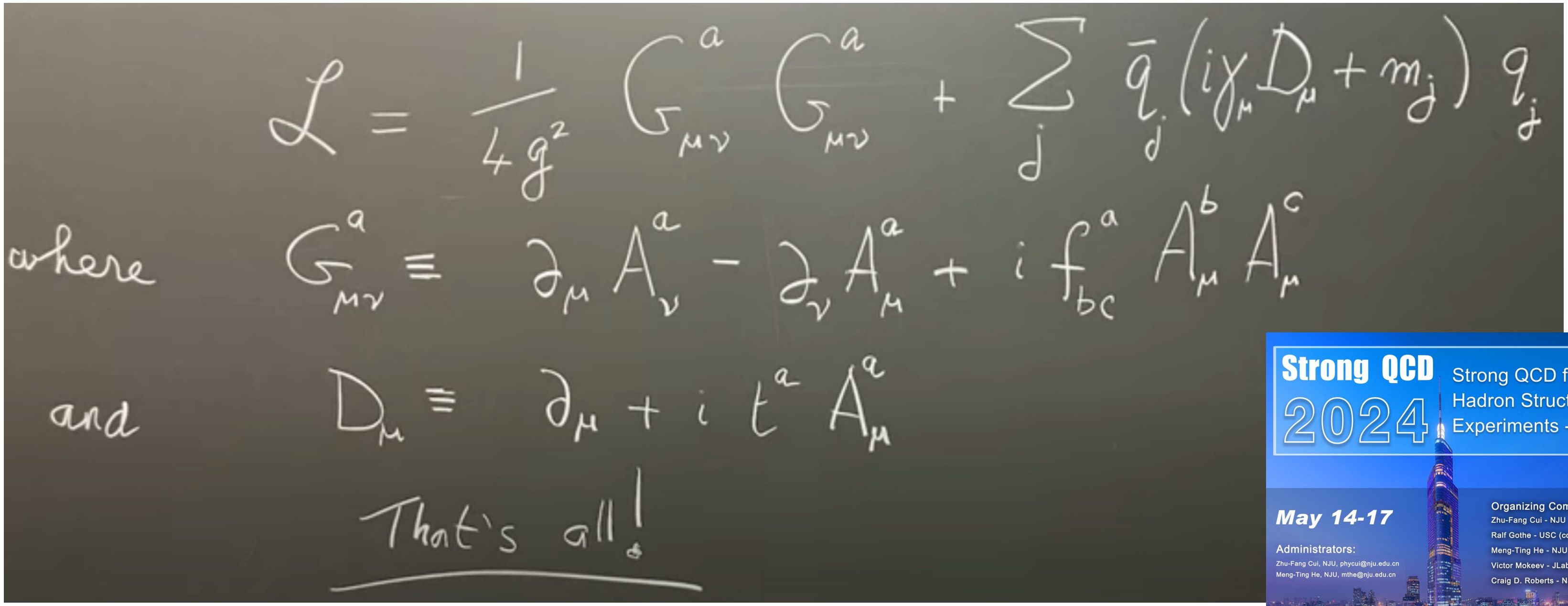
Imaging the Nucleon Interior

QCD Lagrangian



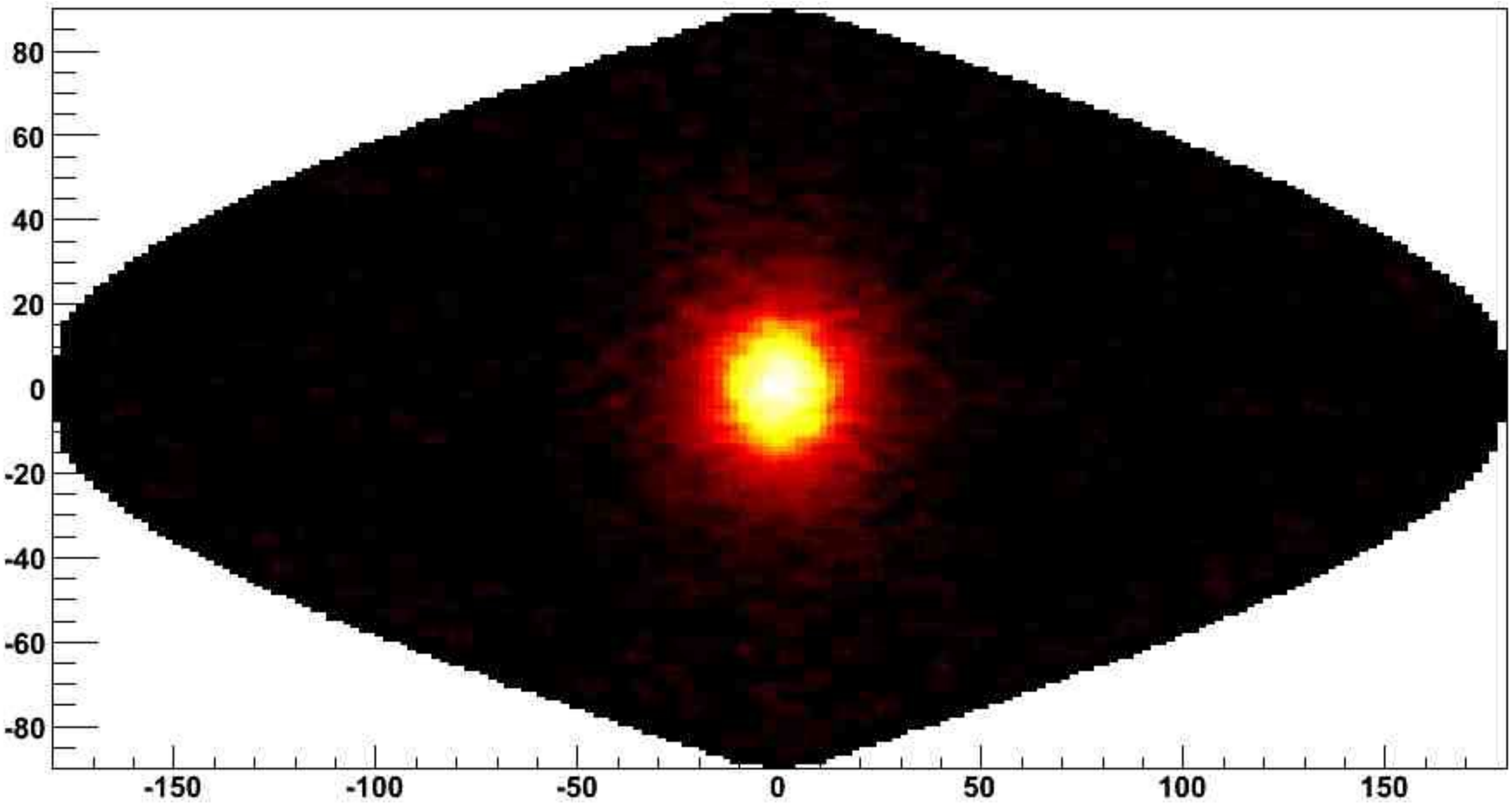
How does the spin-1/2 proton with mass 938 MeV/c^2 arise?

Context

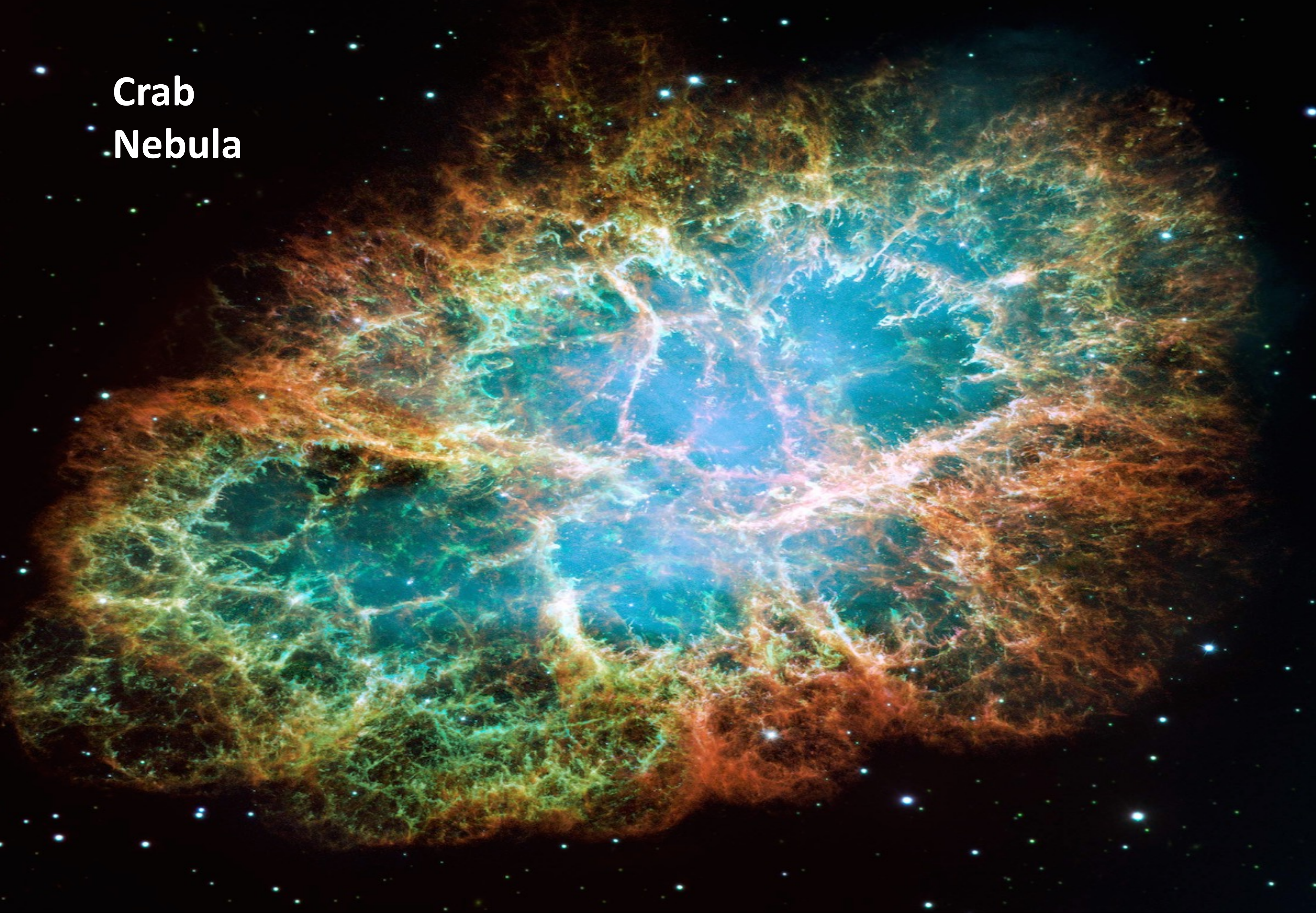
- Visualizations are a powerful means to describe and understand complicated phenomena in physics, *e.g.*
    - free body diagrams in Newtonian mechanics
    - field lines of Faraday in electricity and magnetism
    - Feynman diagrams in quantum field theory
- Physicists have developed the Standard Model which successfully explains the subatomic world.
- Current and planned large-scale facilities should provide a comprehensive set of measurements to inform our understanding of QCD.
- However, the quarks and gluons of QCD are not detectable and the important phenomena are emergent.
- Can this subatomic world be visualized so that the non-expert can begin to appreciate its unique structure?

Earth Rise from the Moon

The Sun as viewed by neutrino detection deep underground

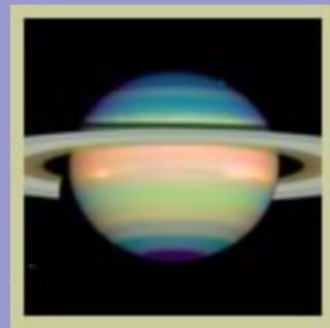


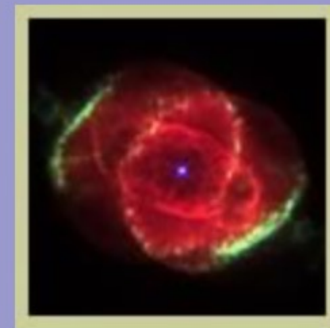
Super-Kamiokande experiment in 4504 days of data taking


Crab
Nebula

From the Hubble web page

Color as a Tool





Natural Color
The colors in this image of a galaxy were chosen to simulate the colors that our eyes might see if we were able to visit it in a spacecraft.

Representative Color
Representative color helps scientists visualize what would otherwise be invisible, such as the appearance of an object in infrared light.

