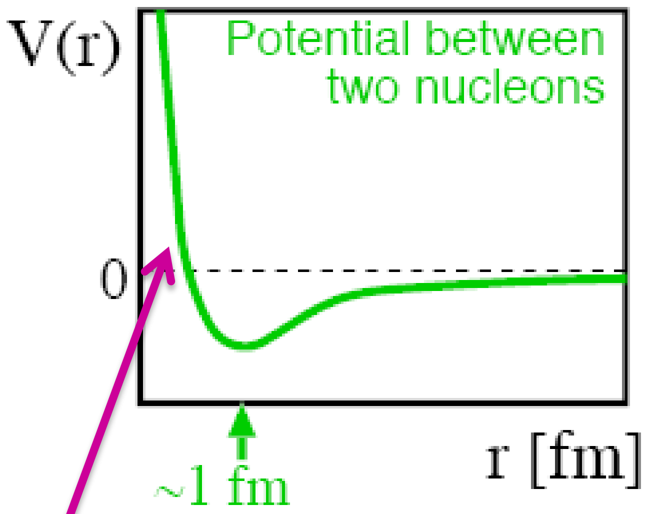
Mass and Radius of the Proton are (almost) completely governed by

$\Lambda_{QCD} \approx 0.213$ GeV

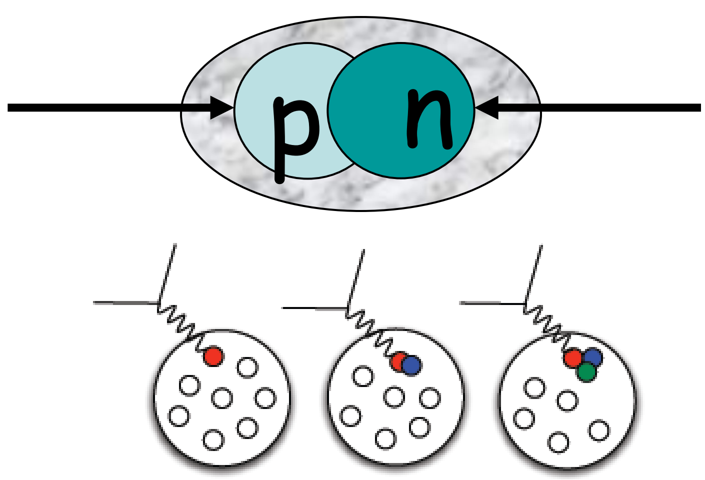
Quark Model

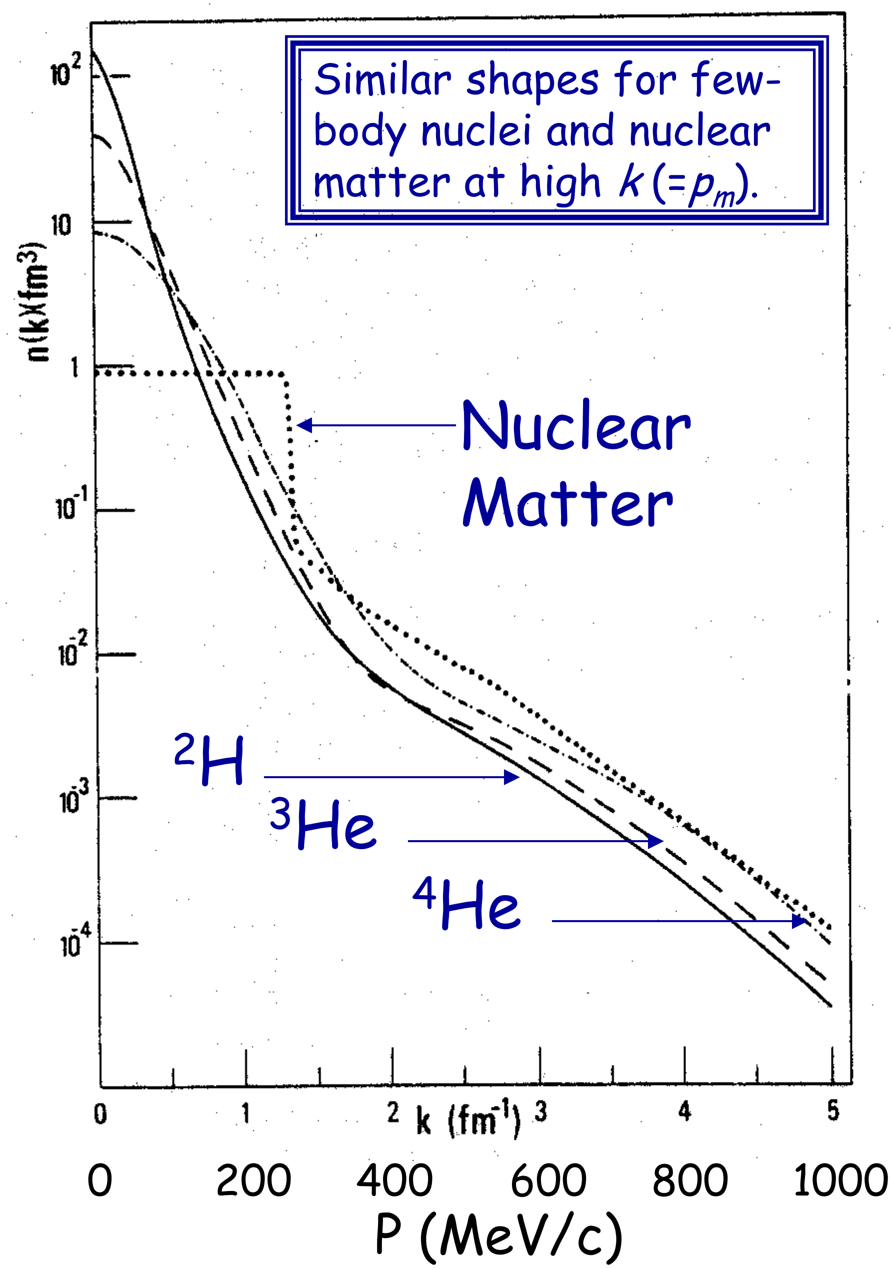
Quark Parton Model

Proton Momenta in the nucleus



Short-range repulsive core gives rise to high proton momenta





QCD

Asymptotic Freedom

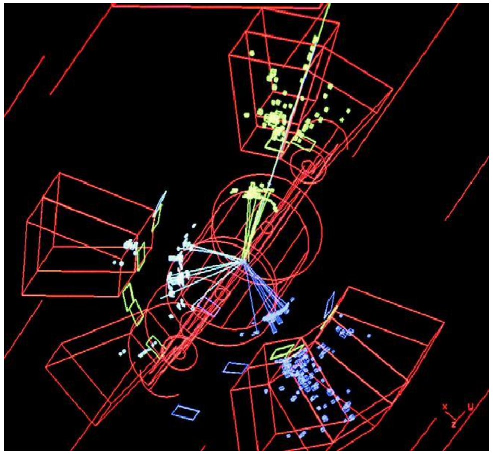
Small Distance
High Energy

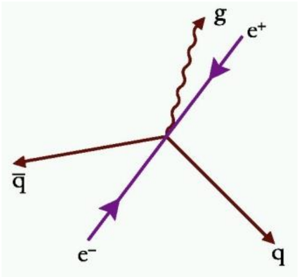
Confinement

Large Distance
Low Energy

Perturbative QCD

High Energy Scattering

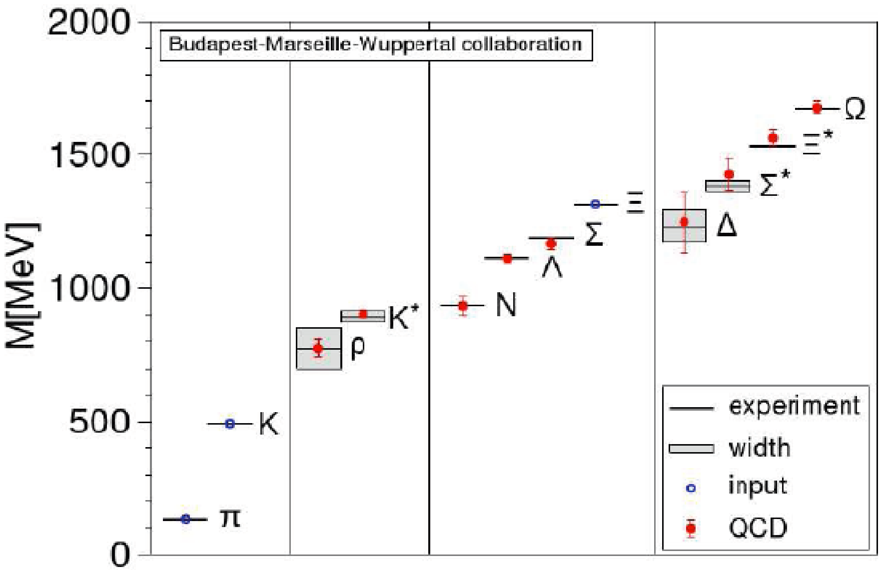




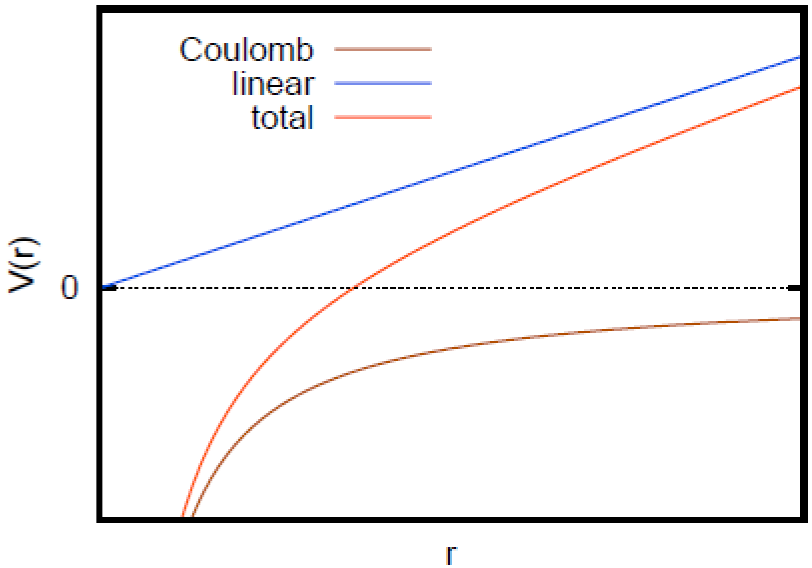
Gluon Jets
Observed

Strong QCD

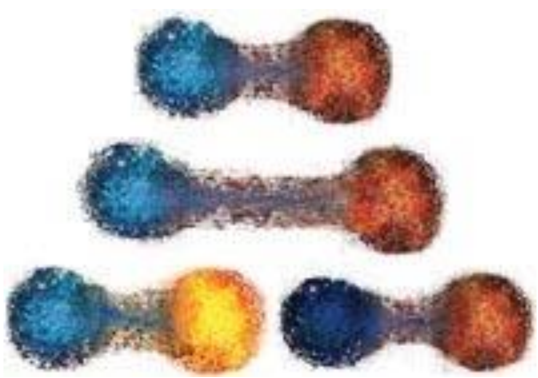
Hadron Spectrum - no signature of gluons?

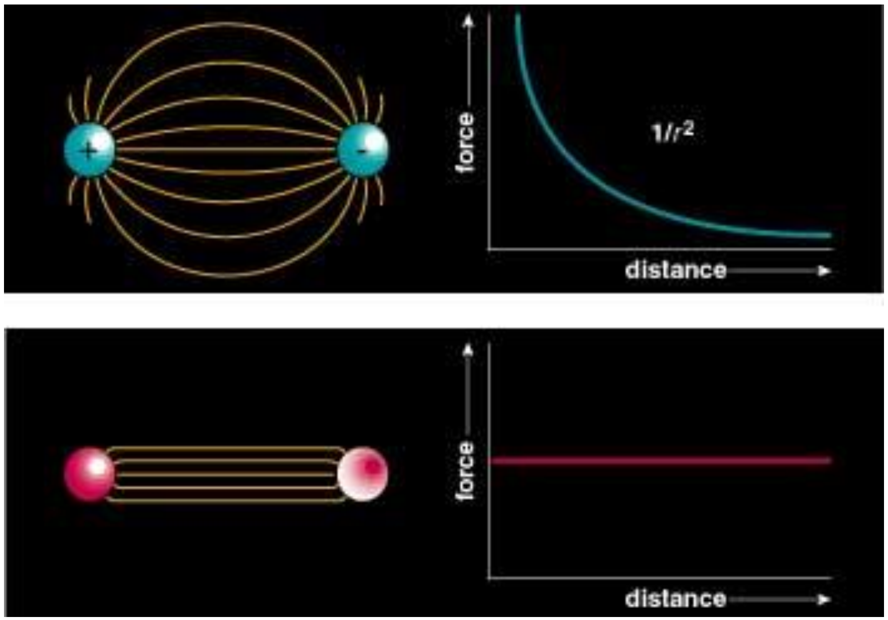


QCD - continued



- At small distance scales we have a Coulomb-like asymptotically free theory.
- At larger distances we have a linear confining potential ~ 1 GeV/fm.





Color Field: the field lines are compressed to vortex lines like the magnetic field in a superconductor

The Structure of the Proton – far more than up + up +down

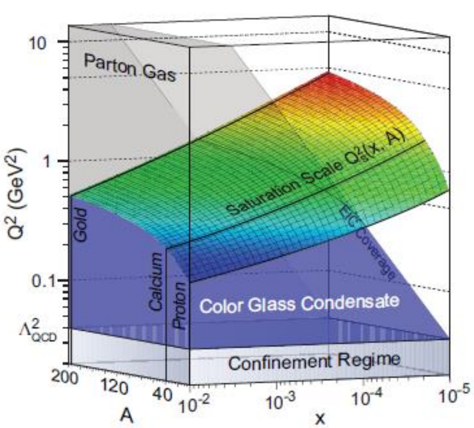
Naïve Quark Model: proton = uud (valence quarks)

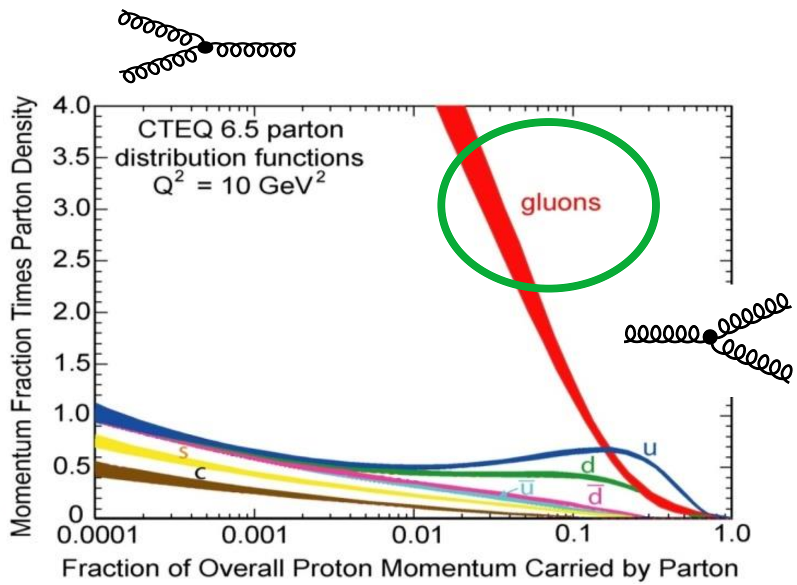
QCD: proton = $uud + u\bar{u} + d\bar{d} + s\bar{s} + \ldots$

The proton sea has a non-trivial structure: $\bar{u} \neq \bar{d}$

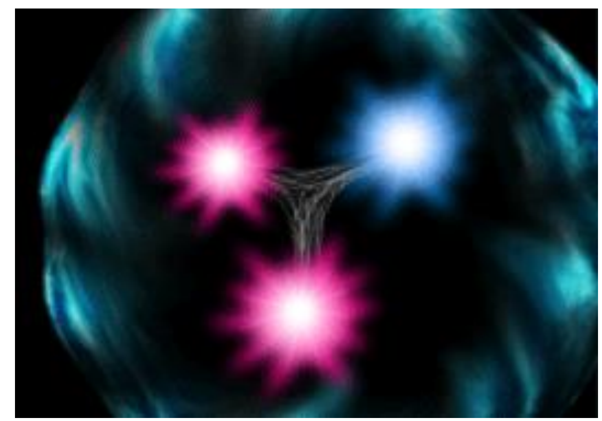
& gluons are abundant

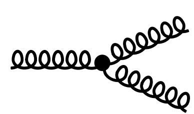
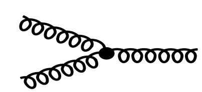
gluon dynamics





Non-trivial sea structure



- Gluon $\neq$ photon: Radiates  and recombines: 

Nuclear physicists are trying to answer how basic properties like mass, shape, and spin come about from the flood of gluons, quark/anti-quark pairs, and a few ever-present quarks.

The Revolution in Hadron and Nuclear Structure

Nuclear Physics in terms of protons, neutrons and pion exchange is a very good effective model. Resolution or Momentum transfer Q is negligible

Protons and Neutrons in terms of constituent (valence) quarks is a very decent effective model:

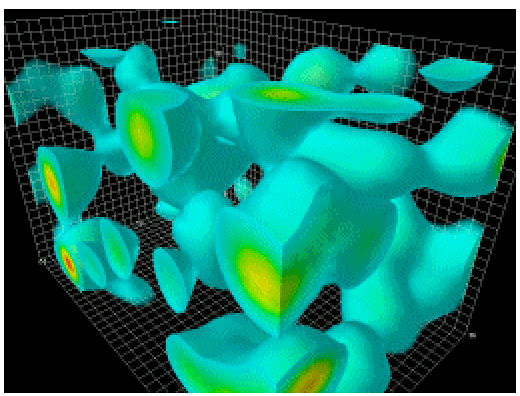
the Constituent Quark Model works surprisingly well.

Resolution or Momentum transfer Q is small

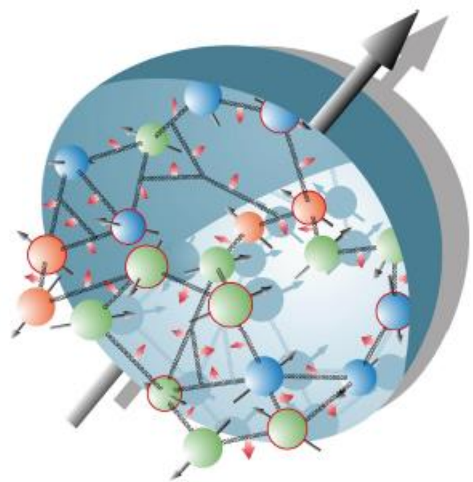
Looking deep inside protons and neutrons:

Quantum fluctuations + special relativity + $M = E/c^2$ gives rise to quark-gluon dynamics (structure and interactions).

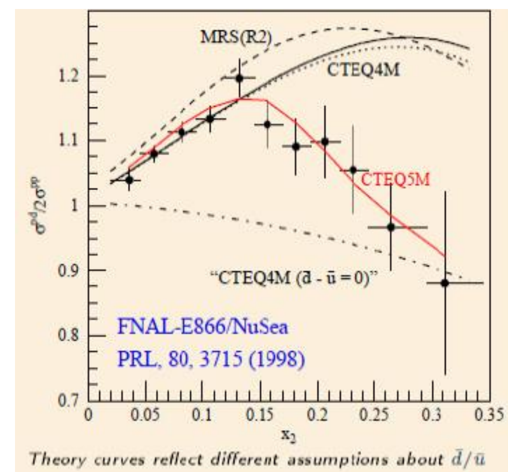
Resolution or Momentum transfer Q is “large”



The QCD vacuum is not empty, but full of gluon fluctuations: deep in the proton is a wall of gluons



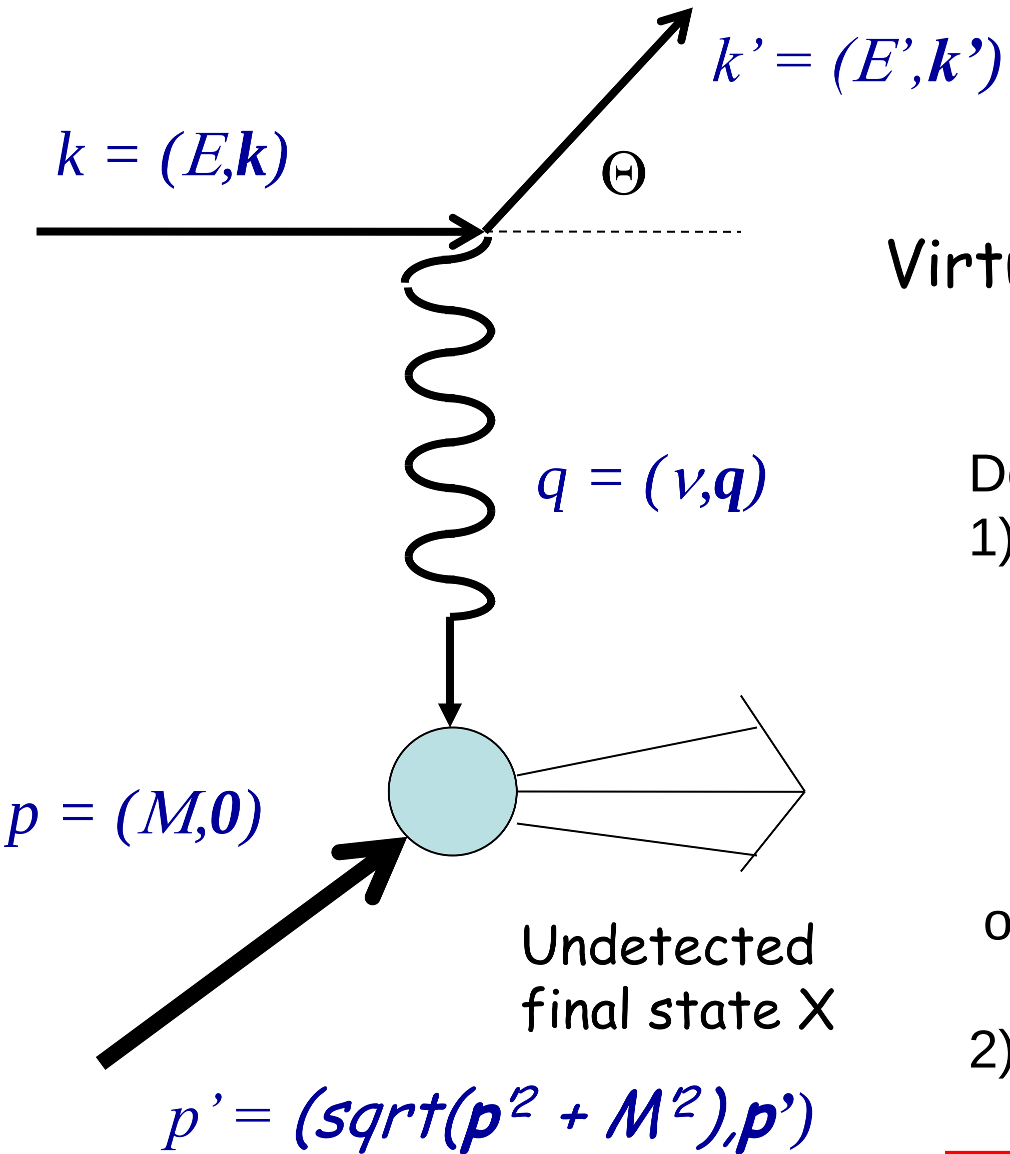
The proton is complex, mass and spin are emergent phenomena



Quantum fluctuations play a role in nucleon structure:

$\bar{d}(x) \neq \bar{u}(x)$

Electron Scattering Kinematics



($\rightarrow$ $p'^2 = M'^2 = W^2$) !!

Virtual photon $\rightarrow$ off-mass shell

$$q_\mu q^\mu = \nu^2 - \mathbf{q}^2 \neq 0$$

Define **two invariants**:

1) $Q^2 = -q_\mu q^\mu$

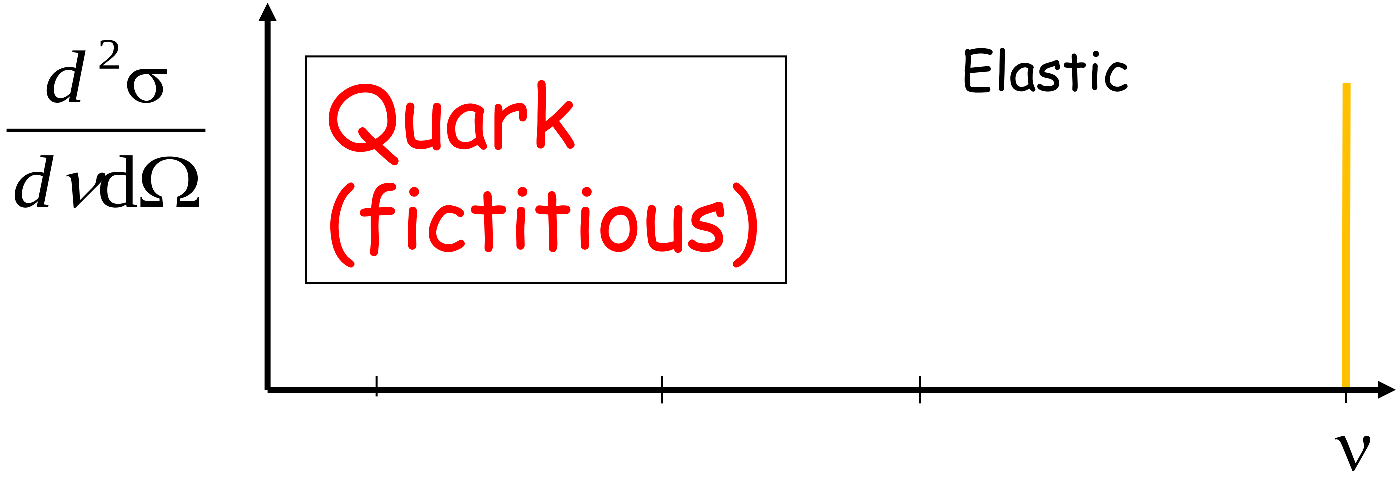
$$\begin{aligned}
Q^2 = -q_\mu q^\mu &= -(k_\mu - k_\mu')(k^\mu - k'^\mu) \\
&= -2m_e^2 + 2k_\mu k'^\mu \\
(m_e \sim 0) \quad &= 2k_\mu k'^\mu \\
(\text{LAB}) \quad &= 2(EE' - \mathbf{k}.\mathbf{k}') \\
&= 2EE'(1-\cos(\Theta)) \\
&= 4EE'\sin^2(\Theta/2)
\end{aligned}$$

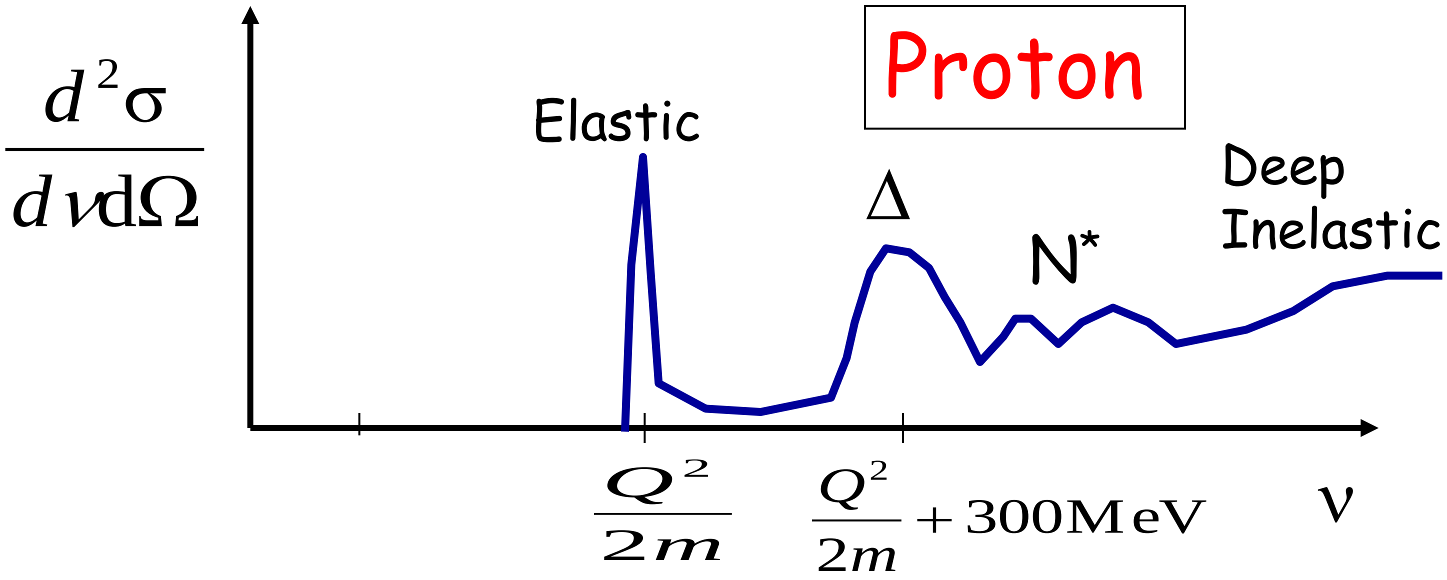
only assumption: neglecting m_e^2!!

