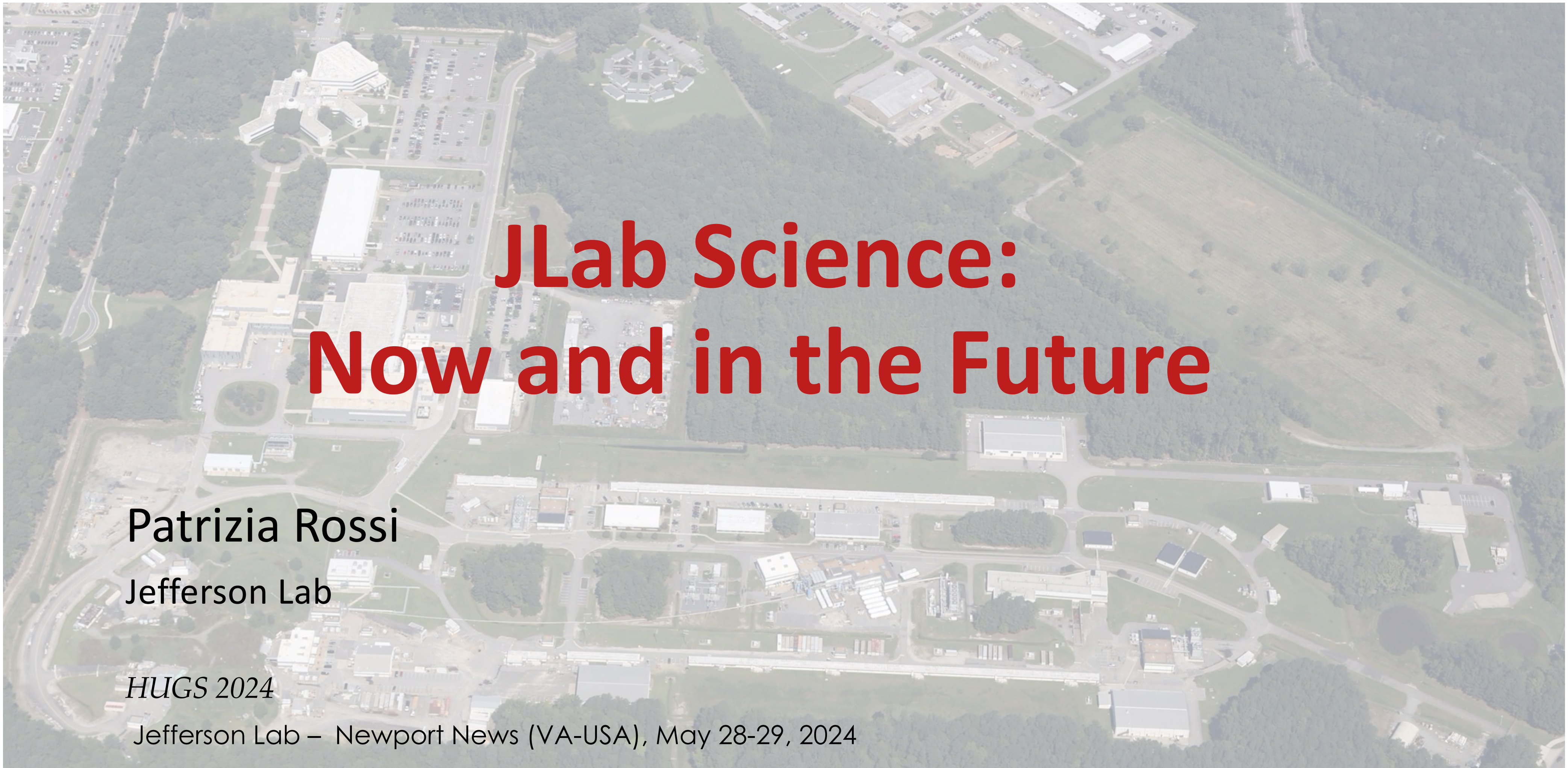
JLab Science: Now and in the Future

Patrizia Rossi

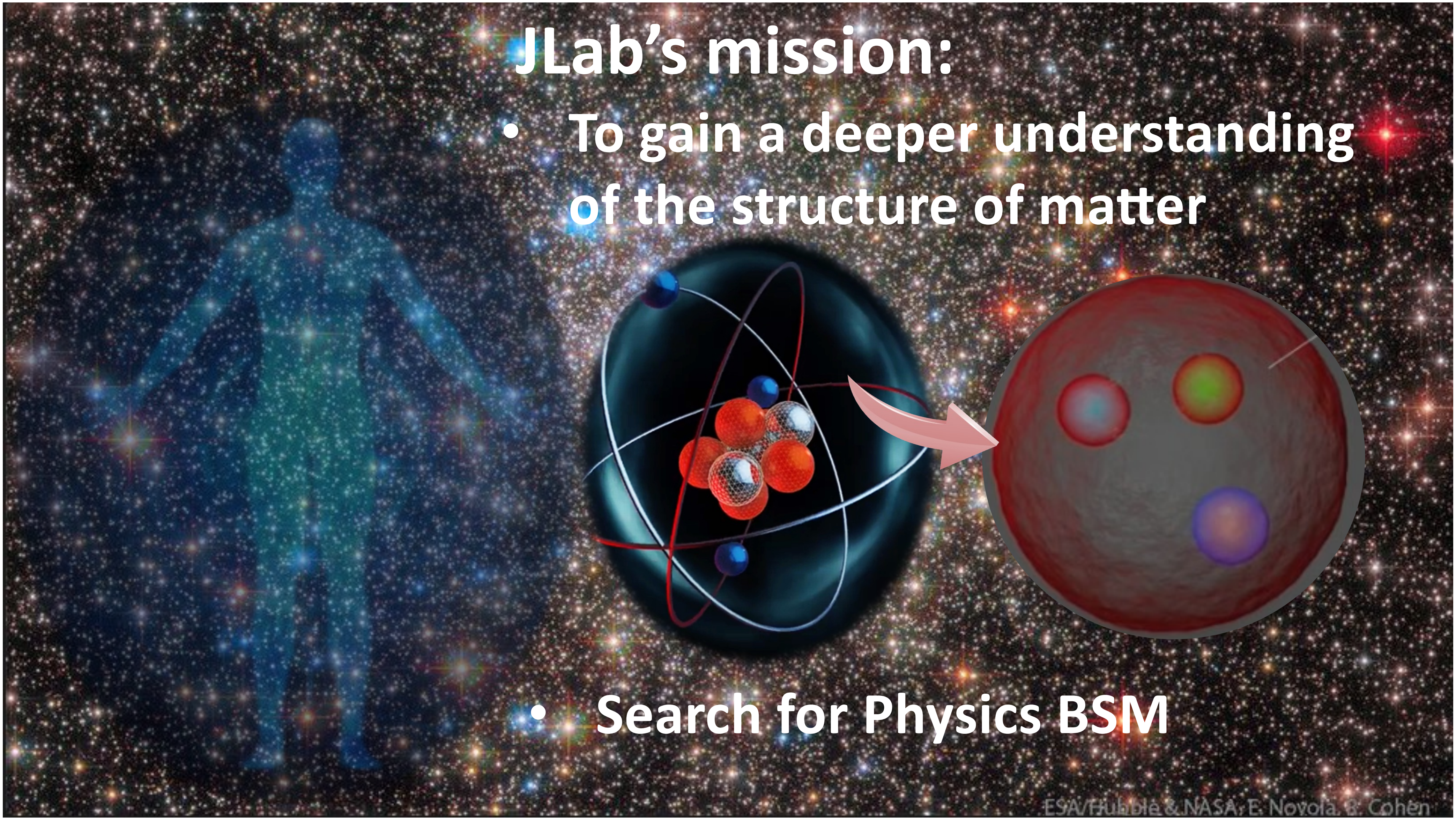
Jefferson Lab

HUGS 2024

Jefferson Lab – Newport News (VA-USA), May 28-29, 2024

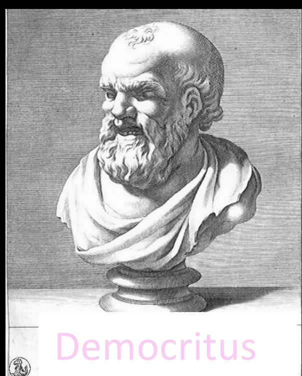


Jefferson Lab
Thomas Jefferson National Accelerator Facility

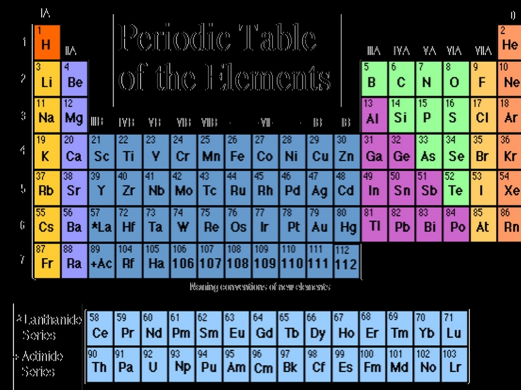

JLab's mission:
• To gain a deeper understanding of the structure of matter
• Search for Physics BSM
ESA/Hubble & NASA, E. Noyola, R. Cohen

The Long Journey through the structure of visible matter

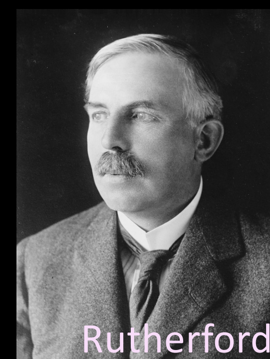
Atomic Hypothesis
$\lesssim 10^{-4}$ m



Molecular Theory
$\lesssim 10^{-9}$ m



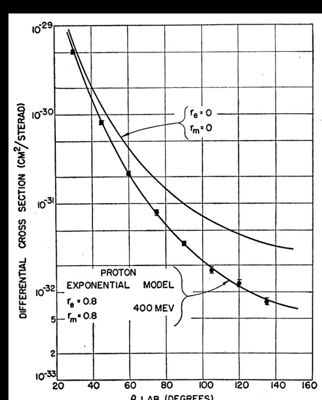
Gold Nucleus
$\sim 7.5\ 10^{-15}$ m



Neutron
$\sim 10^{-15}$ m

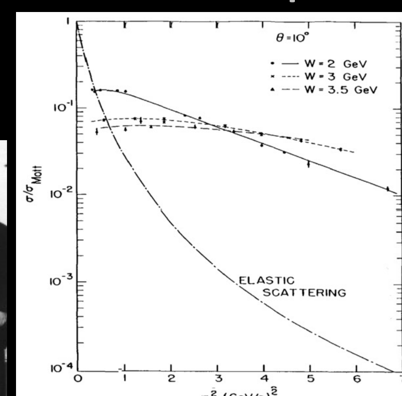
$< 10^{-15}$ m

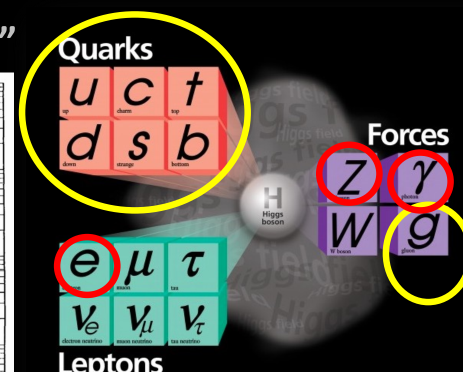
Proton Form Factor



$\lesssim 10^{-18}$ m

Evidence for "quarks"

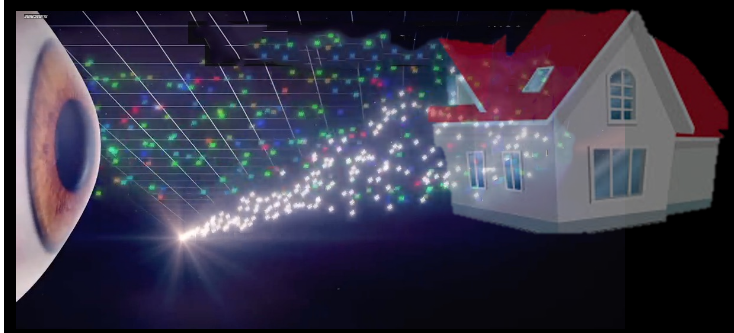


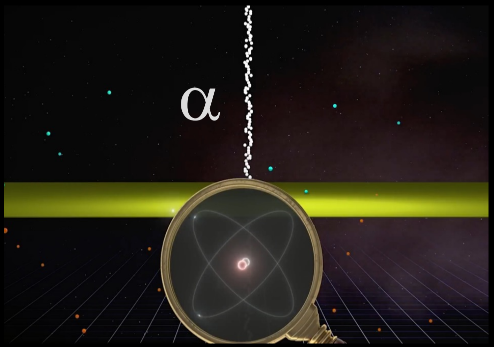


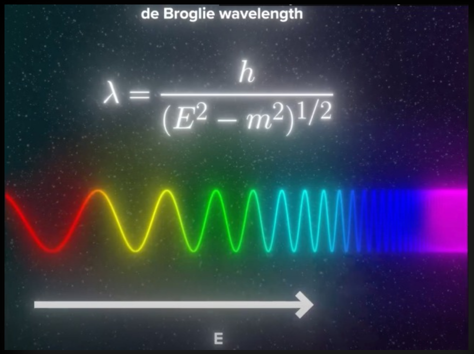
QCD is one of the pillar of the Standard Model!

How do we know any of this?

The power of charged particle scattering







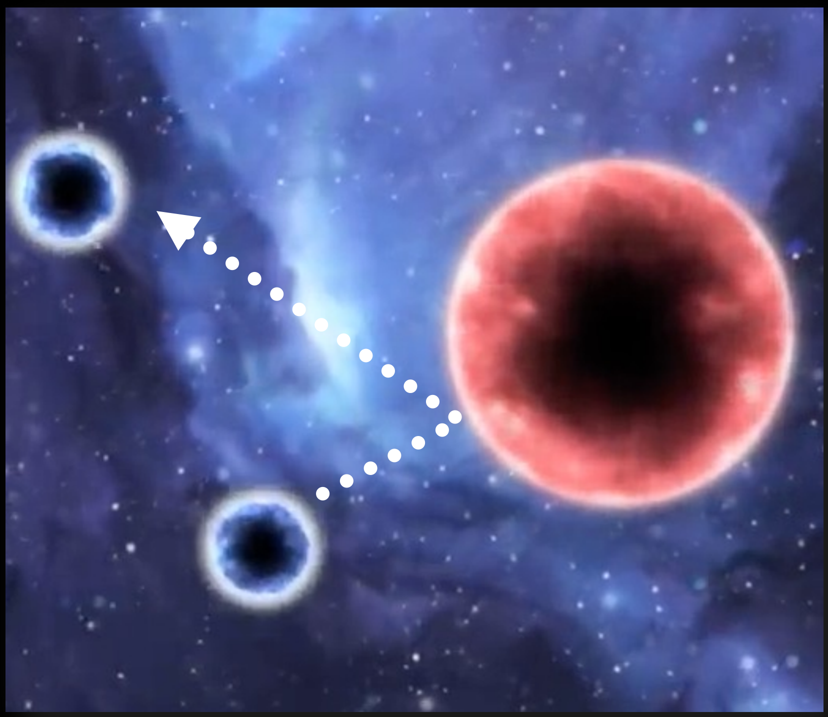
Almost all particle physics experiments today use the same basic elements

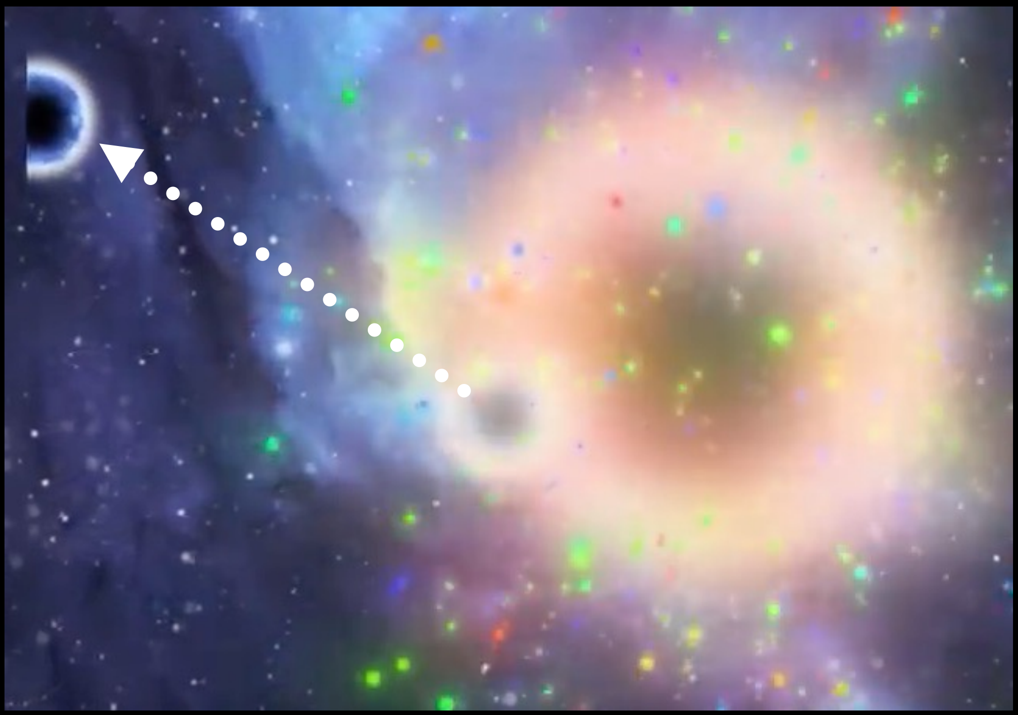
beam + target + detector

- All particles have wave properties.
- A particle can only probe distance ≈ particle's λ
- smaller scales $\Rightarrow$ smaller λ

- quality image limited by the wavelength used

Electron scattering

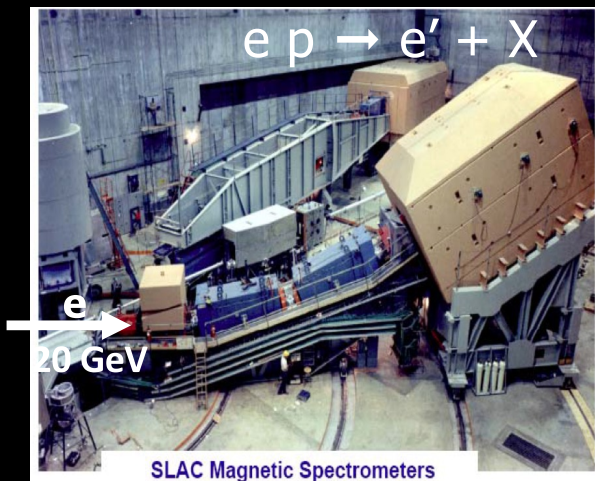


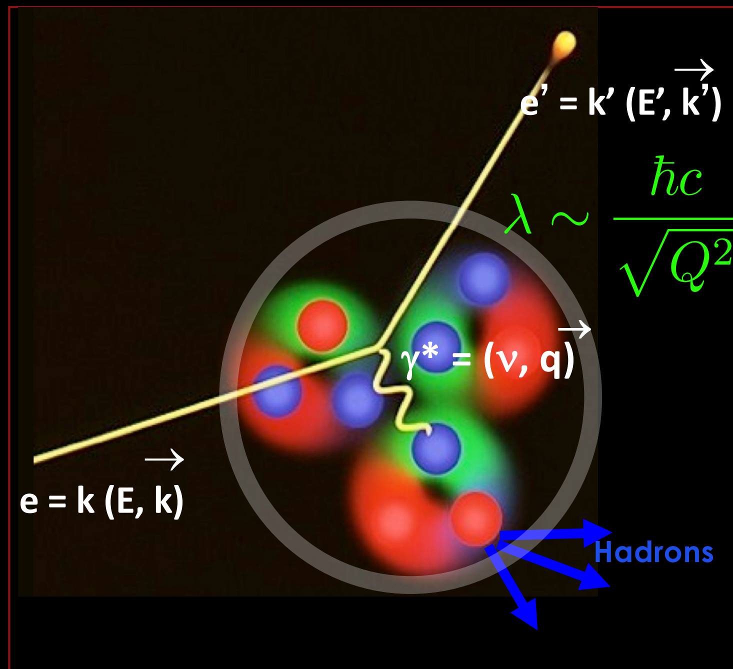


Elastic Scattering
the electron bounces off the proton as a whole

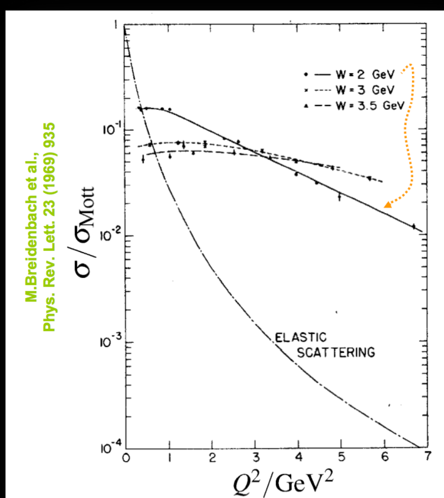
Deep Inelastic Scattering
The electron punches into the proton and then scatter off the proton's internal part

Deep Inelastic Scattering





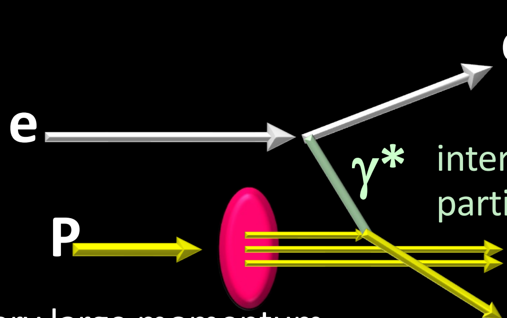
Lorentz inv.		Lab frame	Meaning
$q^2 = -Q^2$	$(k-k')^2$	$-4EE' sin^2(\frac{\theta}{2})$	Virtuality
x_B	$\frac{-q^2}{2p\cdot q}$	$\frac{Q^2}{2M\nu}$	Bjorken scaling variable; Inelasticity of the process
ν	$\frac{p\cdot q}{\sqrt{(p^2)}}$	$E-E'$	Energy lost by the incoming lepton
W^2	$(p+q)^2$	$M^2+2M\nu-Q^2$	Inv. mass squared of the final state
y	$\frac{p\cdot q}{p\cdot k}$	$\frac{\nu}{E}$	Fraction of the electron energy carried by the γ^*
s	$(p+k)^2$	$\approx M^2+2M\nu$	Center of mass energy



Deep Inelastic Scattering cross sections almost independent of Q^2!

The Parton Model

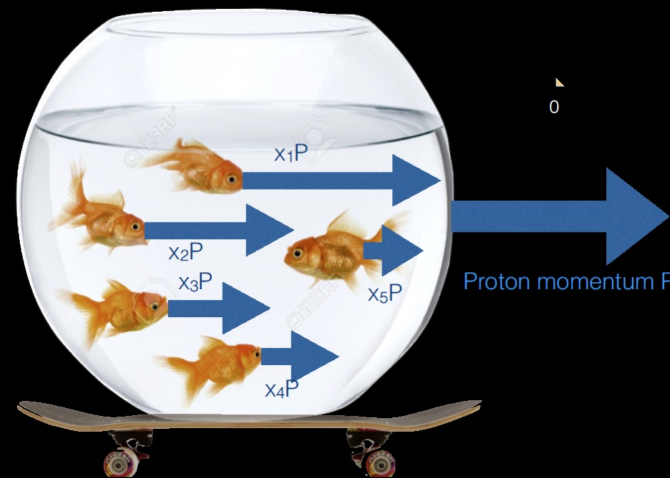
Infinite Momentum Frame



interact with **free** point-like particles (partons)

very large momentum

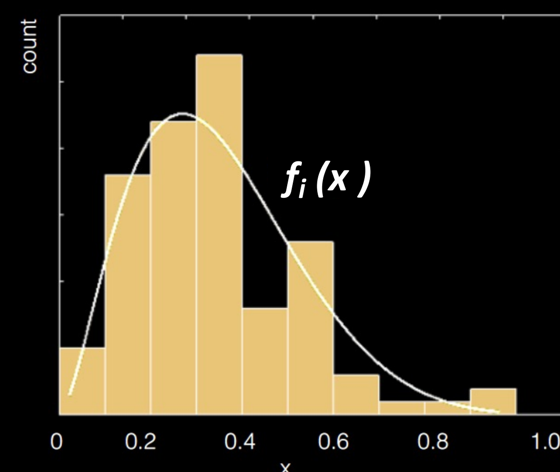
collinear momentum with proton



Each parton of charge e_i has a probability $f_i(x)$ to carry a fraction x of the parent proton mom.

