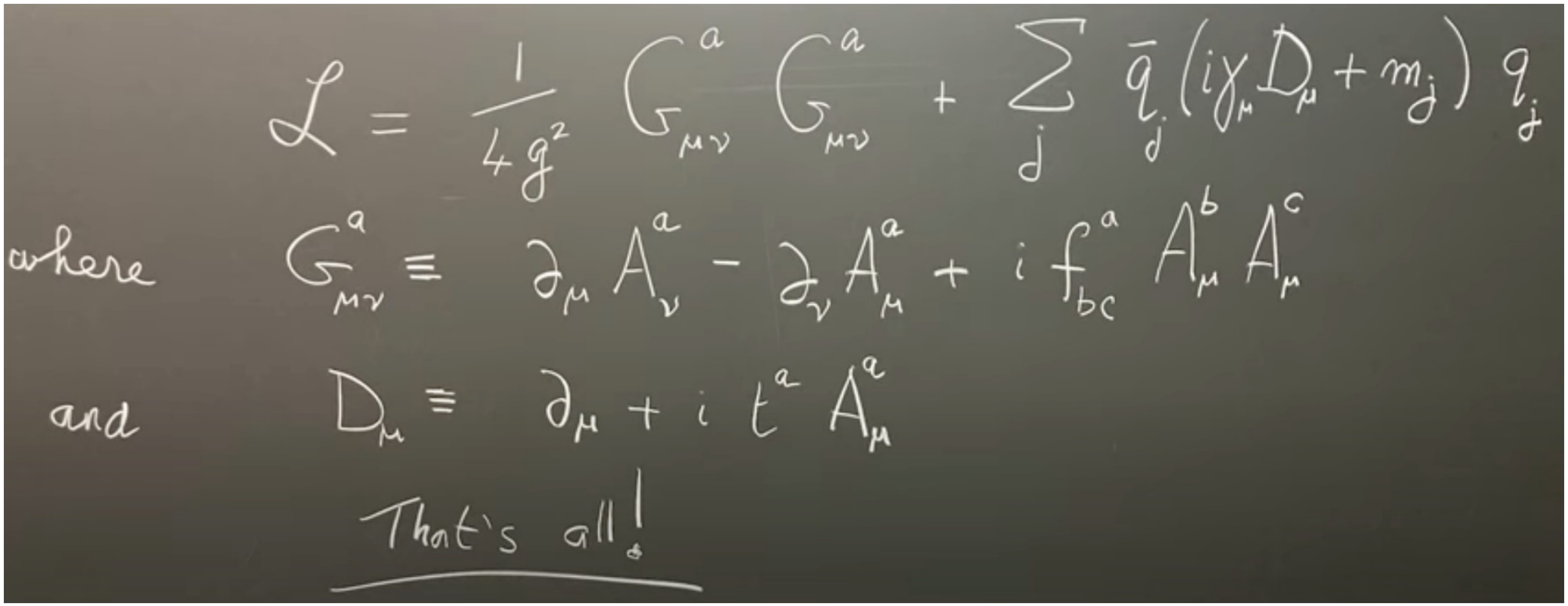
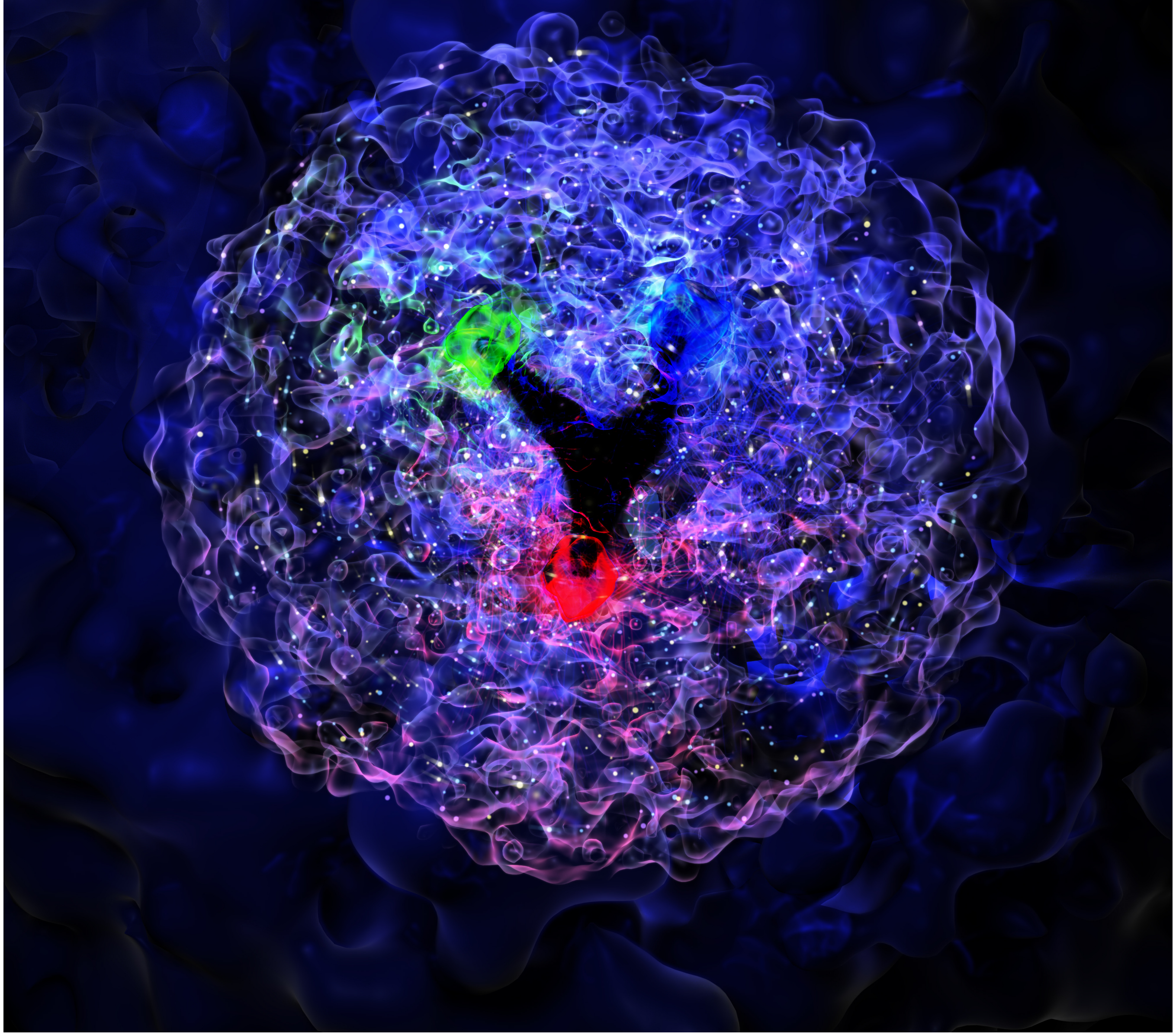
Studying QCD and Beyond with Electron Scattering

