Jefferson Lab in the 12 GeV Era

NNPSS 2019,
University of Tennessee,
Knoxville,
July 08-09, 2019

Rolf Ent (Jefferson Lab)

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Outline

- Cool Facts about QCD and Nuclei
- Introduction to QED and QCD
- The Quest to Understand the Fundamental Structure of Matter
- Why Electron Scattering?
- Electron Scattering Formalism – the Era before Jefferson Lab

- Introduction to Jefferson Lab
- The 6-GeV Science Program – what did we learn?

- Gluons and QCD – The Need for 3D Atomic Structure
- JLab @ 12 GeV – Towards a New Paradigm for Structure
  - Femtography of valence quarks in nucleons and nuclei
  - Role of gluonic excitations in the spectroscopy of light mesons
  - Search for new physics Beyond the Standard Model
- The US-Based Electron-Ion Collider (EIC) – The Role of Gluons
- JLab @ 12 GeV (& EIC) – A Portal to a New Frontier

Overview of Jefferson Lab

Created to build and operate the Continuous Electron Beam Accelerator Facility (CEBAF), world-unique user facility for Nuclear Physics

Jefferson Lab Stats:

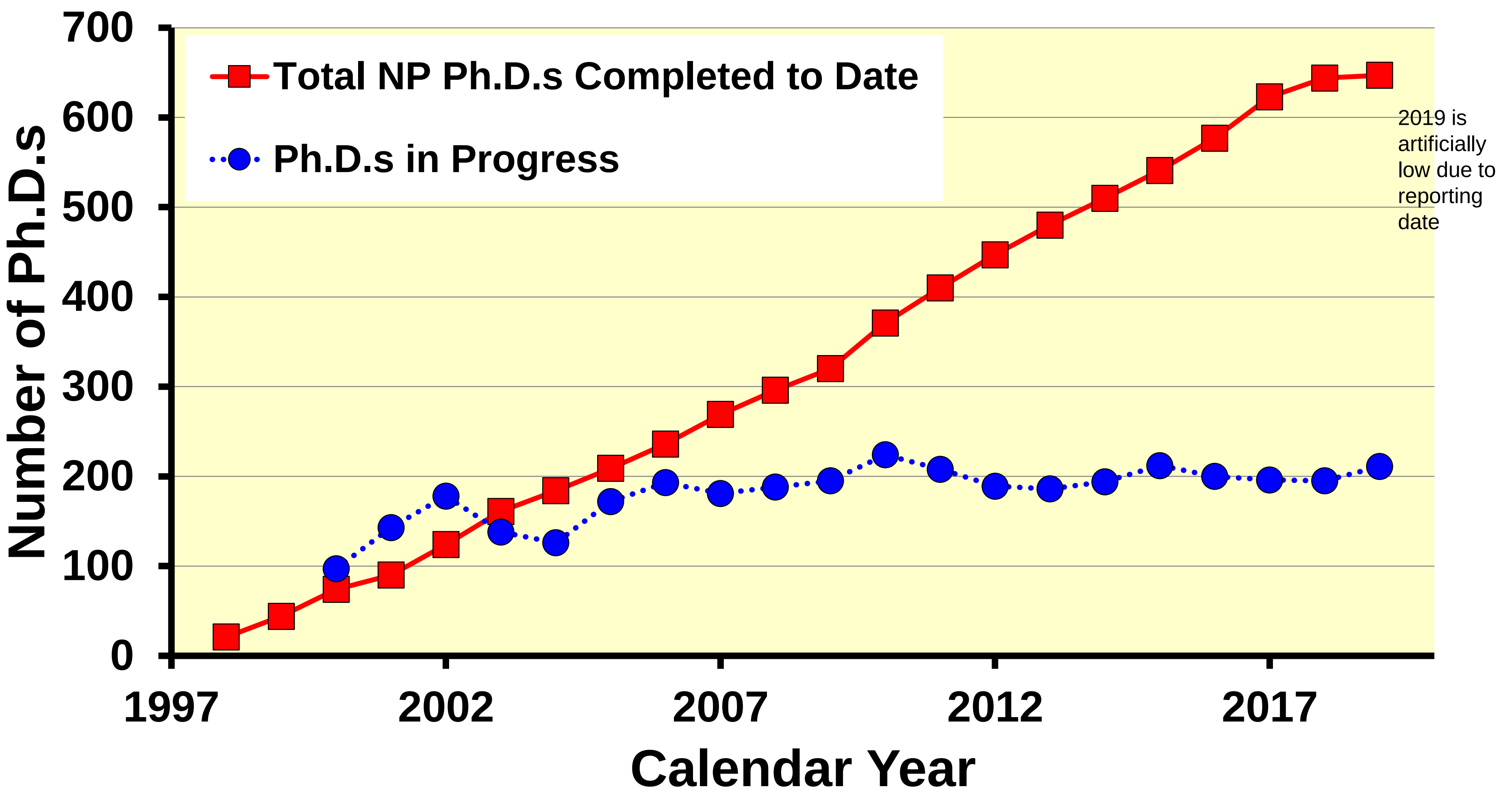
- Located in Newport News, Virginia
- 169 acre site
- In operation since 1995
- ~700 employees
- 1,630 Active Users (FY18)
- 1/3 of Users are from non-US Institutions, from 37 countries
- ~600 PhDs granted to-date
- On average 30% of US PhDs in nuclear physics
- FY2016 Costs: $184.1M

- 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 and nuclear substructure through measurements of new multidimensional distribution functions?
- Can we discover evidence for new physics beyond the Standard Model?

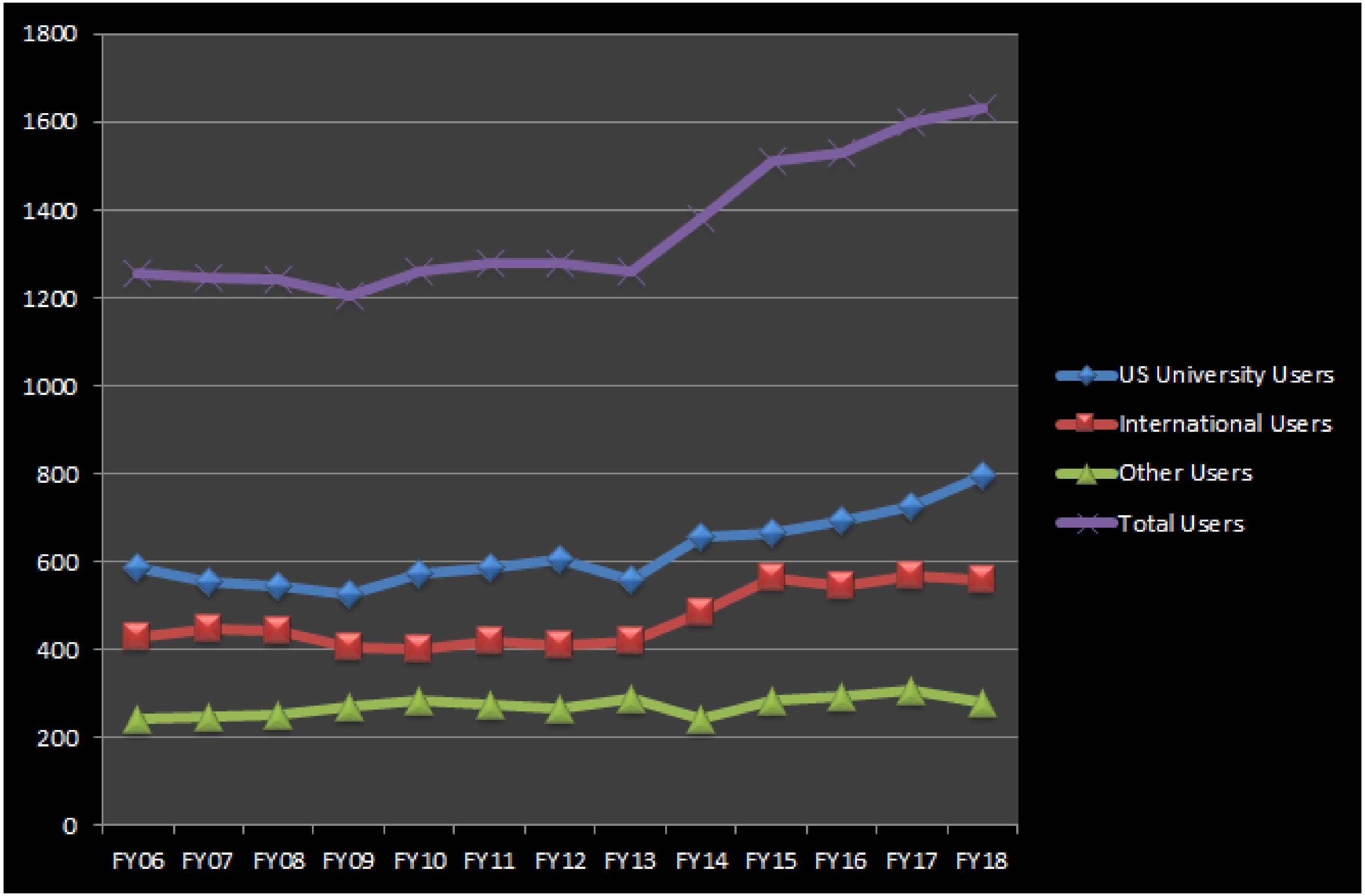
Jefferson Lab

PhDs based on Jefferson Lab Research

On average: 30 PhDs/year. Last few years average: 35 PhDs/year.
Typically 200 PhD students annually engaged in Jefferson Lab research.



JEFFERSON LAB USER GROWTH



“Other Users” include US National Labs and Industry

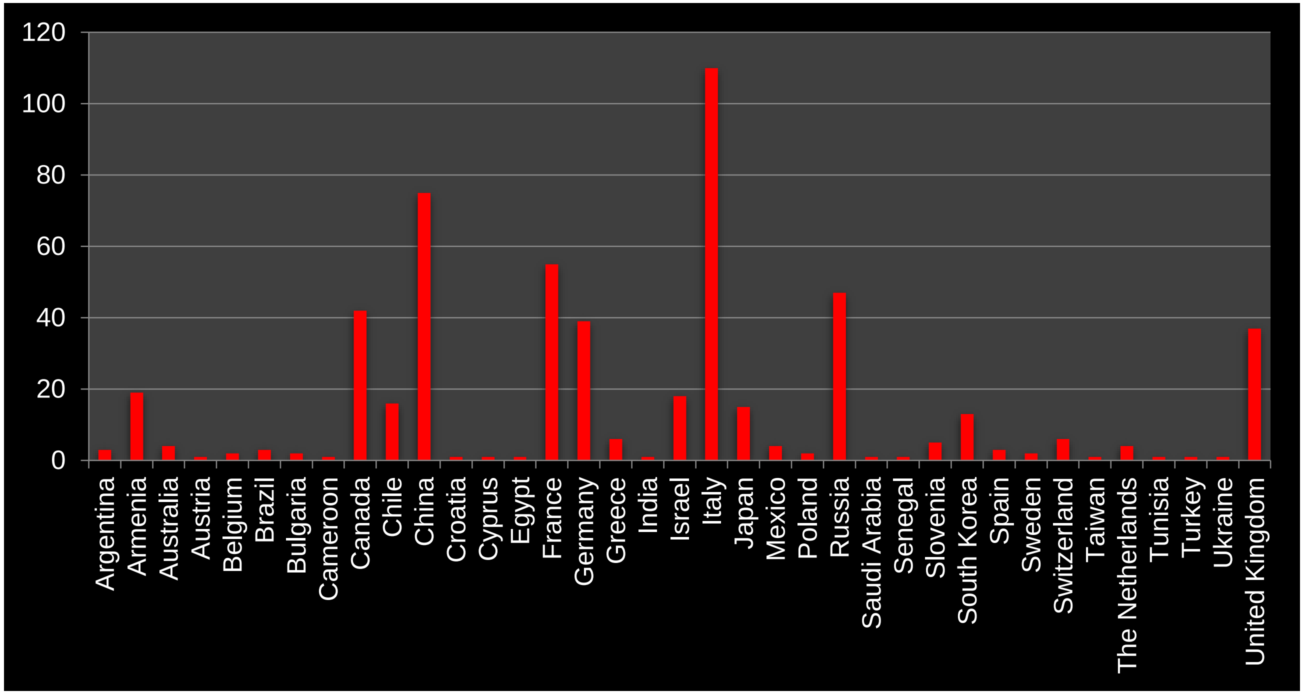
1630 users in 278 institutions from 38 countries worldwide

International Character of Jefferson Lab

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

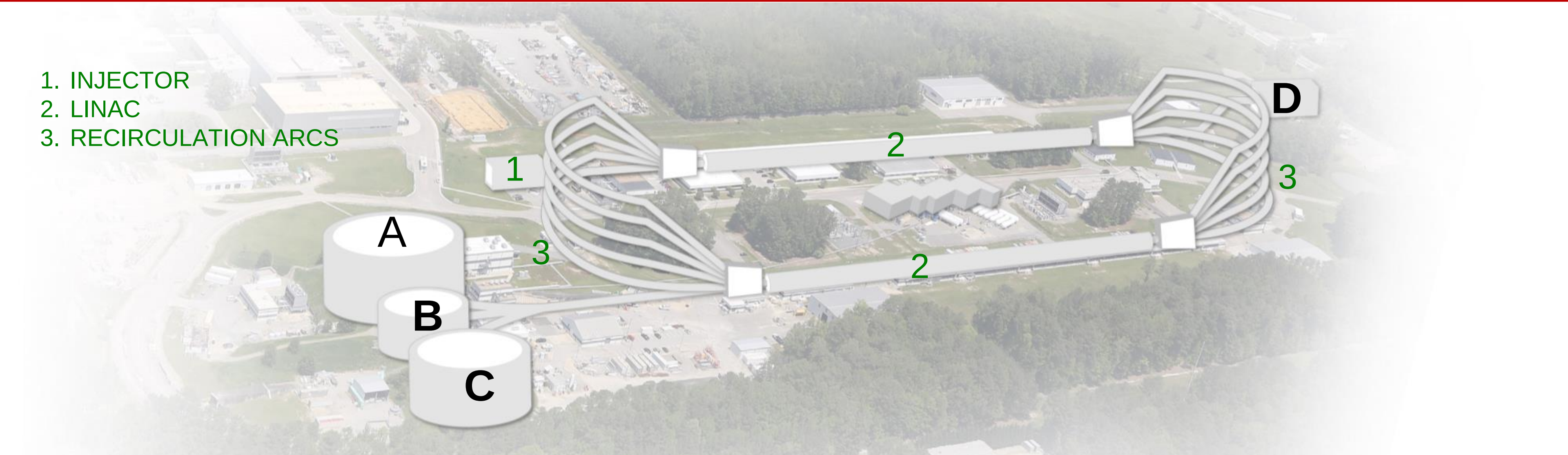
COMPASS at CERN: ~200 GeV muon beam, large acceptance, much lower luminosity.
Mainz (Germany): excellent 2 GeV CW polarized electron beams but limited kinematic reach.
JPARC (Japan): Hadron beam facilities with high intensity kaon and pion beams.
BES (China), BELLE (Japan), BABAR: heavy quark meson spectroscopy 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 users are international, from 38 countries

CEBAF at Jefferson Lab

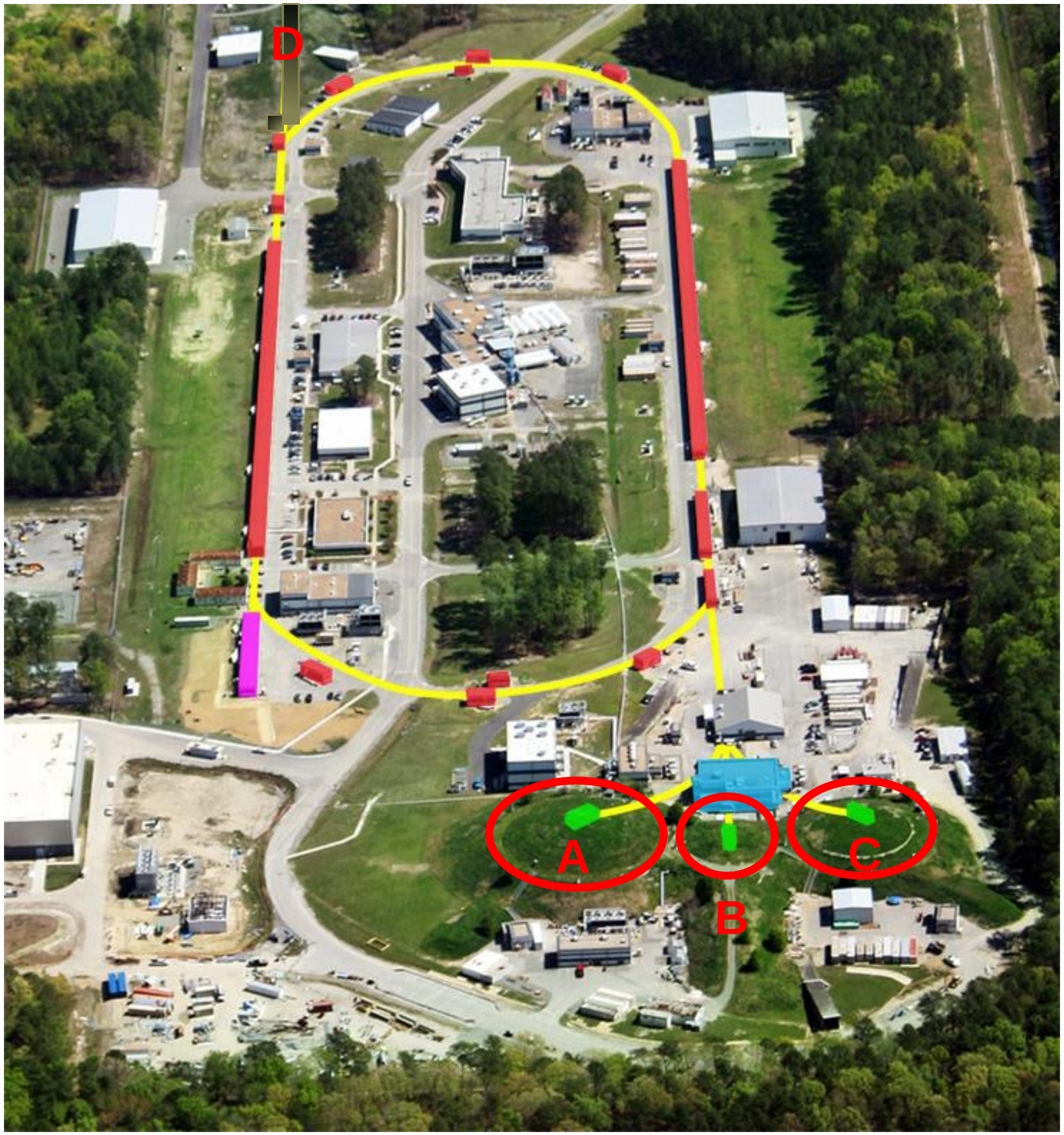


- CEBAF Upgrade completed in September 2017
  - CW electron beam
  - E_{max} = 12 GeV
  - I_{max} = 90 μA
  - Pol_{max} = 90%
- Commissioning:
  - April 2014: hall A
  - October 2014: hall D
  - February/March 2017: halls C & B

CEBAF World-leading Capabilities

- Nuclear experiments at ultra-high luminosities, up to 10^{39} electrons-nucleons /cm^2/ s
- World-record polarized electron beams
- Highest intensity tagged photon beam at 9 GeV
- Ability to deliver a range of beam energies and currents to multiple experimental halls simultaneously
- Unprecedented stability and control of beam properties under helicity reversal

JLab accelerator CEBAF in the 6-GeV era



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

CEBAF'S ORIGINAL MISSION STATEMENT

Key Mission and Principal Focus (1987):

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

The Role of Quarks in Nuclear Physics

Related Areas of Study:

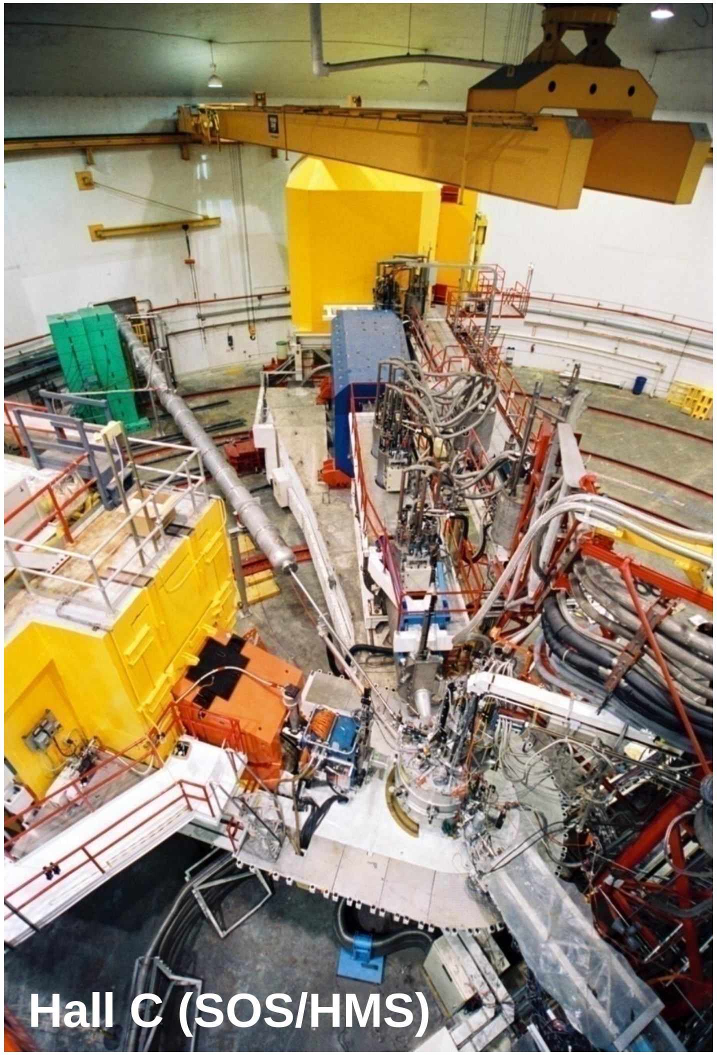
- **Do individual nucleons change their size, shape, and quark structure in the nuclear medium?**
- **How do nucleons cluster in the nuclear medium?**