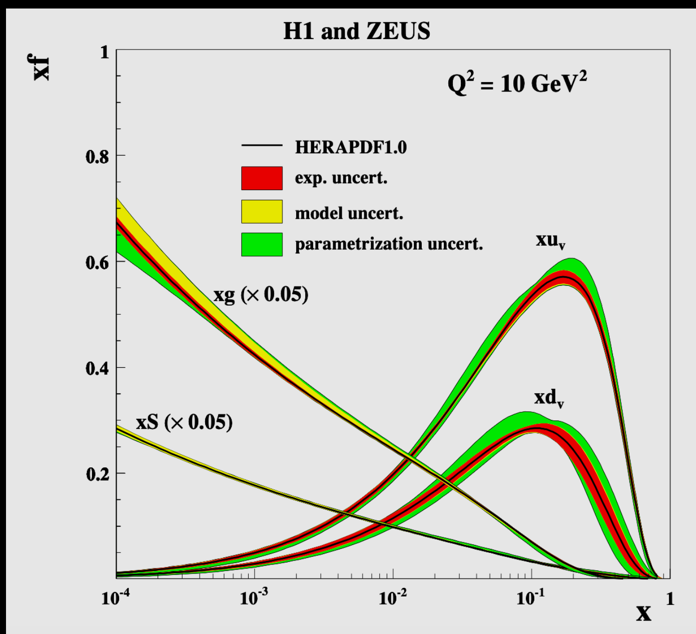
$$\sigma = \sigma_M \,.\, f\,[F_1(x), F_2(x)]$$

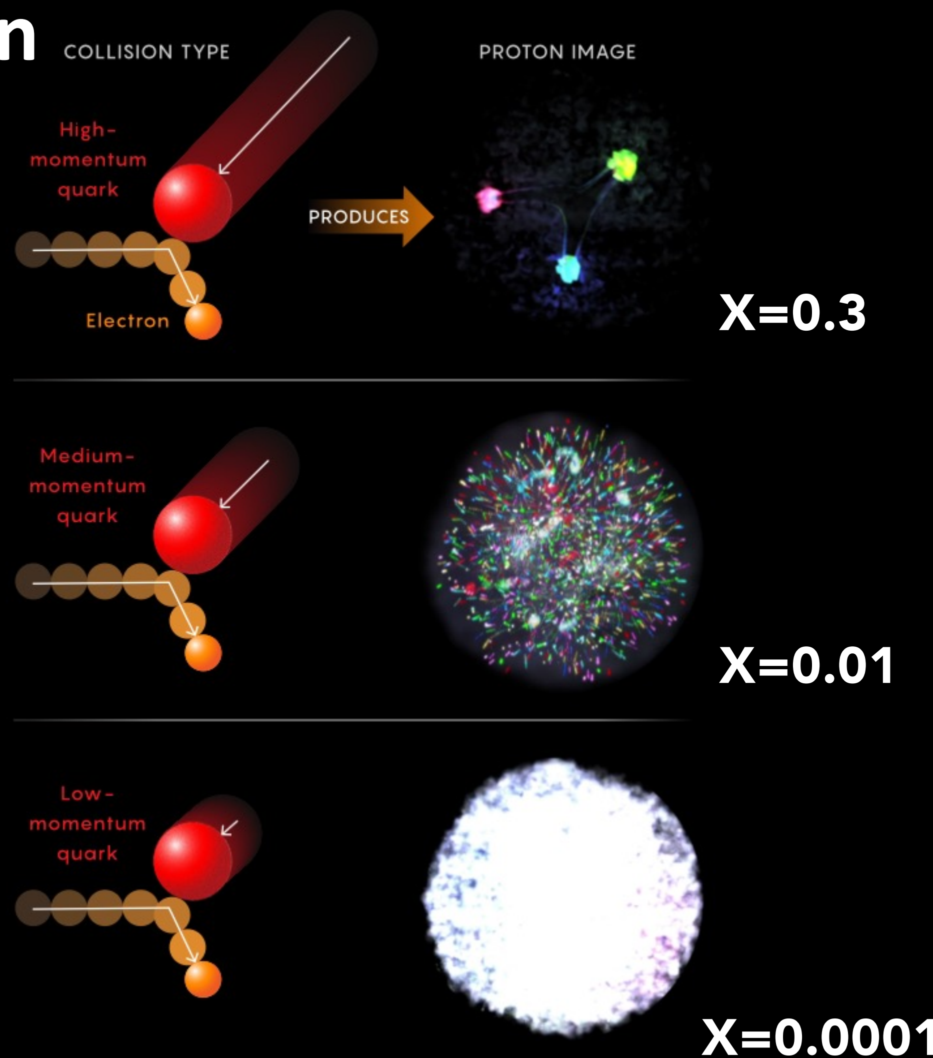
$$F_1(x) = \frac{1}{2}\sum e_i^2 f_i(x) \quad F_2(x) = 2xF_1(x) \qquad x = \frac{Q^2}{2M\nu}$$



Courtesy of W. Detmold

A Closer Look Inside the Proton





https://www.quantamagazine.org/inside-the-proton-the-most-complicated-thing-imaginable-20221019/

Quantum Chromodynamics (QCD)

Eur. Phys. J. C (2023) 83:1125
https://doi.org/10.1140/epjc/s10052-023-11949-2

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Review

50 Years of quantum chromodynamics

Introduction and Review

636 pages
4850 references

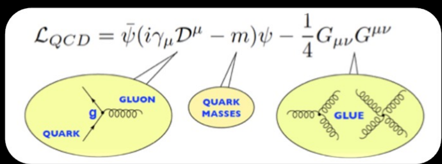
Franz Gross[1,2,a], Eberhard Klempt[3,b], Stanley J. Brodsky[4], Andrzej J. Buras[5], Volker D. Burkert[1], Gudrun Heinrich[6], Karl Jakobs[7], Curtis A. Meyer[8], Kostas Orginos[1,2], Michael Strickland[9], Johanna Stachel[10], Giulia Zanderighi[11,12], Nora Brambilla[5,12,13], Peter Braun-Munzinger[10,14], Daniel Britzger[11], Simon Capstick[15], Tom Cohen[16], Volker Crede[15], Martha Constantinou[17], Christine Davies[18], Luigi Del Debbio[19], Achim Denig[20], Carleton DeTar[21], Alexandre Deur[1], Yuri Dokshitzer[22,23], Hans Günter Dosch[10], Jozef Dudek[1,2], Monica Dunford[24], Evgeny Epelbaum[25], Miguel A. Escobedo[26], Harald Fritzsch[27], Kenji Fukushima[28], Paolo Gambino[11,29], Dag Gillberg[30,31], Steven Gottlieb[32], Per Grafstrom[33,34], Massimiliano Grazzini[35], Boris Grube[1], Alexey Guskov[36], Toru Iijima[37], Xiangdong Ji[16], Frithjof Karsch[38], Stefan Kluth[11], John B. Kogut[39,40], Frank Krauss[41], Shunzo Kumano[42,43], Derek Leinweber[44], Heinrich Leutwyler[45], Hai-Bo Li[46,47], Yang Li[48], Bogdan Malaescu[49], Chiara Mariotti[50], Pieter Maris[51], Simone Marzani[52], Wally Melnitchouk[1], Johan Messchendorp[53], Harvey Meyer[20], Ryan Edward Mitchell[54], Chandan Mondal[55], Frank Nerling[53,56,57], Sebastian Neubert[3], Marco Pappagallo[58], Saori Pastore[59], José R. Peláez[60], Andrew Puckett[61], Jianwei Qiu[1,2], Klaus Rabbertz[33,62], Alberto Ramos[63], Patrizia Rossi[1,64], Anar Rustamov[53,65], Andreas Schäfer[66], Stefan Scherer[67], Matthias Schindler[68], Steven Schramm[69], Mikhail Shifman[70], Edward Shuryak[71], Torbjörn Sjöstrand[72], George Sterman[73], Iain W. Stewart[74], Joachim Stroth[53,56,57], Eric Swanson[75], Guy F. de Téramond[76], Ulrike Thoma[3], Antonio Vairo[77], Danny van Dyk[41], James Vary[51], Javier Virto[78,79], Marcel Vos[80], Christian Weiss[1], Markus Wobisch[81], Sau Lan Wu[82], Christopher Young[83], Feng Yuan[84], Xingbo Zhao[55], Xiaorong Zhou[48]

- **Long-distance physics:** the constituent QM
- **Short-distance physics:** the Parton Picture

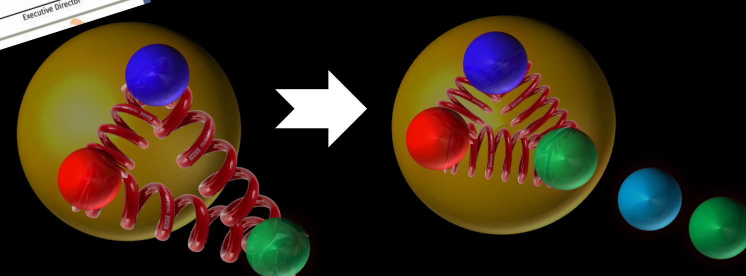
QCD provides the foundation for both

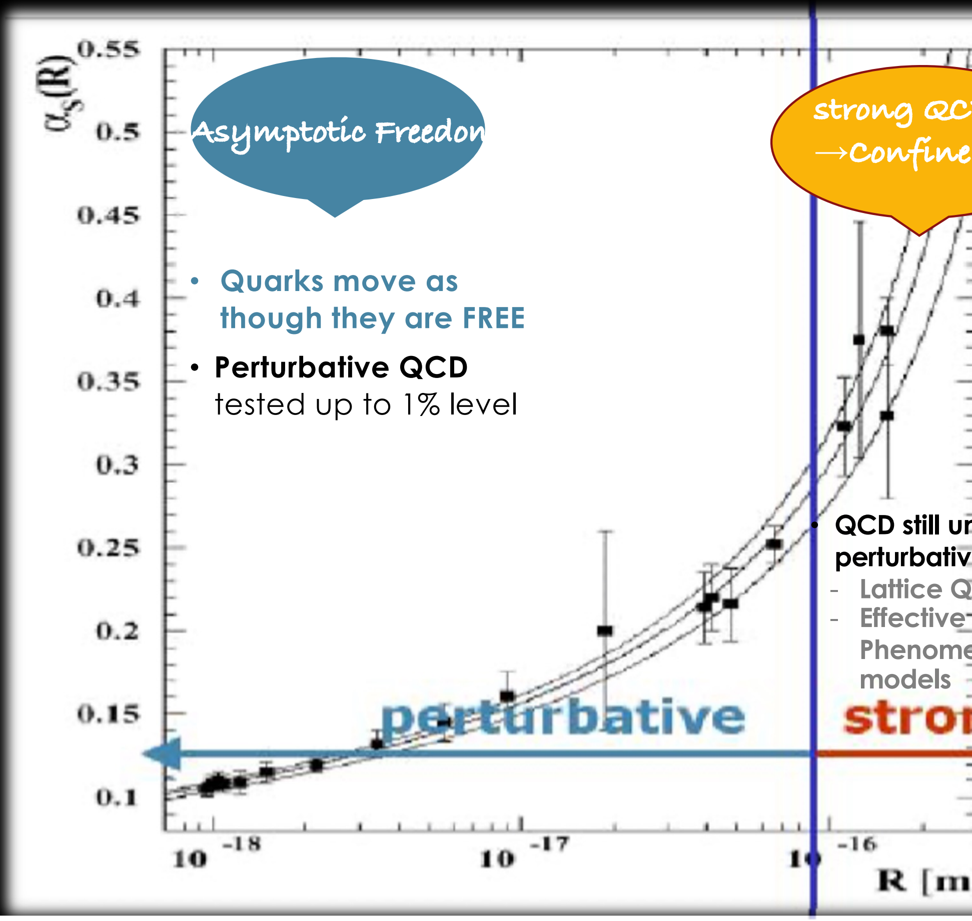
……..
When QCD was "discovered" 50 years ago, the idea that quarks could exist, but not be observed, left most physicists unconvinced. Then, with the discovery of charmonium in 1974 […] the theory was suddenly widely accepted.
………

Quantum Chromodynamics (QCD)



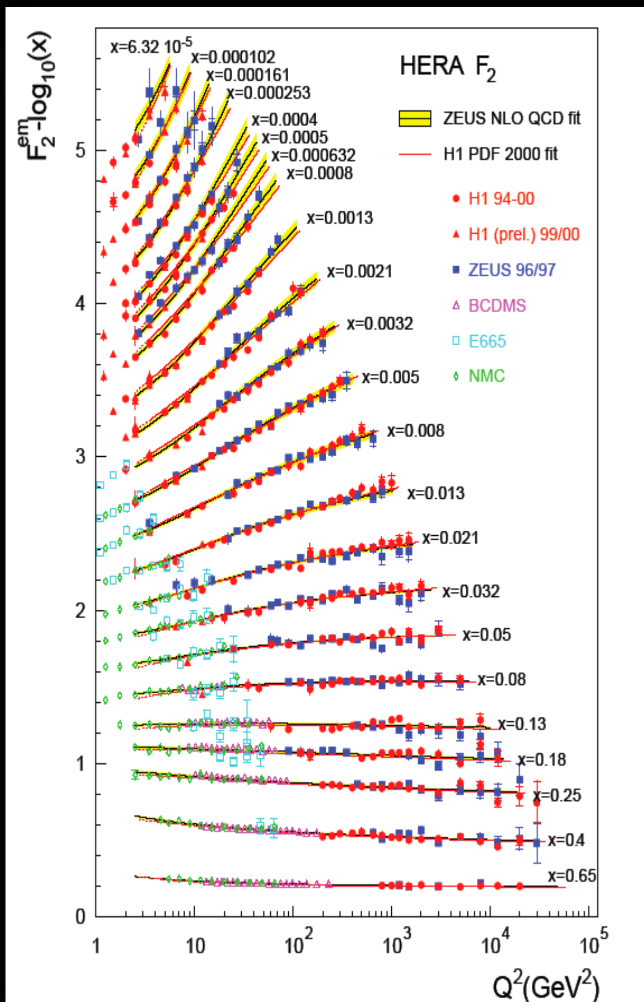
- Both quarks and the gluons carry a new quantum number: colour
- The coupling constant highly dependent on the energy scale
  - Asyntotic freedom
  - Confinement
    - *Quarks cannot be isolated -* ➜ *hadronization*





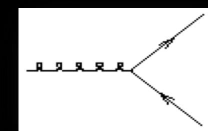
- QCD factorization theorems:
  wide class of physical quantities (inclusive x-sections) which can be factorized into long distance components (not calculable, but universal) & short-distance components (process-dependent,) but calculable).

Success of QCD and QCD Factorization

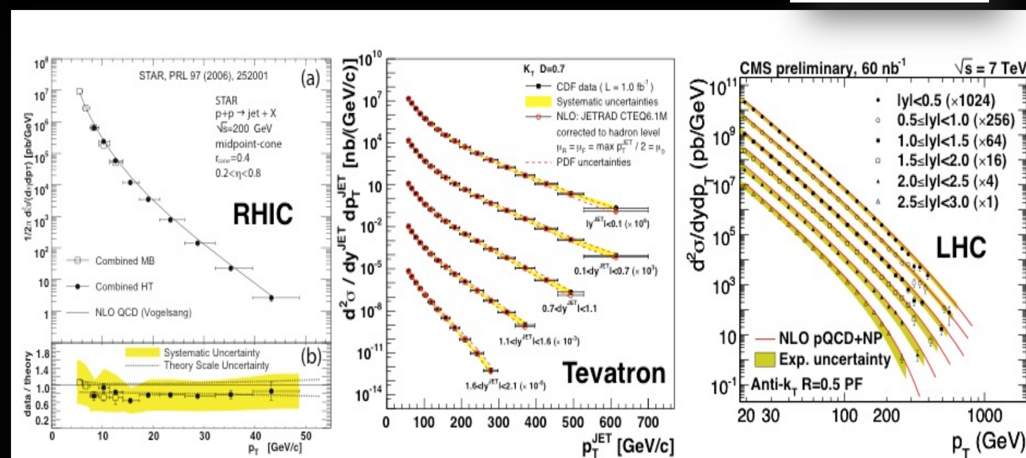


@ High Energy Asymptotic freedom + pQCD

At low x : Gluon splitting enhances quark density➔ F2 rises with Q^2



At high x : Gluon radiation shifts quark to lower x ➔ F2 falls with Q^2



Measure e-p at 0.3 TeV (HERA)

Predict p-p and p-$\bar{p}$ at 0.2, 1.96, and 7 TeV

- It is the highly ***non-perturbative*** behavior that makes the study of QCD so fascinating and at the same time so challenging

QCD: QUESTIONS, CHALLENGES, AND DILEMMAS

James D. Bjorken*

arXiv:hep-ph/9611421

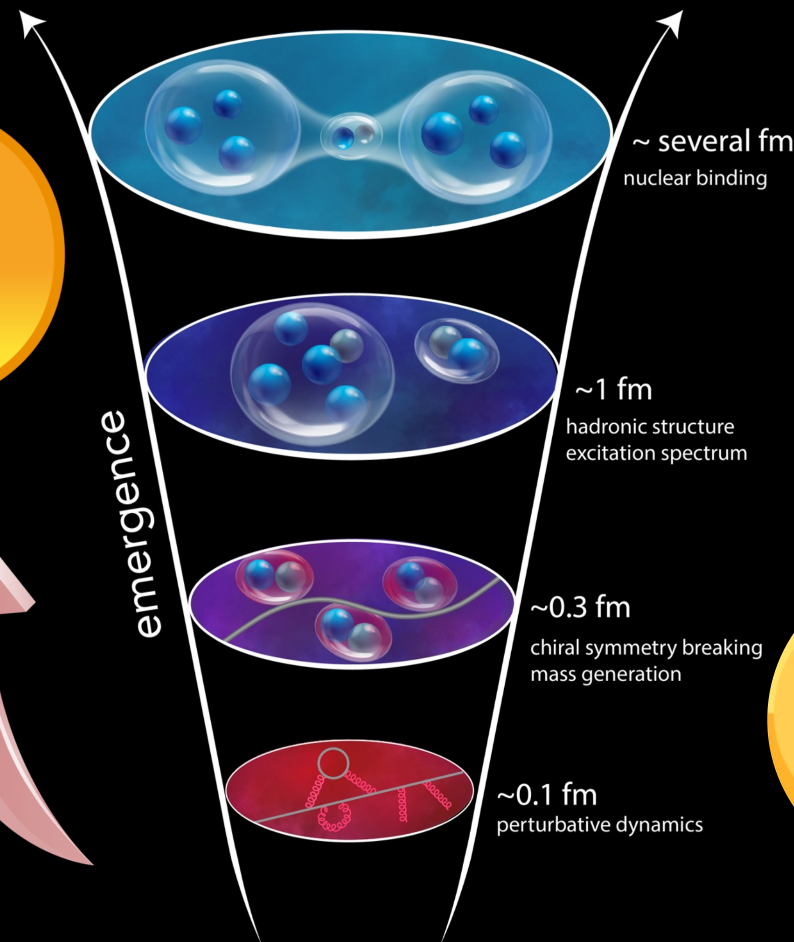
•••• condensed matter theory, chemistry, biology, and more.

Both QED and QCD have their Feynman-diagram perturbation-theory processes, leading to incisive precision tests—which work. Their coupling constants run and are seen to run. QED and QCD are very well "tested."

But just as nonperturbative QED contains very interesting phenomena, as mentioned above, nonperturbative QCD is a most interesting portion of that theory as well. To me, it is *the* most interesting and most important portion of QCD to address, despite the evident difficulty in doing so. The lectures in this school ••••

An Asymmetric Path

How does this arise from QCD?



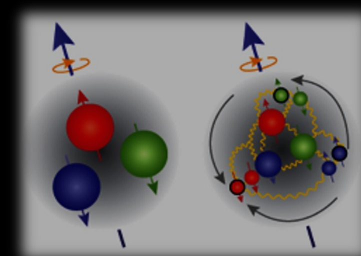
A detailed understanding of the way QCD generates protons, neutrons, and other strongly interacting hadrons remains elusive

Some Challenging Questions…

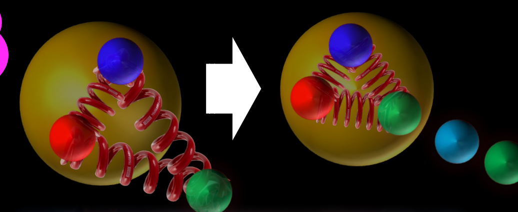
- How the macroscopic properties of the nucleon (mass, spin,..) emerge from QCD?
- How the fundamental particles, quarks and gluons, fit together and interact to create different types of matter in the universe?
- Why the majority of observed hadrons fall into only two very limited sets: baryons (qqq); and mesons $(q\bar{q})$. What is the role of gluonic excitations in the spectroscopy of light mesons?
- What is the relation of short-range nuclear structure and parton dynamics? What's the hadronization mechanism?

proton mass?

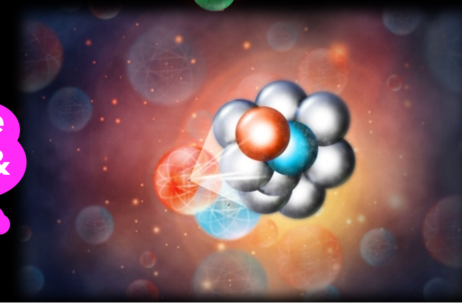
proton spin?



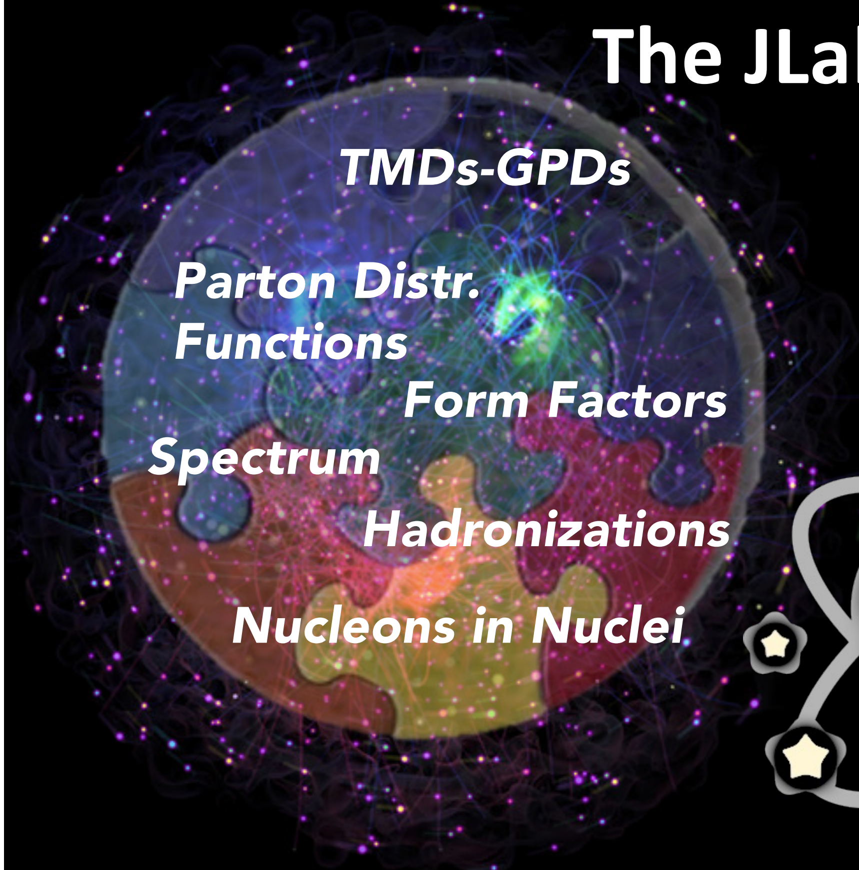
Confinement ?
Hadronization?



Nuclear Force
from quarks &
gluons?



The JLab Physics Program

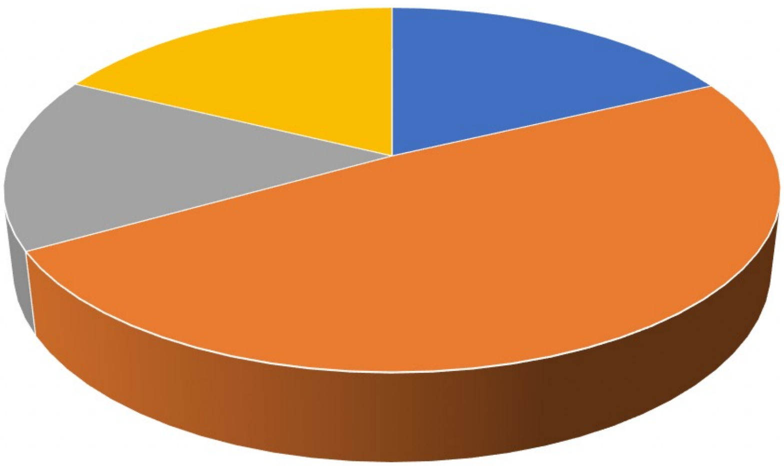


- Explore different facets of the non-perturbative dynamics that manifest in hadron structure
- Multiple observables sensitive to different characteristics of the hadron/nuclear structure
- Studies requiring precise measurements

Many Experiments
Many interesting Results

I can present only few of them!

