The 12 GeV Upgrade in JLab's Hall C

Dave Mack (TJNAF)

The 6th Workshop on Hadron Physics in China
and Opportunities in the US

Lanzhou, China
July 21-25, 2014
Experiments Motivating the Hall C Upgrade

- Pion and nucleon elastic form factors at high momentum transfer
- Deep inelastic scattering at high $x_{\text{Bjorken}}$
- Semi-inclusive scattering with high hadron momenta
- Polarized and unpolarized scattering on nuclei

The program demanded a new partner for the existing High Momentum Spectrometer (HMS) suited for detecting charged particles close to the new beam energy, usually close to the beamline:

- Higher momentum capability (11 GeV/c)
- Smaller angle capability (5.5 degrees)
- Particle identification ($e, \pi, k, p$)
- Accurate and reproducible angle and momentum settings

The SHMS (Super High Momentum Spectrometer) was designed to meet these requirements.
Hall C Base Equipment at 12 GeV

Hall C will provide 2 moderate acceptance, magnetic focusing spectrometers:

High Momentum Spectrometer:
\[ d\Omega \sim 6 \text{ msr}, \quad P_{\text{max}} = 7 \text{ GeV/c} \]
\[ \Theta = 10.5 \text{ to 80 degrees} \]

Super-HMS:
\[ d\Omega \sim 4 \text{ msr}, \quad P_{\text{max}} = 11 \text{ GeV/c} \]
\[ \Theta = 5.5 \text{ to 40 degrees} \]

→ Both spectrometers provide excellent control of systematic uncertainties
→ Kinematic reproducibility, well-understood acceptance

Ideal for:
• precision cross section measurements and response function separations,
• in single arm or coincidence,
• at high luminosity \((10^{38}/\text{cm}^2\text{sec or so})\).
SHMS Overview

Key Features:

Horizontal bend magnet

- The solution to reasonable acceptance at small angles.
  (New design, developed in collaboration with MSU.)

QQQ-D

- Provides easily calibrated optics and wide acceptance
- Uses SC magnets similar to existing HMS where possible

6 element detector package

- Drift Chambers / Hodoscopes / Cerenkovs / Calorimeter

Rigid Support Structure

- To achieve pointing accuracy & reproducibility demonstrated in HMS

Well-Shielded Detector Enclosure

- Essential for high luminosity operation
Fussiness Needed for Small Angle Operation
Top View of SHMS-HMS at Small Angle Separation for Coincidence Studies
SHMS Detectors
excellent PID over a wide momentum range

Trigger hodoscopes
(University of Virginia)

Drift chambers
(Hampton University)

Noble gas Cerenkov
(University of Virginia)

Heavy gas Cerenkov
(University of Regina)

Lead Glass Calorimeter
(Yerevan/Jlab)
“Baby Pictures”
SHMS Detector Construction
SHMS Dipole

Cos(θ) Coil
Collar
Cryostat

Assembled w/Cryo Chimney...
...and 126 ton Warm Iron Yoke

Prototype Coil on Winding Machine

SigmaPhi
Vannes, France

60 cm
Mold being placed onto Dipole Coil “B” Layers 1&2 in preparation for VPI (May 27, 2014).

Dipole Coil “A” Layer 3 being wrapped and readied for winding layer 4 (May 27, 2014).
Support Structure

- Shield House
- Concrete Walls
- Dipole
- Q3
- Q2
- Q1
- SHMS Magnet Power Supplies
- SHMS Steel Support Structure
- HB
- Hall-C Pivot
- Dec. 3, 2013
Platform and Shield House

Magnet power supplies are on the platform.

AC Power Feed is in. Branch circuits, lights, etc., going in now.

Signal/HV Cable pulls done.

Cryogen distribution cans are installed.