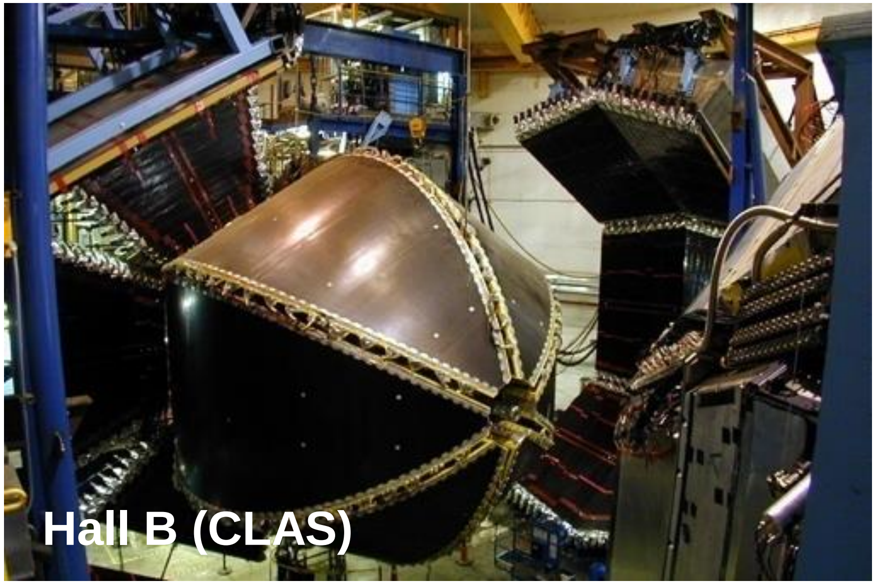
Pushing the Limits of the Standard Model of Nuclear Physics

- **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?**

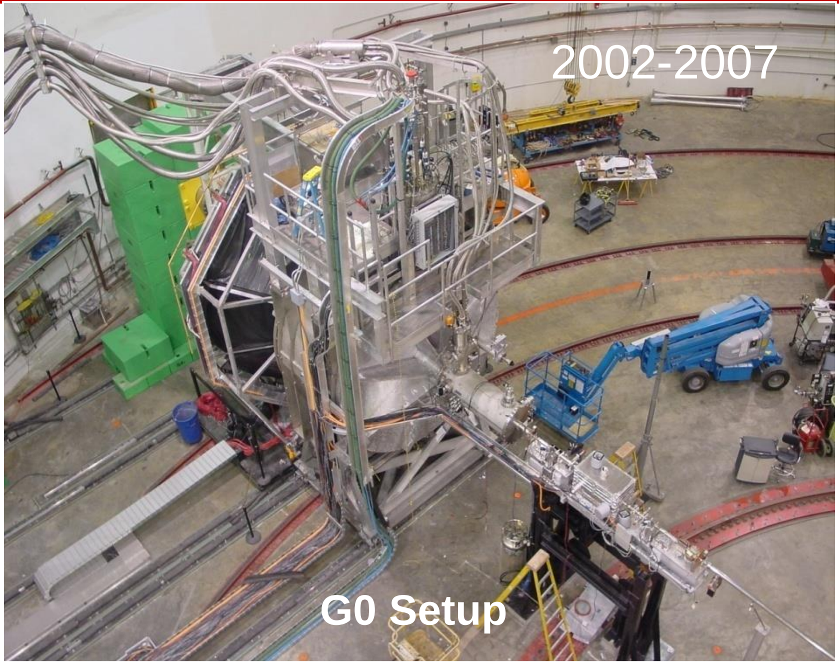
Charge and Magnetization in Nucleons and Pions
The Onset of the Parton Model

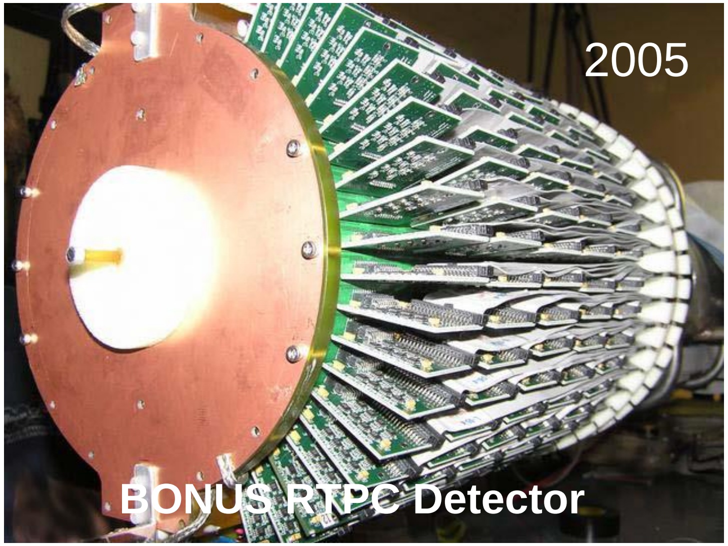
HALLS A/B/C (6-GEV) BASE EQUIPMENT (1994-2012)

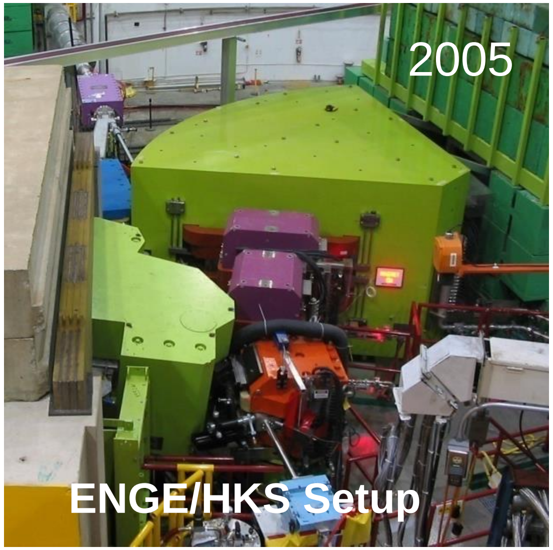




ANCILLARY EQUIPMENT AND EXPERIMENT-SPECIFIC APPARATUS







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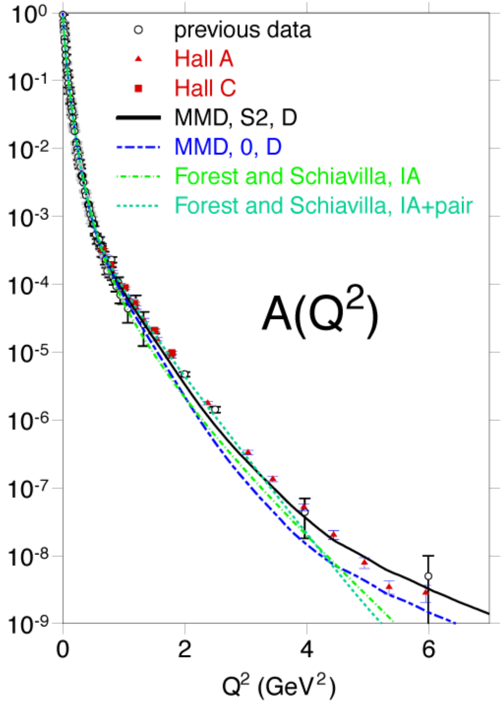
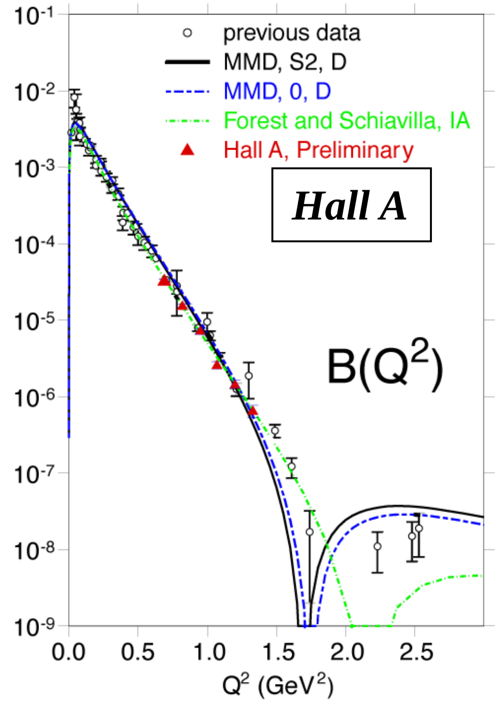
JLAB DATA REVEAL DEUTERON'S SIZE AND SHAPE





For elastic e-d scattering:

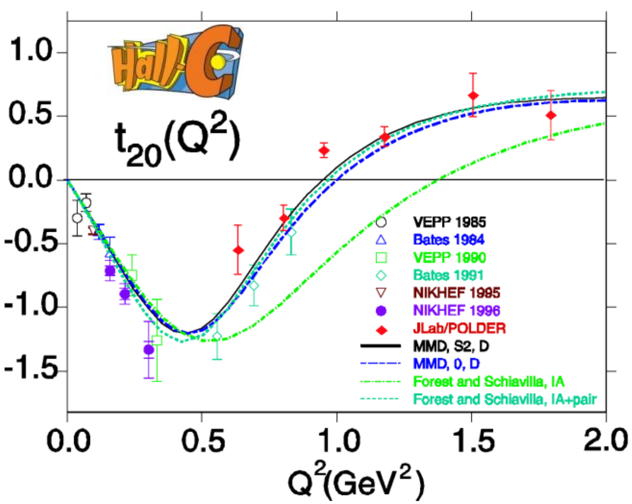
$$\frac{d\sigma}{d\Omega} = \sigma_M \left[A + B \tan^2 \frac{\theta}{2} \right]$$

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

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

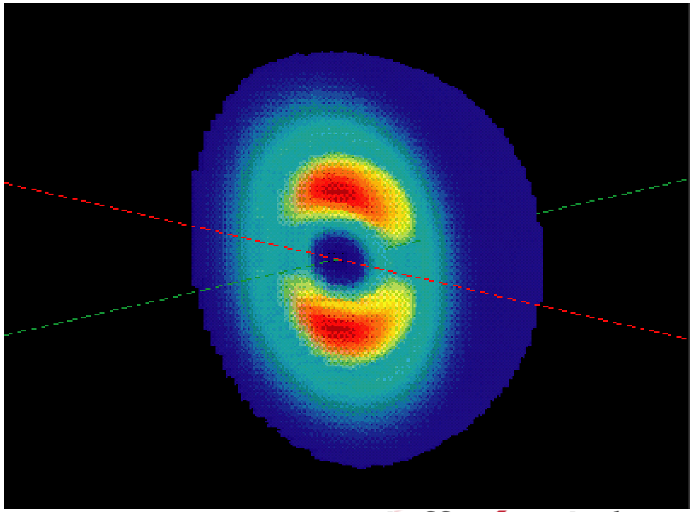
- 3rd observable needed to separate G_C and G_Q

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

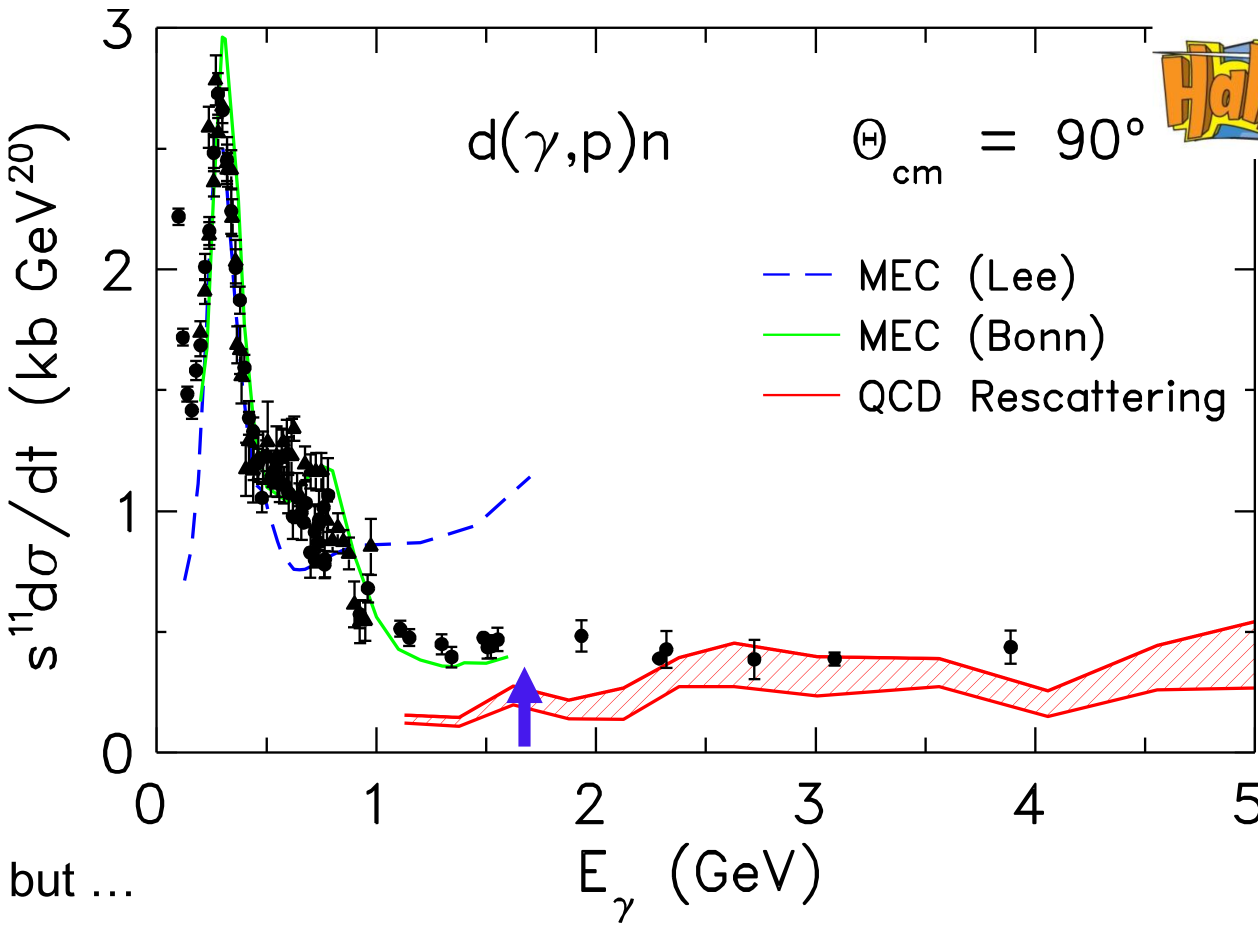


Combined Data -> Deuteron's Intrinsic Shape

The nucleon-based description works down to < 0.5 fm



IS THERE A LIMIT FOR MESON-BARYON MODELS?



Not really but …

… there might be a more economical QCD description.

Scaling behavior ($d\sigma/dt \propto s^{-11}$) for P_T > 1.2 GeV/c (see ↑)

quark-gluon description sets in at scales below ~0.1 fm?

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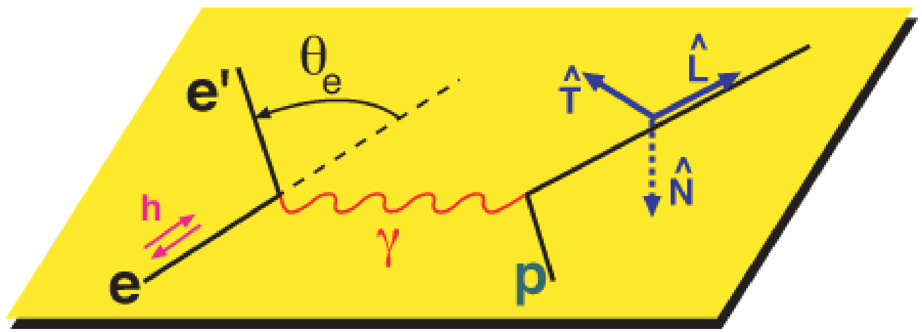
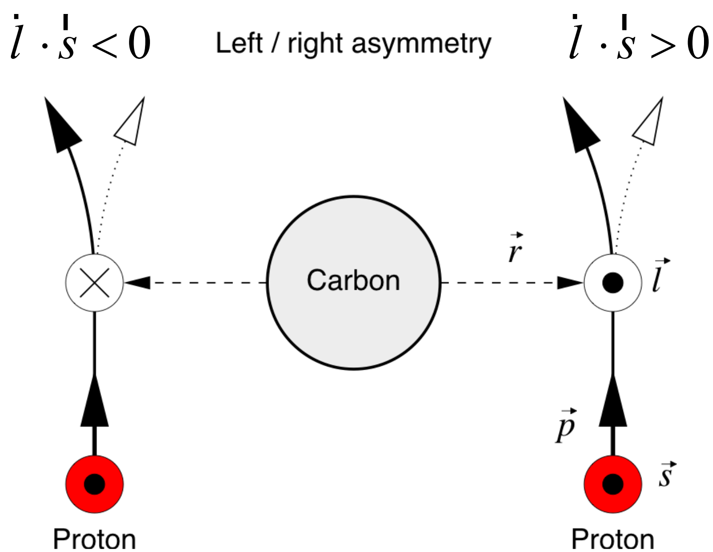
JLAB REVOLUTIONIZED POLARIZATION EXPERIMENTS!

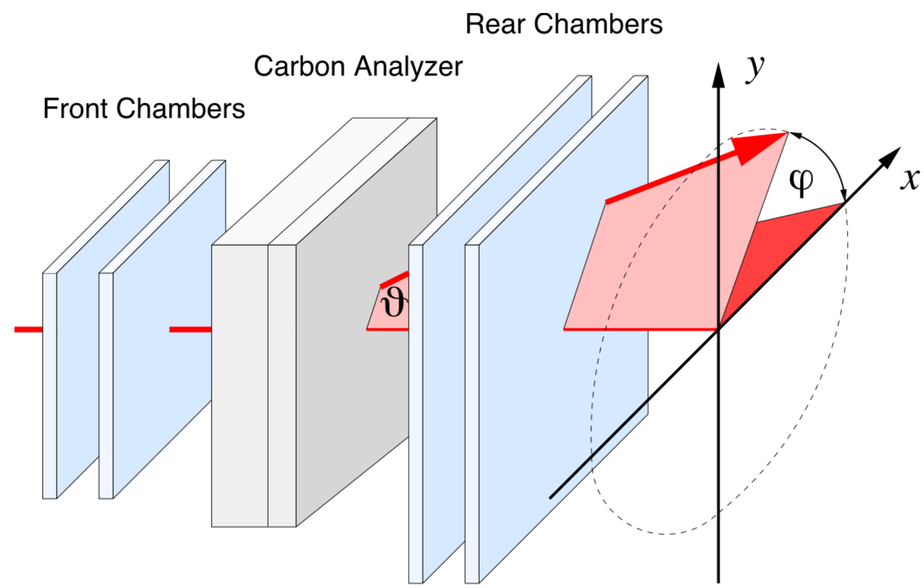
Precise access to (small) charge form factor of proton utilizing polarization transfer technique: $\vec{e} + p \rightarrow e' + \vec{p}$



Spin-dependent scattering



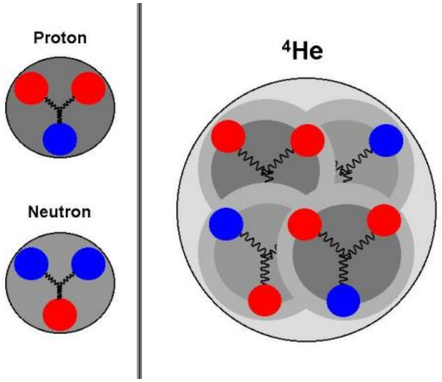
Focal Plane Polarimeter

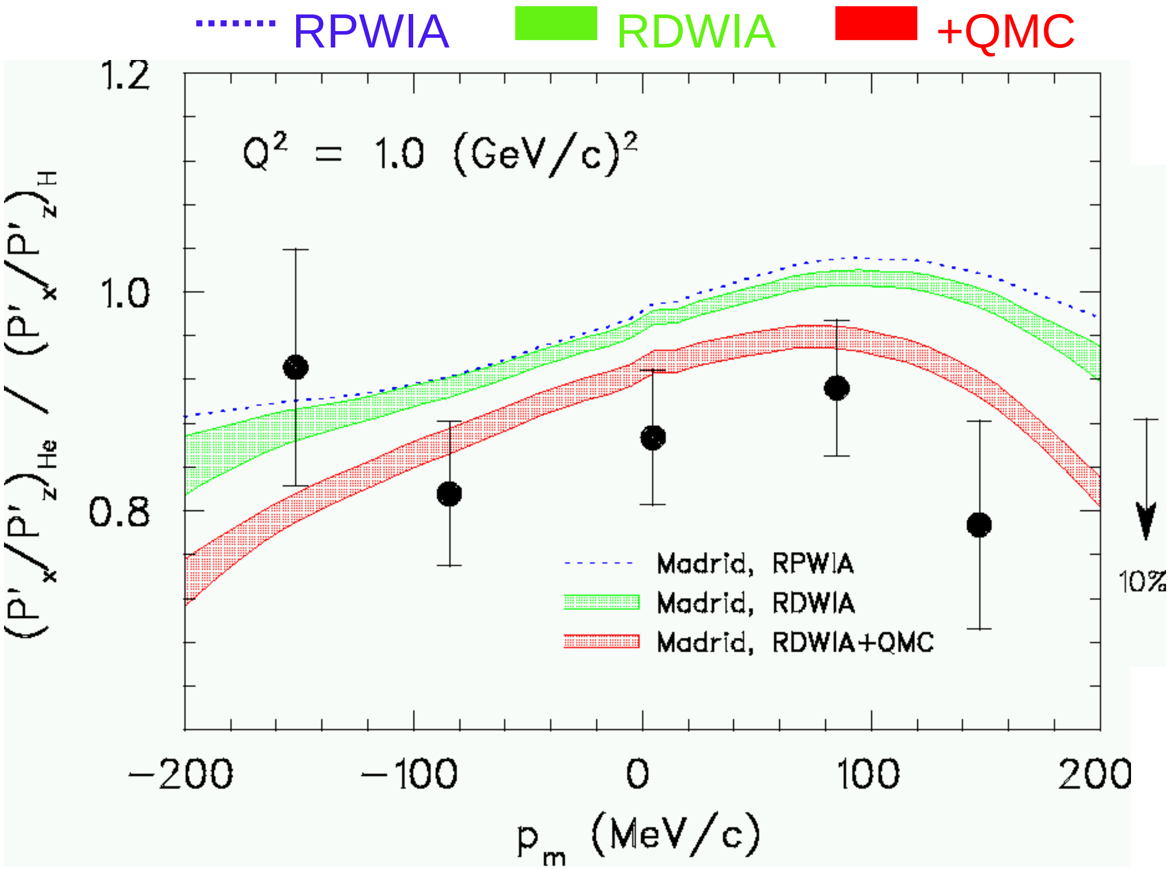


POLARIZATION TRANSFER IN ^{4}HE(E,E'P)^{3}H

- E93-049 (Hall A): Measured $^4He(\vec{e},e'\vec{p})^3H$ in quasi-elastic kinematics for Q^2 = 0.5, 1.0, 1.6 and 2.6 $(GeV/c)^2$ using Focal Plane Polarimeter
- Extracted "Superratio": (P'_x/P'_z) in ^{4}He/(P'_x/P'_z) in ^{1}H

At nuclear matter densities of 0.17 nucleons/fm^3, nucleon wave functions overlap considerably.