QCD Lagrangian



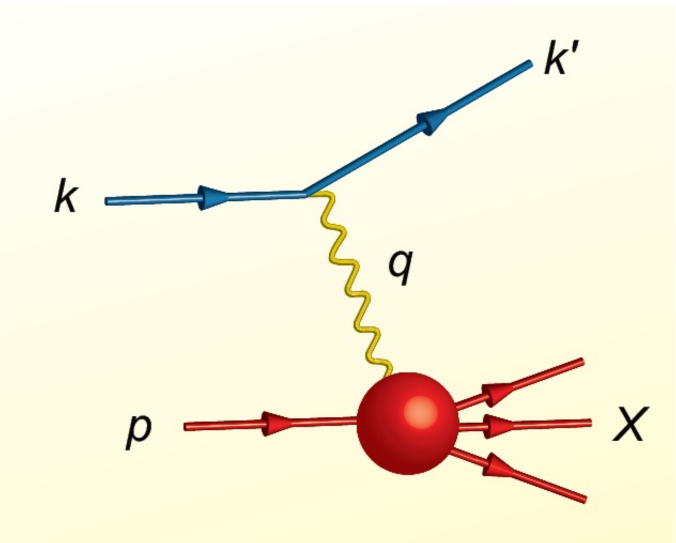
How does the spin-1/2 proton with mass 938 MeV/c^2 arise?

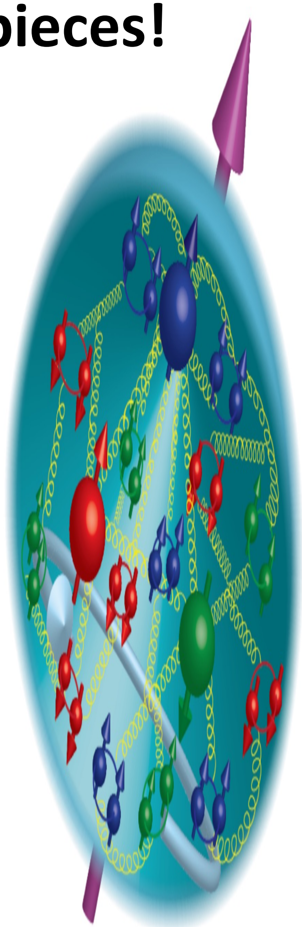
Quark and Gluon Dynamics Dominate the Proton



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

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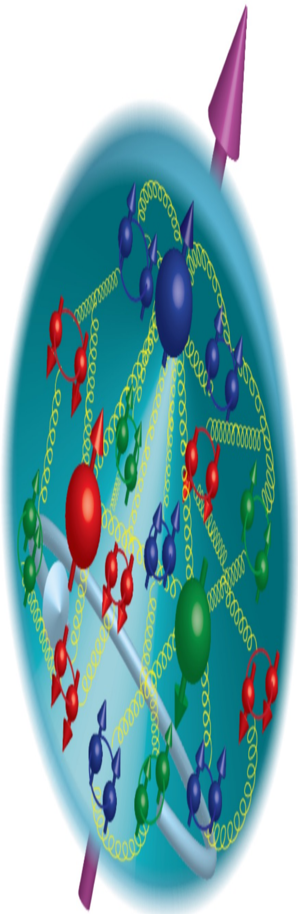
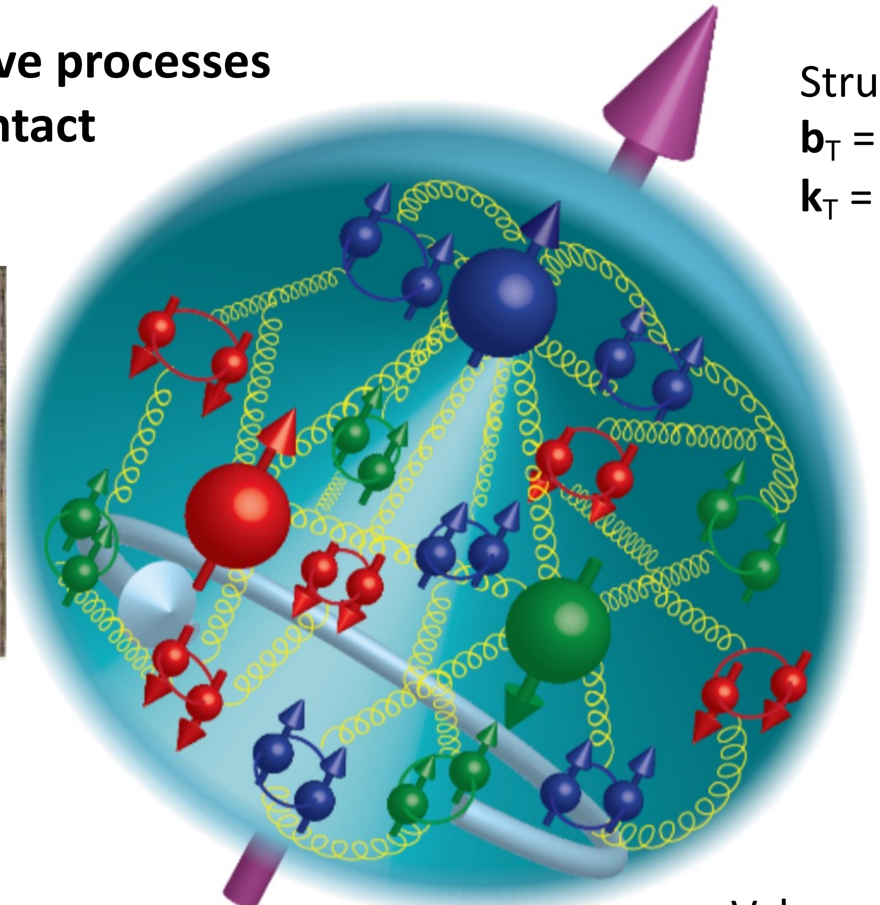


Proton Tomography: 2 New Dimensions Transverse to Longitudinal Momentum

Deeply virtual exclusive processes where proton is left intact



Structure mapped in terms of
b_T = transverse position
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

