Hall B
CLAS12 Physics Program

Latifa Elouadrhiri
Jefferson Lab
Outline

• Introduction to 12 GeV Upgrade
• CLAS12 Detector
• CLAS12 Science Program
• Summary
Generalized Parton Distributions (GPDs)

D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, 

GPDs connect the charge and parton distribution

The size and structure of proton. Proton form factors, **transverse** charge and current distributions 
Nobel prize 1961 - R. Hofstadter

Internal constituents of the nucleon Quark **longitudinal** momentum and helicity distributions 
Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor

Extend longitudinal quark momentum & helicity distributions to transverse momentum distributions - TMDs
3 dimensional imaging of the nucleon

Deeply Virtual Compton Scattering (DVCS)

GPDs depend on 3 variables, e.g. $H(x, \xi, t)$. They describe the internal nucleon dynamics.
Link to DIS and Elastic Form Factors

Form factors (sum rules)
\[ \int dx \sum_q \left[ H^q(x, \xi, t) \right] = F_1(t) \text{ Dirac f.f.} \]
\[ \int dx \sum_q \left[ E^q(x, \xi, t) \right] = F_2(t) \text{ Pauli f.f.} \]
\[ \int dx \tilde{H}^q(x, \xi, t) = G_{A,q}(t), \int dx \tilde{E}^q(x, \xi, t) = G_{P,q}(t) \]

Angular Momentum Sum Rule

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

Universality of GPDs

- Parton momentum distributions
- Elastic form factors
- Real Compton scattering at high t
- Deeply Virtual Compton Scattering
- Single Spin Asymmetries
- Deeply Virtual Meson production
How can we determine the GPDs?
Accessing GPDs in Exclusive Processes

• Deeply virtual Compton scattering (clean probe, flavor blind)
  \[ ep \rightarrow e' p' \gamma \]  
  **Sensitive to all GPDs.**
  \[ ep \rightarrow e' p' L^+ L^- \]  
  **Insensitive to quark flavor**
  ...

• Hard exclusive meson production (quark flavor filter)
  \[ ep \rightarrow e' p' \pi \]  
  **Sensitive to \( \tilde{H}, \tilde{E} \)**
  \[ ep \rightarrow e' p' \rho \]  
  \[ ep \rightarrow e' p' \omega \]  
  \[ \text{Sensitive to } H, E \]
  ...

• 4 GPDs in leading order, 2 flavors (u, d) \( \rightarrow 8 \) measurements
Measuring GPDs through polarization

\[ A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta \sigma}{2\sigma} \]

Polarized beam, unpolarized target:

\[ \Delta \sigma_{LU} \sim \sin \phi \text{Im}\{F_1 \tilde{H} + \xi (F_1 + F_2) \tilde{H} + kF_2 E\} d\phi \]

Unpolarized beam, longitudinal target:

\[ \Delta \sigma_{UL} \sim \sin \phi \text{Im}\{F_1 \tilde{H} + \xi (F_1 + F_2) (H + \xi/(1+\xi)E) - \ldots \} d\phi \]

Unpolarized beam, transverse target:

\[ \Delta \sigma_{UT} \sim \sin \phi \text{Im}\{k(F_2 H - F_1 E) + \ldots \} d\phi \]

\[ \xi = \frac{x_B}{2-x_B} \]

\[ k = \frac{t}{4M^2} \]

Kinematically suppressed
At 12 GeV, CEBAF will be an ideal for GPD studies.

Enhance equipment in existing halls

Add new hall

Add 5 cryomodules

20 cryomodules

Add arc

CHL-2

20 cryomodules

Add 5 cryomodules

Enhance equipment in existing halls
New Capabilities in Halls A, B, & C, and a New Hall D

D

9 GeV tagged polarized photons and a $4\pi$ hermetic detector

B

CLAS12 high luminosity, large acceptance.

C

Super High Momentum Spectrometer (SHMS) at high luminosity and forward angles

A

High Resolution Spectrometer (HRS) Pair, and specialized large installation experiments
Hall B currently houses the CEBAF Large Acceptance Spectrometer (CLAS) \( L = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)

CLAS will be replaced by CLAS12

CLAS12 is designed to operate with an upgraded luminosity of \( L = 10^{35} \text{ cm}^{-2}\text{s}^{-1} \)

CLAS12 will be world wide the only large acceptance high luminosity spectrometer for fixed target electron scattering experiments
**Forward Detector:**
- **TORUS magnet**
- **Forward SVT tracker**
- **HT Cherenkov Counter**
- **Drift chamber system**
- **LT Cherenkov Counter**
- **Forward ToF System**
- **Preshower calorimeter**
- **E.M. calorimeter (EC)**

**Central Detector:**
- **SOLENOID magnet**
- **Barrel Silicon Tracker**
- **Central Time-of-Flight**

**Proposed upgrades:**
- **Micromegas (CD)**
- **Neutron detector (CD)**
- **RICH detector (FD)**
- **Forward Tagger (FD)**
### CLAS12 – Design parameters