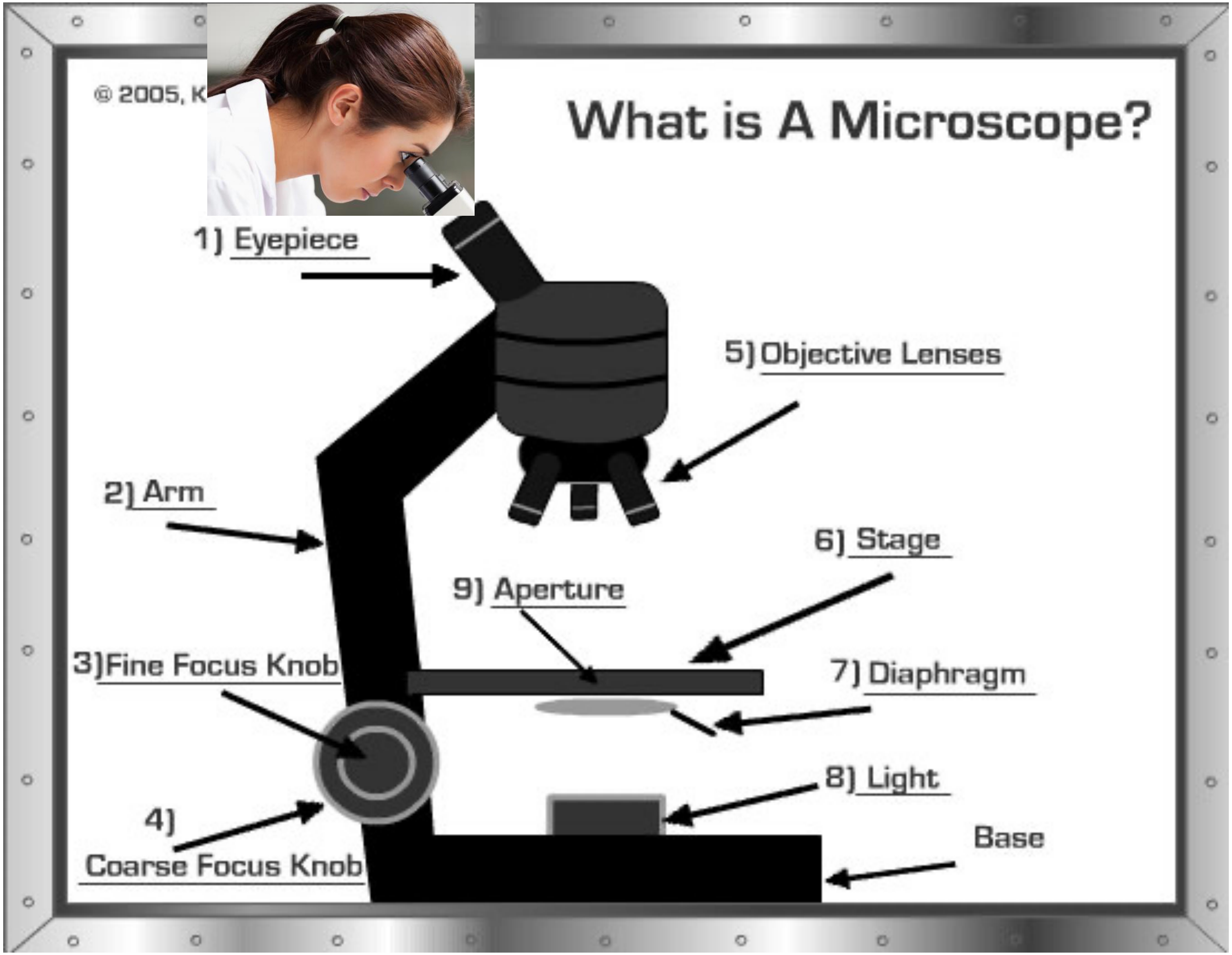
Enhanced Color
Enhancing the visible colors in an image often brings out an object's subtle structural detail.

Color in Hubble images is used to highlight interesting features of the celestial object being studied. It is added to the separate black-and-white exposures that are combined to make the final image.

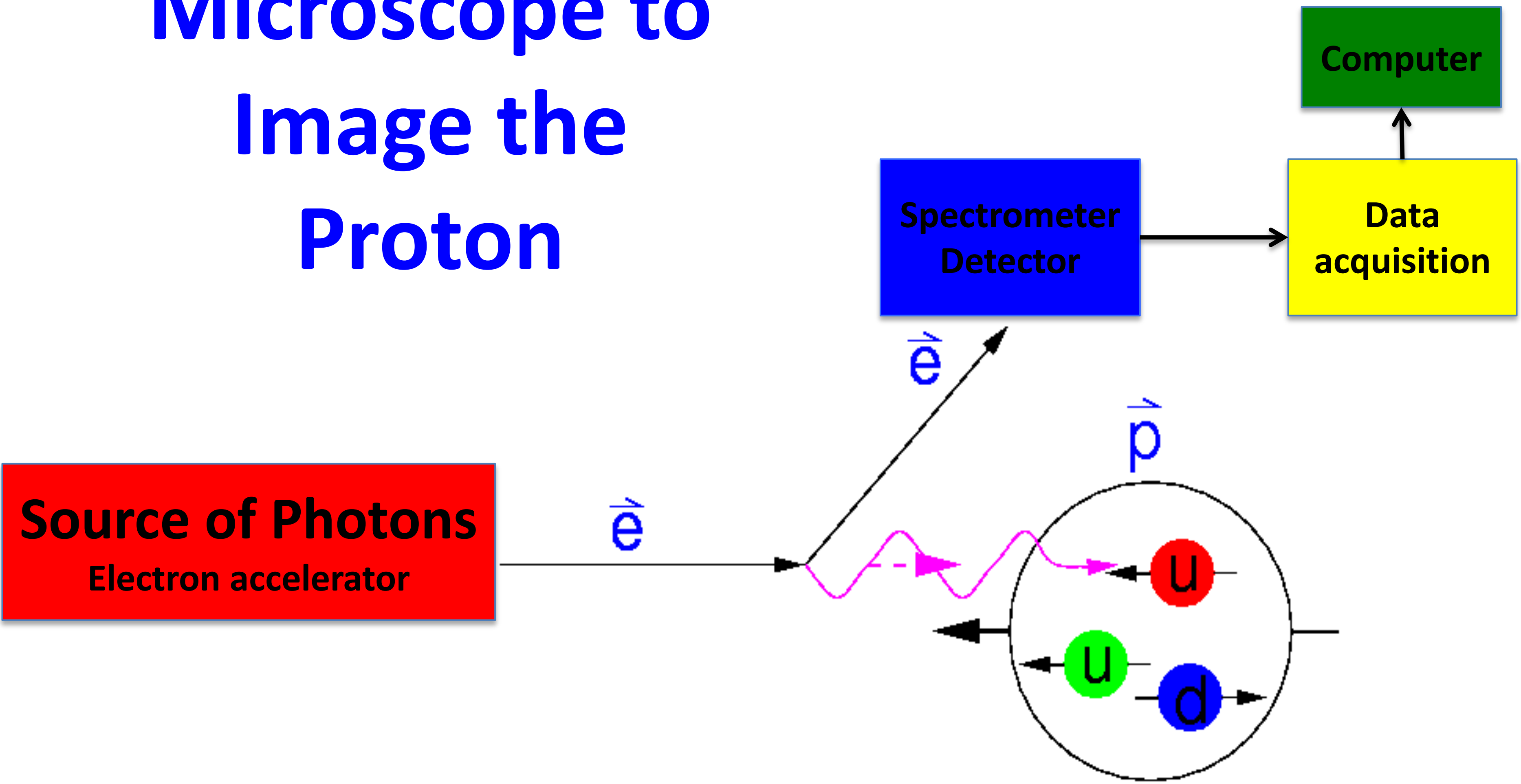
Creating color images out of the original black-and-white exposures is equal parts art and science.

We use color:

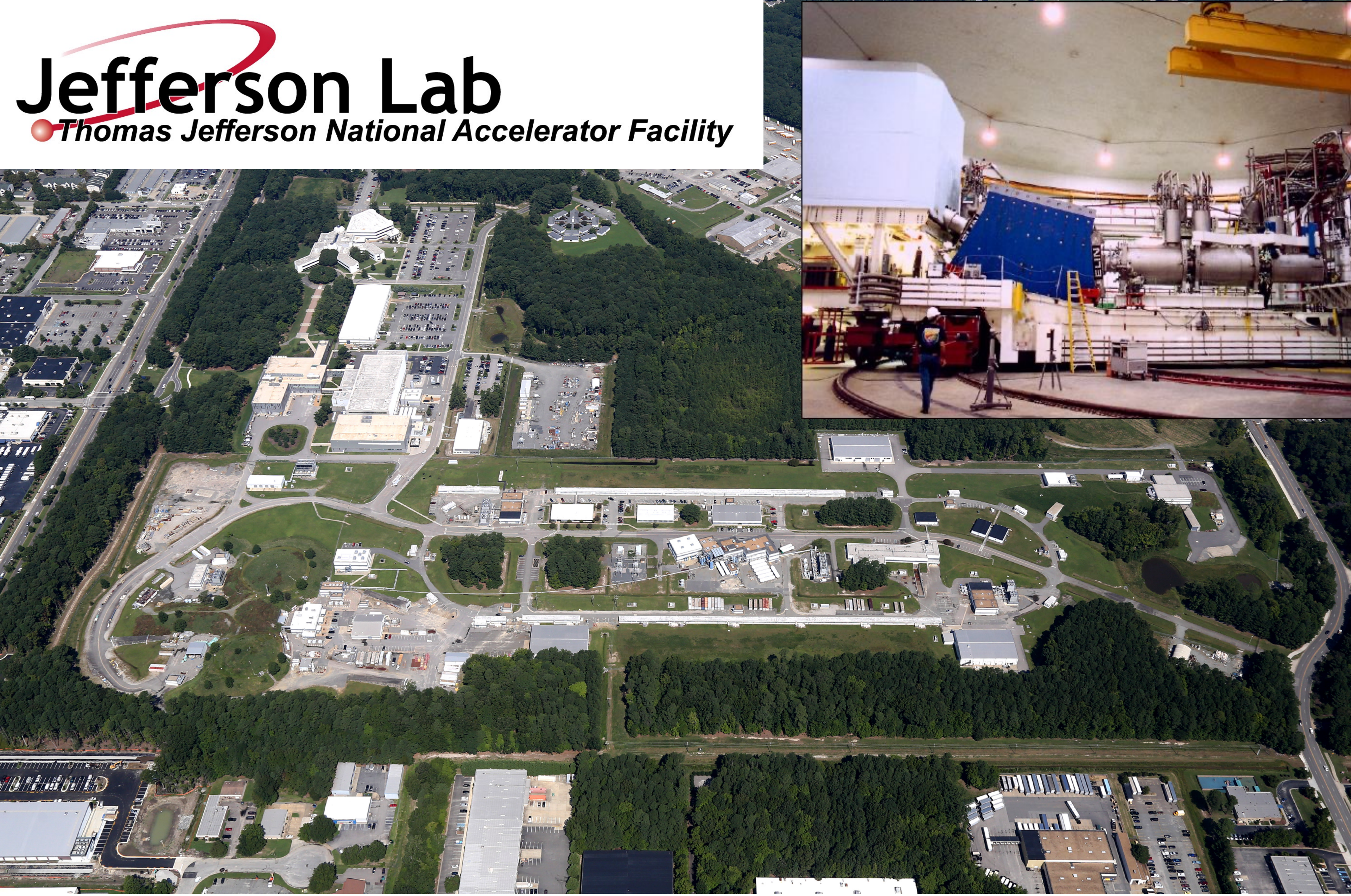
- To depict how an object might look to us if our eyes were as powerful as Hubble
- To visualize features of an object that would ordinarily be invisible to the human eye
- To bring out an object's subtle details.


What is A Microscope?
1) Eyepiece
2) Arm
3)Fine Focus Knob
4)
Coarse Focus Knob
5) Objective Lenses
6) Stage
7) Diaphragm
8) Light
9) Aperture
Base

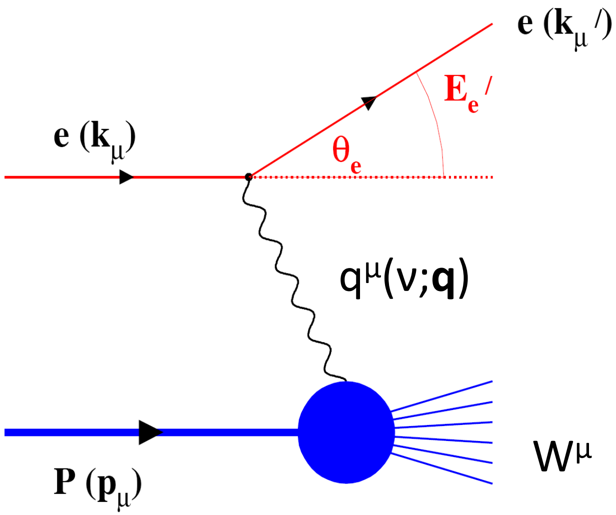
An Electron Microscope to Image the Proton



Jefferson Lab
Thomas Jefferson National Accelerator Facility



Imaging the Proton



- Scatter electron from the proton
- Exchange a virtual photon of mass $Q^2=-q^\mu q_\mu$
- 1/Q determines the spatial resolution (pixel size) probed
- $W^2 = W^\mu W_\mu = M^2 + 2M\nu - Q^2$

- **Elastic scattering**: $W^2 = M^2$ so $Q^2 = 2 M\nu$ *Hofstadter*

  electromagnetic structure of proton described by two form-factors $G_E(Q^2)$ and $G_M(Q^2)$

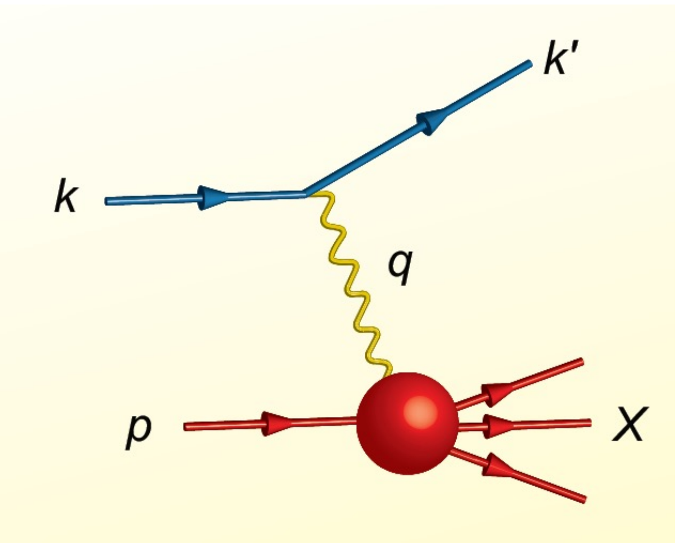
- **High energy, deep inelastic scattering**: $W^2 > 4$, $Q^2 > 1$

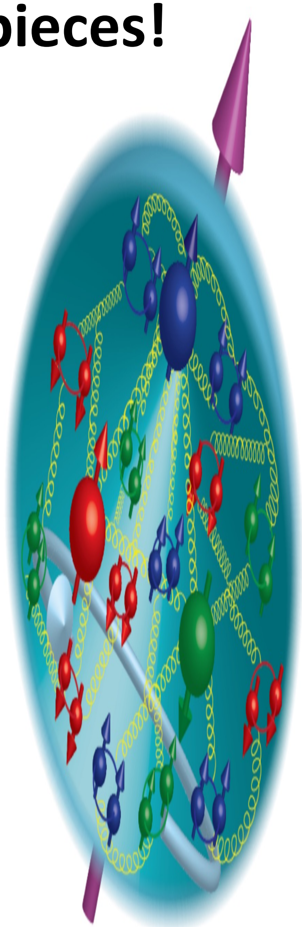
  Friedman, Kendall, Taylor

  quark structure of proton described by structure functions $F_2(x,Q^2)$

Proton Viewed in High Energy Electron Scattering: 1 Longitudinal Dimension

Proton is smashed into pieces!





