“Future Facilities” Summary:
Fixed Target

Wally Melnitchouk

Jefferson Lab
**Outline**

- **electron beams**: JLab at 12 GeV  
  Allison Lung

  - high luminosity, inclusive ➔ exclusive reactions

  - large $x$ PDFs  
    Thia Keppel, Paul Souder, Ben Pecjak

  - SIDIS & TMDs  
    Peter Bosted, Feng Yuan

  - generalized parton distributions  
    Silvia Niccolai, Simonetta Liuti

- **neutrino beams**: MINERvA, Project X  
  Heidi Schellman

  - high intensity beams

  - parity-violating structure functions, nuclear dependence

  - quasi-elastic, resonance production

- **antiproton beams**: PANDA @ FAIR  
  Bjoern Seitz

  - hydrogen, nuclear targets (polarized?)

  - TMDs (Drell-Yan), time-like form factors
Jefferson Lab Today

2000 member international user community engaged in exploring quark-gluon structure of matter

Superconducting accelerator provides 100% duty factor beams of unprecedented quality, with energies up to 6 GeV

CEBAF’s innovative design allows delivery of beam with unique properties to three experimental halls simultaneously

Each of the three halls offers complementary experimental capabilities and allows for large equipment installations to extend scientific reach
Two 0.6 GV linacs

Upgrade magnets and power supplies

Add 5 cryomodules

20 cryomodules

CHL-2

Add arc

20 cryomodules

Add 5 cryomodules

Enhanced capabilities in existing Halls

Lower pass beam energies still available

Two 1.1 GV linacs
## Overview of Upgrade Technical Performance Requirements

<table>
<thead>
<tr>
<th>Hall D</th>
<th>Hall B</th>
<th>Hall C</th>
<th>Hall A</th>
</tr>
</thead>
<tbody>
<tr>
<td>excellent hermeticity</td>
<td>luminosity $10 \times 10^{34}$</td>
<td>energy reach</td>
<td>installation space</td>
</tr>
<tr>
<td>polarized photons</td>
<td>hermeticity</td>
<td>precision</td>
<td></td>
</tr>
<tr>
<td>$E_{\gamma} \sim 8.5–9$ GeV</td>
<td></td>
<td>11 GeV beamline</td>
<td></td>
</tr>
<tr>
<td>$10^8$ photons/s</td>
<td></td>
<td>target flexibility</td>
<td></td>
</tr>
<tr>
<td>good momentum/angle resolution</td>
<td></td>
<td>excellent momentum resolution</td>
<td></td>
</tr>
<tr>
<td>high multiplicity reconstruction</td>
<td></td>
<td>luminosity up to $10^{38}$</td>
<td></td>
</tr>
<tr>
<td>particle ID</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
12 GeV Capabilities

Hall D - exploring origin of **confinement** by studying **exotic mesons**

Hall B - understanding **nucleon structure** via generalized parton distributions

Hall C - precision determination of **valence quark properties** in nucleons and nuclei

Hall A - short range correlations, form factors, hyper-nuclear physics, future **new experiments**
Highlights of the 12 GeV Science Program

- New and revolutionary access to the structure of the proton and neutron
  - particularly at large $x$
  - PDFs, TMDs, GPDs

- Discovering the quark structure of nuclei
  - polarized EMC effect
  - EMC effect in deuterium, light nuclei

- High precision tests of the Standard Model
  - parity-violating DIS
12 GeV Upgrade Provides Substantially Enhanced Access to the DIS Regime

Access to very large $x > 0.4$

- Clean region
  - No strange sea effects
  - No explicit hard gluons to be included

Need also high luminosity, polarized targets, high momentum and large acceptance spectrometers.

![Diagram](image.png)
World data on $F_2^p$

World data on $g_1^p$

Some things we know pretty well....
...and some things we don’t.

d-quarks at large $x$

Proton and deuterium data from SLAC E139 (L. W. Whitlow, et al.), and E140 (J. Gomez, et al.)