Medium Modifications of Nucleon Form Factor?

- Compared to calculations by Udias without and with inclusion of medium effects predicted by Thomas *et al*. (Quark Meson Coupling model).

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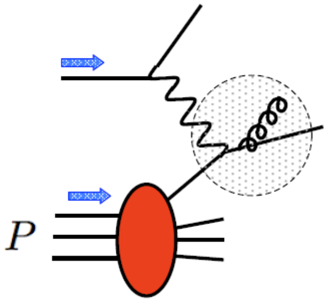
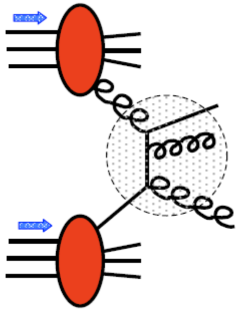
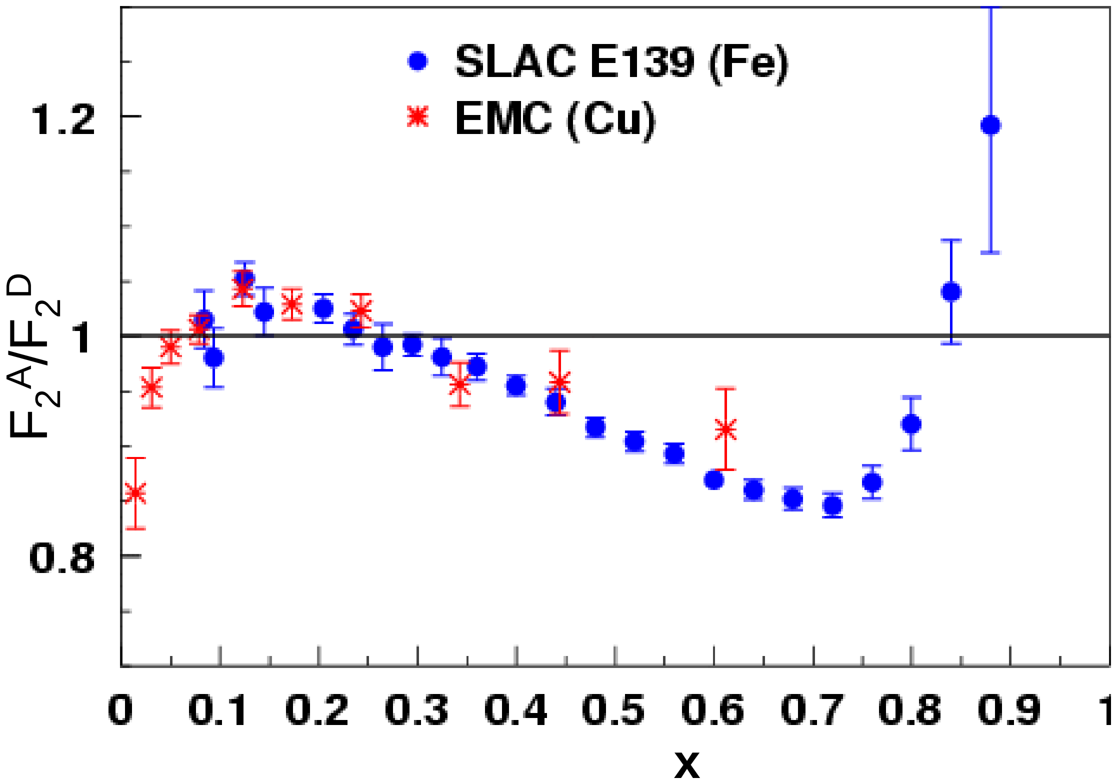
QUARKS & ANTI-QUARKS IN NUCLEI

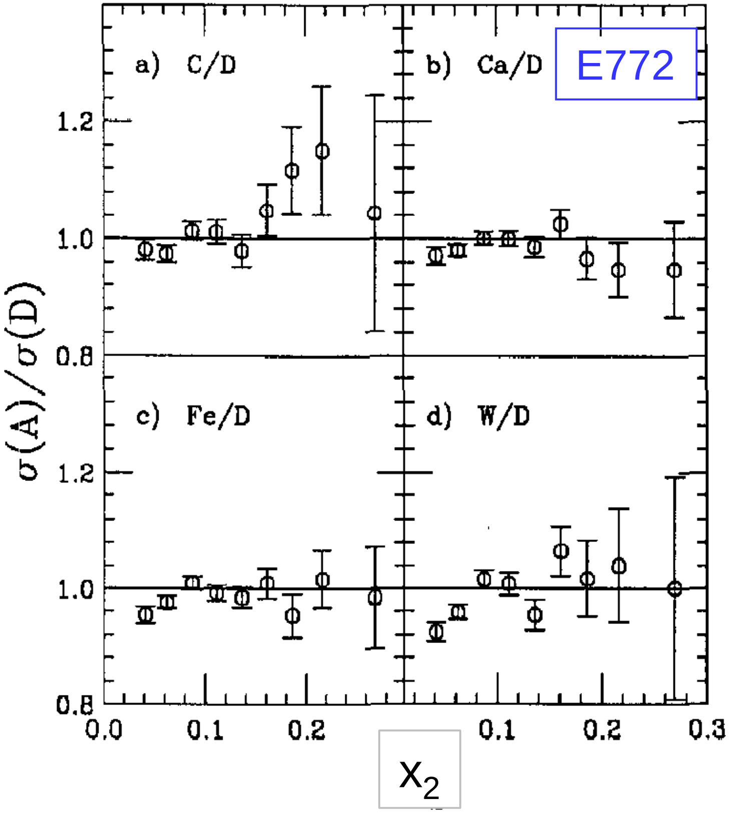


- F_2 **DIS** structure functions, or quark distributions, are altered in nuclei
- ~1000 papers on the topic; the best models explain the curve by change of nucleon structure - BUT we are still learning (e.g. local density effect)

Drell-Yan: Is the EMC effect a valence quark phenomenon or are sea quarks involved? (shouldn't there be?)





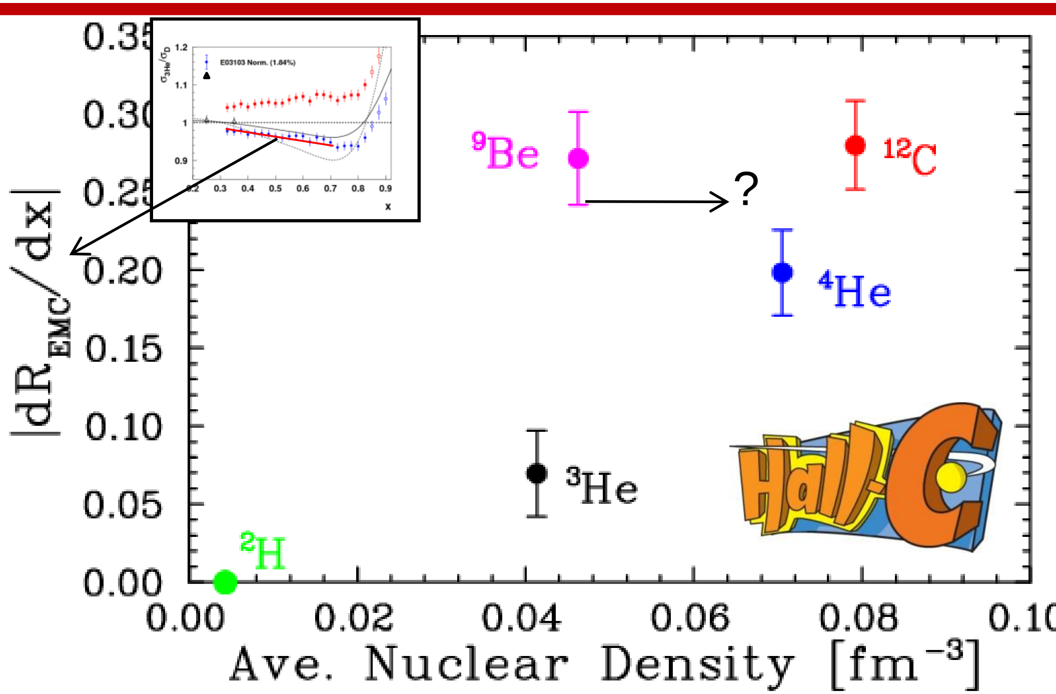


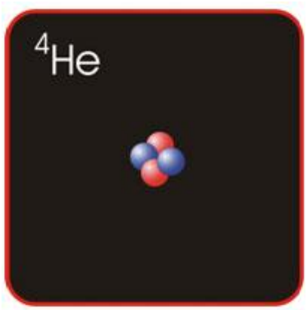
EMC EFFECT IN VERY LIGHT NUCLEI

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)

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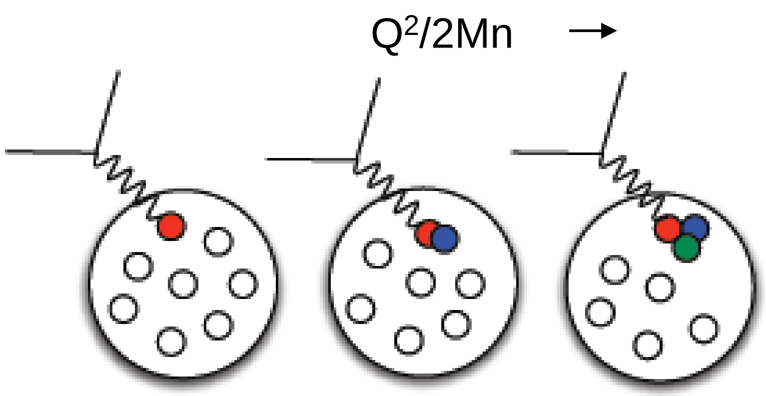
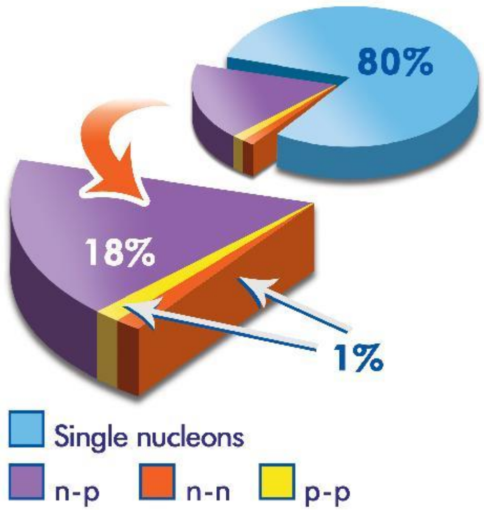
SHORT RANGE CORRELATIONS IN NUCLEI

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



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



Measured Composition (%)

	1N state	**2N** SRC
^{2}**H**	**96** ± 0.7	**4.0** ± 0.7
^{3}**He**	**92** ± 1.6	**8.0** ± 1.6
^{4}**He**	**86** ± 3.3	**15.4** ± 3.3
^{12}**C**	**80** ± 4.1	**19.3** ± 4.1
^{56}**Fe**	**76** ± 4.7	**23.0** ± 4.7

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**.

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MOMENTUM SHARING IN IMBALANCED FERMI SYSTEMS

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

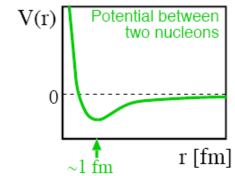
The Jefferson Lab CLAS Collaboration

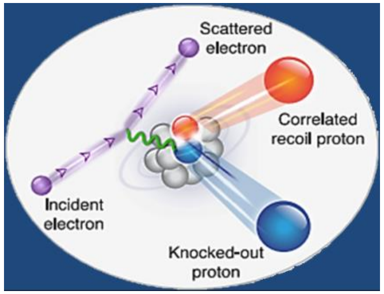
Selected for Science Express (16 October 2014)

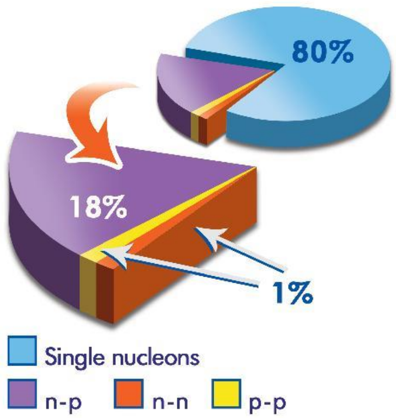
- For heavy nuclei, N (#neutrons) > Z (#protons)

  "Majority" "Minority"

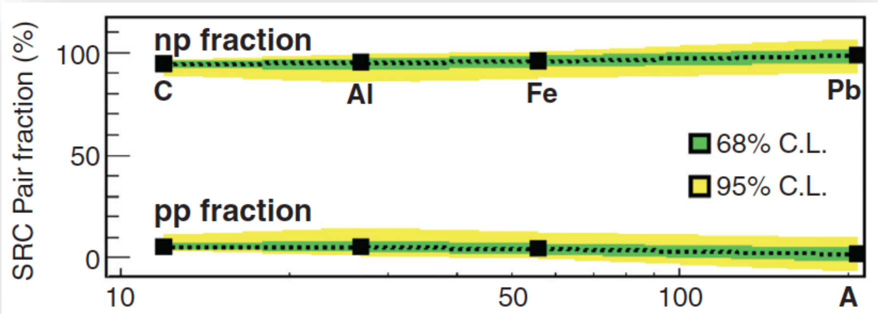
- For non-interacting Fermi gases, neutrons would dominate at all momenta, even above the Fermi momentum k_F
- In reality, short range nucleon-nucleon correlations dominate the population at $k>k_F$
- Isospin dependence of the nucleon-nucleon interaction implies equal numbers of protons and neutrons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



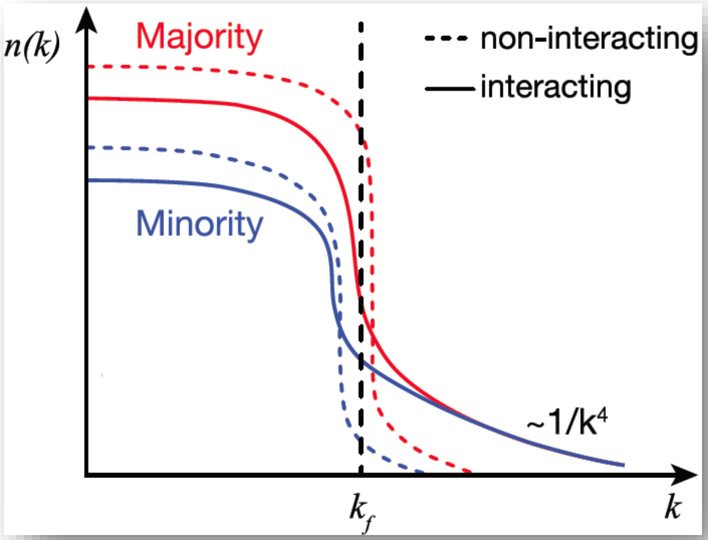




Experimental Result:



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



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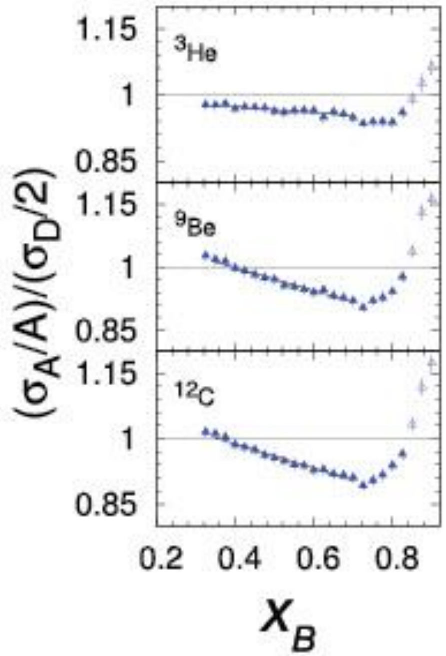
SHORT-RANGE CORRELATIONS (SRC) AND EUROPEAN MUON COLLABORATION (EMC) EFFECT ARE CORRELATED

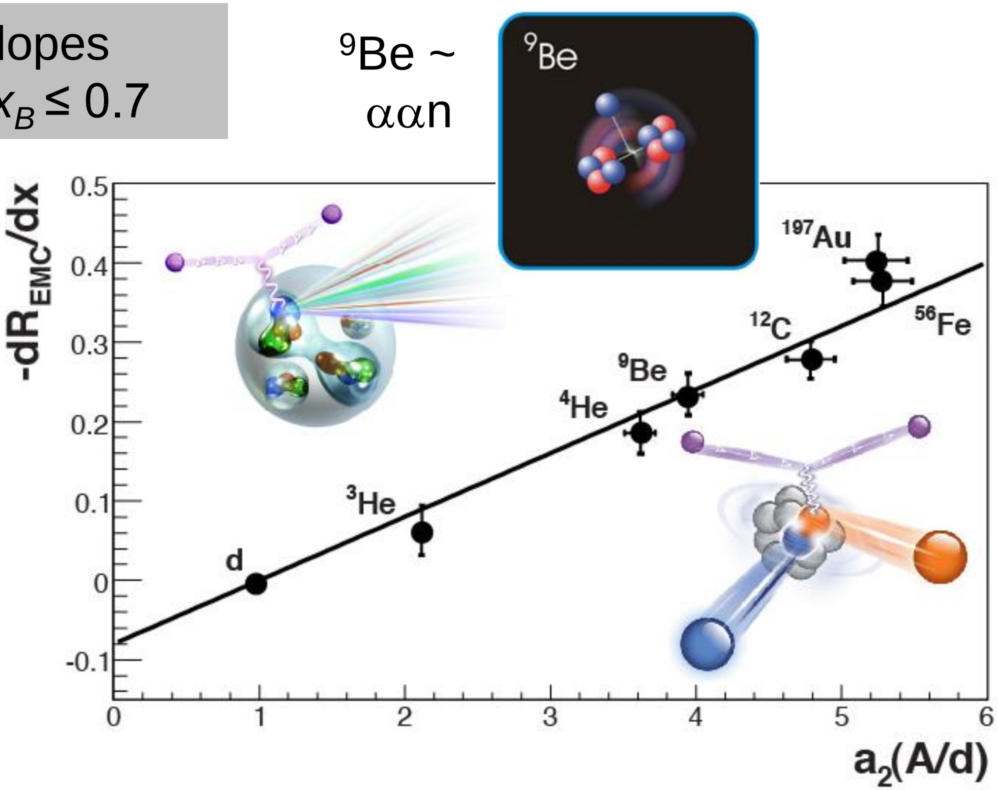
JLab Finding

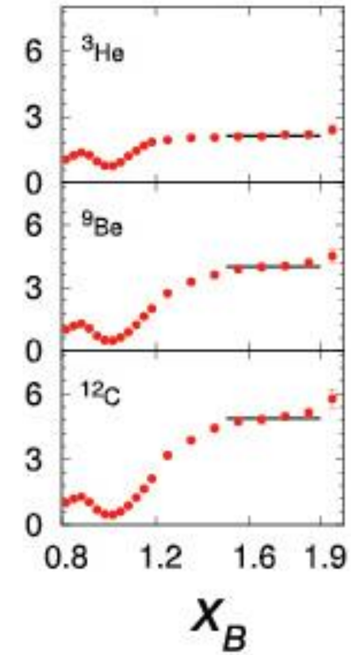
EMC Slopes
$0.35 \le x_B \le 0.7$

^{9}Be ~ ααn

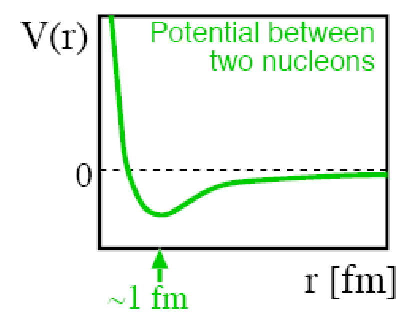
Fomin *et al.*, PRL 108, 092502 (2012)