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<thead>
<tr>
<th></th>
<th>Forward Detector</th>
<th>Central Detector</th>
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<tr>
<td><strong>Angular range</strong></td>
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<tr>
<td>Tracks</td>
<td>5° – 40°</td>
<td>35° – 125°</td>
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<td>Photons</td>
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<td><strong>Resolution</strong></td>
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<td>δp/p (%)</td>
<td>&lt; 1 @ 5 GeV/c</td>
<td>&lt; 5 @ 1.5 GeV/c</td>
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<tr>
<td>δθ (mr)</td>
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<td>&lt; 10 - 20</td>
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<td>Δφ (mr)</td>
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<td>&lt; 5</td>
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<td><strong>Photon detection</strong></td>
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<td>Energy (MeV)</td>
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<td>n.a.</td>
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<tr>
<td>δθ (mr)</td>
<td>&lt;4 @ 1 GeV</td>
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<tr>
<td><strong>Neutron detection</strong></td>
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<tr>
<td>efficiency</td>
<td>&lt; 0.7 (EC+PCAL)</td>
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<td><strong>Particle ID</strong></td>
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<td>e/π</td>
<td>Full range</td>
<td>n.a.</td>
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<tr>
<td>π/p</td>
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<tr>
<td>π/K</td>
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<td>π⁰→γγ</td>
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<td>n.a.</td>
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<tr>
<td>η→γγ</td>
<td>Full range</td>
<td>n.a.</td>
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The B-field transverse to the particle trajectory is approximately matched to the average particle momentum.
- SVT - Charged particle tracking in 5T field
- Vertex reconstruction
- $\Delta T < 60\text{psec}$ in CTOF for particle id
- Moller electron shield
- Polarized target operation $\Delta B/B < 10^{-4}$
  in 3x5 cm cylinder around center
Background Shielding

Background at $L = 10^{32} \text{cm}^{-2}\text{s}^{-1}$, $\Delta T = 150\text{ns}$
Background at $L=10^{35}\text{cm}^{-2}\text{s}^{-1}$, $\Delta T = 150\text{ns}$

One random event

5 T Magnetic Field
Background at $L = 10^{35} \text{cm}^{-2}\text{s}^{-1}$, $\Delta T = 150\text{ns}$
A Program at the Forefront of Hadron Physics

- 3D Structure of the Nucleon Structure - the new Frontier in Hadron Physics

- Nucleon GPDs and TMDs – exclusive and semi-inclusive processes with high precision

- Precision measurements of structure functions and forward parton distributions at high $x_B$

- Elastic & Transition Form Factors at high momentum transfer
### CLAS12 Initial Science Program

<table>
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<tr>
<th>Physics Focus</th>
<th>Approved experiments</th>
<th>LOIs supported</th>
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<td>GPD’s &amp; exclusive Processes</td>
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<td>TMDs &amp; SIDIS</td>
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<td>Parton Distribution Function &amp; DIS</td>
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<td>Elastic &amp; resonance form factors</td>
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<td>Hadronization &amp; Color Transparency</td>
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<tr>
<td>Baryon Spectroscopy</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>13</strong></td>
<td><strong>7</strong></td>
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Approved experiments correspond to about 5 years of scheduled beam operation.
## CLAS12 Institutions

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<tr>
<th>Institution</th>
<th>Focus Area</th>
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<tbody>
<tr>
<td>Argonne National Laboratory (US)</td>
<td>Cerenkov Counter</td>
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<td>California State University (US)</td>
<td>Cerenkov Counters</td>
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<tr>
<td>Catholic University of America (US)</td>
<td>Software</td>
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<tr>
<td>College of William &amp; Mary (US)</td>
<td>Calorimetry, Magnet Mapping</td>
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<tr>
<td>Edinburgh University (UK)</td>
<td>Software</td>
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<tr>
<td>Fairfield University (US)</td>
<td>Polarized Target</td>
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<td>Florida International University, Miami (US)</td>
<td>Beamline/Moller polarimeter</td>
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<tr>
<td>Glasgow University (UK)</td>
<td>Central Detector, DAQ, Forward Tagger, RICH</td>
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<tr>
<td>Grenoble University/IN2P3 (France)</td>
<td>Central Detector</td>
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<tr>
<td>Idaho State University (US)</td>
<td>Drift chambers</td>
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<tr>
<td>INFN – University Bari (Italy)</td>
<td>tbd, interest in RICH</td>
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<tr>
<td>INFN – University Catania (Italy)</td>
<td>tbd</td>
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<tr>
<td>INFN – Frascati and Fermi Center (Italy)</td>
<td>tbd, interest in RICH</td>
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<tr>
<td>INFN – University Ferrara (Italy) (will join in 2010)</td>
<td>Central Neutron Detector+ interest show in RICH</td>
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<tr>
<td>INFN – University Genoa (Italy)</td>
<td>tbd, interest in RICH</td>
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<tr>
<td>INFN – ISS/Rome 1 (Italy)</td>
<td>Central Neutron Detector+ interest in Forward Tagger</td>
</tr>
<tr>
<td>INFN – University of Rome Tor Vergata (Italy)</td>
<td>tbd</td>
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<tr>
<td>Institute of Theoretical and Experimental Physics (Russia)</td>
<td>Central Neutron Detector+ HD target</td>
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<td>James Madison University (US)</td>
<td>SC. Magnets, Simulations</td>
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<td>Kyungpook National University (Republic of Korea)</td>
<td>Calorimetry</td>
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<td>Los Alamos National Laboratory (US)</td>
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<td>Moscow State University, Skobeltsin Institute for Nuclear Physics (Russia)</td>
<td>Silicon Tracker</td>
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<td>Moscow State University (High Energy Physics) (Russia)</td>
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<td>Norfolk State University (US)</td>
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<td>Ohio University (US)</td>
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<td>Orsay University/IN2P3 (France)</td>
<td>Preshower Calorimeter</td>
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<tr>
<td>Old Dominion University (US)</td>
<td>Central Neutron Detector</td>
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<td>Renseale Polytechnic Institute (US)</td>
<td>Drift Chambers</td>
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<td>CEA Saclay (France)</td>
<td>Cerenkov Counters</td>
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<td>Temple University, Philadelphia (US)</td>
<td>Central Tracker, Reconstruction software</td>
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<td>Thomas Jefferson National Accelerator Facility (US)</td>
<td>Cerenkov Counters</td>
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<td>University of Connecticut (US)</td>
<td>Project coordination &amp; oversight</td>
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<td>University of New Hampshire (US)</td>
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<td>University of Richmond (US)</td>
<td>Central Tracker, Offline Software</td>
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<td>University of South Carolina (US)</td>
<td>Offline Software</td>
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<tr>
<td>University of Virginia (US)</td>
<td>Forward TOF</td>
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<tr>
<td>Yerevan Physics Institute (Armenia)</td>
<td>Beamline/Polarized Targets</td>
</tr>
</tbody>
</table>
DVCS/BH- Beam Asymmetry