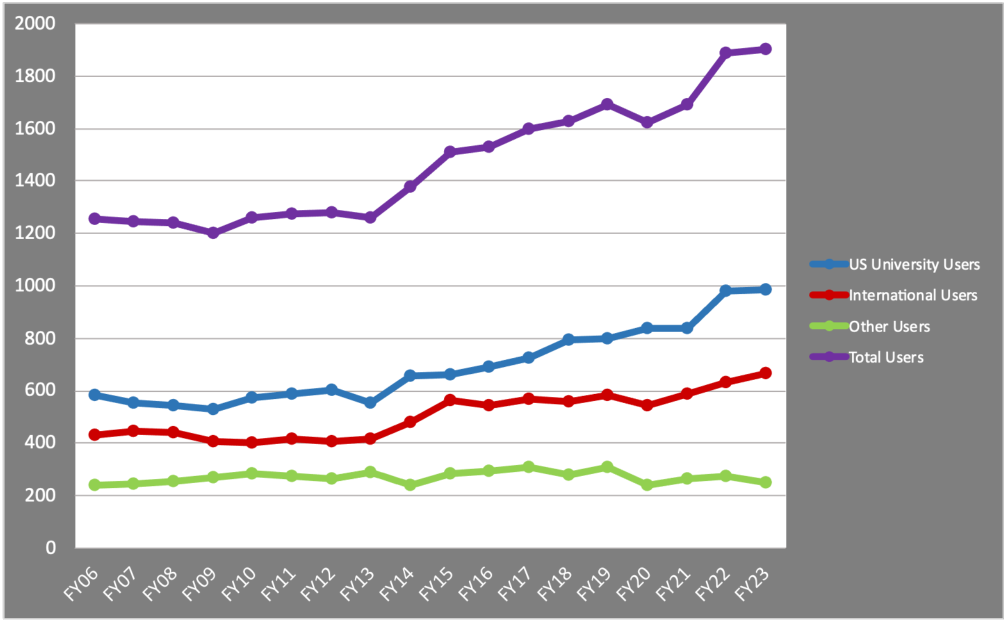
The JLab 12 GeV program & User Community



- Approved 12 GeV program by PAC days (125 Exps)

  Hadron Spectra
  1D-3D Nucleon Structure
  Hadrons & Cold Nuclear Matter
  Test of SM & Fundamental Sym.

Supported by a vibrant user community !



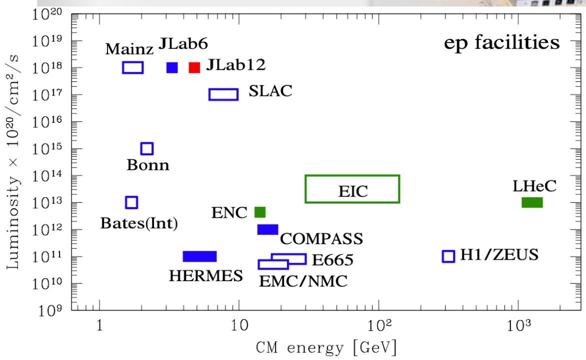
- ~ 50% of the program completed
- New Experiments submitted to PAC every year

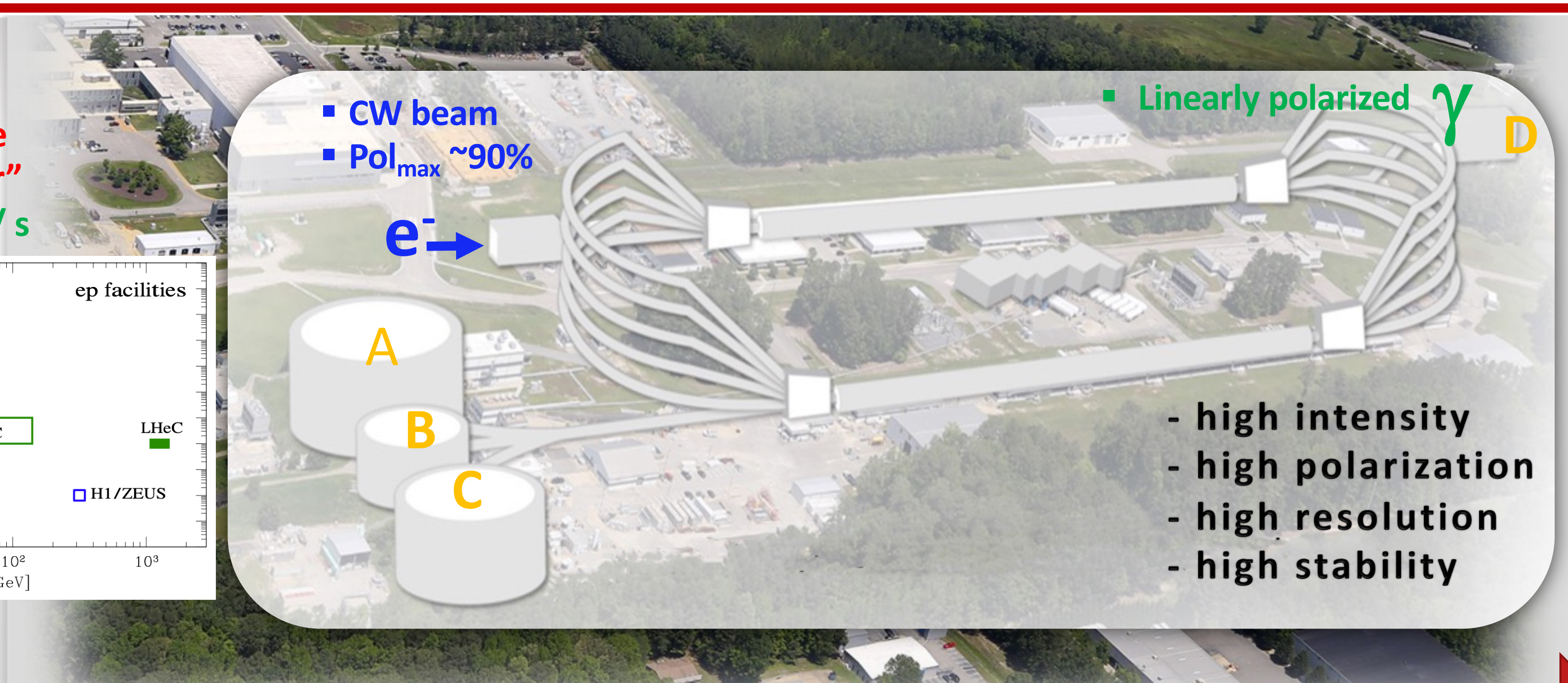
The approved program equals well beyond a decade

Jefferson Lab and CEBAF

Fixed target experiments at the "luminosity frontier"

up to 10^{39} e-N /cm²/ s





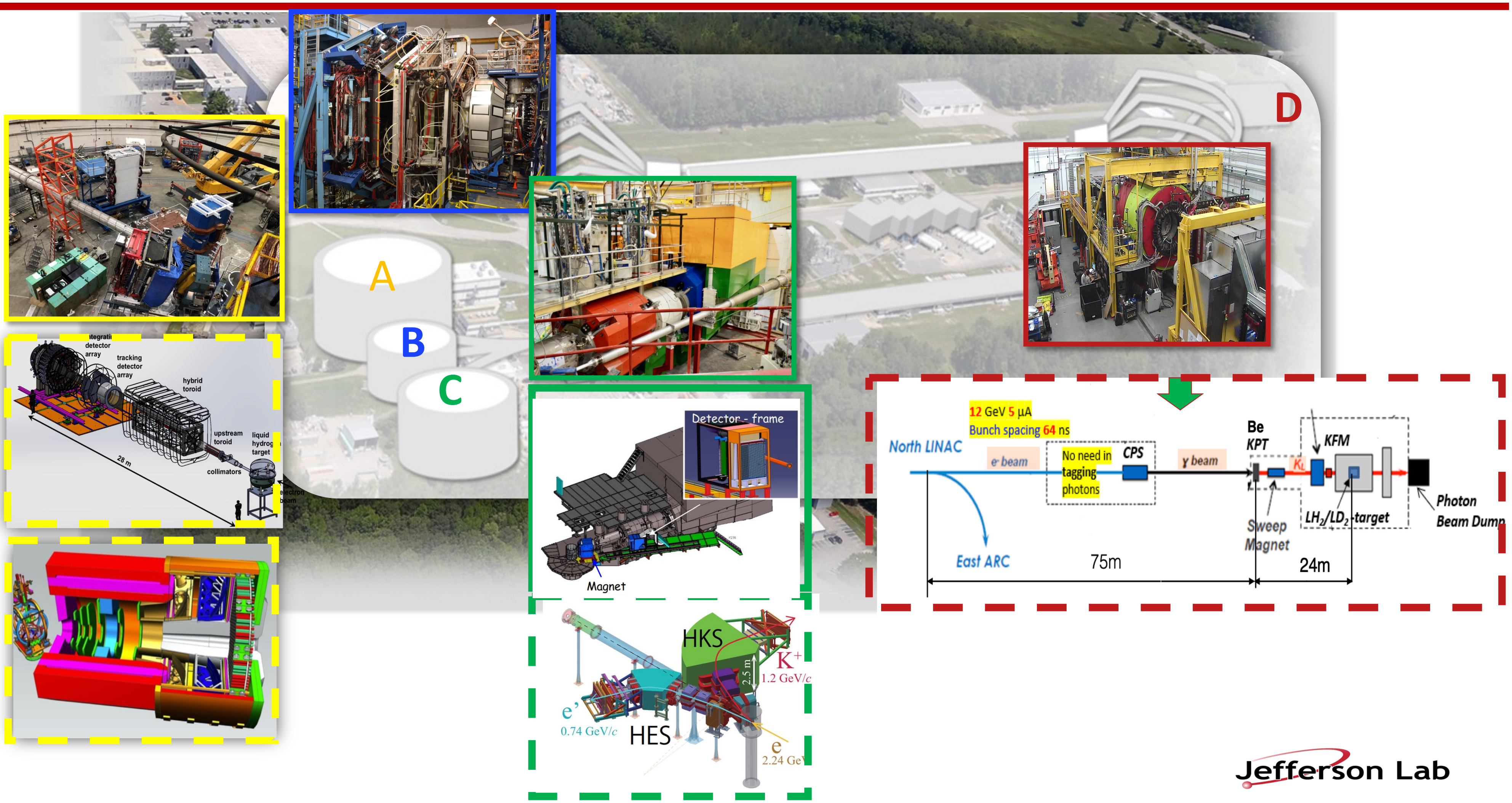
4 GeV	6 GeV	12 GeV
1995	2000	2015

u	d	s		c	b	t
~2 MeV	~5 MeV	~100 MeV	$\ll \Lambda_{QCD} \ll$	~1.3 GeV	~4.2 GeV	~173 GeV

Light quarks — Heavy quarks

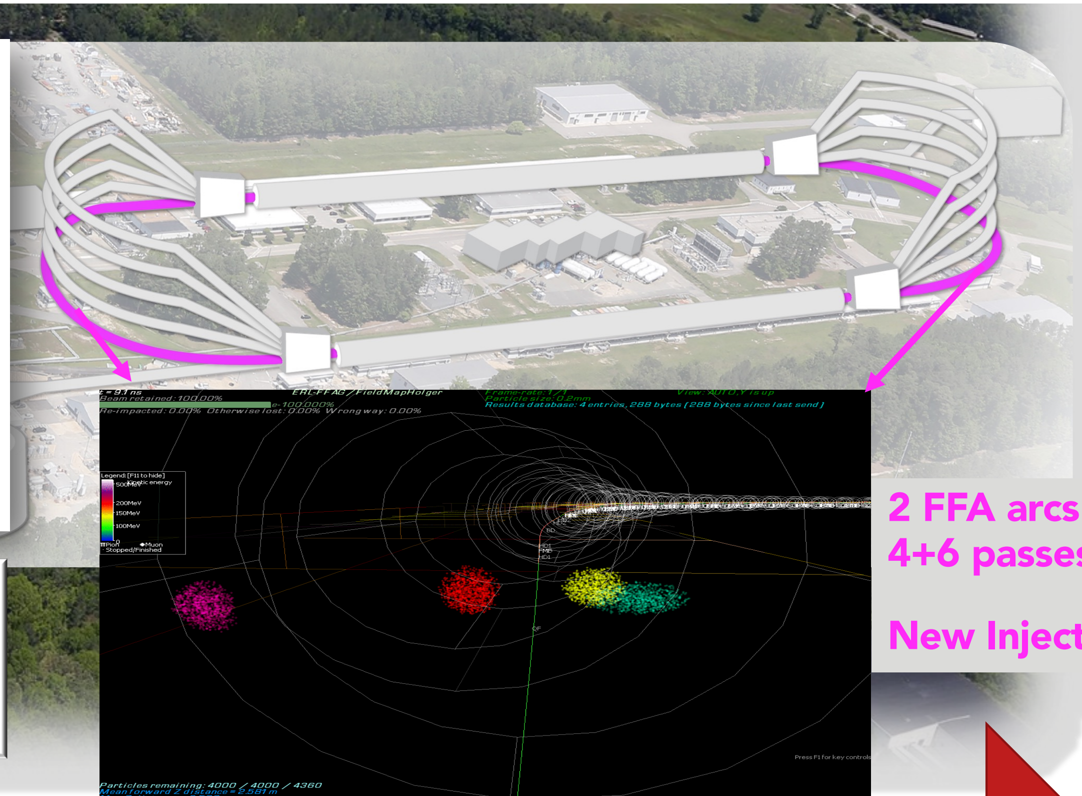
Jefferson Lab

Equipment


A
B
C
D
tracking detector array
hybrid toroid
upstream toroid
liquid hydrog target
collimators
28 m
Detector - frame
Magnet
HKS
HES
K+
1.2 GeV/c
2.5 m
e'
0.74 GeV/c
e
12 GeV 5 µA
Bunch spacing 64 ns
North LINAC
e- beam
No need in tagging photons
CPS
γ beam
Be KPT
KFM
Photon Beam Dump
Sweep Magnet
LH2/LD2 target
East ARC
75m
24m

Planning a future for CEBAF

- **A NEW territory to explore**
  → $c\bar{c}$ states in large quantities and with additional light quarks d.o.f.
- **A BETTER insight into our current program**
  → Enhancement of the phase space
- **A BRIDGE between JLab @ 12 GeV and EIC**
  → Low to high energy theory validation with high precision



2 FFA arcs
4+6 passes = 22 GeV

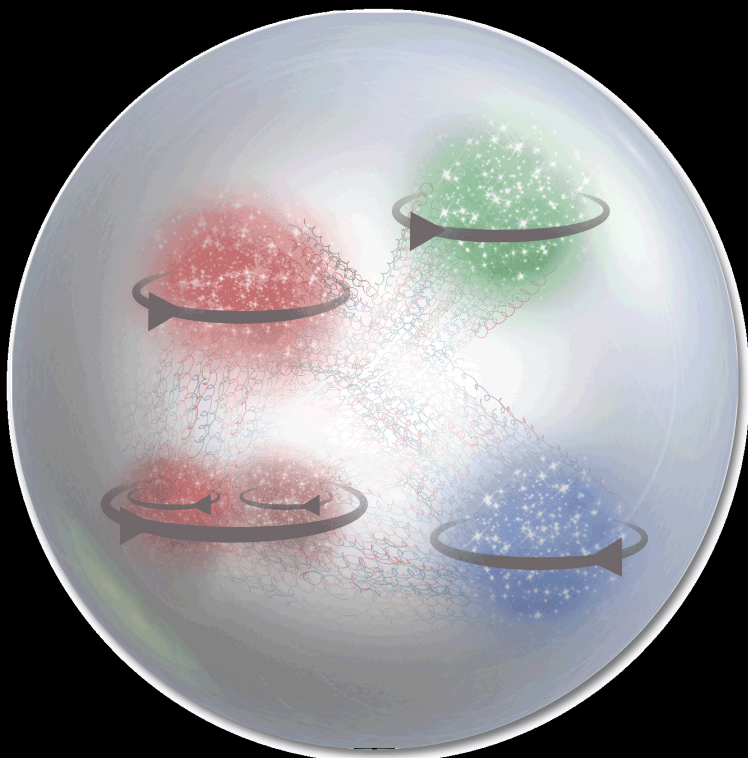
New Injector

The physics program will:
- **Leverage on the uniqueness of CEBAF HIGH LUMINOSITY**
- **Utilize largely EXISTING OR ALREADY-PLANNED HALL EQUIPMENT**

Proposed > 2030

CEBAF @ 22 GeV
e^+ @ 12 GeV

Proton's Structure



Intrinsic properties:

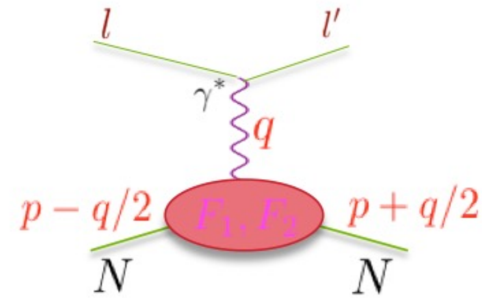
- Electric/Magnetic charge
- Mass
- Spin

Insights into Quarks and Gluon Dynamics

Elastic Electron Scattering & Electromagnetic Form Factors

- Elastic e p → e p scattering used for more than 60 years to investigate nucleon structure
- In 1-photon exchange approximation:

  nucleon structure parameterized by two form factors



$$\begin{aligned} A^{\mu}_{\lambda\lambda'} &= \langle p+\frac{1}{2}q, \lambda' \mid J^{\mu}(0) \mid p-\frac{1}{2}q, \lambda\rangle \\ &= \bar{u}(p+\frac{1}{2}q, \lambda')\left[F_1(Q^2)\gamma^{\mu} + F_2(Q^2)\frac{i}{2m}\sigma^{\mu\nu}q_{\nu}\right] u(p-\frac{1}{2}q, \lambda) \end{aligned}$$

Dirac Pauli

F_1 helicity conserving, F_2 helicity flip form factors

- In experiments we measure the Sachs form factors

$$\frac{d\sigma}{d\Omega}(E,\theta) = \sigma_M \left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2(\frac{\theta}{2})\right]$$

Rosenbluth Formula

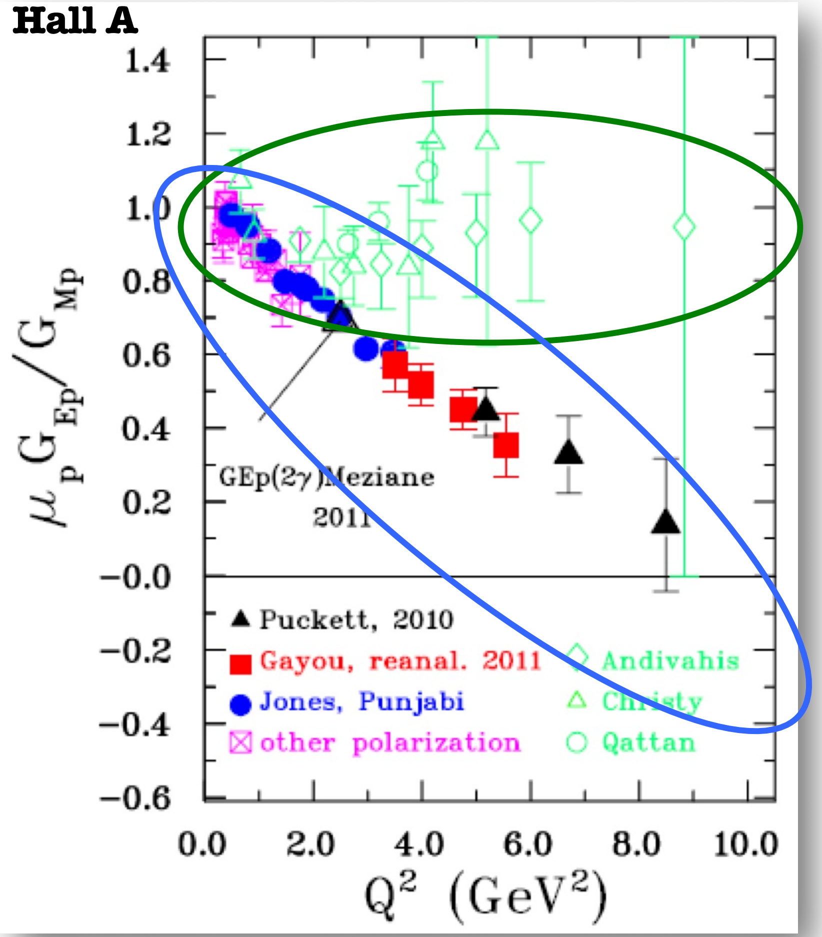
$$\sigma_M = \frac{\alpha^2 E' \cos^2(\frac{\theta}{2})}{4E^3 \sin^4(\frac{\theta}{2})}$$

$$\tau = \frac{Q^2}{2M}$$

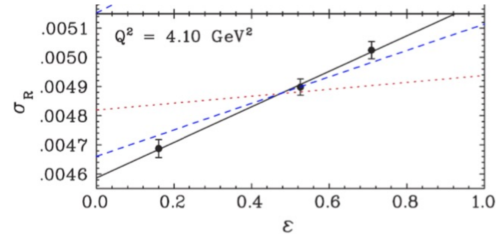
$$\begin{aligned} G_E(Q^2) &= F_1(Q^2) - \tau F_2(Q^2) \\ G_M(Q^2) &= F_1(Q^2) + F_2(Q^2) \end{aligned}$$

FFs: essential in understanding the nucleon electromagnetic structure

Nucleon's e.m. Form Factors



- $\sigma_R = \frac{d\sigma}{d\Omega} / (\frac{d\sigma}{d\Omega})_M \epsilon (1+\tau) = \epsilon (G_E^p)^2 + \tau (G_M^p)^2$



$\epsilon = [1 + 2(1+\tau) tan^2 \frac{\theta_e}{2}]^{-1}$

Measure angular dependence of cross section at fixed Q^2
ε-dependence of "reduced" cross section σ_R is linear with slope G_E^2 and intercept τG_M^2.

Rosenbluth separation

- $\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_l} \frac{(E_{beam} + E_e)}{2M_p} \tan \frac{\vartheta_e}{2}$

• Polarization transfer technique gives different results!

• All double polarization experiments are consitents

Double polarization experiments only possible with high intensity, high polarized beam

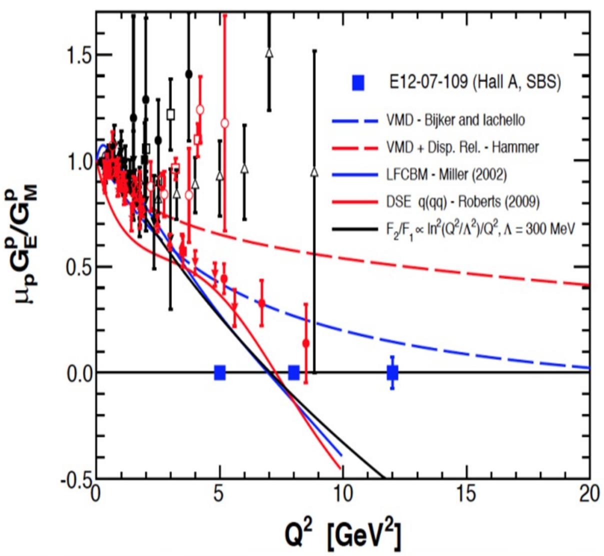
Jefferson Lab

Nucleon's Form Factors @ High Q^2

Complementary equipment/capabilities of Halls A, B, C allow optimal matching of (Luminosity x Acceptance) of the detectors to the luminosity capabilities of the targets, including state-of-the-art polarized target technology.