Lorentz Invariants

- $E^2_{CM} = (p+k)^2$
- $Q^2 = -(k-k')^2$
- $x = Q^2/(2p\bullet q)$

- Viewed from boosted frame, length contracted by

$$\gamma_{Breit} = \sqrt{1 + \frac{Q^2}{4M^2}}$$

- Internal motion of the proton's constituents is slowed down by time dilation – the <u>instantaneous</u> charge distribution of the proton is seen.
- In boosted frame x is understood as the <u>longitudinal momentum fraction</u>

  valence quarks: $0.1 < x < 1$

  sea quarks: $x < 0.1$

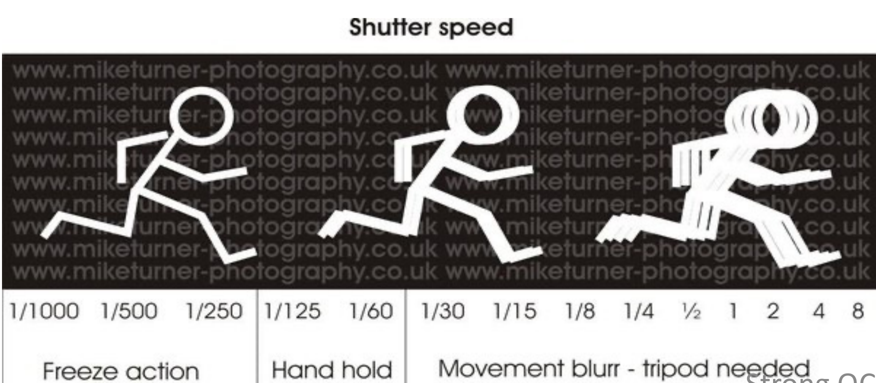
J. Bjorken, SLAC-PUB-0571 March 1969

Visualization

- The camera is a device to capture an image on a desired medium, e.g. CCD or film.
- Movie cameras capture a series of individual images in time to give the illusion of having captured motion.
- Essential elements of any camera are

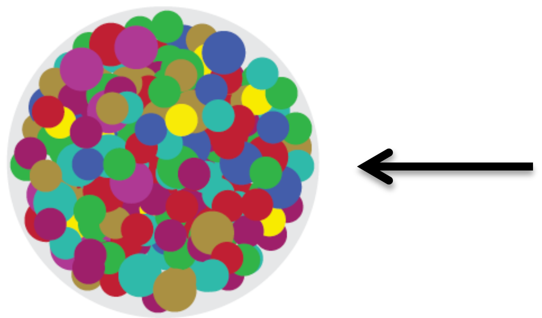
  - the focus which uses a lens to gather light from a selected image => pixel size

  - the shutter which is a door that opens for a definite time to allow selected light to reach the medium.

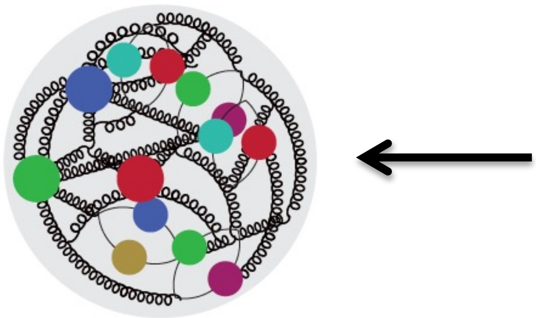


High Energy Electron Scattering

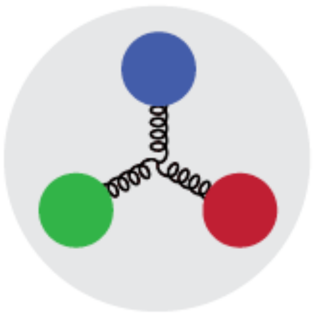
Snapshots where 0 < x < 1 is the shutter exposure time



$x \approx 10^{-4}$
Probe non-linear dynamics
short exposure time

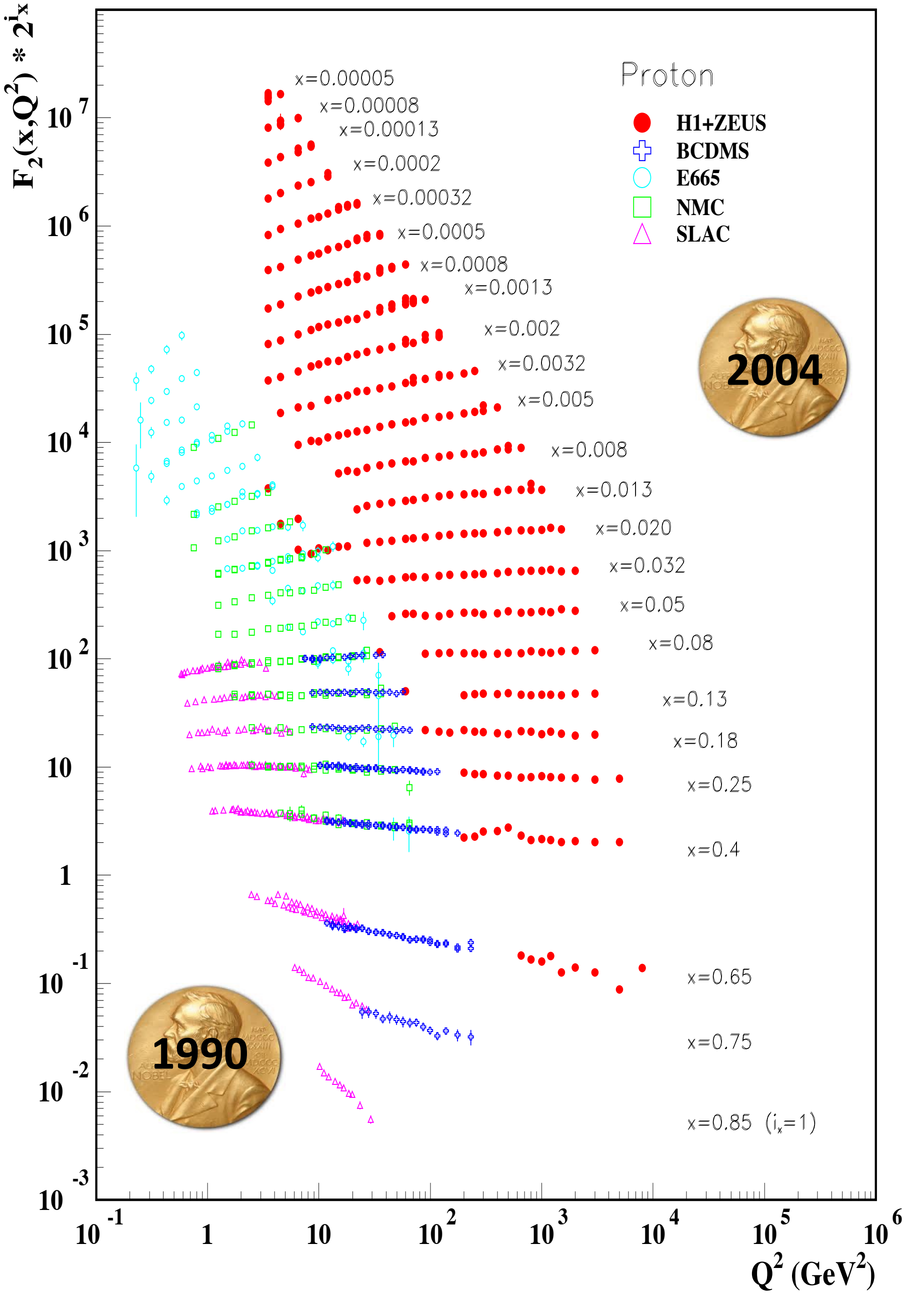


$x \approx 10^{-2}$
Probe rad. dominated
medium exposure time



$x \approx 0.3$
Probe valence quarks
long exposure time

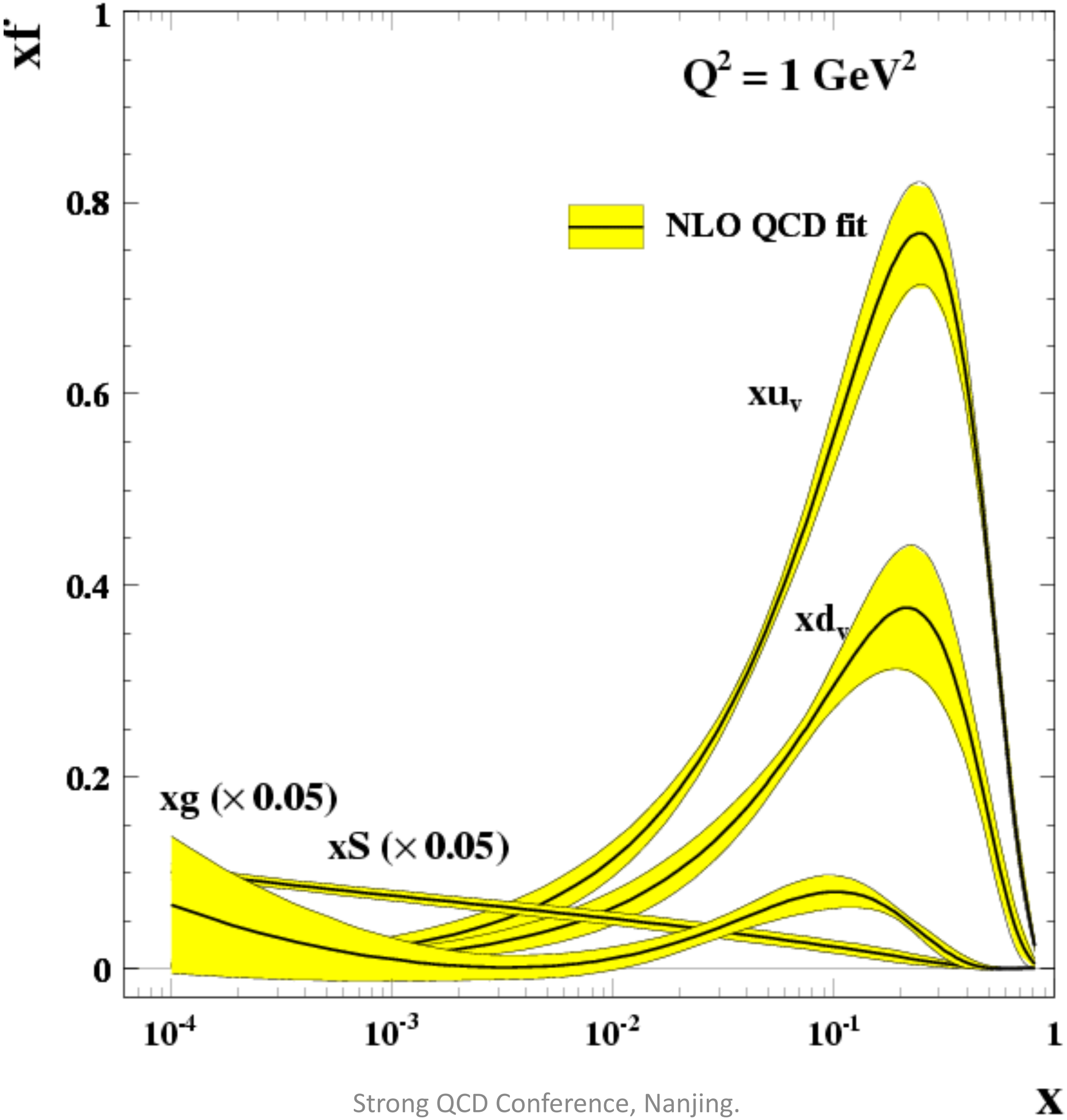
Shutter speed



Quark Structure of Proton from High-Energy Lepton Scattering

e-p cross section ≈ $\sigma_{Mott} \bullet F_2(x,Q^2)$

- Snap shots of the charged structure of the proton taken in the boosted frame
- *1/Q* spatial resolution: pixel size
- *x* exposure time, *1/x* shutter speed
- QCD prescribes evolution with Q^2 which connects quarks and gluons