$E_e = 11 \text{ GeV}$

With large acceptance, measure large $Q^2, x_B, t$ ranges simultaneously.

$A(Q^2, x_B, t)$

$\Delta\sigma(Q^2, x_B, t)$

$\sigma(Q^2, x_B, t)$
$E_{e} = 11$ GeV

Luminosity = 720$fb^{-1}$

$Q^2=5.5$ GeV$^2$

$x_{B} = 0.35$

$-t = 0.25$ GeV$^2$
CLAS12 - DVCS/BH Beam Asymmetry

$e^+p \rightarrow e\gamma$

$E = 11$ GeV

$\Delta \sigma_{LU} \sim \sin\phi \text{Im}\{F_1 H^+\}d\phi$

Selected Kinematics

$L = 1 \times 10^{35}$

$T = 2000$ hrs

$\Delta Q^2 = 1$ GeV$^2$

$\Delta x = 0.05$
$e \vec{p} \rightarrow e p \gamma$

Longitudinally polarized target

$\Delta \sigma \sim \sin \phi \text{Im}\{F_1 \widetilde{H} + \xi (F_1 + F_2) H \ldots\} d\phi$

$E = 11 \text{ GeV}$

$L = 2 \times 10^{35} \text{ cm}^2 \text{s}^{-1}$

$T = 1000 \text{ hrs}$

$\Delta Q^2 = 1 \text{GeV}^2$

$\Delta x = 0.05$
**CLAS12 - DVCS/BH Target Asymmetry**

\[
e p^\uparrow \rightarrow e p \gamma \quad E = 11 \text{ GeV}
\]

Transverse polarized target

\[
\Delta \sigma \sim \sin \phi \text{Im}\{k_1(F_2H - F_1E) + \ldots\}d\phi
\]

- \( A_{UTx} \): Target polarization in the scattering plane
- \( A_{UTy} \): Target polarization perpendicular to the scattering plane

- Asymmetries highly sensitive to the u-quark contributions to the proton spin.

**Sample kinematics**

\[Q^2 = 2.2 \text{ GeV}^2, \ x_B = 0.25, \ -t = 0.5 \text{GeV}^2\]
Exclusive $\rho^0$ production on transverse target

$$A_{UT} \sim 2\Delta_{\perp}(\text{Im}(AB^*))$$

$Q^2 = 5$ GeV$^2$

$-t = 0.5$ GeV$^2$

$J^u = 0.1$

$J^d = 0$

$\rho^0$

$A \sim 2H^u + H^d$

$B \sim 2E^u + E^d$

$\rho^+$

$A \sim H^u - H^d$

$B \sim E^u - E^d$

$E^u, E^d$ allow to map the orbital motion of quarks.

K. Goeke, M.V. Polyakov, M. Vanderhaeghen, 2001
The Promise of GPDs:
2-D & 3-D Images of the Proton

\[ \varepsilon(x, b_L) = \int \frac{d^2 \Delta_L}{(2\pi)^2} e^{i \Delta_L b_L} E_q(x, \Delta_L) \]

M. Burkardt

Cat scan of the human brain

Target polarization

\[ d_X(x, b_x) \quad u_X(x, b_x) \]

Flavor dipole

Shift depends on \( \varepsilon(x, b_x) \)
TMDs are complementary to GPDs in that they allow to construct **3-D images** of the nucleon in **momentum** space.

TMDs are connected to orbital angular momentum (OAM) in the nucleon wave function – for a TMD to be non-zero OAM must be present.

TMDs can be studied in experiments measuring azimuthal asymmetries or moments.

Several proposals have been accepted by PAC34 that propose to upgrade CLAS12 with Kaon id.
SIDIS on unpolarized protons.