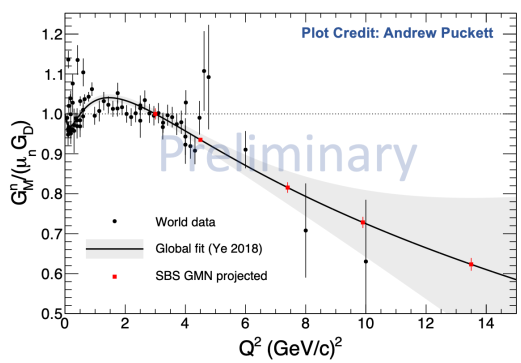
Hall A: SBS Program

G_E^p/G_M^p

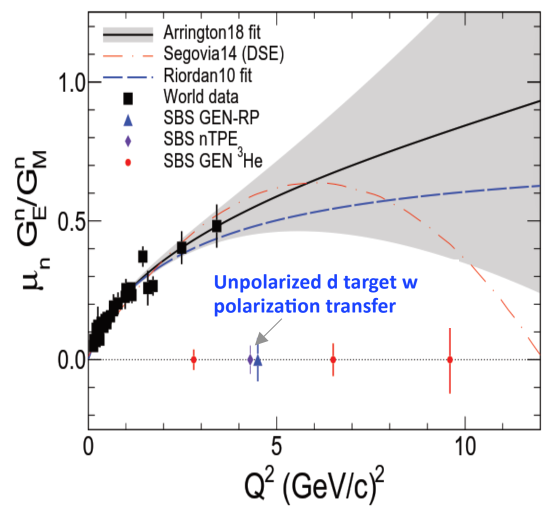


- Measurement of the ratio **G_E^p / G_M^p** in a wide range of momentum transfer Q^2 using the **polarization transfer method**
- **SBS G_E^p / G_M^p** exp. currently scheduled start running by the end of 2024

G_M^n



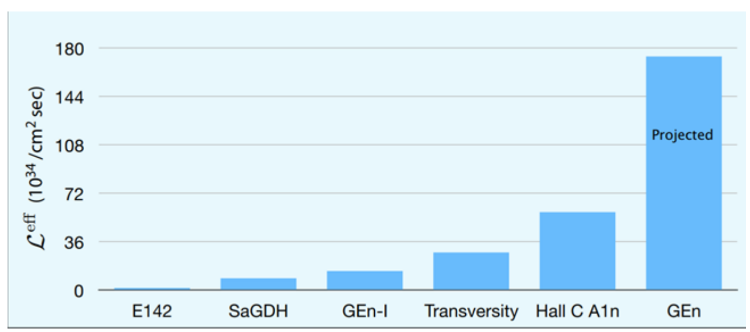
G_E^n/G_M^n



$$A_N = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta}{\Sigma}$$

$$A_N = -\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2)\frac{G_E^n}{G_M^n}\sin\theta^*\cos\phi^*}{\left(\frac{G_E^n}{G_M^n}\right)^2 + \tau + 2\tau(1+\tau)\tan^2(\theta/2)} - \frac{2\tau\sqrt{1+\tau+(1+\tau)^2\tan^2(\theta/2)}\tan(\theta/2)\cos\theta^*}{\left(\frac{G_E^n}{G_M^n}\right)^2 + \tau + 2\tau(1+\tau)\tan^2(\theta/2)}$$

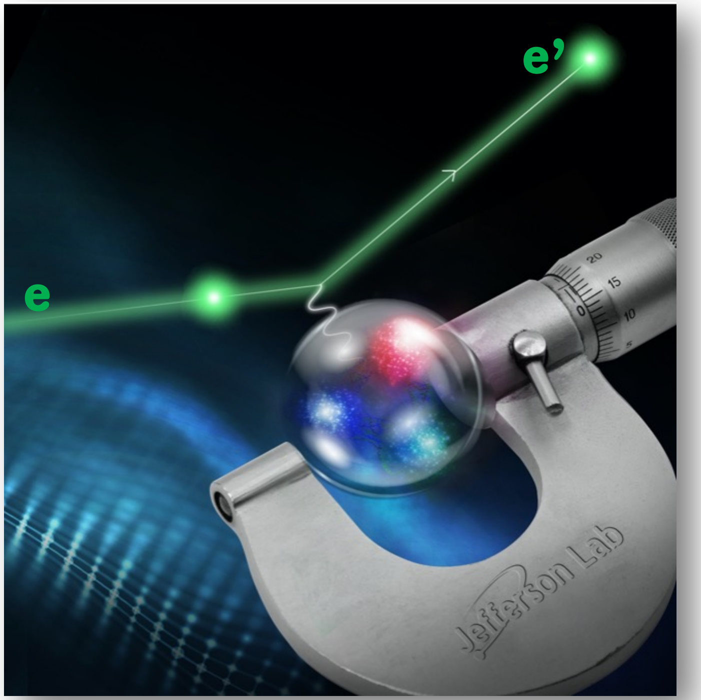
- **Polarized 3He target Double polarization method**



- Polarized ^{3}He target – highest $\mathcal{L}$ to date!
  - First time 60 cm long target
  - 42 – 50% target polarization

Jefferson Lab

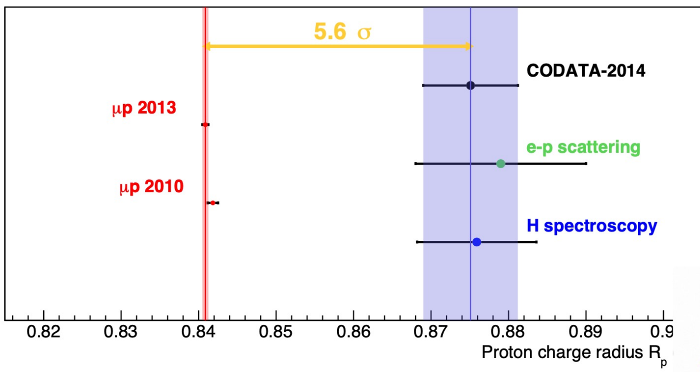
Proton's FF @ Very Low Q^2:Proton's Charge Radius



- A fundamental quantity for understanding how QCD works in the non-perturbative regime
- Has major impact on atomic physics
- Two methods to measure it:
  - Hydrogen spectroscopy (atomic physics)
  - Lepton-proton el. scattering (nuclear physics)

$$\langle r^2 \rangle = -6 \left. \frac{dG_E^p(Q^2)}{dQ^2} \right|_{Q^2=0}$$

Proton's charge radius puzzle

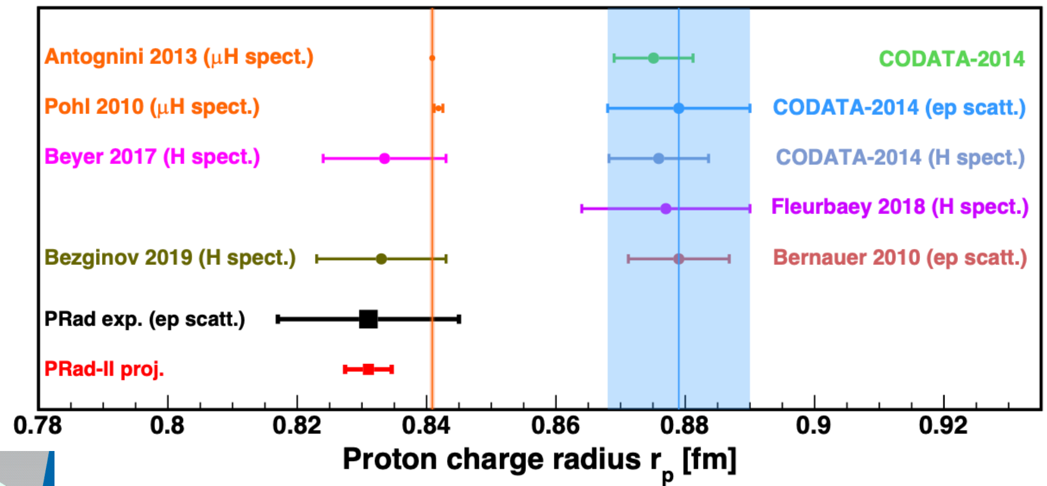


Regular hydrogen and electron scattering:	0.8751 ± 0.0061 fm (CODATA 2014)
Muonic hydrogen:	0.8409 ± 0.0004 fm (CREMA 2010, 2013)

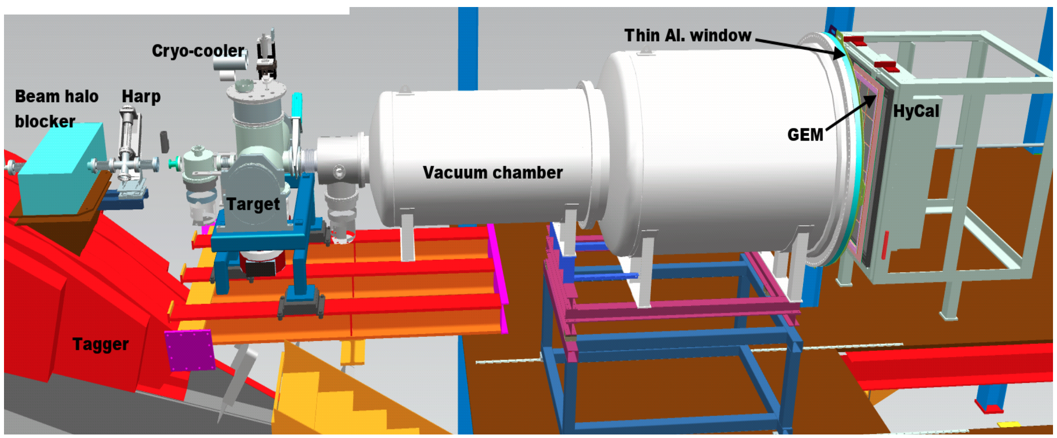
Proton's FF @ Very Low Q^2:Proton's Charge Radius

- **The first new method in half a century for measuring the size of the proton via ep scattering**
  - Scattered electrons in e.m. calorim.
  - Windowless hydrogen gas target

- **The first high-precision e – p experiment since the emergence of the "proton radius puzzle"**
  - Very low Q^2 ($2.4\times10^{-4} - 6\times10^{-2}$)$GeV^2/c^2$
  - e-p events normalized to e-e events



PRAD in Hall B



$r_p = 0.831 \pm 0.007_{stat} \pm 0.012_{syst}$

Nature volume 575, pages147–150(2019)

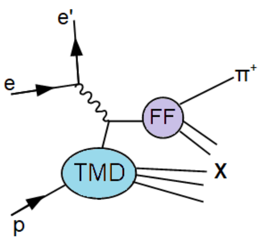
PRad-II: A New Upgraded High Precision Measurement of the Proton Charge Radius

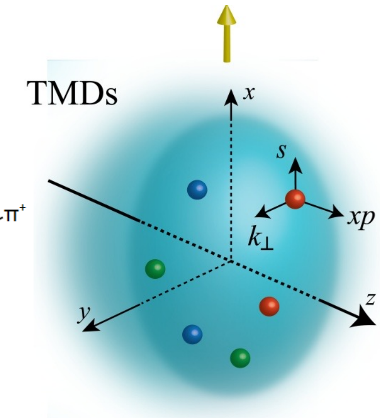
Jefferson Lab

Unified View of Nucleon Structure

$W_p^u(x,k_T,\boldsymbol{r})$ Wigner distributions

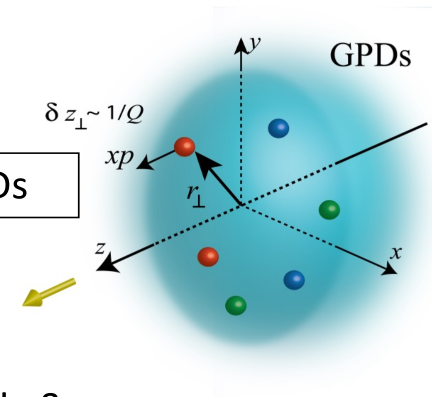
$d^3\boldsymbol{r}$ $\qquad$ $d^2k_T\,dr_z$

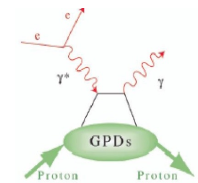




TMD $f_1^u(x,k_T)$, .. $h_1^u(x,k_T)$

GPDs/IPDs

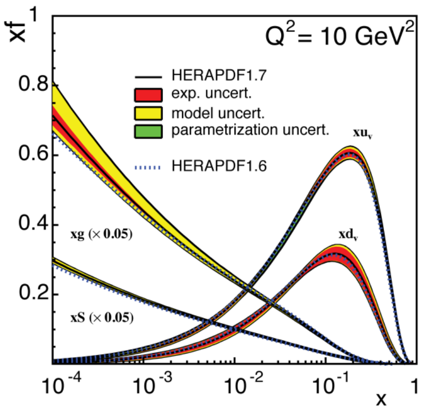




3D imaging

d^2k_T $\qquad$ d^2r_T

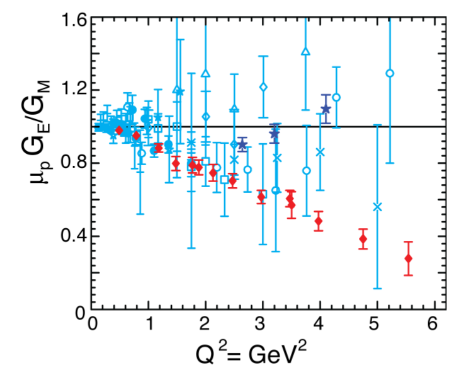
dx &
Fourier Transformation



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

1D

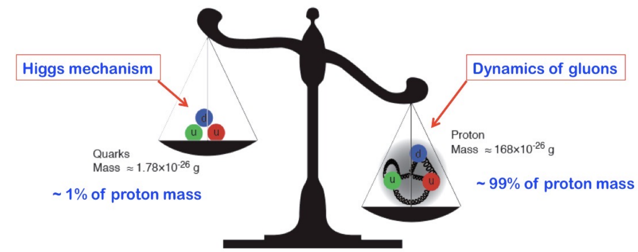
Form Factors
$G_E(Q^2)$, $G_M(Q^2)$



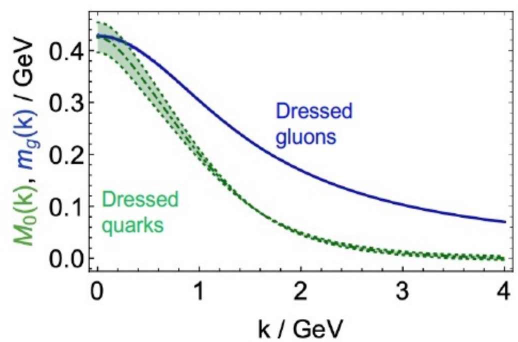
26

Proton's Mass

- How much quark and how much gluon is a proton?
- How do massless gluons provide for the large proton mass?



C.D. Roberts, Symmetry 12, 1468 (2020), AAPS Bull 31, 6 (2021)



- Electromagnetic charge and spin of the proton well-studied through electron scattering
- Gluons are harder to directly access, as they do not carry electromagnetic charge
- Description of mass still in infancy, as most energy (and hence mass) carried by the gluons

- How is the proton mass distributed inside its confinement size?

PROTON MASS: REST-FRAME DECOMPOSITION

X. Ji PRL 74, 1071 (1995) & PRD 52, 271 (1995)

$$M_N = M_q + M_m + M_g + M_a$$

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right) M_N$$ q & qbar kinetic + potential energies

$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)} b M_N$$ q mass

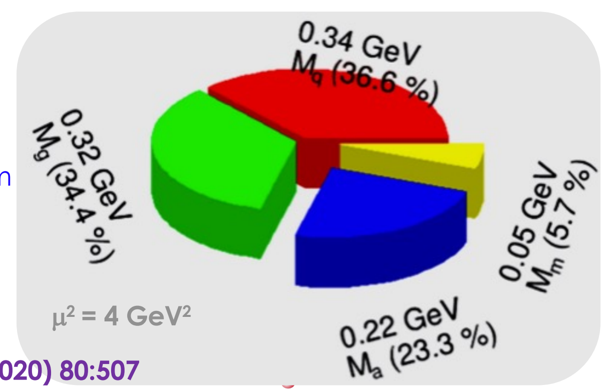
$$M_g = \frac{3}{4}(1-a) M_N$$ gluon energy

$$M_a = \frac{1}{4}(1-b) M_N$$ gluon energy from trace anomaly

γ_m= quark mass anomalous dimension - can be calculated by pQCD

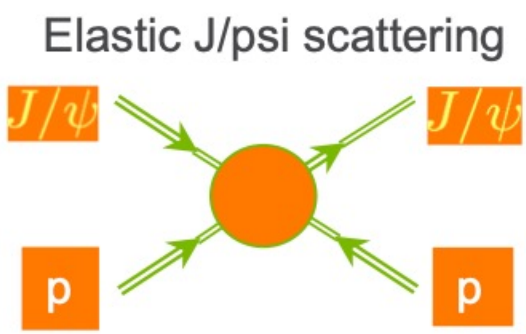
$a(\mu^2)$= related to PDF – well constrained

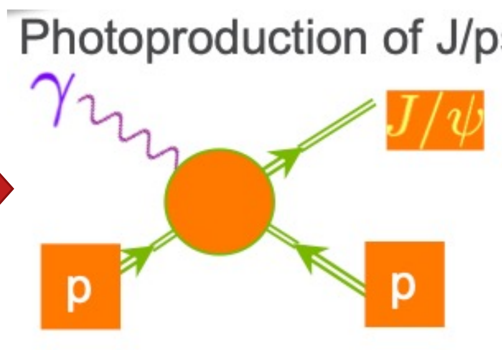
b = unknown

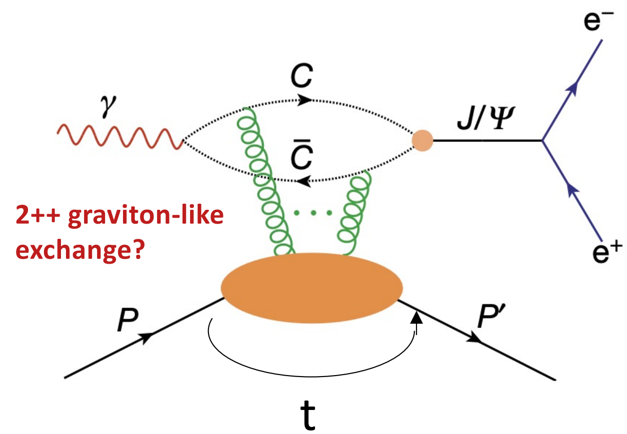


Wang et al. Eur. Phys. J. C (2020) 80:507

Accessing the Proton Color Charge Distribution







GFFs are the form factors (matrix elements) of the QCD EMT for quarks and gluons

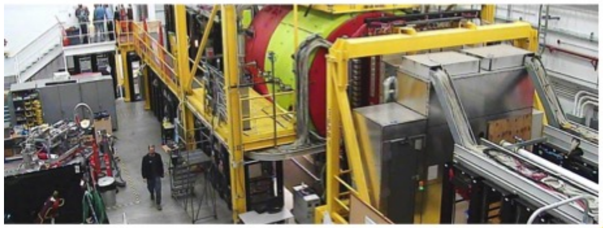
$$\langle N' \mid T^{\mu,\nu}_{q,g} \mid N\rangle = \bar{u}(N')\left(A_{g,q}(t)\gamma^{\{\mu}P^{\nu\}} + B_{g,q}(t)\frac{iP^{\{\mu}\sigma^{\nu\}}\rho\Delta_\rho}{2M} + C_{g,q}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} + \overline{C}_{g,q}(t)Mg^{\mu\nu}\right)u(N)$$

- $A_{g,q}(t)$: Related to quark and gluon momenta, $A_{g,q}(0) = \langle x_{q,g}\rangle$
- $J_{g,q}(t) = 1/2\left(A_{g,q}(t) + B_{g,q}(t)\right)$: Related to angular momentum, $J_{\text{tot}}(0) = 1/2$
- $D_{g,q}(t) = 4C_{g,q}(t)$: Related to pressure and shear forces

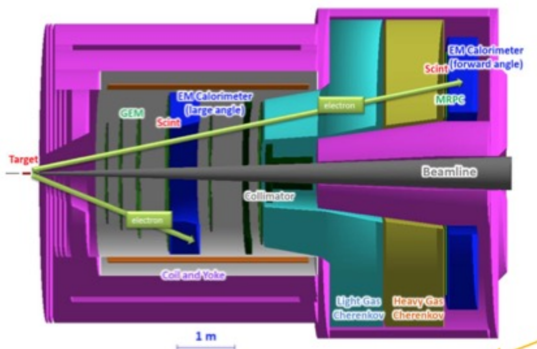
$$\langle r_m^2\rangle = \frac{6}{A_g(0)}\frac{dA_g(t)}{dt}\bigg|_{t=0} - \frac{6}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

- Formation of J/ψ via hadronization of cc pair
- The reaction is expected to be dominated by two-gluon exchange
- Assuming factorization (coupling of the gluons to the proton is described by local gluonic operator) the process involves the gluonic Generalized Parton Distributions (GPDs)
- The gluonic GPD in can be related to the gluonic Gravitational Form Factors (gGFFs)

12 GeV J/ψ Experiments @ Jefferson Lab

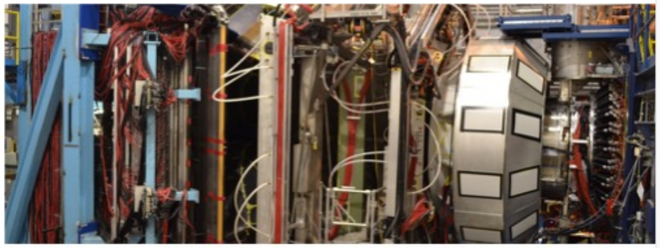


Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



Hall A has experiment E12-12-006 at **SoLID** to measure J/ψ in electro- and photoproduction, and an LOI to measure double polarization using **SBS**

Hall C has the **J/ψ-007** experiment (E12-16-007) LHCb hidden-charm pentaquark search

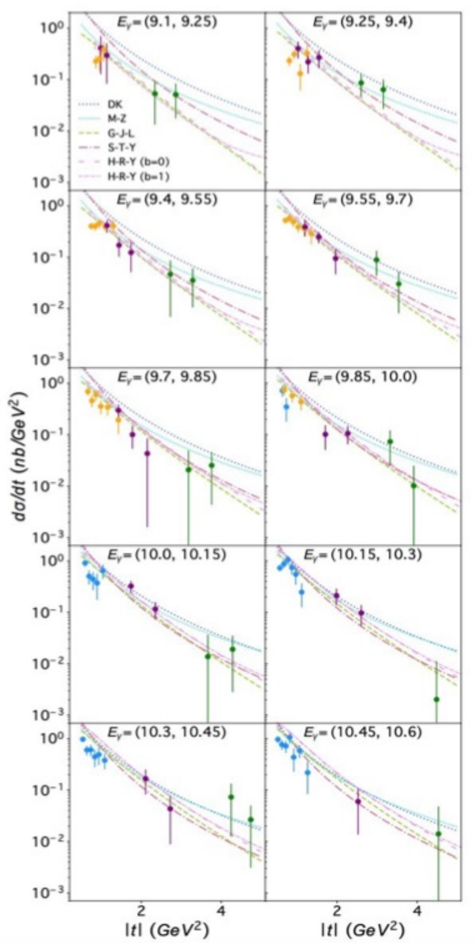


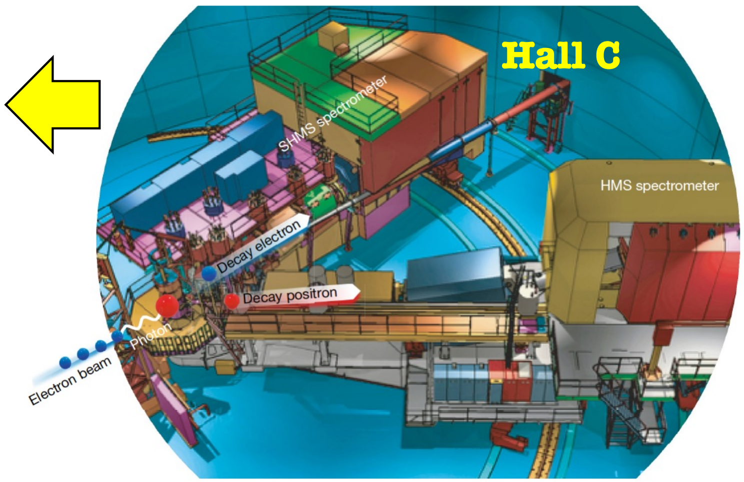
Hall B - CLAS12 has experiments to measure TCS + J/ψ in photoproduction as part of Run Groups A (hydrogen) and B (deuterium): E12-12-001, E12-12-001A, E12-11-003B