On-shell prescription
(W. Melnitchouk, A.W. Thomas)
(A. Bodek, S. Dasu, S.E. Rock)

Off-shell prescription
(W. Melnitchouk, A.W. Thomas)

Scaled EMC effect
(A. Bodek, S. Dasu, S.E. Rock)
(Frankfurt and Strikman)

$A_1^n$

$pQCD$

Broken SU(6)

SU(6) symmetric

$F_2^n/F_2^p$
Plots from Nadolskys talk.
Unpolarized Neutron to Proton Ratio

**Spectator tagging**

- Nearly free neutron target by tagging low-momentum proton from deuteron at backward angles

**DIS from A=3 Nuclei**

- Mirror symmetry of A=3 nuclei
  Extract $F_2^n/F_2^p$ from ratio of $^3\text{He}/^3\text{H}$ structure functions
  \[
  \frac{F_2^n}{F_2^p} = \frac{2R - F_2^3\text{He}/F_2^3\text{H}}{2F_2^3\text{He}/F_2^3\text{H} - R}
  \]
  *Super ratio*
  
  $R = $ ratio of "EMC ratios" for $^3\text{He}$ and $^3\text{H}$ Calculated to within 1%

- Small $p$ (70-100 MeV/c)
  Minimize on-shell extrapolation (neutron only 7 MeV off-shell)

- Backward angles ($\theta_{pq} > 110^\circ$)
  Minimize final state interactions

*Most systematic and theoretical uncertainties cancel*
Unpolarized Neutron to Proton Ratio

BONUS in Hall B 11 GeV with CLAS12

Hall A 11 GeV with HRS

\[ Q^2 = 4-9 \text{ GeV}^2 \]

\[ Q^2 = 9-15 \text{ GeV}^2 \]

SU(6) \[ d/u = 1/2 \]

Helicity conservation \[ d/u = 1/5 \]

Scalar diquark dominance \[ d/u = 0 \]

\[ F_{2n}/F_{2p} \]

JLab Projected Data \[ ^3\text{H}/^3\text{He} \text{ DIS} \]
Rosenbluth Separations up to $Q^2 \sim 12 \text{ GeV}^2$ $\Rightarrow R = \frac{\sigma_L}{\sigma_T}$, $F_L$

“DIS” ($W^2 > 4 \text{ GeV}^2$) Limit

$\Rightarrow$ moments of $F_2$ and $F_L$ $\rightarrow$ moments of $G$
Spin Structure Function
Projections for JLab at 11 GeV

$A_1^n$ at 11 GeV

$A_1^p$ at 11 GeV

$2 \leq Q^2 \leq 10 \text{ (GeV/c)}^2$
$W \geq 2 \text{ GeV}$

$pQCD$

$SU(6)$
Polarized Parton Densities at Present

Moments of Polarized Parton Densities

More Lattice Results: upcoming; different (dynamical) fermion-types studied.

Low values of $m_\pi$ crucial.

$m_\pi$ 270 MeV at present.

<table>
<thead>
<tr>
<th>Moment</th>
<th>BB, NLO</th>
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</thead>
<tbody>
<tr>
<td>$\Delta u_\nu$</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.926</td>
</tr>
<tr>
<td>1</td>
<td>0.163 ± 0.014</td>
</tr>
<tr>
<td>2</td>
<td>0.055 ± 0.006</td>
</tr>
<tr>
<td>$\Delta d_\nu$</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>−0.341</td>
</tr>
<tr>
<td>1</td>
<td>−0.047 ± 0.021</td>
</tr>
<tr>
<td>2</td>
<td>−0.015 ± 0.009</td>
</tr>
<tr>
<td>$\Delta u_\nu - \Delta d_\nu$</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1.267</td>
</tr>
<tr>
<td>1</td>
<td>0.210 ± 0.025</td>
</tr>
<tr>
<td>2</td>
<td>0.070 ± 0.011</td>
</tr>
</tbody>
</table>
Twice as large as unpolarized EMC effect!

\[ g_1(A) - \text{“Polarized EMC Effect”} \]

\[ \frac{F_{2A}}{F_{2D}} \]

\[ \frac{g_{1A}}{g_{1p}} \]

\( Q^2 = 10.0 \text{ GeV}^2 \)

\( \rho = 0.17 \text{ fm}^{-3} \)

Infinite Nuclear Matter Data:

modified NJL model

Cloet et al.
PRL 95, 052302 (2005)
$g_1(A)$ - "Polarized EMC Effect"

$\frac{g_{1A}(^7Li)}{g_{1p}}$

- Projected errors $Q^2 > 1.0 \text{ GeV}^2$, $W > 2.0 \text{ GeV}$
- Cloet/Bentz/Thomas $R^{(3/2 \ 1)}$
- Cloet/Bentz/Thomas $R^{(3/2 \ 3/2)}$