R. Yoshida
C. Gwenlan

Charting the Inner Structure of the Proton

https://www.youtube.com/watch?v=G-9I0buDi4s

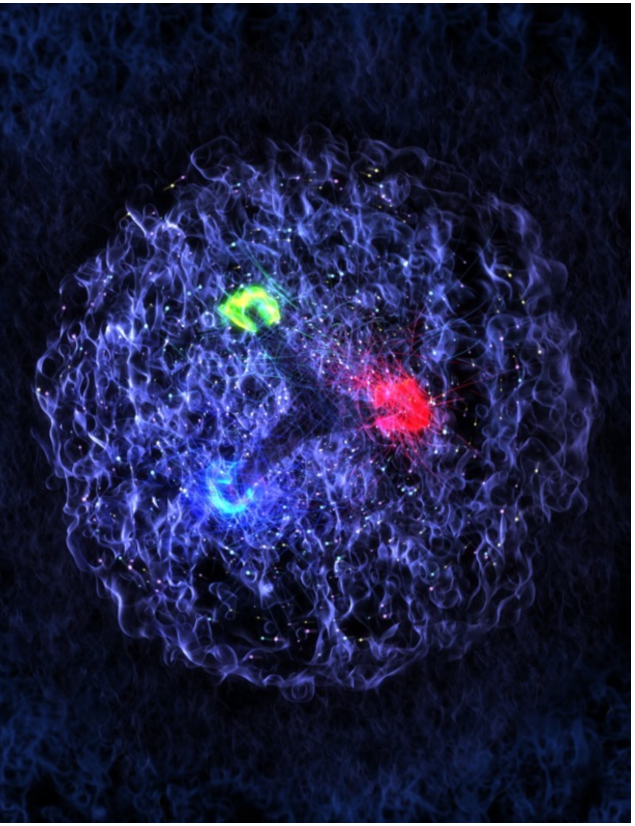
Christopher Boebel
Rolf Ent
James LaPlante
Joseph McMaster
Richard Milner

Jefferson Lab

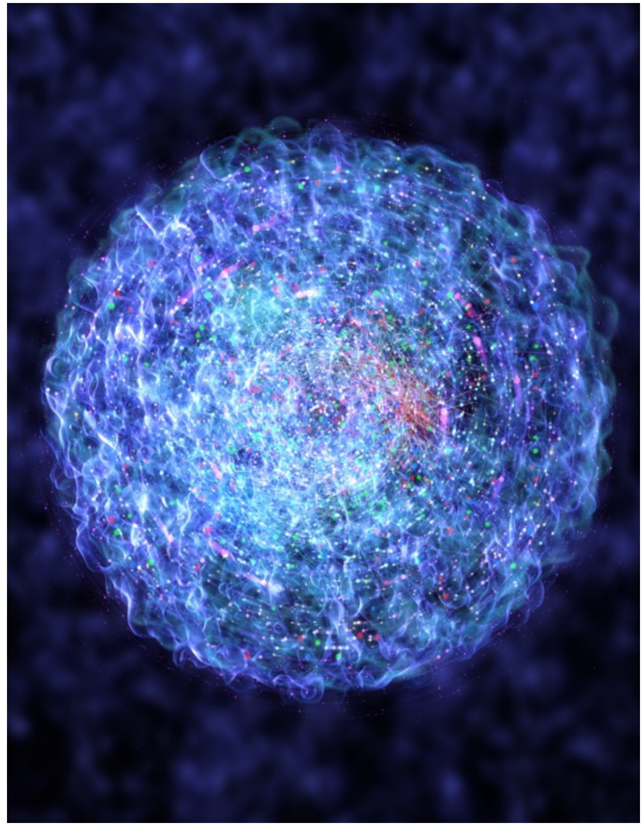
SPUTNIK ANIMATION

ARTS CENTER FOR ART, SCIENCE & TECHNOLOGY AT MIT

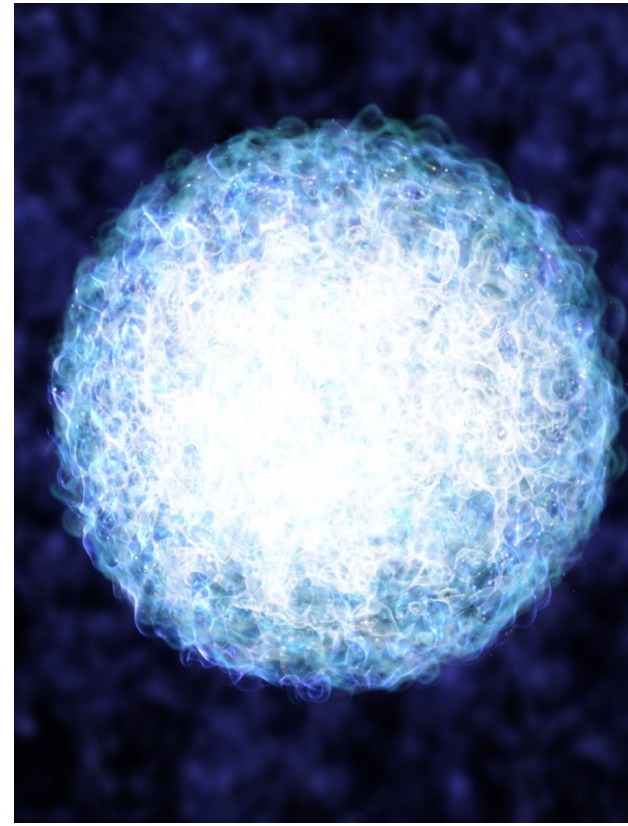
Quark and Gluon Dynamics Dominate Proton Structure



High x ~0.3



Medium x ~ 10^{-2}



Low x ~10^{-4}

Quark and Gluon Dynamics Dominate Proton Structure

High x ~0.3

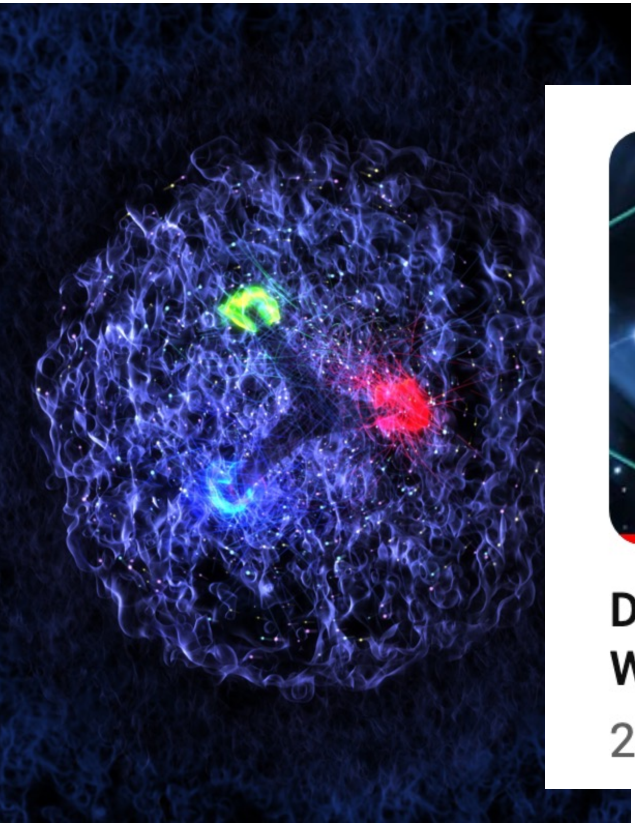
Medium x ~ 10^{-2}

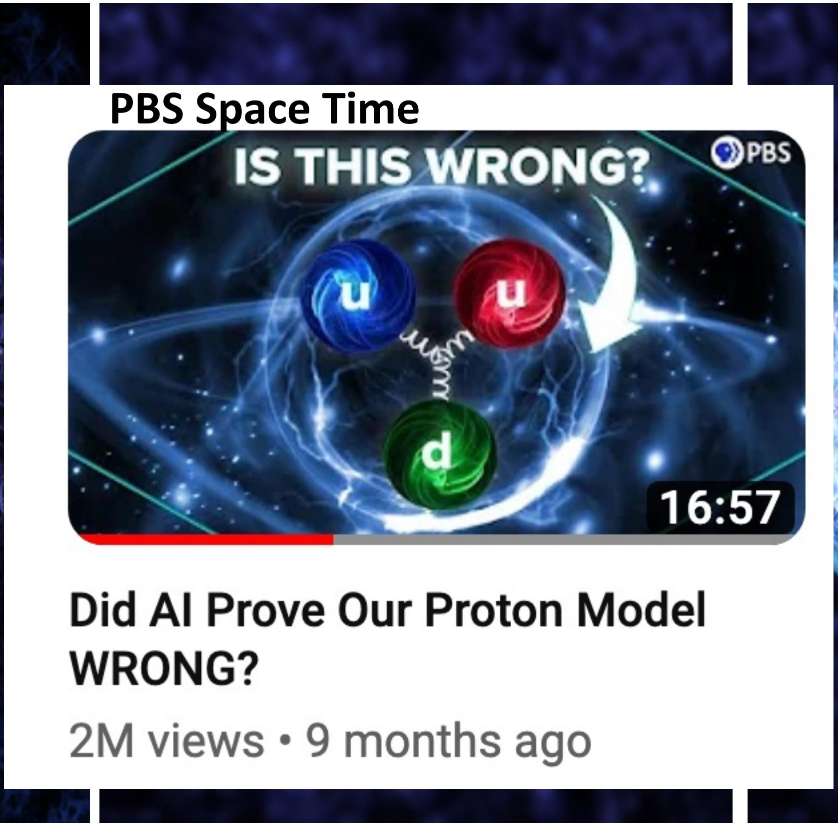
Low x ~10^{-4}

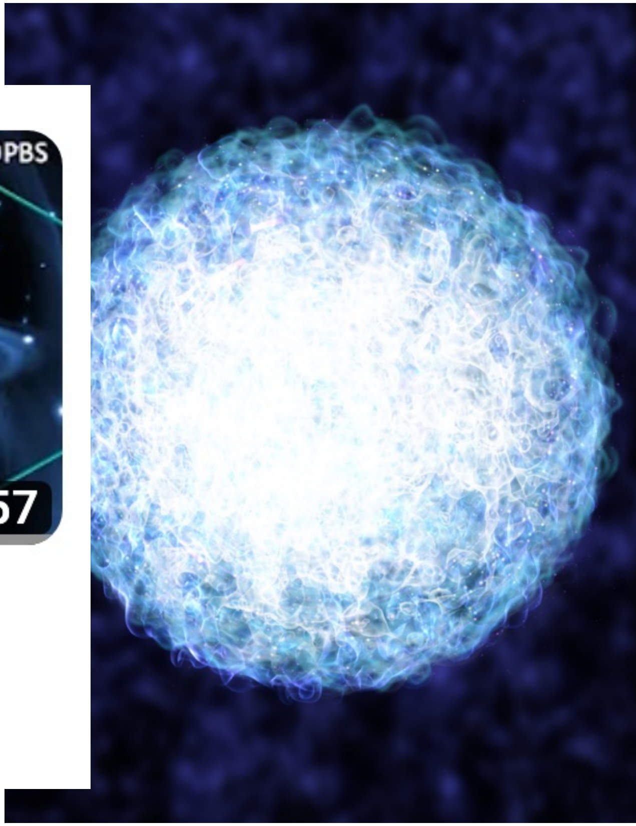
Quark and Gluon Dynamics Dominate Proton Structure

High x ~0.3 **Medium x ~ 10^{-2}** **Low x ~10^{-4}**

Quark and Gluon Dynamics Dominate Proton Structure

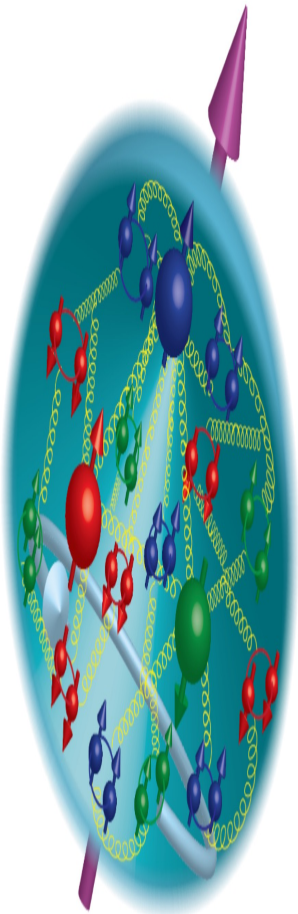






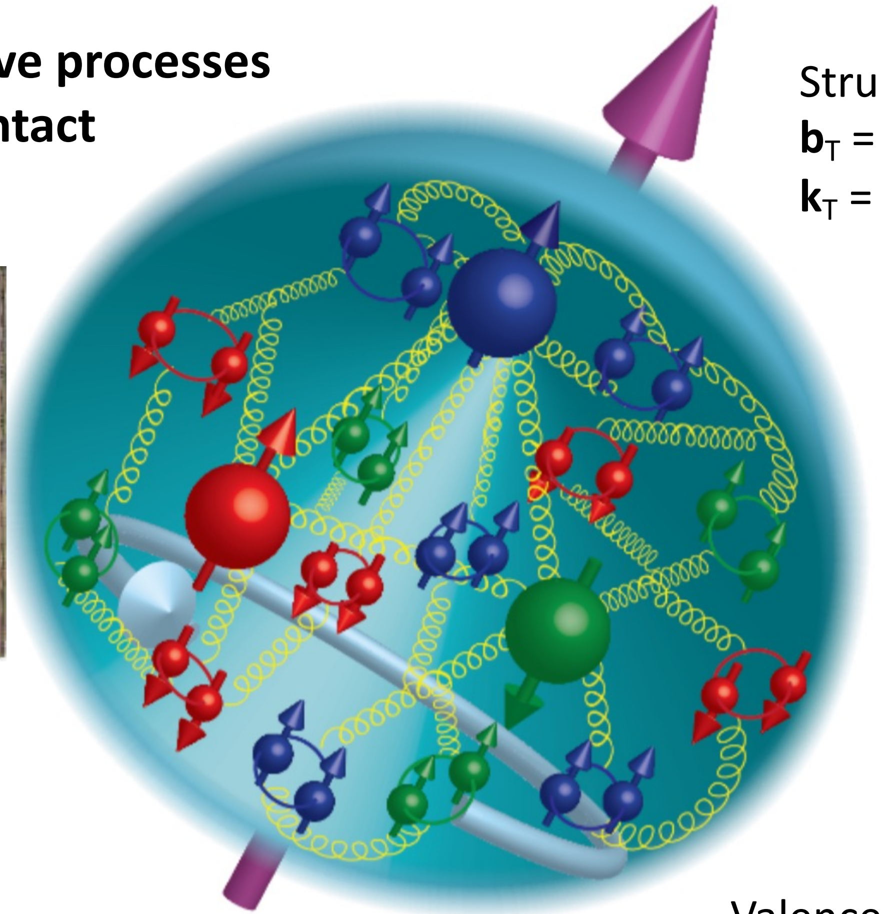
High x ~0.3 | **Medium x ~ 10^{-2}** | **Low x ~10^{-4}**

Proton Viewed in High Energy Electron Scattering: 1 Longitudinal Dimension



Proton Tomography: 2 New Dimensions Transverse to Longitudinal Momentum

Deeply virtual exclusive processes where proton is left intact



Structure mapped in terms of
$\mathbf{b}_T$ = transverse position
$\mathbf{k}_T$ = transverse momentum

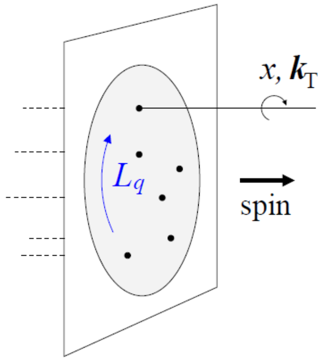
Nuclei!