2) $2M\nu = 2p_\mu q^\mu = Q^2 + W^2 - M^2$

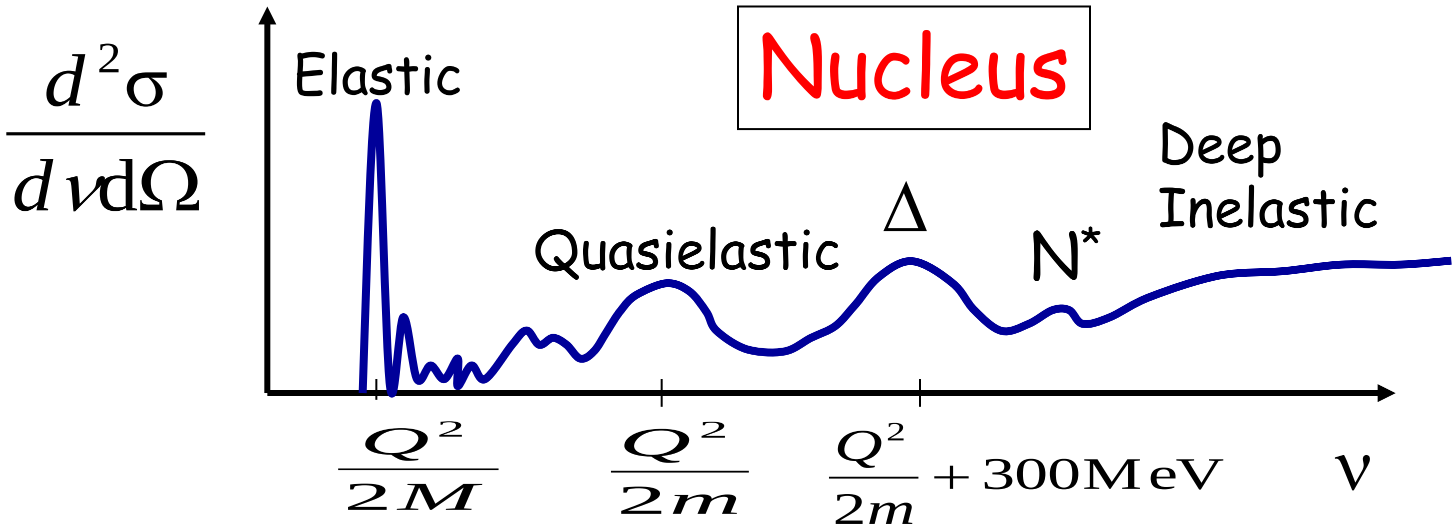
Elastic scattering
$\rightarrow$ $W^2 = M^2$ $\rightarrow$ $Q^2 = 2M(E-E')$

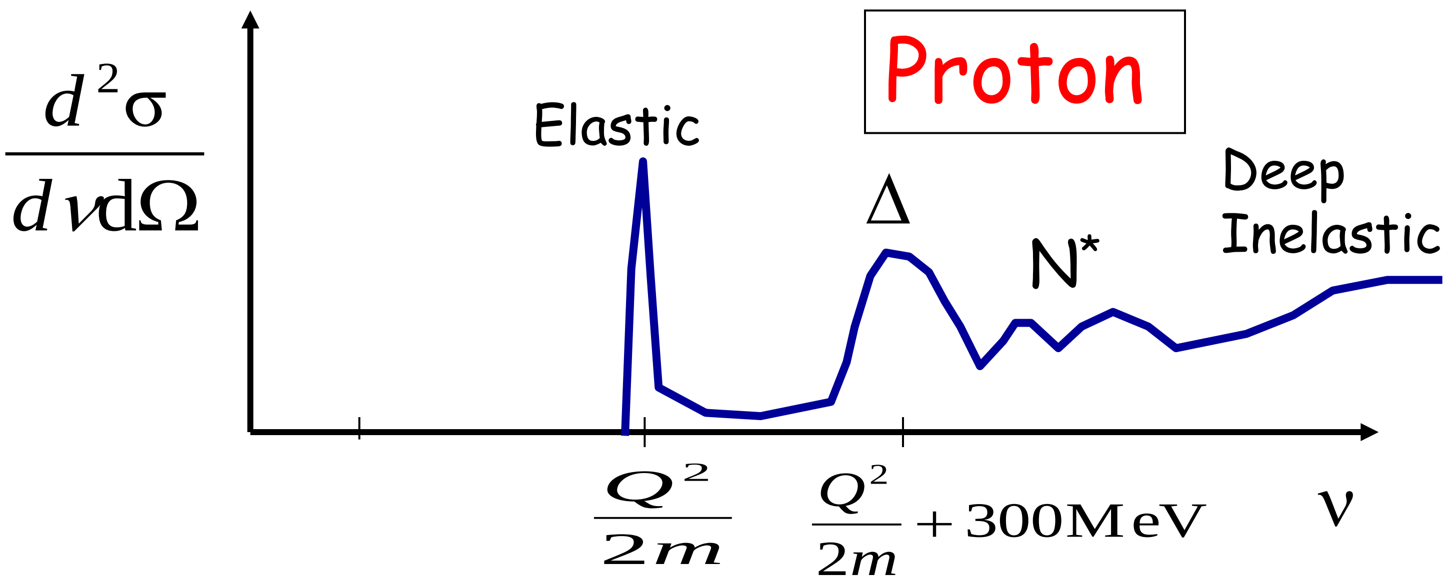
Electron Scattering at Fixed Q^2



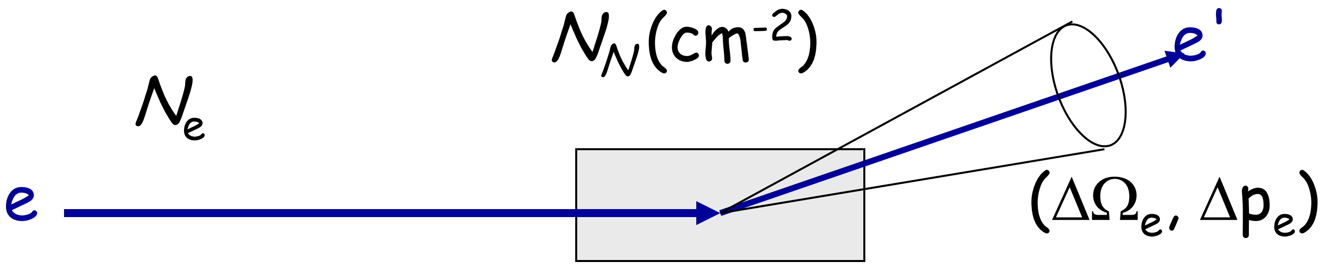


Electron Scattering at Fixed Q^2





Extracting the (e,e') cross section

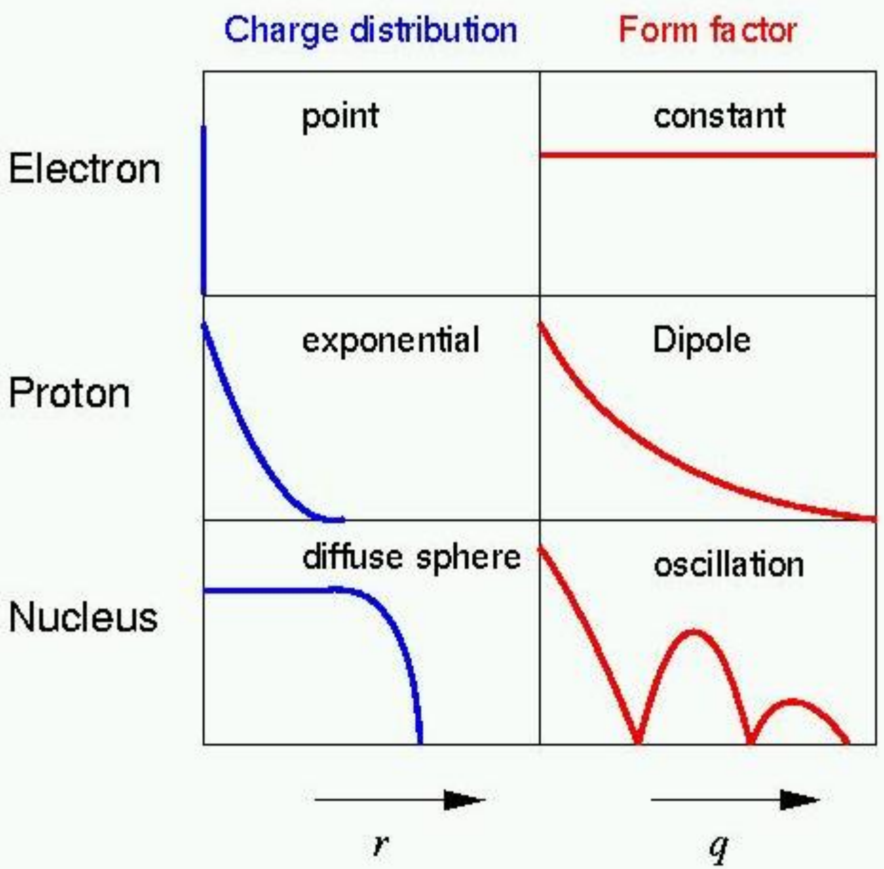


Scattering probability or cross section

$$\boxed{\left\langle \frac{\mathrm{d}^3\sigma}{\mathrm{d}\Omega_\mathrm{e}\,\mathrm{d}p_e} \right\rangle = \frac{\text{Counts}}{N_e N_N \Delta\Omega_e \Delta p_e}}$$

Electron-Charge Scattering

Form Factors characterize internal structure of particles



- Elastic cross section

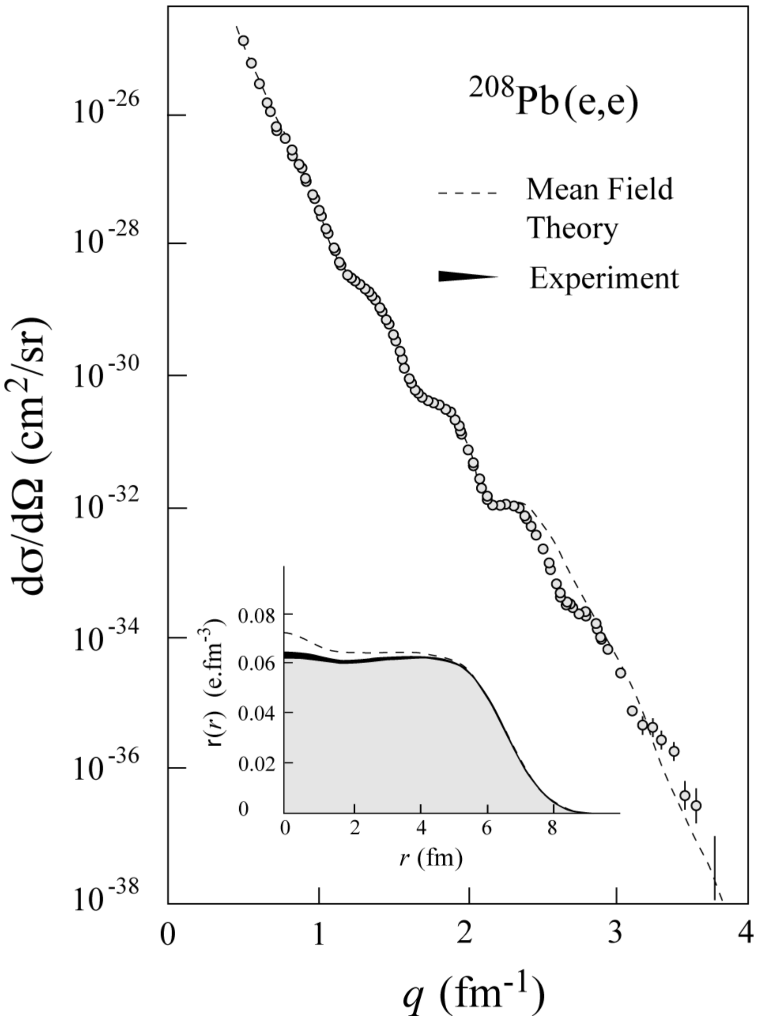
$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{exp}} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \left|F(q^2)\right|^2$$

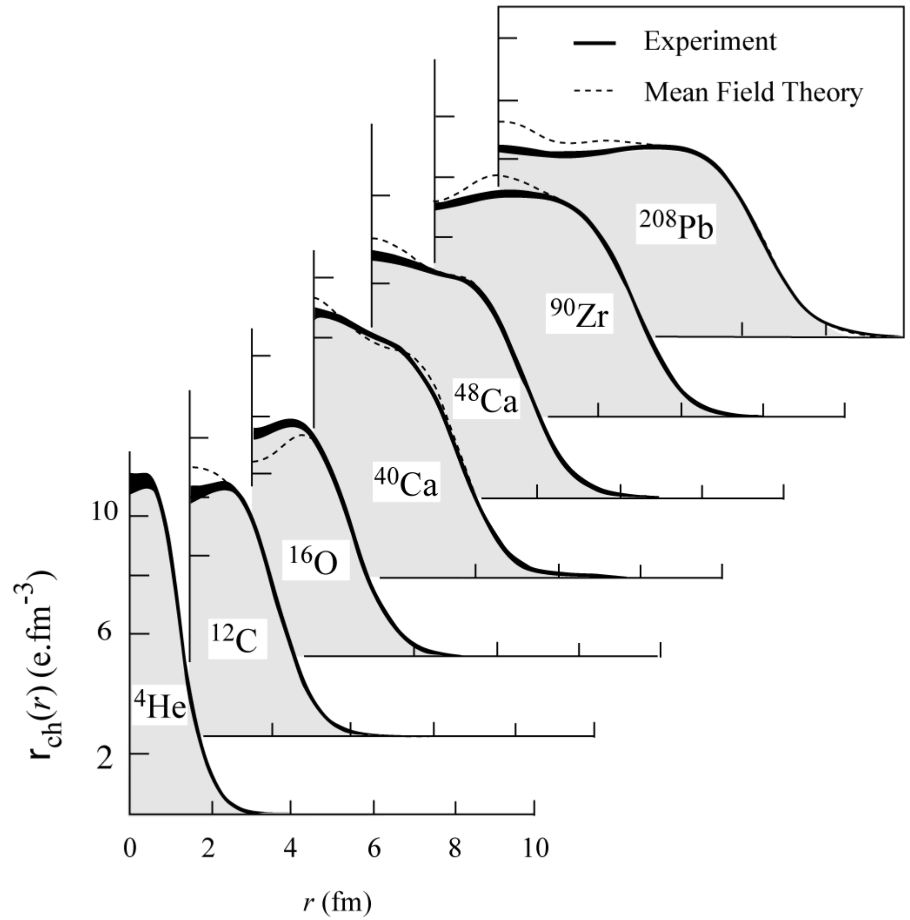
- Form factor

$$F(q^2) = \int e^{iqx/\hbar}\rho(x)d^3x$$

The form factor as a Fourier transformation of the charge distribution is a non-relativistic concept.

History - Charge Distributions



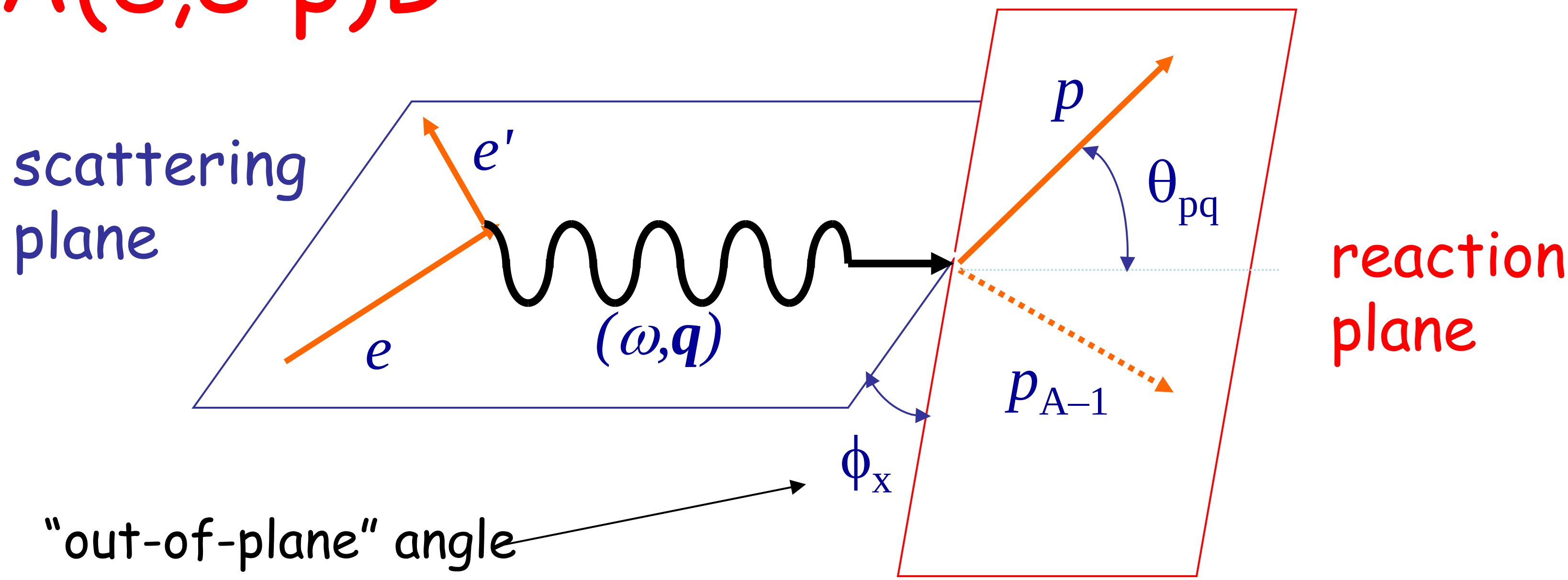


In '70s large data set was acquired on elastic electron scattering (mainly from Saclay) over large Q^2-range and for variety of nuclei

"Model-independent" analysis provided accurate results on charge distribution well described by mean-field Density-Dependent Hartree-Fock calculations

A(e,e'p)B

Knock a Proton out of a Nucleus



Neglecting m_e: $Q^2 \equiv - q_\mu q^\mu = q^2 - \omega^2 = 4ee' \sin^2\theta/2$

Known: e and A + Detect: e′ and p → Infer:

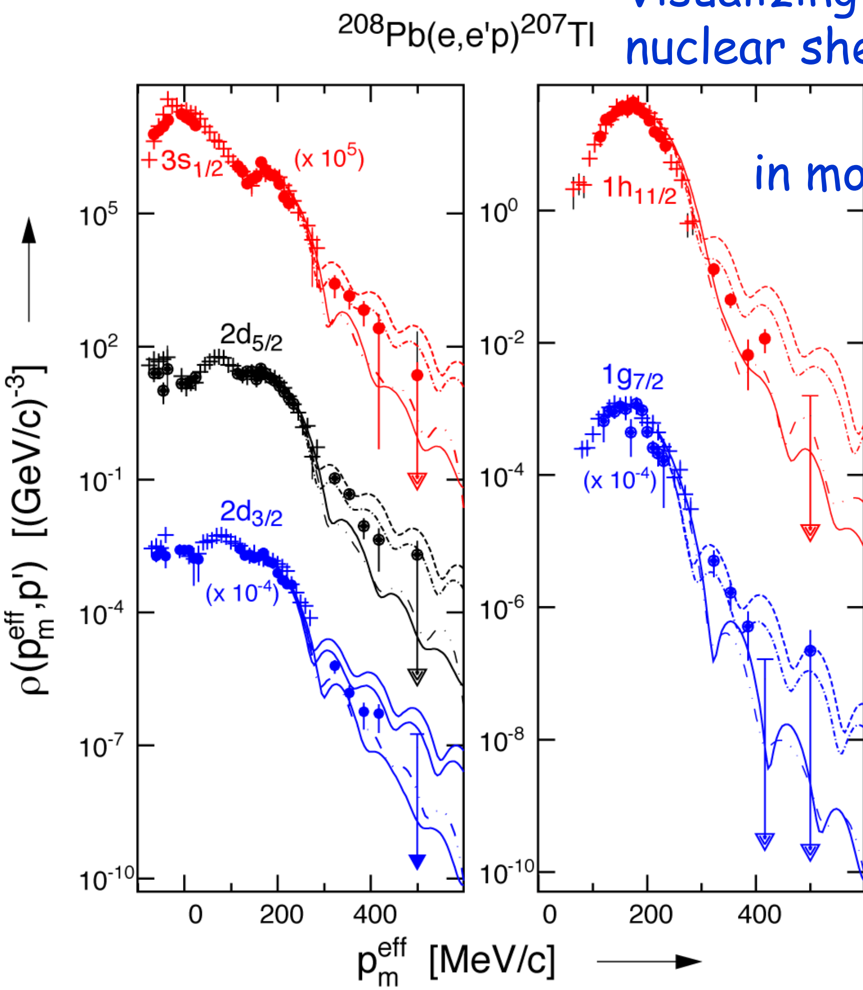
Missing momentum: $\boldsymbol{p}_m = \boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_{A-1}$

Missing mass: $\varepsilon_m = \omega - T_p - T_{A-1}$

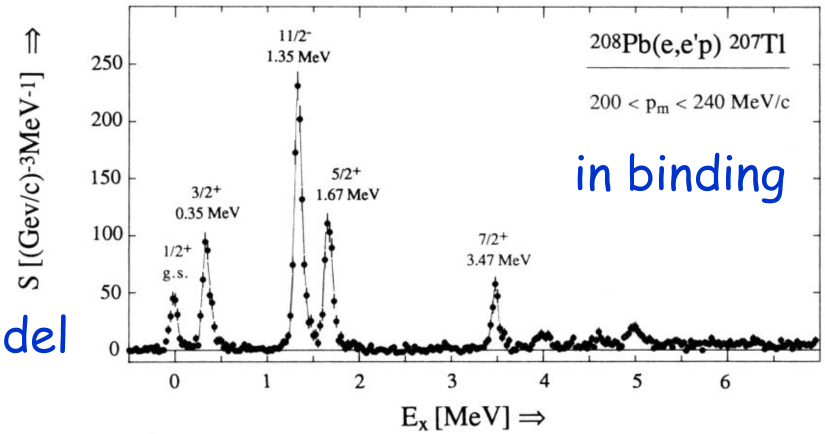
History - Proton Knock-out

$$p_m = E_e - E_{e'} - p = q - p$$
$$E_m = \nu - T_p - T_{A-1} = E_{sep} + E_{exc}$$

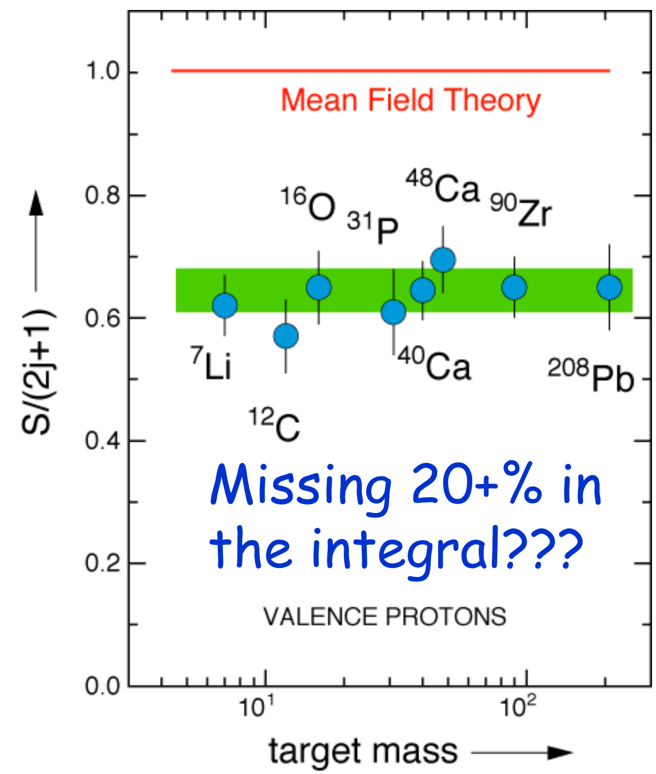
Visualizing the nuclear shell model



in momentum



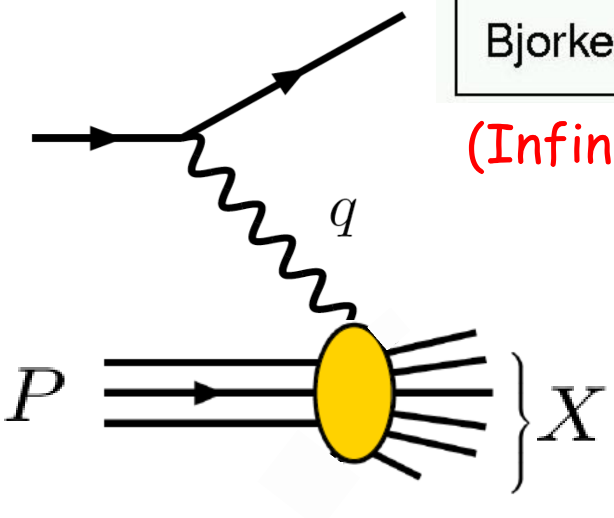
in binding



Missing 20+% in the integral???

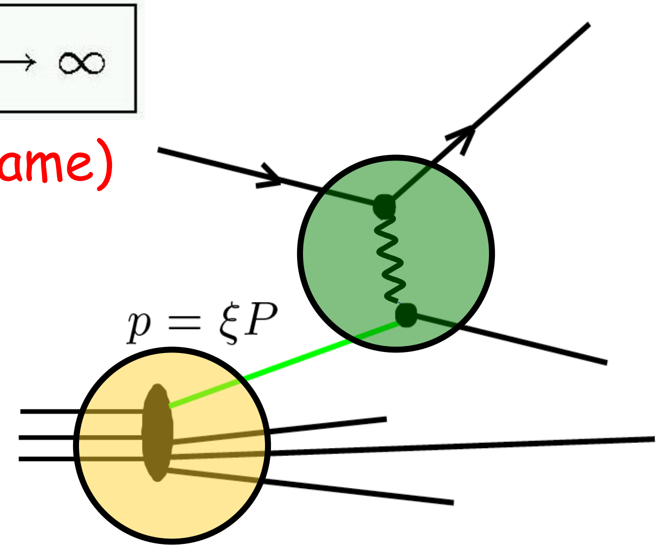
Deep Inelastic Scattering and the Parton Model

Deep Inelastic Scattering –
knock a nucleon apart



Bjorken Limit: $Q^2 \to \infty, \nu \to \infty$

(Infinite Momentum Frame)



$$x = \frac{Q^2}{2P \cdot q}$$

Parton Model :
Feynman; Bjorken, Paschos

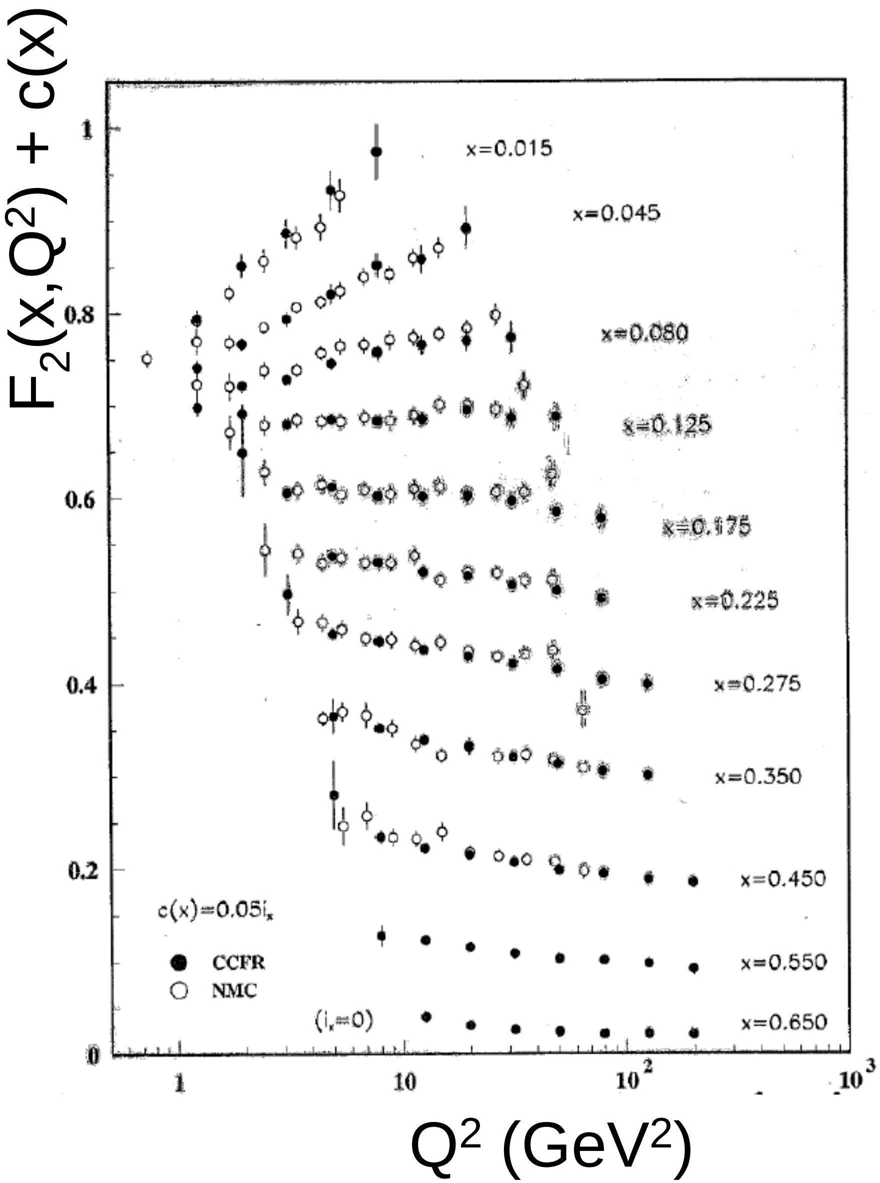
$$\xi = x$$

→ access through Structure Functions F_2
to Parton Distribution Functions

$$\mathbf{F_2(x) = \sum_i e_i^2 x q_i(x)}$$

Empirically, DIS region is where logarithmic scaling is observed
$Q^2 > 1$ GeV^2, $W^2 > 4$ GeV^2