In inclusive electroproduction of pions the diff. cross section has an azimuthal modulation.

\[
d\sigma/d\Omega = \sigma_T + \varepsilon\sigma_L + \varepsilon\sigma_{TT}\cos 2\Phi + [\varepsilon(1+\varepsilon)]^{1/2}\sigma_{LT}\cos\Phi
\]

The \(\cos 2\Phi\) moment of the azimuthal asymmetry gives access to the Boer-Mulders Function which measures the momentum distribution of transversely polarized quarks in unpolarized nucleons.
The sin2Φ moment gives access to the Kotzinian-Mulders function which measures the momentum distribution of transversely polarized quarks in the longitudinally polarized nucleon.

- The sin2Φ moment is sensitive to spin-orbit correlations: the only leading twist azimuthal moment for longitudinally polarized target.
DOE Project Critical Decisions – 12 GeV Schedule

• CD-0 Approve Mission Need (Mar 2004)

• CD-1 Approve Alternative Selection and Cost Range (Feb 2006)
  • Permission to develop a Conceptual Design Report
  • Defines a range of cost, scope, and schedule options

• CD-2 Approve Performance Baseline (Nov 2007)
  • Fixes “baseline” for scope, cost, and schedule
  • Now develop design to 100%
  • Begin monthly Earned Value progress reporting to DOE
  • Permission for DOE-NP to request construction funds

• CD-3 Approve Start of Construction
  • DOE Office of Science CD-3 Approval: September 15, 2008

• CD-4 Approve Start of Operations or Project Close-out
CLAS12 In Construction

DC
PCAL
PCAL
FTOF
HTCC
SVT
CTOF
SVT
SVT
We recommend the completion of the 12 GeV Upgrade at Jefferson Lab.

- It will enable **three-dimensional imaging of the nucleon**, revealing hidden aspects of its internal dynamics.

- It will complete our understanding of the **transition between the hadronic and quark/gluon descriptions** of nuclei.

- It will test definitively the **existence of exotic hadrons**, long-predicted by QCD as arising from quark confinement.

- It will provide **low-energy probes of physics beyond the Standard Model** complementing anticipated measurements at the highest accessible energy scales.
Summary

• The CLAS12 with the 12 GeV Upgrade has a well defined physics goals of fundamental importance for the future of hadron physics, addressing in new and revolutionary ways the quark and gluon structure of hadrons by

  – accessing GPDs & TMDs

  – mapping the valence quark structure of nucleons with high precision

  – understanding hadronization processes

  – extending nucleon form factors to short distances

• Construction started October 2008
This is a very exciting time for hadronic physics, and the perfect time for new collaborators to make significant contributions to the physics and equipment of **CLAS12**
Jefferson Laboratory
12 GeV Upgrade Science, Technology & Education Center Stage
GPDs & PDFs

3-D Golden Retriever

Deeply Virtual Exclusive Processes & GPDs

Deep Inelastic Scattering & PDFs

2-D Golden Retriever

1-D Golden Retriever

probability

Water

Calcium

Carbon
Tomographic Images of the Proton

\[ q(x, b_\perp) = \int \frac{d^2t}{(2\pi)^2} e^{-i \cdot t \cdot b_\perp} E(x, 0, t) \]

Target polarization

\[ E_d(x, t) \quad E_u(x, t) \]

Target polarization

CAT scan slice of human abdomen

M. Burkardt
Jefferson Lab Today

Two high-resolution 4 GeV spectrometers

Large acceptance spectrometer electron/photon beams

7 GeV spectrometer, 1.8 GeV spectrometer, large installation
**Pioneering Experiments Observe Interference**

**First GPD analyses of HERA/CLAS/HERMES data in LO/NLO consistent with $\alpha \sim 0.20$.**

A. Freund (2003), A. Belitsky et al. (2003)
CEBAF Large Acceptance Spectrometer

**Torus Magnet**
- 6 Superconductive Coils

**Electromagnetic Calorimeter**
- Lead/plastic scintillator, 1296 PMTs

**Jefferson Lab CLAS Detector**

**Target + start counter**
- e mini-torus

**Drift Chamber**
- 35,000 cells

**Time of Flight**
- Plastic Scintillator, 684 PMTs

**Cherenkov Counter**
- e/π separation, 256 PMTs
### 12 GeV Schedule

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>FY 04</th>
<th>FY 05</th>
<th>FY 06</th>
<th>FY 07</th>
<th>FY 08</th>
<th>FY 09</th>
<th>FY 10</th>
<th>FY 11</th>
<th>FY 12</th>
<th>FY 13</th>
<th>FY 14</th>
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#### Key Dates:

- **May ’11 - Oct ‘11**: 6-month “down” for initial installations
- **Nov ’11 - May ‘12**: 6-month run 6GeV
- **Jun ’12 - May ‘13**: 1-year “down” for major installation
- **June ’13 - Sep ‘13**: Accelerator commissioning
12 GeV Schedule

- Oct '13: Hall A commissioning start
- Apr '14: Hall D commissioning start
- Oct '14: Hall B & C commissioning start
DOE Generic Project Timeline

Initiation Phase

Definition Phase

Execution Phase

Range of Alternatives

Cost Range

Critical Decisions

CD-0 Approve Mission Need

CD-1 Approve Alternative Selection and Cost Range

CD-2 Approve Performance Baseline

CD-3 Approve Start of Construction

CD-4 Approve Start of Operations or Project Closeout

We are here

Performance Measurement

Earned Value (for projects over $20M)