Goal:
Unprecedented
21st Century Imaging
of Hadronic Matter

Direction of longitudinal momentum normal to plane of slide

Valence Quarks: JLab 12 GeV
Sea Quarks and Gluons: EIC

3D Partonic Picture



Theorists have developed a powerful formalism for studying the 3D partonic picture of the nucleon and the nucleus. It is encoded in **Generalized Parton Distributions** and **Transverse Momentum Dependent Distributions**

Wigner distribution

$$W(\mathbf{p}, \mathbf{x})$$

Transverse Momentum Dependent distributions

d^3r

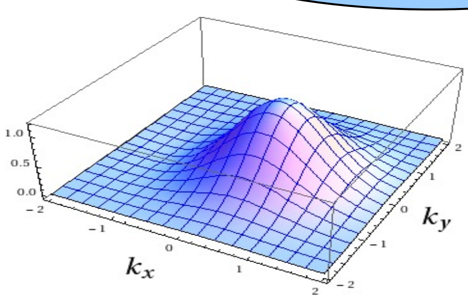
d^3p

Generalized Parton Distributions

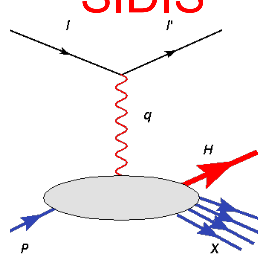
Orbital motion accessible!

$$f(x, \mathbf{k}_\perp)$$

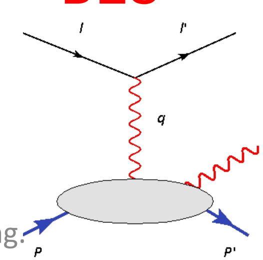
$$H(x, \xi, t)$$

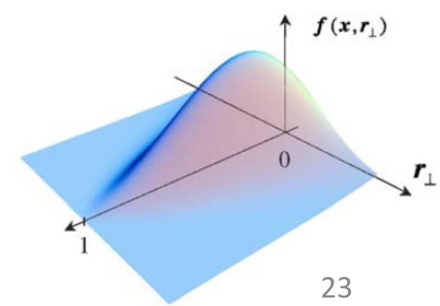


SIDIS



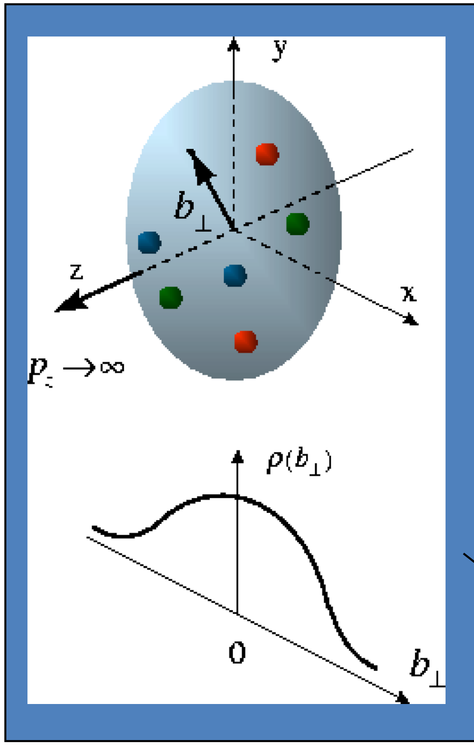
DES



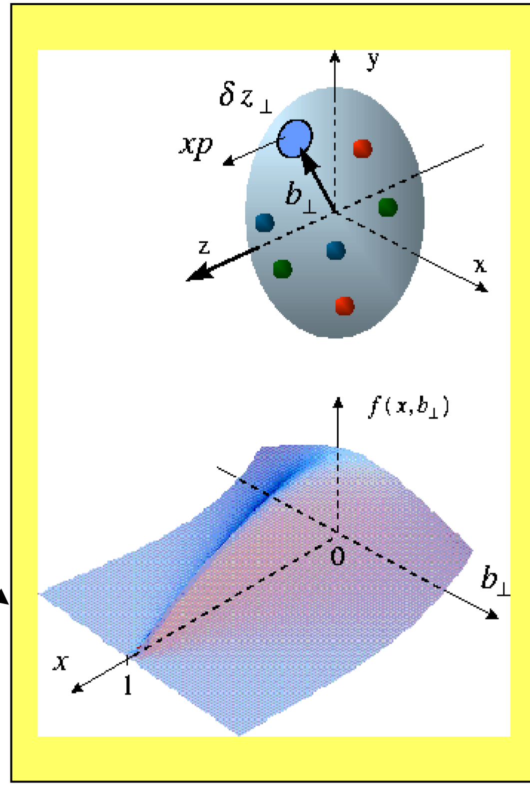


Generalized Parton Distributions

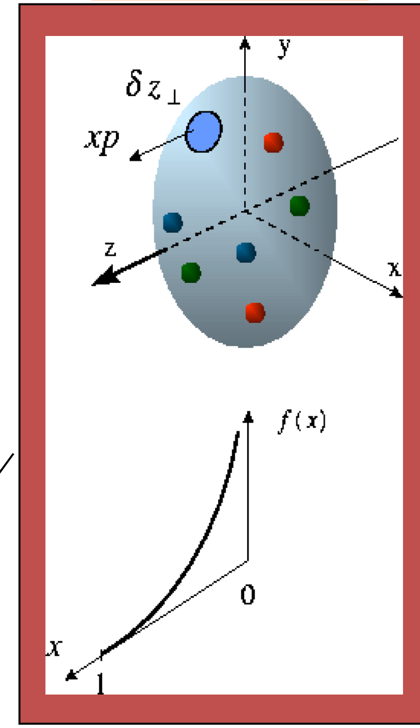
Last 60 years



Last 20 years



Last 45 years



Elastic form factors → **Transverse** charge & current densities $F_1(t)$, $F_2(t)$.

Deeply exclusive processes → GPD's and **3 D** images in transverse space and longitudinal momentum.
4 GPDs **H, E, $\tilde{H}$, $\tilde{E}$ (x,ξ,t)**

DIS structure functions → **Longitudinal** parton momentum & helicity densities, $F_2(x)$, $g_1(x)$.

Generalized Parton Distributions

(Quantum phase-space quark distribution in the nucleon)

$$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{W}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle \ ,$$

$$W_\Gamma(\mathbf{r},\mathbf{k}) = \int \frac{dk^-}{(2\pi)^2} W_\Gamma(\mathbf{r},k)$$

Integrate over **transverse momentum** space

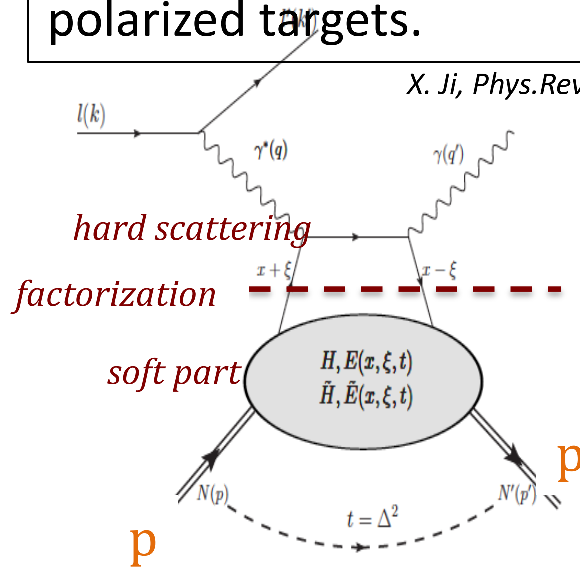
GPDs H E $\tilde{H}$, $\tilde{E}$

Probe 3D structure 2D – euclidean space and 1D - momentum space.

D. Müller et al., F. Phys. 42,1994
X. Ji, PRL 78, 610, 1997
A. Radyushkin, PLB 380, 1996

Polarized DVCS probes GPDs. JLab @ 12GeV has broad DVCS program with polarized beams and polarized targets.

X. Ji, Phys.Rev.D55, 7114 (1997)



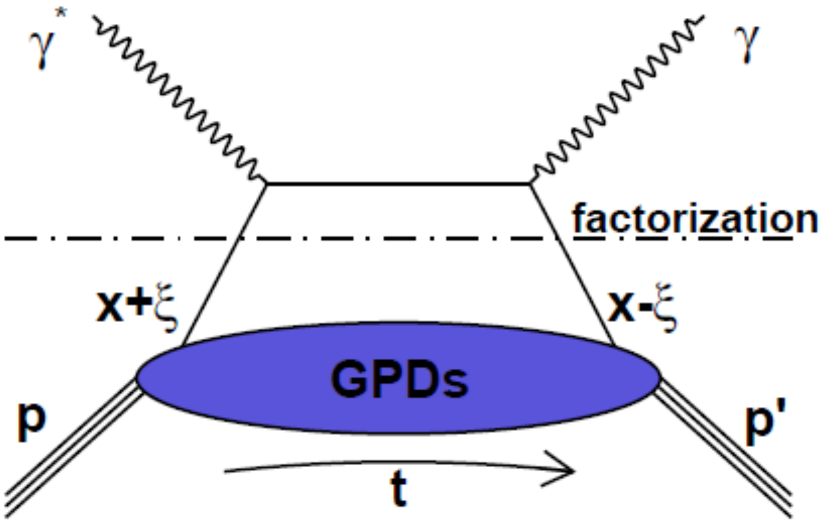
$$\xi \approx \frac{x_B}{2 - x_B}$$

GPD ***H*** of special Importance as it gives access to the gravitational properties.

M. V. Polyakov, Physics Letters B 555 (2003) 57
I.V. Anikin and O.V. Teryaev, Phys.Rev.D76, 056007 (2007)
M. Diehl and D.Y. Ivanov, Eur. Phys. J. C52, 919, (2007)

Deeply Virtual Compton Scattering (DVCS) and GPDs

DVCS and Generalized Parton Distributions



$$\gamma^* p \to \gamma p'$$

Bjorken regime :
$Q^2 \to \infty$, x_B fixed

t fixed $\ll Q^2$, $\xi \to \frac{x_B}{2-x_B}$

$$\frac{P^+}{2\pi}\int dy^-\, e^{ixP^+y^-}\langle p'|\bar{\psi}_q(0)\gamma^+(1+\gamma^5)\psi(y)|p\rangle$$

$$= \bar{N}(p')\left[H^q(x,\xi,t)\gamma^+ + E^q(x,\xi,t)i\sigma^{+\nu}\frac{\Delta_\nu}{2M}\right.$$

$$\left. + \tilde{H}^q(x,\xi,t)\gamma^+\gamma^5 + \tilde{E}^q(x,\xi,t)\gamma^5\frac{\Delta^+}{2M}\right] N(p)$$

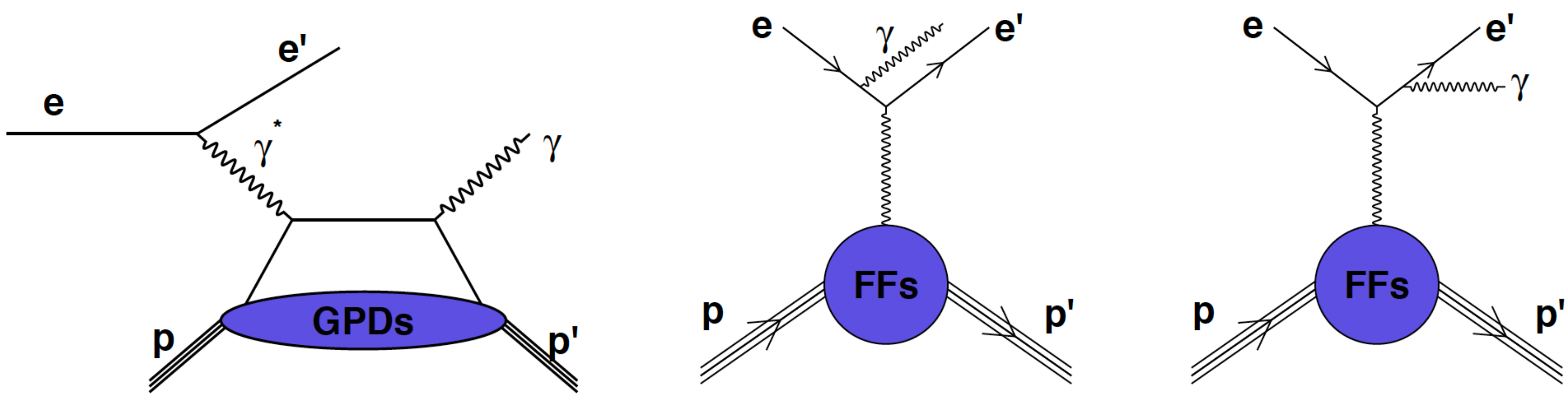
x: average fraction of quark longitudinal momentum