Structure Function by Different DIS Probes



○ $F_2^{\mu D}$ μ DIS

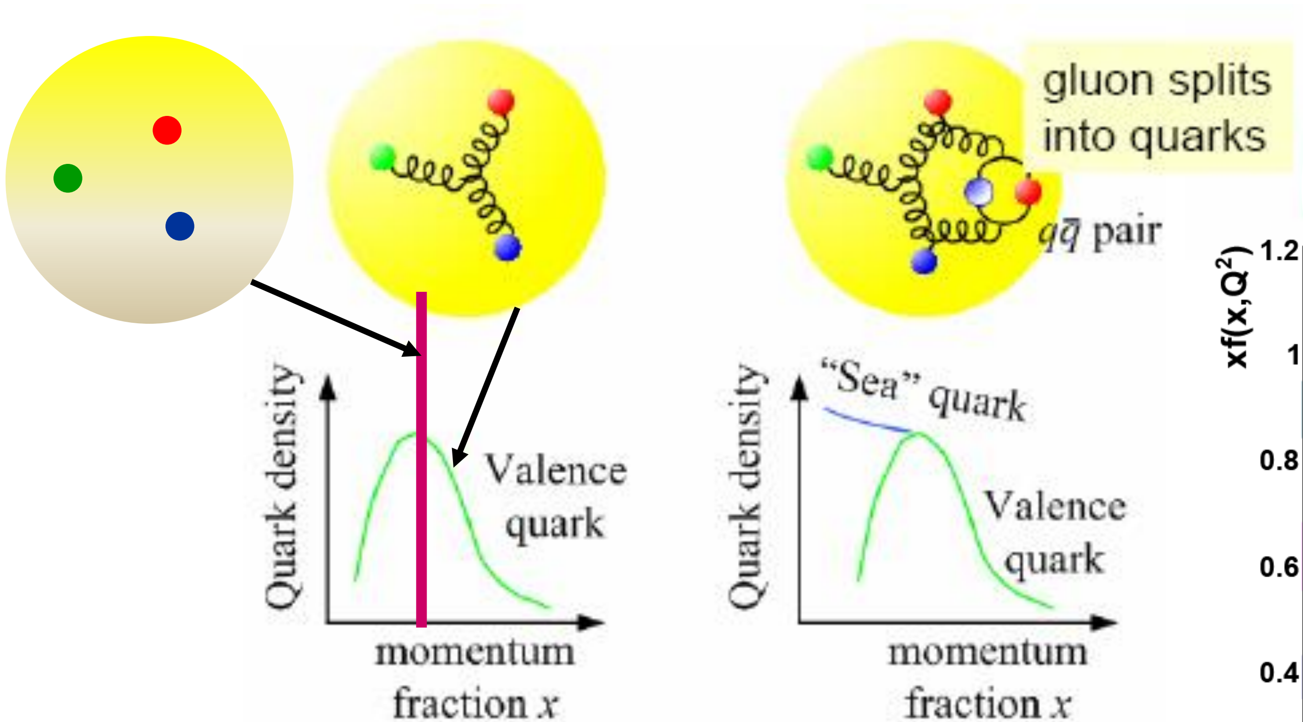
● $F_2^{\overset{(-)}{\nu}N} \times \frac{5}{18}$ ν DIS

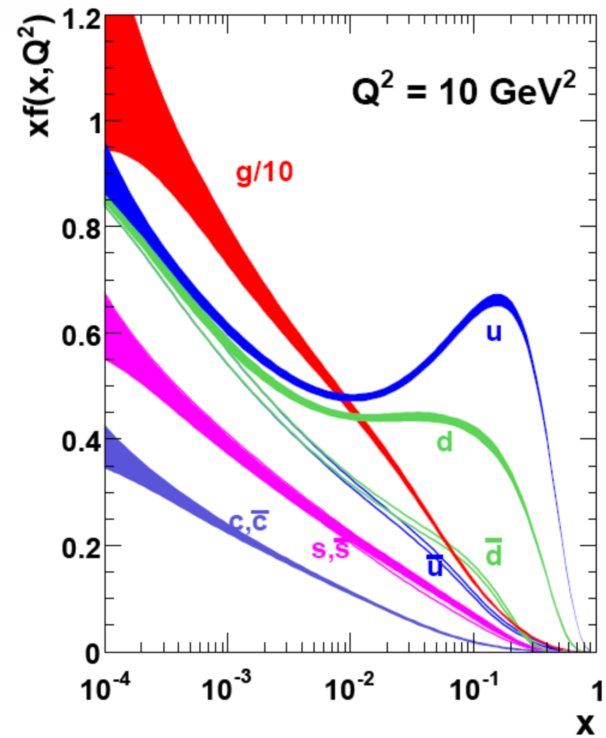
The Classic Example

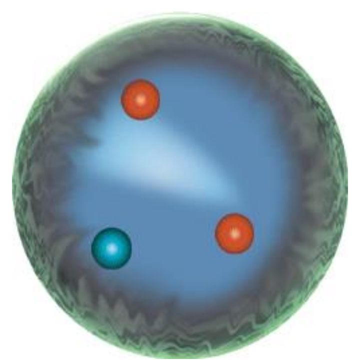
- Extending the scaling found by the venerable SLAC (electron scattering) experiment.
- Confirming the basis of the Quark-Parton Model: the expected 5/18 charge weighting works well.
- Logarithmic Scaling Violations as anticipated from a renormalizable field theory (QCD) are clearly shown, with both muon and neutrino probes.

Parton Distribution Functions (PDFs)

PDF q(x): probability that a quark (or gluon) has fraction x of proton's momentum

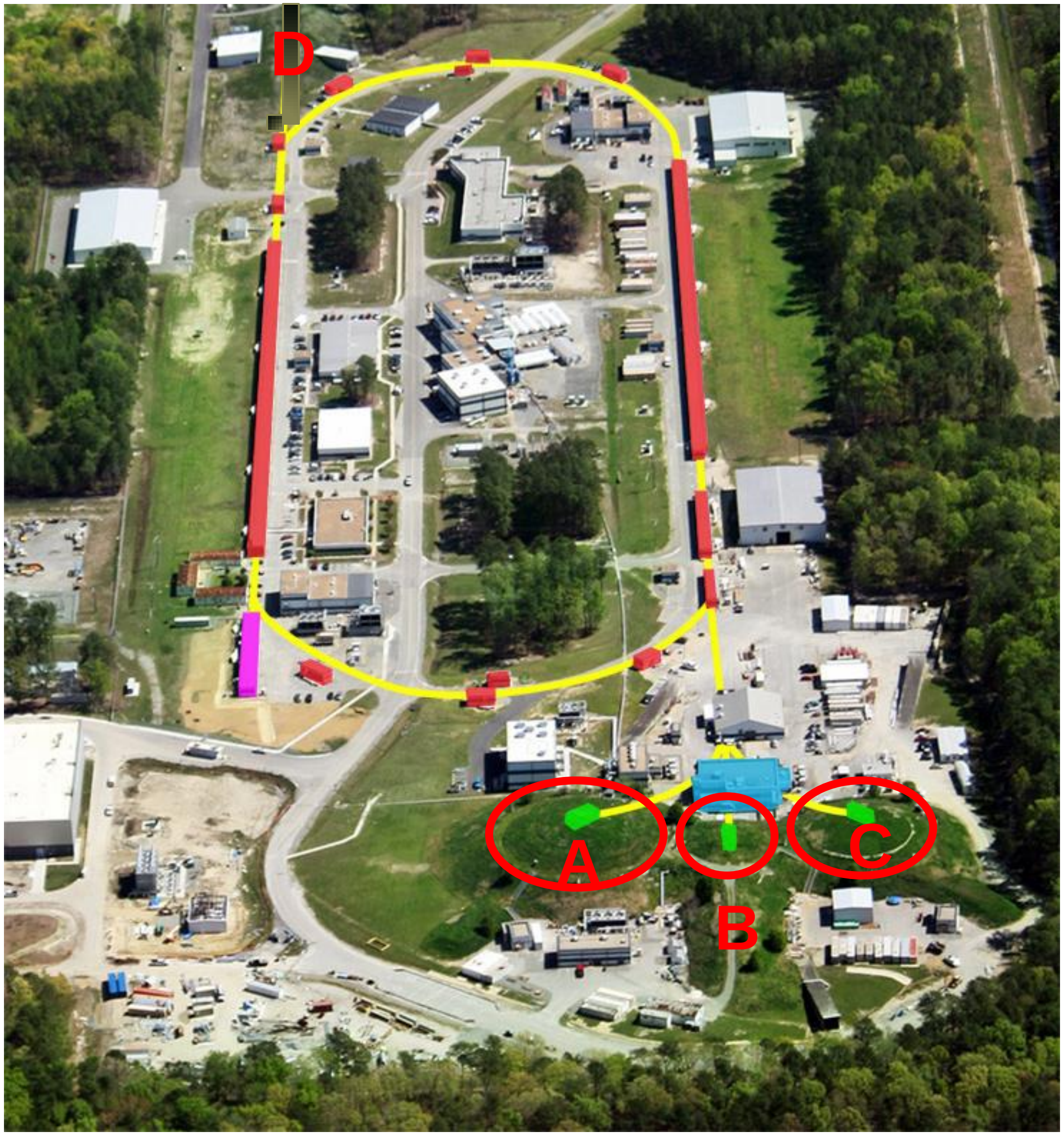






proton: **uud** + uū + dđ + …

JLab accelerator CEBAF (up to 2012)



Continuous Electron Beam
- Energy 0.4 – 6.0 GeV
- 200 μA, polarization 85%
- 3 x 499 MHz operation
- Simultaneous delivery 3 halls

- 500+ PhDs completed
- On average 22 US PhDs per year, roughly 25-30% of US PhDs in nuclear physics
- On average 50 undergrads per year involved in research at Jefferson Lab
- 1530 users in FY16
- **International: non-US nuclear physics users = 1/3 of total, from 37 countries**

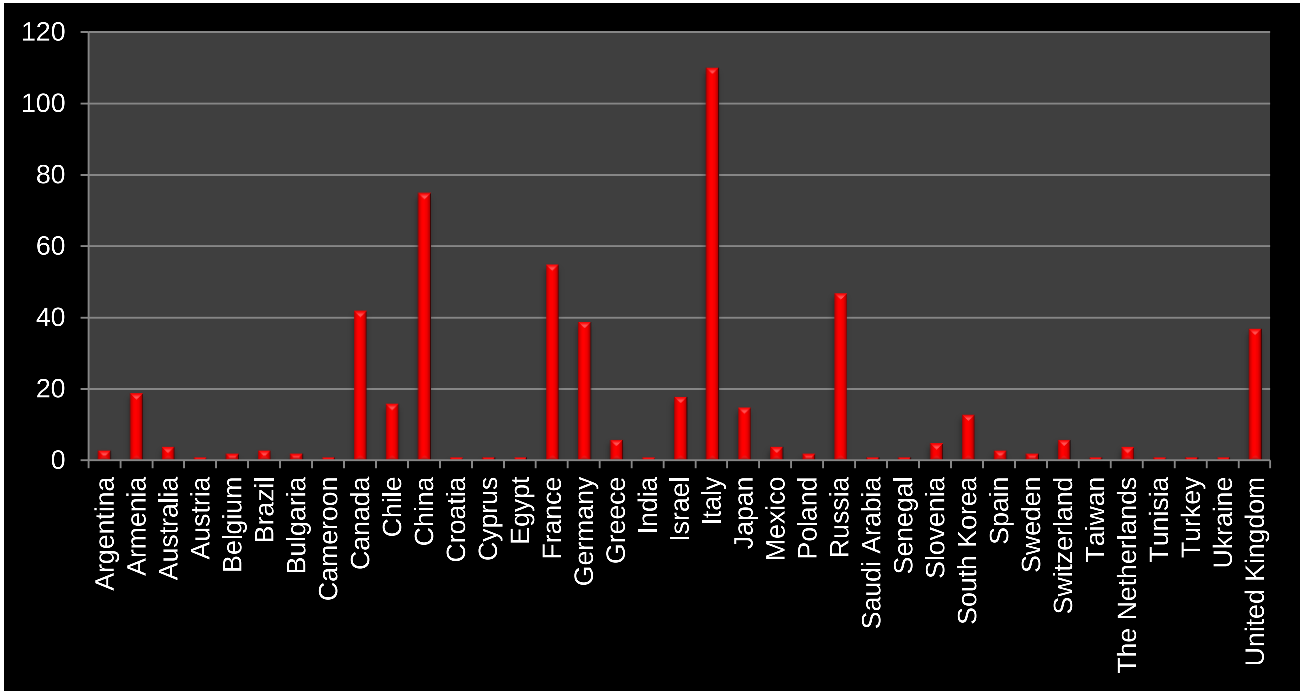
FY18: First try simultaneous delivery to 4 halls – A, B, C, D

International Character of Jefferson Lab

Remarkable and unique facility, complementary efforts in the international scene for the hadron physics program:

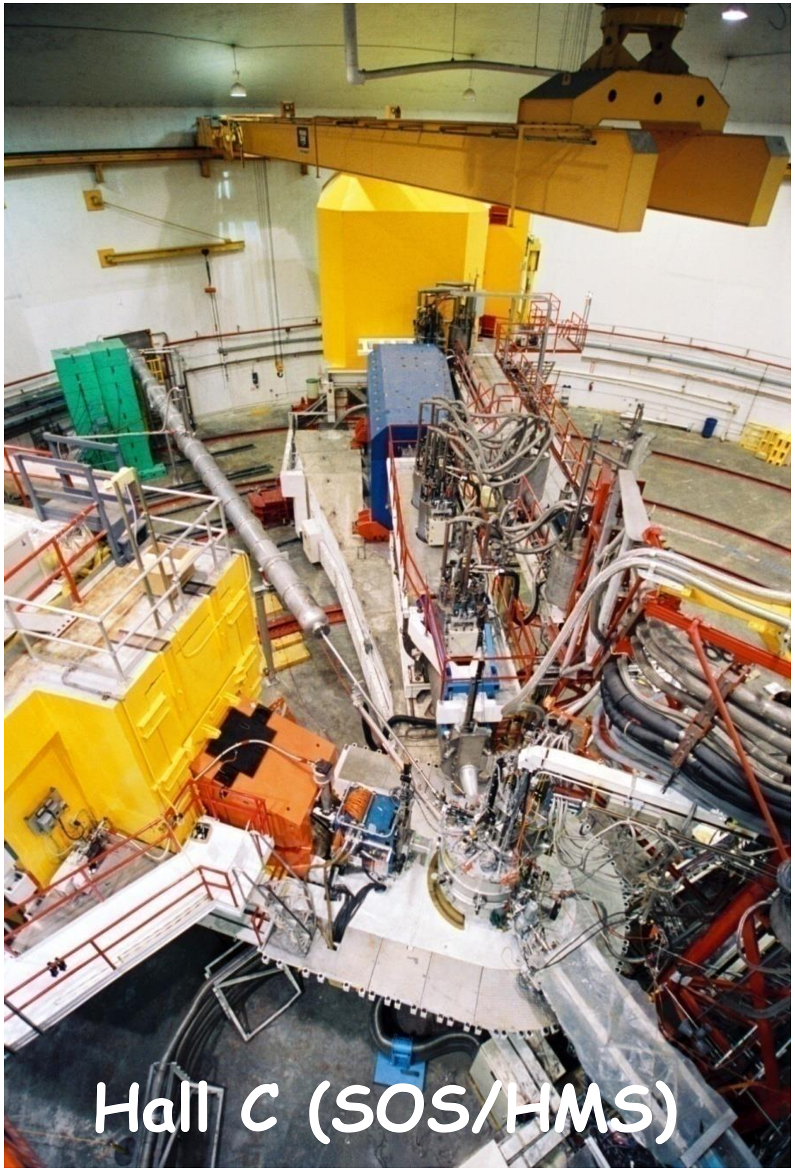
COMPASS at CERN: ~200 GeV muon beam, large acceptance, much lower luminosity.
Mainz (Germany): excellent 2 GeV CW polarized electron beams but limited kinematic reach.
JPARC (Japan): Hadron beam facilities with high intensity kaon and pion beams.
BES (China), BELLE (Japan), BABAR: heavy quark meson spectroscopy in e^+-e^- collisions.
PANDA at GSI (Germany): heavy quark meson spectroscopy in proton-antiproton collisions.

International Users at Jefferson Lab

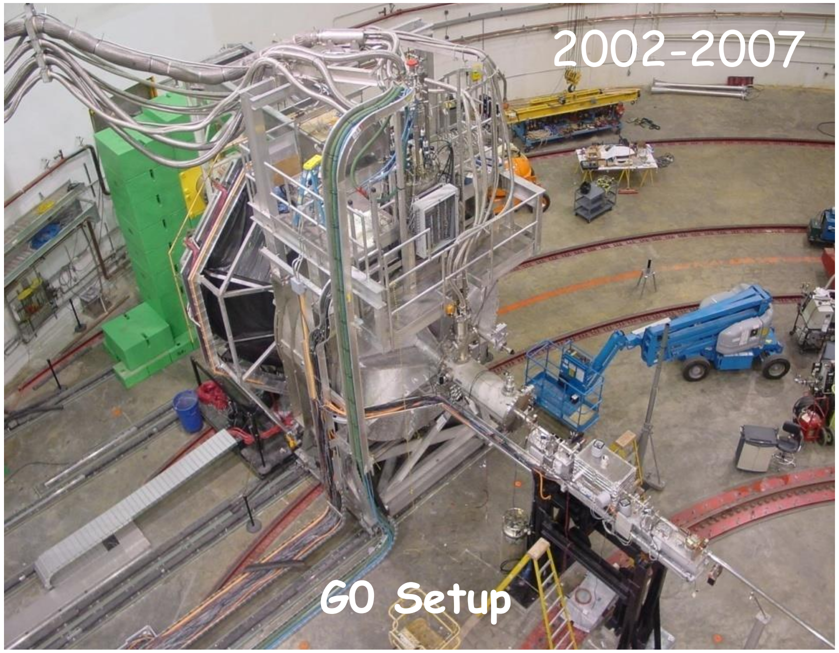


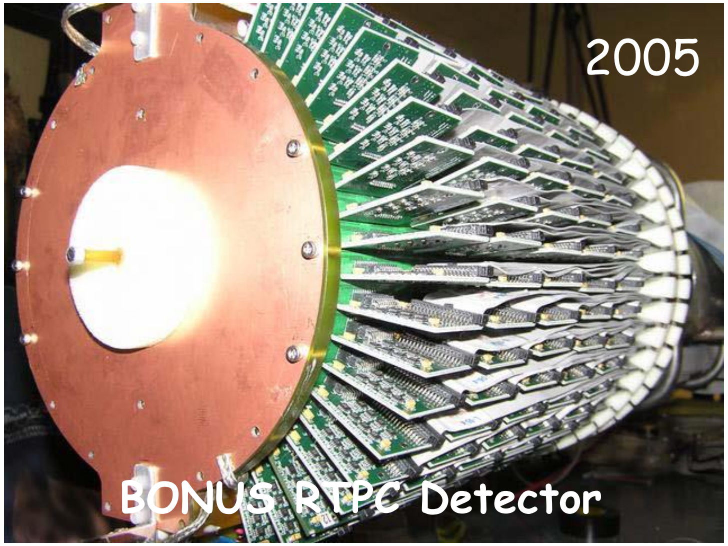
~1/3 of our 1530 users (FY16) are international, from 37 countries

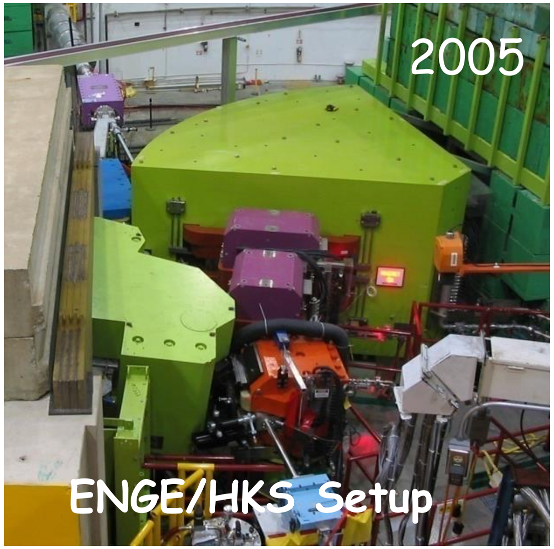
Halls A/B/C (6-GeV) Base Equipment (1995-2012)



Ancillary Equipment and Experiment-Specific Apparatus







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  Charge and Magnetization in Nucleons and Pions

  The Onset of the Parton Model

Cross section for *ep* elastic scattering

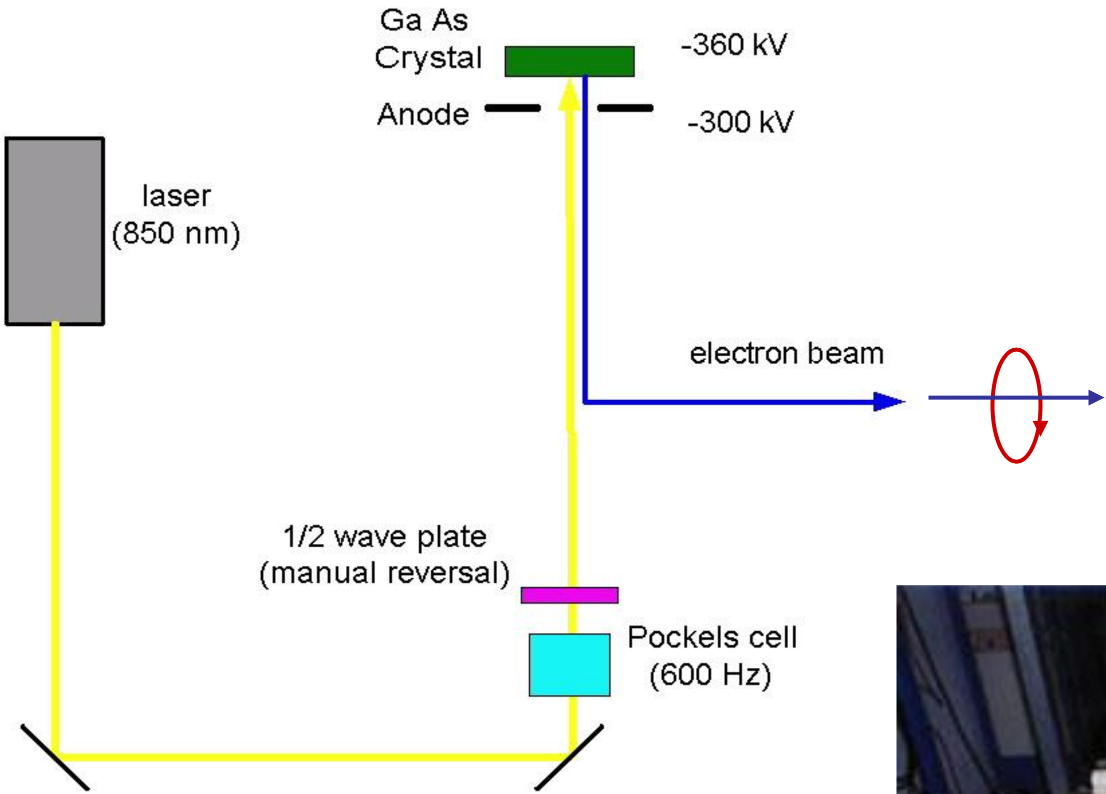
$$\frac{d\sigma}{d\Omega} = f_{rec}\sigma_{\mathrm{M}}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau\tan^2\frac{\theta}{2}G_M^2\right]$$

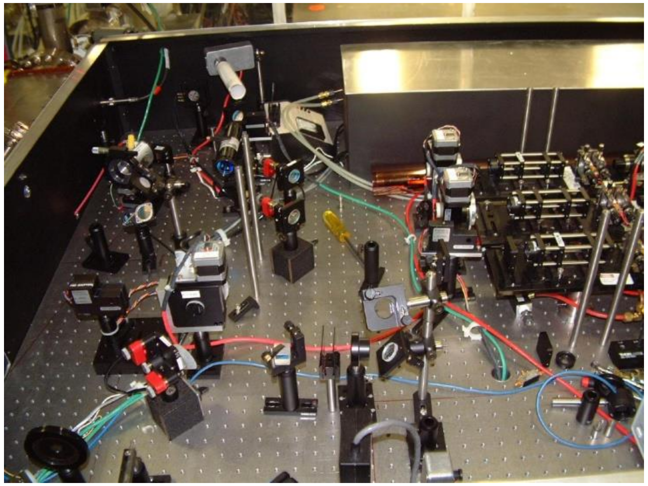
Two form factors reflecting the charge and magnetization distribution

$$\frac{d\sigma}{d\Omega} = f_{rec}\sigma_{\mathrm{M}}\left[\mathrm{A} + \mathrm{B}\tan^2\frac{\theta}{2}\right]$$

Can disentangle with two measurements

JLab: Polarized Electrons!!!

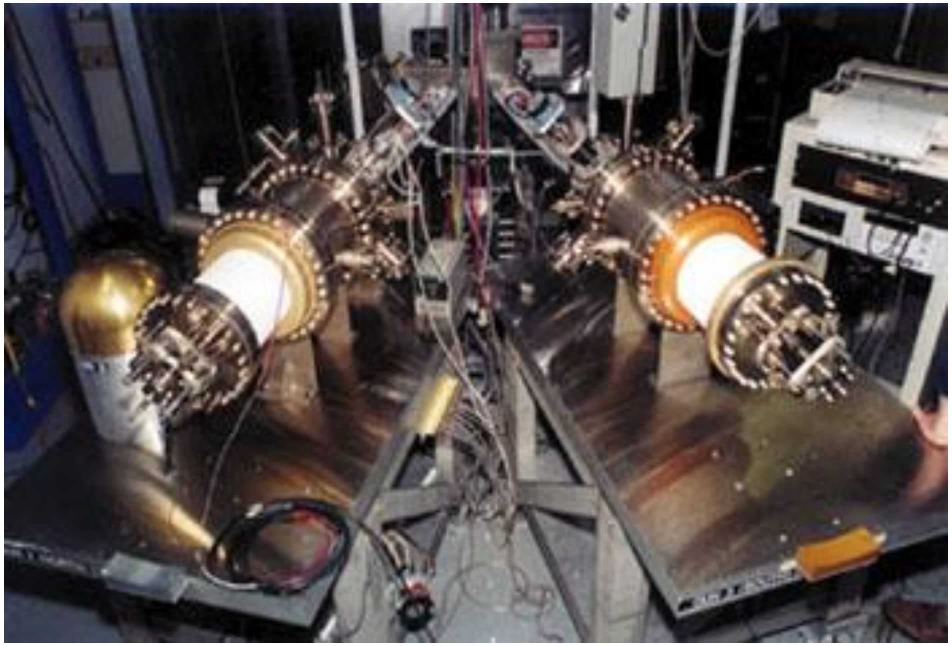




Electron retains circular polarization of laser beam

Reverse polarization of beam at rate of 30 Hz (now 1 kHz)

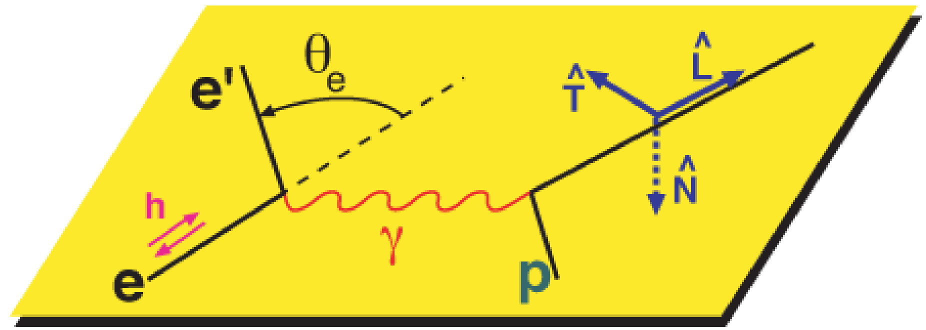
Feedback on laser intensity and position at high rate



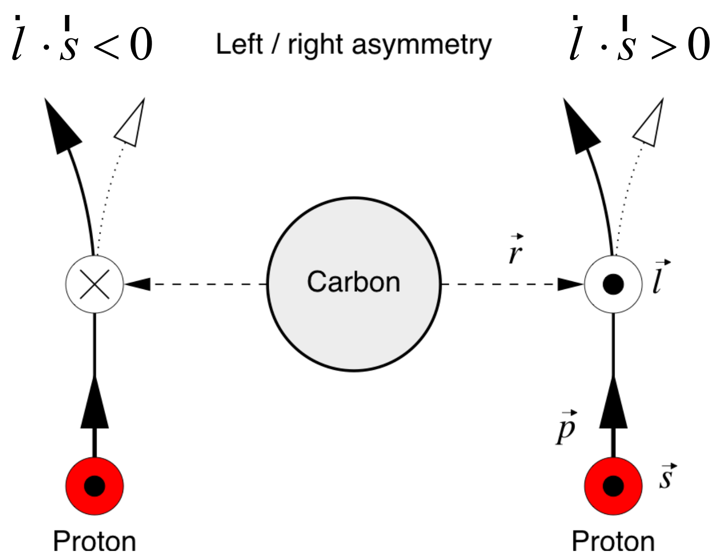
JLab Revolutionized Polarization Experiments!