Jefferson Lab

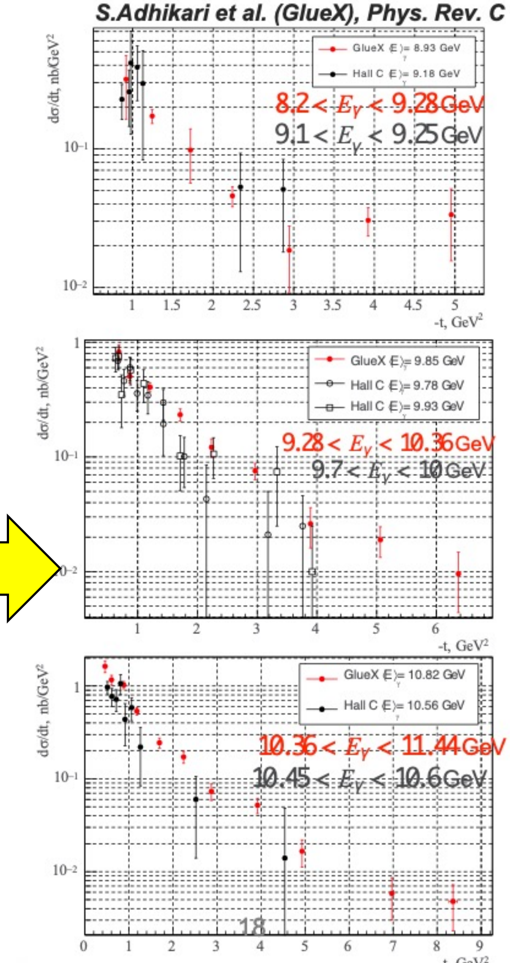
Proton's Mass Radius

B. Duran et al. (J/ψ-007), Nature 615 (2023)





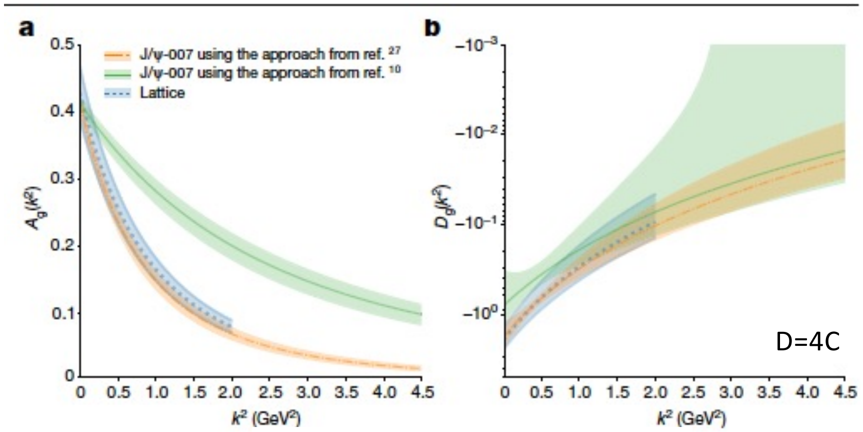
S.Adhikari et al. (GlueX), Phys. Rev. C 108, 025201



Jefferson Lab

Proton’s Mass Radius

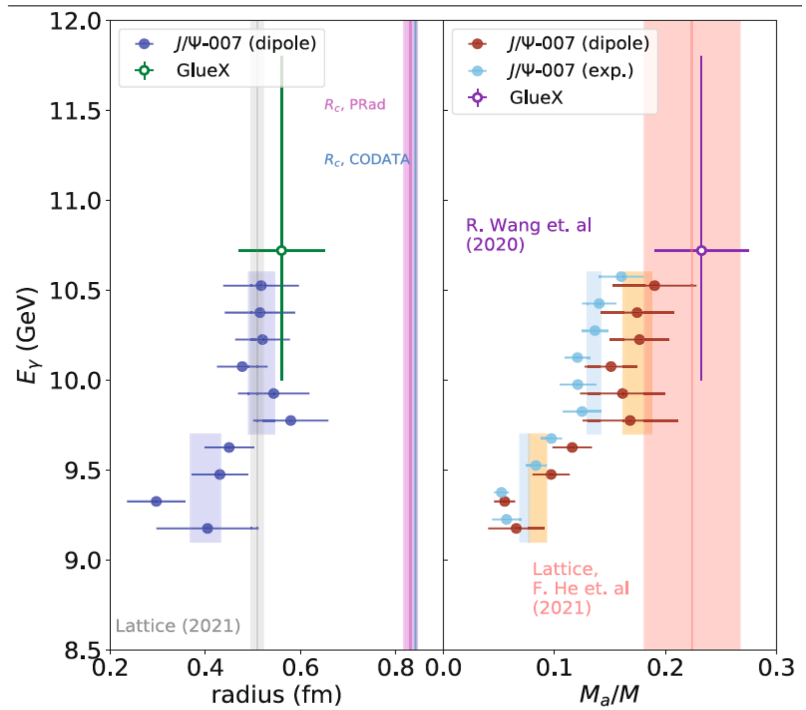
Nature volume 615, pages 813–816 (2023)



$$\langle r_m^2\rangle_g = 6\frac{1}{A_g(0)}\frac{dA_g(t)}{dt}\Big|_{t=0} - 6\frac{1}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

$$\langle r_s^2\rangle_g = 6\frac{1}{A_g(0)}\frac{dA_g(t)}{dt}\Big|_{t=0} - 18\frac{1}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

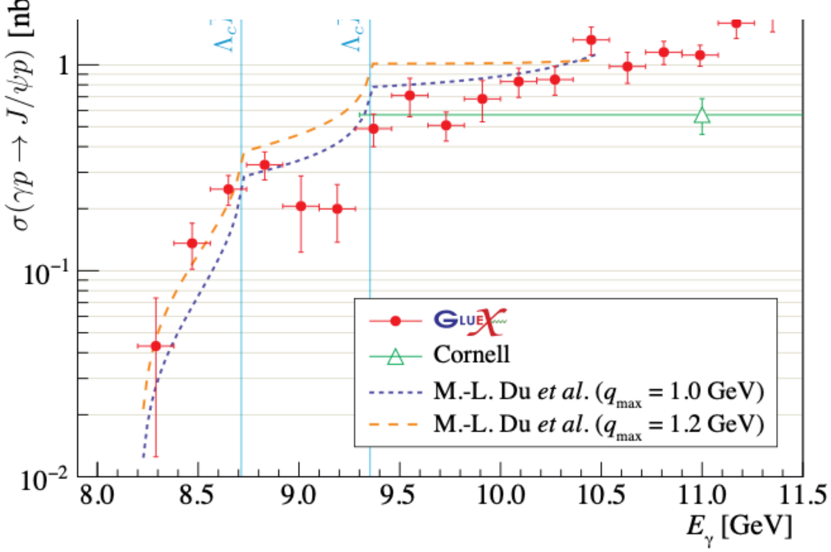
- Inner Gluon radius: 0.52 +/- 0.03 fm
- Scalar gluon radius: 1.069+/-0.056 fm
- Charge radius: ~0.84-0.88 fm



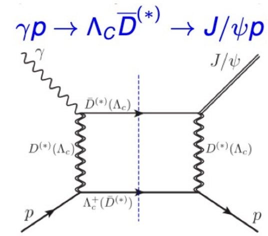
- This work paves the way for a deeper understanding of the salient role of gluons
- **Detailed studies of the reaction $\gamma p \rightarrow J/\psi p$ are needed in order to verify the validity of the assumptions**

J/ψ photoproduction: GlueX Results

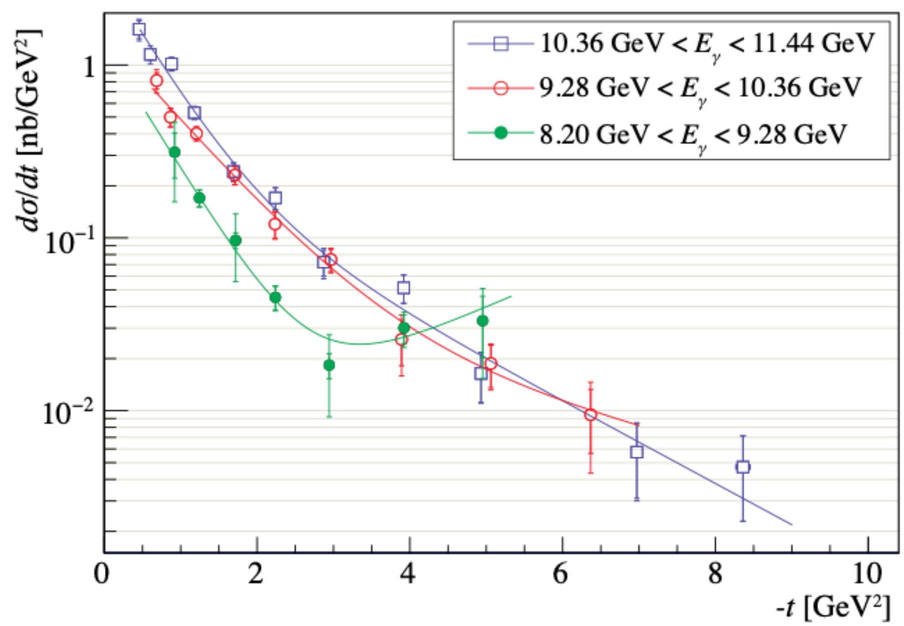
First exclusive measurement very close to the threshold



PHYSICAL REVIEW C 108, 025201 (2023)



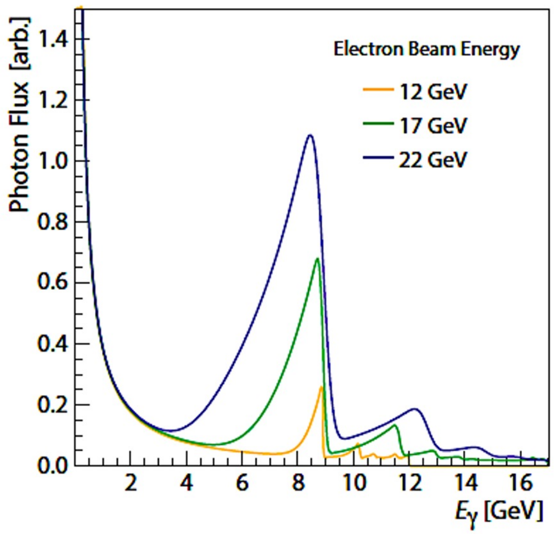
- Cusps at the thresholds of $\Lambda_C \overline{D}$, $\Lambda_C \overline{D}^*$
- Production via open-charm and rescattering?
- This mechanism is not a 2-gluon exchange and may reduce the relation between $\gamma p \to J/\psi p$ and GFF of the nucleon

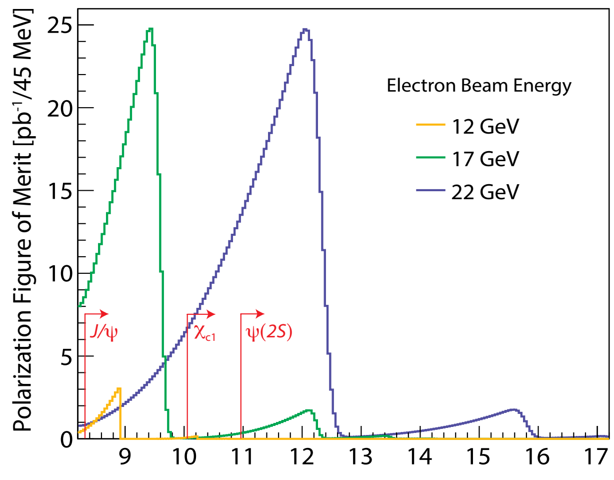


- Exponential slopes indicating t-channel generally consistent with the gluon-exchange mechanism
- Enhancement of $d\sigma/dt$ for lowest energy -> other mechanisms into the game

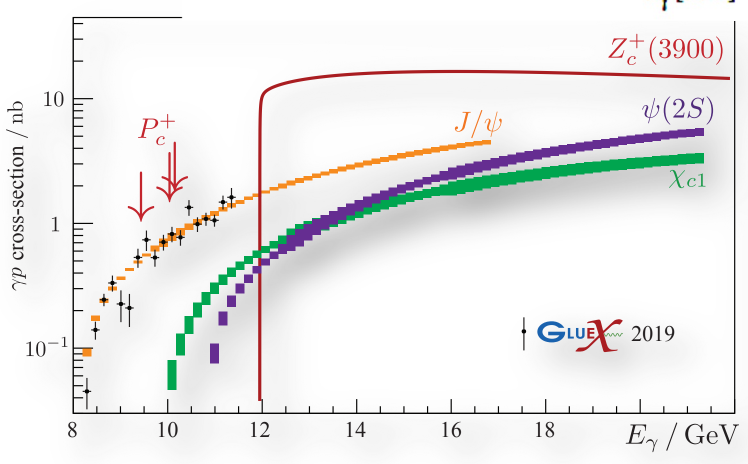
J/ψ photoproduction with GlueX @ 22 GeV

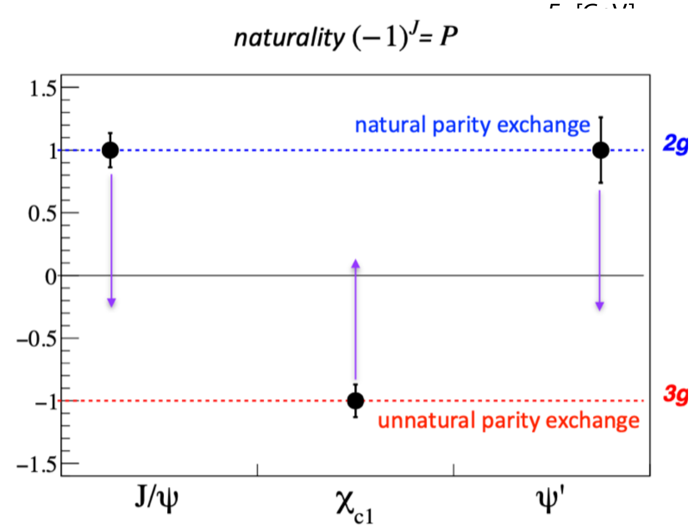
- Increasing the electron beam energy results in a larger fraction of useful high-energy photons





- Energy upgrade gives significant increase of polarization FOM, allowing unique studies of the gluon exchange for J/ψ and higher charmonium states



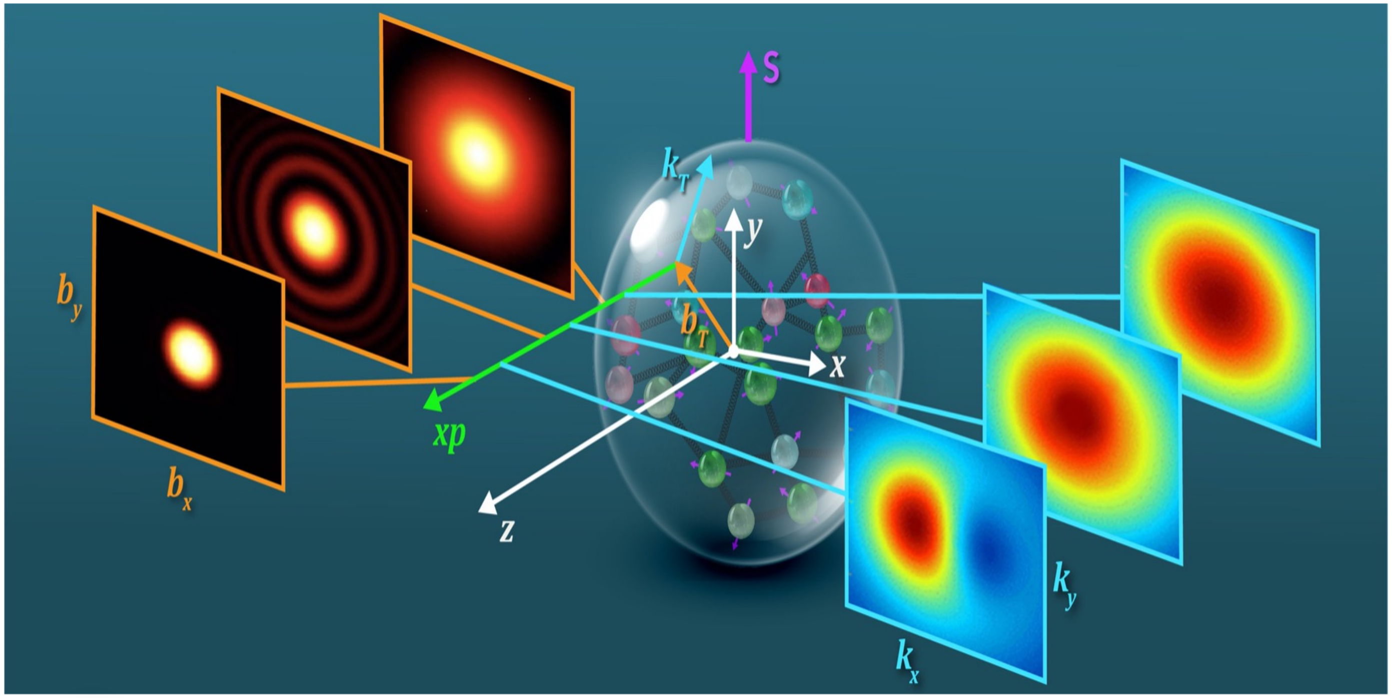


- Any deviation from the expected naturality (+ or -1) indicates contribution of mechanism different from what is needed to study mass properties of the proton

Jefferson Lab

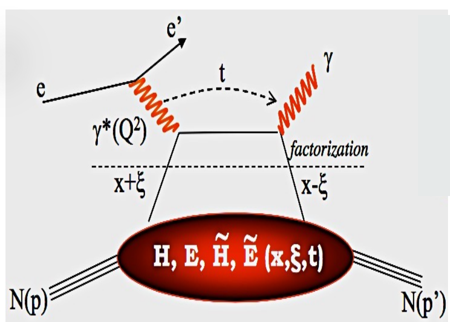
Hadron/Nuclear 3D Imaging

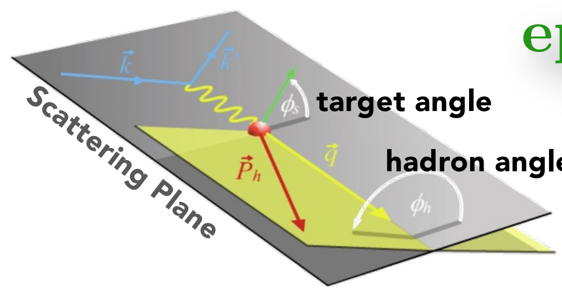
Generalized
Parton
Distributions



Transverse
Momentum
Dependent
Parton
Distributions

$\mathbf{ep \rightarrow e'p'\gamma(\eta, \pi^0, ..)}$





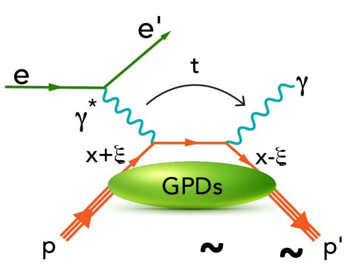
$\mathbf{ep \rightarrow e'hX}$

Jefferson Lab

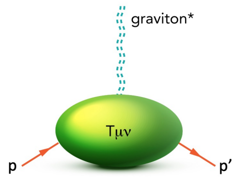
Nucleon Gravitational FFs

- **Matrix elements of QCD EMT** $\langle P'|T^{\mu\nu}|P\rangle = \bar{u}(P')\left[A(t)\gamma^{(\mu}\bar{P}^{\nu)} + B(t)\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M} + D(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M}\right]u(P)$

DVCS



H, E, H̃ , Ẽ



t = (p′ −p)2
$\xi = x_B/(2-x_B)$,
x integrated over

- A massless spin-2 field would couple to the stress–energy tensor in the same way that gravitational interactions do → **D –term accessible through DVCS measurements**

Related to Pressure and Shear Forces

- The leading contribution to DVCS is described in terms of four GPDs.
- Two of them, Hq(x, ξ, t) and Eq(x, ξ, t), give access to quark GFFs as follows

$$\int_{-1}^{1} dx\, xH_q(x,\xi,t) = A_q(t) + \xi^2 D_q(t), \quad \int_{-1}^{1} dx\, xE_q(x,\xi,t) = B_q(t) - \xi^2 D_q(t),$$

The actual observables in DVCS are Compton FFs (CFFs), complex-valued convolution integrals

$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx H(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right)$$

Unpol. DVCS x-section: Re $\mathcal{H}(\xi, t)$
$\Delta\sigma_{LU} \sim \sin\phi$ Im {F1 $\mathcal{H}(\xi, t)$ +…)

related by the fixed-t dispersion relation

$$\mathrm{Re}\mathcal{H}(\xi,t) = \mathcal{C}_{\mathcal{H}}(t) + \frac{1}{\pi}\mathrm{P.V.}\int_0^1 d\xi' \left[\frac{1}{\xi - \xi'} - \frac{1}{\xi + \xi'}\right]\mathrm{Im}\mathcal{H}(\xi',t),$$

$$\mathcal{C}_{\mathcal{H}}(t) = 2\sum_q e_q^2 \int_{-1}^{1} dz \frac{D^q_{\mathrm{term}}(z,t)}{1-z}, \quad D^q_{\mathrm{term}}(z,t) = (1-z^2)\sum_{\mathrm{odd}\ n} d_n^q(t)\, C_n^{3/2}(z)$$

In the limit of renormalization scale μ → ∞, all Dq n(t) go to zero except dq 1(t)

$$D_q(t) = \frac{4}{5}\, d_1^q(t)$$

Mechanical Properties of the Proton

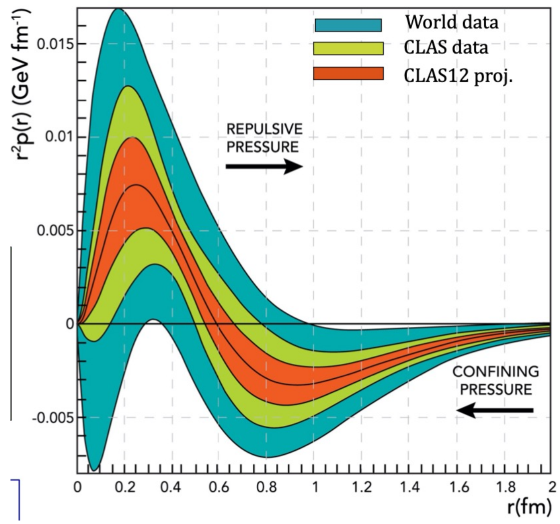
$$d_1(t) \propto \int d^3\mathbf{r}\, \frac{j_0(r\sqrt{-t})}{2t}\, p(r)$$

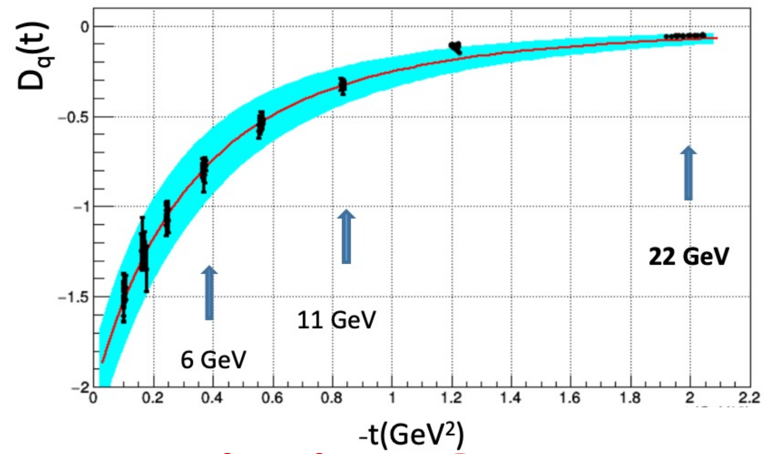
Repulsive pressure near center
$p(r{=}0) = 10^{35}$ Pa
Confining pressure at r > 0.6 fm
(in χQSM due to the pion field)

Atmospheric pressure: 10^5 Pa
Pressure in the center of neutron stars ≤ 10^{34} Pa

V.Burkert ., L. Elouadrhiri, F.X. Girod
Nature 557 (2018) no.7705, 396-399

PRESSURE



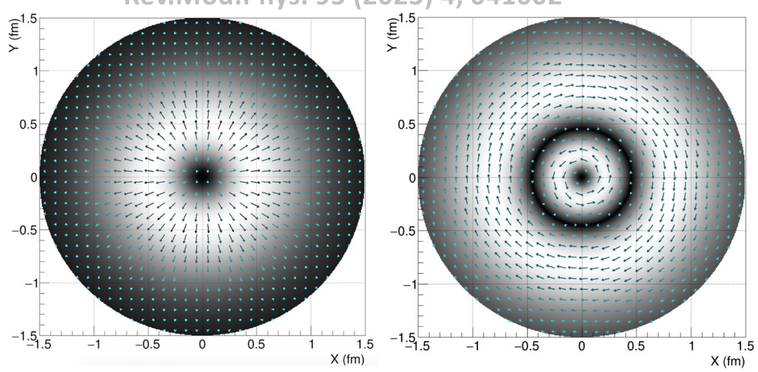


Projections @ 22 GeV

DISTRIBUTION OF FORCES

Rev.Mod.Phys. 95 (2023) 4, 041002

<u>Normal</u> forces as a function of distance from the center.
The arrows change magnitude and point always radially outwards.