Expected errors with 11 GeV beam
PV Asymmetries

Weak Neutral Current (WNC) Interactions at $Q^2 \ll M_Z^2$

Longitudinally Polarized Electron Scattering off Unpolarized Fixed Targets

\[ \sigma \propto |A_\gamma + A_{\text{weak}}|^2 \]

\[ -A_{LR} = A_{PV} = \frac{\sigma_\downarrow - \sigma_\uparrow}{\sigma_\downarrow + \sigma_\uparrow} \sim \frac{A_{\text{weak}}}{A_\gamma} \sim \frac{G_F Q^2}{4 \pi \alpha} (g_A e g_V^T + \beta g_V e g_A^T) \]

\[ C_{1u} = -\frac{1}{3} + \frac{4}{3} \sin^2 (\theta_W) \approx -0.19 \]
\[ C_{1d} = \frac{1}{2} - \frac{2}{3} \sin^2 (\theta_W) \approx 0.35 \]
\[ C_{2u} = -\frac{1}{2} + 2 \sin^2 (\theta_W) \approx -0.04 \]
\[ C_{2d} = \frac{1}{2} - 2 \sin^2 (\theta_W) \approx 0.04 \]
in DIS

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2 \pi \alpha}} \left[ a(x) + Y(y) b(x) \right]$$

$$\sum_i C_{1i} Q_i f_i^+(x) \quad \sum_i C_{2i} Q_i f_i^-(x)$$

$$\sum_i Q_i^2 f_i^+(x) \quad \sum_i Q_i^2 f_i^+(x)$$

For an isoscalar target like $^2H$, structure functions largely cancel in the ratio:

$$a(x) = \frac{3}{10} \left( 2C_{1u} - C_{1d} \right) \left( 1 + \frac{2s^+}{u^+ + d^+} \right)$$

$$b(x) = \frac{3}{10} \left( 2C_{2u} - C_{2d} \right) \left( \frac{u_v + d_v}{u^+ + d^+} \right) + \ldots$$

→ At high $x$, $A_{PV}$ becomes independent of $x$, $W$

→ Sensitive to new physics at the TeV scale

Exploratory measurements at 2% precision will be made at 6 GeV (2009)

Michaels, Reimer Zheng et al.
\[ A_{PV} = \frac{G_F Q^2}{\sqrt{2} \pi \alpha} \left[ a(x) + Y(y) b(x) \right] \]

\[ \sum_i c_{1i} Q_i f_i^+(x) \left/ \sum_i Q_i f_i^+(x) \right. \]

\[ \sum_i c_{2i} Q_i f_i^-(x) \left/ \sum_i Q_i f_i^+(x) \right. \]
A Design for Precision PV DIS Physics

High Luminosity on \( LH_2 \) & \( LD_2 \) Cryotargets

Better than 1% errors
  - It is unlikely that any effects are larger than 5-6%

\( x \)-range 0.25-0.75

\( W^2 \) well over 4 GeV\(^2\)

\( Q^2 \) range a factor of 2 for each \( x \)
  - (Except \( x \sim 0.75 \))

Moderate running times

- Need BaBar, CDF or CLEO\( \text{II} \) Solenoid
- State-of-the-art fast tracking, particle ID and “parity” counting electronics
- Precision polarimetry (\( \rightarrow 0.5\% \))
- Diverse physics topics addressed
  - Standard Model test, CSV, d/u, nuclear EMC effect, semi-inclusive physics, detailed studies of spin structure functions...
Charge Symmetry

Parton-level charge symmetry assumed in deriving $^2\text{H }A_{PV}$

**Charge Symmetry Violation**

$$\delta u(x) = u^p(x) - d^n(x)$$
$$\delta d(x) = d^p(x) - u^n(x)$$

- $u, d$ quark mass difference
- Electromagnetic effects

- **Direct observation of parton-level CSV would be very exciting!**
- **Important implications for high energy collider pdfs**
- **Could explain significant portion of the NuTeV anomaly**

**MRST PDF global with fit of CSV**

Martin, Roberts, Stirling, Thorne [Eur Phys J C35, 325 (04)]:

- Broad minimum (90% C.L.)
- Fully explains NuTeV
- Doubles NuTeV deviation
For PV-DIS from $^2H$:

$$R_{CSV} = \frac{\delta A_{PV}(x)}{A_{PV}(x)} = 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

Sensitivity will be enhanced if $u+d$ falls off more rapidly than $\delta u - \delta d$ as $x \to 1$