June 2, 2014
Schedule
### Three year plan

#### Dec 2013

**Jefferson Lab Three-Year Schedule**

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- **Beam for Commissioning**
- **Beam for Physics**
- **Non-CLAS12 Ops**

*Mildly obsolete*
# Approved and Conditional 12 GeV Hall C Experiments

<table>
<thead>
<tr>
<th>Number</th>
<th>Experiment</th>
<th>Grade</th>
<th>Approved Days</th>
<th>Cond. Days</th>
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<td>E12-11-009</td>
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<td>E12-11-107</td>
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**Total Days** 638  **7.3 Years @ 25 Weeks/year**

High Impact Experiments (PAC41)
Hall C Early running plans – Year 1

- 2016:
- Precommissioning – detector checkout
- ~25 PAC days – Commissioning “Experiment”
  - 9 days of E12-06-107 search for color transparency
  - $A(e,e'p)$ only – “easy” coincidence measurement
  - E12-10-002 $F_2^{p,d}$ structure functions at large $x$
  - Momentum scans help understand acceptance
  - 2 days E12-10-108 EMC Effect
  - Integrate light nuclei with $F_2$ run,
  - Point target helps acceptance studies.
  - 3 days of E12-10-003 $d(e,e'p)$
  - If time available
  - Push to lower cross sections
Early running plan – Years 2-3

- 2017:
  - E12-09-017 \( P_t \) dependence of basic SIDIS cross sections
  - Push particle ID capabilities of SHMS
  - E12-09-002 Precise \( \pi^+\pi^- \) ratios in SIDIS – Charge Symmetry Detector efficiencies
  - E12-09-011 L/T separated \( p(e,e'K^+) \) factorization test
    Easiest L/T separation

- 2018:
  - Choose a “High Impact Experiment”?
  - E12-06-101 Pion Form Factor (needs well understood SHMS)
  - E12-06-105 \( x > 1 \)
  - E12-06-110 \( A_1^n \) (needs high L \(^3\text{He}\))
At the 5th Workshop on Hadron Physics in HuangShan last year, I highlighted an experiment to constrain Charge Symmetry Violation in $\pi^+/-$ electroproduction.

This year, I’ve selected the Charged Pion Form Factor whose spokespersons are G. Huber (U. Regina) and D. Gaskell (Jlab).

Slides are from a colloquium by Dave Gaskell.
Pion Form Factor

The pion is attractive as a QCD laboratory:

→ Simple, 2 quark system

→ Electromagnetic form factor can be calculated exactly at large momentum transfer (small distances)

→ For $Q^2$ less than the mass of the universe, however, it remains a fun challenge for theorists.

Downside for experimentalists:

→ No "free" pions

→ Measurements at large momentum transfer difficult

Another perplexing Quark-gluon cartoon to add to Professor Saito’s collection.
pQCD and the Pion Form Factor

At large $Q^2$, pion form factor ($F_\pi$) can be calculated using perturbative QCD (pQCD)

$$F(Q^2) = \frac{4}{3} \int_0^1 dx \int_0^1 dy \frac{2}{3} \frac{1}{xyQ^2} (x)(y)$$

at asymptotically high $Q^2$, the pion wave function becomes

$$(x) \rightarrow \frac{3f}{\sqrt{n_c} Q^2} x(1-x)$$

and $F_\pi$ takes the very simple form

$$\left. F(Q^2) \rightarrow \frac{16}{Q^2} \frac{(Q^2)f^2}{Q^2} \right|_{Q^2 \rightarrow \infty}$$

$f_\pi = 93$ MeV is the $\pi^+ \rightarrow \mu^+\nu$ decay constant.

Pion Form Factor at Finite $Q^2$

At finite momentum transfer, higher order terms contribute

→ Calculation of higher order, “hard” (short distance) processes difficult, but tractable

There are “soft” (long distance) contributions that cannot be calculated in the perturbative expansion

→ Understanding the interplay of these hard and soft processes is a key goal
Measurement of $\pi^+$ Form Factor - Low $Q^2$

At low $Q^2$, $F_\pi$ can be measured model-independently via high energy elastic $\pi^-$ scattering from atomic electrons in Hydrogen → CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV$^2$ [Amendolia et al, NPB277, 168 (1986)]

→ Data used to extract pion charge radius $r_\pi = 0.657 \pm 0.012$ fm

Maximum accessible $Q^2$ roughly proportional to pion beam energy

$Q^2 = 1$ GeV$^2$ requires 1 TeV pion beam
Measurement of $\pi^+$ Form Factor - Larger $Q^2$

At larger $Q^2$, $F_\pi$ must be measured indirectly using the “pion cloud” of the proton via pion $p(e,e'\pi^+)n$

$\rightarrow |p> = |p>_0 + |n\pi^+> + .....