Precise access to (small) charge form factor of proton utilizing polarization transfer technique: $\vec{e} + p \rightarrow e' + \vec{p}$

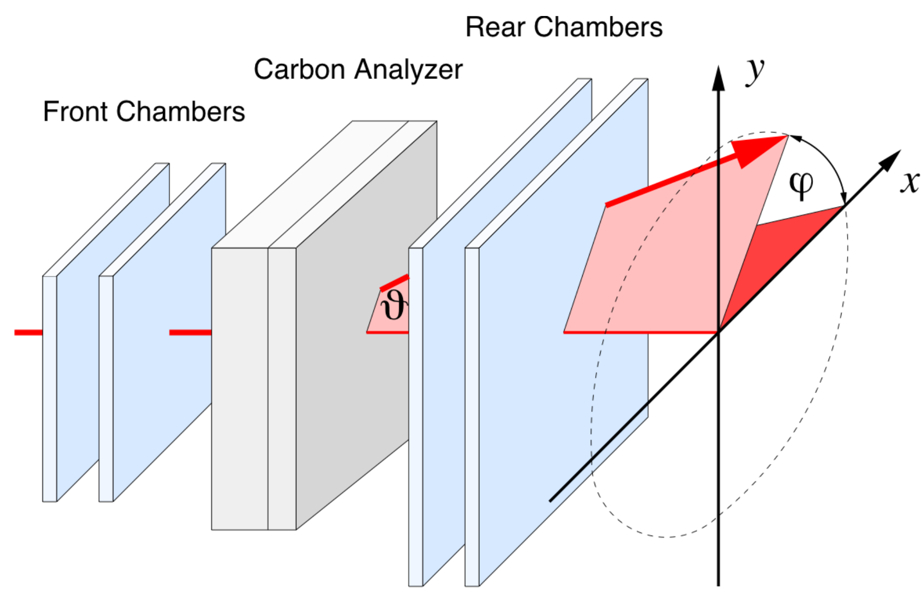
$$\boxed{\frac{G_E}{G_M} = -\frac{P'_x}{P'_z}\frac{(E_i + E_f)}{2m}\tan\frac{\Theta_e}{2}}$$



Spin-dependent scattering

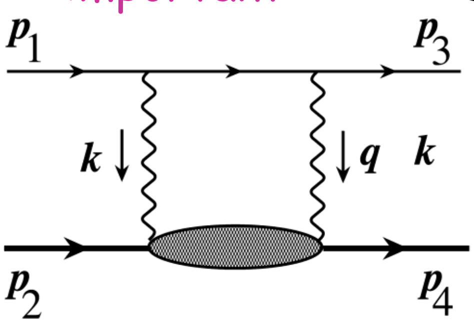


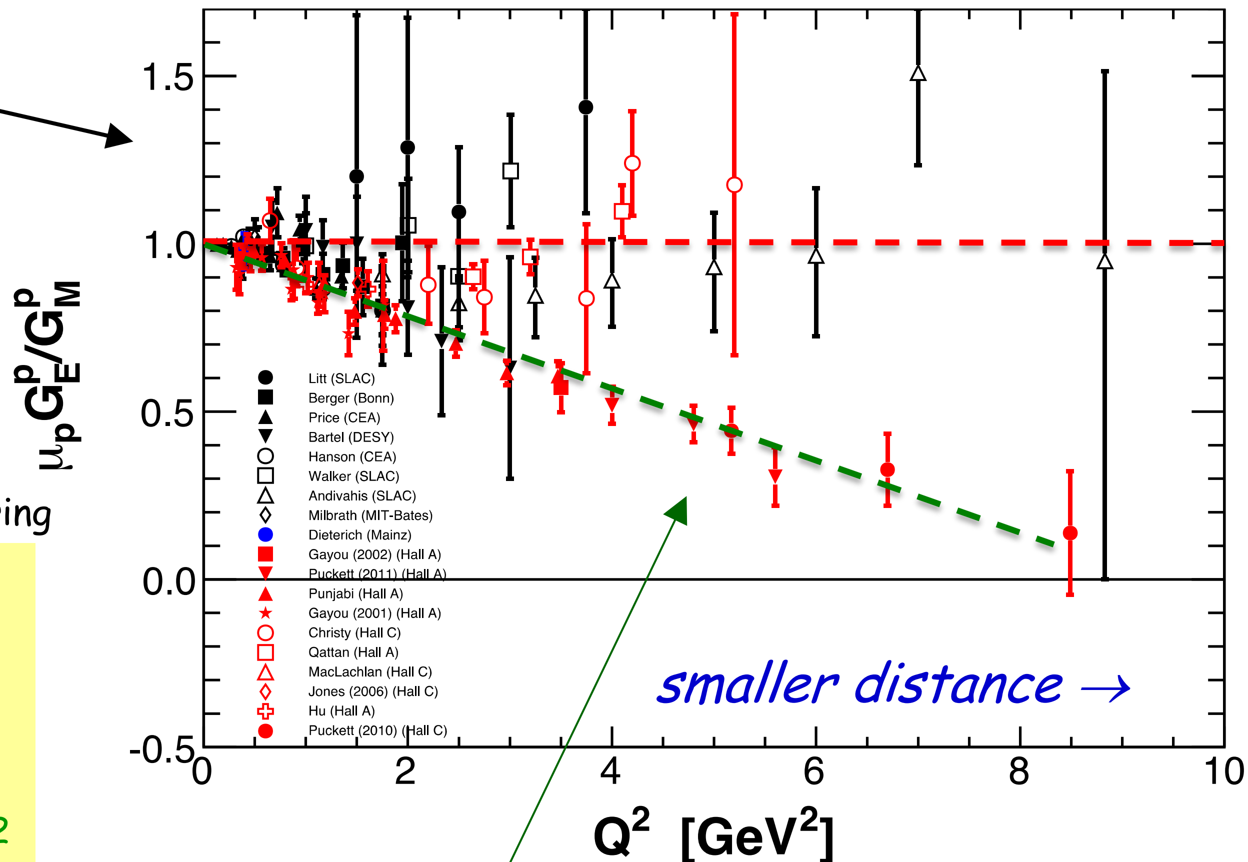
Focal Plane Polarimeter



Proton Charge and Magnetization

2-γ exchange important





Elastic electron-proton scattering

1) $e + p \to e' + p$
G_E^p/G_M^p constant

2) $\vec{e} + p \to e' + \vec{p}$
G_E^p/G_M^p drops with Q^2

Charge & magnetization distributions in the proton **<u>are different</u>**

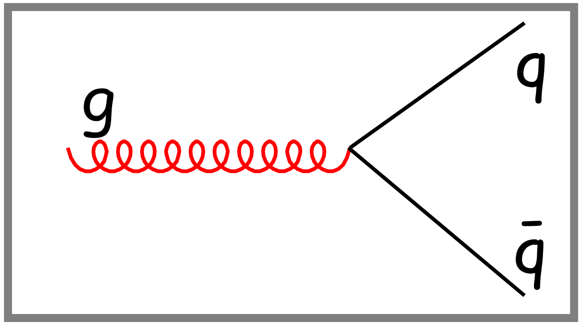
JLab Finding

charge depletion in interior of proton

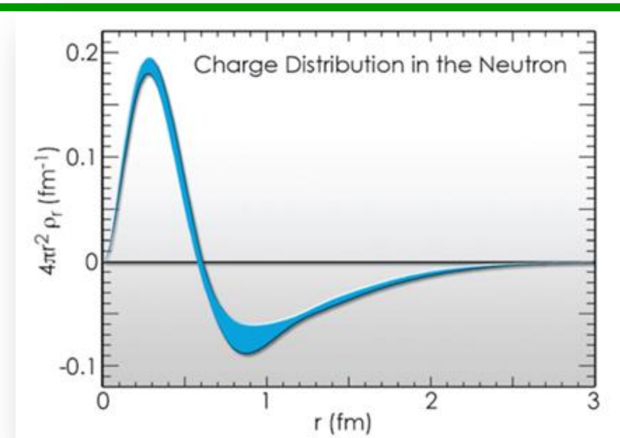
Orbital motion of quarks play a key role
(Belitsky, Ji + Yuan PRL 91 (2003) 092003)

A Sea Quark PDFs Surprise ~ 1995

High energy lore: gluon splits in quark and antiquark pair & $m_u \sim m_d$: $\bar{d} = \bar{u}$

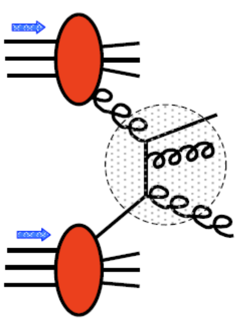


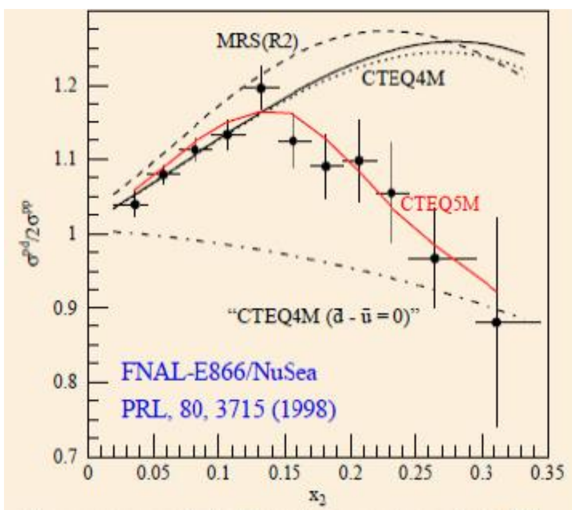
Low energy: Neutron has no charge, but does have a charge distribution: $n = p + p^-$, $n = ddu, duud\bar{u}$



FNAL Drell-Yan

$\sigma_{pd}/2\sigma_{pp}$



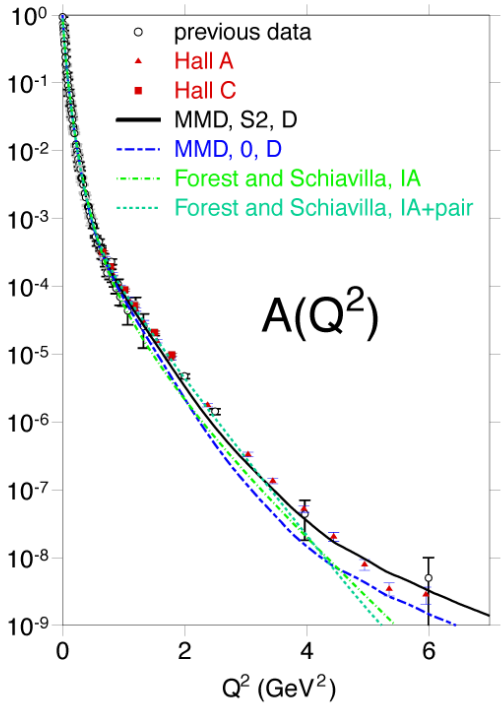


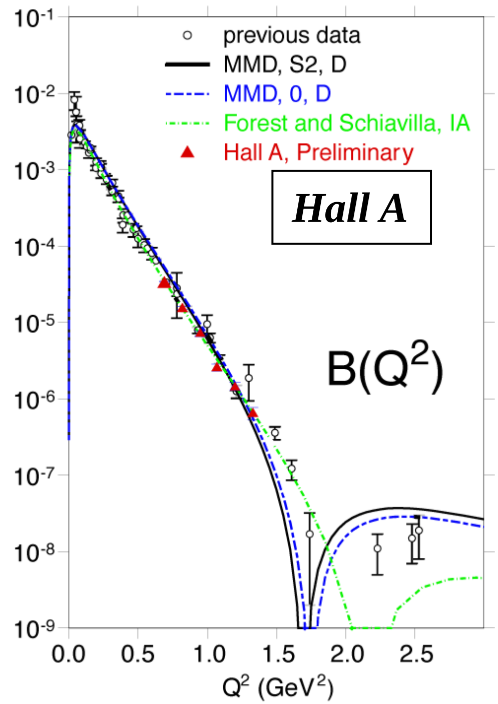
Theory curves reflect different assumptions about $\bar{d}/\bar{u}$

→ $\bar{d}(x) \neq \bar{u}(x)$

Even at high energies …
The low-energy signatures persist

JLab Data Reveal Deuteron's Size and Shape





For elastic e-d scattering:

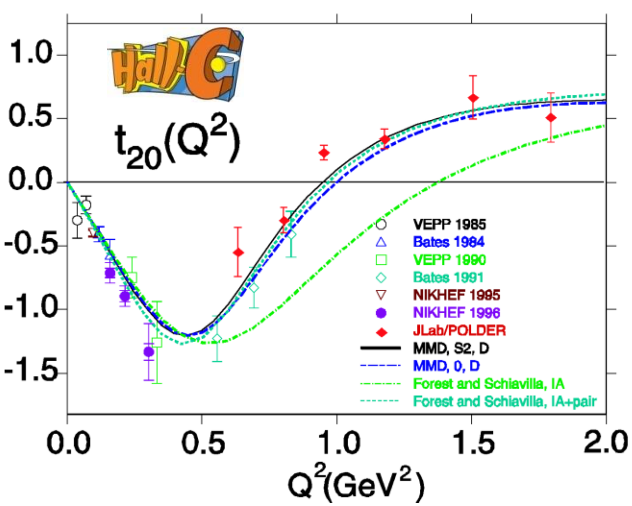
$$\boxed{\frac{d\sigma}{d\Omega} = \sigma_M \left[A + B \tan^2 \frac{\theta}{2}\right]}$$

$$A(Q^2) = G_C^2 + \tfrac{8}{9}\tau^2 G_Q^2 + \tfrac{2}{3}\tau G_M^2$$

$$B(Q^2) = \tfrac{4}{3}\tau(1+\tau)G_M^2$$

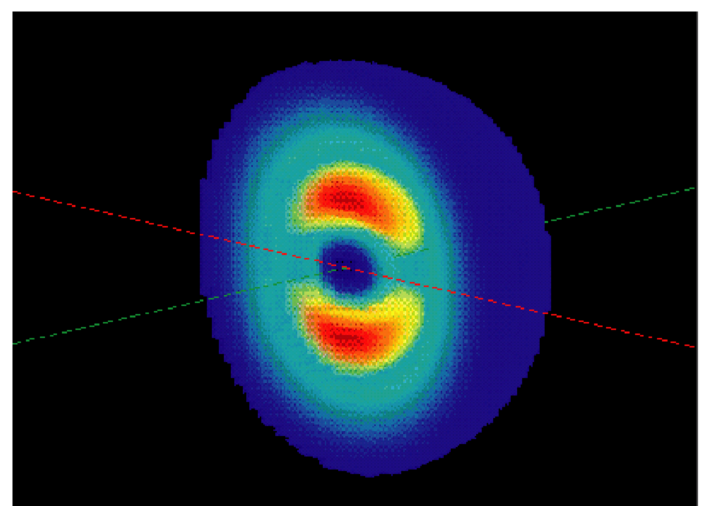
- 3rd observable needed to separate G_C and G_Q

$\rightarrow$ *tensor polarization t_{20}*



Combined Data -> Deuteron's Intrinsic Shape

The nucleon-based description works down to < 0.5 fm



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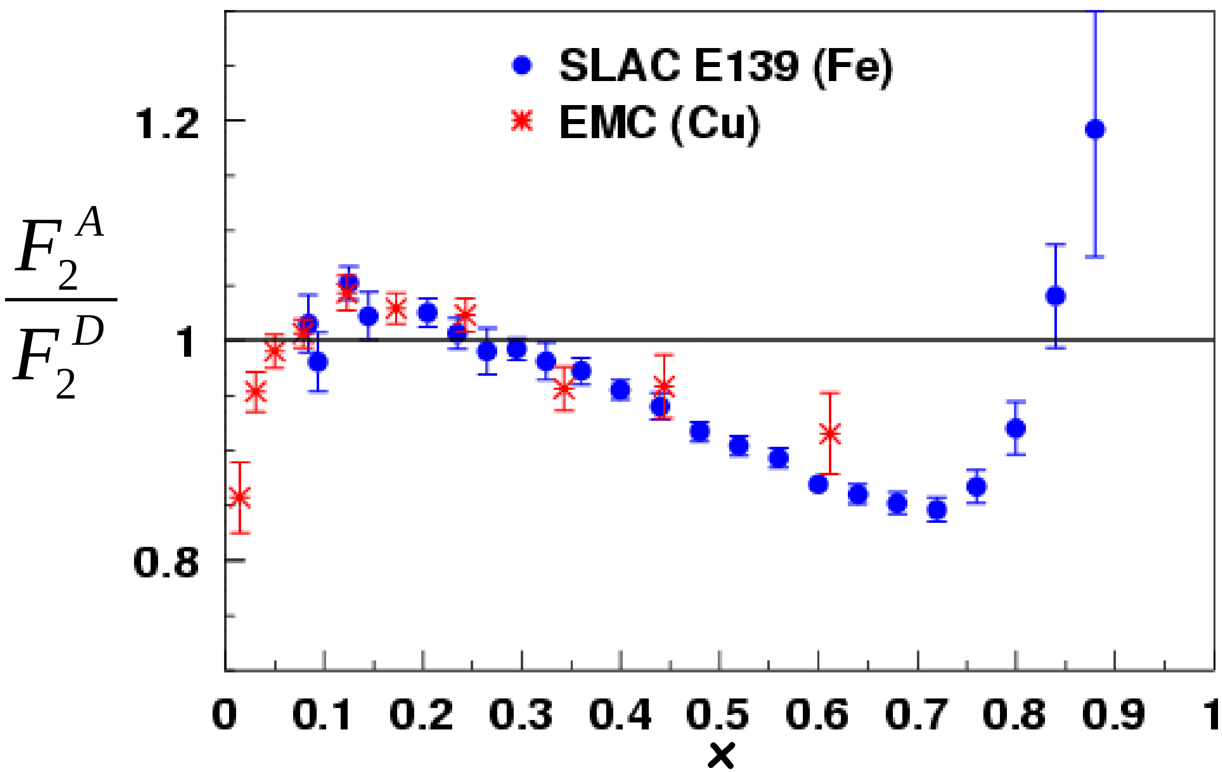
  The Onset of the Parton Model
  Use the Nuclear Arena to Study QCD

Quarks in Nuclei - History: the EMC Effect

- Observation that structure functions are altered in nuclei stunned much of the HEP community 3 decades ago
- ~1000 papers on the topic; the best models explain the curve by change of nucleon structure, BUT more data are needed to *uniquely* identify the origin

What is it that alters the quark momentum in the nucleus?



J. Ashman *et al.*, Z. Phys. **C57**, 211 (1993)

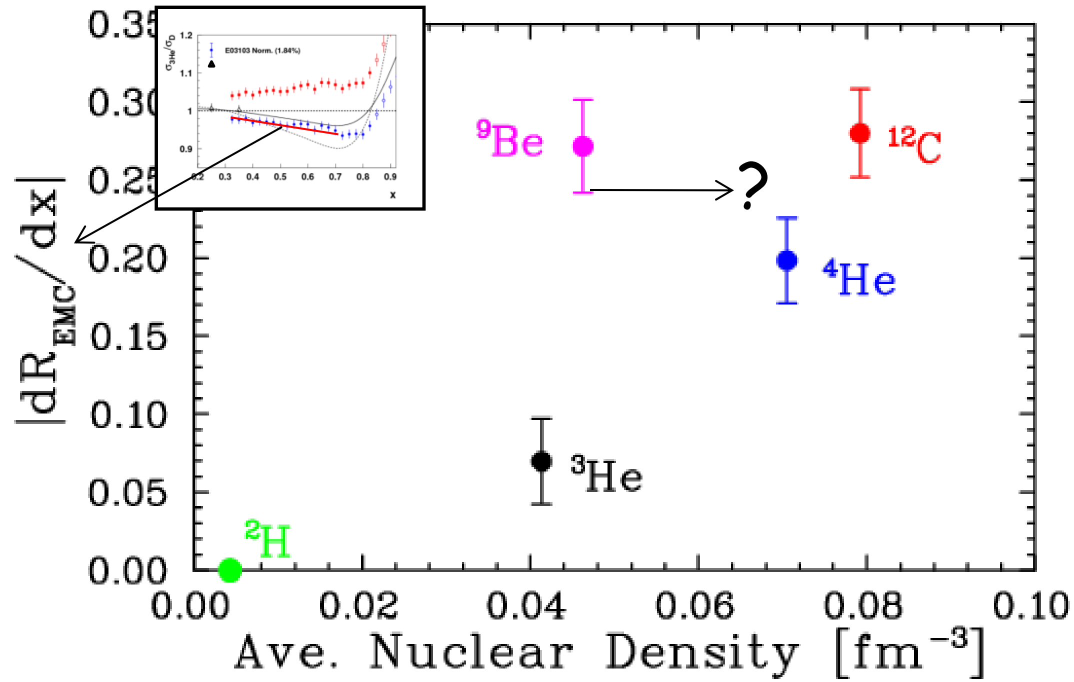
J. Gomez *et al.*, Phys. Rev. **D49**, 4348 (1994)

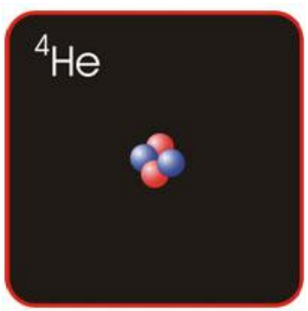
EMC Effect in very light nuclei

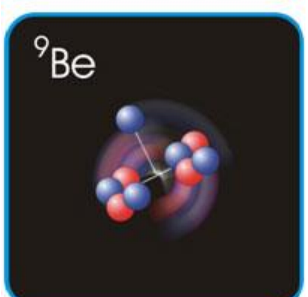
EMC effect scales with average nuclear density if we ignore Be

Be = 2 α clusters (^{4}He nuclei) + "extra" neutron

Suggests EMC effect depends on *local* nuclear environment







dR/dx = slope of line fit to *A/D* ratio over region *x=0.3* to *0.7*

Nuclear density extracted from *ab initio* GFMC calculation – scaled by *(A-1)/A* to remove contribution to density from "struck" nucleon

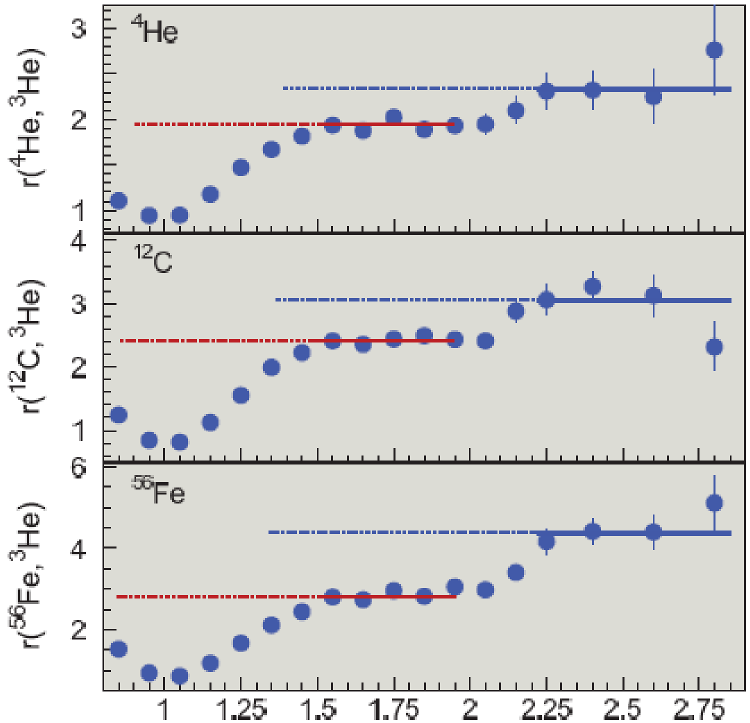
C. Seely, A. Daniel, et al, PRL 103, 202301 (2009)

CLAS

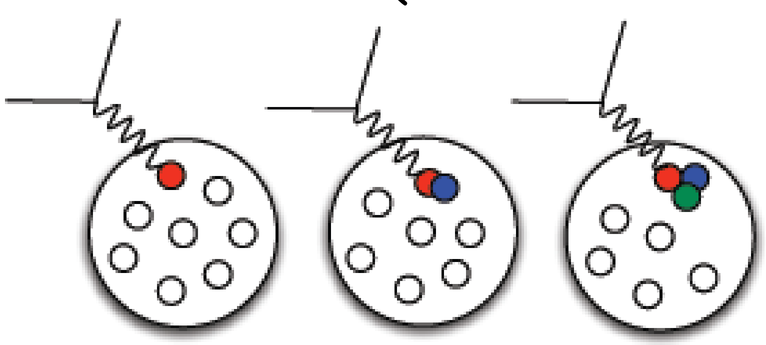
Short Range Correlations in Nuclei

Hall A

$A(e,e')X$, $A = {}^3He, {}^4He, {}^{12}C, {}^{56}Fe$



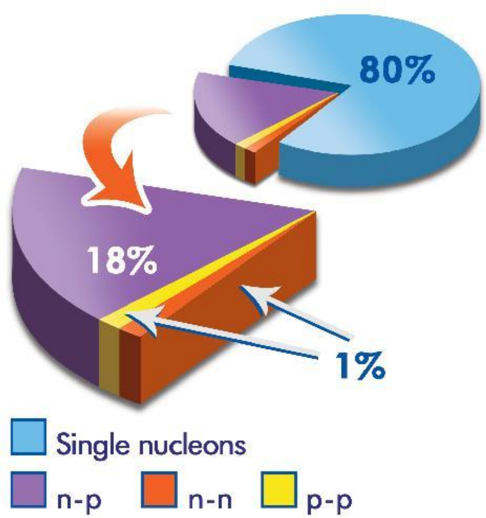
$Q^2/2M\nu$ →



Measured Composition (%)

	1N state	2N SRC	3N SRC
^{2}H	96 ± 0.7	4.0 ± 0.7	---
^{3}He	92 ± 1.6	8.0 ± 1.6	0.18 ± 0.06
^{4}He	86 ± 3.3	15.4 ± 3.3	0.42 ± 0.14
^{12}C	80 ± 4.1	19.3 ± 4.1	0.55 ± 0.18
^{56}Fe	76 ± 4.7	23.0 ± 4.7	0.79 ± 0.25

$A(e,e'pN)X$, $A = {}^{12}C$



Proton-neutron rate is ~20 x proton-proton rate →
two nucleons close together are almost always a p-n pair!
Expected to be due to (**short-range) tensor correlations**.

Momentum Sharing in Imbalanced Fermi Systems

O. Hen *et al.*, Science **346** (2014) 614, *doi:10.1126/science.1256785*

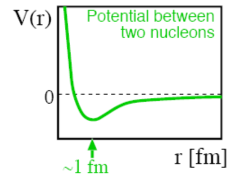
The Jefferson Lab CLAS Collaboration

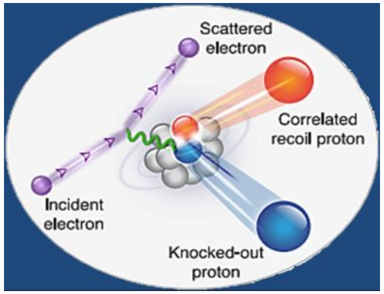
Selected for Science Express (16 October 2014)

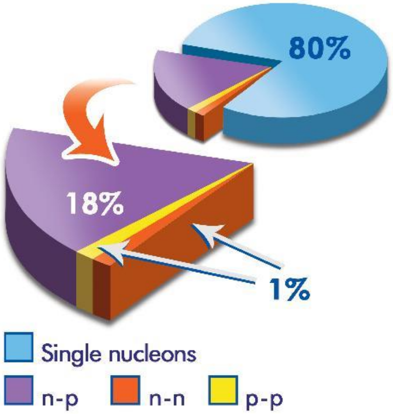
- For heavy nuclei, N (#neutrons) > Z (#protons)

  "Majority" "Minority"

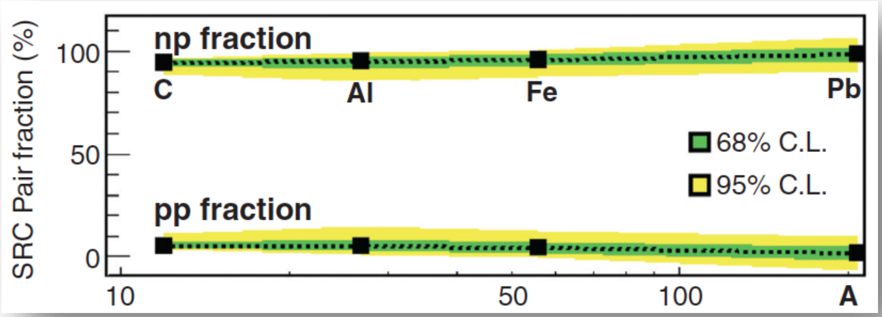
- For non-interacting Fermi gases, neutrons would dominate at all momenta, even above the Fermi momentum k_F
- In reality, short range nucleon-nucleon correlations dominate the population at $k>k_F$
- Isospin dependence of the nucleon-nucleon interaction implies equal numbers of protons and neutrons at $k>k_F$

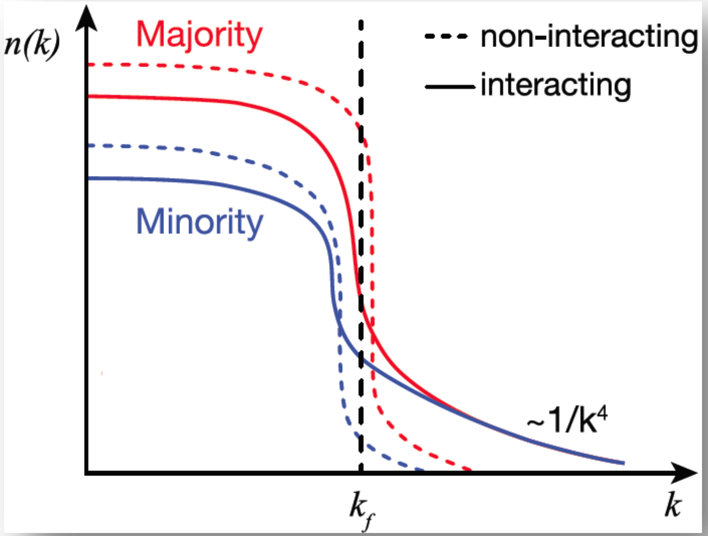






Experimental Result:





This has implications for the equations of state of neutron stars and atomic interactions in ultra-cold atomic gases.