Effects at high-$x$ are predicted to be very large

[Graph showing $R_{CSV}$ estimates and $\frac{\delta A_d}{A_d}$ vs. $x$ from Londergan, using MRST fit]
Proton target

Deuteron analysis has nuclear corrections

$A_{PV}$ for the proton has no such corrections

Must simultaneously constrain higher twist effects

statistical and systematic errors $\sim 2\%$
Complications at large $x$

Factorization formula for structure function $F_2$:

$$F_2(x, Q^2) = C(Q^2, M_x^2, \mu) \otimes \phi_q(\mu)$$

Straightforward for generic $x$: $M_x^2 \sim Q^2$

- $C$ is calculated as an expansion in $\alpha_s(Q)$
- Non-perturbative effects in $\phi_q$

Problematic at large $x$: $M_x^2 \ll Q^2$

- $C$ contains large “threshold” logarithms $\alpha_s^n \ln^{2n}(Q^2/M_x^2)$
- Scale in coupling: $\alpha_s(Q)$ or $\alpha_s(M_x)$?

Need factorization and resummation for $x \to 1$
Factorization formula for $x \to 1$

\[ F_2(x, Q^2) \bigg|_{x \to 1} = H(Q^2, \mu) J(M_x^2, \mu) \otimes \phi_q(\mu) \]

Each function depends only on one scale:

- $H$ is a “hard function” depending on hard scale $Q^2$
- $J$ is a “jet function” depending on jet scale $M_x^2$
- $\phi_q$ is the parton distribution function in $\xi \to 1$ limit

Scales are separated **but**

- No choice of $\mu$ eliminates large logs in $Q^2/M_x^2$

Also need resummation
Comparison between SCET and standard results

\[ K(\mu_f) = \frac{F_2^{ns}(x, Q^2)}{\sum_q e_q^2 x \phi_q^{ns}(x, \mu_f)} \]

\[ Q = 5 \text{ GeV} \]

- Solid = SCET results in momentum space
- Dashed = Mellin-inverted moment space results
- green = LO, red = NLO, black = NNLO

Numerical differences very small at NLO and NNLO
SIDIS and TMDs
(Semi-Inclusive DIS and Transverse Momentum-Dependent Distributions at 12-GeV Jefferson Lab)

- Flavor decomposition of PDFs
- Spin Sum Rule implies significant angular momentum of quarks and gluons in nucleon
  → Quark Orbital Motion
- Should lead to observable differences in TMD of up and down quarks.
TMD Physics

- A way to measure Transversity Distribution, the last **unknown leading twist** distribution
  - Collins 1993
- The Novel Single Spin Asymmetries
- Connections with GPDs, and Quantum Phase Space Wigner distributions
- Quark Orbital Angular Momentum and Many others ...
TMD Distribution: the definition

\[ Q(x, k_\perp, \mu, x\zeta) = \frac{1}{2} \int \frac{d\xi^-}{2\pi} e^{-ix\xi^-p^+} \int \frac{d^2b_\perp}{(2\pi)^2} e^{ib_\perp \cdot k_\perp} \times \langle P | \bar{\psi}_q(\xi^-, 0, \vec{b}_\perp) \mathcal{L}_v^+(\infty; \xi^-, 0, \vec{b}_\perp) \gamma^+ \mathcal{L}_v(\infty; 0) \psi_q(0) | P \rangle \]

Gauge Invariance requires the Gauge Link

This definition is consistent with QCD factorization
Factorization

\[
F(x_B, z_h, P_{h\perp}, Q^2) \\
= \sum_{q=u,d,s,...} e_q^2 \int d^2 k_\perp d^2 p_\perp d^2 \ell_\perp \\
\times q \left( x_B, k_\perp, \mu^2, x_B \zeta, \rho \right) \tilde{q}_h \left( z_h, p_\perp, \mu^2, \zeta/z_h, \rho \right) S(\ell_\perp, \mu^2, \rho) \\
\times H \left( Q^2, \mu^2, \rho \right) \delta^2 \left( z_h k_\perp + p_\perp + \ell_\perp - P_{h\perp} \right)
\]
$k_T$-dependent SIDIS

Final transverse momentum of the detected pion $P_t$ arises from convolution of the struck quark transverse momentum $k_t$ with the transverse momentum generated during the fragmentation $p_t$.

$$p_t = P_t - z k_t + O(k_t^2/Q^2)$$

Linked to framework of Transverse Momentum Dependent Parton Distributions

$$\sum e_q^2 q(x) D_{q\rightarrow M}(z)$$

$TMD_u(x, k_T)$

e.g. T-odd Sivers function, Collins effect, etc.
WHAT IS NEEDED

- Much more data in many bins in $z$, $Q^2$, $x$, $P_t$, $\varepsilon$, and azimuthal angle

- Need study of diffractive $\rho$ contribution, dependence on missing mass $M_x$, ...