Charting the Inner Structure of the Proton

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

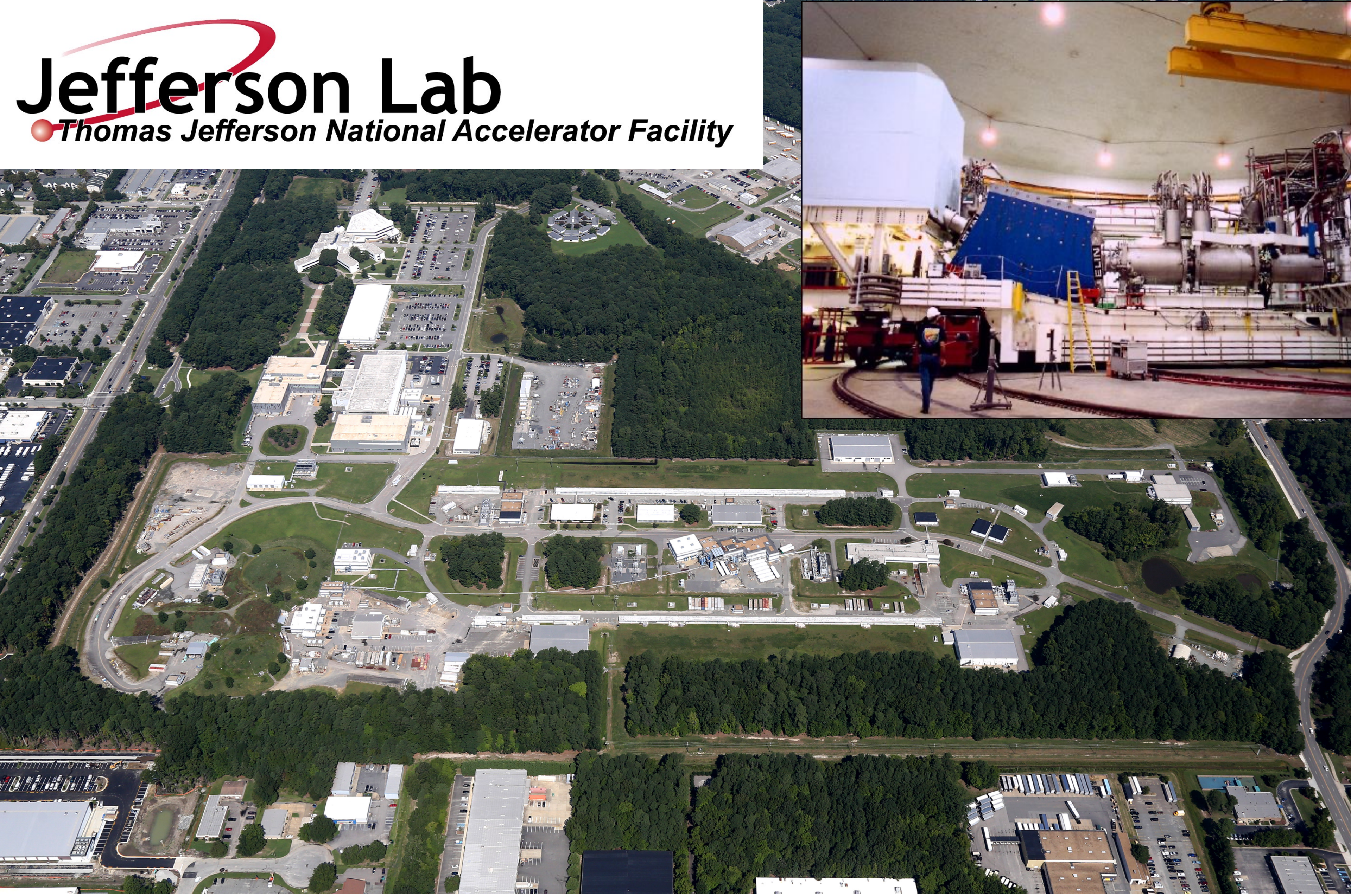
Christopher Boebel
Rolf Ent
James LaPlante
Joseph McMaster
Richard Milner

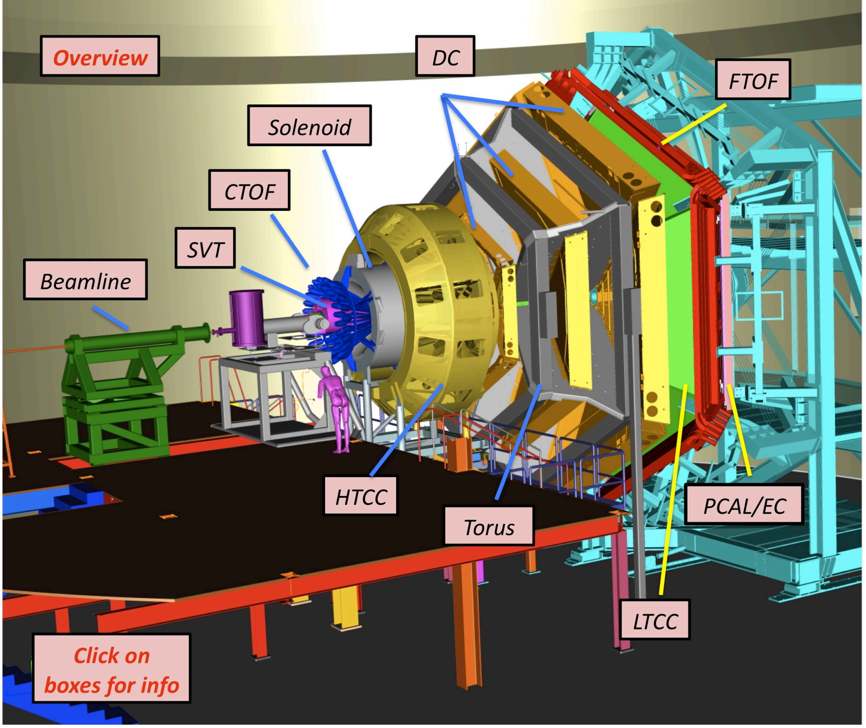
Jefferson Lab

SPUTNIK ANIMATION

ARTS CENTER FOR ART, SCIENCE & TECHNOLOGY AT MIT

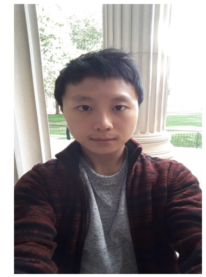
Jefferson Lab
Thomas Jefferson National Accelerator Facility