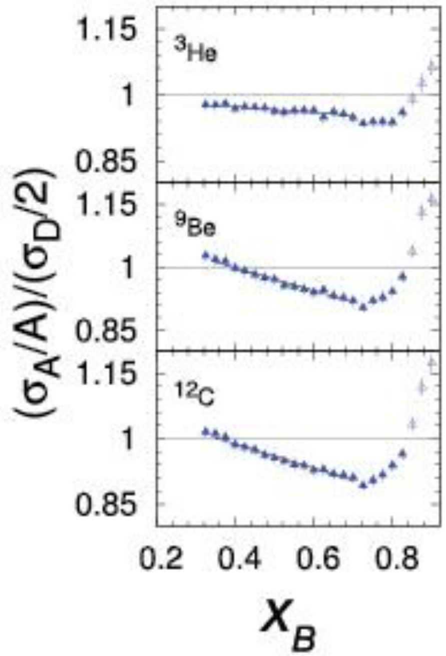
Short-Range Correlations (SRC) and European Muon Collaboration (EMC) Effect Are Correlated

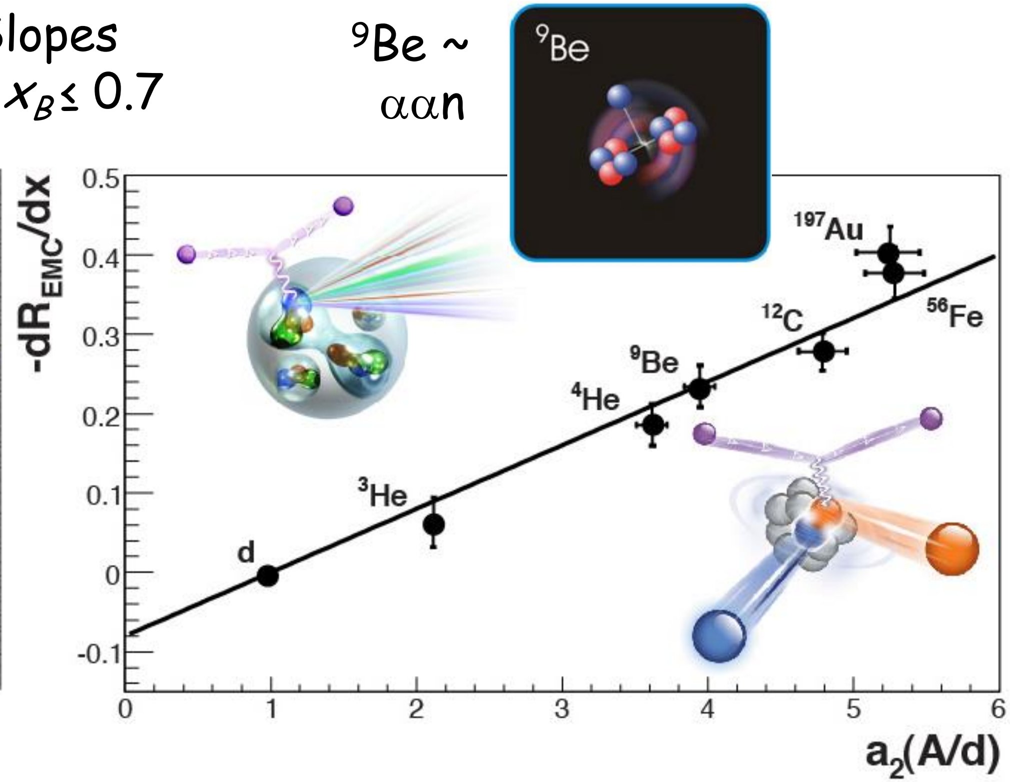
JLab Finding

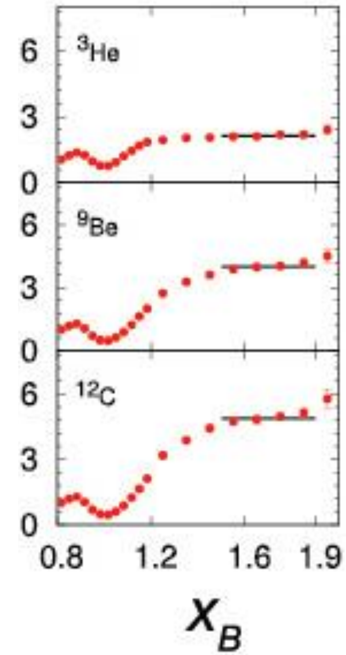
EMC Slopes $0.35 \leq x_B \leq 0.7$

^{9}Be ~ $\alpha\alpha n$

Fomin *et al.*, PRL 108, 092502 (2012)





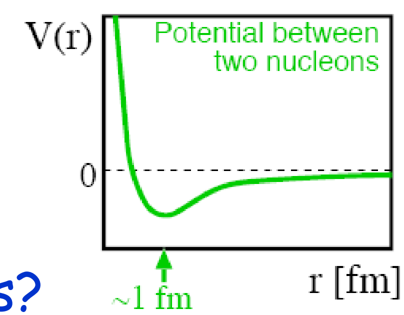


SRC Scaling factors $x_B \geq 1.4$

SRC: nucleons see strong repulsive core at short distances

EMC effect: quark momentum in nucleus is altered

Weinstein *et al.*, PRL 106, 052301 (2011)



How about gluon dynamics and gluon-gluon correlations?

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The Spin of the Proton

Otto Stern

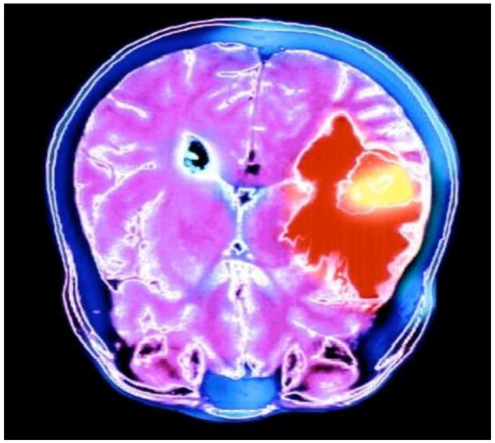
Nobel Prize, 1943: "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"

μ_p = 2.5 nuclear magnetons, ± 10% (1933)

Proton spins are used to image the structure and function of the human body using the technique of *magnetic resonance imaging*.

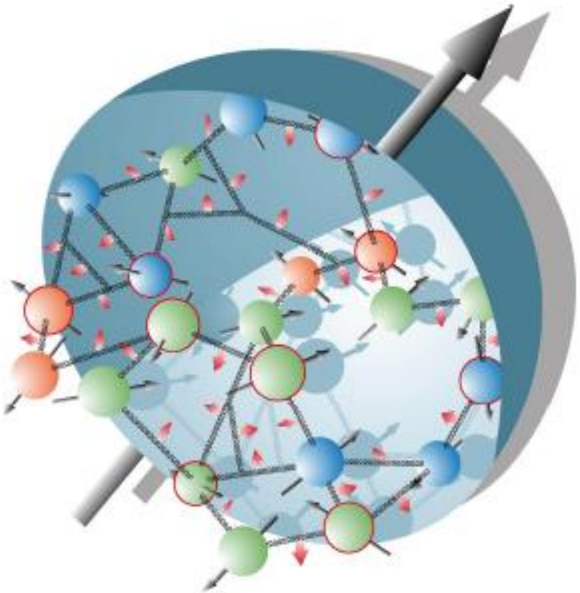
Paul C. Lauterbur

Sir Peter Mansfield



Nobel Prize, 2003: "for their discoveries concerning magnetic resonance imaging"

The Incomplete Nucleon: Spin Puzzle



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

This implies that the sum of angular momentum of quarks and gluons together must amount to 1/2. Can be due to:

Quark spin	Quark orbital momentum
Gluon spin	Gluon orbital momentum

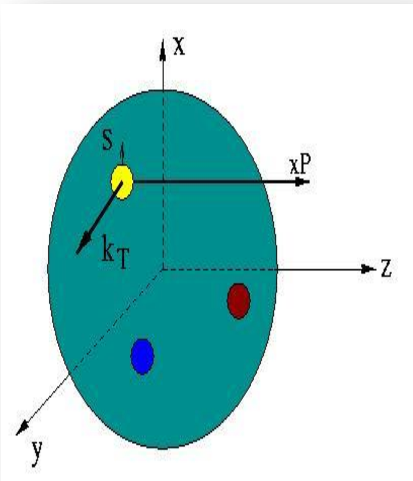
$\boxed{\text{Classical: } \sim \mathbf{r} \times \mathbf{p}}$

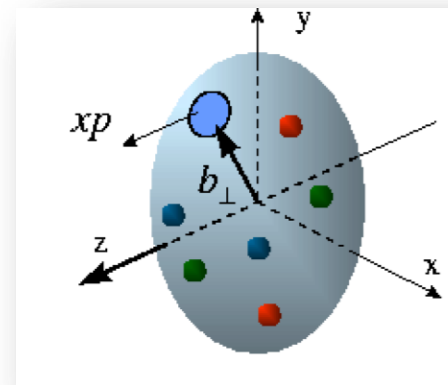
Needs a cross-product or something three-dimensional!

Unified View of Nucleon Structure

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

5D Dist.





d^2r_T

d^2k_T

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

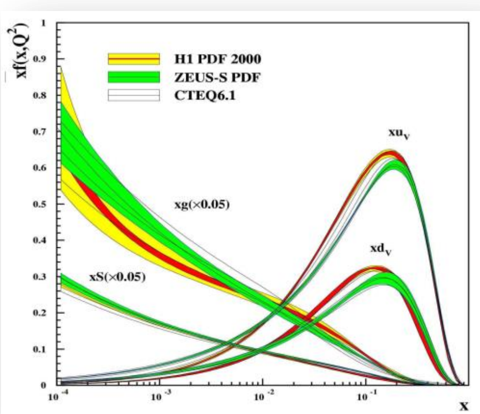
GPDs/IPDs

3D imaging

d^2k_T

d^2r_T

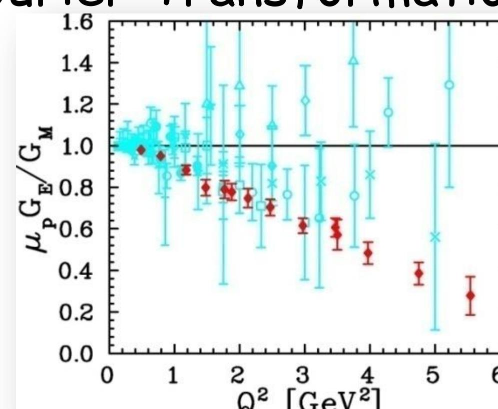
dx &
Fourier Transformation



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

1D

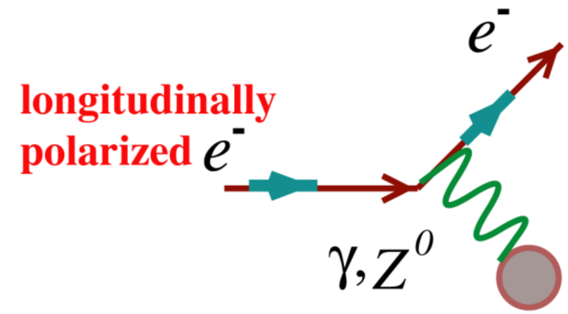
Form Factors
$G_E(Q^2)$,
$G_M(Q^2)$



Parity-Violating Asymmetries

Weak Neutral Current (WNC) Interactions at $Q^2 \ll M_Z^2$

Longitudinally Polarized Electron
Scattering off Unpolarized Fixed Targets



$$\boxed{\sigma \;\; \alpha \, | A_\gamma + A_{weak} |^2}$$

$$A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha} \left(g_A^e g_V^T + \beta\, g_V^e g_A^T\right)$$

The couplings *g* depend on both electroweak physics and the weak vector and axial-vector hadronic current, and are functions of $\sin^2\Theta_W$

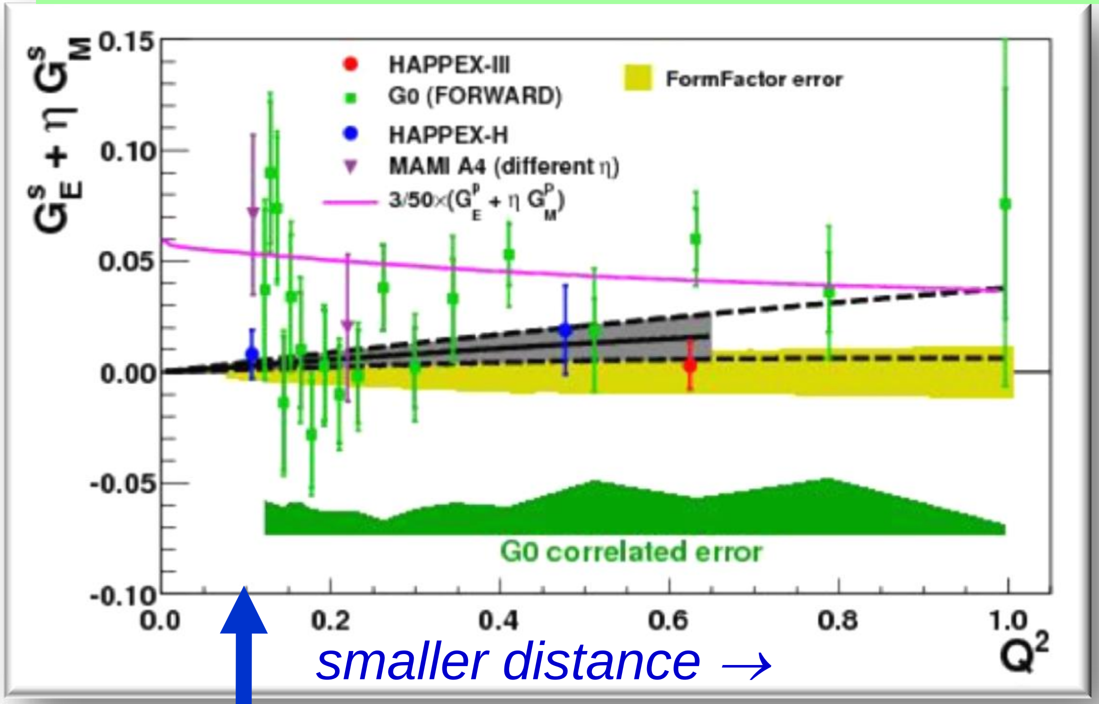
Mid 70s	goal was to show $\sin^2\Theta_W$ was the same as in ν scattering
1990-2010	target couplings probe novel aspects of hadron structure
Ongoing	precision measurements with carefully chosen kinematics to probe new physics at multi-TeV high energy scales

The spatial distribution of quarks and the proton's magnetism

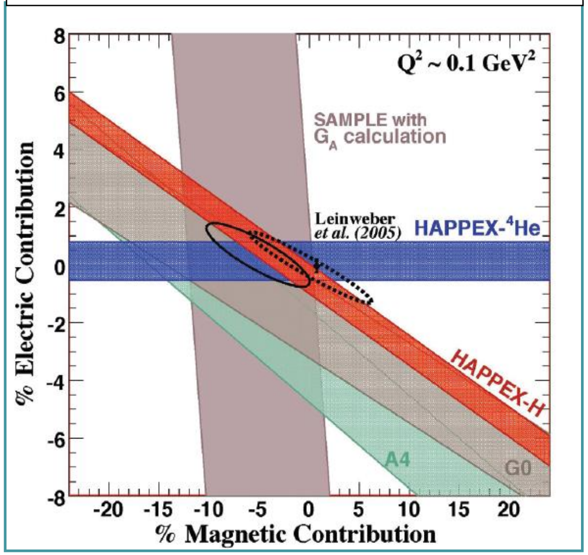
Hall A

$$G_M^p(Q^2) = \tfrac{2}{3}G_M^u(Q^2) - \tfrac{1}{3}G_M^d(Q^2) - \tfrac{1}{3}G_M^s(Q^2)$$

strange quarks **do not play a substantial role** in the long-range electromagnetic structure of nucleons



1st Separation using G0, HAPPEx-II & HAPPEx-He, and A4 & SAMPLE data

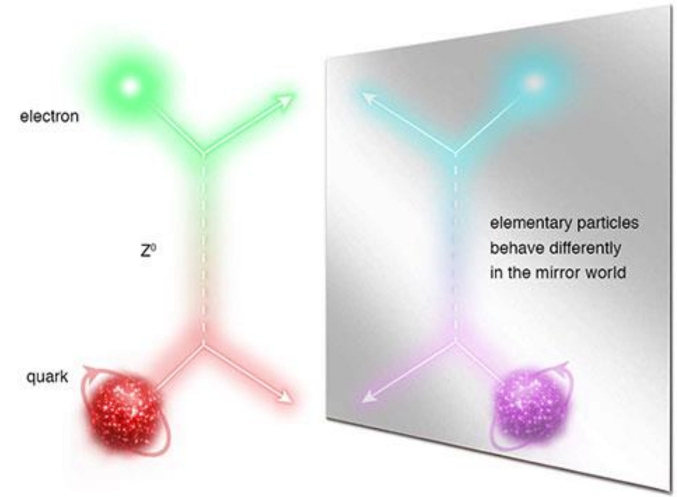


Measurement of the Parity-Violating Asymmetry in eD Deep Inelastic Scattering

Nature 506, 67-70 (06 February 2014)

The Jefferson Lab PVDIS Collaboration

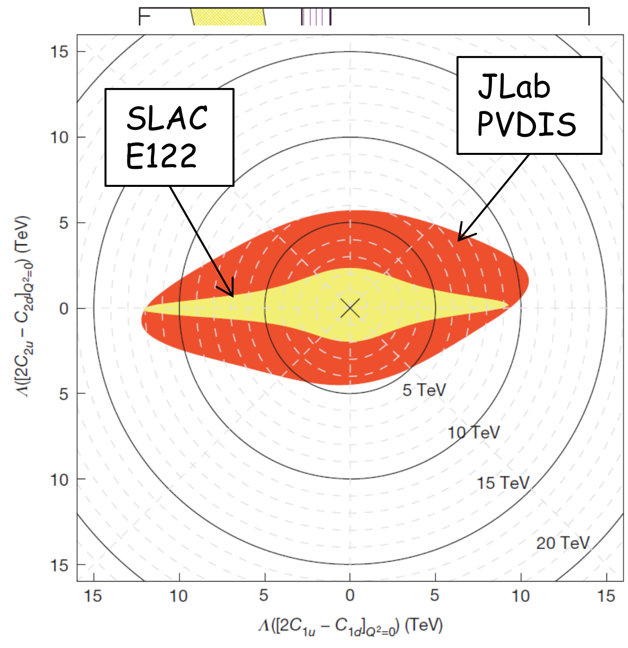
See also News & Views, *Nature* 506, 43-44 (06 February 2014)



Longitudinally Polarized Electron Scattering from Unpolarized Deuterium

$$A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}(\alpha\,[2C_{1u} - C_{1d}] + \beta\,[2C_{2u} - C_{2d}])$$

- The present result leads to a determination of the effective electron-quark weak coupling combination $2C_{2u} - C_{2d}$ five times more precise than previously determined.
- First experiment to isolate, when combined with previous experiments like Qweak, a non-zero C_{2q} (95% conf. level).
- This C_{2q} coupling describes how much of the mirror-symmetry breaking in the electron-quark interaction originates from the quarks' spin preference in the weak interaction. **The result provides a mass exclusion limit on the electron and quark compositeness and contact interactions of ~5 TeV.**



15+ Years of Physics Experiments at JLab

- Experiments have successfully addressed original Mission Statement:

  "The study of the largely unexplored transition between the nucleon-meson and the quark-gluon descriptions of nuclear matter"

  Highlight 1: The Role of Quarks in Nuclear Physics

  Probing the Limits of the Traditional Model of Nuclei

- Emphasis has shifted to third sub-area of intended CEBAF research:

  "What are the properties of the force which binds quarks into nucleons and nuclei at distances where this force is strong and the quark confinement mechanism is important?"

- *Highlight 2: Charge and Magnetization in Nucleons and Pions*

Charge distribution in proton differs from magnetization distribution
Elusive charge distribution of neutron well mapped out to high resolution
Strange quarks play small role in mass of proton.

- *Highlight 3: The Onset of the Parton Model at Low Energies*

High quality hadronic structure function data at JLab at 6 GeV have been accumulated spanning the nucleon resonance and low-W^2 deep inelastic region. The data indicate a surprisingly smooth parton-hadron transition at relatively low Q^2, allowing, for $x > 0.1$, an unprecedented access to partons with the 12 GeV Upgrade, allowing to finally go beyond 1-dimensional snapshots.

Intermezzo

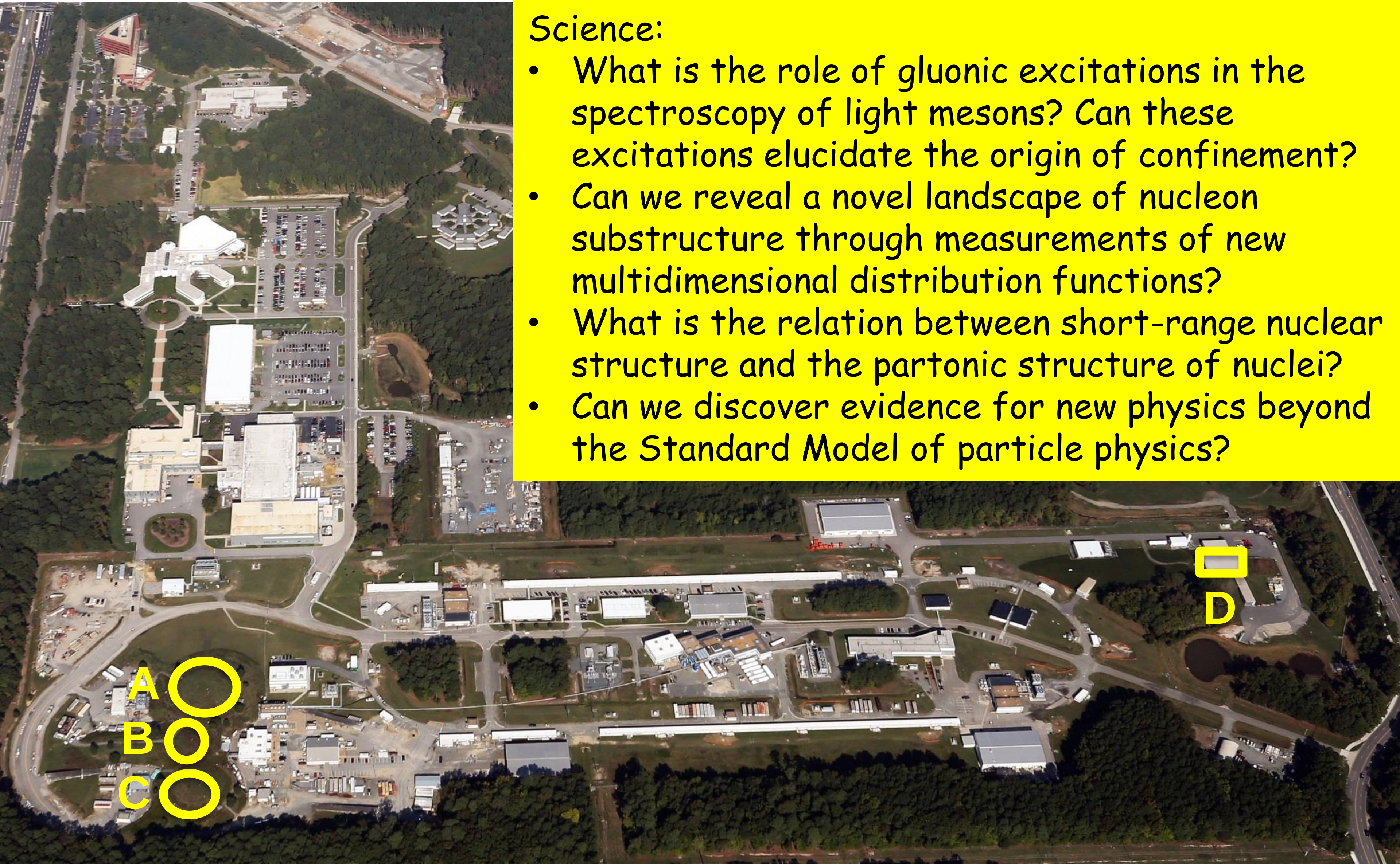
- General Introduction – some basic facts of Nuclear Science
- Introduction to QCD and Quarks and Gluons
- Some findings of JLab-6 GeV Science Program
- Modern Issues in QCD (not complete…)

  - How do the sea quarks in the proton contribute to its structure?
  - The gluons also must play an important role in structure, but exactly what?
  - Why do we not see indications of the role of gluons in the hadron spectrum?
  - What tames the growth of gluons? It can not go on forever & must be tamed!
  - What is the 3D structure of the proton? And the orbital angular momentum?
  - Is the dynamics of quarks correlated with two nucleons close together?
  - What is the quark-gluon origin of proton spin? Of nuclear binding?
  - How did the protons and neutrons emerge from quarks and gluons in the early universe?

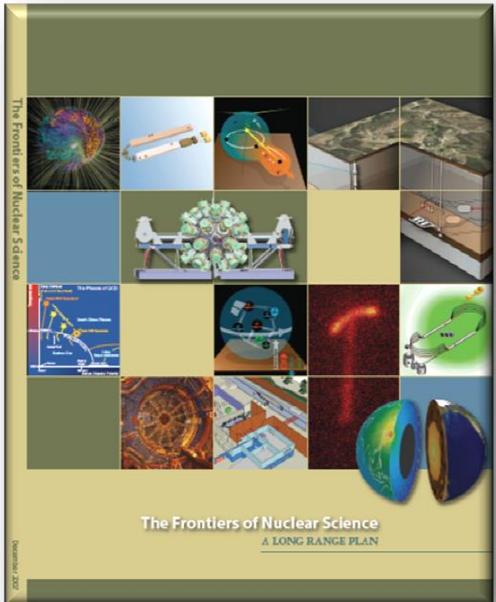
JLab – a 12 GeV CW Electron Accelerator

Science:

- What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of confinement?
- Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?
- What is the relation between short-range nuclear structure and the partonic structure of nuclei?
- Can we discover evidence for new physics beyond the Standard Model of particle physics?

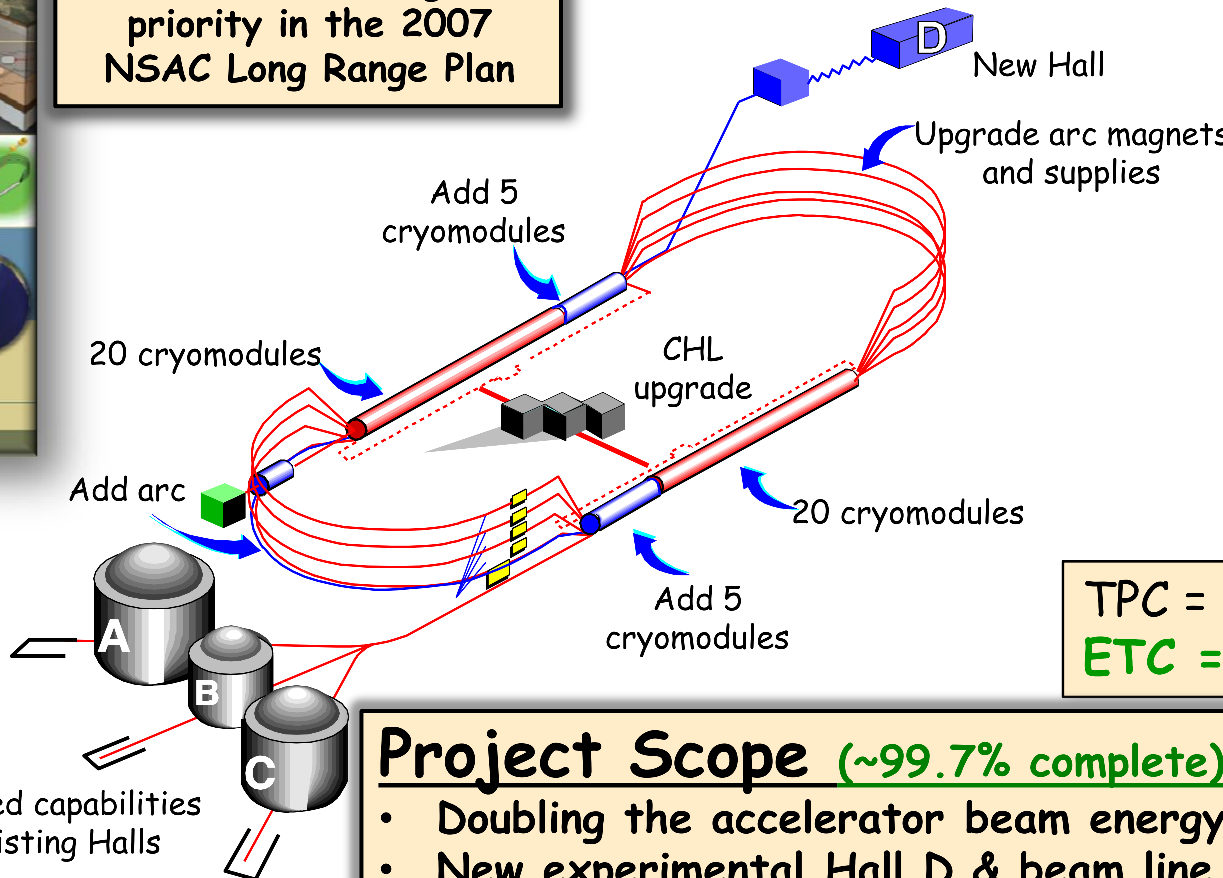


12 GeV Upgrade Project



Completion of the 12 GeV CEBAF Upgrade was ranked the highest priority in the 2007 NSAC Long Range Plan

Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use.



TPC = $338M
ETC = <$2M

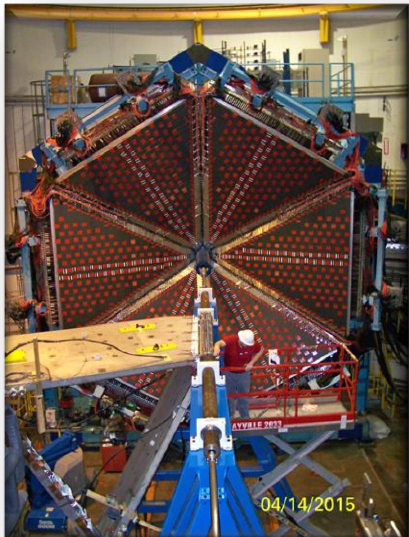
Maintain capability to deliver lower pass beam energies: 2.2, 4.4, 6.6….