- Some already taken with Jlab CLAS 6 GeV

- Much more possible with 12 GeV upgrade, especially with CLAS 12 (Halll B).
WHAT IS PLANNED

- Accurate neutron/proton ratios for SIDIS pion and kaons with CLAS in many bins

- Extend data with longitudinally and transversely polarized protons and deuterons using CLAS6 and CLAS12 (maybe HD)

- Accurate $\pi^+/\pi^-$ (and $K^+/K^-$) ratios for proton and deuteron using spectrometers Hall C

- $\varepsilon$-dependence using spectrometers Hall C
New, comprehensive view of hadronic structure

**Elastic Scattering**
- transverse quark distribution in Coordinate space

**DIS**
- longitudinal quark distribution in momentum space

**GPDs**
- The fully-correlated Quark distribution in both coordinate and momentum space
GPDs: where we stand, where we are going

- Pioneering dedicated experiments on **DVCS** (Hall A, CLAS), show evidence for **handbag (twist-2) dominance** (asymmetry $\sim \sin\phi$) and **unexpected scaling** at $Q^2 \sim 2$ GeV$^2$ (Hall A)
- **GPD models** fail to reproduce consistently the **DVCS cross section and asymmetry** data
- **DVMP** experiments at CLAS ($\rho$, $\omega$, $\pi^0$) and Hall A ($\pi^0$) hint that either **scaling cannot be reached** for $Q^2$ as low as for DVCS or **something is missing** in GPDs parameterizations
- Hall A’s first attempt to measure **nDVCS** showed the importance of this channel for Ji’s **sum rule** and the extraction of $J_q$

**n-DVCS**: access to $E$, the least known and constrained GPD

---

**PhD thesis of M. Mazouz**
More data needed on DVCS and DVMP:

- High $Q^2$ to verify scaling for DVCS on a wider $Q^2$ range, and to approach GPD validity regime for DVMP
- Wide $x_B$ coverage
- High accuracy on measured observables to test models (high luminosity required)
- Measurements of spin-asymmetries AND cross sections

**JLab @ 12 GeV will be the optimal facility for these goals**
What goes into a theoretically motivated parametrization...?

The name of the game: Devise a form combining essential dynamical elements with a flexible model that allows for a fully quantitative analysis constrained by the data

\[ H_q(X,t) = R(X,t) \cdot G(X,t) \]

“Regge”  Quark-Diquark

Q^2 Evolution is an essential element!!
DOE Generic Project Timeline

We are here

Critical Decisions

<table>
<thead>
<tr>
<th>CD-0</th>
<th>CD-1</th>
<th>CD-2</th>
<th>CD-3</th>
<th>CD-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approve Mission Need</td>
<td>Approve Alternative Selection and Cost Range</td>
<td>Approve Performance Baseline</td>
<td>Approve Start of Construction</td>
<td>Approve Start of Operations or Project Closeout</td>
</tr>
</tbody>
</table>

| Nov 2007 | Sept 2008 |

Performance Measurement Earned Value (for projects over $20M)

1 year
### 12 GeV Upgrade: Phases and Schedule

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Project Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-2005</td>
<td>Conceptual Design (CDR)</td>
<td>finished</td>
</tr>
<tr>
<td>2004-2008</td>
<td>Research and Development (R&amp;D)</td>
<td>ongoing</td>
</tr>
<tr>
<td>2006</td>
<td>Advanced Conceptual Design (ACD)</td>
<td>finished</td>
</tr>
<tr>
<td>2006-2009</td>
<td>Project Engineering &amp; Design (PED)</td>
<td>ongoing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009-2013</td>
<td>Construction – <em>starts in ~ 6-9 months!</em></td>
</tr>
<tr>
<td></td>
<td><em>Parasitic machine shutdown – May 2011 through Oct 2011 (6 months)</em></td>
</tr>
<tr>
<td></td>
<td><em>Accelerator shutdown start mid-May 2012</em></td>
</tr>
<tr>
<td></td>
<td><em>Accelerator commissioning mid-May 2013</em></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013-2015</td>
<td>Pre-Ops (beam commissioning)</td>
</tr>
<tr>
<td></td>
<td><em>Hall A commissioning start ~October 2013</em></td>
</tr>
<tr>
<td></td>
<td><em>Hall D commissioning start ~April 2014</em></td>
</tr>
<tr>
<td></td>
<td><em>Halls B and C commissioning start ~October 2014</em></td>
</tr>
</tbody>
</table>
ELIC Conceptual Design

30-225 GeV protons
15-100 GeV/n ions

Electron Cooling
Snake

IR

Prebooster

12 GeV CEBAF Upgrade

3-9 GeV electrons
3-9 GeV positrons

Green-field design of ion complex directly aimed at full exploitation of science program.