<u>Tangential</u> forces as a function of distance from the center.
The forces change direction and magnitude and sign near 0.4 fm from the proton center.

Jefferson Lab

3D Picture of the Nucleon in Momentum Space (TMD)

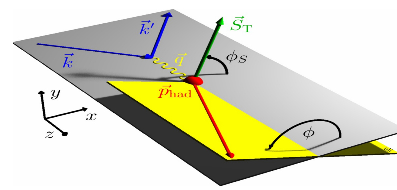
1-D

$$\mathrm{ep} \rightarrow \mathrm{e}'\mathrm{X}$$

$$\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y)\frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right]$$

3-D

$$\mathrm{ep} \rightarrow \mathrm{e}'\mathrm{hX}$$



$$\nu = E - E'$$
$$Q^2 = 4EE'\sin(\theta/2)$$
$$x = Q^2/2M\nu$$
$$z = E_h/\nu$$
$$\mathbf{P_T} = \mathbf{z k_T} + \mathbf{k_T}$$

$$\mathbf{F_{ij}(x, Q^2, z, P_T) = TMD \otimes FF}$$

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,y\,Q^2}\frac{y^2}{2(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi_h}$$
$$+ \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h} + S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h) F_{UL}^{\sin 2\phi_h}\right]$$
$$+ S_L\lambda_e\left[\sqrt{1-\varepsilon^2}F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\right]$$
$$+ S_T\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\sin(\phi_h+\phi_S) F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+ \varepsilon\sin(3\phi_h-\phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}$$
$$+ \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S) F_{LT}^{\cos(\phi_h-\phi_S)}$$
$$+ \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S} + \sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

Leading Order – Leading Twist

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Probability denstities

Higher Twist

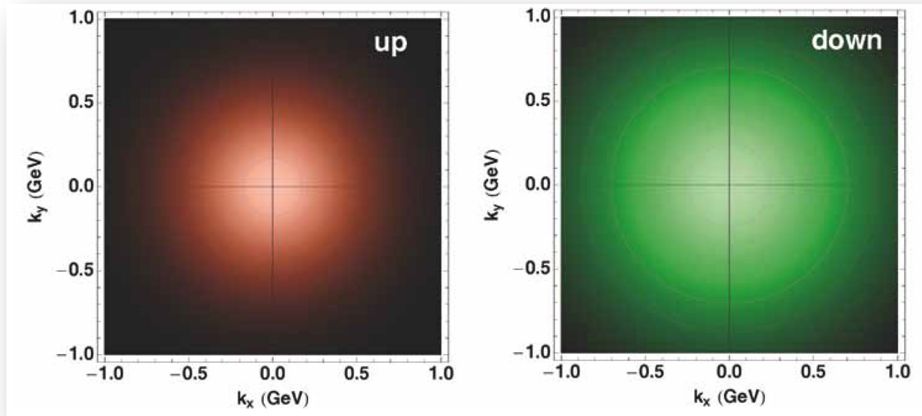
N/q	U	L	T
U	$f^\perp$	$g^\perp$	h, e
L	$f_L^\perp$	$g_L^\perp$	h_L, e_L
T	$f_T, f_T^\perp$	$g_T, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

quark-gluon correlations ➔
a key for understanding long-range quark-gluon dynamics

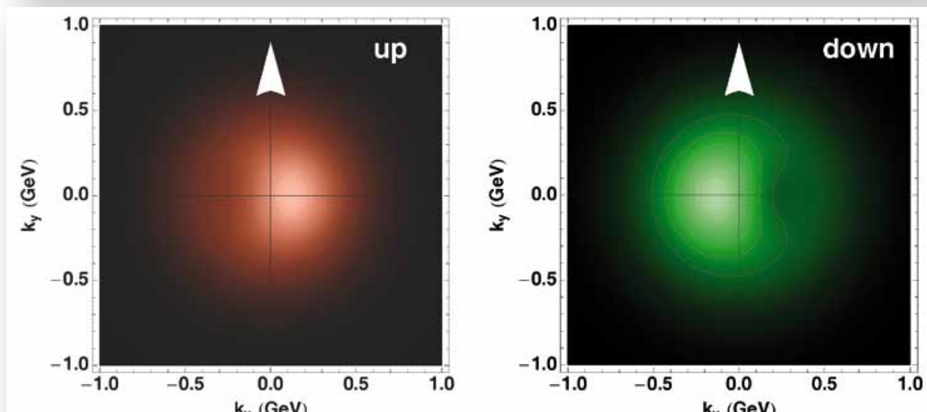
Multi-dimentional analysis mandatory !
High luminosity experiments mandatory!

TMDs

Upolarized proton: indications (from exp data and lattice calc.) that the up-quarks are closer to the center than the down-quarks.
[PLB, 665 (2008) 20 - PRD 83 (2011) 094507]

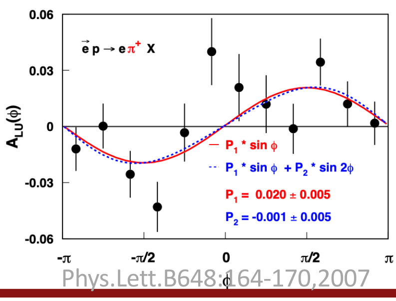


Transversely polarized proton:
Polarization-averaged distributions not anymore cylindrically symmetric. Images show that the distortion for up- and down-quarks is opposite
[Images elaborated from data: EPJA (2009) 89 – PRL107 (2011) 212001]



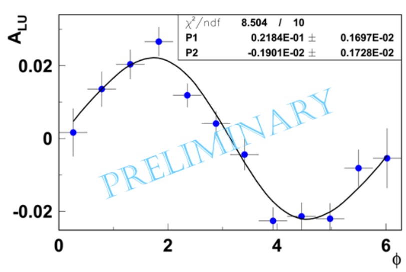
TMD: High Statistics Crucial!

HERMES - **1996-2000**

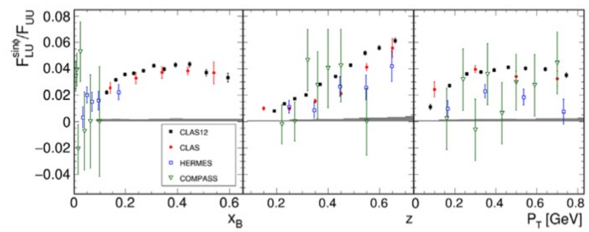


Phys.Lett.B648:164-170,2007

JLab – CLAS12 1 day



Phys. Rev. Lett. 128, 062005 (2022).

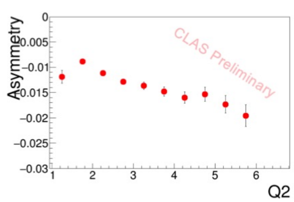


ep→e'π+ X

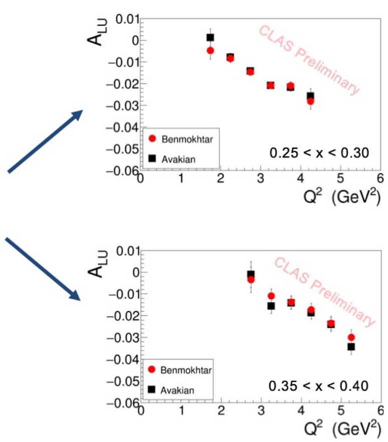
- F_{LU} containis information on quark- gluon correlations

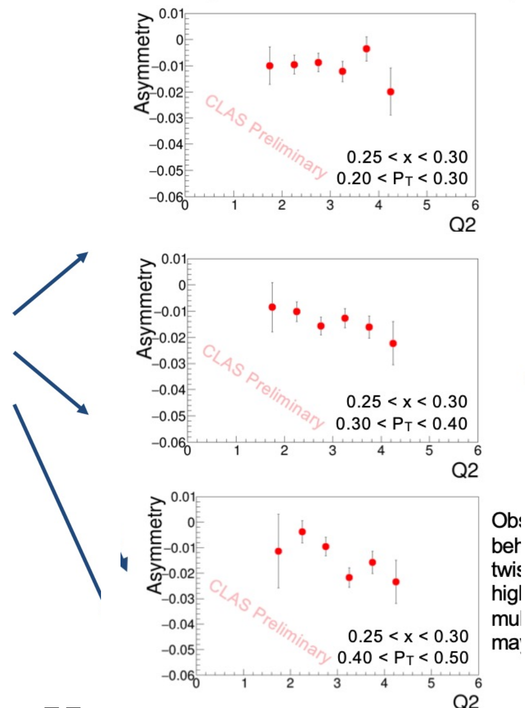
$$F_{LU}^{\sin\phi} \propto \frac{M}{Q}\sum_a e_a^2 (e^a H_1^{\perp a} + f_1^a \tilde{G}^{\perp a} + g^{\perp a} D_1^a + h_1^{\perp a} \tilde{E}^a)$$

e(x) (q-g-q correlations) as force on the quarks (Burkardt PRD88 (2013) 114502)



All plots $x_F < 0$.



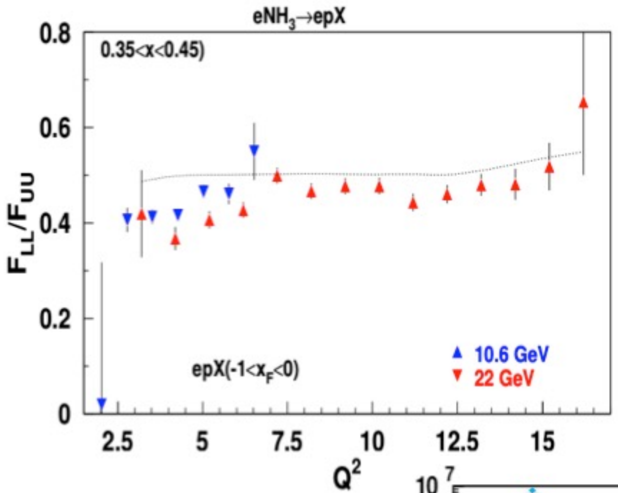


ep → e'pX

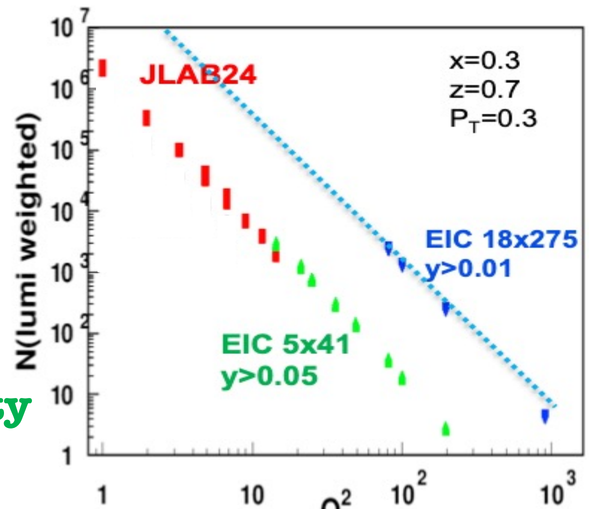
Onward to 4D

- QCD predicts only the Q^2 dependence
- Studies of the Q^2 behavior requires high precision and multi-dimensional analysis

SIDIS Enhanced Multi-D Phase Space @ 22 GeV



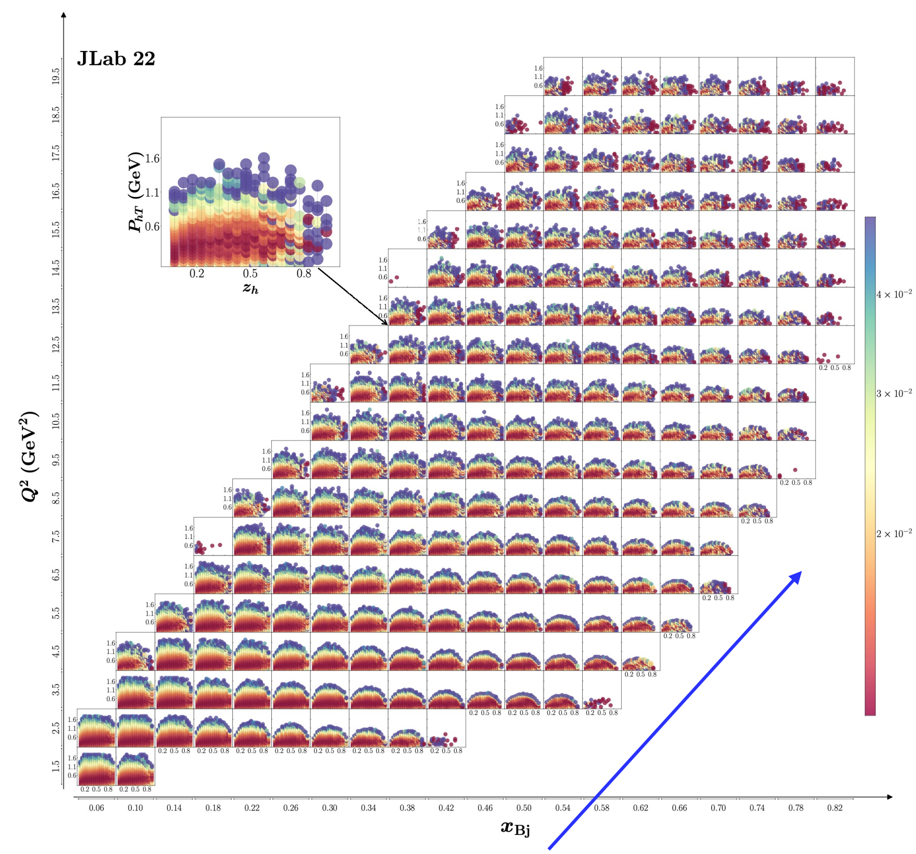
- **Q^2 evolution studies possible**



- **Complementarity with EIC**

x-section from Bacchetta et al, 1703.10157

Projections for 100 days of running with L= 10^{35} $cm^{-2}s^{-1}$ using the existing CLAS12 simulation/reconstruction chain

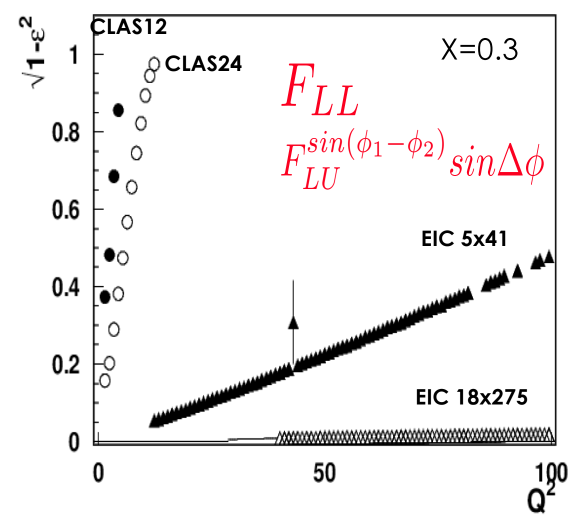


Expected uncertainties for SIDIS cross sections in 4D bins

The Nucleon Structure in 3D

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\quad + S_L\,\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\quad + S_T\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] + S_T\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}
\end{aligned}
$$

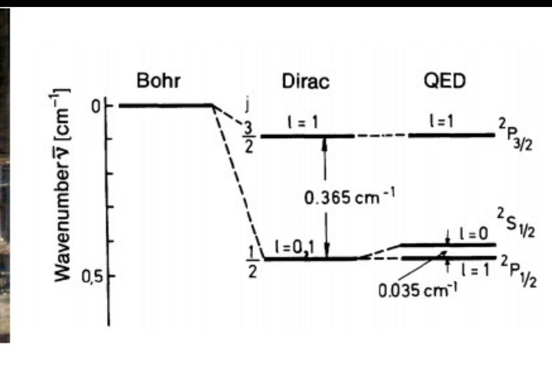
ε = ratio of long. and trans. photon flux



At large x fixed target experiments are sensitive to ALL Structure Functions

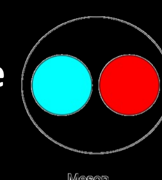
Spectroscopy

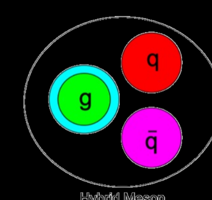
Joseph v. Fraunhofer, 1814



- Study of the interaction between matter and electromagnetic radiation
- Precision measurements of the hydrogen atom spectrum ultimately led to the development of QED

- The study of the empirical spectrum of the hadrons first introduced the concept of quarks and their threefold color charge → experimental foundation of QCD
- An important area of exploration in the field of spectroscopy is to create in the lab hadrons not excluded by QCD but that do not fall neatly into two limited set: *qqq*, $q\bar{q}$
- Mesons in quark model have $P = (-1)^{l+1}$ and $C = (-1)^{l+s}$
  - Some J^{PC} combinations are forbidden for $q\bar{q}$ states, (0^{--}, 0^{+-}, 1^{-+}, 2^{+-} ...)
  - The forbidden J^{PC} can be accessed if there are additional d.o.f. in the final state
    - Additional quarks: tetraquarks or molecular mesons
    - Gluonic excitations: glueball state or a hybrid meson

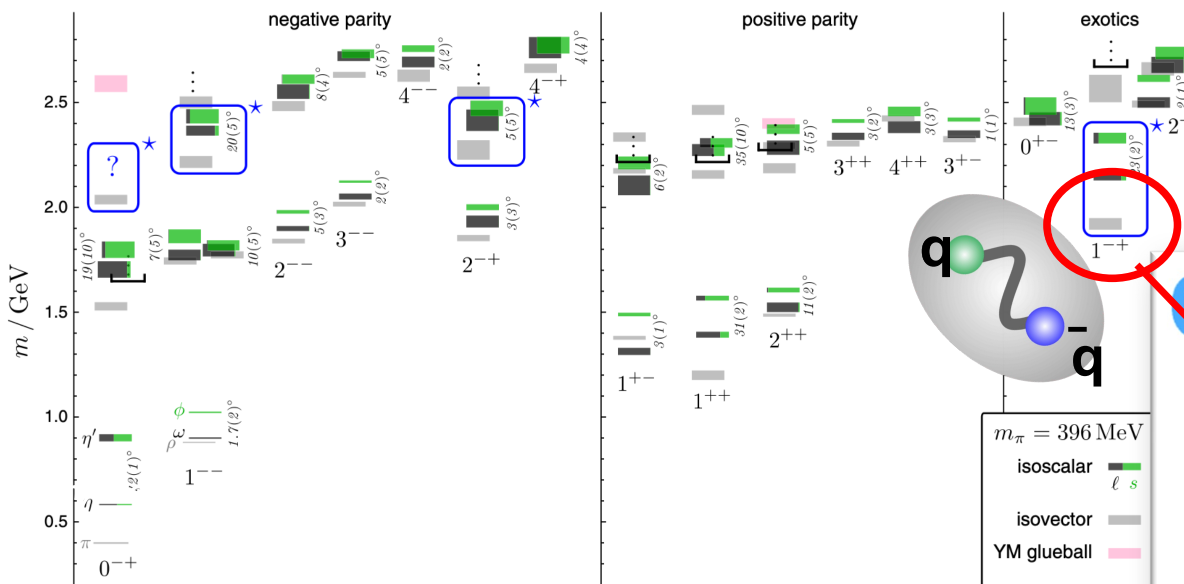




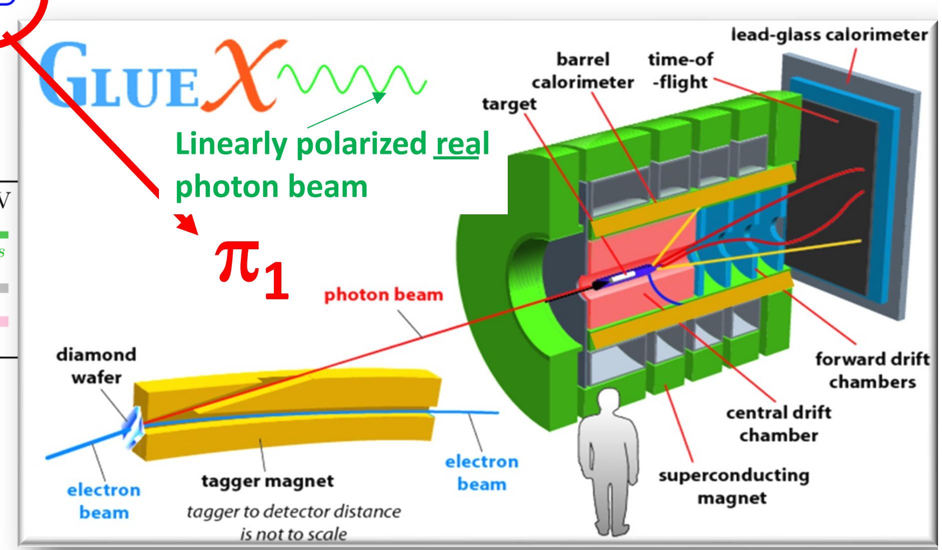
- Study of the missing resonances

Search for Hybrids

…aka flushing out the hidden gluons

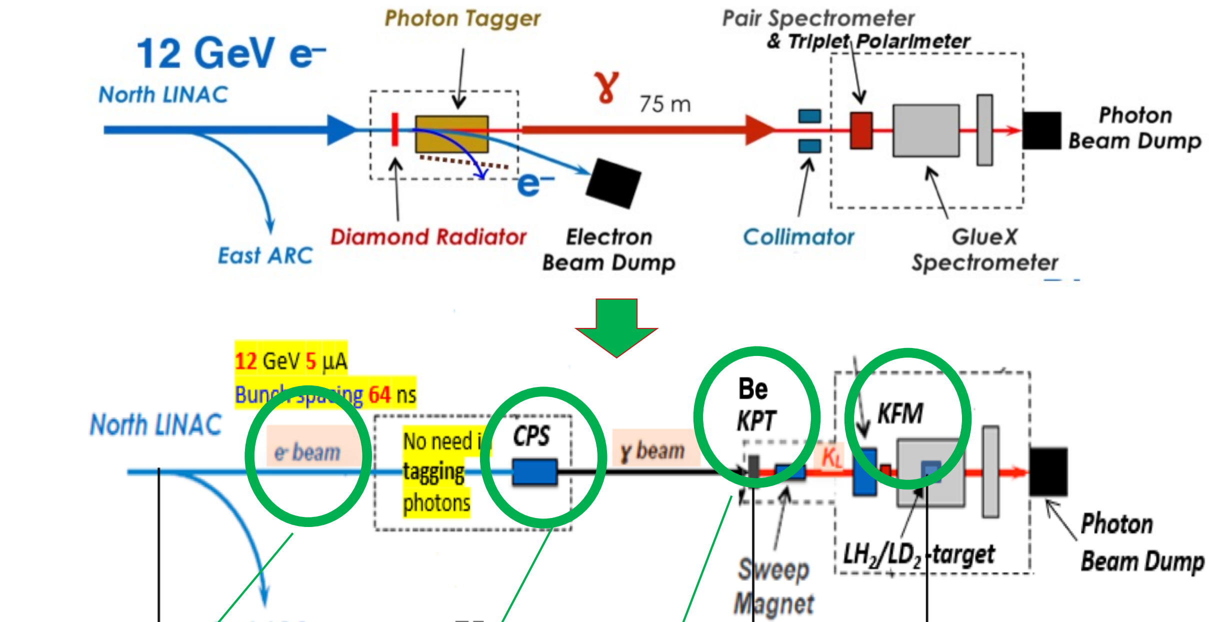


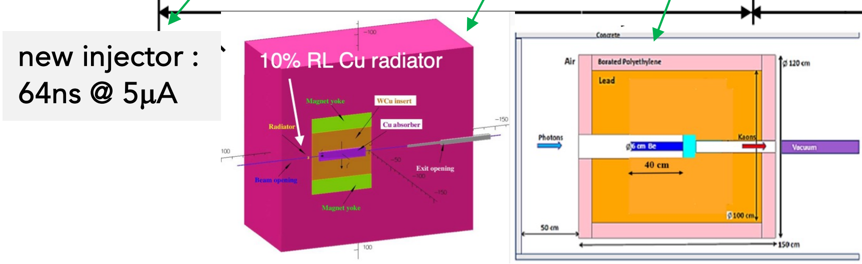
- **Hybrids predicted at relatively low energy mass**
- **Majority of (few) experimental data to date is related to one state, the π_1**



Upper limit on the relative photoproduction cross section of π_1 to a_2 released soon

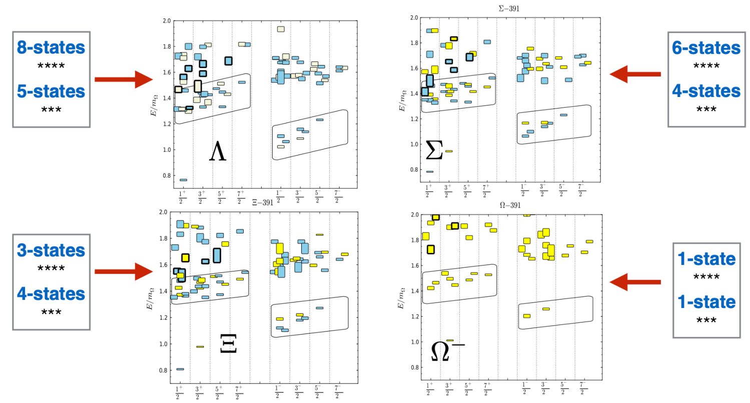
K-Long Facility (KLF)



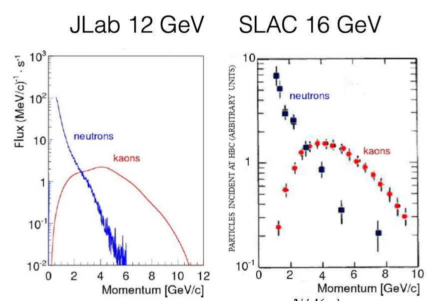


Hyperon Spectroscopy

According to ***LQCD***
many more states including hybrids (thick bordered)



Edwards, Mathur, Richards and Wallace, Phys. Rev. D 87, 054506 (2013)



$N(K_L)/sec \sim 10^4$

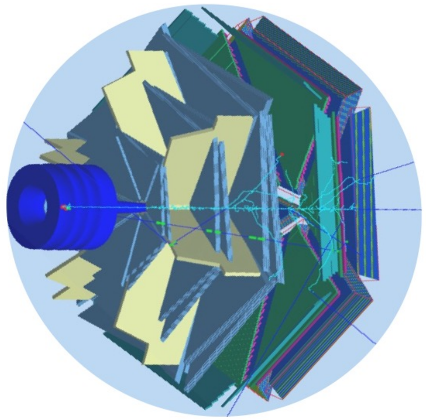
$\frac{N(K_L)_{JLAB}}{N(K_L)_{SLAC}} \sim 10^3$

Beryllium KL production target yields ~10^4 K_L / sec

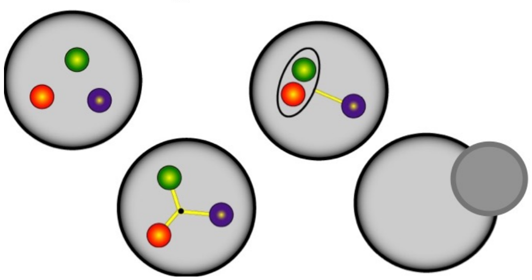
- **Many more states expected than observed! Rich spectrum of uds baryons**
- **Study of properties with # of strange-quarks gives insight into baryon interactions, d.o.f.**
- **Important input to high-density/temperature hadron physics**

The Hall B Spectroscopy Program

BARYON SPECTROSCOPY



N* degrees of freedom??