CLAS12
Deeply Virtual Processes

Bobby Johnston



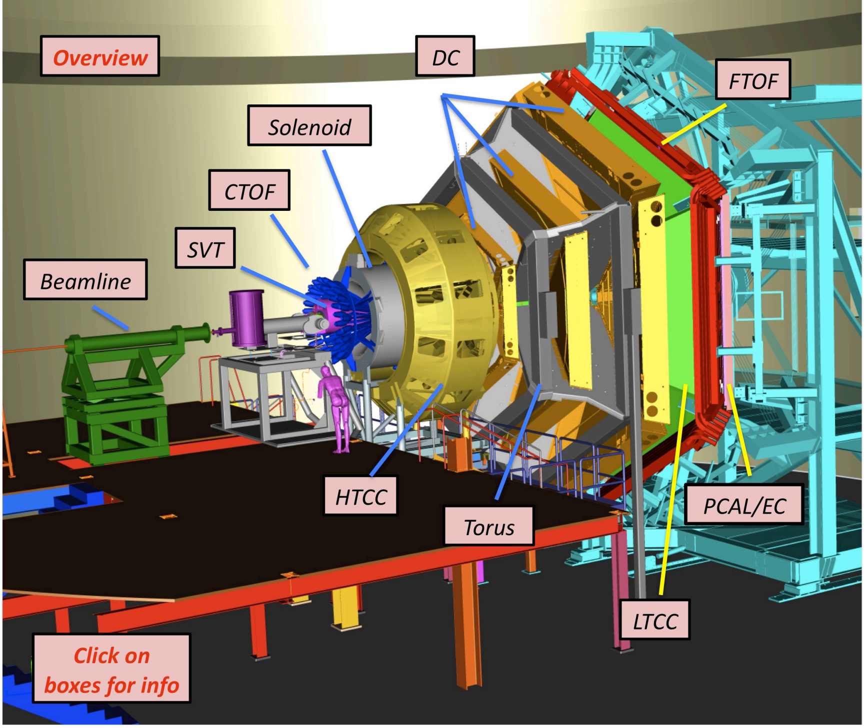
Sangbaek Lee

Patrick Moran

- 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 analysis of CLAS12 data.

Bobby:	$p(e,e'\pi^0)p$
Sangbaek:	$p(e,e'\gamma)p$
Patrick:	$p(e,e'\varphi)p$

- Seek new insights into the quark and gluon structure of the proton



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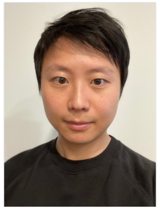
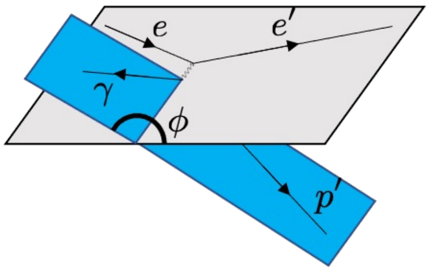
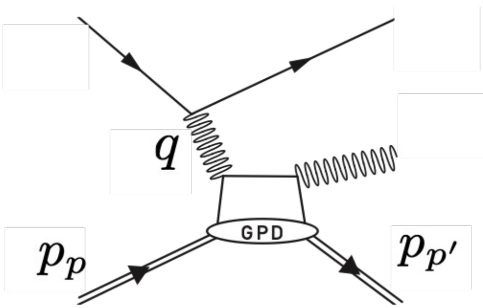
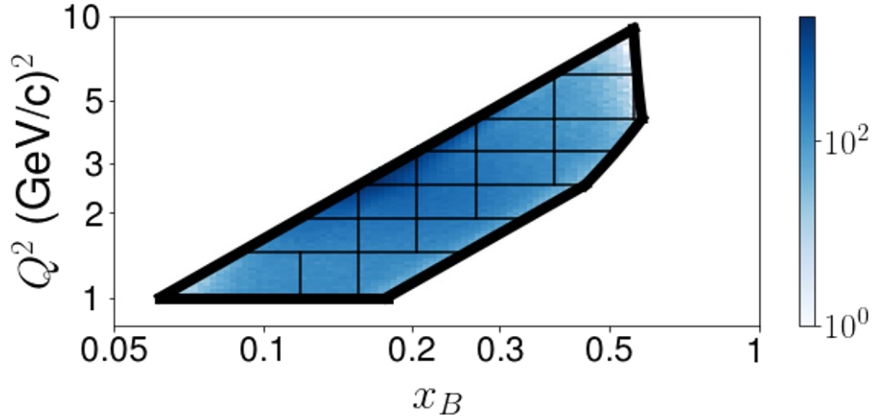
DVCS cross section measurement at CLAS12

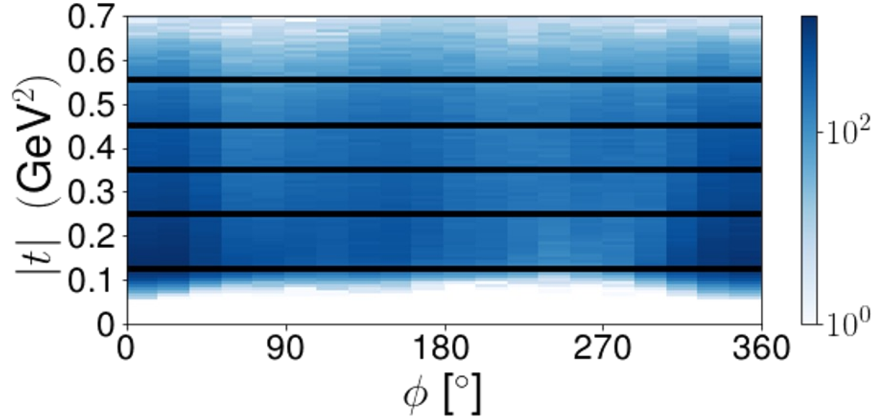


Sangbaek Lee









Bjorken x $\quad 0 < x_B \equiv \dfrac{Q^2}{2p_p \cdot q} < 1$

4-momentum transfer $\quad Q^2 \equiv -q^2 > 1$

Mandelstam variable $\quad t \equiv (p_{p'} - p_p)^2$

angle between scattering planes $\quad \phi$

$$\frac{d\sigma}{dx_B dQ^2 d(-t) d\phi} = \frac{N_{\mathrm{DVCS+BH}}}{L \times \mathrm{Vol_{bin}}} \frac{1}{\mathrm{F_{correction}}}$$

DVCS Cross Section Results

Measurement of the Deeply Virtual Compton Scattering Cross Section from the Proton at 10.6 GeV using the CLAS12 Detector

by

Sangbaek Lee

B.S., Seoul National University (2016)