Simultaneous operation of collider and CEBAF fixed target program
The MINERvA Experiment

Heidi Schellman for the MINERvA collaboration
The NuMI Beam Configurations.

- For MINOS, the majority of the running will be in the "low-energy" (LE) configuration.
- Post-MINOS: NOvA would use the ME beam,
- MINERvA would prefer LE (≥ one year) and ME beam
"MINERvA" in the NUMI beamline
MINERvA Physics Goals

- Axial form factor of the nucleon
  - Accurately measured over a wide Q2 range.
- Resonance production in both NC & CC neutrino interactions
  - Study of “duality” with neutrinos
- Coherent pion production
- Strange particle production
- Parton distribution functions (DIS) at high x
- Generalized parton distributions
- Nuclear dependence of all of these
  - Expect some significant differences for ν-A vs e/μ-A nuclear effects
### MINERvA measurements

<table>
<thead>
<tr>
<th>Main CC Physics Topics</th>
<th>Statistics in active target only - CH</th>
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</thead>
<tbody>
<tr>
<td>Quasi-elastic</td>
<td>0.8 M events</td>
</tr>
<tr>
<td>Resonance Production</td>
<td>1.7 M total</td>
</tr>
<tr>
<td>Transition: Resonance to DIS</td>
<td>2.1 M events</td>
</tr>
<tr>
<td>DIS, Structure Funcs. and high-x PDFs events</td>
<td>4.3 M DIS</td>
</tr>
<tr>
<td>Coherent Pion Production</td>
<td>89 K CC / 44</td>
</tr>
<tr>
<td>K NC</td>
<td></td>
</tr>
<tr>
<td>Strange and Charm Particle Production</td>
<td>&gt; 240 K fully reconstructed events</td>
</tr>
<tr>
<td>Generalized Parton Distributions</td>
<td>~ 10 K</td>
</tr>
</tbody>
</table>

All absolute cross section results will be limited by the flux normalization (~5%)
Precision
Quasi Elastic

\[ \sigma(10^{-38} \text{ cm}^2) \]

\[ E_\nu (\text{GeV}) \]

- Fermi Gas, \( C_{12} \), \( E_{\text{BIND}} = 25 \text{ MeV} \)
- FNAL 83, \( D_2 \)
- ANL 77, \( D_2 \)
- BNL 81, \( D_2 \)
- ANL 73, \( D_2 \)
- SKAT 90, \( CF_3Br \)
- GGM 79, \( C_3H_8 \)
- GGM 77, \( CF_3Br \)
- BEBC 1990, \( D_2 \)
- Serpukov 85, \( Al \)

\[ \sigma(10^{-38} \text{ cm}^2) \]

\[ E_\nu (\text{GeV}) \]

- Fermi Gas, \( C_{12} \), \( E_{\text{BIND}} = 25 \text{ MeV} \)
- Minerva, \( C_{12} \)

MINERvA Quasielastic

4/7/2008
A-dependence in $\nu$ scattering

- A dependence observed in $e/\mu$ DIS
- Could be different for neutrinos
  - Presence of axial-vector current.
  - Different nuclear effects for valence and sea
  - Leads to different shadowing for $x F_3$ compared to $F_2$.

If we understand at 10-20 GeV, will that help at 100 GeV? Comparing with JLAB will help.
Large $x$ PDFs from $\nu$ - $p$ Scattering (He designed for H,D)

$F_2^{\nu p} = 2x (d + \bar{u} + s)$

$F_2^{\bar{\nu} p} = 2x (\bar{d} + u + \bar{s})$

At high $x$

$\frac{F_2^{\nu p}}{F_2^{\bar{\nu} p}} = \frac{d}{u}$

Add in...