Transition/Closeout Phase

Operating funds/Program funds

PED funds

Project funds
Hall B - DVCS Solenoid and Calorimeter

Solenoid cryostat

Calorimeter
Deeply Virtual Compton Scattering & GPDs

Unprecedented set of Deeply Virtual Compton Scattering data accumulated in Hall A and with CLAS

Polarized beam, unpolarized target:

\[ A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma_{LU}}{2\sigma} \]

\[ \Delta\sigma_{LU} \sim \sin\phi \left( F_1 H + \xi (F_1 + F_2) H + k r_2^E \gamma u \phi \right) \]
First measurement with CLAS

$e \vec{p} \rightarrow ep\gamma$

Accessing GPDs through DVCS

\[ \frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T^{DVCS} + T^{BH}|^2 \]

\( T^{BH} \): given by elastic form factors \( F_1, F_2 \)

\( T^{DVCS} \): determined by GPDs

\[ I \sim (T^{BH}) \text{Im}(T^{DVCS}) \]

BH-DVCS interference generates beam and target polarization asymmetries that carry the proton structure information.
eg1-dvcs setup

1) Polarized NH₃ (2000, 5 days)
2) Polarized NH₃/ND₃ (2009 30+30 days)

Inner Calorimeter (424 PbWO₄ crystals) to detect high energy photons at forward lab angles.
A dedicated CLAS experiment with longitudinally polarized target will provide a statistically significant measurement of the kinematical dependences of the DVCS target SSA.
A dedicated CLAS experiment with longitudinally polarized target will provide a statistically significant measurement of the kinematical dependences of the DVCS target SSA.
TMDs are complementary to GPDs in that they allow to construct 3-D images of the nucleon in momentum space.

TMDs are connected to orbital angular momentum (OAM) in the nucleon wave function – for a TMD to be non-zero OAM must be present.

TMDs can be studied in experiments measuring azimuthal asymmetries or moments.

Several proposals have been accepted by PAC34 that propose to upgrade CLAS12 with Kaon id.
In inclusive electroproduction of pions the diff. cross section has an azimuthal modulation.

\[ \frac{d\sigma}{d\Omega} = \sigma_T + \varepsilon\sigma_L + \varepsilon\sigma_T\cos2\Phi + [\varepsilon(1+\varepsilon)]^{1/2}\sigma_{LT}\cos\Phi \]

The \( \cos2\Phi \) moment of the azimuthal asymmetry gives access to the Boer-Mulders Function which measures the momentum distribution of transversely polarized quarks in unpolarized nucleons.
Transverse momentum dependence of longitudinally polarized quarks in longitudinally polarized protons.

The double polarization asymmetry is sensitive to difference in the $K_T$ distribution of quarks with spin orientation parallel and anti-parallel to proton spin.

- Current data not sensitive enough to clearly identify the effect. CLAS12 has much more sensitivity and reaches higher $P_T$
## Scope of the 12 GeV Upgrade

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Present JLab</th>
<th>Upgraded JLab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Halls</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Number of passes Halls A/B/C</td>
<td>5 (for max energy)</td>
<td>5 (for max energy)</td>
</tr>
<tr>
<td>Max Energy to Halls A/B/C</td>
<td>up to ~6 GeV</td>
<td>up to ~11 GeV</td>
</tr>
<tr>
<td>Number of passes to Hall D</td>
<td>New Hall</td>
<td>5.5</td>
</tr>
<tr>
<td>Energy to Hall D</td>
<td>New Hall</td>
<td>12 GeV</td>
</tr>
<tr>
<td>Current – Hall A &amp; C</td>
<td>max ~180 μA combined</td>
<td>max ~85 μA combined (higher at lower energy)</td>
</tr>
<tr>
<td>Current – Hall B &amp; D</td>
<td>(B) Up to 5 μA max</td>
<td>(B, D) Up to ~5 μA max each</td>
</tr>
<tr>
<td>Central Helium Liquefier (CHL)</td>
<td>4.5 kW</td>
<td>9 kW</td>
</tr>
<tr>
<td># of cryomodules in LINACS</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Accelerator energy per pass</td>
<td>1.2 GeV</td>
<td>2.2 GeV</td>
</tr>
</tbody>
</table>
Deeply Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade

Study of high $x_B$ domain requires high luminosity
Hall B Overview

• Hall B currently houses the CLAS detector. CLAS is a large acceptance detector and will be modified and upgraded to CLAS12, which will be worldwide the only large acceptance, multi-purpose detector for fixed target electron scattering experiments.

• CLAS12 is expected to operate with an upgraded luminosity of $L=10^{35}\text{cm}^{-2}\text{s}^{-1}$, more than an order of magnitude increase over CLAS, and with improved particle identification.