Submitted to the Department of Physics
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Physics

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2022

Author ....
Department of Physics
August 22, 2022

Certified by ....
Richard G. Milner
Professor of Physics
Thesis Supervisor

Accepted by ....
Deepto Chakrabarty
Associate Department Head of Physics

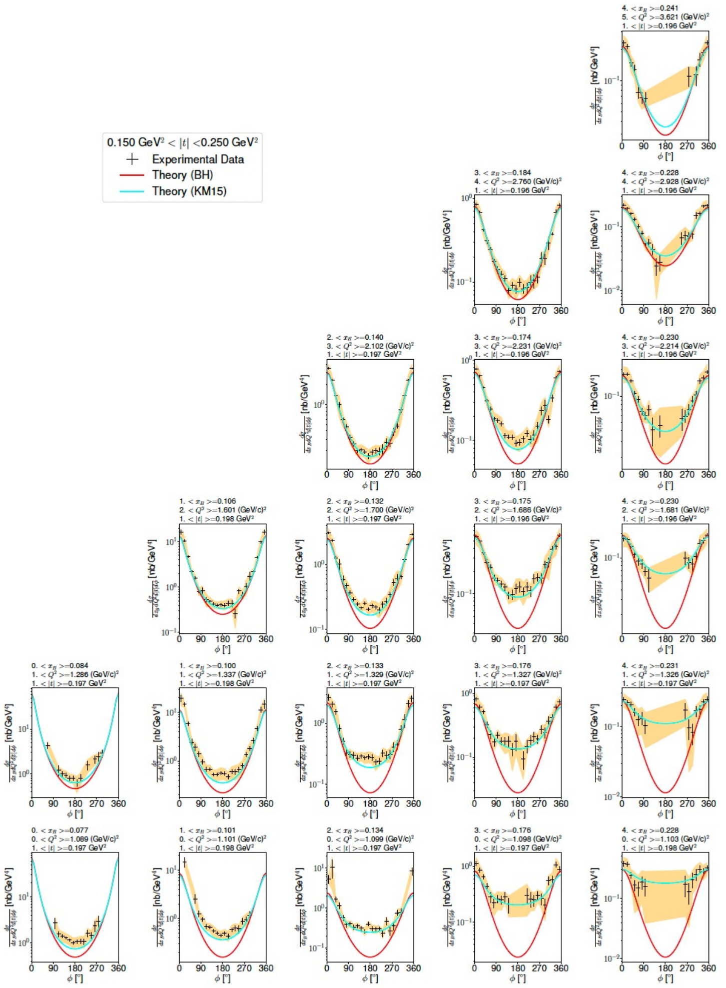
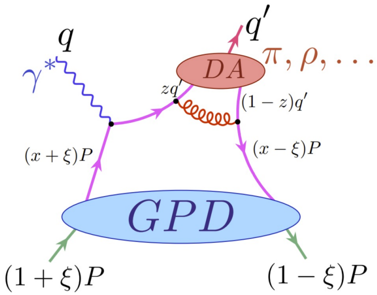
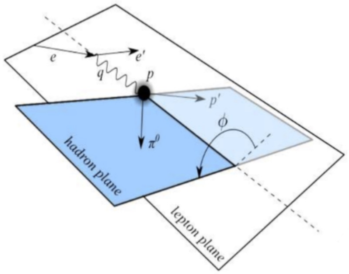
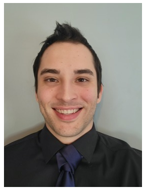


Figure 5-25: The unpolarized cross section in $x_B < 0.268$, $Q^2 < 4.326$ (GeV/c)^2, 0.150 GeV^2 < $|t|$ < 0.250 GeV^2 bins.

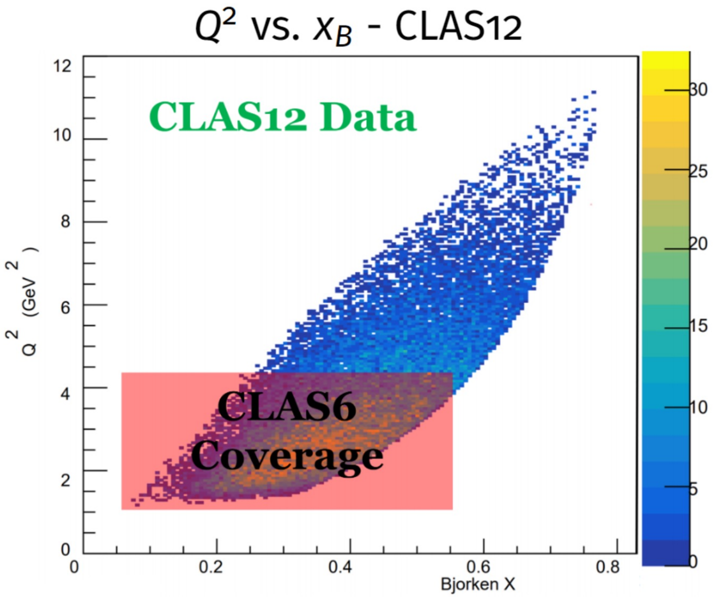
Deeply Virtual π^0 cross section measurement at CLAS12







Bobby Johnston



$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)|\langle\tilde{H}\rangle|^2 - 2\xi^2\text{Re}[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle] - \frac{t'}{4m^2}\xi^2|\langle\tilde{E}\rangle|^2\right\},$$

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle\bar{E}_T\rangle|^2\right],$$

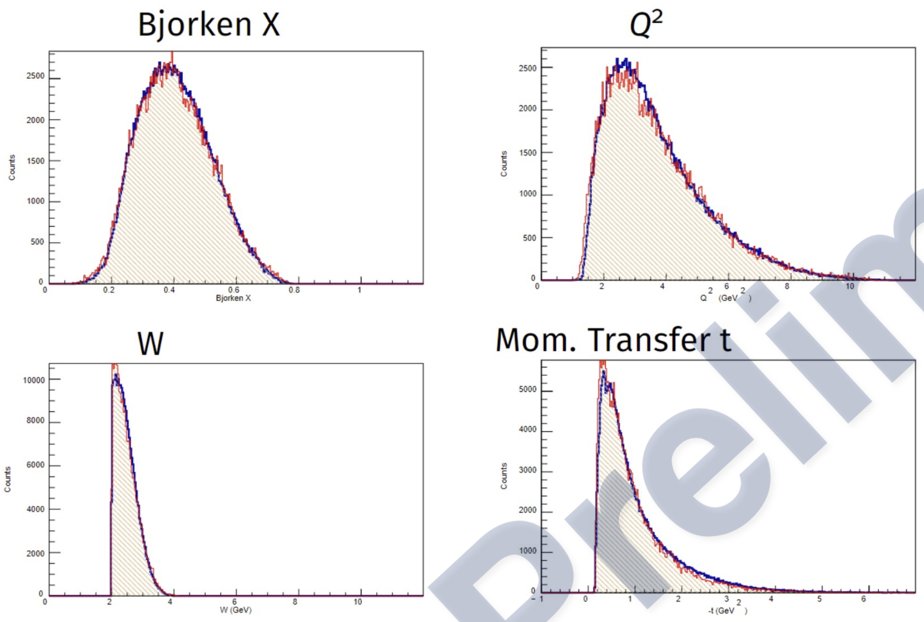
$$\frac{d\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\text{Re}[\langle H_T\rangle^*\langle\tilde{E}\rangle],$$