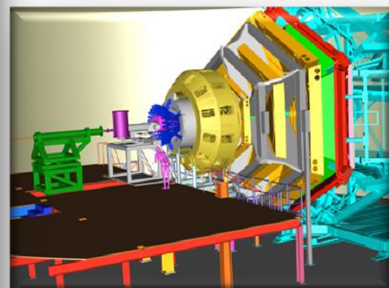
Project Scope (~99.7% complete):

- Doubling the accelerator beam energy - DONE
- New experimental Hall D & beam line - DONE
- Civil construction including utilities - DONE
- Upgrade to Experimental Hall C - DONE
- Upgrade to Experimental Hall B - 99%
  - Solenoid only scope remaining

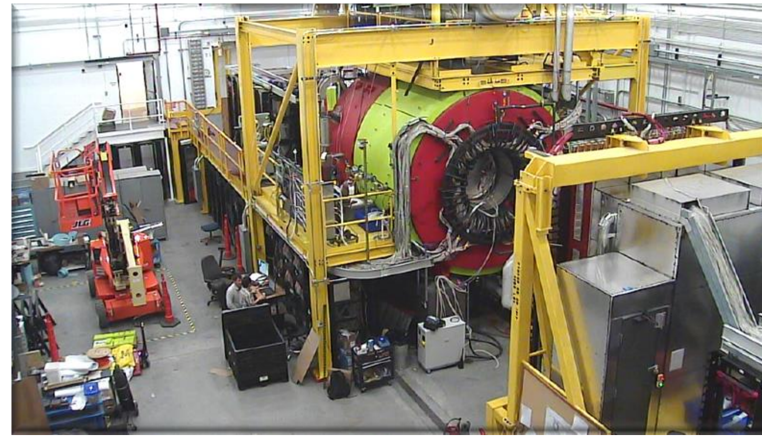
12 GeV Scientific Capabilities

Hall B – understanding nucleon structure via generalized parton distributions

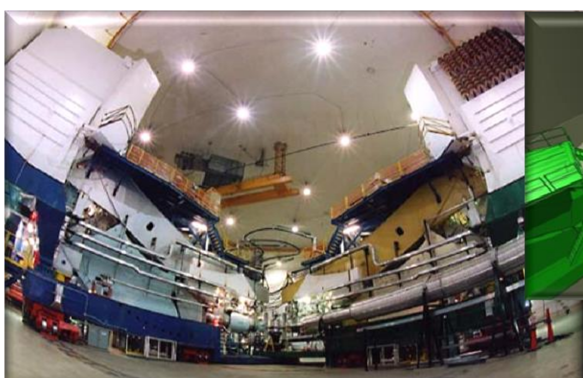


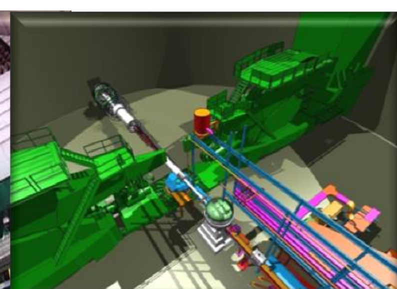


Hall D – exploring origin of confinement by studying exotic mesons

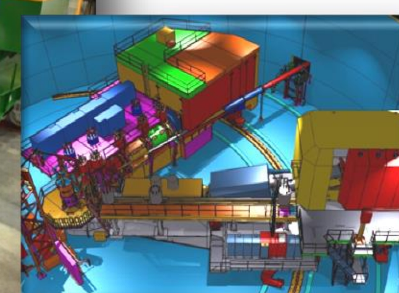


Hall A – form factors, future new experiments (e.g., SoLID and MOLLER)





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



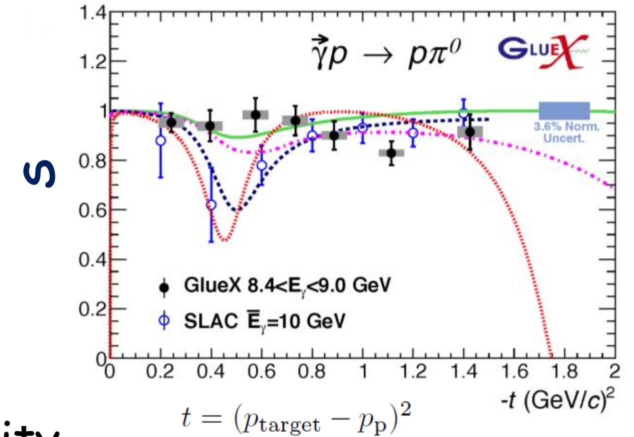
CEBAF Highlights 2016/2017

Summer 2016:
- Hall B - Proton Radius Experiment (PRad)
- First completed experiment in 12 GeV era!
- LERF: DarkLIGHT commissioning

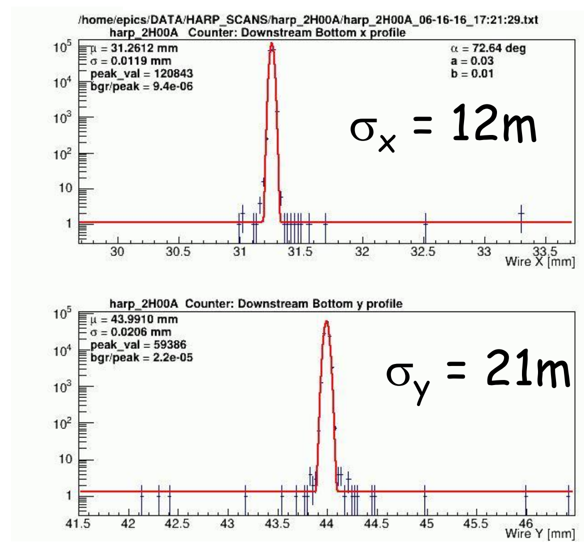
Fall 2016:
- *Re-plan due to box power supply issue*
- Hall D – short GlueX run verifying physics capability
- Hall A – completed GMp; Phase I DVCS (50%)

Spring 2017:
- Hall D – GlueX physics run (20/90 PAC days)
- Hall A – completed Ar spectral function
- Hall B – KPP run
- Hall C – KPP run
- *Early stop due to cryoplant hardware failure*

Early science - physics running accomplished!



Hall B – PRad beam scan



... and Hall C/Qweak has unblinded results – expect Fall Conference presentation

Gluonic Excitations and the mechanism for confinement

QCD predicts a rich spectrum of as yet to be discovered gluonic excitations - whose experimental verification is crucial for our understanding of QCD in the confinement regime.

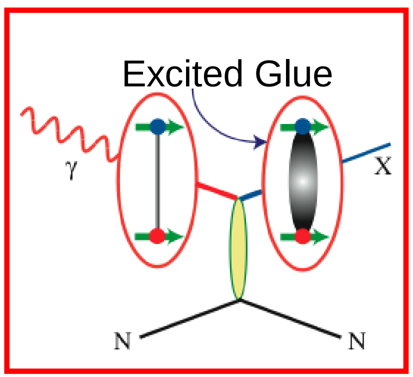
With the upgraded CEBAF, a linearly polarized photon beam, and the **GlueX detector**, Jefferson Lab will be <u>uniquely poised</u> to:
- discover these states
- map out their spectrum
- measure their properties

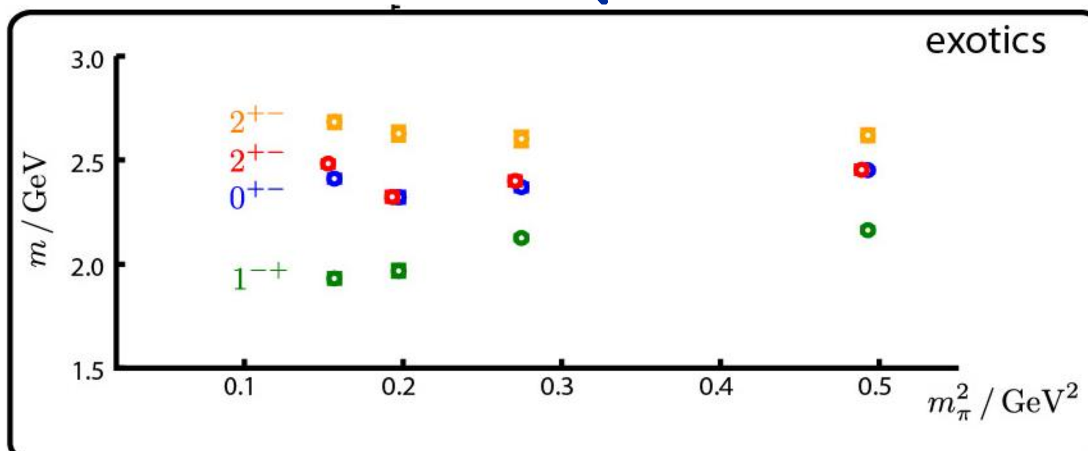
12 GeV electrons

States with Exotic Quantum Numbers

Dudek et al.

γ beam





DIRC-based Cherenkov will allow access to decay channels with charged kaons

Measuring Elastic Form Factors

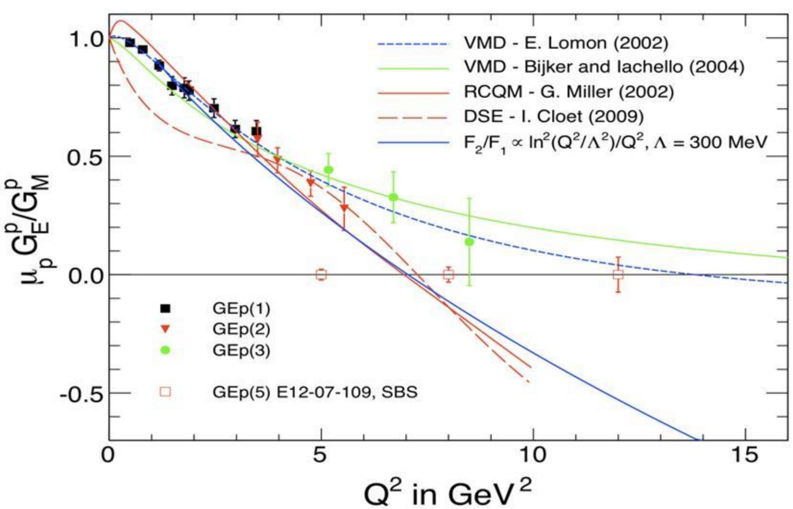
PRad: Proton Radius Puzzle

- Elastic e-p scattering
- Use H gas target & an electromagnetic calorimeter

Pushes to low Q^2 (~0) to constrain the proton radius

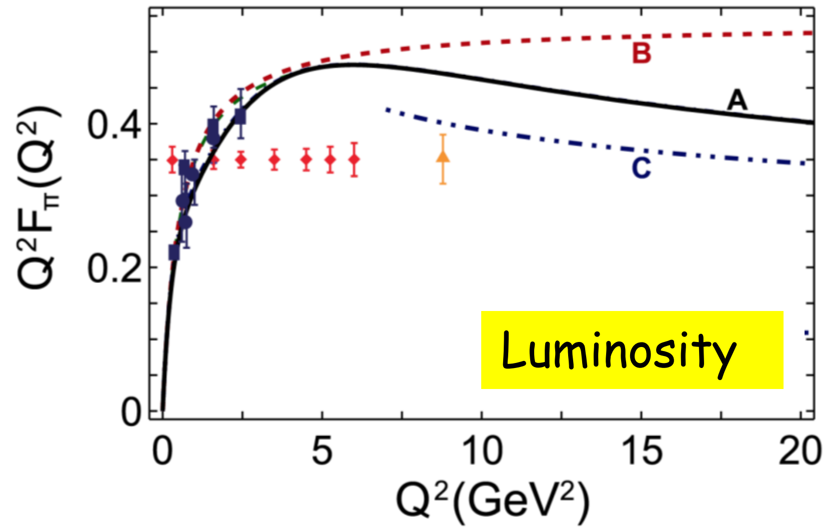
SBS: Nucleon Form Factors

- Use high luminosity + open geometry + GEM detector
- Pushes G_E^p/G_M^p, G_E^n, G_M^n to high Q^2 (>10 GeV^2)



HMS + SHMS: Charged Pion Form Factor

- Use precision spectrometers
- Precise extraction of F^p to Q^2 = 6 GeV^2
- recent knowledge → push to high Q^2 (~10 GeV^2)

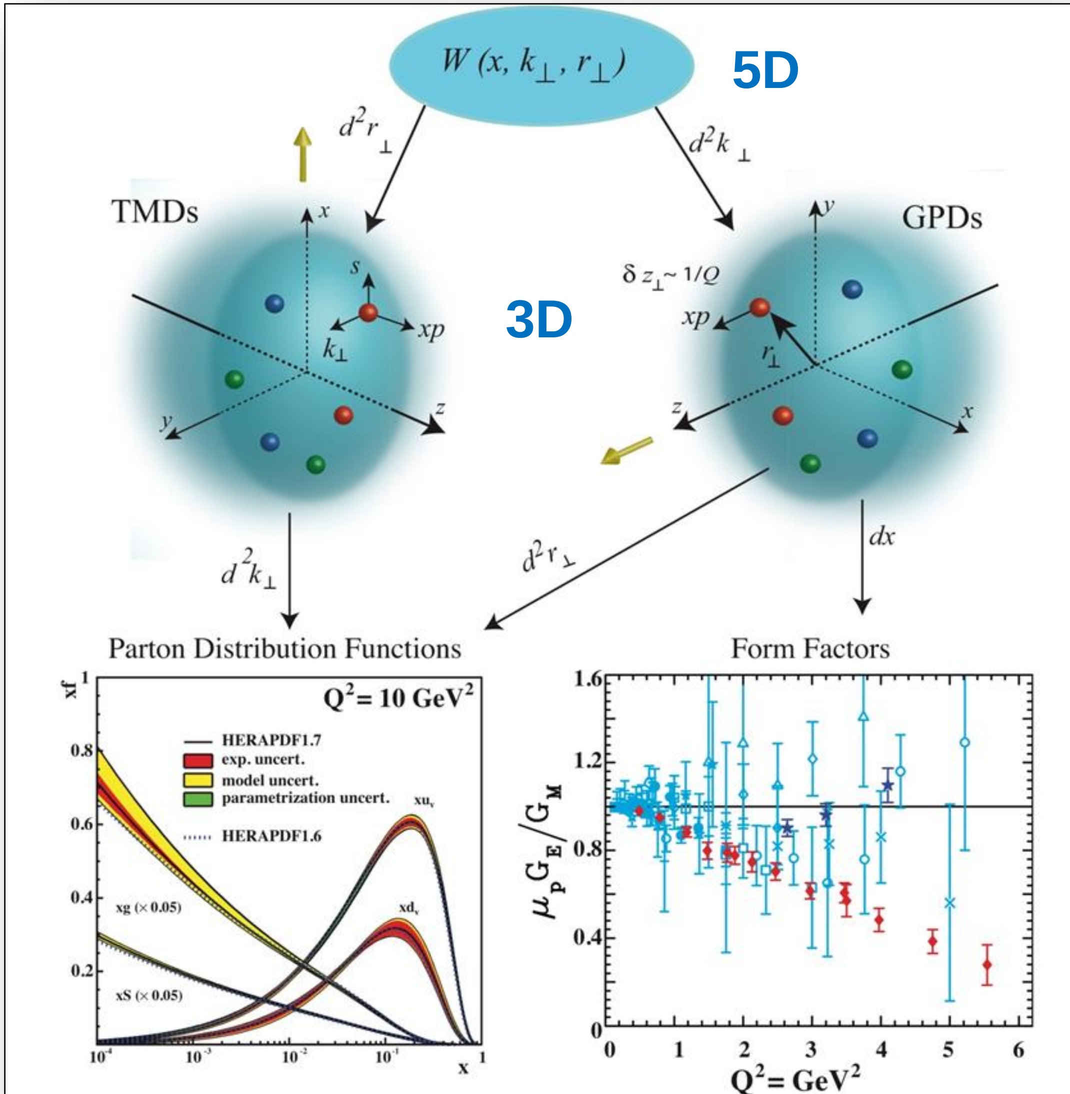


Where does the dynamics of the q-q interaction make a transition from the strong (confinement) to the perturbative (QED-like) QCD regime?

Allows for flavor separation of charge and magnetization to distance scales deep inside the nucleon

Luminosity, polarization

New Paradigm for Nucleon Structure



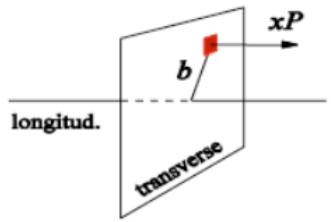
- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)
- GPDs
  - Spatial imaging (exclusive DIS)
- Requires
  - High luminosity
  - Polarized beams and targets

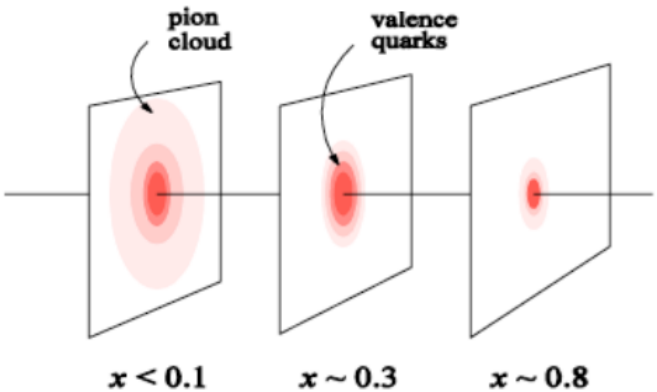
➡ **Major new capability with JLab12**

Hard Exclusive Processes → GPDs

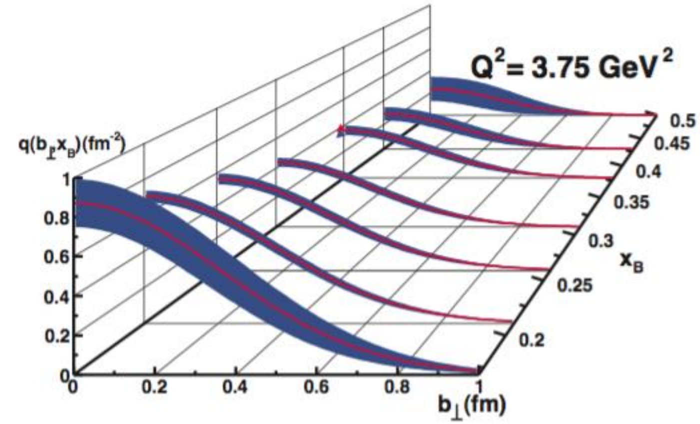
Goal 1: Transverse Imaging of Nucleon

Fourier transform of t-dependence



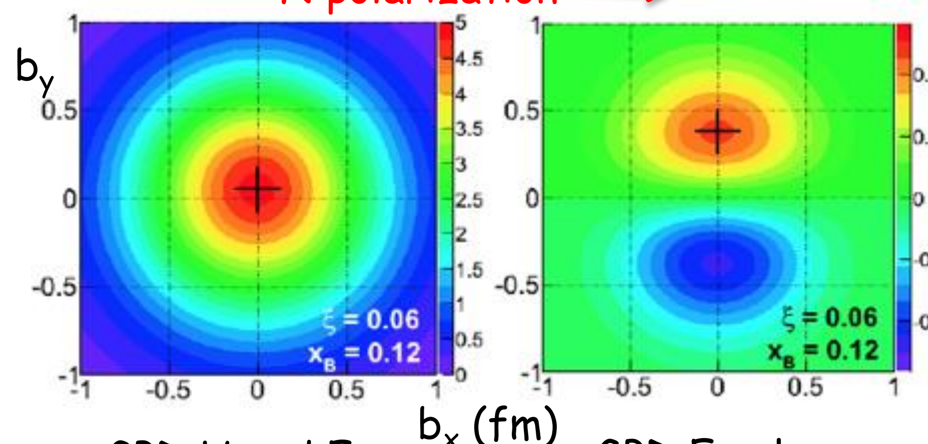


The proton's transverse profile as function of the impact parameter b



Distortions induced by spin direction

N polarization →



GPD H and E

GPD E only

Goal 2: Orbital Angular Momentum

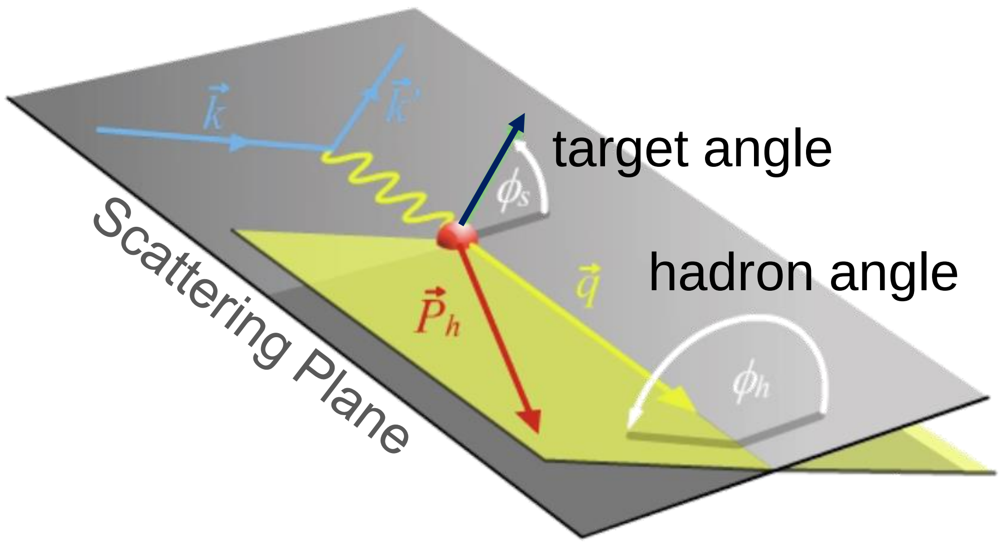
Ji's Sum Rule for $J^q = \frac{1}{2}\Delta\Sigma + L^q$

$$J^q = \frac{1}{2}\int_{-1}^{1} x\,dx\,[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)]$$

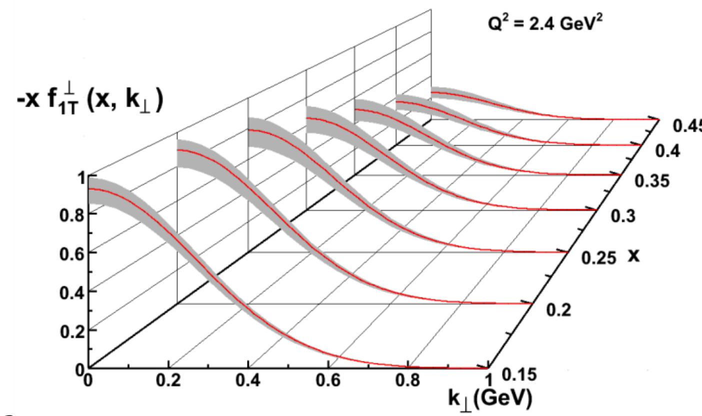
CLAS12 with help from Halls A & C

SIDIS Electroproduction of Pions

- Separate Sivers and Collins effects

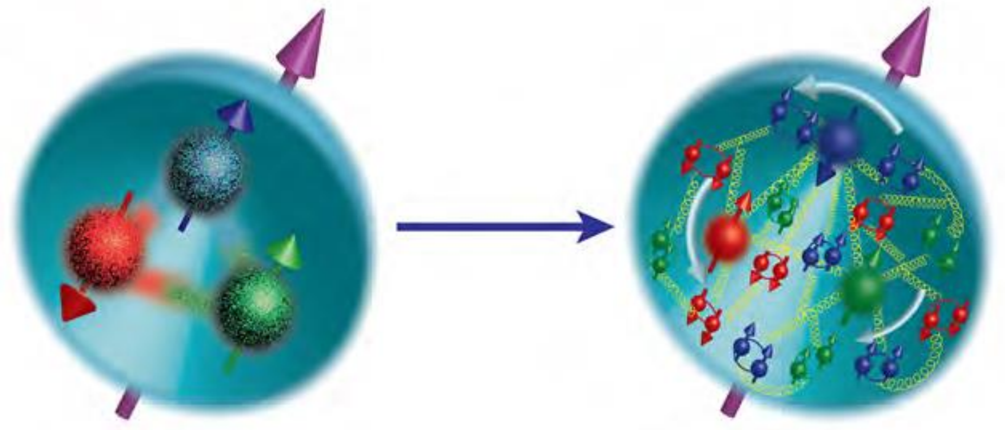


- Previous data from HERMES,COMPASS
- New landscape of TMD distributions
- Access to orbital angular momentum



- **Sivers** angle, effect in distribution function: $(\phi_h-\phi_s)$
- **Collins** angle, effect in fragmentation function: $(\phi_h+\phi_s)$
- **Kaons enabled by Hall B RICH (INFN/DOE) and Hall C Aerogel (NSF)**

The Incomplete Nucleon: Spin Puzzle



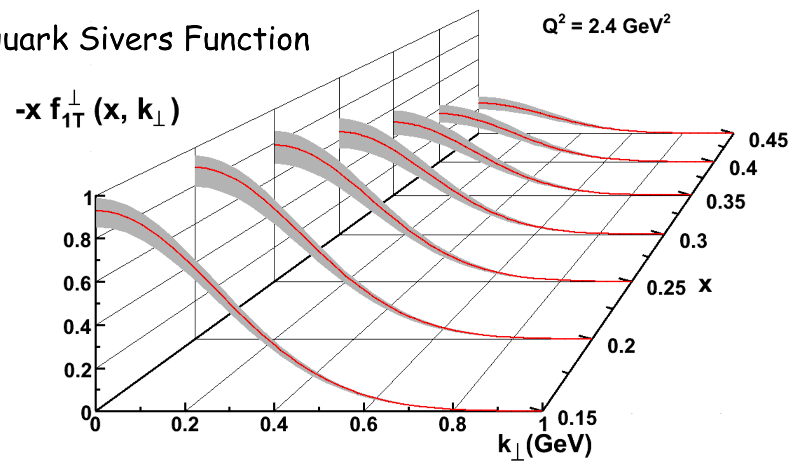
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

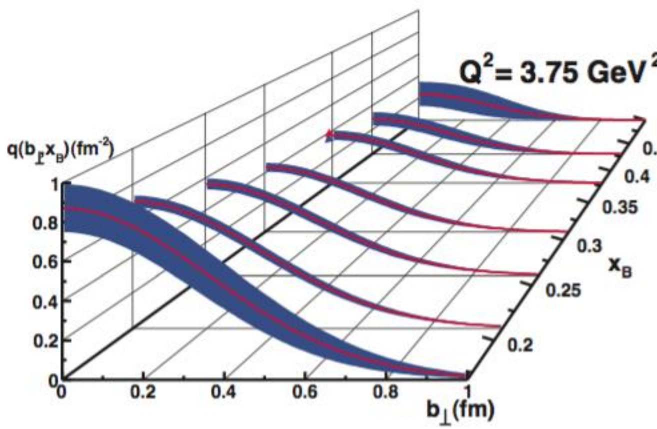
- $\Delta\Sigma \sim 0.25$ (world DIS)
- ΔG similar (?) (RHIC+DIS)
- L_q?