SRC Scaling factors $x_B \ge 1.4$



SRC: nucleons see strong repulsive core at short distances
EMC effect: quark momentum in nucleus is altered

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

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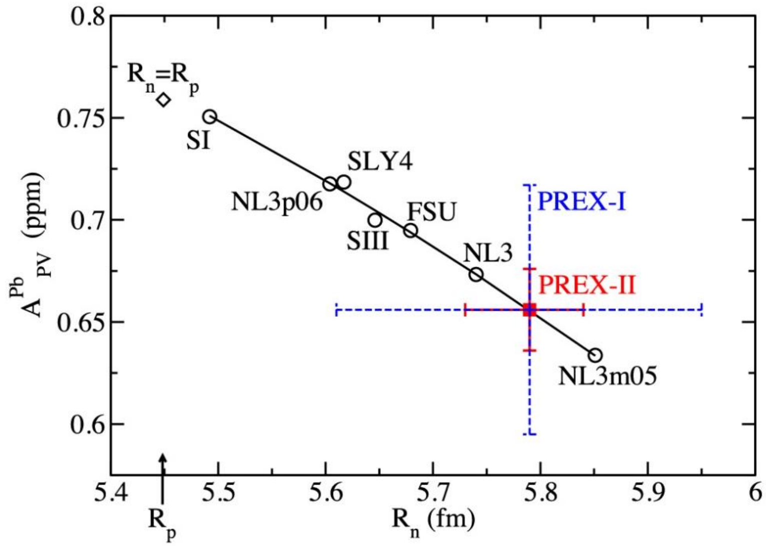
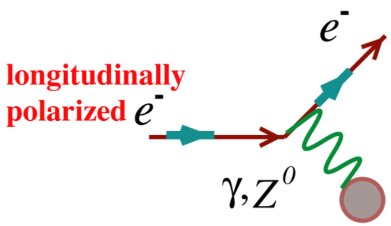
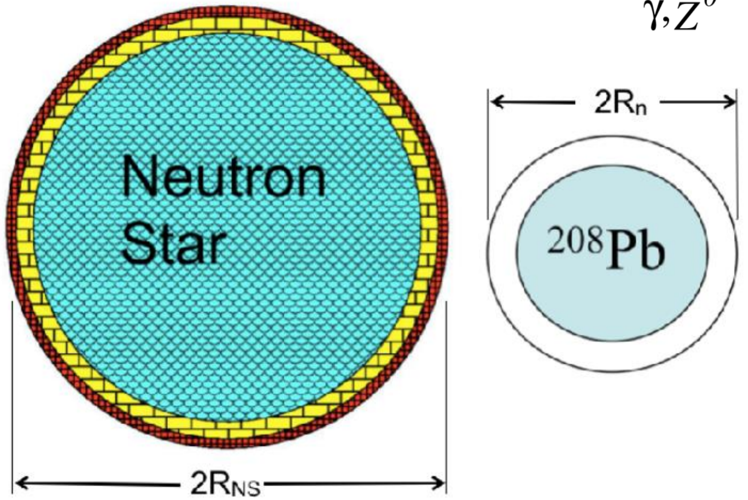
MEASURING THE NEUTRON "SKIN" IN THE PB NUCLEUS

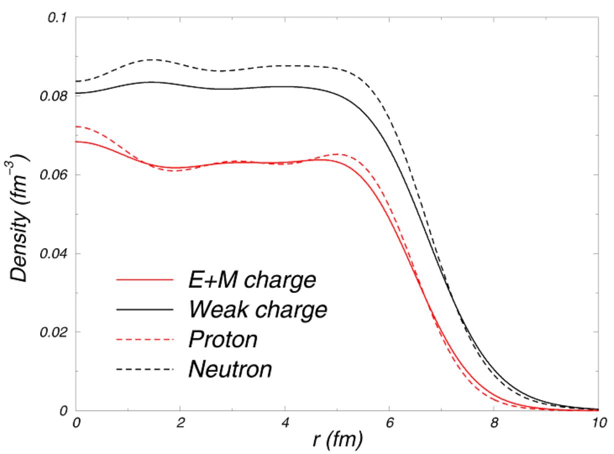
Elastic Scattering Parity-Violating Asymmetry A_{PV}

Z^0 : Clean Probe Couples Mainly to **Neutrons**









Neutron star is 18 orders of magnitude larger than Pb nucleus but has same neutrons, strong interactions and equation of state.

A neutron skin of 0.2 fm or more has implications for our understanding of neutron stars and their ultimate fate

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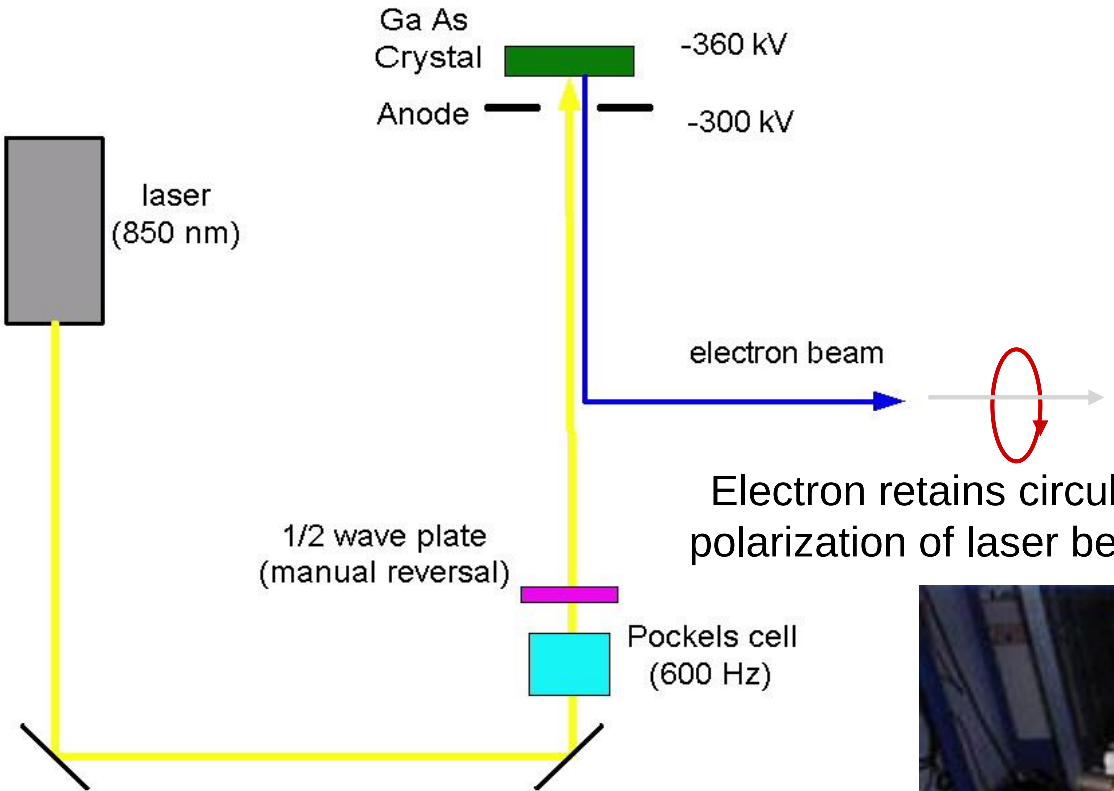
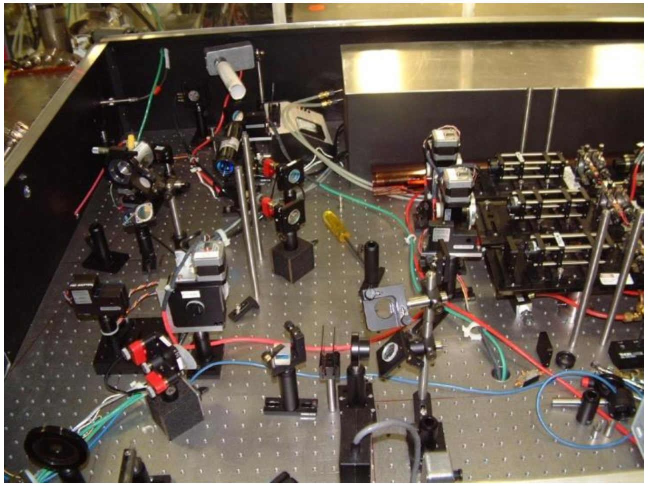
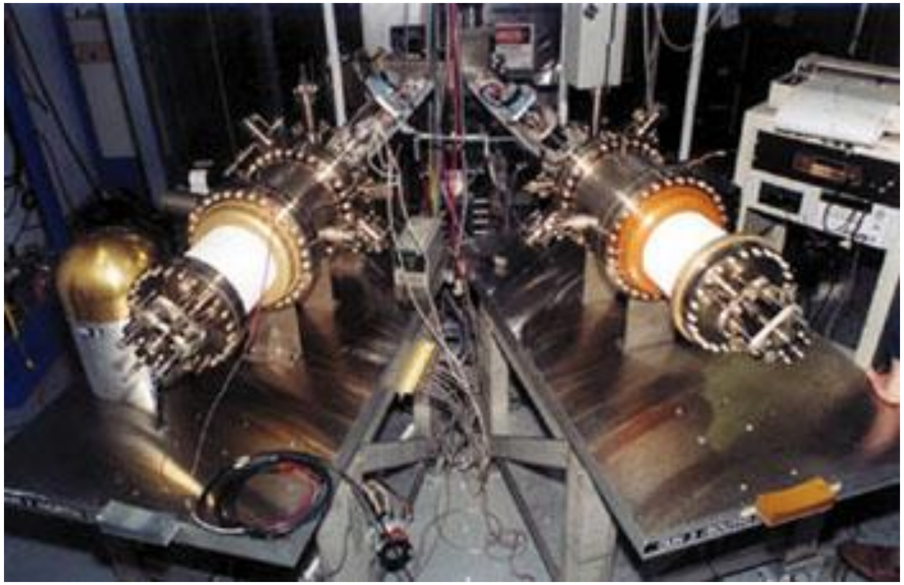
JLab: Polarized Electrons!!!



Electron retains circular polarization of laser beam



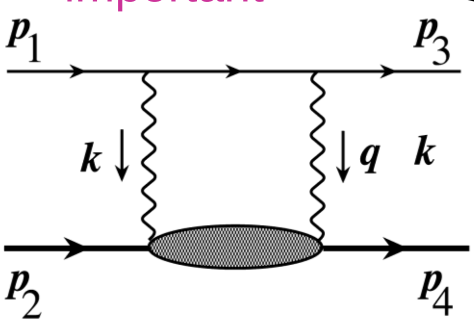


Reverse polarization of beam at rate of 30 Hz (now 1 kHz)

Feedback on laser intensity and position at high rate

PROTON CHARGE AND MAGNETIZATION

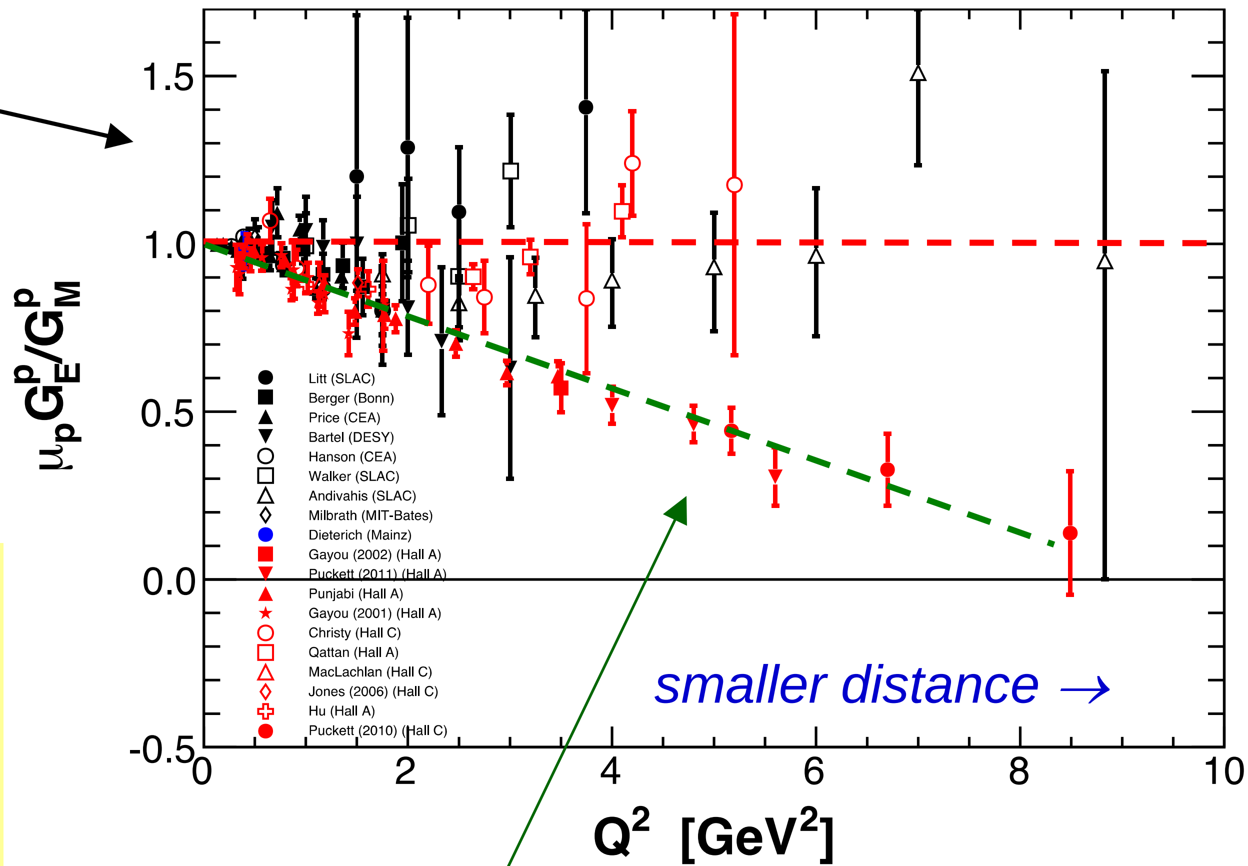
2-γ exchange important



Elastic electron-proton scattering

1) e + p → e' + p
G_E^p/G_M^p constant

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



charge depletion in interior of proton

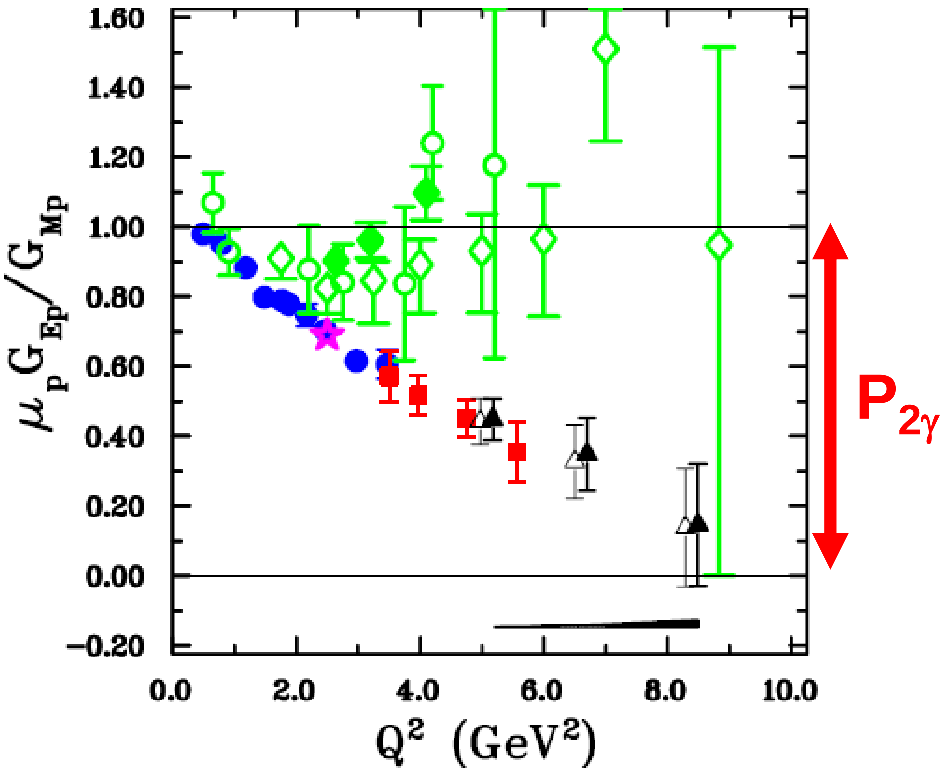
Charge & magnetization distributions in the proton **are different**

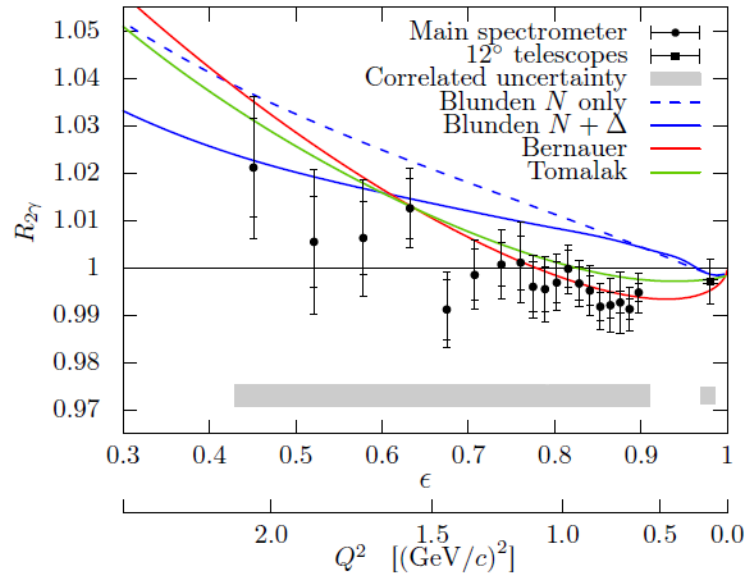
JLab Finding

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

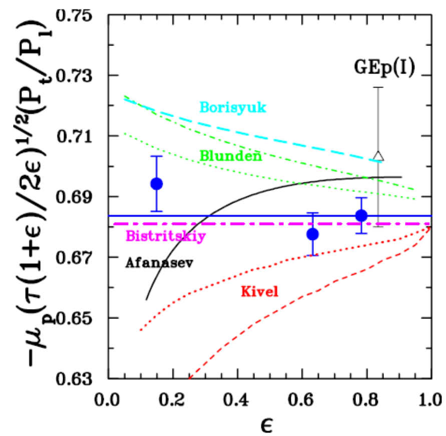
PROTON FORM FACTORS

The discrepancy between the proton form factor ratio as determined by the Rosenbluth and the Polarization Transfer technique is well established.





e^+/e^- ratio



Polarization transfer

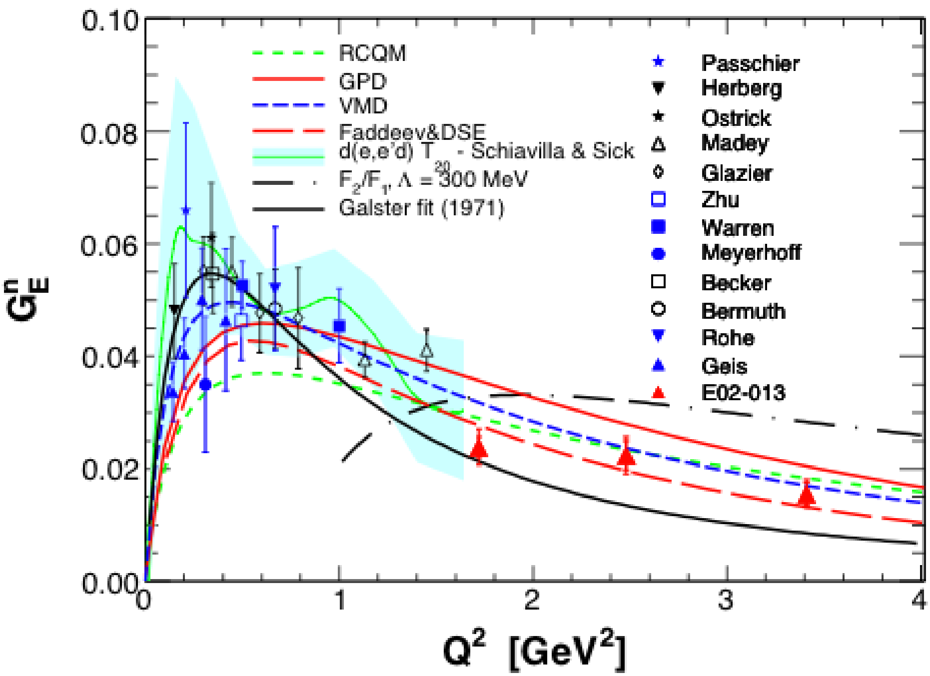
We believe **two-photon exchange** causes the difference. Problem remains that positron-electron comparisons undershoot the required effect, and are at lower Q^2.