$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}|\langle\bar{E}_T\rangle|^2.$$

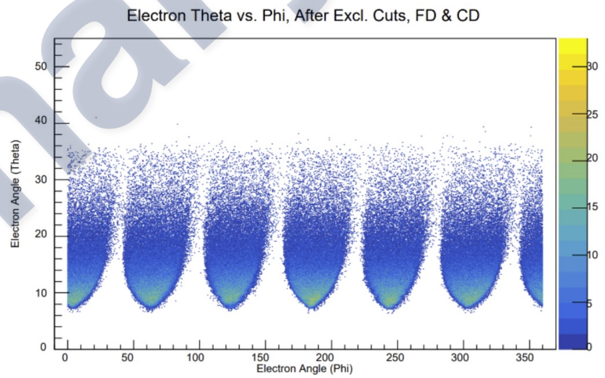
Deeply virtual π^0 cross section measurement at CLAS12

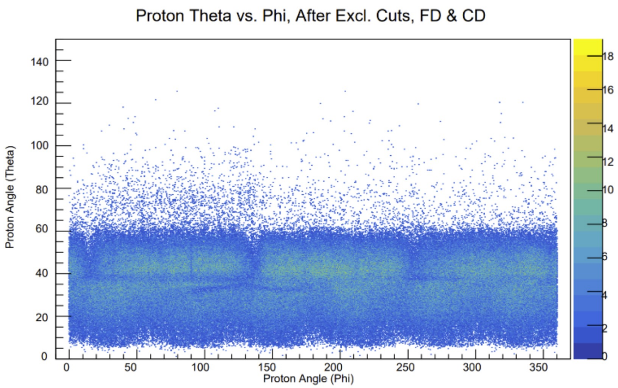
Simulation-Data Comparison

Simulation (red) vs. Data (blue)



Particle Kinematics

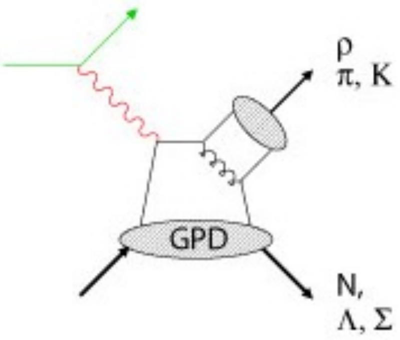


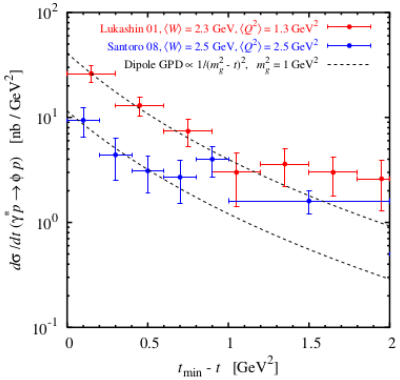


Deeply Virtual Phi Production (DVφP) at CLAS12, JLab Hall B

Patrick Moran

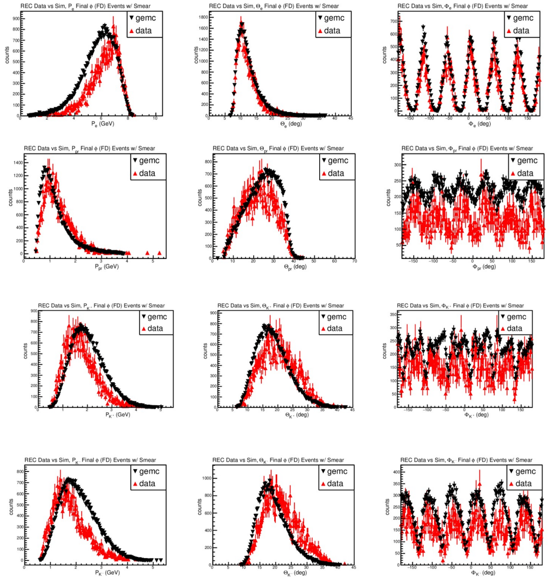
- Goal: to measure the exclusive phi electroproduction cross section
- Signal event: $(e, e'p'K^+K^-)$
- DVϕP accesses gluon GPDs, information about gluonic radius of the proton