$xF_3^{\nu p} = 2x (d - \bar{u} + s)$

$xF_3^{\bar{\nu} p} = 2x (-\bar{d} + u - \bar{s})$

$F_2^{\nu p} - xF_3^{\nu p} = 4x\bar{u}$

$F_2^{\bar{\nu} p} + xF_3^{\bar{\nu} p} = 4xu$

Unprecedented valence / sea separation
MINERvA schedule

- MINERvA received DOE critical decision (CD) 3a approval Spring 07
  - Authorization for advanced purchases
  - Beginning purchases for PMT’s, WLS fiber, Clear fiber, PMT box components, steel and lead
- Approved for full construction authorization (CD 3b) Fall 07
  - Included in FY08 Presidential Budget for Department of Energy
  - Construction is beginning
- Detector installation and commissioning in 2009

We’ll bring results to DIS 2010
Project X

Replace the 35 year old LINAC/Booster complex with an 8GeV SC LINAC

8 GeV slow spill
200 kW
2.2E14 protons/1.4 sec

120 GeV fast extraction
2.3 MW
1.7E14 protons/1.4 sec

NOvA initially, DUSEL later?

0.4 GeV Front End
0.4 - 8 GeV ILC style linac
ILC Style 8 GeV H⁻ Linac:
9mA x 1 msec x 5 Hz

Recycler
3 linac pulse/fill

Stripping Foil

Main Injector
1.4 sec cycle

Single turn transfer @ 8 GeV

Flavor and low energy neutrino program
The future: Beam power vs Energy

- **NuMI (MINOS)**
  - what we have now
- **NuMI (NOvA)**
  - near term upgrades
- **SNU MI**
  - big upgrades
- **Project X**
  - replace the whole injection system with an 8 GeV Linac
MINERvA with Hydrogen and Deuterium

Nucleon structure - PDF’s, especially high-x behavior, can be cleanly studied with $\nu/\bar{\nu} H$.

$$F_2^{\nu p} = 2x (d + \bar{u} + s)$$
$$F_2^{pp} = 2x (u + \bar{d} + \bar{s})$$

At high x,

$$\frac{F_2^{\nu p}}{F_2^{pp}} = \frac{d}{u}$$

Combine with other MINERvA measurements ($\nu$He, $\nu$C, $\nu$Fe, $\nu$Pb) to determine neutrino induced nuclear effects.

MINERvA I
Expected CC event samples:
9.0 M $\nu$ events in 3 tons of CH
0.6 M $\nu$ events in He

MINERvA X
Project X Event rates:
Assume $32.0 \times 10^{20}$ protons in ME beam (2 years, 4 years?)
0.6 M $\nu$ events in H
1.2 M $\nu$ events in D
### Conventional neutrino experiments @FNAL

<table>
<thead>
<tr>
<th></th>
<th>Fiducial mass</th>
<th>Energy</th>
<th>POT, x</th>
<th>Technology</th>
<th>Status</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>DONuT</td>
<td>0.3 T</td>
<td>20-300 GeV</td>
<td>0.03</td>
<td>Emulsion</td>
<td>complete</td>
<td>$\tau$ neutrino</td>
</tr>
<tr>
<td>NuTeV</td>
<td>680 T</td>
<td>20-300 GeV</td>
<td>0.03</td>
<td>Iron/Scint</td>
<td>complete</td>
<td>$\theta_w$, DIS, charm</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>440 T</td>
<td>0.3-2 GeV</td>
<td>10</td>
<td>Mineral Oil</td>
<td>running</td>
<td>$\sigma$, anomaly</td>
</tr>
<tr>
<td>SciBooNE</td>
<td>10 T</td>
<td>0.3-2 GeV</td>
<td>2</td>
<td>Scintillator</td>
<td>running</td>
<td>$\sigma$, QE, Coh</td>
</tr>
<tr>
<td>MINOS near</td>
<td>100 T</td>
<td>1-20 GeV</td>
<td>25</td>
<td>Iron/Scint.</td>
<td>running</td>
<td>$\sigma$, QE, Coh, DIS</td>
</tr>
<tr>
<td>Minerva</td>
<td>5T</td>
<td>1-20 GeV</td>
<td>15</td>
<td>Scintillator</td>
<td>2010</td>
<td>$\sigma$, QE, Coh, excl., A dep., DIS</td>
</tr>
<tr>
<td>MicroBoone</td>
<td>50 T</td>
<td>0.3-2 GeV</td>
<td>6</td>
<td>Liquid Argon</td>
<td>Proposal</td>
<td>$\sigma$, QE, Coh, low E excess</td>
</tr>
<tr>
<td>HiResMNu</td>
<td>7.4T</td>
<td>1-20 GeV</td>
<td>120</td>
<td>magnetic tracker</td>
<td>LOI</td>
<td>$\theta_w$, $\sigma$ excl.</td>
</tr>
<tr>
<td>NuSonG</td>
<td>3000 T</td>
<td>20-300 GeV</td>
<td>2</td>
<td>Glass</td>
<td>EOI</td>
<td>$\theta_w$, DIS, A dep.</td>
</tr>
</tbody>
</table>
Drell-Yan scattering:
FNAL E906