• With these capabilities CLAS12 will support a broad experimental program in fundamental nuclear physics.
Present-day CLAS
CLAS12 - Initial 12 GeV Physics Program

- GPD’s and 3D-Imaging of the Nucleon
  - Deeply Virtual Compton Scattering - DVCS
  - Deeply Virtual Meson Production at low/high t

- Valence Quark Distributions
  - u- and d-Quark Spin Distributions in Proton and Neutron
  - Neutron Structure Function $F_{2n}(x,Q^2)$ , d/u
  - TMD Quark Distribution Functions in SIDIS

- Form Factors and Resonance Excitations
  - The Magnetic Structure of the Neutron – $G_{Mn}$
  - $N^*$ Transition Form Factors at high $Q^2$

- Hadrons in the Nuclear Medium
  - Space-Time Characteristics of Quark Hadronization
  - Color Transparency
  - Short Distance Dynamics of Light Nuclei

- Spectroscopy of Strange Baryons
<table>
<thead>
<tr>
<th>Proposal</th>
<th>Physics</th>
<th>Experiment days</th>
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</thead>
<tbody>
<tr>
<td>E12-06-119a</td>
<td>DVCS with polarized beam</td>
<td>80</td>
</tr>
<tr>
<td>E12-06-112</td>
<td>$ep \to e\pi^{+/0} X$</td>
<td>60</td>
</tr>
<tr>
<td>E12-06-108</td>
<td>DVMP in $\pi^0,\eta$ production and L/T separation</td>
<td>120</td>
</tr>
<tr>
<td>E12-06-119b</td>
<td>DVCS on polarized target</td>
<td>120</td>
</tr>
<tr>
<td>E12-06-109</td>
<td>Nucleon Spin Structure Functions</td>
<td>80</td>
</tr>
<tr>
<td>E12-07-107</td>
<td>Single Spin Asymmetries</td>
<td>103</td>
</tr>
<tr>
<td>E12-06-106</td>
<td>Color Transparency $\rho^0$</td>
<td>40</td>
</tr>
<tr>
<td>E12-06-117</td>
<td>Quark Hadronization</td>
<td>60</td>
</tr>
<tr>
<td>E12-07-104</td>
<td>Neutron magnetic form factor</td>
<td>56</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>719</strong></td>
</tr>
</tbody>
</table>
CLAS12 – Upgrade Goals

Capabilities to measure exclusive processes at 12 GeV
- Operating luminosity up to $10^{35} \text{ cm}^{-2}\text{sec}^{-1}$
- Particle ID to higher momentum ($e^{-}/\pi^{-}$, $\pi^{-}/K^{-}$, $\gamma/\pi^{0}$)
- Momentum & angle resolution for use of missing mass techniques
- Coverage of large range in polar and azimuth angle
- Identify detached vertices

Solution:

• Reduce DC occupancies to reach higher luminosities
  - Move DC’s further downstream reducing solid angle seen by each cell
  - Improved magnetic shielding for Møller background electrons

• Upgrade the forward PID system
  - Additional threshold Cherenkov detector
  - Timing resolution of the Time-of-Flight detectors
  - Calorimeter granularity for $\pi^{0}/\gamma$ separation
  - Add tracking capabilities for improved vertex resolution

• Complement the forward detection system with central detector
  - Tracking and magnetic analysis at large angles
  - Particle identification capabilities
  - Operation of a dynamically polarized target
Distribution of $\pi^+$, $K^+$ in DIS Kinematics

$e^-p \rightarrow e^-hX, \ h=\pi^+, K^+$

- **Forward**
- **Central**

![Graphs showing distribution of $\pi^+$ and $K^+$ in DIS kinematics.](image-url)
CLAS12 in Hall B

Faraday cup, Beam monitors

Polarimeters, Beam monitors, Raster system, ..
Utilization of existing Hall B Equipment

• Re-use existing CLAS detector components
  – Forward electromagnetic calorimeters
  – Low threshold gas Cherenkov counters
  – Time-of-flight scintillators
  – Drift chamber electronics and gas system
  – Inner PbW0$_4$ small-angle calorimeter
  – DAQ and readout electronics

• Re-use other Hall B components
  – Cryogenic targets
  – Møller polarimeter
  – Raster magnets & power supplies
  – Faraday cup
  – Beam diagnostics
  – Photon energy tagging system
  – Coherent bremsstrahlung/goniometer
  – Frozen spin polarized target
  – Pair spectrometer magnet & power supplies
  – Utility distribution & space frames