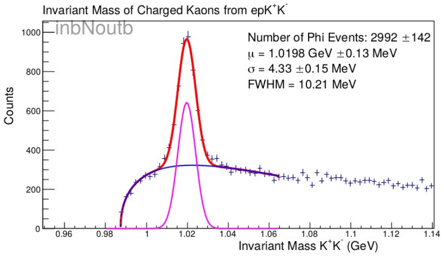


Previous diff. cross section measurements from CLAS

Simulation vs. data for final state particle kinematics

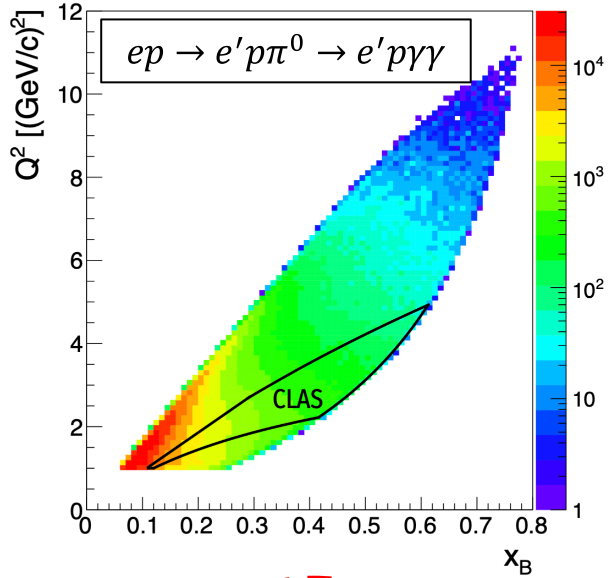


Total number of phi events in the final state



Transition GPDs $ep \rightarrow \gamma\, N^* \rightarrow \gamma p\, Meson$

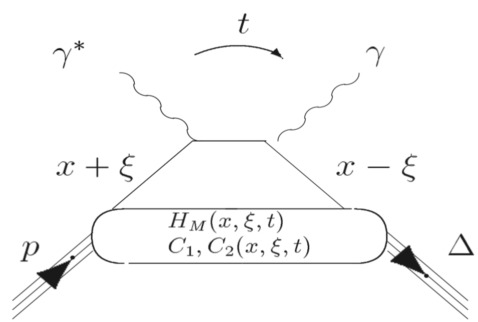
Reaction Mechanism: Factorization



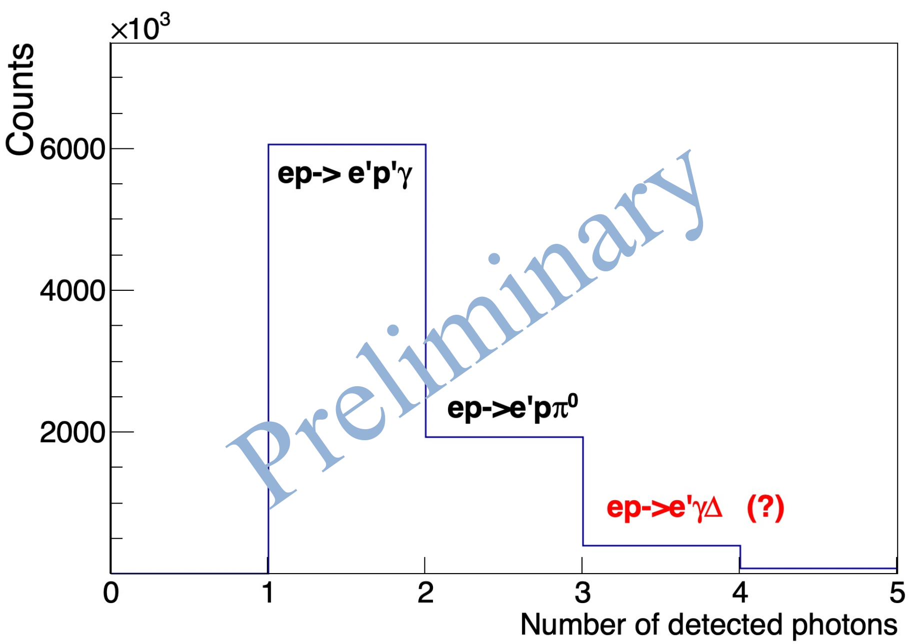
$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right].$$

Two beam energies: 5.75 GeV and 10.6 GeV

σ_L/σ_T separation over wide (x_B, Q^2) range

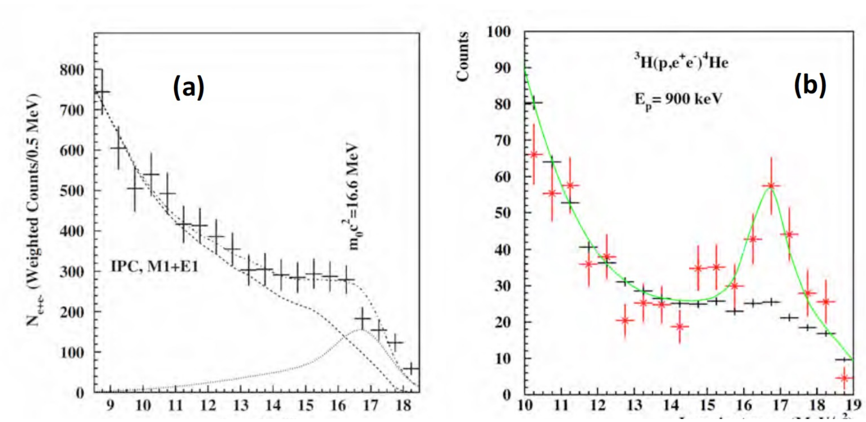


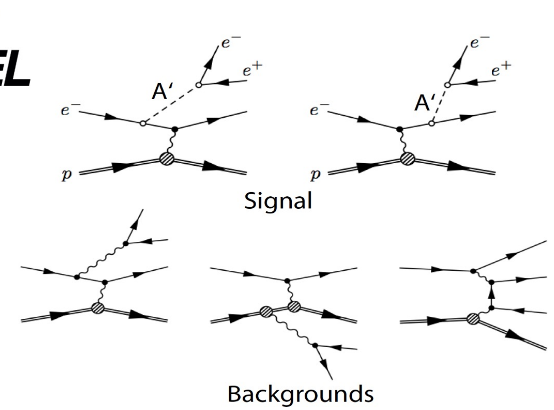
Dr. Igor Korover



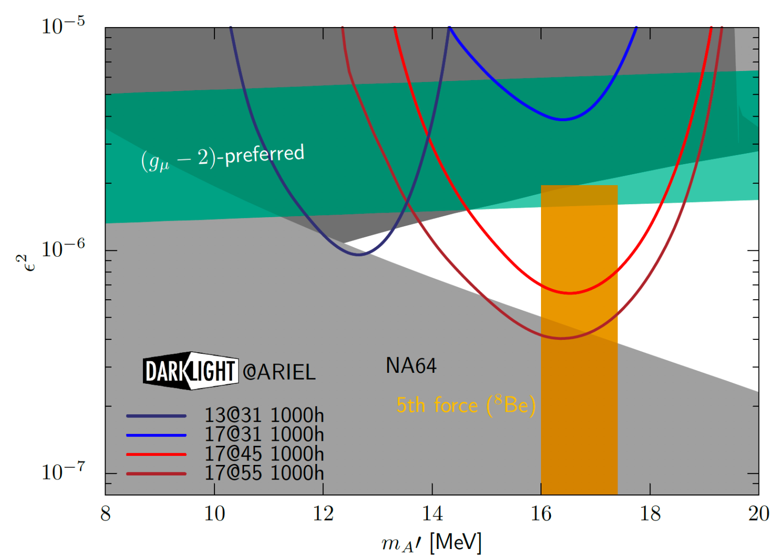
April, 2021 S2134	Search for New Physics in e^+e^- Final States With an Invariant Mass of 13-17 MeV using the ARIEL Electron Accelerator	J. C. Bernauer, R.C. Corliss, R.G. Milner	Approved for 1300 hours with high priority