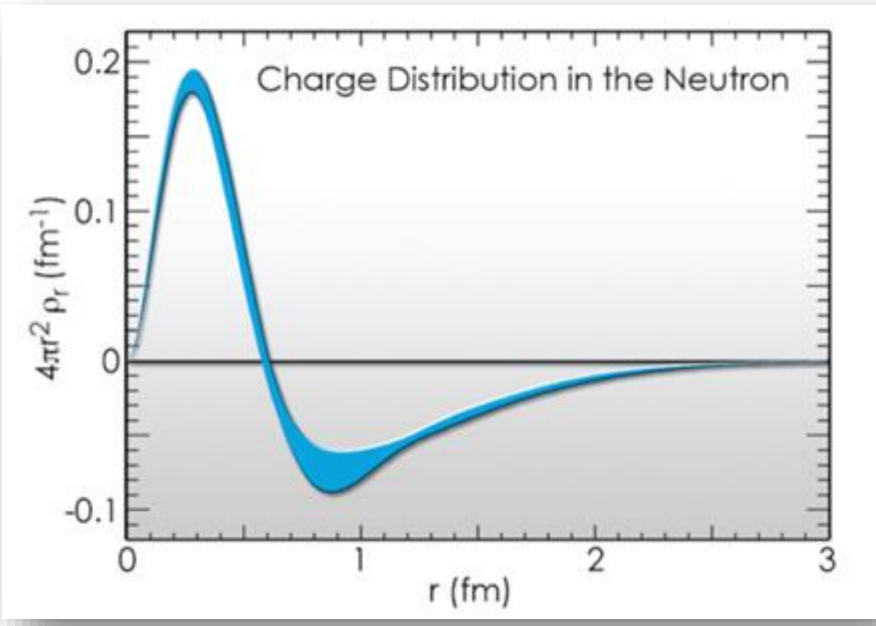
Hall A

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.*

(Polarization Experiments only)

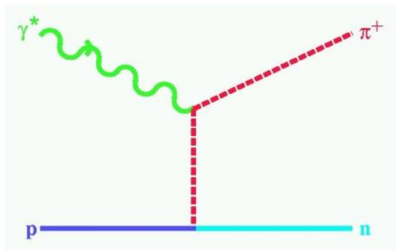




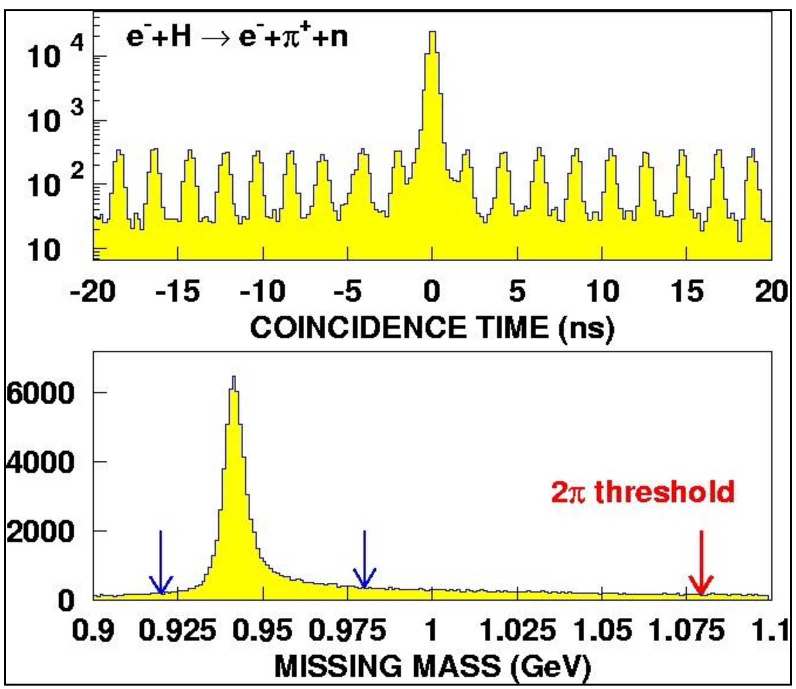
Combining proton and neutron: down quark has <u>more extended</u> spatial charge distribution. Is this due to the influence of di-quarks?

PION'S CHARGE DISTRIBUTION

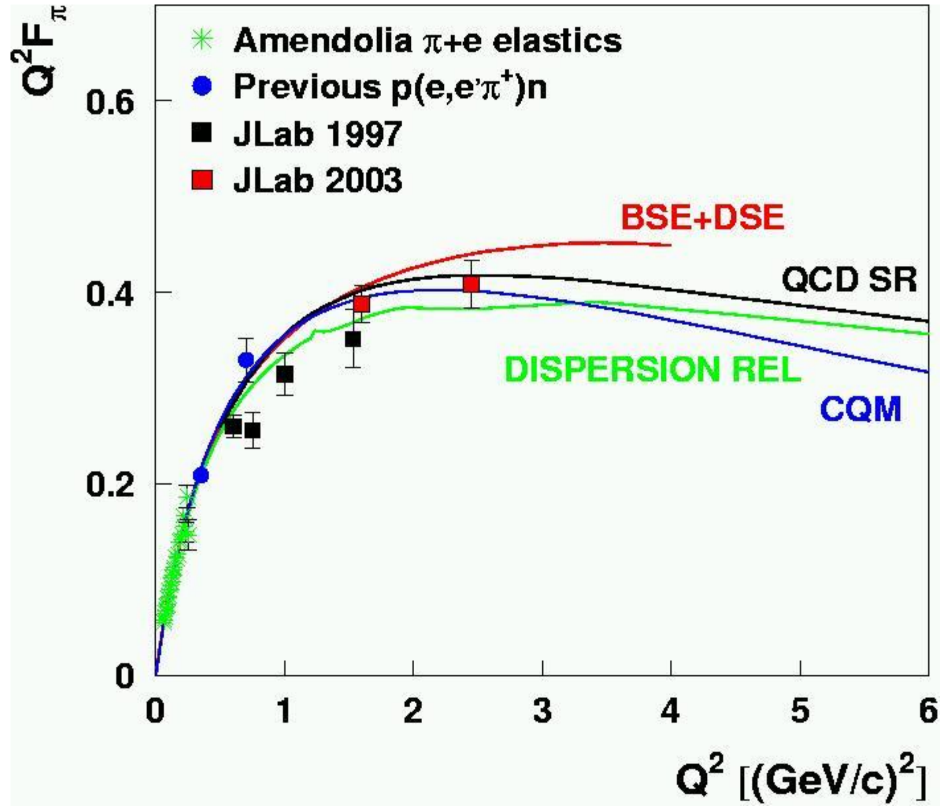
- At low Q^2 (< 0.3 $(GeV/c)^2$): use π + e scattering → R_{rms} = 0.66 fm
- At higher Q^2: use $^1H(e,e'\pi^+)n$



- Use a realistic pion electroproduction (Regge-type) model to extract F_π



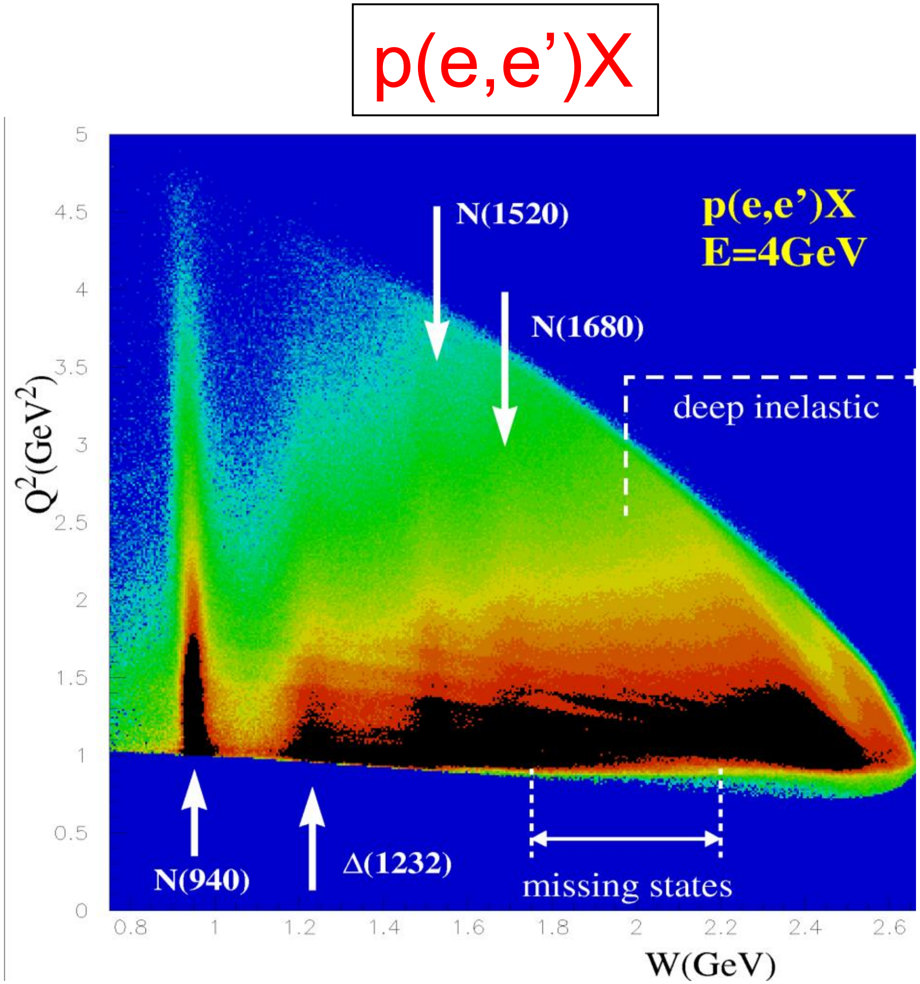
- In asymptotic region, $F_\pi \rightarrow 8\pi\alpha_s f_\pi^2 Q^{-2}$

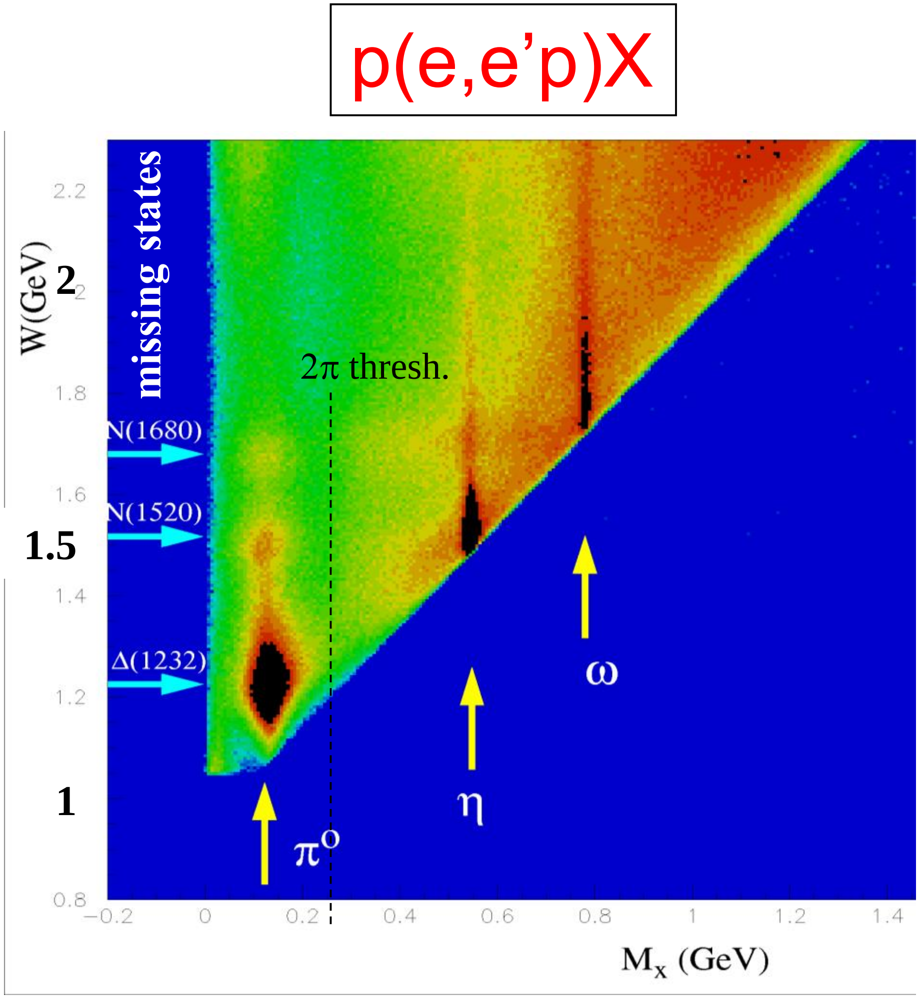


T. Horn et al., PRL 97 (2006) 192001
G. Huber et al., PRC 78 (2008) 045203

First measurements away from region where F_π is simply given by the π radius

Hall B ELECTRON SCATTERING CLAS





➢ Resonances cannot be uniquely separated in inclusive scattering → measure exclusive processes.

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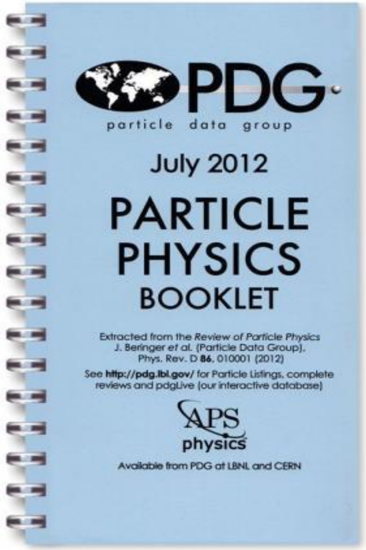
SOLVING THE "MISSING RESONANCES" PUZZLE



Star ratings of PDG before 2012 and projections for 2018, following worldwide experimental and theoretical effort.

****	Existence is certain
***	Existence is very likely
**	Evidence of existence is fair
*	Evidence of existence is poor

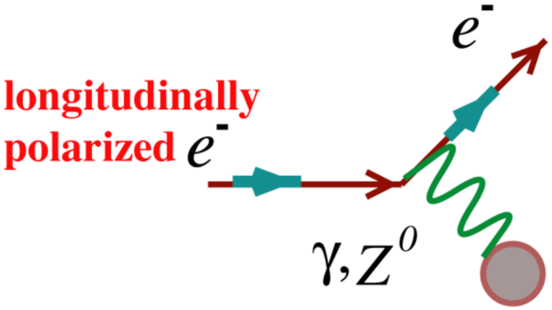
State N(mass)J^P	PDG pre 2012	PDG 2018*
N(1710)$1/2^+$	***	****
N(1880)$1/2^+$		***
N(1895)$1/2^-$		****
N(1900)$3/2^+$	**	****
N(1875)$3/2^-$		***
N(2120)$3/2^-$		**
N(2000)$5/2^+$	*	**
N(2060)$5/2^-$		**
Δ(2200)$7/2^-$	*	***

*) projected

PARITY-VIOLATING ASYMMETRIES

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

Longitudinally Polarized Electron Scattering
off Unpolarized Fixed Targets



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

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

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

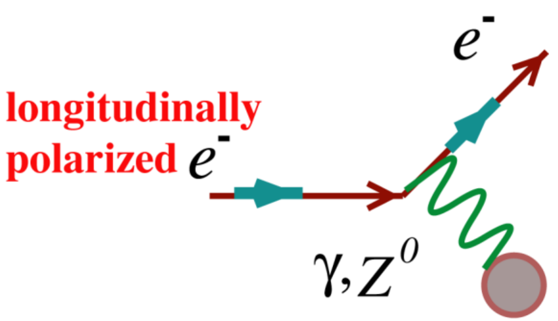
1990-2010 target couplings probe novel aspects of hadron structure

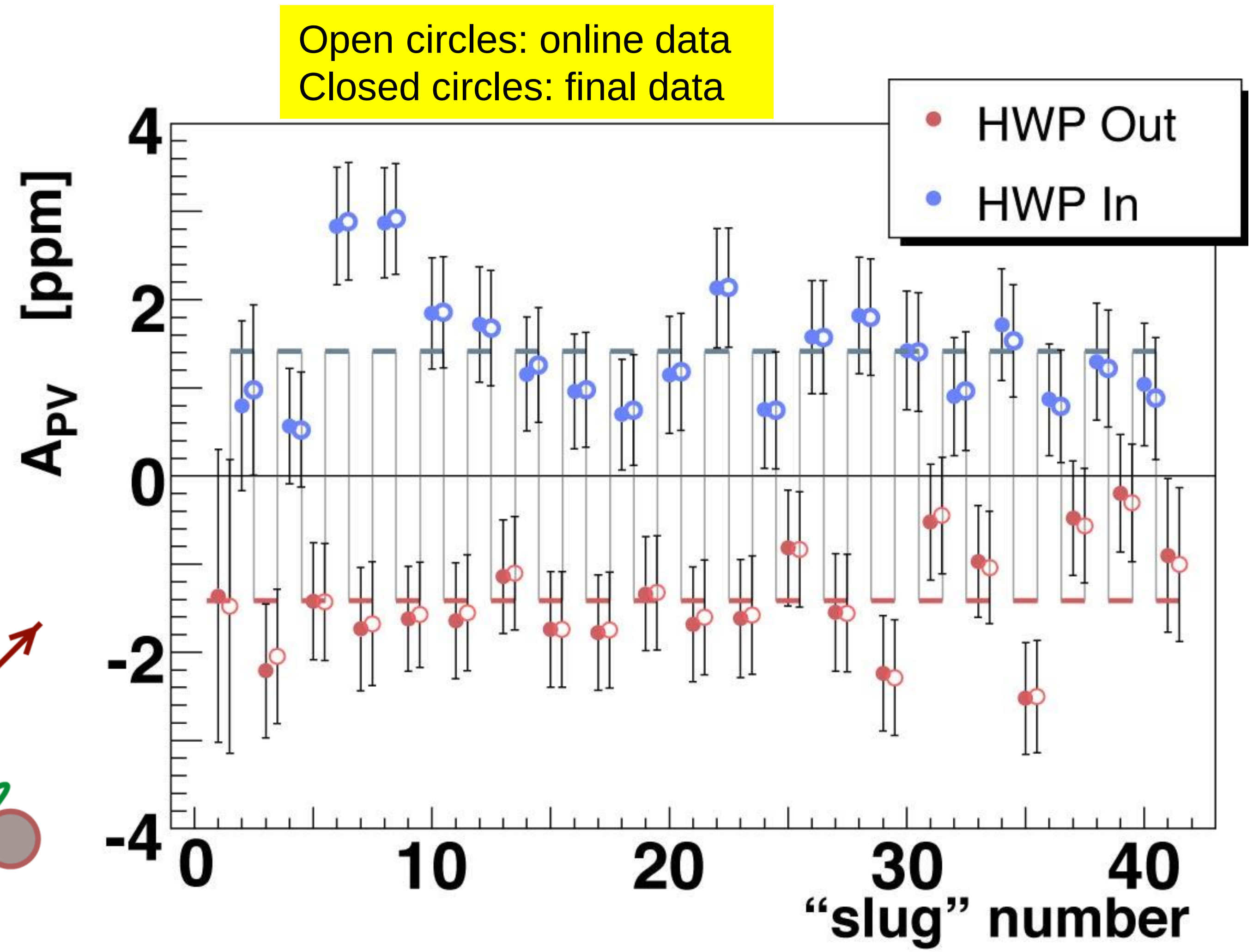
Ongoing precision measurements with carefully chosen kinematics to probe new physics at multi-TeV high energy scales

JLab: Parity Violation Program!!!

Example: The HAPPEx Program - Strange Quark Contributions to the Proton

Parity-violating asymmetry due to interference of electromagnetic + weak couplings





JLAB POLARIZED BEAM

G0 forward running beam:

- strained GaAs (P_B ~ 73%)
- 32 ns pulse spacing
- 40 μA beam current

HAPPEX-II beam (2005):

- superlattice (P_B > 85%)
- 2 ns pulse spacing
- 35 μA beam current

Beam Parameter	G0 beam (Hall C)	HAPPEx beam (Hall A)
Charge asymmetry	-0.14 ± 0.32 ppm	-2.6 ± 0.15 ppm
Position difference	**4 ± 4 nm**	**-8 ± 3 nm**
angle difference	1.5 ± 1 nrad	4 ± 2 nrad
Energy difference	29 ± 4 eV	66 ± 3 eV
Total correction to Asymmetry	-0.02 ± 0.01 ppm	0.08 ± 0.03 ppm

THE SPATIAL DISTRIBUTION OF QUARKS AND THE PROTON'S MAGNETISM

Naïve Quark Model: proton = uud (valence quarks)

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

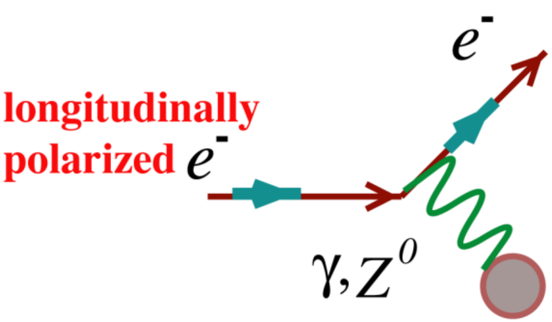
The proton sea has a non-trivial structure: $\bar{u} \neq \bar{d}$

How much do virtual strange quark-antiquark pairs contribute to the structure of the proton?