Equivalent to $26.5M assuming 2.3% escalation rate
CLAS12 - Detector

- Central Detector
- Solenoid 5T
- Forward Detector
- TORUS
Central Detector

SVT

CTOF

HTCC

TORUS

DC R1, R2, R3

LTCC

FTOF 1a

FTOF 1b

PCAL

EC

Forward Detector

(talk by D. Kashy)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Forward Detector</th>
<th>Central Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracks</td>
<td>$5^0 - 40^0$</td>
<td>$35^0 - 125^0$</td>
</tr>
<tr>
<td>Photons</td>
<td>$3^0 - 40^0$</td>
<td>n.a.</td>
</tr>
<tr>
<td>Resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta p/p$ (%)</td>
<td>$&lt; 1 @ 5 \text{ GeV/c}$</td>
<td>$&lt; 5 @ 1.5 \text{ GeV/c}$</td>
</tr>
<tr>
<td>$\delta \theta$ (mr)</td>
<td>$&lt; 1$</td>
<td>$&lt; 10 - 20$</td>
</tr>
<tr>
<td>$\Delta \phi$ (mr)</td>
<td>$&lt; 3$</td>
<td>$&lt; 5$</td>
</tr>
<tr>
<td>Photon detection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy (MeV)</td>
<td>$&gt;150$</td>
<td>n.a.</td>
</tr>
<tr>
<td>$\delta \theta$ (mr)</td>
<td>$4 @ 1 \text{ GeV}$</td>
<td>n.a.</td>
</tr>
<tr>
<td>Neutron detection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{\text{eff}}$</td>
<td>$&lt; 0.7 \ (\text{EC+PCAL})$</td>
<td>n.a.</td>
</tr>
<tr>
<td>Particle ID</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e/\pi</td>
<td>Full range</td>
<td>n.a.</td>
</tr>
<tr>
<td>$\pi/p$</td>
<td>Full range</td>
<td>$&lt; 1.25 \text{ GeV/c}$</td>
</tr>
<tr>
<td>$\pi/K$</td>
<td>Full range</td>
<td>$&lt; 0.65 \text{ GeV/c}$</td>
</tr>
<tr>
<td>K/p</td>
<td>$&lt; 4 \text{ GeV/c}$</td>
<td>$&lt; 1.0 \text{ GeV/c}$</td>
</tr>
<tr>
<td>$\pi^0 \rightarrow \gamma \gamma$</td>
<td>Full range</td>
<td>n.a.</td>
</tr>
<tr>
<td>$\eta \rightarrow \gamma \gamma$</td>
<td>Full range</td>
<td>n.a.</td>
</tr>
</tbody>
</table>
CLAS12
Central Detector

- Superconducting 5T Solenoid Magnet, w/ 78cm φ warm bore.
- Central scintillator array (CTOF).
- Silicon Vertex Tracker, barrel part (BST), forward part (FST).
- Space for cryogenic target.
Charged Particle ID in central region.

50 plastic scintillators with trapezoidal cross section

100 channels PMT, fADC, TDC

(talk by V. Baturin)
**CLAS12 – Silicon Vertex Tracker**

Central tracking in solenoid magnet
Forward tracking with drift chambers

**Forward part, 6 stereo layers ±12°**
With forward DC systems provide vertex

**66,000 strips**

**Barrel part, 8 stereo layers w/ 3°**
Standalone Tracking in 5T magnetic field
**CLAS12 - High Threshold Cerenkov Counter (HTCC)**

- **Radiator gas:** $\text{CO}_2 @ 1 \text{ atm}$
- **$\pi$ threshold:** 4.9 GeV/c
- **$\pi$ rejection:** 200
- **# of PMTs (5"):** 48
- **# sectors:** 12
- **Mirror weight:** $< 200 \text{mg/cm}^2$

**Electron identification up to 5GeV/c**

**$\pi/K.p$ separation $> 5 \text{ GeV/c}$**

**Level 1 Trigger**

(talk by S. Stepanyan)
**CLAS12 - Forward Drift Chambers**

Charged particle tracking at forward angles.

- 6 sectors
- 3 regions R1, R2, R3
- 2 super layers per region
- 6 layers per super layer
- V, W stereo readout
- Stereo angle $\pm 6$ degrees
- 24,192 sense wires

**Torus Coils**

(talk by M. Mestayer)
**CLAS12 - Forward Carriage**

**PCAL/EC:** Electron, photon, neutron detection

**LTCC:** Electron & pion separation

**Level 1 Trigger**

**EC, PCAL:** Pb/scintillators sandwich u,v,w stereo readout 22 radiation lengths longitudinal/transverse shower sampling

**LTCC:** Gas Cherenkov counter \( \pi \)-threshold: 2.7 GeV/c 216 5” photomultipliers

(talk by S. Stepanyan)
**CLAS12 - Forward TOF Counters**

- **Charged particle ID**
  - $\pi/K/p$ separation

- **Level 1 Trigger**

- **FTOF**
- 2 arrays per sector of scintillators
- 60 paddles/sector in array 1b (new)
- 23 paddles/sector in array 1a (existing)
- 2 PMTs per paddle

- **TORUS**
- Cryostat

(talk by D. Carman)
The Torus transverse field becomes weaker with increasing angle while the Solenoid transverse field component increases in strength.
Torus and Solenoid Magnets

Reference Design:
# coils: 6
Radial thickness: 294mm
Width: 100mm
Stored energy: 14MJ

Reference Design:
Max. field: B=5 Tesla
Homogeneity: ΔB/B<10^-4
Main coil windings: 4000
Shielding coil: 1880
Stored energy: 25 MJ
Examples of Physics Reactions

- Deeply Virtual Compton Scattering
- Excited nucleon states
- Cascade spectroscopy
- Use of missing mass techniques
Measurement of Generalized Parton Distributions

Critical for tracking of recoil protons that occupy phase space at Lab angles greater than 35 degrees.
Kinematics for $ep \rightarrow eN^*(N^* \rightarrow p\pi^+\pi^-)$

Measurement in full angular range needed for $N^*$ spectroscopy and partial wave analysis of final state hadrons.
Kinematics for $\gamma p \rightarrow K_1^+ K_2^+ \Xi^{-*}$

$(\Xi^{-*} \rightarrow \Lambda \pi^-, \Lambda \rightarrow p \pi^-)$

Strange baryon spectroscopy – Search for cascade states

Direct reconstruction of $\Xi^{+*}$ with tracking in FST/BST of detached vertices, e.g. $\Xi^{-*} \rightarrow \Lambda \pi^-, \Lambda \rightarrow p \pi^-$
$ep \rightarrow e\Lambda(p\pi^-)X$
Rates & Background
Low energy electromagnetic processes, especially Møller scattering of beam electrons off atomic electrons are the main contributor to the background load in an open large acceptance spectrometer such as CLAS12.