$\rightarrow$ At small $-t$, the pion pole process dominates the longitudinal cross section, $\sigma_L$

$\rightarrow$ In Born term model, $F_\pi^2$ appears as,

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t - m^2_\pi)} g^2_{\pi NN}(t) F_\pi^2(Q^2, t)$$

Drawbacks of this technique
1. Isolating $\sigma_L$ experimentally challenging
2. Theoretical uncertainty in form factor extraction.
Check of Pion Electroproduction Technique

• Does electroproduction really measure the on-shell form-factor?
• Test by making $p(e,e'\pi^+)$ measurements at same kinematics as $\pi^+e$ elastics

*Can’t quite reach the same $Q^2$, but electro-production appears consistent with extrapolated elastic data*

An improved test will be carried out after the JLAB 12 GeV upgrade

→ smaller $Q^2$ (=0.30 GeV$^2$)
→ -t closer to pole (=0.005 GeV$^2$)
Pion Electro-production Cross Section

\[ 2\pi \frac{d^2 \sigma}{dt d\phi} = \epsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon (1 + \epsilon)} \frac{d\sigma_{LT}}{dt} \cos \phi + \epsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi \]

For electroproduction, \( t < 0 \)

Magnitude of \(-t\) smallest when pion emitted along direction of virtual photon

At fixed \( W \), \(-t_{\text{min}}\) increases as \( Q^2 \) increases

At small \(-t\), the pion pole process dominates \( \sigma_L \)

\[ F_{\pi}^2 \text{ in Born term model} \]

\[ \frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t - m_{\pi}^2)} \ g_{\pi NN}^2 (t) F_{\pi}^2 (Q^2, t) \]
Extracting the Longitudinal Xsect $\sigma_L$

$$2\pi \frac{d^2\sigma}{dtd\phi} = \epsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon (1 + \epsilon)} \frac{d\sigma_{LT}}{dt} \cos \phi + \epsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$

Simple extraction – no LT/TT terms

4-parameter fit: $L/T/TT/LT$
$F_{\pi^+}(Q^2)$ Models

  → relativistic treatment of bound quarks
  (Bethe-Salpether equation + Dyson-Schwinger expansion)

  → Green’s function analyticity used to extract form factor

  
  ![Graph showing $Q^2 F_{\pi}$](image)

  - Amendolia $\pi^+e$ elastics
  - Ackermann (DESY)
  - Brauel (DESY) - Reanalyzed
  - $F_{\pi}-1 (2006)$
  - $F_{\pi}-2$
  - QCD Sum Rule
  - Bakulev Hard QCD
  - ADS/CFT
  - BSE+DSE
  - Hard + Soft

  → Anti-de Sitter/Conformal Field Theory approach
$F_\pi(Q^2)$ after JLAB 12 GeV Upgrade

JLab 12 GeV upgrade will allow measurement of $F_\pi$ up to $Q^2 = 6$.

No other facility can do this measurement.

New overlap point at $Q^2 = 1.6$ will be closer to pole to constrain $-t_{\text{min}}$ dependence.

New low $Q^2$ point will provide best comparison of the electroproduction extraction of $F_\pi$ vs elastic $\pi^+e^-$ data.

Approved with “A” scientific rating – awarded 52 days (G. Huber and D. Gaskell, spokespersons)
Acknowledgements

• Hall A/C colleagues for slides and/or discussions:
  Dave Gaskell, Howard Fenker, Cynthia Keppel, and Steve Wood.

• The organizers of this workshop and their support staff.

• Jlab management for supporting this conference and my travel.
Extras
Model for $F_\pi$ Extraction

Model is required to extract $F_\pi(Q^2)$ from $\sigma_L$

Model incorporates $\pi^+$ production mechanism and spectator neutron effects:

1. The experimentalist would like to use a variety of models to extract $F_\pi(Q^2)$ from the electroproduction data, so that the model dependence can be better understood.

2. The Vanderhaeghen-Guidal-Laget (VGL) Regge model \cite{Vanderhaeghen, Guidal, Laget, PRC 57, 1454 (1998)} is the only reliable model available for our use at present.

3. It would be useful to have additional models for the pion form factor extraction.

The experimental $F_\pi(Q^2)$ result is not permanently “locked in” to a specific model.
\[ F_{\pi} (Q^2) = \frac{1}{1 + \frac{Q^2}{L^2}} \]

**VGL Regge Model**

Feynman propagator replaced by $\pi$ and $\rho$ Regge propagators

→ Represents the exchange of a series of particles, compared to a single particle

Model parameters fixed from pion photoproduction

**Free parameters:** $\Lambda_{\pi}$, $\Lambda_{\rho}$

*(trajectory cutoff)*
Calculation including only perturbative contributions dramatically under-predicts form factor.