Longitudinal momentum fraction x and transverse momentum images

Longitudinal momentum fraction x and transverse spatial images

Up quark Sivers Function





TMDs

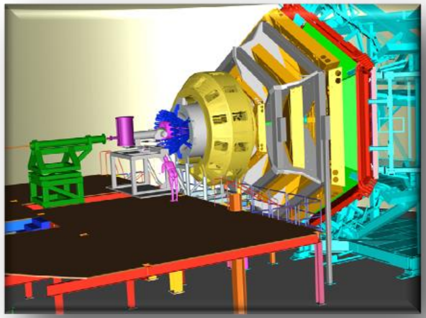
12 GeV projections: valence quarks well mapped

GPDs

Together stronger: SIDIS Studies with 12 GeV

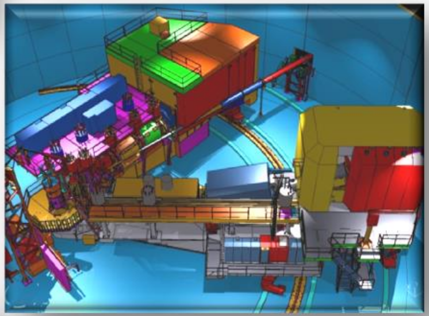
- **CLAS12 in Hall B**

  General survey, medium lumi



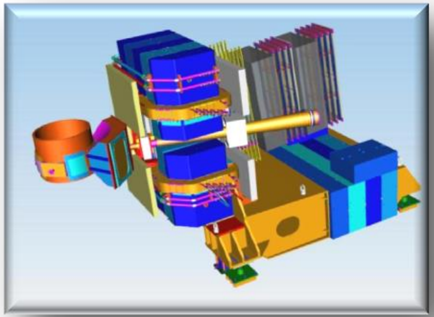
- **SHMS, HMS, NPS in Hall C**

  L-T studies, precise $\pi^+/\pi^-/\pi^0$ ratios



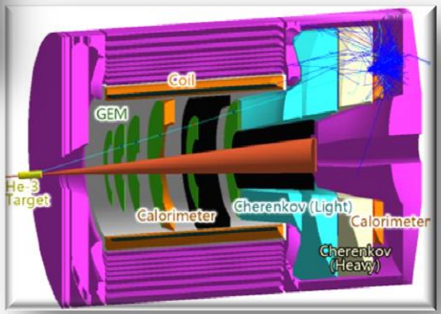
- **SBS in Hall A**

  High x, High Q^2, 2-3D



- **SOLID in Hall A**

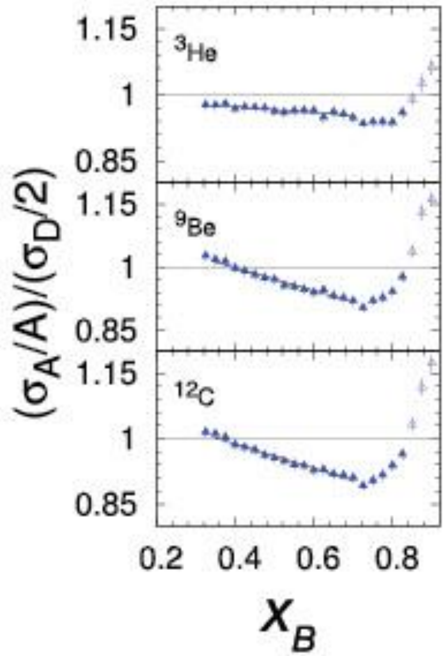
  High lumi and acceptance – 4D

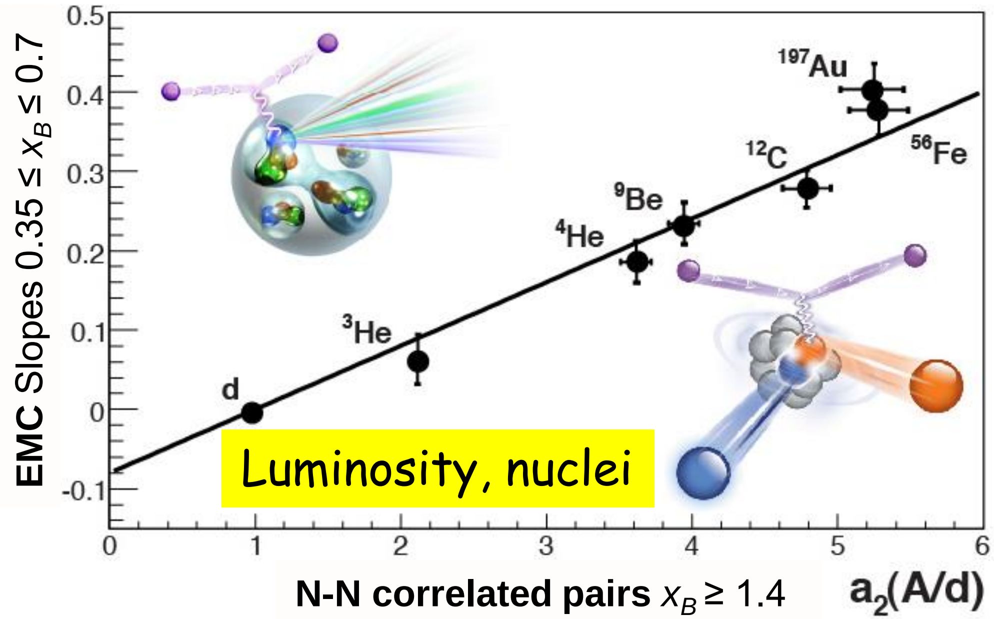


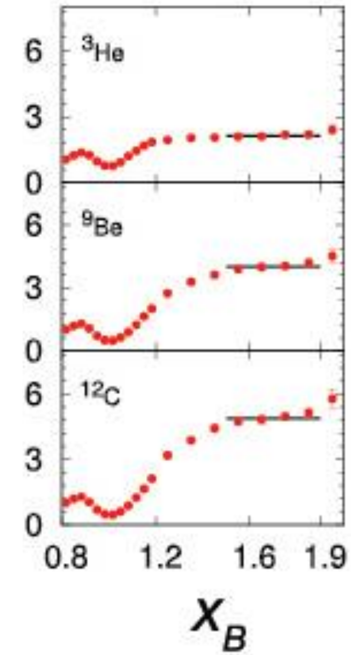
Parton Dynamics and N-N Correlations

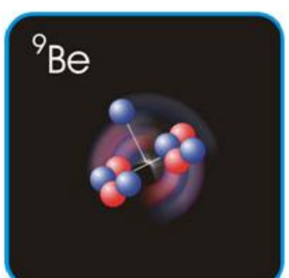
EMC effect: quark momentum in nucleus is altered

N-N Correlations: pairing due to tensor force and strong repulsive





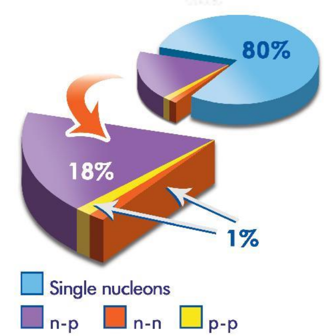




12 GeV science quest:

- isospin dependence: ^{3}H, ^{3}He, ^{6,7}Li, ^{9}Be, ^{10,11}B
- spin dependence
- "tagged" deep-inelastic scattering off ^{2}H with both slow and fast protons

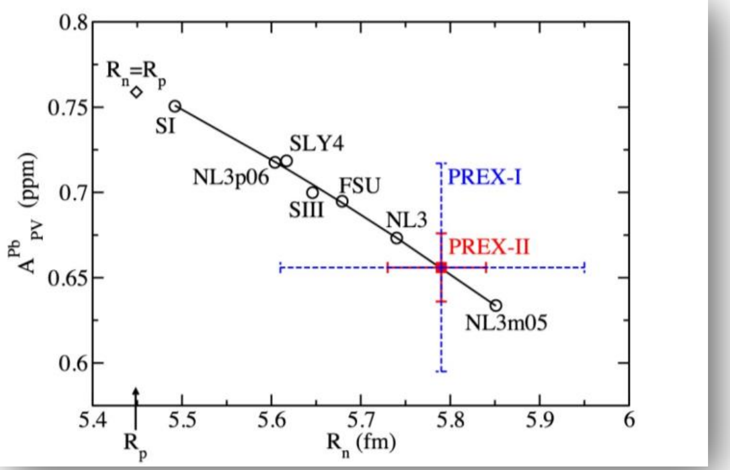
→ **BONuS Upgrade, LAD detector**



Parity Violation at JLab

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

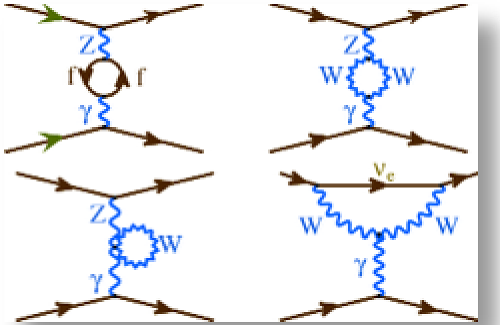
Luminosity, polarization

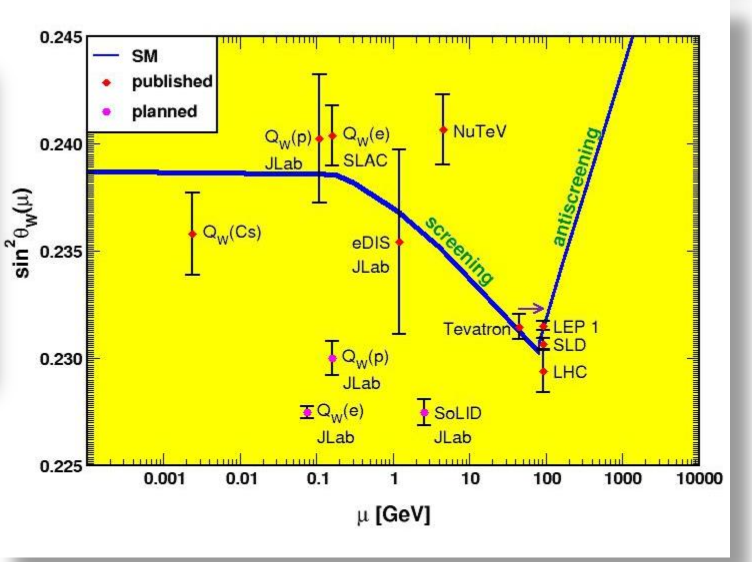


- PREX neutron skin

  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

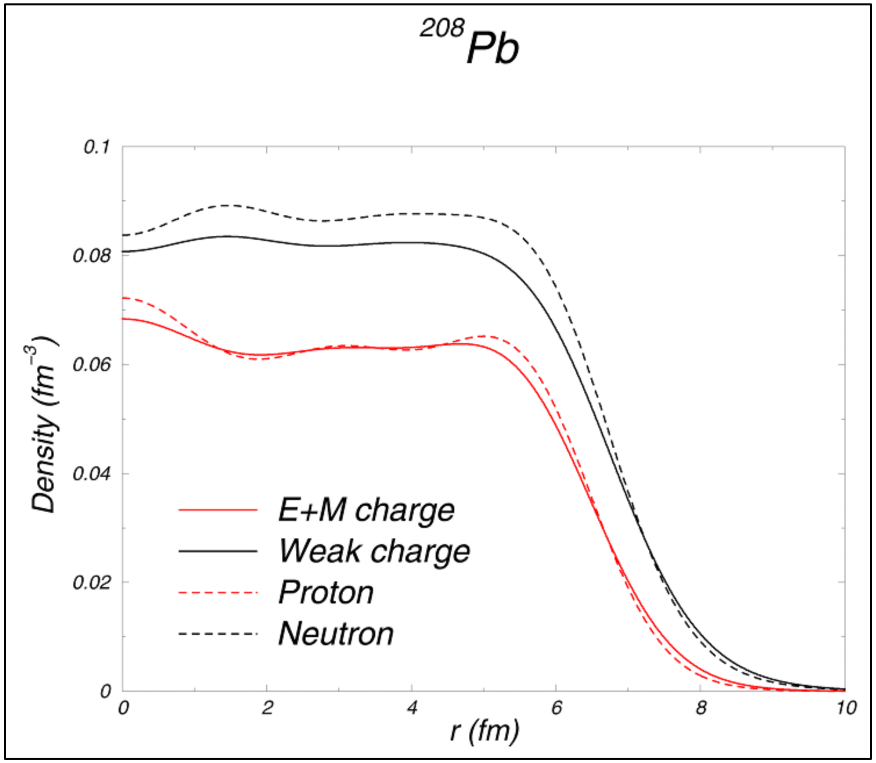
- SoLID
  lepto-quark couplings
  lepto-phobic Z'
  d/u, higher-twist

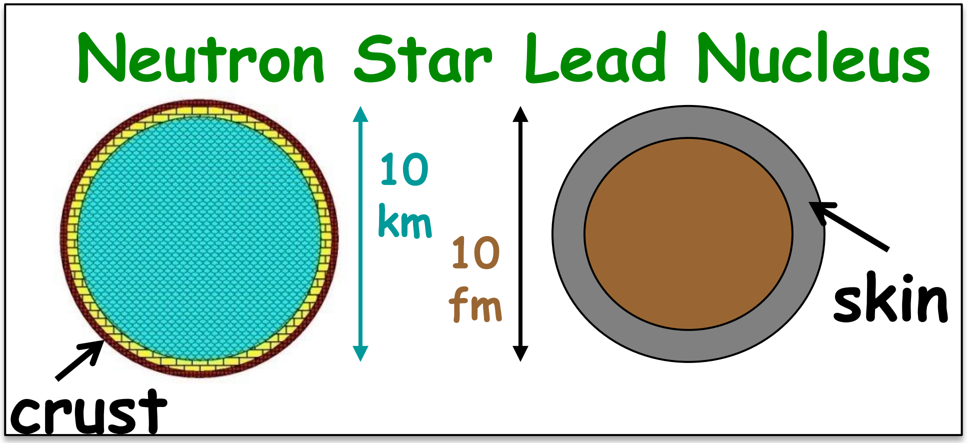
Measuring the Neutron "Skin" in the Pb Nucleus

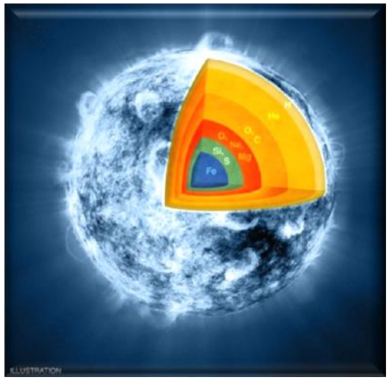
$Q_W{}^p = (1 - 4\sin^2\theta_W)$
$Q_W{}^n = -1$

Weak interaction selects neutrons

- Parity violating electron scattering
- Sensitive to neutron distribution





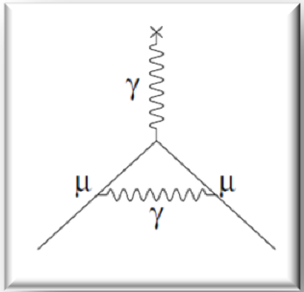


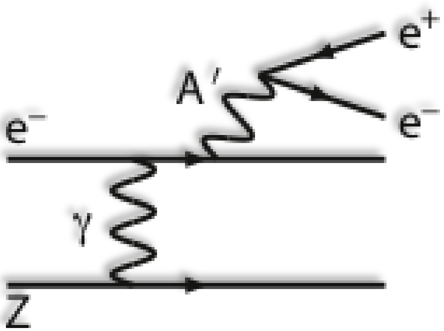
See also: Nature Physics DOI: 10.1038/ nphys3529 (11/2/2015)

<u>Applications</u>: Nuclear Physics, Neutron Stars, Atomic Parity, Heavy Ion Collisions

New Opportunity: Search for A' at Jefferson Lab

- BNL "g-2" expt: Δa_μ(expt-thy) = (295±88) x 10^{-11} (3.4 σ)
- No evidence for SUSY at LHC (yet)
- Another solution: A', a massive neutral vector boson

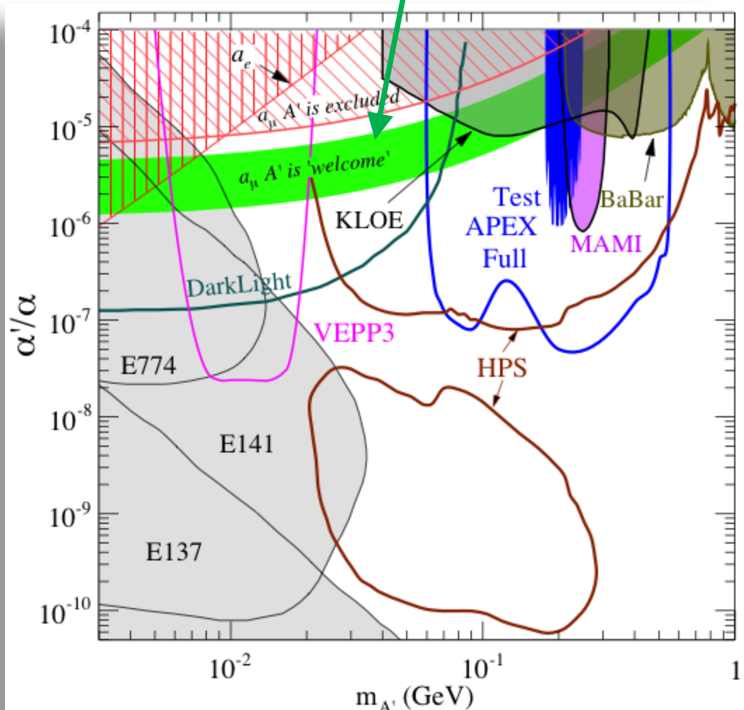




  - also useful for dark matter models

- 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

g – 2 preferred!

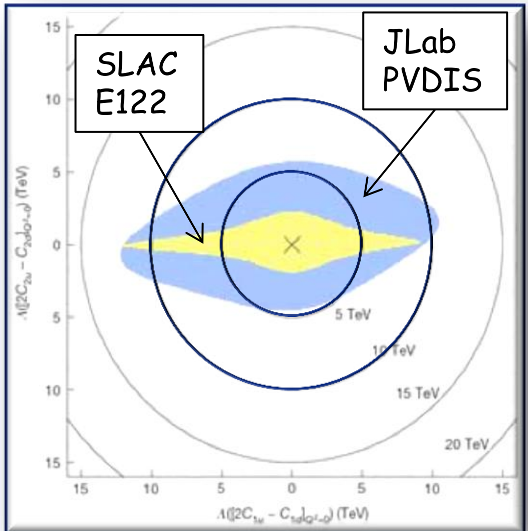


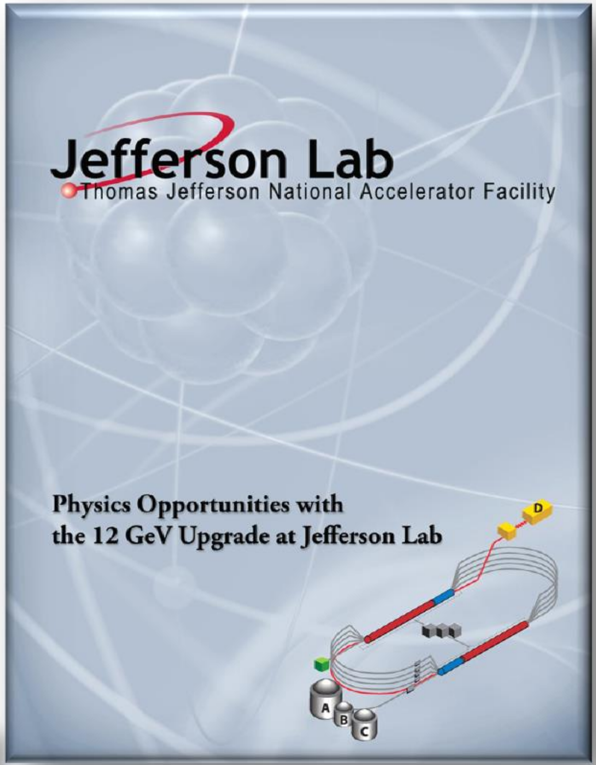
JLab 2014 Near-Future Future

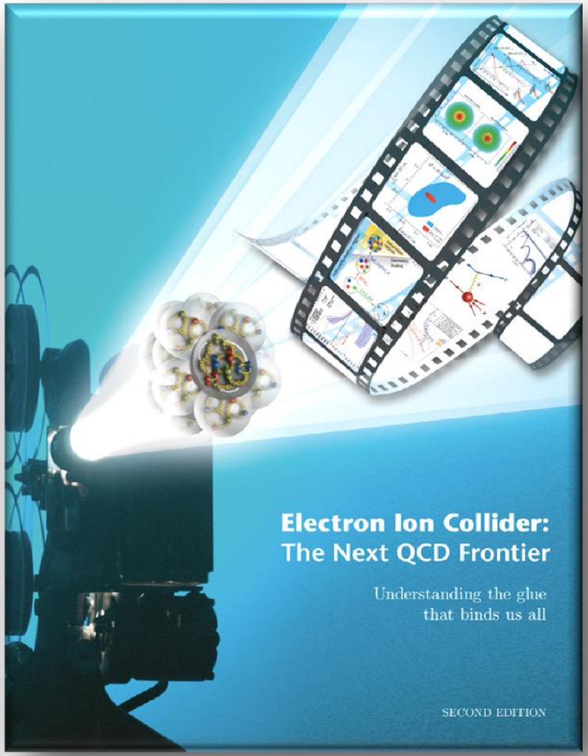
Nature 506, 67 (6 February 2014)
Parity Violating DIS

Decade of Experiments Approved
Start of 12-GeV Science!

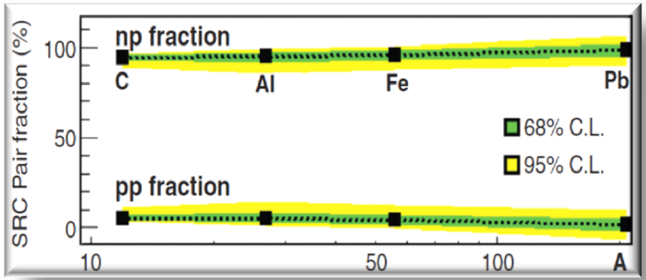
Seeking Realization
The Next QCD Frontier







Science 346, 614 (October 2014)
Short Range NN Correlations



- Confinement
- Hadron structure
- Nuclear Structure and Astrophysics
- Fundamental Symmetries

Role of Quark Sea and Gluons in Nucleon and Nuclear Structure

The Electron Ion Collider

For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 3-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-~100 (140) GeV Variable CM Energy

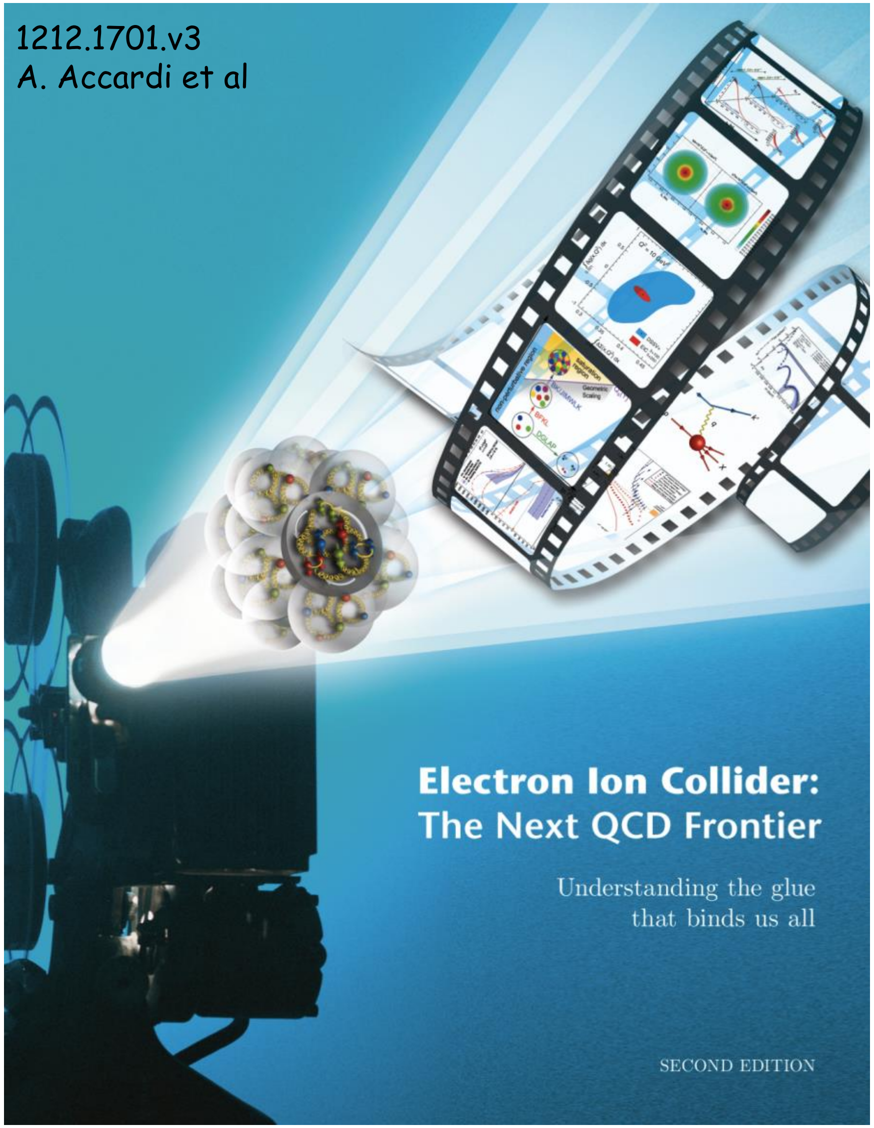
For e-A collisions at the EIC:

- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Two proposals for realization of the science case -
both designs use DOE's significant investments in infrastructure

1212.1701.v3
A. Accardi et al



Electron Ion Collider

NSAC 2007 Long-Range Plan:

"An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia."

EIC Community White Paper arXiv:1212.1701v3

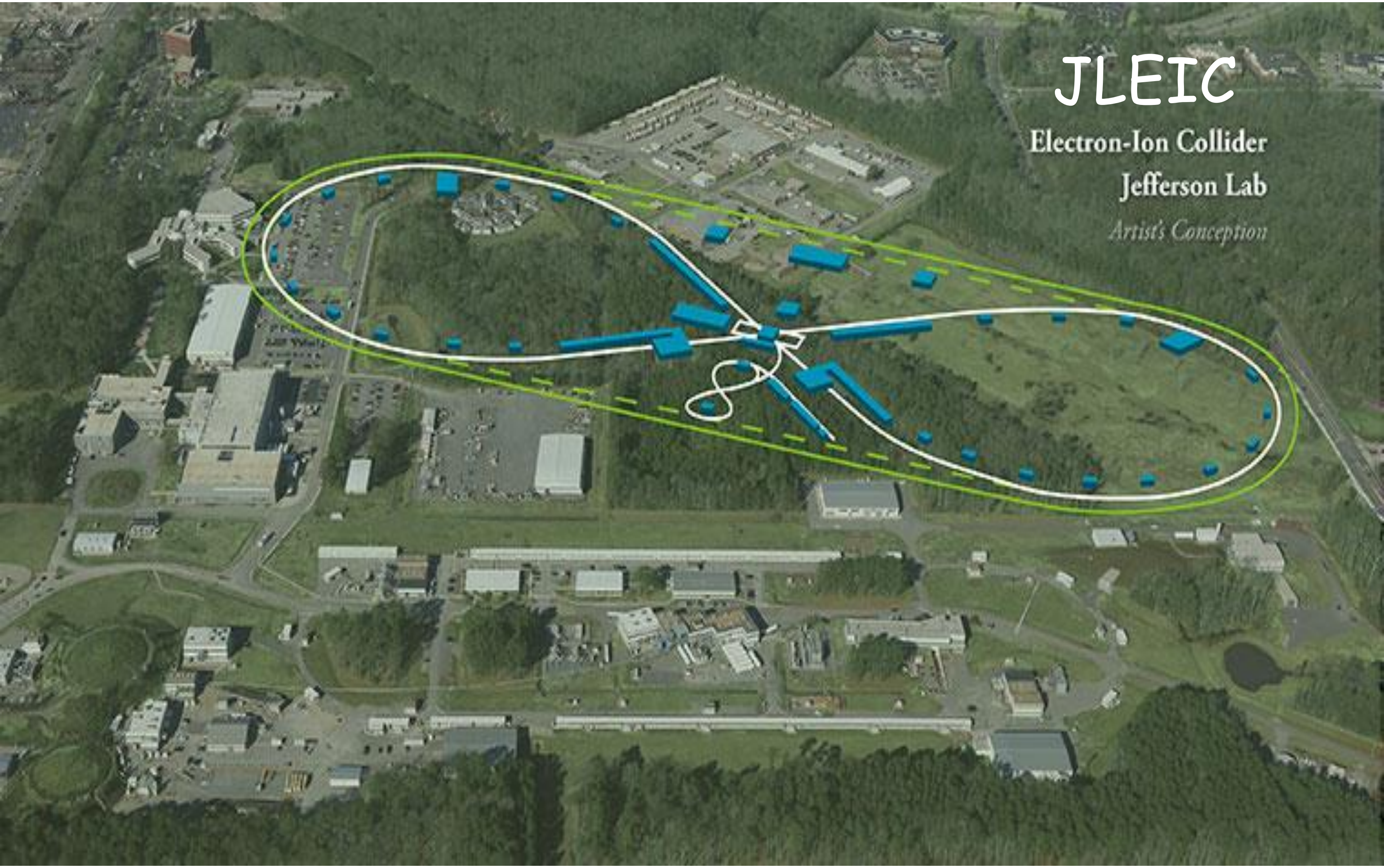
- Highly polarized ($\sim 70\%$) electron and nucleon beams
- Ion beams from deuteron to the heaviest nuclei (uranium or lead)
- Variable center of mass energies from $\sim 20 - \sim 100$ GeV, upgradable to ~ 140 GeV
- High collision luminosity $\sim 10^{33-34}$ cm^{-2}s^{-1}
- Possibilities of having more than one interaction region

NSAC 2015 Long-Range Plan:

3rd recommendation – out of 4:

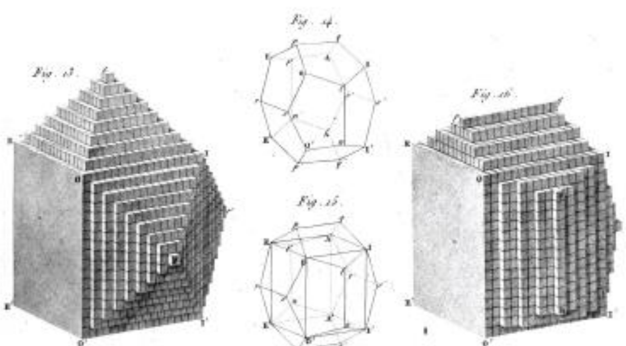
"We recommend a high-energy high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB."

An Electron-Ion Collider @ Jefferson Lab



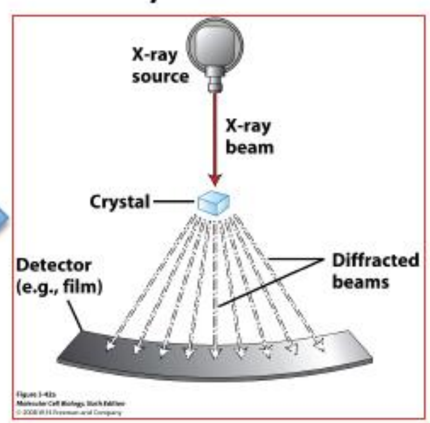
The Goal of the Electron-Ion Collider

- To revolutionize the understanding of hadron and nuclear structure
- An analogy: Atomic and Molecular structure revolutionized through a new tool



Haűy's Crystal Structure: 1801

X-ray Diffraction

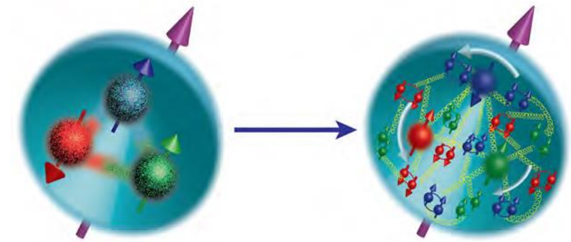


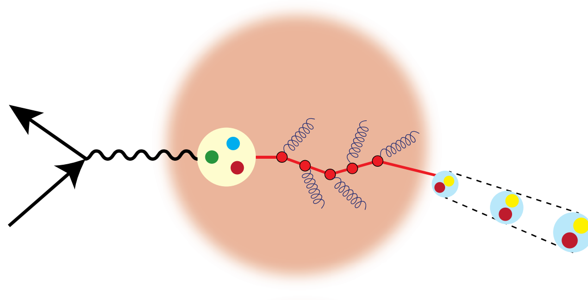
Crick and Watson: Double Helix
1953: New Science!

EIC Science Questions

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?

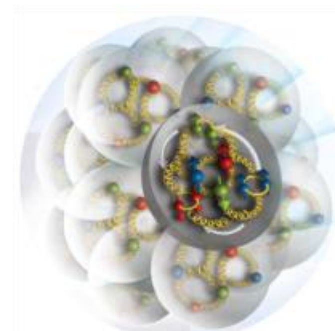




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

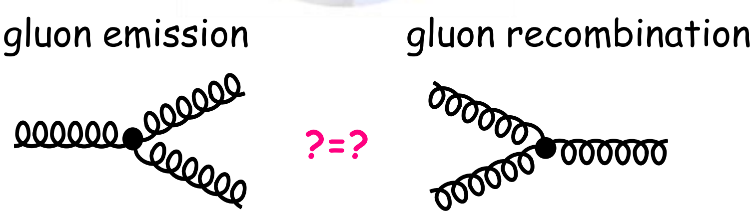
How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?