ξ fraction of longitudinal momentum transfer

H, E, $\widetilde{H}$, $\widetilde{E}$: **G**eneralized **P**arton **D**istributions (**GPDs**)

3-D Imaging conjointly in transverse impact parameter and longitudinal momentum

Deeply Virtual Compton Scattering - Experiment



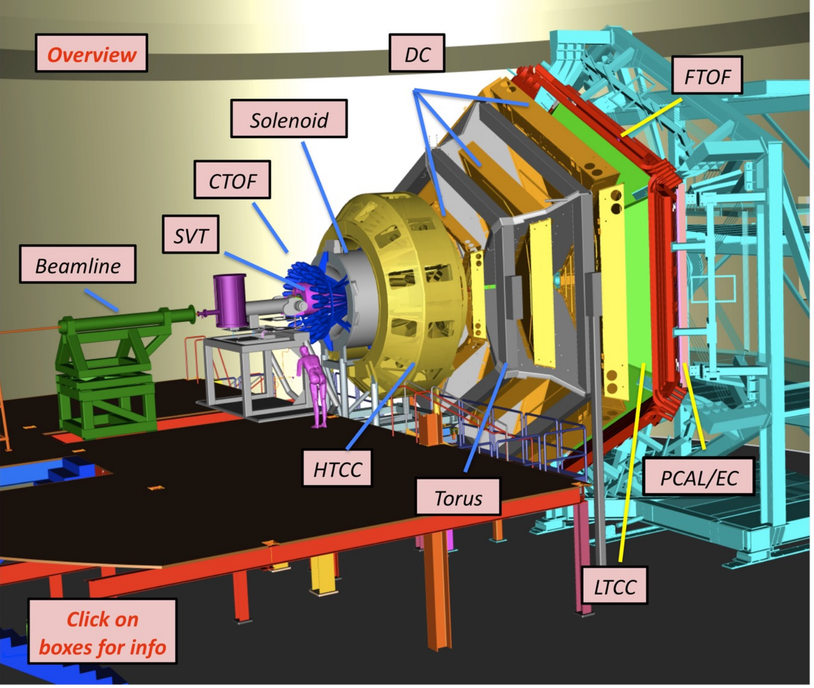
The Bethe-Heitler and DVCS processes interfere at the amplitude level :

$$|\mathcal{T}_{\mathrm{BH}} + \mathcal{T}_{\mathrm{DVCS}}|^2 = |\mathcal{T}_{\mathrm{BH}}|^2 + |\mathcal{T}_{\mathrm{DVCS}}|^2 + \mathcal{I}$$

The GPDs enter the DVCS amplitude through a complex integral. This integral is called a *Compton form factor* (CFF).

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

Measured both asymmetries and cross sections



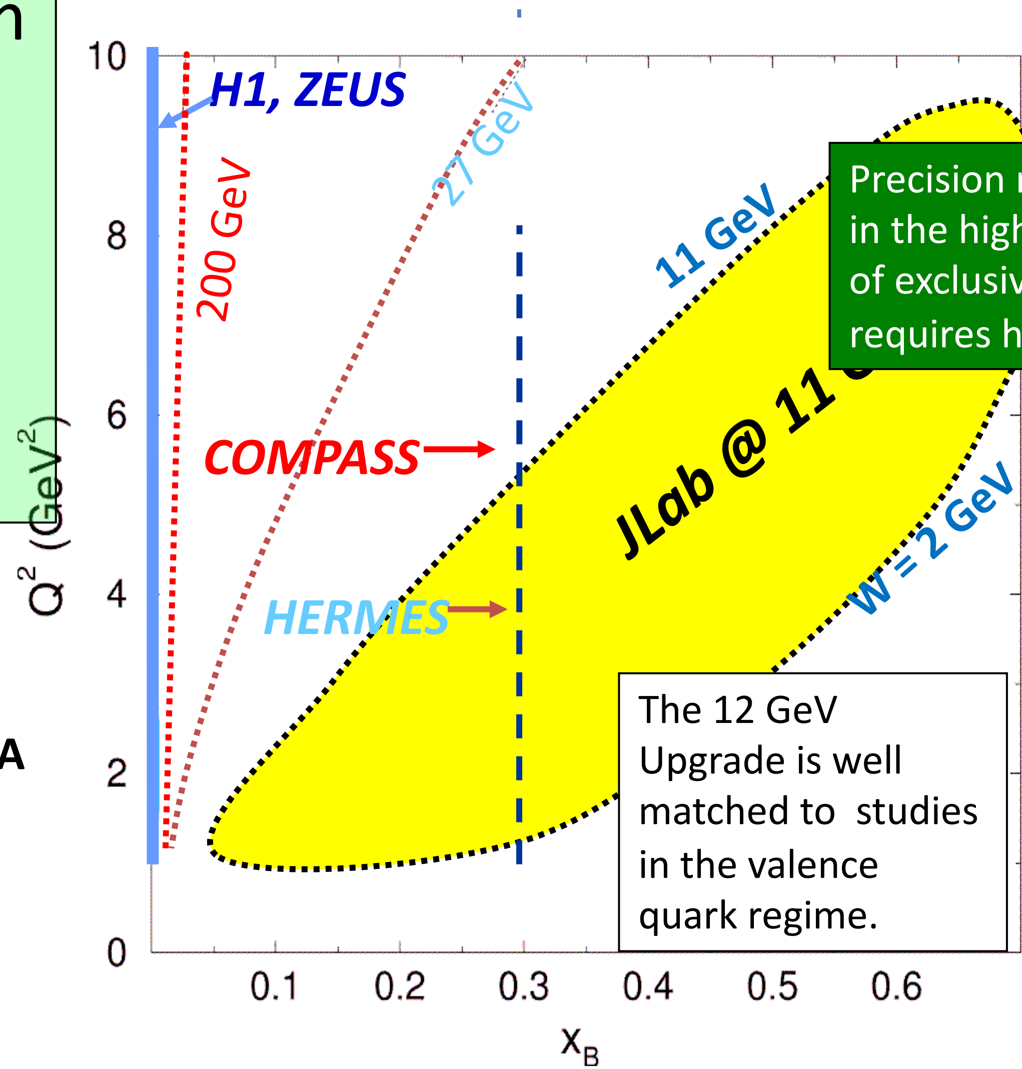
CLAS12
Deeply Virtual Processes

Access to new Generalized Parton Distributions

- Our group is a member of the CLAS12 collaboration at Jefferson Lab, VA
- Have developed with MIT-LNS high performance computing group (computers located at Bates) the capability to run the CLAS12 Monte-Carlo code by collaborators worldwide
- Working on determination of the absolute cross sections for the following processes: $p(e,e'\pi^0)p$ – sensitive to GPDs
  $p(e,e'\gamma)p$ - Deeply Virtual Compton Scattering (DVCS)
  $p(e,e'\varphi)p$ - sensitive to gluonic radius
- Seek new insights into the quark and gluon structure of the proton

Kinematic coverage for Imaging @ 11GeV

A flagship program of structure studies in deeply exclusive and semi-inclusive processes.

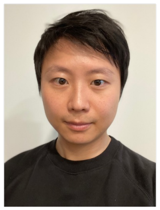


Precision measurements in the high x_B domain of exclusive processes requires high luminosity.

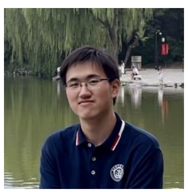
The 12 GeV Upgrade is well matched to studies in the valence quark regime.

2018 data taking with RG-A
Liquid hydrogen target
Energy = 10.6 GeV

DVCS Absolute Cross Section



Dr. Sangbaek Lee (ANL)



Yijie Wang (MIT)

- Analysis based on Fall 2018 data.
- Much more data already taken.
- Manuscript in preparation

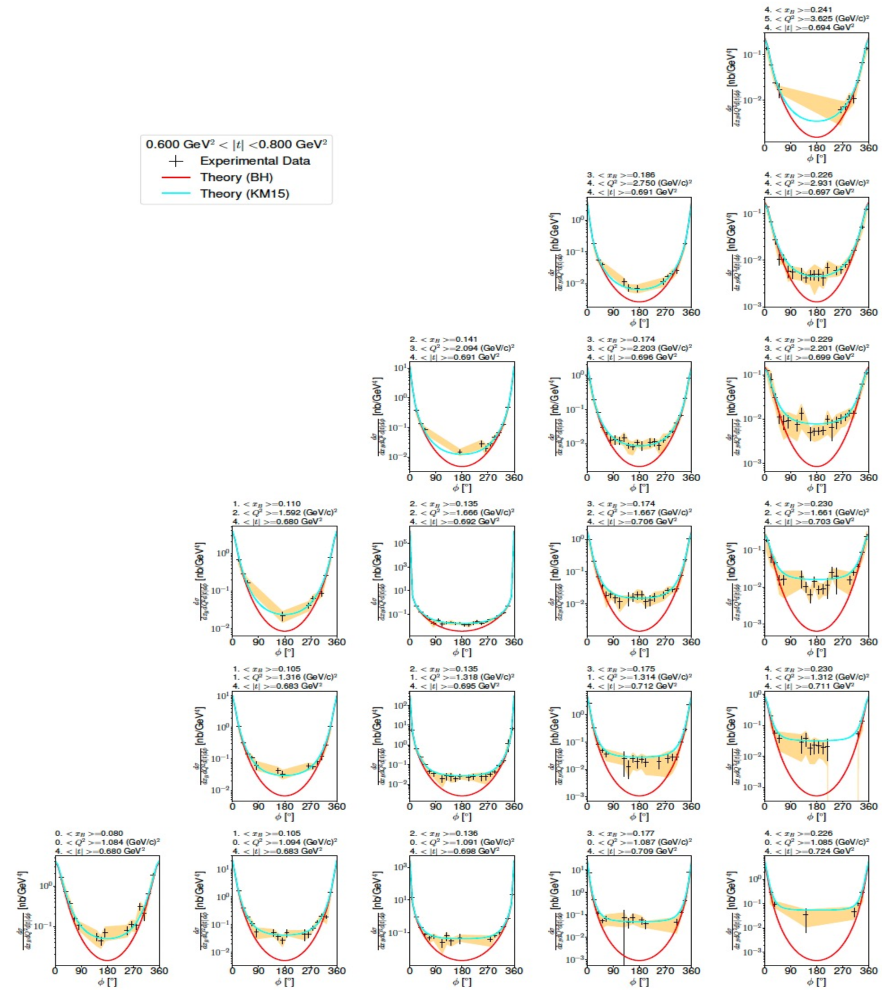


Figure 5-28: The unpolarized cross section in $x_B < 0.268$, $Q^2 < 4.326$ $(\mathrm{GeV/c})^2$, $0.600\ \mathrm{GeV}^2 < |t| < 0.800\ \mathrm{GeV}^2$ bins.

DV π^0 absolute cross section

Dr. Robert Johnston

Dr. Igor Korover

- **Analysis based on Fall 2018 data.**
- **Much more data already taken.**
- **Analysis note in preparation**

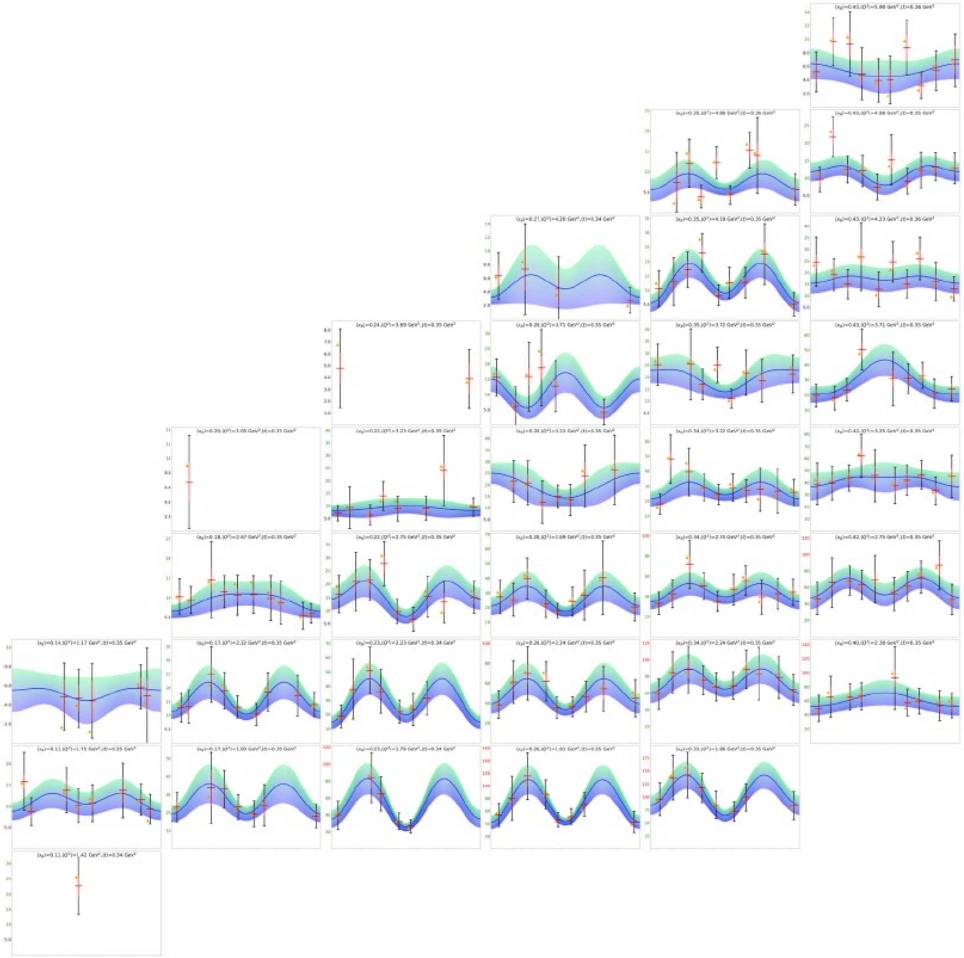
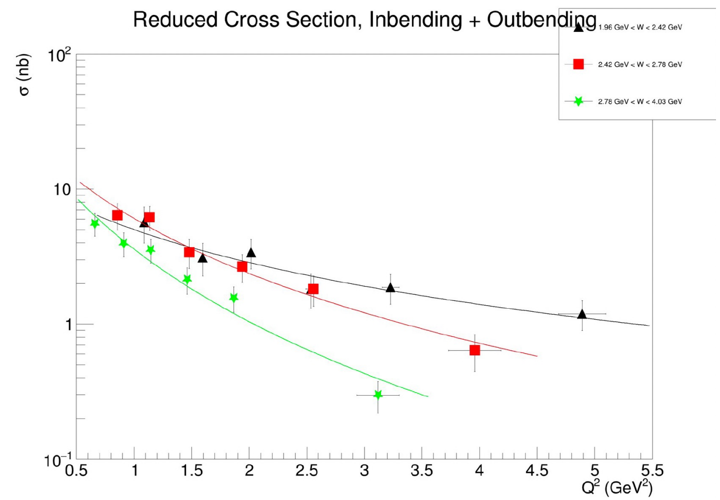


Figure 6-2: Reduced Cross Section for 0.3 $GeV^2 < t <$ 0.3 GeV^2 in bins of x_B (increasing left to right) and Q^2 (increasing vertically upwards).