Good agreement with data only achieved after including “soft” model dependent contribution.

Modeled using “local duality” – equivalence of hadronic and partonic descriptions.

\[ F_\pi = \int \text{(Free quark spectral density)} \]

Asymptotic form of $F_\pi$ can be improved
→ Include higher order terms, i.e., more than just 1 gluon exchange
→ Use pion wave function (Distribution Amplitude) more appropriate to lower $Q^2$

DA constrained by $\gamma^*\gamma\rightarrow \pi^0$ (old) transition form factor data

Even this improved calculation dramatically underpredicts $F_\pi$ at moderate $Q^2$

Rosenbluth Separation and Kinematics

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

To isolate \( \sigma_L \), need to vary virtual photon polarization, \( \epsilon \)

\( \rightarrow \) Make measurements at multiple values of electron beam energy and scattering angle

\[ \sigma_L = \sigma_L(Q^2, W, -t) \]

At each value of \(-t\), must keep \(Q^2\) and \(W\) constant
If you have a great idea for one of our end-stations, you can propose it to our Program Advisory Committee (PAC). Your proposal will be judged on the merit of the physics as well as the technical feasibility. An internal co-spokesperson may be helpful but is not required.

A tremendous amount of information can be gain from our website at [http://www.jlab.org/](http://www.jlab.org/) and looking under topics such as “Nuclear Physics”, “Experiment Research”, and “12 GeV Upgrade”.

Proposals now mostly fall into two categories: standard 12 GeV equipment, or major new apparatus. Proponents are expected to help build or commission standard 12 GeV equipment as well as new apparatus.

Of course, funding, manpower (both collaboration and Jlab), and multi-endstation scheduling issues will eventually be looked at carefully.
# SHMS Design Parameters

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<th>SHMS Design</th>
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<td>Range of Central Momentum</td>
<td>2 to 11 GeV/c for all angles</td>
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<tr>
<td>Momentum Acceptance $\delta$</td>
<td>-10% to +22%</td>
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<td>Momentum Resolution</td>
<td>0.03-0.08%</td>
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<td>(SRD: “&lt;0.2%”)</td>
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<tr>
<td>Scattering Angle Range</td>
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<td>Vertex Length Resolution</td>
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As part of the entire 12GeV upgrade...

By Subsystem...

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<td>1.4.3.4</td>
<td>Electronics</td>
<td>-</td>
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<td>1.4.3.5</td>
<td>Beamline</td>
<td>751</td>
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<tr>
<td>1.4.3.6</td>
<td>Infrastructure</td>
<td>5,989</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>19,670</td>
</tr>
</tbody>
</table>
Bender Fit to HMS Q1
... an incredible 3-dimensional jigsaw puzzle for our engineers and designers.

Getting Both Spectrometer to Small Angles

Top View

Bottom View
SHMS Elements

Dipole
18.4 Degree Bend
Max Field: 4.76 T
EFL: 2.85 m

Q2 Q3
Max Gradient:
14.4 T/m
EFL: 1.61 m

Q1
Max Gradient:
10.63 T/m
EFL: 1.86m

Bender
3 Degree Bend
Max Field: 3.11 T
EFL: 0.75 m
Kinematics of Some Approved Hall C Proposals
I’ve tried to introduce some of the standard apparatus for Hall C at 12 GeV. More detailed information on the SHMS can be obtained at

http://www.jlab.org/Hall-C/upgrade/index.html
### SHMS Experiment Resolution Requirements

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$p$ (GeV/c)</th>
<th>$\Delta p/p$ (%)</th>
<th>$\Delta \theta$ (rad)</th>
<th>$\Delta \varphi$ (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pion Form Factor</td>
<td>2.2-8.1</td>
<td>$2 \times 10^{-3}$</td>
<td>$1.5 \times 10^{-3}$</td>
<td>$1.5 \times 10^{-3}$</td>
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<tr>
<td>(12-06-101)</td>
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</tr>
<tr>
<td>Transition Form Factors*</td>
<td>1.0-8.5</td>
<td>$1 \times 10^{-3}$</td>
<td>$1.0 \times 10^{-3}$</td>
<td>$1.0 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