The N* program is one of the key physics foundations of Hall B

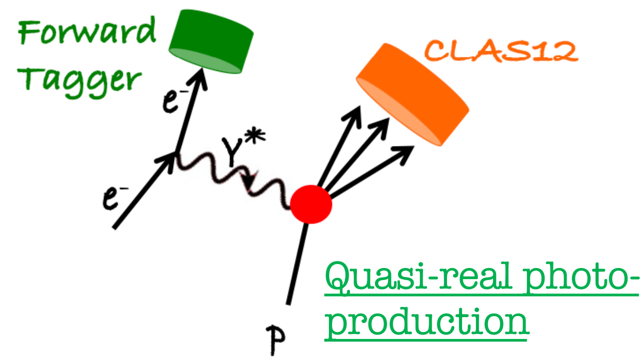
- CLAS12 is designed to study exclusive reaction channels over a broad kinematic range:

  πN, ωN, ϕN, ηN, $\eta' N$, $\pi\pi N$, KY, K*Y, KY*

- Goal is to explore the ***spectrum*** and ***structure*** of N* states
  - Search for "missing" states, studying poorly known or rare decay modes (strangeness-rich)
  - Probe their underlying degrees of freedom via studies of the Q^2 evolution of the electroproduction amplitudes

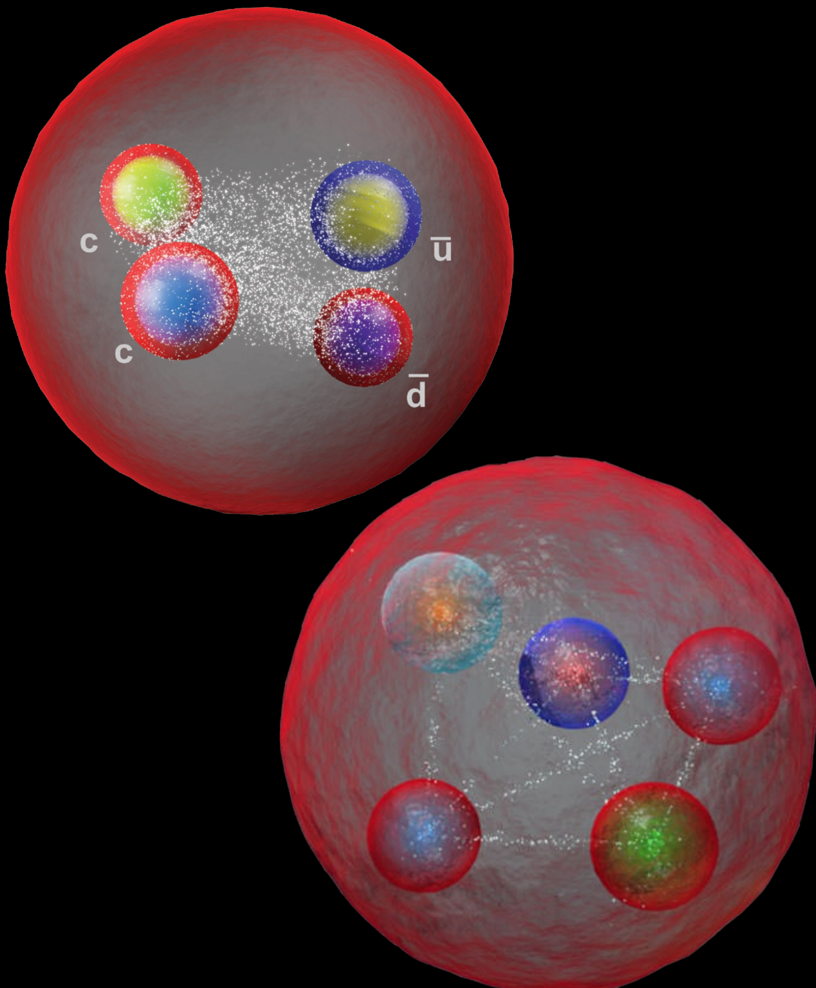
Measure exclusive electroproduction final states from unpolarized proton target with longitudinally polarized electron beam

MESON SPECTROSCOPY



MesonEx:

- Detailed mapping of the meson spectrum up to masses of 2.5 GeV
- Search for rare or poorly known states (strangeness-rich, scalars, …)
- Search states with unconventional quark-gluon configurations

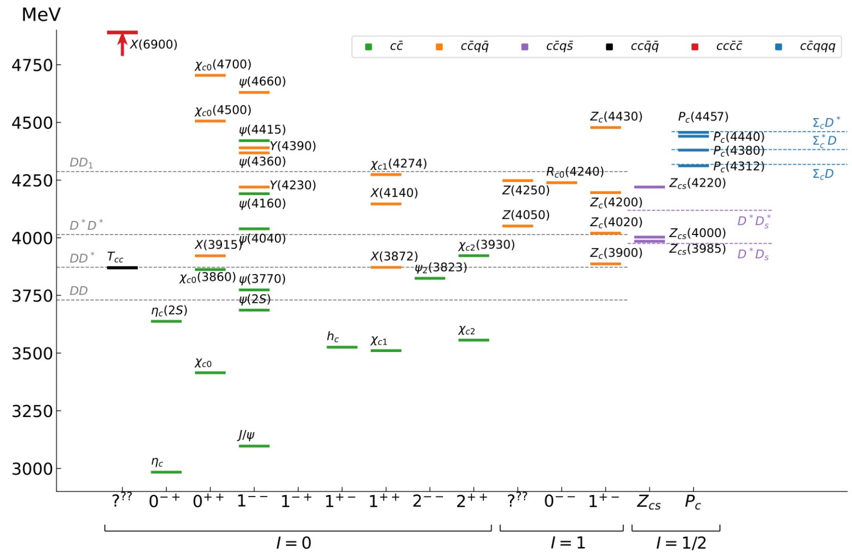


More Exotics Configurations with and Energy Upgrade

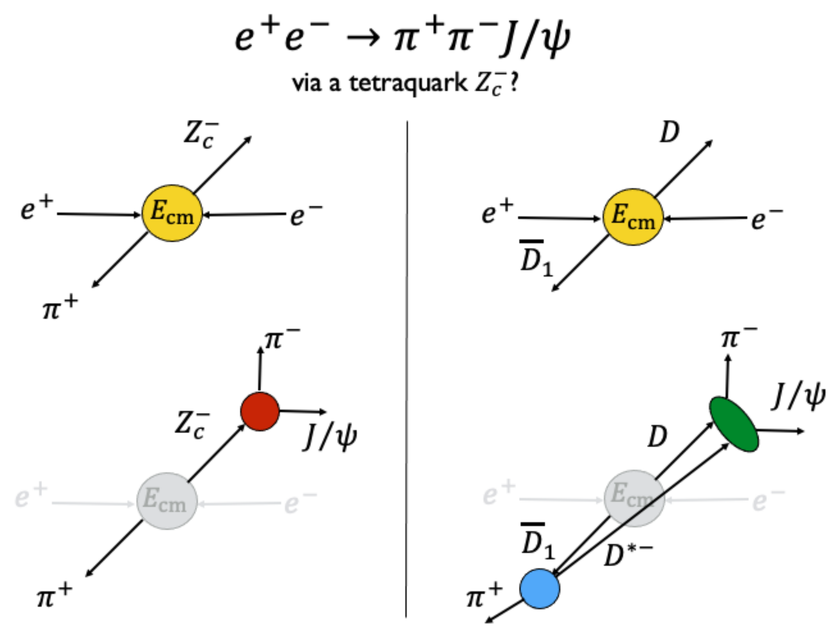
A unique production environment of charmed exotic states can be probed that should help to demystify some puzzles

Photoproduction of Hadrons with Charm Quarks

JLab @ 22 GeV: Potentially decisive information about the nature of some 4-quark (XYZ) candidates



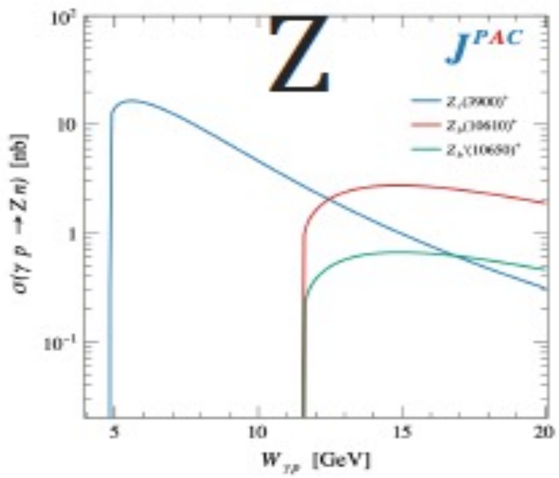
JPAC Collaboration, arXiv:2112.13436

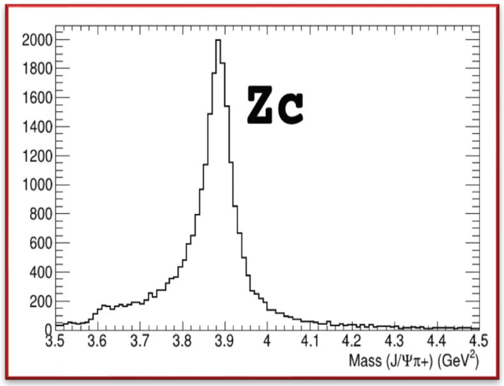


Interpretation of data is complicated by nonresonant $D^{*-}D \to J/\psi\pi^-$ scattering that can produce peaks in invariant mass spectra for certain choices of E_{cm} and π^+ momentum that result in a $D^{*-}D$ interaction. These peaks are effects of initial state kinematics and do not require a resonance in $\pi^- J/\psi$.

- **Many "XYZ" states observed in B decays, e^+e^- colliders**
- **Scarce consistency between various production mechanisms - internal structure not understood yet**

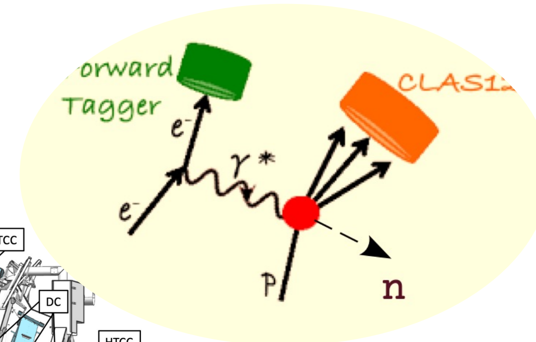
Projections

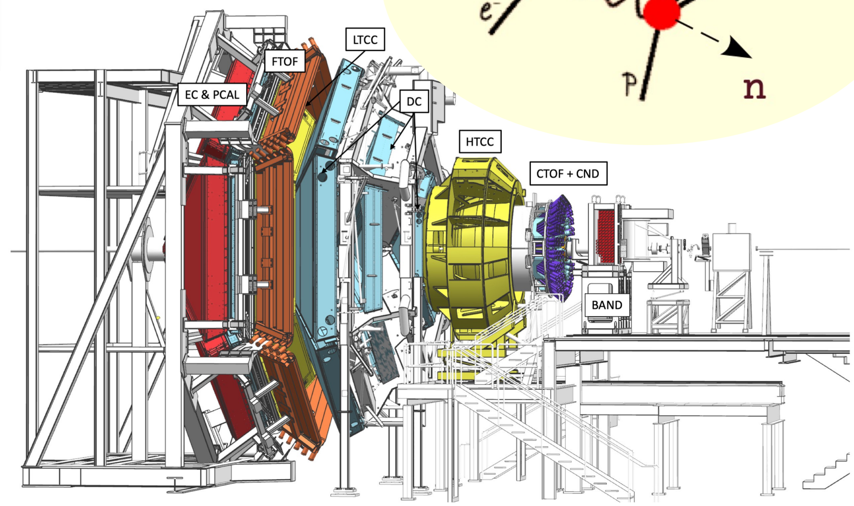


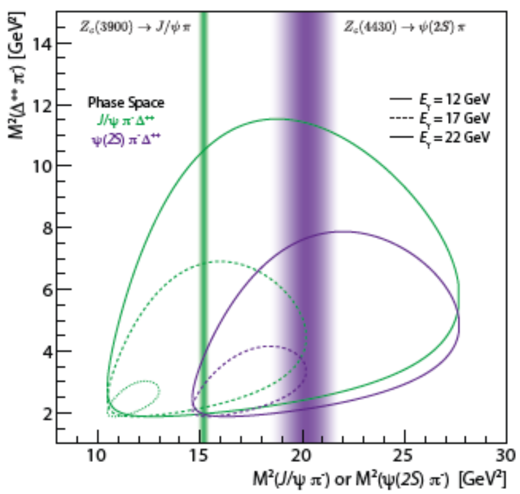


CLAS12 – HALL B

e$^-$ 2.5-4.5^o →
Q^2<0.03 (GeV/c)^2





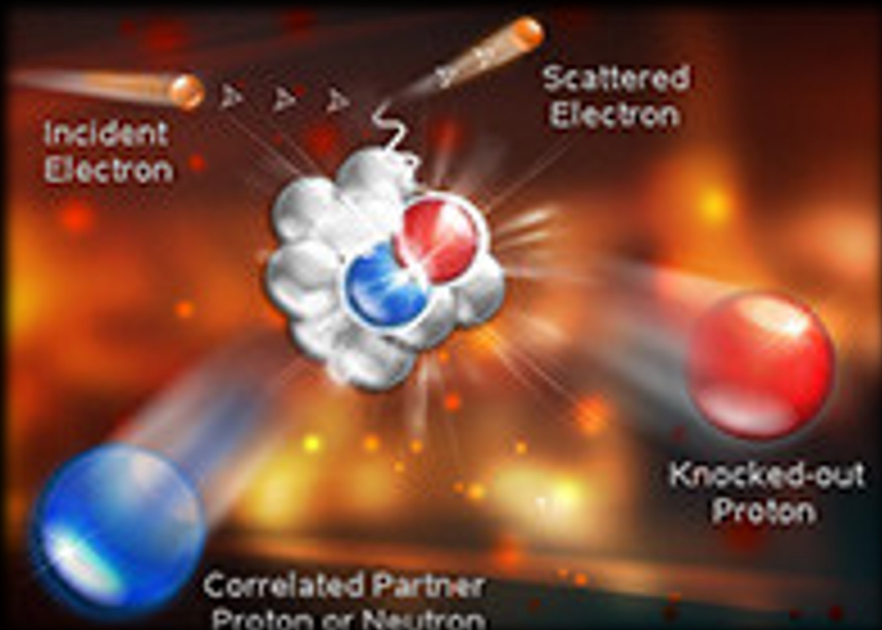


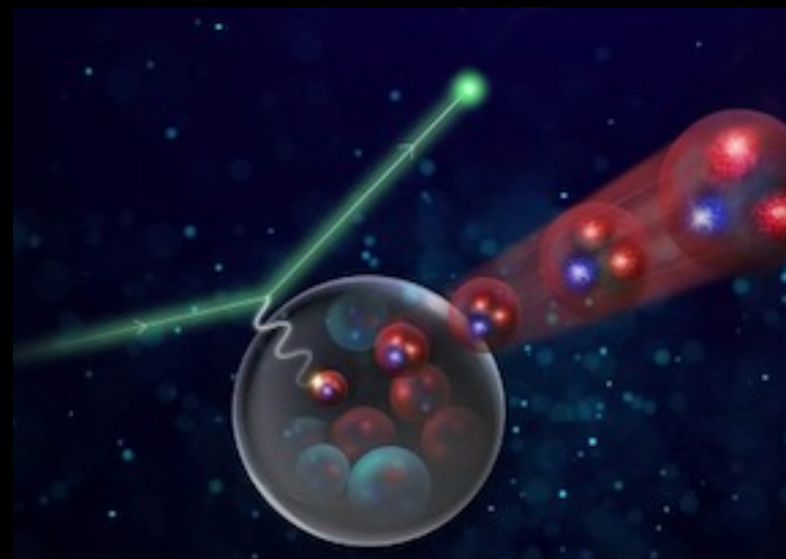
GlueX – Hall D

- **Q^2 evolution** of any new state produced

Nuclear Dynamics

- Nuclear forces dominated by nuclear repulsion – short space-time separation in nuclei

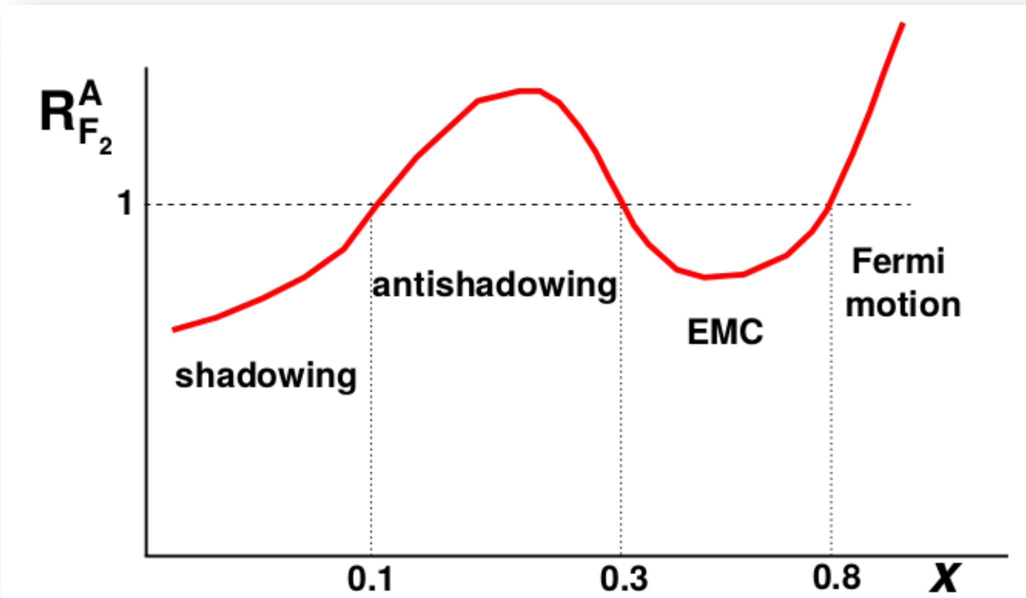




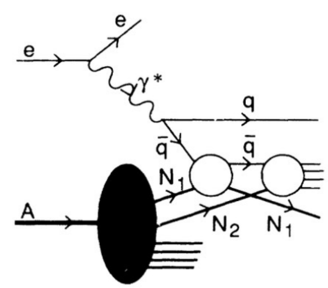
- Nuclear-medium modifications of hadronic structure

Modification of Nucleon Structure in Nuclei

Quark momentum distributions in nucleons bound inside nuclei are different from those of free nucleons.