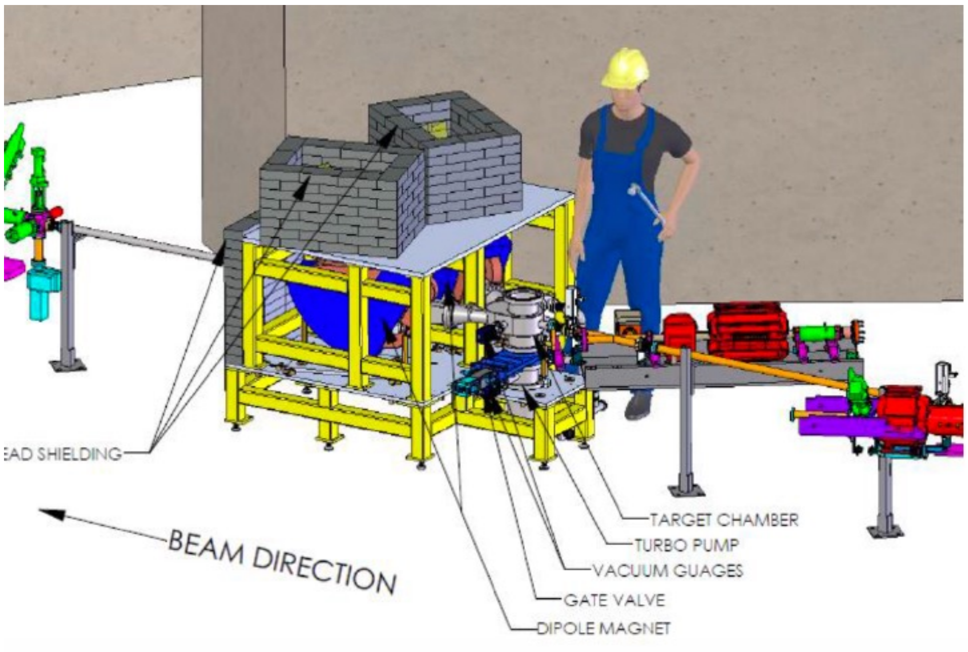
DARKLIGHT @ ARIEL





Arizona State University, Tempe, AZ, USA
University of British Columbia, Canada
Hampton University, Hampton, VA, USA
TJNAF, Newport News, VA, USA
Massachusetts Institute of Technology, Cambridge, MA, USA
St. Mary's University, Halifax, Nova Scotia, Canada
Stony Brook University, NY, USA
TRIUMF, Vancouver, British Columbia, Canada
University of Manitoba, Canada
University of Winnipeg, Manitoba, Canada





Realization

Funding secured in FY2022 and construction will take place in FY2023

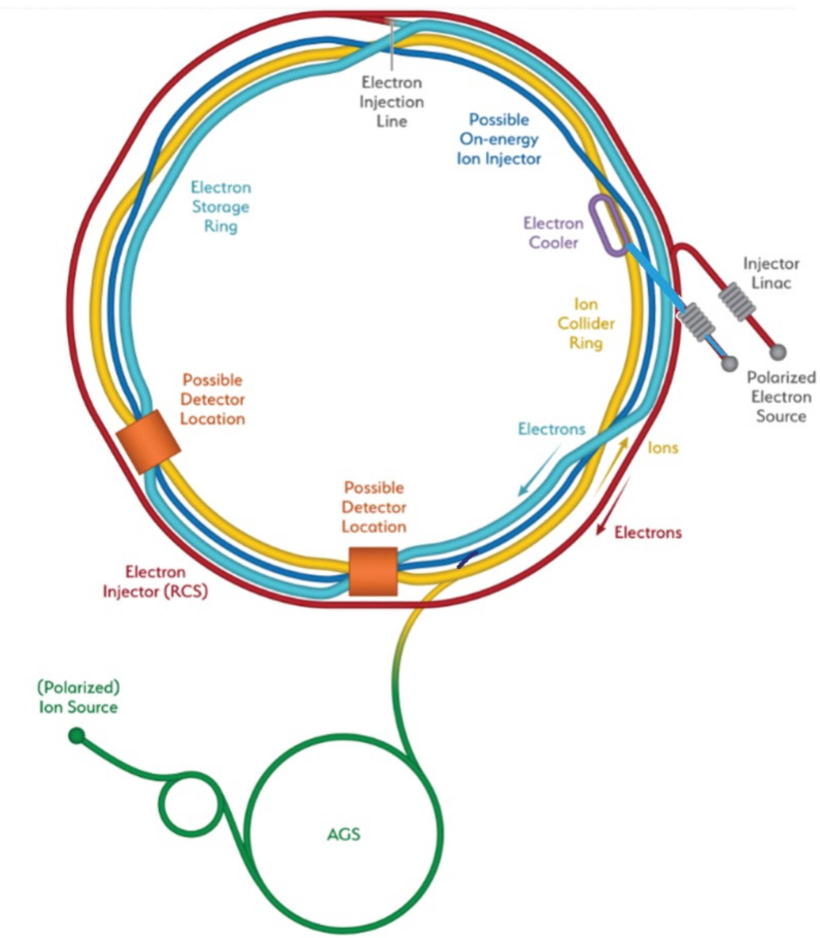
Data taking in 2024

Table 2: Major tasks and responsibilities for the proposed experiment.

Task	Lead Group	
Magnetic spectrometers	MIT	$ 165 K
Target and Scattering Chamber	MIT	$ 50 K
GEM detectors	Hampton U	
Data Acquisition	Stony Brook U.	
Trigger hodoscopes	TRIUMF, UW, and SMU	
Integration with ARIEL	TRIUMF, UofM	

MIT-Bates lab is coordinating design and construction of the experiment.

Electron-Ion Collider (EIC)



- New high luminosity collider **to study QCD** to be constructed using RHIC at BNL and expected to come online in early 2030s.
- MIT-LNS has played a leadership role in making the case for EIC over two decades: Bates Lab one of the points of origin
- Prof. Hen leader of EPIC (detector 1)
- EIC R&D: Polarized ^{3}He ion source, EM calorimeter and streaming readout development
- Beginning graduate students in 2022 will be young faculty who will drive the scientific program at EIC.

Seeking New Students

To work on

- the design and construction of the DarkLight experiment at TRIUMF, Vancouver, Canada
- the data taking and analysis of deeply virtual exclusive processes using CLAS12 at Jefferson Lab
- the design and construction of the EPIC detector for EIC

Contact info: Email: milner@mit.edu Office 26-411