\[
\frac{d^2 \sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1 x_2 s} \sum e^2 \left[ \bar{q}_t(x_t) q_b(x_b) + q_t(x_t) \bar{q}_b(x_b) \right]
\]

E906 Detector acceptance chooses \( x_{\text{target}} \) and \( x_{\text{beam}} \).
- Fixed target high \( x_F = x_{\text{beam}} - x_{\text{target}} \)
- Valence Beam quarks at high-\( x \).
- Sea Target quarks at low/intermediate-\( x \).
Extracting $\overline{d}/\overline{u}$ from Drell-Yan Scattering

Ratio of $p,d$ Drell-Yan cross sections

$$\frac{\sigma^{pd}}{2\sigma^{pp}} \bigg|_{x_b \gg x_t} \approx \frac{1}{2} \left[ 1 + \frac{\overline{d}(x_t)}{\overline{u}(x_t)} \right]$$

(Approximation in Leading Order. Data analysis and parton distribution fits confirmed in NLO)

- Global NLO PDF fits which include E866 cross section ratios agree with E866 results
- Fermilab E906/Drell-Yan will extend these measurements and reduce statistical uncertainty.
- E906 expects systematic uncertainty to remain at approx. 1% in cross section ratio.
PANDA @ FAIR

Antiproton Annihilation at Darmstadt @ Facility for Antiproton and Ion Research

- High intensity are Isotope beam
- up 45 GeV/u heavy ion beams for QCD studies
- 15 GeV/c cooled and stored antiproton beam
- Versatile facility serving a multitude of user communities in parallel
High Energy Storage Ring

- antiproton momentum: $1.5 \text{ GeV/c} < p < 15 \text{ GeV/c}$
- Stochastic and electron cooling: $\Delta p/p < 10^{-5}$
- Luminosity: $> 10^{31} \text{cm}^{-2}\text{s}^{-1}$
- Hydrogen pellet or jet target, polarised Hydrogen under study
- Variety of nuclear targets
Physics at PANDA

- Precision Charmonium Spectroscopy
- Time-like Formfactors
- Generalised Distribution Amplitudes
- New Forms of Hadronic matter (hybrids, Glueballs)
- Hypernuclei
- CP Violation in charmed systems
- Medium modifications of mesons
- Non $k_T$ integrated structure functions (Drell Yan)
Time-like Formfactors

- All existing data measure absolute cross section $G_E = G_M$
- PANDA will provide independent measurements of $G_E$ and $G_M$
- Widest kinematic range in a single experiment
- Time-like form factors are complex
- Precision experiments will reveal these structures
Measurement of Sivers Function

- Single polarised transverse target provides measurement of Sivers function
- Sign provides crucial test for QCD and factorisation
- Model predictions based on HERMES data look promising

\[(f_{1T}^{\perp})_{DY} = -(f_{1T}^{\perp})_{DIS}\]

\[A_{N}^{DY} \propto f_{1T}^{\perp}(x_1, k_{1\perp}) \otimes f(x_2)\]
Polarised Physics at PANDA

- Transversely polarised protons increase PANDA physics potential
  - SSA in Drell Yan
  - Phase difference between $G_E$ and $G_M$
- Polarised target inside solenoid very difficult
- Exploit modular upstream design for polarised target with storage cell

Possible target location
In short ...

- **Jefferson Lab at 12 GeV**
  - unique access to large-$x$ region
  - PDFs ($d/u$, $\Delta d$), TMDs, GPDs ($J_u, J_d$), EMC effect
  - CD-3 (start of construction) expected Sep. 2008

- **MINERvA, Project X at Fermilab**
  - PDFs at high $x$, neutrino-nucleus cross sections, neutrino GPDs
  - construction beginning, detector installation 2009

- **PANDA at FAIR**
  - time-like form factors, TMDs in Drell-Yan
  - experiments from 2014
Thank you to speakers, organiser!