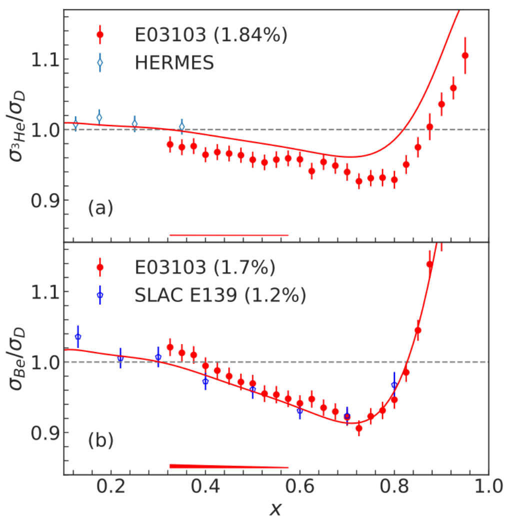
- Fermi motion: bound nucleons moving in nuclear medium
- EMC ??
- Antishadowing ??
- Shadowing: multiple-scattering (diffractive)

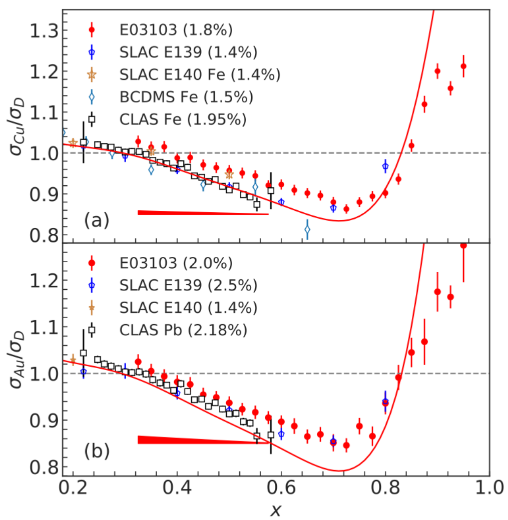


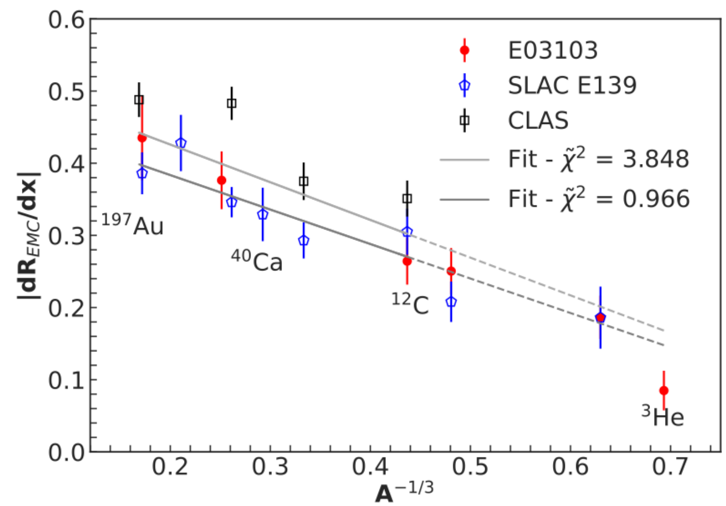
Modification of Nucleon Structure in Nuclei

Extensive Program at Jlab to measure F2 in different nuclei

DIS regime: Q^2 > 2





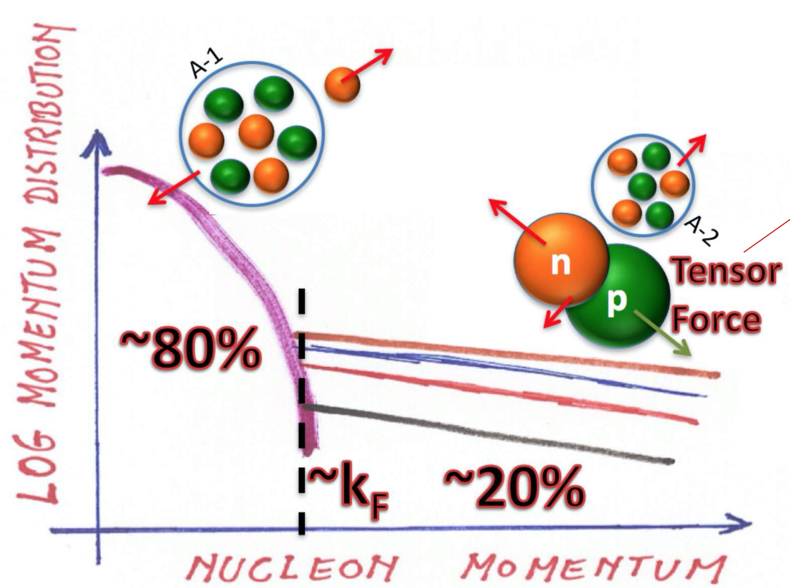


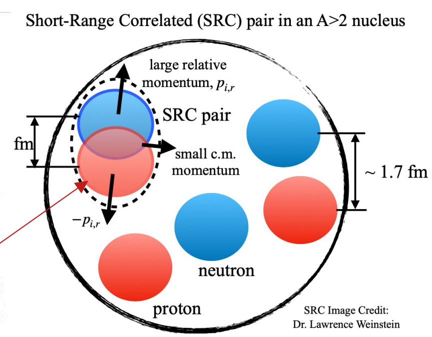
J. Arrington *et al.* Phys. Rev. C 104, 065203 (2021)

Nuclear Forces at Short N-N Separation

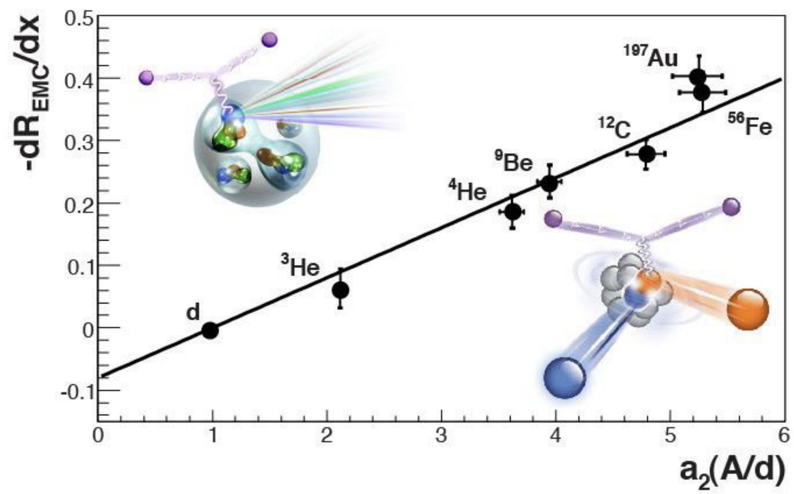
Extensive sets of data related to SRCs have become available from our experimental program

Rev. Mod. Phys. 89, 045002





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

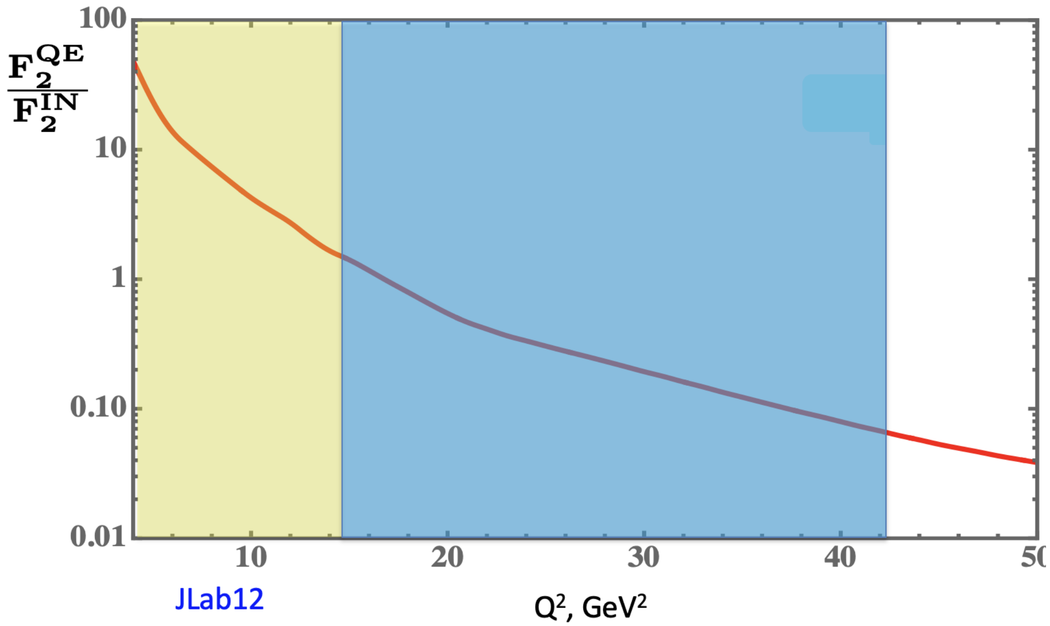


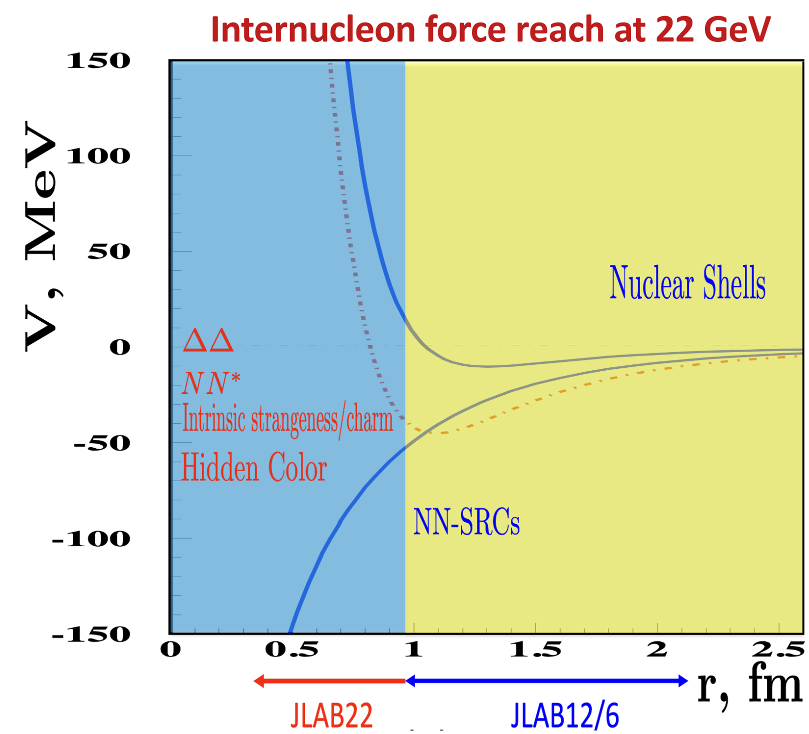
The size of the EMC effect in different nuclei correlates linearly with the density of SRC pairs.

Nuclear Dynamics at Extreme Conditions

A 22 GeV upgrade will provide reach to the nuclear forces dominated by nuclear repulsion

QCD gives new perspective to dynamical origin of the nuclear core predicting possibility of sizable contribution to the nuclear wave function from non-nucleonic components including the hidden color





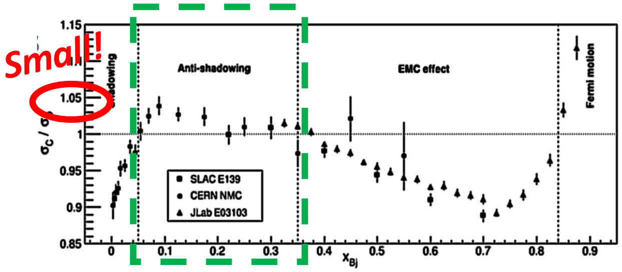
Probing Superfast Quarks (associated with nucleons at very large internal momenta) →by Isolating DIS processes

The high Q^2 reach will allow

- the suppression of quasi-elastic contributions,
- the first-ever direct study of nuclear DIS structure function at Bjorken $x > 1.2$ (r~ 0.5 fm,)

Jefferson Lab

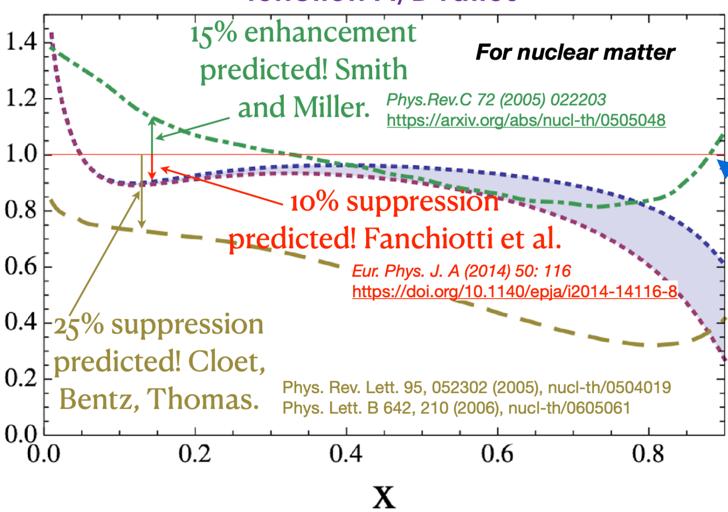
Anti-shadowing: solving a multi-decade puzzle



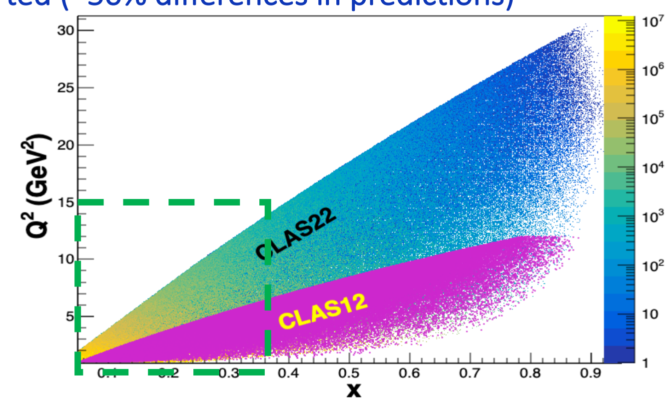
With a 22 GeV e- beam JLab can access the anti-shadowing region (x~0.1-0.3) at moderate Q^2

- Region extremely interesting, near-equally dominated by valence quarks, sea-quarks, and gluons → many many models!!

Theory predictions for polarized structure function A/D ratios



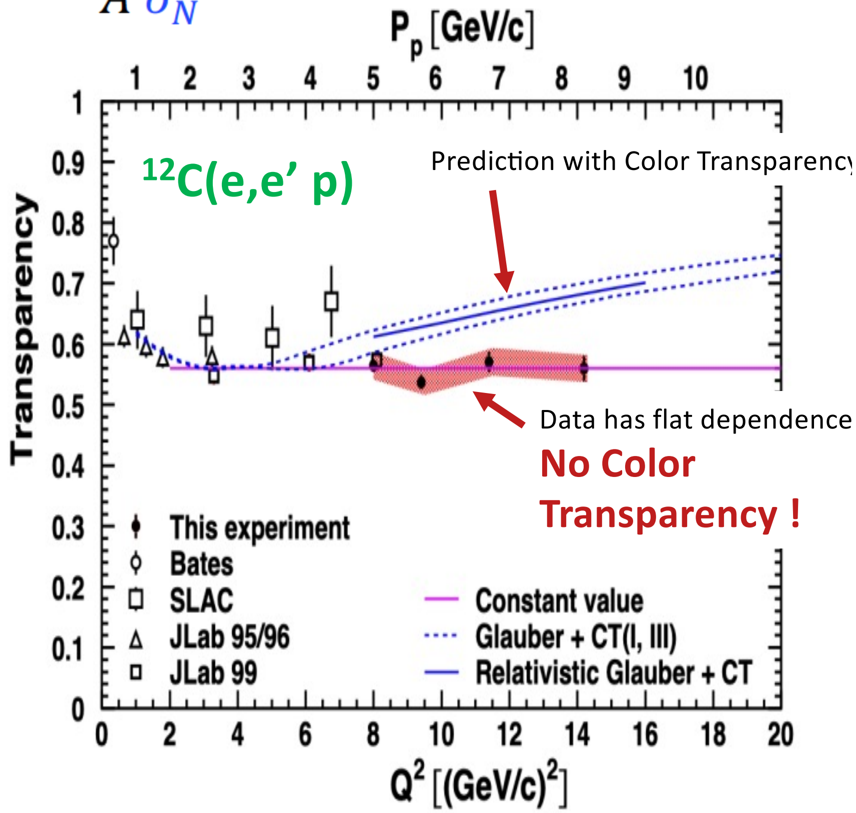
- Anti-Shadowing is the *least studied* nuclear structure function effect experimentally – ***small effect requiring precision and high luminosity***
  - flavor dependence essentially uncharted
  - spin dependence essentially uncharted (~50% differences in predictions)
  - no tagged measurements
  - no L/T separations



A rigorous testing ground between shadowing, EMC regimes – models and theory must describe ALL

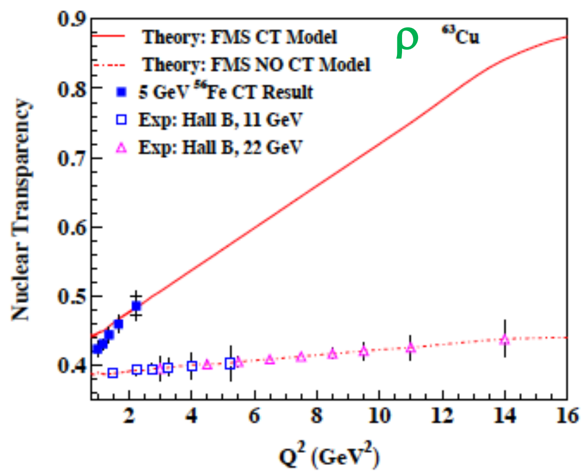
Color Transparency: new nuclear data challenge theory

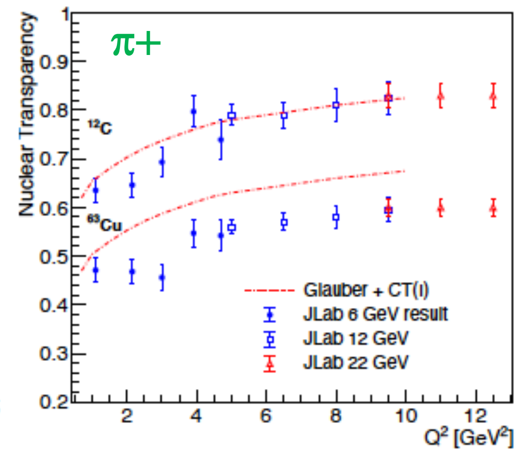
$$T_A = \frac{\sigma_A}{A\,\sigma_N}$$



Phys. Rev. Lett. 126, 082301

- **Fundamental prediction of QCD : a small size color singlet has vanishing interaction in a nucleus when it is produced at high transverse momentum, Q.**





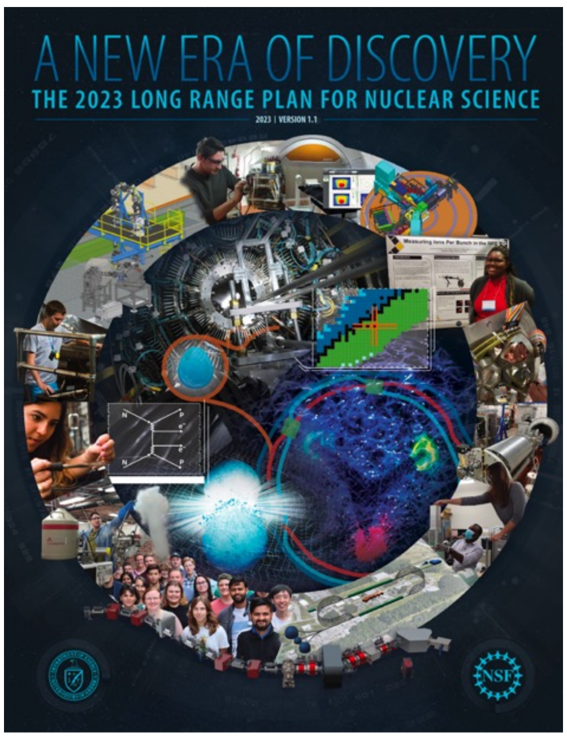
Both energy and A dependence of TA consistent with models inclusive of CT effects!

Onset of CT for mesons and absent protons (at >> Q^2) may provide strong clues regarding the differences between two- and three-quark systems.

Jefferson Lab

Jefferson Lab: Present and Future

- The approved experimental program will be 86% complete by FY29 without SoLID, 70% complete with SoLID …not including new proposals
- We are working on a CEBAF energy upgrade and a positron beam



RECOMMENDATION 1

The highest priority of the nuclear science community is to capitalize on the extraordinary opportunities for scientific discovery made possible by the substantial and sustained investments of the United States. We must draw on the talents of all in the nation to achieve this goal.

…..

- Continuing effective operation of the national user facilities ATLAS, CEBAF, and FRIB, and completing the RHIC science program, pushing the frontiers of human knowledge.

…..

… The staged upgrade plan for CEBAF foresees a first phase to establish intense polarized positron beam capability at 12 GeV, allowing for new measurements in nucleon tomography and providing precision extraction of contributions from higher order electromagnetic processes. The nontrivial operation with positron beams (polarized and unpolarized) will open a new area of study for CEBAF in the future. The subsequent phase is an energy upgrade of CEBAF to more than 20 GeV. Recently, the Cornell Brookhaven Electron Test Accelerator (CBETA) facility demonstrated eight-pass recirculation of an electron beam with energy recovery employing arcs of fixed-field alternating gradient magnets. This exciting new technology could enable a cost-effective method to double the energy of CEBAF, allowing wider kinematic reach for nucleon femtography studies in the existing tunnels and with no new cryomodules required.

RECOMMENDATION 4

We recommend capitalizing on the unique ways in which nuclear physics can advance discovery science and applications for society by investing in additional projects and new strategic opportunities.

…..

1.3 STRATEGIC OPPORTUNITIES

Strategic investments in forward-thinking projects and cross-cutting opportunities are important to ensure that the field continues to advance. They enable capitalization on emerging technologies and help ensure that the United States continues to maintain competitiveness and leadership throughout the next decade.

1.3.1. Opportunities to Advance Discovery

Strategic opportunities exist to realize a range of projects that lay the foundation for the discovery science of tomorrow. These projects include the 400 MeV/u energy upgrade to FRIB (FRIB400), the Solenoidal Large Intensity Device (SoLID) at Jefferson Lab, targeted upgrades for the LHC heavy ion program, emerging technologies for measurements of neutrino mass and electric dipole moments, and other initiatives that are presented in the body of this report.

Future advances in nuclear physics rely upon a vibrant program of detector and accelerator R&D, pushing for instance the current limits on detector sensitivity and on accelerator beam transport technology. R&D for novel nuclear physics detector and accelerator ideas influence fields such as medicine and national security. Such developments must continue.

…..

JLab Present & Future Physics Programs

CEBAF @ 22 GeV

- Program developed through a series of workshops in 2022-2023
- **Next one at LNF-INFN (Italy) December 9-13,2024**

Cornell University

We gratefully acknowledge ... member ins

arXiv > nucl-ex > arXiv:2306.09360

Accepted for publication in EPJA

Search...

Help | Advanced

Nuclear Experiment

[Submitted on 13 Jun 2023 (v1), last revised 24 Aug 2023 (this version, v2)]

Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab

A. Accardi, P. Achenbach, D. Adhikari, A. Afanasev, C.S. Akondi, N. Akopov, M. Albaladejo, H. Albataineh, M. Albrecht, B. Almeida-Zamora, M. Amaryan, D. Androić, W. Armstrong, D.S. Armstrong, M. Arratia, J. Arrington, A. Asaturyan, A. Austregesilo, H. Avagyan, T. Averett, C. Ayerbe Gayoso, A. Bacchetta, Bashir, M. Battaglieri, V. Bellini, I. Belov, O. Benhar, B. Benkel, F Benmokhtar, W. Bentz, V. Bertone, H. Bhatt, A. Bianconi, L. Bibrz S.A. Bogacz, M. Boglione, M. Bondí, E.E. Boos, P. Bosted, G. Bozzi, E.J. Brash, R. A. Briceño, P.D. Brindza, W.J. Briscoe, S.J Brodsk Cardman, D.S. Carman, M Carpinelli, G.D. Cates, J. Caylor, A. Celentano, F.G. Celiberto, M. Cerutti, Lei Chang, P. Chatagnon, C. Chudakov, E. Cisbani, I. C. Cloët, J.J. Cobos-Martinez, E. O. Cohen, P. Colangelo, P.L. Cole, M. Constantinou, M. Contalbrigo, G. Dusa, V. Crede, Z.-F. Cui, A. D'Angelo, M. Döring, M. M. Dalton, I. Danilkin, M. Davydov, D. Day, F. De Fazio, M. De Napoli, R. D authors not shown)

2306.09360 [nucl-ex] *444 authors*

ELSEVIER

Progress in Particle and Nuclear Physics

Volume 127, November 2022, 103985

Review

Physics with CEBAF at 12 GeV and future opportunities

J. Arrington [a], M. Battaglieri [b o], A. Boehnlein [b], S.A. Bogacz [b], W.K. Brooks [j], E. Chudakov [b], I. Cloët [c], R. Ent [b], H. Gao [d], J. Grames [b], L. Harwood [b], X. Ji [e f], C. Keppel [b], G. Krafft [b], R.D. McKeown [b h], J. Napolitano [g], J.W. Qiu [b h], P. Rossi [b n], M. Schram [b], S. Stepanyan [b], J. Stevens [h], A.P. Szczepaniak [l m b], N. Toro [i], X. Zheng [k]

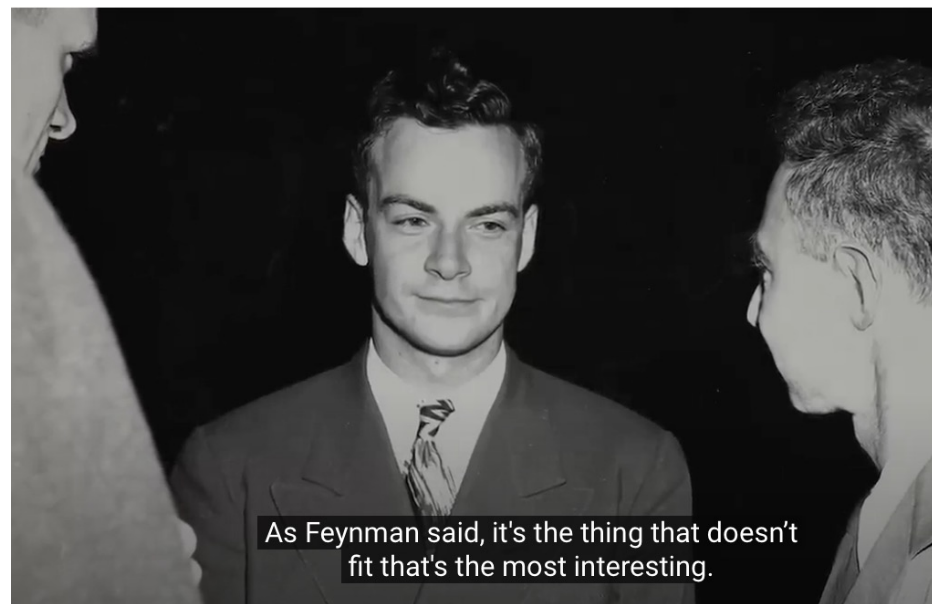
CEBAF @ 12 GeV

Conclusions and Outlook

- **QCD manifests fascinating complexity and facility at luminosity frontier are required to understand the implications of QCD in experiments**

- **At CEBAF a groundbreaking experimental program has been developed stretching well into the 2030s with existing or planned new equipment**

- **A new round of upgrades to CEBAF are presently under technical development: an energy upgrade to 22 GeV and an intense polarized positron beams**
  - This scientific program can provide a unique insight into the non-pQCD dynamics
  - It is complementary to the envisioned EIC program
  - Strong support by a Broad Community



THANK YOU!