Hall A

$$G_{E,M}^{\gamma,p}(Q^2) = \frac{2}{3}G_{E,M}^{u}(Q^2) - \frac{1}{3}G_{E,M}^{d}(Q^2) - \frac{1}{3}G_{E,M}^{s}(Q^2)$$

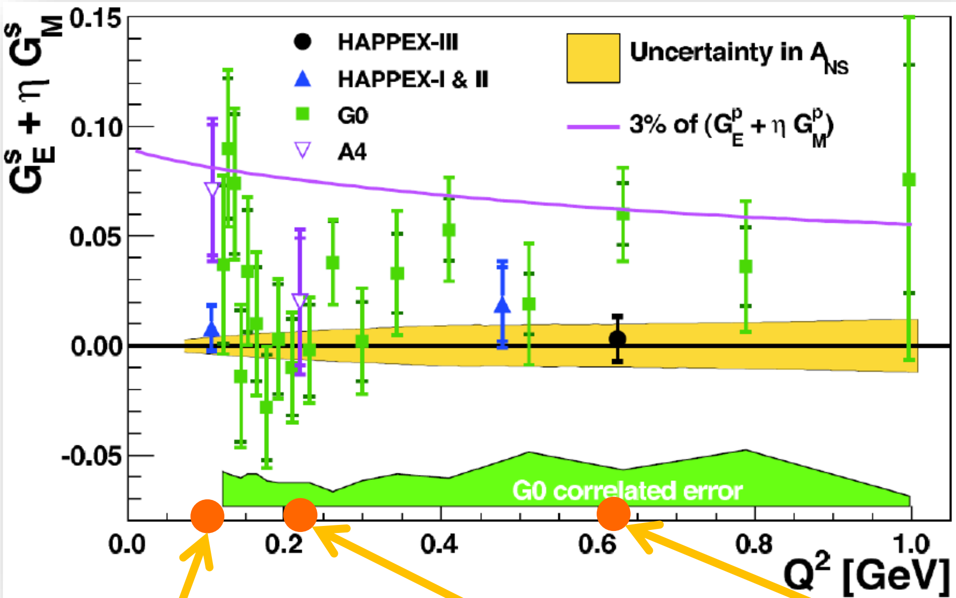
proton charge/magnetism	up
neutron charge/magnetism	down
proton response to Weak force	strange



$$G_{E,M}^{Z,p}(Q^2) = \left(1 - \frac{8}{3}\sin^2\Theta_W\right)G_{E,M}^{u}(Q^2) + \left(-1 + \frac{4}{3}\sin^2\Theta_W\right)G_{E,M}^{d}(Q^2) + \left(-1 + \frac{4}{3}\sin^2\Theta_W\right)G_{E,M}^{s}(Q^2)$$

STRANGENESS CONTRIBUTION TO NUCLEON FORM FACTORS

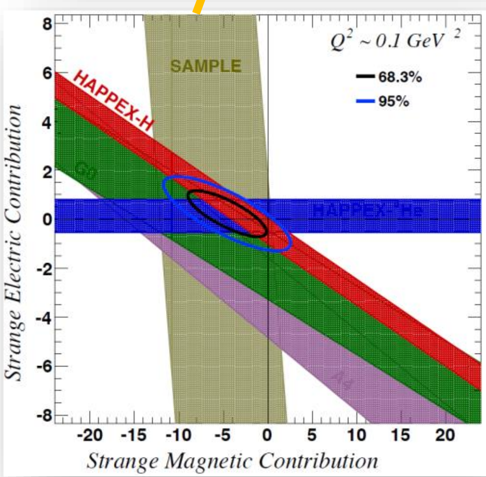
Hall A

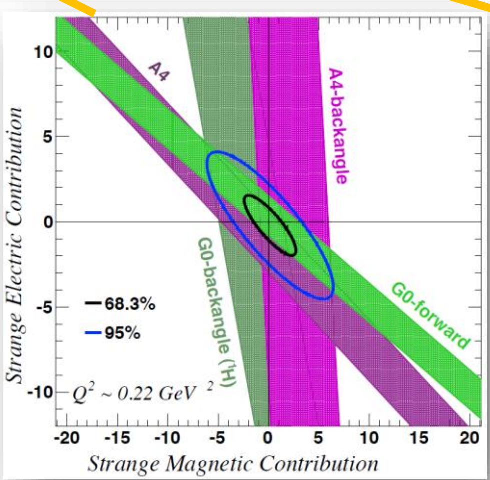


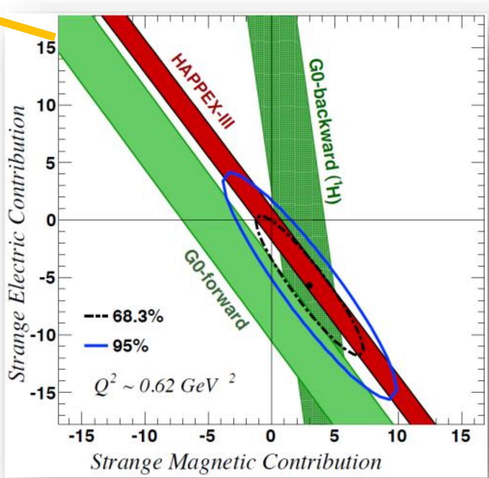
HAPPEx-3: PRL 108 (2012) 102001
G0-Backward: PRL 104 (2010) 012001

Purple line represents 3% of the proton form factors
→ strange quarks **do not play a substantial role** in the long-range electromagnetic structure of nucleons

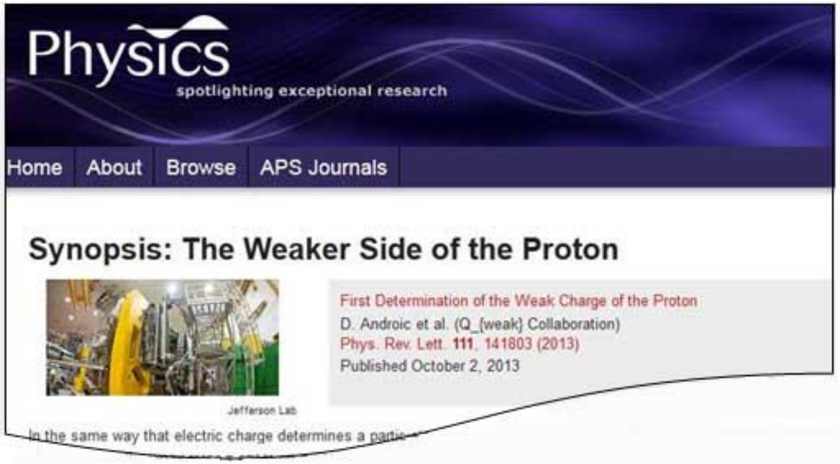
Data available for E/M separation at three Q^2 values



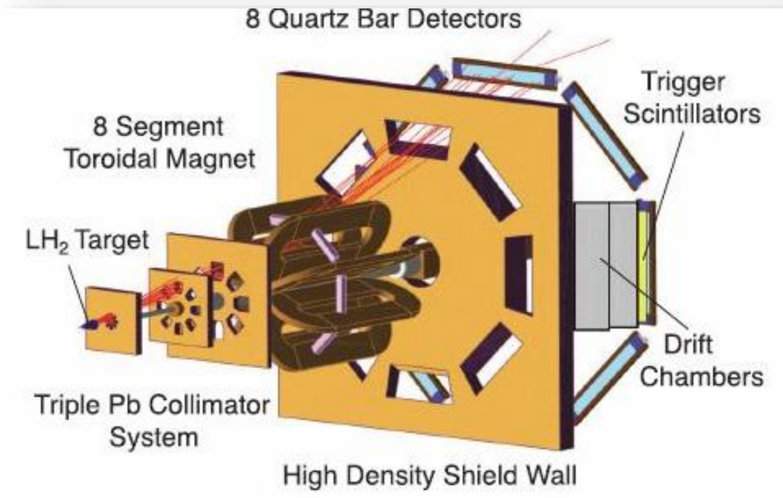


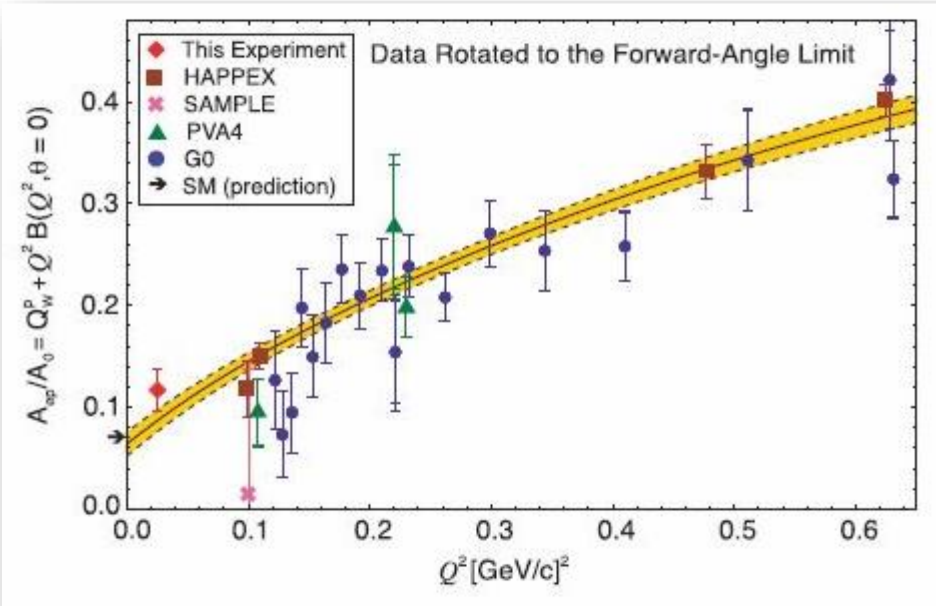


DETERMINING THE WEAK CHARGE OF THE PROTON (NEUTRON)



If you know the strangeness is constrained, go to a region where it is minimized more, and perform a Physics Beyond the Standard Model test!





Electroweak elastic electron-proton scattering

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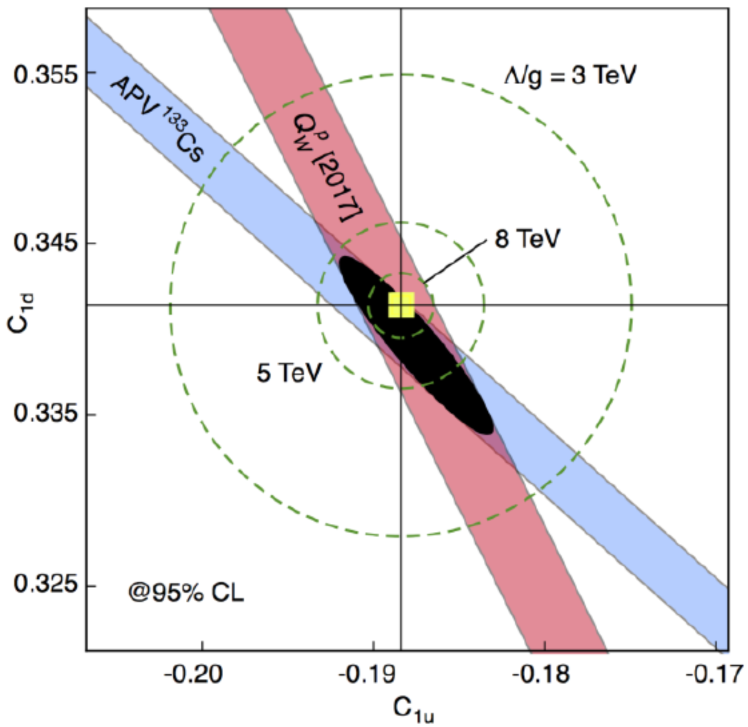
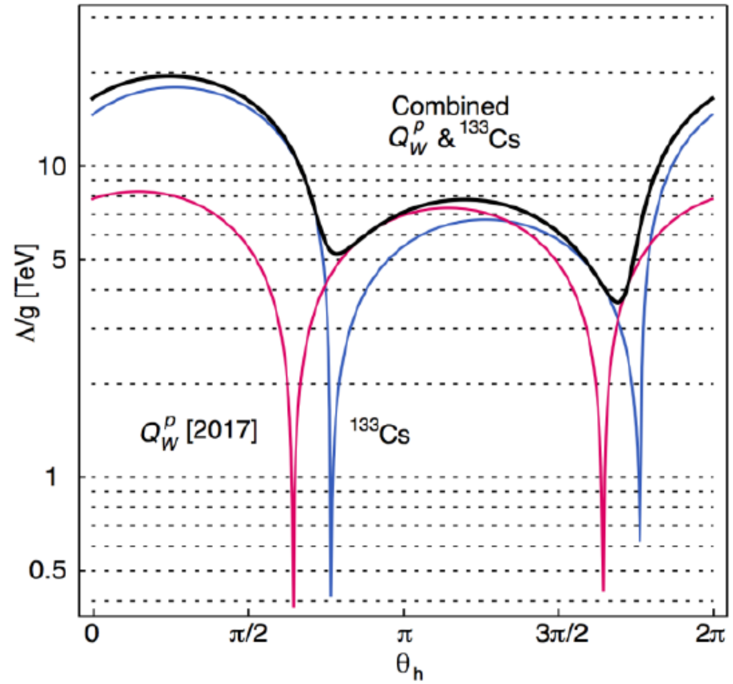
QWEAK EXPERIMENT RESULTS → CONSTRAINTS

Qweak was one of the last 6-GeV era experiments to run, up to FY12





Constraints on the vector-quark, axial-electron weak coupling constants C_{1u} and C_{1d} provided by the Qweak and APV results.

Combined constraint raises the Θ_h-independent for generic new semi-leptonic Parity-Violating Beyond the Standard Model physics to 3.6 TeV (mass reach in Λ/g).

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CEBAF'S ORIGINAL MISSION STATEMENT

Key Mission and Principal Focus (1987):

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

The Role of Quarks in Nuclear Physics

Related Areas of Study:

- **Do individual nucleons change their size, shape, and quark structure in the nuclear medium?**
- **How do nucleons cluster in the nuclear medium?**

Pushing the Limits of the Standard Model of Nuclear Physics

- **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?**

Charge and Magnetization in Nucleons and Pions

The Onset of the Parton Model

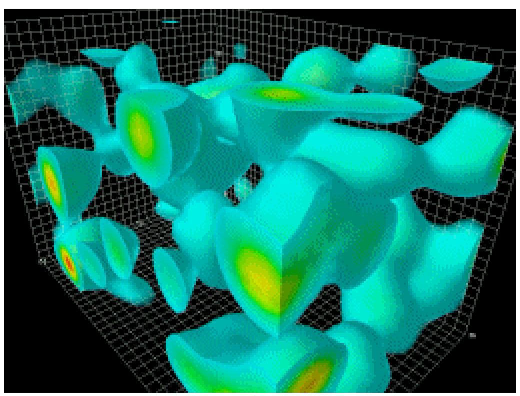
THE REVOLUTION IN HADRON AND NUCLEAR STRUCTURE

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

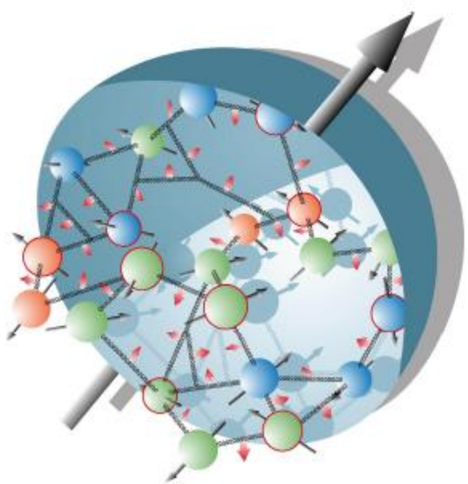
Protons and Neutrons in terms of constituent (valence) quarks is a very decent effective model: the Constituent Quark Model works surprisingly well.
Resolution or Momentum transfer Q is small

Looking deep inside protons and neutrons:

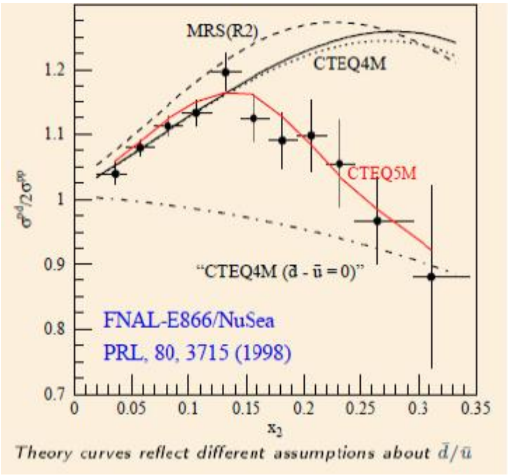
Quantum fluctuations + special relativity + $M = E/c^2$ gives rise to quark-gluon dynamics (structure and interactions).
Resolution or Momentum transfer Q is "large"



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



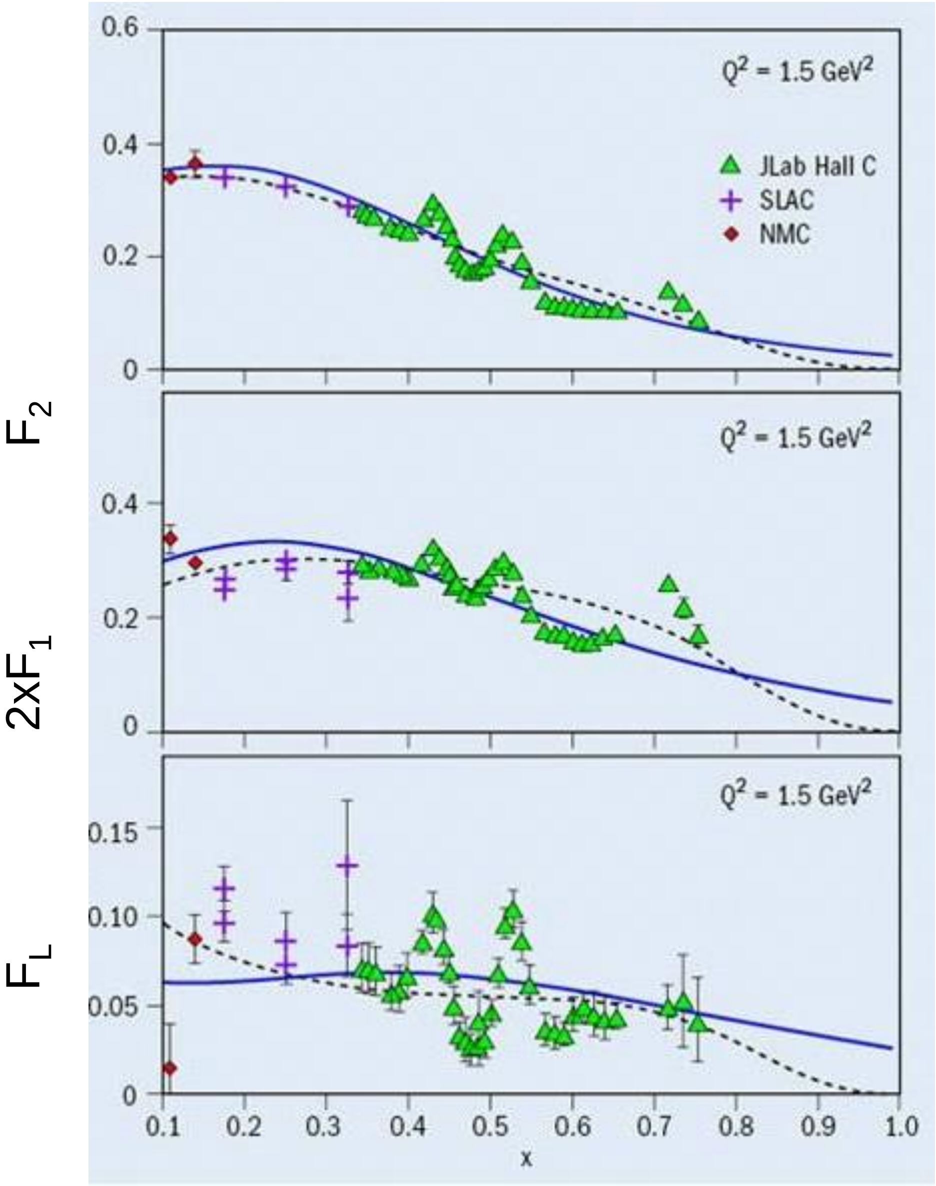
The proton is complex, mass and spin are emergent phenomena



Quantum fluctuations play a role in nucleon structure:

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

SEPARATED STRUCTURE FUNCTIONS: QUARK-HADRON DUALITY WORKS WELL FOR F_2, $2xF_1$ (F_T), AND F_L

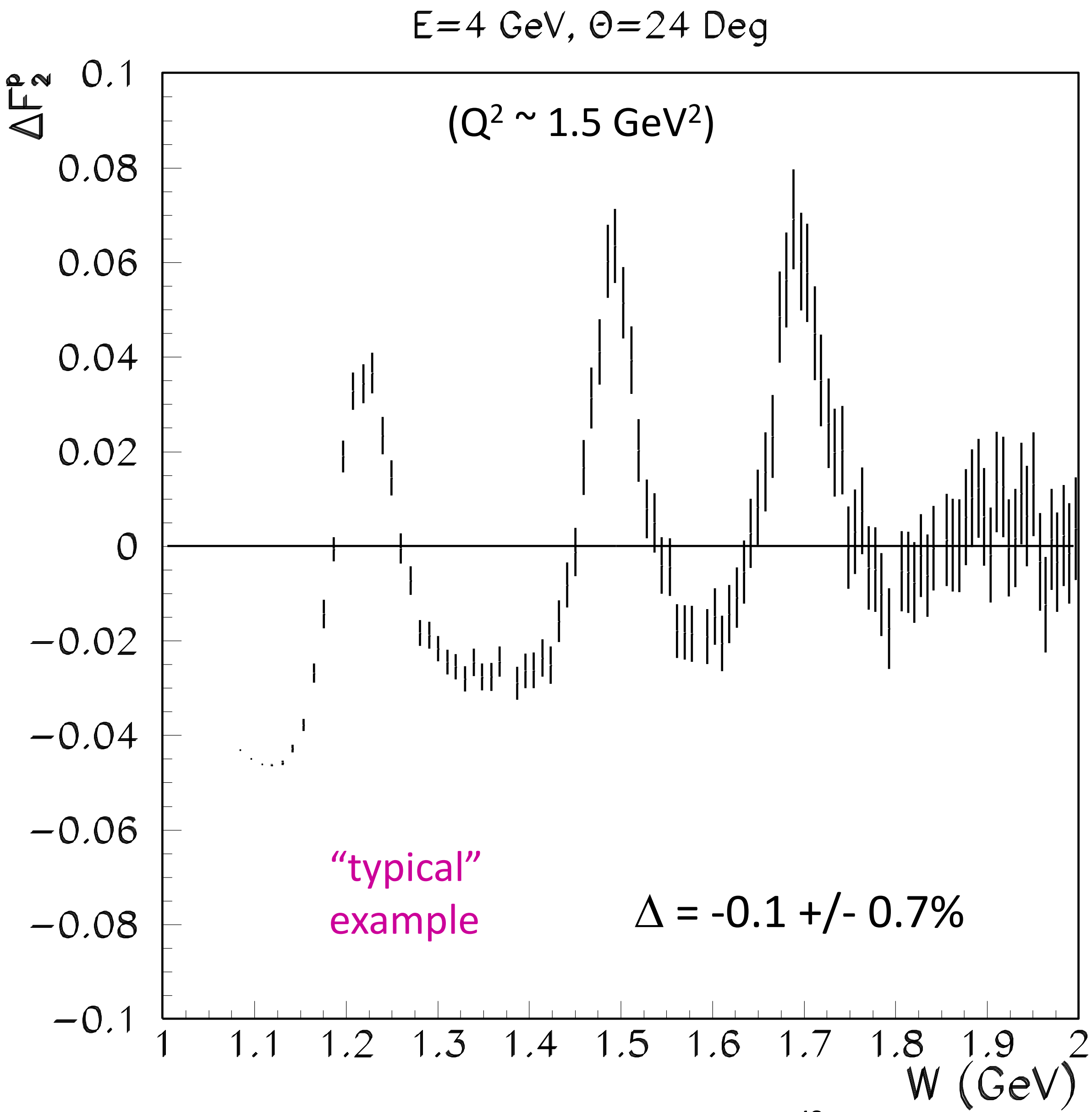


- The resonance region is, on average, well described by NNLO QCD fits.
- This implies that Higher-Twist (FSI) contributions cancel, and are on average small. "Quark-Hadron Duality"
- The result is a smooth transition from Quark Model Excitations to a Parton Model description, or a smooth quark-hadron transition.
- This explains the success of the parton model at relatively low W^2 (=4 GeV^2) and Q^2 (=1 GeV^2).