How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

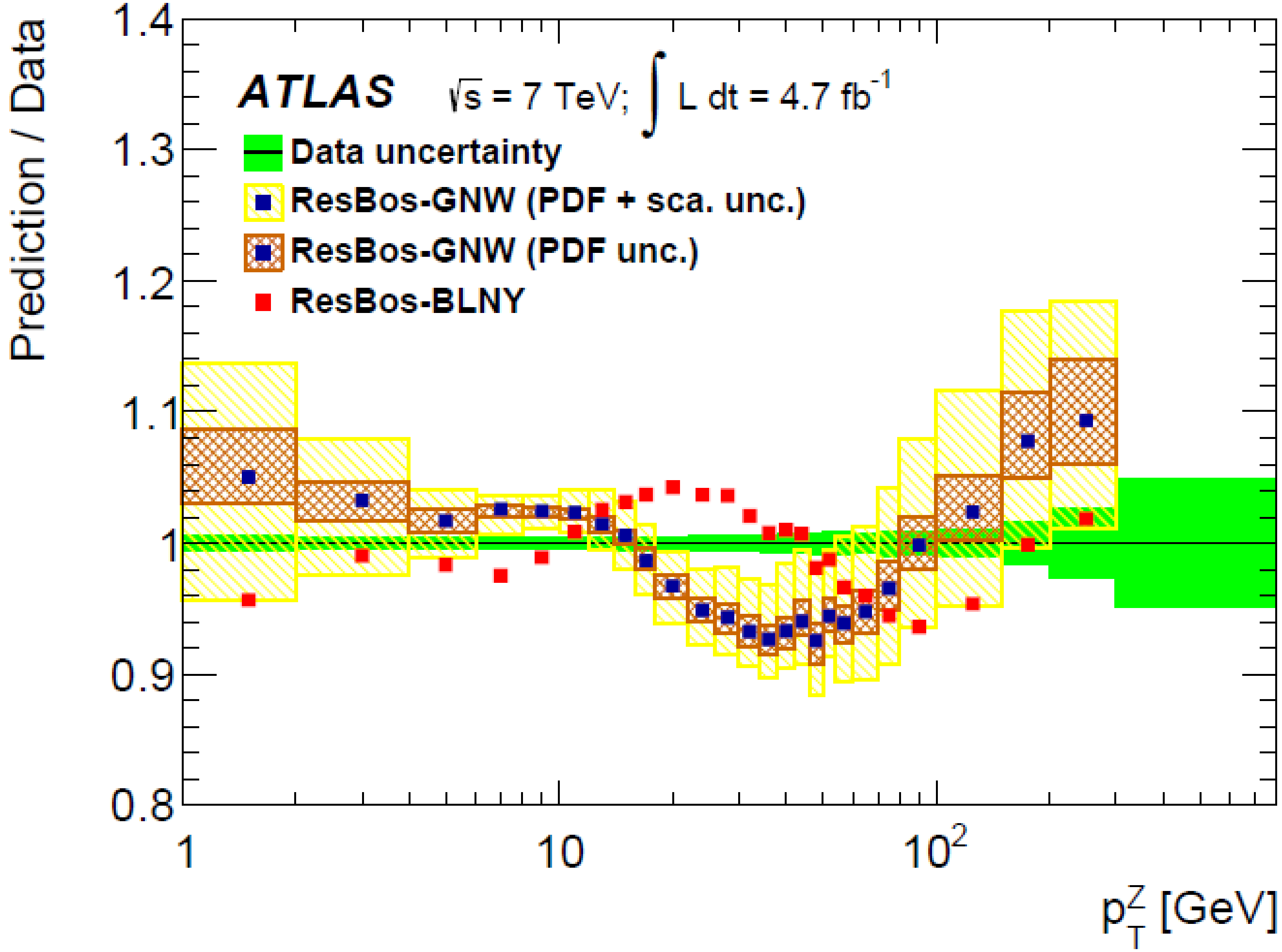


A Laboratory for Nuclear Science

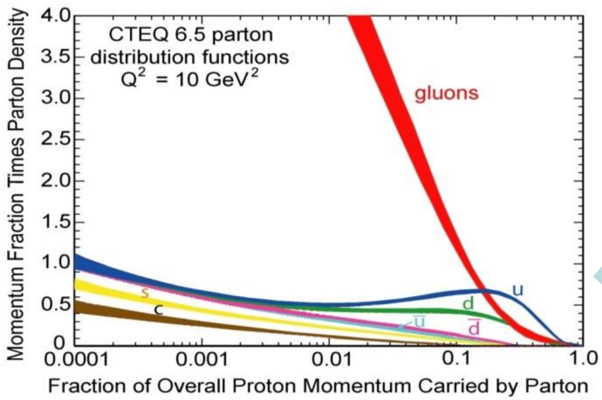
- The Jefferson Lab electron accelerator is a unique world leading facility for nuclear physics research, with a strong and engaged international user community
- These are exciting times at Jefferson Lab
  - Upgraded accelerator operational, Halls commissioned
  - Have begun 12-GeV physics program
  - Construction of Hall B continues through FY17
- 12 GeV program ensures at least a decade of excellent opportunities for discovery
  - New vistas in QCD
  - Growing program Beyond the Standard Model
  - Additional equipment: MOLLER, SoLID
- EIC moving forward:
  - JLab design well developed and low risk, with modest R&D
  - Time scale following 12 GeV program is "natural".

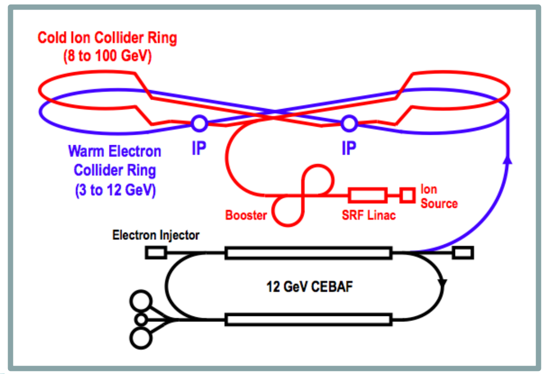
Successful perturbative predictions

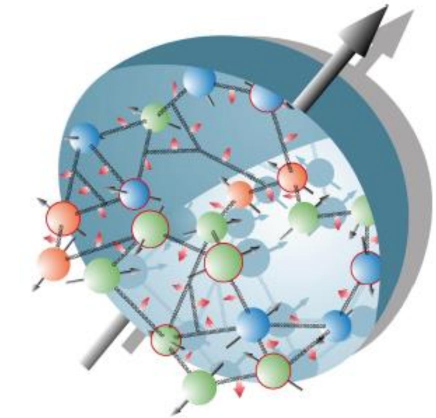
Z production at the LHC



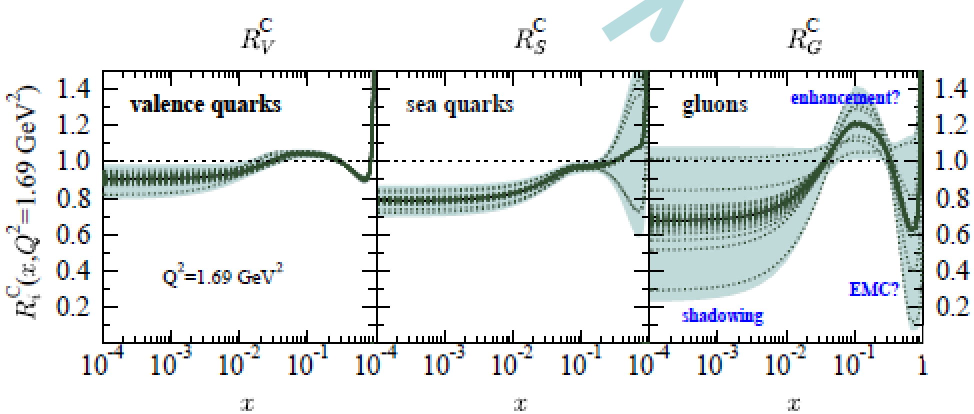
EIC is the New Tool

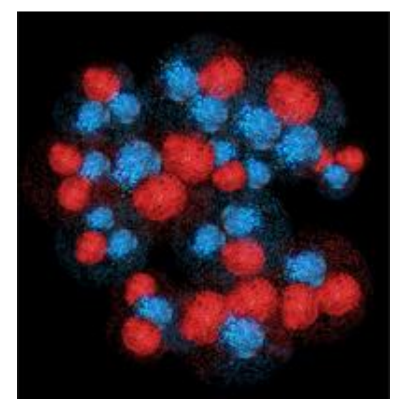






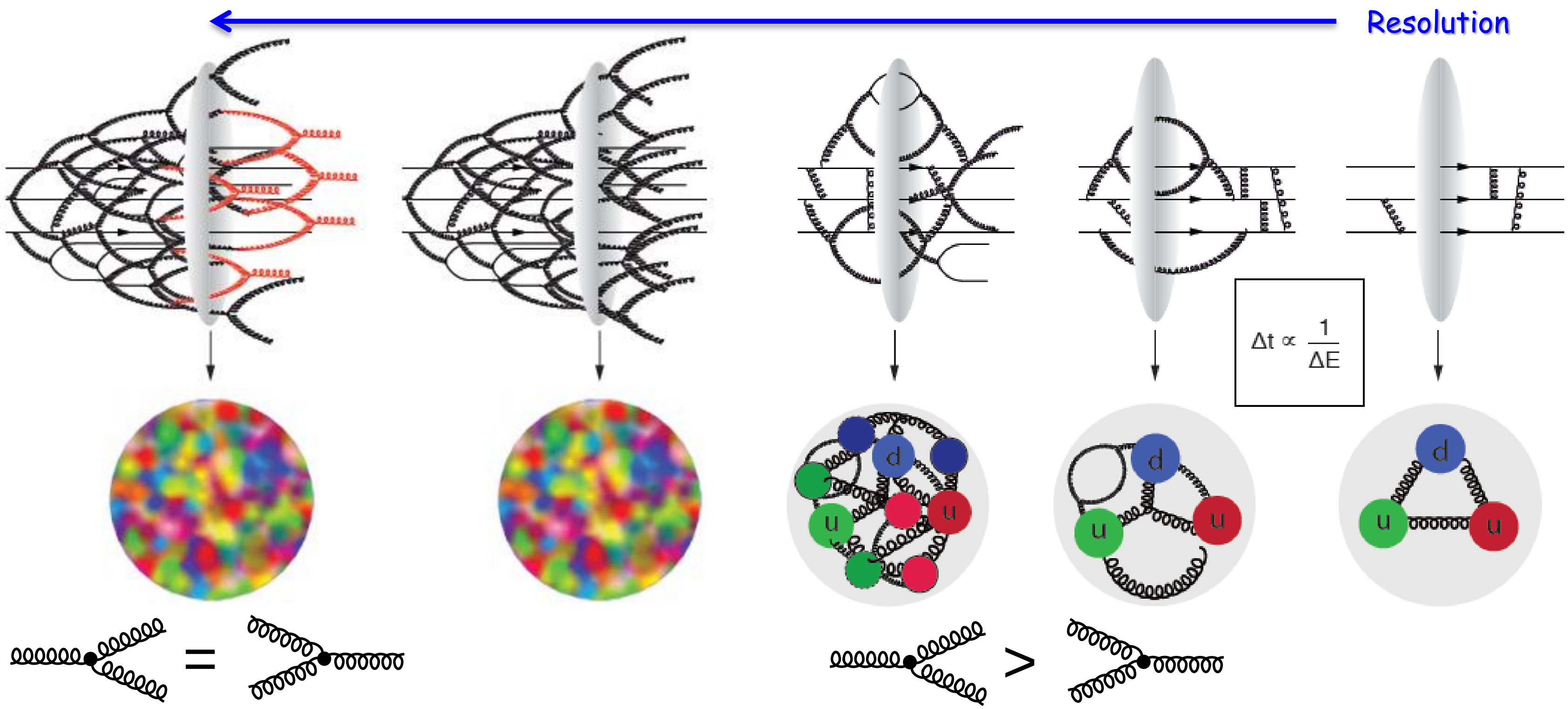
Multi-dimensional understanding of the hadron at precision!

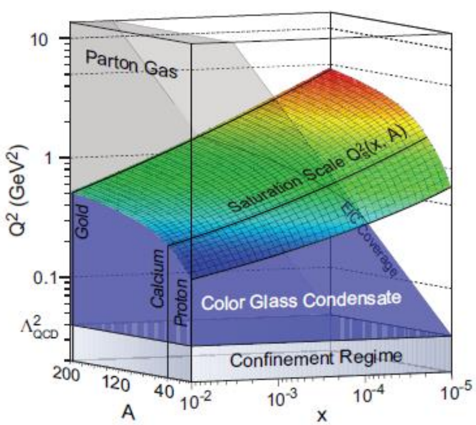




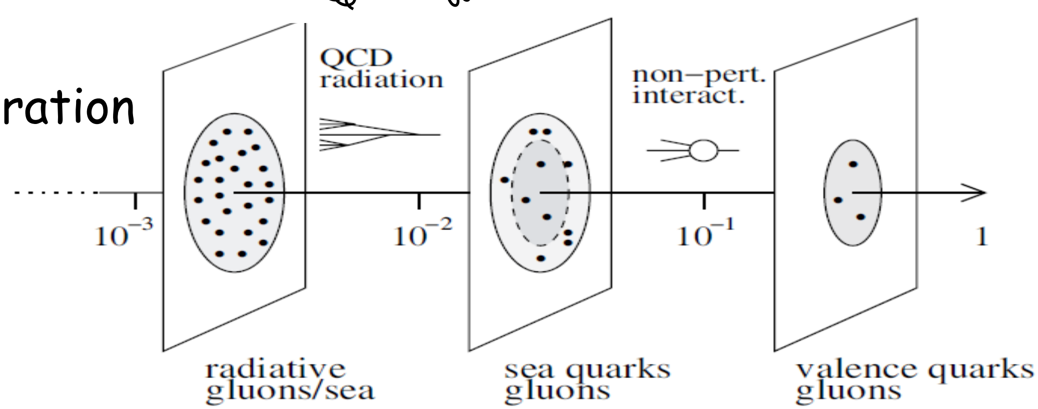
Understanding of the quark-gluon origin of the nuclear force!

The Evolution of a Proton – Deep into the Sea



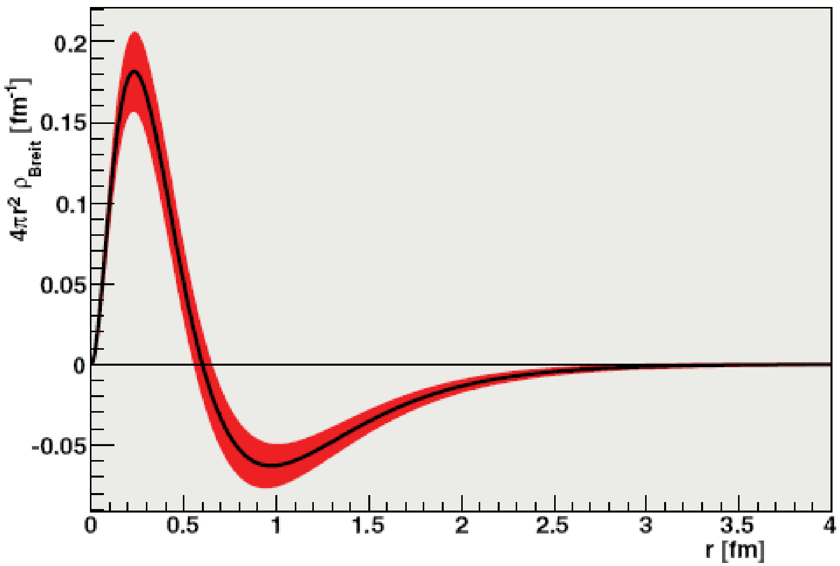


Saturation



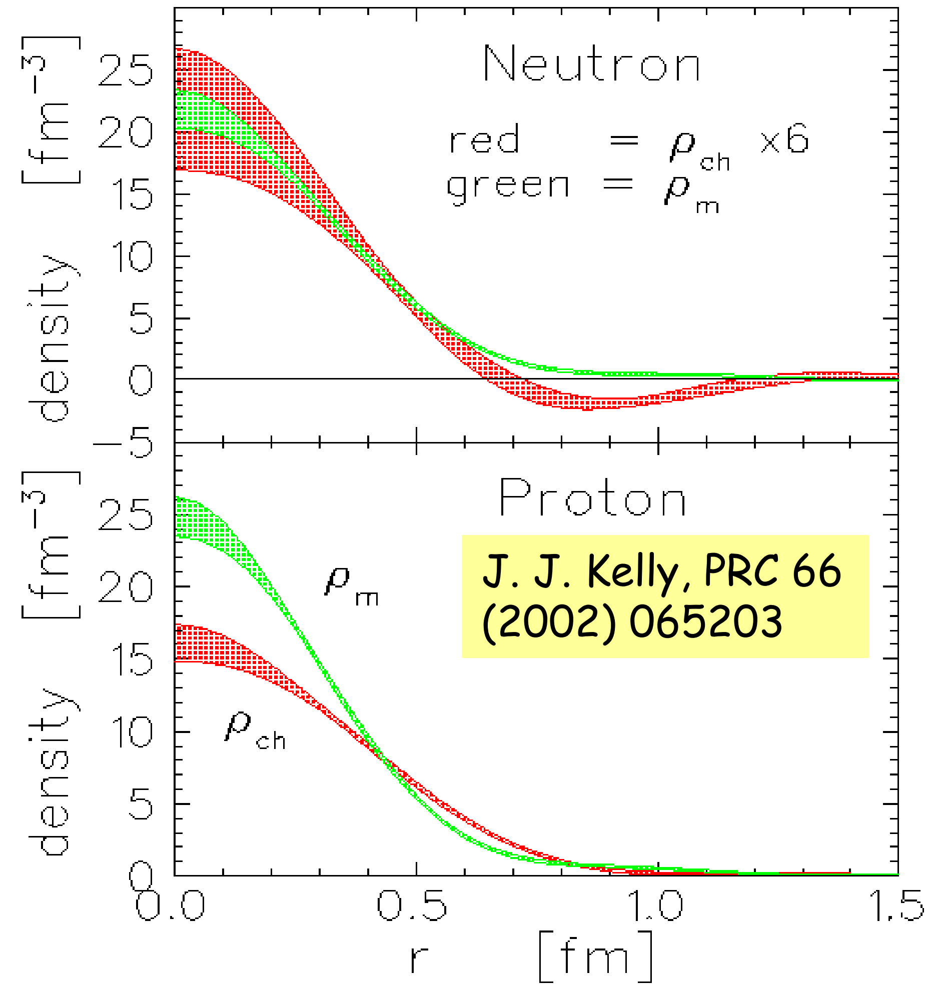
What about the neutron?

Neutron has no charge, but does have a charge distributions: n = p + π^-, n = ddu.
Use polarization and ^{2}H(e,e'n) to access.
"Guarantee" that electron hits a neutron AND electron transfers its polarization to this neutron.



Properly normalized (volume integral) charge of course zero

charge and magnetization density



Combining proton and neutron: down quark has more extended spatial charge distribution. Is this due to the influence of di-quarks?

Features of partonic 3D non-perturbative distributions

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

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

Understanding of the 3D structure of nucleon requires studies of spin and flavor dependence of quark transverse momentum and space distributions

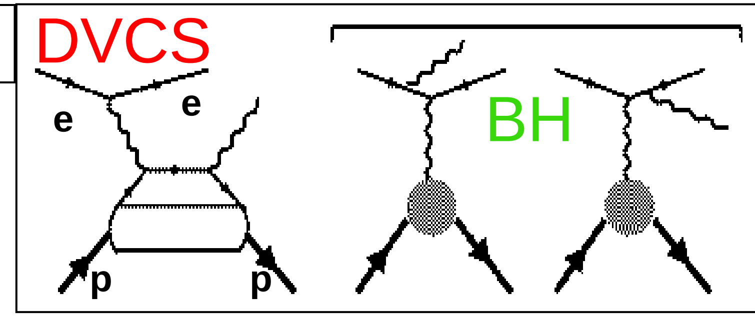
nucleon polarization \ quark polarization	U	L	T
U	f_1		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 $h_{1T}^\perp$

transversity 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

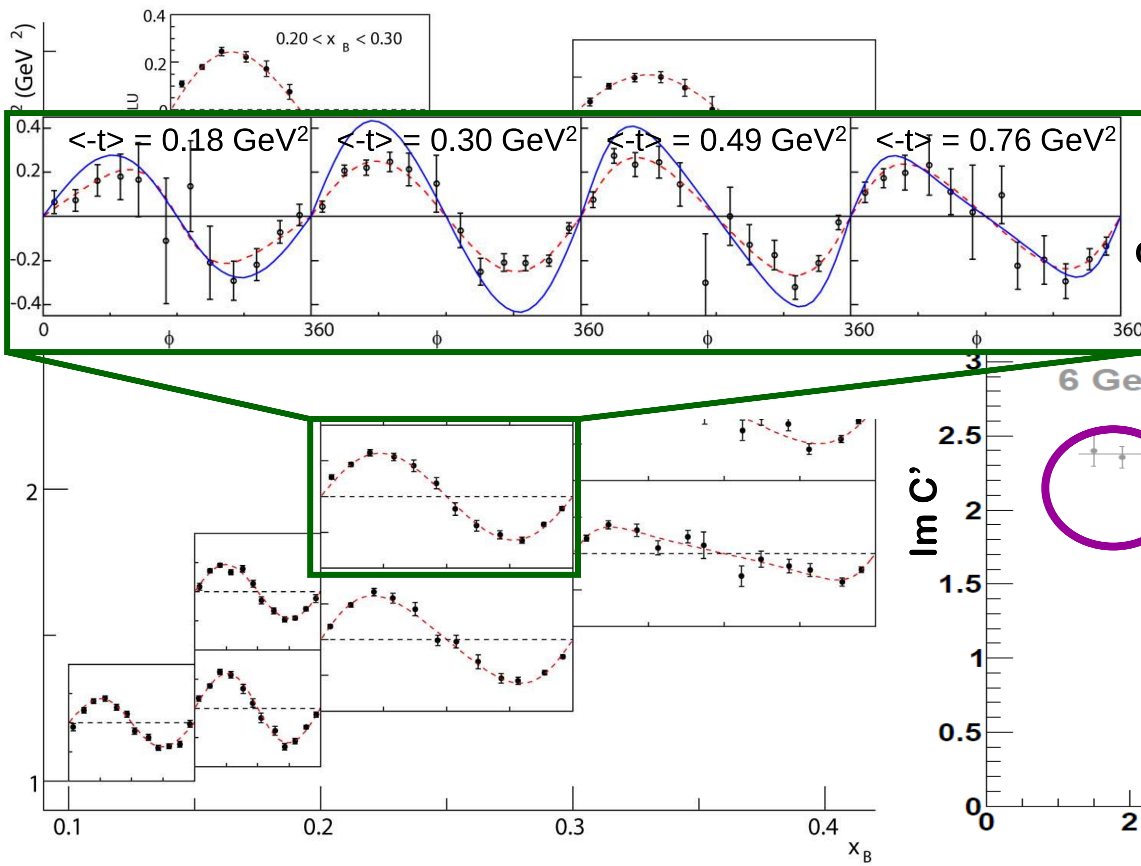
Towards the 3D Structure of the Proton: GPDs

Simplest process: e + p → e' + p + γ (DVCS)



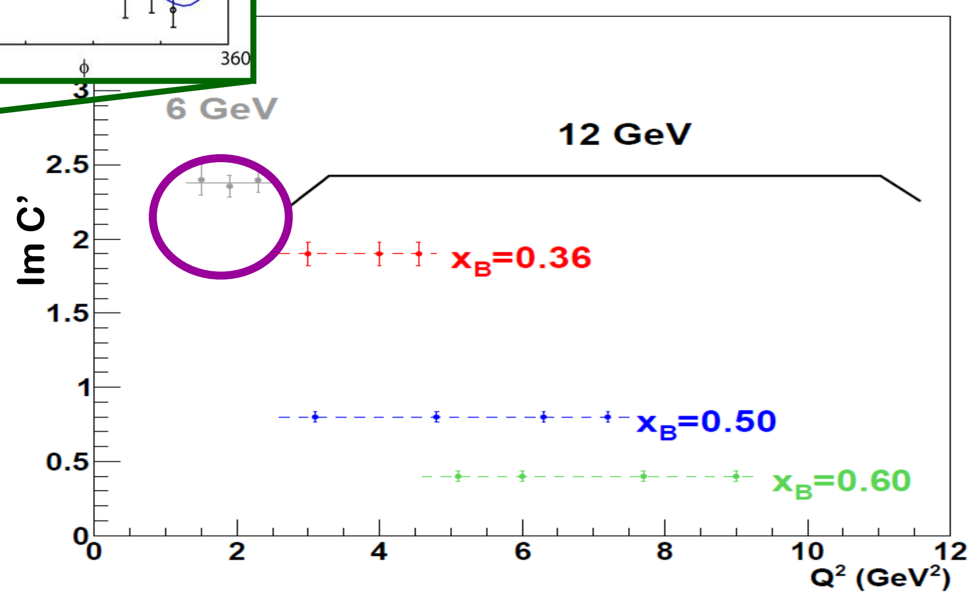
Hall B beam-spin asymmetry data show potential for imaging studies from analysis in x, Q^2 and t

F-X. Girod *et al*., PRL 100, 162002 (2008)



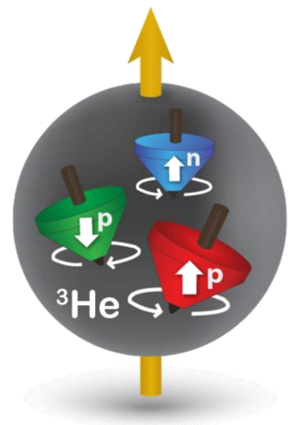
Hall A data for Compton form factor (over *limited* Q^2 range) agree with hard-scattering

C. Munoz Camacho *et al*., PRL 97, 262002 (2006)

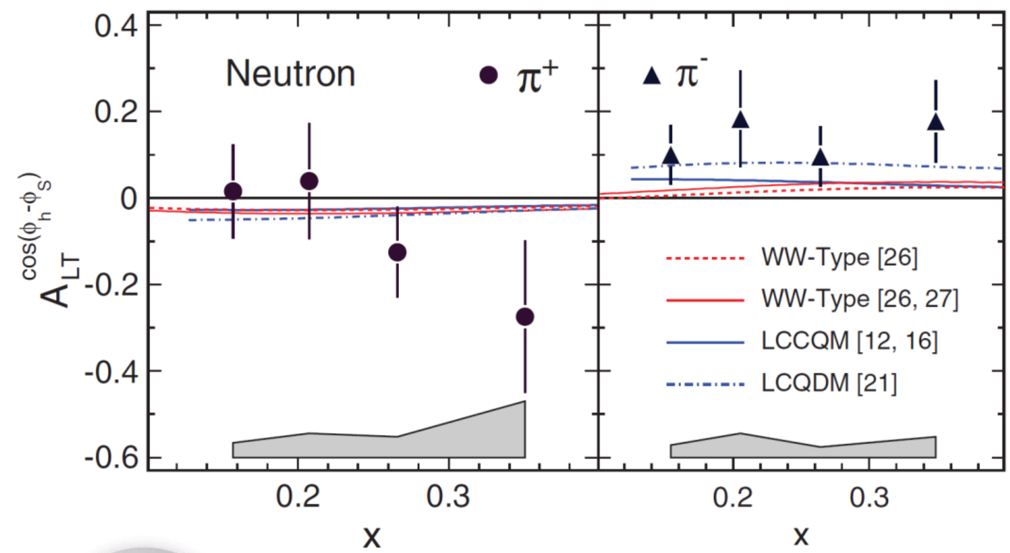


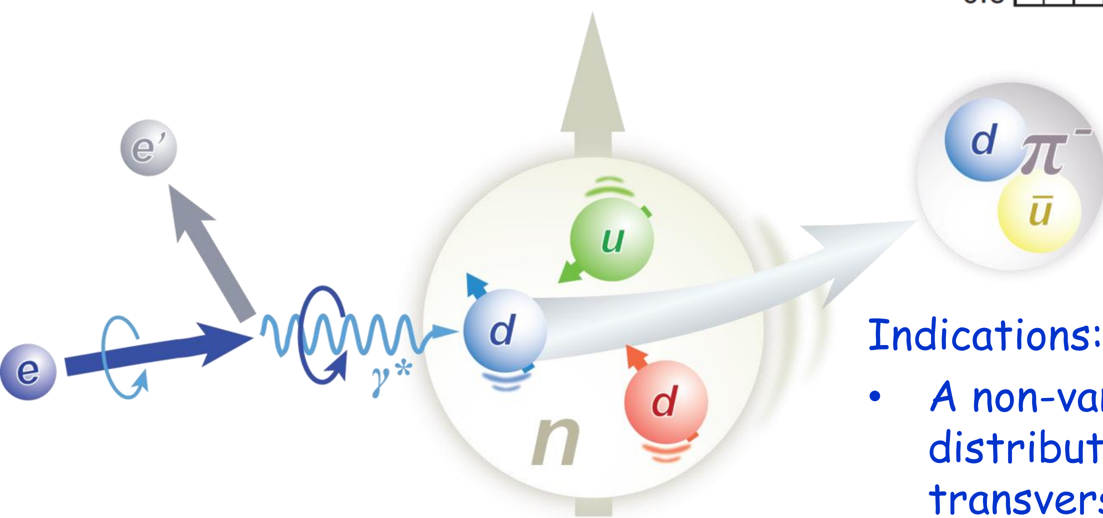
New Observable Reveals Interesting Behavior of Quarks

Target:
(transversely)
polarized ^{3}He ~
polarized neutron



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





1st measurement of A_{LT}

beam-target double-spin asymmetry

Indications:

- 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

Also 1st measurements of ^{3}He (neutron) single-spin asymmetries

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