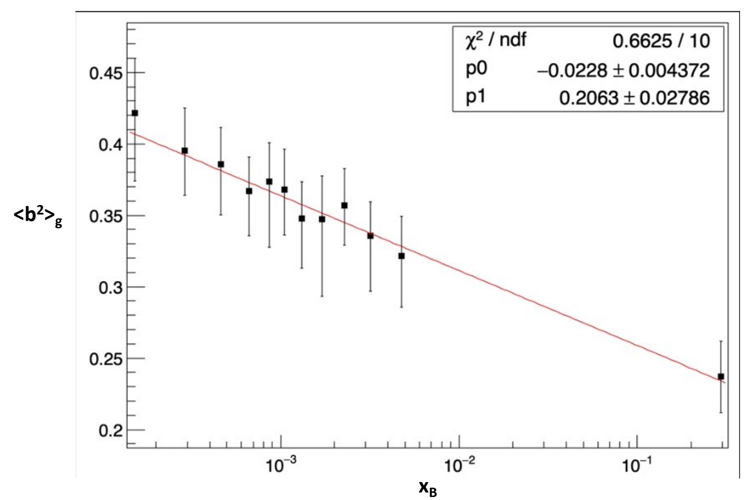
DV p(e,e'p)Φ absolute cross section

Dr. Patrick Moran (College of Wm&Mary)

Dr. Igor Korover



Gluonic radius of proton



- **Preliminary analysis based on Fall 2018 data.**
- **Further analysis in progress by F.X. Girod (JLab)**

Transverse Momentum Structure of Nucleon – TMDs

(Quantum phase space quark distribution in the nucleon)

<u>Wigner Function</u>

$$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{\mathcal{W}}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle$$

$$W_\Gamma(\mathbf{r},\mathbf{k}) = \int \frac{dk^-}{(2\pi)^2} W_\Gamma(\mathbf{r},k)$$

Integrate over ***spatial*** dimensions

Transverse Momentum-dependent Distributions (TMD)

3D imaging of the nucleon in momentum space

Quark spin polarization

Nucleon polarization

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 $h_{1T}^\perp$

JLab has planned a complete SIDIS program with π/K to access quark TMDs

TMD Handbook

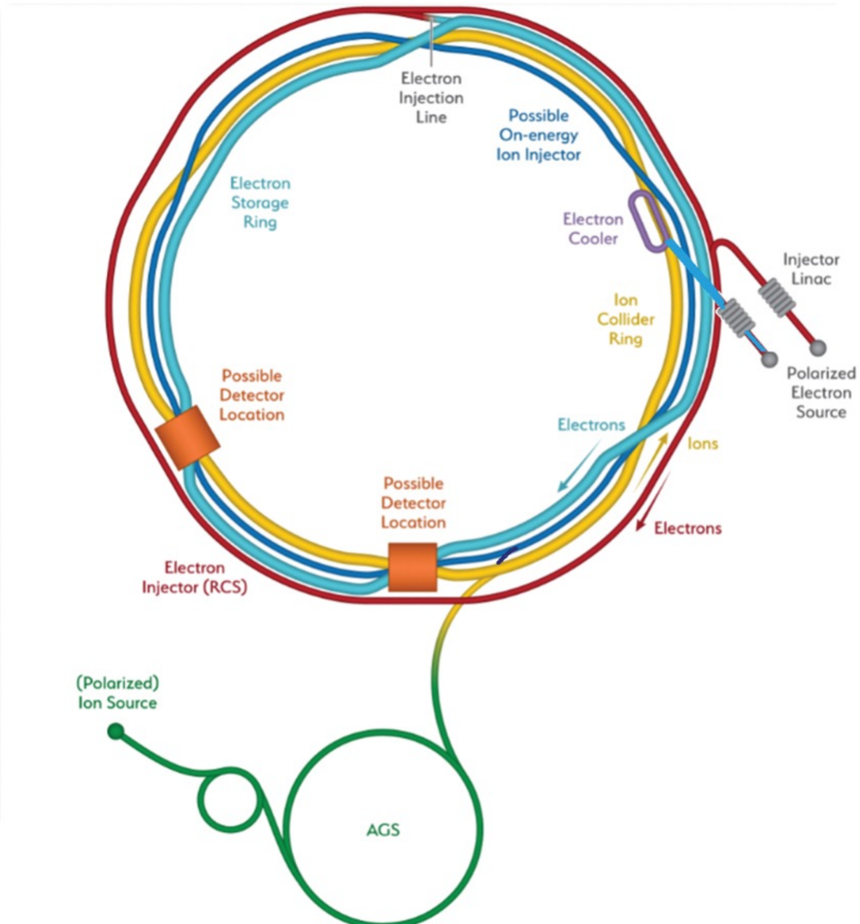
January 14, 2022

A modern introduction to the physics of
Transverse Momentum Dependent distributions

TMD Collaboration

13 chapters
4 appendices

Electron-Ion Collider: add counter-circulating electron storage ring in existing RHIC tunnel



- 275 GeV/nucleon max. on 18 GeV e-beam
- High luminosity: 10^{34} e-nucleon $cm^{-2}s^{-1}$
- 70% polarized electron, nucleon beams
- Full range of ions: p to U
- Two collider detectors
- Actively considered since about 2000
- EIC highest priority for new facility construction by NP since 2015
- Blessed by NAS committee 2018
- Project officially launched by US DOE in January 2020
- Present schedule: accelerator turn-on 2031
- Project cost: $ 2 billion approx.

Large Reach of EIC in x and Q^2

with greatly increased luminosity

inclusive, semi-inclusive, exclusive

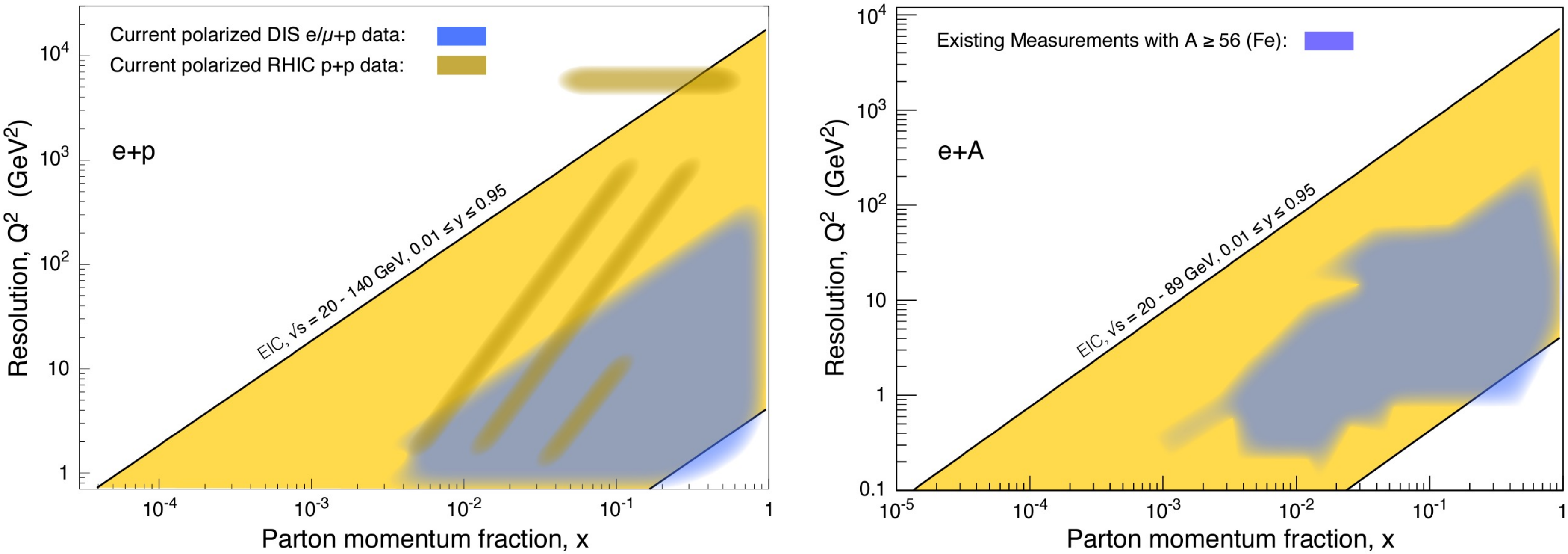
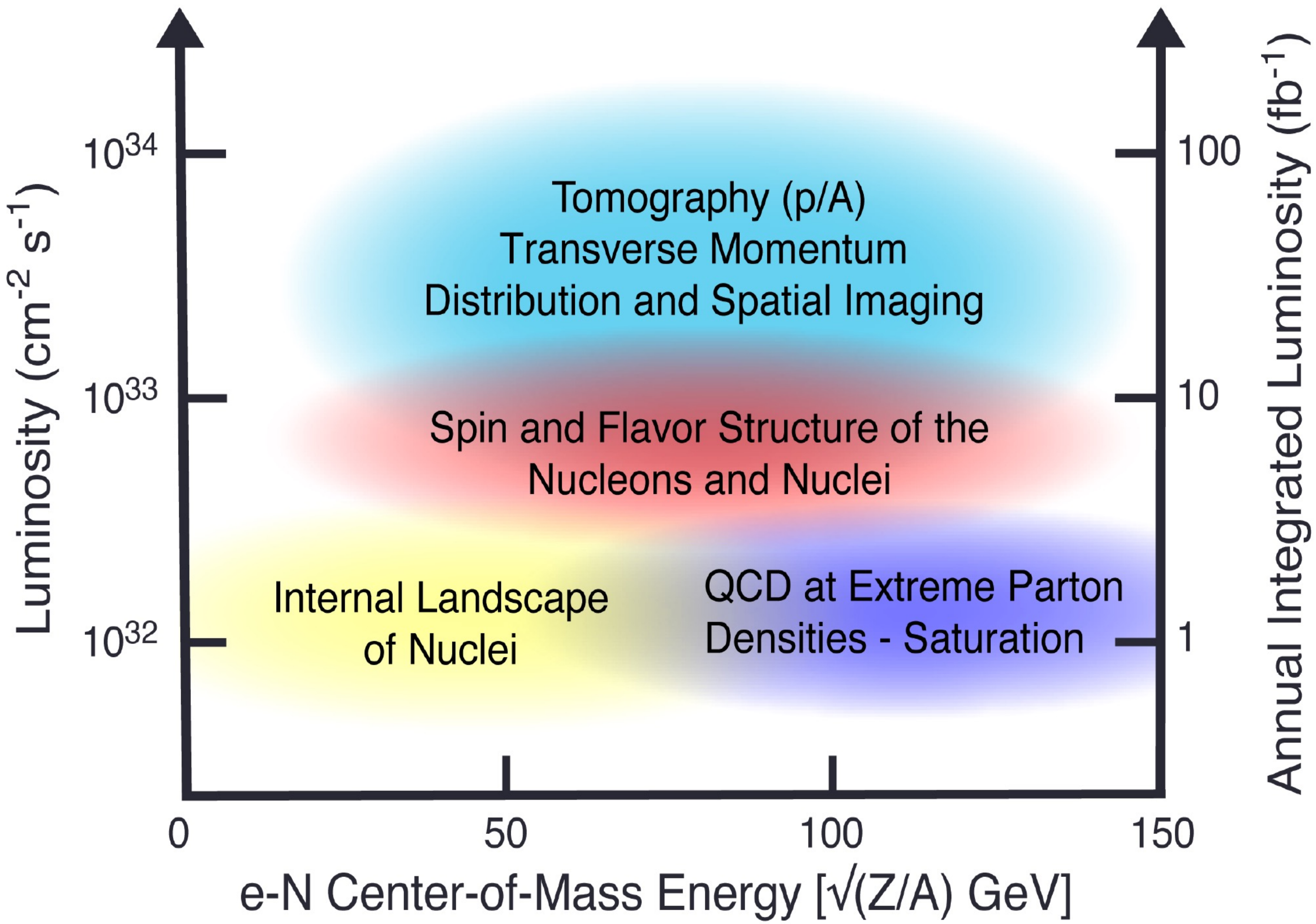
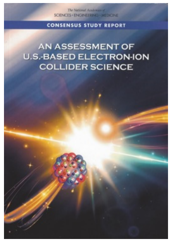


Figure 2.1: Left: The x-Q^2 range covered by the EIC (yellow) in comparison with past and existing polarized e/μ+p experiments at CERN, DESY, JLab and SLAC, and p+p experiments at RHIC. Right: The x-Q^2 range for e+A collisions for ions larger than iron (yellow) compared to existing world data.