The full event and background load has been measured with CLAS, e.g. for DVCS process at 5.7 GeV. The GEANT simulation reproduces hit occupancy on tracking chambers.

We used the calibrated simulation code to extrapolate to 11 GeV and simulate the same process at higher luminosity for CLAS12 situation.

This background was also studied in a full Geant4 simulation.
Background at $L=10^{32}\text{cm}^{-2}\text{s}^{-1}$, $\Delta T = 150\text{ns}$

No magnetic field
Background at $L=10^{35}\text{cm}^{-2}\text{s}^{-1}$, $\Delta T = 150\text{ns}$

5 T Magnetic Field
Background at $L=10^{35}\text{cm}^{-2}\text{s}^{-1}$, $\Delta T = 150\text{ns}$

5 T Magnetic Field and Shielding
# CLAS12 – Expected Rates in DC R1

<table>
<thead>
<tr>
<th></th>
<th>CLAS</th>
<th>CLAS12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>5.75</td>
<td>11</td>
</tr>
<tr>
<td>Luminosity (cm^{-2}s^{-1})</td>
<td>$2 \times 10^{34}$</td>
<td>$10^{35}$</td>
</tr>
<tr>
<td>Total rate</td>
<td>5.94</td>
<td>5.76</td>
</tr>
<tr>
<td>Electrons from $\gamma$’s</td>
<td>0.74</td>
<td>1.7</td>
</tr>
<tr>
<td>Scattered electrons</td>
<td>4.65</td>
<td>1.0</td>
</tr>
<tr>
<td>Hadrons</td>
<td>0.55</td>
<td>3.06</td>
</tr>
</tbody>
</table>
Simulations show that typical deep inelastic events contain
- 3.5 charged particles per event at θ < 35° (Forward Detector)
- 0.75 charged particles at θ > 35° (Central Detector)

The total hadronic interaction rate is \( \sim 5 \times 10^6 \text{ sec}^{-1} \)

Expected level 1 trigger rate is up to 10KHz (inclusive electron rate\(~4\)KHz, non-electron triggers ~5KHz), (talk by Boiarinov)

Expected data rate is 50-80Mbsec\(^{-1}\) for beam energies from 6.6 to 11 GeV.
A full event reconstruction is available for CLAS detectors that has been used to aid the R&D and design effort for **CLAS12**.

The collaboration is developing new simulation and reconstruction software packages making use of modern tools.

The current effort is focused on Geant4 as simulation package (talk by Ungaro), and track reconstruction using the Kalman Filter approach (talk by Procureur).
The physics program allows to firmly establish requirements for the **CLAS12** performance in terms of rate capability, particle ID, and resolution.

At 12 GeV typical events contain high momentum tracks at forward angles. The toroidal magnetic field of **CLAS12** and the forward tracking system provide excellent angle and momentum reconstruction.

Essential parts of the physics program require tracking of low momentum at large angles. This is achieved by the Silicon Tracker.

The increase in luminosity is achieved by improved background shielding and high rate capability of the tracking devices.

The new Cerenkov and Scintillation counters in **CLAS12** are designed to improve particle separation at higher momentum.

An experienced team is in place that built, installed, commissioned and operates **CLAS**, and collaboration members have taken on responsibilities for the construction of new detector components, and for state-of-the-art event simulation and reconstruction.
Backup Slides
Rate of Møller electrons in SVT during 125nsec at 1/50 of full luminosity.

Solenoid B-field - OFF
Rate of Møller electrons in SVT during 125nsec at 1/50 of full luminosity.

Solenoid B-field - ON
Drift chamber R1 occupancy

- DVCS experiment.
- E=5.7 GeV, L=2*10^{34} cm^{-2} s^{-1}
- DVCS solenoid
## Electromagnetic and Hadronic Rates

**(in MHz)**

### SVT (5°-35°)

<table>
<thead>
<tr>
<th></th>
<th>Photons</th>
<th>Hadrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>31.3</td>
<td>2.5</td>
</tr>
<tr>
<td>L2</td>
<td>31.1</td>
<td>2.2</td>
</tr>
<tr>
<td>L3</td>
<td>24.6</td>
<td>2.2</td>
</tr>
</tbody>
</table>

### SVT (35°-125°)

<table>
<thead>
<tr>
<th></th>
<th>Photons</th>
<th>Hadrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>57.7</td>
<td>2.6</td>
</tr>
<tr>
<td>L2</td>
<td>50.8</td>
<td>3.7</td>
</tr>
<tr>
<td>L3</td>
<td>44.6</td>
<td>4.8</td>
</tr>
<tr>
<td>L4</td>
<td>32.7</td>
<td>3.4</td>
</tr>
<tr>
<td>CTOF</td>
<td>93.3</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Deposited Energy > 20 KeV