*Not yet submitted to PAC*
Misc shms detector slides
Progress: the SHMS Detectors

- **Shower Counter**
- **S2 Hodoscope**
- **S1 Hodoscope**
- **Drift Chambers**
- **Heavy Gas Cerenkov**
- **Noble Gas Cerenkov**
- **Calorimeter**
- **Detector Frames**

(Funding Color Codes)
- 12 GeV Project Funded
- NSF MRI Funding
- Gift from NIKHEF and NSL

- **3 Planes Scintillator**
- **1 Plane Quartz**

*HGC is largely funded by NSERC grant to U. Regina*
The SHMS Detector System

Trigger Hodoscopes: basic trigger; efficiency determination.

- **3 Planes Scintillator Paddles + 1 Plane Quartz Bars**

  - **S1X**: 12 bars 8cm x 110 cm x 5mm
  - **S1Y**: 14 bars 8cm x 90cm x 5mm
  - **S2X**: 14 bars 8cm x 105cm x 5mm
  - **S2Y**: 10 quartz bars: 11cm 115cm x 2.5 cm

  0.5 cm overlap / 2 PMTs on each bar
Detector Frames

“FRAMES” HOLD DETECTOR ELEMENTS TOGETHER AS A UNIT

- Frames for Hodoscopes and for Drift Chambers
- Responsibility: College of William and Mary
- Funded by NSF MRI 2008-2011
- Status
  - Complete

Test-fit of Scintillator Paddles on their Frame.
Heavy-Gas Cerenkov

- Sub-atmospheric to Atmospheric C₄F₁₀D
- Responsibility: University of Regina
- Funding:
  - Almost entirely on NSERC grant
  - 12-GeV scope: Mirror aluminization & related items
- Status
  - Arrived at JLab in June, 2013.
  - Complete
Calorimetry

• Shower Counter: 228 HERMES Pb-Glass Blocks
  Sit in a window in the rear wall of the SHMS shield house
• Preshower: 24 re-used SOS Pb-Glass Blocks
  Sit in frame attached to interior of rear shield house wall
• Provided by Yerevan / NSL. HERMES blocks arrived in 2008.
• Yerevan team has...
  Characterized performance of each module and logged results to database.
  Revised optical joints, wrapping, etc.
  Optimized MC and analysis software.

• Status: Complete

This detector has been ready to install since 2010.

Published!
NIM A 719 (2013) 85
Calorimeter (NSL Yerevan)

- Shower made from 250 blocks from Hermes
- Refurbished and tested

- Preshower made from 30 blocks from Hall C SOS
- Each 10x10x70 cm³

GEANT4 simulation of $\pi^-$ suppression

250:1 at all momentum
Noble Gas Cerenkov (U. of Virginia)

- $e/\pi^-$ PID 50:1 discrimination
- Operate at STP
- Placed in front of drift chamber
  - Use only at high momentum so multiple scattering is reduced
- When not in use replace by vacuum pipe

Final tank design

Particle Separation via Cerenkov

- Argon $\pi$ threshold at 6 GeV/c
- Add Neon to extend reach to 11
Heavy Gas Cerenkov (U. of Regina)

- $\pi^+/K$ separation above 3.4 GeV/c
- Rejection factor of 1000:1
- Vary gas pressure with momentum to keep $\pi^+/K$ separation
Aerogel Detector

- K/p PID in 2-6 GeV/C range  1000:1
- Need two indices of refraction to cover different momentum regions
- Using aerogel and PMTs from BLAST at MIT-BATES

\[ \text{Index: 1.03} \]

\[ \text{Index: 1.015} \]

SHMS kaon aerogel Cerenkov
Aerogel and PMTs from BLAST experiment at Bates ready for shipping.
Particle ID: Limitations of TOF

• TOF over the short ~2.2m baseline inside the SHMS hut will be of little use for most of the momentum range anticipated for the SHMS.

• Even over a 22.5m distance from the target to the SHMS detector stack, TOF is of limited use.

Effect of finite timing resolution ($\pm 1.5\sigma$ with $\sigma=200$ps). Separation $<3\sigma$ to the right of where lines intersect.
SHMS Particle Identification: +hadrons

Rejection Power

Momentum (GeV/c)

known experiments