Collider Specifications from Science





New Tools

Development of a Polarized He-3 Ion Source

Brookhaven National Laboratory
Gregor Atoian, Edward Beebe, Sergey Kondrashev, Deepak Raparia, John Ritter
Massachusetts Institute of Technology
Noah Wuerfel and Richard Milner

since 2012

and a

Polarized He-3 Target

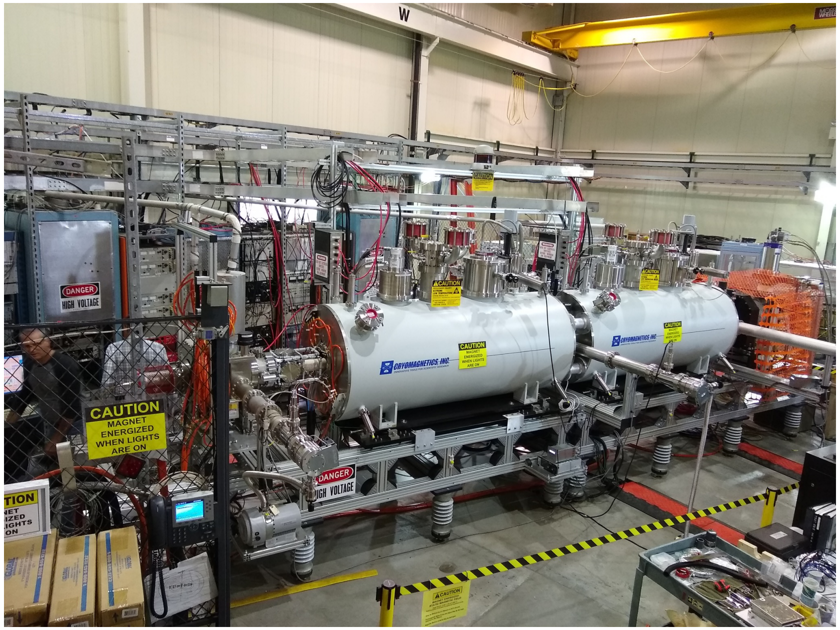
Jefferson Laboratory
James Brock, Chris Keith, James Maxwell
Massachusetts Institute of Technology
Pushpa Pandey and Richard Milner
University of Tennessee
Dien Nguyen

since 2021

Using High-Field Optical Pumping

BNL-MIT Development of MEOP in High Magnetic Field

- Allows polarization of gas directly in EBIS.
- Direct transfer of polarized gas to EBIS vacuum system.
- Motivated development of tandem EBIS configuration which also benefits other ions.
- Polarized ^{3}He ion source for the EIC at RHIC at Brookhaven National Lab



Dr. Noah Wuerfel

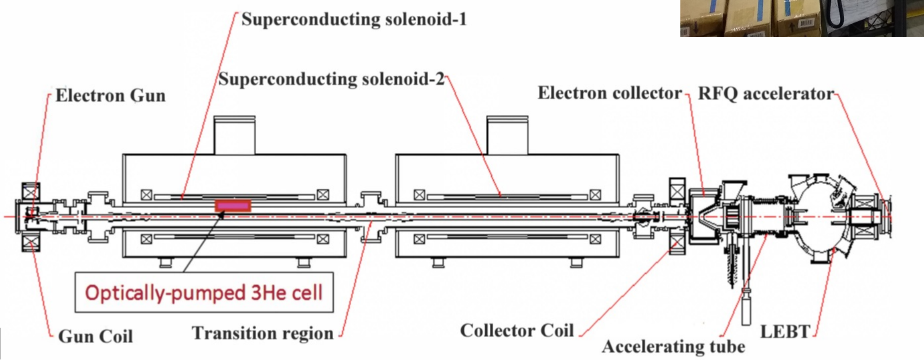


Figure 1: Schematic diagram of the extended EBIS. The polarized ^{3}He gas is injected into the drift tube of the new "injector" EBIS section. Here, RFQ means Radio Frequency Quadrupole and LEBT is the Low Energy Beam Transport.

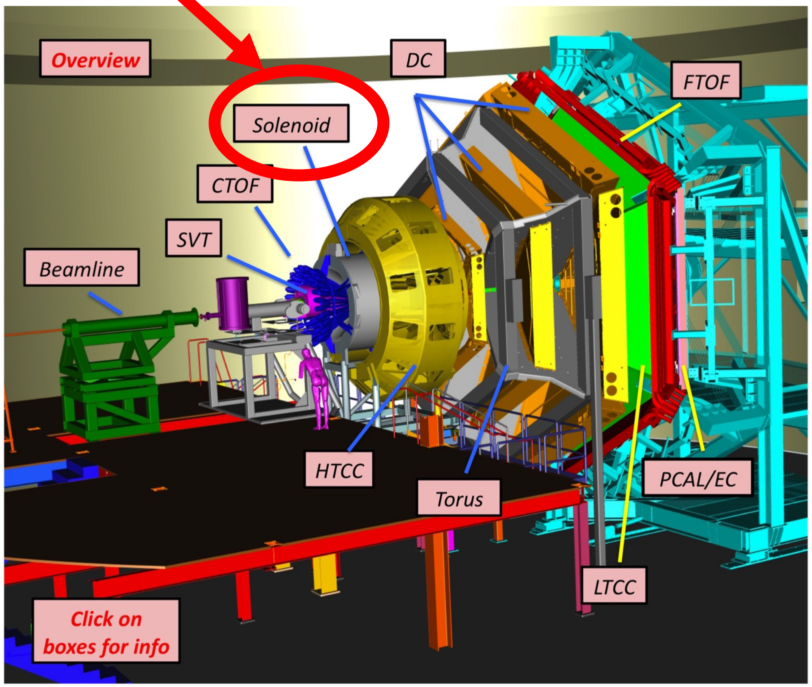
Extraction and measurement of He-3 nuclear polarization anticipated in 2025.

A. Zelenski *et al.*, Nucl. Instr. and Meth. A 1055, 168494 (2023)

Proposed Experiment Using Polarized ^{3}He at CLAS12 JLab

- CLAS12: CEBAF Large Acceptance Spectrometer for operation at 12 GeV
  - High luminosity electron scattering
  - Multi-particle final-state response
- PR12-20-002: A program of spin-dependent electron scattering using a polarized ^{3}He target at CLAS12
  - Spokespeople: H. Avakian, J. Maxwell, R. Milner, and D. Nguyen.
  - Approved with A- rating conditionally on the high-field MEOP target development
- Novel target design to accommodate to the standard CLAS12 configuration

5-T solenoid surrounding the interaction region



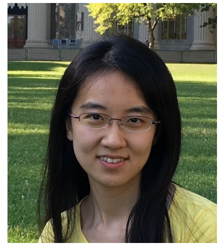
Target Development Status

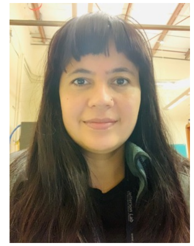
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 1057, December 2023, 168792

Full Length Article

Metastability exchange optical pumping of ^{3}He at low pressure and high magnetic field

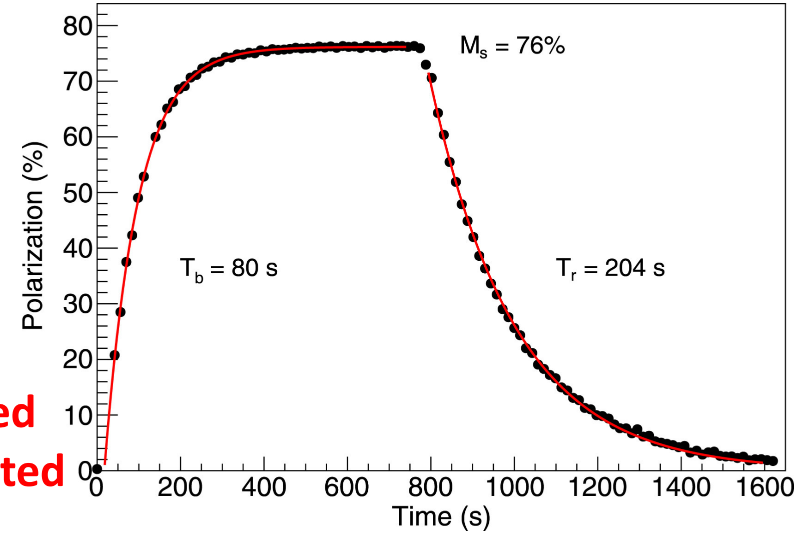
X. Li[a], J.D. Maxwell[b], D. Nguyen[b], J. Brock[b], C.D. Keith[b], R.G. Milner[a], X. Wei[b]



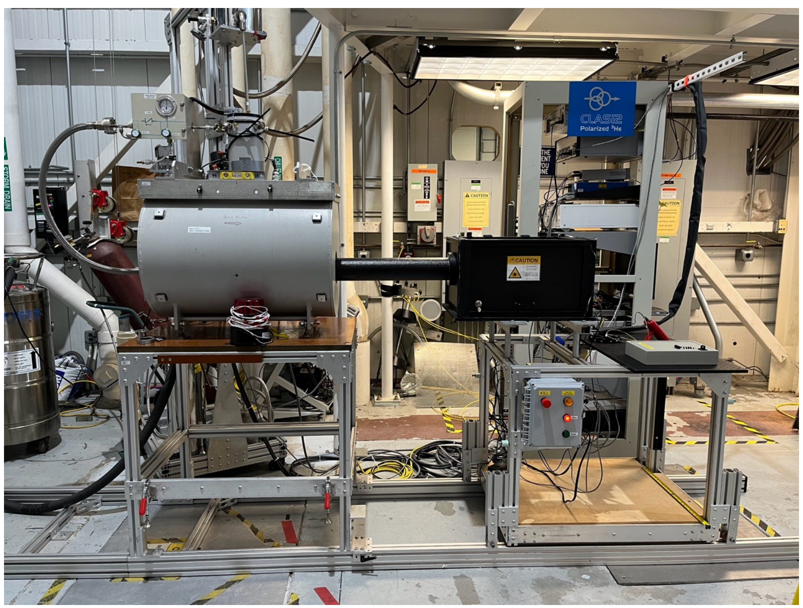


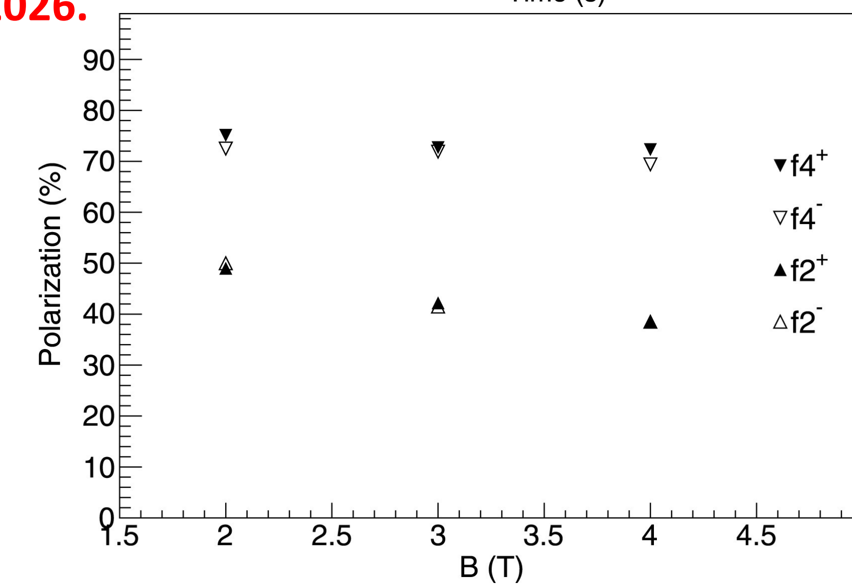
Dr. Xiaqing Li 2021-2023

Dr. Pushpa Pandey



Beam test with polarized target anticipated in 2026.





Opportunity for China to Build a World Class QCD Machine in the Next Decade

- Need lepton scattering to access DIS and DVEP
  - 10 GeV on fixed target provides access to valence quarks
- Both transversely and longitudinally polarized targets of proton, deuteron and ^{3}He
  - Determine GPDs and TMDs
- Desire positron as well as electron beam
  - beam charge asymmetry for DVEP
  - test QED expansion
- Desire complementarity to Jefferson Lab as well as synergy with EIC-China

Realization

- 10 GeV electron/positron storage ring with 200 mA of circulating current
    - Is an existing ring available?
- Self polarization of stored e+/e- using the Sokolov-Ternov effect
- Polarized gas targets of H, D, ^{3}He and unpolarized gas targets
- Dedicated magnetic spectrometer with state-of-the-art particle identification
- Technically unique and complementary to Jefferson Lab
    - polarized targets: undiluted, longitudinal and transverse poln.
    - high intensity polarized positron beams
- Should come online in about a decade

Summary

- One of the central goals of twenty first century physics is to fully understand QCD.
- Lepton scattering over a broad kinematic range will be the principal experimental tool.
- Theory and simulation will be equal partners to experiment in this ambitious endeavor.
- The U.S. is a major player with the Jefferson Lab world class capability and the EIC anticipated at BNL in about a decade.
- China is building its community and making plans.
- Together we can make enormous progress.