"The successful application of duality to extract known quantities suggests that it should also be possible to use it to extract quantities that are otherwise kinematically inaccessible."

(CERN Courier, December 2004)

QUANTIFICATION: RESONANCE REGION F_2 W.R.T. ALEKHIN NNLO SCALING CURVE

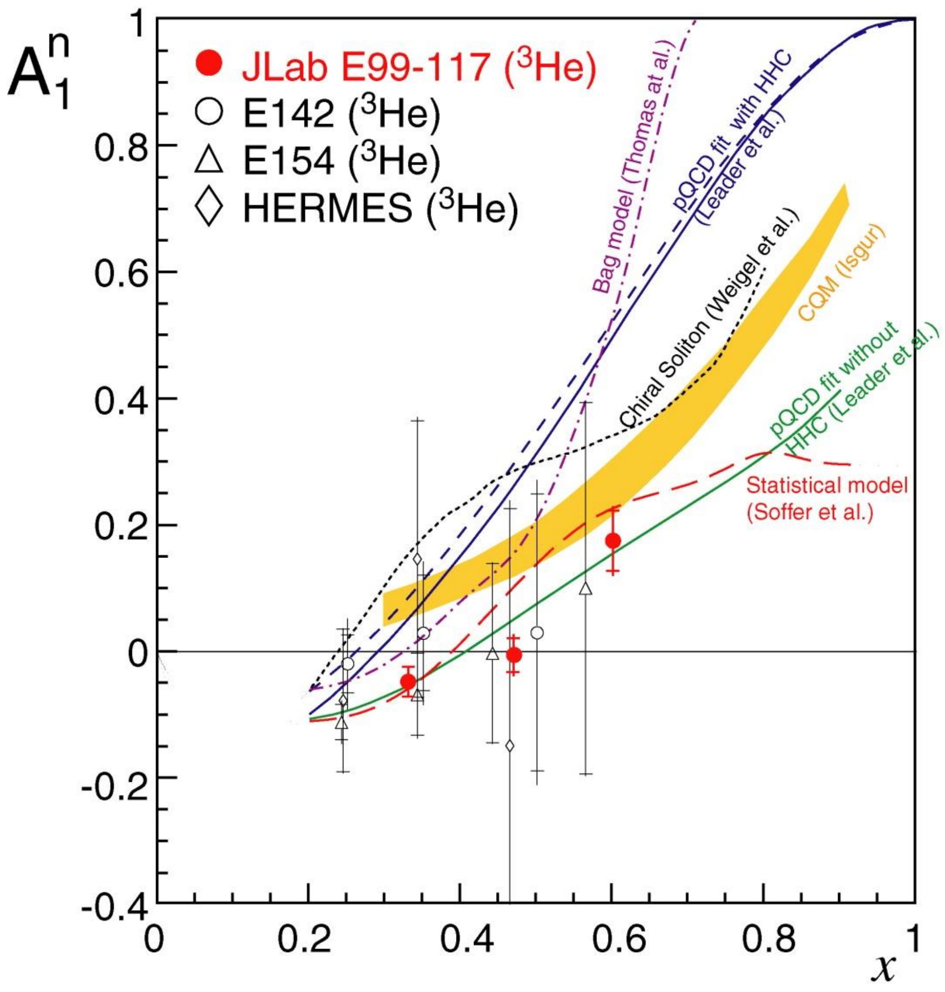


- Evidence of resonance transitions is "bumps and valleys" around the expected parton model behavior.
- Similar as standard textbook example of $e^+e^- \rightarrow$ hadrons
- **"Resonances build the parton subprocess cross section because of a separation of scales between hard and soft processes."**
- **Confinement is Local**

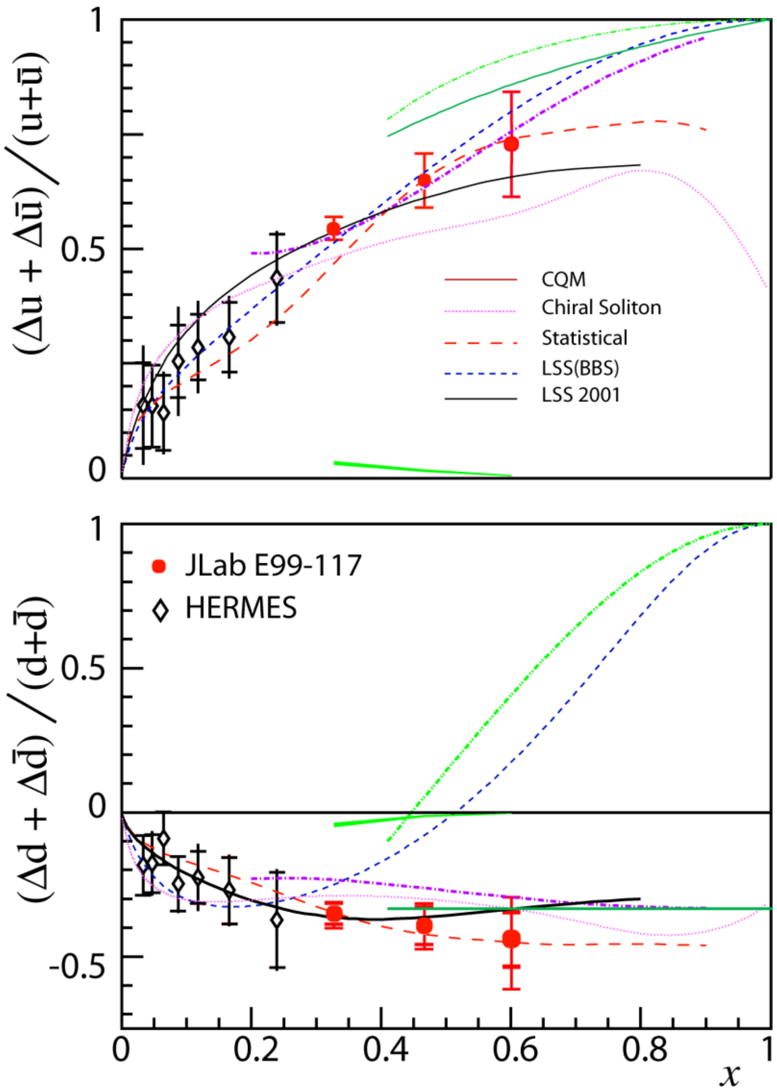
PARTON MODEL IDEAS VALID @ 6 GEV

Hall A

First measurement in large-x region unambiguously showing that $A_1^n > 0$ ($A_1^n = 0$ in the SU(6) Quark Model)



Allows for Flavor Decomposition:



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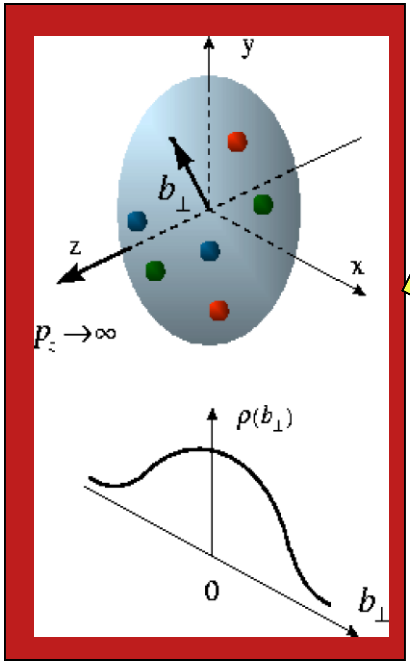
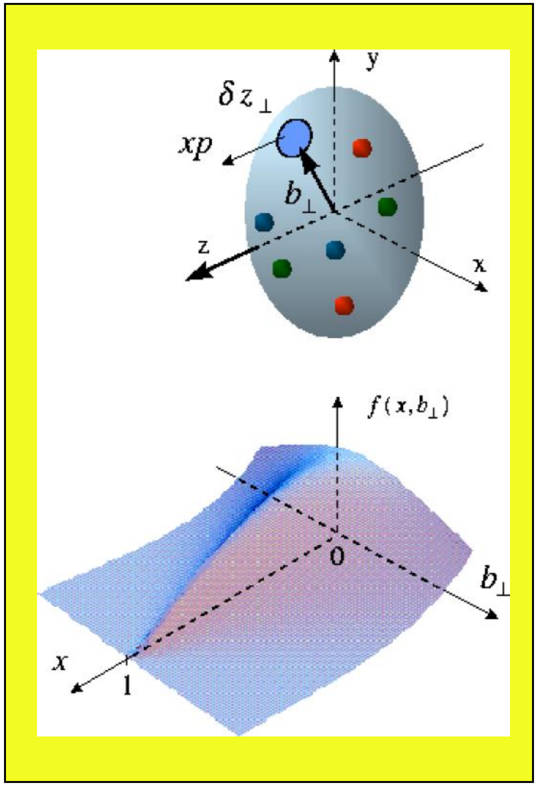
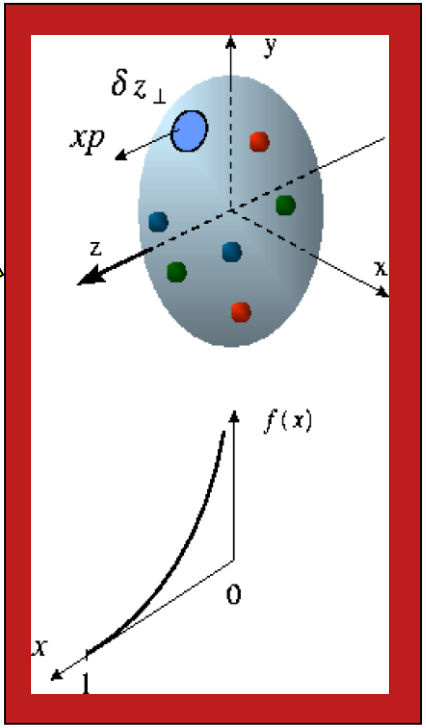
BEYOND FORM FACTORS AND QUARK DISTRIBUTIONS

Generalized Parton and Transverse Momentum Distributions







1990's

Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

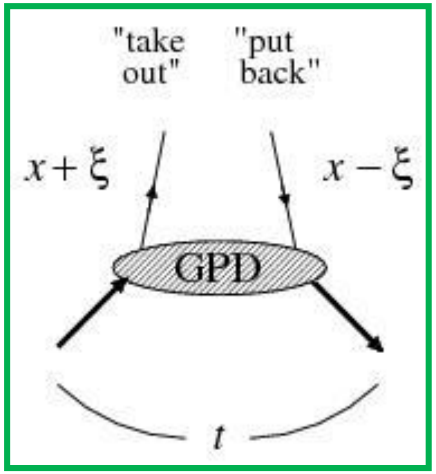
Structure functions, quark longitudinal momentum & helicity distributions

2000's

Extend longitudinal quark momentum & helicity distributions to transverse momentum distributions - TMDs

WHAT'S THE USE OF GPDS?

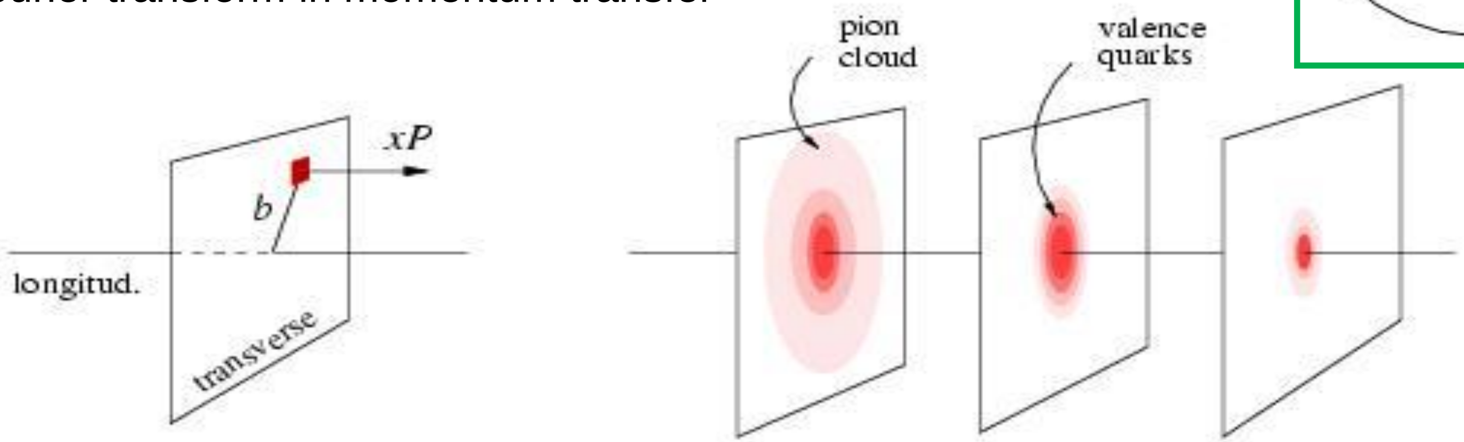
1. Allows for a unified description of form factors and parton distributions



2. Describe correlations of quarks/gluons

3. Allows for Transverse Imaging

Fourier transform in momentum transfer



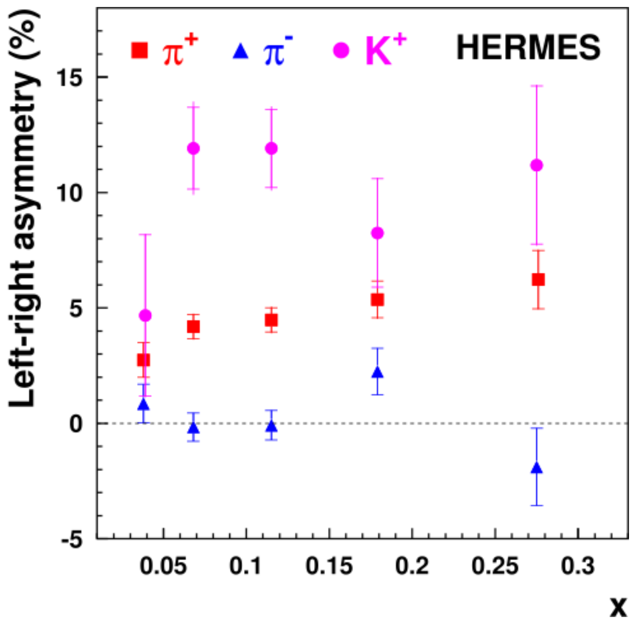
x < 0.1 x ~ 0.3 x ~ 0.8

gives transverse spatial distribution of quark (parton) with momentum fraction x

4. Allows access to quark angular momentum (in model-dependent way)

3D PARTON DISTRIBUTIONS: TMDS

A surprise of transverse-spin experiments



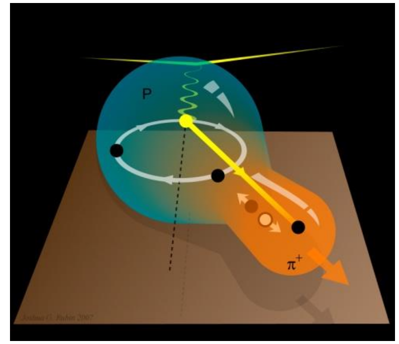


Illustration of the possible correlation between the internal motion of an up quark and the direction in which a positively-charged pion ($u\bar{d}$) flies off.

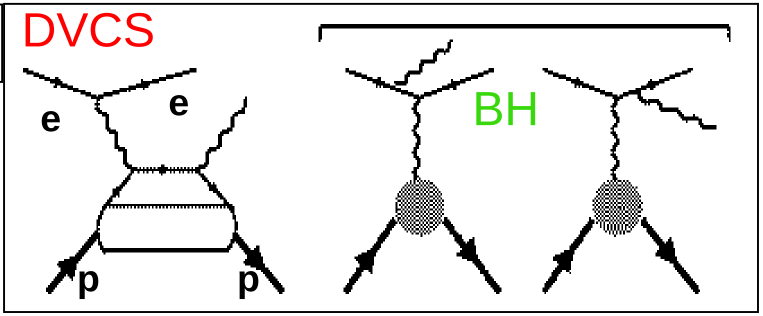
- Access **orbital motion of quarks** → contribution to the proton's spin
- Observables: Azimuthal asymmetries due to correlations of spin q/n and transverse momentum of quarks, *e.g.*, Boer-Mulders:

$$h_1^{\perp q}(x, k_T^2)\,\frac{(\mathbf{P}\times \mathbf{k_T})\cdot \mathbf{S_q}}{M}$$

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

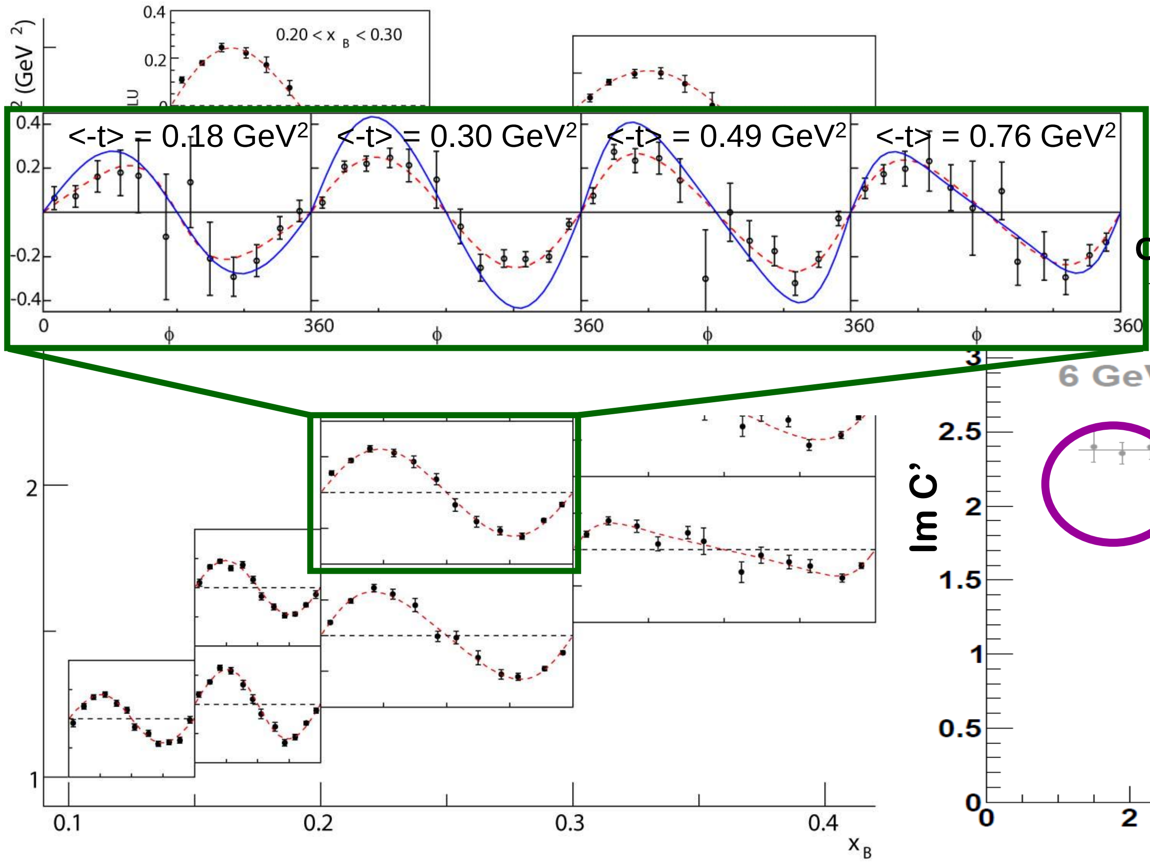
TOWARDS THE 3D STRUCTURE OF THE PROTON

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



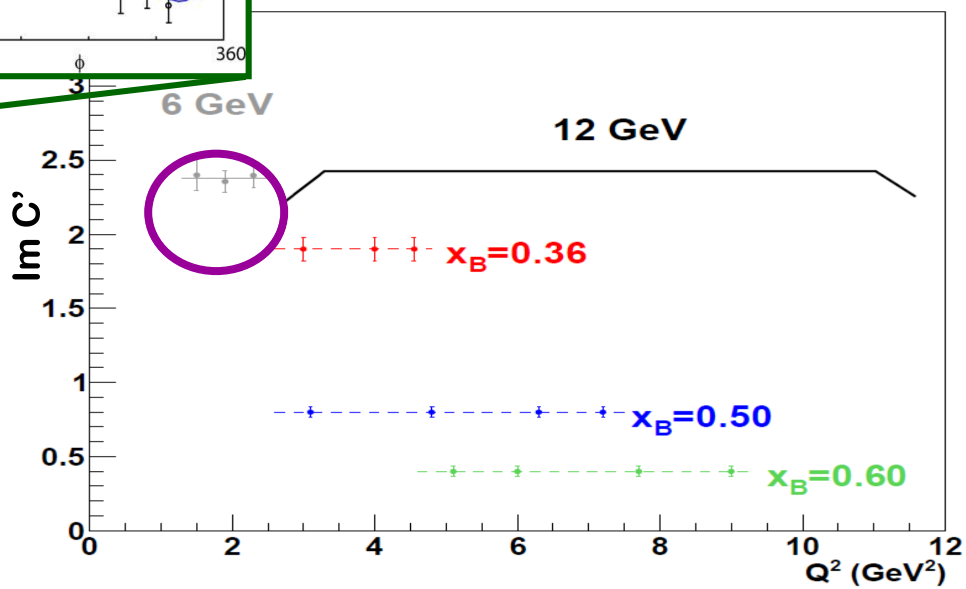
Hall B beam-spin asymmetry data show potential for imaging studies from analysis in x, Q^2 and t

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

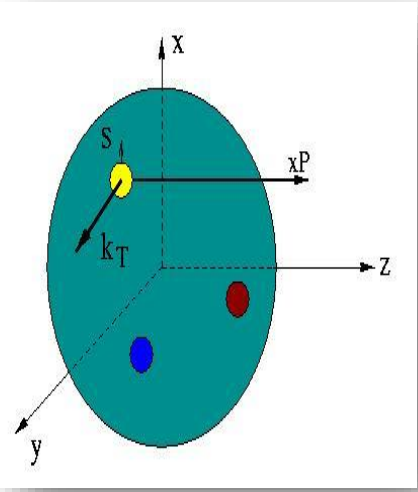
C. Munoz Camacho *et al*., PRL 97, 262002 (2006)

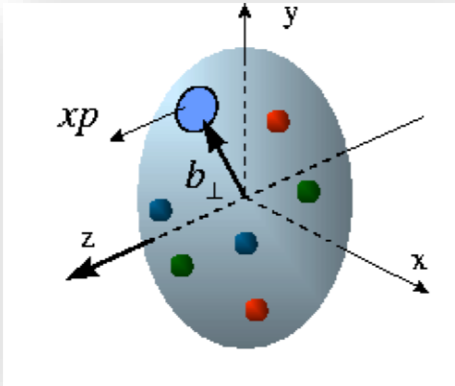


UNIFIED VIEW OF NUCLEON STRUCTURE

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

5D Dist.





d^2r_T

d^2k_T

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

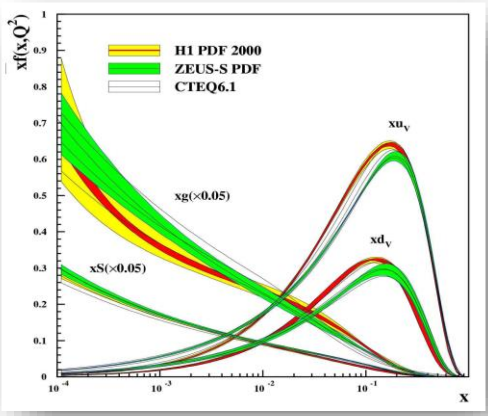
GPDs/IPDs

3D imaging

d^2k_T

d^2r_T

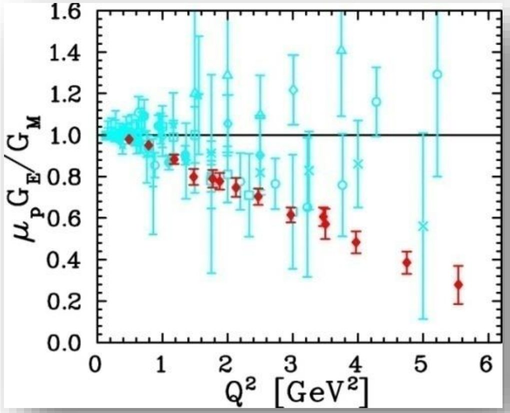
dx &
Fourier Transformation



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

1D

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



EXPLORING THE 3D NUCLEON STRUCTURE

- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to systematically move beyond a 1D momentum fraction (x_{Bj}) picture of the nucleon.
  - High luminosity, large acceptance experiments with polarized beams and targets.
  - Theoretical description of the nucleon in terms of a 5D Wigner distribution that can be used to encode both 3D momentum and transverse spatial distributions.

- **Deep Exclusive Scattering (DES)** cross sections give sensitivity to electron-quark scattering off quarks with longitudinal momentum fraction (Bjorken) x at a transverse location b.

- **Semi-Inclusive Deep Inelastic Scattering (SIDIS)** cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum (k_T) of a parton and transverse momentum (p_T) created during the [parton → hadron] fragmentation process.

Nuclear Femtography

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*

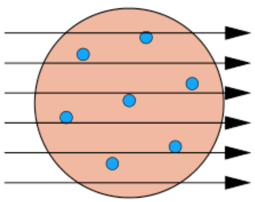
High quality hadronic structure function data at JLab at 6 GeV have been accumulated spanning the nucleon resonance and low-W^2 deep inelastic region. The data indicate a surprisingly smooth parton-hadron transition at relatively low Q^2, allowing, for $x > 0.1$, an unprecedented access to partons with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

From 3D atomic structure to the quantum world

- Atomic structure: dating back to Rutherford's experiment :

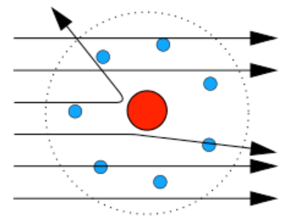
  $\alpha + Au \rightarrow \alpha + X$ Over 100 years ago

Atom:



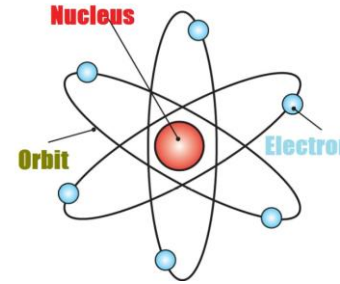
J.J. Thomson's plum-pudding model

Experiment



Rutherford's Experiment - Data

Theory

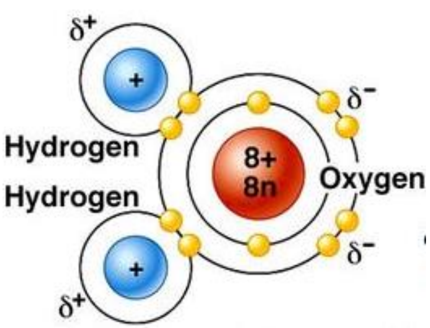


Quantum orbitals

Discovery:
- ✧ Tiny nucleus - *less than 1 trillionth in volume of an atom*
- ✧ Quantum probability - *the Quantum World!*

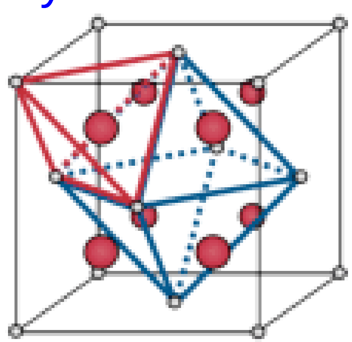
- Localized mass and charge centers – vast "open" space:

Molecule:



"Water"

Crystal:



Rare-Earth metal

Nanomaterial:

Carbon-based

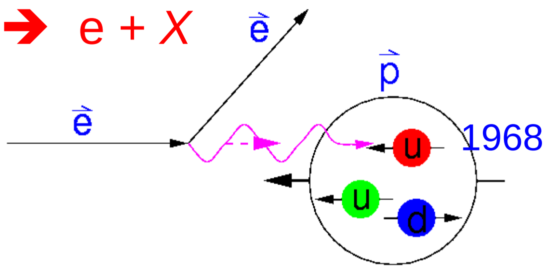
- Not so in proton structure!

From 3D hadron structure to QCD

- A modern "Rutherford" experiment (about 50 years ago):

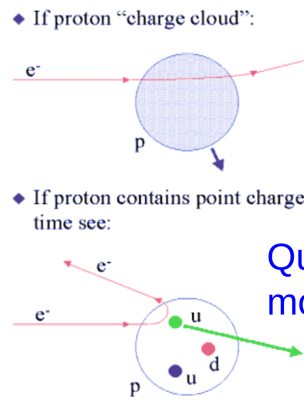
Nucleon: *The building unit of all atomic nuclei*

e + *p* ➔ e + *X*



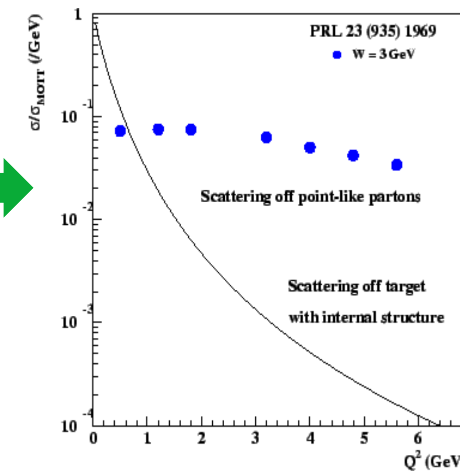
Discovery of quarks!

Prediction

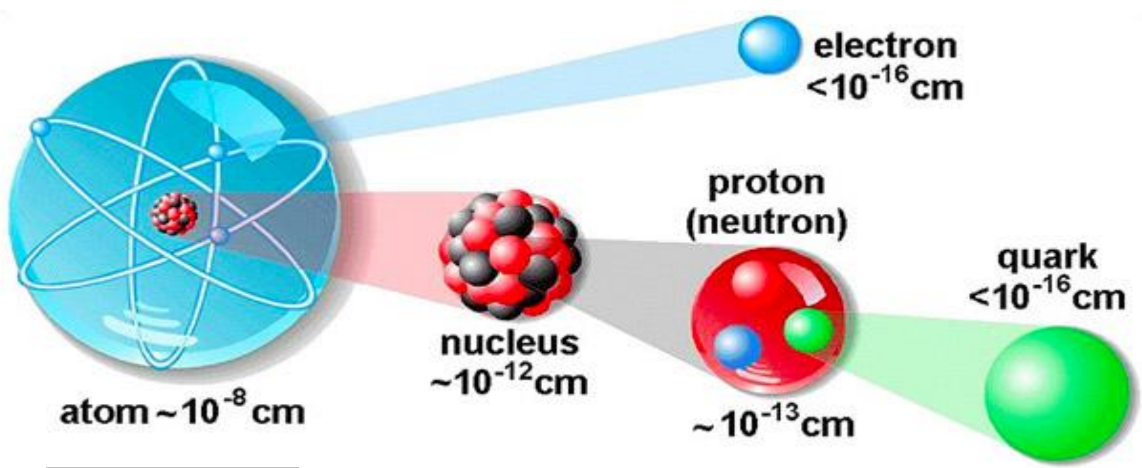


Quark model

Discovery



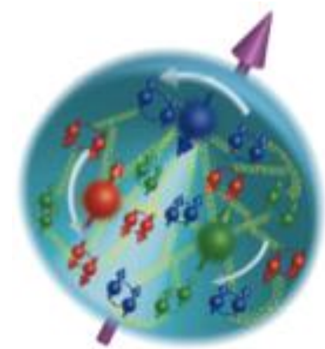
- Discovery of Quantum Chromodynamics (QCD):



Nanometer

Femtometer

Gluons

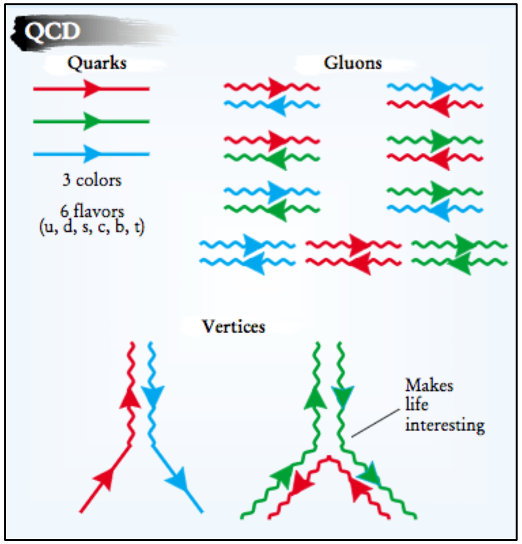


No still picture!
No fixed structure!

Quantum Probability

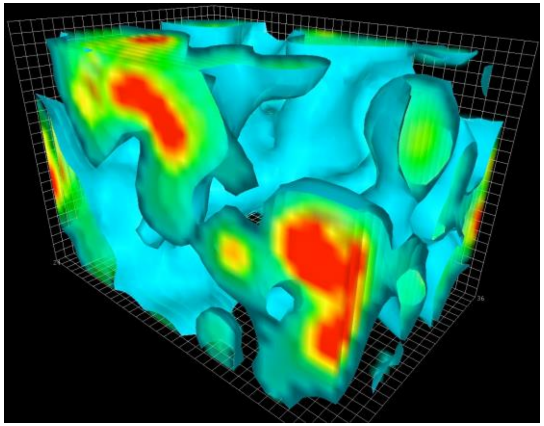
Jefferson Lab

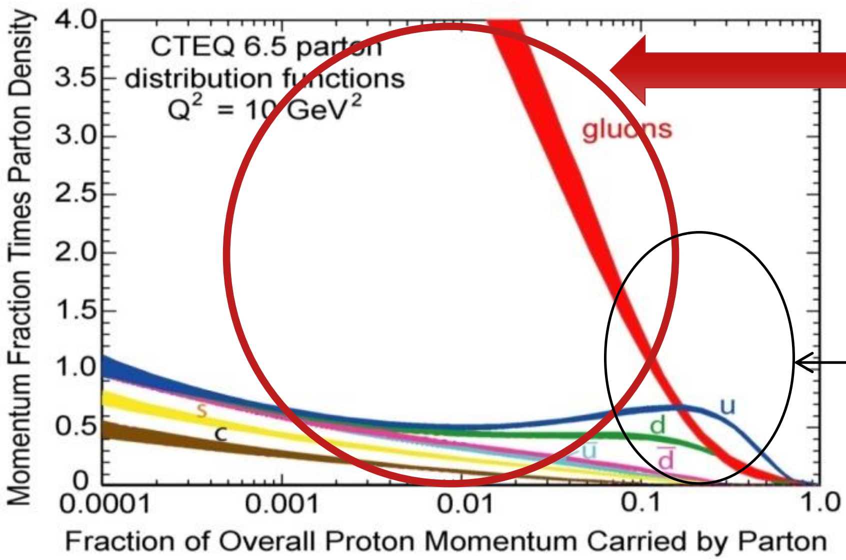
Subatomic Matter is Unique



Interactions and Structure are entangled
because of gluon self-interaction.

Observed properties such as mass and spin emerge from this complex system.

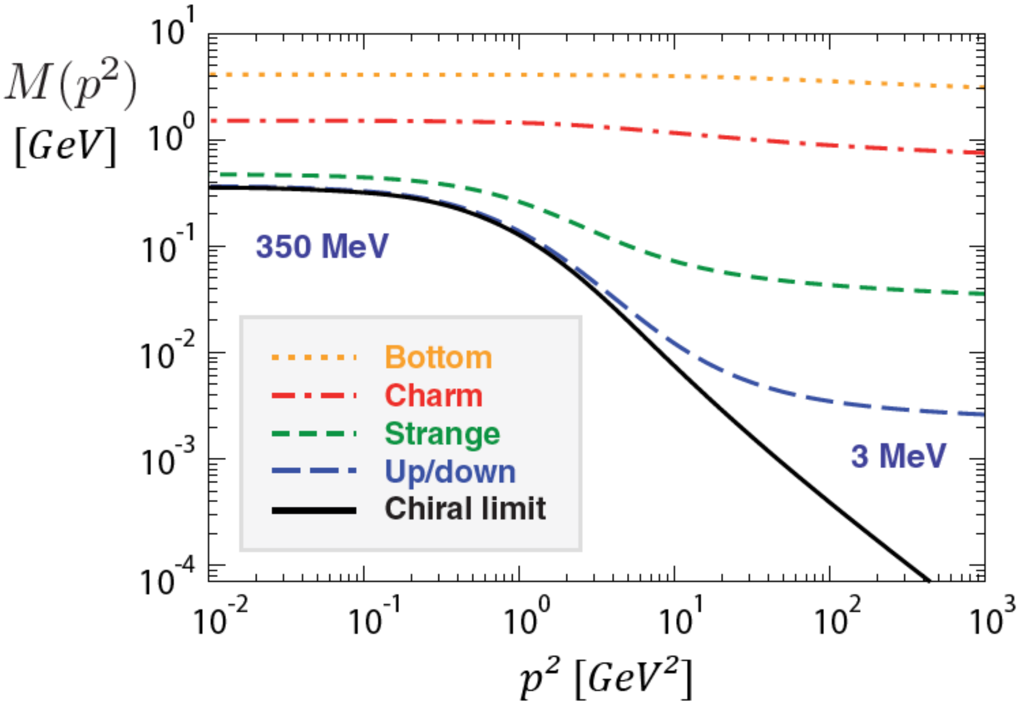




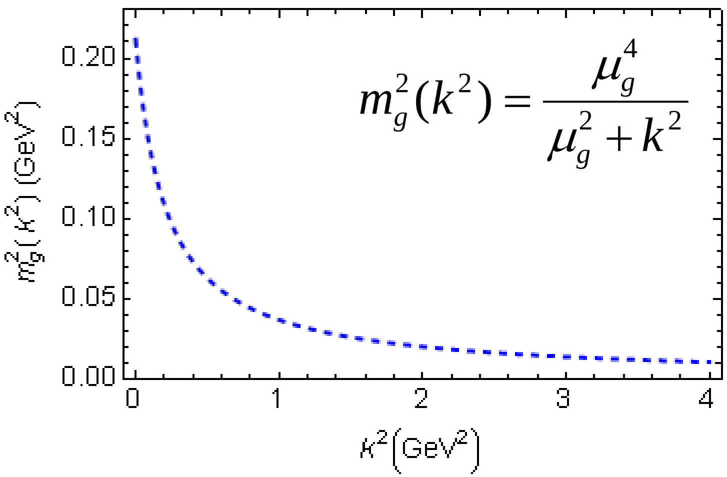
EIC needed to explore the gluon dominated region

JLAB 12 to explore the valence quark region

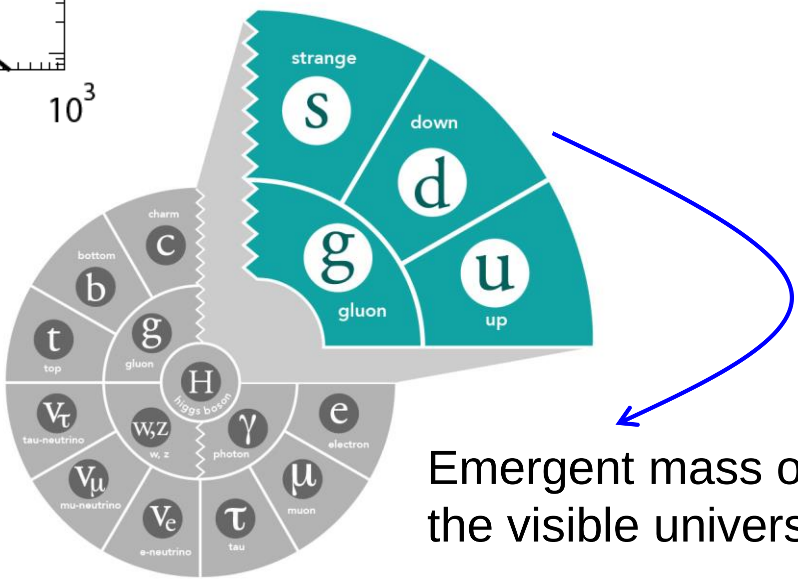
MASS OF THE VISIBLE UNIVERSE



Gluon mass-squared function



The strange quark is at the boundary - both emergent-mass and Higgs-mass generation mechanisms are important.



Emergent mass of the visible universe